Math 353 Lecture Notes
Laplace Transform: Fundamentals

Fall 2020

Topics covered

- Introduction to the Laplace transform
- Theory and definitions
  - Domain and range of $\mathcal{L}$
  - Inverse transform
  - Fundamental properties
    - linearity
    - transform of derivatives
- Use in practice
  - Standard transforms
  - A few transform rules
  - Using $\mathcal{L}$ to solve constant-coefficient, linear IVPs
  - Some basic examples

1 The idea

We turn our attention now to *transform methods*, which will provide not just a tool for obtaining solutions, but a framework for understanding the structure of linear ODEs.

The idea is to define a transform operator $\mathcal{L}$ on functions,

$$\mathcal{L} : \text{origin space} \to \text{transformed space}$$

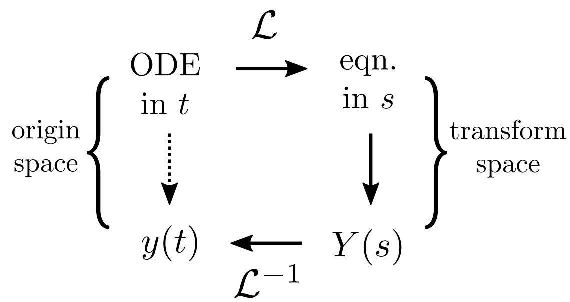
such that the ODE in the transformed space is much easier to solve. We will consider an **integral transform**, which takes the form

$$\mathcal{L}[f(t)] = \int_D K(s,t) f(t)\, dt$$

where D is some domain (usually $(-\infty, \infty)$ or $(0, \infty)$) and $K(s, t)$ is a function called the **kernel** of the transform. One of the two most important integral transforms[1] is the **Laplace transform** $\mathcal{L}$, which is defined according to the formula

$$\mathcal{L}[f(t)] = F(s) = \int_0^\infty e^{-st} f(t)\, dt, \tag{1}$$

i.e. $\mathcal{L}$ takes a function $f(t)$ as an input and outputs the function $F(s)$ as defined above.



They key properties of the Laplace transform (which we'll look at in detail) are:

- $\mathcal{L}$ is a linear operator
- $\mathcal{L}$ turns differentiation in t into *multiplication* by s (almost):

$$\mathcal{L}[f'] = s\mathcal{L}[f] - f(0).$$

- $\mathcal{L}^{-1}$ exists and both $\mathcal{L}$ and $\mathcal{L}^{-1}$ can be computed in practice

Because of these properties, given an ODE

$$y^{(n)} + a_{n-1}y^{(n-1)} + \cdots + a_1 y' + a_0 y = f(t)$$

we can:

1) Use the transform to convert this into an **algebraic** equation for $Y = \mathcal{L}[y]$.
2) solve for Y in the s-space
3) Apply $\mathcal{L}^{-1}$ to return to the t-space and get $y(t)$

Typically, the equations in (2) are much easier to work with than the ODE. The s-space will tell us information about the solution that would be difficult to obtain directly.

[1]the other is the Fourier transform; we'll see a version of it later.

motivating example For example, let's solve

$$0 = y' - y$$

Let $Y(s) = \mathcal{L}[y(t)]$ be the Laplace transform of the solution. Applying $\mathcal{L}$ to the equation, we obtain the transformed equation

$$\mathcal{L}[0] = \mathcal{L}[y'] - \mathcal{L}[y] = sY - y(0) - Y.$$

Since $\mathcal{L}[0] = 0$, we get

$$0 = (s-1)Y - y(0),$$

which is trivial to solve! The transformed solution to the ODE is then

$$Y(s) = \frac{y(0)}{s-1}.$$

Here is the point at which we have to do actual work - the price of transforming the ODE is that we have to undo the transformation to get the desired solution, $y(t)$. In this case, it is easy to show that $\mathcal{L}[e^t] = 1/(s-1)$, from which we can conclude that

$$y(t) = y(0)e^t.$$

2 The laplace transform

Now we go through the basic theory. The treatment here is not be completely rigorous; some technical details are omitted in favor of getting to the key points.

Definition: The **Laplace transform** $F(s)$ of a function $f(t)$ is

$$\mathcal{L}[f(t)] = F(s) = \int_0^\infty e^{-st} f(t)\, dt, \tag{2}$$

defined for all s such that the integral converges.

