Plan of the Lecture

- Review: transient and steady-state response; DC gain and the FVT
- Today's topic: system-modeling diagrams; prototype 2nd-order system

Goal: develop a methodology for representing and analyzing systems by means of block diagrams; start analyzing a prototype 2nd-order system.

Reading: FPE, Sections 3.1–3.2; lab manual

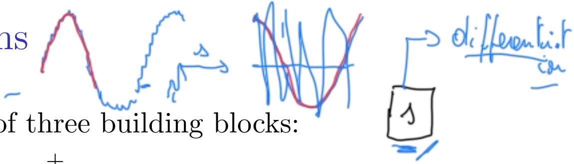
System Modeling Diagrams

$$\text{large system} \underset{\text{compose}}{\overset{\text{decompose}}{\rightleftharpoons}} \text{smaller blocks (subsystems)}$$

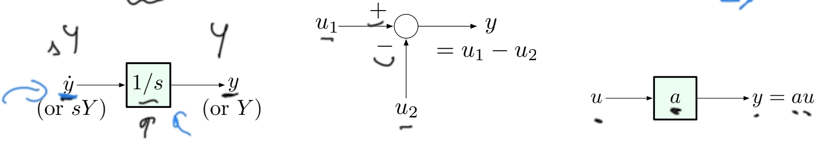
— this is the core of systems theory

We will take smaller blocks from some given *library* and play with them to create/build more complicated systems.

All-Integrator Diagrams



Our library will consist of three building blocks:



integrator   summing junction   constant gain

Two warnings:

- We can (and will) work either with u, y (time domain) or with U, Y (s-domain) — will often go back and forth
- When working with block diagrams, we typically ignore initial conditions.

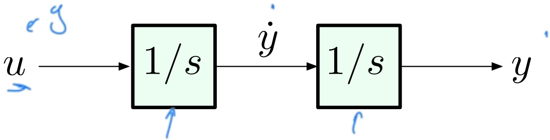
This is the *lowest level* we will go to in lectures; in the labs, you will implement these blocks using op amps.

Example 1

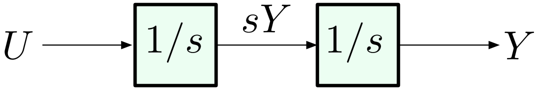
Build an all-integrator diagram for

$$\ddot{y} = u \qquad \Longleftrightarrow \qquad s^2 Y = U$$

This is obvious:



or



Example 2

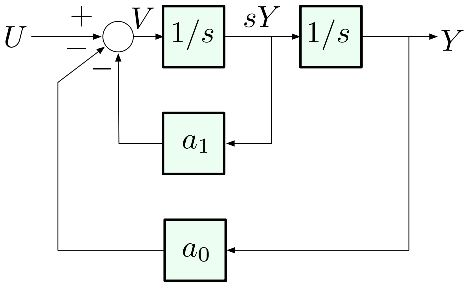
(building on Example 1)

$$\ddot{y} + a_1\dot{y} + a_0 y = u \qquad \Longleftrightarrow \qquad s^2 Y + a_1 s Y + a_0 Y = U$$

$$\text{or} \qquad Y(s) = \frac{U(s)}{s^2 + a_1 s + a_0}$$

Always solve for the highest derivative:

