Dynamics on Graphs

Rick Durrett

For Tom Liggett, and Harry Kesten
Mentors, colleagues, and friends, now departed

An extensive revision of Random Graph Dynamics
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Preface

Mathematicians are like Frenchmen: whatever you say to them they translate into their own language and forthwith it is something entirely different,

Johann Wolfgang von Goethe

This volume is an extensive rewrite of the 2007 book Random Graph Dynamics. Frankly I wrote that book to learn the subject. The previous version concentrated on the geometry of random graphs and covered a wide variety of examples: Erdős-Rényi random graphs, the configuration model, preferential attachment, small worlds, Chung-Lu model, and the CHKNS model named in honor of the five authors: Duncan Callaway, John Hopcroft, Jon Kleinberg, Mark Newman, and Steve Strogatz.

That book surveyed the then well developed theory of random walks on graphs and touched on the theory that was just beginning to be developed for the voter model and contact process. Fifteen years has brought a lot of progress on the study of interacting particle systems on graphs. Because of this the new version studies a wide variety of dynamics on a small number of graphs, primarily the Erdős-Rényi model, configuration model, and inhomogeneous random graphs, which are covered in the first three chapters. After that we turn to the processes: epidemics, the contact process, random walks and the voter model. The final chapter explores the difficult and still poorly understood subject of evolving networks, where the states of the vertices and the edges in the graph coevolve.

While it is natural to think of this as a book about random graphs, we have been careful to write Dynamics on Graphs, since we will often consider the complete graph and on occasion will consider systems in $d$-dimensional torus because the results are interesting. In fact since random graphs are “infinite dimensional” they often exhibit mean-field behavior in contrast to the more complex behavior on $\mathbb{Z}^d$.

Each chapter has its own set of references. This scheme has the advantage that each chapter has a reference list that is 2-3 pages on the topic, so the reader does not have to look for the reference among a 300 others. There is trouble when a paper is cited in two chapters but (a) this is rare for research papers so we just cite them twice, and (b) to solve the problem that a few references (e.g. the fifth edition of Probability: Theory & Examples) are cited many times, we have made a list of important books and long survey papers at the end of the book. This list of references is both a bug and a feature. As with the chapter reference lists, it allows one to quickly survey the many options for learning about random graphs and related topics in probability theory such as branching processes, martingales,
Markov chains. This list also helps bring home the messages that (i) there are many reasons to be interested in random graphs and (ii) they have been studied from many perspectives.

I have tried (and failed) to write a book that has the style of a good seminar talk. The goal was to focus on the ideas that go into the proofs, and not get bogged down in technical details. In many cases this means we will not give a full proof of the most exciting result in the paper we are discussing. As Tom Liggett once said: a book should not just be a union of papers.

I would like to my coauthors and others who helped me write the material included here: Shankar Bhamidi, Tom Britton, Shirshendu Chatterjee, Alice Ding, Zoe Huang, Nicholas Lanchier, Laurent Ménard, Peter Mucha, David Sivakoff, Dong Yao, the DOMath teams on 2018, 2020, and 2022, and the 2010-2011 SAMSI working groups that studied dynamics on and off networks. Like most mathematicians I have been inspired by the writings of others. That list is very long but I would like to mention David Aldous, Svante Janson, Yuval Peres, Allan Sly, and Remco van der Hofstad.

It is inevitable that the there will be typos and errors. One review of the 2007 version of this book said “You should not trust every proof in this book.” Though I am now retired from Duke, mail sent to rtd@math.duke.edu will for the foreseeable future reach me. While I appreciate corrections, and get a chuckle from snarky comments, I am more enthusiastic to hear suggestions for improvements and to learn about new results.

It has been a long road from growing up in Anniston, Alabama to college at Emory during the Vietnam war era, and in 1973 choosing graduate school in Operations Research at Stanford, since I didn’t want to have to move back home to live with my mom when I couldn’t get a job. After 3 years (supported by an NSF graduate fellowship that paid $300 a month) and 6 papers I did get a job at UCLA. I taught there for 9 years, where I was mentored by Tom Liggett. In 1985 I moved with my wife Susan to Ithaca where we lived for 25 years in a town described as 10 square miles surrounded by reality. We raised two children and I had a front row seat to watch Harry Kesten in prime of his problem solving. I also and experienced his no nonsense mentoring. I once excitedly told him about an idea I had in the middle of the night. He looked at me calmly said “You should have gone back to sleep”. Various forces brought me to Durham in 2010, where again I live on an island of dark blue in a gerrymandered sea of red. An example of the voter model on a random graphs?

Rick Durrett, January 2024
Notation

In general we follow the notation of the paper whose results we are describing. We do this to make it easier for the reader find the missing details. A consequence of this is that the notation can change from section to section.

For concepts from probability theory, the notation will in most cases follow that used in the 5th edition of my graduate probability book, *Probability: Theory and Examples*, referred to here as PTE5. Some basic examples:

If a sequence of random variables *converges in distribution* to \( X \) we write \( X_n \xrightarrow{d} X \).

We use \( \chi \) for the *standard normal distribution*. This notation derives from the fact that the square of a normal has a chi-squared distribution.

We will uses many comparisons or “couplings.” So the concept of stochastic order is important: \( X \leq_d Y \) means that \( P(X \leq z) \geq P(Y \leq z) \) for all \( z \), or equivalently \( Eh(X) \leq Eh(Y) \) for all bounded nondecreasing \( h \). In this case we can define random variables \( X' =_d X \) and \( Y' =_d Y \) so that \( X \leq Y \) (almost surely).

Being a matheamtician, when log is written, it means the natural logarithm. When we need another base \( b \) we will write \( \log_b \).

Like a chameleon I have picked up some of my colors from the literature. You can’t find the phrase in PTE5 but *with high probability* (or w.h.p.) means that the statement holds with a probability that \( \to 1 \) as some parameter often called \( n \to \infty \).

If \( f(t), g(t) > 0 \) then

\[
\begin{align*}
  f(t) &= o(g(t)) \quad \text{or} \quad f \ll g & \text{if} \quad f(t)/g(t) \to 0 \quad \text{as} \quad t \to \infty \\
  f(t) &\sim g(t) & \text{if} \quad f(t)/g(t) \to 1 \quad \text{as} \quad t \to \infty \\
  f(t) &= O(g(t)) & \text{if} \quad f(t)/g(t) \leq C \quad \text{for all} \quad t \\
  f(t) &= \Omega(g(t)) & \text{if} \quad f(t)/g(t) \geq c > 0 \quad \text{for all} \quad t \\
  f(t) &= \Theta(g(t)) & \text{if} \quad c \leq f(t)/g(t) \leq C \quad \text{for all} \quad t
\end{align*}
\]

We have only recently been converted to using the last two, so you may find places where \( O \) is written instead of something more accurate.
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Chapter 1
Erdős-Rényi Random Graphs

In this chapter we will analyze the random graph model introduced by Erdős and Rényi in the late 1950’s. This example has been extensively studied and a very nice account of many of the results can be found in the classic book of Bollobás (2001), where it has been studied by combinatorial methods. In contrast to many other treatments, we mainly rely on methods from probability.

To define the model, we begin with the set of vertices \( V = \{1, 2, \ldots, n\} \). For \( 1 \leq x < y \leq n \) let \( \eta_{x,y} \) be independent \( = 1 \) with probability \( p \) and \( = 0 \) otherwise. Let \( \eta_{y,x} = \eta_{x,y} \). If \( \eta_{x,y} = 1 \) there is an edge connecting \( x \) and \( y \). Here, we will be primarily concerned with situation \( p = \lambda/n \) and in particular with showing that there is a phase transition

- when \( \lambda < 1 \) all of the components are small, with the largest \( O(\log n) \),
- when \( \lambda > 1 \) there is a giant component with \( \sim g(\lambda)n \) vertices, and the second largest component is of size \( O(\log n) \)
- at the critical value \( \lambda = 1 \) the largest components have size \( n^{2/3} \),
- as the reader will learn in sections 1.6 and 1.7, the critical value is surrounded by a critical regime when \( \lambda = 1 + tn^{-1/3} \)

In words, there is a double jump transition: the size of the largest component goes from \( \log n \) to \( n^{2/3} \) to \( n \). The intuition behind this result is that a site has a Binomial(\( n - 1, \lambda/n \)) number of neighbors, which has mean \( \approx \lambda \). To compute the cluster (connected component) containing 1, we set \( I_0 = \{1\} \) let \( I_1 \) be the neighbors of 1, and for \( t \geq 2 \) let \( I_t \) be the vertices in for which the distance \( d(1, x) = t \). In Section 1.2 we will show that when \( t \) is not too large \( Z_t = |I_t| \), is approximately a branching process in which each individual has an average of \( \lambda \) children. If \( \lambda < 1 \) the branching process dies out quickly and all components are small. When \( \lambda > 1 \), the branching process survives with probability \( g(\lambda) \), and all sites with surviving branching processes combine to make the giant component.
1.1 Branching processes

In this section we define branching processes and describe their basic properties. Since \( n \) will be the number of vertices in our graph, we will use \( t \) and \( s \) for our discrete time parameter. Let \( \xi_i^t, i, t \geq 0 \), be i.i.d. nonnegative integer-valued random variables. Define a sequence \( Z_t \), \( t \geq 0 \) by \( Z_0 = 1 \) and

\[
Z_{t+1} = \begin{cases} 
\xi_1^{t+1} + \cdots + \xi_{Z_t}^{t+1} & \text{if } Z_t > 0 \\
0 & \text{if } Z_t = 0
\end{cases}
\]

\( Z_t \) is called a Galton-Watson process. The idea behind the definition is that \( Z_t \) is the number of individuals in the \( t \)th generation, and each member of the \( t \)th generation gives birth independently to an identically distributed number of children. \( p_k = P(\xi_i^t = k) \) is called the offspring distribution.

Lemma 1.1.1. Let \( F_t = \sigma(\xi_i^t : i \geq 1, 1 \leq s \leq t) \) and \( \mu = E \xi_i^t \in (0, \infty) \). Then \( Z_t/\mu^t \) is a martingale w.r.t. \( F_t \).

Proof. Clearly, \( Z_t \) is measurable with respect to \( F_t \), or \( Z_t \in F_t \). Recall, see Theorem 4.1.2 in PTE5, that if \( X = Y \) on \( B \in F \) then \( E(X|F) = E(Y|F) \) on \( B \). On \( \{Z_t = k\} \),

\[
E(Z_{t+1}|F_t) = E(\xi_1^{t+1} + \cdots + \xi_k^{t+1}|F_t) = k\mu = \mu Z_t
\]

Dividing both sides by \( \mu^{t+1} \) now gives the desired result. \( \Box \)

Theorem 1.1.2. If \( \mu < 1 \) then \( Z_t = 0 \) for all \( t \) sufficiently large.

Proof. \( E(Z_t/\mu^t) = E(Z_0) = 1 \), so \( E(Z_t) = \mu^t \). Now \( Z_t \geq 1 \) on \( \{Z_t > 0\} \) so

\[
P(Z_t > 0) \leq E(Z_t; Z_t > 0) = E(Z_t) = \mu^t \to 0
\]

exponentially fast if \( \mu < 1 \). \( \Box \)

The last answer should be intuitive. If each individual on the average gives birth to less than one child, the species will die out. The next result shows that after we exclude the trivial case in which each individual has exactly one child, the same result holds when \( \mu = 1 \).

Theorem 1.1.3. If \( \mu = 1 \) and \( P(\xi_i^t = 1) < 1 \) then \( Z_t = 0 \) for all \( t \) sufficiently large.

Proof. When \( \mu = 1 \), \( Z_t \) is itself a nonnegative martingale, so the martingale convergence theorem, Theorem 4.2.12 in PTE5. implies that \( Z_t \) converges to an a.s. finite limit \( Z_\infty \). Since \( Z_t \) is integer valued, we must have \( Z_t = Z_\infty \) for large \( t \). If \( P(\xi_i^t = 1) < 1 \) and \( k > 0 \) then \( P(Z_t = k \text{ for all } t \geq T) = 0 \) for any \( T \), so we must have \( Z_\infty \equiv 0 \). \( \Box \)

To state the next result we need a definition. For \( \theta \in [0, 1] \), let \( \phi(\theta) = \sum_{k \geq 0} p_k \theta^k \) be the generating function for the offspring distribution \( p_k \).

Theorem 1.1.4. If \( \mu > 1 \) then \( \sigma = P(Z_t > 0 \text{ for all } t) > 0 \). The extinction probability \( \rho = 1 - \sigma \) is the unique solution of \( \phi(x) = x \) with \( x \in [0, 1] \).
1.1. BRANCHING PROCESSES

Figure 1.1: Generating function for the Poisson distribution with mean 1.25. The alternating vertical and horizontal lines illustrate the iteration of the generating function: 

\((0, 0) \rightarrow (0, \theta_1) \rightarrow (\theta_1, \theta_1) \rightarrow (\theta_1, \theta_2) \ldots\) Fixed point \(\rho = 0.62861\).

**Proof.** Differentiating gives for \(\theta < 1\)

\[
\phi'(\theta) = \sum_{k=1}^{\infty} kp_k \theta^{k-1} \geq 0
\]

\[
\phi''(\theta) = \sum_{k=2}^{\infty} k(k-1)p_k \theta^{k-2} \geq 0
\]

So \(\phi\) is increasing and convex, and \(\lim_{\theta \uparrow 1} \phi'(\theta) = \sum_{k=1}^{\infty} kp_k = \mu\). Our interest in \(\phi\) stems from the following facts.

(a) If \(\theta_t = P(Z_t = 0)\) then \(\theta_t = \sum_{k=0}^{\infty} p_k \theta_{t-1}^k = \phi(\theta_{t-1})\)

**Proof of (a).** If \(Z_1 = k\), an event with probability \(p_k\), then \(Z_t = 0\) if and only if all \(k\) families die out in the remaining \(t-1\) units of time, independent events with probability \(\theta_{t-1}^k\). Summing over the disjoint possibilities for each \(k\) gives the desired result. \(\square\)

(b) If \(\phi'(1) = \mu > 1\) there is a unique \(\rho < 1\) so that \(\phi(\rho) = \rho\).

**Proof of (b).** \(\phi(0) \geq 0, \phi(1) = 1,\) and \(\phi'(1) > 1\), so \(\phi(1 - \epsilon) < 1 - \epsilon\) for small \(\epsilon\). The last two observations imply the existence of a fixed point. To see it is unique, observe that \(\mu > 1\) implies \(p_k > 0\) for some \(k > 1\), so \(\phi''(\theta) > 0\) for \(\theta > 0\). Since \(\phi\) is strictly convex, it follows that if \(\rho < 1\) is the smallest fixed point, then \(\phi(x) < x\) for \(x \in (\rho, 1)\). \(\square\)
(c) As \( t \uparrow \infty \), \( \theta_t \uparrow \rho \).

**Proof of (c).** \( \theta_0 = 0 \), \( \phi(\rho) = \rho \), and \( \phi \) is increasing, so induction implies \( \theta_t \) is increasing and \( \theta_t \leq \rho \). Let \( \theta_\infty = \lim \theta_t \). Taking limits in \( \theta_t = \phi(\theta_{t-1}) \), we see \( \theta_\infty = \phi(\theta_\infty) \). Since \( \theta_\infty \leq \rho \), it follows that \( \theta_\infty = \rho \).

Combining (a)–(c) shows \( P(Z_t = 0 \text{ for some } t) = \lim_{t \to \infty} \theta_t = \rho < 1 \).

**Example.** Consider the Poisson distribution with mean \( \lambda \), i.e.,

\[
P(\xi = k) = e^{-\lambda} \frac{\lambda^k}{k!}
\]

In this case \( \phi(s) = \sum_{k=0}^{\infty} e^{-\lambda s} \frac{\lambda^k}{k!} = \exp(\lambda(s - 1)) \) so the fixed point equation is

\[
\rho = \exp(\lambda(\rho - 1)) \tag{1.1.1}
\]

Theorem 1.1.4 shows that when \( \mu > 1 \), the limit of \( Z_t/\mu^t \) has a chance of being nonzero. The next theorem is not the best possible but it suffices for our purposes. For a proof see Example 4.4.9 in PTE5.

**Theorem 1.1.5.** If \( \sum_k p_k > 1 \) and \( \sum k^2 p_k < \infty \) then \( W = \lim Z_t/\mu^t \) is not \( \equiv 0 \).

The ultimate result about this question is due to Kesten and Stigum (1966). For a “conceptual proof” see Lyons, Pemantle, and Peres (1995).

**Theorem 1.1.6.** Suppose that \( \mu = \sum_k Kp_k > 1 \) then \( W = \lim Z_t/\mu^t \) is not \( \equiv 0 \) if and only if \( \sum_{k=1}^{\infty} k \log kp_k < \infty \)

Our next result shows that when \( W \) is not \( \equiv 0 \), it is positive on the set where the branching process does not die out.

**Theorem 1.1.7.** If \( P(W = 0) < 1 \) then \( \{W > 0\} = \{Z_n > 0 \text{ for all } n\} \), i.e., the symmetric difference of the two sets has probability 0.

**Proof.** Let \( r = P(W = 0) \). In order for \( Z_t/\mu^t \) to converge to 0 the limit must be 0 for the branching process started by each of the children in the first generation. Breaking things down according to the number of children in the first generation

\[
r = \sum_{k=0}^{\infty} p_k r^k = \phi(r)
\]

This shows \( r < 1 \) is a fixed point of the generating function and hence \( r = \rho = P(Z_t = 0 \text{ for some } t) \). Clearly, \( \{W > 0\} \subset \{Z_t > 0 \text{ for all } t\} \). Since the two sets have the same probability \( P(\{Z_t > 0 \text{ for all } t\} - \{W > 0\}) = 0 \), which is the desired result.
The limit theorems above describe the growth of the process when it does not die out. Our next question is: what happens in a supercritical branching process when it dies out?

**Theorem 1.1.8.** A supercritical branching process conditioned to become extinct is a subcritical branching process. If the original offspring distribution is \( \text{Poisson}(\lambda) \) with \( \lambda > 1 \) then the conditioned one is \( \text{Poisson}(\lambda \rho) \) where \( \rho \) is the extinction probability.

**Proof.** Let \( T_0 = \inf\{t : Z_t = 0\} \) and consider \( \tilde{Z}_t = (Z_t | T_0 < \infty) \). To check the Markov property for \( \tilde{Z}_t \) note that the Markov property for \( Z_t \) implies:

\[
P(Z_{t+1} = z_{t+1}, T_0 < \infty | Z_t = z_t, \ldots, Z_0 = z_0) = P(Z_{t+1} = z_{t+1}, T_0 < \infty | Z_t = z_t)
\]

To compute the transition probability for \( \tilde{Z}_t \), observe that if \( \rho \) is the extinction probability then

\[
P_x(T_0 < \infty) = \rho^x.
\]

Let \( \tilde{p}(x, y) \) be the transition probability for \( \tilde{Z}_t \). The Markov property implies

\[
\tilde{p}(x, y) = \frac{P_x(Z_1 = y, T_0 < \infty)}{P_x(T_0 < \infty)} = \frac{P_x(Z_1 = y)P_y(T_0 < \infty)}{P_x(T_0 < \infty)} = \frac{p(x, y) \rho^y}{\rho^x}
\]

Taking \( x = 1 \) and computing the generating function

\[
\tilde{\phi}(s) = \sum_{y=0}^{\infty} \tilde{p}(1, y) \theta^y = \rho^{-1} \sum_{y=0}^{\infty} p(1, y)(\theta \rho)^y = \rho^{-1} \phi(\theta \rho)
\]

where \( p_y = p(1, y) \) is the offspring distribution.

\( \tilde{p}_y = \tilde{p}(1, y) \) is the distribution of the size of the family of an individual, conditioned on the branching process dying out. If we start with \( x \) individuals then in \( Z_n \) each gives rise to an independent family. In \( \tilde{Z}_n \) each family must die out, so \( \tilde{Z}_n \) is a branching process with offspring distribution \( \tilde{p}(1, y) \). To prove this formally observe that

\[
p(x, y) = \sum_{j_1, \ldots, j_x \geq 0, j_1 + \cdots + j_x = y} p_{j_1} \cdots p_{j_x}
\]

Writing \( \sum_* \) as shorthand for the sum in the last display

\[
\frac{p(x, y) \rho^y}{\rho^x} = \sum_* \frac{p_{j_1} \rho^{j_1} \cdots p_{j_x} \rho^{j_x}}{\rho} = \sum_* \tilde{p}_{j_1} \cdots \tilde{p}_{j_x}
\]

In the case of the Poisson distribution \( \phi(s) = \exp(\lambda(s - 1)) \) so if \( \lambda > 1 \), using the fixed point equation (1.1.1)

\[
\frac{\phi(s \rho)}{\rho} = \frac{\exp(\lambda(s \rho - 1))}{\exp(\lambda(\rho - 1))} = \exp(\lambda \rho(s - 1))
\]

which completes the proof. \( \square \)
Formula (1.1.2) shows the generating function of a supercritical branching process conditioned to die out is obtained by taking the graph of $\phi$ over $[0, \rho]$ and rescaling to make the domain and range $[0, 1]$.

**Theorem 1.1.9.** Consider a supercritical branching process with offspring distribution $p_k$ and generating function $\phi$. If we condition on nonextinction and look only at the individuals that have an infinite line of descent then the number of individuals in generation $t$, $\tilde{Z}_t$ is a branching process with offspring generating function

$$
\tilde{\phi}(\theta) = \frac{\phi((1 - \rho)\theta + \rho) - \rho}{1 - \rho}
$$

(1.1.3)

where $\rho$ is the extinction probability, i.e., the smallest solution of $\phi(\rho) = \rho$ in $[0, 1]$.

In words, we take the graph of $\phi$ over $[\rho, 1]$ and rescale to make the domain and range $[0, 1]$.

**Proof.** There is nothing to prove if $\rho = 0$ so suppose $0 < \rho < 1$. If $Z_0 = 1$ and we condition on survival of the branching process, then the number of individuals in the first generation who have an infinite line of descent has distribution

$$
\tilde{p}_j = \frac{1}{1 - \rho} \sum_{k=j}^{\infty} p_k \binom{k}{j} (1 - \rho)^j \rho^{k-j}
$$
Multiplying by $\theta^j$, summing, and interchanging the order of summation

$$
\sum_{j=1}^{\infty} \hat{p}_j \theta^j = \frac{1}{1 - \rho} \sum_{j=1}^{\infty} \sum_{k=1}^{\infty} p_k \binom{k}{j} (1 - \rho)^j \rho^{k-j} \theta^j
$$

Using the binomial theorem and noticing that the $j = 0$ term is missing the above

$$
= \frac{1}{1 - \rho} \sum_{k=1}^{\infty} p_k \{(1 - \rho)\theta + \rho\}^k
$$

We can add the $k = 0$ term to the sum since its value is $1 - 1 = 0$. Doing this the result is

$$
\phi((1 - \rho)\theta + \rho) - \phi(\rho)
$$

Since $\phi(\rho) = \rho$ the result follows.

1.2 Cluster growth as a branching process

In this section we use branching process results to study the connected component, or cluster, containing 1. To do this we introduce a process that is the same as a discrete time epidemic. To begin the process, we let $S_0 = \{2, 3, \ldots, n\}$, $I_0 = \{1\}$, and $R_0 = \emptyset$. The letters are motivated by the epidemic interpretation of the growing cluster. $S_t$ are the susceptibles, $I_t$ are infected, and $R_t$ are removed (recovered and immune to further infection). In graph theory terms, we have already examined the connections of all sites in $R_t$, $I_t$ are the sites to be investigated on this turn, and $S_t$ are unexplored. These sets evolve as follows:

$$
R_{t+1} = R_t \cup I_t
$$

$$
I_{t+1} = \{y \in S_t : \eta_{x,y} = 1 \text{ for some } x \in I_t\}
$$

$$
S_{t+1} = S_t - I_{t+1}
$$

(1.2.1)

where $\eta_{x,y} = \eta_{y,x} = 1$ if and only if there is an edge between $x$ and $y$. The cluster containing 1, $C_1 = \cup_{t=0}^{\infty} I_t = R_\infty$.

Kendall (1956) was the first to suggest a branching process approximation for epidemics. We begin with the easy result

**Theorem 1.2.1.** If $\lambda < 1$ then $E|C_1| \leq 1/(1 - \lambda) < \infty$.

**Proof.** To define a comparison branching process we introduce a new independent set of variables $\zeta_{x,y}^t$, $x, t \geq 1$, $1 \leq y \leq n$ that are independent, $= 1$ with probability $\lambda/n$, and 0
otherwise. Let $Z_0 = 1$, $S^c_t = \{1, 2, \ldots, n\} - S_t$ and

$$Z_{t+1} = \sum_{x \in I_t, y \in S_t} \eta_{x,y} + \sum_{x \in I_t} \sum_{y \in S^c_t} \zeta^t_{x,y} + \sum_{x=n+1}^{n+Z_t-|I_t|} \sum_{y=1}^n \zeta^t_{x,y}$$

(1.2.2)

Here, the second term is the set of extra births in the branching process due to the fact that $|S_t| < n$. The third term produces births for these individuals that are in the branching process but not in the epidemic.

It is immediate from the construction that $Z_t$ is a branching process with offspring distribution $\text{Binomial}(n, \lambda/n)$ and it provides an upper bound on the growing cluster $Z_t \geq |I_t|$.

When $\lambda < 1$, $E Z_t = \lambda^t$, so the mean cluster size

$$E|C_1| = E \left( \sum_{t=0}^{\infty} |I_t| \right) \leq \sum_{t=0}^{\infty} \lambda^t = 1/(1 - \lambda)$$

which proves the desired result.

**Theorem 1.2.2.** Suppose $\lambda > 1$ and let $\rho < 1$ be the probability the branching process $Z_t$ dies out. Then the probability vertex 1 belongs to a giant component, one with size $\geq \epsilon n$ for some $\epsilon > 0$, tends to $1 - \rho$ as $n \to \infty$.

In the next section we will give a simpler proof that there is a unique giant component and it has $\sim (1 - \rho)n$ members.

**Proof.** Since $Z_t$ is an upper bound on $I_t$ the probability of a giant component is $\leq 1 - \rho$. To prove the result in the theorem, we want to define a branching process that lower bounds the growing cluster. To be able to control the growth of the branching process we build it using a **breadth-first search**. If the word search sounds strange note that the construction gives an algorithm that can be used to compute the cluster. Modifying the notation used above,

**At time 0,** $A_0 = \{1\}$ is an ordered list of active sites, $U_0 = \{2, \ldots, n\}$ are unexplored sites, and $R_0 = \emptyset$ are removed sites whose neighbors are known.

**At time 1,** $R_0 = \{1\}$, $A_1 = \{y : \eta_{1,y} = 1\}$ and $U_1 = U_0 - A_1$.

**At time 2,** we let $i_2$ be the smallest member of the ordered set $A_1$, let $N_2 = \{y \in U_1 : \eta_{i_2,y} = 1\}$, and let $U_2 = U_1 - N_2$.

**At time m,** if $A_m = \emptyset$ we are done and $R_m$ is the cluster containing 1. If $A_m \neq \emptyset$ we pick the smallest element $i_m$ in this ordered set, let $N_m = \{y \in U_{m-1} : \eta_{i_m,y} = 1\}$, let $U_m = U_{m-1} - N_m$ and $n_m = |N_m|$. To create $A_m$ we put the elements of $N_m$ in increasing order and add them after the current elements of $A_{m-1}$,
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A picture is useful to help explain the definitions.

The branching process is embedded in the breadth first search. Let $Z_0 = 1$ and $Z_1 = n_1$. Define $Y_0 = 1$ and for $m \geq 2$

$$Y_{m-1} = Z_0 + \cdots + Z_{m-1} = Y_{m-2} + Z_{m-1}$$

be the total number of children up to generation $m - 1$, and

$$Z_m = n_{Y_{m-2}+1} + \cdots + n_{Y_{m-1}}$$

To check the definitions in the example, $Y_0 + 1 = 2$ and $Y_1 = Z_0 + Z_1 = 4$, so

$$Z_2 = z_2 + z_3 + z_4 = 2 + 4 + 1 = 7$$

This means $Y_2 = 4 + 7 = 11$ and hence $Z_3 = n_5 + n_6 + \cdots + n_{11}$.

Turning to the proof of Theorem 1.2.2, let $\delta$ be chosen so that $\bar{\lambda} = \lambda(1 - \delta) > 1$. While the total number of offspring $Y_m \leq \delta n$ the number of offspring $n_m$ dominates a binomial$(n, (1 - \delta)\lambda/n) \approx \text{Poisson}(\lambda(1 - \delta))$. The extinction probability of the Poisson branching process satisfies

$$\rho_\delta = \exp(\lambda(1 - \delta)(\rho_\delta - 1))$$

It is easy to see that $\rho_\delta \to \rho$ as $\delta \to 0$. Completing the proof is a little slippery because we need to interchange the limits $\delta \to 0$ and $n \to \infty$ Fix a small value of $\delta$ so that $\rho_\delta < \rho + \eta$. If we let $m(n, \delta)$ be the the number of generations that are completed before the total number of births reaches $\delta n$ then $m(n, \delta) \to \infty$. Since the probability the branching process dies out in the first $k$ generations can be computed by iterating the generating function, it follows that the probability that the Poisson$((1 - \delta)\lambda)$ survives until generation $k$ and then dies out out is $< \eta$ if $k$ is large. \hfill \Box
An important application of breadth first search is the qualitative property “ER clusters are locally tree like.” Let $T_\alpha = \min\{t : U_t \leq n - n^\alpha\}$, and note that at time $m$ when we make connections from $i_m$ to its neighbors we cannot make a connection to a vertex in $R_m$ since we have identified all of their neighbors, but we can make a connection to another member of the set of active vertices $A_m$. If this occurs, an event we call a collision, then we create a loop in the graph and it is no longer a tree.

**Theorem 1.2.3.** The expected number of collisions at times $t < T_\alpha$ is $\lambda n^{2\alpha - 1}$. Taking $\alpha = 1/2 - \epsilon$ this result implies that the cluster will with high probability be a tree until it contains $n^{1/2 - \epsilon}$ vertices.

**Proof.** At times $t < T_\alpha$, $|A_t| \leq n^\alpha$. If $T_\alpha < \infty$ then $T_\alpha \leq n^\alpha$ since at each time we add a vertex to the removed set. These two observations imply that the number of pairs of vertices that can be connected is $n^{2\alpha}$ while the probability a connection is made is $\leq \lambda/n$.

**Remark 1.2.4.** A better upper bound on the probability results if we note that the number of collisions is dominated by a binomial($n^{2\alpha}, \lambda/n$) random variable. In some cases we will need a conclusion that holds for every cluster in the graph. We can do that for Erdős-Rényi graphs by choosing $\alpha$ to be smaller and using the domination by a binomial.

### 1.2.1 Distances on the giant component

The branching process results derived earlier in this section can be used to study the typical distance between two points on the giant component.

**Theorem 1.2.5.** Suppose $\lambda > 1$ and pick two points $x$ and $y$ at random from the giant component. Then $d(x, y)/\log n \to 1/\log \lambda$ in probability.

The answer in Theorem 1.2.5 is intuitive. Consider the cluster growing from 1. The size of the branching process at time $t$ is $\sim \lambda^t W$. When $t = 1 - \epsilon/(\log n)/(\log \lambda)$ only $n^{1-\epsilon}$ can be reached, but when $\epsilon = 0$ the number is $\Theta(n)$.

**Proof.** The lower bound on the distance comes from the last observation and the fact that branching process is an upper bound on the growth of the cluster. To prove the upper bound requires more work since the branching process approximation is not valid out to time $t = (\log n)/\log \lambda$. To get around this difficulty we will grow clusters starting from $x$ and $y$ for time $t(\epsilon, n) = (1/2 + \epsilon)/(\log n)/\log \lambda$. If there were no collisions then the number of offspring is of order $n^{1/2+\epsilon}$. Lemma 1.2.3 implies that the expected number of collisions up to time $t(\epsilon, n)$ is $\lambda n^{2\epsilon}$. When we have a collision we lose not only that vertex but also all of its children. Theorem 1.2.3 shows that with high probability there is no collision before time $(1/2 - \epsilon)/(\log n)/\log \lambda$. I we are conservative and suppose that the clusters of the vertices lost to collisions all have time $2\epsilon(\log n)/\log \lambda$ to grow the number of lost particles is $n^{4\epsilon} \ll n^{1/2+\epsilon}$ if $\epsilon$ is small.

At time $t(\epsilon, n)$ there are two cases to consider: (i) The clusters grown from $x$ and $y$ have already intersected. In this case the distance form $x$ to $y$ is $\leq 2t(\epsilon)$ or (ii) they have not
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If the clusters growth from $x$ and $y$ have not died out and $\delta$ is small then with high probability they will be $\geq \delta n^{1/2+\epsilon}$ active vertices in the growing cluster at time $t(\epsilon, n)$, so the probability they will not intersect on the next step is

\[
\leq \left(1 - \frac{\lambda}{n}\right)^{\delta n^{1/2+\epsilon}} \to 0
\]

which completes the proof.

Dangling ends and the diameter

Our next goal is to show that the diameter $D = \max d(x, y)$ of the giant component in an Erdős-Rényi random graph is larger by a constant factor than the distance between two randomly chosen points on it. To do this we define a dangling end to be a self-avoiding path $v_0, v_1, \ldots, v_{k+1}$ with the degree $d(v_0) = 1$ and $d(v_i) = 2$ for $1 \leq i \leq k$, and $d(v_k) \geq 3$. The final requirement is imposed so that two dangling ends cannot intersect, except possibly at $v_k$. This definition is designed so that the limiting number will be Poisson. To prove this we use the following.

**Lemma 1.2.6.** Let $x^{(k)} = x(x - 1) \cdots (x - k + 1)$ and let $Z_n$ be a sequence of nonnegative integer valued random variables with $EZ_n^{(k)} \to \lambda^k$ for all positive integers $k$. Then $Z_n$ converges in distribution to $Z_{\infty} = \text{Poisson}(\lambda)$.

**Proof.** It is easy to check that if $Z = \text{Poisson}(\lambda)$ then $EZ_{\infty}^{(k)} = \lambda^k$. Since there are constants $c_{k,j}$ so that

\[
x^{k} = \sum_{j=1}^{k} c_{k,j} x^{(j)}
\]

we have $EZ_n^{k} \to EZ_{\infty}^{k}$. The Poisson distribution is determined by its moments so the conclusion follows, see e.g., Section 3.3.5 in PTE5.

**Theorem 1.2.7.** Let $p_1 = e^{-\lambda}\lambda$ and choose $k(n) = \alpha[\log n / \log(1/p_1)]$ so that $c_n = np_k^{k(n)+1}$ stays bounded away from 0 and $\infty$. The number of dangling ends of length $\geq c_n$, $M_n \approx \text{Poisson}(c_n)$. If $\alpha$ is small then $M_n > 0$ with high probability.

**Proof.** To use Lemma 1.2.6 we need to compute the moments of $M = M_n$. Let $A_{(x,y)}$ be the event that there is dangling end $v_0 = x, v_1, \ldots, v_{k+1} = y$. Let $P_{n,k+1} = n \cdot (n - 1) \cdots (n - k)$ be the number of ways to pick the vertices $v_0, \ldots, v_k$

\[
P(\cup_{(x,y)} A_{(x,y)}) \leq \sum_{(x,y)} P(A_{(x,y)}) \sim P_{n,k+1}(\lambda/n)^k(1 - \lambda/n)^{(n-1)k - \left\lfloor \frac{k}{2} \right\rfloor} \cdot q_2
\]

where $q_2 = P(\text{Poisson}(\lambda) \geq 2)$. 

\[\square\]
Our next step is to investigate the second factorial moment \( E[M(M - 1)] \). To simplify the calculation we will ignore the possibility of two that end at the same place, which will not change the order of magnitude. Thus our goal is to compute

\[
\sum_{x \neq w, y \neq z, z \neq x} P(A_{(x,y)} \cap A_{(w,z)})
\]

To construct the two dangling ends let \( v_0 = x, v_1, \ldots, v_k = y \) be the path that produces the first one and let \( u_0 = w, u_1, \ldots, u_k = z \) be the path that produces the second one.

- There are \( P_{m,2(k+1)} \) ways of picking the two sequences. Note that if \( k = O(\log n) \),
  \[
P_{m,2(k+1)}/P_{m,(k+1)}^2 \to 1
\]
- There are \( 2k \) edges that must be present, producing a factor \( (\lambda/n)^{2k} \)
- Ignoring overcounting there are \( 2k(n-1) \) edges that must be vacant. It is tricky to get the countin exactly right but fortunately that is irrelevant. If we are off by something \( \leq ck^2 \) then this is not important since \( (1 - \lambda/n)^{ck^2} \to 1 \) when \( k = O(\log n) \)
- Given the existence of a path satisfying the first two conditions, we have \( d(v_k) \) with probability \( \to q_2 \).

It is straightforward to extend the last argument to show asymptotic independence of \( m \) events for any \( m \).

If \( \alpha \) is small then \( \mu_{\alpha, n} \) is large so with high probability there is at least one dangling end. To show that it is connected to the giant component with positive probability run the cluster growth process starting from \( v_k \) and notice that the only effect of the dangling end is to reduce the number of vertices. If one wants the construction to succeed with high probability replace 3 by a much larger number.

The result we have just proved is not very precise. Riordan and Wormald (2010) have found the exact order. To state the result we will need a fact from Section 1.6, see (1.6.4).

If \( \rho \) is the extinction probability of a Poisson(\( \lambda \)) branching process then

\[
\lambda \rho e^{-\lambda \rho} = \lambda e^{-\lambda}
\]

**Theorem 1.2.8.** Let \( \lambda > 1 \) and \( \lambda_* = \lambda \rho \).

\[
diameter(G(n, \lambda/n)) = \frac{\log n}{\log \lambda} + \frac{2 \log n}{\log(1/\lambda_*)} + O_p(1)
\]

where \( O_p(1) \) denotes a term \( X_n \) with \( P(X_n > K_n) \to 0 \) for any \( K_n \to \infty \).
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The first term on the right is the typical distance between two points while the second gives the contribution of two dangling ends.

There are a large number of results about what happens when $\lambda \to \infty$ at different rates. See Chung and Lu (2001) for details. For example if $\lambda/(\log n) \to \infty$ the diameter is concentrated on at most 2 values while if $\lambda/\log n = c$ then it is concentrated on at most 2, 3, or 4 values if $c > 8$, $c \in (2, 8]$, or $c \in (1, 2]$. In addition there are four other results.

1.3 Cluster growth as a random walk

Although the connection with branching processes is intuitive, it is more convenient technically to grow the cluster by adding the neighbors of one site at a time in order to obtain something that can be approximated by a random walk. In this section we will introduce that approach, use it to prove the existence of a giant component when $p = \lambda/n$ with $\lambda > 1$ and show that as $n \to \infty$ has $\sim (1 - \rho(\lambda))n$ vertices where $\rho(\lambda)$ is the extinction probability for the Poisson$(\lambda)$ branching process.

As in the previous section, we let $R_t$ be the set of removed sites, $U_t$ the unexplored sites and $A_t$ the active sites. However, here we do not need a close connection with a branching process, so we do not need to impose an order on $A_t$. The initial conditions are $R_0 = \emptyset$, $U_0 = \{2, 3, \ldots, n\}$, and $A_0 = \{1\}$. At time $\tau = \inf\{t : A_t = \emptyset\}$ the process stops, and $R_\tau$ is the cluster containing 1. Since one vertex is added to the removed set at each time, there are $\tau$ points in the cluster. If $A_t \neq \emptyset$, pick $i_t$ from $A_t$ according to some rule that is measurable with respect to $A_t = \sigma(A_0, \ldots A_t)$ and let

$$
R_{t+1} = R_t \cup \{i_t\}
$$

$$
A_{t+1} = A_t - \{i_t\} \cup \{y \in U_t : \eta_{i_t,y} = 1\}
$$

(1.3.1)

$$
U_{t+1} = U_t - \{y \in U_t : \eta_{i_t,y} = 1\}
$$

**Upper bound for $\lambda < 1$.** To define a comparison random walk, we introduce a new independent set of variables $\zeta'_y$, $t \geq 1$, $y \leq n$ that are independent, $= 1$ with probability $\lambda/n$, and 0 otherwise. Let $S_0 = 1$ and for $t \geq 0$, let $U'_t = \{1, 2, \ldots, n\} - U_t$

$$
S_{t+1} = S_t - 1 + \left\{ \begin{array}{ll}
\sum_{y \in U_t} \eta_{i_t,y} + \sum_{y \in U'_t} \zeta'_y & \text{if } A_t \neq \emptyset \\
\sum_{y=1}^n \zeta'_y & \text{if } A_t = \emptyset
\end{array} \right.
$$

$S_t$ is a random walk with $S_t \geq |A_t|$ if $t \leq \tau$, so if $T = \inf\{t : S_t = 0\}$ then $\tau \leq T$. We continue the definition after $A_t = \emptyset$ because it is convenient to have the random walk defined for all time.

The increments $X_t = S_t - S_{t-1}$, $t \geq 1$ of the random walk are $-1 + \text{Binomial}(n, \lambda/n)$. If $\lambda < 1$ stopping the martingale $S_t - (\lambda - 1)t$ at the bounded stopping time $T \wedge t$ gives

$$
ES_{T\wedge t} - (\lambda - 1)E(T \wedge t) = ES_0 = 1.
$$
Since $E S_{T_M} \geq 0$, it follows that $E(T \wedge t) \leq 1/(1-\lambda)$. Letting $t \to \infty$ we have $ET \leq 1/(1-\lambda)$. Having verified that $ET < \infty$ we can now use Wald’s equation, see Theorem 4.8.6 in PTE5 to conclude $E(S_T - S_0) = (\lambda - 1)ET$ and hence

$$ET = 1/(1-\lambda).$$  \hfill (1.3.2)

We can get a much better result by using the exponential martingale:

**Theorem 1.3.1.** Suppose $\lambda < 1$ and let $\alpha = \lambda - 1 - \log(\lambda) > 0$. If $a > 1/\alpha$ then

$$P\left(\max_{1 \leq x \leq n} |C_x| \geq a \log n\right) \to 0$$

**Remark.** This bound is very accurate. Corollary 5.11 of Bollobás (2001) shows that the size of the largest component is asymptotically

$$\frac{1}{\alpha} \left(\log n - \frac{5}{2} \log \log n\right) + O(1)$$

**Proof.** We begin by computing the moment generating function of $X_i = -1 + \text{binomial}(n, \lambda/n)$

$$E \exp(\theta X_i) = e^{-\theta}(1 - \lambda/n + (\lambda/n)e^{\theta})^n \leq \exp(-\theta + \lambda(e^{\theta} - 1)) = \psi(\theta)$$  \hfill (1.3.3)

since $1 + x \leq e^x$. Note that the right-hand side is the moment generating function of $-1 + \text{Poisson}(\lambda)$. $\psi'(0) = E X_i = \lambda - 1$ so if $\lambda < 1$ then $\psi(\theta) < 1$ when $\theta > 0$ is small. To optimize we set the derivative

$$\frac{d}{d\theta}(-\theta + \lambda(e^{\theta} - 1)) = -1 + \lambda e^{\theta} = 0$$

which occurs for $\theta_1 = -\log \lambda$. At this point $\psi(\theta_1) = \exp(\log(\lambda) + 1 - \lambda) \equiv e^{-\alpha} < 1$. $\exp(\theta_1 S_t)/\phi(\theta_1)^t$ is a nonnegative martingale, so using the optional stopping theorem for the nonnegative supermartingale $M_t = \exp(\theta_1 S_t)/\psi(\theta_1)^t$, see e.g., Theorem 4.8.4 in PTE5.

$$1/\lambda = e^{\theta_1} \geq E(\psi(\theta_1)^{-T}) = E(e^{\alpha T})$$

Using Chebyshev’s inequality now

$$e^{ka} P(T \geq k) \leq 1/\lambda$$  \hfill (1.3.4)

Letting $C_x$ denote the cluster containing $x$, noting that $T \geq |C_x|$ in distribution, and taking $k = (1 + \epsilon)(\log n)/\alpha$

$$P(|C_x| \geq (1 + \epsilon)(\log n)/\alpha) \leq n^{-(1+\epsilon)/\lambda}$$

from which the desired result follows.
1.3. CLUSTER GROWTH AS A RANDOM WALK

**Lower Bound for** $\lambda > 1$. To get a lower bound on the growth of the cluster let $\hat{U}_t^\delta$ consists of the $(1 - \delta)n$ vertices in $\hat{U}_t$ with the smallest indices. As long as $\hat{A}_t \neq \emptyset$ and $\hat{U}_t \geq (1 - \delta)n$ which corresponds to $|\hat{A}_t| + t \leq n\delta$, we can define

$$
\hat{R}_{t+1} = \hat{R}_t \cup \{j_t\}
$$

$$
\hat{A}_{t+1} = \hat{A}_t - \{j_t\} \cup \{y \in \hat{U}_t^\delta : \eta_{j_t,y} = 1\}
$$

$$
\hat{U}_{t+1} = \hat{U}_t - \{y \in \hat{U}_t^\delta : \eta_{j_t,y} = 1\}
$$

where in this construction $i_t = \min \hat{A}_t$. Since we have reduced the size of $U_t$, we have $|A_t| \geq |\hat{A}_t|$. To define a comparison random walk, we let $W_0 = 1$, let

$$
T_W = \inf\{s : W_s = 0, \text{ or } W_s + s \geq n\delta\}
$$

define

$$
W_{t+1} = W_t - 1 + \begin{cases} \sum_{y \in \hat{U}_t^\delta} \eta_{i_t,y} & \text{if } t < T_W \\ \sum_{y=1}^{n(1-\delta)} \zeta_t^y & \text{if } t \geq T_W \end{cases}
$$

It is easy to see that for $t \leq T_W$, $|\hat{A}_t| = W_t$ so $\tau \geq T_W$.

We will use the new lower bound $W_t$ and the earlier upper bound $S_t$ to prove

**Theorem 1.3.2.** Suppose $\lambda > 1$. There is a constant $\beta$ so that with high probability, there is only one component of the random graph with more than $\beta \log n$ vertices. The size of this component $\sim (1 - \rho(\lambda))n$ where $\rho(\lambda)$ is the extinction probability for the Poisson($\lambda$) branching process.

Here with high probability means that the probability tends to 1 as $n \to \infty$.

![Figure 1.4: Graph of 1 − ρ(λ).](image)
Proof. There are four steps.

Step 1. There is a constant \( \gamma \) so that if \( W_s \geq \gamma \log n \) then the probability \( W_t \) hits 0 at some time \( t \geq s \) is \( \leq n^{-2} \).

Step 2. There is a constant \( \beta \) so that \( P(0 < |A(\beta \log n)| < \gamma \log n) = o(n^{-1}) \).

Step 3. If \( A(\beta \log n) > \gamma \log n \) then with probability \( \geq 1 - \exp(-\eta n^{2/3}) \) we have \( \varepsilon n^{2/3} \leq |A(n^{2/3})| \leq 2\lambda n^{2/3} \). Combined with the first two steps, this shows that with probability \( \to 1 \), all clusters reaching size \( \beta \log n \) will grow to size \( O(n^{2/3}) \) and will intersect producing a giant component.

Step 4. We show that the number of sites \( x \) with clusters \( C_x \) of size \( \geq \beta \log n \) is asymptotically \( (1-\rho)n \). Here the fact that we only have to run the cluster exploration process to time \( \beta \log n \) reduces the dependence between the events \( \{|C_x| \geq \beta \log n\} \) so that we can prove the result by computing second moments and using Chebyshev’s inequality.

Turning to the details of the proofs.

Step 1. The increments generating function of an increment

\[
\phi_\delta(\theta) \leq \exp(-\theta + \lambda(1-\delta)(e^\theta - 1))
\]

Choose \( \delta > 0 \) so that \( \lambda(1-\delta) > 1 \). \( \phi_\delta'(0) = -1 + \lambda(1-\delta) > 0 \) so \( \psi_\delta(-\theta) < 1 \) when \( \theta > 0 \) is small. Since \( \psi_\delta(\theta) \) is convex and tends to \( \infty \) as \( \theta \to \infty \) there is a unique positive solution of \( \phi_\delta(-\theta_\delta) = 1 \). \( M_t = \exp(-\theta_\delta W_t) \) is a nonnegative (super)martingale. We put super in parentheses since it is a martingale but we will only use that it is a supermartingale. Suppose \( W_0 = k \) and let \( T_0 = \inf\{t : W_t = 0\} \). Using Theorem 4.8.4 in PTE5 (the stopping theorem for nonnegative supermartingales) and noting that \( W_t \to \infty \) on \( \{T_0 = \infty\} \) we have

\[
e^{-k\theta_\delta} \geq P_h(T_0 < \infty)
\]

If we take \( k_\delta = (2/\theta_\delta) \log n \) we make the left-hand side \( = n^{-2} \).

Step 2. To control the behavior of \( W_t \) and \( S_t \) with good error bounds we use the following:

Lemma 1.3.3. Let \( Z = X_1 + \cdots + X_t \) where the \( X_i \) are i.i.d. and have \( E \exp(\theta X_i) < \infty \) for \( |	heta| < \theta_0 \). Let \( \mu = EX_s \). if \( b < \mu < a \) then there are constant \( \eta(b), \eta(a) > 0 \) so that

\[
P(Z \geq ta) \leq \exp(-t\eta(a))
\]

\[
P(Z \leq tb) \leq \exp(-t\eta(b))
\]

Proof. These are standard results on large deviations, see Example ??

Let \( X_1, \ldots, X_t \) be i.i.d. \( -1 + \text{binomial}(n, \lambda) \), write \( S_t \) instead of \( Z \). Let \( a = 2\lambda - 1 > \mu = \lambda - 1 \). Using Lemma 1.3.3 there are \( \eta_1, \eta_2 > 0 \) so that

\[
P(S_t \geq (2\lambda - 1)t) \leq \exp(-\eta_1 t)
\]
1.3. CLUSTER GROWTH AS A RANDOM WALK

Let \( r = \beta \log n \) where \( \beta(\lambda - 1)/2 > 2\gamma \) and \( \exp(-\eta_1 \beta \log n) \leq n^{-2} \). When \( |A_r| > 0 \), \( S_t \) has not hit 0 at times \( t \leq r \) so it provides an upper bound on \( A_t \). When \( S_r + r \leq 2\lambda r \) we have \( |U_s| \geq n - 2\lambda r \) for all \( t \leq r \). The number of times that the upper bound process adds a vertex not added to \( A_t \) is at most \( B(r, \lambda) \) which is the sum of \( r \times 2\lambda r \) Bernoulli random variables with success probability \( \lambda/n \).

From this it follows that

\[
P(|A_r| > 0, S_r - |A_r| \geq 2) \leq \left( \frac{2\lambda r^2}{2} \right)(\lambda/n)^2 \leq C \frac{(\log n)^2}{n}
\]

Combining our results

\[
P(0 < |A(\beta \log n)| \leq \gamma \log n) \leq C \frac{(\log n)^2}{n^2}
\]

**Step 3.** Let \( \epsilon_\delta = (\lambda(1-\delta)-1)/2 \). Using Lemma 1.3.3 twice with \( X_i = \text{binomial}((1-\delta)n, \lambda/n) \) we have

\[
P_1(W(n^{2/3}) - W(0) \leq \epsilon_\delta n^{2/3}) \leq \exp(-\eta_2 n^{2/3}) \tag{1.3.8}
\]
\[
P_1(W(n^{2/3}) - W(0) + n^{2/3} \geq 2\lambda n^{2/3}) \leq \exp(-\eta_3 n^{2/3}) \tag{1.3.9}
\]

We take \( W(0) = |A_r| \leq 2\beta \log n \) in (1.3.9). Since \( W_t + t \) is nondecreasing this shows that with probability \( 1 - O(n^{-2}) \), \( W_s + s \leq \delta n \) for all \( s \leq n^{2/3} \), and the coupling between \( W_s \) and \( |A(s + r)| \) remains valid for \( 0 \leq s \leq n^{2/3} \).

The bound in (1.3.8) implies that if a cluster reaches size \( r = \beta \log n \) then the set of active sites at time \( r + n^{2/3} \) is \( \geq \epsilon_\delta n^{2/3} \) with high probability. Thus if we have two such clusters of size \( \geq \beta \log n \) then either (a) they will intersect by time \( r + n^{2/3} \) or (b) at time \( r + n^{2/3} \) they have disjoint sets \( V_1 \) and \( V_2 \) of active sites of size \( \geq \epsilon_\delta n^{2/3} \). The probability of no edge connecting \( V_1 \) and \( V_2 \) is

\[
= \left( 1 - \frac{\lambda}{n} \right)^{\epsilon_\delta n^{4/3}} \leq \exp(-\eta_4 n^{1/3}) \tag{1.3.10}
\]

This proves the first assertion in Theorem 1.3.2.

**Step 4.** To prove the second assertion it suffices to show that

\[
|\{ x : |C_x| \leq \beta \log n \}|/n \to \rho(\lambda) \tag{1.3.11}
\]

The first step is to note that the branching process approach to cluster growth implies

\[
P(|C_x| \leq \beta \log n) \to \rho(\lambda).
\]

To complete the proof we bound the correlation of the random variables \( Y_x = 1 \) if \( |C_x| \leq \beta \log n \) and 0 otherwise and use Chebyshev’s inequality. We isolate the reasoning as
Lemma 1.3.4. Let $F$ be an event that involves exposing $J$ vertices starting at 1, and let $G$ be an event that involves exposing $K$ vertices starting at 2. Then

$$|P(F \cap G) - P(F)P(G)| \leq JK \cdot \frac{2\lambda}{n}$$

Proof. Let $R_t, U_t$ and $A_t$ be the process of exposing the cluster of 1. Introduce independent copies of the basic indicator random variables $\eta_{x,y}$. Let $R'_0 = \emptyset$, $A'_0 = \{2\}$ and $U'_0 = \{1, 2, \ldots, n\} - \{2\}$. If $A'_t \neq \emptyset$, pick $i'_t = \min A'_t$. If $i'_t \notin R_{J \beta \log n}$ let

$$R'_{t+1} = R'_t \cup \{i'_t\}$$
$$A'_{t+1} = A'_t - \{i'_t\} \cup \{y \in U'_t : \eta_{i'_t,y}' = 1\}$$
$$U'_{t+1} = U'_t - \{y \in U'_t : \eta_{i'_t,y}' = 1\}$$  \hspace{1cm} (1.3.12)

However if $i'_t \in R_J$, an event we call a collision, we use $\eta_{i'_t,y}$ instead of $\eta_{i'_t,y}'$. In words if while growing cluster 2 we choose a site that was used in the growth of cluster 1, we use the original random variables $\eta_{x,y}$. Otherwise we use independent random variables. It should be clear from the construction that

$$|P(F \cap G) - P(F)P(G)| \leq P(R_J \cap R'_K \neq \emptyset) \leq JK \cdot \frac{\lambda}{n}$$

which proves the desired result. \hfill \Box

Using Lemma 1.3.4 with $J = K = \beta \log n$, the probability of a collision is at most $\lambda(\beta \log n)^2/n$. Using our bound on the covariance with the formula for the variance of a sum of random variables

$$\var \left( \sum_{x=1}^{n} Y_x \right) \leq n + n(n - 1) \frac{\lambda(\beta \log n)^2}{n} \leq Cn \log n$$

so it follows from Chebyshev’s inequality that

$$P \left( \sum_{x=1}^{n} (Y_x - EY_x) \geq n^{2/3} \right) \leq \frac{Cn \log n}{n^{4/3}} \to 0$$

This proves (1.3.11) and completes the proof of Theorem 1.3.2.

1.4 Long paths

At this point we know that the giant component exists for $\lambda > 1$ and is unique, but we do not know much about what it looks like. Ajtai, Komlós, and Szemeredi (1981) proved that there was a function $\alpha : (1, \infty) \to (0, 1)$ so that the Erdős-Rényi random graph with $\lambda = c/n$ contains a path of length at least $\alpha(c)n$. When we study the contact process on graph this result can be used to give a very easy proof that when $\lambda$ is large enough the contact survives for time $\exp(\theta n)$.
1.4. LONG PATHS

1.4.1. Krivelevich and Sudakov (2012)

have recently given a simple proof based on depth-first search. Given a graph \( G = (V, E) \), which we will assume is undirected the algorithm uses an ordering \( \sigma \) on the vertices of \( V \) and divides them into three disjoint sets that change over time.

\( S \) the set of vertices for which the exploration is complete.

\( T \) is the set of unvisited vertices

(B1) At all stages of the algorithm there are no edges between \( S \) and \( T \).

\( U = V - (S \cup T) \) are the active vertices kept in a stack using a last in, first out data structure.

It follows from the construction and induction that

(B2) the vertices in \( U \) at any time are on a path.

On each step of the algorithm we might have a vertex moves from \( T \) to \( U \) or from \( U \) to \( S \), but on most steps nothing happens. To be precise a step consists of one query - when we inspect the graph to see if there is an edge from \( i \) to \( j \). The edge is present if \( X_{ij} = 1 \) where \( X_{ij} = X_{ji} \) are random variable defined on the edges.

If \( U \neq \emptyset \), we let \( v \) be the vertex at the top of the stack. If \( v \) does not have a neighbor in \( T \) then \( v \) is popped out of \( U \) and added to \( S \). However, for the proof it is important to note that this is not just one step but we have to query “is there an edge from \( v \) to \( x \)?” for all the vertices in \( T \) before we can move the vertex to \( S \).”

If \( v \) has a neighbor in \( T \) then the first one, \( u \), is chosen according to the ordering \( \sigma \). \( u \) is deleted from \( T \) and added to \( U \). It replaces \( v \) as the top vertex in the stack. Again it will take multiple queries to locate the first neighbor in the ordering.

If \( U = \emptyset \), then we have just completed computing one of the components. The algorithm chooses the first vertex in \( T \) according to the ordering \( \sigma \). When \( U \cup T = \emptyset \) all the connected components have been determined. The period of time between two successive emptyings of \( U \) is called an epoch. The length of the peoch is the size of othe corresponding component.

Erdős-Rényi \((n, (1 + \epsilon)/n)\). The \( X_{ij} \) with \( i < j \) are i.i.d. Bernoulli\(((1 + \epsilon)/n)\)

Lemma 1.4.1. Let \( F \) be a set of edges. If \(|F| = cn^2\) then whp

\[
\left| \sum_{ij \in F} X_{ij} - a(1 + \epsilon)n \right| \leq n^{2/3}
\]

Proof. The sum has mean \( c(1 + \epsilon)n \) and variance \( \leq c(1 + \epsilon)n \) so

\[
P\left( \left| \sum_{ij \in F} X_{ij} - c(1 + \epsilon)n \right| \leq n^{2/3} \right) \leq \frac{c(1 + \epsilon)n}{n^{4/3}}
\]

bt Chebyshev’s inequality proving the desired result. \( \square \)
Theorem 1.4.2. If $b < 1/4$ and $\eta > 0$ is small enough then when $\epsilon < \epsilon_0(b, \eta)$ whp Erdős-Rényi $(n, (1 + \epsilon)/n)$ contains a path of length $be^2n$.

Proof. We lower bound the size of $U$ at time $N = \epsilon n^2/2$ and the result follows from (B2).

To make the arithmetic easier we get rid of the explicit choices of constants used previously.

We first show that if $\eta$ is small and $\eta > 2\epsilon$ then $|S_N| \leq \eta n$. Suppose not, and let $t$ be the first time $|S_t| = \eta n$. At that moment

$$|U| \leq 1 + \sum_{s=1}^{t} X_s \leq \epsilon(1 + \epsilon)n/2 - n^{2/3} < \eta n$$

by the Lemma with $c = \epsilon/2$ and the choice of $\eta$. This implies

$$|T| = n - |S| - |U| \geq n(1 - 2\eta) \geq 2n/3$$

At this point the algorithm must have queried all of the edges and found them to be missing but this is impossible.

We now return to time $N$. If $|S| \leq \eta n$ and $|U| \leq \epsilon^2 n$ then we have $T \neq \emptyset$. This means that we are still revealing connected components of $G$. Each positive answer we get resulted in moving a vertex from $T$ to $U$ (some of which may have been later moved to $S$). By the lemma the number of positive answers at that point must be at least $\epsilon(1 + \epsilon)n/2 - n^{2/3}$ and hence we have

$$|S \cup U| \geq \frac{\epsilon n}{2} + 0.5\epsilon^2 n - n^{2/3}$$

If $|U| \leq b\epsilon^2 n$ then

$$|S| \geq \frac{\epsilon n}{2} + (0.5 - b)\epsilon^2 n - n^{2/3}$$

$$|T| = n - |S| - |U| \geq n - |S| - b\epsilon^2 n$$

Using $|S| \leq \eta n$ and then the lower bound on $|S|$ with the fact that $m \to m(n - m)$ is increasing on $[0, n/2]$

$$|S| \cdot |T| \geq |S|(n - |S|) - \eta b\epsilon^2 n$$

$$\geq \left(\frac{\epsilon n}{2} + (0.5 - b)\epsilon^2 n - n^{2/3}\right) \cdot \left(n - \frac{\epsilon n}{2} - (0.5 - b)\epsilon^2 n + n^{2/3}\right) - \eta b\epsilon^2 n^2$$

$$\geq \frac{\epsilon n^2}{2} + (0.5 - b)\epsilon^2 n^2 - \frac{\epsilon^2 n^2}{4} - \eta b\epsilon^2 n^2 - O(\epsilon^3 n^2) - O(n^{5/3})$$

To check the multiplication call the terms in the first parenthesis 1, 2, and 3, and those in the second $w$, $x$, $y$, and $z$. The first term is $1x$, the second $2x$, the third $1y$. $2x$, $(1+2)y$ are $O(\epsilon^3 n^2)$ while terms involving 3 or $z$ are $O(n^{5/3})$ The sum of the second third and fourth terms in the

$$[(0.5 - b) - 0.25 - b\eta]\epsilon^2 n > 0$$

if $b < 1/4$ and $\eta$ is small, so the right hand side is again $> N$ and we have a contradiction. \qed
1.4.2. Enriquez, Faraud, and Ménard (2017)

To quote their abstract, “we show that the profile of the tree constructed by the depth first search algorithm on the giant component of an Erdős-Rényi graph with \( N \) vertices and connection probability \( c/N \) with \( c > 1 \) converges to an explicit deterministic shape.” This makes it possible to prove

**Theorem 1.** Let \( H_N \) be the length of the longest simple path is

\[
\lim_{N \to \infty} \inf H_N/N \geq \rho_c - Li_2(\rho_c)/c
\]

Here \( Li_2(x) \) is the **dilogarithm function** which can be defined as \( \sum_{k=1}^{\infty} z^k/k^2 \) or

\[
Li_2(z) = - \int_0^z \frac{\log(1-t)}{t} dt \tag{1.4.1}
\]

![Graph of \( Li_2(x) \) for 0 \( \leq \) x \( \leq \) 1. Only the first 15 terms of the series were used so the graph is not very accurate when \( x \) is near 1. \( Li_2(1) = \pi^2/6 = 1.645 \)](image)

Their definition of depth-first search is a little different from the previous discussion. At each step we define the following objects. The set \( S_n \) is the set of vertices that have not been visited by time \( n \). The vertices in \( R_n \) have no neighbors in \( S_n \). The algorithm is designed so that at any time \( A_n \) is a path.

- \( A_n \) is an ordered set of **active vertices**.
- \( a_n \) is the last element in \( A_n \)
- \( S_n \) is a set of **sleeping vertices**, previously denoted by \( T \) and called unvisited
- \( R_n = \{1, 2 \ldots n\} - (A_n \cup S_n) \) is a set of **retired vertices**.
Initially $A_0 = \{1\}$, $S_0 = \{2, 3, \ldots, n\}$, $R_0 = \emptyset$.

- If $a_n$ has a neighbor in $S_n$ we set $a_{n+1} = \min\{b \in S_m : \{a_m, b\} \in E_N\}$ where $E_N$ is the set of edges of the graph. $A_{n+1} = A_n \cup \{b\}$ i.e., $b$ is added as the last element of $A_{n+1}$, $S_{n+1} = S_n - \{a_{n+1}\}$, $R_{n+1} = R_n$.

- If $a_n$ has no neighbor in $S_n$ we set $A_{n+1} = A_n - \{a_n\}$. $R_{n+1} = R_n \cup \{a_n\}$.

The process stops at $\tau = \min\{n : A_n = \emptyset\}$. The sequence of vertices $a_n$ is a nearest neighbor walk on $C_1$ the connected component containing 1. The current height of the walker is denoted by $X_n = |A_n| - 1$. This defines a path that starts at 0, has increments in $\{-1, 1\}$ and is nonnegative except at its final value, which is $-1$. This occurs when $\tau = 2|C_1| - 1$ where $|C_1|$ is the number of vertices in the component containing 1.

![Figure 1.6: DFS path 1,4,3,4,7,4,1,8,2,5,2,9,2,8,6,8,1,\emptyset. |C_1| = 9, \tau = 17.](image)

**Scaling limit of DFS**

Since we are primarily interested in the geometry of the giant component, we study the behavior of $X_n$ conditioned on $S$ the event that 1 belongs to the giant component.

**Theorem 2.** Conditional on $S$

$$\lim_{n \to \infty} \frac{X_{\lfloor tN \rfloor}}{N} = h(t)$$

where $h$ is continuous and defined on $[0, 2\rho_c]$. 
To define \( h \) we introduce functions \( f(\rho) \) and \( g(\rho) \) defined on \([0, \rho_c]\) by

\[
f(\rho) = \frac{1}{c} \left[ \log(1 - \rho) - \log(1 - \rho_c) \right] - \frac{1}{c} \left[ \log(1 - \rho) - \log(1 - \rho_c) \right]
\]

\[
g(\rho) = \frac{1}{c} \left[ \log(1 - \rho) - \log(1 - \rho_c) \right]
\]

The graph of \( h \) has an increasing part and a decreasing part which are defined by

\[
(t, h(t))_{0 \leq t \leq f(0)} = (f(\rho), g(\rho))_{0 \leq \rho \leq \rho_c}
\]

\[
(t, h(t))_{f(0) \leq t \leq 2\rho_c} = (f(\rho) + 2\rho[1 - (f(\rho) + g(\rho))/2], g(\rho))_{0 \leq \rho \leq \rho_c}
\]

Theorem 1 is obtained from this by computing the maximum height of the curve given in Theorem 2 which is

\[
g(0) = \frac{1}{c}(-\log(1 - \rho_c) - \log(1 - \rho_c)) = \rho_c - \frac{Li_2(\rho_c)}{c}
\]

where in the second equaity we have use the equation satisfied by the survival probability

\[
1 - \rho_c = \exp(-c\rho_c)
\]

which implies

\[
\frac{\log(1 - \rho_c)}{\rho_c} = -c
\]

To understand the formulas for \( f \) and \( g \) it is useful to have a concrete example. We choose \( c = 1.5 \) since there is a graph in the paper for this value of \( c \). A little computation shows that

\[
\rho_c = 0.58282 \quad Li_2(\rho_c) = 0.701584 \quad \log(1 - \rho_c) = -0.874227
\]

As a check on our computations we note that \( \log(1 - \rho_c)/\rho_c = -1.5 \)

\[
f(0) = \frac{1}{c}[\log(1 - \rho) - 2(-c + 1)] = 0.551565
\]

\[
g(0) = \frac{1}{c}[-Li_2(\rho_c) - \log(1 - \rho_c)] = 0.115102
\]

while \( f(\rho_c) = g(\rho_c) = 0 \)

**Main ideas that lead to the proof**

Let \( \alpha_n = |A_n \cup R_n|/N \) be the fraction of the vertices explored up to time \( n \). The authors say that “it is straightforward to check that \( \alpha_n = (X_n + n)/2N \)” I think they meant to say \( \alpha_n = (X_n + n + 2)/2N \). To prove the revised formula by induction we note that \(|A_0| = 1, |R_0| = 0, X_0 = 0\) so

\[
\alpha_n = 1/N = (X_n + n + 2)/2N
\]

If \( a_n \) has a neighbor in \( S_n \), then \(|R_n|\) does not change while \(|A_n|, X_n, n\) increase by 1. If \( a_n \) does not have a neighbor in \( S_n \), \( a_n \) moves from \( A_n \) to \( R_n \), so \( \alpha_n \) does not change while \( n \) increases by 1 and \( X_n \) decreases by 1.
When $A_n$ shrinks, the evolution of $X_n$ is quite complicated since the walk has returned to a vertex whose neighbors have been partially explored. In contrast when the process visits a vertex $a_n$ for the first time, things are very simple. At such a time the algorithm has never examined the connections between $a_n$ and the vertices of $S_n$, so the number of neighbors of $a_n$ in $S_n$,

$$C(a_n) = \text{binomial}((1 - \alpha_n)N, c/N) \approx \text{Poisson}((1 - \alpha_n)c).$$

This motivates the division of the process into two phases

If $(1 - \alpha_n)c > 1$ then we are “on the way up.” i.e., we are in the increasing part of $h$.

If $(1 - \alpha_n) < c$ then we are “on the way down,” i.e., we are in the decreasing part of $h$.

Since we will be happy with lower bounds on the path length we only have to worry about the way up. However, it turns out that the argument for the way down is very short.

**Renewal times.** The evolution on the way up is simplified by the fact that at some times the path will reach levels that it will no go back below until it begins to go back down. Unfortunately the $\tau_i$ we are about to define are not stopping times in the since of Markov chains. Let $\tau_0 = 0$, and

$$\tau_{i+1} = \inf\{n > \tau_i : X_n = i + 1, \inf\{k : X_{n+k} = i\} > \sqrt{N}\} \wedge 2N$$

It is important to note that at time $\tau_{i+1}$ the process is at height $i + 1$. For the moment ignore the second part of the definition which is needed to take care of problems that can occur when $(1 - \alpha_n)c$ is only a little larger than 1. For this reason we begin with the study of the way up while $(1 - \alpha_n)c > 1 + \eta$ with $\eta$ positive, or what is the same while $\alpha_n < 1 - (1 + \eta)/c$. 

---

Figure 1.7: Graph of $(t, h(t)$ for $0 \leq f(0) \leq 2\rho_c$. The graph looks symmetric but $f(0) = 0.551565$ while $2\rho_c = 2(0.58282)$.
The next result explains our interest in the elapsed time being $> N^{1/2}$. This result is obvious if we notice that the graph with vertex set $S_n$ is Erdős-Rényi($(1 - \alpha_n)N, c/N$). See Theorem 1.3.2 for a crude result or Theorem 1.6.5 for one with an optimal constant

**Lemma 3.** Let $G$ be the event that at every time with $\alpha_n < 1 - (1 + \eta)/c$ the graph $S_n$ has no components between $N^{1/10}$ and $N^{9/10}$ and maximum degree vertex is at most $\log N$. Then

$$\lim_{N \to \infty} P(G) = 1.$$  

Denote by $F_n$ the event that this is the first visit to $a_n$. Conditional on $F_n$ the number of neighbors $C(a_n)$ and clusters of the neighbors $x_1 < \cdots < x_{C(a_n)}$ are independent of the excursions outside $S_n$. When we move from $a_n$ to $x_i$ then we have to explore the entire component of $x_i$ before we return to $a_n$. If the component containing $x_i$ is small ($< N^{1/10}$ this takes time $< 2N^{1/10}$) while if $x_i$ is part of the giant component in $S_n$ the exploration will take time $> 2N^{9/10} > N^{1/2}$ so at the times $\tau_i$ we are exploring the giant component of $S_n$ and we will not return to $x_i$ until we begin to go back down.

**Remark.** If the index of the successful $x_k$ is $k > 1$ then the evolution after $\tau_i$ is not independent of what happened before.

**Grouping the $\tau_i$ based on their height.** Let

$$h_k = \inf \{ i : \alpha_{\tau_i} > k \epsilon \} \quad (1.4.7)$$

For the proof of Lemma 5 it is important to know that

$$h_{k+1} - h_k \text{ is the hitting time of } 2\epsilon N \text{ by the sequence } \tau_{h_{k+1}} - \tau_{h_k} + n\quad (1.4.8)$$

To check this note that $\alpha_n$ only changes by $\pm 1/N$ on each step so

$$2\epsilon N = 2[\alpha(\tau(h_{k+1})) - \alpha(\tau(h_k))]$$

$$= X(\tau(h_{k+1})) + \tau(h_{k+1}) - X(\tau(h_k)) - \tau(h_k)$$

$$= \tau(h_{k+1}) + h_{k+1} - (\tau(h_k) + h_k)$$

In order to have $(1 - \alpha_n)c > 1 + \eta$ we only look at

$$k \leq K = [1 - (1 + \eta)/c]/\epsilon.$$  

The parameter $\alpha$ varies only slightly between two successive $h_k$ so $\tau_{i+1} - \tau_i, h_k \leq i \leq h_{k=1}$ are almost i.i.d. The part of the proof that takes the most work is

**Lemma 4.** There is a constant $C$ so that of $N$ is large enough then for all $i \in [h_k, h_{k+1}]$ with $k \leq K$

$$\frac{2}{\rho(1-k\epsilon)c} - 1 - C\epsilon \leq E[\tau_{i+1} - \tau_i | \tau_i] \leq \frac{2}{\rho(1-k\epsilon)c} - 1 + C\epsilon$$

Being lazy we refer the reader to their paper for the details, and we content ourselves to show how it implies the desired conclusion.
Lemma 5. There is a constant $C$ depending only on $\eta$ so that for every $k \leq K$ with high probability
\[
\epsilon \rho(1-k\epsilon) - C\epsilon^2 \leq \liminf_{N \to \infty} \frac{h_{k+1} - h_k}{N} \leq \limsup_{N \to \infty} \frac{h_{k+1} - h_k}{N} \leq \epsilon \rho(1-k\epsilon) + C\epsilon^2
\]

Proof. Fix $k \leq K$. We are going to construct a martingale involving the sequence $\{\tau_i\}_{h_k \leq i \leq h_{k+1}}$. Recall that on $G$ the sequence $\tau_i$ is a Markov chain and that $h_k$ is a stopping time for it. Indeed as we saw earlier, $\tau_{i+1} - \tau_i$ has an explicit distribution depending only on $\tau_i + i$.

\[
M_n^k = \begin{cases} 
\tau_{h_k + n} - \tau_{h_k} - \sum_{i=0}^{n-1} E(\tau_{h_k+i+1} - \tau_{h_k+i}|\tau_{h_k+i}) & n \leq h_{k+1} - h_k \\
\tau_{h_{k+1}} - \tau_{h_k} - \sum_{i=0}^{h_{k+1}-h_k-1} E(\tau_{h_k+i+1} - \tau_{h_k+i}|\tau_{h_k+i}) & n \geq h_{k+1} - h_k 
\end{cases}
\]

On $G$ the difference $|\tau_{h_k+i+1} - \tau_{h_k+i}| \leq N^{1/10} \log N$ By Lemma 4 for every $i \geq 0$

\[
\frac{2}{\rho(1-k\epsilon)c} - 1 - C\epsilon \leq E[\tau_{h_k+i+1} - \tau_{h_k+i}|\tau_{h_k+i}] \leq \frac{2}{\rho(1-k\epsilon)c} - 1 + C\epsilon
\]

Since the increments of our martingale are bounded we can use

Theorem 1.4.3 (Azuma-Hoeffding inequality.) If $M_k$ is a martingale and $|M_k - M_{k-1}| \leq c_k$ then

\[
P(M_n - M_0 \geq \epsilon) \leq \exp\left(\frac{-\epsilon^2}{2 \sum_{k=1}^{n} c_k^2}\right)
\]

Taking $c_k = N^{1/10} \log N$ and using $n \leq N$ gives

\[
P(M_n^k > N^{3/4}) \leq 2 \exp\left(-\frac{(N^{3/4})^2}{2N(N^{1/10} \log N)^2}\right) \leq C \exp(-N^{1/4})
\]

Therefore by a union bound

\[
P\left(\sup_{n \leq \epsilon N} M_n^k > N^{3/4}\right) \leq \epsilon N \cdot C \exp(-N^{1/4})
\]

and since $K \leq C/\epsilon$

\[
P\left(\sup_{k \leq K} \sup_{n \leq \epsilon N} M_n^k > N^{3/4}\right) \leq CN \exp(-N^{1/4})
\]

This implies that with high probability

\[
|\tau_{h_k+n} - \tau_{h_k} - \sum_{i=0}^{n-1} E(\tau_{h_k+i+1} - \tau_{h_k+i}|\tau_{h_k+i})| < N^{3/4}
\]

so using Lemma 4

\[
n\left(\frac{2}{\rho(1-k\epsilon)c} - C\epsilon\right) \leq \tau_{h_k+n} - \tau_{h_k} + n \leq n\left(\frac{2}{\rho(1-k\epsilon)c} + C\epsilon\right)
\]
Using (1.4.8) we have
\[(h_{k+1} - h_k) \left( \frac{2}{\rho(1-\epsilon)c} - C\epsilon \right) \leq 2N\epsilon \leq (h_{k+1} - h_k) \left( \frac{2}{\rho(1-\epsilon)c} + C\epsilon \right)\]
or rearranging
\[2\epsilon \left( \frac{2}{\rho(1-\epsilon)c} + C\epsilon \right)^{-1} \leq \frac{(h_{k+1} - h_k)}{N} \leq 2\epsilon \left( \frac{2}{\rho(1-\epsilon)c} - C\epsilon \right)^{-1}\]
which gives the desired conclusion.

Proof of Theorem 2. Introducing a superscript \(\epsilon\) to allow us to keep track of the dependence on this parameter, and applying Lemma 5
\[\sum_{i=0}^{k-1} \varepsilon \rho(1-\epsilon)c - C\epsilon^2 \leq \liminf_{N \to \infty} \frac{h_k}{N} \leq \limsup_{N \to \infty} \frac{h_k}{N} \leq \sum_{i=0}^{k-1} \varepsilon \rho(1-\epsilon)c + C\epsilon^2\]
Taking \(k = \lceil u/\epsilon \rceil\)
\[\int_0^u \rho(1-x)c \, dx - C\epsilon^2 \leq \liminf_{N \to \infty} \frac{h_k}{N} \leq \limsup_{N \to \infty} \frac{h_k}{N} \leq \int_0^u \rho(1-x)c \, dx + C\epsilon^2\]
The \(k\) points of the normalized profile \((n/N, X_n/N)\) can be written as
\[\left( \frac{\tau_{h_k}}{N}, \frac{X(\tau_{h_k})}{N} \right) = \left( \frac{\tau_{h_k}}{N}, \frac{h_k}{N} \right) = \left( 2k\epsilon + O(N^{-4/5}) - \frac{h_k}{N}, \frac{h_k}{N} \right)\]
the last equality coming from the fact that on the event \(G\) each increment \(\tau_{i+1} - \tau_i\) is bounded by \(N^{1/10} \log N\). Combining the last two equations we see that as \(N \to \infty\) these \(K\) points are uniformly within \(C\epsilon\) of the following parametrized curve
\[x(u) = 2u - \int_0^u \rho(1-x)c \, dx \quad (1.4.9)\]
\[y(u) = \int_0^u \rho(1-x)c \, dx\]
Finally, (1.4.8) implies
\[\left( \frac{\tau_{h_k} - \tau_{h_k+1}}{N} \right) + \left( \frac{X(\tau_{h_k+1}) - X(\tau_{h_k})}{N} \right) = 2\epsilon\]
and that the slope of the renormalized profile is smaller than 1 in absolute value, we can conclude that the whole renormalized profile stays within \(C\epsilon\) of the curve defined in (1.4.9).
To relate the curve defined in (1.4.9) to the one in (1.4.4) we parametrize the curve by 
\( \rho_{(1-u)c} \) instead of \( u \) and note that 
\[ \log(1 - \rho_{(1-u)c}) = (1 - u)c \rho_{(1-u)c} \] (1.4.10)
which rearranges to
\[ u = 1 + \frac{\log(1 - \rho_{(1-u)c})}{c \rho_{(1-u)c}} = \frac{\log(1 - \rho_{(1-u)c})}{c \rho_{(1-u)c}} - \frac{\log(1 - \rho_c)}{c \rho_c} \]
where we have used (1.4.10). The last calculation shows that \( 2u \) is the last term in (1.4.2).

To complete the proof now we need to show that
\[ \int_{1-u}^{1} \rho_{xc} \, dx = \frac{1}{c} \left[ Li_2(\rho_{(1-u)c}) - Li_2(\rho_c) + \log(1 - \rho_{(1-u)c}) - \log(1 - \rho_c) \right] \]
To do this we note that replacing \( (1-u) \) by \( x \) in (1.4.10) gives
\[ \frac{cp'_{xc}}{1 - \rho_{xc}} = cp_{xc} + c^2 x \rho_{xc} \]
Rearranging the last equation and dividing by \( c \) gives
\[ \int_{1-u}^{1} \rho_{xc} \, dx = \int_{1-u}^{1} \frac{\rho'_{xc}}{1 - \rho_{xc}} - \int_{1-u}^{1} cx \rho_{xc} \]
\[ = \frac{1}{c} \left( \ln(1 - \rho_{(1-\mu)c}) - \ln(1 - \rho_c) \right) - \int_{1-\mu}^{1} \frac{\log(1 - \rho_{xc})}{\rho_{xc}} \rho'_{xc} \, dx \]
where we have used (1.4.10) in the second term. Integrating using the definition of \( Li_2 \) given in (1.4.1) shows that the last term is
\[ -\frac{1}{c} \left( Li_2(\rho_c) - Li_2(\rho_{(1-\mu)c}) \right) \]
We would like to thank Laurent Ménard for taking time to write out the proof and email it to us.

1.5 CLT for the size of the giant component

Up to this point we have been content to study the growth of clusters while they are \( o(n) \).
In this section we will use an idea of Martin-Löf (1986) to follow the random walk approach all of the way to the end of the formation of the giant component and prove a central limit theorem for the size of the giant component.

To avoid the problem caused by the process dying out, it is convenient to modify the rules so that if \( A_t = \emptyset \) we pick \( i_t \in U_t \), and rewrite the recursion as
\[ R_{t+1} = R_t \cup \{i_t\} \]
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\[ A_{t+1} = A_t - \{i_t\} \cup \{y \in U_t : \eta_{i_t,y} = 1\} \]
\[ U_{t+1} = U_t - (\{i_t\} \cup \{y \in U_t : \eta_{i_t,y} = 1\}) \]

In words, when one cluster is finished we pick a new vertex and start exposing its cluster.

When \( A_t = \emptyset \) we subtract \( 1 + \text{Binomial}(|U_t|, \lambda/n) \) points from \( U_t \) versus \( \text{Binomial}(|U_t|, \lambda/n) \) points when \( A_t \neq \emptyset \). However, we will experience only \( O(1) \) failures before finding the giant component, so this difference can be ignored. Let \( \mathcal{F}_t \) be the \( \sigma \)-field generated by the process up to time \( t \). Let \( u^n_t = |U_t| \).

**Lemma 1.5.1.** \( u^n_{[ns]} / n \) converges in distribution to \( u_s \) the solution of

\[ \frac{du_s}{ds} = -\lambda u_s \quad u_0 = 1 \]

and hence \( u_s = \exp(-\lambda s) \).

**Proof.** Let \( \Delta u^n_t = u^n_{t+1} - u^n_t \). If \( A_t \neq \emptyset \) then

\[ E(\Delta u^n_t | \mathcal{F}_t) = -u^n_t \frac{\lambda}{n} \]
\[ \text{var} (\Delta u^n_t | \mathcal{F}_t) = u^n_t \frac{\lambda}{n} \left(1 - \frac{\lambda}{n}\right) \]

If we let \( t = [ns] \) for \( 0 \leq s \leq 1 \) and divide by \( n \) then

\[ E\left( \frac{\Delta u^n_{[ns]}}{n} \bigg| \mathcal{F}_{[ns]} \right) = -u^n_{[ns]} \frac{\lambda}{n} \cdot \frac{1}{n} \]
\[ \text{var} \left( \frac{\Delta u^n_{[ns]}}{n} \bigg| \mathcal{F}_{[ns]} \right) = u^n_{[ns]} \frac{\lambda}{n} \left(1 - \frac{\lambda}{n}\right) \cdot \frac{1}{n^2} \quad (1.5.1) \]

Dividing each right-hand side by \( 1/n \), the time increment in the rescaled process, we see that \( \Delta u^n_{[ns]} \) has

infinitesimal mean \( = -u^n_{[ns]} \frac{\lambda}{n} \)

infinitesimal variance \( = u^n_{[ns]} \frac{\lambda}{n} \left(1 - \frac{\lambda}{n}\right) \cdot \frac{1}{n} \)

Letting \( n \to \infty \), the infinitesimal variance \( \to 0 \), so the result follows from the degenerate case of Theorem 4.1 in Section 7.4 of Ethier and Kurtz (1986) in which the infinitesimal variance is 0. \( \square \)

The last proof is simple and intuitive, but may be too sophisticated for some reader’s tastes, so we now give
Alternative Proof. The calculations above show that

\[ M_t^n = \left(1 - \frac{\lambda}{n}\right)^{-t} u_t^n/n \]

is a martingale with

\[ E(M_t^n - M_0^n)^2 = \sum_{s=0}^{t-1} E(M_{s+1}^n - M_s^n)^2 \]

\[ \leq \sum_{s=0}^{t-1} \left(1 - \frac{\lambda}{n}\right)^{-s+1} \frac{\lambda/n^2}{\lambda/n^2} \to 0 \]

so by Kolmogorov’s maximal inequality

\[ E \left( \max_{0 \leq s \leq n} (M_s^n - M_0^n)^2 \right) \to 0 \]

Since \( M_0^n = 1 \), this says that when \( n \) is large \( M_s^n \approx 1 \) uniformly in \( s \), so \( u_{[ns]}^n/n \approx (1 - \lambda/n)[ns] \to e^{-\lambda s} \).

To determine the size of the giant component, we note that when \( u_t^n + r_t^n = n \), \( A_t = \emptyset \). This may occur several times for small \( t \) while we are searching for the giant component, but the solution we are looking for is the first occurrence after an excursion of \( O(n) \). To locate roughly the time at which this occurs, we note that scaling \( r_t^n = |R_t| \equiv t \) as we did \( u_t^n \), \( r_{[ns]}^n/n \to s \). (Here and for the rest of this section we will use \( t \) for the original integer time scale and \( s \in [0,1] \) for rescaled time.) After scaling

\[ u_t^n + r_t^n = n \quad \Rightarrow \quad e^{-\lambda s} + s = 1 \]

Solving we have \( 1 - s = \exp(\lambda((1 - s) - 1)) \), which is the fixed point equation for the extinction probability, \( 1 - s \). As the graph in Figure 1.8 shows \( e^{-\lambda s} + s > 1 \) for \( s > 1 - \rho \), so we are interested only in \( u_{[ns]}^n/n \) for \( 0 \leq s \leq 1 - \rho + \epsilon \). In this part of the process we first generate a geometrically distributed number of small clusters and then find the giant component.

Consider now \( y_{[ns]}^n = (u_{[ns]}^n - n \exp(-\lambda s))/\sqrt{n} \) for \( 0 \leq s \leq 1 - \rho \).

**Lemma 1.5.2.** As \( n \to \infty \), \( y_{[ns]}^n \) converges in distribution to a normal with mean 0 and variance \( e^{-\lambda s} - e^{-2\lambda s} \).

**Proof.** If \( A_{[ns]} \neq \emptyset \) then using the formulas in (1.5.1)

\[ E(\Delta y_{[ns]}^n | \mathcal{F}_{[ns]} ) = -\frac{1}{\sqrt{n}} \left( -u_{[ns]}^n \cdot \frac{\lambda}{n} - n \exp(-\lambda s)(\exp(-\lambda/n) - 1) \right) \]
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Figure 1.8: Example of Lemma 1.5.1 with $\lambda = 2$.

\[
\sim -\frac{\lambda}{n} \left( \frac{u_{[ns]}^n - n \exp(-\lambda s)}{\sqrt{n}} \right) = -\lambda y_{[ns]}^n \cdot \frac{1}{n}
\]

\[
\text{var} (\Delta y^n_{[ns]} | \mathcal{F}_{[ns]}) = \text{var} \left( \frac{\Delta u_{[ns]}^n}{\sqrt{n}} \right) = \frac{1}{n} \cdot \frac{\lambda}{n} \cdot \frac{1}{n} \left( 1 - \frac{\lambda}{n} \right) \sim \lambda e^{-\lambda s} \cdot \frac{1}{n}
\]

Using Theorem 4.1 in Section 7.4 of Ethier and Kurtz (1986), we see that $y_{[ns]}^n$ converges in distribution to the solution of the following stochastic differential equation.

\[
dy_s = -\lambda y_s \, ds + \sqrt{\lambda e^{-\lambda s}} \, dB_s \quad y_0 = 0
\]

The solution to this equation is

\[
y_s = \int_0^s e^{-\lambda (s-r)} \sqrt{\lambda e^{-\lambda r}} \, dB_r \quad (1.5.2)
\]

To check this, note that if one continuously invests an amount $g_s$ in an exponentially decaying stock market then your net wealth $x_s$ satisfies

\[
\frac{dx_s}{ds} = -\lambda x_s + g_s
\]

Since computation of interest is linear, each amount decays exponentially from its date of investment, and this differential equation has solution

\[
x_s = \int_0^s e^{-\lambda (s-r)} g_r \, dr
\]
Readers who want a more rigorous proof can use stochastic calculus to check this.

Since the integrand in the stochastic integral (1.5.2) is deterministic, \( y_s \) has a normal distribution with mean 0 and variance

\[
\int_0^t \exp(-2\lambda(s-r))\lambda e^{-\lambda r} \, dr = e^{-2\lambda s} \int_0^s \lambda e^{\lambda r} \, dr = e^{-\lambda s} - e^{-2\lambda s}
\]

which proves the result. To prove the fact about the stochastic integral note that any approximating sum has a normal distribution and then pass to the limit.

**Remark.** Again if one wants to avoid stochastic calculus, the theorem can be proved by applying the martingale central limit theorem to

\[
M^n_t - M^n_0 = \left(1 - \frac{\lambda}{n}\right) u^n_t / n - 1
\]

The key observation is that

\[
\sum_{r=0}^{[ns]-1} E((M^n_{r+1} - M^n_r)^2 | \mathcal{F}_r) \to \int_0^s \lambda e^{\lambda u} \, du = e^{\lambda s} - 1
\]

i.e., the quadratic variation has a deterministic limit. Multiplying the martingale by \( e^{-\lambda s} \), multiplies the variance by \( e^{-2\lambda s} \) and we arrive at the same limit as before.

We have analyzed the fluctuations of \( u^n_{[ns]} \). To determine the fluctuations of the point where \( u^n_t + t = n \), we can now prove the result as we do the central limit theorem of renewal theory. To briefly recall that approach, let \( \xi_1, \xi_2, \ldots \) be i.i.d. positive random variables with \( E\xi_i = \mu \) and \( \text{var} (\xi_i) = \sigma^2 \in (0, \infty) \). Let \( T_n = \xi_1 + \cdots + \xi_n \) and \( N(t) = \inf \{ n : T_n > t \} \). The central limit theorem implies

\[
T_n \approx n\mu + \sigma \sqrt{n} \chi
\]

where \( \chi \) is a standard normal. Setting \( n = t/\mu \)

\[
T_{t/\mu} \approx t + \sigma \sqrt{\frac{t}{\mu}} \chi
\]

If \( \chi > 0 \) then \( N(t) < t/\mu \). The law of large numbers implies \( T_n - T_m \approx (n - m)\mu \) when \( n - m \) is large so we will have

\[
\frac{t}{\mu} - N(t) \approx \frac{\sigma}{\mu} \sqrt{\frac{t}{\mu}} \chi
\]

The same reasoning applies in the current situation. Taking \( s = 1 - \rho \) in Lemma 1.5.2 and letting \( Z \) denote a normal with variance \( e^{\lambda(1-\rho)} - e^{-2\lambda(1-\rho)} \) we have

\[
u^n_{[n(1-\rho)]} \approx n \exp(-\lambda(1 - \rho)) + \sqrt{n} Z \quad (1.5.3)
\]
$A_{[ns]} = \emptyset$ when $u^n_{[ns]} = n - [ns]$. To find out when this occurs, we suppose equality holds at $s_0 = (1 - \rho) + \mathcal{Y}/\sqrt{n}$. Using (1.5.3) and noting $s_0 \to (1 - \rho)$ as $n \to \infty$

$$n \exp(-\lambda((1 - \rho) + \mathcal{Y}/\sqrt{n})) + \sqrt{n} \mathcal{Z} = u^n_{[n s_0]} = n - [n s_0]$$

or rearranging

$$\exp(-\lambda s_0) - 1 + s_0 = -\sqrt{\mathcal{Z}/n}$$

Let $h(t) = e^{-\lambda t} - 1 + t$ which is $= 0$ at $t = 1 - \rho$. $h'(t) = -\lambda e^{-\lambda t} + 1$, so we can write the above as

$$h'(1 - \rho) \mathcal{Y}/\sqrt{n} \approx -\sqrt{\mathcal{Z}/n}$$

or $\mathcal{Y} \approx \mathcal{Z}/h'(1 - \rho)$. $h'(1 - \rho) = 1 - \lambda \rho$. Putting the pieces together.

**Theorem 1.5.3.** Suppose $\lambda > 1$. The size of the largest component $\mathcal{C}^{(1)}$ satisfies

$$\frac{|\mathcal{C}^{(1)}| - n(1 - \rho)}{\sqrt{n}} \Rightarrow \chi$$

where $\Rightarrow$ means convergence in distribution and $\chi$ has a normal distribution with mean 0 and variance $(\rho - \rho^2)/(1 - \lambda \rho)^2$.

For other approaches to this result see Pittel (1990) and Barraez, Boucherno, and Fernandez de la Vega (2000). To compare variances note that Pittel’s $c = \lambda$ and $T = \rho/\lambda$.

### 1.6 Combinatorial approach

Combinatorial methods give more refined results about the Erdős-Rényi model. However, we first need some graph theoretic preliminaries about the nature of components. It is easy to see by using induction that a tree with $k$ vertices has $k - 1$ edges. We call a graph with $k$ vertices and $k$ edges, a **unicyclic graph**, since it will have exactly one cycle, i.e., a path of adjacent vertices $x_0, x_1, \ldots, x_k = x_0$, and $x_j \neq x_0$ for $1 \leq j < k$. We call a graph with $k$ vertices and $k + \ell$ edges with $\ell \geq 1$ a **complex component** with complexity $\ell$. Section 5.4 of Bollobás (2001) gives combinatorial results for unicyclic and complex components. In Section 1.7 we will use Adlous’ result give some results about much less explicit results about complex components in the critical regime. See Theorem 1.7.5. Repeating the proof of Theorem 1.2.3

**Lemma 1.6.1.** Let $A < \infty$ be a constant, and consider only “small” components with $\leq A \log n$ vertices. The probability a small components is unicyclic is $\leq (A \log n)^2/n$. The probability a small component has complexity $\ell \geq 1$ is $\leq (A \log n)^3/n^2$.

**Proof.** We run breadth-first search for $\leq A \log n$ steps and have a probability of collision of $\leq (A \log n)/n$ on each step. The probability of at least one collision is $\leq (A \log n)^2/n$, while
the probability of two collisions is bounded above by the expected number of pairs of steps on which collisions occur which is

\[ \leq \left( A \log n \right) \left( A \log n/n \right)^2 \]

which proves the desired result.

**Theorem 1.6.2.** *Complex components are rare unless \( \lambda \) is close to 1.*

*Proof.* Theorem 1.3.1 implies that if \( \lambda < 1 \) there is a \( C_\lambda \) so that with high probability the largest component is \( \leq C_\lambda \log n \). Theorem 1.3.2 implies that if \( \lambda > 1 \) there is a \( \beta_\lambda \) so that with high probability the second largest component is \( \leq \beta_\lambda \log n \). Lemma 1.6.1 implies that when the largest component is \( \leq A \log n \) then with high probability there are no complex components. The expected number of unicyclic components is \( \leq (A \log n)^2 \). In this section we are interested in the fraction of clusters that have size \( k \) so we can also ignore unicyclic components.

Theorem 1.6.2 implies that for fixed \( \lambda \neq 1 \), we can restrict our attention to tree components. In 1889 Cayley showed that there are \( k^{k-2} \) trees with \( k \) labeled vertices. When \( p = \lambda/n \) the expected number of trees of size \( k \) present is

\[
\left( \frac{n}{k} \right) k^{k-2} \left( \frac{\lambda}{n} \right)^{k-1} \left( 1 - \frac{\lambda}{n} \right)^{k(n-k) + \binom{k}{2} - (k-1)} \tag{1.6.1}
\]

since each of the \( k-1 \) edges in the tree needs to be present and there can be no edges connecting its \( k \) vertices to its complement or any other edges connecting the \( k \) vertices. For fixed \( k \), we can drop \( -k^2 + \binom{k}{2} - k + 1 \) from the exponent of the last term and the above is asymptotic to \( nq_k \) where

\[
q_k = k^{k-2} \frac{\lambda^{k-1} e^{-\lambda k}}{k!} \tag{1.6.2}
\]

Recalling that in the subcritical regime cluster sizes have the same distribution as the total progeny in a Poisson(\( \lambda \)) branching process, we get the following corollary, which is "well-known," but not easy to prove directly from the definition of the branching process:

**Corollary 1.6.3.** *The probability distribution of the total progeny \( \tau \) of a Poisson(\( \lambda \)) branching process with \( \lambda < 1 \) is given by

\[
P(\tau = k) = kq_k = \frac{1}{\lambda} \frac{k^{k-1}}{k!} (\lambda e^{-\lambda})^k \tag{1.6.3}
\]

There is an extra factor of \( k \) due to the fact that a tree of size \( k \) is \( C_x \) for \( k \) values of \( x \).

This distribution was first discovered by Borel in 1942. It is called the Borel-Tanner distribution, since Tanner (1961) showed that when \( \lambda < 1 \) it gave the distribution of the total number of customers served in the first busy period of a queue with Poisson rate \( \lambda \) arrivals and service times always equal to 1. Of course, this becomes a branching process if we think of the customers that arrive during a person’s service time as their children.
1.6. COMBINATORIAL APPROACH

1.6.1 Super/subcritical duality

Suppose \( \lambda > 1 \) and let \( \rho \) be the extinction probability for the branching process with a Poisson(\( \lambda \)) offspring. The title of this subsection refers to the fact that there is a close relationship between Erdős-Rényi random graphs with mean degrees \( \lambda > 1 \) and \( \lambda \rho < 1 \).

Using the fixed point equation \( \rho = e^{\lambda (\rho - 1)} \) for the extinction probability \( \rho \) gives

\[
\lambda \rho e^{-\lambda \rho} = \lambda e^{\lambda (\rho - 1)} e^{-\lambda \rho} = \lambda e^{-\lambda} \tag{1.6.4}
\]

Let Erdős-Rényi(\( n, p \)) denote an Erdős-Rényi graph with \( n \) vertices and edges present with probability \( p \). Let \( m = n \rho \) and consider Erdős-Rényi(\( m, \lambda \rho \)) an Erdős-Rényi graph with number of vertices equal to the number of vertices in non-giant components of Erdős-Rényi(\( n, \lambda / n \)). Changing variables in (1.6.2) we see that

\[
\frac{m}{\lambda \rho} k^{k-2} (\lambda \rho e^{-\lambda \rho})^k = \frac{n}{\lambda} k^{k-2} (\lambda e^{-\lambda})^k
\]

In words, the expected number of trees of size \( k \) is the same in Erdős-Rényi(\( m, \lambda \rho / m \)) and Erdős-Rényi(\( n, \lambda / n \)). Changing variables in the same way in (1.6.3)

\[
\frac{1}{\lambda \rho} k^{-1} (\lambda \rho e^{-\lambda \rho})^k = \frac{1}{\lambda} k^{-1} (\lambda e^{-\lambda})^k \cdot \frac{1}{\rho}
\]

In words, the total progeny of a Poisson(\( \lambda \)) branching process conditioned on extinction is the same as that of a Poisson(\( \lambda \rho \)) branching process, which is Theorem 1.1.8.

(1.6.2) is a result about the expected number of trees. The next result is a law of large numbers, which says that the actual number is close to the expected value.

**Theorem 1.6.4.** Let \( T_k^n \) be the number of tree components of size \( k \) in the Erdos-Renyi graph with \( n \) vertices. As \( n \to \infty \), \( T_k^n / n \to q_k \) in probability, where \( q_k \) is defined in (1.6.2)

**Proof.** This proof comes from Bollobás (2001), 106–107. The expected number of ordered pairs of tree components of size \( k \) (with the second tree different from the first) is

\[
\left(\begin{array}{c} n \\ k \end{array}\right) k^{k-2} \left(\frac{\lambda}{n}\right)^{k-1} \left(1 - \frac{\lambda}{n}\right)^{k(n-k)+(\binom{k}{2})-k+1} \\
\left(\begin{array}{c} n-k \\ k \end{array}\right) k^{k-2} \left(\frac{\lambda}{n}\right)^{k-1} \left(1 - \frac{\lambda}{n}\right)^{k(n-2k)+(\binom{k}{2})-k+1}
\tag{1.6.5}
\]

The second formula differs from the first only in two places: first we have only \( n-k \) vertices to choose from, and the first term already takes into account the fact that there are no connections from the first tree to the second. Since \( \binom{n-k}{k} \leq \binom{n}{k} \) the above is

\[
\leq (ET_k)^2 \left(1 - \frac{\lambda}{n}\right)^{-k^2} \leq (ET_k)^2 e^{\lambda k^2 / n}
\]
From this we get
\[ \text{var} (T_k) = E(T_k(T_k - 1)) + ET_k - (ET_k)^2 \leq ET_k + (ET_k)^2 (e^{\lambda k^2/n} - 1) \]

Using Chebyshev’s inequality
\[ P(|T_k - ET_k| \geq n^{2/3}) \leq \frac{ET_k + (ET_k)^2 (e^{\lambda k^2/n} - 1)}{n^{4/3}} \rightarrow 0 \]
since \( ET_k \sim nq_k \) and \( e^{\lambda k^2/n} - 1 \sim \lambda k^2/n \). This gives the desired result. Note that we could replace \( n^{2/3} \) in the last display by \( \omega(n)n^{1/2} \) where \( \omega(n) \rightarrow \infty \) as \( n \rightarrow \infty \).

The results above allow us to verify the remark we made about the largest non-giant component for \( \lambda > 1 \).

