

# Laplace Transform

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# 1 Laplace Transform

## 1.1 Definition and Existence

### Definition 1.1.1: Laplace Transform

Let  $F$  be a real-valued function of the real variable  $t$ , defined for  $t > 0$ . Let  $s$  be a variable that we shall assume to be real, and consider the function  $f$  defined by

$$f(s) = \int_0^{\infty} e^{-st} F(t) dt \quad (1)$$

for all values of  $s$  for which this integral exists. The function  $f$  defined by the integral (1) is called the Laplace Transform of the function  $F$ . We shall denote the Laplace transform of  $F$  by  $\mathcal{L}\{F(t)\}$ .

Thus the Laplace transform of a function  $f$  is given by

$$\mathcal{L}\{F(t)\} = f(s) = \int_0^{\infty} e^{-st} F(t) dt = \lim_{R \rightarrow \infty} \int_0^R e^{-st} F(t) dt \quad (2)$$

Some ways to write Laplace transforms:

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

$$\mathcal{L}\{G(t)\} = g(s)$$

$$\mathcal{L}\{u(t)\} = \tilde{u}(s)$$

**Theorem 1.1.2: Hypothesis:** Let  $F$  be a real function that has the following properties:

1.  $F$  is a piecewise continuous in every finite closed interval  $0 \leq t \leq a$  ( $a > 0$ ).
2.  $F$  is of exponential order, i.e, there exists  $\alpha$ ,  $M > 0$ , and  $t_0 > 0$  such that

$$e^{-\alpha t} |F(t)| < M \text{ for } t > t_0$$

**Conclusion:** The Laplace transform of  $F$  exists for  $s > \alpha$ .

$$\mathcal{L}\{F(t)\} = \int_0^{\infty} e^{-st} F(t) dt$$

## 1.2 Some Functions and Their Laplace Transforms

$F(t)$	$\mathcal{L}\{F(t)\} = f(s)$	$F(t)$	$\mathcal{L}\{F(t)\} = f(s)$
1	$\frac{1}{s}$	$n$	$\frac{n}{s}$
$t$	$\frac{1}{s^2}$	$t^n$	$\frac{n!}{s^{n+1}}$
$e^{at}$	$\frac{1}{s-a}$	$e^{-at}$	$\frac{1}{s+a}$
$\sin at$	$\frac{a}{s^2 + a^2}$	$\sinh at$	$\frac{a}{s^2 - a^2}$
$\cos at$	$\frac{s}{s^2 + a^2}$	$\cosh at$	$\frac{s}{s^2 - a^2}$

Table 1: Functions and their Laplace Transform

Proofs :

$$\mathcal{L}\{n\} = \frac{n}{s}$$

$$\mathcal{L}\{t\} = \frac{1}{s^2}$$

Let  $F(t) = n$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{n\} &= \int_0^\infty e^{-st} \cdot n \, dt \\ &= n \frac{-e^{-st}}{s} \Big|_0^\infty \\ &= \frac{n}{s} \quad \square\end{aligned}$$

Let  $F(t) = t$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{t\} &= \int_0^\infty e^{-st} \cdot t \, dt \\ &= -t \frac{e^{-st}}{s} + \int_0^\infty \frac{e^{-st}}{s} \, dt \\ &= -e^{-st} \frac{t}{s} \Big|_0^\infty - e^{-st} \frac{1}{s^2} \Big|_0^\infty \\ &= \frac{1}{s^2} \quad \square\end{aligned}$$

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

Let  $F(t) = t^n$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{t^n\} &= \int_0^\infty e^{-st} t^n \, dt \\ &= -t^n \frac{e^{-st}}{s} + \int_0^\infty n t^{n-1} \frac{e^{-st}}{s} \, dt \\ &= -n t^{n-1} \frac{e^{-st}}{s^2} \Big|_0^\infty + \int_0^\infty n(n-1) t^{n-2} \frac{e^{-st}}{s^2} \, dt \\ &= -n(n-1) t^{n-2} \left( \frac{e^{-st}}{s^3} \right) \Big|_0^\infty + \int_0^\infty n(n-1)(n-2) t^{n-3} \frac{e^{-st}}{s^3} \, dt \\ &= \dots \\ &= n! t^{n-n} \frac{e^{-st}}{s^{n+1}} \Big|_0^\infty + \int_0^\infty n(n-1) \dots (n-n) \frac{e^{-st}}{s^{n+1}} \, dt \\ &= \frac{n!}{s^{n+1}} \quad \square\end{aligned}$$

Let  $F(t) = e^{at}$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{e^{at}\} &= \int_0^\infty e^{-st} e^{at} \, dt \\ &= \int_0^\infty e^{(a-s)t} \, dt \\ &= \frac{e^{(a-s)t}}{a-s} \Big|_0^\infty \\ &= \frac{1}{s-a} \quad \square\end{aligned}$$

Let  $F(t) = e^{-at}$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{e^{-at}\} &= \int_0^\infty e^{-st} e^{-at} \, dt \\ &= \int_0^\infty e^{-(a+s)t} \, dt \\ &= \frac{e^{-(a+s)t}}{s+a} \Big|_0^\infty \\ &= \frac{1}{s+a} \quad \square\end{aligned}$$

Let  $F(t) = \sin at$ , for  $t > 0$   
Then

$$\begin{aligned}\mathcal{L}\{\sin at\} &= \int_0^\infty e^{-st} \sin at \, dt \\ &= -\frac{e^{-st}}{s^2 + a^2} (s \sin at + a \cos at) \Big|_0^\infty \\ &= \frac{a}{s^2 + a^2} \quad \square\end{aligned}$$

