Integrating factors

$$y' + P(x)y = Q(x)$$
$$I(x) = \exp\left(\int P(x)dx\right)$$
$$y(x) = \frac{1}{I(x)}\int Q(x)I(x)dx + \frac{\alpha}{I(x)}$$

Change of variables

$$y^{(n)} = F(y, y', \ldots, y^{(n-1)}, t)$$

Let $x_{i+1} = y^{(i)}$ where $i \in \{0, 1, \ldots, n-1\}$.

Picard-Lindelöf statement

Consider IVP: $x_i' = F_i(t, x_1, \ldots, x_n)$ or that $\boldsymbol{x}' = \boldsymbol{F}(t, \boldsymbol{x})$ with $\boldsymbol{x}(t_0) = \boldsymbol{x}_0$ and $\boldsymbol{x}$ is a vector with n entries.

It has **unique** solutions if:

$$F_i,\ \frac{\partial F_i}{\partial x_j} \text{ and } \frac{\partial F_i}{\partial t} \text{ are } \underline{\text{continuous}} \text{ in}$$

$R \subset \mathbb{R}^{n+1}$ where $(t, \boldsymbol{x}_0^T) \in R$.
Here $i, j \in \{1, \ldots, n\}$.

Homogeneous systems

Consider $\boldsymbol{x}' = \mathbf{A}\boldsymbol{x}$ where $\mathbf{A}$ is a $n \times n$ matrix. Substituting $\boldsymbol{x} = e^{rt}\boldsymbol{\xi}$ gives:

$$(\mathbf{A} - r_i\mathbf{I_n})\boldsymbol{\xi^{(i)}} = \mathbf{0}$$

where $i \in \{1, 2, \ldots, n\}$.
Our general solution is then:

$$\begin{aligned}\boldsymbol{x}(t) &= \sum_{i=1}^{n} c_i e^{r_i t}\boldsymbol{\xi}^{(i)} \\ &= \sum_{i=1}^{n} c_i \boldsymbol{x}^{(i)} \\ &= \boldsymbol{\Psi}(t)\boldsymbol{c}.\end{aligned}$$

If initial conditions $\boldsymbol{x}(t_0) = \boldsymbol{x}_0$ are given:

$$\boldsymbol{c} = \boldsymbol{\Psi}^{-1}(t_0)\boldsymbol{x}(t_0)$$
$$\boldsymbol{x}(t) = \boldsymbol{\Psi}(t)\boldsymbol{\Psi}^{-1}(t_0)\boldsymbol{x}_0.$$

Matrix exponentials

Given a $n \times n$ matrix $\boldsymbol{A}$:

$$\begin{aligned}e^{\boldsymbol{A}t} &= \sum_{n=0}^{\infty} \frac{(\boldsymbol{A}t)^n}{n!} \\ &= \boldsymbol{I}_n + \boldsymbol{A}t + \frac{1}{2!}\boldsymbol{A}^2t^2 + \ldots.\end{aligned}$$

For system $\boldsymbol{x}' = \boldsymbol{A}\boldsymbol{x}$:

$$\boldsymbol{x}(t) = e^{\boldsymbol{A}t}\boldsymbol{x}(0)$$

and that $e^{\boldsymbol{A}t} = \boldsymbol{\Psi}(t)\boldsymbol{\Psi}^{-1}(0)$.

Diagonalisation

For $\boldsymbol{x}' = \boldsymbol{A}\boldsymbol{x}$ we have $\boldsymbol{A} = \boldsymbol{T}\boldsymbol{D}\boldsymbol{T}^{-1}$.
If $\boldsymbol{x} = \boldsymbol{T}\boldsymbol{y}$ then $\boldsymbol{y}' = \boldsymbol{D}\boldsymbol{y}$.

Since our fundamental matrix with respect to $\boldsymbol{y}$ is a <u>diagonal</u> matrix $\boldsymbol{Q} = e^{\boldsymbol{D}t}$, the fundamental matrix with respect to $\boldsymbol{x}$ is $\boldsymbol{\Psi}(t) = \boldsymbol{T}e^{\boldsymbol{D}t}$ and:

$$e^{\boldsymbol{A}t} = \boldsymbol{T}e^{\boldsymbol{D}t}\boldsymbol{T}^{-1}.$$

Generalised eigenvectors

If eigenvalues do not generate enough eigenvectors to form n linearly independent solutions for a $n \times n$ matrix $\boldsymbol{A}$, then consider the following ansatz:

$$\boldsymbol{x} = te^{rt}\boldsymbol{\xi} + e^{rt}\boldsymbol{\eta}.$$
$$\therefore (\mathbf{A} - r_i\mathbf{I_n})\boldsymbol{\eta^{(i)}} = \boldsymbol{\xi^{(i)}}$$

Then this r_i produces <u>two</u> solutions:

$$\boldsymbol{x}^{(1)} = e^{rt}\boldsymbol{\xi}$$
$$\boldsymbol{x}^{(2)} = te^{rt}\boldsymbol{\xi} + e^{rt}\boldsymbol{\eta}.$$

Non-homogeneous systems

Consider non-homogeneous ODE system:

$$\boldsymbol{x}' = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{g}.$$

- **Change of basis**

  Let $\boldsymbol{x} = \boldsymbol{T}\boldsymbol{y}$ and since $\boldsymbol{A} = \boldsymbol{T}\boldsymbol{D}\boldsymbol{T}^{-1}$:

  $$\boldsymbol{y}' = \boldsymbol{D}\boldsymbol{y} + \boldsymbol{T}^{-1}\boldsymbol{g}$$

  which is solved by integrating factors. Finally <u>revert back</u> to $\boldsymbol{x}$.

- **Variation of parameters**

  Find solution $\boldsymbol{x}_H = \boldsymbol{\Psi}\boldsymbol{c}$ to $\boldsymbol{x}' = \boldsymbol{A}\boldsymbol{x}$. Then let the non-homogeneous solution be $\boldsymbol{x} = \boldsymbol{\Psi}\boldsymbol{u}(t)$.

  $$\therefore \boldsymbol{\Psi}\boldsymbol{u}'(t) = \boldsymbol{g}(t)$$

  Row reduce before integrating.