**Theorem 1.6.5.** Suppose \( \lambda > 1 \) and let \( C^{(2)} \) be the second largest component. If \( \alpha = \lambda - 1 - \log \lambda \) and \( a > 1/\alpha \) then as \( n \rightarrow \infty \)
\[ P \left( |C^{(2)}| \geq a \log n \right) \rightarrow 0 \]

**Proof.** For simplicity we will do our calculations for the limit (1.6.2) rather than for the exact formula (1.6.1). Stirling’s formula tells us that
\[ k! \sim k^{k+1/2}e^{-k}\sqrt{2\pi} \quad \text{as} \quad k \rightarrow \infty \quad (1.6.6) \]
so we have (Lemma 1.6.6 will show this is valid for \( k = o(n^{1/2}) \))
\[ q_k = \frac{1}{\lambda} \cdot \frac{k^{k-2}}{k!} (\lambda e^{-\lambda})^k \sim \frac{1}{\lambda \sqrt{2\pi}} k^{-5/2} (\lambda e^{1-\lambda})^k \]

Now \( g(\lambda) \equiv \lambda e^{1-\lambda} = 1 \) when \( \lambda = 1 \) and \( g'(\lambda) = (1 - \lambda)e^{1-\lambda} \). Thus \( g(\lambda) \) is increasing for \( \lambda < 1 \), decreasing for \( \lambda > 1 \), and has \( g(\lambda) < 1 \) when \( \lambda \neq 1 \). Summing and using the fact that \( k^{-5/2} \) is decreasing and \( \lambda e^{1-\lambda} < 1 \)
\[ Q_K = \sum_{k=K}^{\infty} q_k \sim \frac{1}{\lambda \sqrt{2\pi}} K^{-5/2} (\lambda e^{1-\lambda})^K \]

Taking \( K = a \log n \)
\[ (\lambda e^{1-\lambda})^{a \log n} = \exp((\log \lambda - \lambda + 1)a \log n) = n^{-(1+\epsilon)} \]
when \( a = (1 + \epsilon)/\alpha \), which proves the desired result.
1.6. COMBINATORIAL APPROACH

1.6.2 Cluster sizes near criticality

In the next section we will use weak convergence to look at component sizes near \( \lambda = 1 \). Here we will use combinatorics to derive some results. We begin with a calculation that is simple and gives the right answer, but is not completely rigorous. (1.6.2) tells us that the expected number of trees of size \( k \) is, for large \( k \),

\[
n \frac{k^{k-2}}{k!} \lambda^{k-1} e^{-\lambda k} \sim \frac{n}{\lambda \sqrt{2\pi}} k^{-5/2} (\lambda e^{1-\lambda})^k.
\]

By Stirling’s formula

\[
k! \sim k^k e^{-k} \sqrt{2\pi k}
\]

When \( \lambda = 1 \), \( \lambda e^{1-\lambda} = 1 \) so summing from \( k = K \) to \( \infty \), the expected number of tree of size \( \geq K \) is

\[
\sum_{k=K}^{\infty} \frac{n}{\sqrt{2\pi}} k^{-5/2} \sim \frac{2}{3\sqrt{2\pi}} nK^{-3/2}
\]

This is small when \( K > > n^{2/3} \) suggesting that the largest tree components are of order \( n^{2/3} \).

Having figured out what to guess, we will now go back and do the calculation carefully. For the moment \( \lambda \) is a general parameter value, which you should think of as being close to 1.

**Lemma 1.6.6.** Let \( \alpha(\lambda) = \lambda - 1 - \log(\lambda) \). If \( k \to \infty \) and \( k = o(n^{3/4}) \) then the expected number of tree components of size \( k \) in an Erdős-Rényi graph with \( n \) vertices

\[
\gamma_{n,k}(\lambda) \sim n \cdot \frac{k^{-5/2}}{\lambda \sqrt{2\pi}} \exp \left(-\alpha(\lambda)k + (\lambda - 1) \frac{k^2}{2n} - \frac{k^3}{6n^2} \right)
\]

**Proof.** (1.6.1) tells us that

\[
\gamma_{n,k}(\lambda) = \left( \frac{n}{k} \right) k^{k-2} \left( \frac{\lambda}{n} \right)^{k-1} \left( 1 - \frac{\lambda}{n} \right)^{k(n-k)+(\frac{k}{2})-k}
\]

Using Stirling’s formula (1.6.8) and \( k = o(n) \) in the last exponent gives

\[
\gamma_{n,k}(\lambda) \sim n \left[ \prod_{j=1}^{k-1} \left( 1 - \frac{j}{n} \right) \right] \cdot \frac{k^{-5/2}}{e^{-k} \sqrt{2\pi}} \cdot \lambda^{k-1} \left( 1 - \frac{\lambda}{n} \right)^{kn-k^2/2}
\]

Using the expansion \( \log(1-x) = -x - x^2/2 - x^3/3 - \ldots \) we see that if \( k = o(n) \) then

\[
\left( 1 - \frac{\lambda}{n} \right)^{kn-k^2/2} \sim \exp(-\lambda k + \lambda k^2/2n)
\]

while if \( k = o(n^{3/4}) \) we have

\[
\prod_{j=1}^{k-1} \left( 1 - \frac{j}{n} \right) = \exp \left(-\frac{1}{n} \sum_{j=1}^{k-1} j - \frac{1}{2n^2} \sum_{j=1}^{k-1} j^2 + O \left( \frac{k^4}{n^2} \right) \right) \sim \exp \left(-\frac{k^2}{2n} - \frac{k^3}{6n^2} \right)
\]

Combining our calculations gives the desired formula. \( \square \)
Taking $\lambda = 1$ in Lemma 1.6.6 we have

$$
\gamma_{n,k}(\lambda) \sim \frac{nk^{-5/2}}{\sqrt{2\pi}} e^{-k^3/6n^2} 
$$

(1.6.10)

Note that the right-hand side behaves like a power law when $k = o(n^{2/3})$ but decays to 0 exponentially fast on $[n^{2/3}, \infty)$.

1.7 Critical regime

In contrast to the previous section, probabilistic methods, specifically martingales and weak convergence will take center stage. We begin with a result for the critical case $\lambda = 1$ that is simple to prove but then move on to result which describe the emergence of the giant component in the critical regime $\lambda = 1 + \theta n^{-1/3}$ where $-\infty < \theta < \infty$

1.7.1 An inequality of Nachmias and Peres (2010)

We will prove what they call the easy upper bound

**Theorem 1.7.1.** Suppose $\lambda = 1$. Let $C_1$ be the largest component. If $x > 1$

$$
P(|C_1| > xn^{2/3}) \leq \frac{6}{x^{3/2}}
$$

By working harder and using exponential martingales one can show that

**Theorem 1.7.2.** For any $n > 1000$ and $x > 8$

$$
P(|C_1| > xn^{2/3}) \leq \frac{4}{x} \exp(-x^2(x - 4)/32)
$$

As the authors say in their paper, upper bounds were proved by Bolobás (1984) and Luczak (1990) but their methods are remarkable for their simplicity, especially in comparison to the machinery that will be used in Section 1.7.2.

**Proof of Theorem 1.7.1.** To begin, we recall the recursion defined in (1.3.1) in Section 1.3 (and used again in Section 1.5) for the set of active sites when we add the neighbors of one site at each step:

$$
|A_{t+1}| = |A_t| - 1 + \xi_{t+1} 
$$

(1.7.1)

where $\xi_{t+1}$ is the number of vertices added on step $t + 1$, and we start with $A_0 = 1$. Since the number of vertices to which a connection can be made decreases with time, $\xi_t \leq_d X_t = \text{binomial}(n, 1/n)$, where $\leq_d$ us a stochastic ordering between the distributions. Before we forget we would like to record the facts

$$
EX = n \cdot (1/n) = 1 \quad \text{var} (X) = n(1/n)(1 - 1/n) = 1 - 1/n 
$$

(1.7.2)
The size of the cluster is 
\[ \tau = \min\{i \geq 1 : A_i = 0\} \]
If we let \( S_t = 1 + \sum_{k=1}^{t} (X_k - 1) \) then \( S_t \geq_{d} A_t \) and
\[ \sigma = \min\{i \geq 1 : S_i = 0\} \]
has \( \sigma \geq_{d} \tau \). If we arrange things so that \( \xi_i \leq X_i \) almost surely for \( i \leq \tau \) then we have \( \tau \leq \sigma \) almost surely.

We are interested in how large the cluster can get so we let
\[ \gamma = \min\{i \geq 1 : S_i = 0 \text{ or } S_i \geq H\} \]
Since \( E(X_i - 1) = 0 \), \( S_{t\wedge \sigma} \) is a nonnegative martingale. Using the optional stopping theorem for nonnegative supermartingales (Theorem 4.8.4 in PTE5) we conclude that
\[ 1 = ES_0 \geq ES_\gamma \geq HP(S_\gamma \geq H) \]
so the probability \( S_i \) reaches \( \geq H \) before hitting 0 is
\[ P(S_\gamma \geq H) \leq 1/H \quad (1.7.3) \]

**Lemma 1.7.3.** Let \( p \in (0,1) \), let \( X_i \) be i.i.d. random variables with binomial\((n,p)\) distributions, and let \( S_t = 1 + \sum_{i=1}^{t} X_i \). Fix an integer \( H \) and define
\[ \gamma = \min\{t \geq 1 : S_t = 0 \text{ or } S_t \geq H\}. \]
Given \( S_\gamma \geq H \) the overshoot \( S_\gamma - H \) is dominated by the binomial\((n,p)\) distributions.

**Proof.** Suppose we condition instead on \( \{S_\gamma \geq H, \gamma = k\} \). Let \( r = H - S_{k-1} + 1 \). Let \( I_1, \ldots, I_n \) be i.i.d. Bernoulli\((p)\) so that \( I_1 + \cdots + I_n = X_k \). If \( S_k \geq H \) let \( J \) be the smallest value of \( m \) so that \( I_1 + \cdots + I_m = r \). The overshoot \( S_\gamma - H = I_{J+1} + \cdots + I_n \) which is clearly smaller in distribution than binomial\((n,p)\). Since the result holds if we condition on the time \( \gamma = k \) then it also holds if we only condition on \( S_\gamma \geq H \).

Using Lemma 1.7.3 with \( f(x) = 2Hx + x^2 \) we see that if \( X = \text{binomial}(n,1/n) \) then
\[
E(2H(S_\gamma - H) + (S_\gamma - H)^2|S_\gamma \geq H) \leq E(2HX + X^2)
\leq 2H + 1 + (1 - 1/n) \leq 2H + 2
\]
where we have used \( EX = 1 \) and \( EX^2 = (EX)^2 + \text{var}(X) \) and (1.7.2). Writing \( S_\gamma^2 = H^2 + 2H(S_\gamma - H) + (S_\gamma - H)^2 \) we have for \( H \geq 2 \)
\[
E(S_\gamma^2|S_\gamma \geq H) \leq H^2 + 2H + 2 \leq H^2 + 3H \quad (1.7.4)
\]
We now introduce a second martingale. Consulting Section 4.8.1 in PTE5 we see that
\[
S_t^2 - (1 - 1/n)t
\]
is the quadratic martingale associated with the random walk $S_t$. Since Lemma 1.7.3 controls how far the martingale jumps over $H$ we can use the optional stopping theorem to conclude that

$$E \left( S_\gamma^2 - (1 - 1/n)\gamma \right) = 1$$

To prove this, we note that since $\gamma \wedge m$ is a bounded stopping time so

$$E S_{\gamma \wedge m}^2 = 1 + (1 - 1/n)E(\gamma \wedge m)$$

Using the dominated convergence theorem on the left and the monotone convergence theorem on the right we get

$$1 + (1 - 1/n)E(\gamma) = ES_\gamma^2 = P(S_\gamma \geq H)E((S_\gamma)^2 | S_\gamma \geq H) \leq H + 3$$

by (1.7.3) and (1.7.4). Rearranging gives

$$E\gamma \leq \frac{H + 2}{1 - 1/n} \leq H + 3$$

if $H \leq n - 3$.

We conclude that for $2 \leq H \leq n - 3$

$$P(\gamma > H^2) \leq \frac{H + 3}{H^2} \leq \frac{2}{H}$$

Define $\bar{\gamma} = \gamma \wedge H^2$. If $\gamma < H^2$ and $S_\gamma < H$ then $S_{\bar{\gamma}} = S_\gamma = 0$ so we have

$$P(S_{\bar{\gamma}} > 0) \leq P(S_\gamma \geq H) + P(\gamma \geq H^2) \leq 3/H$$

Let $K = H^2$ and note that if $\mathcal{C}(v) > H^2$ we must have $S_{\bar{\gamma}} > 0$ because if not then the cluster size would be $\leq \bar{\gamma} \leq H^2$. From this we deduce that if $9 \leq K \leq (n - 3)^2$ then

$$P(|\mathcal{C}(v)| > K) \leq \frac{3}{\sqrt{K}}$$

Let $N_K$ be the total number of vertices contained in components of size larger than $K$. Then three trivial inequalities give

$$P(|\mathcal{C}_1| > K) \leq P(N_K > K) \leq \frac{EN_K}{K} \leq \frac{nP(|\mathcal{C}(v)| > K)}{K}$$

Putting $K = (\lceil \sqrt{xn^{2/3}} \rceil)^2$ where $x > 1$ yields

$$P(\mathcal{C}_1 > xn^{2/3}) \leq P(\mathcal{C}_1 > K) \leq \frac{3n}{(\lceil \sqrt{xn^{2/3}} \rceil)^3} \leq \frac{6}{x^{3/2}}$$

which completes the proof.
1.7. CRITICAL REGIME

1.7.2 Aldous’ theorem

In this section we continue to use the recursion in (1.7.1) but use some less elementary probability. In our first use of this process here, we will stop at \( \tau = \inf \{ t : A_t = \emptyset \} \), but to make sure we find a large component while we will start with \(|A_0| \) large. The ideas here are from Martin-L"of (1998), but we carry out the details somewhat differently.

As in our study of the giant component, we will speed up time and rescale the sizes of our sets to get a limit. To see what to guess, note that the combinatorial calculations suggest that the largest components are of order \( n^{2/3} \). Since \( R_t = t \) and \( R_\tau \) is the size of the clusters containing \( A_0 \), we will scale time by \( n^{2/3} \). When \( \lambda = 1 + \theta n^{-1/3} \), \(|A_t| \) will be almost a mean zero random walk. In this case \(|A_t| - |A_0| \) will be \( O(t^{1/2}) \) so we will scale the number by \( n^{1/3} \).

Having decided on the scaling, we compute the infinitesimal mean and variance. Let \( a_t = |A_t|, \Delta a_t = |A_{t+1}| - |A_t| \), and note that \( u_t = |U_t| = n - t - a_t \). Since the number of new vertices is binomial \((u_t, \lambda/n)\) with \( \lambda = 1 + \theta n^{-1/3} \) we have

\[
E(\Delta a_t | F_t) = -1 + (n - t - a_t)(1 + \theta n^{-1/3})/n \\
= -t + a_t / n + (\theta n^{-1/3})(1 - (t + a_t)/n) \\
\text{var}(\Delta a_t | F_t) = (n - t - a_t) 1 + \theta n^{-1/3}/n \left( \frac{1}{n} \right)
\]

Speeding up time by \( n^{2/3} \), dividing by \( n^{1/3} \), and using \( a_{[sn^{2/3}]} = O(n^{1/3}) \),

\[
E \left( \frac{\Delta a_{[sn^{2/3}]} }{n^{1/3}} \bigg| F_{[sn^{2/3}]} \right) = -\left[ \frac{sn^{2/3}}{n} - a_{[sn^{2/3}]} \right] / n \cdot n^{1/3} + \frac{\theta n^{-1/3}(1 + \theta n^{-1/3})}{n^{1/3}} \\
= -sn^{-2/3} + O(n^{-1}) + \theta n^{-2/3} + O(n^{-1})
\]

The variance is much easier

\[
\text{var} \left( \frac{\Delta a_{[sn^{2/3}]} }{n^{1/3}} \bigg| F_{[sn^{2/3}]} \right) \sim \frac{1}{n^{2/3}}
\]

Letting \( n \to \infty \) we see that \( a_{[sn^{2/3}]} / n^{1/3} \) converges in distribution to the solution of

\[
dB_s^\theta = (-s + \theta) \, ds + dB_s
\]

which is simply \( B_s^\theta = B_s + \theta s - s^2/2 \) (run until the first time it hits zero).

This calculation above leads to a remarkable result of Aldous (1997) that gives the joint distribution of the sizes of the large clusters divided by \( n^{2/3} \). Consider now the version of the exploration process in which we choose \( i_t \in U_t \) when \( A_t = \emptyset \). This adds one to \(|A_t|\) each time it hits zero which has the effect of creating a reflecting barrier at 0 but is perhaps better seen through the eyes of Paul Lévy:

\[
W_t^\theta = B_t^\theta - \min_{0 \leq s \leq t} B_s^\theta
\]
We say that \((u, v)\) is an excursion interval of \(W_t^\theta\) if \(W_u^\theta = W_v^\theta = 0\) but \(W_t^\theta \neq 0\) for \(t \in (u, v)\). During excursions \(|A_t|\) does not hit 0. Since we expose one vertex at a time, the lengths of the excursion intervals represent cluster sizes in the random graph.

**Theorem 1.7.4.** Let \(K_1^n \geq K_2^n \geq \ldots\) be the ordered component sizes of Erdős-Rényi \((n, (1 + \theta n^{-1/3})/n)\). Then as \(n \to \infty\), \(\{n^{-2/3}K_j^n : j \geq 1\}\) converges in distribution to \(\{L_j : j \geq 1\}\) where \(L_1 > L_2 > L_3 > \ldots\) are the ordered lengths of excursion intervals in \(\{W_s^\theta : s \geq 0\}\).

By working harder in this framework it is possible to prove a result about the “topology” of the clusters. A cluster of size \(k\) must have at least \(k - 1\) edges. Changing from the notation used in the previous section, we define the number of edges in excess of this number to be the surplus of the cluster, since that is the number of “collisions” needed to create such a component. Let \(N^\theta(t)\) be a counting process with intensity \(W_t^\theta\). That is \(N^\theta\) has jumps of size 1 and

\[
N^\theta - \int_0^t W_u^\theta \, du \quad \text{is a martingale.}
\]

The arrivals in this point process are called marks. Intuitively connections between vertices in the cluster are produced at a rate proportional to the size of the active set.

**Theorem 1.7.5.** Let \(\sigma_1^n \geq \sigma_2^n \geq \ldots\) be the surpluses ordered component sizes defined in Theorem 1.7.4. Then as \(n \to \infty\),

\[
\{(n^{-2/3}K_j^n, \sigma_j^n) : j \geq 1\}
\]

converges in distribution to \(\{(|\gamma_j|, \mu(\gamma_j)) : j \geq 1\}\) where the \(\gamma_j\) are the excursion intervals listed in order of decreasing length and \(\mu(\gamma_j)\) is the number of marks in \(\gamma_j\).


### 1.7.3 Multiplicative coalescent.

While Theorem 1.7.5 is a nice limit theorem, the truly remarkable part of multiplicative contribution was to note that if we divide the sizes of clusters in Erdős-Rényi \((n, (1 + tn^{-1/3})/n)\) by \(n^{2/3}\) to create a process indexed by \(-\infty < t < \infty\) then there is a simple and intuitive description of the limit. Each pair of clusters of sizes \((x, y)\) merges at rate \(xy\) to a cluster of size \(x + y\). To see why this is true consider two clusters of sizes \(xn^{2/3}\) and \(yn^{2/3}\). In a short interval of time \((t, t + h)\), an edge is added between two vertices with probability \(hn^{-4/3}\), so the probability of making a connection between clusters of size \(x\) and \(y\) in time \(h\) is \(\approx xyh\).

To have an honest Markov process, we need a state space. Aldous chose \(\ell_\infty^2\), the collection of decreasing sequences \(x_1 \geq x_2 \geq x_3 \geq \ldots\) with \(\sum_k x_k^2 < \infty\). The other thing that should be noticed is that the time interval is \(-\infty < t < \infty\) so there is no initial distribution. In Aldous’ original paper he solved this problem by showing that there was only one “standard
multiplicative coalescent” that had the one dimensional distributions consistent with Theorem 1.7.4. Aldous and Limic (1999) later characterized all processes on $-\infty < t < \infty$ in which each pair of clusters of sizes $(x, y)$ merges at rate $xy$ to a cluster of size $x + y$. (In terms of the theory of Markov processes one is finding all of the entrance laws.) In addition to the constant process $(x_1 = v > 0, x_i = 0, i \geq 2)$ there are some nonstandard ones, which are irrelevant for the following application.

**Theorem 1.7.6.** Let $K_1^n(t) \geq K_2^n(t) \geq \ldots$ be the ordered component sizes of Erdős-Rényi$(n, (1 + tn^{-1/3})/n)$. As $n \to \infty$, $\{K_j^n(t)/n^{2/3} : j \geq 1\}$, $-\infty < t < \infty$ converges in distribution to the standard multiplicative coalescent.

The convergence of rescaled large components to the multiplicative coalescent, provides a nice intuitive process of the growth of clusters in the critical regime.

### 1.8 Critical exponents

Let $p(s, \mu)$ be the limit as $n \to \infty$ of the probability a randomly chosen vertex in an Erdős-Rényi graph with mean degree $\mu$ belongs to a cluster of size $s$. The critical exponents for the Erdős-Rényi random graph are defined much like they are for ordinary percolation on $\mathbb{Z}^d$. See e.g., page 236 in Grimmett’s (1999) book.

- The percolation probability $\theta(\mu) = 1 - \sum_{s=1}^{\infty} p(s, \mu)$ has
  $$\theta \approx (\mu - \mu_c)^\beta \quad \text{as } \mu \downarrow \mu_c$$
  (1.8.1)
  In the physics literature the meaning of $\approx$ is not precisely defined. It could be something as weak as
  $$\frac{\log \theta}{\log(\mu - \mu_c)} \to \beta \quad \text{as } \mu \downarrow \mu_c$$
  In order to derive relations between exponents we will suppose $\theta \sim C(\mu - \mu_c)^\beta$ where $a(t) \sim b(t)$ means $a(t)/b(t) \to 1$
- Let $C_x$ be the cluster containing $x$. To have the mean cluster size finite for $\mu \neq \mu_c$ we exclude the giant component
  $$\chi(\mu) = E(|C_x|; |C_x| < \infty) \approx |\mu - \mu_c|^{-\gamma}$$
  (1.8.2)
  It is not clear (to me at least) why the exponent should be the same when $\mu \uparrow \mu_c$ and $\mu \downarrow \mu_c$, but it is true and the constants are the same as well, see (1.8.8).
- We let $\chi_k = E(|C_\rho|^k; |C_x| < \infty)$ for integers $k \geq 2$,
  $$\chi_k(\mu) \approx |\mu - \mu_c|^{-\Gamma(k)}$$
  (1.8.3)
  and let $\Delta_k = \Gamma(k) - \Gamma(k - 1)$. As in the case of percolation it is expected that $\Delta_k = \Delta$ is independent of $k$. 
• There is an exponent for the decay of the cluster size at criticality

\[ p(s, \mu_c) \approx s^{1-\tau} \quad (1.8.4) \]

In the first three cases the Erdős-Rényi Greek letters are the same as those for percolation. In this case the percolation exponent is

\[ P_{pc}(|C| \geq n) \approx n^{-1/d} \]

• Finally there is another exponent for the behavior near criticality

\[ p(s, \mu) \approx s^{1-\tau} f(s^{\delta/\sigma}) \quad \delta = \mu - \mu_c \quad (1.8.5) \]

although it is probably more accurate to call this a scaling relationship.

**d-dimensional percolation.** The most significant difference from the critical exponents for Erdős-Rényi random graphs and those for is that the Erdős-Rényi graph is not a spatial model, so we do not have a correlation length \( \xi(p) \) that gives the spatial size of a typical finite cluster. This quantity is often defined in terms of the exponential decay of probability if 0 and \( x \) are in the same finite cluster.

\[ \tau^f(0, x) = P_p(0 \leftrightarrow x, |C_0| < \infty). \]

For example, if \( e_1 \) is the first unit vector

\[ \xi(p) = \lim_{n \to \infty} -\frac{1}{n} \log \tau^f(0, ne_1) \]

A simpler approach taken by Kesten (1987) is to define the correlation length by

\[ \xi(p) = \left( \frac{1}{\chi_1(p)} \sum_y |y|^2 P(0 \to y; |C_0| < \infty) \right)^{1/2} \]

and the critical exponent \( \nu \) by \( \xi(p) \approx |p - p_c|^{-\nu} \). Finally on a d-dimensional graph we have another exponent \( \eta \) called the anomalous dimension

\[ P_{cr}(0 \to x) \approx |x|^{2-d-\eta} \]

The relationship between the Erdős-Rényi critical exponents and those for percolation is more than an analogy: the values are equal for percolation in dimensions \( d > d_c \). The word that makes the connection is “mean-field theory.” In the Ising model this refers to a version in which each spin interacts equally with all the others. If one makes this modification to percolation then the Erdős-Rényi model results. Physicists tell us that above the upper critical dimension, which is \( d_c = 6 \) for percolation then the critical exponents take on their mean-field values: \( \beta = 1, \gamma = 1, \Delta = 2 \). To compute the others we need a spatial object which is usually taken to be percolation on trees. This leads to \( \nu = 1/2 \) and \( \eta = 0 \). Thanks to work of Aizenmann and Newman (1984) and Hara and Slade (1989, 1994), etc there are a number of rigorous results confirming this picture. See Section 10.3 of Grimmett (1999) for more details. The key words are tree graph inequalities and the lace expansion.
1.8. CRITICAL EXONENTS

1.8.1 Survival probability, $\beta = 1$

Let $x$ be a randomly chosen vertex and let $Z_m$ be the number of vertices at distance $m$ from $x$. When the growing cluster containing $x$ has size $\leq n^{1/2-\epsilon}$ the cluster is whp a tree (see Theorem 1.2.3, so $Z_m$ is a branching process in which each individual in generation $m$ has a Poisson($\mu$) number of offspring. In Section 1.3 we showed that if $\mu > 1$ then there is a constant $C(\mu)$ so that a vertex is in the giant component if and only if it is in a cluster of size $\geq C(\mu) \log n$, so the probability of this event can be computed using the branching process.

Consider a branching process with offspring distribution $r_k$ with mean $\mu > 1$ and finite second moment. Let $\phi(z) = \sum_{k=0}^{\infty} r_k z^k$ be the generating function. If $r_K$ is Poisson($\mu$) then

$$\phi(z) = \sum_{k=0}^{\infty} e^{-\mu} \frac{\mu^k}{k!} z^k \exp(-\mu(1-z)) \quad (1.8.6)$$

Let $\rho$ be probability the system dies out. Breaking things down according to the number of children in the first generation

$$\rho = \sum_{k=0}^{\infty} r_k \rho^k = \phi(\rho)$$

$\rho(1) = 1$ is a trivial solution. $\rho$ is the unique solution of $\phi(\rho) = \rho$ in $[0, 1)$.

$$\phi(1) = 1 \quad \phi'(1) = \sum_{k=0}^{\infty} k r_k = \mu \quad \phi''(1) = \sum_{k=0}^{\infty} k(k-1) r_k = \mu_2$$

If $\mu$ is close to 1 then $\rho$ will be close to 1. Ignoring a few details, if $x$ is close to 1 expanding $\phi$ in power series around 1 gives

$$\phi(1-x) = 1 - \mu x + \mu_2 x^2 / 2$$

so for a fixed point at $(1-x)$ we want

$$(\mu - 1)x = \mu_2 x^2 / 2$$

or $x = 2(\mu - 1) / \mu_2$. If we let $\theta(\mu) = P(|C_x| = \infty)$ which is the same as the fraction of vertices in the giant component

$$\theta(\mu) \sim \frac{2}{\mu_2} (\mu - 1) \quad (1.8.7)$$

so the critical exponent $\beta = 1$. Note that this holds whenever the offspring distribution has finite variance. If the distribution is a power law with infinite variance then the power changes. Section 2.7 for results for the configuration model.
1.8.2 Mean cluster size, $\gamma = 1$

Let $C_x$ be the cluster containing $x$. Taking the branching process viewpoint, if $\mu < 1$

$$E|C_x| = \sum_{n=0}^{\infty} EZ_m = \sum_{m=0}^{\infty} \mu^m = \frac{1}{1 - \mu}.$$  

so $\gamma = 1$. In the supercritical regime we consider

$$E(|C_x|; |C_x| < \infty)$$

The cluster size is the same as the total progeny in a supercritical branching process conditioned to die out. In Section 1.1 we proved the following result

**Theorem 1.8.1.** A supercritical branching process conditioned to become extinct is a subcritical branching process. If the original offspring distribution is Poisson($\mu$) with $\mu > 1$ then the conditioned one is Poisson($\mu\rho$) where $\rho$ is the extinction probability.

Using the result for the subcritical case in (1.8.8)

$$E(|C_x|; |C_x| < \infty) = \frac{1}{1 - \mu\rho}$$

Since $\mu_2 = \mu^2$ for Poisson, (1.8.7) shows that if $\mu$ is close to 1

$$\rho \approx 1 - \frac{2(\mu - 1)}{\mu^2}$$

so we have

$$1 - \mu\rho = 1 - \mu + \frac{2(\mu - 1)}{\mu} = \frac{2(\mu - 1) - \mu(\mu - 1)}{\mu}$$

From this we see that

$$E(|C_x|; |C_x| < \infty) = \frac{1}{1 - \mu\rho} \sim \frac{1}{1 - \mu}$$  

(1.8.9)

thus the asymptotic behavior of the mean cluster size as $\mu \downarrow 1$ is the same as as $\mu \uparrow 1$, not just the exponent $\gamma = 1$ but also the constant $C = 1$.

1.8.3 Higher moments, $\Delta = 2$

To compute higher moments it is convenient to use the random walk approach developed in Section 1.3. Let $R_t$ be the set of removed sites, $U_t$ be the unexplored sites and $A_t$ is the set of active sites. At time $\tau = \inf\{t : A_t = \emptyset\}$ we have found all the sites in the cluster and the process stops. $|R_t| = t$ for all $t \leq \tau$, so the cluster size is $\tau$. If $|A_t| > 0$ and the number of removed sites is small

$$S_{t+1} \approx S_t - 1 + \text{Poisson}(\mu)$$
To have the process defined for all time let \( \xi_1, \xi_2, \ldots \) be i.i.d. \(-1 + \text{Poisson}(\mu)\) and \( S_{t+1} = S_t + \xi_{t+1} \).

We begin by computing the moment generating function of \( \xi_i \)

\[
\psi(\theta) = \sum_{m=0}^{\infty} e^{-\mu} \frac{\mu^m}{m!} e^{\theta m} = \exp(\mu(e^\theta - 1)) 
\]

(1.8.10)

\( M_t = \exp(\theta S_t) / \psi(\theta)^t \) is a nonnegative martingale, so using the optional stopping theorem for the nonnegative supermartingales Theorem 4.8.4 in PTE5,

\[
M_0 = e^\theta \geq E(\psi(\theta)^{-\tau}) 
\]

(1.8.11)

\( \psi'(0) = E \xi_i = 1 - \mu \) (CHECK) so if \( \mu < 1 \) then \( \psi(\theta) < 1 \) when \( \theta > 0 \) is small. To optimize we note that the derivative of \( \log \psi(\theta) \)

\[
\frac{d}{d\theta} (-\theta + \mu(e^\theta - 1)) = -1 + \mu e^\theta = 0
\]

when \( \theta_1 = -\log \mu \). At this point \( e^{\theta_1} = 1/\mu \) and

\[
\psi(\theta_1) = \exp(\log(\mu) + 1 - \mu) \equiv e^{-\alpha} < 1
\]

Since \( \psi(\theta_1) = e^{\alpha} > 1 \), using Chebyshev’s inequality with (1.8.11)

\[
e^{\alpha m} P(\tau \geq m) = \psi(\theta_1)^{-m} P(\tau \geq m) \leq E(\psi(\theta_1)^{-\tau}) \leq e^{\theta_1}
\]

One particle dies on each time step so \( 1 + \xi_1 + \cdots + \xi_\tau = \tau \) and we have

\[
P \left( \max_{0 \leq n \leq \tau} S_n \geq m \right) \leq e^{-m\alpha} / \mu 
\]

(1.8.12)

There are several other martingales associated with a random walk. Before we get started we need to recall that the random walk of interest

\[
S_n = S_0 + \xi_1 + \cdots + \xi_n
\]

where \( \xi_i \) have distribution \(-1 + \text{Poisson}(\lambda)\) so we will let \( \nu = E \xi_i = \mu - 1 \). The simplest martingale is

\[
M_n^{(1)} = S_n - n\nu
\]

Using the domination in (1.8.12) we can conclude that

\[
1 = S_0 = E(S_\tau - (\mu - 1)\tau) = (1 - \mu) E\tau
\]

so the expected cluster size is \( E\tau = 1 / (1 - \mu) \).
If $T_n$ is a random walk in which steps have mean 0 and variance $\sigma^2$ then $T_n - n\sigma^2$ is a martingale. Applying this result to $T_n = S_n - n\nu$ and recalling that $-1 + \text{Poisson}(\mu)$ has variance $\nu_2 = \mu$ we see that

$$M_n^{(2)} = (S_n - n\nu)^2 - \nu_2 n$$

is a martingale. Using the domination in (1.8.12) we can stop at time $\tau$ and conclude

$$1 = E(S_\tau - \tau \nu)^2 - \nu_2 E\tau$$

$$= (\mu - 1)^2 E\tau^2 - \frac{\mu}{1 - \mu}$$

Rearranging we have

$$E\tau^2 = \frac{\mu}{(1 - \mu)^3}$$

(1.8.13)

Since $E\tau = 1/(1 - \mu)$ the gap exponent $\Delta_2 = 2$.

To compute higher moments we need more martingales. Let $\kappa(\theta) = \log E \exp(\theta \xi_i)$ be the cumulant generating function. Expanding in power series

$$\exp(ux - n\kappa(u)) = \sum_{k=0}^{\infty} \frac{u^k}{k!} f_k(n, x)$$

$\exp(u S_n - n\kappa(u))$ is a martingale so differentiating we see that $f_k(n, S_n)$ is a martingale. See page 80 of Neveu (1975). The first two martingales we have already seen. To find the third let

$$g_k(u; n, x) = \frac{\partial^k}{\partial u^k} \exp(ux - n\kappa(u))$$

and note that $f_k(n, x) = g_k(0; n, x)$ and

$$g_k(u; n, x) = g_{k-1}(u; n, x) \cdot (x - n\kappa'(u)) + (\partial/\partial u)g_{k-1}(u; n, x)$$

From this we get

$$g_1(u; n, x) = x - n\kappa'(u)$$

$$g_2(u; n, x) = (x - n\kappa'(u))^2 - n\kappa''(u)$$

$$g_3(u; n, x) = (x - n\kappa'(u))^3 - n\kappa''(u)(x - n\kappa'(u))$$

$$- 2(x - n\kappa'(u)) n\kappa'''(u) - n\kappa''''(u)$$

The first three cumulants are the mean $\nu = 1 - \mu$, the variance $\sigma^2 = \nu_2 = \mu$, and $\nu_3 = E(\xi - \nu)^3$ so the third martingale is

$$M_n^{(3)} = (S_n - n\nu)^3 - 3n\sigma^2(S_n - n\nu) - nE(\xi - \nu)^3$$

To check that $M_n^{(3)}$ is a martingale we note that

$$E((S_{n+1} - (n + 1)\nu)^3| F_n) = (S_n - n\mu)^3 + 3(S_n - n\nu)^2 E(\xi_{n+1} - \nu)| F_n$$

$$+ 3(S_n - n\nu) E((\xi_{n+1} - \nu)^2| F_n) - E(\xi_{n+1} - \mu)^3$$

$$= (S_n - n\nu)^3 + 3\sigma^2(S_n - n\nu) - E(\xi - \mu)^3$$
Using the domination in (1.8.12) we can stop at time $\tau$ and conclude
\[ 1 = E(S_\tau - \tau \nu)^3 - 3E[\tau \sigma^2 (S_\tau - \tau \nu)] - E\tau E(\xi - \nu)^3 \]
\[ = -(\mu - 1)^3 E\tau^3 + 3(\mu - 1)\sigma^2 E\tau^2 - \nu_3 E\tau \]
Since $E\tau = O(1/(1 - \mu))$ while $E\tau^2 = O(1/(1 - \mu)^3)$ we have
\[ E\tau^3 \sim \frac{3\sigma^2 E\tau^2}{(\mu - 1)^2} \]
and $\Delta_3 = 2$. We leave it to the energetic reader to compute $\Delta_k$ for $k \geq 4$.

### 1.8.4 Scaling theory

Formula (1.6.10) implies that when $\mu = 1$ the probability of a cluster of size $k$ is
\[ \sim \frac{n k^{-5/2}}{\sqrt{2\pi}} e^{-k^3/6n^2} \]
This says that the largest components are of size $n^{2/3}$. The critical exponent $\tau$ defined in (1.8.4)
\[ P(s, t_c) \sim f(0)s^{1-\tau} \]
has the value $\tau = 5/2$.

To get a result for $\mu$ close to 1, we use (1.6.9)
\[ P(s, \mu) \approx \frac{s^{1-5/2}}{\sqrt{2\pi}} \cdot \exp(-s(\mu - 1)^2/2) \quad (1.8.14) \]
Thus (1.8.5) holds with $\tau = 5/2$, $\sigma = 1/2$ and
\[ f(x) = e^{-x/2} \quad (1.8.15) \]

In the previous section we showed that the cluster size distribution for the Erdős-Rényi graph satisfied
\[ p(s, \mu) \approx s^{1-\tau} f(s|\mu - \mu_c|^{1/\sigma}) \quad (1.8.16) \]
where $f(x) = e^{-x/2}$.

It has long been known for percolation (see Stauffer (1979)) that (1.8.16) implies
\[ \beta = (\tau - 2)/\sigma \quad (1.8.17) \]
\[ \gamma = (3 - \tau)/\sigma \quad (1.8.18) \]
\[ \Delta = 1/\sigma \quad (1.8.19) \]
Since (1.8.16) gives the asymptotics for the cluster size distribution as $\mu \to \mu_c$ it should not be surprising that we can compute the asymptotic behavior of the moments and of the percolation probability. Kesten (1984) has proved a number of rigorous results concerning scaling relations concentrating on the two dimensional case.
Lemma 1.8.2. If $2 < \tau < 3$ and $f$ is bounded, and is Lipschitz continuous at 0.

$$\beta = (\tau - 2)/\sigma$$

Proof. Using (1.8.16) and replacing sum by integration.

$$\theta(t) \approx \int_1^\infty s^{1-\tau} [f(0) - f(s^{1/\sigma})] \, ds$$

Changing variables $s = x\delta^{-1/\sigma}$, $ds = \delta^{-1/\sigma} \, dx$ the above

$$= \delta^{(\tau-2)/\sigma} \int_{\delta^{1/\sigma}}^\infty x^{1-\tau} [f(0) - f(x)] \, dx$$

Since $f$ is bounded and $\tau > 2$ the integral over $[1, \infty)$ is finite. Since $f$ is Lipschitz continuous the integrand is $\leq Cx^{2-\tau}$ near 0. Since $\gamma < 3$, the integral over $[0, 1]$ is finite, and it follows that $\theta(t) \sim C\delta^{(\tau-2)/\sigma}$.

The next result establishes (1.8.18) and (1.8.19)

Lemma 1.8.3. If $2 < \gamma < 3$ and $\int_1^\infty x^m f(x) \, dx < \infty$ for all $m$ then for all $r \geq 1$

$$\Gamma(r) = (r + 2 - \tau)/\sigma$$

It follows that for all integers $k \geq 2$,

$$\Delta_k = \Gamma(k) - \Gamma(k - 1) = 1/\sigma.$$ 

Proof.

$$E|C_x|^r = \int_1^\infty s^{r+1-\tau} f(s^{1/\sigma}) \, ds$$

Changing variables $s = x\delta^{-1/\sigma}$, $ds = \delta^{-1/\sigma} \, dx$ the above

$$= \delta^{(\tau-2-r)/\sigma} \int_{\delta^{1/\sigma}}^\infty x^{\rho+1-\tau} f(x) \, dx$$

The assumption $\int_1^\infty x^m f(x) \, dx < \infty$ for all $m$ implies that the integral over $[1, \infty)$ is finite. Since $\tau < 3$ and $\rho \geq 1$ the integral over $[0, 1]$ is finite.

1.9 Threshold for being connected

In this section we will answer the question: How large does $\lambda$ have to be so that the probability Erdős-Rényi($n, \lambda/n$) is connected (i.e., ALL vertices in ONE component) tends to 1. I learned the following slick proof from the book by Frieze and Karonski who attribute it to Erdős and Rényi in 1959.
Theorem 1.9.1. Let \( p = (c_n + \log n)/n \) and let \( H(n, p) \) be the event that Erdős-Rényi\((n, p)\) is connected.

\[
P(H(n, p)) \to \begin{cases} 
0 & \text{if } c_n \to -\infty \\
e^{-c} & \text{if } c_n \to c \in (-\infty, \infty) \\
1 & \text{if } c_n \to \infty 
\end{cases}
\]

The proof will be completed by proving the next two lemmas. By monotonicity of the event \( H(n, p) \) in \( p \) it suffices to prove the result when \( c_n \to c \in (-\infty, \infty) \).

Lemma 1.9.2. Consider \( G = \text{ER}(n, \lambda/n) \) with \( \lambda = \log n + c_n + o(1) \) and \( c_n \to c \). Then the number of isolated vertices \( I_n \) converges to a Poisson distribution with mean \( e^{-c} \).

Proof. The probability \( x \) is isolated is

\[
\left(1 - \frac{\lambda}{n}\right)^n \sim \exp(-\log n - c_n) \sim e^{-c}/n
\]

so \( EI_n \to e^{-c} \). The expected number of ordered \( k \)-tuples of isolated vertices is

\[
EI_n^{(k)} = (n \cdot (n-1) \cdots (n-k+1)) \left(1 - \frac{\lambda}{n}\right)^{n+(n-1)+\cdots+(n-k+1)} \to e^{-ck}
\]

so the Poisson convergence follows from Lemma 1.2.6. \( \square \)

The next result completes the proof. For simplicity we suppose \( c_n \equiv c \).

Lemma 1.9.3. Let \( X_k \) be the number of clusters with \( k \) vertices. Let \( p = (c + \log n)/n \) and let \( H(n, p) \) be the event that Erdős-Rényi\((n, p)\) is connected.

\[
P(H(n, p)) = P(X_1 = 0) + o(1)
\]

Proof. If the graph is not connected then there is at least one component of size \( \leq n/2 \), so \( P(H(n, p)^c) = P(\cup_{k=1}^{n/2} \{X_k > 0\}) \) and we have

\[
P(X_1 > 0) \leq P(H(n, p)^c) \leq P(X_1 > 0) + \sum_{k=2}^{n/2} P(X_k > 0)
\]

Computing as in Section 1.6 (see (1.6.1))

\[
\sum_{k=2}^{n/2} P(X_k > 0) \leq \sum_{k=2}^{n/2} \binom{n}{k} k^{k-2} (p^{k-1} (1-p)^{(n-k)k}) \equiv \sum_{k=2}^{n/2} u_k
\]
Now for $2 \leq k \leq 10$ using $\binom{n}{k} \leq n^k/k!$ and $e^k \geq k^k/k!$

$$u_k \leq e^k n^k \left( \frac{c + \log n}{n} \right)^{k-1} e^{-k(n-10)(c+\log n)/n}$$

$$\leq e^k n^k \left( \frac{c + \log n}{n} \right)^{k-1} e^{-k(c+\log n)} e^{10k(c+\log n)/n}$$

$$\leq e^{k(1-c)} \left( \frac{c + \log n}{n} \right)^{k-1} \cdot (1 + o(1))$$

while for $10 < k \leq n/2$

$$u_k \leq \left( ne/k \right)^{k-2} \left( \frac{c + \log n}{n} \right)^{k-1} e^{-k(log n+c)/2}$$

$$\leq n \left( \frac{e^{1-c/2}(c + \log n)}{n^{1/2}} \right)^k$$

so we have $\sum_{k=2}^{n/2} u_k \to 0$ which completes the proof. 

Our final result which we state without proof gives a formula for the diameter

**Theorem 1.9.4.** If $\lim \inf np/(\log n) > c > 1$ and $(\log p)/(\log n) \to 0$ then the diameter of Erdős-Rényi $(n, p)$, $D(n, p) \sim (\log n)/(\log np)$.

**Remark 1.9.5.** The first condition guarantees that the probability that the graph is connected tends to 1 as $n \to \infty$. The formula for the diameter is the same as in the sparse case when $np = \lambda$. To explain the second suppose $p = n^{-15/17}$. In this case $np = n^{2/17}$, it is not hard to show that the diameter will be 9 with probability approaching 1, but the formula gives $17/2$. A more delicate situation occurs when

$$p = n^{(1/d)-1}(\log(n^2/c))^{1/d}$$

In this case in the limit the diameter is $d$ with probability $e^{-c/2}$ and $d + 1$ with probability $1 - e^{-c/2}$. See Theorem 10.10 in Bollobás (2001). We mentioned other work by Chung and Lu (2001) and Riordan and Wormald (2010) at the end of Section 1.2. We leave it to the interested reader to explore this topic further.

**References**


1.9. THRESHOLD FOR BEING CONNECTED


Chapter 2

General Degree Distributions

2.1 Configuration model

Molloy and Reed (1995, 1998) were the first to study the phase transition in the cluster sizes of graphs with specified degree distributions. We will describe their work in the next section. In this one we will describe the configuration model which is an efficient algorithm for constructing such graphs.

Examples

The motivation for the study of these graphs with a pre-specified degree distribution comes from the fact that in an Erdős-Rényi random graph, vertices have degrees that have asymptotically a Poisson distribution. However, in social and communication networks, the distribution of degrees is much different from the Poisson and in many cases has a power law form, i.e., the fraction of vertices of degree $k$,

$$p_k \sim Ck^{-\gamma} \quad \text{as } k \to \infty.$$ 

At the turn of this century attention focused on a number of examples. As the reader will see the case in which $2 < \gamma < 3$ turns out to be very interesting. These are called scale-free random graphs.

By the world wide web, we mean the collection of web pages and the oriented links between them. Barabási and Albert (1999) found that the in-degree and out-degrees of web pages follow power laws with $\gamma_{\text{in}} = 2.1$, $\gamma_{\text{out}} = 2.7$.

By the Internet, we mean the physically connected network of routers that move email and files around the Internet. In 2000 there were about 150,000 routers connected by 200,000 links and a degree distribution that could be fit by a power law with $\gamma = 2.3$.

The movie actor network in which two actors are connected by an edge if they have appeared in a film together, has a power law degree distribution with $\gamma = 2.3$. 

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Liljeros et al. (2001) analyzed data gathered in a study of sexual behavior of 4,781 Swedes, and found that the number of partners per year had $\gamma_{\text{male}} = 3.3$ and $\gamma_{\text{female}} = 3.5$. The collaboration graph in a subject is a graph with an edge connecting two people if they have written a paper together. Barabási et al. (2002) studied papers in mathematics and neuroscience published in 1991–1998. The two databases that they used contained 70,901 papers with 70,975 authors, and 210,750 papers with 209,293 authors, respectively. The fitted power laws had $\gamma_{\text{M}} = 2.4$ and $\gamma_{\text{NS}} = 2.1$.

Newman’s (2003) survey paper provides a wealthy of information about “Networks in the Real World.” His discussion makes it clear that the interest in these networks is not new. Alfred Lotka wrote in 1926 about the Law of scientific Productivity, which states that number of papers written by an individual follows a power law. Derek de Solla Price (1965) wrote in a paper published in Science that both the in-degree and out-degree of the collaboration graph had power laws. The paper has 89 pages and 429 references for readers who want to see networks in a broader context.

Definitions

The first appearance of the configuration model came in the construction of random regular graphs. See Bollobas (1980, 1985). Suppose that we want a graph with $n$ vertices, each of which has degree $r$. If $nr$ is even (otherwise the graph is not possible) one partitions $\{1, \ldots n\} \times \{1, \ldots r\}$ into $rn/2$ pairs to define the edges of the graph, which can be done in

$$\frac{(rn)!/2^{rn/2}}{(rn/2)!} = (rn-1)(rn-3)\cdots3\cdot1 = (rn-1)!! \text{ ways.}$$

To do the construction in general let $d_1, \ldots d_n$ be independent and have $P(d_i = k) = p_k$. Since we want $d_i$ to be the degree of vertices in a graph, we condition on $E_n = \{d_1 + \cdots + d_n \text{ is even}\}$. If the probability $P(E_1) \in (0,1)$ then $P(E_n) \to 1/2$ as $n \to \infty$ so the conditioning will have little effect on the finite dimensional distributions. To build the graph we think of $d_i$ half-edges attached to $i$ and then pair the half-edges at random. The picture gives an example with 8 vertices.

If you are using this algorithm in a computer program to construct the graph then it is silly to give up and start again if the sum of the degrees is odd. In practice one either deletes an edge chosen at random, or saves work by deleting an edge from vertex $n$.

As we will see in Section 2.3 it is often advantageous to allow loops and multiple edges and work with $r$-regular multigraphs $G^*(n, r)$ which are constructed by using the procedure described below with $d_i = r$ for $1 \leq i \leq r$. If we condition on the graph being simple then we get a random choice from the set of random regular graphs $G(n, r)$. For people who want clean graphs, we note that if one assumest

$$(A) p_k \text{ has a finite second moment.}$$

then Theorem 2.1.1 below implies that the probability that the graph is simple has a positive limit. Using Theorem 1.2.6 we can prove.
2.1. CONFIGURATION MODEL

Figure 2.1: Example of the construction.

**Theorem 2.1.1.** Let $\mu = \sum_k kp_k$ and $\mu_2 = \sum_k k(k - 1)p_k$. As $n \to \infty$, the number of self-loops $\chi_0$ and the number of parallel edges $\chi_1$ are asymptotically independent Poisson($\mu_2/2\mu$) and Poisson((\mu_2/2\mu)^2).

**Proof.** If $D = d_1 + \cdots + d_n$ then the expected number of self-loops is $\sim \sum_i d_i(d_i - 1)/2D \to \nu/2\mu$ and the expected number of pairs of parallel edges is

$$\sim \frac{1}{2} \sum_i d_i - 1 \sum_{j \neq i} \frac{d_j d_j - 1}{D} \to (\nu/2\mu)^2$$

To check the counting in the second formula, suppose that we connect half-edges 3 and 7 from $i$ connect to half-edges 5 and 2 from $j$. When we pick the two edges for $i$, order is not important, but when it comes to $j$ it is. The $1/2$ in front comes from the fact that $(i, j)$ and $(j, i)$ are both in the double sum.

This gives the asymptotics for the mean, but in almost the same way we can compute the expected number of ordered $k$-tuples to conclude that the self-loops and parallel edges have Poisson limits. After this, we can consider product moments to get convergence of the joint distribution to independent Poissons by using Lemma 1.2.6. \qed

**Phase transition**

As we have seen in our analysis of Erdős-Renyi graphs, the growth of clusters can be approximated in the early stages by a branching process. In this section we will follow Newman, Strogatz, and Watts (2001) who were playing by the rules of *Physical Review E*. If we start with a given vertex $x$ then the number of neighbors (the first generation in the branching process) has distribution $p_j$. This is not true for the second generation. A first generation vertex with degree $k$ is $k$ times as likely to be chosen as one with degree 1, so the distribution of the number of children of a first generation vertex is for $k \geq 1$

$$q_{k-1} = \frac{kp_k}{\mu} \quad \text{where} \quad \mu = \sum_k kp_k$$
The $k-1$ on the left-hand side comes from the fact that we used up one edge connecting to the vertex. Note that since we have assumed $p$ has finite second moment, $q$ has finite mean $\nu = \sum k(k-1)p_k/\mu$.

The random $r$-regular graph is a trivial example. $p_r = 1$ and so $q_{r-1} = rp_r/\mu = 1$. For a little more excitement consider

**Example 2.1.2. Poisson distribution.** if $p_k = e^{-\lambda} \lambda^k/k!$, which is the asymptotic degree distribution for Erdős-Rényi$(n, \lambda/n)$. In this case $\mu = \lambda$, so

$$q_{k-1} = e^{-\lambda} \frac{\lambda^k}{k!} = e^{-\lambda} \frac{\lambda^{k-1}}{(k-1)!}$$

and $q$ is again Poisson. Conversely if $p = q$ we have $p_{k-1} = kp_k/\mu$. Iterating gives $p_k = p_0 \mu^k/k!$, so $p_k$ is Poisson with mean $\mu$.

Having discovered that the growth of the cluster is a “two-phase” branching process in which the first generation has distribution $p$, and the second and subsequent generations have distribution $q$, it is now routine to compute the threshold for the existence of large components and the size of such components. Let $G_0(z) = \sum_k p_k z^k$ and $G_1(z) = \sum_k q_k z^k$ be the two generating functions. These are related:

$$\frac{G_0'(z)}{\mu} = \sum_{k=1}^{\infty} \frac{kp_k}{\mu} z^{k-1} = \sum_{k=1}^{\infty} q_{k-1} z^{k-1} = G_1(z)$$

Let $Z_n$ be the number of vertices in the $n$th generation. For $n \geq 1$, $E Z_n = \mu \nu^{n-1}$ so when $\nu < 1$

$$E \left( \sum_{n=0}^{\infty} Z_n \right) = 1 + \sum_{n=1}^{\infty} \mu \nu^{n-1} = 1 + \frac{\mu}{1 - \nu} \quad (2.1.1)$$

and we have the first part of

**Theorem 2.1.3.** The condition for the existence of a giant component is $\nu > 1$. In this case the fraction of vertices in the giant component is asymptotically $1 - G_0(\rho_1)$ where $\rho_1$ is the smallest fixed point of $G_1$ in $[0, 1]$.

We will prove this result in a more general setting in Section 2.2.2. To explain the second claim: We know that $\rho_1$ is the extinction probability of the homogeneous branching process with offspring distribution $q$. Breaking things down according to the number of offspring in the first generation, the probability that the two phase branching process dies out is $\sum_{k=0}^{\infty} p_k \rho_1^k = G_0(\rho_1)$, since each of the $k$ first generation families must die out and they are independent.

**Example 2.1.4. Miller (2011).** His figure 1 gives an example of the configuration model with 70 vertices and $p_1 = p_3 = 0.5$ There are five clusters of size 2, one of size 4, and the
remaining $56/70 = 0.8$ vertices are in the giant component. To see if this is reasonable we note that $\mu = 2$, so the size biased degree distribution has

$$q_0 = \frac{1p_1}{\mu} = \frac{1}{4}, \quad q_2 = \frac{3p_3}{\mu} = \frac{3}{4}$$

$\nu = 2 \cdot 3/2 \cdot G_1(z) = 1/4 + (3/4)z^2 = (1-z)(1/4-3z/4)$ so $\rho_1 = 1/3$. and $G_0(\rho_1) = (\rho_1 + \rho_1^3)/2$ so $1 - G_0(\rho_1) = 0.814814$

### Cluster sizes

Our next topic is using generating functions to study the cluster size distribution. To compute the distribution of the size of subcritical, or more generally the non-giant components, we begin by considering the homogeneous branching process with offspring distribution $q$. Let $H_1(z)$ be the generating function of the total progeny in the homogeneous branching process. If there are $k$ offspring in the first generation then the total progeny $= 1 + Y_1 + \cdots + Y_k$ where the $Y_i$ are independent and have the same distribution as the total progeny. From this it follows that for $z < 1$

$$H_1(z) = z \sum_{k=0}^{\infty} q_k(H_1(z))^k = zG_1(H_1(z))$$

(2.1.2)

The condition $z < 1$ guarantees $z^\infty = 0$. Similarly, if $H_0(z)$ be the generating function of the total progeny in the two-phase branching process then

$$H_0(z) = z \sum_{k=0}^{\infty} p_k(H_1(z))^k = zG_0(H_1(z))$$

(2.1.3)

We claim that

$$\lim_{z \to 1} H_1(z) = \rho_1.$$ 

This should be obvious because the total progeny is finite if and only if the branching process dies out. To check this, note that when $z < 1$, $G_1(H_1(z))/H_1(z) = 1/z > 1$ so $H_1(z) < \rho_1$, but $\lim_{z \to 1} H_1(z)$ is a fixed point of $G_1$ so the limit must be $\rho_1$.

To find the mean size of finite clusters, we begin with the homogeneous branching process. Differentiating (2.1.2), setting $z = 1$ and recalling $H_1(1) = \rho_1$, $G_1(\rho_1) = \rho_1$,

$$H_1'(z) = G_1(H_1(z)) + zG_1'(H_1(z))H_1'(z)$$

$$H_1'(1) = \rho_1 + G_1'(\rho_1)H_1'(1)$$

Rearranging we have

$$\frac{H_1'(1)}{H_1(1)} = \frac{1}{1 - G_1'(\rho_1)}$$

(2.1.4)

When the branching process dies out, $\rho_1 = 1$, $G_1'(1) = \nu$ and $H_1(1) = 1$, and so this says that the mean cluster size is $1/(1 - \nu)$. To check the result for $\nu > 1$, recall that Theorem 1.1.8
implies that if the homogeneous branching process is supercritical and we condition it to
die out then the result is a branching process with offspring distribution that has generating
function \( G_1(\rho_1 z) / \rho_1 \). Differentiating and setting \( z = 1 \), we see that the mean of the offspring
distribution is \( G'_1(\rho_1) \), so the expected total progeny will be

\[
\sum_{n=0}^{\infty} G'_1(\rho_1)^n = \frac{1}{1 - G'_1(\rho_1)}.
\]

Turning to the two-phase branching process. Differentiating (2.1.3) and setting \( z = 1 \)

\[
H'_0(z) \quad = \quad G_0(H_1(z)) + zG'_0(H_1(z))H'_1(z)
\]

\[
H'_0(1) \quad = \quad H_0(1) + G'_0(\rho_1)H'_1(1)
\]

since \( H_1(1) = \rho_1 \) and \( G_0(\rho_1) = H_0(1) \) is the extinction probability for the two phase process.
When the branching process dies out, \( H_0(1) = 1, \rho_1 = 1, G'_0(1) = \mu, H_1(1) = 1, \) and
\( H'_1(1) = 1/(1 - \nu) \) so we have

\[
H'_0(1) = 1 + \frac{\mu}{1 - \nu}
\]
as we have computed in (2.1.1). To get a result for \( \nu > 1 \), we divide each side by \( H_0(1) \) and
use (2.1.4) to get

\[
\frac{H'_0(1)}{H_0(1)} = 1 + \frac{G'_0(\rho_1)H'_1(1)}{H_0(1)} = 1 + \frac{G'_0(\rho_1)H_1(1)}{H_0(1)(1 - G'_1(\rho_1))} \tag{2.1.5}
\]

To check this, note that in the two-phase branching process the probability \( Z_1 = k \) given that
the process dies out is \( p_k \rho_1^k / G_0(\rho_1) \). (2.1.4) implies that the mean number of descendants of
a first generation individual given the extinction of its family is \( 1/(1 - G'_1(\rho_1)) \). Thus the expected total progeny is

\[
1 + \sum_{k=1}^{\infty} \frac{p_k \rho_1^k}{G_0(\rho_1)} \frac{k}{1 - G'_1(\rho_1)} = 1 + \frac{\rho_1 G'_0(\rho_1)}{G_0(\rho_1)} \cdot \frac{1}{1 - G'_1(\rho_1)}
\]

Since \( H_1(1) = \rho_1 \) and \( G_0(\rho_1) = H_0(1) \) this agrees with the answer in (2.1.5).

**Cluster size distribution at the critical value.**

We will take a more serious look at this topic in Section 2.6. Taking \( w = H_1(z) \) in (2.1.2)
gives

\[
z = H_1^{-1}(w) = w / G_1(w)
\]

In the critical case \( G_1(1) = 1 \) and \( G'_1(1) = 1 \). Taking the derivative of the right hand side
and setting \( w = 1 \) is

\[
\frac{G_1(w) - G'_1(w)w}{G_1(w)^2} = 0
\]
Differentiating again and setting $w = 1$ gives

\[ \frac{[G'_1(w) - G''_1(w)w - G'_1(w)]G_1(w)^2 - 2G_1(w)G'_1(w)[G_1(w) - G'_1(w)w]}{G_1(w)^4} = -G''_1(1) \]

If $q$ has a finite second moment then for some $x_\epsilon \in [1 - \epsilon, 1]$

\[ H_1^{-1}(1 - \epsilon) = 1 - \frac{1}{2} G''_1(x_\epsilon) \epsilon^2 \]

$G''_1(x_\epsilon) \to G''_1(1)$ as $\epsilon \to 0$, so as $\delta \to 0$

\[ 1 - H_1(1 - \delta) \sim \sqrt{2\delta / G''_1(1)} \]

Combining this with (2.1.3) we have

\[ 1 - H_0(1 - \delta) = 1 - (1 - \delta) + (1 - \delta)[G_0(1) - G_0(H_1(1 - \delta))] \sim G'_0(1) \sqrt{2\delta / G''_1(1)} \]  (2.1.6)

Now the rate of convergence of $H_0(1 - \delta)$ to 1 tells us about the rate of convergence of $\sum_{k=K}^{\infty} h_k$ to 0. Tauberian theorems (see e.g., Feller volume II) are the machinery for doing these results rigorously. Here we will be content to argue informally. Suppose that $h_k \sim C_k^{-\alpha}$.

\[ 1 - H_0(1 - \delta) \sim \sum_k Ck^{-\alpha} \{1 - (1 - \delta)^k\} \]

Letting $x = k\delta$ the above is

\[ \sum_{xx/\delta \in \mathbb{Z}^+} C(x/\delta)^{-\alpha} \{1 - (1 - \delta)^{x/\delta}\} \sim \delta^{\alpha-1} \cdot \delta \sum_{xx/\delta \in \mathbb{Z}^+} Cx^{-\alpha} (1 - e^{-x}) \]

\[ \sim \delta^{\alpha-1} \int_0^\infty x^{-\alpha} (1 - e^{-x}) \, dx \]

Comparing with (2.1.6) suggests that $\alpha = 3/2$.

While the calculations above have been for the branching process, they work remarkably well for the random graph. In Section 1.6 we showed that in $ER(n, 1/n)$ the expected number of trees of size $k$ is

\[ \sim \frac{nk^{-5/2}}{\sqrt{2\pi}} e^{-k^3/(3n^2)} \]

so the probability of belonging to a component of size $k$ is asymptotically $Ck^{-3/2}$ while $k \ll n^{2/3}$. When $k = n^{2/3}$ this probability is $O(1/n)$ and there is an exponential cutoff.
2.2 Limiting degree distribution approach

2.2.1 Molloy and Reed (1985,1988)

In their approach one specifies $v_i(n)$, the number vertices of degree $i$. They assumed

(i) $v_i(n) \geq 0$

(ii) $\sum_i v_i(n) = n$

(iii) the degree sequence is feasible, i.e., $\sum_i iv_i(n)$ is even

(iv) the degree sequence is smooth, i.e., $\lim_{n \to \infty} v_i(n)/n = p_i$

(v) the degree sequence is sparse, i.e., $\sum_{i \geq 0} iv_i(n) \to \sum_i ip_i$.

Advantages of this approach. It is more general. The configuration model defined in the previous section has these properties with probability one. In the other direction, while the definition of the configuration model given in the previous section is simple and easy to implement, there are some problems:

(a) In the study of epidemics on graphs in Chapter 4 it is natural to pass to a subgraph by flipping a coin for each edge to determine if we keep it. It is not clear if the resulting graph is a configuration model as defined in the previous section. However it is obvious that the degree sequence of the thinned graph has the properties assumed above.

(b) One way to construct a random regular graph is to take $r$ random perfect matchings and superimpose the edges. This is definitely not something generated by the configuration model, but its degree sequence has the desired asymptotic properties.

(c) Finally, it would be nice if the Erdős-Renyi model emerged when we chosen the degree distribution in the configuration model to be Poisson but this is not the case. It does, however satisfy the conditions listed above.

The initial result of Molloy and Reed imposed stronger conditions on that maximum degrees than needed, but that problem was later removed. To state their main result (Theorem 1 on pages 164–165) recall that our condition for criticality is

$$1 = \sum(k - 1)kp_k/\mu.$$ 

Multiplying each side by $\mu$, recalling that $\mu = \sum_k kp_k$, and then subtracting gives

$$Q \equiv \sum_k k(k - 2)p_k = 0$$

The final detail before we can state their result is that they use asymptotically almost surely (a.a.s) for “with probability tending to 1 as $n \to \infty$,” something we call with high probability.
Theorem 2.2.1. Suppose (i)-(v) hold, and that $v_i(n) = 0$ for $i > n^{1/4-\epsilon}$.

a. If $Q > 0$ there are constants $\zeta_1, \zeta_2 > 0$ so that a.a.s. $G$ has a component with at least $\zeta_1 n$ vertices and $\zeta_2 n$ cycles.

b. Suppose $Q < 0$ and $v_i(n) = 0$ for $i \geq w_n$ where $w_n \leq n^{1/8-\epsilon}$. Then there is a $\beta > 0$ so that a.a.s. there is no cluster with $\beta w_n^2 \log n$ vertices.

Molloy and Reed (1995) did not get the exact size of the giant component since they used their lower bound on the growth starting from one point until the cluster reached size $\delta n$. In their 1998 article they prove a precise result about the size and proved a "duality result" that relates small clusters in the supercritical regime to those in the subcritical regime, which we will return to later. Let $\mu = \sum_i ip_i$ and define

$$\chi(\alpha) = \mu - 2\alpha - \sum_{i \geq 1} ip_i \left(1 - \frac{2\alpha}{\mu}\right)^{i/2}$$

Theorem 2.2.2. Let $\alpha^*$ be the smallest positive solution of $\chi(\alpha) = 0$ in $[0, \mu/2]$. The size of the giant component is

$$\epsilon^* = 1 - \sum_{i \geq 1} p_i \left(1 - \frac{2\alpha^*}{\mu}\right)^{i/2}$$

At first glance these formulas may not look much like the ones in Section 2.1. However, rewriting $\chi(\alpha^*) = 0$, dividing by $\mu$ and the dividing by $(1 - 2\alpha^*/\mu)^{1/2}$ we have

$$\left(1 - \frac{2\alpha^*}{\mu}\right)^{1/2} = \sum_{i \geq 1} \frac{ip_i}{\mu} \left(1 - \frac{2\alpha^*}{\mu}\right)^{(i-1)/2}$$

which shows that $\xi = (1 - 2\alpha^*/\mu)^{1/2}$ is a fixed point of $G_1$ the generating function of $q_{k-1} = kp_k/\mu$. With this established it is easy to see that the expression for $\epsilon^*$ in (2.2.1) is just $1 - G_0(\xi)$, which is the result in Theorem 2.1.3.

In the supercritical regime the finite clusters have the same distribution as a random graph with $(1 - \epsilon^*) n$ vertices and degree distribution

$$\hat{p}_i = \frac{p_i}{1 - \epsilon^*} \left(1 - \frac{2\alpha^*}{\mu}\right)^{i/2}$$

Since $\rho_1 = (1 - 2\alpha^*/\mu)^{1/2}$ this follows from our results for branching processes conditioned to die out. Note that $\hat{p}_k$ decays exponentially fast so the largest finite clusters have size $O(\log n)$.

2.2.2 Janson and Luczak (2009)

For each $n$ let $(d_i)_i^n$ be a sequence of nonnegative integers that give the degree sequence of the $n$th graph. Let $G(n, (d_i)_i^n)$ be a graph chosen at random from all of those with degree sequence $(d_i)_i^n$ (tacitly assuming that such a graph exists).
They also consider multigraphs (with self-loops and parallel edges) with the given degrees. Let \((d_i)^n\) be a degree sequence with \(\sum_{i=1}^{n} d_i^n\) even and let \(G^*(n, (d_i)^n)\) constructed by randomly pairing half-edges as in Section 2.1. \(G^*(n, (d_i)^n)\) is not a random choice from the set of multigraphs with the given degree distribution but when we condition on the graph being simple the result has the same distribution as \(G(n, (d_i)^n)\).

Following in the footsteps of Molloy and Reed they make the following assumptions, which we will call condition A.

(i) \(n_k/n = |\{i : d_i = k\}|/n \to p_k\) as \(n \to \infty\)
(ii) \(\lambda = \sum_k kp_k \in (0, \infty)\)
(iii) \(\sum_i d_i^2 = O(n)\)
(iv) \(p_1 > 0\)

Let \(D_n\) have \(P(D_n = k) = n_k/n\). This implies \(ED_n = n^{-2}d = 2m/n\), where \(m\) is the number of edges in the graph. Let \(D\) have \(P(D = k) = p_k\), and note that (ii) implies \(\lambda = ED\). In the new notation (i) says that \(D_n \Rightarrow D\) where \(\Rightarrow\) denotes convergence in distribution. (iii) says \(E(D^2_n) = O(1)\) so the dominated convergence theorem implies \(ED_n \Rightarrow ED\). Let

\[
g(x) = \sum_{k=0}^{\infty} p_k x^k, \quad h(x) = xg'(x) = \sum_{k=1}^{\infty} kp_k x^k, \quad H(x) = \lambda x^2 - h(x) \tag{2.2.2}
\]

Since \(h(0) = 0\) and \(h(1) = g'(1) = \lambda\) we have \(H(0) - H(1) = 0\). Note also that

\[
H'(1) = 2\lambda - \sum_k k^2 p_k = E(2D - D^2) = E[D(D - 2)]
\]

**Theorem 2.2.3.** Suppose condition A holds and let \(C_1, C_2\) be the two largest components in the resulting random graph \(G(n, (d_i)^n)\), let \(v(C_i)\) be the number of vertices in \(C_i\), let \(e(C_i)\) be the number of edges in \(C_i\), and \(v_k(C_i)\) be number of vertices of degree \(k\) in \(C_i\).

(i) If \(E[D(D - 2)] > 0\) then there is a unique \(\xi \in (0, 1)\) so that \(H(\xi) = 0\). The following convergences occur in probability

\[
\frac{v(C_1)}{n} \to 1 - g(\xi) > 0
\]

\[
\frac{v_k(C_1)}{n} \to p_k (1 - \xi^k) > 0
\]

\[
\frac{e(C_1)}{n} \to (\lambda/2)(1 - \xi^2)
\]

\[
\frac{v(C_2)}{n} \to 0, \quad \frac{e(C_2)}{n} \to 0
\]

(ii) If \(E[D(D - 2)] < 0\) then \(v(C_1)/n \to 0\) and \(e(C_1)/n \to 0\)

To compare with Theorem 2.1.3 we note that \(g\) here is the same as \(G_0\) there so \(\xi\) must the the extinction probability \(p_1\) fo the branching process with the size biased distribution \(q_k = kp_k/\mu\) and \(\mu = \sum_k kp_k\). For a long time I was mystified by the fact that the fixed point of \(G_1\) occurs at the same location of the zero of \(H\). The connection can found from (2.2.9) and (2.2.11) which together say that the number of active vertices \(A(t)/n \approx H(e^{-t})\) so the exploration process terminates at time \(\tau = -\log \xi\). The final piece of the puzzle comes from Lemma 2.2.6 and 2.2.7 which shows that the number of sleeping vertices \(S(t)/n \approx g(e^{-t})\).
Example 2.2.4. *binomial(3, p)* distribution. $p_k = \binom{3}{k} p^k (1-p)^k$. The mean $\lambda = 3p$ so

\[
g(x) = (1 - p + px)^3
\]
\[
h(x) = xg'(x) = x \cdot 3p(1 - p + px)^2
\]
\[
H(x) = 3px^2 - h(x)
\]

$E[D(D - 2)] = -p_1 + 3p_3 = -3p(1 - p)^2 + 3p^3 = 3p(p^2 - (1 - p)^2)$ so $p_c = 1/2$. The size-biased distribution has

\[
q_0 = [1 \cdot 3p(1 - p)^2]/3p = (1 - p)^2
\]
\[
q_1 = [2 \cdot 3p^2 (1 - p)]/3p = 2p(1 - p)
\]
\[
q_2 = [3 \cdot p^2]/3p = p^2
\]

which is *binomial(2,p)*. This surprised me the first time I computed it but it really should not have. The size-biased mean $\nu = 2p$.

The extinction probability for the branching process with the size-biased distribution satisfies $(1 - p + pz)^2 = z$ which expands to

\[
(1 - p)^2 + [2p(1 - p) - 1]z + p^2z^2 = 0
\]

so using the quadratic formula

\[
\rho_1 = \frac{1 - 2p(1 - p) \pm \sqrt{1 - 4p(1 - p)}}{2p^2}
\]
CHAPTER 2. GENERAL DEGREE DISTRIBUTIONS

When $p = 1/2$, $z = 1$ is a double root. For this to be $< 1$ when $p > 1/2$ we want the minus root. For a graph of numerical values see Figure 2.4. To prepare for the next figure note that when $p = 0.6$ the extinction probability is $4/9$.

Proof of Theorem 2.2.3. As in Section 1.3, we build up the cluster by exposing neighbors of vertices one at a time until we have found the cluster. However the details here are somewhat different than for Erdös-Rényi.

Following Janson and Luczak we described the procedure first informally and then give a more precise description. We regard each edge as two half-edges with each half-edge having one vertex. We label the vertices as sleeping or awake ( = used), and the half-edges as sleeping, active, or dead. We start with all vertices and half-edges sleeping.

- Pick a vertex label it as awake and label its half-edges active.
- Then take any half edge $x$ and find its partner $y$ in the graph, and label these two half-edges as dead.
- If the endpoint of $y$ is sleeping, label it as awake and all other half-edges as active.
- Repeat until there are no more active half-edges. When this occurs we have found the first component. Pick a new sleeping vertex and start again.

To implement this for the random multigraph $G^*(n,(d_i)^n)_{1}$ we construct the graph at the same time as we build the cluster. Each time we need to find the partner of a half-edge it is uniformly distributed over all the living half-edges. To make these choices we assign each half-edge $x$ a random variable $\tau_x$ that is exponential(1). The authors think of this as the
time the half-edge dies. We will add “of natural causes” because some half-edges are killed in step 2.

1. If there is no active half-edge select a sleeping vertex, declare it awake and all of its half-edges active. For definiteness we choose the vertex by choosing a sleeping half-edge at random. If there is no sleeping half-edge then the process stops and all the remaining sleeping vertices are isolated.

2. If there is at least one active half-edge pick one at random and kill it. Note that this does not change the number of sleeping edges.

3. Wait until the next half-edge ties and then pair it with the edge just killed. If its vertex is sleeping we make it awake and make all of the other half-edges active. Then repeat step 1.

Let $S(t)$ and $A(t)$ be the number of sleeping and active half-edges at time $t$, and let

$$L(t) = S(t) + A(t)$$

be the number of living edges. (2.2.3)

We start with all $2m$ half-edges sleeping but immediately we do steps 1 and 2 so $L(0) = 2m - 1$. At later stages once one half-edge dies we either perform step 2 or both steps 1 and 2. Since 1 does not change the number of living half-edges while 2 and 3 each decrease it by 1, $L(t)$ is decreased by 2 each time a living half-edge dies.

**Lemma 2.2.5.** As $n \to \infty$

$$\sup_{t \geq 0} \left| \frac{L(t)}{n} - \lambda e^{-2t} \right| \to 0$$

*Proof.* $\sum_i d_i^n = 2m$, so $L(0)/n = \sum_i d_i^n/n \to \lambda$. To see where the 2 comes from in $e^{-2t}$ note that if half-edges $x$ and $y$ are eventually paired to make an edge then these half-edges are only alive if $\tau_x$ and $\tau_y$ are both larger than $t$. The convergence of

$$\sup_{t \geq 0} \left| \frac{1}{m} \left| \{(x, y) : \min\{\tau_x, \tau_y\} > t\} \right| - e^{-2t} \right| \to 0$$

follows from the proof of the Glivenko-Cantelli theorem (Theorem 2.4.9 in PTE5), i.e., if a sequence of decreasing functions converges to a bounded continuous limit then the convergence occurs uniformly. □

Let $V_k(t)$ be the number of sleeping vertices of degree $k$ then

$$S(t) = \sum_{k=1}^{\infty} kV_k(t)$$

Step 2 does not affect the number of sleeping half-edges, while in step 3 each sleeping vertex of degree $k$ is eliminated at rate $k$. To ignore the effect of step 1 we first let $\tilde{V}_k(t)$ be the number of vertices all of whose half-edges have $\tau_x > t$, and note that

$$V_k(t) \leq \tilde{V}_k(t)$$

(2.2.4)
Lemma 2.2.6. As \( n \to \infty \)
\[
\sup_{t \geq 0} \left| \frac{\tilde{V}_k(t)}{n} - p_k e^{-kt} \right| \to 0 \tag{2.2.5}
\]
for every \( k \geq 0 \) and
\[
\sup_{t \geq 0} \left| \sum_{k=0}^{\infty} \frac{\tilde{V}_k(t)}{n} - g(e^{-t}) \right| \to 0 \tag{2.2.6}
\]
where \( g(z) = \sum_k p_k z^k \). Hence if \( \tilde{S}(t) = \sum_k k \tilde{V}_k(t) \) then
\[
\sup_{t \geq 0} \left| \sum_{k=0}^{\infty} \frac{\tilde{S}(t)}{n} - h(e^{-t}) \right| \to 0 \tag{2.2.7}
\]
where \( h(z) = \sum_k p_k z^k \).

Proof. The proof of the first conclusion is almost the same as the proof of Lemma 2.2.6. The next two results follow from the first by summing. To do this rigorously one must use the dominated convergence theorem, but its use is justified by the assumption that \( \sum_k k^2 p_k \) is bounded.

Lemma 2.2.7. If \( d_{\max} = \max_i d_i \) is the maximum degree of \( G^*(n,(d_i)_i^n) \) then
\[
0 \leq \tilde{S}(t) - S(t) \leq \sup_{0 \leq s \leq t} (\tilde{S}(t) - L(t)) + d_{\max} \tag{2.2.8}
\]

Proof. (2.2.4) implies \( S(t) \leq \tilde{S}(t) \). The difference \( \tilde{S}(t) - S(t) \) can only increase as a result of step 1. If step 1 is performed at time \( t \) on a vertex of degree \( j \) then there are no active vertices. Step 2 applies immediately and we have \( A(t) = j - 1 < d_{\max} \) so using (5.4.1)
\[
\tilde{S}(t) - S(t) = \tilde{S}(t) - L(t) + A(t) < \tilde{S}(t) - L(t) + d_{\max}
\]
\( \tilde{S}(t) - S(t) \) is never changed by step 2 and either unchanged or decreased by step 3 so \( \tilde{S}(t) - S(t) \) does not increase until the next time step 1 is performed.

Let
\[
\tilde{A}(t) = L(t) - \tilde{S}(t) = A(t) - (\tilde{S}(t) - S(t)) \tag{2.2.9}
\]
Then by Lemmas 2.2.5 and 2.2.6
\[
\sup_{t \geq 0} \left| \frac{\tilde{A}(t)}{n} - H(e^{-t}) \right| \to 0 \tag{2.2.9}
\]
Lemma 2.2.7 can be written as
\[
0 \leq (\tilde{S}(t) - S(t)) < -\inf_{s \leq t} \tilde{A}(s) + d_{\max} \tag{2.2.10}
\]
From (2.2.8) and (2.2.10) we obtain the relation
\[
\tilde{A}(t) \leq A(t) < \tilde{A}(t) - \inf_{s \leq t} \tilde{A}(s) + d_{\max} \tag{2.2.11}
\]
Lemma 2.2.8. Suppose A holds. Recall \( H(x) = \lambda x^2 - h(x) \) where \( h(x) = \sum_{k=1}^{\infty} kp_k x^k \).

(i) if \( E[D(D - 2)] > 0 \) then there is a unique \( \xi \in (0, 1) \) so that \( H(\xi) = 0 \). Moreover \( H(x) < 0 \) for \( x \in (0, \xi) \) and \( H(x) > 0 \) for \( x \in (\xi, 1) \).

(ii) If \( E[D(D - 2)] \leq 0 \) then \( H(x) < 0 \) for \( x \in (0, 1) \).

Proof. As remarked earlier \( H(0) = H(1) = 0 \) and \( H'(1) = -E[D(D - 2)] \). Let \( \phi(x) = H(x)/x = \lambda x - \sum_{k=1}^{\infty} kp_k x^{k-1} \).

\[
\phi'(x) = \lambda - \sum_{k=2}^{\infty} k(k-1)p_k x^{k-2}
\]

\[
\phi''(x) = -\sum_{k=3}^{\infty} k(k-1)(k-2)p_k x^{k-3}
\]

so \( \phi \) is strictly concave unless \( p_k = 0 \) for \( k \geq 3 \). In this case \( H(x) = (\lambda - p_2)x^2 - p_1 x - p_0 \) is a quadratic. \( H'(1) = -E[D(D - 2)] = p_1 > 0 \) by assumption (iv) so we are in case (ii). Since \( H(0) = 0 \) there can be no roots in \( (0, 1) \) and \( H(x) > 0 \) for \( x \in (\xi, 1) \).

For the rest of the proof we can suppose \( \phi \) is strictly concave. In case (ii) we have \( \phi'(x) = H'(x)/x - H(x)/x^2 \) so \( \phi'(1) = H'(1) - H(1) \geq 0 \). Since \( \phi' \) is decreasing so \( \phi'(y) > 0 \) for \( y < 1 \) and \( \phi(x) < \phi(1) = 0 \).

In case (i) \( H'(1) < 0 \) and thus \( H(x) > 0 \) for \( x \) close to 1. \( H'(0) = -h'(0) = -p_1 < 0 \) and thus \( H(x) < 0 \) for \( x \) close to 0. From this we conclude that there is at least one \( \xi \in (0, 1) \) with \( H(\xi) = 0 \). The strict concavity of \( \phi(x) = H(x)/x \) implies there cannot be another solution in \( (0, 1) \).

Proof of part (i) of Theorem 2.2.3. Let \( \xi \) be the zero of \( H \) given in Lemma 2.2.8 and let \( \tau = -\log \xi \). Then by Lemma 2.2.8 \( H(e^{-t}) > 0 \) for all \( 0 < t < \tau \) and thus \( \inf_{t \leq \tau} H(e^{-t}) = 0 \). Consequently (2.2.9) implies

\[
n^{-1} \inf_{t \leq \tau} \tilde{A}(t) = \inf_{t \leq \tau} n^{-1} \tilde{A}(t) - \inf_{t \leq \tau} H(e^{-t}) \to 0 \tag{2.2.12}
\]

By Condition (iii) \( d_{\max} = O(n^{1/2}) \) and thus \( n^{-1} d_{\max} \to 0 \). Consequently (2.2.10) and (2.2.12) yield

\[
\sup_{t \leq \tau} n^{-1} |A(t) - \tilde{A}(t)| = \sup_{t \leq \tau} n^{-1} |\tilde{S}(t) - S(t)| \to 0 \tag{2.2.13}
\]

and thus by (2.2.9)

\[
\sup_{t \leq \tau} |n^{-1} A(t) - H(e^{-t})| \to 0 \tag{2.2.14}
\]

Let \( 0 < \epsilon < \tau/2 \). Since \( H(e^{-t}) > 0 \) on the compact interval \( [\epsilon, \tau - \epsilon] \), (2.2.14) implies that with high probability \( A(t) \) remains positive on \( [\epsilon, \tau - \epsilon] \) and thus no new component is started during this interval.
On the other hand by (i) of Lemma 2.2.8, \( H(e^{-t}) < 0 \) and (2.2.9) implies \( \tilde{A}(t + \epsilon) \to H(e^{-t}) \). Since \( A(\tau + \epsilon) \geq 0 \), if we let \( \delta = |H(e^{-t})|/2 \)

\[
\tilde{S}(\tau + \epsilon) - S(\tau + \epsilon) = A(\tau + \epsilon) - \tilde{A}(\tau + \epsilon) \geq -\tilde{A}(\tau + \epsilon) > n\delta
\]  

while (2.2.13) gives \( \tilde{S}(\tau) = \tilde{S}(\tau) < n\delta \) whp. Consequently whp

\[
\tilde{S}(\tau + \epsilon) - S(\tau + \epsilon) > \tilde{S}(\tau) - S(\tau)
\]

so step 1 is performed between \( \tau \) and \( \tau + \epsilon \). Let \( T_1 \) be the last time step 1 was performed before \( \tau/2 \) and let \( T_2 \) be the next time it is performed after \( \tau/2 \). We have shown that \( T_1 \leq \epsilon \) and \( \tau - \epsilon \leq T_2 \leq \tau + \epsilon \). In other words, \( T_1 \to 0 \) and \( T_2 \to \tau \).

**Lemma 2.2.9.** Let \( T_1^* \) and \( T_2^* \) be two (random) times when step 1 is performed with \( T_1^* \leq T_2^* \) and assume that \( T_1^* \to t_1 \) and \( T_2^* \to t_2 \) where \( 0 \leq t_1 \leq t_2 \leq \tau \). If \( C^* \) is the union of all the components explored between \( T_1^* \) and \( T_2^* \) then

\[
\begin{align*}
\nu_k(C^*)/n &\to p_k(e^{-kt_1} - e^{-kt_2}) & (2.2.16) \\
\nu(C^*)/n &\to g(e^{-t_1}) - g(e^{-t_2}) & (2.2.17) \\
e(C^*)/n &\to [h(e^{-t_1}) - h(e^{-t_2})]/2 & (2.2.18)
\end{align*}
\]

In particular if \( t_1 = t_2 \) then \( \nu(C^*)/n \to 0 \) and \( e(C^*)/n \to 0 \).

**Proof.** \( C^* \) contains all of the vertices awakened in \([T_1^*, T_2^*]\) and no others so for \( k \geq 1 \)

\[
\nu_k(C^*) = V_k(T_1^*-) - V_k(T_2^*-) = (2.2.19)
\]

Since \( T_2^* \to t_2 \) and \( H \) is continuous

\[
\inf_{t \leq T_2^*} H(t) \to \inf_{t \leq t_2} H(t) = 0
\]

and (2.2.9) and (2.2.10) imply, in analogy with (2.2.12) and (2.2.13) that \( \inf_{t \leq T_2^*} n^{-1}\tilde{A}(t) \to 0 \) and

\[
\sup_{t \leq T_2^*} n^{-1}|\tilde{S}(t) - S(t)| \to 0
\]  

(2.2.20)

Since \( \tilde{V}_j(t) \geq V_j(t) \) for every \( j \) and \( t \geq 0 \) then for all \( k \geq 1 \)

\[
\tilde{V}_k(t) - V_k(t) \leq k^{-1} \sum_{j=1}^{\infty} j(\tilde{V}_j(t) - V_j(t)) \leq k^{-1}(\tilde{S}(t) - S(t))
\]  

(2.2.21)

Hence (2.2.20) implies that for every \( k \geq 1 \)

\[
\sup_{t \leq T_2^*} n^{-1}|\tilde{V}_k(t) - V_k(t)| = o_p(n)
\]  

(2.2.22)
This is trivially true for \( k = 0 \). Consequently using Lemma 2.2.6 we have for \( j = 1, 2 \)
\[
V_k(T_j^*-T_j^*) = \tilde{V}_k(T_j^*-T_j^*) = np_k \exp(-kT_j^*) + o_p(n) = np_k \exp(-kt_j) + o_p(n) \tag{2.2.22}
\]
and (2.2.16) follows from (2.2.19).

Similarly using \( \sum_{k=0}^{\infty} \tilde{V}_k(t) - V_k(t) \tilde{S}(t) - S(t) \)
\[
v(C^*) = \sum_{k=1}^{\infty} V_k(T_1^*-T_2^*) - V_k(T_2^*)
\]
\[
= \sum_{k=1}^{\infty} \tilde{V}_k(T_1^*) - \tilde{V}_k(T_2^*) + o_p(n) = ng(e^{-T_1^*}) - ng(e^{-T_2^*}) + o_p(n)
\]
and
\[
2e(C^*) = \sum_{k=1}^{\infty} k[V_k(T_1^*-T_2^*)] = \sum_{k=1}^{\infty} k[\tilde{V}_k(T_1^*) - \tilde{V}_k(T_2^*)] + o_p(n) = nh(e^{-T_1}) - nh(e^{-T_2}) + o_p(n)
\]
(2.2.17) and (2.2.18) follow.

Let \( C' \) be the component created at \( T_1 \) and explored until \( T_2 \). By Lemma 2.2.9 with \( t_1 = 0 \) and \( t_2 = \tau \).

\[
v_k(C')/n \to p_k(1 - e^{-k\tau}) \tag{2.2.23}
\]
\[
v(C')/n \to g(1) - g(e^{-\tau}) = 1 - g(\xi) = 1 - g(\xi) \tag{2.2.24}
\]
\[
e(C')/n \to [h(1) - h(\xi)]/2 = \frac{\lambda}{2}(1 - \xi^2) \tag{2.2.25}
\]

At this point we have discovered the largest component and discovered its size. We leave it to the reader to show that all the other components have size \( o(n) \), and to prove part (ii) of Theorem 2.2.3. The details can be found in Janson and Luczak.

### 2.3 Subcritical cluster sizes

In subcritical Erdős-Rényi random graphs the largest component is \( O(\log n) \). This result is false for graphs with arbitrary degree distributions. Suppose for example that \( p_k \sim ck^{-\gamma} \) where \( \gamma > 3 \) to make the second moment \( \sum k^2 p_k < \infty \). The tail of the distribution \( \sum_{k=K}^{\infty} p_k \sim cK^{1-\gamma} \) so the largest degree present in a graph with \( n \) vertices is \( O(n^{1/(\gamma-1)}) \).
This is a trivial lower bound on the size of the largest component but it turns out to be accurate up to a constant factor.

In the previous 2007 version of this book this statement was a conjecture. Now, thanks to Janson (2008) it is a theorem. He works in the set-up of the limiting degree distribution approach. Let

\[ \mu_n = E D_n = \frac{1}{n} \sum_{k=0}^{\infty} k n_k = \frac{1}{n} \sum_{i=1}^{n} d_i \]

\[ \nu_n = \frac{1}{n \mu_n} \sum_{k=0}^{\infty} k(k-1) n_k = \frac{1}{n \mu_n} \sum_{i=1}^{n} d_i (d_i - 1) \]

**Theorem 2.3.1.** Suppose \( \mu_n \to \mu_\infty > 0, \nu_n \to \nu_\infty < 1, \) and

\[ P(D_n \geq k) \leq C_1 k^{1-\gamma} \]  \hspace{1cm} (2.3.1)

for some \( \gamma > 3 \) and \( C_1 < \infty, \) then there is a constant \( A \) so that

\[ |C_1| \leq An^{1/(\gamma-1)} \]

To explain this result note that if \( x \) is the vertex with largest degree and \( \Delta_n = m \) then the law of large numbers implies that the number of vertices at distance 2 from \( x \) in \( C_x \) is \( \sim m \nu_n, \) or more generally the number of vertices at distance \( k \) from \( x \) is \( \sim m^{k-1} \nu_n. \) Summing the geometric series and ignoring the interchange of limit and sum we have the first term in the following sharper result.

**Theorem 2.3.2.** Let \( \Delta_n = \max_{1 \leq i \leq n} d_i \) be the maximum degree of \( G(n, (d_i)_i^n). \)

\[ |C_1| = \frac{\Delta_n}{1 - \nu_n} + o_p(n^{1/(\gamma-1)}) \]  \hspace{1cm} (2.3.2)

**Proof of Theorem 2.3.1.** As in the previous section the author finds it convenient to work with multigraphs that allow multiple edges and loops. Let \( (d_i)_i^n \) be a sequence of nonnegative integers such that \( \sum_{i=1}^{n} d_i \) is even. Assign \( d_i \) half-edges to vertex \( i \) and then pair the half-edges at random to make a graph that we again call \( G^*(n, (d_i)_i^n). \) Define \( G(n, (d_i)_i^n) \) by conditioning \( G^*(n, (d_i)_i^n) \) to be simple. The assumption (2.3.1) implies that the limiting probability \( G^* \) is simple is positive.

Fix a vertex \( v \) and explore the component \( C(v) \) by the standard exploration process. The process begins by declaring \( v \) used and all the half-edges at \( v \) to be active. We reveal the random configuration only as we need it, or equivalently we construct the random configuration as we need it. Then for \( i = 1, 2, \ldots, \) as long as there is an active half-edge, we pick one \( x_i. \) We choose its partner half-edge \( y_i \) uniformly among all the half-edges except \( x_i \) and the ones that have been paired and let \( v_i \) be its vertex. If the vertex is not already used we declare its other \( d(v_i) - 1 \) half-edges active. Finally declare \( x_i, y_i, v_i \) used. Repeat.
Let \( S_i \) be the number of active half-edges after \( i \) steps. \( S_0 = d(v) \) while
\[
S_i = S_{i-1} + \xi_i - 1
\]
where \( \xi_i \) is the number of new half-edges found at the \( i \)th step. \( \xi_i = 0 \) if \( v_i \) is used and \( \xi_i = d(v_i) - 1 \) if not. The process stops at \( \tau = \inf \{ t : S_t = 0 \} \). The component \( C(v) \) has \( \tau \) edges and at most \( \tau + 1 \) vertices. In particular, for any integer \( M > 0 \) if \( |C(v)| > M \) then \( \tau \geq M \). This implies
\[
S_M = d(v) + \sum_{i=1}^{M}(\xi_i - 1)
\]
and thus
\[
d(v) + \sum_{i=1}^{M} \xi_i \geq M
\]

The random variables \( \xi_i \) are dependent but we can bound them by independent random variables. Suppose that \( i \leq \sqrt{n} \). \( (\gamma > 3 \text{ so } 1/(\gamma - 1) < 1/2.) \) If \( \xi_i = k \geq 1 \) then \( d(v_i) = k + 1 \) so there are at most \( n_{k+1} = nP(D = k + 1) \) possible choices for \( v_i \) and thus
\[
(k + 1)n_{k+1} = n(k + 1)P(D = k + 1)
\]
choices for the half-edge \( y_i \). When \( y_i \) is chosen we have revealed the pairing of \( 2(i - 1) \) half-edges and chosen \( x_i \) but \( y_i \) is uniformly distributed over all \( \sum_{j=1}^{n} d_i - 2(i - 1) - 1 = n\mu - O(n^{1/2}) \)
remaining half-edges. Hence given all the history of the process up to step \( i \)
\[
P(\xi_i = k) \leq \frac{n(k + 1)P(D = k + 1)}{n\mu - O(n^{1/2})} \leq \frac{(k + 1)P(D = k + 1)}{\mu}(1 + O(n^{-1/2}))
\]
Note that the correction term in the last equation is independent of \( k \) and \( i \leq \sqrt{n} \)

Fix \( \epsilon > 0 \) with \( 4\epsilon < 1 - \nu_\infty \) and let \( \nu' = \nu + \epsilon \). We suppose \( n \) is large enough so that \( \nu = \nu_n < 1 - 3\epsilon \) so \( \nu' < 1 - 2\epsilon \). Let \( X \) be an integer value random variable with
\[
P(X \geq k) = \max \left( 1, \frac{\nu'}{\nu} \sum_{k \geq x} \frac{(k + 1)P(D = k + 1)}{\mu} \right)
\]
If \( n \) is large enough (not depending on \( k \)) the factor \( (1 + O(n^{-1/2})) \) in (2.3.4) is smaller than \( \nu'/\nu \) so
\[
P(\xi_x \geq x) \leq P(X \geq x)
\]
even if we condition on \( \xi_1, \ldots, \xi_i \). Thus the \( \xi_i \) can be coupled with independent random variables \( X_i \) so that
\[
\xi_i \leq X_i \quad \text{for all } 1 \leq i \leq \sqrt{n}
\]
In addition we trivially have
\[ \xi_i \leq \Delta \] (2.3.7)

For the remainder of the proof we will only use the last two properties of \( \xi_i \).

By (2.3.5) and the assumptions of the theorem
\[
EX = \sum_{m=1}^{\infty} P(X \geq m) \leq \frac{\nu'}{\nu} \sum_{m=1}^{\infty} \sum_{k=m}^{\infty} \frac{(k+1)P(D = k + 1)}{\mu}
\]
\[
\leq \frac{\nu'}{\nu} \sum_{k=1}^{\infty} \frac{k(k+1)P(D = k + 1)}{\mu} = \frac{\nu'}{\nu} \cdot \nu' = \nu'
\] (2.3.8)

where to go from the first line to the second we have interchanged the order of summation. If we let \( m = \lceil x \rceil \) then using various definitions along with some simple arithmetic we conclude that for all \( x \geq 0 \)
\[
P(X \geq x) \leq \frac{\nu'}{\nu} \sum_{k=m}^{\infty} \frac{(k+1)P(D = k + 1)}{\mu}
\]
\[
\leq C_3 \sum_{k=m+1}^{\infty} kP(D = k) \]
\[
= C_3 \left( mP(D > m) + \sum_{j=m+1}^{\infty} P(D \geq j) \right)
\]
\[
\leq C_4 m^{2-\gamma} + C_4 \sum_{j=m+1}^{\infty} j^{1-\gamma} \leq C_5 m^{2-\gamma} \leq C_5 x^{2-\gamma}
\] (2.3.9)

For some \( A \) large and \( \delta < 1/(\gamma - 1) \) small to be chosen later let
\[
M = An^{1/(\gamma - 1)} \quad \text{and} \quad M_1 = n^{1/(\gamma - 1) - \delta}
\] (2.3.10)

Note that \( M \) is the desired upper bound on \( C_1 \). If we define the truncated random variables
\( Y_i = X_i 1_{(X_i \leq M_1)} \) then by (2.3.8), \( EY_i \leq EX_i \leq \nu' \). If \( |C(v)| > M \) then (2.3.3) holds and so using \( \xi_i \leq \Delta \)
\[
M \leq d(v) + \sum_{i=1}^{M} d_i \leq \Delta + \sum_{i=1}^{M} \xi_i 1_{(X_i \leq M_1)} + \sum_{i=1}^{n} \xi_i 1_{(X_i > M_1)}
\]
\[
\leq \sum_{i=1}^{M} Y_i + \Delta \left( 1 + \sum_{i=1}^{M} 1_{(X_i > M_1)} \right) \]
\[
\leq \nu' M + \sum_{i=1}^{M} (Y_i - EY_i) + \Delta \left( 1 + \sum_{i=1}^{n} 1_{(X_i > M_1)} \right)
\] (2.3.11)
and thus recalling $\nu' < 1 - 2\epsilon$
\[
P(|C(v)| \geq M) \leq P \left( \sum_{i=1}^{M} (Y_i - EY_i) > \epsilon M \right) + P \left( \sum_{i=1}^{M} 1_{(X_i > M_1)} > \epsilon \frac{M}{\Delta} - 1 \right) \tag{2.3.12}
\]

For the first sum in (2.3.12) fix a number $r \geq \gamma$ so that $r\delta > 2$. Rosenthal’s inequality for nonnegative random variables states (this is Theorem 3.9.1 of Gut (2005) but if you don’t have that book you can consult (2) in Ibragimov and Sharakhmentov (2001))
\[
E \left( \sum_{k=1}^{n} Z_i \right)^r \leq C_r \max \left( \left( \sum_{k=1}^{n} EZ_i^2 \right)^{r/2}, \sum_{k=1}^{n} EZ_i^r \right) \tag{2.3.13}
\]

Letting $Z_i = |Y_i - EY_i|$ we have
\[
E \left( \sum_{k=1}^{n} |Y_i - EY_i| \right)^r \leq C_r \left( (nE(Y_i - EY_i)^2)^{r/2} + nE|Y_i - EY_i|^r \right)
\]

Taking $n = M$ and numbering the constants as Janson has done in his proof, we have
\[
E \left( \sum_{i=1}^{M} |Y_i - EY_i| \right)^r \leq C_6 M^{r/2}(E|Y_i - EY_i|^2)^{r/2} + C_7 ME|Y_1 - EY_1|^r
\leq C_6 M^{r/2}(EY_1^2)^{r/2} + C_8 MEY_1^r \tag{2.3.14}
\]

To go from the first line to the second we note that $E(X - c)^2$ is minimized when $c = EX$. For the second term we note that using $E(Y; A)$ for the integral of $Y$ over $A$
\[
E|X - EX|^r = E(|X - EX|^r; X \geq EX) + E(|X - EX|^r; X \leq EX)
\leq E(|X|^r; X \geq EX) + |EX|^r P(X \leq EX) \leq 2E|X|^r
\]

where on the second line we have used the fact that $X \geq 0$ and then Jensen’s inequality to put the $r$th power inside.

We estimate the second moment of $Y_1$ using (2.3.9)
\[
EY_1^2 = \int_{0}^{\infty} 2xP(Y_1 > x) \, dx = \int_{0}^{M_1} 2xP(X > x) \, dx
\leq 1 + C_5 \int_{1}^{M_1} 2x^{3-\gamma} \, dx \leq C_9 M_1 \tag{2.3.15}
\]

since $\gamma > 3$. Trivially $EY_1^r \leq M_1^r$. Using Markov’s inequality on (2.3.14), the second moment estimate in (2.3.15), $Y_1 \leq M_1$ and $M_1/M = A^{-1}n^{-\delta}$
\[
P \left( \sum_{i=1}^{M} |Y_i - EY_i| > \epsilon M \right) \leq (\epsilon M)^{-r} E \left( \sum_{i=1}^{M} |Y_i - EY_i|^r \right)\]
\leq C_{10}(EY_1^2/M)^{r/2} + C_{11}M^{1-r}EY_1^r
\leq C_{12}(M_1/M)^{r/2} + C_{13}M(M_1/M)^r
\leq C_{14}n^{-r\delta/2} + C_{15}n^{1-r\delta} = o(n^{-1}) \tag{2.3.16}
\]
since \( r\delta > 2 \).

For the second sum in (2.3.12) write \( I_i = 1_{(X_i > M)} \) and note that

\[
P\left( \sum_{i=1}^{M} I_i \geq L \right) \leq \binom{M}{L} P(I_k = 1, 1 \leq k \leq L)
= \binom{M}{L} P(I_1 = 1)^L = \binom{M}{L} P(X > M)^L \leq (MP(X > M_1))^L
\]

(2.3.17)

Now by (2.3.9) and the choice of \( M \)

\[
MP(X_1 > M_1) \leq C_5 An^{1/(\gamma - 1) + (2-\gamma)[1/(\gamma - 1) - \delta]} = CA n^{(\gamma - 2)\delta - (\gamma - 3)/(\gamma - 1)}
\]

Choose \( \delta > 0 \) so that \( \delta_1 = (\gamma - 3)/(\gamma - 1) - (\gamma - 2)\delta > 0 \). Then \( MP(X_1 > M_1) = O(n^{-\delta_1}) \) and

\[
P\left( \sum_{i=1}^{M} I_i \geq L \right) = O(n^{-L\delta_1}) \tag{2.3.18}
\]

Now choose \( L > 1/\delta_1 \) and then \( A \geq C_2(L + 1)/\epsilon \). Since \( \Delta \leq C_2 n^{1/(\gamma - 1)} \)

\[
\frac{M}{\Delta} \geq \frac{A}{C_2} \geq \frac{L + 1}{\epsilon}
\]

(2.3.19)

It follows from (2.3.18) that

\[
P\left( \sum_{i=1}^{M} I_i \geq \frac{\epsilon M}{\Delta} - 1 \right) \leq P\left( \sum_{i=1}^{M} I_i \geq L \right) = O(n^{-L\delta_1}) = o(n^{-1})
\]

Consequently (2.3.12) shows that that \( P(|C(v)| > M) = o(n^{-1}) \). Since this holds for every vertex it follows that with high probability \( |C(v)| \leq M = An^{1/(\gamma - 1)} \) and the proof of Theorem 2.3.1 is complete.

\[
\square
\]

2.4 Distance between two randomly chosen vertices

In this section we will consider the distance between two vertices chosen randomly from the giant component of a random graph generated by the configuration model.