Let  $F(t) = \cos at$ , for  $t > 0$   
Then

$$\begin{aligned}\mathcal{L}\{\cos at\} &= \int_0^\infty e^{-st} \cos at \, dt \\ &= \frac{e^{-st}}{s^2 + a^2} (-s \cos at + a \sin at) \Big|_0^\infty \\ &= \frac{s}{s^2 + a^2} \quad \square\end{aligned}$$

## 2 Basic Properties of the Laplace Transform

### 2.1 Linearity Property

**Theorem (The Linearity Property):**

Let  $F_1$  and  $F_2$  be functions whose Laplace transform exist, and let  $c_1$  and  $c_2$  be constants.  
Then

$$\mathcal{L}\{c_1 F_1(t) + c_2 F_2(t)\} = c_1 \mathcal{L}\{F_1(t)\} + c_2 \mathcal{L}\{F_2(t)\}$$

**Proof :**

Let  $F(t) = c_1 F_1(t) + c_2 F_2(t)$ , for  $t > 0$

Then

$$\begin{aligned}\mathcal{L}\{c_1 F_1(t) + c_2 F_2(t)\} &= \int_0^\infty e^{-st} [c_1 F_1(t) + c_2 F_2(t)] \, dt \\ &= c_1 \int_0^\infty e^{-st} F_1(t) \, dt + c_2 \int_0^\infty e^{-st} F_2(t) \, dt \\ &= c_1 \mathcal{L}\{F_1(t)\} + c_2 \mathcal{L}\{F_2(t)\} \quad \square\end{aligned}$$

**Example 2.1:**

$$\mathcal{L}\{4t^2 - 3 \cos 2t + 5e^{-t}\}$$

$$\begin{aligned}\mathcal{L}\{4t^2 - 3 \cos 2t + 5e^{-t}\} &= 4\mathcal{L}\{t^2\} - 3\mathcal{L}\{\cos 2t\} + 5\mathcal{L}\{e^{-t}\} \\ &= 4 \cdot \frac{2!}{s^3} - 3 \cdot \frac{s}{s^2 + 4} + 5 \cdot \frac{1}{s + 1} \\ &= \frac{8}{s^3} - \frac{3s}{s^2 + 4} + \frac{5}{s + 1}\end{aligned}$$

**Example 2.2:** Find  $\mathcal{L}\{F(t)\}$ , when  $F(t) = \begin{cases} 5 & \text{for } 0 < t < 3 \\ 0 & \text{for } t > 3 \end{cases}$

$$\begin{aligned}\mathcal{L}\{F(t)\} &= \int_0^\infty e^{-st} F(t) \, dt = \int_0^3 e^{-st} \cdot 5 \, dt + \int_3^\infty 0 \, dt \\ &= \int_0^3 e^{-st} \cdot 5 \, dt \\ &= \frac{5e^{-st}}{s} \Big|_0^3 \\ &= \frac{5}{s} (1 - e^{-3s})\end{aligned}$$

**Example 2.3:** Find  $\mathcal{L}\{F(t)\}$ , when  $F(t) = \begin{cases} (t-1)^2 & \text{for } t > 1 \\ 0 & \text{for } 0 < t < 1 \end{cases}$

$$\begin{aligned}
\mathcal{L}\{F(t)\} &= \int_0^\infty e^{-st} F(t) dt = \int_0^1 0 dt + \int_1^\infty e^{-st} (t-1)^2 dt \\
&= \int_1^\infty e^{-st} (t^2 - 2t + 1) dt \\
&= -t^2 \frac{e^{-st}}{s} \Big|_1^\infty - 2 \int_1^\infty t \cdot \frac{e^{-st}}{s} dt - 2 \int_1^\infty t \cdot e^{-st} dt - \frac{e^{-st}}{s} \\
&= \frac{e^{-s}}{s} + 2 \left[ -\frac{t}{s} \left( \frac{e^{-st}}{s} \right) \Big|_1^\infty + \int_1^\infty \frac{e^{-st}}{s^2} dt + 2t \frac{e^{-st}}{s} \Big|_1^\infty - \int_1^\infty \frac{e^{-st}}{s} dt \right] + \frac{e^{-st}}{s} \\
&= \frac{e^{-s}}{s} - 2 \frac{e^{-s}}{s^2} + 2 \frac{e^{-s}}{s^2} - 2 \frac{e^{-st}}{s} + 2 \frac{e^{-s}}{s^2} + \frac{e^{-st}}{s} \\
&= 2 \frac{e^{-s}}{s^3}
\end{aligned}$$

## 2.2 First Translation Property

**Theorem 2.2.1 (First Translation or Shifting Property):**

If

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

then

$$\mathcal{L}\{e^{at}F(t)\} = f(s-a)$$

**Proof:**

Let  $G(t) = e^{at}F(t)$ , for  $t > 0$

Then

$$\begin{aligned}
\mathcal{L}\{e^{at}F(t)\} &= \int_0^\infty e^{-st} e^{at} F(t) dt \\
&= \int_0^\infty e^{-(s-a)t} F(t) dt \\
&= \mathcal{L}\{F(t)\} \Big|_{s-a} \\
&= f(s-a) \quad \square
\end{aligned}$$

**Example 2.4:**

$$\mathcal{L}\{e^{-t} \cos 2t\}$$

Since  $\mathcal{L}\{\cos 2t\} = \frac{s}{s^2 + 4}$ , we have

$$\mathcal{L}\{e^{-t} \cos 2t\} = \frac{s+1}{(s+1)^2 + 4} = \frac{s+1}{s^2 + 2s + 5}$$