- **Undetermined coefficients**

  Let non-homogeneous ODE system have solutions of form:

  $$\boldsymbol{x} = \boldsymbol{x}_H + \boldsymbol{x}_p$$

  where $\boldsymbol{x}_H$ is our homogeneous solution and $\boldsymbol{x}_p$ our <u>particular</u> solution.

Critical points

Consider non-linear ODE system

$$x' = F(x, y),$$
$$y' = G(x, y).$$

We define $\boldsymbol{x^0} = \begin{bmatrix} x^0 \\ y^0 \end{bmatrix}$ as a **critical point** when $F(\boldsymbol{x^0}) = G(\boldsymbol{x^0}) = 0$.

Linearisation and stability

Let $\boldsymbol{u} = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} = \begin{bmatrix} x - x^0 \\ y - y^0 \end{bmatrix}$.

$$\begin{aligned}\therefore u_1' &\approx F(x^0, y^0) + \left(\frac{\partial F}{\partial x}\right)_{x^0}(x - x^0) \\ &\quad + \left(\frac{\partial F}{\partial y}\right)_{y^0}(y - y^0) \\ \therefore u_2 &\approx G(x^0, y^0) + \left(\frac{\partial G}{\partial x}\right)_{x^0}(x - x^0) \\ &\quad + \left(\frac{\partial G}{\partial y}\right)_{y^0}(y - y^0) \\ \therefore \boldsymbol{u}' &= \boldsymbol{A}\boldsymbol{u} \\ &= \begin{bmatrix} \partial F/\partial x & \partial F/\partial y \\ \partial G/\partial x & \partial G/\partial y \end{bmatrix}_{\boldsymbol{x}=\boldsymbol{x^0}} \begin{bmatrix} x - x^0 \\ y - y^0 \end{bmatrix}\end{aligned}$$

Critical points $\boldsymbol{x^0}$ may also be classified:

Eigenvalues	Critical Points	Stability
$r_1 > r_2 > 0$	Node (source)	unstable
$r_1 < r_2 < 0$	Node (sink)	asymp. stable
$r_2 < 0 < r_1$	saddle	unstable
$r_1 = r_2 > 0$	Proper/Improper node	unstable
$r_1 = r_2 < 0$	Proper/Improper node	asymp. stable
$r_1, r_2 = \lambda \pm i\mu$ $(\lambda > 0)$	focus	unstable
$r_1, r_2 = \lambda \pm i\mu$ $(\lambda < 0)$	focus	asymp. stable
$r_1 = i\mu, r_2 = -i\mu$	center	stable

Linearisation preserves critical point behaviour **except** when eigenvalues are of $r = \pm i\mu$ form, for which then classification is unknown.

Stable critical points $\boldsymbol{x^0}$:
All solutions <u>start</u> and <u>stay near</u> $\boldsymbol{x^0}$.

$$\forall\epsilon > 0; \exists\delta > 0; \forall\boldsymbol{x}(t) = \boldsymbol{\phi}(t) : |\boldsymbol{x}(0) - \boldsymbol{x^0}| < \delta$$
$$\implies |\boldsymbol{x}(t) - \boldsymbol{x^0}| < \epsilon \text{ for } \forall t \geq 0$$

Attracting critical points $\boldsymbol{x^0}$:
All solutions <u>tends</u> to $\boldsymbol{x^0}$.

$$\forall\delta > 0 : |\boldsymbol{x}(0) - \boldsymbol{x^0}| < \delta$$
$$\implies \lim_{t\to\infty} \boldsymbol{x}(t) = \boldsymbol{x^0}$$

Asymptotically stable critical points $\boldsymbol{x^0}$: Attracting **and** stable.

Lyapunov's theory and limit cycles

Consider $\dot{x} = F(x, y)$ and $\dot{y} = G(x, y)$ and let $\boldsymbol{x^0} \in D$ be a critical point. Let $E : D \subset \mathbb{R}^2 \to \mathbb{R}$ is defined such that $E(x^0, y^0) = 0$.

$$\therefore \frac{\mathrm{d}E}{\mathrm{d}t} = \frac{\partial E}{\partial x}F + \frac{\partial E}{\partial y}G$$

- Let $E > 0$ for $\forall\boldsymbol{x} \neq \boldsymbol{x^0}$.

  If $\frac{\mathrm{d}E}{\mathrm{d}t} \leq 0$ then $\boldsymbol{x^0}$ is stable.

  If $\frac{\mathrm{d}E}{\mathrm{d}t} < 0$ then $\boldsymbol{x^0}$ is asymptotically stable.

- $E(\boldsymbol{x}^*) > 0$ and $\frac{\mathrm{d}E}{\mathrm{d}t} > 0$

  $\implies$ unstable $\boldsymbol{x^0}$. (flip both signs)

Postive definite: $E(\boldsymbol{x}) > 0$ for $\forall \boldsymbol{x} \neq \boldsymbol{x^0}$

Postive semidefinite:
$E(\boldsymbol{x}) \geq 0$ for $\forall \boldsymbol{x} \neq \boldsymbol{x^0}$

Limit cycles are periodic solutions such that at least one other non-closed trajectory approaches it as $t \to \infty$.

Generally if our trajectory is enclosed by finite non-simple region and F, G have continuous partials then there is a limit cycle.

Real Fourier series

The Fourier expansion of piecewise continuous $f(x)$ on $[-L, L]$ is:

$$f_{FS}(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} (a_n \cos \frac{n\pi x}{L} + b_n \sin \frac{n\pi x}{L})$$

where $f_{FS}(x) = f_{FS}(x + \boldsymbol{2L})$. If α is a discontinuous point:

$$f_{FS}(\alpha) = \frac{f(\alpha^+) + f(\alpha^-)}{2}$$

for α^+ is the limit from the left.