2.4.1 Finite variance

To be precise, we assume that the random degree \( D \) has \( P(D \geq x) \leq x^{-\gamma + 1} \) with \( \gamma > 3 \). The results here follow van der Hofstad, Hooghiemstra, and Van Mieghem (2005). Let \( \mu = ED \) and let \( \nu = E(D(D - 1))/ED \) be the mean of the size biased distribution. Let \( Z_m \) be the two phase branching process and let

\[
W = \lim_{m \to \infty} \frac{Z_m}{\mu \mu^{m-1}} \tag{2.4.1}
\]
2.4. DISTANCE BETWEEN TWO RANDOMLY CHOSEN VERTICES

Theorem 2.4.1. Suppose \( \nu > 1 \). Let \( H_n \) be the distance between 1 and 2 in the random graph on \( n \) vertices. For \( k \geq 1 \), let \( a(k) = \lfloor \log_\nu k \rfloor - \log_\nu k \in (-1,0] \). As \( n \to \infty \)

\[
P(H_n = k|H_n < \infty) = P(R_{a(n)} = k) + o(1)
\]

If \( \kappa = \mu(\nu - 1)^{-1} \) then for \( a \in (-1,0] \)

\[
P(R_a > k) = E(\exp(-\kappa\nu^{a+k}W_1W_2)|W_1W_2 > 0)
\]

where \( W_1 \) and \( W_2 \) are independent copies of \( W \) defined in (2.4.1).

\[
x = \log_\nu k \text{ has } \nu^x = k, \text{ i.e., } x = \log n/\log \nu, \text{ so the answer has the same intuitive explanation as the one in Theorem 1.2.5 for Erdös-Rényi random graph. The strength of this result is that it shows that the fluctuations around the limit are } O(1). \text{ The statement is made complicated by the fact that } H_n \text{ is always an integer so the support of } H_n - \log_\nu n \text{ changes with } n.
\]

The proof of Theorem 2.4.1 is done by a careful comparison of the growing cluster and branching process. The proof is about 30 pages, so we will content ourselves to explain where the formula for the distribution of \( R_a \) comes from and refer the reader to the original paper for details. The total number of oriented edges is \( \sim \mu n \) as \( n \to \infty \), so for our sketch we will suppose that it is always equal to \( \mu n \). Taking turns growing each cluster by one branching step,

\[
P(H_n > k) \approx E \exp \left( -\sum_{i=2}^{k+1} \frac{Z_{[i/2]}^1 Z_{[i/2]}^2}{\mu n} \right)
\]

Here, one needs to look closely at the indices. We round up in the first case, and down in the second, so for \( i = 2, 3, 4, \ldots \) we get \((i/2], [i/2]) = (1,1), (2,1), (2,2), \ldots \). When \( k = 1 \) there is only one term in the sum: \( Z_1^1 Z_2^2 / \mu n \). This gives the expected number of the \( Z_1^1 \) half-edges from 1 that are paired with one of the \( Z_2^2 \) half-edges from 2. The distance is \( > 1 \) if and only if the number of such pairings is 0. Since the events are almost independent, the number of pairings (conditional on the values of \( Z_1^1 \) and \( Z_2^2 \)) is roughly Poisson and the probability of 0 is \( E \exp(-Z_1^1 Z_2^2 / \mu n) \).

Letting \( \sigma_n = \lfloor \log_\nu n \rfloor \) and writing \( n = \nu^{\log_\nu n} = \nu^{\sigma_n - a_n} \) we have

\[
P(H_n > \sigma_n + j) \approx E \exp \left( -\mu \nu^{\sigma_n + k} \sum_{i=2}^{\sigma_n+j+1} \frac{Z_{[i/2]}^1 Z_{[i/2]}^2}{\mu^2 \nu^{\sigma_n+j}} \right)
\]

\([i/2] + [i/2] = i\) so using (2.4.1)

\[
\frac{Z_{[\sigma_n+j+1/2]}^1 Z_{[(\sigma_n+j+1)/2]}^2}{\mu^2 \nu^{\sigma_n+j-1}} \to W_1^2 W^2
\]

and it follows that

\[
\sum_{i=2}^{\sigma_n+j+1} \frac{Z_{[i/2]}^1 Z_{[i/2]}^2}{\mu^2 \nu^{\sigma_n+j}} \to \nu^{-1} W_1 W_2 \sum_{k=0}^{\infty} (1/\nu)^k = \frac{1}{\nu - 1}
\]
Combining our results gives
\[ P(H_n > \sigma_n + j|H_n < \infty) \approx E(\exp(-\kappa\nu^{\alpha n} + jW_1W_2)|W_1W_2 > 0) \]
with \( \kappa = \mu/(\nu - 1) \).

### 2.4.2 Power laws \( 2 < \gamma < 3 \)

Consider a random graph with degree distribution \( p_k \sim C_pk^{-\gamma} \) where \( 2 < \gamma < 3 \). In this case, \( q_{k-1} = kp_k/\mu \sim C_qk^{1-\gamma} \), so the mean is infinite and the tail of the distribution

\[ Q_K = \sum_{k=K}^{\infty} q_k \sim C_Qk^{2-\gamma} \tag{2.4.2} \]

where \( C_Q = C_q/(\gamma - 2) \). Here we are keeping track of the values of the C's, a decision we will soon regret.

To study the average distance between two randomly chosen points on the giant component, we will first investigate the behavior of the branching process in order to figure out what to guess. The power \( 0 < \gamma - 2 < 1 \), and \( q_k \) is concentrated on the nonnegative integers so \( q_k \) is in the domain of attraction of a one-sided stable law with index \( \alpha = \gamma - 2 \).

**Theorem 2.4.2.** Let \( X_1, X_2, \ldots \) be i.i.d. with distribution \( q_k \) which satisfies (2.4.2) with \( 2 < \gamma < 3 \), and let \( S_m = X_1 + \cdots + X_m \). As \( m \to \infty \),

\[ S_m/(C_Qm)^{1/\alpha} \Rightarrow \Gamma_\alpha \]

where \( E(\exp(it\Gamma_\alpha)) = \exp(\int_0^\infty (e^{itx} - 1)/x^{\alpha+1} \, dx) \)

**Proof.** To begin to understand the asymptotic behavior of \( S_m \), let

\[ N_m(a, b) = |\{k \leq m : X_k/(C_Qm)^{1/\alpha} \in (a, b)\}| \]

for \( 0 < a < b < \infty \). For each \( k \) the probability \( X_k \in (a(C_Qm)^{1/\alpha}, b(C_Qm)^{1/\alpha}) \) is

\[ \sim \frac{1}{n}(a^{-\alpha} - b^{-\alpha}) \]

Since the \( X_k \) are independent, \( N_m(a, b) \Rightarrow N(a, b) \) with a Poisson distribution with mean

\[ a^{-\alpha} - b^{-\alpha} = \int_a^b \frac{\alpha}{x^{\alpha+1}} \, dx \tag{2.4.3} \]

If we interpret \( N(a, b) \) as the number of points in \((a, b)\) the limit is a Poisson point process on \((0, \infty)\) with intensity \( \alpha x^{-(\alpha+1)} \). In the limit there are finitely many points in \((\delta, \infty)\) for \( \delta > 0 \) but infinitely many in \((0, \delta)\).
The last paragraph describes the limiting behavior of the random set

\[ X_m = \{ X_k / (CQm)^{1/\alpha} : 1 \leq k \leq m \} \]

To describe the limit of \( S_m / (CQm)^{1/\alpha} \), we will “sum up the points.” Let \( \epsilon > 0 \) and

\[ I_m(\epsilon) = \{ k \leq m : X_k > \epsilon(CQm)^{1/\alpha} \} \]

\[ \hat{S}_m(\epsilon) = \sum_{k \in I_m(\epsilon)} X_m \]

\[ \tilde{S}_m(\epsilon) = S_m - \hat{S}_m(\epsilon) \]

\( I_m(\epsilon) \) are the indices of the “big terms,” i.e., those > \( \epsilon n^{1/\alpha} \) in magnitude. \( \hat{S}_m(\epsilon) \) is the sum of the big terms, and \( \tilde{S}_m(\epsilon) \) is the rest of the sum.

In the central limit theorem all the \( X_i \) make small contributions to the limit. In contrast, here the sum is determined by the big values, i.e., the contribution of \( \tilde{S}_m(\epsilon) \) is small if \( \epsilon \) is.

To do this we note that

\[ E \left( \frac{X_k}{(CQm)^{1/\alpha}} ; X_k \leq \epsilon(CQm)^{1/\alpha} \right) \approx \frac{1}{(CQm)^{1/\alpha}} \sum_{k=1}^{\epsilon(CQm)^{1/\alpha}} k \cdot C_q k^{-1-\alpha} \]

\[ \sim \frac{C_q}{(CQm)^{1/\alpha}} \cdot \frac{(\epsilon(CQm)^{1/\alpha})^{1-\alpha}}{1 - \alpha} = C_a \epsilon^{1-\alpha} m^{-1} \]

where \( C_a \) is a constant that only depends on \( \alpha \). Multiplying on each side by \( m \) gives

\[ E(\tilde{S}_m(\epsilon) / (CQm)^{1/\alpha}) \rightarrow C_a \epsilon^{1-\alpha} \downarrow 0 \quad \text{as } \epsilon \downarrow 0 \quad (2.4.4) \]

If \( Z = Poisson(\lambda) \) then

\[ E(\exp(it\epsilon Z)) = \sum_{k=0}^{\infty} e^{-\lambda} \frac{\epsilon^{itak} \lambda^k}{k!} = \exp(\lambda(e^{it} - 1)) \]

Dividing \((\epsilon, \infty)\) into small strips, using independence of the number of points in different strips, and passing to the limit gives

\[ E \exp(it\hat{S}_m(\epsilon) / (CQm)^{1/\alpha}) \rightarrow \exp \left( \int_{\epsilon}^{\infty} (e^{itx} - 1) \frac{\alpha}{x^{\alpha+1}} \, dx \right) \quad (2.4.5) \]

Now \( e^{itx} - 1 \sim itx \) as \( t \rightarrow 0 \) and \( \alpha < 1 \) so combining (2.4.4) and (2.4.5) and letting \( \epsilon \rightarrow 0 \) slowly we have

\[ E(\exp(itS_m / (CQm)^{1/\alpha}) \rightarrow \exp \left( \int_{0}^{\infty} (e^{itx} - 1) \frac{\alpha}{x^{\alpha+1}} \, dx \right) \]

which completes the proof of Theorem 2.4.2
Limiting behavior of the two-type branching process. It is enough to understand the behavior of the branching process with the size-biased distribution. Since the original degree distribution is a power law with $\gamma \in (2, 3)$, this branching process has infinite mean. The next result and its proof come from Davies (1978). That paper is a little strange because the main focus is to prove the result with an assumption that is more general than 

$$P(D > k) = x^{-\alpha}L(x)$$

where $L(x)$ is slowly varying.

Theorem 2.4.3. Consider a branching process with offspring distribution $\xi$ with 

$$P(\xi > k) \sim Ck^{-\alpha}$$

where $\alpha = \beta - 2 \in (0, 1)$. As $m \to \infty$, $\alpha^m \log(Z_m + 1) \to W$ with $P(W = 0) = \rho$ the extinction probability for the branching process.

Proof. Copying from page 474 of the paper, if $Z_m > 0$ then

$$Z_{m+1} = \sum_{i=1}^{Z_m} \xi_{m,i}$$

where the $\xi_{m,i}$ are independent and have the same distribution as $\xi$. We can write

$$\log(Z_{m+1} + 1) = \frac{1}{\alpha} \log(Z_m + 1) + \log Y_m$$

where

$$Y_m = \left(1 + \sum_{i=1}^{Z_m} \xi_{m,i}\right) / (Z_m + 1)^{1/\alpha}$$

where the +1’s are to avoid taking log 0. Multiplying each side by $\alpha^n$ and iterating we have

$$\alpha^m \log(Z_{m+1} + 1) = \alpha^m \log Y_m + \cdots + \alpha \log(Y_1) + \log(Z_1 + 1)$$

In our special case of Davies’ result, Theorem 2.4.2 shows that as $m \to \infty$, $Y_m$ converges to $\Gamma_\alpha$, a one sided stable law. To quote the precious edition, “straightforward but somewhat tedious estimates on the tail of the distribution of $Y_n$ show that, see pages 474–477 of Davies (1978),”

$$E\left(\sum_{m=1}^{\infty} \alpha^m \log^+ Y_m\right) < \infty \quad \text{and} \quad E\left(\sum_{m=1}^{\infty} \alpha^m \log^- Y_m\right) < \infty$$

This shows that $\lim_{m \to \infty} \alpha^m \log(Z_{m+1} + 1) = W$ exists.

The limit can be 0 and will be when $Z_n$ dies out. However when it does not Markov chain theory tells us that $Z_n \to \infty$ and we have $W > 0$. next step to show that the limit $W$ is nontrivial. Davies has shown that if $J(x) = P(W > x)$ then $P(J > 0) = \rho$ and

$$\lim_{x \to \infty} -\frac{\log(1 - J(x))}{x} = 1$$

i.e., the distribution of $W$ is asymptotically exponential(1)
The double exponential growth of the branching process associated with the power law degree distribution with $2 < \gamma < 3$ suggests that the average distance between two randomly chosen members of the giant component will be $O(\log \log n)$. To determine the constant we note that our limit theorem says

$$\log(Z_t + 1) \approx \alpha^{-t}W$$

so $Z_t + 1 \approx \exp(\alpha^{-t}W)$. We replace $Z_t + 1$ by $n^{1/2}$ since we grow the branching processes from the two points up to this size to get them to intersect. Solving gives $(1/2) \log n = \alpha^{-t}W$. Discarding the $W$ and writing $\alpha^{-t} = \exp(-t \log \alpha)$ we get

$$t \sim \frac{\log \log n}{\log(1/\alpha)} \quad (2.4.6)$$

Notice that the $1/2$ disappears so the time to grow the cluster to $n^\beta$ is independent of $\beta$. The distance between the two vertices is

$$\approx 2t = \frac{2 \log \log n}{\log(1/\alpha)} \quad (2.4.7)$$

van der Hofstad, Hooghiemstra, and Znamenski (2007)

The paper in the section title contains a rigorous proof of (2.4.7). To state their result we need some notation

$$m_{\tau, n} = 2 \left\lfloor \frac{\log \log n}{\log(\tau - 2)} \right\rfloor$$

$$a_n = \left\lfloor \frac{\log \log n}{\log(\tau - 2)} \right\rfloor - \frac{\log \log n}{\log(\tau - 2)}$$

Theorem 2.4.4. If $\tau \in (2, 3)$ then there are random variables $R_{\tau, \alpha}$ so that as $n \to \infty$

$$P(H_n = m_{\tau, n} + \ell | H_n < \infty) = P(R_{\tau, \alpha, \ell} = \ell)$$

The random variables here are the ones in Theorem 2.4.1.

This trio of authors has also proved results in (2005) for $\tau \in (1, 2)$ but in this case the world is very tiny and the size biased distribution is weird because it has infinite mass.

$$\lim_{n \to \infty} P(H_n = 2) = 1 - \lim_{n \to \infty} P(H_n = 3)$$

In general, we will ignore this case. To prove Theorem 2.4.4, HHZ start with Davies’ result, then describe a coupling between the SPG (shortest path graph) and the branching process. The proof is nicely organized and carefully written so we refer the reader to the paper for the details.
CHAPTER 2. GENERAL DEGREE DISTRIBUTIONS

Chung-Lu model

It is easy to prove the result for the pairwise distances in the Chung-Lu power-law model. This is an inhomogeneous random graph in which the edges are independent with the edge from $i$ to $j$ present with $p(i, j)$. These systems will be the focus Chapter 3, but for our purposes here it is enough to know that

$$p(i, j) = \frac{w_i w_j}{\text{vol}(G)}$$

where $w_i = (i/Bn)^{-1/(\gamma-1)}$ is the expected degree of $i$, and $\text{vol}(S) = \sum_{i \in S} w_i$

Theorem 2.4.5. Consider Chung and Lu’s power-law graphs with $2 < \gamma < 3$. Then the distance between two randomly chosen vertices in the giant component, $H_n$, is asymptotically at most

$$(2 + o(1)) \log \log n/(-\log(\gamma - 2)).$$

Proof. Let $t = n^{1/\sqrt{\log \log n}} = \exp(\log n \sqrt{\log \log n})$. Note that $t$ goes to $\infty$ slower than any power $n$ and faster than any power of $\log n$. Consider the vertices $H_0 = \{i : w_i \geq t\}$. Looking at the definition of $w_i$, we have

$$w_i \geq t \quad \text{if and only if} \quad i \leq nBt^{1-\gamma} \quad \text{(2.4.8)}$$

Recalling that $i, j \in H_0$ are connected with with probability $\geq t^2/(\text{vol}(G))$ and when $\gamma > 2$, $\text{vol}(G) \sim \mu n$ we see that two vertices in $H_0$ are connected with probability $p_0$ where $np_0 \to \infty$ faster than $\log n$ so by Theorem 1.9.1 the probability $H_0$ is connected tends to 1. Using Theorem 1.9.4 we see that if $n' = |H_0|$ then the diameter of $H_0$ is

$$\sim \frac{\log n'}{\log(n'p)} \sim \frac{\log n}{(3-\gamma) \log t} = \Theta(\sqrt{\log \log n})$$

To expand out from $H_0$ we let $H_k = \{i : w_i > t^k\}$ for $k \geq 1$ and use the following easy result:

Lemma 2.4.6. If $S \cap T = \emptyset$ and $\text{vol}(S)\text{vol}(T) \geq c\text{vol}(G)$ then the distance from $S$ to $T$ satisfies $P(d(S, T) > 1) \leq e^{-c}$.

Proof.

$$P(d(S, T) > 1) = \prod_{i \in S, j \in T} 1 - \frac{w_i w_j}{\text{vol}(G)} \leq \exp \left( - \sum_{i \in S, j \in T} \frac{w_i w_j}{\text{vol}(G)} \right) \leq e^{-c}$$

since $1 - x \leq e^{-x}$.  \hfill \Box
Using (2.4.8), the volume of \( \{ i : w_i > r \} \) is asymptotically
\[
(Bn)^{1/(\gamma - 1)} \sum_{i=1}^{Bnr^{1-\gamma}} i^{-1/(\gamma - 1)} \sim (Bn)^{1/(\gamma - 1)} \cdot C(Bnr^{1-\gamma}((\gamma - 2)/(\gamma - 1)) \sim C'nr^{2-\gamma}
\]
(2.4.9)

Using this result with \( S \) a single vertex gives the next result

**Lemma 2.4.7.** Let \( 1 > \alpha > \gamma - 2, 0 < \epsilon < \alpha - (\gamma - 2) \), and \( r \geq (\log n)^{1/\epsilon} \). If \( w_i \geq r^\alpha \) and \( T = \{ j : w_j > r \} \) then for large \( n \)
\[
P(d(\{i\}, T) > 1) \leq \exp(-Cr^\alpha/(2\mu)) \leq n^{-2}
\]

**Proof.** Plugging into Lemma 2.4.6 using \( w_i \geq r^\alpha, \) vol(\( T \)) \( \sim \) \( nr^{1-\gamma}, \) which comes from (2.4.9) vol(G) \( \leq 2n\mu \) which holds for large \( n \) gives the result. \( \square \)

This will allow us to prove the existence of connections from \( i \in H_{k+1} \) to \( H_k \) as long as the degrees of the vertices are large enough. Suppose \( t^\alpha k \geq (\log n)^{1/\epsilon} \). Using the previous lemma we see that if \( j \in H_{k+1} \) then with probability \( \geq 1 - n^{-2} \), \( j \) is connected to a point in \( H_k \). Since \( H_0 \) is connected it follows that each \( H_k \) with \( k \leq \ell \equiv \inf \{ i : t^\alpha i < (\log n)^{1/\epsilon} \} \) is connected. Let \( m = (\log \log n)/(-\log \alpha) \). This is chosen so that
\[
\frac{\alpha^m \log n}{\sqrt{\log \log n}} < 1
\]
and \( t^\alpha m < e \), so \( \ell \leq m \).

\( H_0 \) has diameter \( O(\sqrt{\log \log n}) \), so at this point we have shown that \( H_\ell \) is connected and has diameter smaller than \( 2m + O(\sqrt{\log \log n}) \). To connect the remaining points we note that if \( n \) is large then \( T = H_\ell \) has volume at least \( (Cn/2)(\log n)^{(2-\beta)/\epsilon} \), so if \( S \) has volume \( \geq n^{\alpha/\epsilon} \) then Lemma 2.4.6 implies
\[
P(d(S, T) > 1) \leq \exp(-C(\log n)^{(\alpha-(\beta-2))/\epsilon}/2\mu) \leq n^{-2}
\]
Thus the component of a site \( i \) will connect to \( H_\ell \) if it reaches size \( (\log n)^{\alpha/\epsilon} \). It is easy to see that collisions in the growth of the cluster to size \( (\log n)^{\alpha/\epsilon} \) and since the branching process grows doubly exponentially fast the amount of time required to reach this size is \( O(\log \log \log n) \). \( \square \)

### 2.5 First passage percolation

This topic has been extensively studied on \( \mathbb{Z}^d \) since its introduction by Hammersley and Welsh (1995). Some of the important milestones in the development of the theory are the Springer Lecture Notes written by Smythe and Weirman (1978), Kesten’s St. Flour Notes
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(1986), and Auffinger, Damron, and Hanson’s (2016) survey Fifty years of first passage percolation, available in book form from the AMS.

As in the well studied case of first passage percolation on $\mathbb{Z}^d$, we think of FPP as describing fluid flow through a porous medium. One can also think of it as an $SI$ model in which infecteds are never cured, though I personally prefer to instead think of the spread of information or a rumor, although in that context some models have people stop spreading the rumor when it is too boring to tell. On $\mathbb{Z}^d$ the main focus is on the asymptotic behavior of the wet region as function of time $t$. There is a strong law of large numbers called the shape theorem. As this is being written the “central limit theorem” for the fluctuation of the shape are an important open problem. We put central limit theorem in quotes since the fluctuations do not have the usual $n^{1/2}$ and the limit is not Gaussian.

On graphs this topic is covered in great detail in Chapter 3 of Remco van der Hofstad’s notes for the 47th Summer School in Saint-Flour, or StFl for short. The chapter is 71 pages long, so we will only provide a summary of the main results and describe some ideas important for the proofs. FPP is constructed by assigning i.i.d. positive random variables $Y_e$ to the edges. These can be thought of as the time to traverse the edge, its length or its weight. The main objects of study are what Remco van der Hofstad calls $C_n(i,j) = \min_{\pi:i\to j}\sum_{e\in\pi} Y_e$ $H_n(i,j) = |\pi_n(i,j)|$

$H_n$ is for hopcount is the length of the shortest path. I guess $C$ is the cost of the path but since we use $C$ for clusters and $T$ for trees, we will denote the passage time by $t_n(i,j)$.

On our finite graphs we let $U_1$ and $U_2$ be randomly chosen vertices and examine the typical behavior

$$H_n = H_n(U_1, U_2) \quad t_n = t_n(U_1, U_2)$$

which are analogues of the average pairwise distance. One can also study $\max_j t_n(i,j)$, the time until everyone knows the rumor and $\max_{i,j} t_n(i,j)$.

Janson (1993) proved the following result

**Theorem 2.5.1.** Let $\ell(n) = (\log n)/n$. On the complete graph with exponential(1) edge weights.

(i) for any fixed $i$ and $j$ $C_n(i,j)/\ell(n) \to 1$.

(ii) for any fixed $i$ $\max_{1\leq j\leq n} C_n(i,j)/\ell(n) \to 2$.

(iii) $\max_{1\leq i,j\leq n} C_n(i,j)/\ell(n) \to 3$.

Almost all of the results in this section assume what StFl calls Condition 1.6 (Regularity conditions for vertex degrees)

(a) The degree distributions $D_n$ converge in distribution to a limit $D$.

(b) As $n \to \infty$, $E D_n \to ED$.

(c) As $n \to \infty$, $E D_n^2 \to ED^2$. 
Obviously (b) follows from (a) and (c), but some results in StFl use (b) and not (c). In addition in all case we will assume that the mean of the size-biased degree distribution \( \nu = E[D(D - 1)]/ED > 1 \) so there is a giant component.

Here we will primarily concerned with four papers written by Shankar Bhamidi, Remco can der Hofstad and Gerard Hooghiemstra which we will refer to as BHH (2010a), (2010b), (2011), and (2017). In discussing these results we will follow the notation in the papers with a few exceptions.

### 2.5.1 Exponential passage times, finite variance degrees

The discussion here follows BHH (2010b). We assume throughout this subsection that edge weights are i.i.d. exponential(1). When this holds the set of wet sites is a Markov process. As in Section 2.4, when we studied the distance between randomly chosen vertices, the key will be to run FPP from vertices \( i \) and \( j \) until they intersect.

In Theorem 3.7 of StFl it is assumed that

\[
\nu_n = E[D_n(D_n - 1)]/ED_n = \nu + o(1/\log n) \quad \text{and} \quad \lim_{n \to \infty} ED_n^{2+\epsilon} = ED^{2+\epsilon}
\]

Despite the +\( \epsilon \), we will call this the finite variance case.

Theorem 3.1 of BHH(2010b) gives the following version. Throughout the discussion in this section we have replaced their power law exponent of \( \tau \) by our traditional \( \gamma \).

**Theorem 2.5.2.** Suppose that \( P(D \geq 2) = 1, \gamma > 3 \) and

\[ P(D \geq x) \leq cx^{-(\gamma-1)} \]

(a) Then the hopcount \( H_n \) satisfies the central limit theorem

\[
\frac{H_n - \alpha \log n}{\sqrt{\alpha \log n}} \Rightarrow \chi
\]

where \( \chi \) has a standard normal distribution and \( \alpha = \nu/(\nu - 1) > 1 \).

(b) There is a random variable \( V \) so that

\[
t_n - \frac{1}{\nu - 1} \log n \Rightarrow V
\]

The limiting random variable \( V \) is

\[
V = \frac{-\log W_1}{\nu - 1} - \frac{\log W_2}{\nu - 1} - \frac{\Lambda}{\nu - 1} + \kappa
\]

where \( W_1 \) and \( W_2 \) are two independent copies of the limiting random variable of a continuous time branching process and \( \Lambda \) has a Gumbel distribution.
CHAPTER 2. GENERAL DEGREE DISTRIBUTIONS

This answer is remarkably explicit. On the two-dimensional lattice the passage time from 
(0, 0) to (n, 0) when edge weights are exponential(1) scales like $\gamma n$ where the time constant 
$\gamma$ can only be calculated by simulation. The simple explicit constant $1/(\nu - 1)$ reflects the fact 
that random graphs are infinite dimensional and hence are a mean-field version of the 
system on $\mathbb{Z}^d$.

The reader will see the three amigos in the definition of $V$ several times, so we will now 
give our own intuitive explanation of the how they arise. There is not a tight connection to 
the developments in this section since the process works in discrete time but as the reader 
sees more examples in this section and in Section 4.6 the picture will become more clear. 
If we let $\lambda = \nu - 1$ then the number of alive half-edges at time $t A_i^t$ in the shortest weight 
graph starting from $i$ has $e^{-\lambda t} A_i^t \to W_i$. If we let $S_i = (-\log W_i)/\lambda$ then 
$$A_i^t((1/2\lambda) \log n + S_i + s/2\lambda) \approx e^{s/2} n^{1/2}$$

The probability of a connection at time $(1/\lambda) \log n + S_1 + S_2 + s/\lambda$ is $\approx \exp(-e^s)$

Main ideas of the proofs

The key idea is to grow the shortest weight graph from vertex 1, $SWG_1^m$, until time $\sqrt{n}$ 
which is order of magnitude of the size at which a connection is made. Then we grow the 
shortest weight graph from vertex 2, $SWG_2^m$ until they intersect. To define these growing 
graphs we let $SWG_0^i = \{i\}$ then repeatedly add the edge adjacent to $SWG_i^m$ with minimal 
weight. The rules for the growth of $SWG_2^m$ in the same way.

We know from results in Section 1.2 that the growing cluster starting from an individual 
it a tree while the number of vertices is $\leq n^{1/2-\epsilon}$. We now describe Construction 3.1 in 
StFl, which supposes that the graph always a tree. In their analysis the degree of the ith 
unexplored vertex is deterministic, so that they can prove results in the setting of a limiting 
degree sequence described in Section 2.3. We will content ourself to study the process on 
graphs generated by the configuration model. In this case the $d_i$ will be independent. $d_1$ has 
the original degree distribution, but the $d_i$ for $i \geq 2$ have the size biased degree distribution.

Here as in the proof of the Miller-Volz equations, which will be described in Section 4.5, 
we build the graph as we run the process. We start with $d_i$ half-edges attached to each 
vertex $1 \leq i \leq n$. We find it convenient to talk about first passage percolation as an $S - I$ 
epidemic. Infected individuals are the ones who know the rumor. They infect neighboring 
individual at rate 1.

1. Start with the root, $v_0$, which is infected and has $d_1$ alive half edges (which BHH call 
stubs) attached. Immediately we choose one of the half-edges to pass on the infection.

2. After the first step, each alive half-edge lives for an independent exponential(1) amount 
of time before the infection crosses the edge.

3. When the infection crosses a half-edge for the $m$th time, it pairs with one chosen at 
random from the (unpaired half-edges. The new vertex called $v_m$, is infected, and we let 
$d_{m+1}$ be the number of half-edges not counting the one used to make the connection.
An example drawn in Figure 2.3 should help explain the definitions.
The number of alive half-edges on the $i$th step of the construction, when $v_i$ is chosen,

$$s_i = d_1 + d_2 + \cdots + d_i - (i - 1) = d_1 + B_2 + \cdots + B_i - (i - 1)$$

where $B$ is the size biased version of $d$. The first formula is the notation used in BBH and StFl. In order to make formulas easier to write, we will use it here with the understanding that $d_i = B_i$ for $i \geq 2$.

The next result is Proposition 3.8 in StFl (and Proposition 4.2 in BBH(2010a)).

**Lemma 2.5.3.** Let $v_m$ be the vertex added on the $m$th step of the construction.

(a) The weight $T_m$ of the shortest-weight path from the root to $v_m$, has distribution

$$T_m = \sum_{i=1}^{m} E_i/s_i$$

where $E_i$ are exponential(1) random variables.

(b) The generation number of $v_m$ is equal in distribution to

$$G_m = \sum_{i=1}^{m} I_i$$

where $I_i$ are independent Bernoulli with $P(I_i = 1) = d_i/s_i$.

**Remark 2.5.4.** Note that since $m \to T_m$ is increasing, the distance to vertices added after time $m$ are larger than $T_m$.

**Proof.** To prove (a) note that at each time, the lack of memory property of the exponential implies that $T_m - T_{m-1}$ is exponential with rate $s_M$ and is independent of $T_i$, $1 \leq i < m$. 

Figure 2.4: $d_1 = 3$, $d_2 = 2$, $d_3 = 3$, $d_4 = 1$. $E_1/s_1 = 0.7$, $E_2/s_2 - 0.4$, $E_3/s_3 - 0.2$. 

(b) is proved by induction on \( m \). The result is trivial for \( m = 1 \). A little thought reveals that

\[
P(G_{m+1} = k) = \frac{d_{m+1}}{s_{m+1}} P(G_m = k - 1) + \left(1 - \frac{d_{m+1}}{s_{m+1}}\right) P(G_m = k)
\]

The first term corresponds to choosing one of the \( d_{m+1} \) vertices that were added at time \( m \) and the second term to the complement of this event.

Having determined the distributions of the quantities of interest, it is fairly routine to use results about sums of independent random variables to show the following result. Here we following the notation and formulation of Corollary 3.9 in StFl

**Lemma 2.5.5.** Let \( B_i \) be an i.i.d. sequence with \( EB_i^{1+\epsilon} < \infty \) and let \( \nu = EB_i \). Let \( S_i = d_1 + B_2 + \cdots + B_{i-1} - (i-1) \). (a) Let \( \lambda = \nu - 1 \). There is a random variable \( X \) so that

\[
T_m - \frac{1}{\lambda} \log m \Rightarrow X
\]

(b) If \( \alpha = \nu/(\nu - 1) \) then the generation number \( G_m \) has

\[
\frac{G_m - \alpha \log m}{\sqrt{\alpha \log m}} \Rightarrow \chi
\]

where \( \chi \) has a standard normal distribution.

**Proof.** The first formula follows from the facts that

\[
s_i/i \to \nu - 1 \text{ almost surely} \quad \text{var} \left(\frac{E_i}{s_i}|s_i\right) = 1/s_i^2
\]

The second from the Lindberg-Feller central kimit theorem and \( EB_i = \nu \).

We next identify the distribution of \( X \).

\[
T_m - \frac{1}{\lambda} \log m = \sum_{i=1}^{m} \frac{E_i - 1}{S_i} + \sum_{i=1}^{m} \left(\frac{1}{S_i} - \frac{1}{(\nu - 1)i}\right) + \frac{1}{\nu - 1} \left(\sum_{i=1}^{m} \frac{1}{i} - \log m\right)
\]

**Proof.** The key fact is the law of large numbers \( S_i/i \to \nu - 1 \). \( M_m = \sum_{i=1}^{m} \frac{E_i - 1}{S_i} \) is a martingale with \( EM_m^2 \) bounded so it converges almost surely. Using the law of large numbers, little analysis, see StFl for details shows that the second series converges. Finally the last term converges to the Euler-Masheroni constant.

**Technicalities.** If we were physicists we would be done with analyzing the growth of a single SWG. Theorem 1.2.3 implies that the expected number of collisions in an Erdös-Rényi random graph before the cluster reaches size \( n^\alpha \) is \( \leq Cn^{2\alpha - 1} \). That result generalizes easily to the current setting. Taking \( \alpha = 1/2 \), we expect only \( O(1) \) collisions, which should only rarely alter the distance.
On the other hand, mathematicians who are publish papers in journals are required to prove things, so BHH(2010b) create a coupling of the tree and CM versions, called Construction 4.4. Proposition 4.5 quantifies the differences between the two systems. Proposition 4.6 shows that the conclusions in Lemma 2.5.5 do not change as long as \( m \leq \overline{m} n \) where 
\[
\log(\frac{\overline{m} n}{a n}) = o(\sqrt{\log n})
\]
where \( a n \) is a constant that we will soon define.

**Connection time.** Having mentioned these technical problems, we will ignore them. To compute the distance from 1 to 2, we will grow \( SW G^1 \) until time \( a n = n^{1/2} \) and then grow \( SW G^2 \) until the time they first intersect (which BBH and STFL call \( C_n \)):

\[
\sigma_n = \min\{ m \geq 0 : SW G^1_{\alpha(n)} \cap SW G^2_m \neq \emptyset \}
\]

This is the first time the vertex added to \( SW G^2 \) is in \( SW G^1_{\alpha(n)} \). When we computed the distance in the finite variance case in Section 1.4, we grew each cluster until it had size \( n^{1/2} + O(1) \). Part (a) of Proposition 4.9 in BBH(2010b) shows that

\[
(4.27) \quad \log \sigma_n - \log a(n) = o_p(\sqrt{\log n})
\]

where the subscript \( p \) means in probability. This formula number and the next three are from BBH(2010b)

**Passage time from 1 to 2, and hopcount for the minimum weight path.** Here we are following Section 4.4 in BHH(2010b), which can be consulted for more detail. If \( v \) is the vertex in the intersection then the path from 1 to \( v \) in \( SW G^1 \) is the shortest weight path from 1 to \( v \) and the path from 2 to \( v \) in \( SW G^2 \) is the shortest weight path from 2 to \( v \). To see that this is the shortest weight path from 1 to 2 see the remark after Lemma 2.5.3. It follows that weight of the path (or passage time) from 1 to 2 is

\[
(4.20) \quad t_n = T^1_{\alpha(n)} + T^2_{\sigma(n)}
\]

Let \( w \) be the vertex in \( SW G_{\sigma(n)-1} \) that connected to \( v \). By the way the algorithm runs the vertex \( v \) is chosen with probability proportional to the number of live edges attached to it. This is the procedure used to add to \( SW G^1 \) so the hopcount in the shortest path from 1 to 2 is

\[
(4.19) \quad H_n = G^1_{\alpha(n)+1} + G^2_{\sigma(n)} - 1
\]

Since \( G^1 \) and \( G^2 \) are independent, \( a n = n^{1/2} \), and \( \log(\sigma_2(\rightarrow 1/2), part (b) of Theorem 1 follows. See (4.28) and the proof of Proposition 4.9 for more details.

Turning to the more delicate first conclusion, Proposition 4.9 shows that

\[
(4.29) \quad (T^1_{\alpha(n)} - (1/\lambda) \log a(n)), T^2_{\sigma(n)} - (1/\lambda) \log a(n)) \rightarrow (X_1, X_2)
\]

with the \( X_i \) independent. The formula for the limit \( V \) given is (2.5.3) is derived in Appendix C, see (C.19).

**Erdös-Rényi graphs.** Theorems 2.1 and 2.2 in BHH(2011) give the analogue of Theorem 2.5.2. in the case \( np \rightarrow \lambda \). They also consider what happens when \( np \rightarrow \infty \). The absence of the assumption \( P(D \geq 2) = 1 \) causes some inconvenience, but due to the restriction to Erdös-Rényi graphs, the proofs are shorter and less technical.
2.5.2 Exponential passage times, power law degrees

The next result is Theorem 3.31 in StFl. We will not discuss the case $\gamma \in (1, 2]$, which is covered in BHH (2010a).

**Theorem 2.5.6.** Suppose that $P(D \geq 2) = 1$, and for some $\gamma \in (2, 3)$

$$c_1 x^{-(\gamma-1)} \leq P(D \geq x) \leq c_2 x^{-(\gamma-1)}$$

(a) Then the hopcount $H_n$ satisfies the central limit theorem

$$\frac{H_n - \alpha \log n}{\sqrt{\alpha \log n}} \Rightarrow \chi$$

where $\chi$ has a standard normal distribution and $\alpha = 2(\tau - 2)/(\tau - 1) < 1$.

(b) There is a random variable $V$ so that

$$t_n \Rightarrow V$$

The limiting random variable $V$ is shown to be

$$V = V_1 + V_2$$

where $V_1$ and $V_2$ are two independent copies of the explosion time of an infinite-mean Markovian continuous time branching process.

This result is surprising since (i) the minimum weight path is $O(1)$ independent of $n$ and has length $\sim \alpha \log n$ despite the fact that the distance between the two points is $\sim 2 \log \log n/\log(\gamma - 2)$. As the authors say “Thus it is worthwhile to make large detours to avoid high weight edges.”

**Main ideas of the proof**

The proof is similar to the previous result. Indeed in BHH(2010b) the proofs of Theorems 2.5.2 and 2.5.6 are done in parallel. Let $B_i$ be the sized biased version of $d_i$. Let

$$S_i = B_1 + \cdots + B_i$$

Here (i) we have dropped the first degree which is not sized biased from the sum and (ii) since $\hat{S}_m/m^{1/(\gamma-2)}$ converges in distribution to a one sided stable law with index $\gamma - 2$, we have dropped the $-(i-1)$ which is insignificant.

Let $v_m$ be the vertex added on the $m$th step of the construction. Lemma 2.5.3 extends immediately to the new setting, so our next step is to extend Lemma 2.5.5. Here

$$\hat{T}_m = \sum_{i=1}^m E_i/S_i \quad \text{and} \quad \hat{G}_m = \sum_{i=1}^m \hat{I}_i$$

where $\hat{I}_i$ are independent Bernoulli with $P(\hat{I}_i = 1) = B_i/S_i$. 
Lemma 2.5.7. (a) There is a random variable $X$ so that

$$\hat{T}_m \rightarrow X \text{ a.s. and in } L^1$$

(b) The generation number $\hat{G}_m$ has

$$\frac{\hat{G}_m - \log m}{\sqrt{\log m}} \Rightarrow \chi$$

where $\chi$ has a standard normal distribution.

Proof. (a) Let $\eta \in (1, 1/(\gamma - 2))$. In order for $\hat{S}_m \leq m^\eta$ we must have $B_i \leq m^\eta$ for $i \leq m$.

Since $P(B_i > x) \leq Cx^{2-\gamma}$

$$P(S_m \leq m^\eta) \leq (1 - Cm^{-(\eta - 2)})^m \leq \exp(-Cm^{1-\eta(\gamma - 2)})$$

and we have $P(S_m \leq m^\eta$ infinitely often) $= 0$. Since the $E_i$ are exponential mean 1, $\max_{1 \leq i \leq m} E_i \leq C \log m$, and $\Sigma \equiv \sum_{i=1}^\infty E_i/\hat{S}_i < \infty$ a.s. The bounds we have obtained imply that the convergence occurs in $L^1$ and hence that $E\Sigma < \infty$.

(b) Let $F'_m$ the the $\sigma$-field generated by $\hat{S}_m, \hat{S}_{m+1}, \ldots$. Assuming $i_1 < \ldots < i_k$, let

$$H(i_1, i_2, \ldots, i_m) = \{\hat{I}_{i_j} = 1 \text{ for } 1 \leq j \leq k\}.$$

Since the distribution of $B_1, \ldots, B_i$ given $F'_i$ is exchangeable

$$P(H(i_1, i_2, \ldots, i_m)|F'_i) = E \left( \prod_{j=1}^k B_{i_j}/\hat{S}_{i_k} \right) = \frac{1}{i_1} \cdot E \left( \prod_{j=2}^k B_{i_j}/\hat{S}_{i_k} \right)$$

It follows by induction that $P(H(i_1, i_2, \ldots, i_m) = \prod_{j=1}^k 1/i_j$, so the events $\hat{I}_k$ are independent and have $P(I_{i_j} = 1) = 1/i_j$. \qed

Connection time. As in the proof of Theorem 2.5.2, to compute the distance from 1 to 2, we will grow $SWG^1$ until time $a_n$ and then grow $SWG^2$ until the time they first intersect (which BBH and STFL call $C_n$):

$$\sigma_n = \min\{m \geq 0 : SWG^1_{a(n)} \cap SWG^2_m \neq \emptyset\}$$

However now $a_n = n^{(\gamma - 2)/(\gamma - 1)}$. To see why this value is chosen note that at time $a_n$ the number of alive stubs in $SWG^1$ is of order $a_n^{1/(\gamma - 2)}$ and we have

$$a_n \cdot a_n^{1/(\gamma - 2)} = n^{(\gamma - 2)/(\gamma - 1) \cdot [1 + (\gamma - 2)/(\gamma - 1)]} = n$$

Again part (a) of Proposition 4.9 implies

$$\log \sigma_n - \log a(n) = o_p(\sqrt{\log n})$$
Passage time and hopcount from 1 to 2. As in the proof of Theorem 2.5.2 we have

\[ t_n = \hat{T}^1_{a(n)} + \hat{T}^2_{\sigma(n)} \quad H_n = \hat{G}^1_{a(n)+1} + \hat{G}^2_{\sigma(n)} - 1 \]

and Proposition 4.9 shows that

\[ (T^1_{a(n)}, T^2_{\sigma(n)}) \to (X_1, X_2) \]

with the \( X_i \) independent. The fact that the limit \( V = X_1 + X_2 \) is proved in Section 6.

2.5.3 General continuous passage times

We will mainly discuss the case of finite variance degrees but will briefly mention the work of Baroni et al (2017) on power law case with \( \gamma \in (2, 3) \) at the end. The result for the finite variance case here is from BHH(2017), and we will follow their notation which differs slightly from StFl. The next result is their Theorem 1.2.

**Theorem 2.5.8.** Suppose that the edge weights have a continuous distribution \( F_\xi \). For the graph we assume weak convergence of the distribution of vertex degrees, convergence of their second moments, and

\[
ED_n^2 \log^+(D_n) \to ED^2 \log^+(D) < \infty \tag{2.5.4}
\]

Then there are constants \( \alpha, \lambda, \beta \in (0, \infty) \), and \( \alpha_n \to \alpha, \gamma_n \to \gamma \) so that

\[
\left( \frac{H_n - \gamma_n \log n}{\sqrt{\beta \log n}}, t_n - \frac{1}{\alpha_n} \log n \right) \Rightarrow (\chi, Q)
\]

where \( \chi \) and \( Q \) are independent. \( \chi \) has a standard normal distribution, while \( Q \) has a continuous distribution that will be described in Theorem 2.5.9.

Again we will approximate the number of active half-edges by a branching process. Since passage times are no longer exponential, the approximating branching process is more complex. Let \( F \) be the degree distribution, and define the distribution function of the size biased degrees \( D^* \) by

\[
F^*(x) = E[D1_{(D \leq x)}] / ED
\]

Now let \( BP^*(t) \) denote the following branching process.

(a) At time \( t = 0 \) we start with one individual we refer to as the original ancestor or the root of the branching process.

(b) Each individual \( v \) lives for an amount of time that has distribution \( F_\xi \) and the dies. At the time of its death it gives birth to \( X^*_v = D^* - 1 \) children.

(c) Each of the children starts an independent copy of the original process.

The process just described is often called an **age-dependent branching process** but it is sometimes called a **Bellman-Harris** process in honor of the pioneering work of Bellman and Harris (1948). The results stated here are explained in more detail in Section A.3.1.
The expected number of children $EX^*_v = \nu > 1$. The **Malthusian parameter**, gives the exponential growth rate of the branching process $BP^*$. It is the unique solution $\alpha \in (0, \infty)$ of the equation

$$\nu \int_0^\infty e^{-\alpha t} dF_\xi(t) = 1 \quad \text{(2.5.5)}$$

When $\nu > 1$, $\alpha > 0$.

Assumption (2.5.4) in the theorem implies that $EX^*_v \log X^*_v < \infty$. “Standard theory” implies that there is a random variable $W^*$ so that

$$e^{-\alpha t}|BP^*(t)| \Rightarrow W^* \quad \text{a.s. and in } L^1 \quad \text{(2.5.6)}$$

and $W^* > 0$ when the branching process does not die out.

By (2.5.5) we can define a **stable age distribution** by

$$\bar{F}_\xi(x) = \nu \int_0^x e^{-\alpha y} dF_\xi(y) \quad \text{(2.5.7)}$$

As the name suggests it gives an approximation to the age of a randomly chosen individual which becomes exact as time $t \to \infty$. Let

$$\bar{\nu} = \int_0^\infty xe^{-\alpha x} d\bar{F}_\xi(x) \quad \bar{\sigma}^2 = \int_0^\infty (x - \bar{\nu})^2 e^{-\alpha x} d\bar{F}_\xi(x) \quad \text{(2.5.8)}$$

be the mean and variance of the stable age distribution $\bar{F}_\xi$.

**Theorem 2.5.9.** The parameter $\alpha$ is the Malthusian growth rate defined in (2.5.5), $\alpha_n$ is the solution with $\nu$ replaced by $\nu_n$ while

$$\gamma = \frac{1}{\alpha \bar{\nu}} \quad \gamma_n = \frac{1}{\alpha_n \bar{\nu}_n} \quad \beta = \frac{\bar{\sigma}^2}{\bar{\nu}^3 \bar{\alpha}} \quad \text{(2.5.9)}$$

Further $Q$ can be identified (see (3.5.7) in StFlas

$$Q = \frac{1}{\lambda} \left(- \log(W^{(1)}) - \log(W^{(2)}) - \Lambda + c\right)$$

where $P(\Lambda \leq x) = \exp(-e^{-x})$ has the Gumbel distribution. $W^{(1)}$ and $W^{(2)}$ are two independent copies of the random variable in (2.5.6), are independent of $\Lambda$ and

$$c = \log[ED(\nu - 1)/(\nu \alpha \bar{\nu})] \quad \text{(2.5.10)}$$

**Power law degrees** $2 < \gamma < 3$. Baroni, van der Hofstad, and Komathy (2017) considered this case. To a large extent the difficulties are the union of those in Sections 2.5.2 and 2.5.3 above. One feature not seen in Section 2.5.2 is that the age-dependent branching process does not always explode. There is still universality in that all of those that are explosive have the same behavior (Theorem 4). A simple nonexplosive case occurs when the passage times are bounded below, e.g., $Y = 1 + X$ where $X \geq 0$. In this situation (Theorem 5) then the weight and hopcount of the optimal path have the same behavior as the distance. For details see the paper or StFl.
2.6 Critical regime

Dhara et al (2017) studied the case in which the third moment of the degree distribution is finite, and hence the size-biased distribution has a finite second moment. In this case the critical behavior is the same as in the Erdős-Rényi case as described in Section 1.7, i.e., rescaled cluster sizes converge to the multiplicative coalescent.

They assumed what we will call **condition A**$_3$

(i) If $D_n$ is the degree of a randomly chosen vertex then as $n \to \infty$, $D_n$ converges in distribution to a limit $D$ with $E[D^3] < \infty$

(ii) $E(D^3_n) \to E(D^3)$

(iii) For some $t \in \mathbb{R}$

$$\nu_n = \frac{\sum_{i=1}^{n} d_i (d_i - 1)}{\sum_{i=1}^{n} d_i} = 1 + t n^{-1/3} + o(n^{-1/3})$$

(iv) $P(D = 1) > 0$

To state their results we need some notation. Let $m_r = E[D^r]$

$$\mu = m_1 \quad \eta = m_3 m_1 - m_2^2 \quad \beta = 1/\mu$$

Let $B_{\mu, \eta}^\lambda(s)$ be a nonhomogeneous Brownian motion given by

$$B_{\mu, \eta}^\lambda(s) = \frac{\sqrt{\eta}}{\mu} B(s) + \lambda s - \frac{\eta s^2}{2\mu^3}$$

where $B$ is a standard Brownian motion, and define the reflected version by

$$W^\lambda(s) = B_{\mu, \eta}^\lambda(s) - \min_{0 \leq t \leq s} B_{\mu, \eta}^\lambda(s)$$

We say that $\gamma = (\ell, r)$ is an excursion interval of $W^\lambda(s)$ if $W^\lambda(\ell) = W^\lambda(r) = 0$ and $W^\lambda(s) > 0$ for $s \in (\ell, r)$. Let $\gamma_j^\lambda$, $j \geq 1$ be the ordered excursion lengths of $W^\lambda(s)$. Their Theorem 3.2 states

**Theorem 2.6.1.** Fix any real number $\lambda$. Under assumption A$_3$

$$n^{-2/3} |C_j|, j \geq 1 \Rightarrow \gamma_j^\lambda, j \geq 1$$

where $\Rightarrow$ indicates convergence in distribution.
Power-laws $3 < \gamma < 4$

Dhara et al (2020) studied the situation in which the tail of the degree distribution

$$P(d_i > k) = k^{-\gamma + 1}L_0(k)$$

where $3 < \gamma < 4$ and $L_0$ is a slowly varying function defined by the property that for any $x$, $L_0(tx)/L_0(t) \rightarrow 1$ as $t \rightarrow \infty$. Functions that converge to positive constants are slowly varying, as are the functions $K(t) = \log t$ or $\log \log t$.

To state their results we need some notation (their $\tau$ is our $\gamma$)

$$\alpha = \frac{1}{(\gamma - 1)} \quad \rho = \frac{\gamma - 2}{(\gamma - 1)} \quad \eta = \frac{\gamma - 3}{(\gamma - 1)}$$

$$a_n = n^\alpha L(n) \quad b_n = n^\rho / L(n) \quad c_n = n^\eta / L^2(n)$$

Generalizing a definition from the discussion of Aldous’ theorem

$$\ell_p \downarrow = \left\{ x = (x_1, x_2, \ldots) : x_1 \geq x_2 \geq \ldots \right\}$$

Assumption 1. Let $d = (d_1, d_2, \ldots, d_n)$ be the degree sequence

1. $d_i/a_n \rightarrow \theta_i$ where $\theta = (\theta_1, \theta_2, \ldots) \in \ell_3^3 \setminus \ell_2^2$
2. Let $D_n$ be the degree of a randomly chosen vertex. Then $D_n \Rightarrow D$

$$\frac{1}{n} \sum_{i=1}^{n} d_i \rightarrow \mu \quad \frac{1}{n} \sum_{i=1}^{n} d_i^2 \rightarrow E[D^2]$$

and $\lim_{K \rightarrow \infty} \limsup_{n \rightarrow \infty} a_n^{-3} \sum_{i>K} d_i^3 = 0$

3. For some $\lambda$

$$\nu_n(\lambda) = \frac{\sum_{i=1}^{n} d_i(d_i - 1)}{\sum_{i=1}^{n} d_i} = 1 + \lambda c_n^{-1} + o(c_n^{-1})$$

4. $P(D = 1) > 0$.

Theorem 2.6.2. Under assumption 1, if $C_j$ is the $j$th largest cluster

$$\{b_n^{-1}|C_j|, j \geq 1\} \Rightarrow \{\tilde{L}_j^\lambda, j \geq 1\}$$

where $\tilde{L}_j(\lambda)$ is the $j$th largest excursion of a process $\tilde{S}_\infty^\lambda$ which we will now define.

Let $\theta = (\theta_1, \theta_2, \ldots) \in \ell_3^3 \setminus \ell_2^2$ be the sequence from (i) in Assumption 1. Let $I_j(s) = 1_{\{\xi_i \leq s\}}$ where $\xi_j$ are independent with distribution exponential($\theta_i/\mu$). Let

$$\tilde{S}_\infty^\lambda(t) = \sum_{i=1}^{\infty} \theta_i(I_j(s) - (\theta_i/\mu)t) + \lambda t$$

$$\text{refl}(\tilde{S}_\infty^\lambda(t)) = \tilde{S}_\infty^\lambda(t) - \min_{0 \leq u \leq t} \tilde{S}_\infty^\lambda(u)$$
Recall that if $B_t$ is a one-dimensional Brownian motion starting at 0 then

$$\text{refl}(B_t) = B_t - \min_{0 \leq s \leq t} B_s$$

is a reflecting Brownian motion that has the same distribution as $|B_t|$. If this is not a familiar fact note that $\text{refl}(B_t) \geq 0$ and that $\min_{0 \leq s \leq t} B_s$ only increases when $\text{refl}(B_t) = 0$.

**Remark.** Theorem 2.6.2 is analogous to Theorem 1.7.2. As in that result the key to prove convergence of the exploration process to a limit. One can also prove a version of Theorem 1.7.3 which describes the complexity of the components.

### 2.7 Percolation

Percolation is one of the simplest processes to study on random graphs. If we take a random graph and independently delete edges with probability $1 - p$ then we have another random graph, although as noted in Section 2.2 if the original graph was an instance of the configuration model then the reduced graphs is not. For those who want a fully rigorous treatment we see Fountoulakis (2007) or Janson (2009), who also considers phase transition results for the $k$-core.

Here, we will content ourselves to compute the degree distribution for the thinned graph and use the two-phase branching process to determine the probability of a giant component. Suppose that the original degree distribution was $p_k$. If we keep edges with probability $p$ then the probability a vertex chosen at random will have $j$ neighbors after thinning is

$$\hat{p}_j = \sum_{k=j}^{\infty} p_k \binom{k}{j} p^j (1 - p)^{(k-j)}$$

and the mean degree is $\hat{\mu} = p \mu$. As we explore the cluster containing a vertex, individuals in the first and subsequent generations will have $k$ neighbors (excluding their parent) with probability $q_k = (k + 1)p_{k+1}/\mu$ for $k \geq 0$. The probability that they will have $j$ children after thinning is

$$\hat{q}_j = \sum_{k=j}^{\infty} q_k \binom{k}{j} p^j (1 - p)^{(k-j)}$$

Some readers may wonder: what would happen if we took the size biased version of the thinned distribution instead? Using $\bar{q}$ for this distribution

$$\bar{q}_{j-1} = \frac{j \hat{p}_j}{\mu p} = \frac{j}{\mu p} \sum_{k=j}^{\infty} \frac{k!}{(k-j)!j!} p^j (1 - p)^{(k-j)}$$

$$= \sum_{k=j}^{\infty} \frac{k p_k}{\mu} \frac{(k-1)!}{(k-j)!(j-1)!} p^{j-1} (1 - p)^{(k-j)}$$
Setting $m = k + 1$
\[ q_m \left( \frac{m}{j - 1} \right) p^{j-1} (1 - p)^{m+1-j} = \hat{q}_{j-1} \]

If $\nu$ is the mean of $q$, the mean of $\hat{q}$ is $\nu = \nu p$, and the condition for a giant component is\[ \nu p > 1 \quad (2.7.3) \]

Let $G_0$ be the generating function of $p_k$ and $G_1$ be the generating function of $q_k$. Let $\hat{G}_0$ be the generating function of $\hat{p}_k$ and $\hat{G}_1$ be the generating function of $\hat{q}_k$.
\[ \hat{G}_0(z) = \sum_{j=0}^{\infty} \hat{p}_j z^j = \sum_{j=0}^{\infty} \sum_{k=j}^{\infty} p_k \left( \binom{k}{j} \right) p^j (1 - p)^{k-j} z^j \]
\[ = \sum_{k=0}^{\infty} p_k \sum_{j=0}^{k} \left( \binom{k}{j} \right) (pz)^j (1 - p)^{k-j} = G_0(pz + (1 - p)) \]

An almost identical calculation gives $\hat{G}_1(z) = G_1(pz + (1 - p))$.

The results for the giant cluster in percolation are the same as the ones for the configuration model in Theorem 2.1.3.

**Theorem 2.7.1.** The condition for the existence of a giant component is $\hat{\nu} = \nu p > 1$. In this case the fraction of vertices in the giant component is asymptotically $1 - \hat{G}_0(\hat{\rho}_1)$, where $\hat{\rho}_1$ is the smallest fixed point of $\hat{G}_0$ in $[0, 1]$.

In the remainder of this section we will apply this result to various examples, most of which have power law degree distributions. $p_k \sim Ck^{-\gamma}$.

<table>
<thead>
<tr>
<th>$p_c$</th>
<th>$1 - \hat{G}_0(\hat{\rho}_1)$</th>
<th>$1 - \hat{G}_0(\hat{\rho}_1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>finite variance</td>
<td>$&gt; 0$</td>
<td>$C(\theta - 1)$</td>
</tr>
<tr>
<td>$3 &lt; \gamma &lt; 4$</td>
<td>$&gt; 0$</td>
<td>$C(\theta - 1)^{1/(\gamma-3)}$</td>
</tr>
<tr>
<td>$\gamma = 3$</td>
<td>$= 0$</td>
<td>$\exp(-(1 + o(1))/cp)$</td>
</tr>
<tr>
<td>$2 &lt; \gamma &lt; 3$</td>
<td>$= 0$</td>
<td>$cp^{(\gamma-2)/(3-\gamma)}$</td>
</tr>
</tbody>
</table>

The graph in Figure 2.5 is probably easier to understand than the table.

**When $q$ has finite variance**

The computation in this case is essentially the same as the one done for the Erdős-Rényi graph in Section 1.8.1. Consider a branching process with offspring distribution $r_k$ with mean $\theta > 1$ and finite second moment. Let $\phi$ be the generating function of $r_k$ and $\rho$ be probability the system dies out, which is the unique solution of $\phi(\rho) = \rho$ in $[0, 1]$.

\[ \phi(1) = 1 \quad \phi'(1) = \sum_{k=0}^{\infty} kr_k = \theta \quad \phi''(1) = \sum_{k=0}^{\infty} k(k-1)r_k \equiv \theta_2 \]
If $\theta$ is close to 1 then $\rho$ will be close to 1. If $x$ is close to 1 expanding $\phi$ in power series around 1 gives

$$\phi(1 - x) \approx 1 - \theta x + \theta_2 x^2 / 2 + \cdots$$

For a fixed point at $x$ we want $1 - x = \phi(1 - x)$, which means

$$(\theta - 1)x = \theta_2 x^2 / 2 \quad \text{or} \quad x = 2(\theta - 1)/\theta_2.$$  \hspace{1cm} (2.7.4)

Applying this result on the brenaching process with the size biased distribution.

$$1 - \rho_1 \sim C_1(\theta - 1) \quad \text{where} \quad \theta = \hat{\nu} = \mu p$$

This implies

$$1 - \hat{G}_0(\rho_1) \approx 1 - \hat{G}_0(1 - C_1(\theta - 1)) \sim \hat{G}_0'(1) C_1(\theta - 1)$$  \hspace{1cm} (2.7.5)

This calculation generalizes easily to all of the other examples: the asymptotic behavior of $1 - \hat{G}_0(\rho_1)$ is the same as that of $1 - \rho_1$

**Power law distributions** $3 < \gamma < 4$

When $3 < \gamma < 4$ the mean of $q_k$ is finite but the variance of $q_k$ is infinite. To understand the behavior of the generating function as $z \to 1$, we will use the following Tauberian theorem, which is Theorem 5 in Section XIII.5 of Feller, Volume 2. To state this result we need a definition: $L(t)$ varies slowly at infinity if for any $0 < x < \infty$, $L(tx)/L(t) \to 1$. This obviously holds if $L(t)$ converges to a positive limit. $L(t) = (\log t)^a$ is a more interesting example.
Theorem 2.7.2. Let $q_n \geq 0$ and suppose that $Q(s) = \sum_{n=0}^{\infty} q_n s^n$ converges for $0 \leq s < 1$. If $L$ varies slowly at $\infty$ and $0 \leq \alpha < \infty$ then each of the two following relations implies the other

\[ Q(s) \sim (1 - s)^{-\alpha} L(1/(1 - s)) \quad \text{as } s \uparrow 1 \]
\[ q_0 + \cdots + q_n \sim n^\alpha L(n)/\Gamma(\alpha + 1) \quad \text{as } s \uparrow 1 \]

Note that the result only gives us conclusions for the sum of the $q$'s. To see that one cannot hope to get a result for the $q$'s rather than their sums, define $\tilde{q}_2n = q_{2n-1} + q_{2n}, \tilde{q}_{2n-1} = 0$, and note that

\[ \tilde{Q}(s) \leq Q(s) \leq \tilde{Q}(s)/s \]

so the two generating functions have the same behavior at $s = 1$.

The Tauberian theorem requires that we work with quantities that diverge as $s \uparrow 1$ so we start from

\[ G''_1(z) = \sum_k k(k-1)(k-2)p_k z^{k-3}/\mu \]

When $2 < \gamma < 3$ we start with $G'_1(z)$. The reader might want to look at the simpler argument first. If $p_k \sim ck^{-\gamma}$ with $\gamma < 4$ then

\[ \sum_{k=1}^{n} k(k-1)(k-2)p_k/\mu \sim cn^{4-\gamma} \]

so our Tauberian theorem implies

\[ G''_1(z) \sim C(1 - z)^{\gamma - 4} \]

Integrating and allowing the $C$ to change from line to line gives

\[ G_1(1) - G_1(1 - x) \sim \int_0^x C'u^{\gamma - 3} du = C'x^{\gamma - 2} \]

It follows that

\[ (\theta - 1)x \approx Cx^{\gamma - 2} \]

so $x \approx (\theta - 1)^{1/(\gamma - 3)}$. Using the last computation we see that

\[ 1 - \rho_1 \sim (\theta - 1)^{1/(\gamma - 3)} \]

Using (2.7.5) the same result holds for $1 - \hat{G}_0(\rho_1)$.

Theorem 2.7.3. Suppose $p_k \sim C\gamma k^{-\gamma}$ as $k \to \infty$ with $3 < \gamma < 4$ and let $\theta = pv$. Then the percolation probability for the type one branching process satisfies

\[ 1 - \hat{G}_0(\rho_1) \sim C(\theta - 1)^{1/(\gamma - 3)} \]

Skipping over the borderline case $\gamma = 3$ for the moment.
Scale-free networks: $2 < \gamma < 3$

**Theorem 2.7.4.** Given a degree distribution with $p_k \sim ck^{-\gamma}$ with $2 < \gamma \leq 3$, the critical percolation probability is 0. If $2 < \gamma < 3$ the size of the giant component $\sim cp^{(\gamma-2)/(3-\gamma)}$ as $p \to 0$.

Theorem 2.7.2 requires that we work with quantities that diverge as $s \uparrow 1$ so we consider

$$G'_1(z) = \sum_k k(k-1)p_k z^{k-2}/\mu$$

If $p_k \sim ck^{-\gamma}$ with $2 < \gamma < 3$ then

$$\sum_{k=1}^n k(k-1)p_k/\mu \sim cn^{3-\gamma}$$

so our Tauberian theorem implies

$$G'_1(z) \sim c(1 - z)^{\gamma-3}$$

Integrating gives

$$G_1(1) - G_1(1 - x) \sim \int_x^1 cu^{\gamma-3} du = c' x^{\gamma-2}$$

To solve $G_1(1 - p + px) = x$ we write

$$1 - x = G_1(1) - G_1(1 - p + xp) \sim c(p(1 - x))^{\gamma-2}$$

Rearranging we have

$$(1 - x) \sim cp^{(\gamma-2)/(3-\gamma)}$$

This gives the asymptotics for the survival probability $1 - \rho_1$ for the homogeneous branching process. Using (2.7.5) the same result holds for $1 - \hat{G}_0(\rho_1)$.

**Borderline case $\gamma = 3$**

**Theorem 2.7.5.** If $\gamma = 3$ the size is $\exp(-(1 + o(1))/cp)$.

**Proof.** If $p_k \sim ck^{-3}$ then

$$\sum_{k=1}^n k(k-1)p_k/\mu \sim c \log n$$

so our Tauberian theorem implies

$$G'_1(z) \sim -c \log(1 - z)$$
Integrating gives

\[ G_1(1) - G_1(1-x) \sim -\int_0^x c \log u \, du \sim cx \log(1/x) \]

To solve \( G_1(1-p+px) = x \) we write

\[ 1 - x = G_1(1) - G_1(1-p+xp) \sim cp(1-x) \log(1/p(1-x)) \]

Rearranging we have \( 1/cp = \log(1/p) + \log(1/(1-x)) \). Since \( \log(1/p) \ll 1/p \) we have

\[ 1 - x = \exp\left(-\left(1 + o(1)\right)/cp\right) \]

This give the asymptotics for the survival probability \( 1 - \rho_1 \). Using (2.7.5) the same result holds \( 1 - \hat{G}_0(\rho_1) \).

References


2.7. PERCOLATION


Chapter 3

Inhomogeneous random graphs

In maximum generality an inhomogeneous random graph is one in which an edge between vertices $i$ and $j$ is present with probability $p(i, j)$. However, it is not possible to prove anything significant in this level of generality. Bollobás, Janson, and Riordan (2007), a reference we will refer to as BJR(2007), have found a framework that is very general and allows for a rich theory to be developed. In the special case that we will consider, we imagine the vertices embedded in $(0, 1]$ which is equipped with the Borel sets and Lebesgue measure, and there is a kernel $\kappa$ defined on $(0, 1] \times (0, 1]$ (with properties to be specified later) so that

$$p(i, j) = \kappa(i/n, j/n)/n.$$ 

We will describe the set-up in Section 3.3 after we have introduced a number of examples in Section 3.2 to show that this framework is useful. In the Section 3.1 we will consider the situation in which there are only a finite number of different types of vertices. This is the simplest possible example but it is important, because results for this case are an important first step for proving things in general.

3.1 Finitely many types

For each $1 \leq k \leq m$, there $n_k$ individuals of type $k$, and there is an edge from an individual of type $j$ to one of type $k$ with probability $a(j, k)/n$ where $n = \sum_k n_k$. If we let $\ell(x)$ be the type of vertex $x$ then

$$p(x, y) = \frac{a(\ell(x), \ell(y))}{n}$$

It is natural to arrange the indices so that the first $n_1$ vertices are of type 1, the next $n_2$ are of type 2, etc and to assume that $n_k/n \to \pi_k$. Let $V_k$ be the set of vertices of type $k$.

When there is only one type and $a(1, 1) = \lambda$, we have a Erdős-Rényi graph. In the limit $n \to \infty$ vertices have degrees that are Poisson with mean $\lambda$. In Section 1.2 we compared the growth of clusters to a branching process in which individuals have a Poisson($\lambda$) number of offspring and concluded that
(i) there is a giant component (with size of order \( n \)) if and only if \( \lambda > 1 \).

(ii) if \( \lambda > 1 \) then as \( n \to \infty \) the fraction of vertices in the giant component converges to the survival probability of the branching process.

In the multitype case, if we let \( N_{j,k} \) be the number of neighbors of type \( k \) for a vertex of type \( j \) then (i) the \( N_{j,k} \) have a distribution that is

\[
\text{binomial}(n_k, a(j,k)/n) \approx \text{Poisson}(a(j,k)\pi_k)
\]

and (ii) \( N_{j,1} \ldots N_{j,m} \) are independent.

Our first goal is to generalize results for the Erdős-Rényi case and show that the phase transition can be understood by studying a multitype branching process. Let \( \mu(j,k) = EN_{j,k} \). If there is \( \ell \) so that if \( \mu_{jk}^\ell > 0 \) for all \( j,k \) (in which case Athreya and Ney (1972) say the branching process is positive regular) then the Perron-Frobenius theorem implies

\[\text{Theorem 3.1.1.}\] As \( t \to \infty \)

\[
\mu_{jk}^t \sim \alpha^t v_j u_k \tag{3.1.1}
\]

where \( \alpha \) is the largest eigenvalue of \( \mu \), and \( u, v \) are the associated left \((1 \times m)\) and right \((m \times 1)\) eigenvectors normalized so that \( u \cdot v = 1 \).

The maximum eigenvalue is often denoted by \( \rho \) but here that letter is reserved for the survival probability of the branching process.

It may seem strange to have the right eigenvector on the left in the limit in (3.1.1), but this is dictated by the fact that \( vu \) is a \( m \times m \) matrix. As a further check, note that in the case \( \mu(j,k) \) is a Markov chain transition probability (i.e., the rows sum to 1), the maximum eigenvalue \( \alpha = 1 \), the left eigenvector \( u \) is the stationary distribution while the right eigenvector \( v \) is a vector of all 1’s, so \( v^i u^j \) is a matrix in which each row is the stationary distribution.

**Phase transtion**

It follows easily from (3.1.1) that

**Theorem 3.1.2.** If \( \alpha < 1 \) then the branching process is subcritical and \( \sup_i E|C_i| < \infty \).

This conclusion holds for the random graph since the branching process provides an upper bound on cluster growth.

The key to studying the case \( \alpha > 1 \) is a result of about supercritical multitype branching process.

**Theorem 3.1.3. Kesten and Stigum (1966).** If \( \alpha > 1 \) then there is a one-dimensional random variable \( W \) so that with probability 1

\[
Z_n/\alpha^n \to W v
\]
where \( v \) is the right eigenvector. One has either (i) \( E(W|Z_n = e_i) = u_i \) or (ii) \( w = 0 \) with probability one. (i) holds if and only if
\[
E(Z_i^j \log^+ Z_i^j | Z_0 = e_i) < \infty \quad \text{for all } 1 \leq i, j \leq n
\]
Here the positive part is to make \( \log^+ 0 = 0 \). This result gives a necessary and sufficient condition for the limit to be nontrivial. In the random graph with finitely many types, the number of offspring \( N_{ij} \) is binomial so \( E(Z_i^j)^2 < \infty \).

**Theorem 3.1.4.** If \( \alpha > 1 \) then the inhomogeneous random graph with finitely many types has a giant component. In the limit the fraction of vertices of type \( k \) in this component is \( \rho_k \), the probability the multitype branching process starting from a single type \( k \) individual does not die out.

**Proof.** This time we cannot reduce the cluster growth process to a random walk, so we will instead run the branching process using a breadth-first search. That is, we first generate the children of the ancestor at time \( t = 1 \), let the number be \( Y_1 \), and write them in an ordered list. We generate the offspring of the first individual in the list, then the second, and so until we have generated all the children of the first generation. We then order the \( Y_2 \) individuals in the second generation and generate their offspring one at a time. Note that there are two time scales here. The time \( t \) counts the number of individuals that have given birth, \( m \to Y_m \) gives the size of the \( m \)th generation, which is known at time \( T_m \) on the birth counting time scale.

**Lemma 3.1.5.** Let \( \delta \) be chosen so that \( \tilde{\alpha} = \alpha(1 - \delta) > 1 \). At the times \( T_m \) when the growing cluster has \( \leq \delta n_k \) vertices in \( V_k \) for all \( k \) the process \( Y_m \) dominates a multitype branching process with mean matrix \( (1 - \delta)\mu_{j,k} \).

**Proof.** Suppose that at the \( t \)th step of the construction we are generating the offspring of a type \( j \) individual. If the growing cluster does not yet contain \( \delta n_k \) vertices in \( V_k \) for any \( k \), we can pick sets \( G_{t,k} \subset V_k \) that have \( |G_{t,k}| = (1 - \delta)n_k \) and \( G_{t,k} \) does not contain any sites of the growing cluster. We allow the vertex \( x \) of type \( j \) to give birth onto each \( y \in G_k \) with probability \( a(j,k)/n \) independent of everything that has happened so far in the construction. This completes the proof of the lemma.

There is no need to do the comparison at time \( t = 1 \) but if we do then \( Y_m \) is exactly multitype branching process with mean matrix \( (1 - \delta)\mu(j,k) \) and in addition the number of individuals of type \( k \) of an individual of type \( j \) is binomial(\( n_k, a(j,k)/n \)). We say that the process \( Y_m \) survives if the total number of offspring reaches \( n^{2/3} \). Note that if \( n \) is large it follows that the growing cluster does not yet contain \( \delta n_k \) vertices in \( V_k \) for any \( k \).

If the ancestor has type \( k \) then the probability the branching process survives converges to \( \rho_k \) as \( n \to \infty \). Using the limit theorem for supercritical branching processes in Theorem 3.1.3, it is easy to see that if the total progeny reaches \( n^{2/3} \) at time \( M \) then the exponential growth in Theorem 3.1.3 implies that with high probability \( Y_M > n^{0.6} \). Reasoning as in Step
3 in Section 1.3 (and noting that there is an $\ell$ so that we have $\mu^\ell(j,k) > 0$) it follows that two supercritical branching processes that survive will intersect with high probability.

To complete the proof now we note that part (i) of Theorem 3.1.8 below, there is a $\beta > 0$ so that if the multitype branching process has $\beta \log n$ particle total then the probability that it survives is $\geq n^{-2}$ independent of the actual collection of types that are present.

**Computing the survival probability**

The basic data for a multitype branching process is

$$p^j(i_1, \ldots i_m)$$

The probability an individual of type $j$ gives birth to $i_1$ individuals of type 1, $i_2$ individuals of type 2, $\ldots$, $i_m$ individuals of type $m$. Here we are following Chapter V of the book of Athreya and Ney (1972) so we will use their notation. In particular the superscript $j$ here and in $f^j(s)$ below are superscripts and not powers. Define the multivariate generating function by

$$f^j(s) = \sum_i p^j(i_1, \ldots i_m) s_1^{i_1} \cdots s_m^{i_m}$$  \hfill (3.1.2)

where $s = (s_1, \ldots s_m)$ and combine these into a vector

$$f(s) = (f^1(s), \ldots f^m(s))$$

**Example. Random graph.** Since $N_{j,k}$ are independent binomial($n_k, a(j,k)/n$) and the generating function of binomial($m, r$) is

$$\phi(z) = \sum_{\ell=0}^m z^\ell \binom{m}{\ell} r^\ell (1 - r)^{m-\ell} = (1 - p + pz)^m$$

the generating function defined in (3.1.2) is

$$f^j(s) = \prod_{k=1}^m \left(1 - \frac{a(j,k)}{n} (1 - z)\right)^{n_k}$$

$$\approx \exp \left(- \sum_{k=1}^m a(j,k) \pi_k (1 - z)\right)$$

By analogy with the one type case we should expect

**Lemma 3.1.6.** Let $f_k$ be the generating function of $(Z^1_k, \ldots Z^m_k)$. Then $f_{k+\ell}(s) = f_k(f_\ell(s))$

Throughout this section, we will regard facts about multitype branching processes as well-known and not provide proofs. The reader can consult Athreya and Ney for details, although in this case one must go back to Harris’ (1963) book to find the proof.

In the one-type case we have to exclude the situation in which each individual has exactly one offspring. In the multitype case we say that $Z_n$ is **singular** if this holds.
Lemma 3.1.7. If $Z_n$ is positive regular and nonsingular then

$$P(Z_n = j \text{ infinitely often}) = 0$$

for any $j \geq 0$ with $j \neq 0$.

To prove this it is enough to show that for each $j \geq 0$ with $j \neq 0$ the probability the process dies out is $\geq \epsilon_j > 0$ for then the result follows from Lévy’s 0-1 law, Theorem 4.6.9 in PTE5.

Let $q^i$ be the probability of extinction for the multitype branching process starting from one individual of type $i$, and let $q = (q^1, \ldots, q^m)$

Theorem 3.1.8. Assume $Z_n$ is positive regular and nonsingular and let $\alpha$ be the maximum eigenvalue of the mean matrix $\mu$.

(i) If $\alpha \leq 1$ then $q^i = 1$ for all $i$. If $\alpha > 1$, $q^i < 1$ for all $i$.

(ii) $\lim_{n \to \infty} f_n(s) = q$ if $s \in Q = \{ s : 0 \leq s < 1 \}$.

(iii) $q$ is the only solution of $f(s) = s$ in $Q$

(iii) follows immediately from (ii). In the one type case we start from $s = 0$ and iterate to find $q$.

Subcritical regime

The goal of this section is to show that

Theorem 3.1.9. If $\alpha < 1$, there are constants $\theta, \epsilon > 0$ so that

$$P(|C_x| \geq k) \leq e^{\theta(1-\epsilon k)}$$

Proof. To prove this we will find the cluster by revealing the neighbors of the vertices one at a time as in Section 1.3. Let $A^t_i$ be the number of active vertices of type $i$ at time $t$. Let $v_i$ be the right-eigenvector of the mean matrix and let $Y_t = \sum_i A^t_i v_i$. Let $r_t$ be the type of the vertex whose neighbors are revealed at time $t + 1$. Since $\sum_j \mu(i,j)v_j = \lambda v_i$ if we ignore collisions then $Y_t$ has negative drift

$$E(Y_{t+1} - Y_t | r_t = i) = (\lambda - 1)v_i$$

The assumption of no collisions is valid since with high probability the number of sites involved will be $O(\log n)$. $Y_t$ is not a random walk but it only has finitely many different types of jumps, so we can find an exponential martingale. Let $\mathcal{F}_t$ be the information known at time $t$ and let $\epsilon > 0$. On $\{r_t = i\}$

$$E(e^{\theta|Y_{t+1}|+\epsilon(t+1)}|\mathcal{F}_t) = e^{\theta|Y_t|+\epsilon t}E \left( \exp \left( \epsilon - \theta v_i + \theta \sum_j N_{i,j}v_j \right) \bigg| \mathcal{F}_t \right)$$

(3.1.3)
Ignoring the $e^{-\theta v_i}$, the conditional expectation on the right-hand side is

$$\prod_j \left( 1 - \frac{a(i,j)}{n} + \frac{a(i,j)}{n} e^{\theta v_j} \right)^{n_j} \approx \exp \left( \mu(i,j)[e^{\theta v_j} - 1] \right)$$

(3.1.4)

since $\mu(i,j) = a(i,j)\pi_j$.

The inequality $e^{\theta v_j} - 1 \geq \theta v_j$ goes the wrong way for finding a supermartingale so we need a complimentary upper bound. The next result is routine and the proof is easy but we include the details for completeness

**Lemma 3.1.10.** Let $\eta > 0$. If $\delta$ is small enough then for all $0 \leq x \leq \delta$, $e^x - 1 \leq (1 + \eta)x$.

**Proof.** Using the power series expansion for $e^x$ we see that if $0 \leq x \leq \delta$

$$e^x - 1 = \sum_{m=1}^{\infty} \frac{x^m}{m!} \leq x + x \left( \frac{\delta}{2!} + \frac{\delta^2}{3!} + \cdots \right)$$

$$\leq x \left( 1 + \frac{\delta}{2(1 - \delta)} \right)$$

since $k! \geq 2$ for $k \geq 2$. Choosing $\delta$ small proves the result. \qed

Using (3.1.3) and (3.1.4) with the Lemma, we see that if $\theta$ is chosen small enough so that $0 \leq \theta v_i \leq \delta$ for all $i$ then on $\{r_t = i\}$

$$E(e^{\theta|Y_{t+1} + \epsilon(t+1)|}|F_t) \leq e^{\theta|Y_t + \epsilon t|} \exp \left( \epsilon - \theta v_i + \theta(1 + \eta) \sum_j \mu(i,j)v_j \right)$$

The last quantity on the right

$$\epsilon - \theta v_i + \theta(1 + \eta) \sum_j \mu(i,j)v_j = \epsilon - \theta v_i(1 - \lambda(1 + \eta)).$$

If we pick $\eta$ small enough so that $\lambda(1+\epsilon) < 1$ and then $\epsilon$ small $\exp(\theta|Y_t + \epsilon t|)$ is a supermartingale. Let $\tau$ be time that the exploration process terminates and recall that if we start with one active site $x$ then $\tau = |C_x|$. Using stopping theorem for nonnegative supermartingales, Theorem 4.8.4 in PTE5, we have

$$e^\theta \geq Ee^{\theta \epsilon \tau} \geq e^{\theta \epsilon k} P(|C_x| \geq k)$$

which proves the desired result. \qed

### 3.2 Motivating examples

The concept of an inhomogeneous graphs, as we define it here, was introduced in BJR(2007), which fills an entire issue of *Random Structures and Algorithms*. To motivate the machinery that needs to be developed, we will first show that it covers a number of interesting examples.
3.2. MOTIVATING EXAMPLES

3.2.1 Uniformly grown random graphs

Kalikow and Weiss (1988) considered a random graph on the positive integers $\mathbb{N}$ in which there is an edge between $i$ and $j$ with probability

$$p_{ij} = \left( \frac{\lambda}{\max\{i, j\}} \right) \wedge 1$$

where $a \wedge b = \min\{a, b\}$. The existence of an infinite component is trivial: for any $\lambda \in (0, 1]$, $p_{1,j} = \lambda/j$, so $\sum_{j} p_{1,j} = \infty$ and the component containing 1, $C_1$ is always infinite. Because of this, they considered the question: Is $\mathbb{N}$ connected with positive probability? They showed that the answer was yes if $\lambda > 1$ and no if $\lambda < 1/4$. Dubins had earlier conjectured that the critical value $\lambda_c = 1$. Shepp (1989) later proved that the answer to the question was yes if $\lambda > 1/4$ and no if $\lambda \leq 1/4$, so $\lambda_c = 1/4$

Callaway, Hopcroft, Kleinberg, Newman, and Strogatz (2001) introduced the following simple version of a randomly grown graph. Start with one vertex labelled 1 and no edges. At each time $n \geq 2$, we add one vertex labelled $n$ and with probability $\delta$ add one edge between two randomly chosen vertices $1 \leq i < j \leq n$. Note that the newly added vertex is not necessarily an endpoint of the added edge and when $n$ is large, it is likely not to be.

CHKNS began their analysis by examining $N_k(t) = \text{the expected number of components of size } k \text{ at time } t$. Ignoring terms of $O(1/t^2)$, which come, for example, from picking the same cluster twice:

$$N_1(t + 1) = N_1(t) + 1 - 2\delta \frac{N_1(t)}{t}$$

(3.2.1)

$$N_k(t + 1) = N_k(t) - 2\delta \frac{kN_k(t)}{t} + \delta \sum_{j=1}^{k-1} jN_j(t) \cdot \frac{(k-j)N_{k-j}(t)}{t}$$

(3.2.2)

To explain the first equation, note that at each discrete time $t$ one new vertex is added, and a given isolated vertex becomes the endpoint of an added edge with probability $\approx 2\delta/t$. For the second equation, note that the probability an edge connects to a given cluster of size $k$ is $\approx 2\delta k/t$, while the second term corresponds to mergers of clusters of size $j$ and $k-j$. There is no factor of 2 in the last term since we sum from 1 to $k-1$.

**Theorem 3.2.1.** As $t \to \infty$, $N_k(t)/t \to a_k$ where $a_1 = 1/(1 + 2\delta)$ and for $k \geq 2$

$$a_k = \frac{\delta}{1 + 2\delta} \sum_{j=1}^{k-1} j a_j \cdot (k-j) a_{k-j}$$

To solve for the $a_k$, which gives the limiting number of clusters of size $k$ per site, CHKNS used generating functions. Let

$$h(x) = \sum_{k=1}^{\infty} x^k a_k \quad \text{and} \quad g(x) = \sum_{k=1}^{\infty} x^k k a_k.$$
Multiplying the formulas for $a_k$ in Theorem 3.2.1 by $(1 + 2\delta_k)x^k$, recalling the formula for $a_1$ is different from the others, and summing gives

$$h(x) + 2\delta g(x) = x + \delta g^2(x) \quad (3.2.3)$$

Since $h'(x) = g(x)/x$ differentiating (3.2.3) gives $g(x)/x + 2\delta g'(x) = 1 + 2\delta g(x)g'(x)$. Rearranging we have $2\delta g'(x)(1 - g(x)) = 1 - g(x)/x$

$$g'(x) = \frac{1}{2\delta x} \cdot \frac{x - g(x)}{1 - g(x)} \quad (3.2.4)$$

Let $b_k = ka_k$ be the number of vertices that belong to clusters of size $k$. $g(1) = \sum_{k=1}^{\infty} b_k$ gives the fraction of vertices that belong to finite components. $1 - g(1)$ gives the fraction of sites that belong to clusters whose size grows in time. Even though it is not known that the missing mass in the limit belongs to a single cluster, it is common to call $1 - g(1)$ the fraction of sites that belong to the giant component. The next result gives the mean size of finite components. Here and throughout the motivating examples we state results without proving them.

![Figure 3.1: Graph of the result in Theorem 3.2.3.](image)

Using the differential equation (3.2.4) one can show

**Lemma 3.2.2.** (i) If $g(1) < 1$ then $\sum_{k=1}^{\infty} kb_k = g'(1) = 1/2\delta$.

(ii) If $g(1) = 1$ then $g'(1) = (1 - \sqrt{1 - 8\delta})/4\delta$.

**Theorem 3.2.3.** The critical value $\delta_c = \sup\{\delta : g(1) = 1\} = 1/8$ and hence

$$\sum_k kb_k = \begin{cases} (1 - \sqrt{1 - 8\delta})/4\delta & \delta \leq 1/8 \\ 1/2\delta & \delta > 1/8 \end{cases}$$
Note that this implies that the mean cluster size \( g'(1) \) is always finite, but is discontinuous at \( \delta = 1/8 \), since the value there is 2 but the limit for \( \delta \downarrow 1/8 \) is 4.

**Durrett (2003)**

modified the model so that a Poisson mean \( \delta \) number of vertices are added at each step. This version is nicer since in the Poisson case if we let \( A_{i,j,k} \) be the event no \((i,j)\) edge is added at time \( k \) then \( P(A_{i,j,k}) = \exp\left(-\delta/(k!)\right) \) for \( i < j \leq k \) and these events are independent.

\[
P(\cap_{k=j}^n A_{i,j,k}) = \prod_{k=j}^n \exp\left(-\frac{2\delta}{k(k-1)}\right) \\
= \exp\left(-2\delta \left(\frac{1}{j-1} - \frac{1}{n}\right)\right) \geq 1 - 2\delta \left(\frac{1}{j-1} - \frac{1}{n}\right) \tag{#1}
\]

The last formula is not simple, so he also consider two approximations

\[
\approx 1 - 2\delta \left(\frac{1}{j} - \frac{1}{n}\right) \tag{#2}
\]

\[
\approx 1 - \frac{2\delta}{j} \tag{#3}
\]

Referring to these three models by their numbers, he showed that

**Theorem 3.2.4.** In models \#1, \#2, or \#3, the critical value for the existence of a component of order \( n \) is \( \delta_c = 1/8 \).

In addition Durrett (2003) obtained some results about the decay of connection probabilities at the critical value and in the subcritical regime. See Section 7.3 in RGD.

**Bollobás, Janson, and Riordan (2005)**

were not aware of Durrett’s work when they wrote their paper. They did an independent analysis of the CHKNS model, proving a remarkable result about the supercritical phase: the size of the giant component is infinitely differentiable at the critical value. To put their work into context we need to describe previous work on the size of the giant component.

To investigate the size of the giant component, CHKNS integrated the differential equation (3.2.4) near \( \delta = 1/8 \). Letting \( S(\delta) = 1 - g(1) \) the fraction of vertices in the infinite component they plotted \( \log(-\log S) \) vs \( \log(\delta - 1/8) \) and concluded that

\[
S(\delta) \sim \exp(-\alpha(\delta - 1/8)^{-\beta})
\]

where \( \alpha = 1.132\pm0.008 \) and \( \beta = 0.499\pm0.001 \). Based on this they conjectured that \( \beta = 1/2 \). Inspired by their conjecture Dorogovstev, Mendes, and Samukhin (2001) calculated (using results that were not completely rigorous but turned out to be very accurate) that as \( \delta \downarrow 1/8 \),

\[
S \equiv 1 - g(1) \approx c \exp(-\pi/\sqrt{8\delta - 1}) \tag{3.2.5}
\]
This result shows $\beta = 1/2$ and $\alpha = \pi/\sqrt{8} = 1.1107$. For a look at the awesome power of physics to study problems of this type see the survey article by Dorogovstev and Mendes (2002)

BJR(2005) used $c = 2\delta$ as their parameter. They showed that if $\eta > 0$

$$\exp\left(-\frac{\pi + \eta}{2\sqrt{\epsilon}}\right) \leq C_1(G_n(1/4 + \epsilon)) \leq \exp\left(-\frac{1 - \eta}{2\sqrt{\epsilon}}\right)$$

Riordan (2005)

improved the result to give the sharp constant.

$$C_1(G_n(1/4 + \epsilon)) \approx \exp\left(-\frac{\pi}{2\sqrt{\epsilon}} + O(\log(1/\epsilon))\right)$$

which agrees with (3.2.5)

### 3.2.2 Preferential attachment

Barabási and Albert (1999)

introduced this model. Intuitively, at every time step, we add a new vertex with $m$ edges that link the new vertex to $m$ different vertices already present in the system. To incorporate preferential attachment, we assume that the probability $\Pi$ that a new vertex will be connected to a vertex $i$ depends on the degree of that vertex.

To have a precise definition, we will suppose that the process starts at time 1 with two vertices linked by $m$ parallel edges, so that the total degree at any time $t$ is $2mt$. When we add a new vertex we will add edges one a time, with the second and subsequent edges doing preferential attachment using the updated degrees. This scheme has the desirable property that a graph of size $n$ for a general $m$ can be obtained by running the $m = 1$ model for $nm$ steps and then collapsing vertices $km, km - 1, \ldots, (k - 1)m + 1$ to make vertex $k$.

They did simulations that suggested a power law distribution with power $\gamma = 2.9 \pm 0.1$ and gave the following argument for $\gamma = 3$. If we consider the degree of $i$, $k_i$, to be a continuous variable then

$$\frac{\partial k_i}{\partial t} = m \cdot \frac{k_i}{\sum_j k_j} = \frac{k_i}{2t}$$

since $\sum_j k_j = 2mt$. The solution to this differential equation is

$$k_i(t) = m(t/t_i)^{1/2}$$

where $t_i$ is the time the vertex was introduced. From this we see that

$$P(k_i(t) > k) = P(t_i < tm^2/k^2) = m^2/k^2$$
since vertices are added uniformly on \([0, t]\). Differentiating
\[
P(k_i(t) = k) = 2m^2/k^3
\]

**Dorogovstev, Mendes, and Samukhin (2000)**

took a different approach, using what they call the “master equation,” which can be used to obtain rigorous asymptotics for the mean number of vertices of degree \(k\), \(N(k, t)\). By considering what happens on one step, in which vertices of degree \(k\) can be created from those of degree \(k - 1\) or lost by becoming degree \(k + 1\), we see that
\[
N(k, t + 1) - N(k, t) = \frac{m(k - 1)}{2mt}N(k - 1, t) - \frac{mk}{2mt}N(k, t) + \delta_{k,m}
\]  
(3.2.6)

Here we ignore the possibility of more than one edge being attached to one vertex, and the updating of edges that occurs as the \(m\) edges are added. The last term takes care of the fact that when \(k = m\) we add one vertex of degree \(m\) at each time. To make the equation correct for \(k = m\) we suppose \(N(j, t) = 0\) for \(j < m\).

Letting \(p_k = \lim_{t \to \infty} N(k, t)/t\), and using (3.2.6) we conclude that
\[
\begin{align*}
  p_m &= 2/(m + 2) \\
p_k &= \frac{(k - 1)p_{k-1}}{2} + \frac{2}{k + 2} = p_{k-1} \frac{k - 1}{k + 2}
\end{align*}
\]

The solution to this recursion is
\[
p_k = \frac{2m(m + 1)}{k(k + 1)(k + 2)}
\]  
(3.2.7)

**Bollobás and Riordan (2004)**

have performed a rigorous analysis of the diameter of the graphs produced by the Barabási-Albert model. First, consider the case \(m = 1\). They inductively define a sequence of directed random graphs \(G^t_1\) on \(\{i : 1 \leq i \leq t\}\). Start with \(G^1_1\) the graph with one vertex and one loop. Given \(G^{t-1}_1\) form \(G^t_1\) by adding the vertex \(t\) together with a directed edge from \(t\) to \(I\) where \(I\) is chosen randomly with
\[
P(I = i) = \begin{cases} 
  \frac{d_{i}^{t-1}/(2t - 1)}{1/2t - 1} & 1 \leq i \leq t - 1 \\
  \frac{1/(2t - 1)}{1/2t - 1} & i = t
\end{cases}
\]  
(3.2.8)

where \(d_{i}^{t-1}\) = the degree of \(i\) in \(G^{t-1}_1\). In words, we consider the outgoing edge from \(t\) when we consider where to attach the other end of the edge. Note that each vertex will have out degree 1. To extend the definition to \(m > 1\), use the definition above to define random graphs \(G^{mt}_1\) on \(\{v_i : 1 \leq i \leq mt\}\) then combine the vertices \(v_{(k-1)m+1}, \ldots, v_{km}\) to make vertex \(k\).

Their main result is:
Theorem 3.2.5. Let \( m \geq 2 \) and \( \epsilon > 0 \). Then with probability tending to 1, \( G^m \) is connected and
\[
(1 - \epsilon) \log n / (\log \log n) \leq \text{diameter}(G^m) \leq (1 + \epsilon) \log n / (\log \log n)
\]
The case \( m = 1 \), in which the graph is a tree, is excluded because the upper bound is false in this case.

In order to prove the lower bound they consider \( G_N^N \) with \( N = nm \) and compare \( G_N^N \) with a random graph in which an edge from \( i \) to \( j \) is present with probability \( c / \sqrt{ij} \). Let \( g_j \) be the vertex to which \( j \) sends an edge when it is added to the graph.

Lemma 3.2.6. (a) If \( 1 \leq i < j \) then \( P(g_j = i) \leq C_1 (ij)^{-1/2} \).
(b) If \( 1 \leq i < j < k \) then \( P(g_j = i, g_k = i) \leq C_2 i^{-1} (jk)^{-1/2} \).

This proof motivates the consideration of the inhomogeneous graph with
\[
p(i, j) = c / \sqrt{ij}
\]
which is often called the mean-field version of preferential attachment because edges are independent. There is a giant component in this graph for all \( c > 0 \).

Riordan (2005) has shown for the square root model defined in (3.2.9) that there is a function \( f(c) \) so that with high probability the largest component has \( (f(c) + o(1))n \) vertices as \( n \to \infty \) where
\[
f(c) \sim 2e^{1-\gamma} \exp(-1/(2c))
\]

3.2.3 Chung-Lu model

In this model weights \( w_i \) are assigned to vertices and we define the probability of an edge between \( i \) and \( j \) to be
\[
p(i, j) = \frac{w_i w_j}{\sum_k w_k} \wedge 1
\]
The weight \( w_i \) is the expected degree of \( i \) since (ignoring the \( \wedge 1 \) and including the \( j = i \) (self-loop) term in the sum.)
\[
\sum_j w_i w_j = w_i
\]
If we let
\[
w_i = (i/Cn)^{-1/(\gamma-1)}
\]
then \( w_i > w \) if and only if \( i/n < Cw^{-1/(\gamma-1)} \) so the graph has a power law degree distribution. \( P(w_i > w) \sim Cw^{-(\gamma-1)} \). If \( \gamma > 2 \) then \( Ew_i < \infty \) so \( \sum_k w_k \sim \mu n \).

To get the Chung-Lu model we take \( a = 1/(\gamma - 1) \), \( \psi(x) = x^{-a} \) and \( \kappa(x, y) = c\psi(x)\psi(y) \)
In this case
\[
p(i, j) = \kappa(i/n, j/n) / n = \frac{c(i/n)^{-a}(j/n)^{-a}}{n}
\]
Earlier we have proved a result for the average distance between two randomly chosen vertices, see Theorem 2.4.5. In this chapter we will prove results about the phase transition.
3.3 Welcome to the machine

The description of the framework used in BJR(2007) will require a number of definitions. We will restrict ourselves to a level of generality that is enough to cover the examples we are interested in.

A ground space is a pair $(\mathcal{S}, \mu)$ where $\mathcal{S}$ is a separable metric space and $\mu$ is a Borel probability measure. For us this will usually be $\mathcal{S} = (0, 1]$ and $\mu = \text{Lebesgue measure}$, i.e., $d\mu(x) = dx$.

A vertex space $\mathcal{V}$ is a triple $(\mathcal{S}, \mu, \{x^n\}_{n \geq 1})$ where $(\mathcal{S}, \mu)$ is a ground space and $x^n = (x^n_1, \ldots, x^n_n)$ is a random sequence of points in $\mathcal{S}$ so that

$$\nu_n(A) = \#\{i \leq n : x^n_i \in A\}/n \rightarrow \mu(A)$$

(3.3.1)

for every $\mu$-continuity set, i.e., $\mu(\partial A) = 0$ where $\partial A$ is the boundary of $A$. In most of our examples $x^n_i = i/n$. We will not consider generalized vertex spaces where the number of vertices is random.

A kernel $\kappa$ on a ground space $(\mathcal{S}, \mu)$ is a symmetric non-negative Borel measurable function on $\mathcal{S} \times \mathcal{S}$.

Given a vertex space and a kernel, we can define a random graph $G^\mathcal{V}(n, \kappa)$ in which an edge from $i$ to $j$ is present with probability

$$p^n_{ij} = \kappa(x^n_i, x^n_j)/n \wedge 1$$

To avoid taking the minimum with 1 one can define

$$p^n_{ij} = 1 - \exp(-\kappa(x^n_i, x^n_j)/n)$$

A kernel $\kappa$ is graphical if (i) $\kappa$ is continuous almost everywhere on $\mathcal{S} \times \mathcal{S}$, (ii) $\kappa \in L^1(\mathcal{S} \times \mathcal{S}, \mu \times \mu)$ and (iii) if $e(G)$ is the number of edges in $G$

$$\frac{1}{n} E e(G^\mathcal{V}(n, \kappa)) \rightarrow \frac{1}{2} \iint \kappa(x, y) d\mu(x) d\mu(y)$$

(ii) and (iii) imply that the expected number of edges is $O(n)$.

If $\kappa \in L^1(\mathcal{S} \times \mathcal{S}, \mu \times \mu)$ then $\int_\mathcal{S} \kappa(x, y) d\mu(y) < \infty$ for $\mu$-a.e. $x$. It is convenient to assume that

$$\int_\mathcal{S} \kappa(x, y) d\mu(y) < \infty \text{ for all } x \in \mathcal{S}$$

(3.3.2)

It seems to me that the main reason for allowing $\kappa$ to be discontinuous is to allow for finitely many types example. Since we will consider only examples on $(0, 1]$ we will restrict our attention to kernels that are piecewise continuous. That is there are $0 = a_0 < a_1 < a_2 <$
\[ \ldots < a_k = 1 \] so that \( \kappa \) is continuous on each \((a_{i-1}, a_i)\). In addition we require that on each interval \((a_{i-1}, a_i)\) \( \kappa \) converges to a finite limit as either endpoint is approach, unless \( a_{i-1} = 0 \) in which case we can have \( \kappa \to \infty \).

It is useful to have some concrete examples to consider. In all these cases \( S = (0, 1] \), \( \mu \) is Lebesgue measure and \( x^n_i = i/n \).

**Finitely many types.** For \( 1 \leq k \leq K \) we have intervals \( I_k = (a_{k-1}, a_k] \) with \( 0 = a_0 < a_1 < \ldots < a_K = 1 \). For \( x \in I_k, y \in I_\ell \), \( \kappa(x, y) = a(k, \ell) \).

**Square root model.** \( \kappa(x, y) = c/\sqrt{xy} \). In this case \( \kappa \notin L^1 \). As we will see this implies that the critical value \( c_c = 0 \).

**Dubins model.** \( \kappa(x, y) = c/\max\{x, y\} \)

**Chung and Lu (2002).** \( \kappa(x, y) = c\psi(x)\psi(y) \) with \( \psi(x) = x^{-(\gamma-1)} \).

**Durrett and Kesten (1990) considered a model with** \( \kappa(x, y) = c/(x^p + y^p)^{1/p} \). They suppose \( p > 0 \). Here we will suppose \( p \geq 1 \) so that condition (ii) holds. Letting \( p \to \infty \) gives the Dubins model.

### Phase transition

To begin we define an integral operator

\[
(T_\kappa f)(x) = \int_S \kappa(x, y) f(y) d\mu(y)
\]

The norm \( \|T_\kappa\| = \sup\{|T_\kappa f| : f \geq 0, \|f\| \leq 1\} \). In the finite type case this operator is essentially the mean matrix, and the norm is the same as the maximum eigenvalue. To be precise if we let \( g(x) = w_k \) for \( x \in I_k \) (defined in Example 1 above) then

\[
(T_\kappa g)(x) = \sum_k \mu(j, k) w_k \quad \text{for } x \in I_j
\]

In addition we define

\[
\Phi_\kappa f = 1 - \exp(-T_\kappa f)
\]

The survival probability \( \rho_\kappa(x) \) is the maximum fixed point of \( \Phi \). Recall that in the Erdös-Rényi and configuration models the extinction probability is defined in terms of the smallest fixed point of generating functions. In the Erdös-Rényi case when the mean degree is \( \lambda > 1 \) the extinction probability satisfies

\[
z = \exp(-\lambda(1 - z))
\]

so \( \rho = 1 - z \) satisfies \( \rho = 1 - \exp(-\lambda\rho) \).