**Example 2.5: Evaluate**  $\mathcal{L}\{e^{-2t}(3 \cos 6t - 5 \sin 6t)\}$

Now,

$$\begin{aligned}
f(s) &= \mathcal{L}\{3 \cos 6t - 5 \sin 6t\} \\
&= \frac{3s}{s^2 + 36} - \frac{30}{s^2 + 36} \\
&= \frac{3s - 30}{s^2 + 36}
\end{aligned}$$

$$\begin{aligned}
\therefore \mathcal{L}\{e^{-2t}(3 \cos 6t - 5 \sin 6t)\} &= f(s+2) \\
&= \frac{3(s+2) - 30}{(s+2)^2 + 36} \\
&= \frac{3s - 24}{s^2 + 4s + 40}
\end{aligned}$$

## 2.3 Second Translation Property

**Theorem 2.3.1 (Second Translation or Shifting Property):**

If

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

and

$$G(t) = \begin{cases} F(t-a) & \text{for } t > a \\ 0 & \text{for } t < a \end{cases}$$

then

$$\mathcal{L}\{G(t)\} = e^{-as}f(s)$$

**Proof:**

$$\text{Let } G(t) = \begin{cases} F(t-a) & \text{for } t > a \\ 0 & \text{for } t < a \end{cases}$$

Then

$$\begin{aligned} \mathcal{L}\{G(t)\} &= \int_0^{\infty} e^{-st} F(t-a) dt \\ &= \int_a^{\infty} e^{-st} F(t-a) dt \\ &= \int_0^{\infty} e^{-s(u+a)} F(u) du \quad \text{where } u = t-a \\ &= e^{-as} \int_0^{\infty} e^{-su} F(u) du \\ &= e^{-as} \mathcal{L}\{F(t)\} \\ &= e^{-as} f(s) \quad \square \end{aligned}$$

**Example 2.6:** Find  $\mathcal{L}\{G(t)\}$  where  $G(t) = \begin{cases} \cos\left(t - \frac{2\pi}{3}\right) & \text{for } t > \frac{2\pi}{3} \\ 0 & \text{for } t < \frac{2\pi}{3} \end{cases}$

$$\begin{aligned} \mathcal{L}\{G(t)\} &= e^{-\frac{2\pi}{3}s} \cdot \mathcal{L}\{\cos t\} \\ &= e^{-\frac{2\pi}{3}s} \cdot \frac{s}{s^2 + 1} \\ &= \frac{se^{-\frac{2\pi}{3}s}}{s^2 + 1} \end{aligned}$$

**Example 2.7:** Find  $\mathcal{L}\{F(t)\}$ , if  $F(t) = \begin{cases} (t-1)^2 & \text{for } t > 1 \\ 0 & \text{for } t < 1 \end{cases}$

Let

$$G(t) = t^2$$

$$\therefore \mathcal{L}\{G(t)\} = \frac{2!}{s^3}$$

Now,

$$F(t) = \begin{cases} G(t-1) & \text{for } t > 1 \\ 0 & \text{for } t < 1 \end{cases}$$

$$\therefore \mathcal{L}\{F(t)\} = \frac{e^{-s} \cdot 2!}{s^3} = \frac{2e^{-s}}{s^3}$$

## 2.4 Change of Scale Property

**Theorem 2.4.1 (Change of Scale Property):**

If

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

then

$$\mathcal{L}\{F(at)\} = \frac{1}{a} f\left(\frac{s}{a}\right)$$

**Proof:**

Let  $G(t) = F(at)$ , for  $t > 0$

Then

$$\begin{aligned} \mathcal{L}\{G(t)\} &= \int_0^\infty e^{-st} F(at) dt \\ &= \int_0^\infty e^{-\frac{s}{a}u} F(u) d(u/a) \quad \text{where } u = at \\ &= \frac{1}{a} \int_0^\infty e^{-\frac{s}{a}u} F(u) du \\ &= \frac{1}{a} \mathcal{L}\{F(t)\} \\ &= \frac{1}{a} f\left(\frac{s}{a}\right) \quad \square \end{aligned}$$

**Example 2.8: Evaluate  $\mathcal{L}\{\sin 3t\}$**

$$\begin{aligned} \mathcal{L}\{\sin 3t\} &= \frac{1}{3} \cdot \frac{1}{\left(\frac{s}{3}\right)^2 + 1} \\ &= \frac{1}{3} \cdot \frac{3^2}{s^2 + 3^2} \\ &= \frac{3}{s^2 + 9} \end{aligned}$$

**Example 2.9: If  $\mathcal{L}\left\{\frac{\sin t}{t}\right\} = \tan^{-1} \frac{1}{s} = f(s)$ , then evaluate  $\mathcal{L}\left\{\frac{\sin at}{t}\right\}$**

$$\begin{aligned} \mathcal{L}\left\{\frac{\sin at}{t}\right\} &= \mathcal{L}\left\{a \cdot \frac{\sin at}{t}\right\} \\ &= a \cdot \mathcal{L}\left\{\frac{\sin at}{at}\right\} \\ &= a \cdot \frac{1}{a} f\left(\frac{s}{a}\right) \\ &= \tan^{-1} \frac{a}{s} \end{aligned}$$

## 2.5 Multiplication by $t$

**Theorem 2.5.1 (Multiplication by  $t^n$ ):**

If

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

then

$$\mathcal{L}\{t^n F(t)\} = (-1)^n \frac{d^n}{ds^n} f(s)$$

**Proof:**

Let  $G(t) = t^n F(t)$ , for  $t > 0$

Then

$$\begin{aligned}
\mathcal{L}\{G(t)\} &= \int_0^\infty e^{-st} t^n F(t) dt \\
&= (-1)^n \int_0^\infty e^{-st} \frac{d^n}{ds^n} F(t) dt \\
&= (-1)^n \frac{d^n}{ds^n} \int_0^\infty e^{-st} F(t) dt \\
&= (-1)^n \frac{d^n}{ds^n} f(s) \quad \square
\end{aligned}$$

### Alternative Proof:

We have

$$f(s) = \int_0^\infty e^{-st} F(t) dt$$

Then by Leibnitz's rule for differentiating under the integral sign, we have

$$\begin{aligned}
\frac{df}{ds} = f'(s) &= \frac{d}{ds} \int_0^\infty e^{-st} F(t) dt \\
&= \int_0^\infty \frac{d}{ds} (e^{-st} F(t)) dt \\
&= \int_0^\infty e^{-st} (-te^{-st} F(t) + F'(t)) dt \\
&= - \int_0^\infty e^{-st} \{tF(t)\} dt \\
&= -\mathcal{L}\{tF(t)\}
\end{aligned}$$

$$\therefore \mathcal{L}\{tF(t)\} = -\frac{d}{ds} f(s) = f'(s)$$

This proves the theorem for  $n = 1$ .

