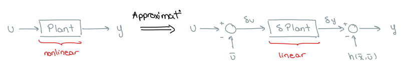
Modelling CS u: control input, y: plant output
State variable CS is in state variable form if
$\dot{x}_1 = f_1(t, x_1, \dots, x_n, u), \dots, \dot{x}_n = f_n(t, x_1, \dots, x_n, u)$
$y = h(t, x_1, \dots, x_n, u)$ is a collection of n 1st order ODEs.
Time-Invariant (TI) CS is TI if $f_i(\cdot)$ does not depend on t.
State space (SS) TI CS is in SS form if $\dot{x} = f(x, u)$, $y = h(x, u)$ where $x(t) \in \mathbb{R}^n$ is called the state.
Single-input-single-output (SISO) CS is SISO if $u(t), y(t) \in \mathbb{R}$.
LTI CS in SS form is LTI if $\dot{x} = Ax + Bu$, $y = Cx + Du$
$A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$, $C \in \mathbb{R}^{p\times n}$, $D \in \mathbb{R}^{p\times m}$
where $x(t) \in \mathbb{R}^n$, $u(t) \in \mathbb{R}^m$, $y(t) \in \mathbb{R}^p$.
Input-Output (IO) LTI CS is in IO form if
$\frac{d^n y}{dt^n} + a_{n-1}\frac{d^{n-1}y}{dt^{n-1}} + \cdot + a_1\frac{dy}{dt} + a_0 y = b_m\frac{d^m u}{dt^m} + \cdot + b_1\frac{du}{dt} + b_0 u$
where $m \le n$ (causality)

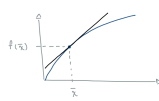
IO to SS Model 1. Define x s.t. highest order derivative in $\dot{x}$
2. Write $\dot{x} = Ax + Bu = f(x, u)$ by isolating for components of $\dot{x}$
3. Write $y = Cx + Du = h(x, u)$ by setting measurement output y to component of x
Equilibria y_d (steady state) b/c if $y(0) = y_d$ at $t = 0$, then $y(t) = y_d$ $\forall t \ge 0$.

Equilibrium pair Consider the system $\dot{x} = f(x, u)$. The pair $(\bar{x}, \bar{u})$ is an equilibrium pair if $f(\bar{x}, \bar{u}) = 0$.
Equilibrium point $\bar{x}$ is an equilibrium point w/ control $u = \bar{u}$.
*If $u = \bar{u}$ and $x(0) = \bar{x}$ then $x(t) = \bar{x}$ $\forall t \ge 0$ (i.e. a system that starts at equilibrium remains at equilibrium).
Find Equilibrium Pair/Point 1. Set $f(x, u) = 0$
2. Solve $f(x, u) = 0$ to find $(x, u) = (\bar{x}, \bar{u})$.
3. If specific $u = \bar{u}$, then find $x = \bar{x}$ by solving $f(x, \bar{u}) = 0$.

Linearization of Nonlinear System Consider system $\dot{x} = f(x, u)$ w/ equ. pair $(\bar{x}, \bar{u})$, then error coordinates around equ. pair $\delta x = x - \bar{x}$, $\delta u = u - \bar{u}$, $\delta y = y - h(\bar{x}, \bar{u})$ w/
$\delta\dot{x} = A\delta x + B\delta u$, $A = \frac{\partial f(\bar{x},\bar{u})}{\partial \underline{x}} \in \mathbb{R}^{n_1\times n_1}$, $B = \frac{\partial f(\bar{x},\bar{u})}{\partial u} \in \mathbb{R}^{n_1}$,
$\delta y = C\delta x + D\delta u$, $C = \frac{\partial h}{\partial \underline{x}}(\bar{x}, \bar{u}) \in \mathbb{R}^{1\times n_1}$, $D = \frac{\partial h(\bar{x},\bar{u})}{\partial u} \in \mathbb{R}$
*Only valid at equ. pairs.

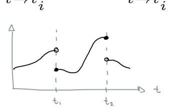


Linear Approx. Given a diff. fcn. $f : \mathbb{R} \to \mathbb{R}$, its linear approx. at $\bar{x}$ is $f_{\text{lin}} = f(\bar{x}) + f'(\bar{x})(x - \bar{x})$.
*Remainder Thm: $f(x) = f_{\text{lin}} + r(x)$ where $\lim_{x\to\bar{x}} \frac{r(x)}{x-\bar{x}} = 0$.