To state the next result we need a definition. \( \kappa \) is **reducible** if there is an \( A \) with \( 0 < \mu(A) \leq \mu(S) \) so that \( \kappa(x, y) = 0 \) on \( A \times (S - A) \). Otherwise it is **irreducible.**
Theorem 3.3.1. (i) If $\|T_\kappa\| < 1$ then the largest component $C_1$ is $o(n)$ while if $\|T_\kappa\| > 1$ it is $\Theta(n)$. (ii) If $\kappa$ is irreducible then

$$(1/n)|C_1| \to \rho = \int_0^1 \rho_\kappa(x) d\mu(x).$$

The reasoning is similar to that for Erdős-Rényi. $x$ is part of the giant component if the branching process started at $x$ does not die out.

**Rank-one case** When $\kappa(x, y) = c\psi(x)\psi(y)$ the operator $T$ has

$$T_\kappa f = c \left( \int f \psi d\mu \right) \cdot \psi$$

Since $T$ maps all functions to multiples of $\psi$, $\psi$ is the only possible eigenvector. It has eigenvalue $c \int \psi(x)^2 dx$ and critical value

$$c_c = 1/\int \psi(x)^2 dx.$$ 

**Square root model.** $\psi(x) = cx^{-1/2}$ which has $\int \psi^2 dx = \infty$, so $c_c = 0$.

**Chung-Lu model.** $\psi(x) = x^{-1/(\gamma-1)}$ so $c_c = 0$ if $\gamma \leq 3$ while it is $> 0$ if $\gamma > 3$.

**Dubins model.** BJR observe in their Section 16.1 that

$$U : f \to e^{-x/2}f(e^{-x})$$

is an isometry from $L^2(0, 1)$ onto $L^2(0, \infty)$. The operator $\tilde{T}_\kappa = UT_\kappa U^{-1}$ has kernel

$$\tilde{\kappa}(x, y) = e^{-x/2}\kappa(e^{-x}, e^{-y})e^{-y/2} = e^{-x/2-y/2+x\wedge y} = e^{-|x-y|/2}$$

Thus $\tilde{T}_\kappa$ is the restriction to $(0, \infty)$ of the convolution with $h(x) = ce^{-|x|/2}$. “Taking Fourier transforms we find $\|T_\kappa\| = 4c.$” Since it is not hard to find the critical value of the model directly, will not go into the details.

**Durrett and Kesten (1990).** $\kappa(x, y) = c/(x^p + y^p)^{1/p}$ is homogeneous of degree $-1$, i.e., $\kappa(ax, ay) = a^{-1}$ so

$$p(i, j) = \kappa(i/n, j/n)/n = c/(i^p + j^p)^{1/p}$$

independent of $n$. In Dubins’ model $\kappa(x, y)$ is homogeneous of degree $-1$.

The main result in DK(1990) is

**Theorem.** Suppose $p(i, j) = \min\{\lambda h(i, j), 1\}$ where the function $h : [0, \infty)^2 - \{0\} \to (0, \infty)$ is symmetric $h(x, y) = h(y, x)$, homogeneous of degree $-1$, and continuous and strictly positive on $\{(x, y) : x + y = 1\}$. Then the critical value for $\lambda$ is

$$\lambda_c = \left( \int_0^1 \frac{h(u, 1-u)}{\sqrt{u(1-u)}} du \right)^{-1} = \left( \int_0^1 \frac{h(1, y)}{\sqrt{y}} dy \right)^{-1}$$
As in the work of Kalikow and Weiss (1988) mentioned in the discussion of Dubins model, DK(1990) was concern with the threshold for the positive integers $N$ to be connected with positive probability. However if one assumes that $h$ is decreasing in each of its arguments which holds for $h(x, y) = 1/(x^p + y^p)^{1/p}$ and writes $H_{K,M}$ for the submatrix of $h(i, j)$ with $K \leq i, j, \leq M$ then
\[
\lim_{M \to \infty} \rho(H_{1,M}) = \int_0^1 \frac{h(u, 1 - u)}{\sqrt{u(1-u)}} du
\]
so $\lambda_c$ is also the critical value for a giant component in $\{1, 2, \ldots, n\}$.

To compute the critical value DK(1990) show that as Shepp(1989) suggested $w_k = k^{-1/2}$ is a good approximation of the eigenvector associated with the largest eigenvalue $\rho$ so
\[
\lambda_c(p) = p \Gamma(1/p) [\Gamma(1/2p)]^{-2}
\]
where $\Gamma$ is the usual Gamma function.

**Degree distribution**

In the special case $\mathcal{S} = (0, 1]$ with $\mu$ Lebesgue measure, we define
\[
\lambda(x) = \int_0^1 \kappa(x, y) dy
\]
to be the expected degree of $x$.

**Theorem 3.13 in BJR.** Writing $Z_k$ for the number of vertices of degree $k$,
\[
Z_k/n \to P(D = k) = \int_0^1 e^{-\lambda(x)} \frac{\lambda(x)^k}{k!} dx
\]
In words, the degree $D$ of a randomly chosen vertex has the mixed Poisson distribution
\[
\int_0^1 \text{Poisson}(\lambda(x)) dx.
\]
Let $\Lambda$ be the expected degree of a randomly chosen vertex. That is, $\Lambda = \lambda(U)$ where $U$ is uniform on $(0, 1]$.

**Corollary 3.13 in BJR.** Suppose that
\[
P(\Lambda > t) = \mu\{x : \lambda(x) > t\} \sim at^{-\alpha}
\]
for some $a > 0$ and $\alpha > 1$. Let $Z_{\geq k}$ be the number of vertices with degree $\geq k$ then
\[
Z_{\geq k}/n \to P(D \geq k) \sim ak^{-\alpha}
\]
3.4. RESULTS FOR THE SURVIVAL PROBABILITY

Proof. By Theorem 3.13 it suffices to show that $P(D \geq k) \sim ak^{-\alpha}$. To do this we note that if $Z = \text{Poisson}(\lambda)$ then $(Z - \lambda)/\lambda^{1/2}$ converges to a Normal distribution as $\lambda \to \infty$ so if $1/2 < b < 1$

$$P(\lambda - b < \text{Poisson}(\lambda) < \lambda + b) \to 1$$

Using this we conclude that if $k$ is large and $\epsilon > 0$

$$P(\text{Poisson}(\lambda(x)) \geq k) \approx \begin{cases} 1 & \text{if } \lambda(x) \geq (1 + \epsilon)K \\ 0 & \text{if } \lambda(x) \leq (1 - \epsilon)K \end{cases}$$

If we suppose for simplicity that $\lambda(x)$ is decreasing we have

$$P(D \geq k) \approx \mu\{x : \lambda(x) \geq k\}$$

which gives the desired result. □

Rank-one model

$$\lambda(x) = c\psi(x) \int_{0}^{1} \psi(y) dy$$

If $\psi(x) = x^{-a}$ and $a < 1$ then

$$\lambda(x) = cx^{-a} \int_{0}^{1} y^{-a} dy = cx^{-a}/(1 - a)$$

Letting $B = c/(1 - a)$ we have $\lambda(x) > t$ if $Bx^a > t$ or $x < (t/B)^{-1/a}$. If $t > B$ then

$$P(\Lambda > t) = (t/B)^{-1/a}$$

In the Chung-Lu model $a = 1/(\gamma - 1)$, so $P(\Lambda > t) \sim Ct^{-\gamma+1}$ so the degree distribution has $p_k \sim C^n k^{-\gamma}$.

3.4 Results for the survival probability

This is done by comparing with a multitype branching process. Here we follow Section 5 of Riordan (2005). To define the branching process we declare that the children of $y$ are a Poisson process with mean measure $\kappa(y, z) dz$ on $(0, 1]$. That is, if we let $N(A)$ be the number of points in $A$ then

(i) If $A_1, \ldots, A_n$ are disjoint $N(A_1), \ldots, N(A_k)$ are independent

(ii) $N(A)$ has Poisson $\left( \int_A \kappa(y, z) dz \right)$ distribution.

The next result will make this definition more explicit.
Lemma 3.4.1. If a particle in $X_k$ has type $a$ and $m$ children they will have joint distribution

$$f_m(a, b_1, \ldots, b_m) = \exp \left( - \int_0^1 \kappa(a, b) \, db \right) \frac{1}{m!} \prod_{i=1}^m \kappa(a, b_i)$$

Proof. To see this suppose we have points $1/n, 2/n, \ldots, 1$ and a random graph with

$$p(i, j) = \kappa(i/n, j/n)/n$$

The probability that $j$ connects to $k_1, \ldots, k_m$ and to no other vertices is

$$= \prod_{k \neq k_i} (1 - \kappa(j/n, k/n)/n) \prod_{i=1}^m \kappa(j/n, k_i/n) \cdot \frac{1}{n}$$

Letting $a = j/n$ nd $b_i = k_i/n$, the first term is

$$\approx \exp \left( - \int_0^1 g(\alpha, \beta) \, d\beta \right)$$

If we think of $b_i$ as an interval of length $1/n$ and $g(a, b)$ as a density function the second term is

$$\approx \prod_{i=1}^m g(a, b_i)$$

If we get rid of the ordering $\beta_1 < \cdots \beta_m$ we need to divide by $m!$.

Our next task is to define the success probability. In Riordan (2005)'s approach we let

$$F(g)(a) = \sum_{m \geq 0} \int_{b_1, \ldots, b_m \in S} f_m(a, b_1, \ldots, b_m) \left( 1 - \prod_{i=1}^m (1 - g(b_i)) \right) db_m \cdots db_1$$

If we assign to each child $b$ an event called success that has probability $g(b)$ then $F(g)(a)$ is probability of success of at least one child of $a$. If we let $S_\infty(b)$ be the probability that the branching process starting with one individual of type $b$ does not die out then $S_\infty = F(S_\infty)$.

To develop the properties of $S_\infty$ we need we will follows Section 5 in BJR who write things using a different notation.

Lemma 3.4.2. Consider the random offspring of a single particle of type $x$ and let $N$ be the total number of children. If $0 \leq g \leq 1$ is measurable

$$(\Phi_n g)(x) \equiv 1 - E \prod_{i=1}^N (1 - g(\xi_i)) = 1 - e^{-(T_x g)(x)} \tag{3.4.1}$$

where $\equiv$ indicates that the first equality is a definition.
3.4. RESULTS FOR THE SURVIVAL PROBABILITY

Proof. Let \( dv(y) = \kappa(x, y) dy \) and \( \nu' = \nu/\nu(S) \) Given \( N = n \), if we list the locations in random order \( \xi_1, \xi_2, \ldots, \xi_n \) the locations are independent with distribution \( \nu' \) so

\[
\prod_{i=1}^{n} E(1 - g(\xi_i)) = (E[1 - g(\xi_1)])^n = \left( 1 - \int_0^1 g(y) \, d\nu'(y) \right)^n = \left( 1 - \frac{(T_\kappa g)(x)}{\nu(S)} \right)^n
\]

Using \( P(N = n) = e^{-\nu(S)}\nu(S)^n/n! \) taking expectation, and writing \( h(x) = (T_\kappa g)(x) \) to simplify the formulas gives

\[
E \prod_{i=1}^{N} (1 - g(\xi_i)) = \sum_{n=0}^{\infty} e^{-\nu(S)}\frac{\nu(S)^n}{n!} \left( 1 - \frac{h(x)}{\nu(S)} \right)^n = e^{-h(x)} \sum_{n=0}^{\infty} e^{-\nu(S)+h(x)} \left[ \frac{\nu(S) - h(x)}{n!} \right]^n = e^{-h(x)}
\]

which proves the second equality. \( \square \)

Lemma 3.4.3. (i) For \( m \geq 0 \) the probability that a particle of type \( x \) has descendants in at least \( m \) further generations is \( (\Phi^m_\kappa 1)(x) \)

(ii) As \( m \to \infty \), \( (\Phi^m_\kappa 1)(x) \) decreases to a limit we call \( \rho_\kappa(x) \)

(iii) \( \rho_\kappa \) satisfies \( \Phi_\kappa \rho_\kappa = \rho_\kappa \)

(iv) If \( f(x) \) is any other solution \( \rho_\kappa(x) \geq f(x) \).

Proof. Let \( g_m(x) \) be the probability that a particle of type \( x \) has descendants in at least \( m \) further generations. If we let \( g = g_m \) in (3.4.1) then \( E \prod_{i=1}^{N} (1 - g_m(\xi_i)) \) is the probability that none of the children of \( x \) has descendants in the \( m + 1 \) generation. This is \( 1 - \Phi_\kappa g_m \) and the result follows by induction.

(ii) follows immediately from (i). To prove (iii) we note that

\[
\Phi^{m+1}_\kappa 1 = \Phi_\kappa (\Phi^m_\kappa 1)
\]

then let \( m \to \infty \) and use the dominated convergence theorem. To prove (iv) we note that if \( 1 \geq f(x) \) and \( f \) is a solution of \( \Phi_\kappa f = f \) then it follows by induction that \( \Phi^m_\kappa 1 \geq f \). Letting \( m \to \infty \) gives the desired result. \( \square \)

Lemma 3.4.4. Suppose that \( f \geq 0 \) with \( f = \Phi_\kappa f \) then

(i) \( 0 \leq f < 1 \).

(ii) \( T_\kappa f \geq f \) with strict inequality when \( f(x) > 0 \).

(iii) \( T_\kappa f \leq f/(1 - f) \) with strict inequality when \( f(x) > 0 \).

(iv) If \( \kappa \) is irreducible then either \( f = 0 \) everywhere or \( f > 0 \) almost everywhere.
Proof. (i) $f(x) = 1 - e^{-T_\kappa f}(x) \leq 1$ so

$$(T_\kappa f)(x) \leq (T_\kappa 1)(x) \leq \int_S \kappa(x, y) \, d\mu(y) < \infty$$

by the assumption in (3.3.2) and it follows that $f(x) < 1$. (ii) This is immediate from $f = 1 - e^{-T_\kappa f} \leq T_\kappa f$ with equality only when $T_\kappa f = 0$. (iii) $e^{-T_\kappa f} = 1 - f$. Since $f < 1$, $e^{T_\kappa f} = 1/(1 - f)$ and we have

$$T_\kappa f \leq e^{T_\kappa f} - 1 = \frac{1}{1 - f} - 1 = \frac{f}{1 - f}$$

with equality only when $T_\kappa f = 0$.

(iv) Let $A = \{ x \in S : f(x) = 0 \}$. For $x \in A$, $(\Phi_\kappa f)(x) = f(x) = 0$. It follows that if $x \in A \ \kappa(x, y) = 0$ for $y \in S - A$, and the conclusion follows from the assumption of irreducibility.

Lemma 3.4.5. Suppose that $\kappa$ is irreducible. Suppose that $f = \Phi_\kappa f$ and $g = \Phi_\kappa g$ with $0 \leq f \leq g$ then either $f = 0$ or $f = g$.

Proof. By part (iv) of Lemma 3.4.4 we can suppose that $f > 0$ a.e. Let $h = (g - f)/2 \geq 0$ so that $f + h = (f + g)/2$. The function $t \to 1 - e^{-t}$ is strictly convex so

$$1 - e^{-(u+v)/2} \geq \frac{1}{2}(1 - e^{-u}) + \frac{1}{2}(1 - e^{-v})$$

and we have

$$\Phi_\kappa((f + g)/2) = 1 - e^{-T_\kappa (f+g)/2} = 1 - e^{-[T_\kappa (f) + T_\kappa (g)]/2}$$

$$\geq \frac{1}{2}(1 - e^{-T_\kappa f}) + \frac{1}{2}(1 - e^{-T_\kappa g}) = \frac{1}{2}(f + g) = f + h$$

where the $\leq$ is strict inequality at every point where $f < g$ and thus $\Phi_\kappa f < \Phi_\kappa g$ and $T_\kappa f < T_\kappa g$. On the other hand

$$1 - \Phi_\kappa((f + g)/2) = e^{-T_\kappa (f+g)} = e^{-T_\kappa f} e^{-T_\kappa h}$$

$$= (1 - f)e^{-T_\kappa h} = (1 - f)(1 - T_\kappa h)$$

Combining the last two computations

$$(1 - f)(1 - T_\kappa h) \leq 1 - (f + h) = 1 - f - h$$

and thus $(1 - f)T_\kappa h \geq h$ with strict inequality when $g > f$.

Suppose now that $g > f$ on a set of positive measure. Then the last inequality and (iii) of Lemma 3.4.4 imply

$$\int_S f T_\kappa h \, d\mu > \int_S f \cdot \frac{h}{1 - f} = \int_S h \cdot \frac{h}{1 - f} \geq \int_S h T_\kappa f \, d\mu$$

(3.4.2)

The integrals are finite because $\kappa \in L^1$ and $f, h \leq 1$. However, since $\kappa$ is symmetric $T_\kappa$ is a symmetric operator contradicting (3.4.2) which implies $f = g$ a.e.  \qed
Taking \( g = \rho \kappa \) which is a solution

**Lemma 3.4.6.** If \( \kappa \) is irreducible then \( f = 0 \) and \( f = \rho \kappa \) are the only solutions. These solutions may coincide.

**Lemma 3.4.7.** If \( \|T_\kappa\| \leq 1 \) then \( \rho \kappa = 0 \).

*Proof.* Suppose that \( f \) is a solution and that we do not have \( f = 0 \) a.e. (ii) in Lemma 3.4.4 implies that \( T_\kappa f \geq f \) with \( T_\kappa > f \) on a set of positive measure so \( \|T_\kappa\| > 1 \) contradicting the assumption \( \|T_\kappa\| \leq 1 \) so \( f = 0 \) a.e. and \( f = \Phi_\kappa f = 0 \).

To approximately calculate \( S_\infty \) Riordan uses (see page 912)

**Lemma 3.4.8.** If \( \phi : (0, 1] \to [0, 1] \) satisfies \( F(\phi) \geq \phi \) then \( S_\infty \geq \phi \).

**Lemma 3.4.9.** If \( \phi : (0, 1] \to [0, 1] \) satisfies \( F(\phi) \leq \phi \) and \( F(\phi) \) is not \( \equiv 0 \) then \( S_\infty \leq \phi \).

### 3.5 Survival probabilities for examples

#### 3.5.1 Square-root model

If the initial type is \( a \) then the expected number of first generation children that survive is

\[
\mu = \int_0^1 \frac{c}{\sqrt{ab}} S_\infty(b) \, db
\]

The set of offspring is a Poisson process on \((0, 1]\). We thin the process by keeping only the points that survive. Survival events are independent and independent of the Poisson process so the number of survivors has a Poisson distribution.

If the number that survive is Poisson with mean \( \mu \) the probability at least one survives is \( 1 - e^{-\mu} \) so

\[
S_\infty(a) = 1 - \exp \left( - \int_0^1 \frac{c}{\sqrt{ab}} S_\infty(b) \, db \right) \tag{3.5.1}
\]

If we let \( A_c = \int_0^1 (c/\sqrt{b}) S_\infty(b) \, db \) then

\[
S_\infty(a) = 1 - \exp(-A_c/\sqrt{a})
\]

so using (3.5.1), equating the exponentials, and multiplying by \( \sqrt{a} \) we have

\[
A_c = c \int_0^1 \frac{1}{\sqrt{b}} \left[ 1 - \exp(-A_c/\sqrt{b}) \right] \, db \tag{3.5.2}
\]

We want to solve for \( A_c \), or at least determine the behavior of \( A_c \) as \( c \to 0 \). Let

\[
g(x) = \int_0^1 \frac{1}{\sqrt{b}} \left[ 1 - \exp(-x/\sqrt{b}) \right] \, db
\]

With this notation \( A_c = cg(A_c) \).
Lemma 3.5.1. \(g(x) \sim 2x \log(1/x)\) as \(x \to 0\).

Proof. The first step is to change variables \(z = \sqrt{b}, \, dz = (1/2)b^{-1/2}db\) to get
\[
g(x) = 2 \int_0^1 dz \left[ 1 - e^{-x/z} \right]
\]
Noting that
\[
1 - e^{-x/z} \approx \begin{cases} 
  x/z & z \gg x \\
  1 & z \ll x
\end{cases}
\]
suggests an approach to approximating the integral
\[
2 \int_0^{Kx} dz \left[ 1 - e^{-x/z} \right] \in [0, 2Kx]
\]
If \(K\) is large
\[
2 \int_{Kx}^1 dz \left[ 1 - e^{-x/z} \right] \approx 2x \int_{Kx}^1 \frac{dz}{z} = -2x \ln Kx = 2x \log(1/x) - 2x \log(K)
\]
Taking \(K = \log \log(1/x)\) now gives the desired result.

To compute the asymptotics for the critical value now we note that
\[
c = \frac{A_c}{g(A_c)} \sim \frac{1}{2 \log(1/A_c)} \quad \text{or} \quad \log(1/A_c) \sim 1/2c
\]
which implies \(A_c = \exp(- -(1 + o(1))/2c)\)

Riordan says one can get more precise results by using
\[
g(x) = 2 - 2e^{-x} + 2x E_1(x) \quad \text{where} \quad E_1(x) = \int_1^x \exp(-xt)/t \, dt
\]
This leads to the result given earlier in (3.2.10)
\[
f(c) \sim 2e^{1-\gamma} \exp(-1/2c)
\]

3.5.2. Chung-Lu model

Our first step is to repeat the argument above for a general rank-1 model
\[
\kappa(x, y) = c\psi(x)\psi(y).
\]
If the initial type is \(a\) then the expected number of first generating children that survive is
\[
\mu = \int_0^1 c\psi(a)\psi(b)S_\infty(b) \, db
\]
If the number that survive is Poisson with mean $\mu$ the probability at least one survives is $1 - e^{-\mu}$ so

$$S_\infty(a) = 1 - \exp \left( - \int_0^1 c\psi(a)\psi(b)S_\infty(b) \, db \right) \tag{3.5.3}$$

If we let $A_c = \int_0^1 c\psi(b)S_\infty(b) \, db$ then

$$S_\infty(a) = 1 - \exp(-A_c\psi(a))$$

so we have

$$A_c = c \int_0^1 \psi(b)[1 - \exp(-A_c\psi(b))] \, db \tag{3.5.4}$$

Again if we let

$$g(x) = \int_0^1 \psi(b)[1 - \exp(-x\psi(b))] \, db \tag{3.5.5}$$

With this notation $A_c = cg(A_c)$

$\gamma > 3$

In the Chung-Lu model $\psi(x) = x^{-1/(\gamma-1)}$. When $\gamma > 3$

$$\int_0^1 \psi(x)^2 \, dx < \infty \tag{3.5.6}$$

so $c_c = 1/\int_0^1 \psi(x)^2 \, dx > 0$. If (3.5.6) holds then as $x \to 0$

$$g(x) \sim x \int_0^1 \psi(y)^2 \, dy$$

so, in contrast to the square root model, $g$ has a finite slope at 0.

$$g'(x) = \int_0^1 \psi^2(b) \exp(-x\psi(b)) \, d\beta$$

so $g'(x)$ decreases as $x$ increases i.e., $x$ is concave.

Since $g(0) = 0$, $g'(0) = \int_0^1 \psi(x)^2 \, dx$, and (3.5.5) implies that as $x \to \infty$

$$g(x) \to \int_0^1 \psi(b) \, db \quad \text{and hence} \quad g(x)/x \to 0.$$ 

Thus we will have a solution of $x/c = g(x)$ only if $1/c < \int_0^1 \psi(x)^2 \, dx$, i.e., $c > c_c$. Expanding $g$ in power series about 0

$$g(x) = xg'(0) + \frac{x^2}{2}g''(0) + \cdots$$
so dropping the three dots (and leaving it to the reader to justify the computation that follows by replacing \(g''(0)\) by \(g''(y)\) with \(y \in (0, x)\)) we have

\[
A_c = cg(A_c) \approx cg'(0)A_c + g''(0)\frac{A_c^2}{2}
\]

Solving and recalling \(c_c = 1/g'(0)\) we have

\[
A_c = \frac{2(cg'(0) - 1)}{-g''(0)} = \frac{2g'(0)}{-g''(0)}(c - c_c)
\]

If the constant looks weird recall that \(g''(0) < 0\) since \(g\) is concave.

\[
S_\infty(a) = 1 - \exp(-A_c\psi(a)) \sim \psi(a)A_c
\]

as \(A_c \to 0\) so as \(c \downarrow c_c\)

\[
S_\infty(a) \sim C\psi(a)(c - c_c)^\beta \quad \text{with} \quad \beta = 1.
\]

So in the Chung-Lu model with \(\gamma > 3\) the critical behavior of the survival probability has the same behavior in the Erdős-Rényi case.

\[2 < \gamma < 3\]

When \(\gamma = 3\) we have \(\psi(x) = x^{-1/2}\) this essentially the square root model, so we move on to the case \(2 < \gamma < 3\) in which case

\[
g(x) = \int_0^1 \frac{1}{b^{1/(\gamma-1)}}(1 - \exp(-x/b^{1/(\gamma-1)})) \, db
\]

Imitating the proof for the square-root model we change variables

\[
z = b^{1/(\gamma-1)}, \quad dz = \frac{1}{\gamma - 1} b^{1/(\gamma-1)-1} \, db
\]

which means

\[
\frac{db}{\gamma - 1} = b^{-1/(\gamma-1)+1} dz = (\gamma - 1)z^{-1+(\gamma-1)} \, dz = (\gamma - 1)\frac{dz}{z^{2-\gamma}}.
\]

Thus we have

\[
g(x) = (\gamma - 1) \int_0^1 \frac{1}{z^{3-\gamma}}(1 - \exp(-x/z)) \, dz
\]

To deal with this formula we change variables again \(z = x/y, \, dz = -(x/y^2)dy\) to get

\[
g(x) = x^{\gamma-2} \int_x^\infty y^{1-\gamma}(1 - e^{-y}) \, dy
\]
When $\gamma > 2$ we have $1 - \gamma < -1$ so the integral is convergent at $\infty$. Near 0 we have $1 - e^{-y} \sim y$. The exponent $2 - \gamma < -1$ when $\gamma < 3$ so the integral is convergent at 0 and the above is
\[
\sim C_\gamma x^{\gamma - 2} \quad \text{where} \quad C_\gamma = \int_0^\infty y^{1-\gamma}(1 - e^{-y}) \, dy
\]
As $x \to 0$, $x/g(x) \sim x^{3-\gamma}/C_\gamma$. Using $c = A_c/g(A_c)$ we have $c \sim A^{3-\gamma}/C_\gamma$ and
\[
A_c \sim (C_\gamma x)^{1/(3-\gamma)}
\]
Recall that $A_c = \int_0^1 cb^{-1/(\gamma-1)}S_\infty(b) \, db$ so this is the survival probability starting from a random point chosen according to a measure that is finite when $\gamma > 2$.

3.6 Component sizes in the subcritical case

Cases when the max is $O(\log n)$

Theorem 3.12 in BJR shows that if
\[
(A) \quad \sup_{x,y} \kappa(x, y) < \infty
\]
then in the subcritical regime the largest component is $O(\log n)$.

The proof given in Section 12 of their paper (see Theorem 12.5) is more than a little mysterious (to me at least) but if one is willing to assume instead

(A') There is a subcritical kernel $\bar{\kappa}$ for an inhomogeneous graph with finitely many types that has $\bar{\kappa}(x,y) \geq \kappa(x,y)$

then the conclusion follows easily from the reasoning in Section 3.1.3.

Turova (2011)

For the rest of the section we will concentrate on the rank-1 case because in that situation we can define a cluster exploration process that is a random walk. For simplicity, we will work with the limiting object in which the children of $y$ in the branching process approximation are a Poisson process with mean measure $\kappa(y,z) \, dz$ on $(0,1]$. See Section 3.4 for a little more detail. In the rank-1 case $\kappa(y,z) = c\psi(y)\psi(z)$ and hence
\[
c_c = 1/\int_0^1 \psi(y)^2 \, dy
\]
In order to have a subcritical phase we will suppose $\int \psi(y)^2 \, dy < \infty$ Using the notation of Turova (2011), we let
\[
M = \int \psi(u) \, du < \left( \int \psi(y)^2 \, dy \right)^{1/2} < \infty
\]
When $M < \infty$ the set of offspring of the vertex $y$ can be constructed in two steps.

(i) The total number of offspring is $N(y) = \text{Poisson with mean}$

$$\int \kappa(y, z) \, dz = c\psi(y)M.$$ 

(ii) Conditional on $N(y) = m$, the labels of the $m$ offspring are distributed according to

$$\bar{\psi}(z) = \frac{\psi(z)}{M}.$$ 

Given this procedure we can construct the exploration process as follows. If we start from $X_0 = x_0$ then the number of offspring $N(x_0) = \text{Poisson with mean } c\psi(x_0)M$. Since $A_0 = 1$ we have

$$A_1 = N(x_0)$$

For all $t \geq 1$ the vertex $X_t$ whose neighbors are added on the $t$th step is distributed according to $\bar{\psi}(z)$, and

$$A_{t+1} = A_t - 1 + N(X_t)$$

The distribution of $N(X_t)$ is a mixture

$$\int_0^1 \bar{\psi}(y) \text{Poisson}(c\psi(y)M) \, dy$$

At time $\tau = \inf\{t : A_t = 0\}$ we have found the $\tau$ members of the cluster.

The process is easier to analyze if it is homogeneous in time so we will suppose that $X_0$ is distributed according to $\bar{\psi}(z)$. To simplify typing let $Y_t = -1 + N(X_t)$. Recalling the formula for the Poisson and dropping the subscript $t$, the moment generating function of $Y$ is

$$\phi(\theta) \equiv E e^{\theta Y} = e^{-\theta} \int_0^1 \bar{\psi}(y) e^{c\psi(y)M \cdot (e^\theta - 1)} \, dy$$

$W_t = \exp(\theta A_t) / \phi(\theta)^t$ is a martingale for $t \leq \tau$. To choose $\theta$ we note that

$$\phi'(\theta) = -\phi(\theta) + e^{-\theta} \int_0^1 \frac{\psi(y)}{M} e^{c\psi(y)M \cdot (e^\theta - 1)} \cdot c\psi(y)Me^\theta \, dy$$

Taking $\theta = 0$ we have

$$\phi'(0) = -1 + \int_0^1 c\psi(y)^2 \, dy < 0$$

since we are supposing $c < c_c$.

Since $\phi(0) = 1$ and $\phi'(0) < 0$, if we choose $\theta_0 > 0$ small enough then $\phi(\theta_0) < 1$. Using the optional stopping theorem for the nonnegative supermartingale $W_t$ at time $\tau$ which has $A_\tau = 0$

$$e^{\theta_0} \geq E(\phi(\theta_0)^{-\tau})$$

If we let $e^\alpha = 1 / \phi(\theta_0)$ then we have $E e^{\alpha \tau} \leq e^{\theta_0}$ and

$$P(\tau \geq k) \leq e^{\theta_0} e^{-\alpha k}$$
The last result is for the cluster size when we start from a random vertex chosen according to $\bar{\psi}(y)$. If we start from a fixed vertex $x$ then $A_1 = N(x)$ and $X_1$ has distribution $\bar{\psi}(y)$ so by (3.6.2)

$$P(\tau \geq k + 1|X_0 = x, N(x) = m) \leq e^{\theta_0 m} e^{-\alpha k}$$

Here the martingale starts when $A_1 = m$ instead of $A_0 = 1$. Multiplying by $P(N(x) = m)$ and summing over $m$

$$P(\tau \geq k + 1|X_0 = x) \leq e^{-\alpha k} E e^{\theta_0 N(x)} = e^{-\alpha k} \exp(c \psi(x) M(e^\theta - 1))$$

To bound this it is natural to assume that

$$(A1) \quad C_a = \int_0^1 \exp(a \psi(x)) \, dx < \infty \quad \text{for some } a > 0$$

To be able to relate the integral to $\sum_{i=1}^n \exp(a \psi(i/n))$ we will assume that

(A2) $x \to \psi(x)$ is decreasing.

(Together these two assumptions are a little stronger than Turova’s Assumption 1.1.) If $\theta_0$ is small then $c_e M(e^\theta_0 - 1) \leq a$ so

$$\frac{1}{n} \sum_{i=1}^n P(\tau \geq k + 1|X_0 = i/n) \leq e^{-\alpha k} \int_0^1 e^{a \psi(x)} \, dx$$

so we have

$$\sum_{i=1}^n P(\tau \geq k + 1|X_0 = i/n) \leq n C_a e^{-\alpha k}.$$ 

If we take $k = ((1 + \epsilon)/\alpha) \log n$ then the probability that the largest cluster $> (1 + \epsilon/\alpha) \log n$ is $\leq C_a / n^\epsilon \to 0$ so

$$P \left( \max_{1 \leq i \leq n} |C_i| > \frac{1 + \epsilon}{\alpha} \log n \right) \to 0 \quad (3.6.3)$$

Here we have gotten an upper bound on component sizes that are $O(\log n)$. Turova (2011) obtained results that were asymptotically sharp.

**Theorem 1.3. in Turova (2011).** Let $\kappa(x, y) = c \psi(x) \psi(y)$ ad define $r(c)$ by

$$c^{cr} = \left( \int \psi^2(x) \, dx \right)^{-1}$$

As $n \to \infty$ we have

$$\frac{C_1(n, \kappa)}{\log n} \to \frac{1}{\log r(c)}$$

Her Theorem 1.4 gives an explicit formula for $r(c)$. Intuitively this is done by optimizing the $\theta$ in the bound that comes from the moment generating function, but it takes ore than a little work to carry out the plan announced in the previous sentence. We refer the reader to her paper for details.
Cases where the max is a power of $n$

We will consider the Chung-Lu model introduced in Section 3.2.3. \( \kappa(x, y) = c\psi(x)\psi(y) \) where \( \psi(x) = x^{-a} \) with \( a = 1/(\gamma - 1) \) and we assume \( \gamma > 3 \). To make it easier to do computations we will have self-loops at \( i \) with probability \( p(i, i) \) and assume they add only 1 to the degree of \( i \) instead of 2.

Degree distribution

The probability of an edge between \( i \) and \( j \) is

\[
p(i, j) = \kappa(i/n, j/n)/n = ci^{-a}j^{-a}n^{2a-1}
\]

Lemma 3.6.1. As \( n \to \infty \)

\[
E(d_i) \sim \frac{c}{1 - a} \cdot \frac{n^a}{i^a}
\]

Proof. The expected degree of \( i \)

\[
E(d_i) = \frac{c}{i^a}n^{2a-1} \sum_{j=1}^{n} \frac{1}{j^a}
\]

To evaluate the sum, we think about Riemann approximating sums for the integral of \( 1/x^a \) when the end points of the intervals are integers. Since \( 1/x^a \) is decreasing, if we evaluate at the left end point

\[
\sum_{j=1}^{n} \frac{1}{j^a} \geq \int_{1}^{n+1} x^{-a} \, dx = \frac{(n + 1)^{1-a} - 1}{1 - a}
\]

To get a bound in the other direction note that if we evaluate at the right endpoint

\[
\sum_{j=2}^{n} \frac{1}{j^a} \leq \int_{1}^{n} x^{-a} \, dx \leq \frac{n^{1-a}}{1 - a}
\]

which proves the desired result.

Given the formula for the mean degree in Lemma 3.6.1 the next result should not be surprising, but to prove it we need estimates of the deviations of the degrees from their means.

Lemma 3.6.2.

\[
P \left( d_1 = \max_{1 \leq i \leq n} d_i \right) \to 1 \tag{3.6.4}
\]

\( d_1/Ed_1 \to 1 \) as \( n \to \infty \) and hence

\[
\max_{1 \leq i \leq n} d_i / Ed_1 \to 1 \tag{3.6.5}
\]
Proof. Our first step is to compute the variance.

\[
\text{var} (d_i) = \sum_{j=1}^{n} p(i, j)(1 - p(i, j)) \leq \sum_{i=1}^{n} p(i, j) = Ed_i
\]

Chebyshev’s inequality says that if \( E(Y^2) < \infty \)

\[
P(|Y - EY| > y) \leq \frac{\text{var} (Y)}{y^2}
\]

so taking \( y = (Ed_i)^{2/3} \) we have

\[
P(|d_i - Ed_i| > (Ed_i)^{2/3}) \leq \frac{Ed_i}{(Ed_i)^{4/3}} \to 0.
\]

From this it follows that \( d_i/Ed_i \to 1 \) in probability, i.e., for any fixed \( i \) if \( \delta > 0 \)

\[
P(1 - \delta < d_i/Ed_i < 1 + \delta) \to 0
\]

as \( n \to \infty \). Since \( Ed_i = Ed_1/i^a \), we can conclude that for any fixed \( I \)

\[
P \left( d_1 = \max_{1 \leq i \leq I} d_i \right) \to 1
\]

The argument cannot be used to prove (3.6.4) because the error bound from Chebyshev’s inequality is not good enough. To get a better bound we turn to the moment generating function. The analogue of Chebyshev’s inequality is:

**Lemma 3.6.3.** If \( \theta > 0 \) and the moment generating function, m.g.f., \( \phi(\theta) = E e^{\theta Y} < \infty \) then

\[
e^{\theta y} P(Y \geq y) \leq \phi(\theta)
\]

**Proof.** This holds since \( e^{\theta Y} \geq e^{\theta y} \) when \( Y \geq y \). \( \square \)

Since oriented edges from \( i \) to \( j \) are independently present with probability \( p(i, j) \)

\[
E e^{\theta d_i} = \prod_{j=1}^{n} (1 - p(i, j) + p(i, j)e^\theta) = \prod_{j=1}^{n} (1 + p(i, j)[e^\theta - 1])
\]

since the m.g.f. of a sum of independent random variables is the product of the m.g.f. We need to simplify the last expression. To do this we are guided by the fact that the sum of independent Bernoulli random variables is a approximately Poisson, while if \( Z \) is Poisson with mean \( \mu \) the mgf is

\[
E e^{\theta Z} = \sum_{k=0}^{\infty} e^{-\mu} \frac{\mu^k}{k!} e^{\theta k} = \exp(\mu[e^\theta - 1])
\]
Using $1 + x \leq e^x$ in (3.6.10) and letting $\mu_i = \sum_j p(i, j)$ we have

$$Ee^{\theta d_i} \leq \exp(\mu_i[e^\theta - 1])$$

so using (A.1.2), if $c > 1$

$$P(d_i \geq c\mu_i) \leq \exp(\mu_i[1 - c \log 2])$$

This is a very powerful inequality but we have to manipulate it to be useful. A more systematic approach is to optimize over $\theta$ but that can get messy. To simplify our inequality we set $\theta = \log 2$ to get

$$P(d_i \geq \mu_1/2) \leq \exp \left( \mu_i \left[ -\frac{1}{4\mu_i} \log 2 \right] \right) = \exp \left( -\frac{\mu_1}{4 \log 2} \right)$$

It follows that

$$\sum_{i=I+1}^{n} P(d_i \geq \mu_1) \leq n \exp \left( -\frac{\mu_1}{2 \log 4} \right)$$

as $n \to \infty$ since $\mu_1 \sim Cn^{1-a}$. Combining this with (3.6.8) proves (3.6.4). (3.6.5) now follows from (3.6.7).

Subcritical cluster sizes

As in Section 3.6.1, we use the exploration process. If we start from $X_0 = x_0$ then the number of neighbors $N(x_0) = \text{Poisson with mean } c\psi(x_0)M$ where $\psi(x) = x^{-1/(\gamma-1)}$, $M = \int_0^{1/\psi} \psi(z) \, dz$. Since initially the active set $A_0 = 1$ we have

$$A_1 = N(x_0)$$

For all $t \geq 1$ the index of the vertex $X_t$ whose neighbors are revealed on the $t$th step is distributed according to $\tilde{\psi}(z) = psi(z)/M$, and

$$A_{t+1} = A_t - 1 + N(X_t). \quad (3.6.11)$$

The distribution of $N(X_t)$ is a mixture

$$\int_0^{1} \tilde{\psi}(y) \text{Poisson}(c\psi(y)M) \, dy$$
while the expected value is
\[ EN(X_t) = c \int_0^1 \psi(y)^2 \, dy < 1 \quad \text{if } c < c_c. \] (3.6.12)

Using the reasoning from Section 3.2.3, when we compute the degree distribution we can think of \( \text{Poisson}(c\psi(y)M) \) as being a point mass at the mean. \( c\psi(y)M \geq x \) when
\[ y^{-1/(\gamma-1)} \geq x/cM \quad \text{or} \quad y \leq (x/cM)^{-(\gamma-1)} \]
Letting \( z = (x/cM)^{-(\gamma-1)} \) we have
\[ P(N(X_t) \geq x) = \int_0^z \frac{\psi(y)}{M} \, dy = \frac{C}{M} x^{1-1/(\gamma-1)} = C_5 x^{-(\gamma-1)+1} \] (3.6.13)
where the two \( C \)'s are constants whose values are not important. The sudden appearance of the subscript 5 is to make it easier to compare with Section 2.5. Taking the derivative with respect to \( y \) we see that, as in the configuration model, the distribution of the number of vertices added is \( Cy \) times the original degree distribution.

Our next goal is to show that in the subcritical regime of the Chung-Lu model with \( \gamma > 3 \) the size of the largest cluster is of the same order as the largest degree.

**Theorem 3.6.4.** In the Chung-Lu model with \( \gamma > 3 \) then for any \( c < c_c \) there is a constant \( C_{\gamma,c} \) so that
\[ P \left( \max_v |C(v)| \geq C_{\gamma,c} n^{-1/(\gamma-1)} \right) \to 0 \]

By analogy with Janson's result for the configuration model, (2.5.3), it is natural to expect that
\[ C_{\gamma,c} = Ed_1/(1 - \nu) \]
where \( \nu = EN(X_t) \).

**Proof.** We proved a version of Theorem 3.6.4 for the configuration model in Section 2.5. To be able to more easily compare with the previous proof we rewrite the recursion (3.6.11) to look like the one in Section 2.5
\[ S_{t+1} = S_t - 1 + \xi_t \]
where \( S_t = A_t \) and \( \xi_t = N(X_t) \). The new proof is almost the same as before but easier. We do not need the first part of the argument where we develop a comparison of the \( \xi_i \) with independent random variables \( X_i \).

If \( |C(x_0)| \geq M \) then \( \tau \geq M \) and
\[ S_M = d(x_0) + \sum_{i=1}^M (\xi_i - 1) \] (3.6.14)
which is (2.5.4). As noted in (3.6.12) we have $E\xi_i = \nu < 1$.

For some $A$ large and $\delta < 1/(\gamma - 1)$ small, to be chosen later, let

$$M = An^{1/(\gamma - 1)} \quad \text{and} \quad M_1 = n^{1/(\gamma - 1) - \delta}$$

(3.6.15)

Note that $M$ is the desired upper bound on $C_1$. If we define the truncated random variables $Y_i = \xi_i 1(\xi_i \leq M_1)$ then $EY_i \leq E\xi_i = \nu$. If $|C(x_0)| > M$ then (3.6.14) holds and so using $\xi_i \leq \Delta = \max_i d_i$ and computing as in (2.5.12)

$$M \leq d(x_0) + \sum_{i=1}^M \xi_i \leq \Delta + \sum_{i=1}^M \xi_i 1(\xi_i \leq M_1) + \sum_{i=1}^M \xi_i 1(\xi_i > M_1)$$

$$\leq \sum_{i=1}^M Y_i + \Delta \left(1 + \sum_{i=1}^M 1(\xi_i > M_1)\right)$$

$$\leq \nu M + \sum_{i=1}^M (Y_i - EY_i) + \Delta \left(1 + \sum_{i=1}^M 1(\xi_i > M_1)\right)$$

(3.6.16)

Thus if $\nu < 1 - 2\epsilon$ (which holds for $\epsilon = (1 - \nu)/3$)

$$P(|C(x_0)| \geq M) \leq P \left(\sum_{i=1}^M |Y_i - EY_i| > \epsilon M\right) + P \left(\sum_{i=1}^M 1(\xi_i > M_1) > \epsilon \frac{M}{\Delta} - 1\right)$$

(3.6.17)

For the first sum fix a number $r \geq \gamma$ so that $r\delta > 2$. Rosenthal’s inequality for nonnegative random variables given in (2.5.14) states

$$E \left(\sum_{k=1}^n Z_i\right)^r \leq C_r \max \left(\left(\sum_{k=1}^n EZ_i^2\right)^{r/2}, \sum_{k=1}^n EZ_i^r\right)$$

Letting $Z_i = |Y_i - EY_i|$ we have

$$E \left(\sum_{k=1}^n |Y_i - EY_i|\right)^r \leq C_r \left((nE(Y_i - EY_i)^2)^{r/2} + nE|Y_i - EY_i|^r\right)$$

Taking $n = M$ we have

$$E \left|\sum_{i=1}^M |Y_i - EY_i|\right|^r \leq C_6 M^{r/2}(E|Y_1 - EY_1|^2)^{r/2} + C_7 M E|Y_1 - EY_1|^r$$

$$\leq C_6 M^{r/2}(EY_1^2)^{r/2} + C_8 M EY_1^r$$

(3.6.18)

To go from the first line to the second we note that $E(X - c)^2$ is minimized when $c = EX$. For the second term writing $E(Y^2; A)$ for the integral of $Y$ over $A$

$$E|X - EX|^r = E(|X - EX|^r; X \geq EX) + E(|X - EX|^r; X < EX) \leq E(|X|^r; X \geq EX) + |EX|^r P(X < EX) \leq 2E|X|^r$$
where on the second line we have used the fact that $X \geq 0$ and then Jensen’s inequality to put the $r$th power inside the expected value.

We estimate the second moment of $Y_1$ using (3.6.13)

$$EY_1^2 = \int_0^\infty 2xP(Y_1 > x)\,dx = \int_0^{M_1} 2xP(\xi_1 > x)\,dx$$

$$\leq 1 + C_5 \int_1^{M_1} 2x^{3-\gamma}\,dx \leq C_9 M_1$$  

(3.6.19)

since $\gamma > 3$. Trivially $EY_1^r \leq M_1^r$. Using Markov’s inequality, (3.6.18), the second moment estimate in (3.6.19), $Y_1 \leq M_1$ and $M_1/M = A^{-1}n^{-\delta}$ we get (here $C_{10} = c_6\epsilon^{-r}C_6$ and $C_{11} = c_6\epsilon^{-r}C_8$ but $\epsilon$ is fixed)

$$P\left(\sum_{i=1}^{M} |Y_i - EY_i| > \epsilon M\right) \leq (\epsilon M)^{-r}E\left|\sum_{i=1}^{M} |Y_i - EY_i|\right|^r \leq C_{10} (EY_1^2/M)^{r/2} + C_{11} M^{1-r}EY_1^r$$

(3.6.20)

$$\leq C_{12} (M_1/M)^{r/2} + C_{13} M (M_1/M)^r$$

$$\leq C_{14} n^{-r\delta/2} + C_{15} n^{1-r\delta} = o(n^{-1})$$

since $r\delta > 2$.

For the second sum in (3.6.17) write $I_i = 1_{(\xi_i > M)}$ and following (2.5.17) conclude that

$$P\left(\sum_{i=1}^{M} I_i \geq L\right) \leq \binom{M}{L} P(I_k = 1, 1 \leq k \leq L)$$

$$= \binom{M}{L} P(I_1 = 1)^L = \binom{M}{L} P(X > \xi_1)^L \leq (MP(\xi_1 > M_1))^L$$  

(3.6.21)

Now by the tail bound on $\xi_i$ in (3.6.13) and the choices of $M$ and $M_1$ in (3.6.15)

$$MP(\xi_1 > M_1) \leq MC_5 M_1^{-\gamma_1+1}$$

$$\leq C_5 An^{1/(\gamma_1) + (2-\gamma)[1/(\gamma_1)-\delta]} = C_5 n^{(\gamma_2)\delta - (\gamma_3)/(\gamma_1)}$$

Choose $\delta > 0$ so that $\delta_1 = (\gamma - 3)/(\gamma - 1) - (\gamma - 2)\delta > 0$. Then $MP(\xi_1 > M_1) = O(n^{-\delta_1})$ and

$$P\left(\sum_{i=1}^{M} I_i \geq L\right) = O(n^{-L\delta_1})$$  

(3.6.22)

If we choose $L > 1/\delta_1$ so that the last error term is $o(n^{-1})$. (3.6.5) and Lemma 3.6.1 imply that

$$\Delta/Ed_1 \to 1 \quad Ed_1 \sim cN^a/(1-a)$$
where \( a = 1/(\gamma - 1) \). By (3.6.15) \( M = An^{1/(\gamma - 1)} \) so if \( A \) is chosen large enough

\[
\epsilon M - 1 > L \quad \text{for large } n.
\] (3.6.23)

Combining this with (3.6.22) and (3.6.20) we have shown that the right-hand side of (3.6.17) is \( o(n^{-1}) \), which gives the conclusion of Theorem 3.6.4.

To show that all of our constants can be chosen the way we want them, we note that 
\[
\epsilon = (1 - \nu)/3 \quad \text{where } \nu = E\xi_i, \quad \delta \text{ was chosen small enough so that }
\[
\frac{\gamma - 3}{\gamma - 1} - \delta(\gamma - 2) > 0
\]

\( r \geq \gamma \) was chosen so that \( r\delta \geq 2 \), and finally \( A \) was chosen to give (3.6.23).

\[\square\]

References


3.6. COMPONENT SIZES IN THE SUBCRITICAL CASE


Chapter 4

Epidemics

In this chapter we will consider four epidemic models whose names are abbreviated as SI, SIR, SIS, and SIRS. At any time each vertex $v$ is in state $S =$ susceptible, $I =$ infected, or $R =$ removed (is immune to infection). Common to all four dynamics is the infection step $S$ edges become $I$ at rate $\lambda$. Once an individual becomes infected they stay infected for an amount of time $T$. These times for the various vertices are independent. We will primarily be concerned with three situations:

(i) $T = \infty$ is the SI model, a depressing scenario in which individuals never recover, so I prefer to think of it as the spread of rumor or other information, which is modeled by first passage percolation, which we considered in Section 2.5.

(ii) $T$ is a fixed constant, which leads to a simple process with connections to percolation,

(iii) $T$ is exponential with rate $\gamma$, i.e., $P(T > t) = e^{-\gamma t}$, which is special because the system has the Markov property.

In the SIR system, when the infected period is over the individual enter the removed state and is immune to further infection. In the SIS model, which is the contact process considered in Chapter 5, when the infected period is over the individual is again susceptible to the disease. Finally there is the SIRS model in which immunity is only temporary.

4.1 On the complete graph

On the complete graph each individual interacts equally with all the members of the population, so the system is often referred to as a homogeneously mixing population. Let $\beta$ be the total rate at which an individual sends out germs so that $\lambda = \beta/N$ is the infection rate per edge (and we forget about the fact that there are only $N-1$ edges.

SI model

In Bailey’s classic book The Matheamtical Theory of Infectious Diseases (first edition 1957, second 1975) the SI model is called the simple epidemic. Since there are only susceptibles
and infecteds we have \( S = N - I \) and when the population size is large we have one differential equation

\[
\frac{dS}{dt} = -\beta \frac{SI}{N} = -\frac{dI}{dt}
\]

Bailey rescales time to make \( \beta/N = 1 \), takes \( N = n + 1 \), \( S(0) = n \), \( I(0) = 1 \) to arrive at

\[
S(t) = \frac{n(n+1)}{n + e^{(n+1)t}} \quad I(t) = \frac{n + 1}{1 + ne^{(n+1)t}}
\]

If we rescale time \( t = r/(n + 1) \) and let \( s = S/(n + 1) \), \( i = I/(n + 1) \) then we have

\[
s(r) = \frac{n}{n + e^r} \quad i(r) = \frac{1}{1 + ne^r}
\]

The rate at which new cases occur \( i'(r) = ne^{-r}/(1 + ne^{-r})^2 \).

![SI epidemic curve with n = 1000. Solid line is i(t), dotted line is i'(t)](image)

**SIR model**

In this case we assume that an infected individual stays infected for an exponentially distributed time \( T \) with mean \( 1/\gamma \), i.e., \( P(T > t) = e^{-\gamma t} \). The following differential equations hold when the population size is large:

\[
\begin{align*}
\frac{dS}{dt} &= -\beta \frac{SI}{N} \\
\frac{dI}{dt} &= \beta \frac{SI}{N} - \gamma I \\
\frac{dR}{dt} &= \gamma I
\end{align*}
\] (4.1.1)
4.1. ON THE COMPLETE GRAPH

In the SIR epidemic if most of the individuals are susceptible, an infected person creates new infecteds at rate $\beta$ and becomes healthy at rate $\gamma$. A basic fact about the exponential distribution is that if $S = \text{exponential}(\beta)$ and $T = \text{exponential}(\gamma)$ then

$$P(S < T) = \frac{\beta}{\beta + \gamma} \quad (4.1.2)$$

This implies that the number of individuals $Y$ infected by one infected in an otherwise susceptible population has distribution.

$$P(Y = k) = \left(\frac{\beta}{\beta + \gamma}\right)^k \frac{\gamma}{\beta + \gamma} \quad \text{for } k = 0, 1, 2, \ldots \quad (4.1.3)$$

This is the shifted geometric distribution with parameter $p = \gamma/(\beta + \gamma)$, which gives the distribution number of failures before the first success in a sequence of independent trials. The ordinary geometric distribution, which gives the number of trials to get the first success has mean $1/p$, so the shifted one has mean

$$\frac{1}{p} - 1 = \frac{\beta + \gamma}{\gamma} - 1 = \frac{\beta}{\gamma}$$

$\beta/\gamma$ is called the basic reproduction number and is usually denoted by $R_0$, although in this book we will write simply $R$. No matter what notation is used, it is the number of secondary infections caused by one infection in the initial phase of the epidemic when only a small fraction of the individuals are removed.

Asymptotic behavior. Suppose $\beta > \gamma$ so that $R > 1$. Letting $s = S/N$, $i = i/N$, and $r = R/N$, the equations in (4.1.1) become

$$\frac{ds}{dt} = -\beta si \quad \frac{di}{dt} = \beta si - \gamma i \quad \frac{dr}{dt} = \gamma i \quad (4.1.4)$$

We cannot solve these equations explicitly, but we can extract some useful information about the limiting behavior. Using the first two equations

$$\frac{di}{ds} = \frac{di/dt}{ds/dt} = \frac{\beta si - \gamma i}{-\beta si} = -1 + \frac{\gamma}{\beta s}$$

Solving we have

$$i = -s + \frac{\gamma}{\beta} \ln s + C \quad \text{where } C = i(0) + s(0) - (\gamma/\beta) \ln(s(0)). \quad (4.1.5)$$
For initial conditions, we choose $i(0) = \epsilon$, $s(0) = 1 - \epsilon$. We have set $I(0) = \epsilon N$ since the ODE is not accurate when the number of infecteds is small. For this initial condition

$$C = 1 - (\gamma/\beta) \ln(1 - \epsilon),$$

so using (4.1.5) we have

$$i(t) + s(t) = 1 + \frac{\gamma}{\beta} \ln(s(t)/(1 - \epsilon)).$$

As $t \to \infty$, $i(t) \to 0$, $s(t) \to s(\infty)$. The limit of $s(t)$ exists since $s(t)$ is decreasing. If we let $\epsilon \to 0$ then

$$s(\infty) = 1 + \frac{\gamma}{\beta} \ln(s(\infty)).$$

Rearranging we have

$$s(\infty) = \exp(-\beta/\gamma)[1 - s(\infty)].$$

(4.1.6)

**Extinction probability.** If we think of the people infected by an individual as their children then in the initial stages of the epidemic we have a branching process. As noted in (4.1.3) the probability of $k$ children is

$$p_k = \left(\frac{\beta}{\beta + \gamma}\right)^k \frac{\gamma}{\beta + \gamma}$$

for $k = 0, 1, 2, \ldots$

The generating function of this distribution is

$$\phi(x) = \sum_{k=0}^{\infty} \left(\frac{\beta x}{\beta + \gamma}\right)^k \frac{\gamma}{\beta + \gamma}$$

$$= \frac{\gamma}{\beta + \gamma} \left(1 - \frac{\beta x}{\beta + \gamma}\right)^{-1} = \frac{\gamma}{\gamma + \beta(1 - x)},$$

$\phi(x) = x$ is a quadratic equation:

$$0 = -\gamma + \gamma x + \beta x - \beta x^2 = (\beta x - \gamma)(1 - x),$$

(4.1.7)

so if $\beta > \gamma$ then the extinction probability

$$\rho = \gamma/\beta$$

(4.1.8)

For a simpler proof, note that the first event is either the death of the ancestor with probability $\gamma/(\gamma + \beta)$ or the birth of a second particle with probability $\beta/(\beta + \gamma)$, so

$$x = \frac{\gamma}{\gamma + \beta} \cdot 1 + \frac{\beta}{\gamma + \beta} \cdot x^2,$$

since when we have two particles the probability both of their families die out is $x^2$. Rearranging we have the quadratic in (4.1.7).
4.2. FIXED INFECTION TIMES

Note that the probability that the epidemic dies out given in (4.1.8) is not the same as the limiting number of susceptibles since \( s(\infty) = \gamma/\beta \) does not solve the equation in (4.1.6). To explain this suppose that for each ordered pair of individuals with probability \( \lambda/(\gamma+\lambda) \approx \lambda/\gamma \) (recall \( \lambda = \beta/N \)) we draw an arrow from \( x \) to \( y \) to indicate that if \( x \) infected it will infect \( y \). To see if \( y \) will become infected we can work backwards from \( y \) crossing arrow in the direction opposite their orientation. In the limit as \( n \to \infty \) the result is a branching process with a Poisson distribution with mean \( n\lambda/\gamma = \beta/\gamma \). The probability that this backward branching process dies out is the solution of (4.1.6).

4.2 Fixed infection times

4.2.1 Discrete time: Reed-Frost model

During the 1920s, mathematician Lowell Reed and physician Wade Hampton Frost developed a stochastic model for disease propagation, used in their biostatistics and epidemiology classes at Johns Hopkins University. They did not publish their work but it has been the subject of a large number of papers. See Jacquez (1987) for references to early work. In 1950 their model was the subject of a television program entitled *Epidemic theory: What is it?*, which is available on YouTube.

The basic version of their model is as follows: A set of \( n \) individuals is given, indexed by \( i \in \{1, \ldots, n\} \). At time 0 a single individual is infected. Once infected the individual is infectious for one unit of time, after which it enters the removed state. While infectious it will succeed in infecting a susceptible individuals with probability \( p \), with the attempts independent for all target individuals and all infectious individuals. Thus if there are \( I(t) \) infected individuals at time \( t \) the probability a susceptible is infected at time \( t+1 \) is

\[
1 - (1 - p)^{I(t)}
\]

so the transition probability for the number of infecteds is

\[
P(I(t+1) = m | I(t) = k) = \binom{S(t)}{m} (1 - (1 - p)^k)^m (1 - p)^{(S(t) - m)}
\]

The susceptibles and infecteds are updated by

\[
S(t+1) = S(t) - I(t) \quad R(t+1) = R(t) + I(t)
\]

Barbour and Mollison (1990) noticed that there was a close relationship between the Reed-Frost epidemic model and the Erdős-Rényi random graph. The key observation is that each edge \( e \) will be \( S - I \) (or \( I - S \)) only once, so if we let \( \eta(e) \) be independent, 1 with probability \( p \), and 0 with probability \( 1 - p \) then we can use the \( \eta \) to determine what infections will occur in the Reed-Frost model. If we use the same variables to determine which edges are present in the Erdős-Rényi graph then the set of individuals infected in the Reed-Frost model coincides with \( C_x \) the cluster containing \( x \) in the Erdős-Rényi graph.
4.2.2 Continuous time

In the Reed-Frost epidemic we start with \( G = K_n \) the complete graph on \( n \) vertices. We can also start with some fixed graph \( G \) which represents the social structure of the population. For example we could take \( G \) to be Erdős-Rényi \((n, \mu/n)\). If we let the time until the infection spreads across the edge \( S \) to exponential \((\lambda)\) and be the time until the infected vertex becomes removed \( T \equiv 1 \), then the infection will be transmitted to the susceptible with probability

\[
\tau_f = P(S \leq 1) = 1 - e^{-\lambda}
\]  

(4.2.1)

Here, superscript ‘\( f \)’ is for “fixed time.” The last formula generalizes easily to other distributions of \( T \), see (4.3.1) below, but only in the the fixed time case are the transfers for different edges are independent.

Due to the last observation, we can delete edges with probability \( e^{-\lambda} \) and the connected components of the resulting graph will give the epidemic sizes when one member of the cluster is infected. Thus, we can have a large epidemic if and only if the reduced graph has a giant component. In the physics literature this idea is attributed to Grassberger (1983), and in complex networks to Newman (2002). Results for percolation on random graphs generated by the configuration model were given in Section 2.7, so there is not much to say about the critical value for a large epidemic. Since the epidemic is equivalent to percolation, the probability of a large epidemic and its size are the same.

**Theorem 4.2.1.** If the original graph is Erdős-Rényi with mean degree \( \mu \), then the reduced graph is Erdős-Rényi with mean degree \( \mu \tau_f \). Thus, a large epidemic occurs with positive probability if \( \mu \tau_f > 1 \). If \( z_0 \) is the fixed point smaller than 1 of the generating function

\[
G(z) = \exp(-\mu \tau_f (1 - z)),
\]

(4.2.2)

then \( 1 - z_0 \) gives both the limiting probability an infected individual will start a large epidemic, and the fraction of individuals who will become infected when a large epidemic occurs.

This result can also be applied to Reed-Frost model. If \( p = c/n \) with \( c > 1 \) and we let \( \sigma \) be the solution of \( 1 - \sigma = \exp(-c\sigma) \) then \( \sigma \) gives the faction of susceptibles that remain after a large epidemic. This is equation (2) in Ball and Mollison (1990). Other results can be obtained for the Reed-Frost epidemic by computing the corresponding quantity for the Erdős-Rényi graph. If you are interested in techniques for analyzing this model you should take a look at Martin-Löf (1986).

4.3 General infection times

We now turn to the case in which the duration of the infection, \( T \), is random. By conditioning on the value of \( T \) we see that the probability an infected site fails to infect a given susceptible neighbor is

\[
P(S < T) = \int_0^\infty dt \, f_T(t) e^{-\lambda t} = E e^{-\lambda T}
\]

(4.3.1)
This implies that the probability that the infection is transmitted in the model with a general random duration is
\[ \tau_g = E(1 - e^{-\lambda\sigma}) \] (4.3.2)
(where \( g \) is for general). Using the reasoning for (4.3.1), the probability two neighbors both escape infection is
\[ \int_0^\infty dt f_T(t)(e^{-\lambda t})^2 = E(e^{-2\lambda T}) > (Ee^{-\lambda T})^2 \]
where in the last step we have used \( E(X^2) > (EX)^2 \) with \( X = e^{-\lambda T} \). Hence if \( y_1 \) and \( y_2 \) are neighbors of \( x \) then the events “\( x \) infects \( y_1 \)” and “\( x \) infects \( y_2 \)” are not independent. The presence of the edges out of \( x \) are positively correlated events since they are more likely to be present if \( T_x \) is large.

**Construction and connection with percolation**

To we split each edge \( \{x, y\} \) in the graph into two oriented edges \( (x, y) \) and \( (y, x) \). Let \( T_x \) be the duration of the infection at \( x \) and for each oriented edge \( (x, y) \) let \( S_{(x,y)} \) be independent infection times that are exponential with rate \( \lambda \). To define a graph we say that the oriented edge \( (x, y) \) is present if \( T_x > I_{(x,y)} \). (4.3.3)

As noted earlier two edges coming from the same vertex are not independent, but edges out of different vertices are.

The goal of this section is to compute the probability of a large epidemic and the fraction of individuals that will be infected if one occurs. When the duration of the infection is constant these quantities are the same (see Theorem 4.2.1), but not if the duration is random. Following the oriented edges out from \( x \), the set of all sites that can be reached \( C_x \) is the outward cluster. If we want to know whether \( y \) will be infected in the epidemic, we start at \( y \) and cross edges in the direction opposite their orientation. The set of points that can be reached (the inward cluster), \( D_y \), is the set of starting points that will lead to an infection of \( y \).

**Simplified computation**

Suppose for the moment, that we have a graph generated by the configuration model in which \( p_k \) is the degree distribution, \( q_k = (k + 1)p_{k+1}\mu \) is the size-biased distribution (ignoring the edge that brought the infection to the vertex) and \( \nu \) is the mean of the size biased distribution. Then the condition for a giant component is
\[ \nu \tau^g > 1 \] (4.3.4)

To simplify computations, we will, for the moment, ignore the fact that the first individual has a different distribution, i.e., we pretend that the epidemic is a branching process with
an offspring distribution that is a thinned version of \( q_k \), i.e., we only retain edges that the infection crosses. To be ready for the real computation define the generating functions

\[
G_0(z) = \sum_{k=0}^{\infty} p_k z^k \\
G_1(z) = \sum_{k=0}^{\infty} q_k z^k
\]

**Outward infection degree.** Since \( G_1 \) is the generating function for \( q_k \), the generating function of the number of neighbors that will become infected is

\[
G_1(z) = \int_0^\infty dt \, f_\sigma(t) \sum_{j=0}^{\infty} z^j \sum_{k=0}^{j} p_k \begin{pmatrix} k \\ j \end{pmatrix} (1 - e^{-\lambda t})^j e^{-(k-j)t \lambda} \tag{4.3.5}
\]

Interchanging the order of summation, and using the binomial theorem, we have

\[
= \int_0^\infty dt \, f_\sigma(t) \sum_{k=0}^{\infty} p_k \sum_{j=0}^{k} z^j \begin{pmatrix} k \\ j \end{pmatrix} (1 - e^{-\lambda t})^j e^{-(k-j)t \lambda} \\
= \int_0^\infty dt \, f_T(t) \sum_{k=0}^{\infty} p_k (e^{-\lambda t} + z(1 - e^{-\lambda t}))^k \\
= \int_0^\infty dt \, f_T(t) G(e^{-\lambda t} + z(1 - e^{-\lambda t})) \\
= \int_0^\infty dt \, f_T(t) G(1 - 1 + e^{-\lambda t} + z(1 - e^{-\lambda t})) \\
= EG_1(1 + (z - 1)[1 - e^{-\lambda T}])
\]

**Inward infection degree.** Since the edges that come in to a site \( y \) come from different sites, the infection crosses them with probability \( \tau_g \) and the events are independent. In this case the computation is simpler since we do not have to integrate over \( t \).

\[
\tilde{G}_1(z) = \sum_{j=0}^{\infty} z^j \sum_{k=0}^{\infty} p_k \begin{pmatrix} k \\ j \end{pmatrix} \tau_g^j (1 - \tau_g)^{k-j} \\
= \sum_{k=0}^{\infty} p_k (\tau_g z + (1 - \tau_g))^k = G_1(z \tau_g + 1 - \tau_g) \tag{4.3.6}
\]

**Comparison.** If \( p_k > 0 \) for some \( k \geq 3 \) then \( q_k > 0 \) for some \( k \geq 2 \) and the generating function is strictly convex. and \( E[1 - e^{-\lambda T}] = \tau_g \) so

\[
\tilde{G}_1(z) = EG_1(1 + (z - 1)[1 - e^{-\lambda T}]) \\
> G_1(1 + (z - 1)\tau_g) = \tilde{G}_1(z)
\]

Thus if \( \hat{\rho} = \tilde{G}_1(\hat{\rho}) \) then \( \hat{\rho} > \tilde{G}_1(\hat{\rho}) \) its fixed point

\[
\tilde{\rho} < \hat{\rho} \tag{4.3.7}
\]

Note also that correlation does not affect the expected value of the sum so both distributions have mean \( \nu \tau_g \).
Real computation

To define $\hat{G}_0$ and $\tilde{G}_0$ replace the subscript 1 in (4.3.5) and (4.3.6) by 0. By the reasoning above $\hat{G}_0(z)\tilde{G}_1(z)$. Using (4.3.7)

$$\hat{G}_0(\hat{\rho}) > \tilde{G}_0(\hat{\rho}) > G_0(\tilde{\rho})$$

Using the usual branching process arguments

**Theorem 4.3.1.** Suppose $\mu \tau_g > 1$. In this case the probability of a large epidemic is $1 - \tilde{G}_0(\tilde{\rho})$ where $\tilde{\rho}$ is the smallest fixed point of $\tilde{G}_1$ in $[0,1]$

**Theorem 4.3.2.** Suppose $\mu \tau_g > 1$. In this case the fraction of vertices infected is asymptotically $1 - G_0(\tilde{\rho})$ where $\tilde{\rho}$ is the smallest fixed point of $\tilde{G}_1$ in $[0,1]$

Thus in the case of nonconstant infection times, the final size of a large epidemic is not the same as the probability of a large epidemic. Since $\tilde{G}(z) > \hat{G}(z)$ the fixed point $z_0 > z_1$.

**Concrete Example.** It is not easy to compute $\hat{G}(z)$ so, we will take a rather extreme infection time distribution $P(\tau = \infty) = p$ and $P(\tau = 0) = 1 - p$. In this case an infected node either infects no one with probability $1 - p$ or all of its neighbors with probability $p$. To further simplify assume that the degree distribution is Poisson with mean $\mu$. In this case the backwards branching process is Poisson($\mu p$) and has $\tilde{G}(z) = \exp(-\mu p(1-z))$ while

$$\hat{G}(z) = (1 - p) + pG(z) = 1 - p + p \exp(-\mu(1-z))$$

Intuitively this is like the difference between site percolation where an open site can reach all of its neighbors, and bond percolation where we flip independent coins for different edges.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4_2.png}
\caption{$\tilde{G}(z)$ (solid line) versus $\hat{G}(z)$ (dashed line) for the concrete example with $\mu = 3$.}
\end{figure}
4.4 Miller-Volz equations

In 2008 Erik Volz published a remarkable paper deriving differential equations for the spread of epidemics on random graphs with specified degree distributions. In 2011 Miller reduced Volz’s system of ODE to a single equation. I think that at the time people viewed the arguments as heuristic and the results approximate. Indeed the papers take pains to say that “calculations closely match simulations.” Surprisingly it turns out that, as we will explain later in this section, one can prove they are exact in the limit of large population size.

Although the networks Miller and Volz considered were undirected in the sense that either of two neighbors can transmit the infection to the other, it is useful to keep track of who infects who, so we replace each undirected edge \{a, b\} we have two directed edges (a, b) and (b, a), which will be referred to as arcs. To quote Volz, ”the first element in the ordered pair will be called the ego and the second the alter.” Let \( A_{X,Y} \) be the set of arcs with ego in \( X \) and alter in \( Y \), \( A_X \) be the set of arcs with ego in \( X \), and let \(|A|\) be the number of arcs. Let

\[
M_{X,Y} = \frac{|A_{X,Y}|}{|A|} \quad \text{and} \quad M_X = \frac{|A_X|}{|A|}
\]

be the fraction of arcs in \( A_{X,Y} \) and in \( A_X \).

To describe the equations we will use the notation of Miller rather than Volz since it is Miller’s argument that we will follow. Miller uses base instead of ego and target instead of alter. Let \( \beta \) be the rate at which infected individuals infect susceptible neighbors, \( \gamma \) be the recovery rate (\( I \rightarrow R \) transitions). Let \( S, I, \) and \( R \) be the fraction of susceptible, infected, and removed nodes at time \( t \). Let \( g(x) \) be the probability generating function of the degree distribution \( p_k \) let

\[
p_I = \frac{M_{S,I}}{M_S} \quad \text{and} \quad p_S = \frac{M_{S,S}}{M_S}.
\]

Last but most important, we define an infectious contact from \( v \) to a neighbor \( u \) is a contact that would cause the infection of \( u \) if it was susceptible. Here \( v \) must be infected but \( u \) can be \( S, I, \) or \( R \). Let \( \theta(t) \) is the probability an edge has not transmitted an infectious contact. To compute this pick an edge at random, and then give it an orientation from \( v \) (the base) to \( u \) (the target). We disallow infectious contacts from \( u \) to \( v \). \( \theta(\infty) \) probability of no infectious contact from \( v \) to \( u \).

To calculate the size of an epidemic it suffices to calculate the probability that a vertex that is not allowed to infect its neighbors is infected, since a vertex cannot start a chain of infection that leads to its initial infection. The infections along the different edges incident to such a vertex are independent so

\[
S(t) = \sum_{k=0}^{\infty} p_k \theta(t)^k = g(\theta(t))
\]
Volz’s (2018) equations are (we have changed his $r$ to $\beta$)

\[ S = g(\theta) \]
\[ \frac{d\theta}{dt} = -\beta p_I \theta \]  
\[ \frac{dI}{dt} = \beta p_I g'(\theta) - \gamma I \]  
\[ \frac{dp_I}{dt} = \beta p_S p_I \left( \frac{g''(\theta)}{g'(\theta)} \right) - \beta p_I (1 - p_I) - \gamma p_I \]  
\[ \frac{dp_S}{dt} = \beta p_S p_I \left( 1 - \theta \frac{g''(\theta)}{g'(\theta)} \right) \]

We will not give Volz’s argument for his equations, but will instead describe the reasoning that led Miller (2011) to his single equation,

\[ \theta'(t) = -\beta \theta + \gamma (1 - \theta) + \beta \frac{g'(\theta)}{g'(1)} \]  

To find the values of $S$, $I$, and $R$ from $\theta(t)$ we note that

\[ S = g(\theta) \]
\[ I = 1 - R - S \]
\[ R' = \gamma I \]

**Derivation of (4.4.7).** Let $\phi$ be the probability the base is infected but has not transmitted infection to the target.

\[ \theta'(t) = -\beta \phi(t) \]  

An edge no longer satisfies the definition of $\phi$ when the infection crosses the edge or when the base node recovers. The rate at which neighbors become infectious matches the rate at which neighbors stop being infectious so

\[ \phi'(t) = -(\beta + \gamma) \phi(t) - \sigma'(t) \]  

where $\sigma(t)$ be the probability that a neighbor of a randomly chosen vertex is susceptible. (Miller calls this $h$ but we will have many $h$’s in the next section.) Neighbors of a randomly chosen vertex have the size-biased degree distribution. That is, if $\mu = \sum_j j p_j$ then

\[ \sigma(t) = \frac{\sum_{k=1}^{\infty} k p_k \theta(t)^{k-1}}{\mu} = \frac{g'(\theta(t))}{g'(1)} \]

Differentiating the last equation, we see that neighbors become infected at rate

\[ -\sigma'(t) = -\frac{g''(\theta(t)) \theta'(t)}{g'(1)} = \frac{\beta \phi(t) g''(\theta(t))}{g'(1)} \]
by (4.4.8). Using (4.4.9) and (4.4.11) we have
\[ \phi'(t) = \left[ -\beta - \gamma + \frac{\beta g''(\theta(t))}{g'(1)} \right] \phi(t). \] (4.4.12)

So using (4.4.8) we have
\[ \phi'(t) = \left[ 1 - \frac{\gamma}{\beta} + \frac{g''(\theta(t))}{g'(1)} \right] \theta'(t) \]
Integrating gives
\[ \phi(t) = \theta - \frac{\gamma}{\beta} (1 - \theta) - \frac{\psi'\theta}{\psi'(1)} \]
Using (4.4.8) gives the result in (4.4.7).

Final epidemic size. Letting \( t \to \infty \) in (4.4.2) we have \( S(\infty) = g(\theta_\infty) \). Let
\[ \tau = \frac{\beta}{\beta + \gamma} \]
be the probability that a randomly chosen neighbor of \( u \), call it \( v \), has an infectious contact with \( u \) given that \( v \) has become infected. If \( \sigma_\infty \) is the probability the neighbor is never infected then the probability of an infectious contact is \( \tau (1 - \sigma_\infty) \). Thus the probability of not transmitting the infection along the chosen edge is
\[ \theta_\infty = 1 - \tau + \tau \sigma_\infty \]
(4.4.10) tells us that \( \sigma(t) = g'(\theta(t))/g'(1) = g_1(\theta(t)) \) where \( g_1(z) = \frac{g'(z)}{g'(1)} \) is the generating function of the size biased distribution. so
\[ \theta_\infty = 1 - \tau + \tau g_1(\theta_\infty). \] (4.4.13)
The fixed point equation can be solved to determine \( \theta_\infty \) in the same way that we compute the extinction probability of a branching process.

Example 4.4.1. Random regular graphs. When all vertices have degree \( k \) the generating function of the size biased degree distribution has \( g_1(z) = z^{k-1} \). If \( k = 3 \) then (4.4.13) is a quadratic equation,
\[ \theta = 1 - \tau + \tau \theta^2 \]
or \( 0 = \tau \theta^2 - \theta + (1 - \tau) = (\tau \theta - (1 - \tau))(\theta - 1). \) \( \theta = 1 \) is the trivial solution. \( \tau_c = 1/2 \) since the mean of the size biased distribution is 2. For \( 1/2 \leq \tau \leq 1 \) we have
\[ \theta_\infty = \frac{1 - \tau}{\tau} \]
When \( \tau = 1/2, \theta_\infty = 1 \) so \( S(\infty) = g(\theta_\infty) = 1. \) As \( \beta \to \infty, \tau = \beta/(\beta + \gamma) \to 1 \). When \( \tau = 1, \phi_\infty = 0 \) and \( S(\infty) = g(\theta_\infty) = 1. \)
Figure 4.3: Epidemic size (as fraction of total population) versus \( \tau = \beta/(\beta + \gamma) \) for random \( k \)-regular graphs. The critical value \( \tau_c = 1/(k - 1) \).

If all vertices have degree \( k = 4 \) then the equation of \( \theta_\infty \) is

\[
0 = \tau \theta^3 - \theta + (1 - \tau) = (\theta - 1)(\tau \theta^2 + \tau \theta - (1 - \tau))
\]

\( \tau_c = 1/3 \) since the mean of the size biased distribution is 3. For \( 1/3 \leq \tau \leq 1 \) we have

\[
\theta = -\frac{\tau + \sqrt{\tau^2 + 4\tau(1 - \tau)}}{2\tau} = -1 + \frac{1 + 4(1 - \tau)/\tau}{2}
\]

Using the first formula, when \( \tau = 1/3 \),

\[
\theta = \frac{-1/3 + \sqrt{1/9 + 8/9}}{2/3} = 1
\]

while when \( \tau = 1 \), \( \theta = (-1 + \sqrt{1})/2 = 0 \).

**Solving the equations for SI epidemics.**

In the homogeneously mixing case when \( \gamma = 0 \), (4.1.4) becomes

\[
\frac{ds}{dt} = -\beta si \quad \frac{di}{dt} = \beta si
\]

The equation for \( i \) is a special case of the logistic differential equation

\[
y'(t) = ry(1 - y/K)
\]

(4.4.14)
where \( r \) is the exponential growth rate and \( K \) is the carrying capacity. The general solution is
\[
y(t) = \frac{Ky(0)e^{rt}}{K + y(0)(e^{rt} - 1)}
\] (4.4.15)

When \( K = 1, r = \beta \), and \( y(0) = \epsilon \) this becomes
\[
i_\epsilon^{MF}(t) = \frac{\epsilon e^{\beta t}}{1 - \epsilon + \epsilon e^{\beta t}}
\]
where the superscript MF is for mean-field.

When \( \gamma = 0 \), equation (4.4.7) becomes
\[
\theta'(t) = \beta(g_1(\theta(t)) - \theta(t))
\]
In the random 3-regular case \( g_1(\theta) = \theta^2 \) so the equation becomes
\[
\theta'(t) = -\beta(1 - \theta) \quad \text{or} \quad [1 - \theta(t)]' = \beta(1 - \theta)
\]
Taking \( y(t) = 1 - \theta(t) \) this is a special case of the logistic differential equation in (4.4.14). When \( K = 1, r = \beta \), and \( y(0) = \epsilon \) this becomes
\[
y_\epsilon(t) = \frac{\epsilon e^{\beta t}}{1 - \epsilon + \epsilon e^{\beta t}}
\]
so the solution \( \theta_\epsilon \) with \( \theta_\epsilon(0) = 1 - \epsilon \) is
\[
\theta_\epsilon(t) = 1 - y_\epsilon(t) = \frac{1 - \epsilon}{1 - \epsilon + \epsilon e^{\beta t}}
\]
\( s(t) = g(\theta(t)) = \theta^3(t) \) so
\[
i_\epsilon^{3R}(t) = 1 - \theta_\epsilon^3(t) = 1 - \left(\frac{1 - \epsilon}{1 - \epsilon + \epsilon e^{\beta t}}\right)^3
\]
where the superscript 3R is for three regular.

### 4.5 Rigorous derivations of the equations

Bohman and Picollelli (2012) and Barbour and Reinert (2013) proved results under the assumption that the degree distribution is bounded. Decreusfond et al (2012) proved a result under the assumption that the fifth moment of the degree distribution was finite. Here we will follow Janson, Luczak and Windridge (2015), a source we call JLW, who proved the result for random graphs with a fixed degree distribution under minimal assumptions.

For each integer \( n \) and sequence of nonnegative integers \( (d_i)_{i=1}^n \) let \( G \) be a simple graph (i.e., with no loops or parallel edges) on \( n \) vertices chosen at random from all simple graphs
4.5. RIGOROUS DERIVATIONS OF THE EQUATIONS

with degree sequence \((d_i)_1^n\). We tacitly assume that there is some such graph, so e.g. \(\sum_{i=1}^n d_i\) is even.

Given the graph, the SIR model evolves as a Markov chain in which \(S - I\) edges turn to \(I - I\) at rate \(\beta\) and infecteds become removed at rate \(\gamma\). (JLW use \(\rho\) but we want to minimize the differences with the papers of Miller and Volz.) We assume that initially there are \(n_S\) susceptible, \(n_I\) infecteds, and \(n_R\) removed individuals, where \(n_S + n_I + n_R = n\), and let \(n_{S,k}\), \(n_{I,k}\) and \(n_{R,k}\) be the number of such vertices among those with degree \(k\).

JLW make the following assumptions

(D1) \(n_S/n \to \alpha_S > 0\), \(n_I/n \to \alpha_I\), and \(n_R/n \to \alpha_R\)

(D2) \(n_{S,k}/n_S \to p_k\) with \(\lambda = \sum_k kp_k \in (0, \infty)\)

(D3) \(\sum_k kn_k/n \to \mu\).

(D4) \(\sum_k kn_{S,k}/n \to \mu_S\), \(\sum_k kn_{I,k}/n \to \mu_I\), \(\sum_k kn_{R,k}/n \to \mu_R\). (\(\mu = \mu_S + \mu_I + \mu_R\))

(D5) \(\max\{k : n_{I,k} > 0\} = o(n)\).

(D6) \(p_1 > 0\).

In the situation considered by Volz and Miller \(\alpha_S = 1 - \epsilon\), \(\alpha_I = \epsilon\), \(\alpha_R = 0\).

**Remark 4.5.1.** Assumptions (D1)-(D3) imply \(\sum_k kn_{S,k}/n\) is uniformly summable, i.e., for any \(\epsilon > 0\) there is a \(K\) so that for large \(n\)

\[
\sum_{k > K} kn_{S,k}/n < \epsilon
\] (4.5.1)
As in Section 2.2, it is convenient to work with multigraphs which may have loops or parallel edges. If we condition the multigraph to be simple then the result is uniform on the set of simple graphs. For their proof to work they need for the probability that the multigraph is simple is bounded away from 0 which holds if, see Janson (2009),

\[(G1) \sum_k k^2 n_k = O(n),\] which implies \(\sum_k k^2 p_k < \infty.\)

To study the epidemic on the multigraph JLW reveal the edges of the graph at the same time as the epidemic spreads. They call a half-edge free if it has not yet been paired to another half-edge. The construction starts with \(d_i\) half-edges attached to vertex \(i\) and all half edges free. Half-edges are called susceptible, infective, or removed according to the state of the vertex they are attached to it. The dynamics are as follows

- Each free infective half-edge chooses a free half-edge at rate \(\beta\) at random from all of the free half-edges.
- Together the two half-edges form an edge and are removed from the pool of half-edges.
- If the chosen half-edge is susceptible it becomes infective.
- Infective half edges recover at rate \(\gamma\).

We stop the process when there are no more infective half-edges, at which point the epidemic stops spreading. Some infective vertices may remain but they will recover without infecting other vertices. Susceptible or removed half-edges may also remain but they can paired at random to complete the construction of the graph.

Let \(S_t, I_t, R_t\) be the number of such vertices at time \(t\). \(S_t\) is decreasing in \(t\) and \(R_t\) is increasing so their limits exist. This implies \(I_t = n - S_t - R_t\) converges to a limit, which must be 0. Let \(X_{S,t}, X_{I,t}\) and \(X_{R,t}\) be the number of half-edges with these states at time \(t\). JLR show that under suitable scaling \(S_t, I_t, R_t, X_{S,t}, X_{I,t}\) and \(X_{R,t}\) converge to deterministic limits. The limiting functions will be written in terms of the \(\theta\) which gives the probability that an initial susceptible half-edge has not been paired with a (necessarily infective) half-edge at time \(t\). If the initial number of infecteds are \(o(n)\) then \(\theta\) will start at 1 and decrease,

JLW define the following notation. (We have set \(\mu_R = 0\) for simplicity.)

\[
\begin{align*}
\nu_S(\theta) &= \alpha_S \sum_k p_k \theta^k = \alpha_S g(\theta) \\
h_S(\theta) &= \alpha_S \sum_k k p_k \theta^k = \alpha_S \theta g'(\theta) \\
h_X(\theta) &= \theta^2 \\
h_R(\theta) &= \frac{\mu \gamma}{\beta} \theta (1 - \theta) \\
h_I(\theta) &= h_X(\theta) - h_S(\theta) - h_R(\theta) = \theta^2 - \alpha_S \theta g'(\theta) - \frac{\mu \gamma}{\beta} \theta (1 - \theta)
\end{align*}
\]
To connect with the work of Miller and Volz they let
\[ p_I(\theta) = \frac{h_I(\theta)}{h_X(\theta)} \]
\[ p_S(\theta) = \frac{h_S(\theta)}{h_X(\theta)} \]

The first results in JLW concerns the situation in which the initial fraction of infecteds \( \mu_I > 0 \). They have two theorems for this situation: Theorem 2.6 for the multigraph and Theorem 2.7 for the simple graph. In both cases (D1)-(D6) are assumed. In the second they also assume (G1). The conclusions of the two theorems are almost identical and are given in the next result.

**Theorem 4.5.2.** (a) There is a unique \( \theta_\infty \) with \( h_I(\theta_\infty) = 0 \). \( h_I > 0 \) on \( (\theta_\infty, 1] \) and \( < 0 \) on \( (0, \theta_\infty) \).

(b) There is a unique \( \theta_t : [0, \infty) \to (\theta_\infty, 1] \) so that \( \theta_t \downarrow \theta_\infty \) as \( t \to \infty \)

\[ \frac{d}{dt}\theta_t = -\beta \theta_t p_I(\theta_t) \tag{4.5.3} \]

(c) Let \( \hat{I}_t \) be the solution to

\[ \frac{d}{dt}\hat{I}_t = -\frac{\beta h_I(\theta_t) h_S(\theta_t)}{h_X(\theta_t)} - \gamma \hat{I}_t \tag{4.5.4} \]

If we let \( \hat{R}_t = 1 - \nu_S(\theta_t) - \hat{I}_t \) then

\[ S_t/n \to \nu_S(\theta_t) \quad I_t/n \to \hat{I}_t \quad R_t/n \to \hat{R}_t \]

\[ X_{a,t}/n \to h_a(\theta_t) \] for \( a = S, I, R \). Hence \( X_t/n \to h_X(\theta_t) \) and \( S_\infty/n \to \nu_S(\theta_\infty) \).

(4.5.3) is the same as (4.4.3). Using \( p_I = \frac{h_I(\theta)}{h_X(\theta)} \) and \( h_S(\theta) = \theta g'(\theta) \) we see that (4.5.4) is the same as (4.4.4). To get (4.4.6) we note that

\[ p_S(\theta) = \frac{h_S(\theta)}{h_X(\theta)} = \frac{g'(\theta)}{\theta} \]

so differentiating and using (4.4.3) gives

\[ \frac{d}{dt}p_S(\theta) = \frac{g''(\theta)\theta - g'(\theta)}{\theta^2} \cdot \frac{d\theta}{dt} \]

\[ = \frac{g'(\theta)}{\theta} \cdot \left( \frac{g''(\theta)}{g'(\theta)} - \frac{1}{\theta} \right) \cdot (-\beta p_I) = \beta p_I p_S \cdot \left(1 - \theta \frac{g''(\theta)}{g'(\theta)}\right) \]

Similar calculations, left as an exercise for the reader show that \( dp_I/dt \) is given by (4.4.5). See the proof of (2.30 in JLR.

The also have results in Theorems 2.9 and 2.10 for the multigraph and for the simple graph when the initial fraction of infecteds \( \to 0 \). This brings into play the possibility of the infection dying out, so the statements get more complicated. They apply the last two results to the problem of optimal vaccination strategies considered in Britton, Janson, and Martin-Löf (20070
Main ideas of the proof

The most important of these is to speed up the process so that each free susceptible half-edge gets infected at rate 1. Specifically if there are $x_t \geq 1$ free infective half-edges and $x$ free half-edges of any type we multiply the transition rates for such a state by

$$\frac{x - 1}{\beta x_t}$$

JLW add a $'$ to the variables to indicate the time change and use $\tau$ and $\sigma$ for the time variables in the sped-up process, for example $X_{I,\tau}'$ is the number of free infective half-edges in this time-changed process. Let $\tau^* = \inf\{\tau : X^I_{I,\tau} = 0\}$.

Lemma 4.5.3. (Lemma 3.1 in JLW.) Suppose that (D1)–(D5) hold and let $\tau_1 > 0$. Then uniformly over $[0, \tau_1 \wedge \tau^*]$,

$$S_{\tau}/n \to \nu_S(e^{-t}) \quad X_{S,\tau}/n \to h_S(e^{-t})$$

$$X_{I,\tau}/n \to h_X(e^{-t}), \ X_{R,\tau}/n \to h_R(e^{-t}), \text{ and } X_{I,\tau}/n \to h_I(e^{-t}).$$

Proof. Let $S_{\tau}(k)$ be the number of susceptible vertices with $k$ half-edges at time $\tau$ which we assume $< \tau^*$. The only jumps in $S_{\tau}(k)$ are by $-1$ and occur when an infective half-edge pairs and chooses one of the susceptible vertices with degree $k$. Taking into account the rate at which infective half-edges pair with other half-edges, the time change, and the conditional probability of choosing a susceptible half-edge of degree $k$

$$dS_{\tau}'(k) = -\beta X_{I,\tau}' \left( \frac{X_{I,\tau}' - 1}{\beta X_{I,\tau}'} \right) \left( \frac{ks_{\tau}'(k)}{X_{I,\tau}'} \right) d\tau + dM_{S,\tau}(k)$$

$$= -kS_{\tau}(k)d\tau + dM_{S,\tau}(k) \quad (4.5.5)$$

where $M_{S,\tau}(k)$ is a martingale with $M_{S,\tau}(k) = 0$. The result we have just used is often referred to as

Dynkin’s formula. If $Y_t$ is a Markov process with infinitesimal generator $L$ then

$$f(X_t) - f(X_0) - \int_0^t Lf(Y_s) ds \quad \text{is a martingale}$$

See Proposition 1.7 in Ethier and Kurtz (1986).

The relationship written informally in (4.5.3) can be written formally as an integral equation

$$S_{\tau}'(k) - S_0'(k) - k \int_0^\tau S_{\sigma}'(k) d\sigma + M_{S,\tau}(k)$$

Using Gronwall’s inequality (see Appendix 1 of Revuz and Yor (1999))

$$\sup_{\tau \leq \tau_1} |S_{\tau}'(k) - n_{S,k} e^{-k\tau}| \leq e^{k\tau_1} \sup_{\tau \leq \tau_1} |M_{S,\tau}(k)|$$
Computing the quadratic variation of the martingale and using the $L^2$ maximal inequality for martingales, we conclude that the last term in the previous equation $o(n)$ so we have

$$\sup_{\tau \leq \tau_1} |S'_\tau(k)/n - \alpha_S p_k e^{-k\tau}| \to 0$$

Using (4.5.1) we can sum the last conclusions over $k$ to get

$$\sup_{\tau \leq \tau_1} |S'_\tau/n - \nu_S(e^{-\tau})| \to 0$$
$$\sup_{\tau \leq \tau_1} |X'_S,\tau/n - h_s(e^{-\tau})| \to 0$$

To derive the next equation we start with

$$dX'_\tau = -2(X'_\tau - 1) d\tau + dM_{X,\tau}$$

Arguing as above gives

$$\sup_{\tau \leq \tau_1} |X'_\tau - X'_0 e^{-2\tau}| \to 0$$

For the fourth equation we begin with

$$dX'_{R,\tau} = [(X'_{R,\tau} - 1) + \gamma/\beta^{-1}(X'_\tau - 1)] d\tau + dM_{R,\tau}$$

Differentiating gives

$$\frac{d}{d\sigma} h_R(e^{-\sigma}) = -h_r(e^{-\sigma}) + \gamma/\beta^{-1} h_X(e^{-\sigma})$$

so we arrive at

$$\sup_{\tau \leq \tau_1} |X'_{R,\tau} - h_R(-\tau)| \to 0$$

The final result follows from

$$X'_{I,\tau} = X'_\tau - X'_{I,\tau} - X'_{R,\tau}$$

which completes the discussion of Lemma 4.5.3

To return to the original time scale and obtain Theorem 4.5.2 we let

$$A_\tau = \int_0^\tau \frac{1}{\beta} \left( \frac{X'_{\sigma} - 1}{X'_{I,\sigma}} \right) d\sigma$$

where we regard the bracketed term as $1/2$ if $X'_{I,\sigma} = 0$, i.e., $\sigma \geq \tau^*$, since until then the terms is $\geq 1/2$. $A_\tau$ is strictly increasing and continuous. Let $\tau(t)$ be its strictly increasing continuous inverse defined by $A_{\tau(t)} = t$. As demonstrated in Appendix A.1 of JLW the original process can be recovered by

$$S_t = S'_{\tau(t)} \quad I_t = I'_{\tau(t)} \quad R_t = R'_{\tau(t)}$$
4.6 Household model

The assumption of a homogeneously mixing population is reasonable for a number of diseases, but in some situations heterogeneities can dramatically change the rate of spread and the severity of the epidemic. A simple example is a community of people who live in separate houses: it is natural to assume that transmission between individuals within a household occurs at a higher rate than between households, while all of the households interact equally.

It would be natural to allow the households to be different sizes, but we will follow Ball, Mollison, and Scalia-Tomba (1997) and consider the simplest situation (i) we let the population of size $N$ be split into $m$ households of size $n$ and (ii) we consider the case of fixed infection time.

Let $p_H$ ($H$ is for household) be the probability an individual $i$ infects individual $j$ who is another member of the same house.

Let $p_G$ ($G$ is for global) be the probability of directly infecting individual $j$ who is not in the same house as individual $i$.

To construct the epidemic we will build a random graph where edges indicate the infections that will occur.

**Step 1:** Connect each pair of individuals in the same house with probability $p_H$.

**Step 2:** Make long distance connections between individuals in different households with probability $p_G$.

To do computations we need some notation. Consider the infection process restricted to one house, and started one with infected. Let $\pi_k$ be the probability that $k$ individuals are infected. Let $G_H(z) = \sum_{k=0}^{\infty} \pi_k z^k$.

The number of long distance infections caused by one person is $Y_1 \approx \text{Poisson}(Np_G)$ if $N$ is large. Rather than for write $G_G$, the generating function of $Y_1$ is $G_{\nu}(z) = \exp(Np_G(z-1))$. From steps 1 and 2, we see that

$$R_0 = \mu N p_G.$$ 

To compute the generating function, we recall that if $X, Y \geq 0$ are independent with generating functions $\phi_X$ and $\phi_Y$, then $X + Y$ has generating function $\phi_X \phi_Y$. This implies that the generating function of the number of individuals infected by a cluster of size $k$ is $\exp(Np_G(z-1))^k$ and hence that the number of individuals infected by the cluster of a randomly chosen individual is

$$\sum_{k=0}^{\infty} \pi_k \exp(Np_G(z-1))^k = G_H(G_{\nu}(z)).$$

The probability $\rho = 1 - \zeta$ that the process dies out is the fixed point $< 1$ of the generating function of the offspring distribution:

$$1 - \zeta = G_H(G_{\nu}(1 - \zeta)).$$ (4.6.1)
Our epidemic is essentially a percolation process, so the size of a large epidemic is the same as the size of the giant component in percolation, which is the same in our homogeneous graph to the probability of a large epidemic.

**Dorm Model (Duke REU 2020)**

Due to the covid epidemic, the DOMath 2020 summer program was held virtually with students in Long Island, NY, Birmingham, Alabama, Cary, NC, and Taiwan. A big question on everyone’s mind was: what would happen when students came back to campus in the Fall? That motivated us to ask: To what extent would the spread of COVID-19 on the Duke campus be reduced if all students had single rooms? To address this question we used variants of the household model.

**Single Rooms.** The case of single rooms is essentially the household model, except that (i) \( p_H \) will instead be written as \( p_D \), since we are concerned with a dorm rather than a household, and \( G_H \) will instead be written as \( G_D^1 \), with the superscript 1 indicating single rooms. (ii) when we are thinking about households \( n \) is typically < 10 but in the case of college dorms, \( n \) is large, e.g., 120 is the size of a typical freshman dorm. Before the pandemic, about 6000 students live on campus, which means 50 dorms.

We first compute \( R_0 \). The total number of individuals infected in one dorm as a result of one infected is the total progeny of a branching process. Since \( n \) is large, the branching process will have the offspring distribution Poisson(\( \lambda_1 \)), where \( \lambda_1 = np_D \). We assume \( np_D < 1 \) so that the mean of the total progeny is

\[
\mu_1 = 1 + \lambda_1 + \lambda_1^2 + \cdots = \frac{1}{1 - \lambda_1}, \tag{4.6.2}
\]

This assumption \( np_D < 1 \) seems reasonable because if not then \( R_0 \geq 50 \) and there is no hope for containing the spread.

Each individual infected in the dorm infects an average of \( np_G \) individuals outside the dorm so the basic reproduction number is

\[
R_0 = \mu_1 np_G = \frac{np_G}{1 - np_D}. \tag{4.6.3}
\]

Now, we solve for \( G_D^1 \). Breaking things down according to the number of individuals directly infected by the first individual, the generating function of the size of the epidemic within the dorm caused by one infected is

\[
G_D^1(z) = z \sum_{k=0}^{\infty} e^{-\lambda_1} \frac{\lambda_1^k}{k!} G_D^1(z)^k
= z \exp(\lambda_1 (G_D^1(z) - 1)) = z G_0^1(G_D^1(z)), \tag{4.6.4}
\]
where \( G^1_b(z) = \exp(np_D(z - 1)) \), the generating function of the spread of the infection within the dorm. We solve (4.6.4) by iteration. We start with \( h_0(z) = z \), which corresponds to 1 individual in generation 0, and then iterate

\[
h_\ell(z) = z \exp(\lambda_1(h_{\ell-1}(z) - 1)).
\]

(4.6.5)

\( h_\ell(z) \) is the generating function of the number of individuals infected in the first \( \ell \) generations of the process, so \( h_\ell(z) \downarrow h(z) \), a solution of the recursion.

In the case of single rooms, an explicit solution for \( G^1_D \) can be found by taking the derivative of equation (4.6.4) to get the differential equation

\[
G^\prime_D(z) = G_D(z)/z + \lambda_1 z G_D(z) G^\prime_D(z),
\]

with the boundary condition \( G^1_D(1) = 1 \). It is well known that the solution to the differential equation is

\[
G^1_D(z) = -W(zW - 1(-\lambda_1))/\lambda_1,
\]

(4.6.6)

where \( W \) is the Lambert \( W \) function which is defined by \( W - 1(ze^z) = ze^z \).

Figure 4.5: Generating function \( G^1_D(z) \) for \( np_D = .1, .3, .5, .7, .9 \). Solved by iteration with Equation (4.6.6). \( z \) represents the initial proportion of students within the dorm that were infected.

By (4.6.1), the probability of a large epidemic is the largest solution of

\[
1 - \zeta = G^1_D(\exp(-Np_G\zeta)).
\]

(4.6.7)

This can be further simplified. Plugging in \( G^1_D \) yields

\[
1 - \zeta = -W(e^{Np_G\zeta}(-\lambda_1e^{-\lambda_1}))/\lambda_1
= -W(e^{-(Np_G+\lambda_1)\zeta}e^{\lambda_1(-1)}(-\lambda_1))/\lambda_1.
\]
Multiplying through by $-\lambda_1$, then applying $W^{-1}$ to both sides gives
\[ \lambda_1 (\zeta - 1) e^{\lambda_1 (\zeta - 1)} = e^{-(N p_G + \lambda_1)} e^{\lambda_1 (\zeta - 1)} (-\lambda_1). \]

Recalling that $\lambda_1 = np_D$ and simplifying, we obtain
\[ (1 - \zeta) = e^{-(N p_G + np_D) \zeta}, \]
which is the survival probability for a branching process with a Poisson($R_0 = N p_G + np_D$) distribution.

**Double Rooms.** Suppose now that we have $m_1$ dorms with $n_1$ double rooms, so that $N = 2m_1n_1$. For the sake of comparison, we let the number of people in a dorm be the same, regardless of whether they have only single rooms or only double rooms, i.e., $n = 2n_1$. Let $p_L$ be the probability of infecting your roommate, and $p_D$ be the probability of infecting an individual within your dorm. To find the analogue of $G_1^b$ in this scenario, we think of a generation as having a first step where the ancestor splits into two with probability $p_L$, stays 1 with probability $1 - p_L$ and then a second step in which long range connections are formed within the dorm. The offspring distribution is now a mixture of two Poissons:
\[ p_L \text{Poisson}(2 \cdot 2n_1 p_D) + (1 - p_L) \text{Poisson}(2n_1 p_D). \]

The mean number of infections in one generation, $\lambda_2$, will be the sum of the means of the two Poisson distributions so $\lambda_2 = (1 + p_L)2n_1 p_D$.

Imitating the calculations for single rooms, if $\lambda_2 < 1$, the mean of the total progeny of the branching process is
\[ \mu_2 = 1 + \lambda_2 + \lambda_2^2 + \cdots = \frac{1}{1 - \lambda_2}, \quad (4.6.8) \]
and the basic reproduction number is
\[ R_0 = \mu_2 N p_G = \frac{N p_G}{1 - (1 + p_L)2n_1 p_D}. \quad (4.6.9) \]

To compute $G_D^2$, the analogue of $G_D^1$ for the double room scenario, we note that the generating function of the number of infections in one generation is
\[ G_b^2(z) = p_L \exp(2n_1 p_D (z - 1))^2 + (1 - p_L) \exp(2n_1 p_D (z - 1)), \]
so $G_D^2$ satisfies
\[ G_D^2(z) = z G_b^2(G_D^2(z)). \quad (4.6.10) \]

$G_D^2$ can then be solved using iteration.