To establish the theorem in general, we use mathematical induction. Suppose that the theorem is true for  $n = k$ , i.e

$$\int_0^\infty e^{-st} \{t^k F(t)\} dt = (-1)^k f^{(k)}(s) \quad (2.5.1)$$

Then

$$\frac{d}{ds} \left[ \int_0^\infty e^{-st} \{t^k F(t)\} dt \right] = (-1)^k f^{(k+1)}(s)$$

Or by Leibnitz's rule,

$$- \int_0^\infty \frac{d}{ds} (e^{-st} \{t^{k+1} F(t)\}) dt = (-1)^{(k)} f^{(k+1)}(s)$$

i.e

$$\int_0^\infty e^{-st} \{t^{k+1} F(t)\} dt = (-1)^{(k+1)} f^{(k+1)}(s) \quad (2.5.2)$$

It follows that if (2.5.1) is true for  $n = k$ , then (2.5.2) is true for  $n = k + 1$ . Since (2.5.1) is true for  $n = 1$ , it follows that (2.5.1) is true for all positive integers  $n$ .  $\square$

**Example 2.10:** Find  $\mathcal{L}\{t^2 \cos at\}$

$$\begin{aligned}
\mathcal{L}\{t^2 \cos at\} &= (-1)^2 \cdot \frac{d^2}{dx^2} \left( \frac{s}{s^2 + a^2} \right) \\
&= \frac{d}{ds} \left[ \frac{s^2 + a^2 - 2s^2}{(s^2 + a^2)^2} \right] \\
&= \frac{d}{ds} \left[ \frac{a^2 - s^2}{(s^2 + a^2)^2} \right] \\
&= \frac{(s^2 + a^2)^2 (-2s) - (-s^2 + a^2) 2(s^2 + a^2) \cdot 2s}{(s^2 + a^2)^4} \\
&= \frac{2s^3 - 6a^2s}{(s^2 + a^2)^3}
\end{aligned}$$



## 2.6 Division by $t$

**Theorem 2.6.1 (Division by  $t$ ):**

If

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

then

$$\mathcal{L}\left\{\frac{F(t)}{t}\right\} = \int_s^\infty f(x) dx$$

**Proof:**

Let  $G(t) = \frac{F(t)}{t}$ , for  $t > 0$ . Then  $F(t) = tG(t)$ . Taking the Laplace Transform of both sides, we get

$$\begin{aligned}\mathcal{L}\{F(t)\} &= \mathcal{L}\{tG(t)\} \\ f(s) &= -\frac{d}{ds}\mathcal{L}\{G(t)\} = -\frac{d}{ds}g(s)\end{aligned}$$

Then integrating, we have

$$\begin{aligned}g(s) &= -\int_s^\infty f(u) du \\ \mathcal{L}\{G(t)\} &= \int_s^\infty f(u) du \\ \mathcal{L}\left\{\frac{F(t)}{t}\right\} &= \int_s^\infty f(u) du \quad \square\end{aligned}$$

**Example 2.11:** Find  $\mathcal{L}\left\{\frac{\sin t}{t}\right\}$

$$\begin{aligned}\mathcal{L}\left\{\frac{\sin t}{t}\right\} &= \int_s^\infty \frac{1}{s^2 + 1} du \\ &= \tan^{-1} u \Big|_s^\infty \\ &= \frac{\pi}{2} - \tan^{-1} s = \cot^{-1} s \\ &= \tan^{-1} \frac{1}{s}\end{aligned}$$

## 2.7 Laplace Transform of Integral

**Theorem 2.7.1 (Laplace transform of Integral):**

If

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

then

$$\mathcal{L}\left\{\int_0^t F(x) dx\right\} = \frac{1}{s}f(s)$$

**Proof:**

Let  $G(t) = \int_0^t F(x)dx$ , for  $t > 0$ . Then  $G'(t) = F(t)$  and  $G(0) = 0$ . Taking the Laplace Transform of both sides, we have

$$\begin{aligned}\mathcal{L}\{G'(t)\} &= \mathcal{L}\{F(t)\} \\ s\mathcal{L}\{G(t)\} - G(0) &= f(s) \\ s\mathcal{L}\{G(t)\} &= f(s) \\ \mathcal{L}\{G(t)\} &= \frac{f(s)}{s} \\ \mathcal{L}\left\{\int_0^t F(u) du\right\} &= \frac{f(s)}{s} \quad \square\end{aligned}$$

**Example 2.12: Evaluate**  $\mathcal{L}\left\{\int_0^t \frac{\sin u}{u} du\right\}$

$$\begin{aligned}\mathcal{L}\left\{\frac{\sin u}{u}\right\} &= \tan^{-1} \frac{1}{s} \\ \mathcal{L}\left\{\int_0^t \frac{\sin u}{u} du\right\} &= \frac{f(s)}{s} = \frac{1}{s} \tan^{-1} \frac{1}{s}\end{aligned}$$