$$\ddot{y} = \underbrace{-a_1\dot{y} - a_0 y + u}_{=v}$$

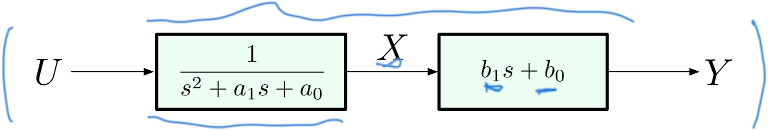


Example 3

Build an all-integrator diagram for a system with transfer function

$$H(s) = \frac{b_1 s + b_0}{s^2 + a_1 s + a_0}$$

Step 1: decompose $H(s) = \dfrac{1}{s^2 + a_1 s + a_0} \cdot (b_1 s + b_0)$

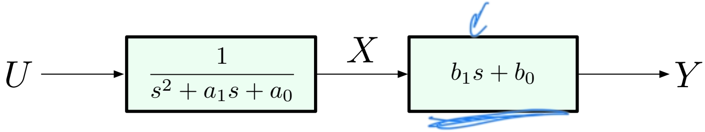


— here, X is an auxiliary (or intermediate) signal

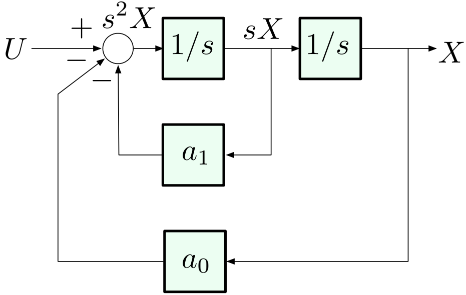
Note: $b_0 + b_1 s$ involves *differentiation*, which we cannot implement using an all-integrator diagram. But we will see that we don't need to do it directly.

Example 3, continued

Step 1: decompose $H(s) = \dfrac{1}{s^2 + a_1 s + a_0} \cdot (b_1 s + b_0)$



Step 2: The transformation $U \to X$ is from Example 2:

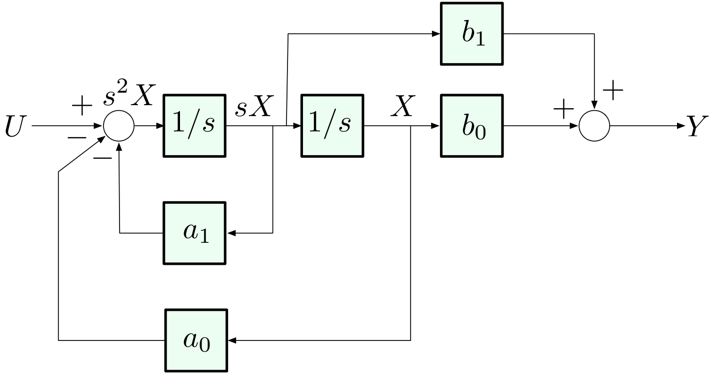


Example 3, continued

Step 3: now we notice that

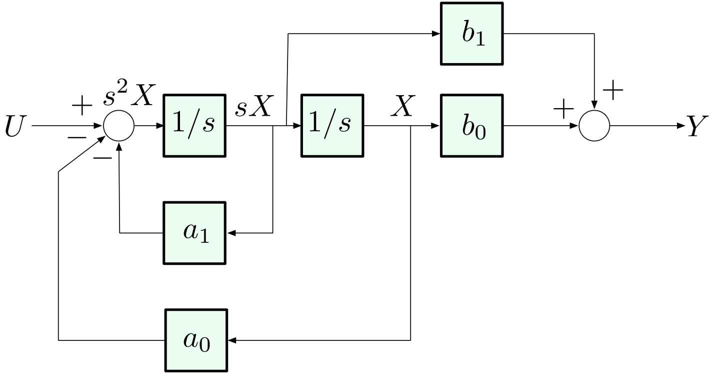
$$Y(s) = b_1 sX(s) + b_0 X(s),$$

and both X and sX are available signals in our diagram. So:



Example 3, continued

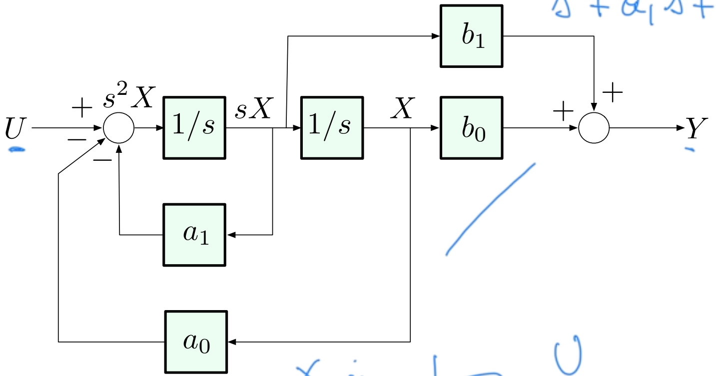
All-integrator diagram for $H(s) = \dfrac{b_1 s + b_0}{s^2 + a_1 s + a_0}$



Can we write down a state-space model corresponding to this diagram?