2.1 Domain/range of the Laplace transform

We want to find a set of functions for which (2) is defined for large enough s. For (2) to be defined, we need that:

- f is integrable and defined for $[0, \infty)$
- f grows more slowly than the e^{-st} term

Hereafter, **we shall assume that** f is defined on the domain $[0, \infty)$ unless otherwise noted.

Definitions: A function $f(t)$ is **piecewise continuous** if it is continuous except for an isolated set of jump discontinuities.[2]

A function $f(t)$ is of **exponential type** if there are constants a and k such that

$$|f(t)| \leq Ke^{at}. \tag{3}$$

Note: Technically, this need only hold as $t \to \infty$, but the distinction is not important here.

These two properties are enough to guarantee $\mathcal{L}$ is defined:

Theorem: If f is piecewise continuous and of exponential type as in (3) then

$$\mathcal{L}[f(t)] = F(s) \text{ is defined for all } s > a.$$

Informally: If f grows slower than e^{st} then $F(s)$ is defined, so if f grows slower than e^{at} for some a then $F(s)$ is defined for all $s > a$.

Proof. (Sketch.) We need to show that $\int_0^\infty e^{-st} f(t)\, dt$ is finite when $s > a$. Use the bound on f to estimate

$$\left| \int_0^\infty e^{-st} f(t)\, dt \right| \leq \int_0^\infty Ke^{-(s-a)t}\, dt = \frac{K}{s-a}$$

which is finite so long as $s > a$. It follows (omitting technical details) that the integral exists and is finite, so $\mathcal{L}$ is defined for $s > a$. □

Note on the theorem and proof: The condition (3) can be replaced with the weaker condition that $|f(t)| \leq Ke^{at}$ for $t > M$ for some M (that is, f is eventually bounded by an exponential). It does not matter what f does in a finite interval, which allows the assumptions to be relaxed a bit.

For the proof, there is a problem since $\int_0^\infty e^{-st} f(t)\, dt$ is not known to exist in the first place. To be correct, we must use a comparison test for integrals: If there is an 'upper bound' function $h(t)$ such that

$$|g(t)| \leq h(t) \text{ and } \int_0^\infty h(t)\, dt < \infty$$

then $\int_0^\infty g(t)\, dt$ exists (and is finite).

3 Fundamental properties

The most basic property is also the most essential, so it gets a box:

Linearity: The Laplace transform $\mathcal{L}$ is a linear operator.

Proof: Suppose f_1, f_2 are functions for which $\mathcal{L}$ is defined and $c_1, c_2 \in \mathbb{R}$. Then

$$\begin{aligned}\mathcal{L}[c_1 f_1 + c_2 f_2] &= \int_0^\infty e^{-st}(c_1 f_1(t) + c_2 f_2(t))\,dt \\ &= c_1 \int_0^\infty e^{-st} f_1(t)\,dt + c_2 \int_0^\infty e^{-st} f_2(t)\,dt \\ &= c_1 \mathcal{L}[f_1] + c_2 \mathcal{L}[f_2].\end{aligned}$$

Note that if $\mathcal{L}[f_1]$ and $\mathcal{L}[f_2]$ are defined for $s > a$ then the same is true of the linear combination $c_1 f_1 + c_2 f_2$.

The other key property is that it acts in a nice way on derivatives:

Theorem: Suppose f is of exponential type (i.e. (3) holds) and f' is piecewise continuous. Then $\mathcal{L}[f'(t)]$ exists on the same domain as $\mathcal{L}[f]$ and

$$\mathcal{L}[f'(t)] = s\mathcal{L}[f(t)] - f(0). \tag{4}$$

Conceptually, it is essential to understand to that the above means

derivatives in the original space $\iff$ multiplication in the transformed space

up to the extra terms. The proof is straightforward and worth knowing. For simplicity, assume that f is continuous. Let a be the constant in (3); that is,

$$|f(t)| \le Ke^{at}.$$

To get the formula, integrate by parts (carefully):

$$\begin{aligned}\int_0^\infty e^{-st} f'(t)\,dt &= \lim_{b\to\infty} e^{-bt} f(t) - f(0) - \lim_{b\to\infty} \int_0^b (-se^{-st}) f(t)\,dt \\ &= -f(0) + s \lim_{b\to\infty} \int_0^b e^{-st} f(t)\,dt \\ &= -f(0) + s\mathcal{L}[f(t)].\end{aligned}$$

The first limit is zero by the bound on f since

$$|e^{-st} f(t)| \le Ke^{-(s-a)t} \to 0 \text{ as } t \to \infty.$$

For the second limit, we can take $b \to \infty$ since we have already established the improper integral converges in the proof that $\mathcal{L}[f]$ exists.