**Example 2.13: Evaluate**  $\mathcal{L}\left\{\int_0^t \frac{\sin u}{u} du\right\}$

Let  $F(t) = \frac{\sin t}{t}$

$$\begin{aligned}\mathcal{L}\left\{\frac{\sin t}{t}\right\} &= \int_s^\infty \frac{1}{u^2 + 1} du \\ &= \tan^{-1} u \Big|_s^\infty \\ &= \tan^{-1} \frac{1}{s} \\ \therefore \mathcal{L}\left\{\int_0^t \frac{\sin u}{u} du\right\} &= \frac{1}{s} \cdot \tan^{-1} \frac{1}{s}\end{aligned}$$

**Example 2.14: Evaluate**  $\mathcal{L}\left\{\int_0^t \sin 2u du\right\}$

$$\begin{aligned}\mathcal{L}\{\sin 2t\} &= \frac{2}{s^2 + 4} \\ \therefore \mathcal{L}\left\{\int_0^t \sin 2u du\right\} &= \frac{2}{s^3 + 4s}\end{aligned}$$

## 2.8 Laplace Transform of Periodic Functions

**Theorem 2.8.1 (Periodic functions):**

If

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

then

$$\mathcal{L}\{F(t)\} = \frac{1}{1 - e^{-Ts}} \int_0^T e^{-st} F(t) dt$$

where  $T$  is the period of  $F(t)$ .

**Proof:**

Let  $F(t)$  has period  $T$ . Then  $F(t) = F(t + T)$  for all  $t$ . Then

$$\begin{aligned}\mathcal{L}\{F(t)\} &= \int_0^\infty e^{-st} F(t) dt \\ &= \int_0^T e^{-st} F(t) dt + \int_T^{2T} e^{-st} F(t) dt + \int_{2T}^{3T} e^{-st} F(t) dt + \dots \\ &= \int_0^T e^{-st} F(t) dt + \int_0^T e^{-s(t+T)} F(t+T) dt + \int_0^T e^{-s(t+2T)} F(t+2T) dt + \dots \\ &= \int_0^T e^{-st} F(t) dt + e^{-sT} \int_0^T e^{-st} F(t) dt + e^{-2sT} \int_0^T e^{-st} F(t) dt + \dots \\ &= \left[1 + e^{-sT} + e^{-2sT} + \dots\right] \int_0^T e^{-st} F(t) dt \\ &= \frac{1}{1 - e^{-sT}} \int_0^T e^{-st} F(t) dt \quad \square\end{aligned}$$

**Note:-**

Sum of an infinite series  $1 + r + r^2 + \dots = \frac{1}{1-r}$  for  $|r| < 1$ .

**Example 2.15:** Find  $\mathcal{L}\{F(t)\}$  for

$$F(t) = \begin{cases} \sin t & \text{for } 0 < t < \pi \\ 0 & \text{for } \pi < t < 2\pi \end{cases}$$

$$\begin{aligned} \mathcal{L}\{F(t)\} &= \frac{1}{1 - e^{-2\pi s}} \int_0^{2\pi} e^{-st} \sin t \, dt \\ &= \frac{1}{1 - e^{-2\pi s}} \int_0^{\pi} e^{-st} \sin t \, dt \end{aligned}$$

**Example 2.16:** Find  $\mathcal{L}\{F(t)\}$  for

$$F(t) = \begin{cases} t & \text{for } 0 < t < 1 \\ 0 & \text{for } 1 < t < 2 \end{cases}$$

$$\begin{aligned} \mathcal{L}\{F(t)\} &= \frac{1}{1 - e^{-2s}} \int_0^1 e^{-2t} t \, dt \\ &= \frac{1}{1 - e^{-2s}} \left[ -t \frac{e^{-2t}}{2} + \frac{1}{2} \int e^{-2t} \, dt \right]_0^1 \\ &= \frac{1}{1 - e^{-2s}} \left\{ -\frac{e^{-2}}{2} - \frac{1}{4}(e^{-2} - 1) \right\} \\ &= \frac{1 - 3e^{-2}}{4(1 - e^{-2})} \end{aligned}$$

## 2.9 Laplace Transform of Derivatives

**Theorem 2.9.1 (Laplace transform of derivatives):**

If

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

then

$$\mathcal{L}\{F'(t)\} = sf(s) - F(0)$$

$$\mathcal{L}\{F''(t)\} = s^2 f(s) - sF(0) - F'(0)$$

$$\mathcal{L}\{F'''(t)\} = s^3 f(s) - s^2 F(0) - sF'(0) - F''(0)$$

$$\mathcal{L}\{F^{(n)}(t)\} = s^n f(s) - s^{n-1} F(0) - s^{n-2} F'(0) - \dots - F^{(n-1)}(0)$$

$$\mathcal{L}\{F^{(n)}(t)\} = s^n f(s) - \sum_{i=n-1}^0 \sum_{j=0}^{n-1} s^i F^{(j)}(0)$$

**Proof:**

Using integration by parts, we have

$$\begin{aligned} \mathcal{L}\{F'(t)\} &= \int_0^{\infty} e^{-st} F'(t) \, dt \\ &= e^{-st} F(t) \Big|_0^{\infty} + s \int_0^{\infty} e^{-st} F(t) \, dt \\ &= -F(0) + s \int_0^{\infty} e^{-st} F(t) \, dt \\ &= sf(s) - F(0) \quad \square \end{aligned}$$