Example 3, continued

$H(s) = \dfrac{b_1 s + b_0}{s^2 + a_1 s + a_0}$



X is $\dfrac{1}{s^2 + a_1 s + a_0} U$

State-space model:

$$s^2X = U - a_1 sX - a_0 X \qquad Y = b_1 sX + b_0 X$$

$$\ddot{x} = -a_1\dot{x} - a_0 x + u \qquad y = b_1\dot{x} + b_0 x$$

Example 3, continued

$\ddot{x} = -a_1\dot{x} - a_0 x + u$

State-space model:

$\begin{cases} x_1 = x \\ x_2 = \dot{x} \end{cases} \Rightarrow \begin{array}{l} \dot{x}_1 = \dot{x} = x_2 \\ \dot{x}_2 = \ddot{x} = \underbrace{-a_1\dot{x}}_{-a_1 x_1} - a_0 x + u \end{array}$

$$\ddot{x} = -a_1\dot{x} - a_0 x + u \qquad y = b_1\dot{x} + b_0 x$$

$= b_1 x_2 + b_0 x_1$

$$x_1 = x,\ x_2 = \dot{x}$$

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -a_0 & -a_1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u \qquad y = \begin{pmatrix} b_0 & b_1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

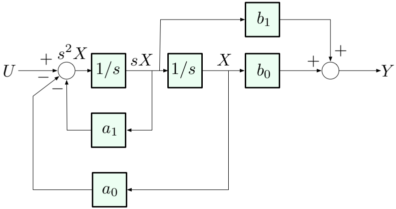
This is called *controller canonical form*.

[Come back later in semester)

- Easily generalizes to dimension > 1
- The reason behind the name will be made clear later in the semester

Example 3, wrap-up

All-integrator diagram for $H(s) = \dfrac{b_1 s + b_0}{s^2 + a_1 s + a_0}$



State-space model:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -a_0 & -a_1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix} u \qquad y = \begin{pmatrix} b_0 & b_1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$$

Important: for a given $H(s)$, the diagram is *not unique*. But, once we build a diagram, the state-space equations are unique (up to coordinate transformations).

Basic System Interconnections

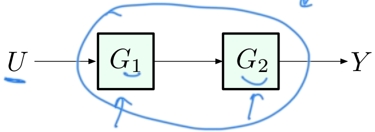
Now we will take this a level higher — we will talk about building complex systems from smaller blocks, without worrying about how those blocks look on the inside (they could themselves be all-integrator diagrams, etc.)

Block diagrams are an *abstraction* (they hide unnecessary "low-level" detail ...)

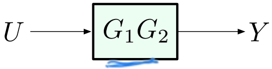
Block diagrams describe the *flow of information*

Basic System Interconnections: Series & Parallel

Series connection



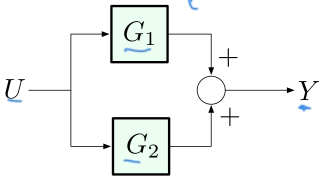
(G is common notation for t.f.'s)

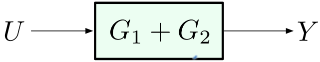


$$\frac{Y}{U} = G_1 G_2$$

(for SISO systems, the order of G_1 and G_2 does not matter)

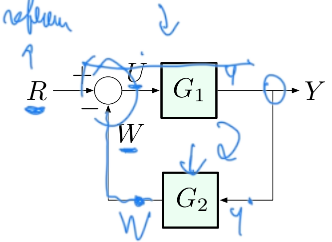
Parallel connection





$$\frac{Y}{U} = G_1 + G_2$$

Basic System Interconnections: Negative Feedback



Find the transfer function from R (reference) to Y

$$\Longrightarrow \quad Y = \frac{G_1}{1 + G_1 G_2} R$$

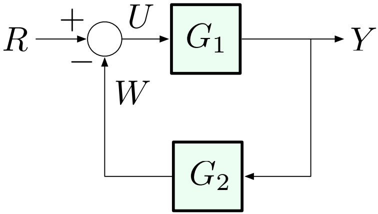
$$U = R - W$$

$$\begin{aligned} Y &= G_1 U \\ &= G_1 (R - W) \\ &= G_1 R - G_1 G_2 Y \end{aligned}$$