Having computed $G_D^2$ we can compute the probability of a large epidemic as in the previous case by numerically solving
\[ 1 - \zeta = G_D^2(\exp(-N p_G \zeta)). \quad (4.6.11) \]
A comparison of the epidemic probabilities $\zeta$ for double-room and single-room dorms is given in Figure 4.7. Note that in the double-room situation when $2n_1p_D = 0.7$ or $0.9$, there is a positive probability of a large epidemic within a single dorm, so the curves are positive when $Np_G = 0$. When $2n_1p_D = 0.3$ or $0.5$, $p_G$ needs to exceed a positive threshold for there to be an epidemic in a university with double-room dorms, but those thresholds are higher when there are only single-room dorm.

Figure 4.7: Size of the epidemics in the single and double room scenarios of the household model when $np_D = 2n_1p_D = 0.3, 0.5, 0.7, 0.9$ and $Np_G$ varies.
4.7 Forest fires and epidemics on $\mathbb{Z}^2$

Mollison (1977, 1978) was one of the first to study spatial models for epidemics. With Kuulasmaa (1985) he used the theory developed to study fox rabies in Europe. The spatial epidemic model independently arose in the physics literature as a description of a forest fire (infected = on fire, recovered = burnt). McKay and Jan (1984) is one example but there were many others.

To construct the epidemic model on a graph we have i.i.d. positive random variables $T_x$ for the vertices with a distribution $F$ that give the duration of the infection at $x$. Associated with each oriented edge $(x, y)$ is an independent exponential($\lambda$) random variable $I_{x,y}$ which is the amount of time after the infection of $x$ until $x$ tries to infect $y$. To identify the individuals infected in the epidemic we draw an oriented edge from $x$ to $y$ if (and only if) $T_x > I_{x,y}$ and let $C_0$ be the set of sites that can be reached from 0 by a path of edges in the graph.

Cox and Durrett (1988) studied the model on $\mathbb{Z}^2$. Formulating the model in forest fire terms

1. A burning tree emits sparks at rate $\alpha$.
2. A spark emitted at $x$ goes to one of the four nearest neighbors chosen at random.
3. If a spark hits a live tree it catches fire immediately and begins to emit sparks.
4. It burns for an exponentially distributed amount of time then burns out.

4.7.1 Probability of a large SIR epidemic

We set $\lambda = \alpha / 2d$, where $\alpha$ is total rate at which a site sends out germs to be sent to a randomly chosen neighbor. If $x$ and $y$ are neighbors, $x \sim y$, the probability $x$ tries to infect $y$

$$p_d = 1 - \int_0^\infty e^{-\alpha s/4} dF(s)$$

In ordinary bond percolation where there is one (unoriented) edge connecting $x$ to $y$. Here, we have two oriented edges connecting each pair of neighbors, but Frisch and Hammersley (1963) have shown that the critical value remains the same and that for any two sets of sites $U$ and $V$ the probability there is a path from $U$ to $V$ is the same in the two models. This result is part of a circle of ideas that led to the “clutter percolation” which encapsulates a number of comparisons between percolation processes, see McDiarmid (1980).

Kuulasmaa (1982) who called these structures locally dependent random graphs has derived a number of properties of the model. If $A \subset \{z : |z| = 1\}$ let $\phi(A)$ be the probability that all edges $(0, z)$ are closed for $z \in A$. Let $B$ be a collection of paths in $\mathbb{Z}^2$ and let $\mathcal{B}$ be the event that some path is open.

**Lemma 4.7.1.** Suppose we have graphs $G_1$ and $G_2$ with a common set of vertices. If $\phi_1(A) \geq \phi_2(A)$ for all $A \subset \{z : |z| = 1\}$ then $P_1(\mathcal{B}) \leq P_2(\mathcal{B})$.

**Proof.** See Kuulasmaa (1982) pages 749–750.
Since $\phi_{\text{bond}}(A) = (1 - p)^{|A|}$ and $\phi_{\text{site}}(A) = (1 - p)$. It follows that for any model

$$P_{\text{site}}(B) \leq P(B) \leq P_{\text{bond}}(B)$$

Let $\alpha_c(F)$ be the smallest value of $\alpha$ for which $P(C_0 = \infty) > 0$. and let

$$p_c(F) = 1 - \int_0^\infty \exp(-\alpha_c(F)s/4) \, dF(s)$$

then we have

$$p_c^{\text{bond}} \leq p_c(F) \leq p_c^{\text{site}}$$

In two dimensions the lower bound is $1/2$ from Kesten’s rigorous result for bond percolation, see Kesten (1982), while the upper bound is 0.5927 if we use the consensus of a large number of studies in the physics literature.

### 4.7.2 Shape theorem

Suppose that initially the origin is infected while all the other sites are susceptible, let $\zeta_t = \{x : \eta_t(x) = 0\}$ be the set of removed individuals, and let $\xi_t = \{x : \eta_t(x) = i\}$ be the set of infected individuals. The main result of Cox and Durrett (1988) is a shape theorem

**Theorem 4.7.2.** Consider the epidemic model on $\mathbb{Z}^2$ and assume that $\int_0^\infty s^2 \, dF(s) < \infty$ and $\alpha > \alpha_c(F)$. Then there is a convex set $D$ so that for any $\epsilon > 0$ there is a $t_0(\epsilon)$ so that

(i) $P(C_0 \cap (1 - \epsilon) \subset \zeta_t \subset t(1 + \epsilon)D \, t \geq t_0(\epsilon)) = 1$

(ii) $P(\xi_t \subset t(1 + \epsilon)D - t(1 - \epsilon)D \, t \geq t_0(\epsilon)) = 1$

In words, the epidemic spreads linearly and has an asymptotic shape. (i) says that inside $(1 - \epsilon)$ times the growing ball all the individuals that will be ever be infected are in the removed state, while (ii) says that all of the active infections are near the boundary of the growing region. Since the shape is convex and has the rotational and reflection symmetries as $\mathbb{Z}^2$ it will look roughly like a ball.

Proving shape theorems for interacting particle systems was a popular enterprise when Cox and Durrett (1988) was written. The earliest result was due to Richardson (1973) who proved a general result which can be used to prove a shape theorem for Eden’s (1961) growth model, which can be succinctly defined as first passage percolation on $\mathbb{Z}^2$ with exponential(1) passage times. Now this is more commonly done by using Liggett’s version of Kingman’s subadditive ergodic theorem, see Section 6.5 in PTE5.

Cox and Durrett (1981) proved a shape theorem for first passage percolation on $\mathbb{Z}^d$ with necessary and sufficient conditions. Bramson and Griffeath (1980,1981) proved a shape result for the **biased voter model** on $\mathbb{Z}^d$ also known as the **Williams-Bjerknes tumor growth model**. In this system vertices in state 1 change to 0 at a rate equal to the fraction of neighbors in state 0, vertices in state 0 change to 1 at rate $\lambda > 1$ times the fraction of neighbors in state 0. They showed that starting from a single 1 at the origin then if the 1’s do not die out the region that they occupy grows linearly and has an asymptotic shape.
4.7. FOREST FIRES AND EPIDEMICS ON $\mathbb{Z}^2$

Durrett and Griffeath (1982) proved a shape theorem for the $d$-dimensional contact process (see Chapter 5 for the definition) under the assumption that the birth rate $\lambda > \lambda_c(\mathbb{Z})$ the critical value for the model on $\mathbb{Z}$. They showed that if we start from a single 1 at the origin and the process does not die out then with high probability inside $(1 - \epsilon)tD$ the state of the process can be coupled to the upper invariant measure, while outside $(1 + \epsilon)tD$ there are no particles. The proof under the natural assumption $\lambda > \lambda_c(\mathbb{Z}^d)$ had to wait for Bezuidenhout and Grimmett (1990) to provide an important tool for studying the multi-dimensional contact process.

**Main ideas of the proof.** To begin we prove a fact that was stated earlier:

**Lemma 4.7.3.** The cluster containing the origin in the graph $C_0$ is the set of sites that will ever become infected if initially the origin is infected and all other sites are susceptible. Furthermore a site $y \in C_0$ first becomes infected at the first passage time from 0 to $y$.

**Proof.** Clearly if $y$ become infected at some time then $y \in C_0$ since $y$ was infected by a neighbor, who was infected by a neighbor . . . who was infected by 0. We argue the other inclusion by induction on the length of the shortest path. If the path has length 1 this is clear because when 0 tries to infect $y$ either (a) $y$ is not infected or (b) it has already been infected. In either case the result is true.

If $y \in C_0$ and $0, y_1, \ldots y_n = y$ is the shortest path then we apply the last argument with 0 replaced by $y_{n-1}$. The induction hypothesis implies $y_{n-1} \in C_0$. When $y_{n-1}$ tries to infect $y_n$ then either (a) or (b) holds and in either case the result is true. To get the second conclusion, note that if the path achieves the first passage time then alternative (b) is impossible. \qed

The proof follows the approach of Cox and Durrett (1981). To carry this out, Section 2 of their paper extends results from ordinary percolation to the new model with bidirected edges. The proofs are old-school in that they use the machinery of sponge crossings developed by Kesten (1982). The next step, taken in Section 3, is to prove the existence of radial limits for the first passage times. Intuitively this means that on the set where the infection does not die out $\lim_{n \to \infty} \tau(0, nx)/n$ exists. To deal with the fact that $nx$ may not be in $C_0$ we find a ring of sites $\Delta(x)$ around that are infected and we define a passage time $\hat{t}(x, y)$ from $\Delta(x)$ to $\Delta(y)$ where $\Delta(x)$ is $\Delta(x)$ enlarged to include all the open edges inside the ring.

Once it has been shown radial limits exist, then the machinery that was developed to prove the other results listed above takes over to prove the result. An early lemma in the proof of these results (see e.g., Bramson and Griffeath (1981)) is a lemma that shows the existence of a linearly growing solid ball that grows at some small rate $\delta > 0$. Using a finite set of radial limits that are sufficiently dense in the limiting shape $D$ and the small ball result proves that all sites in $C_0$ inside $(1 - \epsilon)tD$ are infected. To prove there are no infecteds outside $(1 + \epsilon)tD$, we use the small ball result to show that if there are then one of the radial limits in a finite set inside $2tDt$ is going too fast.

**Open problem.** Use the version of the shape theorem for first passage percolation proved in Kesten (1986) to extend the argument to $d$ dimensions.
4.7.3 SIRS epidemics

Given the recent covid epidemic, most readers should be familiar with the fact that individuals resistant to the disease can again become susceptible, in that case because the virus mutates and evades the immunity to previous strains. On a slower time scale, the regrowth of the susceptible population in the case of measles occurs when immune individuals die and are replaced by new individuals susceptible to the disease.

Our main purpose in this section is to state a result of Durrett and Neuhaus (1994). They formulated their result using the forest fire interpretation. 0 = live tree, 1 = on fire, 2 = burnt. They add a fifth transition to the four described earlier.

5. Burnt trees return to life at rate $\beta$.

At first glance, the spontaneous reappearance of trees may not seem reasonable. This can be justified biologically by the fact that in real forests, trees regrow from seeds in the ground. However, the real motivation for making this assumption is that if we assume new trees appear by births from existing trees the next result is a difficult open problem.

Theorem 4.7.4. Suppose that $\alpha > \alpha_c(0)$ the critical value for the epidemic with no regrowth. Then for all $\beta > 0$ there is a stationary distribution that puts no mass on the all healthy state.

The proof of the result uses a block construction. A number of examples are described in Durrett’s 1993 St. Flour notes so a detailed description is beyond the scope of this book. The key fact, which requires considerable ingenuity to prove, is that if we have a large patch of woods (an $L \times L$ box) then the fire will burn for a long time. To do this they show if that if the fire has dwindled to only $L^{1/2}$ burning trees then it will with high probability return to size $\delta L^{0.7}$ before hitting 0. The challenge is to prove this happens so matter how the burning, live, and burnt trees are distributed.

Bak, Chen, and Tang (1990) studied a similar model. In their system:

(i) Trees grow with a small probability $p$ from empty sites in each time step.
(ii) Trees on fire burn down at the next time step.
(iii) The fire on a site will spread to trees at its nearest neighbors at the next time step.

They described this as a system in which energy is injected uniformly (through the growth of trees) and dissipated on a fractal set (the forest fires). They claimed this was an example of self-organized criticality. However, the physics community eventually decided it was not. Simulations show that the epidemic persists due to the formation of spiral-shaped fire fronts but that conclusion seems far out of the reach of rigorous arguments.

References

Here we have concentrated on rigorous results. For approximate methods such as degree-based mean field theory and the pair approximation, see Pastor-Satoras, Castellano, van
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4.7. FOREST FIRES AND EPIDEMICS ON Z^2


Chapter 5

Contact Process

The contact process is often used as a simple spatial model for the spread of species. In this case the state at time $t$, $\xi_t$, is the set of occupied sites, and sites in $\xi_t^c$ are vacant. In the contact process on a graph $G$, occupied sites $x \in \xi_t$ become vacant at rate 1, and give birth onto each vacant neighbor at rate $\lambda$. The contact process can also be viewed as a spatial SIS epidemic model. In this case $\xi_t$ is the set of infected sites, and sites in $\xi_t^c$ are susceptible.

With most diseases, individuals have some immunity to reinfection after they recover, but we are not really concerned with applications here. The contact process in which deaths occur at a constant rate, and the birth rate is linear is a very simple and fundamentally important example of a stochastic spatial model.

5.1 Basic properties

Harris (1974) introduced the contact process on $G = \mathbb{Z}^d$ in 1974. Let $\xi^x_t$ be the process starting from only $x$ occupied. Harris defined the critical value

$$\lambda_c = \inf\{\lambda : P(\xi^x_t \neq \emptyset \text{ for all } t) > 0\},$$

(this value is independent of $x$ on connected graphs.) He proved that on $\mathbb{Z}^d$ we have $0 < \lambda_c < \infty$. On $\mathbb{Z}^d$, or on any graph with all degrees $\leq M$, the lower bound is trivial $\lambda_c \geq 1/M$.

In the early days of the theory, upper bounds on critical values seemed harder than lower bounds, but when it came to random graphs with unbounded degree distributions lower bounds were easier because one only had to find a mechanism that ensured survival. On graphs with power law degree distribution or even subexponential distributions the critical value is 0, so the question of lower bounds is moot. The question for random graphs with exponentially decaying degree distributions, considered in Section 5.7, turned out to be quite difficult and it took many years to show that $\lambda_c > 0$.

A rich theory has been developed for the contact process on $\mathbb{Z}^d$ and on regular trees. See Liggett’s 1999 book for a summary of much of what is known in these settings. In this section we will review some of the definitions and results that are the most important for our
work. If you want to see more details consult Liggett’s book. I am not a big fan of calling things beautiful, but this book is.

The first item on our agenda is a special construction of the process from a graphical representation that is built using independent Poisson processes.

- For each site there is an independent rate 1 Poisson process \( T_n^x, n \geq 1 \). At the arrivals of this process if there is a particle at \( x \), it will die. To facilitate later definitions we write a dot at \( x \) at the times \( T_n^x \). In early versions of the construction people wrote \( \delta \) for death.

- For each oriented edge \((x, y)\) we have a rate \( \lambda \) Poisson process \( T_n^{x,y} \). At these times we draw an arrow from \( x \) to \( y \) to indicate that if \( x \) is occupied there will be a birth from \( x \) to \( y \). If \( y \) is vacant it will become occupied. If \( y \) is occupied there is no change.

![Figure 5.1: Graphical representation for the contact process.](image)

Let \( \xi_t^A \) denote the contact process starting from \( A \) occupied at time 0. A point \( y \in \xi_t^A \) if for some \( x \in A \) there is path from \((x, 0)\) to \((y, t)\) that goes up the graphical representation without passing through \( \bullet \)s and crosses edges in the direction of their orientation. A nice feature of the graphical representation is that it allows us to construct all of the \( \xi_t^A \) on the same space in such a way that

\[
\text{if } A \subset B \text{ then } \xi_t^A \subset \xi_t^B. \quad (5.1.1)
\]
When a set-valued Markov process has this property, it is called **attractive**. The term originated from the Ising model in which each site was in state 1 (spin up) or \(-1\) (spin down). In this case attractive meant that the spins had a tendency to align. An important consequence of a process being attractive is

**Theorem 5.1.1.** If we let \(\xi^1_t\) be the system starting from all sites occupied then \(\xi^1_t\) converges in distribution to a limit \(\xi^1_\infty\), which is a stationary distribution.

The reader can find the proofs of these and other assertions in Liggett’s (1999) book. Due to monotonicity property in (5.1.1), \(\xi^1_\infty\) is the largest possible stationary distribution. Thus, if \(\xi^1_\infty = \delta_\emptyset\) then there are no nontrivial stationary distributions.

![Contact process duality](image)

**Figure 5.2:** Contact process duality. We think of fluid flowing down the structure, across arrows in the direction opposite orientation, but being stopped by dots.

A second important consequence of the construction is that it allows us to define for each \(x\) a **dual process** \(\zeta^{x,t}_s, s \leq t\), that works backwards in time to answer the question “Is the site \(x\) occupied at time \(t\)?” The dual process can be constructed by a variant of the rule used for the contact process: \(y \in \zeta^{x,t}_s\) if there is a path from \((x, t)\) to \((y, t - s)\) that goes down the graphical representation without passing through \(\bullet\)s and crosses edges in the direction opposite their orientation.

We extend the definition of the dual to an initial set \(B\) by setting

\[
\zeta^{B,t}_s = \bigcup_{x \in B} \zeta^{x,t}_s
\]

A little thought shows that

\[
\{\xi^A_t \cap B = \emptyset\} = \{A \cap \zeta^{B,t}_t = \emptyset\}
\]  (5.1.2)
The almost sure equality in (5.1.2) is convenient for establishing the equation but it is useful to rewrite the equality without the superscript $t$. To do this we note that if $t < t'$ then the joint distribution of the $\zeta_s^{x,t}$, $s \leq t$ with $x \in \mathbb{Z}^d$ is the same as that of $\zeta_s^{x,t'}$, with $x \in \mathbb{Z}^d$ when $s \leq t'$, so using the Kolmogorov extension theorem there is a family of processes $\zeta_s^x$ whose joint distributions agree with $\zeta_s^{x,t}$ on $s \leq t$.

$$P(\xi_t^A \cap B \neq \emptyset) = P(A \cap \zeta_t^B \neq \emptyset)$$  (5.1.3)

With future generalizations in mind we will ignore for the moment that contact process on a graph $G$ is self dual. Taking $A = G$ and $B = \{x\}$ the duality equation becomes

$$P(x \in \xi^1_t) = P(\zeta_t^x \neq \emptyset)$$

Since the empty set is an absorbing state for the dual

$$\lim_{t \to \infty} P(x \in \xi^1_t) = P(\zeta_t^x \neq \emptyset \text{ for all } t)$$

In words the density of particles in $\xi^1_\infty$ is the probability that the dual process lives forever starting from one site. Replacing $x$ by a finite set $B$

$$\lim_{t \to \infty} P(\xi_t^1 \cap B \neq \emptyset) = P(\zeta_t^B \neq \emptyset \text{ for all } t)$$

The fact that this holds for all $B$ implies that $\xi^1_t$ converges in distribution.

A consequence of the construction from a graphical representation is that the interaction is additive

$$\xi_t^A \cup \xi_t^B = \xi_t^{A \cup B}$$

Harris (1978) identified the processes with this property and showed that they had dual processes. The study of this class of processes was greatly advance by the work of Griffeath (1979). In Chapter 7 we will encounter another member of this family, the voter model.

### 5.2 Trees, random regular graphs

Pemantle (1992) was the first to study the contact process on the tree $\mathbb{T}^d$ in which each vertex has degree $d + 1$. Here, and in what follows, we assume $d \geq 2$ since $\mathbb{T}^1 = \mathbb{Z}$. Let 0 be the root of the tree and let $P_0$ be the probability measure for the process starting from only the root occupied. Pemantle found that the contact process on $\mathbb{T}^d$ has two critical values:

$$\lambda_1 = \inf\{\lambda : P_0(\xi_t \neq \emptyset \text{ for all } t) > 0\},$$
$$\lambda_2 = \inf\{\lambda : \liminf_{t \to \infty} P_0(0 \in \xi_t) > 0\}.$$

In words, the contact process survives when $\lambda > \lambda_1$ but survives locally when $\lambda > \lambda_2$, i.e., with positive probability 0 is occupied infinitely many times, though the definition is chosen to be stronger than that.
By deriving bounds on the critical values, he showed that $\lambda_1 < \lambda_2$ when $d \geq 3$. Liggett (1996) settled the case $d = 2$ by showing

$$\lambda_1 < 0.605 < 0.609 < \lambda_2.$$  

At about the same time, Stacey (1996) gave a proof that $\lambda_1 < \lambda_2$ which did not rely on numerical bounds on the critical value.

**Open problem.** Stacey’s argument is simple and elegant but relies heavily on the fact that the graph is a tree. It would be nice to generalize it to Galton-Watson trees, but the randomness of the graph may pose a substantial problem. A simpler problem is to consider the Big World of Durrett and Jung (2017), which is the free product $\mathbb{Z}^d \ast \{0, 1\}$. More intuitively it the covering space of the Bollobás-Chung (1988) small world which preceded the more highly cited small world of Watts and Strogatz (1998). In the BC small world one starts with a circle with an even number of vertices, pairs them at random and connects each pair by an edge. The Big World gives the limit as $n \to \infty$ of the view point of a bug walking on the small world. Moving through a long range edge brings it to a new copy of $\mathbb{Z}$. If the verbal description is not enough, eee their paper for a picture.

**Contact process on finite graphs.** We begin by considering $\{-n, \ldots, n\}$. Suppose it starts from all sites occupied and let $\tau_n = \inf\{t : \xi_t = \emptyset\}$. Combining results of Durrett and Liu (1988) and Durrett and Schonmann (1988) gives the following results

(i) If $\lambda < \lambda_c$ then there is a constant $\gamma_1(\lambda)$ so that

$$\frac{\tau_n}{\log n} \to \gamma_1(\lambda) \quad \text{in probability.}$$

(ii) If $\lambda > \lambda_c$ then there is a constant $\gamma_2(\lambda)$ so that

$$\frac{(\log \tau_n)}{n} \to \gamma_2(\lambda) \quad \text{in probability.}$$

(iii) When $\lambda > \lambda_c$ there is “metastability”:

$$\frac{\tau_n}{E\tau_n} \Rightarrow \text{exponential}(1)$$

where $\Rightarrow$ means convergence in distribution. Intuitively, when $\lambda > \lambda_c$ the process on the interval stays exponentially long in a state that looks like the stationary distribution for the process on $\mathbb{Z}$. (This conclusion is implied by the method of proof.) The lack of memory property of the survival time suggests that the death of the process comes suddenly and without warning, but we know of no result that makes this precise.

Results on $\mathbb{Z}^d$ with $d > 1$ had to wait for the work of Bezuidenhout and Grimmett (1990), who showed that in $d > 1$ the contact process dies out at the critical value and in doing so introduced a **block construction** that can be used to study the supercritical process. Mountford proved the metastability result in 1993 and that $(\log \tau_n)/n^d \to \gamma(\lambda)$ in 1999.

Stacey (2001) studied the contact process on a tree truncated at height $\ell$, $T_d^\ell$. To be precise, the root has degree $d$, vertices at distance $0 < k < \ell$ from the root have degree $d + 1$, while those at distance $\ell$ have degree 1. Cranston, Mountford, Mourrat, and Valesin (2014) improved Stacey’s result to establish that the time to extinction starting from all sites occupied $\tau^d_\ell$ satisfies
Theorem 5.2.1. (a) For any \( 0 < \lambda < \lambda_2(\mathbb{T}^d) \) there is a \( c \in (0, \infty) \) so that as \( \ell \to \infty \)
\[
\frac{\tau^d_\ell}{\log |\mathbb{T}^d_\ell|} \to c \quad \text{in probability.}
\]
(b) For any \( \lambda_2(\mathbb{T}^d) < \lambda < \infty \) there is a \( c \in (0, \infty) \) so that as \( \ell \to \infty \)
\[
\frac{\log(\tau^d_\ell)}{|\mathbb{T}^d_\ell|} \to c \quad \text{in probability.}
\]
Moreover \( \tau^d_\ell / E \tau^d_\ell \) converges to a mean one exponential.

When a tree is truncated at a finite distance, a positive fraction of the sites are on the boundary. A more natural finite version of a tree is a random regular graph in which all vertices have degree \( d + 1 \). In this case there is no boundary and the graph has the same distribution viewed from any point. If there are \( n \) vertices, the graph looks like \( \mathbb{T}^d \) in neighborhoods of a point that have \( \leq n^{1/2 - \epsilon} \) vertices, see Theorem 1.2.3. Mourrat and Valesin (2016) have shown for a random regular graph, the time to extinction starting from all sites occupied \( \tau_n \) satisfies:

Theorem 5.2.2. (a) For any \( 0 < \lambda < \lambda_1(\mathbb{T}^d) \) there is a \( C < \infty \) so that as \( n \to \infty \)
\[
P(\tau_n < C \log n) \to 1,
\]
(b) For any \( \lambda_1(\mathbb{T}^d) < \lambda < \infty \) there is a \( c > 0 \) so that as \( n \to \infty \)
\[
P(\tau_n > e^c n) \to 1.
\]

Notice that the threshold in the second result comes at \( \lambda_1 \), while the one in Stacey’s result comes at \( \lambda_2 \). The difference is that when \( \lambda \in (\lambda_1, \lambda_2) \) on the infinite tree the origin is in the middle of linearly growing vacant region. On the truncated tree the system dies out when the vacant region is large enough, or more poetically the particles like lemmings run over the edge of cliff. However, on the random regular graph the occupied sites will later return to the origin. Durrett and Jung (2017) investigated the qualitative differences between \( \lambda \in (\lambda_1, \lambda_2) \) and \( \lambda > \lambda_2 \) on the small world graph.

Lalley and Su (2017) also proved Theorem 5.2.2. In addition they established an interesting “cutoff” result about convergence to equilibrium. Their Theorem 1.1 shows that if we start from only 1 occupied then there are constants \( c_\lambda \) and \( g_n(\epsilon) \to 0 \) so that
\[
P(2 \in \xi_t) \quad \text{at times}
\leq g_n(\epsilon) \quad \leq (1 - \epsilon)c_\lambda \log n
\geq \rho^2(1 - g_n(\epsilon)) \quad \geq (1 + \epsilon)c_\lambda \log n
\]
where \( \rho \) is the survival probability, which by duality is the fraction of sites that are occupied.

Mourrat and Valesin (2016) extended their result on random reguar graphs to graphs with bounded degree. The following is their Theorem 1.3.
Theorem 5.2.3. Let $G_{n,d}$ be the set of connected graphs with $n$ vertices and degree bounded by $d + 1$. (a) For any $0 \in (0, \lambda_c(\mathbb{T}^d))$ there is a $C < \infty$ so that
\[
\lim_{n \to \infty} \inf_{G \in G_{n,d}} P(\tau_G < C \log n) = 1
\]
(b) For any $\lambda \in (\lambda_c(\mathbb{Z}), \infty)$ there is a $c > 0$ so that
\[
\lim_{n \to \infty} \inf_{G \in G_{n,d}} P(\tau_G > e^{cn}) = 1
\]
Note that the constants are uniform over $G \in G_{n,d}$. The form of the result in (b) suggests the method of proof: we are going to find a large path in the graph and compare with the one dimensional contact process.

Proofs of Theorems 5.2.2 and 5.2.3

The two proofs are independent of each other. Both are from Mourrat and Valesin (2016).

Proof of part (a) of Theorem 5.2.3

We prove the more general result by comparing the contact process on the graph with the contact process on the tree. In the statement of the first lemma we use a notation for the projection $\pi$ from $T$ to $G$ that is defined in the proof. The parenthetical names of results refer to their (2016) paper published in EJP. As usual $\tau^C$ are the extinction times for the contact process starting from sites in $C$ occupied.

Lemma 5.2.4. (Lemma 4.2.) For any $G \in G_{n,d}$, $A \subset V$, and $B \subset \mathbb{T}^d$ for which $\pi(B) \supset A$
\[
P_G(\tau^A > t) \leq P_{\mathbb{T}^d}(\tau^B > t)
\]
Proof. To prove this we introduce the universal cover of the graph $G$. Fix a reference vertex $x \in V$. Given an oriented edge $\vec{e}$ let $v_0(\vec{e})$ be the vertex points away from, and $v_1(\vec{e})$ be the vertex points away from. We say that a sequence of oriented edges $(\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_m)$ is a nonbacktracking path from $x$ if $v_0(\vec{e}_1) = x$, for $2 \leq i \leq m$, $v_1(\vec{e}_{i-1}) = v_0(\vec{e}_i)$, and $v_0(\vec{e}_{i-1}) \neq v_1(\vec{e}_i)$.

Let $\mathcal{V}$ be the set of non-backtracking paths, including the empty path which is denoted by $o$. For any $\gamma = (\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_m)$ and $\gamma' = (\vec{e}_1, \vec{e}_2, \ldots, \vec{e}_m, \vec{e}_{m+1})$ there is an edge from $\gamma$ to $\gamma'$. This defines the edge set $\mathcal{E}$ of the tree $T$, which has degree $\leq d + 1$.

To map the tree into the graph put $\psi(o) = x$ and $\psi(\gamma) = v_1(\vec{e}_m)$. For $y \in V$, $\psi^{-1}(v)$. Define the set of configurations that have at most one particle per fiber by
\[
\Omega_T = \left\{ \zeta \in \{0,1\}^V : \sum_{y \in \psi^{-1}(v)} \zeta(y) \in \{0,1\} \right\}
\]
Define the projection \( \pi: \Omega_T \to \{0, 1\}^V \) by
\[
[\pi(\zeta)](v) = \sum_{y \in \phi^{-1} v} \zeta(y)
\]
In the usual way we will identify configurations \( \zeta \in \{0, 1\}^T \) with the set of sites that are in state 1, \( \{y \in T : \zeta(y) = 1\} \).

**Coupling.** Suppose we have \( A \subset V \) and \( B \subset T \) with \( B \supset A \). and let \( A_t \) and \( B_t \) be the contact process with these initial states. To couple the two processes we let \( \kappa: A_t \to B_t \) so that \( \pi(\kappa(a)) = a \). \( \kappa \) can change over time but there is no reason to let it change between jumps of the process.

We use a graphical presentation to couple the two processes. We use the deaths associated with particles in \( T \) and the births associated with particles on \( G \) and use independent Poisson processes to complete the graphical representation on \( T \)

(i) If a death occurs at \( b \) which is \( = \kappa(a) \) for some \( a \) then we also kill the particle at \( a \).

(ii) Suppose a birth occurs from \( a \) to a neighbor \( a' \). If the corresponding neighbor of \( b = \kappa(a) \) which we will call \( b' \) is vacant then \( b \) will give birth onto \( b' \) and we will let \( \kappa(a') = b' \). If \( b' \) is already occupied then since there are no particles in \( \phi^{-1}(a') \) we can again let \( \kappa(a') = b' \).

The coupling shows that if \( A_t \neq \emptyset \) then \( B_t \neq \emptyset \) which proves the desired result.

To complete the proof we use their formula (4.1)

**Lemma 5.2.5.** For any \( \lambda < \lambda_1(\mathbb{T}^d) \) there are constants \( c_0, C_0 \) so that
\[
E|\xi_0^B| \leq C_0 e^{-c_0 t}
\]

They prove this result by combining several facts from Section 1.4 of Liggett(1999). The details are not useful for other developments here, so we refer the reader to the paper for details. The additivity property of the contact process implies that for \( B \subset \mathbb{T}^d \)
\[
E|\xi_t^B| \leq |B| \cdot C_0 e^{-c_0 t}
\]
which implies the desired conclusion.

**Proof of (b)**

We begin with a classical large deviations result for the binomial.

**Lemma 5.2.6.** (Lemma 3.1.) For every \( \delta \geq 0 \)
\[
P(\text{binomial}(m, p) \geq (p + \delta)m) \leq e^{-m \psi_p(\delta)}
\]
where \( \psi_p(\delta) = \sup_{\lambda}[\lambda(p + \delta) - \log(1 - p + pe^\lambda)] \)
\[
= (p + \delta) \log \left( \frac{p + \delta}{p} \right) + (1 - p - \delta) \log \left( \frac{1 - p - \delta}{1 - p} \right)
\]
(5.2.1)
The next ingredient is a lemma from Salzano and Schonmann (1998). Throughout this section vertices have degree $d \geq 3$

**Lemma 5.2.7.** (Lemma 3.2) For every $\lambda > \lambda_1(\mathbb{T}^d)$ there are constants $S$, $p_0 > 0$ and $\alpha > 1$ so that

$$P_{T,\lambda}( | \{ x \in \xi^0_{tS} : \text{dist}(0, x) = \ell \} | \geq \alpha^{\ell} ) \leq p_0$$

which they generalize as follows

**Lemma 5.2.8.** (Lemma 3.3.) For every $\lambda > \lambda_1(\mathbb{T}^d)$ there are $R$, $\sigma > 0$ so that for every $\ell$ large enough the following holds. For any graph $G$ with vertices $x, y$ so that $\text{dist}(x, y) \leq r$ and $(y, G)$ embeds $(0, \mathbb{T}^{d\ell})$

$$P_{G,\lambda}( | \xi^x_{R\ell} | \geq \alpha^{\ell} ) \geq \sigma$$

**Proof.** This follows from Lemma 5.2.7 and the next two facts

$$P_{G,\lambda}(\xi^x_t (x) = 1) \geq e^{-t}$$

$$P_{G,\lambda}(\xi^x_{\text{dist}(x,y)}(y) = 1) \geq (e^{-2(1-e^{-\lambda})})^{\text{dist}(x,y)}$$

The first estimate is trivial. In order for $x$ to be 1 at time $t$ it is enough that the initial 1 at $x$ survives for time $t$. For the second result suppose $x_0 = x, x_1, \ldots x_k = y$ is a path of length $k$ from $x$ to $y$. We have $\xi^x_k(y) = 1$ if in each time interval $[j-1, j]$ with $1 \leq j \leq k$ there is no death at $j-1$ or $j$ and there is a birth from $x_{j-1} \rightarrow x_j$. \qed

We say that a set of vertices $W \subset V_n$ is $(\ell, r)$-regenerative if there is a family $G'_v$, $v \in W$ of subgraphs of $G_n$ that are pairwise disjoint have $v \in G'_v$, and there is $x$ so that

- the distance in $G'_v$ between $x$ and $v$ is $r$
- and $(x, G'_v)$ embeds $(0, \mathbb{T}^\ell)$

**Theorem 5.2.9.** (Theorem 3.4.) For $k$ and $r$ sufficiently large and for every $\ell$ there is an $\epsilon_0$ so that for all $\epsilon \leq \epsilon_0$ the following holds with high probability: from every $W \subset V_n$ of cardinality at least $k\epsilon n$ one can extract a $(\ell, r)$-regenerative set of cardinality at least $\epsilon n$.

**Proof of (b) assuming Theorem 5.2.9.** Fix $\lambda > \lambda_1(\mathbb{T}^d)$ and choose constants as follows

(i) fix $r$ and $k$ large, as required by Theorem ??
(ii) let $\alpha, R, \sigma$ correspond to $\lambda$ and $r$ as in Lemma 5.2.8.
(iii) take $\ell$ large enough, as required by Lemma 5.2.8 and so that $\alpha^{\ell} > 2k/\sigma$
(iv) take $\epsilon < \epsilon_0$ where $\epsilon_0$ corresponds to $k, r, \ell$ as in Theorem 5.2.9.

Assume $G_n$ has the property stated in Theorem 5.2.9 for every $W \subset V_n$ with $|W| \geq k\epsilon n$ one can extract a $(\ell, r)$-regenerative set $W' = \{v_1, \ldots v_{\epsilon n} \}$ of cardinality at least $\epsilon n$. Let
$G'_{v_1}, \ldots, G'_{v_n}$ be the disjoint subgraphs so that $\text{dist}(v_i, x_i)$ and $(x_i, G'_{v_i})$ embeds $T^d$. We will now show that

$$P_{G_n}(\vert \xi_{R^d}^W \vert \geq k\epsilon n) \geq 1 - e^{-cn}$$

which when iterated gives (b).

For each $i$ let $\zeta_i$ be the contact process on $G'_{v_i}$ starting with only $v_i$ infected. Clearly

$$\xi_t^W \supset \xi_t^{W_i} \supset \cup_{i=1}^{\epsilon n} \zeta_t^i$$

and the $\zeta_t^i$ are independent. Let $E_i = \{\vert \zeta_t^i \vert \geq \alpha \epsilon\}$. Lemma 2.3 implies that $P_{G_n}(E_i) \geq \sigma$. Therefore by the large deviations result in Lemma 2.1

$$P_{G_n} \left( \sum_{i=1}^{\epsilon n} 1_{E_i} \geq \epsilon n \sigma / 2 \right) \geq 1 - \exp(-c(\epsilon, \sigma)n)$$

Finally if the event above occurs we have

$$\vert \xi_{R^d}^W \vert \geq \alpha \epsilon \cdot \epsilon n \sigma / 2 > k\epsilon n$$

by the assumption in (iii).

\[ \square \]

### 5.3 Power-law random graphs

Pastor-Satorras and Vespigniani who we will abbreviate PSV (2001a, 2001b, 2002) have made an extensive study of the contact process on “scale-free” random networks using mean-field methods. For this and many other related results see the survey paper by Pastor-Satorras, Castellano, van Meighem, and Vespigniani (2015).

**Mean-field theory.** To be be precise we will use what is called degree based mean-field theory. The results here are from PSV (2001b) although the arguments will be written differently. Let $\rho_k(t)$ denote the fraction of vertices of degree $k$ that are infected at time $t$, and $\theta(\lambda)$ be the probability that a given link points to an infected vertex. If we make the assumption that there is no correlation between the degree of a site and the state of the vertex pointed to then

$$\frac{d\rho_k(t)}{dt} = -\rho_k(t) + \lambda k[1 - \rho_k(t)]\theta(\lambda).$$

This will turn out to be a bad assumption but it is needed to conclude that the equilibrium frequency $\rho_k$ satisfies

$$0 = -\rho_k + \lambda k[1 - \rho_k]\theta(\lambda)$$

(5.3.1)

Solving and writing $\theta(\lambda)$ simply as $\theta$ we have

$$\rho_k = \frac{k\lambda\theta}{1 + k\lambda\theta}$$
Suppose $p_k$ is the degree distribution in the graph. The probability that a given link points to a vertex of degree $k$ is the size-biased degree distribution $q_k = k p_k / \mu$ where $\mu = \sum_j j p_j$, so we have the following self-consistent equation for $\theta$:

$$
\theta = \sum_k q_k \rho_k = \sum_k q_k \frac{k \lambda \theta}{1 + k \lambda \theta}
$$

(5.3.2)

Once $\theta$ is computed we can compute the fraction of occupied sites from

$$
\rho = \sum_k p_k \frac{k \lambda \theta}{1 + k \lambda \theta}
$$

(5.3.3)

To reduce the problem to computing $\theta$ we begin by noting that in all of the examples we will consider $\mu = \sum_k k p k < \infty$. In examples the critical value $\lambda_c$ may be 0 or positive, but in all cases $\theta(\lambda) \downarrow 0$ as $\lambda \to \lambda_c$. Using the dominated convergence theorem

$$
\rho(\lambda) = \lambda \theta \sum_k k p_k \frac{1}{1 + k \lambda \theta} \sim \lambda \theta(\lambda) \mu
$$

(5.3.4)

Analysis of (5.3.2), which we are about to describe in some detail, suggests the following conjectures about the contact process on power law graph with degree distribution $p_k \sim C k^{-\alpha}$. Here $\beta$ is the critical exponent for the equilibrium density $\rho(\lambda) \approx (\lambda - \lambda_c)^\beta$ as $\lambda \downarrow \lambda_c$.

- If $\alpha \leq 3$ then $\lambda_c = 0$
- If $3 < \alpha < 4$, $\lambda_c > 0$ but the critical exponent $\beta > 1$
- If $\alpha > 4$ then $\lambda_c > 0$ and $\rho(\lambda) \sim C(\lambda - \lambda_c)^1$ so $\beta = 1$.

In Section 1.8 we defined $\beta$ and other exponents associated with the phase transition in Erdős-Rényi graphs. In Section 2.7 we computed the exponent $\beta$ associated with the percolation phase transition in power-law graphs generated by the configuration model. The results presented there in the table after Theorem 2.7.1 are closely related to the ones we will find here. See Figure 5.3.

The results depend on the power $\alpha$ in the degree distribution so our discussion is organized by its value. For reasons that will become clear in the discussion we have abandoned our usual $\gamma$ and will denote the power law by $\alpha$. We begin in the middle of the range of values.

$\alpha = 3$

Since we are following in the footsteps of physicists, we will use the continuous approximation $p(x) = 2 / x^3$ for $x \geq 1$, and enjoy the fact that it simplifies computations. The size biased distribution has $q(x) = 1 / x^2$ for $x \geq 1$ and (5.3.2) becomes

$$
\theta = \int_1^\infty \frac{1}{x} \cdot \frac{\lambda \theta}{1 + \lambda \theta x} \, dx = \int_1^\infty \frac{\lambda \theta}{x} + \frac{\lambda \theta}{x} \left( \frac{1}{1 + \lambda \theta x} - 1 \right) \, dx
$$

$$
= \int_1^\infty \frac{\lambda \theta}{x} - \frac{(\lambda \theta)^2}{1 + \lambda \theta x} \, dx
$$
The two parts of the last integrand are not integrable separately, but if we replace the upper limit of $\infty$ by $M$ the integral is
\[
\lambda \theta \log M - \lambda \theta \{\log(1 + \lambda \theta M) - \log(1 + \lambda \theta)\}
\]
\[
= -\lambda \theta \log(\lambda \theta + 1/M) + \lambda \theta \log(1 + \lambda \theta)
\]
so letting $M \to \infty$ the integral is
\[
-\lambda \theta \left[ (\log(\lambda \theta) - \log(1 + \lambda \theta)) \right] = \lambda \theta \log \left( 1 + \frac{1}{\lambda \theta} \right)
\]
The equation we want to solve is $1 = \lambda \log(1 + 1/\lambda \theta)$. Dividing by $\lambda$ and exponentiating
\[
e^{1/\lambda} = 1 + \frac{1}{\lambda \theta}
\]
Solving for $\theta$ now we have
\[
\theta(\lambda) = \frac{1}{\lambda(e^{1/\lambda} - 1)} = (1/\lambda)e^{-1/\lambda}(1 - e^{-1/\lambda})^{-1} \quad (5.3.5)
\]
Using (5.3.4) and dropping constants
\[
\rho(\lambda) \sim \lambda \theta(\lambda) \approx e^{-1/\lambda}
\]
Notice that $\rho(\lambda) \to 0$ exponentially fast. This agrees with the result for percolation on graphs but with $p_k \sim C k^{-3}$ in Section 2.7 but as we will see later in Figure 5.3 it is not accurate for the contact process.

$2 < \alpha < 3$

In this and future examples, we will let

the degree distribution be $p(x) = (1 + \gamma)x^{-2-\gamma}$ for $x \geq 1$

so the size biased distribution is $q(x) = \gamma x^{-1-\gamma}$.

In the new notation $2 < \alpha < 3$ is $0 < \gamma < 1$ and (5.3.2) becomes
\[
1 = \int_1^{\infty} \frac{\gamma}{x^\gamma} \cdot \frac{\lambda}{1 + \lambda \theta x} \, dx \equiv F(\lambda, \theta)
\]
$\theta \to F(\lambda, \theta)$ a decreasing function of $\theta$ that is $\infty$ when $\theta = 0$ and $\to 0$ when $\theta \to \infty$, so we know there is a unique solution. Changing variables $x = u/\lambda \theta$, $dx = du/(\lambda \theta)$ we have
\[
1 = \lambda^{\gamma \theta^{\gamma-1}} \int_{1/\lambda \theta}^{\infty} \gamma u^{-\gamma} \frac{1}{1 + u} \, du
\]
Since $\gamma < 1$ the integral on the right has a limit $c_\gamma$ as $\lambda \theta \to 0$. Rearranging we have
\[
\theta \sim C \lambda^{\gamma/(1-\gamma)} \quad (5.3.6)
\]
Using (5.3.4) the fraction of occupied sites
\[
\rho(\lambda) \sim C' \lambda^{1/(1-\gamma)} \quad (5.3.7)
\]
5.3. POWER-LAW RANDOM GRAPHS

$\alpha > 3$

In the new notation this case is $\gamma > 1$ and (5.3.2) becomes

$$1 = \int_1^\infty \frac{\gamma}{x^\gamma} \cdot \frac{\lambda}{1 + \lambda \theta x} \, dx$$

(5.3.8)

However, now the integral converges when $\theta = 0$, so for a solution to exist we must have

$$F(\lambda, 0) = \int_1^\infty \frac{\lambda^\gamma}{x^\gamma} \, dx > 1 \quad \text{or} \quad \lambda > \lambda_c$$

For fixed $\lambda > \lambda_c$ we want to solve $F(\lambda, \theta(\lambda)) = 1$. If $\lambda > \lambda_c$, $F(\lambda, 0) = \lambda/\lambda_c > 1$. To find the point where $F(\lambda, \theta)$ crosses 1 we begin by noting that

$$\frac{\partial F}{\partial \theta} = - \int_1^\infty \frac{\lambda^2 x}{x^\gamma (1 + \lambda \theta x)^2} \, dx.$$  

(5.3.9)

When $\gamma \leq 2$, $\partial F/\partial \theta \to \infty$ as $\theta \to 0$ so we will begin with the case $\gamma > 2$ where

$$\frac{\partial F}{\partial \theta}(0) = -b_{\gamma, \lambda}$$

so we have

$$1 - \frac{\lambda}{\lambda_c} = F(\lambda, \theta(\lambda)) - F(\lambda, 0) \sim -b_{\gamma, \lambda} \theta(\lambda)$$

and it follows that

$$\theta(\lambda) \sim \frac{\lambda - \lambda_c}{\lambda_c b_{\gamma, \lambda}}$$

(5.3.10)

Using (5.3.4) we conclude

$$\rho(\lambda) \sim C(\lambda - \lambda_c) \quad \text{as} \ \lambda \to \lambda_c.$$  

(5.3.11)

Turning now to $\gamma < 2$, changing variables $y/\theta = x$ (5.3.9) becomes

$$- \int_\theta^\infty \frac{\gamma \theta^\gamma}{y^\gamma (1 + \lambda y)^2} \, \frac{dy}{\theta} \sim -\theta^{-2} \int_0^\infty \frac{\lambda^2}{y^{\gamma+1} (1 + \lambda y)^2} \, dy$$

Writing $c_{\gamma, \lambda}$ for the integral (which is finite) and integrating

$$1 - \frac{\lambda}{\lambda_c} = F(\lambda, \theta(\lambda)) - F(\lambda, 0) \sim -c_{\gamma, \lambda} \theta^{\gamma-1}/(\gamma - 1)$$

Rearranging

$$\theta(\lambda) \sim C(\lambda - \lambda_c)^{1/(\gamma-1)}$$

Using (5.3.4) we conclude the for $3 < \lambda < 4$

$$\rho(\lambda) \sim C(\lambda - \lambda_c) \quad \text{as} \ \lambda \to \lambda_c.$$  

(5.3.12)
Rigorous results

The first result about the long time survival of the contact process was proved by Berger, Borgs, Chayes, and Saberi in 2005. They considered the preferential attachment model which has a power law with $\alpha = 3$, so when they proved that $\lambda_c = 0$ they confirmed the physicists’ prediction. Chatterjee and Durrett showed in 2009 that $\lambda_c > 0$ is not correct when $\alpha > 3$.

**Theorem 5.3.1.** Consider a graph $G_n$ with $n$ vertices generated by the configuration model with $P(d_i = k) \sim Ck^{-\alpha}$ with $\alpha > 3$ and $P(d_i \leq 2) = 0$. Let $\xi^1_t$, $t \geq 0$ denote the contact process on $G_n$ starting from all sites occupied. Then for any $\lambda > 0$ there is a positive constant $p(\lambda) > 0$ so that for any $\delta > 0$

$$
\inf_{t \leq \exp(n^{-\delta})} P(\xi^1_t/n \leq p(\lambda)) \to 1 \quad \text{as } n \to \infty.
$$

Sections 5.4 and 5.5 are devoted to the proof of this result.

![Figure 5.3](image_url)

Figure 5.3: Mean field critical exponents (solid line) versus rigorous results (dashed line) given in (5.3.13) as $\alpha$ varies from 2 to 4.5.

In 2013 Mountford, Valesin, and Yao extended the results of Chatterjee and Durrett to include $2 < \alpha \leq 3$ and proved upper and lower bounds that had the same dependence on $\lambda$ but different constants, showing that

$$
\rho(\lambda) \sim \begin{cases} 
\lambda^{1/(3-\alpha)} & 2 < a \leq 5/2 \\
\lambda^{2a-3} \log_2^{2-a}(1/\lambda) & 5/2 < a \leq 3 \\
\lambda^{2a-3} \log_4^{4-2a}(1/\lambda) & 3 < a
\end{cases}
$$

(5.3.13)
5.4. RESULTS FOR THE STAR GRAPH

The result for $2 < \alpha \leq 5/2$ agrees with the mean-field calculations quoted above but that formula is claimed to hold for $2 < \alpha < 3$. Figure 5.3 gives a visual comparison of the mean-field and rigorous results for critical exponents. For more about why the change occurs at $5/2$ see the 2013 paper cited above. Three years later, Mountford, Mourrat, Valesin, and Yao (2016) showed that for all $\lambda > 0$, there exists some $c > 0$ so that the survival time $\geq e^{cn}$ with high probability.

5.4 Results for the star graph

Let $G_k$ be a star graph with center 0 and leaves 1, 2, \ldots, $k$ and let $\xi_t$ be set of vertices infected in the contact process at time $t$. Write the state $\xi_t$ as $(i, j)$ where $i$ is the number of infected leaves and $j = 1$ if the center is infected and $j = 0$ otherwise. We write $P_{i,j}$ for the law of the process starting from $(i, j)$.

Here, following the approach in Chatterjee and Durrett (2009), we will reduce to a discrete time one dimensional chain, and we will only look at times when $j = 1$. When the state is $(i, 0)$ with $i > 0$, the next event will occur after exponential time with mean $1/(i\lambda + i)$. The probability that it will be the reinfection of the center is $\lambda/(\lambda + 1)$. The probability it will be the recovery of a leaf is $1/(\lambda + 1)$. Thus, the number of leaf infections $N$ that will be lost while the center is healthy has a shifted geometric distribution with success probability $\lambda/(\lambda + 1)$, i.e.,

$$P(N = j) = \left(\frac{1}{\lambda + 1}\right)^j \cdot \frac{\lambda}{\lambda + 1} \quad \text{for } j \geq 0.$$  

Note that since this version of the geometric counts the number of failures before the first success

$$EN = \frac{\lambda + 1}{\lambda} - 1 = \frac{1}{\lambda}.$$  

The next step is to modify the chain so that the infection rate is 0 when the number of infected leaves is at least

$$L = pk \quad \text{where} \quad p = \lambda/(1 + 2\lambda). \quad (5.4.1)$$

To explain the choice of $p$ note that the number of infected leaves in the modified chain is always $\leq pk$ and the number of uninfected leaves is $\geq (1 - p)k$. Thus if we look at the embedded discrete time process for the contact process on the star and only look at times when the center is infected, the process dominates $Y_n$ where

- $Y_n \rightarrow Y_n - 1$ with prob $pk/D$
- $Y_n \rightarrow \min\{Y_n + 1, pk\}$ with prob $\lambda(1 - p)k/D$
- $Y_n \rightarrow Y_n - N$ with prob $1/D$

Here $N$ is independent of $Y_n$ and the denominator

$$D = pk + \lambda(1 - p)k + 1 \leq k + \lambda k + 1 \leq (2 + \lambda)k.$$
The fact that $Y_n$ has a reflecting barrier at $pk$ will simplify computations. We will use the process to lower bound survival times.

**Lemma 5.4.1.** Let $L = pk$ where $p = \lambda/(1 + 2\lambda)$. Let $e^\theta = 1/(1 + \lambda/2)$. If $k$ is large enough $e^{\theta Y_n}$ is a supermartingale while $Y_n \in (0, pk)$.

**Proof.** We begin by noting that

$$E(\exp(\theta Y_{n+1}) - \exp(\theta Y_n) | Y_n = y) = e^{\theta y}(e^\theta - 1)(1 - p)k/D$$

$$+ e^\theta(e^{-\theta} - 1)pk/D + \frac{e^{\theta y}}{D} \left[ \sum_{j=0}^{\infty} \left( \frac{e^{-\theta}}{1 + \lambda} \right)^j \left( \frac{\lambda}{1 + \lambda} \right) - 1 \right].$$

The term in square brackets is

$$\frac{1}{1 - e^{-\theta}/(1 + \lambda)} \cdot \frac{\lambda}{1 + \lambda} - 1 = \frac{\lambda}{1 + \lambda - e^{-\theta} - 1} = \frac{e^{-\theta} - 1}{1 + \lambda - e^{-\theta}} \geq 0.$$

Note that this implies we must take $e^{-\theta} < 1 + \lambda$.

The first two terms are

$$\frac{e^{\theta y}k}{D} \left( (e^\theta - 1)\lambda(1 - p) + (e^{-\theta} - 1)p \right),$$

so we begin by solving

$$(e^\theta - 1)\lambda(1 - p) + (e^{-\theta} - 1)p = 0.$$

Rearranging and setting $x = e^\theta$ we want

$$x^2\lambda(1 - p) - [\lambda(1 - p) + p]x + p = 0.$$

Factoring we have

$$(\lambda(1 - p)x - p)(x - 1) = 0.$$ 

Since $p = \lambda/(1 + 2\lambda)$ the smaller root is

$$\frac{p}{\lambda(1 - p)} = \frac{\lambda/(1 + 2\lambda)}{\lambda(1 + \lambda)/(1 + 2\lambda)} = \frac{1}{1 + \lambda}.$$

We let $e^\theta = 1/(1 + \lambda/2) \in (1/(1 + \lambda), 1)$ so that there is a $\delta > 0$ with

$$e^\theta \lambda(1 - p) + e^{-\theta} p = [\lambda(1 - p) + p] - \delta$$

and hence

$$(e^\theta - 1)\lambda(1 - p)k + (e^{-\theta} - 1)pk + \frac{e^{-\theta} - 1}{1 + \lambda - e^{-\theta}} = -\delta k + \frac{e^{-\theta} - 1}{1 + \lambda - e^{-\theta}}.$$

From this we see that if $k$ is large enough $e^{\theta Y_n}$ is a supermartingale while $Y_n \in (0, pk)$.  \qed
5.4. RESULTS FOR THE STAR GRAPH

Let $T_\ell^- = \inf\{n : Y_n \leq \ell\}$ and let $T_m^+ = \inf\{n : Y_n \geq m\}$.

**Lemma 5.4.2.** Let $a, b \in (0, L)$. If $b < a$ then

$$P_a(T_b^- < T_L^+) \leq (1 + \lambda/2)^{b-a}.$$ 

*Proof.* To estimate the hitting probability let $\phi(x) = \exp(\theta x)$ where we take $e^\theta = 1/(1 + \lambda/2)$ and note that if $\tau = T_b^- \wedge T_L^+$ then $\phi(Y(t \wedge \tau))$ is a supermartingale. Let $q = P_a(T_b^- < T_L^+)$. Using the optional stopping theorem we have

$$q\phi(Y_b^-) + (1-q)\phi(Y_L^+) \leq \phi(a).$$

It is possible that $Y_b^- < b$. Note that since $\theta < 0$, we have $\phi(x) \geq \phi(b)$ for $x \leq b$. Hence,

$$q\phi(b) + (1-q)\phi(L) \leq \phi(a).$$

Dropping the second term on the left, $q \leq \phi(a)/\phi(b) = (1 + \lambda/2)^{b-a}$, which completes the proof. \qed

**Lemma 5.4.3.** If $R_L = \inf\{n > T_{L-1}^- : Y_n = L\}$ and $b \in [0, L)$ then

$$P_L(T_b^- < R_L) \leq (2 + \lambda)(1 + \lambda/2)^{b-L}.$$ 

**Remark.** Here, and in later lemmas, the computation of explicit constants is somewhat annoying. However, when we consider asymptotics for critical values, $\lambda$ will go to 0, so we will need to know how the constants depend on $\lambda$.

*Proof.* To compute the left-hand side we break things down according to the first jump. The definition of $R_L$ allows us to ignore the attempted upward jumps that do nothing. Recall that $L = pk$. The jump is to $L-1$ with probability $pk/(pk+1)$ and to $L-j$ with probability $\frac{\lambda}{(1+\lambda)^{j+1}} \cdot \frac{1}{1+pk}$. In the first case the probability of returning to $L$ before going below $b$ is

$$\leq (1 + \lambda/2)^{b-(L-1)} = (1 + \lambda/2) \cdot (1 + \lambda/2)^{b-L}.$$ 

In the second we have to sum over the possible values of $L-j$. Using Lemma 5.4.2

$$\leq (1 + \lambda/2)^{b-L} \sum_{j=1}^{\infty} \frac{\lambda}{(1+\lambda)^{j+1}} (1 + \lambda/2)^j + \frac{\lambda}{1+\lambda} P_L(T_b^- < R_L)$$

$$\leq (1 + \lambda/2)^{b-L} \frac{\lambda}{\lambda + 1} \cdot \sum_{j=0}^{\infty} \left(1 + \frac{\lambda/2}{1+\lambda}\right)^j + \frac{\lambda}{1+\lambda} P_L(T_b^- < R_L)$$

$$= 2(1 + \lambda/2)^{b-L} + \frac{\lambda}{1+\lambda} P_L(T_b^- < R_L).$$
CHAPTER 5. CONTACT PROCESS

Noting that \( \max\{2, 1 + \lambda/2\} \leq 2(1 + \lambda/2) - \delta \) for some small \( \delta < \lambda \), we have the following relation,

\[
P_L(T_b^- < R_L) \leq \frac{\lambda}{(1 + \lambda)(1 + pk)} P_L(T_b^- < R_L) + (2 + \lambda - \delta)(1 + \lambda/2)^{b-L}.
\]

Hence for \( k \) sufficiently large, we have

\[
P_L(T_b^- < R_L) \leq (2 + \lambda)(1 + \lambda/2)^{b-L}.
\]

**Lemma 5.4.4.** Let \( b = \epsilon L \) and \( S = \frac{1}{(2+\lambda)2k} (1 + \lambda/2)^{L(1-2\epsilon)} \)

\[
P(L,1) \left( \inf_{t \leq S} \xi_t \leq b \right) \leq (3 + \lambda)(1 + \lambda/2)^{-L\epsilon}.
\]

**Proof.** Let \( M = (1 + \lambda/2)^{L(1-2\epsilon)} \). By Lemma 5.4.3 the probability that the chain fails to return \( M \) times to \( L \) before going below \( \epsilon L \) is

\[
\leq (2 + \lambda)(1 + \lambda/2)^{-L\epsilon}.
\]

Using Chebyshev’s inequality on the sum \( S_M \) of \( M \) exponentials with mean 1 (and hence variance 1),

\[
P(S_M < M/2) \leq 4/M.
\]

When the number of infected leaves is \( \leq L \) maximum jump rate is \( D \leq (2 + \lambda)k \) so

\[
P \left( \frac{S_M}{(2 + \lambda)k} \leq \frac{(1 + \lambda/2)^{L(1-2\epsilon)}}{2(2 + \lambda)k} \right) \leq 4(1 + \lambda/2)^{-L(1-2\epsilon)}.
\]

Adding up the error probabilities completes the proof.

Up to this point we have shown that if a star has \( L \) infected leaves it will remain infected for a long time. To make this useful, we need estimates about what happens when the star starts with only the center infected.

**Lemma 5.4.5.** Let \( \lambda > 0 \) be fixed and \( K = \lambda k^{1/3} \). Then for large \( k \)

\[
P_{0,1}(T_K^+ > T_{0,0}) \leq 2\lambda k^{-1/3},
\]

\[
P_{K,1}(T_{0,0} < T_K^+) \leq k^{-1/3},
\]

\[
E_{0,1}(T_L^+ | T_L^+ < T_{0,0}) \leq 2/\lambda.
\]

**Proof.** Clearly

\[
P_{0,1}(T_K^+ < T_{0,0}) \geq \prod_{j=0}^{K-1} \frac{(k - j)\lambda}{1 + (k - j)\lambda + j}
\]
so subtracting the last inequality from 1 = \prod_{j=0}^{K-1} 1 and using Lemma 3.4.3 from PTE5

\[ P_{0,1}(T_K^+ > T_{0,0}) \leq \sum_{j=0}^{K-1} \frac{1 + j}{(k - j)\lambda} \leq \frac{\lambda^2 k^{2/3}}{(k - \lambda k^{1/3})\lambda} \leq 2\lambda k^{-1/3}. \]

For the second result we use the supermartingale \( e^{\theta Y_n} \) from Lemma 5.5.2. If \( q = P_{K,1}(T_{0,0} < T_L^+) \), using optional stopping theorem we have

\[ q \cdot 1 + (1 - q)e^{\theta L} \leq e^{\theta K}. \]

Dropping the second term on the left,

\[ q \leq e^{\theta K} = (1 + \lambda/2)^{-K} \leq k^{-1/3}. \]

To bound the time we return to continuous time

\[
\begin{align*}
\text{jump} & \quad \text{at rate} \\
Y_t & \rightarrow Y_t - 1 \quad pk \\
Y_t & \rightarrow \min\{Y_t + 1, pk\} \quad \lambda(1 - p)k \\
Y_t & \rightarrow Y_t - N \quad 1
\end{align*}
\]

Before time \( V_L = T_{0,0} \land T_L^+ \) the drift of \( Y_t \) is at least

\[ \mu = \lambda(1 - p)k - pk - 1/\lambda = \lambda pk - 1/\lambda \quad (5.4.3) \]

so \( Y_t - \mu t \) is a submartingale. Stopping this martingale at the bounded stopping time \( V_L \land t \)

\[ E(Y(V_L \land t) - \mu E(V_L \land t) \geq EY_0 \geq 0. \]

Since \( EY(V_L \land t) \leq L \), it follows that

\[ E(V_L \land t) \leq \frac{L}{\mu} = \frac{pk}{\lambda pk - 1/\lambda}, \]

where \( p = \lambda/(1 + 2\lambda) \), so if \( \lambda \) is fixed and \( k \) is large

\[ E(V_L \land t) \leq 2/\lambda \]

which completes the proof. \( \square \)

Combining Lemmas 5.4.4 and 5.4.5 we have the following

**Lemma 5.4.6.** Let \( A_t \) denote the number of infected leaves at time \( t \) and take \( S \) as in Lemma 5.4.4. Define \( G = \{ \inf_{k^{2/3} \leq t \leq S} |A_t| \geq \epsilon L \} \). If \( \lambda > 0 \) is fixed

\[ P_{0,1}(G) \geq 1 - C_\lambda k^{-1/3} \quad (5.4.4) \]

for some constant \( C_\lambda \).

When \( G \) occurs, we say the star at 0 is good.
5.5 Subexponential degree distributions

Given an offspring distribution $p_k$, we construct a Galton-Watson tree as follows. Starting with the root, each individual has $k$ children with probability $p_k$. Pemantle (1992) has shown in his Theorem 3.2 that

**Theorem 5.5.1.** There are constants $c_2$ and $c_3$ so that if $\mu > 1$ is the mean of the offspring distribution, then for any $k > 1$, if we let $r_k = \max\{2, c_2 \log(1/kp_k)/\mu\}$.

$$\lambda_2 < c_3 \sqrt{r_k \log r_k \log(k)/k}. \quad (5.5.1)$$

If the offspring distribution is a stretched exponential $p_k = c_\gamma \exp(-k^\gamma)$ with $\gamma < 1$ then

$$\log(1/kp_k) \sim k^\gamma$$

and hence $\lambda_2 = 0$.

Huang and Durrett (2020a) extended the last result to subexponential distributions, which satisfy

$$\limsup_{k \to \infty} (1/k) \log p_k = 0.$$

**Theorem 5.5.2.** If the offspring distribution $p_k$ for a Galton-Watson tree is subexponential and has mean $\mu > 1$ then $\lambda_2 = 0$.

This result was proved as a consequence of their study of the case in which degrees have a geometric distribution. $p_k = (1 - p)^{k-1}p$ for $k \geq 1$. The goal of their paper was to prove that $\lambda_1 > 0$. The solution of that problem will be described in the next section. The upper bound on $\lambda_1$ is easy.

**Theorem 5.5.3.** $\lambda_1 \leq p/(1 - p)$.

**Proof.** Modify the contact process so that births from a site can only occur on sites further from the root. Each vertex $x$ will be occupied at most once. If $x$ is occupied then it will give birth with probability $\lambda/(\lambda + 1)$ onto each neighbor $y$. The birth events are not independent but that is not important. If we let $Z_n$ be the number of sites at distance $n$ that are ever occupied, $Z_n$ is a branching process in which the offspring distribution has mean $\lambda/((\lambda + 1)\cdot p)$ which is $> 1$ if $\lambda > p/(1 - p)$.

When $p_k = (1 - p)^{k-1}p$, $\log(1/kp_k) \sim c_p k$, so (5.5.1) gives a finite upper bound on $\lambda_2$. However, the resulting bound is much worse than the following:

**Theorem 5.5.4.** If $p_k = 2^{-k}$ for $k \geq 1$, then $\lambda_2 \leq 2.5$.

The proof works for a general geometric $p_k = (1 - p)^{k-1}p$, $k \geq 1$. Huang and Durrett (2020a) could not get a nice formula for the upper bound as a function of $p$ but the upper bounds can easily be computed numerically and graphed. These upper bounds are only interesting for small $p$. A Galton-Watson tree with $p_0 = 0$ and $p_1 < 1$ contains a copy of $\mathbb{Z}$ (start with a vertex with two children and follow their descendants) so using the bound on $\lambda_e(\mathbb{Z})$ proved in Liggett (1995) we conclude $\lambda_2 \leq 2$ for all $0 < p < 1$. 

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Figure 5.4: Upper bounds on $\lambda_1$ (dotted line) from Theorem 5.5.4 and on $\lambda_2$ (solid line) from (5.5.4) as a function of $p$ for the geometric degree distribution. The horizontal line is the bound that comes from using the existence of a copy of $Z$ in the graph.

**Proof** for $p_n = 2^{-n}$, $n \geq 1$. Our proof follows the outline of the proof of Theorem 3.2 in Pemantle (1992), see pages 2109–2110. We can suppose without loss of generality that the root has degree $k$. Otherwise examine the children of the root until we find one with degree $k$ and apply the argument to the children of this vertex. There are two steps in the proof.

1. Push the infection to vertices at a distance $r = k$ that have degree $k$.

2. Bring the infection back to the root at time $t$ using Lemma 5.5.6.

To push the infection we use the following results.

**Lemma 5.5.5.** Let $v_0, v_1, \ldots, v_r$ be a path in a graph. Suppose that $v_0$ is infected at time 0 and that it is good in the sense of Lemma 5.4.6. Then there is a $\gamma > 0$ so that the probability that $v_r$ will become infected by time $2r$ is

$$\geq \left( \frac{\lambda}{\lambda + 1} \right)^r (1 - \exp(-\gamma r)).$$

If $\epsilon > 0$ and we let $\hat{\lambda} = (1 - \epsilon)\lambda/(\lambda + 1)$ then for large $r$ this probability is $\geq \hat{\lambda}^r$.

**Proof.** The probability that $v_{i-1}$ infects $v_i$ before it is cured is $\lambda/(1 + \lambda)$. When this transfer of infection occurs the amount of time is $t_i$, which is an independent exponential with rate $1 + \lambda$. By large deviations for the exponential distribution $P(t_1 + \cdots + t_r > 2r) \leq e^{-\gamma r}$ for some $\gamma > 0$. 

\qed
Lemma 5.5.6. Run the contact process on a graph consisting of a star with \( k \) leaves, to which there has been added a single chain \( v_1, \ldots, v_r \) of length \( r \) where \( v_1 \) is a neighbor of 0, the center of the star. Suppose that at time 0 there are \( L \) infected leaves. For large \( r \) the probability that \( v_r \) will not be infected before time \( T = m(2r + 1) \) is

\[
\leq (1 - \lambda^r)^m.
\]

Proof. Consider a sequence of times \( t_i = (2r + 1)i \) for \( i \geq 1 \). The center 0 may not be infected at time \( t_i \) but since the star at 0 is good the number of infected neighbors is \( \geq \epsilon L \) and it will with high probability be infected by time \( t_i + 1 \). By Lemma 5.5.5 the probability \( v_r \) is successfully infected in \( [t_i, t_i+1) \) is \( \geq \lambda^r \) when 0 is good, even if we condition on the events up to time \( t_i \). The desired result follows.

To use the two lemmas to prove the main result we need the next weird but wonderful result, which is Lemma 2.4 from Pemantle (1992). Let \( \varphi(x) = \sum_{n=0}^{\infty} p_n x^n \) be the generating function of the degree distribution. We will apply Lemma 5.5.7 to \( f(t) = P(0 \in \xi_t) \geq p_k P(0 \in \xi_t | 0 \text{ has at least } k \text{ children}) \).

Lemma 5.5.7. Let \( H \) be any nondecreasing function on the nonnegative reals with \( H(x) \geq x \) when \( x \in [0, x_0] \). If \( f \) satisfies (i) \( \inf_{0 \leq t \leq L} f(t) > 0 \) and (ii) \( f(t) \geq H(\inf_{0 \leq s \leq t-L} f(s)) \) for \( t \geq L \) some \( L > 0 \) then \( \lim \inf_{t \to \infty} f(t) > 0 \).

Proof. For any \( t_0 \) and \( \epsilon > 0 \), (ii) implies that there is a decreasing sequence \( t_i \) with \( t_{i+1} \leq t_i - L \) and \( t_k < L \) for some \( k \)

\[
f(t_i) \geq H(f(t_{i+1})) - \epsilon 2^{-i}.
\]

If \( f(t_i) < x_0 \) for all \( 1 \leq i \leq k \) then

\[
f(t_i) \geq f(t_{i+1}) - \epsilon 2^{-i}
\]

and summing gives \( f(t_0) > f(t_k) - \epsilon \) which gives the desired result. Suppose now that \( j \) is the smallest index with \( f(t_j) > x_0 \). If \( j = 0 \) we have \( f(t_0) > x_0 \). If \( j = 1 \) we have \( f(t_0) \geq H(x_0) \).

If \( j \geq 2 \) we have

\[
f(t_0) \geq f(t_{j-1}) - \epsilon \geq H(x_0) - \epsilon
\]

so in all cases we get the desired conclusion.

Step 1. The mean of the offspring distribution is 2. Let \( Z_r \) be the number of vertices at distance \( r \) from 0 and let \( v_1^r, \ldots, v_J^r \) be the subset of those that have exactly \( k \) children, where \( J \) is a random variable that represents the number of such vertices.

Since the root has degree \( k \) and \( p_k = 2^{-k} \) if we set \( r = k \)

\[
EJ \geq k \mu^{r-1} p_k = k/2,
\]
where $\mu = 2$ is the mean offspring number.

If we condition on the value of $W = Z_r/\langle k \mu^{r-1} \rangle$ and let $\mathcal{J} = (J|W)$ be the conditional distribution of $J$ given $W$ then

$$\mathcal{J} = \text{Binomial}(k2^{r-1}W, 2^{-k}).$$

Let $M$ be the random number of vertices among $v_r^1, \ldots, v_r^J$ that are infected before time

$$S = \frac{1}{2k(2 + \lambda)}(1 + \lambda/2)^{L(1-2\epsilon)}.$$

By Lemma 5.5.6 the probability a given vertex will not become infected by time $S$ is

$$p_{\text{noi}} \leq (1 - \hat{\lambda}^k)^m \quad \text{where} \quad \hat{\lambda} = (1 - \epsilon)\frac{\lambda}{\lambda + 1} \quad \text{and}$$

$$m = \frac{S}{2k + 1} = \frac{(1 + \lambda/2)^{L(1-2\epsilon)}}{2k(2k + 1)(2 + \lambda)} \quad \text{with} \quad L = \frac{\lambda k}{1 + 2\lambda}.$$

Combining the definitions and using $(1 - x) \leq e^{-x}$ we have

$$p_{\text{noi}} \leq \exp \left( -\frac{\Gamma^k}{2k(2k + 1)(2 + \lambda)} \right) \quad \text{where} \quad \Gamma = \hat{\lambda}(1 + \lambda/2)^{(1-2\epsilon)\lambda/(1+2\lambda)}.$$

When $\lambda = 2.5$

$$\frac{\lambda}{\lambda + 1} (1 + \lambda/2)^{\lambda/(1+2\lambda)} = 1.0014 > 1,$$

so $\Gamma > 1$ when $\epsilon$ is small and $p_{\text{noi}} \to 0$ as $k \to \infty$. From this we see that if $\delta > 0$ then for large $k$

$$E M \geq (1 - \delta)EJ.$$

The remark after Lemma 5.5.6 implies that if we condition on the value of $W$ and let $\widetilde{M} = (M|W)$ then

$$\widetilde{M} \geq \text{Binomial}(k2^{r-1}W, 2^{-k}(1 - \delta)).$$

To prepare for the following two generalizations of the result for Geometric(1/2) offspring distribution we ask the reader to verify that in Step 2, all we use is the fact that (5.5.2) implies the bounds on $EM$ and $\widetilde{M}$.

**Step 2.** Let $H_1(t) = P(v_r^i \in \xi_{t-S} \text{ for some } 1 \leq i \leq J)$ and

$$H_2(t) = P(0 \in \xi_t|v_r^i \in \xi_{t-S} \text{ for some } 1 \leq i \leq J),$$

so that $f(t) \geq H_1(t)H_2(t)$. Fix $t > 2S$ and let

$$\chi(t) = \inf\{ f(s) : s \leq t - S \}.$$

Since $t$ is fixed, we simplify the notation and write $\chi(t)$ as $\chi$. 
CHAPTER 5. CONTACT PROCESS

Ignore all but the first infection of each \( v_r \) by its parent. Any of these will evolve independently from the time \( s < S \) it is first infected, and will be infected at time \( t - S \) with probability at least \( \chi \). Thus given \( M \) the number of infected sites at time \( t - S \) will dominate \( N = \text{binomial}(M, \chi) \). If we let \( \bar{N} = \text{binomial}(M, \chi) \) and let \( \delta > 0 \), then by Lemma 2.3 in Pemantle (1992) we see that there exists a \( \epsilon > 0 \) such that

\[
P(\bar{N} \geq 1) \geq (1 - \delta)\chi EM \land \epsilon
\]

Therefore \( H_1(t) \geq (1 - \delta)\chi EM \land \epsilon \) when \( t > 2S \).

Finally, if some \( v_r \) is infected at time \( t - S \) then the probability of finding 0 infected at time \( t \) is bounded below by \( \rho_1 \rho_2 \) where

- \( \rho_1 \) is the probability that the contact process starting with only \( v_r \) infected at time \( t - S \) infects 0 at some time \( s \) with \( t - S \leq s \leq t \). By Lemmas 5.4.5, 5.4.6, and 5.5.6, \( \rho_1 \geq 1 - \delta \).

- \( \rho_2 \) is the probability 0 is infected at time \( t \) given the infection of 0 at such a time \( s \). For any \( \epsilon > 0 \), by Lemma 5.5.6 the probability that 0 has not been infected by time \( S/2 \) is less than \( \epsilon \) when \( k \) is sufficiently large. By Lemma 5.4.6, with probability \( \geq 1 - (2 + 2\lambda)k^{-1/3} \) there should be at least \( \epsilon L \) infected leaves at time \( t - \epsilon \). Hence 0 is infected at \( t \) with probability at least \( (1 - e^{-\lambda^2 r})e^{-\epsilon} \), where the second term guarantees that the root is infected at time \( t \). Choosing \( \epsilon \) sufficiently small and \( k \) sufficiently large gives \( \rho_2 \geq 1 - \delta \).

Thus

\[
f(t) \geq \begin{cases} 
\chi(t)EM(1 - \delta)^3 \land \epsilon & t > 2S, \\
\inf_{0 \leq s \leq 2S} f(s) & S \leq t \leq 2S.
\end{cases}
\]

We can take \( \epsilon < \inf_{0 \leq s \leq 2S} f(s) \) so that \( f(t) \geq \chi(t)EM(1 - \delta)^3 \land \epsilon \) for all \( t \geq S \). The result now follows from Lemma 5.5.7 with \( L = S \) and \( H(x) = (1 - \delta)^3(EM)x \land \epsilon \).

**Proof for** \( p_n = (1 - p)^{n-1}p \). It is now straightforward to replace \( 1/2 \) by \( p \). We only have to pick \( k \) and \( r \) so that we can prove the analogue of (5.5.2). The mean of the offspring distribution is \( 1/p \). Let \( Z_r \) be the number of vertices at distance \( r \) from 0 and let \( v_r^1, \ldots, v_r^J \) be those that have exactly \( k \) children. Since the root has degree \( k \) and \( p_k = (1 - p)^{k-1}p \)

\[
EJ \geq k(1/p)^{r-1}(1 - p)^{k-1}p.
\]

(5.5.3)

In this case we want to pick \( r \) so that \( (1/p)^r(1 - p)^k \approx 1 \). Hence \( EJ \) can be large when \( k \) is large. Ignoring the fact that \( r \) and \( k \) must be integers this means

\[
r/k = \log(1 - p)/\log p.
\]

Let \( M \) be the random number of vertices among \( v_r^1, \ldots, v_r^J \) that are infected before time \( S \). By Lemma 5.5.6 the probability a given vertex will not become infected is

\[
\leq (1 - \lambda^r)^{[S/(2r+1)]} \leq \exp\left(-\frac{-\Gamma^k}{2k(2r+1)(2 + \lambda)}\right)
\]
where \( \Gamma = \hat{r}^{r/k}(1 + \lambda/2)^{(1-2\epsilon)\lambda/(1+2\lambda)} \). That is, if we choose \( \lambda \) such that
\[
\left( \frac{\lambda}{\lambda + 1} \right)^{r/k} \cdot (1 + \lambda/2)^{\lambda/(1+2\lambda)} > 1
\] (5.5.4)
then we have \( \Gamma > 1 \) for large \( k \). By the same reasoning as before this choice of \( \lambda \) gives an upper bound on \( \lambda_2 \).

If we want to graph the bound as a function of \( p \) it is better to work backwards. Given \( \lambda \) the second factor is \( > 1 \) so we can easily find the value of \( r/k \) that makes this 1. Having done this we can easily compute the value of \( p \) for which \( \lambda \) gives the upper bound on \( \lambda_2 \).

**Proof for subexponential distributions.** We suppose that the mean of the offspring distribution is \( \mu > 1 \). If \( p_k \) is subexponential, i.e.,
\[
\limsup_{k \to \infty} (1/k) \log p_k = 0,
\]
then for any \( \delta \) there is a \( k \) with \( p_k \geq (1 - \delta)^k \). It follows from the same reasoning as in (5.5.3) that we can take \( r \) such that
\[
\frac{r}{k} = \frac{-\log(1 - \delta)}{\log \mu}.
\]
Given any \( \lambda > 0 \), (5.5.4) will hold if \( \delta \) is small enough, which implies local survival of the process. Therefore \( \lambda_2 = 0 \).

### 5.6 Exponential tails

In the decade after my 2009 work with Shirshendu Chatterjee on the contact process on power law graphs, one of my favorite open problems was proving that the critical value for the contact process on a Galton-Watson tree is positive if the degree distribution \( D \) has an exponential tail, i.e., \( Ee^{\theta D} < \infty \) for some \( \theta > 0 \). I was so excited by this question that when I gave a talk at the Northeast Probability Seminar held in November 2018 I followed in Erdős’s footsteps and offered $1000 for a proof.

Danny Nam and Oanh Nguyen, two students of Allan Sly at Princeton, were in the audience and it was not long until in joint work with their advisor and Shankar Bhamidi of UNC the problem was solved. It is somewhat surprising that the proof is not very complicated. Ménard and Singh (2016) studied random geometric graphs in \( d \)-dimensions, graphs that are built by connecting points in a spatial Poisson process that are within distance \( R \). The proof that \( \lambda_c > 0 \) for these graphs, which was done by studying “cumulative merging on a weighted graph,” was arduous (and an impressive achievement).

In contrast, the BNNS proof is short and sweet. As the paper explains, there are two important new ideas:

(i) They modified the process by adding a new vertex above the root that is always infected. Recoveries at the root are not allowed unless all of the descendants of the root are healthy.
One might worry that this assumption gives away too much, but the approach has the advantage that while the root is infected then the subtrees below its descendants are independent and this greatly facilitates recursion.

(ii) The second, somewhat more technical, idea is to prove that the probability that the infection goes deeper than depth $h$ decays exponentially fast in $h$. See their Theorem 3.4 (Theorem 5.6.3 below). To see why this is useful the reader will need to wait to see it used in the proof. Here, and in what follows we use a dual numbering system which includes the numbers used in the paper.

Turning to the details, let $D$ be a distribution on the positive integers with an exponential tail, as defined above. Suppose that $ED > 1$ so that the Galton-Watson tree with this offspring distribution $GW(D)$ has positive probability of surviving forever.

**Theorem 5.6.1.** (Theorem 1) Suppose the degree distribution $D$ has an exponential tail. Then there is a $\lambda_0$ so that for $\lambda < \lambda_0$ the contact process starting from a single infection at the root dies out with probability 1.

### 5.6.1 Expected survival time

Let $L$ be a large positive integer, let $T_L$ denote the depth $L$ Galton-Watson tree and let $CP^\lambda(T_L; 1, \rho)$ be the contact process on $T_L$ in which initially there is one infected at $\rho$ and the other sites are healthy. The first of two main steps in the proof of Theorem 5.6.1 is to show:

**Theorem 5.6.2.** (Theorem 3.1) Let $R_L$ be the first time that $CP^\lambda(T_L; 1, \rho)$ reaches 0. There are constants $C$, which is $= e$, and $\lambda_0 > 0$ so that for any $\lambda \leq \lambda_0$, $ER_L \leq C$ for all integers $L$.

A **recursive equation.** As mentioned in (i) we add a new vertex $\rho^+$ as a parent of the root of the tree $\rho$ and set $\rho^+$ to be permanently infected. Since $\rho^+$ is always in state 1, we define the state space of the process to be $\{0, 1\}^{TL}$. Let $X_t$ be the contact process modified to have permanent infection at $\rho^+$ and let $\tilde{X}_t$ be $X_t$ further modified to not allow recovery at $\rho$ until none of its descendants are infected. Let $S_L$ be the time for $X_t$ to reach the all healthy state 0 and let $\tilde{S}_L$ be the time for $\tilde{X}_t$ to reach the all healthy state. The first event in $\tilde{X}_t$ is either

- **A.** $\rho$ recovers
- **B.** $\rho$ infects one of its children $v_i$

In case A, $\tilde{S}_L$ is the exponential(1) time it took for $\rho$ to recover. If the degree of the root $\rho$ is $D$ the probability of event A is $1/(1 + \lambda D)$. In case B, the evolution of the contact process on the subtrees $T_{\rho}$ are independent of each other until the time $\tilde{S}_L$ at which all of them are completely healthy. Let $X_t^\circ$ be the contact process on the union of the subtrees, which has initial state $1_{\rho}$ run until the time $\tilde{S}_L^\circ$ they are all completely healthy.
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At time $\tilde{S}_L^{\otimes}$ the process $\tilde{X}_t$ is again in state $1_\rho$. After a geometric number of returns to this state, we will finally achieve outcome $A$ so

$$E(\tilde{S}_L|T_L) = \sum_{k=0}^{\infty} \left( \frac{\lambda D}{1 + \lambda D} \right)^k \frac{1}{1 + \lambda D} \cdot \left[ (k+1) \cdot \frac{1}{1 + \lambda D} + kE(\tilde{S}^{\otimes}|T_{v_i}) \right]$$

(5.6.1)

where $|T_{v_i})$ is short for conditioning on all of the subtrees $1 \leq i \leq D$. The mean of the geometric($p$) distribution $\sum_{k=0}^{\infty} (1 - p)^k p(k+1) = 1/p$ so the above is

$$= (1 + \lambda D) \cdot \frac{1}{1 + \lambda D} + (1 + \lambda D - 1)E(\tilde{S}^{\otimes}|D)$$

which implies

$$E(\tilde{S}_L|D) = 1 + \lambda DE(\tilde{S}^{\otimes}|D)$$

(5.6.2)

Estimating $E(\tilde{S}^{\otimes}|D)$

We do this by relating this expected value to the stationary distribution of the root-added contact process, which, conditional on $T_L$, is irreducible on a finite state space and hence a unique stationary distribution. Let $\pi^D$ be the stationary distribution of the product chain $\mathbb{CP}_\rho^\otimes(T_L)$. If we let $\pi_i$ be the stationary distribution of $\mathbb{CP}_\rho^\lambda(T_i^+)$, where $T_i^+$ is $T_{v_i}$ with $\rho$ added as a permanently infected added root, then

$$\pi^D = \otimes_{i=1}^{D} \pi_i$$

For any state $\eta$ on $T_L - \{\rho\}$, $\pi^D(\eta)$ is proportional to the time that the chain $X_t^{\otimes} \sim \mathbb{CP}_\rho^\otimes(T_L)$ stays at state $\eta$. The expected time to stay at $0$ (conditional on $D$) is $(\lambda D)^{-1}$. After escaping from $0$ it spends expected time $E(\tilde{S}_L^{\otimes}|T_L)$ before returning to $0$. Therefore

$$\pi^D(0) = \frac{(\lambda D)^{-1}}{(\lambda D)^{-1} + E(\tilde{S}_L^{\otimes}|T_L)} = \frac{1}{1 + \lambda DE(\tilde{S}_L^{\otimes}|T_L)}$$
Similarly we have
\[ \pi_i(0) = \frac{1}{1 + \lambda E(S_{L-1} | T_{v_i})} \]
where \( S_{L-1} \) is the first time \( X_t \sim \mathbb{P}_\rho(T_{v_i}^+, 1_{v_i}) \) reaches state 0. Therefore we obtain
\[ 1 + \lambda D E(S_\circ | T_L) = \prod_{i=1}^D [1 + \lambda E(S_{L-1} | T_{v_i})] \tag{5.6.3} \]
Since \( T_{v_i}, i \geq 1 \) are i.i.d. \( GW(D)_{L-1} \) integrating out the randomness of \( T_{v_i}, i \geq 1 \) we have
\[ 1 + \lambda D E(S_\circ | D) = (1 + \lambda E(S_{L-1}))^D \]
Using \( 1 + x \leq e^x \) this becomes
\[ \leq \exp(\lambda E(S_{L-1})) \]
Using this with (5.6.2) we get
\[ E(S_L | D) \leq \exp(\lambda E(S_{L-1}) \cdot D) \]
and it follows that
\[ ES_L \leq E S_L \leq E_D[\exp(\lambda E(S_{L-1}) | D)] \tag{5.6.4} \]
To complete the proof now let \( c > 0 \) be so that \( M = E \exp(cD) < \infty \). Define \( K \) and \( \lambda \) so that
\[ K = e \cdot \max\{\log M, 1\}, \quad \lambda_0 = c/K \]
To prove Theorem 5.6.2 by induction note that \( ES_0 = 1 \) and suppose that \( ES_{L-1} \leq e \). If \( \lambda < \lambda_0 \) we have
\[ \gamma \equiv \frac{\lambda ES_{L-1}}{c} \leq \frac{\lambda_0 e}{c} = \frac{e}{K} < 1 \]
so using Jensen’s inequality
\[ E \exp(\gamma cD) \leq (E \exp(cD))^{\gamma} = M^\gamma = \exp(\log M \cdot (e/K)) \leq e \]
which completes the proof of Theorem 5.6.2.

### 5.6.2 Exponential decay of infection depth

We continue to use the notation introduced previously. Recall that \( T_L = GW(D) \) and \( T_L^+ \) is the graph obtained by adding a permanently infected vertex \( \rho^+ \) above the root. For each state \( \eta \) of the contact process on \( T_L \) define the depth of \( \eta \) to be
\[ r(\eta) = \max\{d(\rho^+, v) : \eta(v) = 1\} \]
with \( r(0) = 0 \). This definition is natural since \( \rho^+ \) will be permanently occupied. Consider the root added process \( X_t \sim \mathbb{P}_{\rho^+}(T_{L^+}^+, 1_{\rho^+}) \) and let \( S_t \) be the first time the process reaches 0. Let \( H = \max\{r(X_t) : t \in [0, S_L]\} \) be the maximum depth reached. The second main step in the proof of Theorem 5.6.1 is
Theorem 5.6.3. (Theorem 3.4) Let $L > 0$ be an integer. There are constants $K$, $\lambda_0 > 0$ depending only on the degree distribution $D$ so that for all $\lambda \leq \lambda_0$, $h > 0$ and $m > 0$ we have

$$P(H > h|T_L) \leq 2m(K\lambda)^h$$

for a collection of values of $T_L$ with probability $\geq 1 - m^{-1}$.

Delayed contact process

Let $\mathcal{S}^+$ be a finite graph rooted at $\rho^+$. We assume that the graph is finite so that the stationary distributions we define later in this paragraph will exist. Here we will only consider $\mathcal{S} = \mathcal{T}_L^+$, but the general notation saves some typing. Let $\mathcal{S} = \mathcal{S}^+ - \{\rho^+\}$. For any two states $\eta, \zeta \in \{0, 1\}^\mathcal{S}$ let $Q_{\eta,\zeta}$ be the transition rate from $\eta$ to $\zeta$ in $\mathbb{CP}_\rho^{\lambda}(\mathcal{S}^+)$. For a fixed constant $\theta \in (0, 1)$, the delayed contact process, denoted by $\mathbb{DP}_{\rho}^{\lambda,\theta}(\mathcal{S}^+, \eta_0)$ is the continuous time Markov process on $\{0, 1\}^\mathcal{S}$ with initial state $\eta_0$ and transition rate

$$Q_{\eta,\zeta}^\theta = \theta^r(\eta)Q_{\eta,\zeta}$$

If $\pi_s$ and $\nu_s^\theta$ are the stationary distribution for the ordinary and delayed contact processes then it is immediate from the definitions that

$$\nu_s^\theta(\eta) = \frac{\theta^{-r(\eta)}\pi_s(\eta)}{\sum\zeta \theta^{-r(\zeta)}\pi_s(\zeta)} \quad (5.6.5)$$

Lemma 5.6.4. (Lemma 3.6) Let $L > 0$ be an integer. There are constants $K$ and $\lambda_0 > 0$ so that for all $\lambda \leq \lambda_0$ and $L$

$$E[\nu_{T_L}^\theta(0)^{-1}] \leq 2$$

The proof is similar to that of Theorem 5.6.2, but requires more work, so we refer the reader to the paper for details.

Proof of Theorem 5.6.3. To simplify notation write $\pi_L$ for $\pi_{T_L}$ and $\nu_L$ for $\nu_{T_L}^\theta$ with $\theta = K\lambda$ where $K$ is the constant from Lemma 5.6.4. Let $A = \{\eta : r(\eta) \geq h\}$ and note that (8.3.25) implies

$$\frac{\pi_L(A)}{\pi_L(0)} \leq \theta^h \frac{\nu_L(A)}{\nu_L(0)}$$

Lemma 5.6.4 and Markov’s inequality imply that, for a collection of $T_L$ with probability $\geq 1 - m^{-1}$, we have $\nu_L(0)^{-1} \leq 2m$ and hence

$$\frac{\pi_L(A)}{\pi_L(0)} \leq 2m(K\lambda)^h \quad (5.6.6)$$

Now if $X_t \sim \mathbb{CP}_{\rho}^{\lambda}(T_L^+)$ hits $A$ before $0$ then the time needed to escape form $A$ is at least exponential with mean 1, since escape can only happen when there is exactly one infected
at distance $h$ from $\rho^+$. Thus if $\gamma(h) = |\{t \in [0, S_L] : X_t \in A\}|$, where $| \cdot |$ denotes Lebesgue measure then

$$E(\gamma(h)|H \geq h, T_L) \geq 1$$

Combining this with (5.6.6) and noting that $\gamma(h) = 0$ on $H < h$

$$P(H \geq h|T_L) \leq E(\gamma(h)|H \geq h, T_L) \cdot P(H \geq h|T_L) \leq E(\gamma(h)|T_L) \leq \pi_L(A)\pi_L(0) \leq 2m(K\lambda)^h$$

which completes the proof. \(\square\)

At this point the rest is routine.

**Proof of Theorem 5.6.1.** Let $T \sim GW(D, \rho$ be its root, and let $X_t \sim CP(T, 1, \rho)$. Let $K, \lambda_0$ be given in Theorem 5.6.3 and let $\lambda \leq \lambda_0$ so that $K\lambda \leq 1$. Let $\delta > 0$ be small and pick $h$ so that $(K\lambda)^h = \delta^2/8$. Let $E(h)$ be the event that the infection $\inf X_t$ does not go deeper than $h$ before dying out. Taking $m = 2/\delta$ in Theorem 5.6.3 we see that

$$P(H \geq h|T_L) \leq (4/\delta)(\delta^2/8) = \delta/2$$

for a collection of values of $T_L$ with probability $\geq 1 - \delta/2$ so $P(E(h)) \geq 1 - \delta$.

Let $T_h$ be $T$ truncated at depth $h$ and couple the processes $CP(T, 1, \rho)$ and $CP(T_h, 1, \rho)$ by identifying the recoveries and infections inside $T_h$. Let $R$ and $R_h$ be the times $CP(T, 1, \rho)$ and $CP(T_h, 1, \rho)$ reach 0. Then Theorem 5.6.2 tells us that

$$E(R|E(h)) = E(R_h|E(h)) \leq \frac{ER_h}{P(E(h))} < \infty$$

Thus $P(X_t \neq 0$ for all $t \geq 0) \leq \delta$. Since $\delta$ is arbitrary the desired result follows. \(\square\)

### 5.6.3 Bounds on survival time

**Theorem 5.6.5.** (Theorem 3) Suppose that $G_n$ is a graph on $n$ vertices generated by the configuration model with degree distribution $D$ with (i) $ED(D - 2) > 0$, so there is a giant component, and (ii) $E(e^{cD}) < \infty$ for some $c > 0$. Consider the contact process on $G_n$ starting from all sites infected. There are constants $0 < \lambda_i \leq \lambda_{ii} < \infty$ so that

(i) For $\lambda < \lambda_i$ the process survives for time at most $n^{1+o(1)}$

(ii) For $\lambda > \lambda_{ii}$ the process survives for time at least $e^{\Theta(n)}$.

The proof of this result requires hard work, so we will only explain a few ideas from the proof.

**Proof of (i).** It is enough to prove
Theorem 5.6.6. (Theorem 4.1) Fix an arbitrary vertex \( v \in G \) and let \( T_v \) be the time when \( \mathbb{CP}_\lambda(G; 1_v) \) reaches the root 0. There is an event \( H \) so that \( P(G \in H) = 1 - o(1) \) and constants \( B, \lambda_0 > 0 \) depending on \( \mu \) so that for all \( \lambda \in (0, \lambda_0) \) we have

\[
E(T_v | G \in H) \leq B
\]

The result follows from Markov’s inequality. Using this approach we have to estimate the probability the survival time > \( n^{1+o(1)} \) so that \( n \) times the error probability goes to 0.

To prove Theorem 5.6.6, they show that the graph looks locally like a Galton-Watson tree with an augmented distribution defined as follows. Suppose for simplicity that \( k_{\text{max}} = \max \{ k : p_k > 0 \} \) and let

\[
k_0 = \max \{ k : \sum_{j \geq k} \sqrt{p_j} \geq 1/2 \}
\]

They define the augmented distribution by

\[
\hat{\mu}(j) = \begin{cases} 
    p_j / 2Z & \text{if } j \leq k_0 \\
    \sqrt{p_j} / Z & \text{if } j > k_0 
\end{cases}
\]

where \( Z \) is chosen to make the sum of the \( \hat{\mu}(j) = 1 \). In addition to changing the tails of the distribution, one cannot assume that the graph is tree like, but one must allow an extra edge that may form a cycle.

Proof of (ii). To prove prolonged persistence they show that in Section 7 the random graph contains a large \( (\alpha, R) \)-embedded expander. A subset \( W_0 \) of vertices has this property if for every set \( A \subset W_0 \) with \( |A| \leq \alpha |W_0| \)

\[
|N(A, R) \cap W_0| \geq 2|A|
\]

where \( N(A, R) \) is the collection of vertices in \( G_n \) within distance at most \( R \) of \( A \).

Once this is done they can prove

Lemma 5.6.7. (Lemma 5.4) There are constants \( \lambda_0, C, C' \), and \( \beta \) so that for all \( \lambda \geq \lambda_0 \) and integer \( a \in (0, \alpha \beta n] \)

\[
P(|X^0_{t+C} \leq 5a/4|X^0_t = a) \leq 2 \exp(-a/C')
\]

This leads easily to the lower bound on the survival times. For more details see the paper.

Further Reading. Huang (2020) shows that if a contact process on a Galton-Watson tree survives then it dominates a Crump-Mode-Jagers branching process. This implies that the survival probability \( p(\lambda) \) is continuous at \( \lambda = \lambda_1 \)

Nam, Nguyen, and Sly (2022) have studied the asymptotics of critical values \( \lambda_1 \) and \( \lambda_2 \) for the contact process on Galton-Watson trees and finite graphs when the mean degree \( ED \to \infty \) and degree distribution satisfies a concentration condition for \( D/ED \). Theorem 1 shows that \( \lambda_1/ED \to 1 \). Theorem 2 shows that the same result holds for the short and long time survival thresholds.
5.7 Threshold-θ contact process

Reproduction of particles in the contact process is asexual. An individual at \( x \) gives birth to a new individual at a neighboring site \( y \) at rate \( \lambda \). A number of particle systems have been defined that have sexual reproduction: at least two particles are needed to create a new one. In less titilating but more informative terms: the contact process birth rate is linear and the process is additive: when built on the graphical representation

\[
\xi_t^A \cup B = \xi_t^A \cup \xi_t^B
\]

Here we will describe results for one non-additive process with nonlinear flip rates that has been studied on random regular graphs: the threshold \( \theta \geq 2 \) contact process of Chatterjee and Durrett (2013). Along the way we will mention some of the other models. The introduction of CD2013 has examples that have been studied on \( \mathbb{Z}^d \). Before we get lost in the details of what is in CD2013, we should note that Danny Nam (2019) has proved results for graphs that have more general degree distributions. Since our proof of Proposition 5.7.8 does not work when the degree is not constant his proof required some substantial new ideas.

Let \( G_n \) be a random \( r \)-regular graph with \( r \geq 3 \) on \( n \) vertices, constructed for example by the algorithm used in Section 2.1 for the configuration model. Let \( P \) denote the distribution of \( G_n \), which is the first of several probability measures we will define. We condition on the event \( E_n \) that the graph is simple, i.e., it does not contain a self-loop at any vertex, or more than one edge between two vertices. Theorem 2.1.2 implies that \( P(E_n) \) converges to a positive limit \( c_r \) as \( n \to \infty \), and hence

\[
\text{if } \bar{P} = P(\cdot | E_n), \text{ then } \bar{P}(\cdot) \leq c_r P(\cdot) \text{ for some constant } c_r > 0.
\]  

(5.7.1)

Thus conditioning on the event \( E_n \) will not have much effect on the distribution of \( G_n \). It is easy to see that the distribution of \( G_n \) under \( \bar{P} \) is uniform over the collection of all \( r \)-regular (simple) graphs on the vertex set \( V_n \). (We put simple in parentheses since it is redundant: graphs by definition are simple.) We choose \( G_n \) according to the distribution \( \bar{P} \) on simple graphs, and once chosen the graph remains fixed through time.

Having defined the graph, the next step is to introduce the dynamics on the graph. For the proofs it is crucial that we work in discrete time. We write \( x \sim y \) to mean that \( x \) is a neighbor of \( y \), and let

\[
\mathcal{N}_y = \{ x \in V_n : x \sim y \}
\]  

(5.7.2)

be the set of neighbors of \( y \). The distribution \( P_{p,\theta}^{G_n} \) of the (discrete time) threshold-θ contact process \( \xi_t \subseteq V_n \) with parameters \( p \) and \( \theta \) conditioned on \( G_n \) can be described as follows:

\[
\begin{align*}
\Pr_{p,\theta}^{G_n}(x \in \xi_{t+1} \mid |\mathcal{N}_x \cap \xi_t| \geq \theta) &= p \\
\Pr_{p,\theta}^{G_n}(x \in \xi_{t+1} \mid |\mathcal{N}_x \cap \xi_t| < \theta) &= 0,
\end{align*}
\]

where the decisions for different vertices at time \( t + 1 \) are made independently. Let \( \xi_t^A \subseteq V_n \) denote the threshold-θ contact process starting from \( \xi_0^A = A \), and let \( \xi_t^1 \) denote the special case when \( A = V_n \).
Being an attractive processes, the threshold-\(\theta\) contact process on an \(r\)-regular tree has a translation invariant upper invariant measure, \(\xi^1_\infty\), that is the limit as \(t \to \infty\) for the system starting from all 1’s. There are three basic questions for our models.

**Q1.** Let \(\xi^p_t\) be the system starting from product measure with density \(p\), i.e., \(\xi^0_\delta(x)\) are independent and equal 1 with probability \(p\). Does \(\xi^p_t\) die out for small \(p\)? That is, do we have \(P(\xi^p_t(x) = 1) \to 0\) as \(t \to \infty\) if \(p \leq p_0(\lambda)\)?

**Q2.** Let \(\rho(\lambda) = P(\xi^1_\infty(x) = 1)\) and let \(\lambda_c = \inf\{\lambda : \rho(\lambda) > 0\}\). Is \(\rho(\lambda)\) discontinuous at \(\lambda_c\)? If so, then soft results imply that \(P(\xi^1_\infty(x) = 1) > 0\) when \(\lambda = \lambda_c\). (As \(\lambda \downarrow \lambda_c\) the upper invariant measures \(\xi^1_\infty\) decrease to a limit which must be the upper invariant measure at \(\lambda_c\).)

**Q3.** Let \(\xi^{0,\beta}_\infty\) be the limit as \(t \to \infty\) for the system starting from all 0’s when sites become occupied spontaneously at rate \(\beta\) along with the original dynamics. Is \(\lim_{\beta \to 0} P(\xi^{0,\beta}_\infty(x) = 1) = 0\)? If so, we say that 0 is stable under perturbation, and it follows that there are two nontrivial stationary distributions when \(\beta > 0\) is small. (To see this note \(\xi^{1,0}_\infty\) is larger than \(\xi^{1,0}_\infty\), so we have two stationary distributions if the density of particles in \(\xi^{0,\beta}_\infty\) is less than the density in \(\xi^{1,0}_\infty\).

One of the first processes with sexual reproduction that was studied is Toom’s (1974) NEC (north-east-center) rule on \(\mathbb{Z}^2\). In the original formulation it was an example of a stochastic perturbation of a cellular automaton. A 0 at \(x\) is changed to 1 if \(x + e_1\) and \(x + e_2\) are both in state 1. This cellular automaton is an eroder. If the initial configuration has only finitely many 0’s then after a finite number of iterations the configuration is all 1’s. By Toom’s eroder theorem if we add errors that change 1’s to 0’s with probability \(\epsilon\) and \(\epsilon < \epsilon_0\) then there is a nontrivial stationary distribution.