Similarly,

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

Thus using mathematical induction, we get

$$\begin{aligned}
\mathcal{L}\{F^{(n)}(t)\} &= s\mathcal{L}\{F^{(n-1)}(t)\} - F^{(n-1)}(0) \\
&= s[s\mathcal{L}\{F^{(n-2)}(t)\} - F^{(n-2)}(0)] - F^{(n-1)}(0) \\
&= s^2\mathcal{L}\{F^{(n-2)}(t)\} - sF^{(n-2)}(0) - F^{(n-1)}(0) \\
&= s^2[s\mathcal{L}\{F^{(n-3)}(t)\} - F^{(n-3)}(0)] - sF^{(n-2)}(0) - F^{(n-1)}(0) \\
&= s^3\mathcal{L}\{F^{(n-3)}(t)\} - s^2F^{(n-3)}(0) - sF^{(n-2)}(0) - F^{(n-1)}(0) \\
&= \dots \\
&= s^n\mathcal{L}\{F(t)\} - s^{n-1}F(0) - s^{n-2}F'(0) - \dots - F^{(n-1)}(0) \\
&= s^n f(s) - \sum_{i=n-1}^0 \sum_{j=0}^{n-1} s^i F^{(j)}(0) \quad \square
\end{aligned}$$

### 3 Inverse Laplace Transform

#### 3.1 Definition and Existence

**Definition 3.1.1: Inverse Laplace Transform**

If the Laplace Transform of a function  $F(t)$  is  $f(s)$ , i.e

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

then the Inverse Laplace Transform is defined as

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

#### 3.2 Some Functions and their Inverse Laplace Transforms

$f(s)$	$\mathcal{L}^{-1}\{f(s)\} = F(t)$	$f(s)$	$\mathcal{L}^{-1}\{f(s)\} = F(t)$
1	$\delta(t)$	$\frac{n}{s}$	$n$
$\frac{1}{s^2}$	$t$	$\frac{1}{s^n}$	$\frac{t^{n-1}}{(n-1)!}$
$\frac{1}{s-a}$	$e^{at}$	$\frac{1}{s+a}$	$e^{-at}$
$\frac{1}{s^2+a^2}$	$\frac{\sin at}{a}$	$\frac{1}{s^2-a^2}$	$\frac{\sinh at}{a}$
$\frac{s}{s^2+a^2}$	$\cos at$	$\frac{s}{s^2-a^2}$	$\cosh at$

Table 2: Functions and their Inverse Laplace Transform

**Note:-**

#### The Unit Impulse Function or Dirac Delta Function :

Consider the function

$$F_{\epsilon}(t) = \begin{cases} \frac{1}{\epsilon} & \text{for } 0 \leq t \leq \epsilon \\ 0 & \text{for } t > \epsilon \end{cases}$$

where  $\epsilon > 0$ . Then

$$\int_0^{\infty} F_{\epsilon}(t) dt = 1$$

This idea has led some engineers and physicists to think of a limiting function, denoted by  $\delta(t)$ , approached by  $F_{\epsilon}(t)$  as  $\epsilon \rightarrow 0$ . This limiting function they have called the unit impulse function or Dirac delta function.

Some properties of  $\delta(t)$  are

- $\int_0^{\infty} \delta(t) dt = 1$
- $\int_0^{\infty} \delta(t)G(t) dt = G(0)$
- $\int_0^{\infty} \delta(t-a)G(t) dt = G(a)$

Although mathematically speaking such a function does not exist, manipulations or operations using it can be made rigorous.

## 4 Basic Properties of Inverse Laplace Transform

### 4.1 Linearity Property

**Theorem 4.1.1 (Linearity Property):**

If

$$\mathcal{L}^{-1}\{f(s)\} = F(t) \quad \text{and} \quad \mathcal{L}^{-1}\{g(s)\} = G(t)$$

Then,

$$\mathcal{L}^{-1}\{c_1 f(s) + c_2 g(s)\} = c_1 \mathcal{L}^{-1}\{f(s)\} + c_2 \mathcal{L}^{-1}\{g(s)\}$$

**Example 4.1: Evaluate**  $\mathcal{L}^{-1}\left\{\frac{4}{s-2} - \frac{3s}{s^2+16} + \frac{5}{s^2+4}\right\}$

$$\begin{aligned} \mathcal{L}^{-1}\left\{\frac{4}{s-2} - \frac{3s}{s^2+16} + \frac{5}{s^2+4}\right\} &= 4\mathcal{L}^{-1}\left\{\frac{1}{s-2}\right\} - 3\mathcal{L}^{-1}\left\{\frac{s}{s^2+4^2}\right\} + 5\mathcal{L}^{-1}\left\{\frac{1}{s^2+2^2}\right\} \\ &= 4e^{2t} - 3\cos 4t + \frac{5}{2}\sin 2t \end{aligned}$$

### 4.2 First Translation or Shifting Property

**Theorem 4.2.1 (First Translation or Shifting Property):**

If

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

then

$$\mathcal{L}^{-1}\{f(s-a)\} = e^{at}F(t)$$

**Example 4.2: Evaluate**  $\mathcal{L}^{-1}\left\{\frac{6s-4}{s^2-4s+20}\right\}$

$$\begin{aligned} \mathcal{L}^{-1}\left\{\frac{6s-4}{s^2-4s+20}\right\} &= \mathcal{L}^{-1}\left\{\frac{6(s-2)+8}{(s-2)^2+16}\right\} \\ &= 6\mathcal{L}^{-1}\left\{\frac{(s-2)}{(s-2)^2+16}\right\} + 2\mathcal{L}^{-1}\left\{\frac{4}{(s-2)^2+16}\right\} \\ &= 6e^{2t}\cos 4t + 2e^{2t}\sin 4t \end{aligned}$$

### 4.3 Second Translation or Shifting Property

**Theorem 4.3.1 (Second Translation or Shifting Property):**

If

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

then

$$\mathcal{L}^{-1}\{e^{-as}f(s)\} = \begin{cases} F(t-a) & \text{for } t > a \\ 0 & \text{for } t < a \end{cases}$$