Our Fourier coefficients are:

$$a_0 = \frac{1}{L} \int_{-L}^{L} f(x) \mathrm{d}x$$

$$a_n = \frac{1}{L} \int_{-L}^{L} \cos \frac{n\pi x}{L} f(x) \mathrm{d}x$$

$$b_n = \frac{1}{L} \int_{-L}^{L} \sin \frac{n\pi x}{L} f(x) \mathrm{d}x.$$

Orthogonality

Let $S_n = \sin \frac{n\pi x}{L}$ and $C_n = \cos \frac{n\pi x}{L}$.

$$\langle S_n, S_m \rangle = \langle C_n, C_m \rangle = L\delta_{mn}$$

$$\langle S_n, C_m \rangle = 0.$$

Where:

$$\delta_{mn} = \begin{cases} 1 & m = n \\ 0 & m \neq n \end{cases}$$

$$\langle u(x), v(x) \rangle = \int_{-L}^{L} u(x)v(x) \mathrm{d}x$$

$$\cos A \cos B = \frac{1}{2}[\cos(A - B) + \cos(A + B)]$$

$$\sin A \sin B = \frac{1}{2}[\cos(A - B) - \cos(A + B)]$$

$$\sin A \cos B = \frac{1}{2}[\sin(A + B) + \sin(A - B)].$$

Even functions: $f(-x) = f(x)$

$$\therefore \int_{-L}^{L} f(x) \mathrm{d}x = 2 \int_{0}^{L} f(x) \mathrm{d}x$$

Odd functions: $f(-x) = -f(x)$

$$\therefore \int_{-L}^{L} f(x) \mathrm{d}x = 0$$

- **Even** function $f(x)$ on $[-L, L]$:

$$f_{FS}(x) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n \cos \frac{n\pi x}{L}$$

$$a_n = \frac{2}{L} \int_{0}^{L} \cos \frac{n\pi x}{L} f(x) \mathrm{d}x$$

- **Odd** function $f(x)$ on $[-L, L]$:

$$f_{FS}(x) = \sum_{n=1}^{\infty} b_n \sin \frac{n\pi x}{L}$$

$$b_n = \frac{2}{L} \int_{0}^{L} \sin \frac{n\pi x}{L} f(x) \mathrm{d}x$$

Extensions

Consider $f(x)$ defined in $[0, L]$ originally.

1. Define even function:

$$g(x) = \begin{cases} f(x) & x \in [0, L] \\ f(-x) & x \in (-L, 0) \end{cases}$$

with cosine series.

2. Define odd function:

$$h(x) = \begin{cases} f(x) & x \in (0, L) \\ 0 & x = 0, L \\ -f(-x) & x \in (-L, 0) \end{cases}$$

with sine series.

Complex Fourier series

Similarly:

$$f_{FS}(x) = \sum_{n=-\infty}^{\infty} c_n \exp\left(\frac{in\pi}{L} x\right)$$

$$e^{i\theta} = \sin\theta + i\cos\theta.$$

Then $\forall n \in \mathbb{Z}$ we have that:

$$c_n = \frac{1}{2L} \int_{-L}^{L} \exp\left(-\frac{in\pi}{L} x\right) f(x) \mathrm{d}x$$

$$c_n = \begin{cases} (a_n - ib_n)/2 & n > 0 \\ (a_0)/2 & n = 0 \\ (a_n + ib_n)/2 & n < 0. \end{cases}$$

The **inner product** is defined as:

$$\langle f, g \rangle = \int_{-L}^{L} f(x)g^*(x) \mathrm{d}x.$$

$$\therefore \langle \exp\left(\frac{\boldsymbol{i}\boldsymbol{m}\pi}{L} x\right), \exp\left(\frac{\boldsymbol{i}\boldsymbol{n}\pi}{L} x\right) \rangle = 2L\delta_{mn}$$

Parseval's theorem

$$\langle f, f \rangle = \int_{-L}^{L} |f(x)|^2 \mathrm{d}x$$

$$= 2L \sum_{n=-\infty}^{\infty} |c_n|^2$$

$$= L\left[\frac{|a_0|^2}{2} + \sum_{n=1}^{\infty} (|a_n|^2 + |b_n|^2)\right]$$

Heat equation

$$\frac{\partial u}{\partial t} = \alpha^2 \frac{\partial^2 u}{\partial x^2}$$

Let $u(x, t) = X(x)T(t)$.

$$\frac{1}{\alpha^2} \frac{\dot{T}}{T} = \frac{X''}{X} = -\lambda$$

$$X'' + \lambda X = 0$$

$$\dot{T} + \alpha^2 \lambda T = 0$$

$$\lambda = \mu^2; X(x) = b_1 \cos \lambda^{1/2} x + b_2 \sin \lambda^{1/2} x$$

$$\lambda = -\mu^2; X(x) = b_1 \cosh \mu x + b_2 \sinh \mu x$$

$$T(t) = a_1 \exp\left(-\alpha^2 \lambda t\right)$$

Standard boundary conditions

- $u(x, 0) = f(x)$ for $0 \leq x \leq L$
- $u(0, t) = u(L, t) = 0$ for $\forall t > 0$

$$X(0) = X(L) = 0$$

$$\therefore X_n = b_2 \sin \lambda_n^{1/2} x$$

$$\therefore \lambda_n = \left(\frac{n\pi}{L}\right)^2 \text{ for } \forall n \in \mathbb{N}$$

Our general solution must then be:

$$u(x, t) = \sum_{n=1}^{\infty} c_n \exp\left(-\alpha^2 \lambda_n t\right) \sin \lambda_n^{1/2} x$$

$$c_n = \frac{2}{L} \int_{0}^{L} \sin\left(\lambda_n^{1/2} x\right) f(x) \mathrm{d}x.$$

Fixed boundary temperatures

- $u(0, t) = T_1$
- $u(L, t) = T_2$
- $u(x, 0) = f(x)$

$$v(x) = \lim_{t \to \infty} u(x, t)$$

Since $v'' = 0$, $v(0) = T_1$ and $v(L) = T_2$:

$$v(x) = \frac{T_2 - T_1}{L} x + T_1.$$

We then deduce that:

$$u(x, t) = v(x) + \omega(x, t)$$

where $\omega(x, t)$ satisfies conditions:

- $\omega(0, t) = \omega(L, t) = 0$
- $\omega(x, 0) = f(x) - v(x)$

$$\therefore \omega(x, t) = \sum_{n=1}^{\infty} c_n \exp\left(-\alpha^2 \lambda_n t\right) \sin \lambda_n^{1/2} x$$

For $\lambda_n = \left(\frac{n\pi}{L}\right)^2$ and

$$c_n = \frac{2}{L} \int_{0}^{L} \sin\left(\lambda_n^{1/2} x\right) \left(f(x) - v(x)\right) \mathrm{d}x.$$

Insulated rod ends

- $\frac{\partial}{\partial x}u(0,t) = \frac{\partial}{\partial x}u(L,t) = 0$
- $u(x,0) = f(x)$

$$X'(0) = X'(L) = 0$$

$$u(x,t) = \sum_{n=1}^{\infty} c_n \exp\bigl(-\alpha^2\lambda_n t\bigr)\cos\lambda_n^{1/2}x$$

$$c_n = \frac{2}{L}\int_0^L \cos\Bigl(\lambda_n^{1/2}x\Bigr)f(x)\mathrm{d}x$$

$$\lambda_n = \Bigl(\frac{n\pi}{L}\Bigr)^2$$

Wave equation

$$\frac{\partial^2 u}{\partial t^2} = c^2\frac{\partial^2 u}{\partial x^2}$$

Let $u(x,t) = X(x)T(t)$.

$$\frac{X''}{X} = \frac{\ddot{T}}{c^2T} = -\lambda$$

$$X'' + \lambda X = 0$$

$$\ddot{T} + c^2\lambda T = 0$$

Plucked string

- $u(0,t) = u(L,t) = 0$
- $\frac{\partial}{\partial t}u(x,0) = 0$
- $u(x,0) = f(x)$

$$X(0) = X(L) = 0 \text{ and } \dot{T}(0) = 0$$

$$u(x,t) = \sum_{n=1}^{\infty} c_n \sin\lambda_n^{1/2}x\cos c\lambda_n^{1/2}t$$

$$c_n = \frac{2}{L}\int_0^L \sin\Bigl(\lambda_n^{1/2}x\Bigr)f(x)\mathrm{d}x$$

$$\lambda_n = \Bigl(\frac{n\pi}{L}\Bigr)^2$$

General initial conditions

- $u(0,t) = u(L,t) = 0$
- $\frac{\partial}{\partial t}u(x,0) = g(x)$
- $u(x,0) = f(x)$

$$u(x,t) = \sum_{n=1}^{\infty} \sin\lambda_n^{1/2}x \times \Bigl(a_n\cos c\lambda_n^{1/2}t + b_n\sin c\lambda_n^{1/2}t\Bigr)$$

$$a_n = \frac{2}{L}\int_0^L \sin\Bigl(\lambda_n^{1/2}x\Bigr)f(x)\mathrm{d}x$$

$$b_n = \frac{1}{c\lambda_n^{1/2}}\frac{2}{L}\int_0^L \sin\Bigl(\lambda_n^{1/2}x\Bigr)g(x)\mathrm{d}x$$

$$\lambda_n = \Bigl(\frac{n\pi}{L}\Bigr)^2$$

Laplace's equation

$$\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = 0$$

Let $u(x,y) = X(x)Y(y)$.

$$\frac{X''}{X} = -\frac{Y''}{Y} = \lambda$$

$$X'' - \lambda X = 0$$

$$Y'' + \lambda Y = 0$$

Rectangular boundary conditions

- $u(x,0) = u(x,b) = 0$
- $u(0,y) = 0$ and $u(a,y) = f(y)$

Here $x \in [0,a]$ and $y \in [0,b]$.

$$X(0) = 0 \text{ and } Y(0) = Y(b) = 0$$

$$\therefore Y_n = a_1\sin\Bigl(\lambda_n^{1/2}y\Bigr) \text{ for } \lambda_n = \frac{n^2\pi^2}{b^2}$$

$$\therefore X_n = a_3\sinh\Bigl(\lambda_n^{1/2}x\Bigr)$$

$$u(x,y) = \sum_{n=1}^{\infty} c_n\sinh\Bigl(\lambda_n^{1/2}x\Bigr)\sin\Bigl(\lambda_n^{1/2}y\Bigr)$$

$$c_n = \frac{2}{b\sinh\Bigl(\lambda_n^{1/2}a\Bigr)}\int_0^b \sin\Bigl(\lambda_n^{1/2}y\Bigr)f(y)dy$$

Circular boundary conditions

- $u(a,\theta) = f(\theta)$
- $u(r,\theta)$ is bounded

Here $r \in [0,a]$ and $\theta \in [0,2\pi]$.

$$\frac{\partial^2 u}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 u}{\partial\theta^2} + \frac{1}{r}\frac{\partial u}{\partial r} = 0.$$

Let $u(r,\theta) = R(r)\Theta(\theta)$.

$$\therefore r^2\frac{R''}{R} + r\frac{R'}{R} = -\frac{\ddot{\Theta}}{\Theta} = \lambda$$

$$\therefore \ddot{\Theta} + \lambda\Theta = 0$$

$$\therefore r^2R'' + rR' = \lambda R$$

For the first ODE if $\lambda \le 0$ then we get at best constant solutions. If $\lambda > 0$:

$$\Theta(\theta) = a_1\cos\lambda^{1/2}\theta + a_2\sin\lambda^{1/2}\theta$$

and since <u>periodicity</u> must be preserved:

$$\Theta(\theta) = \Theta(\theta + 2\pi)$$

$$\therefore \lambda_n^{1/2} = n \text{ or } \lambda_n^{1/2} = 0$$

where $n \in \mathbb{N}$. So when $\lambda_n = 0$:

$$r^2R'' + rR' = 0$$

and since $u(r,\theta)$ is bounded we get only constant solutions. If $\lambda_n = n^2$ then:

$$r^2R'' + rR' - n^2R = 0$$

with solutions of form $R(r) = r^\alpha$ which yields $R_n(r) = c_nr^n$. Then:

$$u(r,\theta) = \frac{p_0}{2} + \sum_{n=1}^{\infty} r^n\Bigl(q_n\cos\lambda_n^{1/2}\theta + r_n\sin\lambda_n^{1/2}\theta\Bigr)$$

$$p_0 = \frac{1}{\pi}\int_{-\pi}^{\pi} f(\theta)\mathrm{d}\theta$$

$$q_n = \frac{1}{a^n\pi}\int_{-\pi}^{\pi}\cos\Bigl(\lambda_n^{1/2}\theta\Bigr)f(\theta)\mathrm{d}\theta$$

$$r_n = \frac{1}{a^n\pi}\int_{-\pi}^{\pi}\sin\Bigl(\lambda_n^{1/2}\theta\Bigr)f(\theta)\mathrm{d}\theta.$$

Regular S-L problems

A regular S-L problem defined on $[0,1]$ is:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left(p(x)\frac{\mathrm{d}y}{\mathrm{d}x}\right) + q(x)y = \lambda r(x)y$$

- $a_1y(0) + a_2y'(0) = 0$
- $b_1y(1) + b_2y'(1) = 0$
- $p(x)$, $p'(x)$, $q(x)$, $r(x)$ are <u>continuous</u>
- $p(x)$, $r(x)$ are <u>strictly positive</u>

which yields **real** eigenvalues λ_n and **orthonormal** eigenfunctions $\phi_n(x)$:

$$\langle\phi_m,\phi_n\rangle = \int_0^1 r(x)\phi_m(x)\phi_n(x)\mathrm{d}x = \delta_{mn}$$

in Hilbert space $L^2([0,1], r(x)\mathrm{d}x)$.

Let $\phi_n(x) = k_ny_n(x)$.

$$\therefore k_n = \frac{1}{\sqrt{\langle y_n, y_n\rangle}} = \Bigl(\int_0^1 r(x)y_n^2(x)\mathrm{d}x\Bigr)^{-1/2}$$

General 2nd order ODEs

$$-p(x)\frac{\mathrm{d}^2y}{\mathrm{d}x^2} - \omega(x)\frac{\mathrm{d}y}{\mathrm{d}x} + q(x)y = \lambda r(x)y$$

$$F(x) = \exp\Bigl[\int_0^x \frac{\omega(s) - p'(s)}{p(s)}\mathrm{d}s\Bigr]$$

$$-\frac{\mathrm{d}}{\mathrm{d}x}\Bigl[F(x)p(x)\frac{\mathrm{d}y}{\mathrm{d}x}\Bigr] + F(x)q(x)y = \lambda F(x)r(x)y$$

Lagrange's identity

Let functions u and v satisfy regular S-L boundary conditions. Then:

$$\langle \mathcal{L}[u], v\rangle = \langle u, \mathcal{L}[v]\rangle$$

where:

$$\langle u, v\rangle = \int_0^1 uv^* \mathrm{d}x$$

$$\mathcal{L}[u] = -\frac{\mathrm{d}}{\mathrm{d}x}\Big[p(x)\frac{\mathrm{d}u}{\mathrm{d}x}\Big] + q(x)u.$$

$$\begin{aligned}
&\therefore \langle \mathcal{L}[u], v\rangle - \langle u, \mathcal{L}[v]\rangle \\
&= -\Big[p\Big(u'v^* - u(v^*)'\Big)\Big]_0^1 \\
&= -\Big[p(x)(\frac{\mathrm{d}u}{\mathrm{d}x}\cdot v^* - u\cdot\frac{\mathrm{d}v^*}{\mathrm{d}x})\Big]_0^1
\end{aligned}$$

$$\big[pu'v^*\big]' = \big(pu'\big)'v^* + pu'(v^*)'$$

$$\big[pu(v^*)'\big]' = \Big(p(v^*)'\Big)'u + pu'(v^*)'$$

S-L series expansion

The set of orthonormal eigenfunctions $\{\phi_n(x)\}$ from a S-L problem defined on $[0,1]$ may be used to expand function $f(x)$:

$$f_\phi(x) = \sum_{n=1}^\infty c_n\phi_n(x)$$

$$c_n = \int_0^1 r(x)\phi_n(x)f(x)\mathrm{d}x.$$

in $L^2([0,1], r(x)\mathrm{d}x)$. We also have the general Pareseval's identity:

$$\int_0^1 r(x)\big[f(x)\big]^2\mathrm{d}x = \sum_{n=1}^\infty c_n^2.$$

Non-homogeneous S-L problems

$$\mathcal{L}[y] = \mu r(x)y + f(x)$$

$$\mathcal{L}[y] = -\frac{\mathrm{d}}{\mathrm{d}x}\Big[P(x)\frac{\mathrm{d}y}{\mathrm{d}x}\Big] + q(x)y$$

Firstly solve corresponding homogeneous problem:

$$\mathcal{L}[y] = \lambda r(x)y$$

for non-trivial λ_n and $\phi_n(x)$.

Then the general solution is:

$$y(x) = \sum_{n=1}^\infty b_n\phi_n(x)$$

$$b_n = \frac{c_n}{\lambda_n - \mu}$$

$$c_n = \int_0^1 \phi_n(x)f(x)\mathrm{d}x.$$

Non-homogeneous PDEs

Consider the following PDE:

$$\begin{aligned}
r(x)\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\Big[p(x)\frac{\partial u}{\partial x}\Big] \\
- q(x)u(x,t) + F(x,t)
\end{aligned}$$

with conditions:

- $\frac{\partial}{\partial x}u(0,t) - h_1u(0,t) = 0$
- $\frac{\partial}{\partial x}u(1,t) - h_2u(1,t) = 0$
- $u(x,0) = f(x)$.