This result can be iterated to find the Laplace transform of higher order derivatives. For example,

$$\begin{aligned}\mathcal{L}[f''(t)] &= s\mathcal{L}[f'(t)] - f'(0)) \\ &= s(s\mathcal{L}[f(t)] - f(0)) - f'(0) \\ &= s^2\mathcal{L}[f(t)] - sf(0) - f'(0)\end{aligned}$$

and so on. Thus an n-th derivative in the original space correspond to multiplications by s^n in the transformed space (up to some polynomial in s). To be precise, we have:

Theorem (Laplace transform of derivatives): If $f^{(n)}$ is piecewise continuous and f and all its derivatives up to $n-1$ are of exponential type then

$$\mathcal{L}[f^{(n)}(t)] = s^n\mathcal{L}[f(t)] - s^{n-1}f(0) - s^{n-2}f'(0) - \cdots - sf^{(n-2)}(0) - f^{(n-1)}(0). \tag{5}$$

As before, if the transforms of $f, f', \cdots, f^{(n-1)}$ are defined for $s > a$ then the transform of $f^{(n)}$ is also defined for $s > a$.

3.1 Inversion

The Laplace transform has an inverse; for any reasonable nice function $F(s)$ there is a unique f such that $\mathcal{L}[f] = F$.

Inverse of the Laplace transform: If $F(s)$ is defined for $s > a$ then there is a unique function $f(t)$ such that

$$\mathcal{L}[f(t)] = F(s).$$

In this case we write

$$f(t) = \mathcal{L}^{-1}[F(s)].$$

Unfortunately, the details (and definition of $\mathcal{L}^{-1}$ in general) require some complex analysis and are beyond the scope of this course. The inverse is notoriously difficult to work with in general. In practice, one typically computes $\mathcal{L}^{-1}[F(s)]$ by recognizing $F(s)$ as comprised of known transforms. In the next section, we derive some 'standard' transforms; these functions (along with some other known results) will be the things whose inverses are known.

4 Inverses and transforms

In this section we compute some common transforms and show strategies for computing the inverse transform of a function $F(s)$. This discussion will involve deriving some new properties of $\mathcal{L}$ and will make use of a few results from calculus.

4.1 Easy cases (with a bit of algebra)

Constant function: For the constant function $f(t) = 1$,

$$\mathcal{L}[1] = \int_0^\infty e^{-st}\,dt = \frac{1}{s}, \text{ defined for } s > 0.$$

Exponential:

$$\mathcal{L}[e^{at}] = \int_0^\infty e^{-(s-a)t}\,dt = \frac{1}{s-a}, \quad s > a.$$

Sine/cosine: The formula above applies for complex exponentials. In particular,

$$\mathcal{L}[e^{(a+bi)t}] = \frac{1}{s-(a+bi)} = \frac{s-a+bi}{(s-a)^2+b^2}.$$

In particular, because $\mathcal{L}$ is linear we can take real and imaginary parts to get

$$\mathcal{L}[e^{at}\sin bt] = \frac{b}{(s-a)^2+b^2}, \quad \mathcal{L}[e^{at}\cos bt] = \frac{s-a}{(s-a)^2+b^2}.$$

Polynomial: Let $n \geq 1$ be an integer. Then, using integration by parts, we can find the transform of t^n in terms of the transform for t^{n-1}. The result (left as an exercise) is that

$$\mathcal{L}[t^n] = \frac{n!}{s^{n+1}}.$$

Non-integer case: The transform for t^p when p is a real number is not as nice. Define

$$\Gamma(p) = \int_0^\infty e^{-t} t^{p-1}\,dt, \qquad p > 0$$

(the 'Gamma function'). Note that $\Gamma(n) = (n-1)!$ if n is an integer. If $p > -1$ then

$$\mathcal{L}[t^p] = \frac{\Gamma(p+1)}{s^{p+1}}.$$

5 Transform rules/equivalences

Not every $F(s)$ is going to be immediately recognizable as a standard transform. Often, we need to break it into manageable parts. If you see something like

$$\frac{s^2+3}{(s-1)^2(2s-2)^2}$$

you should think: how can this be turned into a sum of easy-to-invert functions? There are a number of rules to break expressions down.