**Example 4.3: Evaluate**  $\frac{e^{-5t}}{(s-2)^4}$

Here

$$\begin{aligned} \mathcal{L}^{-1}\left\{\frac{1}{(s-2)^4}\right\} &= e^{2t}\frac{t^3}{3!} = \frac{e^{2t}}{6}t^3 \\ \therefore \mathcal{L}^{-1}\left\{\frac{e^{-5s}}{(s-2)^4}\right\} &= \frac{e^{2(t-5)}}{6}(t-5)^3, \text{ when } t > 5 \\ \mathcal{L}^{-1}\left\{\frac{e^{-5s}}{(s-2)^4}\right\} &= 0, \text{ when } t < 5 \end{aligned}$$

## 4.4 Change of Scale Property

**Theorem 4.4.1 (Change of Scale Property):**

If

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

then

$$\mathcal{L}^{-1}\{f(ks)\} = \frac{1}{k}F\left(\frac{t}{k}\right)$$

**Example 4.4:** Find  $\mathcal{L}^{-1}\left\{\frac{2s}{(2s)^2 + 16}\right\}$

Since

$$\mathcal{L}^{-1}\left\{\frac{s}{s^2 + 4^2}\right\} = \cos 4t$$

we have

$$\mathcal{L}^{-1}\left\{\frac{2s}{(2s)^2 + 16}\right\} = \frac{1}{2} \cos \frac{4t}{2} = \frac{1}{2} \cos 2t$$

## 4.5 Inverse Laplace Transform of Derivatives

**Theorem 4.5.1 (Inverse Laplace Transform of Derivatives):**

If

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

then

$$\mathcal{L}^{-1}\{f^{(n)}(s)\} = \mathcal{L}^{-1}\left\{\frac{d^n}{ds^n}f(s)\right\} = (-1)^n t^n F(t)$$

**Example 4.5:** Evaluate  $\mathcal{L}^{-1}\left\{\ln\left(1 + \frac{1}{s^2}\right)\right\}$

Here

$$f(s) = \ln\left(1 + \frac{1}{s^2}\right) = \mathcal{L}\{F(t)\}$$

$$\begin{aligned} f'(s) &= \frac{-\frac{2}{s^3}}{1 + \frac{1}{s^2}} \\ &= -2 \left\{ \frac{1}{s(s^2 + 1)} \right\} \\ &= -2 \left( \frac{1}{s} - \frac{s}{s^2 + 1} \right) \end{aligned}$$

$$\mathcal{L}^{-1}\{f'(s)\} = -2(1 - \cos t)$$

$$-tF(t) = -2(1 - \cos t)$$

$$F(t) = \frac{2(1 - \cos t)}{t}$$

$$\therefore \mathcal{L}^{-1}\left\{\ln\left(1 + \frac{1}{s^2}\right)\right\} = \frac{2(1 - \cos t)}{t}$$

## 4.6 Inverse Laplace Transform of Integrals

**Theorem 4.6.1 (Inverse Laplace Transform of Integrals):**

If

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

then

$$\mathcal{L}^{-1}\left\{\int_s^\infty f(u) du\right\} = \frac{F(t)}{t}$$

**Example 4.6: Find**  $\mathcal{L}^{-1}\left\{\int_s^\infty \left(\frac{1}{u} - \frac{1}{u+1}\right) du\right\}$

Let

$$f(s) = \frac{1}{s} - \frac{1}{s+1}$$

$$\begin{aligned}\mathcal{L}^{-1}\{f(s)\} &= \mathcal{L}^{-1}\left\{\frac{1}{s} - \frac{1}{s+1}\right\} \\ &= 1 - e^{-t} = F(t)\end{aligned}$$

$$\begin{aligned}\therefore \mathcal{L}^{-1}\left\{\int_s^\infty f(u) du\right\} &= \frac{F(t)}{t} \\ &= \frac{1 - e^{-t}}{t}\end{aligned}$$

## 4.7 Division by s

**Theorem 4.7.1 (Division by s):**

If

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

then

$$\mathcal{L}^{-1}\left\{\frac{f(s)}{s}\right\} = \int_0^t F(u) du$$

**Example 4.7: Evaluate**  $\mathcal{L}^{-1}\left\{\frac{1}{s^3(s^2+1)}\right\}$

Let

$$f(s) = \frac{1}{s^2+1}$$

$$\begin{aligned}\therefore \mathcal{L}^{-1}\{f(s)\} &= \sin t \\ \therefore \mathcal{L}^{-1}\left\{\frac{1}{s(s^2+1)}\right\} &= \int_0^t \sin u du &= 1 - \cos t \\ \therefore \mathcal{L}^{-1}\left\{\frac{1}{s^2(s^2+1)}\right\} &= \int_0^t (1 - \cos u) du &= t - \sin t \\ \therefore \mathcal{L}^{-1}\left\{\frac{1}{s^3(s^2+1)}\right\} &= \int_0^t (u - \sin u) du &= \frac{t^2}{2} + \cos t - 1\end{aligned}$$

**Alternative approach:**

Let

$$f(s) = \frac{1}{s^4 + s^2} = \frac{1}{s^2} - \frac{1}{s^2 + 1}$$



$$\begin{aligned}
\mathcal{L}^{-1}\left\{\frac{1}{s^2(s^2+1)}\right\} &= \mathcal{L}^{-1}\left\{\frac{1}{s^2} - \frac{1}{s^2+1}\right\} \\
&= t - \sin t \\
&= F(t) \\
\therefore \mathcal{L}^{-1}\left\{\frac{1}{s^3(s^2+1)}\right\} &= \int_0^t F(u) du \\
&= \int_0^t (u - \sin u) du \\
&= \frac{t^2}{2} + \cos t - 1
\end{aligned}$$