Firstly solve the homogeneous case.
Let $u(x,t) = X(x)T(t)$.

$$\therefore \frac{1}{rX}\Big[p'X' + pX'' - qX\Big] = \frac{\dot{T}}{T} = -\lambda$$

This yields two ODEs:

$$\dot{T} + \lambda T = 0$$

$$-\big[pX'\big]' + qX = \lambda rX$$

with boundary conditions:

$$X'(0) - h_1X(0) = 0$$

$$X'(1) - h_2X(1) = 0$$

Clearly our second ODE is of S-L form. We are now going to <u>assume</u> that this regular S-L problem has <u>non-trivial</u> λ_n and orthonormal eigenfunctions $\phi_n(x)$. Then:

$$u(x,t) = \sum_{n=1}^\infty b_n(t)\phi_n(x).$$

Since we have a S-L problem:

$$\begin{aligned}
\sum_{n=1}^\infty \dot{b_n}(t)\phi_n(x) = \sum_{n=1}^\infty b_n(t)\Big[-\lambda_n\phi_n(x)\Big] \\
+ \frac{F(x,t)}{r(x)}
\end{aligned}$$

$$\frac{F(x,t)}{r(x)} = \sum_{n=1}^\infty \gamma_n(t)\phi_n(x)$$

$$\gamma_n(t) = \int_0^1 F(x,t)\phi_n(x)\mathrm{d}x$$

$$\sum_{n=1}^\infty \Big[\dot{b_n}(t) + \lambda_nb_n(t) - \gamma_n(t)\Big]\phi_n(x) = 0$$

$$b_n(t) = e^{-\lambda_nt}\int_0^t \gamma_n(s)e^{\lambda_ns}\mathrm{d}s + e^{-\lambda_nt}b_n(0)$$

finally using initial conditions:

$$b_n(0) = \int_0^1 r(x)f(x)\phi_n(x)\mathrm{d}x$$

and all this is in $L^2([0,1], r(x)\mathrm{d}x)$.

Singular S-L problems

Consider the following ODE:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left(p(x)\frac{\mathrm{d}y}{\mathrm{d}x}\right) + q(x)y = \lambda r(x)y$$

but now some of $p(x)$, $q(x)$ and $r(x)$ are <u>discontinuous</u> at $x=0$ and/or $x=1$. This is a **singular** S-L problem with boundary condition:

$$b_1y(1) + b_2y'(1) = 0$$

<u>or</u>

$$a_1y(0) + a_2y'(0) = 0.$$

Now singular S-L problems at $x=0$ may be <u>self-adjoint</u> or that they yield:

- $\lambda_n \in \mathbb{R}$ (Real eigenvalues)
- $\langle\phi_m, \phi_n\rangle = \delta_{mn}$ (Orthogonal eigenfunctions)

if they satisfy Lagrange's identity.
Consider singular S-L problem at $x=0$:

$$\begin{aligned}
&\int_\epsilon^1 \Big(\mathcal{L}[u]v - u\mathcal{L}[v]\Big)\mathrm{d}x \\
&= \Big[-p(x)\Big(u'(x)v(x) - u(x)v'(x)\Big)\Big]_\epsilon^1 \\
&= p(\epsilon)\Big(u'(\epsilon)v(\epsilon) - u(\epsilon)v'(\epsilon)\Big)
\end{aligned}$$

and tends to zero if and only if:

$$\lim_{\epsilon\to 0}\Big[p(\epsilon)\Big(u'(\epsilon)v(\epsilon) - u(\epsilon)v'(\epsilon)\Big)\Big] = 0,$$

where we define:

$$\mathcal{L}[u] = -\frac{\mathrm{d}}{\mathrm{d}x}\Big[p(x)\frac{\mathrm{d}u}{\mathrm{d}x}\Big] + q(x)u.$$

Therefore this is the condition for our singular S-L problem to have <u>real</u> eigenvalues and <u>orthogonal eigenfunctions</u>.

Similarly for singular S-L problem at $x=1$ it is self-adjoint if:

$$\begin{aligned}
\lim_{\epsilon\to 0}\Big[p(1-\epsilon)\Big(u'(1-\epsilon)v(1-\epsilon) \\
- u(1-\epsilon)v'(1-\epsilon)\Big)\Big] = 0.
\end{aligned}$$

Finally whilst eigenvalues may be real they are <u>not</u> necessarily discrete!

Laplace transforms

So let $f(t)$ be defined for $t\in[0,\infty)$. Its Laplace transform is:

$$\mathcal{L}[f(t)] = \int_0^\infty e^{-st}f(t)\mathrm{d}t.$$

Let **functions of exponential order** be defined as:

$\forall t\in[0,\infty); \exists A > 0$ and $B\in\mathbb{R} : |f(t)| \le Ae^{Bt}$

where f is piecewise continous and we denote such functions as $f\in E$.

For <u>sufficiently</u> large s, the Laplace transform $f\in E$ converges.

Reduction of order

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

For $\forall f, f' \in E$ and generalising:

$$\mathcal{L}[f^{(n)}(t)] = s^n\mathcal{L}[f(t)] - s^{(n-1)}f^{(0)}(0) - s^{(n-2)}f^{(1)}(0) - \cdots - sf^{(n-2)}(0) - f^{(n-1)}(0).$$

Shifts, scaling and derivatives

Let $F(s) = \mathcal{L}[f(t)](s)$. We then have that:

1. **s-shift**:

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

   where $s + c > \gamma$.

2. **t-shift**:
   Let $c \geq 0$ and $f(t) = 0$ if $t < 0$.

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

   In terms of the unit step function:

   $$\mathcal{L}[g(t-c)u_c(t)](s) = e^{-sc}G(s)$$

   where $G(s) = \mathcal{L}[g(t)](s)$ and $g(t)$ any normal function.

3. **s-derivative**:

   $$\mathcal{L}[tf(t)](s) = -\frac{\mathrm{d}}{\mathrm{d}s}F(s)$$

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

4. **scaling**:

   $$\mathcal{L}[f(ct)] = \frac{1}{c}F(\frac{s}{c})$$

   $$\frac{1}{c}\mathcal{L}[f(\frac{t}{c})] = F(cs)$$

   where $c > 0$.