More relevant for us, is the reformulation of Toom’s rule as a growth model, where the state of \(x\) changes

\[
\begin{align*}
1 & \to 0 \quad \text{at rate 1,} \\
0 & \to 1 \quad \text{at rate } \lambda \text{ if } x + e_1 \text{ and } x + e_2 \text{ are both in state 1.}
\end{align*}
\]

For the model in (5.7.3), Durrett and Gray (1985) have proved (a)–(d) below. Until recently the only source was the announcement of results in Durrett (1985), but now a pdf of the original preprint is available (see references).

(a) if we let \(\xi^A_t\) denote the set of all 1’s at time \(t\) starting from \(\xi^A_0 = A\), and

\[
\lambda_f = \inf\{\lambda : P(\xi^A_t \neq \emptyset \text{ for all } t) > 0\}
\]

be the critical value for survival from a finite set, then \(\lambda_f = \infty\), because if all the 1’s in the initial configuration are inside a rectangle, then there will never be any birth of 1’s outside that rectangle.
(b) Durrett and Gray used a contour argument to prove $\lambda_c \leq 110$. Swart, Szabo, and Toninelli (2022) have further developed the method of contours, Bramson and Gray have proved a version of Toom’s eroder theorem in continuous time when implies $\lambda_c < \infty$

(c) if $p^*$ is such that $1 - p^*$ equals the critical value for oriented bond percolation on $\mathbb{Z}^2$, then for any $p < p^*$ the process starting from product measure with density $p$ dies out. This is trivial to prove if there is an oriented path of 0’s that only moves up and to the right then these 0’s are permanent. They can never be changed to 1.

(d) Suppose that sites become occupied spontaneously at rate $\beta$ along with the original dynamics. If $\lambda > \lambda_c$ and $6\beta^{1/4}\lambda^{3/4} < 1$, then there are two stationary distributions.

Chen (1992, 1994) has generalized Toom’s growth model. He begins by defining the following diagonally adjacent pairs for each site $x$.

- pair 1: $x - e_1, x - e_2$
- pair 2: $x + e_1, x - e_2$
- pair 3: $x + e_1, x + e_2$
- pair 4: $x - e_1, x + e_2$

His models are numbered by the pairs that can give birth: Type I (pair 1 = SWC); Type IV (any pair); Type III (pairs 1, 2, and 3); Type 2A (pairs 1 and 2); and Type 2B (pairs 1 and 3). Chen (1992) proves for model IV that if $0 < p < p(\lambda)$, then

$$P(0 \in \xi^p_t) \leq t^{-c\log_2(1/p)}.$$  

He also shows for the same model that

$$\lim_{\beta \to 0} P(0 \in \xi^{0,\beta}_\infty) > 0$$

for large $\lambda$, so 0 is unstable under perturbation. In contrast, Chen (1994) shows that 0 is stable under perturbation in model III (and hence in modes II A, II B, and I).

Results

The first step is to prove that threshold-$\theta$ contact process dies out for small values of $p$ and survives for $p$ close to 1. It is easy to see that on any graph in which all vertices have degree $r$ the threshold-$\theta$ contact process dies out rapidly if $p < 1/r$, because an occupied site has at most $r$ neighbors that it could cause to be occupied at the next time step suggesting $E_{p,\theta}^{G_n} \xi^1_t \leq n(rp)^t$.

Survival from initial density close to 1

Our next result shows that if $\theta \geq 2, r \geq \theta + 2$ and $p$ is sufficiently close to 1, then with high probability the fraction of occupied vertices in the threshold-$\theta$ contact process on $G_n$ starting with all 1’s stays above $1 - \epsilon_1$ for an exponentially long time.
Theorem 5.7.1. Suppose $\theta \geq 2$ and $r \geq \theta + 2$. There are constants $\epsilon_1, \gamma_1 > 0$, and a good set of graphs $G_n$ with $\mathbb{P}(G_n \in G_n) \to 1$ so that if $G_n \in G_n$ and $p \geq p_1 = 1 - \epsilon_1/(3r - 3\theta)$, then

$$P_{p, \theta}^{G_n} \left( \inf_{t \leq \exp(\gamma_1 n)} \frac{|\xi_t^1|}{n} < 1 - \epsilon_1 \right) \leq \exp(-\gamma_1 n).$$

Here and in what follows, all constants will depend on the degree $r$ and threshold $\theta$. If they depend on other quantities, that will be indicated.

The reason for the restriction to $r \geq \theta + 2$ comes from Proposition 5.7.8 (with $j = r - \theta + 1$) below. When $r \leq \theta + 1$, it is impossible to pick $\eta > 0$ so that $(1 + \eta)/(r - \theta) < 1$. There may be more than algebra standing in the way of constructing a proof. We conjecture that the result is false when $r \leq \theta + 1$. To explain our intuition in the special case $\theta = 2$ and $r = 3$, consider a rooted binary tree in which each vertex has two descendants and hence, except for the root, has degree three. If we start with a density $u$ of 1's on level $k$ and no 1's on levels $m < k$, then at the next step the density will be $g(u) = pu^2 < u$ on level $k - 1$. When each vertex has three descendants instead of two, then

$$g(u) = p(3u^2(1 - u) + u^3),$$

which has a nontrivial fixed point for $p \geq 8/9$ (divide by $u$ and solve the quadratic equation).

As the next result shows, there is a close relationship between the threshold-$\theta$ contact process $\xi_t$ on a random $r$-regular graph and the corresponding process $\zeta_t$ on the homogeneous $r$-tree. Following the standard recipe for attractive interacting particle systems, if we start with all sites on the tree occupied, then the sequence $\{\zeta_t^1\}$ of sets of occupied vertices decreases in distribution to a limit $\zeta_\infty^1$, which is called the upper invariant measure, since it is the stationary distribution with the most 1's. Here and later we denote by $0$ any fixed vertex of the homogeneous tree. Writing $P_{p, \theta}$ for the distribution of $\zeta_t$ with parameters $p$ and $\theta$, the critical value is defined by

$$p_c(\theta) := \sup\{p : P_{p, \theta}(\zeta_\infty^1(0) = 1) = 0\},$$

Corollary 5.7.2. Suppose $\theta \geq 2$, $r \geq \theta + 2$ and that $p_1$ and $\epsilon_1$ are the constants in Theorem 5.7.1. If $p \geq p_1$, then there is a translation invariant stationary distribution for the threshold-$\theta$ contact process on the homogeneous $r$-tree in which each vertex is occupied with probability $\geq 1 - \epsilon_1$.

Fontes and Schonmann (2008a) have considered the continuous time threshold-$\theta$ contact process on a tree in which each vertex has degree $b + 1$, and they have shown that if $b$ is large enough, then $\lambda_c < \infty$. Our result improves their result by removing the restriction that $b$ is large.

Dying out from small initial density

If we set the death rate $= 0$ in the threshold-$\theta$ contact process, then we can without loss of generality set the birth rate equal to 1 and the process reduces to bootstrap percolation (with
asynchronous updating). Balogh and Pittel (2007) have studied bootstrap percolation on random regular graphs. They have identified an interval \([p_-(n), p_+(n)]\) so that the probability that all sites end up active goes sharply from 0 to 1. The limits \(p_+(n) \to p_*\) and \(p_+ - p_-\) is of order \(1/\sqrt{n}\). If bootstrap percolation cannot fill up the graph, then it seems that our process with deaths will be doomed to extinction. The next result proves this, and more importantly extends the result to arbitrary initial conditions with a small density of occupied sites.

Here, since processes with larger \(\theta\) have fewer survivals, it is enough to prove the result when \(\theta = 2\).

**Theorem 5.7.3.** Suppose \(\theta \geq 2\) and \(p_2 < 1\). There are constants \(0 < \epsilon_2(p_2), C_2(p_2) < \infty\), and a good set of graphs \(\mathcal{G}_n\) with \(\hat{P}(G_n \in \mathcal{G}_n) \to 1\) so that if \(G_n \in \mathcal{G}_n\), then for any \(p \leq p_2\), and any subset \(A \subset V_n\) with \(|A| \leq \epsilon_2 n\),

\[
P_{G_n}^{p, \theta, \beta} \left( \xi_{[C_2 \log n]}^A \neq \emptyset \right) \leq 2/\sqrt[6]{n}\]

for large enough \(n\).

The density of 1’s \(\rho(p, \theta) := P_{p, \theta}(\xi_1^1(0) = 1)\) in the stationary distribution on the homogeneous \(r\)-tree is a nondecreasing function of \(p\). The next result shows that the threshold-\(\theta\) contact process on the \(r\)-tree has a discontinuous phase transition.

**Corollary 5.7.4.** Suppose \(\theta \geq 2\), let \(p_1\) be the constant from Theorem 5.7.1, and let \(\epsilon_2(\cdot)\) be as in Theorem 5.7.3. \(\rho(p, \theta)\) never takes values in \((0, \epsilon_2(p_1))\).

This result, like Theorem 5.7.3 does not require the assumption \(r \geq \theta + 2\). On the other hand, if \(\rho(p, \theta) \equiv 0\) for \(r \leq \theta + 1\), the result is not very interesting in that case. Again Fontes and Schonmann (2008a) have proved that the threshold-\(\theta\) contact process has a discontinuous transition when the degree \(b + 1\) is large enough.

Fontes and Schonmann (2008b) have studied \(\theta\)-bootstrap percolation on trees in which each vertex has degree \(b + 1\) and \(2 \leq \theta \leq b\). They have shown that there is a critical value \(p_f\) so that if \(p < p_f\), then for almost every initial configuration of product measure with density \(p\), the final bootstrapped configuration does not have any infinite component. This suggests that we might have \(\epsilon_2(p)\) bounded away from 0 as \(p \to 1\).

**Stability of 0**

The previous pair of results are the most difficult in the paper. From their proofs one easily gets results for the process with spontaneous births with probability \(\beta\), i.e., after the threshold-\(\theta\) dynamics has been applied to the configuration at time \(t\), we independently make vacant sites occupied with probability \(\beta\). For this new process, we denote the set of occupied vertices at time \(t\) starting with all 0’s by \(\hat{\xi}_t^0\) and its distribution conditioned on the graph \(G_n\) by \(P_{p, \theta, \beta}^{G_n}\) to have the following:

**Theorem 5.7.5.** Suppose \(\theta \geq 2\). There is a good set of graphs \(\mathcal{G}_n\) with \(\hat{P}(G_n \in \mathcal{G}_n) \to 1\) so that if \(G_n \in \mathcal{G}_n\) and \(p < 1\), then there are constants \(C_3(p), \beta_3(p), \gamma_3(p, \beta) > 0\) so that for \(\beta < \beta_3\),

\[
P_{G_n}^{p, \theta, \beta} \left( \sup_{t \leq \exp(\gamma_3 n)} \frac{|\xi_t^0|}{n} > C_3 \beta \right) \leq 2 \exp(-\gamma_3 n).
\]
Let \( \hat{\zeta}_n^0 \) be the limiting distribution for the process on the homogeneous tree, which exists because of monotonicity.

**Corollary 5.7.6.** If \( \theta \geq 2 \) and \( p < 1 \), then \( \lim_{\beta \to 0} P_{p,\theta,(\hat{\zeta}_n^0)}(\hat{\zeta}_n^0(0) = 1) = 0 \).

**Key ideas for the proof**

We now describe the “isoperimetric inequalities” that are the keys to the proofs of our results. Let \( \partial U := \{ y \in U^c : y \sim x \text{ for some } x \in U \} \) be the boundary of \( U \), and given two sets \( U \) and \( W \), let \( e(U, W) \) be the number of edges having one end in \( U \) and the other end in \( W \). Given an \( x \in V_n \) let \( n_U(x) \) be the number of neighbors of \( x \) that are in \( U \), and let

\[
U^*j = \{ x \in V_n : n_U(x) \geq j \}.
\]

The estimation of the sizes of \( e(U, U^c) \) is key to the study of random walks on graphs, see Chapter 6, and especially Section 6.3. Here we are interested in studying the sizes of \( U^*j \) and having better constants by restricting to small sets. The last remark will make more sense after reading Section 6.3.

**Proposition 5.7.7.** Let \( E^*(m, \leq k) \) be the event that there is a subset \( U \subset V_n \) with size \( |U| = m \) so that \( |U^*j| \leq k \). There are constants \( C_0 \) and \( \Delta_0 \) so that for any \( \eta > 0 \), there is an \( \epsilon_0(\eta) \) which also depends on \( r \) so that for \( m \leq \epsilon_0(\eta)n \),

\[
\mathbb{P}\left[ E^*(m, \leq (r - 1 - \eta)m) \right] \leq C_0 \exp \left( -\frac{\eta^2}{4r}m \log(n/m) + \Delta_0 m \right).
\]

This result yields the next proposition which we need to prove Theorems 5.7.1 and 5.7.3. For Theorem 5.7.1, note that if \( W = V_n \setminus \xi_t \) is the set of vacant vertices at time \( t \), then at time \( t+1 \) the vertices in \( W^{*(r - \theta + 1)} \) will certainly be vacant and the vertices in its complement will be vacant with probability \( 1 - p \). So having an upper bound for \( |W^{*(r - \theta + 1)}| \) will be helpful. On the other hand for Theorem 5.7.3, if \( U \) is the set of occupied vertices at time \( t \), then at time \( t+1 \) the vertices in \( U^{*\theta} \) will be occupied with probability \( p \) and the vertices in its complement will certainly be vacant. So having an upper bound for \( |U^{*\theta}| \) will be helpful.

Keeping these in mind, it is easy to see from the definitions that if \( j > 1 \) and \( |Z| = m \), then

\[
rm \geq \sum_{y \in Z^{*1}} e(\{y\}, Z) \geq |Z^{*1} \setminus Z^{*j}| + j|Z^{*j}| = |Z^{*1}| + (j - 1)|Z^{*j}|.
\]

So for any set \( Z \) of size \( m \), if \( |Z^{*j}| \geq k \), then \( |Z^{*1}| \leq rm - (j - 1)k \). Taking \( k = m(1+\eta)/(j-1) \) so that \( rm - (j - 1)k = (r - 1 - \eta)m \) and using Proposition 5.7.7 we get

**Proposition 5.7.8.** Let \( E^j(\{Z\}, \geq k) \) be the event that there is a subset \( Z \subset V_n \) with size \( |Z| = m \) so that \( |Z^{*j}| \geq k \). For the constants \( C_0, \Delta_0, \) and \( \epsilon_0(\eta) \) given in Proposition 5.7.7, if \( j > 1 \) and \( m \leq \epsilon_0(\eta)n \), then

\[
\mathbb{P}\left[ E^j \left( \{Z\}, \geq \left( \frac{1 + \eta}{j - 1} \right)m \right) \right] \leq C_0 \exp \left( -\frac{\eta^2}{4r}m \log(n/m) + \Delta_0 m \right).
\]
The reasoning that led to Proposition 5.7.8 depends on the fact that all vertices have the same degree. Danny Nam has developed new results to cover the case of variable degree.

References


Chatterjee, S., and Durrett, R. (2009) Contact processes on random graphs with power law degree distributions have critical value 0. *Ann. Probab.* 37, 2332–2356


5.7. **THRESHOLD-θ CONTACT PROCESS**


Chapter 6

Random Walks, Mixing Times

6.1 Basic definitions

Given a finite graph (random or not) one can define a random walk by its transition kernel

\[ K(x, y) = \frac{1}{d(x)} \quad \text{if } y \sim x \]

where \( y \sim x \) is short for \( y \) is neighbor of \( x \) and \( d(x) \) is the degree of \( x \). Also called the transition probability, it is often denoted by \( p \). We will use both notations in this book. If we let \( D = \sum_x d(x) \) then \( \pi(x) = d(x)/D \) is a stationary distribution that satisfies the detailed balance condition

\[ \pi(x)K(x, y) = \frac{1_{x \sim y}}{D} = \pi(y)K(y, x) \]

Stationary distributions with this property are also called reversible, since when started the chain in state \( \pi \) the process has the same distribution going backwards in time. To explain this note that

\[
P_\pi(X_0 = y|X_1 = x) = \frac{P_\pi(X_0 = y, X_1 = x)}{P_\pi(X_1 = x)} = \frac{\pi(y)K(y, x)}{\pi(x)} = \frac{\pi(x)K(x, y)}{\pi(x)} = K(x, y)
\]

To avoid the problem of periodicity, we will often make the random walk lazy

\[ \tilde{K}(x, x) = 1/2 \quad \tilde{K}(x, y) = (1/2)K(x, y) \quad \text{when } x \neq y \]

If the graph is connected then the kernel is irreducible. If lazy it is aperiodic so it converges to equilibrium, i.e. \( \tilde{K}^n(x, y) \to \pi(y) \). Here we will be interested in how fast the convergence occurs. To measure the distance from equilibrium we can use the total variation distance. If \( \mu \) and \( \nu \) are probability distributions then

\[ \|\mu - \nu\|_{TV} = \max_A |\mu(A) - \nu(A)| = \frac{1}{2} \sum_x |\mu(x) - \nu(x)| \]
We will usually drop the subscript TV. The distance from equilibrium at time \( t \) can be defined as
\[
d(t) = \sup_x \| K^t(x, \cdot) - \pi \| = \sup_\mu \| \mu K^t - \pi \|
\]
where \( \mu \) is a probability distribution and \( \mu K^t(y) = \sum_x \mu(x) K^t(x, y) \). It is useful to also define
\[
\tilde{d}(t) = \sup_{x,y} \| K^t(x, \cdot) - K^t(y, \cdot) \| = \sup_{\mu, \nu} \| \mu K^t - \nu K^t \|
\]
\( \tilde{d} \) has the useful property that it is \textbf{submultipliative}
\[
\tilde{d}(s + t) \leq \tilde{d}(s) \cdot \tilde{d}(t) \tag{6.1.1}
\]
It is easy to see that
\[
d(t) \leq \tilde{d}(t) \leq 2d(t) \tag{6.1.2}
\]
The time to get within \( \epsilon \) in total variation distance is
\[
t_{\text{mix}}(\epsilon) = \min\{ t : d(t) < \epsilon \}
\]
We define the \textbf{mixing time} by
\[
t_{\text{mix}} = t_{\text{mix}}(1/4) \tag{6.1.3}
\]
To see why we choose \( \epsilon = 1/4 \) note that using (6.1.2) and (6.1.1)
\[
d(\ell t_{\text{mix}}) \leq \tilde{d}(\ell t_{\text{mix}}) \leq \tilde{d}(t_{\text{mix}})^\ell \leq (2\epsilon)^\ell = 2^{-\ell}
\]
when \( \epsilon = 1/4 \).

\section*{6.1.1 Bounds on convergence}

Consider a Markov chain transition kernel \( K(i, j) \) on \( \{1, 2, \ldots n\} \) with reversible stationary distribution \( \pi_i \), i.e., \( \pi_i K(i, j) = \pi_j K(j, i) \). For the next result we will measure the distance from equilibrium using the \textbf{relative pointwise distance}
\[
\Delta(t) = \max_{i,j} \left| \frac{K^t(i, j)}{\pi_j} - 1 \right|
\]
which is larger than the total variation distance
\[
\Delta(t) \geq \max_i \sum_j \left| \frac{K^t(i, j)}{\pi_j} - 1 \right| \pi_j = \max_i \sum_j |K^t(i, j) - \pi_j|
\]
Let \( D \) be a diagonal matrix with entries \( \pi_1, \pi_2, \ldots \pi_n \) and \( a = D^{1/2} K D^{-1/2} \). Since
\[
a(i, j) = \pi_i^{1/2} K(i, j) \pi_j^{-1/2} = \pi_i^{-1/2} \cdot \pi(i) K(i, j) \cdot \pi_j^{1/2} = \pi_i^{-1/2} \cdot \pi(j) K(j, i) \cdot \pi_j^{-1/2} = \pi_j^{1/2} K(j, i) \pi_i^{-1/2} = a(j, i)
\]
matrix theory tells us that \( a(i,j) \) has real eigenvalues \( 1 = \lambda_0 \geq \lambda_1 \geq \ldots \lambda_{n-1} \geq -1 \). Let \( \lambda_{\text{max}} = \max\{\lambda_1, |\lambda_{n-1}|\} \) be the eigenvalue with largest magnitude. The lazy chain has transition kernel \( \bar{K} = (I + K)/2 \) so all \( \bar{\lambda}_i = (1 + \lambda_i)/2 \geq 0 \) and we do not have to worry about \( |\lambda_{n-1}| \).

To explain the interest in eigenvalues near \(-1\), note that if the chain is periodic with period two then we can find a set \( S \) that \( p(x, S) = 1 \) for \( x \in S \) and \( p(x, S^c) = 1 \) for \( x \in S^c \). The function that has \( f(x) = 1 \) for \( x \in S \) and \( f(x) = -1 \) for \( x \in S^c \) has \( P f = -f \), i.e., it is an eigenvector with eigenvalue \(-1\). Thus \( |\lambda_{n-1}| \) measure how close the chain is to having period 2. In general, Markov chains can have states with any period \( d \geq 3 \) but that is impossible in the reversible case.

The next result is from Sinclair and Jerrum (1989), but similar results can be found in many other places.

**Theorem 6.1.1.** Let \( K \) be the transition matrix of an irreducible reversible Markov chain on \( \{1, 2, \ldots n\} \) with stationary distribution \( \pi \) and let \( \pi_{\text{min}} = \min_j \pi_j \). Then

\[
\Delta(t) \leq \frac{\lambda_{\text{max}}}{\pi_{\text{min}}} \quad |K'(i, j) - \pi_j| \leq \lambda_{\text{max}} \sqrt{\pi_j/\pi_i}
\]

**Proof.** Since \( a \) is symmetric, we can select an orthonormal basis \( e_m, 0 \leq m < n \) of eigenvectors of \( a \), and \( a \) has spectral decomposition:

\[
a = \sum_{m=0}^{n-1} \lambda_m e_m e_m^T
\]

The matrix \( B_m = e_m e_m^T \) has \( B_m^2 = B_m \), and \( B_m B_m = 0 \) if \( \ell \neq m \) so

\[
a'(i, j) = \sum_{m=0}^{n-1} \lambda_m B_m(i, j) = \sum_{m=0}^{n-1} \lambda_m e_m(i) e_m(j)
\]

\( e_0(i) = \pi_i^{-1/2} \) so

\[
K'(i, j) = (D^{-1/2}a'D^{1/2})_{i,j} = \pi_j + \sqrt{\pi_i \pi_j} \sum_{m=1}^{n-1} \lambda_m e_m(i) e_m(j)
\]

From this it follows that

\[
\Delta(t) = \max_{i,j} \frac{\sum_{m=1}^{n-1} \lambda_m e_m(i) e_m(j)}{\sqrt{\pi_i \pi_j}} \leq \lambda_{\text{max}} \max_{i,j} \sum_{m=1}^{n-1} |e_m(i)||e_m(j)| \frac{\pi_{\text{min}}}{ \pi_{\text{min}}}
\]

The Cauchy-Schwarz inequality implies

\[
\sum_{m=1}^{n-1} |e_m(i)||e_m(j)| \leq \left( \sum_{m=1}^{n-1} |e_m(i)|^2 \sum_{m=1}^{n-1} |e_m(j)|^2 \right)^{1/2} \leq 1
\]
To see that $\sum_{m=1}^{n-1} |e_m(i)|^2 \leq 1$ note that if $\delta_i$ is the vector with 1 in the $i$th place and 0 otherwise then expanding in the orthonormal basis $\delta_i = \sum_{m=0}^{n-1} e_m(i)e_m$, so the desired result follows by taking the $L^2$ norm of both sides of the equation. To get the second result combine (6.1.4) and (6.1.5).

### 6.1.2 Continuous time chains

If jumps occur at rate one then there are a Poisson mean $t$ jumps by time $t$ so the transition probability is

$$H_t(x, y) = e^{-t} \sum_{m=0}^{\infty} \frac{t^m}{m!} K^m(x, y)$$  \hfill (6.1.6)

If $\lambda_i$ is an eigenvalue of $K$ then $e^{-t(1-\lambda_i)}$ is an eigenvalue of $H_t$. Thus there are no negative eigenvalues to worry about and we have

**Theorem 6.1.2.** If $\gamma = 1 - \lambda_1$ is the spectral gap of $K$ and $\Delta(t) = \max_{i,j} |H_t(i, j)/\pi(j) - 1|$ then

$$\Delta(t) \leq \frac{e^{-\gamma t}}{\pi_{\min}} |H_t(i, j) - \pi_j| \leq e^{-\gamma t} \sqrt{\frac{\pi_j}{\pi_i}}$$

**Proof.** This follows immediately from (6.1.6) and Theorem 6.1.1.

Given a reversible Markov transition kernel $K(x, y)$ we define an inner product by

$$\mathcal{E}(f, g) = \frac{1}{2} \sum_{x,y} (f(x) - f(y))(g(x) - g(y))\pi(x)K(x, y)$$

and the **Dirichlet form** by

$$\mathcal{E}(f) = \frac{1}{2} \sum_{x,y} (f(x) - f(y))^2\pi(x)K(x, y)$$  \hfill (6.1.7)

Introducing the inner product $<f, g> = \sum_x f(x)g(x)\pi(x)$, a little algebra shows

$$\mathcal{E}(f, f) = <f, (I - K)f>$$

If we define the variance by $\text{var}_\pi(f) = E_\pi(f - E_\pi f)^2$ then the spectral gap can be computed from the **variational formula**

$$1 - \lambda_1 = \min\{\mathcal{E}(f, f) : \text{var}_\pi(f) = 1\}$$  \hfill (6.1.8)

To see this note that $\mathcal{E}(f, f)$ is not affected by subtracting a constant from $f$ so

$$1 - \lambda_1 = \min\{<f, f> - <f, Kf> : E_\pi f = 0, <f, f> = 1\}$$
and the result follows from the usual variational formula for $\lambda_1$ for the nonnegative symmetric matrix $a_{i,j} = \pi(i)K(i,j)$, i.e.,

$$
\lambda_1 = \max \left\{ \sum_{i,j} x_i a_{i,j} x_j : \sum_i x_i^2 = 1 \right\}
$$

Up to this point we have obtained the continuous time results from the discrete case. They can also be proved directly without too much effort. The developments here follow Chapter 2 of Saloff-Coste (1996)

**Lemma 6.1.3.** Let $K$ be a Markov kernel with spectral gap $\gamma$ then the semigroup $H_t = e^{-t(I-K)}$ satisfies

$$
\|H_t f - \pi(f)\|_2^2 \leq e^{-2\gamma t} \operatorname{var}_\pi(f) \quad \text{for all } f \in \ell^2(\pi)
$$

**Proof.** Set $u(t) = \operatorname{var}_\pi(H_t f) = \|H_t(f - \pi(f))\|_2^2 = \|H_t(f) - \pi(f)\|_2^2$. Then

$$
u'(t) = -2\mathbb{E}(H_t(f) - \pi(f), H_t(f) - \pi(f)) \leq -2u(t)
$$

Integrating gives $u(t) \leq e^{-2\gamma t} u(0)$ which gives the desired result.

This leads to a slightly weaker version of Theorem 6.1.2

**Theorem 6.1.4.** Let $h^x_t = H^x_t(\cdot)/\pi(\cdot)$. If $\gamma = 1 - \lambda_1$ is the spectral gap of $K$ then

$$
\|h^x_t - 1\|_2 \leq \sqrt{1/\pi(x)} e^{-\gamma t} \quad |h_t(i,j) - \pi_j| \leq e^{-\gamma t} \sqrt{\pi_j/\pi_i}
$$

**Proof.** Let $g_x(y) = 1/\pi(x)$ if $y = x$, 0 otherwise. Lemma 6.1.3 implies

$$
\|h^x_t - 1\|_2 \leq \sqrt{\frac{1 - \pi(x)}{\pi(x)}} e^{-\gamma t}
$$

To prove the second result note that

$$
|h_t(i,j) - \pi_j| = \left| \sum_z (h_{t/2}(x,z) - 1)(h_{t/2}(z,y) - 1)\pi(z) \right|
\leq \|h^x_{t/2}\|_2 \|h^y_{t/2}\|_2 \leq e^{-\gamma t} \sqrt{\pi_j/\pi_i}
$$

where on the second step we have used a Cauchy-Schwarz inequality.
Relaxation time

There are many ways to quantify the amount of time needed to reach equilibrium. Earlier we defined the mixing time in (6.1.3) in terms of
\[ d(t) = \sup_x \| K^t(x, \cdot) - \pi(\cdot) \| \]
One can define the relaxation time in terms of the absolute spectral gap
\[ \gamma_* = \max \{|\lambda_i| : \lambda_i \neq 1\} \]
where the \( \lambda_i \) are the eigenvalues of the transition matrix, by setting
\[ t_{rel} = \frac{1}{\gamma_*} \] (6.1.9)
Combining Theorems 6.1.1 and 6.1.2 we have that in discrete or continuous time
\[ |\Delta(\ell t_{rel})| \leq \frac{e^{-\ell}}{\pi_{min}} \]

6.2 Markov chains and electrical networks

To lead into the theory developed in the next section, we will describe the connection between reversible Markov chains and electrical networks. The idea goes back to Nash-Williams (1959). One can find a leisurely description accessible to undergraduates in the delightful little book by Doyle and Snell (1984), or a more terse account for professional probabilists in Griffeath and Liggett (1982). Intermediate between these two extremes in Chapter 1 in Grimmett’s Probability on Graphs, which has the same clarity as his excellent book on percolation.

Doyle and Snell work in discrete time, Griffeath and Liggett in continuous time. Our first task is show that for the quantities we want to compute here there is no difference, except in the size of the minimum energy, so it is enough to prove the results in one of the two settings.

Given a Markov chain transition probability \( p(x,y) \) on a finite set \( S \) and a reversible probability measure \( \pi \), we can let
\[ Q(x,y) = \pi(x)p(x,y) = \pi(y)p(y,x) \]
be the flow of probability mass across the unoriented edge \( \{x,y\} \) in equilibrium. Given a continuous time Markov chain that jumps from \( x \) to \( y \) at rate \( \alpha(x,y) \) and a reversible probability measure \( \pi \), we can let
\[ Q(x,y) = \pi(x)\alpha(x,y) = \pi(y)\alpha(y,x) \]
To go from discrete to continuous time we can declare that jumps happen at overall rate 1 and let \( \alpha(x,y) = p(x,y) \). In the other direction if we let \( \alpha(x) = \sum_y \alpha(x,y) \) then \( p(x,y) = \)
$\alpha(x, y)/\alpha(x)$ is the transition probaility of the embedded jump chain. In either case, to create the connection with electrical networks, we define the resistance of the edge to be $R(x, y) = 1/Q(x, y)$.

Given an initial point $a$ and a set $B$ let $V(x) = P_x(T_a < T_B)$ where

\[
T_a = \inf\{n \geq 0 : X_n = a\} \text{ is the time of the first visit to } a \\
T_B = \inf\{n \geq 0 : X_n \in B\} \text{ is the time of the first visit to } B.
\]

Note that the hitting probabilities $P_x(T_a < T_B)$ are the same in discrete or continuous time. Since we have used $n \geq 0$ in the definitions, it follows that $V(x) = 1$ and $V(y) = 0$ if $y \in B$.

We will stop the Markov chain at time $\tau = T_a \land T_B$. Let $C = \{x \in S : x \neq a, x \notin B\}$ be the continuation region where the random walk continues to jump. The Markov property implies that for $x \in C$ we have

\[
V(x) = \sum_y p(x, y)V(y).
\] (6.2.1)

The last equation shows that $V(X_{n\land\tau})$ is a martingale so

\[
V(x) = P_x(T_a < T_B)
\]

Rearranging (6.2.1) we have

\[
0 = \sum_y p(x, y)(V(x) - V(y)) = \frac{1}{\pi(x)} \sum_y Q(x, y)(V(x) - V(y))
\] (6.2.2)

If we think of $V(x)$ as the voltage at $x$, Ohm’s law says that

\[
i(x, y) = Q(x, y)[V(x) - V(y)]
\] (6.2.3)

is the current that flows from $x$ to $y$ and (6.2.2) is Kirchhoff’s law: the net current flowing through any $x \in C$ is 0. Given a function on $S$, define the energy of $f$ by

\[
\mathcal{E}(f) = \sum_{\{x, y\}} (f(x) - f(y))^2 Q(x, y)
\]

where $\{x, y\}$ indicates that we are summing over edges = unordered pairs.

The next result is on page 63 of Doyle and Snell (1984), and is Theorem (2.1) in Griffeath and Liggett (1982) with $a = 0$ and $B = \Lambda$. The minimum energies in discrete and continuous time differ by a constant factor.

**Theorem 6.2.1. Thomson’s Principle.** If we minimize $\mathcal{E}(f)$ over all functions with $f(a) = 1$ and $f(b) = 0$ for all $b \in B$ then the minimum occurs at $V(x) = P_x(T_a < T_B)$. The minimum energy is

\[
i_a = \sum_y Q(a, y)[1 - V(y)],
\] (6.2.4)

i.e., the current flow out of $a$ or $P_0(T_B < T_a^+)$ where $T_a^+ = \inf\{n \geq 1 : X_n = a\}$
Proof. Recall that for a random variable $X$ with $EX^2 < \infty$, $E(X - c)^2$ is minimized when $c = EX$. From this it follows that for fixed $x \in C$, $\sum_y p(x, y)[c - f(y)]^2$ is minimized by $c = \sum_y p(x, y)f(y)$. Thus the minimizer must have $f(x) = \sum_j p(x, y)f(y)$ for all $x \in C$ we have proved the first result.

To prove the second result, we sum over ordered pairs $(x, y)$

$$
\mathcal{E}(f) = \frac{1}{2} \sum_{(x,y)} (V(x) - V(y))^2 Q(x, y)
$$

$$
= \frac{1}{2} \sum_{(x,y)} i(x, y)(V(x) - V(y)) = \sum_{(x,y)} i(x, y)V(x)
$$

since $i(y, x) = -i(x, y)$. If $x \in C$ then $\sum_y i(x, y) = 0$. If $x \in B$ then $V(x) = 0$ so we are only left with the terms with $x = a$. $V(a) = 1$ and $i(a, y) = Q(a, y)(1 - V(y))$ so the desired result follows. \qed

6.2.1 Transience is finite effective resistance

Given an infinite graph and a point $a$, consider now the sequence of minimization problems that come from taking $B_n = \{x : \text{dist}(a, x) = n\}$ and let $S_n = \bigcup_{m=0}^{n} B_m$. Since a function $f$ on $S_n$ with $f = 0$ on $B_n$ can be extended to be 0 on $S_\infty - S_n$ the minimum energy is decreasing in $n$. From the formula for the energy in (6.2.4) we see that the minimum energy tends to 0 if and only if the random walk on the full graph is recurrent.

This gives a result that Doyle and Snell (1984) call **Rayleigh’s monotonicity law**. (2.7) in Liggett and Griffeath (1982) gives a similar result.

**Theorem 6.2.2.** If $X_n$ and $\bar{X}_n$ have flow matrices $Q \leq \bar{Q}$ and $\bar{X}_n$ is recurrent then $X_n$ is

This comparison solves Exercise 9 on page 425 of the third edition of Feller volume I. We have made some minor edits in the statement to make it fit in better.

**Example 6.2.3. Plane random walk with reflecting barriers.** Consider a symmetric random walk in a bounded region $D \subset \mathbb{Z}^2$. The boundary is reflecting in the sense that, whenever the particle in the unrestricted random walk the particle would leave the region, it is not allowed to jump. Show that if every point in the region can be reached from every other point, and the region has $K < \infty$ points there is a stationary distribution with $u(x) = 1/K$, $x \in D$. (If $D$ is unbounded then the states are persistent null states and $u(x) = 1$, $x \in D$ is a stationary measure.)

The bounded case is obvious. In the unbounded case it is clear that $u(x) = 1$ is a stationary measure. However, it is far from obvious how to establish recurrence using elementary computations. Theorem 6.2.4 will provide another proof using the connection with resistance.

To connect with the title of this subsection, we will now change our perspective and look for an energy minimizing flow in which the current flowing from $a$ is 1. The solution
to the new problem $V(x) = V(x)/i_a$. The value at $a$, $V(a) = 1/i_a$ is called the effective resistance, $R_{\text{EFF}}$. In this formulation, we see that the random walk on the infinite graph is recurrent if and only if $R_{\text{EFF}} \to \infty$ as $n \to \infty$.

There are a number of applications of this fact to checking recurrence or transience of Markov chains. See Sections 3.4, 3.6, and 6 in Doyle and Snell (1984). We will only prove one such result, the Nash-Williams recurrence criterion. This result is (2.10) from Griffeath and Liggett (1982) so we will formulate it in continuous time with $\alpha_{i,j}$ the rate of jumps from $i$ to $j$ and $\alpha_i = \sum_j \alpha_{i,j}$. Suppose that

(i) the state space $S$ can be partitioned as $S = \bigcup_{k=0}^{\infty} \Lambda_k$ where $\Sigma$ indicates a disjoint union, and that if $i \in \Lambda_k$ and $\alpha_{i,j} > 0$ then $j \in \Lambda_{k-1} \cup \Lambda_k \cup \Lambda_{k+1}$ where $\Lambda_{-1} = \emptyset$

(ii) $\sum_{i \in \Lambda_k} \alpha_i < \infty$

(iii) $S$ is a graph, $\Lambda_0 = \{0\}$ and $\Lambda_k$ is the set of sites at distance $k$ from 0.

**Theorem 6.2.4.** If $P_0(T_{\Lambda_m} < \infty) = 1$ for all $m \geq 1$ then

$$P_0(T_{\Lambda_m} < T_0^+) \leq (\alpha_0 \Sigma_m)^{-1} \text{ where } \Sigma_m = \sum_{k=1}^{m} (\alpha_k)^{-1}. $$

so $X_t$ is recurrent provided $\sum_{k=1}^{\infty} \alpha_k^{-1} = \infty$.

Suppose that the graph is an unbounded subset of $\mathbb{Z}^2$ that contains 0 and has $\alpha_{i,j} = 1/4$ when $i, j \in G$ are nearest neighbors. If we let $\Lambda_m = \{(i, j) : |i| + (j) = m\}$ then $\alpha \leq Ck$ so the chain is recurrent.

### 6.2.2 A finite energy flow implies transience

Our final result here takes a different approach to checking transience due to Terry Lyons in a paper he wrote when he was an E.R. Assistant Professor at UCLA, where he learned about of the work of Griffeath and Liggett (1982). His proof was motivated a 1952 result of Royden which gave a necessary and sufficient condition for the covering surface of a compact Riemann surface to have a Green’s function.

The result he proved will be used in Section 6.9. There we will say that a function $\theta$ on the vertices of a tree $T$ is a flow if $\theta \geq 0$ and

$$\theta(x) = \sum_{x \rightarrow y} \theta(y)$$

where $x \rightarrow y$ indicates that $y$ is descendant of $x$. To extend this to a general graph define for neighbors $x, y$, define $u_{x,y}$ Which is the flowed through the oriented edge $(x, y)$ to have the following properties

(i) $u_{x,y} = -u_{y,x}$,

(ii) there is an $x_0$ with $\sum_y u_{x_0,y} \neq 0$ and $\sum_y u_{x,y} = 0$ for $x \neq x_0$. 


On the tree, \( x_0 \) is the root. If \( x \) is the parent of \( y \) then \( u(x, y) = \theta(y) - \theta(x) \) and \( u(y, x) = \theta(x) - \theta(y) \).

Lyons considered a discrete time reversible Markov chain with transition probability \( p(x, y) \) with stationary distribution \( \pi(x) \). To fit his work into our notations we let

\[
Q(x, y) = \pi(x)p(x, y) = \pi(y)p(y, x)
\]

**Theorem 6.2.5.** The Markov chain \( p \) with state space \( S \) is transient if (and only if) we can find \( u_{x,y} \) that satisfy (i), (ii), and

\[
(iii) \quad \sum_{x,y \in S} u_{x,y}^2 / Q(x, y) < \infty.
\]

The \( Q \) in the denominator may look strange but as in the case of the current, the optimal \( u(x, y) = [V(x) - V(y)]Q(x, y) \) so the energy is

\[
\sum_{x,y} [V(x) - V(y)]^2 Q(x, y)
\]

**Another physical interpretation.** Suppose the Markov chain is constructed from the flows \( a_{i,j} = a_{j,i} \) with \( \pi_i = \sum_{i,j} a_{i,j} \) and \( p_{i,j} = a_{i,j} / \pi_i \). Suppose \( i \) and \( j \) are connected by a pipe with cross-sectional area \( a_{i,j} \), and let \( u_{i,j} \) be the volume rate at which the fluid flows between them. The mass of the fluid is \( a_{i,j} \), its velocity is \( u_{i,j} / a_{i,j} \) so the total kinetic energy is

\[
\sum_{i,j} a_{i,j} \left( \frac{u_{i,j}}{a_{i,j}} \right)^2 = \sum_{i,j} \frac{u_{i,j}^2}{a_{i,j}}
\]

**Proof.** The first step is an elementary Hilbert space argument. Let \( H \) be the space of all sequences \( v_{ij} \) satisfying (iii), and define an inner product on \( H \) by

\[
\langle v, w \rangle = \sum_{i,j} v_{ij} w_{ij} / a_{i,j}
\]

For each \( m \) define \( \ell_m \in H \) by

\[
\ell^m_{i,j} = \delta_{mi} a_{mk}
\]

where \( \delta_{ij} = 1 \) if \( i = j \) and 0 otherwise. If we think of \( a_{i,j} \) as a matrix then \( \ell^m \) is the \( m \)th row with all the other entries set equal to 0.

To check that \( \langle \ell^m, \ell^m \rangle = \pi_m \) we note that

\[
\langle \ell^m, \ell^m \rangle = \sum_j a_{mj}^2 / a_{mj} = \pi_m
\]

and that \( u \in H \) has property (ii) if

\[
\langle \ell^{i_0} u \rangle \neq 0 \quad \text{and when } m \neq i_0 \quad \langle \ell^m u \rangle = 0 \quad (ii')
\]
Let $E$ be the affine space of $u \in H$ satisfying \((\text{ii}')\). Let $w$ be the unique vector in $E$ that minimizes \((\text{iii})\). By a standard argument from Hilbert space $w$ exists and and characterized by the property
\[
\langle w, w - e \rangle = 0 \quad \text{for all } e \in E
\] (6.2.5)

Our second goal is to construct a function $W$ on $S$ (rather than $w$ on $S \times S$) so that
\[
W_j - W_i = \frac{w_{ij}}{a_{ij}}
\]

To do this we need to show that if $j_0, j_1, \ldots j_n = j_0$ is a chain of vertices with $j_m \neq j_n$ and $p(j_k, j_{k+1}) \neq 0$ then
\[
\sum_{k=0}^{n-1} \frac{w(j_k, j_{k+1})}{a(j_k, j_{k+1})} = 0
\]

Define $f(j_k, j_{k+1}) = 1$ and $f(j_{k+1}, j_k) = -1$ for all $k < n$, with $f = 0$ otherwise, and notice that reversibility implies $\langle f, e^i \rangle = 0$, and hence $w - f \in E$. Using (6.2.5) and then the definition of $f$

\[
0 = \langle f, w \rangle = \sum_{k=0}^{n-1} \frac{w(j_k, j_{k+1})}{a(j_k, j_{k+1})} - \sum_{k=0}^{n-1} \frac{w(j_{k+1}, j_k)}{a(j_{k+1}, j_k)} = 2 \sum_{k=0}^{n-1} \frac{w(j_k, j_{k+1})}{a(j_k, j_{k+1})}
\]

since $w_{ij} = -w_{i,j}$ and $a_{ij} = a_{j,i}$.

$W$ has properties (a) $W(i_0) = 0$, (b) $W \not\equiv 0$ (since $\langle w, e^{i_0} \rangle \neq 0$)

(c) $W_i = \sum_j p_{ij} W_j$ and (d) $\sum_{ij} a_{ij} (W_i - W_j)^2 < \infty$

To complete the proof we will show that the existence of $W$ this is incompatible with recurrence. To do this let $T$ be the hitting time of $i_0$. $W(X_{k\wedge T})$ is a martingale that converges to 0 as $k \to \infty$. If we can show that it is $L^2$ bounded, i.e.,
\[
M_i^j = \sup_k E^i([W(Y_{k\wedge T}) - W(Y_0)]^2) < \infty
\]

then it follows that $W(i) \equiv 0$ contradicting (b). The orthogonality of martingale increments (Theorem 4.4.7) in PTE5 implies that
\[
M_i = \sum_j g(i, j) \sum_k p(j, k)(W_j - W_k)^2
\] (6.2.6)

where $g(i, j)$ is the expected number of visits to $j$ before hitting $i_0$. Reversibility and the Markov property imply
\[
g(i, j) \leq \frac{\pi_j}{\pi_i} g(j, i) \leq \frac{\pi_j}{\pi_i} g(i, i)
\]

The probability of hitting $i_0$ eventually is 1, so the probability of starting from $i$ and hitting $i_0$ before $i$ must be $> 0$ and hence $g(i, i) < \infty$. Using (6.2.6) we see that $M_i < \infty$ which completes the proof.
6.3 Conductance

Let $Q(x, y) = \pi(x)K(x, y)$ be the flow across the edge \{x, y\}, let $Q(S, S^c) = \sum_{x \in S, y \in S^c} Q(x, y)$ and define

$$\Phi(S) = \frac{Q(S, S^c)}{\pi(S)} \quad \Phi_* = \min_{\pi(S) \leq 1/2} \Phi(S)$$

Levin and Peres (2017) call $\Phi_*$ the bottleneck ratio. To see what this has to do with the rate of convergence to equilibrium we will state and prove their Theorem 7.4. The mixing time was defined in (6.1.3).

**Theorem 6.3.1.** $t_{mix}(1/4) \geq 1/4\Phi_*$

**Proof.** Suppose that $X_t$ is stationary, i.e., the distribution is $\pi$ for all $t$.

$$P_\pi(X_0 \in A, X_t \in A^c) \leq \sum_{s=1}^t P_\pi(X_{s-1} \in A, X_s \in A^c) = tQ(A, A^c)$$

This implies $P_\pi(X_t \in A^c|X_0 \in A) \leq t\Phi(A)$ so there is an $x \in A$ with

$$P^t(x, A) \geq 1 - t\Phi(A)$$

and we conclude $d(t) \geq 1 - t\Phi(A) - \pi(A)$. If $\pi(A) \leq 1/2$ and $t < 1/(4\Phi(A))$ then $d(t) > 1/4$.

This shows $t_{mix} \geq 1/\Phi(A))$ and maximizing over $A$ gives the desired result.

\[ L \xrightarrow{\ell} K_n \xrightarrow{r} K_n \xrightarrow{r} R \]

**Figure 6.1: Picture of Example 6.3.2**

**Example 6.3.2.** Take two complete graphs on $n$ vertices, call them $L$ and $R$. Pick $\ell \in L$ and $r \in R$ and connect them by an edge. To simplify the computation we formulate the chain in continuous time with jumps across each edge occur at rate $1/n$. Let $P_R$ denote the law of the Markov chain starting with all states in $R$ having probability $1/n$ and $P_R(X_0 \in L) = 0$. If we let $u(t) = P_R(X_t \in R)$, then

$$u'(t) = \frac{P_R(X_t = r) - P_R(X_t = \ell)}{n} \approx \frac{P_R(X_t \in R) - P_R(X_t \in L)}{n^2} = \frac{u(t) - (1 - u(t))}{n^2}$$
Where in the second step we have used the approximation that all sites in \( R \) at time \( t \) have the same probability. (6.3.1) provides support for this but we leave the tedious details of writing a rigorous proof to the reader. Letting \( v(t) = 2u(t) - 1 \) we have \( v'(t) = 2u'(y) = 2v(t)/n^2 \). Since \( v(0) = 1 \), we have \( v(t) = \exp(-2t/n^2) \) and

\[
\Phi(R, L) = \left( \frac{1}{2n} \right) \cdot \frac{(1/n)}{1/2} = n^{-2}
\]

Since we start with all of the mass on \( R \) and in equilibrium \( \pi(R) = 1/2 \) it follows that the time to equilibrium is at least \( O(n^2) \).

### 6.3.1 Cheeger’s inequality

Since we learned about Markov chain mixing times from Laurent, our next result is Lemma 3.3.7 in Saloff-Coste (1996). His \( I = 2h \) so the constants are different. Saloff-Coste attributes the result to Diaconis and Stroock (1991), who in turn named the result Cheeger’s inequality in honor of the eigenvalue bound in differential geometry. Levin and Peres (2017) cite Sincalir and Jerrum (1989) and Lawler and Sokal (1988).

**Theorem 6.3.3.** The spectral gap has

\[
\frac{h^2}{2} \leq 1 - \lambda_1 \leq 2h
\]

**Proof.** Taking \( f = 1_S \) in the variational formula (6.1.8) we have

\[
\mathcal{E}(1_S, 1_S) = Q(S, S^c)
\]

and \( \text{var}_\pi(1_S) = \pi(S)(1 - \pi(S)) \), so \( 1 - \lambda_1 \leq Q(S, S^c)/\pi(S)(1 - \pi(S)) \). The right-hand side is the same for \( S \) and \( S^c \), so we can restrict our attention to \( \pi(S) \leq 1/2 \). Since \( 1 - \pi(S) \geq 1/2 \), we have \( 1 - \lambda_1 \leq 2h \).

For the other direction, let \( F_t = \{ x : f(x) \geq t \} \) and let \( f_t \) be the indicator function of the set \( F_t \). Since only differences \( f(x) - f(y) \) appear in \( \mathcal{E}(f, f) \), defined in (6.1.7), we can without loss of generality suppose that the median of \( f \) is 0, i.e., \( \pi(F_t) \leq 1/2 \) for \( t > 0 \), and
\[ \pi(F_t^c) \leq 1/2 \text{ for } t < 0. \] Our next step is to compute something that would be the Dirichlet form if we had squared the increment.

\[ \frac{1}{2} \sum_{x,y} |f(x) - f(y)|Q(x, y) = \sum_{f(x) > f(y)} (f(x) - f(y))Q(x, y) = \sum_{x,y} \int_{-\infty}^{\infty} 1_{\{f(y) < t < f(x)\}} Q(x, y) \, dt \]
\[ = \int_0^\infty |\partial F_t| \, dt + \int_{-\infty}^0 |\partial F_t^c| \, dt \]
\[ \geq h \left( \int_0^\infty \pi(F_t) \, dt + \int_{-\infty}^0 \pi(F_t^c) \, dt \right) = h\pi(|f|) \]

Continuing to suppose that the median of \( f \) is 0, let \( g = f^2 \text{sgn}(f) \), where \( \text{sgn}(x) = 1 \) if \( x > 0 \), \( \text{sgn}(x) = -1 \) if \( x < 0 \), and \( \text{sgn}(0) = 0 \). \(|g| = f^2 \) so the last inequality implies

\[ 2h\pi(f^2) \leq \sum_{x,y} |g(x) - g(y)|Q(x, y) \leq \sum_{x,y} |f(x) - f(y)|(|f(x)| + |f(y)|)Q(x, y) \]

To check the last inequality, we can suppose without loss of generality that \( f(x) > 0 \) and \( f(x) > f(y) \). If \( f(y) \geq 0 \) we have an inequality, while if \( f(y) < 0 \) we have \( f^2(x) + f^2(y) < (|f(x)| + |f(y)|)^2 \). Using the Cauchy-Schwarz inequality now the above is

\[ \leq \left( \sum_{x,y} (f(x) - f(y))^2 Q(x, y) \right)^{1/2} \cdot \left( \sum_{x,y} (|f(x)| + |f(y)|)^2 Q(x, y) \right)^{1/2} \]
\[ \leq (2\mathcal{E}(f, f))^{1/2} (4\pi(f^2))^{1/2} \]

Rearranging gives \( (2\mathcal{E}(f, f))^{1/2} \geq h(\pi(f^2))^{1/2} \). Squaring we have

\[ \mathcal{E}(f, f) \geq \frac{h^2}{2} \pi(f^2) \geq \frac{h^2}{2} E_\pi(f - E_\pi f)^2 \]

which proves the desired result. \( \square \)

**Example 6.3.4. Markov chains on graphs.** Let \( G \) be a finite connected graph, \( d(x) \) be the degree of \( x \), and define a transition kernel by \( K(x, x) = 1/2 \), \( K(x, y) = 1/2d(x) \) if \( x \sim y \) and \( K(x, y) = 0 \) otherwise. Our \( K \) can be written \((I + p)/2\) where \( p \) is another transition probability, so all of the eigenvalues of \( K \) are in \([0, 1]\), and \( \lambda_{\text{max}} = \lambda_1 \). \( \pi(x) = d(x)/D \) where \( D = \sum_{y \in G} d(y) \), defines a reversible stationary distribution since \( \pi(x)K(x, y) = 1/2D = \pi(y)K(y, x) \). Letting \( e(S, S^c) \) is the number of edges between \( S \) and \( S^c \), and \( \text{vol}(S) \) be the sum of the degrees in \( S \), we have

\[ h = \frac{1}{2} \min_{\pi(S) \leq 1/2} \frac{e(S, S^c)}{\text{vol}(S)} \]
When \( d(x) \equiv d, \ h = \nu/2d \) where

\[
\nu = \min_{|S| \leq n/2} \frac{e(S, S^c)}{|S|}
\]

is the edge isoperimetric constant.

The next two examples show that both inequalities are “sharp.”

**Example 6.3.5. Random walk on the circle.** To illustrate the use of Theorem 6.3.3 and to show that one cannot get rid of the power 2 from the lower bound, consider random walk on the circle \( \mathbb{Z}/n \) in which we stay put with probability 1/2 and jump from \( x \) to \( x \pm 1 \) with probability 1/4 each. Taking \( S = \{1, 2, \ldots, n/2\} \) we see that

\[
\nu = \frac{2n}{n} = 4/n
\]

To bound the spectral gap, we let \( f(x) = \sin(\pi x/n) \). Since \( \sin(a+b) = \sin a \cos b + \sin b \cos a \) we have

\[
(I - K)f(x) = f(x)(1 - \cos(\pi/n))/2
\]

and \( 1 - \lambda_1 \leq (1 - \cos(\pi/n))/2 \sim \pi^2/4n^2 \) as \( n \to \infty \). Using Theorem 6.1.1 gives an upper bound on the convergence time of order \( O(n^2 \log n) \). However using the local central limit theorem for random walk on \( \mathbb{Z} \) it is easy to see that \( \Delta(t) \leq \epsilon \) at a time \( K_\epsilon n^2 \).

**Example 6.3.6. n-dimensional hypercube.** Consider the lazy random walk on the hypercube \( \{0, 1\}^n \) and let \( S = \{x : x_1 = 0\} \). Since \( \pi(S) = 1/2 \).

\[
\Phi(S) = 2 \sum_{x \in S, y \in S^c} 2^{-n}p(x, y)
\]

\[
= 2^{-n+1} \cdot 2^{n-1} \cdot \frac{1}{2n} = \frac{1}{2n}
\]

To determine the rate of convergence to equilibrium note that the lazy chain may be formulated as: pick a coordinate at random and then flip a fair coin to determine its state. From this it is clear that when we have touched all the coordinates the system is in equilibrium. To compute the spectral gap note that the coordinates are independent so \( \gamma = 1/n \). It is not hard to verify this by hand but the details can be found in Section 12.4 of Levin and Peres (2017) which concerns product chains.

**6.3.2 Mixing times and the conductance profile**

In some examples given an initial state \( i \), it is possible to define stopping times \( T \) (which are called stationary times so that \( X_T \) has the stationary distribution. Define \( H(i, \pi) \) the minimum value of \( ET \) for all such stopping times and let \( H = \max_i H(i, \pi) \). For more on stationary times (and strong stationary times) see Chapter 6 in Levin and Peres (2017)
To be completely accurate we should redefine the mixing time by
\[
T_{\text{mix}} = \max_i \min\{t : d_{TV}(K^t(i, \cdot), \pi) < 1/e\}
\]
Earlier, see (6.1.3), we used $1/4$ instead of $1/e$. The choice of threshold is not important as long as it is small enough, but it does affect the $C_i$ in the next result. Aldous (1988) has shown, see also Aldous, Lovász, and Winkler (1997), that
\[
C_1 \mathcal{H} \leq T_{\text{mix}} \leq C_2 \mathcal{H}.
\]
Define the conductance profile by
\[
\Phi(x) = \min_{S : 0 < \pi(S) \leq x} \frac{Q(S, S^c)}{\pi(S) \pi(S^c)}
\]
Lovász and Kannan (1999) have shown that
\[
\mathcal{H} \leq 32 \int_{\pi_{\text{min}}}^{1/2} \frac{dx}{x \Phi(x)^2}
\]
Morris and Peres (2003) used their notion of evolving sets to sharpen this result to
\[
\text{If } n \geq \int_{\pi(i) \wedge \pi(j)}^{4/e} \frac{dx}{x \Phi(x)^2} \text{ then } \left| \frac{K^n(i, j)}{\pi(i)} - 1 \right| \leq \epsilon
\]
These results are useful for improving rate of convergence results in some examples. However in some of our favorite examples the worst conductance occurs for small sets, so we will instead use a recent result of Fountolakis and Reed (2008).

**Theorem 6.3.7.** If $\Phi_c(x)$ be the minimum $Q(S, S^c)/\pi(S) \pi(S^c)$ over all connected sets $S$ with $x/2 \leq \pi(S) \leq x$ then
\[
T_{\text{mix}} \leq 32 \int_{\pi_{\text{min}}}^{1/2} \frac{dx}{x \Phi_c(x)^2}
\]

### 6.4 Fixed degree distribution, minimum degree 3

Gkantsidis, Mihail, and Saberi (2003) have proved the following:

**Theorem 6.4.1.** Consider a random graph with a fixed degree distribution in which the minimum degree is $r \geq 3$. There is a constant $\alpha_0 > 0$ so that with probability tending to 1 as $n \to \infty$
\[
\min_{\pi(S) \leq 1/2} \frac{e(S, S^c)}{\text{vol}(S)} \geq \alpha_0.
\]
and hence by Theorem 6.1.1 it follows that the mixing time is $\leq C \log n$. 

The diameters of these graphs are of $O(\log n)$ so it cannot occur at a faster rate. The condition $r \geq 3$ is necessary since if there is a positive density of vertices of degree 2 then there will be paths of length $O(\log n)$ in which each vertex has degree 2 and if we start in the middle of the path then the mixing time will be $\geq O(\log^2 n)$. We will consider that case in the next section.

**Proof.** We say that a set of vertices $S$ is bad if $e(S, S^c)/\text{vol}(S) \leq \alpha$. Our goal is to show that $\overline{P}(\exists \text{ bad } S) \to 0$. There are at most $D/r^{k/r}$ sets that have volume $k$.

Let $f(m)$ be the number of ways of dividing $m$ objects into pairs.

$$f(m) = \frac{m!}{(m/2)!2^{m/2}} \quad (6.4.1)$$

Let $P(k, \ell)$ that there is a set $S$ with $\text{vol}(S) = k$ has $e(S, S^c) = \ell$.

$$P(k, \ell) \leq \binom{k}{\ell} \binom{D - k}{\ell} \ell! f(k - \ell) f(D - k - \ell) \frac{1}{f(D)} \quad (6.4.2)$$

To see this recall that in the random configuration model we pair the $D$ half-edges at random, which can be done in $f(D)$ ways. We pick $\ell$ of $k$ half-edges in $S$ and $\ell$ of those $D - k$ in $S^c$. The $\ell$ which will make up $e(S, S^c)$ can be paired in $\ell!$ ways. Then the remaining $k - \ell$ half-edges in $S$ can be paired in $f(k - \ell)$ ways and the $D - k - \ell$ in $S^c$ in $f(D - k - \ell)$ ways.

To make it easier to compare with the argument in GMS we change values $\ell = \alpha k$.

Taking into account the number of choices of $S$, the probability of a bad set with volume $k$ and $e(S, S^c) = \alpha k$ is

$$\binom{D/r^{k/r}}{k/\alpha k} \binom{D - k}{\alpha k} \frac{(\alpha k)! f(k - \alpha k) f(D - k - \alpha k)}{f(D)} \quad (6.4.3)$$

Their formula (10) is this with $s! = (\alpha k)!$ replaced by the larger $f(2\alpha k)$. They also have a factor $\alpha k$ to account for $1 \leq s \leq \alpha k$.

To bound the binomial coefficients, the following lemma is useful

**Lemma 6.4.2.**

$$\binom{n}{m} \leq \frac{n^m}{m!} \leq \frac{n^m}{m^m e^{-m}}$$

**Proof.** The first inequality follows from $n(n - 1) \cdots (n - m + 1) \leq n^m$. For the second we note that the series expansion of $e^m$ has only positive terms so $e^m > m^m/m!$. \hfill \square

From Lemma 6.4.2, we see that the three binomial coefficients in (6.4.3) are

$$\leq \left( \frac{De}{k} \right)^{k/r} \left( \frac{e}{\alpha} \right)^{2\alpha k} \left( \frac{D - k}{k} \right)^{\alpha k} \quad (6.4.4)$$
Here, to prepare for a later step, we have transferred part of the bound for the third term into the second.

To bound the $f$'s in (6.4.3) we use Stirling’s formula to conclude

$$f(m) = \frac{m!}{(m/2)!2^{m/2}} \sim C \frac{m^{m+1/2}e^{-m}}{(m/2)^{m/2+1/2}e^{-m/2}2^{m/2}} = C(m/e)^{m/2}$$

From this we see that the fraction in (6.4.3) is

$$\leq Ck^{1/2}(\alpha k/e)^{ak} (k(1-\alpha)/e)^{k(1-\alpha)/2} \frac{(1+(\alpha)k)/e}{(D-(1+\alpha)k)/2}$$

$$= Ck^{1/2}(\alpha k)^{a-\alpha} \frac{k(1-\alpha)}{D} \left(1 - \frac{(1+\alpha)k}{D}\right)^{D-(1+\alpha)k}/2$$

(6.4.5)

since the exponents in the numerator sum to $D/2$.

Combining (6.4.4) and (6.4.5) gives an upper bound

$$\leq Ck^{1/2}e^{k/r} \left(\frac{e^2}{\alpha}\right)^{a} \left(\frac{D-k}{D}\right)^{a} \left(1 - \frac{(1+\alpha)k}{D}\right)^{(D-(1+\alpha)k)/2}$$

Ignoring the $Ck^{1/2}$'s, the first term is the first term from (6.4.4), the second and third terms come from combining the second and third terms of (6.4.4) and with the first and second terms of (6.4.5), while the remainder of the formula comes from (6.4.5). Using $\alpha > 0$ and $D - k < D$ and rearranging we have

$$\leq Ck^{1/2}e^{k/r} \left(\frac{e^2}{\alpha}\right)^{a} \left(\frac{k}{D}\right)^{k(1-\alpha)/2 - k/r} \left(1 - \frac{(1+\alpha)k}{D}\right)^{(D-(1+\alpha)k)/2}$$

(6.4.6)

Setting $\beta = e^2/\alpha$ and $\gamma = (1-\alpha)/2 - 1/r$ we have

$$\leq Ck^{1/2}e^{k/r} \beta^{ak} \left(\frac{k}{D}\right)^{\gamma k} \left(1 - \frac{(1+\alpha)k}{D}\right)^{(D-(1+\alpha)k)/2}$$

Comparing with formula (17) in Gkantsidis, Mihail, and Saberi (2003), we see that apart from the differences that result from our use of $(ak)!$ instead of $f(2ak)$, they are missing the $e^{k/r}$ and we have retained an extra term to compensate for the error.

Let

$$G(k) = e^{k/r} \beta^{ak} \left(\frac{k}{D}\right)^{\gamma k} \left(1 - \frac{(1+\alpha)k}{D}\right)^{(D-(1+\alpha)k)/2}$$

$Ck^{1/2} \leq Cn^{1/2}$ so we can show $h \geq \alpha_0$ by showing that for $0 \leq \alpha \leq \alpha_0$

$$\sup_{1 \leq k \leq D/2} G(k) = o(n^{-5/2})$$
because then we can sum our estimate over \( k \leq D/2 \) and \( s = \alpha k \) with \( \alpha \leq \alpha_0 \) and end up with a result that is \( o(1) \).

\[
\beta^{\alpha k} \exp(\eta k) \text{ where } \eta = \alpha \log(e^2/\alpha) \to 0 \text{ as } \alpha \to 0.
\]

Ignoring this term, and setting \( k = D/2 \), \( \alpha = 0 \)

\[
G(D/2) = e^{D/2r} (1/2)^{[1/2-1/r]D/2+D/4} = (e^{1/3}(1/2)^{2/3})^{D/2}
\]

when \( r = 3 \), the worst case. Since \( 4 > e \), the quantity in parentheses is \( < 1 \) when \( \alpha = 0 \) and hence also when \( 0 \leq \alpha \leq \alpha_0 \), if \( \alpha_0 \) is small.

To extend this result to other values of \( k \), let

\[
H(k) = \log G(k) = \frac{k}{r} + k\alpha \log \beta + k\gamma \log(k/D) + \frac{D - (1 + \alpha)k}{2} \log \left( 1 - \frac{(1 + \alpha)k}{D} \right)
\]

Since \( G(k) = \exp(H(k)) \), differentiating gives \( G'(k) = G(k)H'(k) \) where

\[
H'(k) = \frac{1}{r} + \alpha \log \beta + \gamma \log(k/D) + \gamma - \frac{(1 + \alpha)}{2} \log \left( \frac{D - (1 + \alpha)k}{D} \right)
\]

\[
+ \frac{D - (1 + \alpha)k}{2} \cdot \frac{D}{D - (1 + \alpha)k} \cdot \left( \frac{-(1 + \alpha)k}{2} \right)
\]

Differentiating again \( G''(k) = G(k)(H'(k)^2 + H''(k)) \) where

\[
H''(k) = \frac{\gamma}{k} - \frac{(1 + \alpha)}{2} \cdot \frac{D}{D - (1 + \alpha)k} \cdot \left( \frac{-(1 + \alpha)}{D} \right) > 0
\]

From the last calculation we see that \( G(k) \) is convex. We have control of the value for \( k = D/2 \). It remains then to inspect the values for small \( k \). Dropping the last factor which is \( < 1 \)

\[
G(k) \leq e^{k/r} \beta^{\alpha k} \left( \frac{1}{\alpha D} \right)^{\gamma k}
\]

When \( 0 \leq \alpha \leq \alpha_0 \leq 1/24 \), \( \gamma \geq 7/48 \) and hence \( G(24) \leq Cn^{-7/2} \). Since \( e(S, S^c) \geq 1 \) there is nothing to prove for \( k \leq 1/\alpha_0 = 24 \) and the proof is complete.

\[
\square
\]

### 6.5 Effect of degree 2 vertices

In the previous section we saw that if the minimum degree on a connected graph with \( n \) vertices is 3 then the random walk mixes in time \( O(\log n) \). This conclusion is false for configuration model graphs if there are vertices of degree 2. It is easy to see that such graphs will have paths of length \( \geq \delta \log n \) in which all the vertices have degree 2. If we start in the middle of such a path, it will with positive probability take time \( \delta^2 \log^2 n \) to escape from it.

I knew this when I was writing the first edition of this book, which was published in 2007. I wanted to prove an upper bound of the same order, but I could not cope with the
complexities of a general graph, so I created a simple example. Start with a random 3-regular graph $H$ with $(1 - a)n$ vertices, and hence $3(1 - a)n/2$ edges. We produce a new graph $G_{23}$ by replacing each edge by a path with a geometric number of edges with success probability $r$, i.e., with probability $(1 - r)^{j-1}r$ we have $j$ edges. The number of vertices of degree 2 in one of these paths has mean $(1/r) - 1$ so if we pick $r$ so that

$$\frac{3(1-a)}{2} \cdot ((1/r) - 1) = a,$$

then we asymptotically have $n$ vertices and $p_2 = a$.

Our main result is that

**Theorem 6.5.1.** The mixing time of the lazy random walk on $G_{23}$ is $\Theta(\log^2 n)$.

To prove an upper bound, we will use mixing time result in Theorem 6.3.7. I appreciate the fact that on a trip to Montreal (circa 2006) Bruce Reed (a) spent a long time explaining the proof to me, and (b) gave me a tutorial on the wonders of Belgian beer.

**Proof.** To begin we need a simple combinatorial result.

**Lemma 6.5.2.** The number of connected subsets of $H$ of size $k$ containing a fixed vertex $v_0$ is $\leq 3^{3k}$.

**Proof.** Given a connected set $V$ of vertices of $H$, define the set $W = \{(x, y) : x, y \in V, x \neq y\}$. Note that if $(x, y) \in W$ then $(y, x) \in W$ and think of these as two oriented edges between $x$ and $y$. We will show that there is a Hamiltonian paths starting from $v_0$ that traverses each oriented edge at most once. The number of edges in $W$ is at most $3k$. At each stage we have at most 3 choices so the number of such paths is $\leq 3^{3k}$ this proves the desired result.

To construct the path start at $v_0$ and pick an outgoing edge. When we are at a vertex $v \neq v_0$ we have used one more incoming edge than outgoing edge so we have at least one way out. This procedure may terminate by coming back to $v_0$ at a time when there are no more outgoing edges. If so, and we have not exhausted the graph, then there is some vertex $v_1$ on the current path with an outgoing edge. Repeat the construction starting from $v_1$ using edges not in the current path. We will eventually come back to $v_1$. We can combine the two paths by using the old path from $v_0$ to the first visit to $v_1$, using the new path to go from $v_1$ to $v_0$, and then the old path to return from $v_1$ to $v_0$. Repeating this construction we will eventually exhaust all of the edges.

Let $B$ be a connected subset of $G$, and let $A = B \cap H$. It is easy to see that $A$ is a connected subset of $H$. By the isoperimetric inequality for random regular graphs, there is an $\alpha > 0$ so that $|\partial A| \geq \alpha|A|$, where $\partial A$ is the set of edges $(x, y)$ with $x \in A$ and $y \not\in A$. From the construction of the graph it is easy to see that $|\partial B| = |\partial A|$.

It remains to see how big $|B|/|A|$ can be. When $|A| = 1$ we can have $|B| = O(\log n)$. The key to the proof is to show that the ratio cannot be big when $|A|$ is. Let $X_i$ be i.i.d with $P(X_i = j) = (1 - r)^j r$ and let $S_m = X_1 + \cdots X_m$. 

Lemma 6.5.3. There are constants $\beta$ and $\gamma$ so that

$$P(S_m \geq \beta \log n + \gamma m) \leq n^{-2}(2/81)^m$$

Proof. The moment generating function

$$\psi(\theta) = E e^{\theta X_i} = \sum_{j=0}^{\infty} (e^{\theta}(1-r))^{j}r = \frac{r}{1-e^{\theta}(1-r)}$$

when $e^{\theta}(1-r) < 1$. If we pick $\theta > 0$ so that $e^{\theta}(1-r) = 1 - r/2$ then $\psi(\theta) = 2$. Markov’s inequality implies

$$P(S_m \geq \beta \log n + \gamma m) \leq \psi(\theta)^m \exp(-\theta[\beta \log n + \gamma m])$$

Letting $\beta = 2/\theta$ and $\gamma = 81/\theta$ the desired result follows.

If $|A| = k$ then the number of edges adjacent to some point in $A$ is $\geq k + 2$, the value for a tree and $\leq 3k$. Since the number of connected sets of size $k$ is $\leq n2^k$ it follows that with probability $1 - O(n^{-1})$ we have $|B| \leq \beta \log n + 3\gamma |A|$ for connected sets $B$. From this it follows that

$$|\partial B| = |\partial A| \geq \alpha |A| \geq \frac{\alpha}{\gamma}(|B| - \beta \log n)$$

if $|B| \geq 2\beta \log n$ then $|\partial B|/|B| \geq c$, while for $|B| \leq 2\beta \log n$, $|\partial B|/|B| \geq 2/|B|$.

To evaluate $\int_{1/3n}^{1} dx/(x\Phi(x)^2)$ up to a constant factor we note that

$$\int_{2\beta \log n/n}^{1/2} \frac{dx}{x} = O(\log n)$$

while changing variables $y = nx, dy = n dx$ shows

$$\int_{1/3n}^{2\beta \log n/n} \frac{dx}{x(2/xn)^2} = \int_{1/3}^{2\beta \log n} \frac{dy}{y(2/y)^2} = O(\log^2 n)$$

and completes the proof.

Other related results:

Fountoulakis and Reed (2008) investigated Erdős-Rényi graphs with $\lambda$ ranging from $(1 + \epsilon)/n$ to $(2 \log n)/n$ and identified the range of values for which the mixing time is $\Theta((\log n)^2)$. See Section 6.6.

Benjamini, Kozma, and Wormald (2014) studied the Erdős-Rényi graph $G(n, m)$ with a fixed number of edges $m$ and $m/n \to c > 1$ and showed that the mixing time was $\Theta(\log^2 n)$. They did this by showing that (i) these graphs are decorated expanders: there is an expander subgraph $B$ which they call the strong core, which leaves only small components when it is deleted, and (ii) proving a mixing time result for decorated expanders.
Ding, Lubetzky, and Peres (2014) gave a description of the giant component of the Erdös-Rényi graph outside the critical window, i.e., $\lambda = (1 + \epsilon)/n$ with $\epsilon^3 n \to \infty$. In rough terms there are three steps (i) one builds a graph with minimum degree 3 using the configuration model, (ii) subdivide each edge into a path using i.i.d. geometrics, and (iii) attach a Poisson number of subcritical Galton-Watson trees to each vertex.

This work is a sequel to a paper the trio wrote in 2011 with J.H. Kim on the “anatomy of a young giant component,” which concentrates on the situation $\epsilon$ is small. In both cases the constructed model is only contiguous to the giant component for the Erdös-Rényi graph. When two random graph models are continuous they have the same qualitative properties: anything that hold a.a.s. (asymptotically almost surely) for one model holds a.a.s for the other, but quantitative properties may differ. See Section 9.6 of Janson, Luczak, and Ruciński’s book *Random Graphs* for a brief course in contiguity or see Kim’s (2008) paper for more thorough treatment.

### 6.6 Connected Erdös-Rényi graphs

In this section we will consider random walk on $ER(n, (c \log n)/n)$ with $c > 1$, which Theorem 1.9.1 has shown is connected with high probability for large $n$. The word “connected” in the title of the section is a bit of a red herring because we make this assumption on the value of $\lambda$ not to avoid the trivial obstruction to convergence that comes from lack of irreducibility, but to have the stability that occurs when all vertices have large degree. At the end of this section we will describe results of Fountoulakis and Reed (2008) that apply to all values of $\lambda \in [(1 + \epsilon)/n, (2 \log n)/n]$ and show how the mixing rate evolves as $\lambda$ is increases.

Let $d(x)$ be the degree of $x$, write $x \sim y$ if $x$ and $y$ are neighbors. To avoid problems associated with periodicity, we run the lazy random walk with $K(x, x) = 1/2$ $K(x, y) = 1/2d(x)$ if $x \sim y$ and $K(x, y) = 0$ otherwise. Our analysis of the mixing time follows Cooper and Frieze (2003) who were primarily interested in the cover time $C_G$, i.e., the time to visit all the vertices.

**Theorem 6.6.1.** Suppose that $np = c_n \log n$ where $c_n = O(1)$ and $(c_n - 1) \log n \to \infty$. Then whp $C_G \sim c \log \left( \frac{c}{c - 1} \right) n \log n$

To prove this result they needed to establish a number of properties of the Erdös-Rényi graph $G_{n,p}$ including

**Theorem 6.6.2.** Consider $ER(n, (c \log n)/n)$ with $c > 1$. The lazy random walk mixes in time $O(\log n)$.
Proof. We begin by estimating the maximum and minimum degrees of vertices.

**Lemma 6.6.3.** There is a constant $\delta > 0$ so that if $n$ is large then
\[
delta c \log n \leq d(x) \leq 4c \log n \quad \text{for all } x
\]

Proof. By the large deviations result in Lemma A.1.8 if $X = \text{Binomial}(n, p)$ then
\[
P(X \geq np(1 + y)) \leq \exp(-npy^2/2(1 + y))
\]
Taking $p = (c \log n)/n$, and $y = 3$
\[
P(X \geq 4c \log n) \leq \exp(-9(c \log n)/8) = n^{-9c/8}
\]
Since we have assumed $c > 1$ with high probability, the maximum degree in the graph is $\leq 4c \log n$.

To get a lower bound, we need the more precise result in Lemma A.1.6. The function
\[
H(a) = a \log(a/p) + (1 - a) \log((1 - a)/(1 - p))
\]
defined there has $H(0) = -\log(1 - p)$, which is sensible since $P(X = 0) = (1 - p)^n$. When $p = c \log n$
\[
(1 - (c \log n)/n)^n \leq n^{-c}
\]
Taking $a = (\delta c \log n)/n$, we have
\[
H(a) = \frac{\delta c \log n}{n} \log \delta + \left(1 - \frac{\delta c \log n}{n}\right) \log \left(\frac{1 - \delta c \log n/n}{1 - c \log n/n}\right)
\]
The logarithm in the second term is
\[
\log \left(1 + \frac{(1 - \delta)c \log n/n}{1 - c \log n/n}\right) \sim (1 - \delta)c \log n/n
\]
as $n \to \infty$. As $\delta \to 0$, $\delta \log \delta \to 0$, so if $\delta$ is small enough then $H(\delta) \sim (b \log n)/n$ with $b > 1$ as $n \to \infty$ and we conclude that with probability that tends to one, the minimum degree in the graph is $\geq \delta c \log n$. \qed

To prove the theorem we will estimate the conductance $h$ introduced in Section 6.3. By considering the number of edges we see that
\[
\text{vol}(G) = 2\text{binomial}\left(\binom{n}{2}, c \log n/n\right)
\]
which has mean $\sim cn \log n$ and variance $\sim cn \log n$, so $\text{vol}(G) \sim cn \log n$. The maximum degree $\leq 4c \log n$ with high probability for large $n$, so if $|S^c| \leq n/10$ then
\[
\text{vol}(S^c) \leq 4c \log n \cdot n/10
\]
and hence for large \( n \) no set with \( |S| \geq 9n/10 \) will have \( \pi(S) \leq 1/2 \).

**Case 1.** Consider \( B = \{ S : n/(c \log n) \leq |S| \leq 9n/10 \} \) and let \( s = |S| \). Using Lemma 6.4.2 we have

\[
(n/s) \leq (n/s)^s e^s = \exp(s[\log(n/s) + 1]) \quad (6.6.1)
\]

Lemma 1.9.5 says that if \( X = \text{binomial}(n, p) \) then

\[
P(X \leq np(1 - y)) \leq \exp(-npy^2/2)
\]

The number of edges from \( S \) to \( S^c \) is binomial\((s(n-s), c \log n)/n\). Using the large deviations result with \( n = s(n-s), p = p \), and \( y = 1/2 \) gives that the binomial probability

\[
\leq \exp(-s(n-s)(c \log n)/8n) \quad (6.6.2)
\]

Combining the last two estimates and using \( n-s \geq n/10, s \geq n/(c \log n) \) we see that there is a \( S \in B \) with \( e(S, S^c) \leq s(n-s)p/2 \) is

\[
\leq n \cdot \exp\left(-\frac{n}{c \log n} \left[ \frac{c \log n}{80} - \log(c \log n) - 1 \right]\right)
\]

which goes to 0 exponentially fast as \( n \to \infty \). To finish up now we note that

\[
s(n-s)p/2 = s(n-s)(c \log n)/2n \geq sc(\log n)/20
\]

while \( \text{vol}(S) \leq 4sc \log n \), so for sets in \( B \) we have \( e(S, S^c)/\text{vol}(S) \geq 1/80 \).

**Case 2.** Finally we have to deal with the small sets \( A = \{ S : 1 \leq |S| \leq n/(c \log n) \} \). In this case we upper bound \( e(S, S) \) in order to conclude \( e(S, S^c) \) is large. \( |e(S, S)| \leq (s^2/2)p \leq s/2 \) so

\[
P(\exists S \in A : e(S, S) \geq s \log \log n) \leq C\left(\frac{n}{s}\right) \left(\frac{s^2/2}{s \log \log n}\right)^{s \log \log n}
\]

The right-hand side is the probability \( e(S, S) = s \log \log n \), ignoring the fact that this may not be an integer. However in this part of the tail, the probabilities decay exponentially fast. Bounding the binomial coefficients using Lemma 6.4.2, and filling in the value of \( p \)

\[
\leq C\left(\frac{ne}{s}\right)^s \left(\frac{s^2/2}{s \log \log n}\right)^{s \log \log n} e^{-s \log \log n} = C\left(\frac{ne}{s}\right)^s \left(\frac{s}{2 \log \log n} \cdot \frac{ec \log n}{n}\right)^{s \log \log n}
\]

Reorganizing we have

\[
= C \exp\left(s[\log(ne) - \log s] + s \log \log n \left[ \log s + \log\left(\frac{ec \log n}{2n \log \log n}\right) \right]\right)
\]

Differentiating the exponent with respect to \( s \) we have

\[
\log(ne) - \log s - 1 + \log \log n[\log s + \log(ec \log n) - \log(2n \log \log n)] + \log \log n
\]
When \(1 \leq s \leq n/(c \log n)\) this is negative, so the worst case is \(s = 1\). In this case the quantity of interest is

\[
= \exp \left( \log(n e) + \log \log n \left[ \log(ec \log n) - \log(2n \log \log n) \right] \right)
\]

which tends to 0 as \(n \to \infty\).

To bound \(e(S, S^c)\) we note that

\[
e(S, S^c) = d(S) - e(S, S) \geq s \delta \log n - s \log \log n \geq s(\delta/2) \log n
\]

when \(n\) is large. \(\text{vol}(S) \leq 4s \log n\), so for sets in \(A\) we have \(e(S, S^c)/\text{vol}(S) \geq \delta/8\).

Mixing time changes from connected to sparse

Fountoulakis and Reed (2008) proved results about the mixing times of random walks on Erdös-Rényi graphs that over the entire range from \((1 + \epsilon)/n\) to \((2 \log n)/n\). In the first result \(p(n)\) is the probability an edge is present and \(d(n) = np(n)\) is the average degree.

**Theorem 6.6.4.** For every \(p = p(n)\) with \(d(n) - \log n \to \infty\) we have

\[
\left| T_{\text{mix}}(G_{n,p}) - \frac{\log n}{\log d} \right| \leq 3
\]

Letting \(H_{n,p}\) be the giant component of \(G_{n,p}\) and writing a.a.s. (asymptotically almost surely) instead of w.h.p.

**Lemma 6.6.5.** For \(p < (\log n)/5n\), \(H_{n,p}\) a.a.s. contains paths of length more than \((\log n)/d\) all of whose interior vertices have degree two.

To state the next result we need some notation. Let

\[
\bar{P}_{x_0}^t = (1/t) \sum_{m=1}^t P^m(x_0, \cdot) \quad T_{\text{mix}}'(G) = \sup_{x_0} \min_t \{ t : d_{TV}(\bar{P}_{x_0}^t, \pi) < 1/e \}
\]

**Theorem 6.6.6.** For every \(p(n)\) with \(\sqrt{\log n} \log \log n \leq np(n) \leq 2 \log n\) we have

\[
\left| T_{\text{mix}}'(G) - \frac{\log n}{\log d} \right| = O((\log n/d)^2)
\]

**Theorem 6.6.7.** For every \(p(n)\) with \(1 + \epsilon \leq np(n) \leq \sqrt{\log n} \log \log n\) we have

\[
|T_{\text{mix}}'(G)| = O((\log n/d)^2)
\]

To explain why the transition between the last two results happens at \(p = \sqrt{\log n} \log \log n\) we note that for this value of \(p\)

\[
(\log n/d)^2 = \frac{\log n}{\log \log n} \sim \frac{\log n}{\log d}
\]
6.7 The Cutoff Phenomenon

A sequence of finite state Markov chains is said to exhibit cutoff if its distance from the stationary distribution $\pi$ drops from 1 to 0 over a window that is $o(t_n)$ where $t_n$ is the time to converge to equilibrium. To make this notion precise we need some more definitions. Let

$$d_n(t) = \max_{x \in S} \|P_x(X_t \in \cdot) - \pi\|_{TV}$$

be the distance from equilibrium and let

$$t_{\text{mix}}^n(\epsilon) = \min\{t : d_n(t) < \epsilon\}$$

We say there is cutoff if for any $\epsilon > 0$

$$\lim_{n \to \infty} t_{\text{mix}}^n(\epsilon)/t_{\text{mix}}^n(1 - \epsilon) \to 1$$

We say there is cutoff at $t_n$ with window size $w_n$ if

$$\lim_{\lambda \to \infty} \liminf_{n \to \infty} d_n(t_n - \lambda w_n) = 1$$
$$\lim_{\lambda \to \infty} \limsup_{n \to \infty} d_n(t_n + \lambda w_n) = 0$$

A nice introduction to cutoff is given in Diaconis (1996). It is an “Inaugural Article” written on the occasion of his election to the National Academy of Science in April 1995. What follows is our rendition of his work, which lacks much of the information presented there and the style of the original. We begin with an example of a Markov chain that does not have cutoff.

**Example 6.7.1. Simple random walk on the integers modulo n.** To avoid problems with periodicity the transition probability has

$$p(i, i + 1) = p(i, i) = p(i, i - 1) = 1/3$$

where the arithmetic is done modulo $n$ so that $p(0, n - 1) = p(n - 1, 0) = 1/3$. The stationary distribution is uniform $\pi(i) = 1/n$. It is easy to show, see e.g., Diaconis (1986).

**Theorem 6.7.2.** $\|P^k_0 - \pi\| \sim Ck/n^2$.

Here and in the next three examples we have changed notation so that $P^k_x = P_x(X_k \in \cdot)$. It is clear from the central limit theorem that the total variation distance is $\approx 1$ when $k = o(n^2)$, and that we need $k \gg n^2$ for the normal distribution of the position of the walk on $\mathbb{Z}$ to flatten out enough so that when reduced modulo $n$ it is almost uniform.

It is surprising (to me at least) that cutoff occurs in
Example 6.7.3. Ehernfest chain. There are two urns and $d$ balls. In the simplest version on each step one ball is chosen at random and transferred to the other urn. However to avoid periodicity, we do nothing with probability $1/(d+1)$.

$$p(i, i) = \frac{1}{d+1}, \quad p(i, i-1) = \frac{i}{d+1}, \quad p(i, i+1) = \frac{d-i}{d+1}$$

Theorem 6.7.4. For the Ehernfest chain started at 0, if $k = \frac{1}{4}(d+1)(\log d + \theta)$ then

$$\|P_0^k - \pi\| \leq \frac{1}{\sqrt{2}}(\exp(e^{-\theta}) - 1)^{1/2}$$

while if $k = (1/4)d(\log d - \theta)$ then the total variation distance tends to 1 as $d, \theta \to \infty$.

Example 6.7.5. Random transpositions. This example considered by Diaconis and Shahshahani (1981) was perhaps the first example where a sharp cutoff was demonstrated. Picture $n$ cards at random on a table. At each time your left and right hands choose cards independently (so left=right with probability $1/n$) and then the cards positions are switched. The stationary distribution is uniform over all the $n!$ arrangements.

Theorem 6.7.6. Let $k = (1/2)n(\log n + \theta)$ with $\theta > 0$, For any starting position $x$,

$$\|P_x^k - \pi\| \leq Ae^{-\theta/2}$$

To explain the answer, suppose we start with the identity permutation. The expected number of fixed points of a randomly chosen permutation is 1, and the distribution is roughly Poisson. By results for the coupon collectors problem, see Example 6.7.10 for more detail, it takes time $\sim (n/2)\log(n)$ until we have moved every card at least once. If there are a lot of cards that have not moved the chain is not in equilibrium because there are too many fixed points.

Example 6.7.7. Riffle shuffles are an approximation of how humans, that are not magicians by training, shuffle cards. The deck is cut into two pieces according to a symmetric binomial distribution. Then the two halves are riffled together according to the following rule. If the pile in the left hand has $A$ cards and the one in the right hand has $B$ cards then the next card drops from the left pile with probability $A/(A+B)$ and from the right pile with probability $B/(A+B)$. Let $p(x, y)$ be the transition probability of this shuffling method, which is called the Gilbert-Shannon-Reeds riffle shuffle. Bayer and Diaconis (1992) proved

Theorem 6.7.8. Let $k = (3/2)\log_2 n + \theta$. Then

$$\|P_x^k - \pi\| = 1 - 2\Phi(-2^\theta/\sqrt{3}) + O(1/\sqrt{n})$$

where $\Phi$ is the standard normal distribution function.
There are by now many examples. We will add two more from Levin and Peres (2017) that are closely related to the first four and then leave it to the reader to explore the subject further. For the next two example references such as the one to Proposition 7.14 are to their book.

**Example 6.7.9. Random walk on the hypercube.** The state space is \(\{0, 1\}^n\). The dynamics are simple. We pick a coordinate at random and flip it. To avoid the problems of periodicity we consider the lazy walk that does nothing with probability 1/2.

This example is used throughout the book by Levin and Peres (2017). Their Proposition 7.14 shows that

\[
t_{\text{mix}}(1 - \epsilon) \geq \frac{1}{2} n \log n - c_{\ell}(\epsilon) n
\]

In their Example 12.19 using the known eigenvalues and eigenfunctions for the chain, it was proved that

\[
t_{\text{mix}}(\epsilon) \leq \frac{1}{2} n \log n - c_u(\epsilon) n
\]

Thus the lazy random walk on the hypercube has cut off at \((1/2)n \log n\) with a window of size \(O(n)\).

**Example 6.7.10. Top to random shuffle.** Suppose to simplify the discussion that initially the Ace of spades (A♠) is at the bottom of the deck. It will gradually rise to the top as cards are inserted below it. It is easy to show by induction that when there are \(k\) cards below the A♠ they are in random order. Thus if we let \(\tau_n\) be the time at which the A♠ is inserted into a random position in the deck, the system is in equilibrium.

In the terminology of Chapter 6 of Levin and Peres (2017) \(\tau_n\) is a stationary time. It has the additional property that

\[
P_x(\tau_n = t, X_\tau = y) = P_x(\tau_n = t) \pi(y)
\]

so it is a strong stationary time, i.e., the chain is stationary even if we condition on when \(\tau\) occurs. Proposition 6.11 says that if \(\tau\) is a strong stationary times then

\[
d_n(t) \equiv \|P^t(x, \cdot) - \pi\|_{TV} \leq P(\tau_n > t)
\]

In the case under consideration \(\tau_n\) is a coupon collectors random variable. It is a sum of independent geometric(\(k/n\)) random variables with \(k = 1, \ldots n\). It is well known that (see e.g., Example 2.2.7 in PTE5) that

\[
E\tau_n \sim n \log n \quad \text{var}(\tau_n) \sim N^2 \sum_{m=1}^{\infty} m^{-2}
\]

Proposition 2.4. says that

\[
P(\tau_n > n \log n + cn) \leq e^{-c}
\]

(6.7.1)

The proof is so easy that we go ahead and give it
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Proof. Let $A_i$ be the probability that card $i$ has not been drawn by time $n \log n + cn$.

$$P(\tau > n \log n + cn) = P(\bigcup_{i=1}^{n} A_i) \leq \sum_{i=1}^{n} P(A_i)$$

$$= n \left(1 - \frac{1}{n}\right)^{n \log n + cn} \leq n \exp(-\log n - c) = e^{-c}$$

which is the desired result. \qed

In Section 7.4.1 they look at the time it it takes for the $j$th card from the bottom to reach the top in order to prove (see their Proposition 7.15).

Theorem 6.7.11. Given $\epsilon > 0$ there is an $\alpha(\epsilon)$ so that for large $n$

$$d_n(n \log n - \alpha n) \geq 1 - \epsilon$$

This shows that there is cut off at $n \log n$ with a window of size $O(n)$.

6.8 Random regular graphs

Let $G(n, d)$ be the collection of random regular graph in which all vertices have degree $d$. The case $d = 1$ is boring: each vertex has degree 1, so the graph is a collection of isolated edges. The case $d = 2$ is not much better: the graph is a union of circles of random sizes. In what follows, we restrict our attention to $d \geq 3$ even if we do not state that explicitly. Using Theorem 6.4.1 implies that when $d \geq 3$ the mixing time on a random $d$-regular graph is $\leq C \log n$.

Lubetzky and Sly (2010) have identified the constant $C$ in the mixing time and shown that there is cutoff with a window of size $O(\log d^{-1} n)$.

Theorem 6.8.1. (Theorem 1.) Let $G \sim G(n, d)$ be a random regular graph in which all vertices have degree $d \geq 3$. Then the simple random walk exhibits cutoff at $t_n = (d/(d-2)) \log_{d-1} n$ with a window of size $w_n = O(\sqrt{\log n})$. Furthermore

$$t_{\text{mix}}(s) = \frac{d}{d-2} \log_{d-1} n - \Phi^{-1}(s)(\Lambda + o(1)) \sqrt{\log_{d-1} n}$$  \hspace{1cm} (6.8.1)

where $\Lambda = 2 \sqrt{d(d-1)/(d-2)^{3/2}}$ and $\Phi$ is the cumulative distribution function of the normal.

It is easy to guess that there is cutoff at time $t_n$ with a window of width $w_n$. Seen from a fixed vertex that we will call 0, the graph $G$ looks locally like a tree in which the root 0 has degree $d$ while the other vertices have one edge pointing back toward 0 and $d-1$ pointing away. If we assume the approximate picture is exactly correct, then the diameter of the graph is $\log_{d-1} n$ and the distance of the random walk from the root, $X_m$, when it is positive, changes by +1 with probability $(d-1)/d$ and by -1 with probability $1/d$. 
The mean of one step of the random walk (ignoring the times it is at 0) is \((d - 2)/d\) so by the law of large numbers the time to distance \(\log_{d-1} n\) is asymptotically

\[
T_n \equiv \frac{d}{d-2} \log_{d-1} n
\]

Clearly we cannot be in equilibrium at time \((1 - \epsilon)T_n\) since there are only \(O(n^{1-\epsilon})\) vertices reachable in that time and the stationary distribution is uniform.

The more precise result given in (6.8.1) comes by reasoning that we cannot be in equilibrium until the random walk has moved by more that \(\log_{d-1} n\) and using the central limit theorem to evaluate that probability. The funky formula for \(\Lambda\) should indicate that there is more to the sharp result in the displayed formula, than just computing the variance of the steps of the random walk, so my advice to the reader is to wait until the formula is done for you in (6.8.7).

**Main ideas of the proof**

The hard part of the proof of Theorem 1 is to show that once the walker has moved a distance larger than \(\log_{d-1} n\) it is in equilibrium. The proof is based on two ideas.

I. The first important idea, which is widely known, is that the graph is **locally tree like**.

To prove a result to quantify this, let

\[B_t(u) = \{v \in V : \text{dist}(u, v) \leq t\} \quad \partial B_t(u) = B_t(u) - B_{t-1}(u)\]

Let \(tx(B_t)\) be the maximum number of edges that can be deleted from \(B_t\) and still keep it connected. Here \(tx\) is short for tree excess. Sharpening the conclusion in our Theorem 1.2.3...
they show the following. Here and for the rest of the sections Lemmas are numbered as in their paper.

**Lemma 2.1.** Let $G \sim G(n, d)$ for a fixed $d \geq 3$ and let $s = \lfloor (1/5) \log_{d-1} n \rfloor$ then with high probability $tx(B_s(u)) \leq 1$ for all $u \in V(G)$.

“Proof.” When we grow the clusters out to distance $s$ there are (ignoring constants) $n^{1/5}$ vertices. In running the exploration process for time $m = n^{1/5}$ the number of collisions will be smaller than binomial$(m, m/n)$. The probability of more than 2 collisions is

$$\leq \left( \frac{m}{2} \right) \cdot (m/n)^2 \leq m^4/n^2 = O(n^{-6/5})$$

so the expected number of vertices for which this occurs is $n^{-1/5}$ and the probability of the existence of such a vertex $\to 0$.

**Theorem 1.2.** For a given vertex the number of collisions before the cluster grows to size $n^{\alpha}$ is $n^{2\alpha-1}$. If $\alpha = 2/3$ then this is $O(n^{1/3})$. While there are a large number of these, vertices with this problem, which we will call bad vertices are rare. Let $A_k$ be the probability that the random walk has stepped on a bad vertex by time $k$. Berestycki and Durrett (2008) who studied random walk on a three regular graph proved that $P(A_{3(1-\epsilon) \log n} \to 0)$, so with high probability the walk will get to time $3(1-\epsilon) \log n$ without noticing that it is not on a 3-regular tree. While the last picture is useful it breaks down badly when the walks reaches a distance equal to the diameter.

II. To analyze what happens beyond distance $\log_{d-1} n$ becomes much easier one uses the notion of the **cover tree of a graph**. Let $G = (V, E)$ be a $d$-regular graph and let $a \in V$. The cover tree is a mapping $\phi : T \to V$ where $T$ is a $d$-regular tree with root $\rho$ so that $\phi(a) = \rho$ which preserves the neighborhood relationship:

$$\mathcal{N}_G(\phi(x)) = \{ \phi(y) : y \in \mathcal{N}_T(x) \}$$

where for $H = G, T$, $\mathcal{N}_H(y)$ are the neighbors of $y$ in $H$.

To prove Theorem 1 we need several result about the structure of the cover tree. In order to conserve the reader’s energy and to make it easier to see the “big picture” we state these without proof, and refer the reader to the paper for details. To state these lemmas we need four definitions

$$K = \lfloor \log_{d-1} \log n \rfloor \quad R = \lfloor (4/7) \log_{d-1} n \rfloor \quad T = \lfloor (1/2) \log_{d-1} n \rfloor$$

A vertex $a \in V$ is a **K-root** if and only if the induced subgraph on $B_K(a)$ is a tree.

**Lemma 3.2.** Suppose that every $u \in V$ has $tx(B_{5K}(u)) \leq 1$. Then for any $v \in V$ the SRW of length $4K$ ends in a $K$-root with probability $1 - o(1)$. In particular, the number of $K$-roots is $n - o(n)$.

**Lemma 3.3.** With high probability every $K$-root $u$ satisfies

$$|\partial B_t(u)| \geq (1 - o(1))d(d - 1)^{t-1} \quad \text{for all } t < R$$
Let $\partial B_t^*(u)$ denote the set of vertices in $\partial B_t(u)$ with a single (simple) path of length $t$ to $u$.

**Lemma 3.4.** With high probability any two $K$-roots with $\text{dist}(u, v) > 2K$ satisfy

$$|\partial B_t^*(u) - B_{t+1}(v)| = (1 - o(1))d(d - 1)^{t-1} \quad \text{for all } t < R - 1$$

Let $S_k$ be the number of simple paths of length $k$ between $u$ and $v$.

**Lemma 3.5.** With high probability any two $K$-roots with $\text{dist}(u, v) > 2K$ satisfy

$$S_{2T+\ell}(u, v) \geq (1 - o(1))\frac{1}{n}d(d - 1)^{2T+\ell-1}$$

for all $2K \leq \ell \leq (1/20) \log_{d-1} n$

**Proof of Theorem 6.8.1.** By Lemma 3.2 after $K$ steps whp the random walk is at a $K$-root. Since we are only seeking to establish $t_{\text{mix}}$ to an accuracy of $o(\sqrt{\log_{d-1} n})$ and since $K = o(\sqrt{\log_{d-1} n})$ it is enough to suppose we are starting at a $K$-root.

By Lemma 3.5

$$S_{2T+\ell}(u, v) \geq (1 - o(1))\frac{1}{n}d(d - 1)^{2T+\ell-1} \quad \text{for all } 2K \leq \ell \leq (1/20) \log_{d-1} n$$

Since each simple path in $G$ corresponds to a simple path in the cover tree $T$

$$|\{ w \in T : \phi(w) = v, \text{dist}(\rho, w) = 2T + \ell \}| \geq S_{2T+\ell}(u, v) \geq (1 - o(1))\frac{1}{n}d(d - 1)^{2T+\ell-1}$$

when $2K \leq \ell \leq (1/20) \log_{d-1} n$.

Let $X_t$ be a SRW on $T$ started from $\rho$ and let $W_t = \phi(X_t)$ be the corresponding SRW on $G$ started from $u$. Note that by symmetry, the random walk conditioned on $\text{dist}(\rho, X_t) = k$ is uniform on the $d(d - 1)^{k-1}$ points at distance $k$ from $\rho$ in $T$.

A random walk on $T$ with $d \geq 3$ is transient so it returns to $\rho$ only finitely many times. If $X_t \neq \rho$ then on the next step the change the distance from $\rho$ increases by 1 with probability $(d - 1)/d$ and decreases by 1 with probability $1/d$. Let $\xi$ be a random variable with this distribution. $E\xi = (d - 2)/d$ and

$$\text{var}(\xi) = 1 - (E\xi)^2 = 1 - \frac{d^2 - 4d + 4}{d^2} = \frac{4(d-1)}{d^2}$$

Therefore the central limit theorem gives

$$\text{dist}(X_t, \rho) = \frac{t(d - 2)/d}{\sqrt{t \cdot 2d - 1/d}} \Rightarrow \text{normal}(0, 1)$$
6.8. RANDOM REGULAR GRAPHS

Let $A$ be the set of vertices that are $K$ roots and whose distance from $u$ is $\geq 2K$. Since the number of vertices with distance $2K$ is $o(n)$ it follows from by Lemma 3.2 that $|A| \geq n - o(n)$. If $v \in A$ and

$$t = \left\lfloor \frac{d}{d-2} \log_{d-1} n + k \sqrt{\log_{d-1} n} \right\rfloor$$

(6.8.4)

There are many points $w \in T$ with $\phi(w) = v$ so

$$P(W_t = v) = \sum_{j=0}^{t} P(\text{dist}(\rho, X_t) = j) \frac{|\{w \in T : \phi(w) = v, \text{dist}(\rho, w) = j\}|}{d(d-1)^{j-1}}$$

Recalling $2T = 2[(1/2) \log_{d-1} n] \approx \log_{d-1} n$ and using (6.8.2) the above

$$= \sum_{\ell = 2K}^{(1/20) \log_{d-1} n} P(\text{dist}(\rho, X_t) = 2T + \ell) \cdot \frac{1 + o(1)}{n}
= \frac{1 + o(1)}{n} \cdot P(\log_{d-1} n + 2K \leq \text{dist}(\rho, X_t) \leq 1.05 \log_{d-1} n)
= \frac{1 + o(1)}{n} \cdot P(\text{dist}(\rho, X_t) - \log_{d-1} n \geq 0)$$

Since in the second line $K = o(\sqrt{\log_{d-1} n})$ and the other inequality holds with probability $\rightarrow 1$. Substituting in the value of $t$

$$\text{dist}(\rho, X_t) - t(d - 2)/d = \log_{d-1} n + k \sqrt{\log_{d-1} n} \cdot (d - 2)/d$$

which implies $P(\text{dist}(\rho, X_t) - \log_{d-1} n \geq 0) =$

$$= P \left( \frac{\text{dist}(\rho, X_t) - t(d - 2)/d}{\sqrt{t} \cdot 2\sqrt{d - 1}/d} \geq \frac{-k \sqrt{\log_{d-1} n} \cdot (d - 2)/d}{\sqrt{t} \cdot 2\sqrt{d - 1}/d} \right)$$

(6.8.5)

Using the central limit theorem in (6.8.3) we have

$$P(\text{dist}(\rho, X_t) - \log_{d-1} n \geq 0) \approx 1 - \Phi(-k/\Lambda)$$

(6.8.6)

where $\Phi$ is the distribution function of the standard normal and

$$\Lambda = \sqrt{\frac{d}{d-2}} \cdot \frac{2\sqrt{d - 1}/d}{(d - 2)/d} = \frac{2\sqrt{d(d - 1)}}{(d - 2)^{3/2}}$$

(6.8.7)

to get to this easily start by flipping the right hand side of (6.8.5) and then use the definition of $t$ in (6.8.4).
To complete the proof now recall that $A$ is the set of vertices that are $K$-roots and we use (6.8.6)

$$\|P(W_t \cdot) - \pi\| = \sum_{v \in V} \max \left( \frac{1}{n} - P(W_t = v), 0 \right)$$

$$\leq \frac{n - |A|}{n} + \sum_{v \in A} \max \left( \frac{1}{n} - P(W_t = v), 0 \right)$$

$$= o(1) + (1 + o(1)) \cdot \frac{1}{n} \Phi(-k/\Lambda)$$

At this point the proof of the matching lower bound is not very hard but again we refer the reader to the paper for details.