## 4.8 Multiplication by $s^n$

**Theorem 4.8.1 (Multiplication by  $s^n$ ):**

If

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

then

$$\mathcal{L}^{-1}\{sf(s)\} = F'(t) + F(0)\delta(t)$$

**Example 4.8: Find**  $\mathcal{L}^{-1}\left\{\frac{s}{s^2+1}\right\}$

Since

$$\mathcal{L}^{-1}\left\{\frac{1}{s^2+1}\right\} = \sin t \quad \text{and} \quad \sin 0 = 0$$

then

$$\mathcal{L}^{-1}\left\{\frac{s}{s^2+1}\right\} = \frac{d}{dt} \sin t = \cos t$$

## 4.9 The Convolution Theorem

**Theorem 4.9.1 (The Convolution Theorem):**

If

$$\mathcal{L}^{-1}\{f(s)\} = F(t) \quad \text{and} \quad \mathcal{L}^{-1}\{g(s)\} = G(t)$$

then

$$\mathcal{L}^{-1}\{f(s)g(s)\} = \int_0^t F(u)G(t-u) du = F * G$$

$$G * F = \int_0^t G(u)F(t-u) du = F * G$$

**Example 4.9: Find**  $\mathcal{L}^{-1}\left\{\frac{1}{s^2(s^2+1)^2}\right\}$

Here,

$$\mathcal{L}^{-1}\left\{\frac{1}{s^2}\right\} = t = F(t)$$

$$\mathcal{L}^{-1}\left\{\frac{1}{(s+1)^2}\right\} = e^{-t}t = G(t)$$

$$\begin{aligned}
\therefore \mathcal{L}^{-1} \left\{ \frac{1}{s^2(s+1)^2} \right\} &= G * F \\
&= \int_0^t u e^{-u} (t-u) \, du \\
&= \int_0^t (ut - u^2) e^{-u} \, du \\
&= -(ut - u^2) \cdot e^{-u} \Big|_0^t + \int_0^t (t - 2u) e^{-u} \, du
\end{aligned}$$

**Example 4.10:** Find  $\mathcal{L}^{-1} \left\{ \frac{s}{(s^2 + a^2)^2} \right\}$

Let

$$\begin{aligned}
f(s) &= \frac{s}{s^2 + a^2} & \text{and} & & g(s) &= \frac{1}{s^2 + a^2} \\
\mathcal{L}^{-1}\{f(s)\} &= \cos at & \text{and} & & \mathcal{L}^{-1}\{g(s)\} &= \frac{\sin at}{a}
\end{aligned}$$

$$\begin{aligned}
F * G &= \frac{1}{a} \int_0^t \cos au \cdot \sin au (t-u) \, du \\
&= \frac{1}{a} \int_0^t \cos au (\sin at \cos au - \cos at \sin au) \, du \\
&= \frac{1}{a} \int_0^t \sin at \cos^2 au \, du - \frac{1}{a} \int_0^t \sin au \cos au \, du \\
&= \frac{1}{2a} \sin at \int_0^t (\cos 2au + 1) \, du - \frac{1}{2a} \cos at \int_0^t \sin 2au \, du \\
&= \frac{1}{2a} \left[ -\frac{1}{2} \sin 2au + u \right]_0^t - \frac{1}{2a} \left[ \frac{1}{2} \cos 2au \right]_0^t \\
&= -\frac{1}{2a} \sin at \cdot \sin 2at - \frac{1}{2a} \cos at \cdot \frac{1}{2} (\cos 2at - 1) + \frac{1}{2a} \sin at \cdot t \\
&= \frac{1}{4a} [\cos at - \cos (at - 2at)] + \frac{t \sin at}{2a} \\
&= \frac{1}{4a} [\cos at - \cos at] + \frac{t \sin at}{2a} \\
&= \frac{t \sin at}{2a}
\end{aligned}$$

## 4.10 Methods of Finding Inverse Laplace Transforms

### 4.10.1 Partial Fractions Method

**Theorem 4.10.1 (Partial Fractions Method):**

Any rational function  $\frac{P(s)}{Q(s)}$  where  $P(s)$  and  $Q(s)$  are polynomials, with degree of  $P(s)$  less than that of  $Q(s)$ , can be written as the sum of rational functions (partial fractions) having the form

$$\frac{A}{(as + b)^r} \quad \text{or} \quad \frac{As + B}{(as^2 + bs + c)^r}$$

where  $r \in \mathbb{N}$  and  $A, B, a, b, c \in \mathbb{R}$ .

By finding the inverse Laplace transform of each of the partial fractions, we can find

$$\mathcal{L}^{-1} \left\{ \frac{P(s)}{Q(s)} \right\}$$

**Example 4.11:** Find  $\mathcal{L}^{-1} \left\{ \frac{5^2 - 15s - 11}{(s+1)(s-2)^2} \right\}$

$$\frac{5^2 - 15s - 11}{(s+1)(s-2)^2} = \frac{-\frac{1}{3}}{s+1} - \frac{7}{(s-2)^3} + \frac{4}{(s-2)^2} + \frac{\frac{1}{3}}{s-2}$$

$$\therefore \mathcal{L}^{-1} \left\{ \frac{5^2 - 15s - 11}{(s+1)(s-2)^2} \right\} = -\frac{1}{e}e^{-t} - 7\frac{t^2}{2}e^{2t} + 4te^{2t} + \frac{1}{3}e^{2t}$$

#### 4.10.2 Series Method

**Theorem 4.10.2 (Series Method):**

If  $f(s)$  has a series expansion in inverse powers of  $s$  given by

$$f(s) = \frac{a_0}{s} + \frac{a_1}{s^2} + \frac{a_2}{s^3} + \cdots = \sum_{n=0}^{\infty} a_n s^{-n}$$

then under suitable conditions we can invert them by term to obtain

$$F(t) = a_0 + a_1 t + a_2 \frac{t^2}{2!} + a_3 \frac{t^3}{3!} + \cdots = \sum_{n=0}^{\infty} a_n \frac{t^n}{n!}$$