Higher order ODEs

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

$$Z(s)\mathcal{L}[y(t)] = \mathcal{L}[f(t)] + Z_0(s)$$

Where $Z(s)$ is a degree n polynomial and $Z_0(s)$ a degree $n-1$ polynomial dependent on our initial conditions.

If the source term is of the following form:

$$f(t) = t^n e^{at}\big(A\cos bt + B\sin bt\big)$$

then $\mathcal{L}[f(t)]$ is rational and therefore:

$$\mathcal{L}[y(t)] = \frac{\mathcal{L}[f(t)]}{Z(s)} + \frac{Z_0(s)}{Z(s)}$$

where we can solve this via standard transforms.

Discontinuous source terms

Consider the following ODE:

$$Ay''(t) + By'(t) + Cy(t) = g(t)$$

where $g(t)$ is piecewise continuous:

$$g(t) = f(t)[u_a(t) - u_b(t)] = \begin{cases} f(t) & t \in [a,b) \\ 0 & t \notin [a,b) \end{cases}$$

for $b > a$. This is the **unit step function**:

$$u_c(t) = \begin{cases} 0 & t < 0 \\ 1 & t \geq c. \end{cases}$$

$$\therefore \mathcal{L}[u_c(t)](s) = \frac{e^{-sc}}{s}$$

Furthermore we can define a <u>shift</u> of $f(t)$ by $c > 0$ to the <u>right</u> by:

$$f(t-c)u_c(t)$$

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

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

Impulse functions

The Dirac delta is defined as:

$$\delta(t) = \begin{cases} \infty & t = 0 \\ 0 & t \neq 0 \end{cases}$$

and has the following properties:

$$\int_{-\infty}^{\infty} \delta(t-t_0)f(t)\mathrm{d}t = f(t_0)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\Big[u_{t_0}(t)\Big] = \delta(t-t_0)$$

$$\mathcal{L}[\delta(t-t_0)] = e^{-st_0}.$$

If $t_0 = 0$ then $\mathcal{L}[\delta(t)] = \lim_{t_0\to 0}\big(e^{-st_0}\big) = 1$. Consider the following impulse ODE:

$$y''(t) + y(t) = \delta(t)$$

with initial conditions $y(0) = y'(0) = 0$:

$$\mathcal{L}[y(t)] = \frac{1}{s^2+1}\lim_{t_0\to 0}\big(e^{-st_0}\big).$$

It is important that we do not evaluate the limit here! Then by inspection:

$$y(t) = \lim_{t_0\to 0}\Big(\sin(t-t_0)u_{t_0}(t)\Big) = \sin(t)u_0(t).$$

Convolutions

Let functions $f, g : [0,\infty) \to \mathbb{R}$.

$$f(t) * g(t) = \int_0^t f(s)g(t-s)\mathrm{d}s = \int_0^t g(s)f(t-s)\mathrm{d}s$$

- $f * (g + h) = f * g + f * h$
- $f * g = g * f$
- $f * (g * h) = (f * g) * h$
- $f * 1 \neq f$
- $f * f \neq f^2$.

Convolution theorem

$$\mathcal{L}[f(t) * g(t)] = \mathcal{L}[f(t)]\mathcal{L}[g(t)]$$

For if $f, g \in E$ then $f * g \in E$. Note:

$$\int_0^t f(s)\mathrm{d}s = \int_0^t f(s)u_0(t-s)\mathrm{d}s$$

$$\mathcal{L}\Big[\int_0^t f(s)\mathrm{d}s\Big] = \frac{\mathcal{L}[f(t)]}{s}.$$

Now consider the following ODE:

$$ay''(t) + by'(t) + cy(t) = g(t)$$

with $y(0) = \alpha$ and $y'(0) = \beta$.
Here $a, b, c, \alpha, \beta \in \mathbb{R}$.

$$\begin{aligned} \therefore \mathcal{L}[y(t)] &= \Phi(s) + \Psi(s) \\ &= \frac{(as+b)\alpha + a\beta}{as^2+bs+c} \\ &\quad + \frac{1}{as^2+bs+c}\mathcal{L}[g(t)] \end{aligned}$$

$$\therefore y(t) = \phi(t) + \psi(t)$$

$$ah''(t) + bh'(t) + ch(t) = \delta(t)$$

$$h(0) = h'(0) = 0$$

$$H(s) = \mathcal{L}[h(t)] = \frac{1}{as^2+bs+c}$$

$$\begin{aligned} \therefore \Psi(s) &= \frac{1}{as^2+bs+c}\mathcal{L}[g(t)] \\ &= H(s)\mathcal{L}[g(t)] \end{aligned}$$

$$\begin{aligned} \mathcal{L}[\psi(t)] &= \mathcal{L}[h(t)]\mathcal{L}[g(t)] \\ &= \mathcal{L}[h(t) * g(t)]. \end{aligned}$$

$$\begin{aligned} \psi(t) &= h(t) * g(t) \\ &= \int_0^t h(s)g(t-s)\mathrm{d}s. \end{aligned}$$