### 6.9 Random walk on Galton-Watson trees

In this section we describe results of Lyons, Pemantle, and Peres (1995). Consider a supercritical Galton-Watson branching process in which each individual has $k$ children with probability $p_k$, the generating function $f(s) = \sum_{k=0}^{\infty} p_k s^k$ and the mean number of children $\mu = f'(1) > 1$. Started with a single progenitor, on the event of nonextinction the process yields a random infinite family tree $T$ called a Galton-Watson tree. The focus of the paper by LPP is on the asymptotic properties of simple random walk on $T$ that on each step jumps from a vertex to a randomly chosen neighbor. To simplify things we will assume that $p_0 = 0$, even though this eliminates the Poisson case.

#### 6.9.1 Transience

The question of transience of random walks on Galton-Watson trees first arose in work of Grimmett and Kesten (1984) on “random electrical networks.” They considered a complete graph on $n + 2$ vertices in which the resistance of an edge has

$$P(R = \infty) = 1 - \frac{\gamma(n)}{n} \quad P(R \leq x) = \frac{\gamma(n)}{n} F(x)$$

where $F$ is a fixed distribution function. If $\gamma(n) \to \gamma \in (0, \infty)$ then the connected set of edges with $R(e) < \infty$ that contain a fixed vertex converges to a Galton-Watson process with a Poisson($\gamma$) offspring distribution.

They proved that if $\gamma(n) \geq n^2$ for some $\beta > 0$ (and hence the probability the graph of finite resistance edges is connected tends to 1) then effective resistance $R_n$ between two random chosen vertices satisfies

$$\gamma(n) R_n \to 2 \left( \int_0^{\infty} x^{-1} dF(x) \right)^{-1}$$

in probability.

They stated two results for the case $\gamma(n) \to \gamma$. 


Theorem 6.9.1. If \( \gamma < 1 \) then \( P(\mathcal{R}_n = \infty) \to 1 \).

Theorem 6.9.2. If \( \gamma > 1 \) then \( \mathcal{R}_n \) converges to a limit \( \mathcal{R}_\infty \) with
\[
P(\mathcal{R}_\infty = \infty) = 2q(\gamma) - q(\gamma)^2
\]
where \( q(\gamma) \) is the extinction probability of the Poisson(\( \gamma \)) branching process.

The work was done while Grimmett was visiting Cornell in 1983, but only in 2001 were the missing proofs put on the arXiv.

In 1990 Russ Lyons published a ground breaking paper on random walks and percolation on a class of trees much more general than Galton-Watson trees. To be precise, he proved results for trees with a well-defined branching number, a growth rate inspired by a method of Furstenberg used to compute Hausdorff dimensions of sets. In the case of Galton-Watson tree, where the branching number is just the mean, his result gives

Theorem 6.9.3. If we assume that \( \mu = \sum_k k p_k > 1 \) and condition on the event that the branching process does not die out, then the random walk on the resulting tree is transient with probability one

Proof. To prove transience using Terry Lyons’ result given in Theorem 6.2.5 we will construct a flow with finite energy. To construct our flow, we will pick \( K \) so that \( \sum_{k=1}^{\infty} p_k \min\{k, K\} > 1 \) and modify the offspring distribution so that \( \bar{p}_K = 1 - \sum_{j=1}^{K-1} p_j \) and \( \bar{p}_j = p_j \) for \( j < K \). From the electrical networks point of view, the truncated branching process yields a tree that is less transient because it has higher resistance. See Theorem 6.2.2.

By arguments in the previous paragraph, it suffices to prove our result when he distribution is bounded or more generally when \( \sum_k k^2 p_k < \infty \). In this case if we let \( B_n \) be the vertices at distance \( n \) from the root, \( Z_n = |B_n| \) then \( Z_n/\mu^n \to W \) in \( L^2 \), so \( EW^2 = 1 \). We will call this value \( W(\rho) \) and set \( \theta(\rho) = W(\rho) \). Given a site \( x \in B_n \), let \( x^+ \) be the tree consisting of \( x \) and the descendants of \( x \). We define a flow by \( \theta(x) = W(x^+)/\mu^n \) where \( W(x^+) \) is the limit random variable \( \lim_{m \to \infty} Z_m(x^+)/\mu^m \) for the tree \( x^+ \). To check the flow property we note that
\[
\theta(x) = \frac{1}{\mu} \sum_{z : x \to z} \theta(z)
\]
and there is a positive flow from the root \( \rho \).

To check (iii) note that \( Q(x, y) \equiv 1 \), so taking expected value
\[
E \sum_{(y, x)} [W(x^+)/\mu^n]^2 = \sum_{n=1}^{\infty} 1/\mu^n < \infty
\]
so for almost every Galton-Watson tree the sum is finite.

Remark 6.9.4. The proofs above generalize easily to the homesick random walk in which jumps back toward the root from vertices with \( k \) children have probability \( \lambda/(\lambda + k) \) where \( \lambda > 1 \). In this case \( Q(y, x) = \lambda^{-n} \) when \( x \in B_n \), so the walk is transient if \( \lambda < \mu \).
6.9.2 Escape rate

In a Galton-Watson tree each vertex has \( k \) descendants with probability \( p_k \). Lyons, Pemantle and Peres (1995) studied the asymptotic behavior of the discrete time random walk \( X_n \) that jumps to each of the neighbors with equal probability.

**Theorem 6.9.5.** If \( \mu = \sum_{k=1}^{\infty} k p_k \in (1, \infty) \) and \( p_0 = 0 \), then

\[
\frac{|X_n|}{n} \to \ell \equiv \sum_k \frac{k - 1}{k + 1} p_k
\]

**Proof.** The limiting speed is remarkably simple. If we are at the root \( \rho \) then the distance from the root will be 1 the next time. Other vertices with \( k \) children have 1 parent so the drift at these vertices is \( \frac{k - 1}{k + 1} \).

The proof in Lyons, Pemantle, and Peres (1995) is only for a sophisticated reader. For people like me it is fortunate that Lyons and Peres (2017) have a proof that stays close to the intuition. Let \( X_n \) be the location on the tree at time \( n \) and define the drift at \( x \) by

\[
\delta(x) = \begin{cases} 1 & x = \rho \\ \frac{k - 1}{k + 1} & x \neq \rho, \text{deg}(x) = k + 1 \end{cases}
\]

From this it is clear that if \(|X_n|\) is the distance from the root then

\[
M_n = |X_n| - \sum_{m=0}^{n-1} \delta(X_m) \quad \text{is a martingale.}
\]

Since jumps of the martingale are bounded by \( K = 2 \), we have a very good bound on the deviations from the mean. See Theorem A.2.2.

**Lemma 6.9.6.** Azuma-Hoeffding inequality.

\[
P(M_n - M_0 \geq L) \leq \exp\left( -\frac{L^2}{2nK} \right)
\]

The last observation is extremely useful but we still need to do some work to show that the fraction of time spent at vertices with \( \delta(x) = \frac{k - 1}{k + 1} \) children is \( p_k \). In order to do this, we need to find a stationary distribution for the environment process, i.e., the tree as seen from the current vertex. As we have defined things the root of the Galton-Watson tree is different from the other vertices since it has stochastically one fewer neighbors. To remedy this defect we consider what LPP call the augmented Galton-Watson tree measure, or AGW. This is obtained by added another neighbor \( z \) of the root and an independent Galton-Watson tree \( T' \) rooted at \( z \). The new neighbor is the missing parent of the root, but we will not interrupt the proof to complete that thought.

To define the dynamics of the environment process, we declare that when the random walks jumps to a randomly chosen neighbor \( x \) of the root(\( T \)) then the environment chain jumps to MoveRoot(\( T, x \)), which, as the notation should suggest, is the tree \( T \) with the root moved to be at \( x \). Theorem 3.1 in LPP shows:
6.10. SPARSE ERDÖS-RÉNYI GRAPHS

**Theorem 6.9.7.** The environment chain with initial distribution \( \text{AGW} \) is stationary and reversible.

We declare this to be obvious and refer the reader to LPP for a proof. From Theorem 6.9.7 it follows that on \( \text{AGW} \) \( \delta(X_n) \) is stationary. A result in Section 8.1 of LPP implies that it is ergodic, so an application of the ergodic theorem completes the proof.

### 6.9.3 Dimension drop

The developments here require mathematics outside the author’s skill set, so we will only describe what is true and refer the reader to LPP for proofs.

**Theorem 6.9.8.** The Hausdorff dimension of harmonic measure on the boundary of a non-degenerate Galton-Watson tree \( T \) is almost surely a constant \( d < \frac{1}{\log \mu} = \dim(\partial T) \) there is a Borel subset of \( \partial T \) of full harmonic measure and dimension \( d \).

The next result explains our interest in that conclusion. In the next result \( |\Gamma^n| \) is the number of vertices in \( \Gamma \) on level \( n \).

**Theorem 6.9.9.** For any \( \epsilon > 0 \) and for almost every Galton-Watson tree \( T \), there is a subtree \( \Gamma \) of \( T \) of growth

\[
\lim_{n \to \infty} |\Gamma^n|^{1/n} = e^d < \mu
\]

such that with probability \( 1 - \epsilon \) the sample path of the random walk on \( T \) is contained in \( \Gamma \).

The proof of Theorem 6.9.8 gives an abstract integral formula for \( d \)

\[
d = \frac{1}{\ell} \int_{s=0}^{\infty} \int_{t=0}^{\infty} \frac{\log(1 + s)}{1 + s^{-1} + t^{-1}} dF(t) dF(s)
\]

where \( F \) is the distribution function of the effective conductance from the root to infinite of the Galton-Watson tree. For example, this gives that \( d = \log 1.47 \) for the tree with generating function \( (s + s^2)/2 \), and hence \( m = 1.5 \). Figure 1.2 in LPP graphs the distribution of the conductance in this case, which has a shape that is reminiscent of a stegosaurus.

### 6.10 Sparse Erdős-Rényi graphs

In Section 6.4 we saw that if we have a random graph generated by the configuration model in which vertices of degree 2 have positive probability then the mixing time of the random walk on the giant component is at least \( C \log^2 n \) since there are paths of length \( \log n \) in which all vertices have degree 2. If the walk starts in the middle of such a path then it takes time \( O(\log^2 n) \) to escape from the set.

Berestycki, Lubetzky, Peres, and Sly (2018) have shown that if we start at a randomly chosen vertex in the giant component then the mixing time becomes \( O(\log n) \) and there is cutoff with a window of \( (\log n)^{1/2+o(1)} \).

Theorem 6.10.1. Let $C_1$ be the giant component of an Erdős-Rényi$(n, \lambda/n)$ random graph with $\lambda > 1$ fixed. For any $0 < \epsilon < 1$ whp the mixing time of the random walk starting from a randomly chosen vertex $x \in C_1$ satisfies

$$|t_{\text{mix}}(\epsilon) - (\nu d)^{-1} \log n| \leq (\log n)^{1/2+o(1)}$$

Here $\nu$ is the speed of a random walk on a Poisson$(\lambda)$ Galton-Watson tree and $d$ is the dimension of harmonic measure on the ends of the tree, concepts that were introduced in the previous section. In addition to the result for Erdős-Rényi they have a result for a graph $G$ with general degree distribution $p_k$. Condition (6.10.1) is strong but weaker than having finite exponential moments.

Theorem 6.10.2. Suppose that for fixed $\delta > 0$ the random variable $Z$ given by $P(Z = k - 1) \propto p_k$ satisfies

$$P(Z > \Delta_n) = o(1/n) \quad \Delta_n \equiv \exp((\log n)^{1/2-\delta})$$

and let $t_* = (\nu d)^{-1} \log n$ where $\nu$ and $d$ are the speed of the random walk and the dimension drop for the Galton-Watson tree with offspring distribution $Z$.

(i) Set $w_n = (\log n)^{1/2}(\log \log n)^3$. If $p_2 < 1 - \delta$ and $1 + \delta < EZ < K$ for all $n$ then whp on the event that $z$ is in the largest component of $G$

$$d_{TV}(t_* - w_n, t_* + w_n) > 1 - \epsilon \quad d_{TV}(t_* + w_n) < \epsilon$$

(ii) Set $w_n = (\log n)^{1/2}$. If $Z > 2$ and $EZ < K$ for all $n$ then for any $\epsilon > 0$ there is a $\gamma < \infty$ sot aht with probability at least $1 - \epsilon - o(1)$

$$d_{TV}(t_* - w_n, t_* + w_n) > 1 - \epsilon \quad d_{TV}(t_* + w_n) < \epsilon$$

The structure theorem of Ding, Lubetzky, and Peres (2014) gives an intuitive explanation. From page 3 of BLPS: “A contiguous model for the giant componet is given by (i) choosing a kernel uniformly over graphs on i.i.d. Poisson truncated to be at least 3, (ii) subdividing every edge into i.i.d. geometric vairables, and (iii) hanging i.i.d. Poisson Galton-Watson trees on every vertex. Observe that steps (ii) and (iii) introduce i.i.d. delays with an expontial tail for the walk; thus starting from a uniform random vertex would essentially eliminate all but the typical $O(1)$ delays and it should mix on the kernel (whp an expander) in time $O(\log n)$”

Dimension drop results in the slow down. Note that while the $k$th generation of the Galton-Watson tree has size $\approx \lambda^k$, the random walk concentrates on a set of size $e^{kd}$. This means that on the cover tree of the random graph the random walk has to get a distance $d^{-1} \log n$ from the root before it can possibly reach all $n$ vertices. To do this it will take time $t_* = (\nu d)^{-1} \log n$.

To see what this means back on the graph, we quote Corollary 3.4 from their paper...
Theorem 6.10.3. Consider the random walk $X_t$ start from a randomly chosen vertex $z \in C_1$ either in the setting of Theorem 6.10.1 or 6.10.2. Let $\nu$ denote the speed of random walk on the corresponding Galton-Watson tree, and let $\lambda$ be the mean of its offspring distribution. For every fixed $a > 0$ if $t = a \log \lambda n$ then

$$\frac{\text{dist}(z, X_t)}{\log \lambda n} \to (\nu a \land 1)$$

in probability.

References


Chapter 7

Voter Models, Coalescing RWs

7.1 On $\mathbb{Z}^d$ and on graphs

The voter model was introduced independently by Clifford and Sudbury (1973) and Holley and Liggett (1975) on the $d$-dimensional integer lattice. It is a very simple model for the competition of two opinions and has been investigated in great detail, see Liggett’s (1999) book for a survey.

As was the case for the contact process in Chapter 5, we construct the voter model using a graphical representation

For each site $x$ there is an independent rate 1 Poisson processes, $T^x_n$, $n \geq 1$. At the times $T^x_n$, $n \geq 1$ the individual at $x$ picks a neighbor $y^x_n$ at random, and at time $t = T^x_n$ we set $\xi_t(x) = \xi_t(y^x_n)$.

To construct the process, we will think about 1’s as occupied and 0’s as vacant rather than two opinions. We put a $\bullet$ at $x$ at times $T^x_n$ (which causes a death as in the contact process) and draw an arrow from $(y^x_n, T^x_n) \rightarrow (x, T^x_n)$ (which causes a birth as in the contact process). The arrow arrives just after the dot (or else it would do nothing). A little thought reveals that the combination of these two events causes the following changes to occur. Here $y$ is short for $y^x_n$.

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To check the table, note that the $\bullet$ kills any particle at $x$ while the arrow gives birth from $y$ to $x$ if there is a particle at $y$. On the last line the $\bullet$ kills the particle at $x$, but then the arrow restores it. No change occurs at $y$. The result of these two mechanisms is a voter event: $x$ imitates the value at $y$. 
This construction allows us to define a **dual process** by working down the graphical representation and crossing arrows in the direction opposite their orientation. The combination of the two events causes the following changes.

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To check the table, note that if \( x \) is in state 0 nothing happens, while if \( x \) is in state 1 then the arrow from \( y \) to \( x \) which is crossed in the direction opposite its orientation, gives birth to a particle at \( y \) and then the \( \bullet \) kills the 1 at \( x \). The result is a **coalescing random walk** step: the particle at \( x \) jumps to \( y \), and if \( y \) is occupied the two particles coalesce.

![Figure 7.1: A realization of the dual process for the voter model. Particles start at \( u \) and \( v \) performing random walks that jump at rate 1 and to a neighbor chosen at random.](image)

As in the contact process, the duality generates an almost sure equality

\[
\xi_t(x) = \xi_{t-s}(\xi^x_s) \quad \text{for } 0 \leq s \leq t
\]  

(7.1.1)

In words, the opinion at \( x \) at time \( t \) is the same as the opinion of \( \xi^x_s \) at time \( t - s \). If \( A = \{ x : \xi_0(x) = 1 \} \) then we let \( \xi^A_t \) be the set of sites in state 1 at time \( t \). If we start with coalescing random walk particles on sites \( B \) in the dual then we let \( \xi^B_t = \bigcup_{x \in B} \xi^x_t \). In this notation the duality becomes

\[
P(\xi^A_t \cap B \neq \emptyset) = P(A \cap \xi^B_t \neq \emptyset)
\]  

(7.1.2)
If we consider the voter model on $\mathbb{Z}^d$ with the usual nearest neighbors then as Holley and Liggett (1975) have shown

**Theorem 7.1.1.** In $d \leq 2$ the voter model approaches complete consensus, i.e., $P(\xi_t(x) = \xi_t(y)) \to 1$. In $d \geq 3$ if we start from product measure with density $p$ (i.e., we assign opinions 1 and 0 independently to sites with probabilities $p$ and $1-p$) then as $t \to \infty$, $\xi_t^p$ converges in distribution to $\nu_p$, a stationary distribution in which a fraction $p$ of the sites have opinion 1.

**Proof.** In $d \leq 2$ recurrence of random walk implies that $P(\zeta_t^x \neq \zeta_t^y) \to 0$ so $P(\xi_t(x) \neq \xi_t(y)) \to 0$. Cox and Griffeath (1986) have proved a number of interesting result about clustering in the two dimensional case, which is the “critical dimension.” Describing them here would require a lengthy excursion away from our main theme so we refer the reader to their paper for details.

Figure 7.2: Clustering in the two-dimensional voter model. Left panel after 4 minutes of simulation, the right after 90 minutes. Figure from Cox and Griffeath (1986).

If we let $\xi_t^p$ be the set of sites occupied by 1’s at time $t$ then the duality equation (7.1.2) and the fact that sites are independently occupied with probability $p$ implies that

$$P(\xi_t^p \cap B = \emptyset) = P(\xi_0^p \cap \zeta_t^B = \emptyset) = E(1-p)^{|\zeta_t^B|}$$

Since the size of the dual never increases $|\zeta_t^B| \downarrow$ a limit.

$$\lim_{t \to \infty} P(\xi_t^p \cap B = \emptyset) = \lim_{t \to \infty} E(1-p)^{|\zeta_t^B|} \quad \text{exists}$$

Knowing the probabilities $P(\xi_\infty^p \cap B \neq \emptyset)$ determines the distribution of $\xi_\infty^p$. Since $\xi_\infty^p$ is the limit in distribution of $\xi_t^p$ as $t \to \infty$ it must be a stationary distribution for the voter model.

**Properties of the equilibria.** Holley and Liggett (1975) showed that in $d \geq 3$ all stationary distributions are convex combinations of $\xi_\infty^p$. Using duality one can compute the finite
dimensional distribution of the $\xi^p_\infty$. Let $\tau_{x,y}$ denote the hitting time of the coalescing random walks starting at $x$ and $y$.

$$P(\xi^p_\infty(x) \neq \xi^p_\infty(y)) = 2p(1 - p)P(\tau_{x,y} = \infty)$$

In $d \geq 3$, well-known results about the behavior of random walks imply that

$$P(\tau_{0,z} < \infty) \sim c_d \|z\|^{2-d} \text{ as } z \to \infty.$$

Bramson and Griffeath (1979) showed that in $d = 3$ if we consider the number of 1’s in the voter model equilibrium with density $\lambda$, $\xi^\lambda$, in a cube $Q(r)$ of side length $r$, then

$$\hat{S}_r = (\lambda(1 - \lambda))^{-1/2}r^{-(d+2)/2}\left(\sum_{x \in Q(r)} \xi^\lambda(x) - \lambda\right) \Rightarrow \text{Normal}(0, C) \quad (7.1.3)$$

Zähle (2001) improved the proof and generalized the result to $d \geq 3$.

### 7.1.1 On the complete graph, Kingman’s coalescent

We consider the complete graph with vertex set $\{1, 2, \ldots n\}$ and edges connecting each pair of vertices. For computations it is convenient to have particles jump with equal probability to all vertices, including the one they are on. If we start the coalescing random walk with $k$ walkers each jumping at rate one then the time until the first coalescence is approximately exponential with rate $k(k-1)/n$. To see this note that our $k$ particles jump at rate $k$ and when one does it hits another particle with probability $(k-1)/n$.

Let $T_m$ be the first time the coalescing random walk has only $m$ particles. By the calculation in the previous paragraph

$$E(T_{m-1} - T_m) = n/(m(m-1))$$

If we follow a common practice in population genetics and let $\tau_m$ be the time $T_m$ measured time in units of $n$ generations then

$$E(\tau_{m-1} - \tau_m) = 1/(m(m-1)) = \frac{1}{m-1} - \frac{1}{m}$$

so telescoping the series

$$E\tau_1 = \sum_{m=2}^{n} \frac{1}{m-1} - \frac{1}{m} = 1 - 1/n$$

The interest in this process in population genetics is that it gives the genealogy of the sample of $m$ individuals in the Wright-Fisher model. As we work backwards in discrete time each individual chooses their parent at random, so two lineages will coalesce with probability $1/n$. If $k$ stays constant then as $n \to \infty$ the genealogy of the sample converges to the continuous time coalescent. For more on this see Kingman (1982) or Wakeley (2009).
The coalescent on the complete graph is sometimes called the mean-field version of the system because each site interacts equally with all the other. In this chapter, we will prove results which show that on many large random graphs coalescing random walks exhibit mean-field behavior, i.e., all pairs of particles have an equal chance of being the next coalesce and the elapsed time between coalescing events converges to

\[ E(\tau_{m-1} - \tau_m) = c/(m(m - 1)) \quad \text{as } n \to \infty. \]

7.1.2 On non-regular graphs

There are two versions of the voter model, which coincide on a regular graph but can have much different behavior in general. In either each site \( x \) has an opinion \( \xi_t(x) \). The first description matches the one we have given above.

**Vertex voter model.** For each vertex \( x \), at the times \( T^x_n \), \( n \geq 1 \) of a rate 1 Poisson process \( x \) decides to change its opinion. To do this it picks a neighbor \( y^x_n \) at random, and at time \( t = T^x_n \) we set \( \xi_t(x) = \xi_t(y^x_n) \).

**Edge voter model.** For each oriented edge \((x, y)\) at times of a rate 1 Poisson process \( T^{x,y}_n \) the voter at \( x \) imitates the voter at \( y \). This can also be formulated as; if \( x \) has degree \( d(x) \) then at the times \( T^x_n \), \( n \geq 1 \) of a Poisson process rate \( d(x) \), \( x \) picks a neighbor \( y^x_n \) at random, and at time \( t = T^x_n \) we set \( \xi_t(x) = \xi_t(y^x_n) \).

In the first case the dual random walk jumps from \( x \) to a neighbor \( y \sim x \) at rate \( p(x, y) = 1/d(x) \) so if we let \( a(x, y) \) be the adjacency matrix of the graph then

\[ d(x)p(x, y) = a(x, y) = a(y, x) = d(y)p(y, x) \]

and the measure that assigns mass \( d(x) \) to vertex \( x \) is a reversible stationary measure. If the graph is finite we can convert it to a stationary distribution by dividing by the sum of the degrees: \( \pi(x) = d(x)/D \) where \( D = \sum_x d(x) \).

In the second case the rate of jumps from \( x \) to \( y \) and from \( y \) to \( x \) are equal so the dual random walk is reversible with respect to the uniform stationary distribution. In the words of Suchecki, Eguíluz and Miguel (2005): “conservation of the global magnetization.” In terms more familiar to probabilists, the number of voters with a given opinion is a time change of simple random walk and hence is a martingale. To see this note that at each edge between a 0 and 1 the 0 changes to 1 at the same rate that the 1 changes to 0.

7.2 In \( d = 1 \) and in your colon

Consider now the voter model on \( \mathbb{Z} \) with the usual nearest neighbors, starting with a different opinion at each site, e.g., let \( \xi_0(x) = x \) for all \( x \). In \( d = 1 \), the set of voters of type 0 is an interval \([\ell_t, r_t]\), so the size \( |\xi^0_t| \) is a random walk on the nonnegative integers, that is absorbed when it hits 0, and when \( k > 0 \) jumps \( k \to k + 1 \) and \( k \to k - 1 \) at rate 1.
Let $\bar{p}_t(i, j)$ be the transition probability for $|\xi_t^0|$ and let $p_t(i, j)$ be the transition probability for the unrestricted random walk $S_t$ that jumps $k \to k + 1$ and $k \to k - 1$ at rate 1 for all $k$. The reflection principle implies that if $i, j > 0$

$$\bar{p}_t(i, j) = p_t(i, j) - p_t(-i, j).$$

To prove this, note that if we have a path that goes from $(0, i)$ to $(n, j)$ and hits 0 in between, then by reflecting the part of the path before 0 is hit we get a path from $(0, -i)$ to $(n, j)$.
\[ P(|\xi_t^0| \geq 1) = \sum_{j=1}^{\infty} \bar{p}_t(1, j) = \sum_{j=1}^{\infty} p_t(1, j) - p_t(-1, j) \]
\[ = \sum_{j=1}^{\infty} p_t(0, j - 1) - p_t(0, j + 1) = p_t(0, 0) + p_t(0, 1) \quad (7.2.1) \]

\[ S_t \text{ is a random walk that jumps at rate 2, and has steps that are 1 or } -1 \text{ with probability } 1/2 \text{ each, so the mean } ES_t = 0, \text{ and the variance } \text{var} (S_t) = 2t. \]

Since \( S_t \) - \( S_{t-1} \), \( S_{t-2} - S_{t-3} \), . . . \( S_0 - S_{-1} \) are independent and have the same distribution, the central limit theorem implies that

\[ P(a < S_t/t^{1/2} < b) \to \int_a^b \frac{1}{\sqrt{4\pi}} e^{-y^2/4} \, dy \quad (7.2.2) \]

where the integrand is the normal density with mean 0 and variance 2. If we apply the last result with \( a = (m - 0.5)/t^{1/2} \) and \( b = (m + 0.5)/t^{1/2} \) we get

\[ P(S_t = m) \approx \int_{(m-0.5)/t^{1/2}}^{(m+0.5)/t^{1/2}} \frac{1}{\sqrt{4\pi}} e^{-y^2/4} \approx \frac{1}{2\sqrt{\pi t}} e^{-m^2/(4t)} \]

The reasoning we have used is not legitimate, but there is a result called the local central limit theorem that makes it rigorous, see e.g., Theorem 3.5.2 in PTE5.

Taking \( m = 0, 1 \) we see that

\[ P(|\xi_t^0| \geq 1) \sim \frac{1}{\sqrt{\pi t}} \quad (7.2.3) \]

Since \( E|\xi_t^0| = 1 \) this implies \( E(|\xi_t^0| \mid |\xi_t^0| > 0) \sim \sqrt{\pi t} \). Generalizing (7.2.1) above we see that if we use \( [y] \) for the largest integer \( \leq y \)

\[ P(|\xi_t^0| \geq [x\sqrt{\pi t}]) \sim 2P(S_t = [x\sqrt{\pi t}]) \sim \frac{1}{\sqrt{\pi t}} e^{-x^2\pi/4} \]

We need the integer part to be able to use the reasoning for (7.2.1), but now we can remove it to conclude that

\[ P(|\xi_t^0| \geq x \cdot \sqrt{\pi t} \mid |\xi_t^0| > 0) \to e^{-x^2\pi/4} \quad (7.2.4) \]

in agreement with Bramson and Griffeath (1990).

**Intestinal stem cells**

Lopez-Garcia et al. and Snippert et al. (2010) have used genetically labeled cells to study stem cell dynamics in the colon crypt. Stem cells reside at the crypt base and feed daughter cells into the transit-amplifying (TA) compartment. TA cells undergo approximately 4-5 rounds of cell division, then move out of the crypt and terminally differentiate. At the lowest level of the crypt are 14–18 Lgr5\(^+\) cells characterized by high levels of Lgr5 expression. As in the case
of epidermal stem cells, it has been long thought that these cells divide asymmetrically to produce one stem cell and one TA cell. However, the phenomenon of monoclonal conversion, whereby crypts become monophenotypic, indicates that this is not the only mechanism for cell division.

Since the stem cells are arranged in a circle at the bottom of the crypt, Lopez-Garcia et al. (2010) modeled the changes in the stem cells in the colon crypt as a voter model on the one-dimensional torus. Using the asymptotics from the previous section they argued that the number of stem cells in a surviving clone should have the form

\[ P_n(t) = \frac{1}{<n(t)>} F \left( \frac{n}{<n(t)>} \right) \]  

(7.2.5)

where \(<n(t)\>\) is the average number of stem cells in a surviving clone. Since they had cell division at rate \(\lambda\), \(<n(t)\> \sim \sqrt{\pi \lambda t}\), and \(F(x) = (\pi x/2) \exp(-\pi x^2/4)\).

Since the number of stem cells \(N\) is small, one should instead compute \(P_n(t)\) directly. This is done in the supplementary materials of Lopez-Garcia et al (2010). See equations (S4)–(S6). Despite the fact that \(N\) is not large, the data shows the scaling relationship predicted by (7.2.5).

### 7.3 Coalescing random walk on the torus in \(d \geq 2\)

Cox (1989) studied the nearest neighbor voter model on a finite torus \((\mathbb{Z} \mod N)^d\). Since the state space is finite the chain will eventually be absorbed in a state in which all individuals have the same opinion. Let \(\tau_N\) be the time to reach consensus. We are interested in the asymptotic behavior as \(N \to \infty\).

This question is easiest to study if we imagine each site starts in a different state, so we let \(\xi_0(x) = x\). Using duality we see that the time to reach consensus, is the same as the time it takes coalescing random walk to be reduced to one particle if we start with one particle at each site. Cox (1989) has shown.

**Theorem 7.3.1.**

\[ \tau_N = \Theta(s_N) \quad \text{where} \quad s_N = \begin{cases} N^2 & d = 1 \\ N^2 \log N & d = 2 \\ N^d & d \geq 3 \end{cases} \]

The case \(d = 1\) of Theorem 7.3.1 is easy. Boundaries between types move like random walks and annihilate when they hit so it takes time of order \(N^2\) for all the boundaries to disappear. The \(d = 2\) case is delicate (and interesting), since the recurrence of random walk produces a \(\log N\) factor in the asymptotics. Most random graphs are highly transient so soon we will restrict our attention here to the case \(d \geq 3\) since the techniques in this case are closest to ones we will use on random graphs. One of the main results of this chapter is
Metatheorem. If the time for a random walk to converge to equilibrium is $\gg$ the time for random walks from two randomly chosen sites to hit, then coalescing random walk behaves like Kingman’s coalescent.

Our first step in studying the coalescing random walk is to consider the coalescence time of two particles. Let $S_n$ be the discrete time random walk on the $d$-dimensional lattice that jumps to the $2d$ nearest neighbors with equal probability, let $p_n$ be its $n$-step transition probability, and let

$$G = \sum_{n=0}^{\infty} p_n(0,0) = 1/\beta_d$$

where $\beta_d = P(S_n \neq 0$ for all $n \geq 1)$. To check the last equality note that the number of visits to 0 (including the one at time 0) has a geometric distribution with “success probability” $\beta_d$. We have put success probability in quotes since success is failing to return to 0.

**Lemma 7.3.2.** Assume $d \geq 3$, and let $a_N = \log N$. Run two independent random walks on the torus. Let $H^2$ be the first time they hit. Then uniformly in starting from points $x, y$ separated by distance $d(x, y) \geq a_N$

$$P(H^2 > tN^d) \to \exp(-2t/G) \quad \text{as} \quad N \to \infty.$$

This is Theorem 4 in Cox (1989), which includes a result for the case $d = 2$. He proves the result in Section 2 by computing Laplace transforms.

Before turning to the coalescence times of $k \geq 3$ particles we will prove an estimate which implies that the hypotheses of the metatheorem hold for random walks on the torus in $d \geq 3$. The mixing time of random walk on the torus (in any dimension) is $O(N^2)$. With the metatheorem in mind the first thing to do is to show that the hitting time of 0, $T_0$, is larger than the mixing time if the particle is not too close to 0.

**Lemma 7.3.3.** Suppose $a_N \to \infty$ and let $b_N = B \log N$ then $P_x(T_0 \leq b_N N^2) \to 0$ uniformly for $x$ with $d(0, x) \geq a_N$.

**Proof.** Let $\epsilon \leq 0.1$. The proof is accomplished in three steps:

(i) If the initial point $x$ has $|x| \geq a_N$ then with high probability the particle will reach a distance $N^{1-\epsilon}$ from 0 before hitting 0.

(ii) A random walk on the torus requires time $\geq r(N) = N^{2(1-2\epsilon)}$ to go a distance $N^{1-\epsilon}$. This lower bounds the additional amount of time to hit 0 if goal (i) is achieved.

(iii) The local central limit theorem implies that for $t = r(N)$

$$\max_x P(S_t = x) \leq CN^{-d(1-2\epsilon)} \quad (7.3.1)$$

The Markov property extends this to $t \geq r(N)$ so the time to hit 0 after goal (ii) is achieved is $\geq N^{d(1-3\epsilon)}$ with high probability.
It suffices to prove (i) and (ii).

Proof of (i). If \(0 < \alpha < d - 2\) then there is a \(K_\alpha\) so that the function \(1/|x|^\alpha\) is superharmonic for the random walk when \(|S_t| \geq K_\alpha\), see e.g., Example 5.3 in Varadhan’s (2001) book. The proof is not hard. Look at \(|x + y|^{-\alpha}/|x|^{-\alpha}\) for \(|y| = 1\), expand in power series assuming \(|x|\) is large, and compute the expected value of the result of one jump.

Using this with the optional stopping theorem for nonnegative supermartingales (Theorem 4.8.4 in PTE5) we see that if \(|S_0| = a_N\), \(T = \inf\{n : S_n \notin (K_\alpha, N^{1-\epsilon})\}\), and \(q = P(S_T = K_\alpha)\) then ignoring the fact that \(N^{1-\epsilon}\) is not an integer

\[
a_N^{-\alpha} \geq qK_\alpha^{-\alpha} + (1 - q)N^{-(1-\epsilon)\alpha} \quad \text{so } q \leq Ca_N^{-\alpha}.
\]

Proof of (ii). If \(S_0 = 0\) then \(E|S_t|^2 = t\), so if \(r(N) = N^{2(1-2\epsilon)}\) then the \(L^2\) maximal inequality for submartingales (Theorem 4.4.4 PTE5) implies that

\[
\leq P\left(\max_{0 \leq t \leq r(N)} |S_t|^2 \geq N^{2(1-\epsilon)}/2\right) \leq 4 \cdot \frac{N^{2(1-2\epsilon)}/2}{N^{2(1-\epsilon)}} \leq 2N^{-2\epsilon}
\]

This completes the proof of (ii) and hence of Lemma 7.3.3.

The next step is to consider \(k\) particles.

Lemma 7.3.4. Run \(k \geq 3\) independent random walks starting from points separated by distances at least \(a_N\). (a) If we let \(\tau_{i,j}\) be the first time \(i\) and \(j\) hit and let \(\tau^k = \min_{1 \leq i < j \leq k} \tau_{i,j}\) then

\[
P(\tau^k > tN^d) \to \exp(-tk(k - 1)/G)
\]

(7.3.2)

(b) The probability that at time \(\tau_{ij}\) there are random walks (other than \(ith\) and \(jth\)) separated by distance \(\leq a_N\) tends to 0.

Proof. To prove (b), we note that by the proof of Lemma 7.3.3 the probability of a pair hitting by time \(\leq b_N N^2\) tends to 0. Using (7.3.1) we conclude that the probability that two pairs of particles \(\{i_1, j_1\}\) and \(\{i_2, j_2\} \neq \{i_1, j_1\}\) are both within distance \(a_N\) at some time \(t \in [b_N N^d, N^d \log N]\) is

\[
\leq k^4 \cdot N^d \log N \left(\frac{2a_N}{N^d(1-2\epsilon)}\right)^2 \to 0
\]

if \(\epsilon < 1/4\).

To prove (a) now, we need to argue that the \(\tau_{i,j}\) are approximately independent. Let \(\alpha_N = GN^2/2\). Let \(H_t(i, j) = \{\tau_{ij} \leq t\alpha_N\}\), \(F_t(i, j) = \{\tau = \tau_{ij} \leq t\alpha_N\}\), and \(q(t) = P(\tau \leq t\alpha_N)\).

\[
P(H_t(i, j)) = P(F_t(i, j)) + \sum_{\{k, \ell\} \neq \{i, j\}} \int_0^{t\alpha_N} P(\tau_{k\ell} = s, \tau_{ij} \leq t\alpha_N) ds
\]

(7.3.3)
where the quantity being integrated on the right is the density of the hitting time \( \tau_{k,\ell} \). To evaluate the \( k, \ell \) term in the sum we break things down according to the locations \( X^s_i \) and \( X^s_j \). By (b) we can ignore the possibility that \( |X^s_i - X^s_j| < a_N \). When the distance is \( \geq a_N \) the argument for Lemma 7.3.2 shows that the positions will become randomized before they hit so the hitting time will be in the limit as \( N \to \infty \) exponentially distributed. Writing \( \epsilon_N \) for a quantity that goes to 0 as \( N \to \infty \)

\[
\int_0^{t\alpha_N} P(\tau = \tau_{kl} = s, \tau_{ij} \leq t\alpha_N) \, ds = \int_0^{t\alpha_N} P(\tau = \tau_{kl} = s) \left[ 1 - \exp \left( -\frac{t - s}{\alpha_N} \right) \right] \, ds + \epsilon_N
\]

Integrating by parts and then changing variables \( u = s/\alpha_N \) and \( r = t/\alpha_N \), the above is

\[
= \int_0^{t\alpha_N} \frac{1}{\alpha_N} \exp(-t-s)/\alpha_N) P(\tau = \tau_{kl} \leq s) \, ds + \epsilon_n
\]

Using this in our initial decomposition (7.3.3), with the convergence of the hitting time \( \tau_{i,j} \) to the exponential distribution, we get

\[
1 - e^{-t} = P(F_t(i, j)) + \sum_{\{k,\ell\} \neq \{i, j\}} e^{-t} \int_0^t e^s P(F_s(k, \ell)) \, ds + \epsilon_N
\]

Summing over all \( \binom{k}{2} \) pairs \( \{i, j\} \)

\[
\binom{k}{2} (1 - e^{-t}) = q(t) + \left[ \binom{k}{2} - 1 \right] \int_0^t e^s q(s) \, ds + \epsilon_N
\]

It follows [see page 365 of Cox and Griffeath (1986) for more details] that as \( N \to \infty \), \( q(t) \) converges to \( u(t) \) the solution of

\[
\binom{k}{2} (1 - e^{-t}) = u(t) + \left[ \binom{k}{2} - 1 \right] \int_0^t e^s u(s) \, ds
\]

Multiplying both sides by \( e^t \) and rearranging we have

\[
e^t u(t) - \binom{k}{2} (e^t - 1) = - \left[ \binom{k}{2} - 1 \right] \int_0^t e^s u(s) \, ds
\]

Differentiating we have

\[
e^t u(t) + e^t u'(t) - \binom{k}{2} e^t = - \left[ \binom{k}{2} - 1 \right] e^t u(t)
\]

The first term on the left cancels the last term on the right. Dividing by \( e^t \) and rearranging gives

\[
\binom{k}{2} (1 - u(t)) = u'(t) = - \frac{d}{dt} (1 - u(t))
\]
which has solution $1 - u(t) = \exp(-k(k - 1)t/2)$.

The final detail is to show that all $\binom{k}{2}$ pairs have equal probability to be the next to coalesce. To do this we go back to (7.3.4) and subtract and add the $\{i, j\}$ term in the sum to get

$$1 - e^{-t} = P(F_t(i, j)) - e^{-t} \int_0^t e^s P(F_s(i, j)) \, ds + e^{-t} \int_0^t e^s q(s) \, ds + \epsilon_N$$

Recalling $u(t) = 1 - e^{-t}$, it follows that $P(F_t(i, j))$ converges to the solution of

$$v(t) - \frac{2}{G} e^{-2t/G} \int_0^t e^{2s/G} v(s) \, ds = u(t) - \frac{2}{G} e^{-2t/G} \int_0^t e^{2s/G} u(s) \, ds$$

Since the limit is independent of $i, j$ we must have $v(t) = u(t)/\binom{k}{2}$, which completes the proof.

Remark 7.3.5. To prepare for later arguments, note that the proof of (a) only requires that $\frac{\tau_{i,j}}{\alpha_N}$ converges to a mean one exponential, and that the time to reach equilibrium is $o(\alpha_N)$.

Lemma 7.3.4 implies that starting from $k$ locations separated by at least $\alpha_N$ the number of particles in the coalescing random walk converges to Kingman’s coalescent. However there is one small technical point remaining: we want to show that as $n \to \infty$ the coalescing random walk converges to Kingman’s coalescent starting from infinitely many particles. We will delay addressing this point until we can use a nice argument of Cooper et al in Section 7.5 to deal with it.

### 7.3.1 Voter model on the torus

As the next result due to Cox and Greven (1990) shows, the voter model has interesting behavior along the road to fixation. In it $\nu_p$ is the one parameter family of stationary distributions from Theorem 7.1.1.

**Theorem 7.3.6.** If the voter model on the torus in $d \geq 3$ starts from product measure with density $p$ then at time $Nt$ it looks locally like $\nu_{\theta(t)}$ where the density $\theta_t$ changes according to the Wright-Fisher diffusion process

$$d\theta_t = \sqrt{\beta_d} \cdot 2\theta_t(1 - \theta_t) dB_t$$

and $\beta_d$ is the probability that two random walks starting from neighboring sites never hit.

Intuitively this holds since the density which is conserved by the microscopic dynamics changes on a much slower time scale than the voter model converges to equilibrium.
7.4 Hitting times for two random walks

When the degrees of vertices in the graph are not constant the random walk does not spend an equal amount of time in all parts of the space. If \( a(i, j) \) is the adjacency matrix of the graph, then the transition probability \( p(i, j) = a(i, j)/d(i) \) where \( d(i) \) is the degree of \( i \), so if we let \( \pi(i) = d(i)/D \) where \( D = \sum_i d(i) \) then the walk is reversible with respect to \( \pi \):

\[
\pi(i)p(i, j) = a(i, j)/D = a(j, i)/D = \pi(j)p(j, i)
\]

The first step in understanding the time to reach consensus in the voter model is to pick two starting points \( x_1 \) and \( x_2 \) at random according to the stationary distribution \( \pi \) for the random walk and investigate the time it takes for their coalescing random walks to hit. For simplicity we consider the discrete time version \((\bar{X}_n^1, \bar{X}_n^2)\) of the two particle chain in which \( \bar{X}_0^i = x_i \) and at each step we pick a particle at random and let it jump. Let \( A = \{(x, x) : x \in G\} \) be the “diagonal” and let

\[
T_A = \inf\{n \geq 1 : X_n^1 = X_n^2\}
\]

be the first hitting time of \( A \) by \((\bar{X}_n^1, \bar{X}_n^2)\), and write \( P_A \) for \( P_{\pi}(\cdot | (X_0^1, X_0^2) \in A) \)

7.4.1 Asymptotics for \( E_{\pi}T_A \)

Theorem 7.4.1. Aldous’ Poisson Clumping Heuristic. Let \( t_{mix} \) be the mixing time for the Markov chain defined in (6.1.3), and suppose that \( t_{mix} \ll E_{\pi}T_A \) then

\[
E_{\pi}(T_A) = \frac{1}{\pi(A)} \cdot \frac{1}{P_A(T_A \gg t_{mix})} \tag{7.4.1}
\]

Proof. Kac’s recurrence theorem (Theorem 6.3.3 in PTE5) implies that

\[
E_A(T_A) = 1/\pi(A)
\]

the expected value on \( T_A \leq t_{mix} \) makes a negligible contribution to the expected value so the convergence

\[
1/\pi(A) \approx P_A(T_A \gg t_{mix})E_{\pi}(T_A)
\]

Rearranging gives the desired formula. \( \square \)

To connect with the Aldous’ (1989) clumping heuristic, we note that the naive guess for the waiting time is \( 1/\pi(A) \) but this must be corrected for by multiplying by the clump size, i.e., the expected number of hits that occur soon after the first one. In nice cases, e.g. the torus or random regular graphs, the number of hits in a clump is geometric and hence has mean \( 1/P_A(T_A \gg t_{mix}) \). However, a geometric distribution of return times is not necessary for (7.4.1) to hold.
Example 7.4.2. **d-dimensional torus**, $d \geq 3$. \((\mathbb{Z} \mod N)^d\) has $n = N^d$ sites. \(\pi(x, x) = N^{-2d}\) so \(\pi(A) = N^{-d}\). \(t_{\text{mix}} = O(N^2)\). In $d \geq 3$, \(P_A(T_A \gg t_{\text{mix}}) \to \beta_d = P_0(S_n \neq 0 \text{ for all } n \geq 1}\), so

\[
E_\pi T_A \sim N^d / \beta_d
\]

**Example 7.4.3. Random $r$-regular graphs.** Locally these graphs look like a tree in which each vertex has degree $r$. The probability that two random walkers that start from the origin on an $r$-regular tree will hit after they separate is the same as the probability that a single random walk will return to the origin, which is $1/(r-1)$. To check this note that \(\phi(x) = 1/(r-1)^x\) is a harmonic function for the distance $S_n$ from the root of the tree, i.e., \(\phi(S_n)\) is a martingale when $S_n > 0$. Since \(P_A(T_A \gg t_{\text{mix}}) \approx (r-2)/(r-1)\), we should have

\[
E_\pi T_A \sim r - 2 / (r - 1) n
\]

**Example 7.4.4. Power law random graphs.** If the graph is generated by the configuration model

\[
\pi(A) = \sum_{i=1}^n d_i^2 / D^2 \quad \text{where} \quad D = \sum_{j=1}^n d_j
\]

If the degree distribution has finite second moment then \(\pi(A) = O(1/n)\). When the degree distribution has infinite variance \(\pi(A)\) will go to 0 more slowly than $1/n$. Consider random graphs with a power law degree distribution $p_k \sim C k^{-\gamma}$. When $\gamma > 3$ the distribution has finite variance. For $2 \leq \gamma \leq 3$ results of Sood and Redner (2005) for the consensus time of the voter model, suggest that

\[
E_\pi T_A \approx \begin{cases} 
\frac{n}{\log n} & \gamma = 3 \\
\frac{n^{(2\gamma-4)/(\gamma-1)}}{n^2} & 2 < \gamma < 3 \\
(\log n)^2 & \gamma = 2 
\end{cases}
\]

where \(\approx\) should be read “is of order.” For simplicity we will only consider the case $2 < \gamma < 3$.

**Lemma 7.4.5.** When $2 < \gamma < 3$ the asymptotic behavior of $1/\pi(A)$ is given by the formulas above.

**Proof.** When $p_k \sim C k^{-\gamma}$ we have

\[
P(d_i > k) \sim C' k^{-(\gamma-1)} \quad \text{and} \quad P(d_i^2 > k) \sim C'' k^{-(\gamma-1)/2}.
\]

To prepare for later, note that the maximum degree is $O(n^{1/(\gamma-1)})$ when $\gamma > 2$.

When $2 < \gamma < 3$, $d_i^2$ is in the domain of attraction of a one-sided stable law with index $\beta = (\gamma - 1)/2$ so

\[
\frac{1}{n^2} \sum_{i=1}^n d_i^2 \sim Y_\beta n^{2/(\gamma-1)}/n^2 = Y_\beta n^{(2\gamma-4)/(\gamma-1)}
\]

where $Y_\beta$ has a one-sided stable distribution with index $\beta$. \(\square\)

If we assume that the minimum degree is 3 then the mixing time $t_{\text{mix}} = O(\log n)$, and in the example $T_A/(\log n) \to \infty$ in probability.
7.4.2 Asymptotic exponential distribution

Proposition 3.23 in Aldous and Fill (2002) implies

$$\sup_t |P_\pi(T_A > t) - \exp(-t/E_\pi T_A)| \leq \tau_2/E_\pi T_A$$

(7.4.3)

where $\tau_2$ is the relaxation time, which they define to be 1 over the spectral gap. In the random regular case if $r \geq 3$ then $\tau_2 \leq C \log n$ and as we have seen

$$E_\pi T_A \sim \frac{r - 1}{r - 2} n$$

(7.4.4)

so the hitting time is approximately exponential.

The proof of (7.4.3) is based on a result of Mark Brown (1983) for IMRL (increasing mean residual life) distributions. If one is willing to give up on the explicit error bound, it is fairly easy to give a proof based on the idea that since convergence to equilibrium occurs much faster than the two particles hitting, then subsequential limits of $T_A/E_\pi T_A$ must have the lack of memory property, and hence the sequence converges to a mean 1 exponential.

**Theorem 7.4.6.** If the mixing time $t_{mix} = o(1/\pi(A))$, and $E_\pi T_A \leq C/\pi(A)$ then under $P_\pi$, $T_A/E_\pi T_A$ converges weakly to an exponential with mean 1.

**Proof.** Since $t_{mix} \ll 1/\pi(A) \leq E_\pi T_A$, we can find $\epsilon_n \to 0$ with $(\epsilon_n E_\pi T_A)/t_{mix} \to \infty$. The expected time that $X^1_1 = X^2_1$ in $[r E_\pi T_A, (r + \epsilon_n) E_\pi T_A + 1]$ is $= \pi(A)(\epsilon_n E_\pi T_A + 1)$. If $X^1_s = X^2_s$ then with probability $\geq e^{-2}$ neither jumps before time $s + 1$ and hence they agree on $[s, s + 1]$. From this we conclude that

$$P_\pi(T_A/E_\pi T_A \in [r; (r + \epsilon_n)]) \leq \delta_n = \pi(A)(\epsilon_n E_\pi T_A + 1) \to 0$$

(7.4.5)

Notice that $\delta_n$ does not depend on $r$. Using this result with $r = s + t$ and writing $X_t = (X^1_t, X^2_t)$, $x = (x_1, x_2)$

$$P_\pi(T_A/E_\pi T_A > (s + t)) = P_\pi(T_A/E_\pi T_A > (s + t + \epsilon_n)) + \delta_n$$

$$= \sum_{x,y} P_\pi(T_A/E_\pi T_A > s, X(s E_\pi T_A) = x)P_x(X(\epsilon_n E_\pi T_A) = y)P_y(T_A/E_\pi T_A > t)$$

Subtracting $\pi(y)$ from $P_x(X(\epsilon_n E_\pi T_A) = y)$ and adding $\pi(y)$ gives two terms. The second is

$$\sum_{x,y} P_\pi(T_A/E_\pi T_A > s, X(s E_\pi T_A) = x)\pi(y)P_y(T_A/E_\pi T_A > t)$$

$$= P_\pi(T_A/E_\pi T_A > s)P_\pi(T_A/E_\pi T_A > t)$$

The absolute value of the first term is bounded by

$$P_\pi(T_A/E_\pi T_A > s)\sup_x \sum_y |P_x(X(\epsilon_n E_\pi T_A) = y) - \pi(y)| \to 0$$

(7.4.6)
due to the definition of the mixing time.

The sequence of random variables $T_A/E_A T_A$ has mean one, so it is tight. Let $F$ denote a subsequential limit. From the calculation above we see that if $s$, $t$, and $s + t$ are continuity points of $F$ then

$$1 - F(s + t) = (1 - F(s))(1 - F(t))$$

$F$ can have at most countably many discontinuity points, so there is a $\theta > 0$ so that $F$ is continuous at all points $m/(\theta 2^n)$ where $m$ and $n$ are positive integers. Define $\lambda$ by $e^{-\lambda} = 1 - F(1/\theta)$. It follows from the equation that if $t = m/(\theta 2^n)$ then $1 - F(t) = e^{-\lambda t}$. To conclude that $\lambda$ is independent of the subsequential limit, note that for all $n$, $P_\pi(T_A/E_A T_A > 2) \leq 1/2$, so using the remark about $\delta_n$ and (7.4.6), we see that if $\gamma > 0$ and $n$ is large

$$P(T_A/E_A T_A > 2(k + 1)) \leq P(T_A > 2k)(\gamma + P(T_A > 2)).$$

This gives an exponential bound on the tail of the distribution, which enables us to conclude that every subsequential limit has mean 1.

### 7.5 A bound on the coalescence time

Suppose we run coalescing random walk starting with one particle at each site of a graph. Let $C$ be the time until only one random walk remains. In this section we describe a result of Cooper, Elsässer, Ono, and Radzik’s (2012) on the expected coalescence time. These authors use lazy discrete time simple random walks, but the result is easier to prove and more closely related to the voter model if the walks have continuous time, so we study that case here.

**Theorem 7.5.1.** Let $G$ be a connected graph with $n$ vertices, average vertex degree $\bar{d}$ and maximum degree $\Delta = O(n^{1-\epsilon})$. Let $\nu = (\sum_{v \in V} d^2(v))/(\bar{d}^2 n)$. Let $C(n)$ be the expected coalescence time for a system of particles making a continuous time random walk starting from each vertex that jumps at rate 1. Then

$$C(n) = O\left(\frac{n}{\nu(1 - \lambda_1)}\right)$$

where $\lambda_1$ is the second largest eigenvalue.

**Remark.** Noting that $\nu/n = \pi(A)$, we see that if the minimum degree is 3 and hence by Theorem 6.4.1 $1 - \lambda_1$ is bounded away from 0, this result gives an upper bound for the coalescence time which is accurate in the case of power law degree distributions $p_k \sim Ck^{-\gamma}$ with $2 < \gamma < 3$. See Lemma 7.4.5
Random walk properties

Let $G = (V, E)$ be a connected graph with $|V| = n$ and let $d(v)$ be the degree of the vertex $v$. Let $W_u(t)$ denote a continuous time random walk that starts from $u$ jumps at rate 1 and jumps from $v$ to each of its neighbors with equal probability. Let $P_u^t(x) = P(W_u(t) = x)$. It follows from Theorem 6.1.1 that

$$|P_u^t(x) - \pi_x| \leq (\pi_x/\pi_u)^{1/2}e^{-(1-\lambda_1)t} \quad (7.5.1)$$

Define the time to reach equilibrium $T_G$ so that for $t \geq T_G$

$$\max_{u,x} |P_u^t(x) - \pi_x| = o(1/n^2) \quad (7.5.2)$$

Let $E\pi(H_w)$ denote the expected hitting time of $w$ starting from the stationary distribution.

**Lemma 7.5.2.** Let $F$ be a graph with eigenvalue gap $1 - \lambda_1$. Then

$$E\pi(H_v) \leq \frac{1}{1 - \lambda_1} \cdot \frac{1}{\pi_v}$$

**Proof.** According to Chapter 2 of Aldous and Fill (2002)

$$E\pi(H_v) = Z_{v,v}/\pi_v \quad (7.5.3)$$

where $Z$ is the recurrent potential kernel

$$Z_{v,v} = \int_0^\infty P_v^t(v) - \pi_v \, dt$$

They prove this result in discrete time in Lemma 11, but as they observe in Section 2.3 the result is the same in continuous time. Using (7.5.1) with $x = u = v$

$$|P_v^t(v) - \pi_v| \leq e^{-(1-\lambda_1)t}$$

Integrating gives the desired result.

Let $A_v(t; u)$ be the event that $W_u$ does not visit vertex $v$ in $[0, t]$.

**Lemma 7.5.3.** $P(A_v(t; u)) \leq \exp(-|t/(T_G + 3E\pi H_v)|)$.

**Proof.** To simplify formulas write $T_G$ as $T$. Let $\rho = P_u^T$ be the distribution of $W_u$ after $T$ steps. Then (7.5.2) and the fact that $\pi_x \geq 1/n^2$ for any connected graph (since $1 \leq d_y \leq n-1$ for all $y \in V$) imply

$$E\rho(H_v) = (1 + o(1))E\pi(H_v)$$

and it follows that

$$E_u(H_v) \leq T_G + (1 + o(1))E\pi(H_v) \quad (7.5.4)$$

If we let $H_v(\rho)$ be the hitting time of $v$ starting from $\rho$ and $\tau = T + 3E\pi(H_v)$ then

$$P(A_v(\tau; u)) = P(A_v(T; u), H_v(\rho) \geq 3E\pi H_v)$$

$$\leq P(H_v(\rho) \geq eE\pi H_v) \leq e^{-1}$$

Iterating this bound $|t/(T_G + 3E\pi H_v)|$ times gives the desired result.
Multiple random walks

To study the coalescence of \( k \geq 2 \) walks on a graph \( G = (V_G, E_G) \), we replace the \( k \) walks by one walk on a new graph \( Q_k \) with vertex set \( V^k \). Since we work in continuous time where only one particle jumps at a time, our edge set is much simpler than the one in Cooper et al: vertices \( v, w \in Q_k \) adjacent if there is a \( j \) so that \( v_i = w_i \) for \( i \neq j \) and \( \{v_j, w_j\} \in E_G \).

Although we are interested in coalescence, our \( k \) random walks will be independent. For any starting positions \( u = (u_1, \ldots, u_k) \) for the walks, let \( M_k \) be the time of the first meeting in \( G \). Let

\[
S_k = \{(v_1, v_2, \ldots, v_k) : v_i = v_j \text{ for some } 1 \leq i < j \leq n\}.
\]

To use results from the previous section it is convenient to contract the set \( S_k \) to be a single vertex \( \gamma \) making a new graph \( \Gamma_k \). On contraction all edges including those that have become loops or parallel edges are retained.

Let \( \pi_k \) and \( \hat{\pi}_k \) be the stationary distributions on \( Q_k \) and \( \Gamma_k \) respectively. For any vertex \( v = (v_1, v_2, \ldots, v_k) \in Q_k \), \( \pi_k(v) = \pi(v_1) \cdots \pi(v_k) \). If \( v \not\in S_k \), \( \hat{\pi}_v = \pi_v \), while \( \hat{\pi}_\gamma = \sum_{x \in S} \pi_x \).

The next order of business is to find a lower bound for \( \hat{\pi}_\gamma \).

**Lemma 7.5.4.** There is a constant \( c_k > 0 \) so that if \( k \leq \log^4 n \)

\[
\hat{\pi}_\gamma \geq \frac{c_k k^2 \nu}{2n}
\]

**Proof.** For \( 1 \leq x < y \leq k \) let \( S_{x,y} = \{(v_1, \ldots, v_k) : v_x = v_y\} \) and note \( S = \bigcup_{1 \leq x < y \leq k} S_{x,y} \).

\[
\pi(S_{k-1,k}) = \sum_{v_1 \cdots v_{k-1}} \pi(v_1) \cdots \pi(v_{k-2}) \pi^2(v_{k-1}) = \sum_v \left( \frac{d(v)}{nd} \right)^2 = \frac{\nu}{n}
\]

The inclusion exclusion formula implies

\[
\pi(S_k) \geq \sum_{x,y} \pi(S_{x,y}) - \sum_{(x,y) \neq (p,q)} \pi(S_{x,y} \cap S_{p,q})
\]

Taking the cases \( \{x, y, p, q\} = 3, 4 \) separately (the second one does not exist if \( k = 3 \))

\[
\pi(S_{k-2,k-1} \cap S_{k-1,k}) = \sum_v \pi(v)^3 \leq \Delta \sum_v \frac{d(v)^2}{n^3 d^3} \leq \frac{\Delta \nu}{n^2 d^2}
\]

\[
\pi(S_{1,2} \cap S_{k-1,k}) = \sum_{u,v} \pi(u)^2 \pi(v)^2 \leq \frac{\nu^2}{n^2}
\]

Combining the last two results

\[
\pi(S) \geq \left( \frac{k}{2} \right) \frac{\nu}{n} - 3 \left( \frac{k}{3} \right) \frac{\Delta \nu}{n^2 d} - 3 \left( \frac{k}{4} \right) \frac{\nu^2}{n^2} \geq \left( \frac{k}{2} \right) \frac{\nu}{n} \left[ 1 - \frac{k \Delta \nu}{nd} - \frac{k^2 \nu}{n} \right]
\]
We have assumed $\Delta = O(n^{1-\epsilon})$ and $k \leq \log^4 n$, so the middle term inside the square brackets is $o(1)$. Noting that
\[ \nu \leq \Delta \sum_v \frac{d(v)}{d^2 n} = \frac{\Delta}{d}, \] (7.5.5)
the last term is also $o(1)$ and the proof is complete.

It follows from (7.5.4) that if $T_\Gamma$ is the time to reach equilibrium satisfying (7.5.2) then
\[ E(M_k) \leq T_\Gamma + (1 + o(1)) E_\#(H_\gamma), \]
To bound the first quantity we use Lemma 7.5.5.

**Lemma 7.5.5.** For the random walks on $G$, $Q$, and $\Gamma$ there are mixing times
\[ T_G \leq \frac{C \log n}{1 - \lambda_1(G)}, \quad T_Q = O(kT_G), \quad T_\Gamma = O(kT_G) \]

**Proof.** The bound on $T_G$ follows from (7.5.1). In the jargon of Markov processes the random walk on $Q_k$ is the tensor product chain. The eigenvectors are the $k$-wise products of those of $G$, so $\lambda_1(Q_k) = \lambda_1(G)$. See page 168 of Levin, Peres, and Wilmer’s book for more details.

In the notation of Aldous and Fill, Chapter 3, the random walk on $\Gamma_k$ is the random walk on $Q_k$ with $S_k$ collapsed to $\gamma_k$. Their Corollary 27 implies that if a subset $A$ of vertices is collapsed to one then the second eigenvalue is not increased.

We get the factor of $k$ in the bounds on the mixing times because we need to have $|P^T_u(x) - \pi_x| = o(1/n^{2k})$ and $\pi_x/\pi_u \leq n^{2k}$ by the trivial bound we used in the proof of Lemma 7.5.3.

**Lemma 7.5.6.** If $k \leq \log^4 n$ then
\[ E_u(M_k) = O\left(\frac{1}{1 - \lambda_1(G)} \left(k \log n + \frac{n}{\nu k^2} \right)\right) \]

**Proof.** Using Lemmas 7.5.2 and 7.5.4
\[ E_\#(H_\gamma) \leq \frac{1}{\pi(\gamma)} \cdot \frac{1}{1 - \lambda_1(\Gamma)} \leq \frac{1}{c_k k^2} \cdot \frac{n}{\nu(1 - \lambda_1(G))} \] (7.5.6)

Using (7.5.4) we have $E_u(M_k) \leq O(kT_G) + (1 + o(1)) E_\# H_\gamma$, so the desired result follows from Lemma 7.5.5.

Summing over $k \leq \log^4 n$
\[ \sum_{k=2}^{\log^4 n} E(M_k) = O \left( \frac{n}{\nu(1 - \lambda_1(G))} \right) + O \left( \frac{\log n}{1 - \lambda_1(G)} \right) \]

From (7.5.5) we have $\nu \leq \Delta/d$, the first term is dominant as long as $\Delta = O(n^{1-\epsilon})$. 

CHAPTER 7. VOTER MODELS, COALESCING RWS

The Big Bang

The last thing to do is to estimate the time for the coalescing random walk to be reduced $n$ particles to $\log^3 n$. We prove that

**Lemma 7.5.7.** With high probability there cannot be a set of $k_* = \log^4 n$ particles that has not had a meeting by time $t^* = k_*^{3/2}(T_{\Gamma} + 3E_{\pi}(H_{\gamma}))$.

**Proof.** Suppose that the starting points are $v = (v_1, \ldots, v_k)$. The probability that the particles do not meet by time $t$ is the same as the probability that the random walk in $\Gamma_k$ starting from $v$ does not visit $\gamma$ by time $t$. By Lemma 7.5.3 this probability is

$$\leq \exp\left(-\left|t^*/(T_{\Gamma} + 3E_{\pi}H_{\gamma})\right|\right) \leq \exp(-k^{3/2}) = e^{-\log^6 n}$$

The probability no set of size $k$ does this is

$$\leq \binom{n}{k} e^{-\log^6 n} \leq n^k e^{-\log^6 n} \leq \exp(-\log^6 n + \log^5 n)$$

To complete the result of Theorem 7.5.1 now, we note that Lemma 7.5.5 and (7.5.6) imply

$$t^* = O\left(\frac{1}{1 - \lambda_1(G)} \left(k^{5/2} \log n + \frac{n}{\nu}\right)\right)$$

and $k^{5/2} \log n = o(n/\nu)$ as long as $\Delta = O(n^{1-\epsilon})$.  

7.6 Mean-field behavior on general graphs

On the torus and random regular graphs we proved convergence of the rescaled coalescence time to Kingman’s coalescent using detailed calculation. In this section we give a general result due to Oliveira (2013). To set the stage we go back to Chapter 14 of Aldous and Fill’s book.

**Open Problem 14.13.** Let $C$ be the coalescent time for a coalescing random walk starting with one particle at each site. Let $T_{hit} = \max_{u,v} E_u T_v$. Prove there is a constant $K$ so that

$$EC \leq KT_{hit}^G$$

It would be more natural to phrase the conjecture in terms of $T_{meet} = \max_{i,j} EM_{i,j}$ where $M_{i,j}$ is the time for two independent random walks starting at $i$ and $j$ to hit. The next two results show that in general this is not possible.

**Proposition 14.5** in Aldous and Fill shows that $T_{meet} \leq T_{hit}^G$. They also show that on a “symmetric” (i.e., vertex transitive) graph $T_{meet} = (1/2)T_{hit}^G$.

**Example 7.6.1.** The star graph has center 0 and leaves $1, \ldots, n$. 

• $T_{meet}^G = \Theta(1)$. Letting $o$ for outside and $c$ for center we can formulate a Markov chain with three states $(o, o)$, $(c, o)$, and $(c, c)$ and conclude that $E_{(o, o)} T_{(c, c)} \to 2$ as $n \to \infty$

• $T_{hit}^G = E_0 T_1 \geq n$, since particle has to return to the center an average of $n$ times before it will jump to 1. A little more thought gives $E_0 T_1 \sim 2n$

• The coalescence time $C$ is $\Omega(\log n)$. To prove the lower bound note that when there are $k + 1$ particles coalescence occurs at rate $\leq (k + 1)$ since the rate is 0 when there is no particle in the center. This shows that unlike Kingman’s coalescent, on the start the coalescent does not come down from infinity in finite time.

Oliveira (2012) proved the conjecture of Aldous and Fill

Let $Q$ be the generator of a reversible, irreducible, continuous time Markov chain on a finite set $V$. Let $C_k$ be the time until only $k$ particles remain.

Theorem 7.6.2. There is a constant $K > 0$ so that for any $n$ and $\vec{x} = (x_1, \ldots x_n) \in V^n$

$$E_{\vec{x}} C_k \leq K \left( T_{hit}^Q / k + T_{mix}^Q \right)$$

This is his Theorem 1.5, which shows that the dependence on $k$ is the same as in Kingman’s coalescent. Theorem 1.3 covers the case $k = 1$, where the second term is not needed.

Sketch of proof of Theorem 1.3. Label the particles $X_t(a), a = 1, \ldots n$. Instead of a coalescence a particle dies when it collides with a lower numbered particle. As in the TV show the dead continue walking. If we let $A_t$ be the particles alive at time $t$ then in this system

$$P(C > t) \leq \sum_{a=2}^{n} P(a \in A_t)$$

Oversimplification #1. We say that particle $a$ dies if it hits a particle $b < a$ even if that particle is dead. This leads to the formula

$$P(a \in A_t | X_s(a) = h_s, 1 \leq s \leq t) = \prod_{b=1}^{a-1} P(X_s(b) \neq h_s \text{ for } 0 \leq s \leq t)$$

Oversimplification #2. Start the particles independent and distributed according to the stationary distribution. This allows the proof of an intriguing “meeting time lemma” which is similar to the previous displayed equation. A few lines leads to the simple bound

$$EC \leq (\ln 2 + 1) T_{hit}^Q.$$
Oliveira’s (2013) proved convergence to Kingman’s coalescent

His first result is for the transitive case: i.e., given \( x \) and \( y \) one can find a permutation of the state space that preserves adjacency and maps \( x \) to \( y \). In addition assumes reversibility i.e., the stationary distribution satisfies detailed balance \( \pi(x)Q(x, y) = \pi(y)Q(y, x) \). There is second similar result is for a general chain, which assumes that the mixing time is small enough relative to the other parameters of the chain. We refer the reader to the paper for details.

To state his result we need some notation.

Let \( X_t \) be a continuous time Markov chain with generator \( Q \). Let \( \pi \) be the stationary distribution of \( Q \), let \( m(Q) \) be the expected meeting time of two independent copies of the chain \( Q \), each starting from the stationary distribution,

Let \( t_{mix}^Q(\alpha) \) be the \( \alpha \)-mixing time, i.e., the smallest value of \( t \) so for all initial states \( x \)

\[
\|P_x(X_t \in \cdot) - \pi(\cdot)\|_{TV} \leq \alpha
\]

where \( TV \) indicates we are considering the total variation distance. The specific value \( t_{mix}^Q(1/4) \) is called the mixing time and denoted by \( t_{mix}^Q \). The constant \( 1/4 \) is chosen, see (6.1.3) so that for all \( \epsilon < 1/4 \),

\[
t_{mix}^Q(\epsilon) \leq C \ln(1/\epsilon)t_{mix}^Q
\]

To define the sense in which convergence occurs define the Wasserstein distance between the distributions of two random variables \( X \) and \( Y \) with finite means by

\[
d_W(X, Y) = \int |P(X > x) - P(Y > x)| \, dx
\]

As is well known \( d_W(X, Y) = \sup \{|Ef(X) - Ef(Y)| : f \text{ is 1-Lipschitz} \} \).

Finally to define the limiting coalescence time of Kingman’s coalescent we let \( Z_i, i \geq 2 \) be independent exponentials with

\[
P(Z_i > t) = \exp \left( -t \left( \frac{i}{2} \right) \right).
\]

**Theorem 7.6.3.** Start with one copy of the Markov chain at each site and let \( C \) be the time needed for all the particles to coalesce to 1. If \( \rho(Q) = t_{mix}^Q/m(Q) \) then

\[
d_W \left( \frac{C}{m(Q)}, \sum_{i \geq 2} Z_i \right) = O \left( \left[ \rho(Q) \ln(1/\rho(Q)) \right]^{1/6} \right)
\]

and hence \( C/m(Q) \Rightarrow \sum_{i \geq 2} Z_i \) if \( \rho(Q) \to 0 \).
The strength of this result is that it provides quantitative bounds. Since he used the Wasserstein distance, he could conclude

\[ EC/m(Q) - 2 = O\left(\left[\rho(Q) \ln(1/\rho(Q))\right]^{1/6}\right) \]

**Ideas that go into the proof.** Let \( C_k \) be the time until only \( k \) particles remain. \( M = C_1 - C_2 \) is the hitting time of

\[ \Delta = \{(x, x) : x \in V\} \]

\( M^{(i+1)} = C_i - C_{i+1} \) is the hitting time of

\[ \Delta^{(i+1)} = \{(x_1, \ldots, x_{i+1}) : x(i_1) = x(i_2) \text{ for some } 1 \leq i_1 < i_2 \leq i + 1\} \]

As Oliveira described in Section 1.4 to prove the result we have to face several difficulties:

At time \( C_{i+1} \) the random walkers are not in equilibrium. This is where the assumption that mixing is faster than hitting comes in.

The mean-field picture suggests that \( M^{i+1}/m(Q) \) should be close in distribution to \( Z_i \). Results of Aldous and Fill suggest that hitting times are exponentially distributed but to control the Wasserstein distance we need better control of the tail of \( M^{(i+1)} \).

We do not expect the exponential approximation to hold when \( \Delta^{(i+1)} \) is too large, so we need different methods to control the Big Bang phase.

We have seen each of these issues in this chapter, so we refer the reader to the paper for further details.

### 7.7 Asymptotics for CRW densities

#### 7.7.1 On the torus in \( d \geq 2 \)

By duality between the voter model \( \xi_t^0 \) and coalescing random walk \( \zeta_t^1 \)

\[ p_t = P(\xi_t^0 \neq \emptyset) = P(0 \in \zeta_t^1). \]

In 1980 Bramson and Griffeath (1980), completed the proof of

\[ p_t \sim \begin{cases} 
\frac{(\log t) / \pi t}{1/\beta_d} & d = 2 \\
1/\beta_d t & d \geq 3
\end{cases} \] (7.7.1)

where \( \beta_d \) is the probability a \( d \)-dimensional simple random walk starting at 0 never returns there.

There is a simple heuristic that gives the answer. If lattice sites on \( \mathbb{Z}^d \) are independent and occupied with probability \( u \), then the instantaneous rate at which collisions occur is
If we assume that the particles are always randomly scattered on the lattice then their density would satisfy the differential equation:

\[
\frac{du}{dt} = -u^2 \quad u(0) = 1
\]

The solution is \( u(t) = 1/(1+t) \). If our random walks do not coalesce when they meet then in \( d \geq 3 \), two that hit once would hit a geometric number of times with mean \( 1/\beta_d \). Removing the over counting from the previous equation

\[
\frac{du}{dt} = -\beta_d u^2
\]

so \( u(t) \sim 1/(\beta_d t) \). To prepare for the next calculation, note that we have multiplied the naive asymptotics, \( 1/u \), by the expected number of collisions given that one occurred.

In \( d = 2 \), this reasoning needs to be modified since random walks are recurrent and hence they hit infinitely many times. In \( d = 2 \) the random walk \( S_t \) that jumps to a randomly chosen nearest neighbor at rate 2 has mean 0 and covariance matrix \( I \) where the \( I \) is the identity matrix, so using the (local) central limit theorem

\[
P(S_t = 0) \sim \frac{1}{2\pi t}
\]

When \( S_t \) hits 0, it stays there for an amount of time that is exponential with mean 1/2. The expected number of times two random walks hit in \([0, t]\) is thus

\[
\sim 2 \int_1^t \frac{1}{2\pi s} \, ds \sim \frac{\log t}{\pi}.
\]

Multiplying the naive asymptotic \( \sim 1/t \) by this gives the result in \( d = 2 \).

The rigorous derivation of (7.7.1) involves a number of clever observations. We follow the summary in Bramson and Griffeath (1980). Unfortunately in that paper the voter model is \( \zeta_t \) and the coalescing random walk is \( \xi_t \). We will write things in our notation. Consider the voter model starting from all sites different and let

\[
N_t = |\{x : \xi_t(x) = \xi_t(0)\}|
\]

be the size of the patch of particles in the voter model at time \( t \) that is the same type as the particle at the origin. Sudbury (1976) observed that

**Lemma 7.7.1.** If \( R_t \) is the number of points visited by our rate 2 random walk by time \( t \), i.e., \( R_t = |\{x : x = S_s \text{ for some } s \leq t\}| \) then

\[
EN_t = ER_t \quad \text{(7.7.2)}
\]

**Proof.** In order for \( \xi_t(0) = \xi_t(x) \), the dual processes must have \( \zeta_s^{0,t} = \zeta_s^x \) for some \( s \leq t \), which has the same probability as \( \zeta_s^{0,t} - \zeta_s^x \) hitting 0 by time \( t \), which is the same as the probability \( S_r \) hits \( x \) by time \( t \) when it starts from 0. \( \square \)
Combining (7.7.2) with results of Dvoretsky and Erdős for the range of random walk we have

\[ EN_t \sim \begin{cases} \frac{2t}{k\log t} & d = 2 \\ 2\beta d & d \geq 3 \end{cases} \]  

(7.7.3)

The reasoning is the same as in our heuristic proof. The rate 2 random walk makes \( \sim 2t \) jumps by time \( t \). To find the range we divide this by the average number of times a site is visited given that it is visited at least once.

Kelly (1977) noticed

**Lemma 7.7.2.** Let \( n_t = |\xi^0_t| \).

\[ P(N_t = k) = kP(n_t = k) \]  

(7.7.4)

**Proof.** Suppose someone shows us a large \( d \)-dimensional cube of side \( L \) from the configuration from time \( t \), not telling us where the origin is located, and then we pick a site at random to be the origin. An opinion with \( k \) representatives will be chosen with probability \( k/L^d \). Thus when we pick a cluster containing a given site, we get a size biased pick from the original distribution. Note that since \( E\xi_t = 1 \), the right-hand side is a probability distribution. □

Combining (7.7.4) with Jensen’s inequality and (7.7.3) we have

\[ p_t = E(N_t^{-1}) \geq (EN_t)^{-1} \]

which gives an asymptotic lower bound of \( 1/2 \) the correct answer in (7.7.1). To close the gap we use the following result of Sawyer (1979).

**Theorem 7.7.3.** For \( d \geq 2 \), and \( k = 1, 2, \ldots \)

\[ \lim_{t \to \infty} E(N_t/EN_t)^k = \frac{(k + 1)!}{2^k} \]

and hence

\[ \lim_{t \to \infty} P(N_t/EN_t \leq x) = \int_0^x 4ye^{-2y} dy \]

In words \( N_t/EN_t \) converges to a limit \( Y \) with gamma(2,2) distribution, the sum of 2 independent exponentials with rate 2. Less formally

\[ N_t \sim Y \cdot EN_t \]

Ignoring the fact that \( x^{-1} \) is unbounded near 0, and hence small probabilities can have a large impact on the expected value, we have

\[ p_t = EN_t^{-1} \sim \frac{EN_t^{-1}}{EN_t} \sim \frac{2}{EN_t} \]

and we have the quoted result.
Bramson and Griffeath (1980) make this rigorous by showing $p_t = \Theta((\log t)/t)$ in $d = 2$ and $p_t = \Theta(1/t)$ in $d \geq 3$. Our description makes it seem that all they did was to cross the t’s and dot the i’s in asymptotics. To complete the proof they had to use an ingenious argument to show that the coalescing random walk had a self-correcting mechanism, i.e., if $p_t$ is larger than it should be then coalescence will be more rapid. A major technical difficulty is that knowing the density does not give one much of an idea about how they are distributed in space.

Open question. It would be nice to have a less devious proof for the asymptotics in (7.7.1). van den Berg and Kesten (2000) have given a much more direct proof but unfortunately it only works in dimensions $d \geq 6$. We will discuss their result in the next section.

### 7.7.2 On graphs

Hermon et al (2022) study CRW on a finite graph $\mathcal{G} = (V, E)$ starting from one particle at each vertex and in which particles perform independent edge simple random walks, i.e., for each edge incident to the current location jumps across that edge occur at rate 1. They also consider the more general situation in which the jump rate is symmetric $r_{x,y} = r_{y,x}$ but depends on the edge. In this case the Markov chain is reversible with respect to counting measure.

They denote by $\xi_t$ the set of elements of $V$ that are occupied by a particle at time $t$ and define the coalescence time

$$\tau_{coal} = \inf\{t : |\xi_t| = 1\}$$

Interest focuses on the rate of decay of $\bar{u}_t = \frac{\sum_x u_t(x)}{|V|}$ where

$$u_t(x) = P(x \in \xi_t).$$

Hermon et al call this $P_t(x)$ but there are already way too many $p$’s in the paper. Being easily confused, we will modify the notation to distinguish the average $\bar{u}_t$ which is a number from the function $u_t(x)$.

Hermon et al are interested in the rate at which $\bar{u}_t \to 0$ for two collections of graphs

(i) Graphs generated by the configuration model with minimum degree 3. In this case it is natural to guess that $\bar{u}_t = \Theta(1/t)$ or even $\lim_{t \to \infty} t\bar{u}_t = c$.

(ii) A family of vertex transitive graphs $\mathcal{G} = (V, E)$ satisfying some general ‘transience-like’ and ‘spectral’ conditions.

To formally state their results we need some definitions. Given two independent walks $X_t$ and $Y_t$ they define the meeting time which is a random variable by

$$\tau_{meet}(X_0, Y_0) = \inf\{t : X_t = Y_t\}$$

For the graph they define a constant by

$$t_{meet}(G_n) = E_{\pi, \pi} \tau_{meet}$$
For each \( x \in V \) they define the **neighborhood distribution** \( \nu_x \), which is the distribution of the particle after it has jumped from \( x \).

In case (i) it is the uniform distribution on the neighbors of \( x \). In case (ii) it is \( \nu_x(y) = r_{x,y}/r(x) \) where \( r(x) = \sum_{y} r_{x,y} \).

The definition in case (i) is a special case of that in case (ii), so in general we can define

\[
\alpha_t(x) = r(x)P_{x,\nu_x}(t_{\text{meet}} > t)
\]  

where the subscript gives the distributions of \( X_0 \) and \( Y_0 \) in the definition of the meeting time. Intuitively \( \alpha_t(x) \) gives the distribution of the meeting time for two particles that start at \( x \). To have a quantity associated with the graph as a whole, we define

\[
\bar{\alpha}_t(G_n) = \frac{1}{|V|} \sum_{x \in V} \alpha_t(x)
\]

\( t_{\text{meet}} \) and \( \bar{\alpha}_t \) depend on the graph \( G_n \), but we will drop the dependence from the notation.

Using the newly introduced notation the two main conclusions can be stated succinctly as

(A1) \( \bar{u}_t \approx 1/t\alpha_t \)

(A2) \( \bar{u}_t \approx 2t_{\text{meet}}/nt \)

Their paper is rather lengthy so we will devote most of our effort here to explaining why these results are true. Our next step is to state the results precisely.

**Results**

**Configuration model.** Assume that the degree distribution \( D \) has \( P(3 \leq D \leq M) = 1 \) for some \( M < \infty \). Let \( G_n \) be the graph on \( n \) vertices generated by the configuration model \( \mathbb{CM}_n(D) \). The lower bound \( D \geq 3 \) implies that the probability \( G \) is connected tends to 1. They also consider the local weak limit of \( \mathbb{CM}_n(D) \) which is a **unimodular Galton-Watson tree** \( \mathcal{G} \sim \mathbb{UGT}(D) \). In this structure the root has offspring distribution \( D \) and later generations have offspring the size biased distribution \( D^* \)

\[
P(D^* = k) = \frac{(k + 1)P(D = k + 1)}{ED}
\]

Here, we are thinking of \( D \) as a random variable, while Hermon et al think of it as a density function, i.e. their \( ED \) is their \( \sum_i iD(i) \).

Let \( o \) be the root of \( \mathcal{G} \), let \( \alpha_\infty(o) = E(\alpha_\infty(o)) \) where \( \alpha_\infty(x) = \lim_{t \to \infty} \alpha_t(x) \). Theorem 1 in Hermon et al is

**Theorem 7.7.4.** Let \( G_n \) be sampled from \( \mathbb{CM}_n(D) \). For any sequence of times \( t_n \) so that \( 1 \ll t_n \ll n \) we have the following sequences converging in probability.

\[
limit_{n \to \infty} t_n u(t_n) = \frac{1}{\alpha_\infty(D)} \tag{7.7.6}
\]

\[
limit_{n \to \infty} t_n u(t_n) \cdot \frac{n}{2t_{\text{meet}}(G_n)} = 1 \tag{7.7.7}
\]
Hermon et al prove in their Section 6.4 that
\[ t_{\text{meet}}(G_n)/n \to 1/(2\bar{\alpha}_\infty(D)). \]
This was proved earlier by Chen (2017) for random regular graphs. Of course (7.7.6) and (7.7.7) both hold then the two must be equal.

**Transitive Markov chains.** Theorem 1.9 in Hermon et al (2022) is

**Theorem 7.7.5.** Suppose \( r(x) = \sum_y r_{x,y} = 1, \) \( t_{\text{meet}}(r_n) \leq |V_n| \) and \( t_{\text{rel}}(r_n) \ll t_{\text{meet}}(r_n) \). For any sequence of times satisfying \( t_{\text{rel}}(r_n) \ll t_n \ll t_{\text{meet}}(r_n) \) we have

\[
\lim_{n \to \infty} \frac{|V_n| t_n}{2t_{\text{meet}}(r_n)} P_{t_n} = 1 \tag{7.7.8}
\]
\[
\lim_{n \to \infty} t_n \alpha_{t_n} P_{t_n} \to 1 \tag{7.7.9}
\]

Their Theorem 4 is a stronger result under a stronger transience condition. We refer the reader to their paper for details.

**A simple explanation for (A1)**

van den Berg and Kesten (2000) have given a simple argument for the asymptotics for a coalescing random walk on \( \mathbb{Z}^d, d \geq 3 \). Unfortunately their proof only works in \( d \geq 6 \) and the proof is 49 pages because they consider very general coalescence rules. Here, inspired by the discussion in Section 1.2.2 of Hermon et al we generalize the argument to graphs. The starting point is the equality

\[
\frac{d}{dt} u_t(x) = -2 \sum_{y : y \sim x} r_{y,x} P(x, y \in \xi_t)
\]

If we reverse the direction of time then the jump from \( y \) to \( x \) that caused coalescence becomes a jump from \( x \) to a neighbor \( y \) according to the neighborhood distribution \( \nu_x \). In order for the jump to be a coalescence in the forward process then the reverse trajectories cannot hit as we work backwrdrs in time, which has probability

\[
\alpha_t(x) = r(x) P_{x,\nu_x}(t_{\text{meet}} > t)
\]

Suppose we follow the trajectories back for a time \( s \) has \( t_{\text{mix}} \ll s \ll n \). Then the locations of endpoints will be independent and (almost) uniformly distributed, and the density of coalescing random walks will not have changes. Thus using duality, we have

\[
P(x, y \in \xi_t) \approx (\bar{u}_t)^2
\]

and it follows that

\[
\frac{d}{dt} u_t(x) = -\alpha_\infty(x)(\bar{u}_t)^2
\]

Averaging over \( x \) we have

\[
\frac{d}{dt} \bar{u}_t = -\bar{\alpha}_\infty(\bar{u}_t)^2
\]

Solving the differential equation we have \( \bar{u}_t \sim 1/(t\bar{\alpha}_\infty) \) which is the desired result.
Outline of the real proof

It is somewhat surprising (to me at least) that they follow the approach described in the previous section that led to the results for the asymptotics on \( \mathbb{Z}^d \). Pick a site at the beginning, call it 0, and let \( N_t \) the number of particles that coalesce with it by time \( t \) including itself. If we consider the voter model \( \zeta_t \) starting from all sites different then

\[
N_t = \{ x : \zeta_t(x) = \zeta_t(0) \}
\]

Let \( \tilde{N}_t = \{ x : \zeta_t(x) = \zeta_t(U) \} \) where \( U \) is a vertex chosen at random. Hermon et al show (see Lemma 2.1) that in the finite set-up we also have \( \bar{u}_t = E(\tilde{N}_t^{-1}) \) so it suffices to study the moments of \( N_t \) and study the behavior near 0.

As the authors say, Sawyer’s result, Theorem 7.7.3 involves a “magical” combinatorial calculation that relies heavily on the structure of \( \mathbb{Z}^d \), so they must use a different approach. The starting point is a result that provides rough upper and lower bounds on the decay of \( u_t(x) \) which holds for general \((V, r)\). We will state the result given in their Theorem 8 in a moment. They then bootstrap the general bounds into bounds sharp to smaller order terms. To do this they derive the asymptotics of moments of \( \tilde{N}_t \) by studying the CRW directly. They say this is “the most difficult part of our argument.” As a corollary they generalize Sawyer’s result for \( \tilde{N}_t/E(\tilde{N}_t) \) to other graphs, see their Section 1.1.2.

A Chinese proverb says “A journey of a thousand miles begins with a single step.” For coalescing random walk densities on graphs that step is:

**Theorem 3.1.** If \( M_t = \sup_{x \in V} \int_0^t p_s(x, x) \, ds \) and \( m_t = \inf_{x \in V} \int_0^t p_s(x, x) \, ds \) then there is a constant \( C_0 \) so that for every Markov chain \((V, r)\) and all \( y \in V \)

\[
\frac{m_t}{C_0t} \leq u_t(y) \leq \frac{C_0M_t}{t}
\]

For a transitive chain \( M_t = m_t = \int_0^t p_s(0, 0) \, ds = I_t^0 \). A little thought (see Remark 3.3) shows that up to a universal constant, \( t/I_t^0 \) is the expected number of vertices visited by the chain up to time \( t \).

A simple and elegant bound with an interesting interpretation should have an informative proof but we don’t want to spoil the fun by revealing the details.

References


CHAPTER 7. VOTER MODELS, COALESCING RWS


Chapter 8

Coevolving systems

This chapter is primarily concerned with models in which the states of the nodes and the connections between them coevolve. This topic has been studied in the physics literature for many years. For a survey see Gross and Blasius (2008). However, there are only a small number of rigorous results, which will be our focus here.

8.1 Voter models

Our starting point is the model of Holme and Newman (2006). They begin with a network of \( N \) vertices and \( M \) edges, where each vertex \( x \) has an opinion \( \xi(x) \) from a set of \( G \) possible opinions and the number of people per opinion \( \gamma_N = N/G \) stays bounded as \( N \) gets large. On each step of the process, a vertex \( x \) is picked at random. If its degree \( d(x) = 0 \), nothing happens. For \( d(x) > 0 \), (i) with probability \( \alpha \) an edge attached to vertex \( x \) is selected and the other end of that edge is moved to a vertex chosen at random from those with opinion \( \xi(x) \); (ii) otherwise (i.e., with probability \( 1 - \alpha \)) a random neighbor \( y \) of \( x \) is selected and we set \( \xi(x) = \xi(y) \). This process continues until the time \( \tau \) at which there are no longer any edges connecting individuals with different opinions.

When \( \alpha = 1 \), only rewiring steps occur, so once all of the \( M \) edges have been touched, the graph has been disconnected into at least \( G \) components, each consisting of individuals who share the same opinion. Since none of the opinions have changed, all the components are small. By classical results for the coupon collector’s problem, requires \( \tau \sim M \log M \) updates.

In contrast, for \( \alpha = 0 \) this system reduces to the voter model on a static graph. If we suppose that the initial graph is an Erdős-Rényi random graph in which each vertex has average degree \( \lambda > 1 \), then there is a “giant component” that contains a positive fraction of the vertices, \( \mu N \). Results in Chapter 7 suggest that the voter model on the giant component will reach consensus in \( O(N^2) \) steps of the vertices. The second largest component is small having only \( O(\log N) \) vertices, i.e., when \( N \) is large the size will be \( \approx C_\lambda \log N \), where \( C_\lambda \) is a constant that depends on \( \lambda \), so the end result is that one opinion has \( \mu N \) followers while all of the other groups are small.
Using simulation and finite size scaling, Holme and Newman showed that there is a critical value $\alpha_c$ so that for $\alpha > \alpha_c$ all of the opinions have a small number of followers at the end of the process, while for $\alpha < \alpha_c$, “a giant community of like-minded individuals forms.” When the average degree $\lambda = 2M/N = 4$ and the number of individuals per opinion $\gamma N \to 10$, this transition occurs at $\alpha_c \approx 0.46$.

In this section we will concentrate on the “linear” version of the evolving voter model. The first subsection states some conjectures that (if established) would give a detailed understanding of its behavior, the second describes rigorous results of Basu and Sly (2017) that prove the existence of a phase transition, while the third introduces approximate and numerical methods for studying the system. This system is well studied and further progress seems difficult. Readers may find more fertile directions for research on nonlinear versions surveyed by Kureh and Porter (2020) where the behavior of a node depends on how well it “fits in” to its neighborhood.

8.1.1 Eight guys at SAMSI (2010-2011)

During 2010-2011 program on Complex Networks at SAMSI, Rick Durrett, James Gleeson, Alun Lloyd, Peter Mucha, Feng Shi, David Sivakoff, Josh Socloar, and Chris Varghese worked on this and other related topics. In their formulation of the evolving voter model, edges are picked at random. If the two connected individuals hold different opinions then: with probability $1 - \alpha$ one imitates the opinion of the other; otherwise, i.e., with probability $\alpha$, the link between them is broken and one of them makes a new connection to an individual chosen at random (i) from those with the same opinion, or (ii) from the network as a whole. The two versions of the model are called “rewire to same” and “rewire to random.” The evolution of the system stops when there are no longer any discordant edges connecting individuals with different opinions.

Letting $\rho$ be the fraction of voters holding the minority opinion after the evolution stops, they were interested in how $\rho$ depends on $\alpha$ and the initial fraction $u$ of voters with opinion 1. In case (i), there is a critical value $\alpha_c$ which does not depend on $u$, with $\rho \approx u$ for $\alpha > \alpha_c$ and $\rho \approx 0$ for $\alpha < \alpha_c$. In case (ii), the transition point $\alpha_c(u)$ depends on the initial density $u$. For $\alpha > \alpha_c(u)$, $\rho \approx u$, but for $\alpha < \alpha_c(u)$ we have $\rho(\alpha, u) = \rho(\alpha, 1/2)$.

Figure 8.1 shows the final fraction $\rho$ of voters with the minority opinion from five realizations for each $u$. For $\alpha > \alpha_c \approx 0.43$ we observe $\rho \approx u$ and for $\alpha < \alpha_c \rho \approx 0$. Again the initial probabilities of opinion 1 are given by $u = 0.5, 0.25, 0.1, 0.05$. When $u = 0.5$ the fraction in the minority is constant at $0.5$ over $[\alpha_c(0.5), 1]$ and then decreases continuously to a value near 0 as $\alpha$ decreases to 0. When $u < 0.5$ there is a critical value $\alpha_c(u)$ so that for $\alpha > \alpha_c(u)$ we have $\rho(\alpha, u) = u$, while for $\alpha < \alpha_c(u)$ we have $\rho(\alpha, u) = \rho(\alpha, 0.5)$. Since all of the $\rho(\alpha, u)$ agree with $\rho(\alpha, 0.5)$ when they are $< u$, we call the graph of $\rho(\alpha, 0.5)$ on $[0, \alpha_c(0.5)]$ the universal curve.

The behavior of our models for $\alpha > \alpha_c$ is easy to understand. As in the case of the Holme and Newman model, we expect consensus to be reached in $O(N \log N)$ steps when $\alpha = 1$ and in $O(N^2)$ steps when $\alpha = 0$. We define the boundary between the fast and slow consensus
Figure 8.1: Simulation results for rewire to same model (left panel) and rewire to random (right panel), starting from Erdös-Rényi graphs with \( N = 100,000 \) nodes and average degree \( \lambda = 4 \). Opinions are initially assigned randomly with the probability of opinion 1 given by \( u = 0.5, 0.25, 0.1, \) and 0.05.

regimes to be the value of \( \alpha \) where the average number of steps needed to reach consensus is \( N^{3/2} \) (any power between 1 and 2 would give the same results when \( N \to \infty \)). When an edge is chosen between voters with different opinions then a rewiring event does not change the number of 1’s, while a voting event will increase and decrease the number of 1’s with equal probability, i.e., the number of 1’s is a random walk that on each step stays constant with probability \( \alpha \). The central limit theorem implies that when consensus is reached in \( O(N^{3/2}) \) steps the typical change in the number of 1’s from the initial configuration is \( O(N^{3/4}) \). Hence, when the initial fractions of 1’s is \( u \leq 1/2 \) the final fraction \( \rho \) with the minority opinion will be approximately equal to \( u \).

**Quasi-stationary distributions**

Let \( N_i \) be the number of vertices in state \( i \). Our first clue to the reason for a universal curve in the rewire to random model came from the next two figures.

The situation becomes clearer if we plot the joint distribution.

In the left panel five simulations starting from \( u = 0.2, 0.35, 0.5, 0.65, \) and 0.8 are plotted. Note that the simulation comes quickly to a curve that then diffuses along it. In the right panel we do five simulations all starting at \( u = 0.5 \). The fact that the values of the statistics \( N_{01}/N \) and \( N_{00}/N \) depend only on the fraction of 1’s suggest that there is a one dimensional family of quasi-stationary distributions indexed by the density. The system converges quickly to it and then diffuses along the curve until it hits an absorbing state. The next result due to Cox and Greven (1990) shows that this true for the voter model on the torus in dimensions \( d \geq 3 \). Here \( \nu_{\rho} \) is the one parameter family of stationary distributions from Theorem 7.1.1.

**Theorem 8.1.1.** If the voter model on the torus in \( d \geq 3 \) starts from product measure with
Figure 8.2: Fraction of nodes with the minority opinion (min\{N_0, N_1\}/N) and the number of discordant edges \(N_{10}\) versus time, for a simulation start with an Erdős-Rényi graph with \(N = 10,000\) and \(\lambda = 4\). Note that the two statistics are strongly correlated

density \(p\) then at time \(Nt\) it looks locally like \(\nu_{\theta(t)}\) where the density \(\theta_t\) changes according to the Wright-Fisher diffusion process

\[
d\theta_t = \sqrt{\beta_d \cdot 2\theta_t(1-\theta_t)} dB_t
\]

and \(\beta_d\) is the probability that two random walks starting from neighboring sites never hit.

Conjectures

Our next goal is to use simulation results to formulate the analogues of the Cox and Greven result for our two evolving voter models, beginning with the more interesting rewire to random case. Figure 8.3 shows results from simulations of the system with \(\alpha = 0.5\). Observations of the pair \((N_1/N, N_{10}/M)\) are plotted every 1,000 steps starting from densities \(u = 0.2, 0.35, 0.5, 0.65\) and \(0.8\). The plotted points converge quickly to a curve that is approximately (fitting to a parabola) \(1.707x(1-x) - 0.1867\) and then diffuse along the curve until they hit the axis near \(0.125\) or \(0.875\). Thus the final fraction with the minority opinion \(\rho \approx 0.125\), a value that agrees with the universal curve in Figure 8.1 at \(\alpha = 0.5\).

The fact that, after the initial transient, \(N_{10}/M\) and \(N_{010}/N\) are functions of \(N_1/N\) supports the conjecture that the evolving voter model has a one parameter family of quasi-stationary distributions, for if this is true then the values of all of the graph statistics can be computed from \(N_1/N\).

The phenomena just described for \(\alpha = 0.5\) also hold for other values of \(\alpha\). Figure 8.4 shows the arches that correspond to \(\alpha = 0.1, 0.2, \ldots, 0.7\). Numerical results show that the curves are well approximated by \(c_{\alpha}u(1-u) - b_{\alpha}\). Let \((v(\alpha), 1-v(\alpha))\) be the support interval where the arch has positive values. Simulations show that if \(u < v(\alpha)\) then the simulated curve rapidly goes almost straight down and hits the axis where \(N_{10} = 0\).
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Figure 8.3: Here the initial graph is the same but $\alpha = 0.5$. The left panel shows a plot of $(N_1/N, N_{10}/M)$ The right panel gives a plot of $\rho$(0,0.5) = $v(\alpha)$ for $\alpha < \alpha_c(0.5)$. In the conjectured generalization of the Cox-Greven result the quantity under the square root is $(1 - \alpha)N_{10}/M$ with $(1 - \alpha)$ = the fraction of steps that are voter steps, since rewiring steps do not change the number of 1’s.

The simple formulas approximating the curves in Figures 8.3 and 8.4 suggest that there might be a simple polynomial formulas. However, when Shi, Durrett, and Mucha (2013) studied the model with three or more opinions, their more accurate numerical results suggested the formulas were good approximation but not exact.
CHAPTER 8. COEVOLVING SYSTEMS

8.1.2 Basu and Sly (2017)

These authors studied the evolving voter model on the dense Erdős-Rényi graph $ER(n, 1/2)$ in which edges between two vertices are independently present with probability 1/2. In order for there to be a transition in this version of the model, one must change the opinion update rate to $1 - \alpha = \beta/n$. Let $\tau$ be the time to reach an absorbing states in which there are no edges in the graph that connect two vertices with different opinions.

The first result holds for the rewire-to-random and for the rewire-to-same versions. It assumes that in the initial condition the states of vertices are independent and take the value 0 and 1 with equal probability. Let $N_*(t)$ be the number of edges with the minority opinion at time $t$, and for $1/2 > \epsilon > 0$ let $\tau^* (\epsilon) = \min\{t : N_*(t) \leq \epsilon n\}$. They proved two main results

**Theorem 8.1.4. (Theorem 1.)** Let $1/2 > \epsilon' > 0$. For both variants of the model there is constant $0 < \beta_0 < \beta_*(\epsilon')$ so that the following hold

(i) For all $\beta < \beta_0$ and any $\eta > 0$, $\{\tau < 6n^2, N_*(\tau) \geq 1/2 - \eta\}$ holds with high probability.

(ii) For all $\beta > \beta_*(\epsilon')$ we have $\tau_*(\epsilon') \leq \tau$ with high probability and

$$\lim_{c \to 0} \lim_{n \to \infty} P(\tau > cn^3) = 1$$

In case (i) the frequency of the minority opinion does not change much by time $\tau$ so we are in the rapid disconnection regime. Conversely in case (ii) there is a substantial change in the minority frequency. Since voter model steps happen at rate $\beta/n$ the number of steps to reach consensus is now $O(n^3)$.

**Theorem 8.1.5. (Theorem 2.)** Let $\beta > 0$ be fixed. For the rewire-to-random model, there exists $\epsilon_*(\beta)$ so that $\tau < \tau_*(\epsilon)$ with high probability.
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The second result is only for rewire-to-random since the graph in the left half of Figure 8.1 shows that it is false for rewire-to-same. Proving that the universal curve exists for rewire-to-random seems very difficult, as is the following

Open problem. Prove that the critical value $\alpha_c(u)$ for rewire-to-same does not depend on the initial density $u$, and that for $\alpha < \alpha_c$ the ending minority fraction tends to 0 as $N \to \infty$.