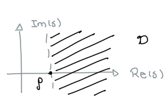


*Note: Can provide a good approx. near $\bar{x}$ but not globally.
*Gen. $f : \mathbb{R}^{n_1} \to \mathbb{R}^{n_2}$, $f(x) = f(\bar{x}) + \frac{\partial f}{\partial x}(\bar{x})(x - \bar{x}) + R(x)$
*Jacobian: $\frac{\partial f}{\partial x}(\bar{x}) = \left[\frac{\partial f}{\partial x_1}(\bar{x}) \quad \cdots \quad \frac{\partial f}{\partial x_{n_1}}(\bar{x})\right] \in \mathbb{R}^{n_2\times n_1}$
Linearization Steps 1. Find equ. pair $(\bar{x}, \bar{u})$
2. Derive A, B, C, D and then evaluate at $(\bar{x}, \bar{u})$
3. Write $\delta\dot{x} = A\delta x + B\delta u$ and $\delta y = C\delta x + D\delta u$

Laplace Transform Given a fcn $f : \mathbb{R}_+ = [0, \infty) \to \mathbb{R}^n$, its Laplace transform is $F(s) = \mathcal{L}\{f(t)\} := \int_{0^-}^{\infty} f(t)e^{-st}\,dt$, $s \in \mathbb{C}$.
*$\mathcal{L} : f(t) \mapsto F(s)$, $t \in \mathbb{R}_+$ (time dom.) & $s \in \mathbb{C}$ (Laplace dom.).
P.W. CTS: A fcn $f : \mathbb{R}_+ \to \mathbb{R}^n$ is **p.w. cts** if on every finite interval of $\mathbb{R}$, $f(t)$ has at most a finite # of discontinuity points (t_i) and the limits $\lim_{t\to t_i^+} f(t)$, $\lim_{t\to t_i^-} f(t)$ are finite.



Exp. Order A function $f : \mathbb{R}_+ \to \mathbb{R}^n$ is of **exp. order** if $\exists$ constants $K, \rho, T > 0$ s.t. $\|f(t)\| \le Ke^{\rho t}$, $\forall t \ge T$.
Existence of LT Thm If $f(t)$ is p.w. cts and of exp. order w/ constants $K, \rho, T > 0$, then $F(\cdot)$ exists and is defined $\forall\, s \in D := \{s \in \mathbb{C} : \text{Re}(s) > \rho\}$ and $F(\cdot)$ is analytic on D.
*Analytic fcn iff differentiable fcn.
*D: Region of convergence (ROC), open half plane.



Unit Step $\mathbf{1}(t) := \begin{cases} 1, & \text{if } t \ge 0 \\ 0, & \text{otherwise} \end{cases}$
Table of Common Laplace Transforms: $f(t) \mid F(s)$
$\mathbf{1}(t) \mapsto \frac{1}{s}$ $\quad t\mathbf{1}(t) \mapsto \frac{1}{s^2}$ $\quad t^k\,\mathbf{1}(t) \mapsto \frac{k!}{s^{k+1}}$ $\quad e^{at}\,\mathbf{1}(t) \mapsto \frac{1}{s-a}$
$t^n e^{at}\,\mathbf{1}(t) \mapsto \frac{n!}{(s-a)^{n+1}}$ $\quad \sin(at)\,\mathbf{1}(t) \mapsto \frac{a}{s^2+a^2}$
$\cos(at)\,\mathbf{1}(t) \mapsto \frac{s}{s^2+a^2}$
Prop. of Laplace Transform Linearity:
$\mathcal{L}\{cf(t) + g(t)\} = c\mathcal{L}\{f(t)\} + \mathcal{L}\{g(t)\}$, $c \sim$ constant.
Differentiation: If the Laplace transform of $f'(t)$ exists, then $\mathcal{L}\{f'(t)\} = s\mathcal{L}\{f(t)\} - f(0^-)$.
If the Laplace transform of $f^{(n)}(t) := \frac{d^n f}{dt^n}(t)$ exists, then
$\mathcal{L}\{f^{(n)}(t)\} = s^n\mathcal{L}\{f(t)\} - \sum_{i=1}^{n} s^{n-i} f^{(i-1)}(0^-)$.
Integration: $\mathcal{L}\left\{\int_0^t f(\tau)d\tau\right\} = \frac{1}{s}\mathcal{L}\{f(t)\}$.
Convolution: Let $(f * g)(t) := \int_0^t f(\tau)g(t-\tau)d\tau = \int_0^t f(t-\tau)g(\tau)d\tau$, then $\mathcal{L}\{(f * g)(t)\} = \mathcal{L}\{f(t)\}\mathcal{L}\{g(t)\}$.
Time Delay: $\mathcal{L}\{f(t-T)\mathbf{1}(t-T)\} = e^{-Ts}\mathcal{L}\{f(t)\}$, $T \ge 0$.
Multiplication by t: $\mathcal{L}\{tf(t)\} = -\frac{d}{ds}[\mathcal{L}\{f(t)\}]$.
Shift in s: $\mathcal{L}\{e^{at}f(t)\} = \mathcal{L}\{f(t)\}\big|_{s\to s-a} = F(s-a)$, where $F(s) = \mathcal{L}\{f(t)\}$ & a const.