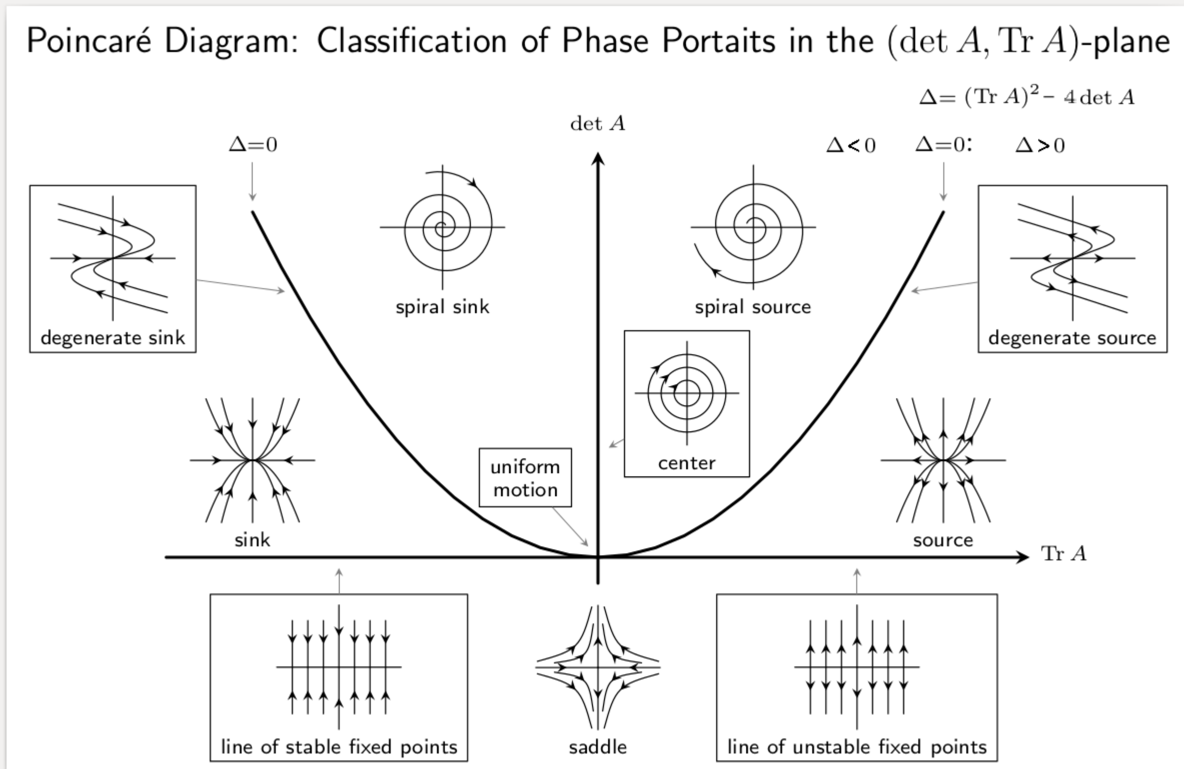
Standard transforms

- $\mathcal{L}[t^n] = \frac{n!}{s^{n+1}}$ where $n \in \mathbb{N}$.
- $\mathcal{L}[e^{at}] = \frac{1}{s-a}$ where $s > a$.
- $\mathcal{L}[\sin at] = \frac{a}{s^2+a^2}$,

  $\mathcal{L}[\cos at] = \frac{s}{s^2+a^2}$ where $s > 0$.
- $\mathcal{L}[\sinh at] = \frac{a}{s^2-a^2}$,

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

  $\mathcal{L}[e^{at}\cos bt] = \frac{s-a}{(s-a)^2+b^2}$
  where $s > a$.
- $\mathcal{L}[u_c(t)] = \frac{e^{-cs}}{s}$ where $s > 0$.
- $\mathcal{L}[\delta(t-c)] = e^{-cs}$.



Miscellaneous

- **Polar coordinates**

$$x = r\cos\theta$$

$$y = r\sin\theta$$

- **Taylor's formula**

$$f(x) = \sum_{n=0}^{\infty} \frac{f^{(n)}(x_0)}{n!}(x - x_0)^n$$

- **Partial fractions**

$$\frac{N(x)}{(ax+b)(cx+d)^2} = \frac{A}{ax+b} + \frac{B}{cx+d} + \frac{C}{(cx+d)^2}$$

$$\frac{N(x)}{(ax+b)(x^2+c)} = \frac{A}{ax+b} + \frac{Bx+C}{x^2+c^2}$$

- **Hyperbolic functions**

$$\sinh x = \frac{1}{2}\left(e^x - e^{-x}\right)$$

$$\cosh x = \frac{1}{2}\left(e^x + e^{-x}\right)$$

Periodicity: $2\pi i$

- **Integrals**

$$\int \frac{\mathrm{d}x}{\sin x} = \ln|\csc x - \cot x| + k$$

$$\int \frac{\mathrm{d}x}{\cos x} = \ln|\tan x - \sec x| + k$$

- **Bessel's equation**
Let $t = \sqrt{\lambda}x$. Then:

$$-(xy')' = \lambda xy$$

$$t\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + \frac{\mathrm{d}y}{\mathrm{d}t} + ty = 0.$$

This is Bessel's equation of order zero. Its general solution is:

$$y = c_1 J_0(t) + c_2 Y_0(t)$$

where J_0 and Y_0 are Bessel functions. Since Y_0 is unbounded we choose $c_2 = 0$ so that the solution is physical and set our orthonormal eigenfunctions to be:

$$\phi_n(x) = k_n J_0(\sqrt{\lambda_n}x)$$

$$J_0(\sqrt{\lambda}x) = 1 + \sum_{m=1}^{\infty} \frac{(-1)^m \lambda^m x^{2m}}{2^{2m}(m!)^2}.$$

- **Inverse formula**

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{ad - bc}\begin{bmatrix} d & -b \\ -c & a \end{bmatrix}$$

- **Further transforms**

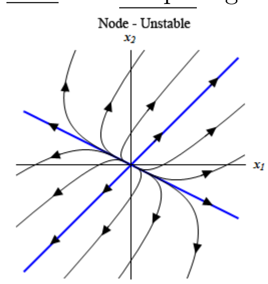
$$\mathcal{L}[t^n e^{at}] = \frac{n!}{(s-a)^{n+1}}$$

where $n \in \mathbb{N}$ and $s > a$.

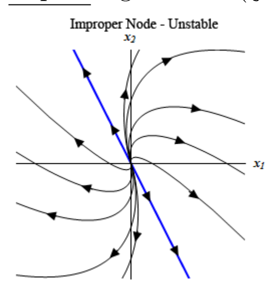
$$\mathcal{L}[\delta(t-c)f(t)] = e^{-cs}f(c).$$

Phase diagrams

- Real and unique eigenvalues:



- Repeat eigenvalues ($\boldsymbol{\xi}$ and $\boldsymbol{\eta}$):



- Repeat eigenvalues
(**two** eigenvectors, $\boldsymbol{\xi}^{(1)}$ and $\boldsymbol{\xi}^{(2)}$):