Constructing the process

$ER(n, 1/2)$ has roughly $n^2/4$ edges so it will rapidly develop a large number of parallel edges, so we will need to carefully choose definitions to keep track of the state. Let $n$ be a fixed positive integer. Let $V$ be a fixed set with $|V| = n$, e.g., $V = \{1, 2, \ldots n\}$. Let $V^{(2)}$ be the set of unordered pairs of elements $\{x, y\}$ in $V$, with $x \neq y$, which are called bonds. Note that while we cannot prevent parallel edges there is no reason to allow self-loops.

Let $E$ be the set of edges of the graph. We consider a discrete time Markov chain with state space

$$(\{0, 1\}^V, (V^{(2)})^E)$$

Deviating from the notation of Basu and Sly, the first coordinate is a function $\xi_t : V \to \{0, 1\}$. $\xi_t(v)$ gives the opinion of $v$ at time $t$ but this is also written less formally as $v(t)$. The second coordinate is a function $Y_t : E \to V^{(2)}$. $Y_t(e)$ gives the location of the edge $e$, which we can think of as little rods that are labeled and are moved around. The resulting multigraph is called $G(t)$. Let $N_i(t) = |\{v : X_t(v) = i\}|$ be the number of vertices in state $i = 1, 2$ and $N_*(t) = \min\{N_1(t), N_0(t)\}$ be the number of vertices with the minority opinion.

We take $G(0)$ to be distributed as $ER(n, 1/2)$ so each bond in $V^{(2)}$ contains one edge with probability $1/2$ and 0 edges with probability $1/2$. The dynamics we are about to describe will preserve the number of edges. The first step is to let $E^\times$ be the set of discordant edges (the opinions are different at the two ends), pick one at random, and give it an orientation, say $u, v$.

To decide which event will occur let $\zeta(t)$ be Bernoulli($\beta/n$).

- If $\zeta(t) = 0$ we perform a rewiring step. To do this we pick $w$ at random from $V - \{u\}$, and move $(u, v)$ to $(u, w)$, i.e., we set $Y_{t+1}(e) = (u, w)$.

- If $\zeta(t) = 1$ we perform a voter step in which $v$ imitates $u$, i.e., we set $X_{t}(v) = X_{t}(u)$.

Proof of part (i) of Theorem 8.1.4

Most of Basu and Sly (2017) is devoted to the proof of part (ii) of Theorem 8.1.4, so following our usual modus operandi we will only prove the easy results. Let $D_{\text{max}}(t)$ denote the maximum degree of a vertex in $G(t)$, which is the number of edges $e \in E$ containing it, not the number of vertices that are connected to it by an edge.

Recall that $\tau$ is the first time there are no discordant edges, Let

$$\tau_1 = \min\{t : D_{\text{max}}(t) \geq 8n\} \quad \tau_2 = \min\{t : N_*(t) \leq n/3\}$$

and $\tau_0 = \tau \wedge \tau_1 \wedge \tau_2$. Let $X_t = |E_t^\times|$ be the number of discordant edges at time $t$.
Lemma 8.1.6. (Lemma 2.1.) There is a $\beta_0$ so that for all $\beta < \beta_0$ we have $\tau_0 \leq 6n^2$ with high probability.

Proof. Let $F_t$ be the filtration generated by the process up to time $t$. Observed that when an edge is rewired either $X_t$ remains the same or decreases by 1. Conditional on $F_t$ the probability that $X_t$ decreases by a rewiring is at least $\left(\frac{N^* - 1}{n - 1}\right)$.

For large $n$ on the event $\{t < \tau_0\}$ we have $\left(\frac{N^* - 1}{n - 1}\right) \leq 1/4$. If we take $\lambda$ sufficiently small so that $e^{8\lambda} \leq 1 + 9\lambda$ and $e^{-\lambda/n} - 1 \leq -\lambda/2n$ then on $\{t < \tau_0\}$ we have

$$E(e^{\lambda X_t/n} | F_t) \leq e^{\lambda X_t/n} \left[1 - \frac{1}{4} \left(\frac{\lambda}{2n}\right)ight] + \frac{\beta}{n}(1 + 9\lambda)$$

Doing some algebra the right hand side is

$$e^{\lambda X_t/n} \left[1 - \frac{1}{8n} - \frac{\beta}{n} \cdot 9\lambda\right]
\leq e^{\lambda X_t/n} \left[1 - \frac{\lambda}{n} \left(\frac{1 - \beta}{8} - 9\beta\right)\right] \leq e^{\lambda X_t/n} \left[1 - \frac{\lambda}{10n}\right]$$

when $\beta < \beta_0$. It follows from the above that

$$P(\tau_0 > t | F_0) \leq E(\exp(\lambda X_t/n) 1_{\{\tau_0 > t\}} | F_0) \leq e^{\lambda X_0/n} e^{-\lambda t/10n} \leq e^{\lambda n/2} e^{-\lambda t/10n}$$

since $X_0 \leq n^2/2$, and it follows that $P(\tau_0 > 6n^2) \leq \exp(-\lambda n/10)$.

Lemma 8.1.7. (Lemma 2.2.) Recall $\tau_1$ is the first time $D_{\max} \geq 8n$. With high probability $\tau_1 > 6n^2$.

Proof. Let $W_i$ be a sequence of i.i.d. random variables uniform on $\{1, \ldots, n\}$. Let $L_0 = 0$. For $i \geq 1$ let $v_i$ be the root of the $i$th rewiring move and let

$$L_i = \min\{j > L_{j-1} : W_j \neq v_i\}$$

$L_i - L_{i-1}$ are independent geometric ($(n - 1)/n$). It follows by a large deviations estimate that

$$L_{6n^2} \leq 13n^2/2 \quad \text{with exponentially high probability.}$$

To fill in the details note that if $X$ is geometric($p$) then

$$E e^{\theta X} = \sum_{k=1}^{\infty} (1 - p)^{k-1} p e^{\theta k} = \frac{p e^\theta}{1 - (1 - p)e^\theta}$$
We are interested in the special case $p = (n - 1)/n$. Formula (A.1.2) from the appendix tells us that $S_m$ is the sum of $m$ geometric((n − 1)/n)

$$\frac{1}{m} \log P(S_m \geq 13m/12) \leq - \left[ \frac{13\theta}{12} - \theta - \log \left( \frac{1}{1 - e^{\theta/n}} \right) \right]$$

If we take $\theta = \log 2$ then the right-hand side converges to $-(\log 2)/12$ as $n \to \infty$. Taking $m = 6n^2$ and using log 2 > 0.5 it follows that for large $n$ we have

$$P(L(6n^2) \leq 13n^2/2) \leq \exp(-n^2/24).$$

Let $N(v) = |\{i \leq 13n^2/2 : W_i = v\}|$. $N(v)$ is binomial(13n^2/2, 1/n). Using Lemma A.1.7 with $m = 13n^2/2$, $p = 1/n$ and $y = 1/13$ (so $1 + y = 14/13$ we have

$$P(N(v) \geq 7n) \leq \exp \left( - \frac{13n}{2} \cdot \frac{1}{(13)^2} \cdot \frac{13}{2(14)} \right) = e^{-n/56}$$

Since $D_{\text{max}}(0) \leq n$ we have

$$P(\tau_1 \leq 6n^2) \leq ne^{-n/56} + P(L_{6n^2} \leq 13n^2/2)$$

which proves the desired result.

**Lemma 8.1.8.** (Lemma 2.3.) Recall $\tau_2$ is the first time $N_*(t) \leq n/3$. With high probability $\tau_2 > 6n^2$.

**Proof.** For $t \geq 1$ the number of relabeling moves up to time $t$, $RL(t)$ is dominated by a binomial$(t, \beta/n)$ random variable. On $\tau > t$ the change in the number of 0 vertices $N_0(t) - N_0(0)$ is a random walk $Z_t$ that jumps by 1 or −1 with equal probability. The probability $\tau_2 \leq 6n^2 \land \tau$ is bounded by

$$P(N_*(0) \leq 2n/5) + P(RL(6n^2) > 12\beta n) + P(\max_{i\leq 12\beta n} |Z_i| \geq 3n/20)$$

Noticing that $P(N_*(0) \leq 2n/5) \leq 2P(\text{binomial}(n, 1/2) < 2n/5)$, and using Lemma A.1.7 with $m = n$, $p = 1/2$ and $y = 1/5$ we have

$$P(N_*(0) \leq 2n/5) \leq \exp(-(n/2) \cdot (1/25) \cdot 1/2) = \exp(-n/100)$$

Using Lemma A.1.7 again with $m = 6n^2$, $p = \beta/n$ and $y = 1$

$$P(RL(6n^2) > 12\beta n) \leq \exp(-6\beta n/4)$$

Finally using the Azuma-Hoeffding bound in A.2.1 with $m = 12\beta n$, $c_k \equiv 1$ and $L = 3n/20$ gives

$$P \left( \max_{i\leq 12\beta n} |Z_i| \geq 3n/20 \right) \leq \exp(-(3n/20)^2/(2 \cdot 12\beta n)) = \exp(-9n/9600\beta)$$

Combining the last four inequalities proves the desired result. In the last three inequalities the constants we have obtained are different from Basu and Sly. This is not a big deal but in the last instance their constant $e^{-2\beta n}$ has the $\beta$ in the numerator when it should be in the denominator.
Proof of part (i) of Theorem 8.1.4. Lemmas 8.1.6, 8.1.7, and 8.1.8 imply that with high probability \( \tau \leq 6n^2 \). Using a random walk estimate as in the proof of Lemma 2.3 we conclude that the probability \( N_*(t) \) drops below \( (1/2 - \eta)n \) in \( 6n^2 \) steps tends to 0 as \( n \to \infty \). \( \square \)

Proof of Theorem 8.1.5

For \( 0 < p < 1 \) let \( G^*(n, p) \) be the collection of multigraphs where \( N_1(G) = pn \) and the number of edges in \( G \) is \([12n^2/50, 13n^2/50]\) which has high probability under \( ER(n, 1/2) \). Theorem 2 follows from

**Theorem 8.1.9.** (Theorem 6.5) Let \( \beta > 0 \) be fixed and run the rewire-to-random dynamics starting from \( G(0) \in G^*(n, p) \). Let

\[
\tau = \min\{t : \mathcal{E}^X(t) = \emptyset\} \quad \tau_* = \tau_*(p/2) = \min\{t : N_*(t) \leq np/2\}
\]

Then there is a sufficiently small \( p(\beta) \) so that for all \( G(0) \in G^*(n, p) \) we have \( \tau < \tau_* \) whp.

Let \( S \) be the vertices with degree \( \leq 10n \). Let \( T \) be the vertices with degree \( > 10n \). Clearly \( |T| \leq n/25 \). Proof: Exercise.

Let \( W_{SS} \) be the number of rewirings for edges with both end points in \( S \) and define \( W_{ST} \) and \( W_{TT} \) similarly. We will run the process for \( 10n^2 \) steps. Let \( Y_{SS} \) be the number of edge sat time \( 10n^2 \) with both end points in \( S \) and define \( Y_{ST} \) and \( Y_{TT} \) similarly.

A special construction of rewire-to-random

- Let \( X_i \) and \( X'_i \) be two sequences of i.i.d. (shifted) geometric(\( \beta/n \)) taking values in \( \{0, 1, 2, \ldots\} \) i.e., the number of failures before the first success.

- Let \( Z_i \) be i.i.d. Bernoulli(1/2).

- Let \( W_i \) be i.i.d. uniform on the vertices of the graph, which we will suppose are \( \{1, 2, \ldots, n\} \)

- For each vertex \( v \) we will define counters \( K_i(v) \), whose value at time \( i \) gives the number of rewiring updates with focal vertex \( v \) which are the number of updates with \( v \) as the focal vertex that are rewirings before it changes its opinion.

- We will define sequences \( L_i, L'_i \) and \( T_i \) recursively. Let \( L_0 = 0, T_0 = 0 \) and \( L'_0 = n \)

The main loop begin with choosing a discordant edge. Suppose the loop counter is \( i \). \( Z_i \) is used to chosen the focal vertex for the edge. It is the end point with state \( Z_i \). Let \( v \) be the chosen vertex.
Case 1. The reason for this construction and in particular the reasons for two sequences $x$ and $X'$ can be seen in the proof of Lemma 6.3. If $v \in S$ and the opinion at $v$ is 0, do the following: Set $L'_i = L'_{i-1}$.

If $K_{i-1}(v) > 0$ then define

$$T_i = \min\{k > T_{i-1} : W_k \neq v\}$$

which is the scheme we used previously to pick a vertex at random which is $\neq v$. Rewire the edge to $(v, W_k)$, reduce $K_i(v)$ by 1, and set $L_i = L_{i-1}$.

If $K_{i-1}(v) = 0$ then change the opinion at $v$ and set $L'_i = L'_{i-1} + 1$, and $K_i(v) = X(L_i)$ the new counter value. Since we did not use any uniformly chosen vertices we set $T_i = T_{i-1}$.

Case 2. If $v \not\in S$ or the opinion at $v$ is 1. Set $L_i = L_{i-1}$.

If $K_{i-1}(v) > 0$ then define

$$T_i = \min\{k > T_{i-1} : W_k \neq v\}$$

Rewire the edge to $(v, W_k)$, reduce $K_i(v)$ by 1, and set $L'_i = L'_{i-1}$.

If $K_{i-1}(v) = 0$ then change the opinion at $v$ and set $L'_i = L'_{i-1} + 1$, and $K_i(v) = X'(L_i)$ the new counter value and set $T_i = T_{i-1}$.

Turning to the proof

**Lemma 8.1.10.** (Lemma 6.2.) For a fixed $p$ and $G(0) \in G^*(n, p)$ the number of vertices of opinion 1 remains between $pn/2$ and $3pn/2$ for the first $10n^2$ steps whp.

**Proof.** The number of voting steps is $\approx 10\beta n$ which is not enough to change the density. \hfill $\square$

An element of the sequence $X$ is said to be stubborn if it is at least $25n$.

**Lemma 8.1.11.** (Lemma 6.3.) Let $Y = |\{i \leq L_{10n^2} : X_i > 25n\}|$. Then with high probability $N_1(10n^2) \geq Y$.

**Proof.** We will be happy on $H = \{\forall v \in G : |\{i \leq T_{10n^2} : W_i = v\} \leq 14n\}$. The sequence of $W_i$ skips over some choices if they are equal to the current vertex but that happens on with probability $1/n$. An argument similar to that used in Lemma 2.2 shows that $P(T_{10n^2} \geq 11n^2)$ is exponentially small in $n$. A Chernoff bound shows that the probability a given $v$ more than $14n$ times in the first $11n^2$ times in the list is exponentially small.

On $H$ if a stubborn $X$ gets assigned to $V$ then that at that point the vertex was in $S$ and in state 1. Since the initial degree is $\leq 10n$ and it will be chosen $\leq 14n$ times and the vertex does not change until after time $10n^2$. It follows from this reasoning that the vertices assigned to stubborn vertices are distinct. \hfill $\square$

Let $RL_{SS}$ be the number of relabelings that occur with both end points in $S$. Let $R_{SS}$ be the number of times an edge with both end points in $S$ was chosen and define $R_{ST}$ and $R_{TT}$ similarly. The proof is now completed by showing that if $p$ is sufficiently small

**Lemma 6.4.** $RL_{SS} \leq \beta n/20$ whp.
Lemma 6.5. $R_{SS} \leq n^2/10$ whp.

Lemma 6.6. $R_{ST} \leq 3n^2$ whp.

Lemma 6.7. $R_{SS} \leq 6n^2$ whp.

The last three results imply $\tau \leq 9.1n^2 < 10n^2$, Theorem 6.1 (and hence Theorem 2) now follows from Lemma 6.2. We refer the reader to Basu and Sly for the proofs of the four lemmas.

8.1.3 Numerical Results, etc.

While it is nice to have a rigorous proof of the existence of a phase transition for the evolving voter model, the work described in the previous section does not provide any insight into why there is such a dramatic difference between the behavior of the rewire-to-random and rewire-to-same models. In addition, as is common in rigorous work, the proofs provide very little quantitative information about the location of the phase transition or the equilibrium density. In view of this it is natural to turn to approximate methods such as mean-field computations, the pair approximation, moment methods, etc. An excellent description of these methods and their application to epidemics on networks can be found in the excellent 2017 book by István Kiss, Joel Miller and Peter Simon.

Here we take a look at these methods in the special case of the rewire-to-random versions of the evolving voter model.

![Figure 8.5: Predictions of the ending minority fraction $\rho(\alpha)$ in rewire-to-random case starting from product measure with density $u = 0.5$, from the pair approximation (dashed line) and approximate master equation (solid line), compared with simulation (x).]

Mean-field approach. Let $u = N_1/N$ be the initial fraction of vertices in state 1. By
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considering all of the possible changes one arrives at the following differential equations.

\[
\frac{dN_{10}}{dt} = -(2 - \alpha)N_{10} + (1 - \alpha)[N_{100} - N_{010} + N_{110} - N_{101}]
\]

\[
\frac{1}{2} \frac{dN_{11}}{dt} = (1 - \alpha(1 - u))N_{10} + (1 - \alpha)[N_{101} - N_{011}]
\]

\[
\frac{1}{2} \frac{dN_{00}}{dt} = (1 - \alpha u)N_{10} + (1 - \alpha)[N_{010} - N_{100}]
\]

(8.1.1)

Here we have used the fact that in the initial phase modeled by these differential equations

\[N_1 \approx Nu\quad \text{and}\quad N_0 \approx N(1 - u)\].

We have \(N_{11} + 2N_{10} + N_{00} = M\) so the sum of the three
differential equations is 0. Note that the derivatives of the two-vertex quantities \(N_{ij}\) involve
two or three vertices. Derivatives of three-vertex quantities involve up to four vertices. To
be able to solve the equations, we need some approximation to close the equations.

The pair approximation is commonly used in physics and ecology (see Ellner (2001)
and references therein). Intuitively, the mean-field approach assumes that the equilibrium
state is a product measure, while the pair approximation assumes it is a Markov chain:

\[N_{100} = N_{10}N_{00}/N_0\].

The calculations we are about to do are similar to the ones in Kimura
and Hayakawa (2008) Omitting the first equation from (8.1.1), which is redundant:

\[
\frac{1}{2} \frac{dN_{11}}{dt} = [1 - \alpha(1 - u)]N_{10} + (1 - \alpha)[N_{101} - N_{011}]
\]

\[
\frac{1}{2} \frac{dN_{00}}{dt} = (1 - \alpha u)N_{10} + (1 - \alpha)[N_{010} - N_{100}].
\]

Using these two equations and the pair approximation:

\[
\frac{1 - \alpha(1 - u)}{1 - \alpha} N_{10} = \frac{N_{01}N_{11}}{uN} - \frac{N_{10}N_{01}}{(1 - u)N}
\]

\[
\frac{(1 - \alpha u)}{1 - \alpha} N_{10} = \frac{N_{10}N_{00}}{(1 - u)N} - \frac{N_{01}N_{10}}{uN}
\]

which leads to the equations

\[
\frac{N_{11}}{uN} - \frac{N_{10}}{(1 - u)N} = 1 + \frac{\alpha u}{1 - \alpha}
\]

(8.1.2)

\[
\frac{N_{00}}{(1 - u)N} - \frac{N_{10}}{uN} = 1 + \frac{\alpha(1 - u)}{1 - \alpha}.
\]

(8.1.3)

Adding \(uN\) times (8.1.2) to \((1 - u)N\) times (8.1.3), we have

\[
N_{11} + N_{00} - \left(\frac{u}{1 - u} + \frac{1 - u}{u}\right) N_{01} = \left[1 + \frac{(u^2 + (1 - u)^2)\alpha}{1 - \alpha}\right] N.
\]

(8.1.4)

Using (8.1.4) with \(N_{11} + N_{00} = \lambda N - 2N_{01}\) we have

\[
\lambda N - 2N_{01} - \left(\frac{u}{1 - u} + \frac{1 - u}{u}\right) N_{01} = \left[1 + \frac{(u^2 + (1 - u)^2)\alpha}{1 - \alpha}\right] N.
\]

(8.1.5)
A little algebra gives
\[ 2 + \frac{u}{1-u} + \frac{1-u}{u} = \frac{2u - 2u^2 + u^2 + 1 - 2u + u^2}{u(1-u)} = \frac{1}{u(1-u)}. \]  
(8.1.6)

Rearranging (8.1.5) and using (8.1.6) gives
\[ \lambda - 1 - \frac{(u^2 + (1-u)^2)\alpha}{1-\alpha} \]  
\[ \frac{1}{u(1-u)N_01}, \]
and solving we get the pair approximation for the arch:
\[ \frac{N_01}{N} = u(1-u) \left( \lambda - 1 - \frac{(u^2 + (1-u)^2)\alpha}{1-\alpha} \right) \]

Note that as \( \alpha \) decreases from \( \alpha_c(1/2) = (\lambda - 1)/(\lambda - 1/2) \) to \( (\lambda - 1)/\lambda \), the arch expands from a point to a curve that spans \((0, 1)\).

The approximate master equation (AME) framework gives much better estimates. Here we follow the approach in Gleeson (2011). A more extensive discussion of the method can be found in Gleeson (2013). Let \( \bar{S}_{k,m}(t) \) [\( \bar{I}_{k,m}(t) \)] be the number of nodes at time \( t \) that are in state 0 (susceptible) [in state 1 (infected)], have degree \( k \), and have \( m \) neighbors in state 1.

To describe the logic behind the AME, let \( x \) be a vertex and let \( y \) be one of its neighboring vertices. Three types of things can happen: (a) rewiring may break the connection between \( x \) and \( y \) or bring a new edge to connect to \( x \), (b) \( x \) or \( y \) may influence the other by a voting step, or (c) the opinion of \( y \) may be changed by imitating one of its neighbors \( z \neq x \). Exact equations can be written for the first two types of events in terms of \( \bar{S}_{k,m} \) and \( \bar{I}_{k,m} \) but the third type requires an approximation.

The AME for the susceptible sites is:
\[ \frac{d}{dt} \bar{S}_{k,m} = \alpha \{- (2-u)m \bar{S}_{k,m} + (1-u)(m+1)\bar{S}_{k,m+1} + (m+1)\bar{S}_{k+1,m+1} \} \]
\[ + \alpha N_01[-2\bar{S}_{k,m} + \bar{S}_{k-1,m-1} + \bar{S}_{k-1,m}] / N \]
\[ + (1-\alpha)[-m\bar{S}_{k,m} + (k-m)\bar{I}_{k,m}] \]
\[ + (1-\alpha)[-\beta^S(k-m)\bar{S}_{k,m} + \beta^S(k-m+1)\bar{S}_{k,m-1}] \]
\[ - \gamma^S m\bar{S}_{k,m} + \gamma^S (m+1)\bar{S}_{k,m+1} \]  
(8.1.7)

where \( \beta^S = \frac{N_{001}}{N_{00}} \) and \( \gamma^S = 1 + \frac{N_{010}}{N_{01}} \). Here \( \beta^S \) gives the expected number of 1 neighbors of a 0-0 edge. In \( \gamma^S \), \( \frac{N_{010}}{N_{01}} \) gives the expected number of 0 neighbors of the 1 at the end of a 0-1 edge, and the +1 counts the 0 on the conditioning edge.

To obtain predictions from numerically solving the system to steady-state. Mathematica’s NDSolve function was used starting with a Poisson degree distribution of mean degree \( \lambda = 4 \), vertices independently assigned the value 1 with probability \( u \), and the equations cutoff at
8.2 SIS EPIDEMICS

8.2.1 Rewiring to avoid infection

In 2006 Gross, D’Lima and Blasius introduced the following model: “we consider a network with a constant number of nodes $N$, and bidirectional links $K$. The nodes represent individuals that can be either susceptible ($S$) or infected ($I$).

On every time step and for every link connecting an infected with a susceptible (an $SI$ link) the susceptible becomes infected with a fixed probability $p$, and the infected recovers from the infection with probability $\gamma$, becoming susceptible again.
In addition we allow susceptible individuals to rewire their links. With probability $w$ for every $SI$ link, the susceptible breaks its link to the infected and rewires to another randomly chosen susceptible. Double connections and self-connections are not allowed to form in this way.

Here to make it easier to compare with the work of Zanette (2007) who uses $r$ for rewire we have replaced their $r$ for recover by $\gamma$

To study the effect of adaptive rewiring consider the threshold infection probability $p^*$ that is necessary to maintain a static epidemic. On a random graph without rewiring ($w = 0$) the basic reproductive number $R_0 = p\langle k \rangle / r$ where $\langle k \rangle = 2K/N$ is the mean degree of nodes. Demanding that exactly one secondary infection is cause yields $p^* = \gamma / \langle k \rangle$. If rewiring is taken into account a single infected node will on average lose a constant fraction $w$ of its links. Therefore the degree of such a node can be written as $k(t) = \langle k \rangle \exp(-wt)$ where $t$ is the time since infection. By averaging over the typical lifetime $1/\gamma$ of an infected node, we obtain the infection rate

$$p^* = \frac{w}{\langle k \rangle \left[ 1 - \exp(-w/\gamma) \right]}$$

Note that this corresponds to $p^* = \gamma / \langle k \rangle$ for $w = 0$ but $p^* = w / \langle k \rangle$ for $w \gg \gamma$.” Simulations suggested the phase diagram drawn in Figure 8.7

![Phase Diagram](image)

Figure 8.7: Simulation with $N = 10^6$, $K = 10^6$ (average degree 20), $\gamma = 0.002$. so that when $w = 0$, $p^* = 0.0001$.

In the Healthy region the infection dies out. In the Endemic region there is positive probability of the infection surviving from a single infected individual and there is a unique equilibrium state, while in the Bistable region the epidemic always dies out starting from a finite set but there is a nontrivial stationary distribution. The authors observe that the Oscillations can only be observed in a relatively small parameter region so perhaps they are a finite size artifact. The clear and most striking observation is that the equilibrium density jumps from 0 to a positive level when moving from the Healthy to the Bistable region.
Zanette (2007) analyzed the model using the tools physicists turn to first: mean-field and pair approximation calculations. He used a formulation different from Gross et al (2006). Consider a population of \( N \) agents at the nodes of the network with \( M \) links.

In the first sub-step and agent is chosen at rate from the whole population. If it is infected it becomes healthy with probability \( \gamma \).

In the second substep a pair of linked agents are chosen. If both agents are susceptible or both infected nothing happens. Otherwise the \( S \) agent breaks the link with probability \( r \). If it does not break the link then it becomes infected with probability \( \lambda \).

A time unit consists of \( N \) evolution steps. Thus each \( I \)-agent has a probability \( \gamma \) per time unit of becoming susceptible, so that the mean duration of the infected period is \( 1/\gamma \). Moreover each \( S \)-agent in contact with an \( I \)-agent becomes in turn infected with probability \( (1-r)\lambda \) per time unit.

Let \( N_S, N_I \) the number of susceptible and the number of infecteds.

\[
N_I + N_S = N \quad n_S = N_S/N \quad n_I = N_I/N
\]

Let \( M_{II}, M_{SI}, M_{SS} \) number of edges of various types.

\[
M_{II} + M_{SI} + M_{SS} = M \quad m_{ij} = M_{IJ}/M.
\]

Run time at rate \( 1/\gamma \). Let \( \tilde{\lambda} = (1-r)\lambda/\gamma, z = 2M/N \) be average degree, \( \tilde{r} = 2r/z\gamma \) since in the second step we are choosing edges instead of vertices.

**Mean-field theory.** In this approach the equilbirum state is always a product measure. We begin with the differential equation

\[
n'_I = -n_I + \tilde{\lambda}m_{IS}
\]

which is exact. \(-n_I\) comes from from \( I \rightarrow S \). \( \tilde{\lambda}m_{IS} \), from \( IS \rightarrow II \). Introducing the mean-field approximation, \( m_{IS} = 2n_In_S = 2n_I(1-n_I) \) and the equation becomes

\[
n'_I = -n_I + 2\tilde{\lambda}n_I(1-n_I) = n_I(2\tilde{\lambda} - 1 - n_I)
\]

The critical value for survival (when \( \tilde{r} = 0 \)), is \( \tilde{\lambda}_c = 1/2 \).

**Pair approximation.** In this approximation we suppose that the state is always a Markov chain. Derivatives of two site probabilities lead to three site probabilities. We write these in terms of two and one site probabilities using the Markov property. Let \( x, y, z \) be a path on the graph and \( a, b, c \in \{0,1\} \).

\[
P(\xi(x) = a, \xi(y) = b, \xi(z) = c) = P(\xi(x) = a, \xi(y) = b)P(\xi(z) = c|\xi(y) = b, \xi(x) = a)
= P(\xi(x) = a, \xi(y) = b)P(\xi(z) = c|\xi(y) = b)
= P(\xi(x) = a, \xi(y) = b)\frac{P(\xi(z) = c, \xi(y) = b)}{P(\xi(y) = b)} = \frac{m_{ab}m_{bc}}{n_b}
\]
where in the second equality we have used the Markov property. To be able to compare with other treatments we will include the third redundant equation.

\[
m'_{II} = -2m_{II} + \tilde{\lambda}m_{IS}m_{SI}/n_S
\]  \hspace{1cm} (8.2.3)

\[
m'_{IS} = 2m_{II} - m_{IS} - \bar{r}n_sm_{IS} + \tilde{\lambda}m_{IS}(2m_{SS} - m_{IS})/n_S
\]  \hspace{1cm} (8.2.4)

\[
m'_{SS} = m_{IS} + \bar{r}n_sm_{IS} - 2(\tilde{\lambda}m_{IS}m_{SS})/n_S
\]  \hspace{1cm} (8.2.5)

(8.2.3). \(-2m_{II}\) from \(II \rightarrow IS\); second term. \(ISI \rightarrow III\) plus pair approximation

(8.2.4). \(2m_{II}\) from \(II \rightarrow SI\). \(-m_{IS}\) from \(IS \rightarrow SS\). \(-\bar{r}n_sm_{IS}\) from \(S\) breaking a connection to \(I\) and reconnecting to an \(S\). Third term \(ISS \rightarrow IIS\), 2 orientations for edge. Fourth term \(ISI \rightarrow III\).

(8.2.5). from \(m'_{II} + m'_{IS} + m'_{SS} = 0\).

Gross et al (2006), see their (3) and (4) use the equations for \(m'_{II}\) and \(m'_{SS}\) but the notation is slightly different.

**Equilibria** satisfy the following equations

\[
m_{IS} = \frac{n_I}{\tilde{\lambda}} \quad m_{II} = \frac{n_I^2}{2\tilde{\lambda}(1 - n_I)}
\]  \hspace{1cm} (8.2.6)

by (8.2.1) and (8.2.3). Using (8.2.4) with \(n_S = 1 - n_I\) and \(2m_{SS} = 2 - 2m_{II} - 2m_{IS}\)

\[0 = 2m_{II} - m_{IS} - \bar{r}m_{IS}(1 - n_I) + \tilde{\lambda}m_{IS}\frac{2 - 2m_{II} - 3m_{IS}}{1 - n_I}
\]

Multiplying by \((1 - n_I)\)

\[0 = 2m_{II}(1 - n_I) - m_{IS}(1 - n_I) - \bar{r}m_{IS}(1 - n_I)^2 + \tilde{\lambda}m_{IS}[2 - 2m_{II} - 3m_{IS}]
\]

Substituting the values of \(m_{IS}\) and \(m_{II}\) from (8.2.6)

\[0 = \frac{2n_I^2}{2\tilde{\lambda}} - \frac{n_I}{\tilde{\lambda}}(1 - n_I) - \bar{r}\frac{n_I}{\tilde{\lambda}}(1 - n_I)^2
\]

\[+ n_I\left[2 - 2\frac{n_I^2}{2\tilde{\lambda}(1 - n_I)} - 3\frac{n_I}{\tilde{\lambda}}\right]
\]

Factoring out an \(n_I\) from the first line and multiplying by \(\tilde{\lambda}(1 - n_I)\) we have

\[0 = n_I\left\{n_I(1 - n_I) - (1 - n_I)^2 - \bar{r}(1 - n_I)^3
\]

\[+ [2\tilde{\lambda}(1 - n_I) - n_I^2 - 3n_I(1 - n_I)]\} \]
Combining the terms with no $\lambda$ or $\bar{r}$ gives

$$n_I - n_I^2 - 1 + 2n_I - n_I^2 - n_I^2 - 3n_I + 3n_I^2 = -1$$

Sorting terms by the powers of $n_I$

$$0 = n_I(2\bar{\lambda} - 1 - \bar{r} + (3\bar{r} - 2\bar{\lambda})n_I - 3\bar{r}n_I^2 + \bar{r}n_I^3)$$

which is formula (5) in Zanette (2007). When $\bar{r} = 0$ this reduces to

$$0 = n_I(2\bar{\lambda} - 1 - n_I)$$

which is the mean-field equation (8.2.2).

In addition to the trivial solution $n_I = 0$ the cubic has three solutions. One of them tends to infinity as $\bar{r} \to 0$ and stays $\geq 1$ for all $\bar{r}$. The other two solutions $n_{I,2} < n_{I,1}$ are

$$1 - \frac{2\bar{\lambda}}{3\bar{r}} \left[ \cos(\alpha/3) \mp \sqrt{3} \sin(\alpha/3) \right] \quad \text{where} \quad \alpha = \arctan \left( \frac{32\bar{\lambda}^3}{27\bar{r}} - 1 \right)$$

These solutions are real when $32\bar{\lambda}^3/(27\bar{r}) > 1$. That is, when $\bar{r} < \bar{r}_0 = (32/27)\bar{\lambda}^3$.

Figure 8.8: Phase diagram as a function of $\bar{\lambda}$ and $\bar{r}$. $\bar{\lambda}_c = 0.5$, the diamond is (0.75, 0.5). The solid line where the equilibrium density drops discontinuously to 0 is $(32/27)\bar{\lambda}^3$. The endemic region occurs when the smaller roots is negative. The zero roots occur when the constant in the cubic (8.2.7) is 0 which is $\bar{r} = 2\bar{\lambda} - 1$.

Further reading. da Silva, Oliveira, and Valesin (2021) and Schapira and Vlesin (2023) have consider contact processed on dynamical $d$-regular graph where the graph evolves by
degree conserving Volz-Meyers edge swap dynamics, scaled so that in the limit as the number of nodes \( n \to \infty \), each edge is involved in exchanges at rate \( v \). The first paper shows that there is a threshold \( \bar{\lambda} \) which depends on \( d \) and \( v \) so that for \( \lambda > \bar{\lambda} \) the process survives exponentially long in \( n \). They show that \( \bar{\lambda} < \lambda_1(T_d) \). Combining this observation a result of Mourrat and Valesin (2016) given in Theorem 5.2.2, they conclude that in some situations the process survives for \( O(\log n) \) on the static graph and exponentially long on the evolving graph.

The second paper completes the picture by showing that when \( \lambda < \bar{\lambda} \), the system survives for time \( \leq C \log n \). In addition they show that for fixed \( d \) \( v \to \lambda(d, v) \) is strictly decreasing.

### 8.2.2 Link inactivation

Rewiring is difficult because the graph is constantly changing. A version of the evolving contact process that is somewhat easier to study is the model in which individuals temporarily suspend interactions with individuals who are infected (and this arguably more sensible for applications). To formulate the model it is convenient to replace each edge in the graph by two oriented edges, each of which may be either active or inactive. An active edge becomes inactive at rate \( \alpha \), and an inactive edge becomes active once its tail vertex becomes healthy.

As usual in the contact process, infected vertices become healthy at rate 1, and infection is transmitted through active edges at rate \( \lambda \).

To construct the process we use a graphical representation. Here we have written occupied instead of infected, and vacant instead of susceptible.

For each site \( x \) there is a Poisson process \( T^x_n \) with rate 1. At each arrival we put a dot (●) at the site to indicate that any particle there will be killed.

For each edge oriented edge \( (x, y) \), there is a birth Poisson process with rate \( \lambda \). At these arrivals we draw an arrow from \( x \) to \( y \) to indicate a birth will occur at \( y \) if it is vacant and \( x \) is occupied. We also have a deactivation Poisson process with rate \( \alpha \). At arrivals we draw an edge from \( x \) to \( (x + y)/2 \) and mark it with a ×. If \( x \) is occupied and \( y \) is vacant the edge will be deactivated until the next time it is vacant.

Chatterjee, Sivakoff and Wascher (2022) have studied this model on infinite and finite graphs. Let \( \mathcal{X} \) be the collection of finite sets of vertices. Since there is no monotonicity there are potentially three different critical values.

\[
\lambda^- = \inf\{\lambda : \exists \xi \in \mathcal{X} \ P_{\xi}(\xi_t \neq \emptyset \text{ for all } t \geq 0) > 0\}
\]

\[
\lambda^+_{\alpha, w} = \sup\{\lambda : \forall \xi \in \mathcal{X} \ P_{\xi}(\xi_t \neq \emptyset \text{ for all } t \geq 0) = 0\}
\]

\[
\lambda^+_\alpha = \sup\{\lambda : \forall \xi \in \mathcal{X} \ P_{\xi}(0 \in \xi_t \text{ infinitely often}) = 0\}
\]

The last two definitions bring in the issue of local versus global survival as in the contact process on trees.

On the integers with the usual nearest neighbors

**Theorem 8.2.1.** \( 1 + \alpha \leq \lambda^- \leq \lambda^+_{\alpha, w} \leq A + B\alpha \)
8.2. SIS EPIDEMICS

Figure 8.9: An example of one graphical representation for the process on \( \{1, 2, 3\} \) with two different initial conditions. Thick lines indicate occupied sites. On the left the deactivation edge has no effect since 3 is vacant. On the right, births from 3 to 2 are not allowed to cross the vertical line because \((3, 2)\) is deactivated. The example shows that this system is not attractive, i.e., \( \xi_0 \supset \xi'_0 \) does not guarantee that \( \xi_t \supset \xi'_t \) for all \( t \geq 0 \).

Ideas behind the proof. To prove the lower bound on the critical value look at \([\ell_t, r_t]\) where \( \ell_t \) is the left most and \( r_t \) is the right-most occupied site. Let \( L_n \) be the jump chain embedded in \( \ell_t \). In order for \( L_{n+1} = L_n - 1 \) the infected at \( L_n \) must try to infect \( L_n - 1 \) before that site avoids \( L_n \) and before \( L_n \) becomes healthy. When \( \lambda < 1 + \alpha \) a downward jump has probability less than \( 1/2 \). When \( L_n \) becomes healthy before infecting \( L_n - 1 \) (and this always happens when that site avoids \( L_n \)) then the process will jump to the right by at least 1. This shows that the left edge has positive drift. A similar argument shows that the right edge has negative drift so survival is impossible.

The proof of the other direction involves a block construction. One defines good events that will have high probability if \( \lambda \) is large enough, and survival follows from a comparison with supercritical oriented percolation. Here the lack of monotonicity rears its ugly head again and the authors have to deal with the dependence between the events in different blocks. Since the details are somewhat complicated we refer the reader to Section 3 of the paper for details.

Consider now the cycle \( \mathbb{Z} \mod n \). Based on results for the contact process and a number of related systems, we expect that the process on the cycle to survive for time \( \leq C \log n \) below the critical value and for time \( \geq \exp(cn) \) above it. However, since one cannot prove the existence of the critical value this goal is out of reach. Using the machinery developed to prove Theorem 8.2.1 the authors were able to prove...
Theorem 8.2.2. There are constants $C, \gamma$ that depend on $\lambda$ and $\alpha$ so that:

(i) If $\lambda < 1 + \alpha$ then $P(\tau > C(\log n)^2) \to 0$.

(ii) If $\lambda > A + B\alpha$ (the constants in the previous result) then $P(\tau \leq e^{\gamma n}) \to 0$.

Intuitively, the contact process with avoidance is monotone in the sense that if we consider it on a graph $G$ and then restrict it to a subgraph $H$ by declaring that all sites in $G - H$ are 0 then the process on $G$ dominates the process restricted to $H$. For this reason, we expect that conclusion (ii) holds whenever there is a self-avoiding path of length $n$. The "inconvenient truth" to use a phrase of Al Gore is that this is hard to prove rigorously, so this is one of the proofs in the book that you should not believe.

Perhaps the most surprising result in the paper is the result for the star graph. Suppose that initially all the sites are infected and all of the edges are active.

Theorem 8.2.3. Let $\tau_{\text{star}}$ be the extinction time of the infection on the star graph with $n$ vertices and let

$$\Delta(\lambda, \alpha) = 2 \left[ (\lambda + \alpha + 1) - \sqrt{(\lambda + \alpha + 1)^2 - 4\alpha} \right]^{-1}$$

Then there is an $N$ so that for $n \geq N$

$$P \left( \frac{1}{K} (n/\log^4 n)^\Delta \leq \tau_{\text{star}} \leq Kn^\Delta \right) \to 1$$

uniformly in $n$ as $K \to \infty$.

Thus except for an annoying factor of $\log^4 n$ in the lower bound the contact process with avoidance survives for time $\approx n^\Delta$ where $\Delta$ depends on $\lambda$ and $\alpha$. This is in contrast to the ordinary contact process, which by results in Theorem 5.3.2. discussed earlier, persists for time $\geq (1/\lambda^2 n) \exp((1 - \eta)\lambda^2 n))$ on a star with $n$ leaves.

Further reading. In the next section we will see a number of papers by Ball, Britton, and collaborators on SIR models with rewiring which include the possibility of dropping of edges.

Linker and Reminik (2020) have proved theorems about a one dimensional contact process in which edges open up at rate $vp$ and close at rate $v(1 - p)$. For small enough $v$ the process dies out, which for large $v$ it behaves like a contact process with births at rate $\lambda p$. For fixed $v$ the infection dies out for small $p$, while if $p$ is close to 1 then survival is possible for large enough $\lambda$. Some of the results hold for general vertex-transitive regular graphs.

This paper is closely related to Reminik’s (2008) paper which was written while he was a Ph.D. student at Cornell. The model is a site version of link inactivation. Sites can be in state $1 = \text{occupied}$, $0 = \text{habitable but vacant}$, and $-1 = \text{uninhabitable}$. The fact that transitions $1, 0 \to -1$ occur at rate $\alpha$ make it possible to do a fairly complete analysis including proving a complete convergence theorem.

Jacobsen, Burch, Tien and Rempala (2016) have proved ODE limits for stochastic epidemic models on dynamic multilayer networks, as Janson, Lukzak, and Windridge did for the Miller-Volz equations in Section 4.6.
Open problems. Three interesting papers for those who want to try their hands at proving results from the physics literature. Szabo-Solticki et al (2016) study the occurrence of oscillatory behavior in a paper in Journal of Mathematical Biology. Tunc et al (2013) writing in the Journal of Statistical Physics, developed a mean-field description and found two distinct regimes: slow network dynamics where the adaptation mechanism simply reduces the number of contacts, and fast dynamics where more efficient adaptation reduces the spread of the disease by targeting dangerous connections. Finally a 13 page paper by Guo et al (2013), and published in Physica Review E also finds two regimes, and concludes that adaptation of the topology suppresses the infection, while it promotes the network evolving towards a topology that exhibits assortative mating, modularity and a binomial like degree distribution.

8.3 SIR epidemics

As discussed in Chapter 4, in the SIR model, individuals are in one of three states: $S = \text{susceptible}$, $I = \text{infected}$, $R = \text{removed}$ (cannot be infected). $S - I$ edges become $I - I$ at rate $\lambda$, i.e., after a time $T$ with an exponential($\lambda$) distribution: $P(T > t) = e^{-\lambda t}$. As in Sections 4.3 and 4.4 we will consider two versions of the model that differ in the length of time individuals remain infected. In the first, infections always last for time 1. In the second, infection times are exponential(1) distributed. Once individuals leave the infected state, they enter the removed state. Our main interest in this section is in the variant of the model in which $S - I$ edges are broken at rate $\rho$ and the susceptible individual connects to an individual chosen at random from the graph. (Note that in this section $\rho$ is the rewiring rate, not the probability the branching process dies out.) We call this process evoSIR.

8.3.1 Volz and Meyers (2007, 2009)

To motivate their work the authors note that homogeneously mixing models ignore three aspects of epidemics

(i) A given individual has contact with only a small number of other individuals in the population at any one time, and contacts that can result in disease transmission are usually short and repeated events.

(ii) The number and frequency of contacts between individuals can be very heterogeneous.

(iii) The numbers and identities of an individual’s contacts will change as time goes by.

The first two points have been addressed by static network models. The authors say that the main motivation for their paper is to address the third point by introducing the neighbor exchange (NE) model. In this model the individual’s number of contacts is fixed while the composition of those contacts changes at a specified rate. The dynamics in which individuals change partners: connections $A - B$ and $C - D$ become $A - D$ and $B - C$ is a little unusual (except for square dancers or hipo southern Californians) but as the reader will see it leads to a system that it is easier to analyze than most evolving networks.
Using notation that should be familiar from Section 4.4 the edge (ego,alter) is reassigned to (ego,alter') at rate $\rho$ (for rewire) or equivalently (for the resulting ODE) the two edges are swapped at rate $\rho/2$. Using notation that was introduced earlier, let $A_{X,Y}$ be the set of arcs with ego in $X$ and alter in $Y$, let $A_X$ be the set of arcs with ego in $X$ and let $|A|$ be the number of arcs in the graph (which is 2 times the number of edges). Define the the fraction of arcs in $A_{X,Y}$ and in $A_X$ by

$$M_{X,Y} = \frac{|A_{X,Y}|}{|A|} \quad \text{and} \quad M_X = \frac{|A_X|}{|A|}.\quad (8.3.1)$$

We replace the rate $r$ at which infected individuals infect susceptible neighbors used in VM, by $\beta$, and the recovery rate $\mu$ used in VM, by our favorite letter $\gamma$. Let $S$, $I$, and $R$ be the fraction of susceptible, infected, and removed nodes at time $t$ and let

$$p_I = \frac{M_{S,I}}{M_S} \quad \text{and} \quad p_S = \frac{M_{S,S}}{M_S}.\quad (8.3.1)$$

Letting $g(x)$ be the probability generating function of the degree distribution $p_k$ and $\theta(t)$ the probability an edge has not transmitted an infectious contact (which is defined precisely right after (8.3.1) we have

$$S = g(\theta)$$

$$d\theta/dt = -\beta p_I \theta$$ \quad (8.3.2)$$

where $p_I$ and $p_S$ satisfy

$$dp_I/dt = \beta p_S p_I \theta \frac{g''(\theta)}{g'(\theta)} - \beta p_I (1 - p_I) - \gamma p_I$$ \quad (8.3.3)$$

$$dp_S/dt = \beta p_S p_I \left(1 - \theta \frac{g''(\theta)}{g'(\theta)}\right)$$ \quad (8.3.4)$$

This agrees with the formulas in Table 3 in Volz and Meyers (2007) except for the unfortunate typo that $g''(\theta)$ has lost its derivatives in the formulas for $dp_I/dt$ and $dp_S/dt$. To confirm that this is indeed a typo look at formulas (2.14) and (2.15) in VM and the result below.

Repeating the reasoning used to derive (8.3.3) and (8.3.4) on the neighbor exchange system leads to

$$dp_I/dt = \beta p_S p_I \theta \frac{g''(\theta)}{g'(\theta)} - \beta p_I (1 - p_I) - \gamma p_I + \rho(M_I - p_I)$$ \quad (8.3.5)$$

$$dp_S/dt = \beta p_S p_I \left(1 - \theta \frac{g''(\theta)}{g'(\theta)}\right) + \rho \left[\frac{\theta g'(\theta)}{g'(1)} - p_S\right]$$ \quad (8.3.6)$$

$$dM_I/dt = -\gamma M_I + \beta p_I \left[\theta^2 g'(\theta) + \theta g'(\theta)\right]$$ \quad (8.3.7)$$
The additional terms in the first two equations come from rewiring. The third equation is needed since $M_I$, the fraction of arcs with an infected ego cannot be expressed in terms of the other three variables.

Simulations of the fraction of individuals that have been infected given in Figure 2 of their paper match the solution of the differential equation, except for a time shift, which seems likely to be due to the fact that in the initial phase the infects are a branching process, so we have

$$I(t) \approx W e^{\alpha t} = e^{\alpha t - S}$$

where $W$ is random and $S = -\log(W)/\alpha$ is a random time shift. Note that in agreement with this computation, the stochastic curves are translates in time of the deterministic curve.

The 2007 paper closes with an application of the NE model to data on syphilis among Atlanta adolescents, so we will now move on to the 2009 paper that computes the reproductive ratio $R_0$ for the model. This quantity introduced in Section 4.1 gives the number of secondary infections caused by one infected individual in an otherwise susceptible population. Since they are dealing with epidemics on graphs generated by the configuration model they instead look at what they call $R_\star$ which gives the number of secondary infections caused by an infected individual early in the epidemic but who is not the first infected, since as we learned in Chapter 4 this is the quantity which gives the condition for the epidemic to be supercritical $R_\star > 1$.

The probability of transmitting the infection to a susceptible neighbor in

$$\tau = \frac{\beta}{\beta + \gamma + \rho}$$

since infection must occur before recovery and rewiring. After a change of notation this is their (3.4). Some mental gymnastics with generating functions leads them to conclude in (3.11) that

$$R_\star = \tau \left( \frac{\rho}{\gamma} + \frac{\gamma + \rho}{\gamma} \cdot \frac{g''(1)}{g'(1)} \right)$$

Using this result they compute epidemic thresholds and branching process approximation to the initial phase of the epidemic. We refer the reader to the paper for details.

### 8.3.2 Jiang et al (2018)

In the summer of 2018, postdoc Matt Junge, graduate student Zoe Huang, and I worked with four students in the Duke math departments 8 week summer REU: Duke Opportunities in Math or DOMath. Three of the students continued to work with Matt and I in the Fall on what we thought was a simple problem that would be a warm-up for doing some real research.

The object of study was SIR dynamics in which each infection lasts for exactly time 1 with the new feature that susceptibles who are neighbors of an infected break their connections at rate $\rho$ and connect to a randomly chosen neighbor. As explained in Section 4.3 the SIR
model with fixed infection times is simple because each edge will be $S - I$ (or $I - S$) only once. When that happens the infection will be transmitted to the other end with probability

$$\tau_f = P(T \leq 1) = 1 - e^{-\lambda}$$

(8.3.8)

and the events for different edges are independent. Here the ‘$f$’ in the superscript is for “fixed time.” Due to the last observation, we can delete edges with probability $e^{-\lambda}$ and the connected components of the resulting graph will give the epidemic sizes when one member of the cluster is infected. In Chapter 4 we proved

**Theorem 4.3.1.** If the original graph is Erdős-Renyi with mean degree $\mu$, then the reduced graph is Erdős-Renyi with mean degree $\mu \tau_f$. So, a large epidemic occurs with positive probability if $\mu \tau_f > 1$. If $z_0$ is the fixed point smaller than 1 of the generating function

$$G(z) = \exp(-\mu \tau_f(1 - z)),$$

(8.3.9)

then $1 - z_0$ gives both the limiting probability an infected individual will start a large epidemic, and the fraction of individuals who will become infected when a large epidemic occurs.

We now introduce rewiring of $S - I$ edges at rate $\rho$, i.e., susceptibles break their connection with infected individuals and rewire to an individual chosen at random. In order for the infection to be transmitted along an edge, it must occur before any rewiring and before time 1. To compute this probability, note that (i) the probability that infection occurs before rewiring is $\lambda/ (\lambda + \rho)$ and (ii) the minimum of two independent exponentials with rates $\lambda$ and $\rho$ is an exponential with rate $\lambda + \rho$, so the transmission probability is

$$\tau_{fr} = \frac{\lambda}{\lambda + \rho}(1 - e^{-(\lambda+\rho)}).$$

(8.3.10)

Here the ‘$r$’ subscript is for “rewire.” Our first result shows that evoSIR has the same critical value as delSIR in which edges are deleted at rate $\rho$

**Theorem 8.3.1.** The critical value for the fixed time epidemic with rewiring is given by the solution of $\mu \tau_{fr} = 1$. Moreover, in the subcritical regime then the ratio of the expected epidemic size in delSIR to the size in evoSIR converges to 1.

**Sketch of proof.** The formula for the critical value is easily seen to be correct for the delSIR since, by the reasoning above, there is a large epidemic if and only if the reduced graph in which edges are retained with probability $\tau_{fr}$ has a giant component. It is clear than the delSIR model has a larger(≥) critical value than evoSIR. Thus, we only have to prove the reverse inequality.

To compare the two evolutions we first run delSIR until it dies out. Once we do this we randomly rewire the edges deleted in delSIR. The number of sites infected in our subcritical delSIR is $\leq C \log n$ with high probability. This gives a trivial upper bound on the number of edges deleted in delSIR and hence rewired in evoSIR. A rewired edge will only produce a new infected if it is rewired to a vertex that is infected or will later become infected.
If we let $Y$ be the number of new infections then $P(Y = 1) \leq \frac{(C \log^3 n)}{n}$ and $P(Y \geq 2) \leq \frac{(C \log^6 n)}{n^2}$. (An extra log $n$ comes from worry about vertices of large degree.) The second possibility will not happen for any possible starting point and hence can be ignored. It remains then to estimate the possible effects of one extra infection. The proof is not difficult but it does take a few pages to write out the details so we refer the reader to Jiang et al. (2019) for details.

When $n$ is large, the degree distribution, which is Binomial($n - 1, \mu/n$), is approximately Poisson with mean $\mu$. Due to Poisson thinning, the number of new infections directly caused by one $I$ is asymptotically Poisson with mean $\mu \tau_f$, and hence has limiting generating function

$$\hat{G}(z) = \exp(-\mu \tau_f (1 - z)).$$

(8.3.11)

**Theorem 8.3.2.** If $z_0$ is the fixed point $< 1$ of $\hat{G}(z)$, then $1 - z_0$ gives the probability of a large delSIR or evoSIR epidemic.

**Sketch of proof.** Again this is obvious for delSIR, since it is just percolation. It remains to show that the probability of a large epidemic in evoSIR is not larger. To do this apply the method of proof of Theorem 1.3.2 [insert ref] to delSIR. Run the exploration process to time $r = \beta \log n$. Let $F_0 = \{A_r = 0\}$, $F_1 = \{0 < A_r < \gamma \log n\}$ and $F_2 = \{A_r \geq \gamma \log n\}$. The probability of a large delSIR cluster $P(B_d) = (1 - o(1))P(F_2)$. A large evoSIR cluster is likely in case $F_2$, very unlikely in case $F_0$ and case $F_1$ has small probability. For more details see Section 3 of Jiang et al (2019).

The delSIR model is essentially percolation so, $1 - z_0$ is also the fraction of individuals infected in a large epidemic. This proportion goes to 0 at the critical value $\mu_c = 1/\tau_f = 1$. In evoSIR, as the simulations in Figures 8.10 suggest, it is discontinuous at the critical value. Here, we have plotted the final size for a large number of simulations at each parameter value, so there are many points near the $x$ axis that correspond to epidemics that died out.

### 8.3.3 Britton et al. (2016–2018)

As the authors of Jiang et al (2019) were finishing up the writing of their paper, they learned of papers by Britton and collaborators that study epidemics on evolving graphs with exponential infection times. Britton, Juher, and Saldana (2016) studied a one parameter family of models (SIR-$\omega$) that interpolates between delSIR and evoSIR.

**SIR-$\omega$ epidemic.** In this model, an infected individual infects each neighbor at rate $\lambda$, and recovers at rate $\gamma$. A susceptible individual drops its connection to an infected individual at rate $\omega$. The edge is rewired with probability $\alpha$ and dropped with probability $1 - \alpha$. Since evoSIR ($\alpha = 1$) and delSIR ($\alpha = 0$) have the same critical values and survival probability it follows that this holds for all $0 \leq \alpha \leq 1$.

These epidemics take place on graphs generated by configuration model with $n$ vertices and degree distribution $D$, $\text{CM}(n, D)$, as defined in Chapter 2. Britton, Juher, and Saldana (2016) studied the initial phase of the epidemic starting with one infected individual at vertex
Figure 8.10: Simulation of the fixed time evoSIR on an Erdős-Rényi graph with \( \mu = 5 \). In the left panel, \( \rho = 4 \) and \( \lambda \) varies with \( \lambda_c \approx 1.0084 \) in agreement with Theorem 8.3.1. In the right panel, \( \lambda = 1 \) and \( \rho \) varies with \( \rho_c \approx 4 \). In both panels the top curve is the final size of the evoSIR epidemic, and solid curve is the final size of the delSIR epidemic with the same parameters. The dashed line is an approximation developed in Jiang et al (2019) that did not do a good job of predicting the final size in evoSIR.

\( x \) (chosen uniformly at random from all vertices) using a branching process approximation. Let \( Z^\alpha_m \) be the number of vertices at distance \( m \) from \( x \) in the graph. For any fixed \( k \in \mathbb{N} \), \( \{Z^\alpha_m, 0 \leq m \leq k\} \) converges to the following two-phase branching process \( \{\bar{Z}^\alpha_m, 0 \leq m \leq k\} \). The number of children in the first generation has the distribution \( D \) while subsequent generations have the distribution \( D^\ast - 1 \) where \( D^\ast \) has the size-biased degree distribution

\[
P(D^\ast = j) = \frac{jp_j}{m_1}, \quad j \geq 0.
\]

Here \( p_j = P(D = j) \) and \( m_1 = E(D) \) is the mean of \( D \). \( D^\ast - 1 \) has mean

\[
E(D^\ast - 1) = \sum_j (j - 1) \frac{jp_j}{m_1} = \frac{m_2 - m_1}{m_1}.
\]

where \( m_j = E(D^j) \)

In the SIR-\( \omega \) model, the probability that an infection will cross an \( S - I \) edge is

\[
\tau = \frac{\lambda}{\lambda + \gamma + \omega}.
\]

Thus we get another two-phase branching process \( Z_k \) defined as follows. \( Z_0 = 1 \), \( Z_1 = \text{Binomial}(D, \tau) \) and future generations have offspring distribution \( \text{Binomial}(D^\ast - 1, \tau) \). One can see from this description that the limiting branching process \( \bar{Z}_m \) will have positive survival probability if

\[
1 < \tau E(D^\ast - 1) = \frac{(m_2 - m_1)\tau}{m_1}.
\]
Correspondingly, there will be a large epidemic in the SIR-\(\omega\) model if
\[
R_0 = \frac{\lambda}{\lambda + \gamma + \omega} \cdot \frac{m_2 - m_1}{m_1} > 1. 
\] (8.3.12)

Thus for fixed values of \(\gamma\) and \(\omega\)
\[
\lambda_c = (\gamma + \omega) \frac{m_1}{m_2 - 2m_1}. 
\] (8.3.13)

When \(\gamma = 0\) (no recovery) and \(\omega = \rho\) which is the SI-\(\omega\) model in our notation,
\[
\lambda_c = \frac{\rho m_1}{m_2 - 2m_1}. 
\] (8.3.14)

The critical values of del\(\text{SI}\) and evo\(\text{SI}\) only depends on the ratio \(\rho/\lambda\), so it is natural to define a parameter (this \(\alpha\) is different from the \(\alpha\) used in the definition of SIR-\(\omega\) model)
\[
\alpha = \frac{\rho m_1}{\lambda} 
\] (8.3.15)

that has \(\alpha_c = m_2 - 2m_1\). We will only consider the del and evo endpoints of the one parameter family of models SIR-\(\omega\), so after the discussion of previous work is completed, there should be no confusion between our \(\alpha\) and theirs.

Work of Leung, Ball, Sirl, and Britton (2016) demonstrated the paradoxical fact that individual preventative measures may lead to a larger final size of the epidemic. They proved this rigorously for SI epidemics on the configuration model with two degrees and conducted simulation studies for many social networks. Note that in Figure ?? (taken from their Figure 1) the final size increases with the rewiring rate when it is small. This simulation does not suggest that the phase transition was discontinuous.

Figure 8.11: Social distancing can lead to an increase in the final epidemic size in the configuration model. The \(x\)-axis indicates the rewiring rate. The horizontal line is the final size when \(\omega = 0\).
8.3.4 Yao and Durrett (2020)

Here we are referring to the never published paper on the arXiv. These authors studied the evolving SIR and SI epidemics but for reasons that will become clear as the story unfolds, we will concentrate on the evoSI and delSI models. Let $I_t$ be the number of infected vertices at time $t$. For evoSI or delSI epidemics the final size is

$$I_\infty = \lim_{t \to \infty} I_t,$$

which exists since $I(t)$ is increasing. We say a large outbreak occurs if a positive fraction of the population becomes infected. To be precise, this means that there is an $\epsilon > 0$ so that

$$\limsup_{n \to \infty} P_1(I_\infty/n > \epsilon) > 0,$$

where $P_1$ is the process starting with one randomly chosen vertex infected.

Our first result identifies $\lambda_c$. Let $Z_m$ be the number of vertices at distance $m$ from $x$, then as $n \to \infty$, the process $Z_m$ converges to the two-phase branching process in which $Z_0 = 1$, the number of children in the first generation has distribution $D$ with $P(D = k) = p_k$, and the number of offspring in subsequent generations has distribution $D^* - 1$, where deviating from the notation used earlier $P(D^* = k) = kp_k/\mu$. Though the term is slightly inaccurate, it is convenient to call the distribution of $D^* - 1$ the size-biased degree distribution. One can see from this description that the limiting branching process will have a giant component if

$$1 < E(D^* - 1) = \frac{m_2}{m_1} - 1 = \frac{m_2 - m_1}{m_1}.$$

Before moving on, we will pause to compute the generating function of $D^* - 1$. Let $G$ be the generating function of $D$,

$$G(z) = \mathbb{E}z^D = \sum_{j=0}^{\infty} d_j z^j.$$

The distribution of $D^* - 1$ satisfies $P(D^* - 1 = j - 1) = jd_j/m_1$, so

$$G^*(z) = \mathbb{E}z^{(D^* - 1)} = \sum_{j=1}^{\infty} \frac{jd_j}{m_1} z^{j-1} = \frac{G'(z)}{m_1}.$$

If we consider the delSI model then the probability the infection will cross a $S - I$ edge is

$$\tau = \lambda/(\lambda + \rho)$$

If we independently keep edges with probability $\tau$ and delete them with probability $1 - \tau$, then there will be a large epidemic in the delSI model if

$$\frac{\lambda}{\lambda + \rho} \cdot \frac{m_2 - m_1}{m_1} > 1.$$
Rearranging gives $\lambda(m_2 - m_1) > (\lambda + \rho)m_1$ which holds if

$$\lambda > \rho m_1 / (m_2 - 2m_1).$$

As noted earlier the critical values of delSI and evoSI only depends on the ratio $\rho/\lambda$, so it is natural to define a parameter $\alpha = \rho m_1 / \lambda$. This $\alpha$ is NOT the one used by Britton et al.

**Theorem 8.3.3.** Suppose $ED^3 < \infty$. (i) The critical values of delSI and evoSI are equal to $\alpha_c = m_2 - 2m_1$. (ii) In addition, when $\alpha < \alpha_c$ the probability of a large epidemic is the same in the two models.

The assumption $ED^3 < \infty$ is natural because it implies that the size-biased distribution has finite variance. The proof of Theorem 8.3.3 is based on two proofs from Jiang et al that we discussed in Section 8.3.1. Here and in what follows, formulas are sometimes easier to evaluate if we use the “factorial moments”

$$\mu_k = E[D(D-1) \cdots (D-k+1)],$$

since these can be computed by from the $k$th derivative of the generating function. To translate between the two notations:

$$\mu_1 = m_1 \quad \mu_2 = m_2 - m_1 \quad \mu_3 = m_3 - 3m_2 + 2m_1$$

In particular $\alpha_c = m_2 - 2m_1 = \mu_2 - \mu_1$.

**Limiting sizes of delSI and evoSI**

To compute the probability of a large epidemic in delSI we note that generating function of degree distribution for the reduced graph is

$$G_0(z) = \sum_{j=0}^{\infty} \sum_{k=j}^{\infty} d_k \binom{k}{j} \tau^j (1 - \tau)^{k-j} z^j = \sum_{k=0}^{\infty} d_k \sum_{j=0}^{k} \binom{k}{j} (\tau z)^j (1 - \tau)^{k-j} = G(z\tau + (1 - \tau))$$

Similarly, in the reduced graph the offspring distribution in the second phase of the branching process has generating function

$$G_1(z) = G^*(z\tau + (1 - \tau)) \quad (8.3.19)$$

To compute the size of the delSI epidemic now, note that the probability the homogeneous branching process started by a first generation particle dies out is the smallest solution of $G_1(\zeta) = \zeta$ therefor the size of the giant component in delSI is $1 - G_0(\zeta)$. 


The computation of the limiting size of a large epidemic in the evoSI model is much more complicated. Recall that $G$ is the generating function of the degree distribution $D$ as defined in (8.3.17). Consider the following function

$$f(w) = \log \left( \frac{m_1 w}{G''(w) + \alpha(1 - w)G(w)} \right) + \frac{\alpha}{2}(w - 1)^2. \quad (8.3.20)$$

This function may look mysterious, but as we will explain below, it allows us to compute the limiting size of the epidemic. Ultimately that recipe turned out to be incorrect but it provided a mechanism to identify when the phase transition in evoSI was discontinuous.

**Theorem 8.3.4.** Suppose $\alpha < \alpha_c$ and let

$$\sigma = \sup \{w : 0 < w < 1, f(w) = 0\} \quad \text{with sup}(\emptyset) = 0 \quad (8.3.21)$$

$$\nu = 1 - \exp \left( -\frac{\alpha}{2}(\sigma - 1)^2 \right) G(\sigma) \quad (8.3.22)$$

If we suppose

(*) if $0 < \sigma < 1$ there is a $\delta > 0$ so that $f < 0$ on $(\sigma - \delta, \sigma)$

then for any $\epsilon > 0$,

$$\lim_{n \to \infty} P_1(I_\infty/n < \nu + \epsilon) = \lim_{\eta \to 0} \liminf_{n \to \infty} P_1(I_\infty/n > \nu - \epsilon|I_\infty/n > \eta) = 1.$$ 

Figure 8.12: The behavior for the Erdős-Renyi graph with mean 1.4, which has $\alpha_c = \mu^2 - \mu = .56$. Notice that as $\alpha$ increases to 0.56 the intersection with the $x$ axis tends to 1, so the transition is continuous.

Using Theorem 8.3.4, we get the following almost necessary and sufficient conditions for a discontinuous phase transition in the final epidemic size. We say “almost” since the case $\Delta = 0$ is left out.
Theorem 8.3.5. Assume $ED^3 < \infty$. Consider the evoSI model on configuration model $\mathbb{CM}(n, D)$. Let
\[
\Delta = -\frac{\mu_3}{\mu_1} + 3(\mu_2 - \mu_1).
\]
If $\Delta > 0$ then there is a discontinuous phase transition. For some $\epsilon_0 > 0$ and some $\delta > 0$,
\[
\lim_{\eta \to 0} \liminf_{n \to \infty} P_1(I_\infty/n > \epsilon_0 | I_\infty/n > \eta) = 1 \quad \text{for all } \alpha_c - \delta < \alpha < \alpha_c. \tag{8.3.23}
\]
If $\Delta < 0$, then there a continuous phase transition. For any $\epsilon > 0$, there exists some $\delta > 0$, so that
\[
\lim_{n \to \infty} P_1(I_\infty/n > \epsilon) = 0 \quad \text{for } \alpha_c - \delta < \alpha < \alpha_c. \tag{8.3.24}
\]

Example 8.3.6. Erdős-Renyi graph with mean degree $\mu$. For $D = \text{Poisson}(\mu)$, $\mu_k = \mu^k$, so the critical value $\alpha_c = \mu_2 - \mu_1 = \mu^2 - \mu$, which is positive if $\mu > 1$. $\Delta = 2\mu^3 - 3\mu^2$ so the phase transition for evoSI is discontinuous if $\mu > 3/2$. The example in Figure 8.12 has $\lambda = 1.4$ and, as predicted, the phase transition is continuous. In Figure 8.13, $\lambda = 3$ so the phase transition is discontinuous.

![Figure 8.13](image-url)

Figure 8.13: The behavior of $f(w)$ for $w$ near 1 for the Erdős-Renyi graph with mean 3, which has $\Delta > 0$. $\alpha_c = \mu^2 - \mu = 6$. Notice that when $\alpha \leq \alpha_c$, $f(w) > 0$ for $w \in [0.9, 1)$, so $\sigma$ is bounded away from 1.

Ideas that go into the proofs

We follow the approach that Janson, Luczak, and Windridge used to prove the Miller-Volz equations. See Section 4.5. Specifically (i) we run the epidemic at the same time as we grow the graph, and (ii) we change time in the process (see Figure 4.5.4) by multiplying all the transition rates by
\[
(X_t - 1)/(\lambda X_{t+1}),
\]
where \( X_t \) is the total number of half-edges and \( X_{I,t} \) is the number of infected half-edges. Since the set of infected half-edges makes new connections at rate \( \lambda X_{I,t} \) and connections to a given half-edge with probability \( 1/(X_t - 1) \), the time change makes connections to a given half-edge occur at rate 1.

In evoSI the dynamics of \( S_{t,k} \), the number of susceptible vertices with \( k \) half-edges is given by,

\[
    dS_{t,k} = -\left( \lambda X_{I,t} \frac{kS_{t,k}}{X_t - 1} \right) dt + \left( \frac{1}{\lambda} \frac{S_{t,k-1}}{n} \right) dt - \left( \frac{\rho X_{I,t}}{n} \right) dt + dM_{t,k}
\]

where \( M_{t,k} \) is a martingale. Using \( \bar{S}_{t,k} \) for the time changed process the new dynamics are

\[
    d \left( \frac{\bar{S}_{t,k}}{n} \right) = -\left( \frac{k}{\lambda} \frac{\bar{S}_{t,k}}{n} \right) dt + \left( \frac{1}{\lambda} \frac{\rho X_t - \bar{S}_{t,k-1}}{n} \right) dt
\]

\[
    -\left( \frac{\rho X_t - \bar{S}_{t,k}}{\lambda} \frac{n}{n} \right) dt + d \left( \frac{M_{t,k}}{n} \right)
\]

(8.3.25)

Note the important fact that the number of infected half-edges no longer appears in the equation.

Let \( \gamma_n \) be the first time there are no infected half-edges, \( w = \exp(-z) \) and \( m_1 = ED \). Most of the work in the proof is to show

\[
    \sup_{0 \leq z \leq \gamma_n} \left| \frac{X_z}{n} - m_1 w^2 \right| \to 0
\]

\[
    \sup_{0 \leq z \leq \gamma_n} \left| \frac{\sum_k kS_{z,k}}{n} - F_0(t) \right| \to 0
\]

\[
    \sup_{0 \leq z \leq \gamma_n} \left| \frac{\sum_k kS_{z,k}}{n} - F_1(t) \right| \to 0
\]

(8.3.26)

If \( a_S \) is the initial fraction of susceptibles then

\[
    F_0(t) = a_S \exp\left(-\left(\frac{\alpha}{2}\right)(w - 1)^2\right)G(w)
\]

\[
    F_1(t) = a_S \exp\left(-\left(\frac{\alpha}{2}\right)(w - 1)^2\right)w(G'(w) + \alpha(1 - w)G(w))
\]

(8.3.27)

From the results above, we see that

\[
    \frac{X_z}{X_{S,z}} \to \frac{m_1 w}{\exp\left(-\left(\frac{\alpha}{2}\right)(w - 1)^2\right) \cdot (G'(w) + \alpha(1 - w)G(w))}
\]

(8.3.28)

The logarithm of the right-hand side is \( f(w) \), so when \( \alpha < \alpha_c \) the largest root \( \sigma < 1 \) of \( f(w) = 0 \) gives the time \( z = -\log(\sigma) \) at which the infection dies out in the time-changed process.
Theorem lost (and regained)

On my birthday (August 17) in 2020 Ball and Britton put their paper *Epidemics on networks with preventative rewiring*. A figure from their paper (see Figure 8.14 made it painfully clear that our result was wrong.

Figure 8.14: Plots of our formula dotted curve versus theirs formula for evoSI when $\mu = 2$, $\lambda = 1$, and $\alpha = 1$ (evoSI). Circles give mean sizes of 1000 simulated major epidemics in a population of size 5,000.

About three months later, we received two referees reports on the paper, one with 160 comments. From these reports we learned that while the 30 pages of calculations needed to carry out the proof were mostly correct, our construction was flawed. In it $I - I$ connections could be broken and rewired, but this should not take place.

Almost immediately we realized our proof was half-right. Our computation provided an upper bound on the amount of the infection. The younger author embarked on a search for lower bounds which would show that the criterion in Theorem 8.3.5 was accurate. With the covid epidemic happening around him, Dong toiled in his apartment and met with me via zoom until he found a solution. The paper was resubmitted in July, 2021, at about the time he completed his Ph.D. at Duke. The final version accepted one year later.

8.3.5 Ball and Britton (2022)

These authors analyzed the evoSIR and evoSI epidemics on Erdős-Rényi graphs. Having just spent a long time on the second model we will restrict our attention to the first. The authors
use a construction which exploits properties that are special to the Erdős-Rényi case. See their Section 2.3 of their paper and also Britton and O’Neill (2002) for earlier examples of the use of this construction.

To prove results about the epidemics on an Erdős-Rényi random graph with mean degree $\mu$ they first consider a tree in which each vertex has a Poisson($\mu$) number of descendants and develop a branching process approximation for the SIR-$\omega$ epidemic in which infections (births) cross an edge with probability $\lambda/(\lambda + \gamma + \omega)$. Let $I(t)$ be the total number of individuals, $I_E(t)$ be the number of infectious edges (in state $I-E$), and $T(t)$ be the total progeny in the branching process on the tree. Let $I^n(t)$, $I^n_E(t)$ and $T^n(t)$ be the corresponding quantities for an Erdős-Rényi($n, \mu/n$) random graph on $n$ vertices where initially a randomly chosen vertex is infected. They show in their Theorem 2.1 that if $t_n = \inf \{ t : T(t) \geq \log n \}$ then the two systems can be defined on the same space so that

$$\sup_{0 \leq t \leq t_n} |(I^n(t), I^n_E(t), T^n(t)) - (I(t), I_E(t), T(t))| \to_p 0$$

as $n \to \infty$.

Let $S^n(t)$ be the number of susceptibles at time $t$ and $W^n(t)$ be the number of susceptible-susceptible edges created by rewiring by time $t$ and let $X^n(t) = (S^n(t), I^n(t), I^n_E(t), W^n(t))$. Let $x(t) = (s(t), i(t), i_E(t), w(t))$ be the solution of the ODE

$$\frac{ds}{dt} = -\lambda i_E,$$

$$\frac{di}{dt} = -\gamma i + \lambda i_E,$$

$$\frac{di_E}{dt} = -\lambda i_E + \lambda \mu i_E s - \lambda i_E^2 / 2 + 2\lambda i_E w s - \omega i_E (1 - \alpha + \alpha (1 - i)),$$

$$\frac{dw}{dt} = w \alpha i_E s - 2\lambda i_E w s.$$

Here $\alpha$ is the probability an edge is rewired as in the definition of SIR-$\omega$ model. Theorem 2.2 in their paper, which is proved by using results of Darling and Norris (2008), shows that for any $t_0 > 0$

$$\sup_{0 \leq t \leq t_0} |X^n(t)/n - x(t)| \to 0$$

as $n \to \infty$, provided that $I^n(t)/n \to i(0) > 0$.

It is interesting to note, see their Section 3, that the ODE in (8.3.29) is closely related to the “pair approximation” for SIR-$\omega$ model. To explain the phrase in quotes, we note that “mean-field equations” come from pretending that the states of site are independent; the pair approximation from assuming it is a Markov chain. In practice, this approach means that probabilities involving three sites are reduced to probabilities involving 1 and 2 sites using a conditional independence property. For the details of the computation see Chapter 7 in Andersson and Britton (2000).
Letting $T^n = n - S^n(\infty)$ (which is the final size of the epidemic) they make Conjecture 2.1 that one can interchange two limits $n \rightarrow \infty$ and $t \rightarrow \infty$ to conclude

$$T^n / n \rightarrow 1 - s(\infty).$$

To formulate a result that is independent of the validity of the conjecture they let

$$x^\epsilon(t) = (s^\epsilon(t), i^\epsilon(t), i_E^\epsilon(t), w^\epsilon(t))$$

be the solution to the ODE when

$$x^\epsilon(0) = (1 - \epsilon, \epsilon, L^{-1}\epsilon, 0) \quad \text{where} \quad L = \frac{\lambda}{\lambda \mu - \omega}. $$

Letting $\tau_{SIR} = 1 - \lim_{\epsilon \downarrow 0} s^\epsilon(\infty)$, their Theorem 2.3 states

$$\lim_{\lambda \downarrow \lambda_c} \tau_{SIR} \begin{cases} 
= 0 & \text{if } \gamma > \omega(2\alpha - 1) \text{ or } \mu < 2\omega\alpha/[\omega(2\alpha - 1) - \gamma], \\
> 0 & \text{if } \gamma < \omega(2\alpha - 1) \text{ and } \mu > 2\omega\alpha/[\omega(2\alpha - 1) - \gamma]. 
\end{cases} \quad (8.3.30)$$

When $\alpha = 1$, $\omega = \rho$ and $\gamma = 1$ then we have a discontinuous phase transition if

$$\rho > 1 \quad \text{and} \quad \mu > \frac{2\rho}{\rho - 1}. $$

For the case of the delSIR model ($\alpha = 0$, $\omega = \rho$ and $\gamma = 1$) studied in Jiang et al (2019), the transition is always continuous. This follows from (8.3.30) since $\gamma = 1 > -\omega$. From the last calculation we see that the phase transition is always continuous if $\alpha < 1/2$.

Theorem 2.4 in Ball and Britton (2021) gives results for the epidemic starting from a single infected individual. If we let $\tau^1_{SIR}$ be the limiting size of an epidemic conditionally on it being large then

$$\lim_{\lambda \downarrow \lambda_c} \tau^1_{SIR} \begin{cases} 
= 0 & \text{if } \gamma > \omega(3\alpha - 1) \text{ or } \mu < 3\omega\alpha/[\omega(3\alpha - 1) - \gamma], \\
> 0 & \text{if } \gamma < \omega(2\alpha - 1) \text{ and } \mu > 2\omega\alpha/[\omega(2\alpha - 1) - \gamma]. 
\end{cases} \quad (8.3.31)$$

See their paper for a precise statement. Remark 2.4 in their paper states the conjecture that the 3’s in the first condition should be 2’s. Recently W. Chen, Y. Hou, and Dong Yao (2022) have proved that this conjecture is correct.

To close this discussion we will state the result from Yao and Durrett (2020) for evoSIR and discuss its relation to (8.3.31)

**Theorem 8.3.7.** Assume $ED^3 < \infty$. Consider the evoSIR model on configuration model $\text{CM}(n, D)$. Let

$$\Delta = \frac{\mu_3}{\mu_1} + \frac{2\rho}{(1 + \rho)}(\mu_2 - \mu_1). $$

If $\Delta > 0$ then we have a discontinuous phase transition, i.e. for some $\epsilon_0 > 0$ and $\delta > 0$

$$\liminf_{\eta \to 0} \liminf_{n \to \infty} P_1(R_\infty/n > \epsilon_0 | R_\infty/n > \eta) > 0 \; \text{for all } \alpha_c - \delta < \alpha < \alpha_c.$$ 

If $\Delta < 0$ then we have a continuous phase transition, i.e. for any $\epsilon > 0$ there is a $\delta > 0$ so that

$$\lim_{n \to \infty} P_1(R_\infty/n > \epsilon) = 0. \; \text{for all } \alpha_c - \delta < \alpha < \alpha_c.$$ 

To make the connection we first transform the last result. In the Poisson case $\mu_i = \mu^i$ so the the limit is 0 if

$$0 > -\frac{\mu^3}{\mu} + \frac{2\rho}{1+\rho} (\mu^2 - \mu)$$

Multiplying by $\mu$ and doing some algebra this is

$$0 > \frac{\rho - 1}{1+\rho} \frac{\mu^3}{\mu} - \frac{2\rho}{1+\rho} \mu^2$$

This is valid if $\rho < 1$ or $\mu < 2\rho/(\rho - 1)$

To connect with (8.3.31) (with 3 replaced by 2) note that Yao and Durrett (2020) only consider the case $\alpha = 1$, take $\gamma = 1$, and use $\rho$ instead of $\omega$ so the limit is 0 if

$$1 > \rho \; \text{or} \; \mu < \frac{2\rho}{\rho - 1}$$

**References**


8.3. SIR EPIDEMICS


Appendix A

Large Deviations

A.1 Chernoff’s theorem

This material is from Section 2.7 of PTE5 which can be consulted for the missing details. Let $X_1, X_2, \ldots$ be i.i.d. and let $S_m = X_1 + \cdots + X_m$. To make the results we develop here easier to concrete examples we will systematically avoid the use of the letter $n$. Suppose that the moment-generating function

\[(H1) \quad \varphi(\theta) = E \exp(\theta X_i) < \infty \quad \text{for some } \theta > 0\]

and the mean $\mu = E X_i > -\infty$ exists. Let $a > \mu$ and $\gamma_m = P(S_m > ma)$.

**Lemma A.1.1.** If $k, \ell \geq 0$ then $\gamma_{k+\ell} \geq \gamma_k \gamma_\ell$, so as $m \to \infty$, $\gamma_m/m \to \sup_{k \geq 1} \gamma_k/k$ and hence

\[P(S_m \geq ma) \leq e^{m\gamma(a)} \quad (A.1.1)\]

**Proof.** Using arithmetic and independence we have

\[P(S_{k+\ell} \geq (k + \ell)a) \geq P(S_k \geq ka, S_\ell \geq \ell a) = P(S_k \geq ka) \cdot P(S_\ell \geq \ell a)\]

For the proof of the limit result see Lemma 2.7.1 in PTE5. The inequality follows from the formula for the limit. \(\square\)

To calculate $\gamma(a)$ we use the **exponential Chebyshev inequality**. If $\theta > 0$ then

\[e^{\theta ma} P(S_m \geq ma) \leq E \exp(\theta S_m) = \phi(\theta)^m\]

Letting $\kappa(\theta) = \log \phi(\theta)$ we have

\[P(S_m \geq ma) \leq \exp(-m[a\theta - \kappa(\theta)]) \quad (A.1.2)\]

This is an upper bound for all $\theta > 0$, so it is natural to optimize it by finding the maximum of $\theta a - \kappa(\theta)$. 

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Suppose for the moment that

\[ (H_1') \quad \varphi'(\theta) = E \exp(\theta X_i) < \infty \quad \text{for all } \theta > 0 \]

In this case if \( \theta > 0 \)

\[ \frac{d}{d\theta} \{ \theta a - \log \varphi(\theta) \} = a - \frac{\varphi'(\theta)}{\varphi(\theta)} \]

so (assuming things are nice) the maximum occurs when \( a = \varphi'(\theta)/\varphi(\theta) \). To show that things are nice when \((H_1')\) holds we begin by defining

\[ F_\theta(x) = \frac{1}{\varphi(\theta)} \int_{-\infty}^{x} e^{\theta y} dF(y) \quad \text{for } \theta > 0. \]

It is easy to see that if the moment generating function is finite on \((\theta - \delta, \theta + \delta)\) \(F_\theta\) is a distribution function with mean

\[ \int x \, dF_\theta(x) = \frac{1}{\varphi(\theta)} \int_{-\infty}^{\infty} x e^{\theta x} dF(x) = \frac{\varphi'(\theta)}{\varphi(\theta)} \]

\[ \varphi''(\theta) = \int_{-\infty}^{\infty} x^2 e^{\theta x} dF(x) \]

\[ \frac{d}{d\theta} \frac{\varphi'(\theta)}{\varphi(\theta)} = \varphi''(\theta) - \left( \frac{\varphi'(\theta)}{\varphi(\theta)} \right)^2 = \int x^2 dF_\theta(x) - \left( \int x dF_\theta(x) \right)^2 \geq 0 \]

since the last expression is the variance of \(F_\theta\). If we assume

\[ (H_2) \quad \text{the distribution } F \text{ is not a point mass at } \mu \]

then \( \varphi'(\theta)/\varphi(\theta) \) is strictly increasing on \( \theta > 0 \). Since we have \( \varphi'(0)/\varphi(0) = \mu \), this shows that for each \( a > \mu \) there is at most one \( \theta_a \geq 0 \) that solves \( a = \varphi'(\theta_a)/\varphi(\theta_a) \).

**Theorem A.1.2.** Let \( \theta_+ = \sup \{ \theta : \varphi(\theta) < \infty \} \). Suppose in addition to \((H1)\) and \((H2)\) that there is a \( \theta_a \in (0, \theta_+) \) so that \( a = \varphi'(\theta_a)/\varphi(\theta_a) \). Then, as \( n \to \infty \),

\[ n^{-1} \log P(S_n \geq na) \to -a\theta_a + \log \phi(\theta_a) \]

**Proof.** Using \((A.1.2)\) we see that the right-hand side is an upper bound on the left-hand side for all \( n \), and hence \( \limsup LHS \leq RHS \). To prove \( \liminf LHS \leq RHS \) the other inequality, pick \( \lambda \in (\theta_a, \theta_+) \), let \( X_1^{\lambda}, X_2^{\lambda}, \ldots \) be i.i.d. with distribution \( F_\lambda \) and let \( S_n^\lambda = X_1^{\lambda} + \cdots + X_n^{\lambda} \). Writing \( dF/dF_\lambda \) for the Radon-Nikodym derivative of the associated measures, it is immediate from the definition that \( dF/dF_\lambda = e^{-\lambda x} \varphi(\lambda) \). If we let \( F_n^\lambda \) and \( F^n \) denote the distributions of \( S_n^\lambda \) and \( S_n \), then

**Lemma A.1.3.** \( \frac{dF_n^\lambda}{dF_\lambda^\lambda} = e^{-\lambda x} \varphi(\lambda)^n \).
We leave the proof to the reader. If \( \nu > a \), then the lemma and monotonicity imply

\[
(*) \quad P(S_n \geq na) \geq \int_{na}^{\nu} e^{-\lambda x} \varphi(\lambda)^n dF_\lambda^n(x) \geq \varphi(\lambda)^n e^{-\lambda n \nu} (F_\lambda^n(n\nu) - F_\lambda^n(na))
\]

\( F_\lambda \) has mean \( \varphi'(\lambda)/\varphi(\lambda) \), so if we have \( a < \varphi'(\lambda)/\varphi(\lambda) < \nu \), then the weak law of large numbers implies

\[
F_\lambda^n(n\nu) - F_\lambda^n(na) \to 1 \quad \text{as} \quad n \to \infty
\]

From the last conclusion and \((*)\) it follows that

\[
\lim\inf_{n \to \infty} n^{-1} \log P(S_n > na) \geq -\lambda \nu + \log \varphi(\lambda)
\]

Since \( \lambda > \theta_a \) and \( \nu > a \) are arbitrary, the proof is complete.

To explain the assumption \( \theta < \theta_+ \) we consider two examples

**Example A.1.4.** Suppose \( F(0) = 0 \). If \( x_0 = \sup\{x : F(x) < 1\} \) \( < \infty \) then \( \varphi'(\theta)/\varphi(\theta) \to x_0 \) as \( \theta \to \infty \). If \( y > x_0 \) then \( P(S_m \leq My) = 1 \) for all \( m \). If \( F(x_0) < 1 \) then

\[
\frac{1}{m} \log P(S_m \geq mx_0) = \log(1 - F(x_0))
\]

so we have large deviations results for all levels.

**Example A.1.5. Perverted exponential.** Consider a density function with \( f(x) = Cx^{-\alpha}e^{-x} \) for \( x \geq 1 \) where \( \alpha > 2 \) and \( C_\alpha \) is chosen so that it integrates to 1. then \( \varphi(\theta) < \infty \) when \( \theta \leq 1 \) and \( \varphi'(\theta)/\varphi(\theta) \to \phi(1)/\phi(1) \equiv a_0 < \infty \) as \( \theta \uparrow 1 \). Theorem 2.7.10 in PTE5 shows that \( \gamma(a) \) is linear for \( a > a_0 \).

**Binomial large deviations**

if \( P(X = 1) = p \) and \( P(X = 0) = 1 - p \) then

\[
\varphi(\theta) = E \exp(\theta X) = (1 - p) + pe^\theta
\]

\( \varphi'(\theta) = pe^\theta \) so in order to solve \( a = \varphi'(\theta_a)/\varphi(\theta_a) \) we want

\[
a(1 - p) + ape^{\theta_a} = pe^{\theta_a}
\]

\[
a(1 - p) = p(1 - a)e^{\theta_a}
\]

\[
\theta_a = \log(a/p) + \log((1 - p)/(1 - a))
\]

This means

\[
\varphi(\theta_a) = (1 - p) + p \cdot a(1 - p)/p(1 - a) = (1 - p)(1 + a/(1 - a)) = \frac{1 - p}{1 - a}
\]

and hence we have

\[
-a \theta_a + \log \varphi(\theta_a) = -a \log(a/p) - a \log((1 - p)/(1 - a)) + \log((1 - p)/(1 - a))
\]

\[
= -a \log(a/p) - (1 - a) \log((1 - a)/(1 - p)) \equiv -H(a)
\]
**Remark A.1.7.** To see why this is the answer, note that from the definition of the Binomial distribution and Stirling’s formula, \( n! \sim n^ne^{-n}\sqrt{2\pi n} \),

\[
P(X = ma) = \left(\frac{m}{ma}\right)p^{ma}(1-p)^{m(1-a)} \approx \frac{m^m}{(ma)^ma(m(1-a))^{ma}(1-p)^{m(1-a)}}
\]

Now cancel the \( m^m \)’s in the fraction and take \( (1/n) \log \) of both sides.

**Proof.** Suppose \( a > p \). Then for any \( \theta > 0 \)

\[
e^{na} P(X \geq na) \leq ((1-p) + pe^\theta)^n
\]

which we can rewrite as

\[
P(X \geq na) \leq \left[ \exp\{-\theta a + \log((1-p) + pe^\theta)\} \right]^n
\]

To optimize we differentiate the term in set braces with respect to \( \theta \) and set

\[
0 = -a + \frac{pe^\theta}{(1-p) + pe^\theta}
\]

Solving we have \( e^\theta = (a(1-p))/(p(1-a)) \). Using \((1-p) + pe^\theta = pe^\theta/a = (1-p)/(1-a)\) and plugging in we have

\[
\exp\left(-a \log\left(\frac{a(1-p)}{p(1-a)}\right) + \log((1-p)/(1-a))\right) = \exp(-H(a))
\]

For \( a < p \) the first equality is valid for \( \theta < 0 \) but the remaining calculations are the same. \( \square \)

In many cases the following simplification is useful

**Lemma A.1.8.** If \( X = \text{Binomial}(n, p) \) then

(a) \( P(X \leq np(p-z)) \leq \exp(-nz^2/2p) \) \hspace{1cm} (b) \( P(X \geq np+z) \leq \exp(-nz^2/2(p+z)) \)

Taking \( z = py \) this becomes

(c) \( P(X \leq np(1-y)) \leq \exp(-npy^2/2) \) \hspace{1cm} (d) \( P(X \geq np(1+y)) \leq \exp(-npy^2/2(1+y)) \)

**Proof.** We begin with (b). The function defined in Lemma A.1.6 has \( H(p) = 0 \) and

\[
H'(a) = \log(a/p) - \log((1-a)/(1-p))
\]

so \( H'(p) = 0 \). If \( p < a \leq 1 \), Taylor’s theorem implies that there is a \( y \in [p,a] \) so that \( H'(a) = H''(y)(a-p)^2/2 \). Differentiating again \( H''(a) = 1/a(1-a) \) which is minimized at \( a = 1/2 \). Therefore if \( a \leq 1/2 \), \( H(a) \geq (a-p)^2/2a \), while if \( a \geq 1/2 \, H(a) \geq 2(a-p)^2 \geq (a-p)^2/2a \). Substituting \( a = p + z \) gives the second result. The argument for (a) is almost identical, but when we substitute \( a = p - z \) we can let \( a = p \) in the denominator. \( \square \)
Four more concrete examples

To prepare for the computations, we recall some important formulas:

\[ \kappa(\theta) = \log \phi(\theta) \quad \kappa'(\theta) = \phi'(\theta)/\phi(\theta) \quad \theta_a \text{ solves } \kappa'(\theta_a) = a \]

\[ \gamma(a) = \lim_{n \to \infty} (1/n) \log P(S_n \geq na) = -a\theta_a + \kappa(\theta_a) \]

Example A.1.9. Normal distribution. Without loss of generality we can assume the mean is 0. If the variance is \( \sigma^2 \), the density function is \( (2\pi\sigma^2)^{-1/2}e^{-x^2/2\sigma^2} \) so

\[ \phi(\theta) = \int (2\pi\sigma^2)^{-1/2}e^{-x^2/2\sigma^2} e^{\theta x} = \exp(\theta^2/2\sigma^2) \]

and it follows that for \( a > 0 \)

\[ \kappa(\theta) = \sigma^2\theta^2/2 \quad \kappa'(\theta) = \sigma^2 \theta \quad \theta_a = a/\sigma^2 \]

\[ \gamma(a) = -a\theta_a + \kappa(\theta_a) = -a^2/2\sigma^2 + a^2/\sigma^2 = a^2/2\sigma^2 \]

One can check the last result by observing that \( S_n \) has a normal distribution with mean 0 and variance \( n\sigma^2 \), and then using the formula for the tail of the distribution function for the normal. See Theorem 1.2.6 in PTE5.

Example A.1.10. Exponential(1) density function is \( f(x) = e^{-x} \) for \( x \geq 0 \) so

\[ \phi(\theta) = \int_0^\infty e^{-x} e^{\theta x} dx = 1/(1-\theta) \quad \text{ for } \theta < 1 \]

and it follows that

\[ \kappa(\theta) = -\log(1-\theta) \quad \kappa'(\theta) = 1/(1-\theta) \quad \theta_a = 1-1/a \]

\[ \gamma(a) = -a\theta_a + \kappa(\theta_a) = -a + 1 + \log a \quad \text{ for } a > 1. \]

To extend to a general \( \lambda \), note that if \( X_i \) are exponential(1) then \( Y_i = X_i/\lambda \) is exponential(\( \lambda \)) so if \( a > 1 \)

\[ P(Y_1 + \cdots + Y_m > ma/\lambda) = P(X_1 + \cdots + X_m > am) \]

Letting \( T_m = X_1 + \cdots + X_m \) and \( T^\lambda_m = Y_1 + \cdots + Y_m \)

\[ \frac{1}{m} \log P \left( T^\lambda_m > \frac{ma}{\lambda} \right) = \frac{1}{m} \log P(T_m > ma) \quad (A.1.3) \]

This simple argument does not work for discrete random variables, so we have to compute for a general parameter.
Example A.1.11. Poisson(\(\lambda\)) has \(P(X = k) = e^{-\lambda} \lambda^k / k!\) for \(k = 0, 1, 2, \ldots\) so

\[
\phi(\theta) = \sum_{k=0}^{\infty} e^{-\lambda} \frac{\lambda^k}{k!} e^{\theta k} = \exp(-\lambda(1 - e^\theta))
\]

Replacing \(e^\theta\) by \(z\) leads to the familiar formula for the generating function.

If \(X = \text{Poisson}(\lambda)\) and \(Y = \text{Poisson}(\mu)\) are independent then \(X + Y = \text{Poisson}(\lambda + \mu)\). From this it follows that

\[
P(S^\lambda_m = k) = e^{-\lambda m} (\lambda m)^k / k!
\]

where we have added a superscript to indicate the parameter. Using Stirling’s formula

\[
k! \sim k^k e^{-k} \sqrt{2\pi k}
\]

we have

\[
P(S^\lambda_m = k) \sim e^{-\lambda m + k} \left(\frac{\lambda m}{k}\right)^k / \sqrt{2\pi k}
\]

and if \(k/\lambda m \to a\) we have a scaling result similar to (A.1.3)

\[
\frac{1}{\lambda m} \log P(S^\lambda_m = k) = -\frac{\lambda m - k}{\lambda m} - \frac{k}{\lambda m} \log \left(\frac{k}{\lambda}\right) + o(1)
\]

\[
\to a - 1 - a \log a = \lim_{m \to \infty} \frac{1}{m} \log P(S^\lambda_m = k)
\]

To convert this into an asymptotic for \(\geq k\) we note that if \(j/(\lambda m) \geq a > 1\) we have

\[
P(S^\lambda_n = j + 1) = \frac{\lambda m}{j+1} P(S^\lambda_n = j) \leq \frac{1}{a} P(S^\lambda_n = j)
\]

From this we see that (ignoring annoying rounding)

\[
P(S^\lambda_m \geq \lambda m) \leq \frac{1}{1 - 1/a} P(S^\lambda_m = \lambda m)
\]

The dominant contribution from values near \(\lambda m\) so \(\leq\) is actually \(\sim\).

Example A.1.12. Geometric(\(p\)) has \(P(X = k) = (1 - p)^{k-1} p\) for \(k = 1, 2, \ldots\) so if \((1 - p)e^\theta < 1\) then

\[
\phi(\theta) = \sum_{k=1}^{\infty} (1 - p)^{k-1} p e^\theta = \frac{pe^\theta}{1 - (1 - p)e^\theta}.
\]

and it follows that \(\kappa(\theta) = \theta + \log p - \log(1 - (1 - p)e^\theta)\)

\[
\kappa'(\theta) = 1 + \frac{(1 - p)e^\theta}{1 - (1 - p)e^\theta}
\]
Setting \( a = \kappa'(\theta) \) leads to \( (a - 1)[1 - (1 - p)e^\theta] = (1 - p)e^\theta \) so

\[
a - 1 = a[(1 - p)e^\theta] \quad \text{and} \quad \theta_a = \log \left( \frac{a - 1}{a(1 - p)} \right)
\]

At this point it takes courage to compute \( \gamma(a) \), but some nice things happen

\[
\kappa(\theta_a) = \theta_a + \log p + \log[1 - (1 - p)e^{\theta_a}]
\]
looks ugly but \( (1 - 1 - p)e^{\theta_a} = 1 - (a - 1)/a = 1/a \) so

\[
\gamma(a) = -a\theta_a + \kappa(\theta_a) = -(a - 1)\theta_a + \log(ap)
\]

To check this result, we note that the sum of \( m \) geometric \((p)\) has a **negative binomial distribution**

\[
P(S_m = k) = \binom{k - 1}{m - 1}p^m(1 - p)^{k - m} \quad \text{for } k \geq m.
\]
To see this note that in order for \( S_m = k \) the \( m \)th success must come at time \( k \) and there must be exactly \( k - 1 \) successes on trials \( 1, 2, \ldots k - 1 \). If \( k = am \) with \( a > 1 \)

\[
P(S_m = am) = \binom{am - 1}{m - 1}p^m(1 - p)^{m(a - 1)}
\]
Dropping the \(-1\)'s, using Stirling’s formula, ignoring the square roots, and noticing that the exponentials cancel out when it is applied to a binomial coefficient

\[
P(S_m = am) \approx \frac{(am)^am}{m^m(m(a - 1))^{m(a - 1)}p^m(1 - p)^{m(a - 1)}}
= (ap)^m \cdot \left( \frac{a(1 - p)}{a - 1} \right)^{m(a - 1)} = (ap)^m \exp(-\theta_ama(a - 1))
\]

### A.2 Azuma-Hoeffding inequality

To quote Wikipedia, “In probability theory, the Azuma–Hoeffding inequality (named after Kazuoki Azuma and Wassily Hoeffding) gives a concentration result for the values of martingales that have bounded differences.”

**Theorem A.2.1.** If \( X_k \) is a supermartingale with \( |X_k - X_{k-1}| \leq c_k \) and \( X_0 \) is constant then

\[
P(X_m - X_0 \geq x) \leq \exp \left( \frac{-x^2}{2\sum_{k=1}^{m} c_k^2} \right)
\]
This immediately implies a result for submartingale and combining the two we have
Theorem A.2.2 (Azuma-Hoeffding inequality). If $M_k$ is a martingale and $|M_k - M_{k-1}| \leq c_k$ and $M_0$ is constant then

$$P(|M_m - M_0| \geq x) \leq 2 \exp \left( \frac{-x^2}{2 \sum_{k=1}^{m} c_k^2} \right)$$

Proof. It suffices to prove Theorem A.2.1. Let $F_k = \sigma(X_0, \ldots, X_k)$, and let $Y_k = X_k - X_{k-1}$ for $1 \leq k \leq m$. Then $\sum_{k=1}^{m} Y_k = X_m - X_0$ and $E(Y_{k+1} | F_k) \leq 0$. Let $\lambda > 0$

$$P(X_m - X_0 \geq x) = P \left( \exp \left\{ \lambda \sum_{k=1}^{m} Y_k \right\} \geq e^{\lambda x} \right)$$

by Markov’s inequality. Since $-c_i \leq Y_i \leq c_i$ and $e^{\lambda x}$ is convex

$$e^{\lambda Y_i} \leq \frac{1 - Y_i/c_i}{2} e^{-\lambda c_i} + \frac{1 + Y_i/c_i}{2} e^{\lambda c_i} = \cosh(\lambda c_i) + (Y_i/c_i) \sinh(\lambda c_i)$$

which implies

$$E(e^{\lambda Y_i} | F_{i-1}) \leq \cosh(\lambda c_i) \quad (A.2.1)$$

From this it follows that

$$E \left( \exp \left\{ \lambda \sum_{k=1}^{n} Y_k \right\} \right) = E \left( E(e^{\lambda Y_n} | F_{n-1}) \cdot \exp \left\{ \lambda \sum_{i=1}^{n-1} Y_i \right\} \right)$$

$$\leq \cosh(\lambda v_n) E \left( \exp \left\{ \lambda \sum_{i=1}^{n-1} Y_i \right\} \right)$$

Using induction gives

$$E \left( \exp \left\{ \lambda \sum_{k=1}^{n} Y_k \right\} \right) \leq \prod_{i=1}^{n} \cosh(\lambda c_i)$$

The right-hand side of the last inequality is

$$\prod_{i=1}^{n} \cosh(\lambda c_i) = \prod_{i=1}^{n} \sum_{m=0}^{\infty} \frac{(\lambda c_i)^{2m}}{(2m)!}$$

$$\leq \prod_{i=1}^{n} \sum_{m=0}^{\infty} \frac{(\lambda c_i)^{2m}}{2^m \cdot m!} = \exp \left( \frac{\lambda^2}{2} \sum_{i=1}^{n} c_i^2 \right)$$

where in the second step we have removed the odd integers from the factorial. Taking $\lambda = x/\sum_{i=1}^{n} c_i^2$ we have

$$e^{\lambda x} = \exp \left( \frac{\lambda^2}{2} \sum_{i=1}^{n} c_i^2 \right)$$

which gives the desired result. ∎
A.2. AZUMA-HOEFFDING INEQUALITY

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