$$(1 + G_1 G_2) Y = G_1 R$$

$$U \longrightarrow \boxed{\dfrac{G_1}{1 + G_1 G_2}} \longrightarrow Y$$

Basic System Interconnections: Negative Feedback



$$\implies Y = \frac{G_1}{1 + G_1 G_2} R$$

The gain of a negative feedback loop:

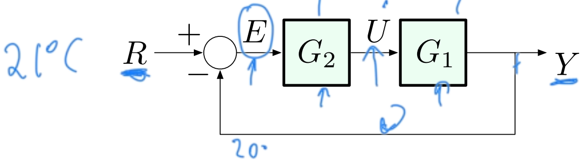
$$\frac{\text{forward gain}}{1 + \text{loop gain}}$$

This is an important relationship, easy to derive — no need to memorize it.

Unity Feedback

Controller System

Other feedback configurations are also possible:

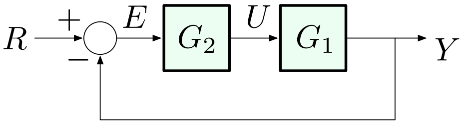


This is called *unity feedback* — no component on the feedback path.

Common structure (saw this in Lecture 1):

- R = reference
- U = control input
- Y = output
- E = error
- G_1 = plant (also denoted by P)
- G_2 = controller or compensator (also denoted by C or K)

Unity Feedback



Let's practice with deriving transfer functions: $\dfrac{\text{forward gain}}{1 + \text{loop gain}}$

- Reference R to output Y:

$$\frac{Y}{R} = \frac{G_1 G_2}{1 + G_1 G_2}$$

- Reference R to control input U:

$$\frac{U}{R} = \frac{G_2}{1 + G_1 G_2}$$

- Error E to output Y:

$$\frac{Y}{E} = G_1 G_2 \qquad \text{(no feedback path)}$$

Block Diagram Reduction

Given a complicated diagram involving series, parallel, and feedback interconnections, we often want to write down an overall transfer function from one of the variables to another.

This requires lots of practice: read FPE, Section 3.2 for examples.

General strategy: (mixes : uninterrupted)

- Name all the variables in the diagram
- Write down as many relationships between these variables as you can
- Learn to recognize series, parallel, and feedback interconnections
- Replace them by their equivalents
- Repeat

Prototype 2nd-Order System

· only have denom (no zeros!)

· 2^{nd} order is sufficient to characterize system behav.

So far, we have only seen transfer functions that have either real poles or purely imaginary poles:

← 1 real pole → 2 real poles → 2 purely imaginary

$$\frac{1}{s+a}, \quad \frac{1}{(s+a)(s+b)}, \quad \frac{1}{s^2+\omega^2}$$

We also need to consider the case of *complex poles*, i.e., ones that have $\mathrm{Re}(s) \neq 0$ and $\mathrm{Im}(s) \neq 0$.

For now, we will only look at *second-order systems*, but this will be sufficient to develop some nontrivial intuition (dominant poles).

Plus, you will need this for Lab 1.

Prototype 2nd-Order System

Consider the following transfer function:

$$\boxed{H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}}$$

Comments:

- $\zeta > 0, \omega_n > 0$ are arbitrary parameters
- the denominator is a general 2nd-degree monic polynomial, just written in a weird way
- $H(s)$ is normalized to have DC gain $= 1$ (provided DC gain exists)

Prototype 2nd-Order System

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

By the quadratic formula, the poles are:

↳ roots of denom!

$$\begin{aligned} s &= -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1} \\ &= -\omega_n \left(\zeta \pm \sqrt{\zeta^2 - 1}\right) \end{aligned}$$

The nature of the poles changes depending on ζ:

- $\zeta > 1$ both poles are real and negative.
- $\zeta = 1$ one negative pole (double pole).
- $\zeta < 1$ two complex poles with negative real parts

$$s = -\sigma \pm j\omega_d$$

σ = real part of pole
ω_d = imag. part.