Many of the rules are really correspondence between operations in the original space and the transform space (like differentiation in t being multiplication by s). They can be used to compute $\mathcal{L}$ or $\mathcal{L}^{-1}$, but are also useful for analysis.

The list will grow considerably as the discussion progresses!

Linearity: The inverse transform $\mathcal{L}^{-1}$ is linear. Thus sums can be inverted term by term and constant factors can be moved in/out of the transform.

$$\mathcal{L}^{-1}[cF(s)] = c\mathcal{L}^{-1}[F(s)],$$

$$\mathcal{L}^{-1}[F_1(s)+\cdots+F_n(s)] = \mathcal{L}^{-1}[F_1(s)]+\cdots+\mathcal{L}^{-1}[F_n(s)].$$

Derivatives in s: A dual property to the rule for $f'(t)$. A derivative in the transformed space corresponds to multiplication by $(-t)$ in the original space:

$$(-t)^n f(t) \rightleftharpoons F^{(n)}(s)$$

For example,

$$\mathcal{L}[te^t] = -\frac{d}{ds}\left(\frac{1}{s-1}\right) = \frac{1}{(s-1)^2}.$$

This could also be used in reverse to find $\mathcal{L}^{-1}[1/(s-1)^2]$.

Partial fractions: See separate notes for a review. We break up rational expressions into recognizable parts that can be inverted directly, e.g.

$$F(s) = \frac{1}{(s-1)(s-2)^2} = \frac{a}{s-1}+\frac{b}{s-2}+\frac{c}{(s-2)^2}.$$

The first three are the most commonly used (and mandatory for most problems). There are a few others to be derived later.

6 Solving ODEs with the Laplace transform

We are now ready to use the Laplace transform to solve linear, constant coefficient initial value problems, that is equations of the form

$$a_n y^{(n)} + a_{n-1} y^{(n-1)} + \cdots + a_1 y' + a_0 y = f$$

where the a_i's are constants.

Remark: Example 2 (below) shows that the transform has no problem with inhomogeneous term, so long as we can transform/inverse transform them. Any order is also fine (see Example 3), but it makes the calculations much more involved.

The procedure is as follows:

1) Apply $\mathcal{L}$ to the ODE to obtain an equation for $Y(s) = \mathcal{L}[y(t)]$. Use the initial conditions to evaluate the $y(0), y'(0)$ etc. terms in (5). (*easy; always the same process*)

2) Solve the equation for $Y(s)$ (*easy*)

3) Decompose $Y(s)$ into a sum of functions that are easy to invert. (*can be tricky depending on the form of $Y(s)$; it can be a mess*).

4) Calculate each term of $\mathcal{L}^{-1}[Y(s)]$ (*mostly straightforward if Step 3 was done well*)

$$\begin{array}{ccc}
t\text{-space} & & s\text{-space} \\
y^{(n)} + \cdots = f(t) & \xrightarrow{\mathcal{L}} & s^n Y(s) + \cdots = F(s) \\
 & & \Big\downarrow \text{solve for } Y \\
 & & Y(s) = \cdots \\
 & & \Big\downarrow \text{decompose} \\
y(t) = \cdots & \xleftarrow[\mathcal{L}^{-1}]{} & Y = Y_1 + Y_2 + \cdots
\end{array}$$

It is worth noting, and we will see later, that the **end goal is not always to get a formula for** $y(t)$. If we are interested in understanding the behavior of solutions, the transform space can be the right place to do analysis.

Example 1 (homogeneous): A simple initial value problem.

$$y'' - 2y' + y = 0, \qquad y(0) = 1, \quad y'(0) = 0.$$

Let $Y(s) = \mathcal{L}[y(t)]$. Take the transform of the ODE, then apply the initial conditions:

$$\begin{aligned} 0 &= s^2Y - sy(0) - y'(0) - 2(sY - y(0)) + Y \\ &= s^2Y - s - 2sY + 2 + Y \\ &= (s^2 - 2s + 1)Y - s + 2 \\ &= (s-1)^2Y - s + 2. \end{aligned}$$