Trig. Id. $2\sin(2t) = 2\sin(t)\cos(t)$, $\sin(a-b) = \sin(a)\cos(b) - \cos(a)\sin(b)$, $\cos(a-b) = \cos(a)\cos(b) + \sin(a)\sin(b)$
LT Steps: 1. Write $f(t)$ as a sum and use linearity
*Trig. id. may be useful.
2. Use prop. of LT and common LT to find $F(s)$
Inverse Laplace Transform Given $F(s)$, its inverse LT is $f(t) = \mathcal{L}^{-1}\{F(s)\} := \frac{1}{2\pi}\int_{c-j\infty}^{c+j\infty} F(s)e^{st}ds$
$= \lim_{w\to\infty} \frac{1}{2\pi}\int_{c-jw}^{c+jw} F(s)e^{st}ds$, $c \in \mathbb{C}$ is selected s.t. the line $L := \{s \in \mathbb{C} : s = c + j\omega, \omega \in \mathbb{R}\}$ is inside the ROC of $F(s)$.

Zero: $z \in \mathbb{C}$ is a zero of $F(s)$ if $F(z) = 0$.
Pole: $p \in \mathbb{C}$ is a pole of $F(s)$ if $\frac{1}{F(p)} = 0$.
Cauchy's Residue THM If $F(s)$ is analytic (complex diff.) everywhere except at isolated poles $\{p_1, \dots, p_N\}$, then
$\mathcal{L}^{-1}\{F(s)\} = \sum_{i=1}^{N} \text{Res}\left[F(s)e^{st}, s = p_i\right]\mathbf{1}(t)$,
*$\text{Res}[F(s)e^{st}, s = p_i]$: Residue of $F(s)e^{st}$ at $s = p_i$.
Residue Computation Let $G(s)$ be a complex analytic fcn w/ a pole at $s = p$, r be the multiplicity of the pole p. Then
$\text{Res}[G(s), s = p] = \frac{1}{(r-1)!}\lim_{s\to p}\frac{d^{r-1}}{ds^{r-1}}\left[G(s)(s-p)^r\right]$.
Inv. LT Partial Frac.: 1. Factorize $F(s)$ into canonical form.
2. Find coefficients of partial fraction and use LT table to find inverse LT.
*Complete the square.
Inv. LT Residue: 1. Find poles of $F(s)$ and their residues.
2. Use Cauchy's Residue THM to find inverse LT.
Transfer Function: Consider a CS in IO form. Assume zero initial conds. $y(0) = \cdots = y^{(n-1)}(0) = 0$ and $u(0) = \cdots = u^{(m-1)}(0) = 0$. Then the TF from u to y is
$G(s) := \frac{y(s)}{u(s)} = \frac{b_m s^m + \cdots + b_0}{s^n + a_{n-1}s^{n-1} + \cdots + a_0}$.
***0 Ini. Conds.:** $y_0(s) = G(s)u(s)$
***$\emptyset$ Ini. Conds.:** $y_\emptyset(s) = y_0(s) + \frac{\text{poly. based on initial conds.}}{s^n + a_{n-1}s^{n-1} + \cdots + a_0}$
Impulse Response: Given CS modeled by TF $G(s)$, its IR is $g(t) := \mathcal{L}^{-1}\{G(s)\}$.
*$y(t) = \mathcal{L}^{-1}\{Y(s)\} = \mathcal{L}^{-1}\{G(s)U(s)\} = (g * u)(t)$.
*If $u(t) = \delta(t)$, then $y(t) = (g * u)(t) = g(t)$ and $\mathcal{L}\{\delta(t)\} = 1$.