$\sqrt{\zeta^2 - 1} = \sqrt{-1[1-\zeta^2]} = j\sqrt{1-\zeta^2}$

where $\sigma = \zeta\omega_n, \; \omega_d = \omega_n\sqrt{1 - \zeta^2}$

Prototype 2nd-Order System

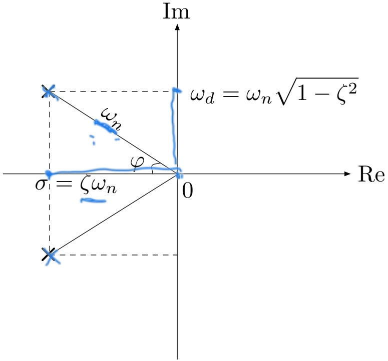
$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}, \qquad \zeta < 1$$

The poles are

$$s = -\zeta\omega_n \pm j\omega_n\sqrt{1-\zeta^2} = -\sigma \pm j\omega_d$$

$\sigma = \zeta\omega_n$

$\omega_d = \omega_n\sqrt{1-\zeta^2}$



Note that

$$\sigma^2 + \omega_d^2 = \zeta^2\omega_n^2 + \omega_n^2 - \zeta^2\omega_n^2$$
$$= \omega_n^2$$

$$\cos\varphi = \frac{\zeta\omega_n}{\omega_n} = \zeta$$

2nd-Order Response

Let's compute the system's impulse and step response:

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{\omega_n^2}{(s+\sigma)^2 + \omega_d^2}$$

- Impulse response:

$$h(t) = \mathscr{L}^{-1}\{H(s)\} = \mathscr{L}^{-1}\left\{\frac{(\omega_n^2/\omega_d)\omega_d}{(s+\sigma)^2 + \omega_d^2}\right\}$$

$$= \frac{\omega_n^2}{\omega_d} e^{-\sigma t} \sin(\omega_d t) \qquad \text{(table, \# 20)}$$

- Step response: ✓

$$\mathscr{L}^{-1}\left\{\frac{H(s)}{s}\right\} = \mathscr{L}^{-1}\left\{\frac{\sigma^2 + \omega_d^2}{s[(s+\sigma)^2 + \omega_d^2]}\right\}$$

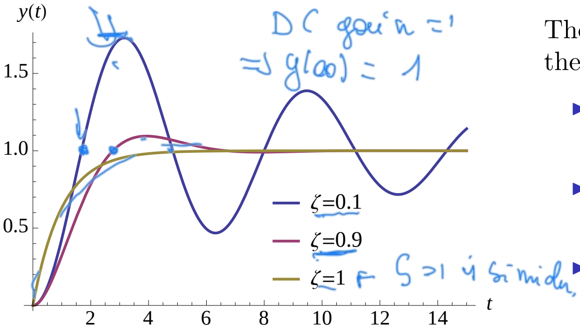
$$= 1 - e^{-\sigma t}\left(\cos(\omega_d t) + \frac{\sigma}{\omega_d}\sin(\omega_d t)\right) \qquad \text{(table, \#21)}$$

2nd-Order Step Response

$$H(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} = \frac{\omega_n^2}{(s+\sigma)^2 + \omega_d^2}$$

$$u(t) = 1(t) \qquad \longrightarrow \qquad y(t) = 1 - e^{-\sigma t}\left(\cos(\omega_d t) + \frac{\sigma}{\omega_d}\sin(\omega_d t)\right)$$

where $\sigma = \zeta\omega_n$ and $\omega_d = \omega_n\sqrt{1-\zeta^2}$ (damped frequency)



The parameter ζ is called the *damping ratio*

- $\zeta > 1$: system is overdamped
- $\zeta < 1$: system is underdamped
- $\zeta = 0$: no damping ($\omega_d = \omega_n$)