The solution in the transformed space is therefore

$$Y(s) = \frac{s-2}{(s-1)^2}.$$

Now we write (this is an example of partial fractions)

$$Y(s) = \frac{s-2}{(s-1)^2} = \frac{1}{s-1} - \frac{1}{(s-1)^2}.$$

The first term is $\mathcal{L}[e^t]$; for the second, see below. Inverting, we get

$$\begin{aligned} \mathcal{L}^{-1}[Y(s)] &= \mathcal{L}^{-1}[\frac{1}{s-1}] + \mathcal{L}^{-1}[\frac{1}{(s-1)^2}] \\ &= e^t + (-t)e^t \\ &= (1-t)e^t. \end{aligned}$$

For the second term: Use the derivative-in-s rule, observing that

$$-\frac{1}{(s-1)^2} = \frac{d}{ds}\left(\frac{1}{s-1}\right). \tag{6}$$

We know that d/ds corresponds to multiplication by $-t$, i.e.

$$\mathcal{L}[(-t)^n f(t)] = F^{(n)}(s)$$

so we can use this to take the inverse transform of (6) to get

$$\mathcal{L}^{-1}[1/(s-1)^2] = (-t)e^t.$$

Alternate method: Use the translation in s rule,

$$\mathcal{L}[e^{ct}f(t)] = F(s-c)$$

and the fact that $\mathcal{L}[t] = 1/s^2$ to get

$$\mathcal{L}^{-1}[\frac{1}{(s-1)^2}] = e^t cL^{-1}[\frac{1}{s^2}] = te^t.$$

Example 2 (inhomogeneous): An initial value problem with a forcing term.

$$y'' + y = \sin \omega t, \quad y(0) = 0, y'(0) = 1, \qquad \omega \neq \pm 1.$$

Take the transform (using the standard result for sine):

$$s^2 Y - sy(0) - y'(0) + Y = \frac{\omega}{s^2 + \omega^2}.$$

Apply the initial condition and obtain

$$(s^2 + 1)Y = 1 + \frac{\omega}{s^2 + \omega^2}.$$

so we get

$$Y = \frac{1}{s^2 + 1} + \frac{\omega}{(s^2 + 1)(s^2 + \omega^2)}.$$

Now use partial fractions:

$$\frac{1}{(s^2 + 1)(s^2 + \omega^2)} = \frac{A}{s^2 + 1} + \frac{B}{s^2 + \omega^2}$$

which gives

$$1 = As^2 + A\omega^2 + Bs^2 + B$$

so $A + B = 0$ and $A\omega^2 + B = 1$, solved by $A = 1/(\omega^2 - 1)$ and $B = -1/(\omega^2 - 1)$. Thus Y, after using partial fractions, is

$$Y = \frac{1}{s^2 + 1} + \frac{\omega}{(\omega^2 - 1)} \left(\frac{1}{s^2 + 1} - \frac{1}{s^2 + \omega^2} \right).$$

Now we recognize that

$$\mathcal{L}[\sin t] = \frac{1}{s^2 + 1}, \quad \mathcal{L}[\sin \omega t] = \frac{\omega}{s^2 + \omega^2},$$

and use the known transforms to invert each term of Y:

$$Y = \frac{\omega^2 + \omega - 1}{\omega^2 - 1} \sin t - \frac{1}{\omega^2 - 1} \sin \omega t.$$

Example 3 (higher order ODE): A fourth order IVP. The method works for any linear constant-coefficient ODE (of any order). We solve

$$y^{(4)} - 5y'' + 4y = 0, \qquad y(0) = 1,\ y'(0) = 0,\ y''(0) = 3,\ y'''(0) = 0.$$

Take the Laplace transform and use the initial conditions:

$$(s^4 Y - s^3 - 3s) - 5(s^2 Y - s) + 4Y = 0.$$

Solve for Y to obtain

$$Y(s) = \frac{s^3 - 2s}{s^4 - 5s^2 + 1} = \frac{s^3 - 2s}{(s-1)(s+1)(s-2)(s+2)}.$$

Notice that the denominator just the characteristic polynomial of the ODE (which will be true in general). We can invert $Y(s)$ by using partial fractions to write it in the form

$$Y(s) = \frac{1/6}{s-1} + \frac{1/6}{s+1} + \frac{1/3}{s-2} + \frac{1/3}{s+2}.$$

(The calculation here is tedious but straightforward). Each term can be inverted using $\mathcal{L}[e^{at}] = 1/(s-a)$ to obtain the solution

$$y(t) = \frac{1}{6}(e^t + e^{-t}) + \frac{1}{3}(e^{2t} + e^{-2t}).$$