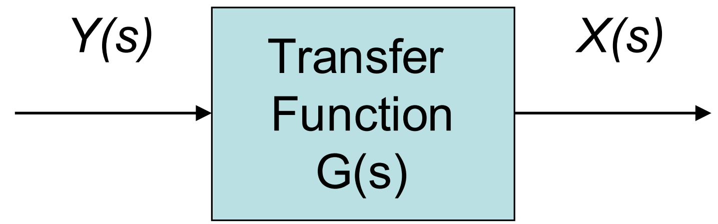
Advanced Mechatronics Design

Transfer Function

Definition

Time domain

s domain



$$G = gain = \frac{output}{input}$$

$$G(s) = Transfer\ \ Function = \frac{Laplace\ transform\ \ of\ \ output}{Laplace\ transform\ \ of\ \ input}$$

Laplace Transform Definitions

One (Easy) Way to Solve ODEs

Laplace transform

$$F(s) = L\{f(t)\} = \int_{0}^{\infty} e^{-st} f(t) dt$$

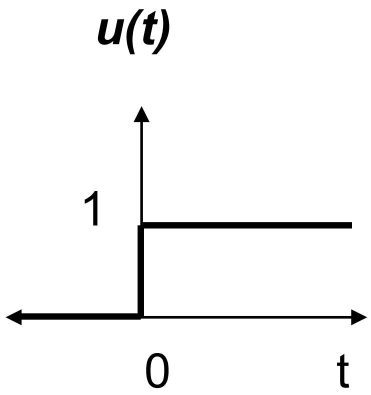
$$F(s) = L\{f(t)\}$$

Inverse Laplace transform

$$f(t) = \frac{1}{2\pi j} \int_{\sigma - jw}^{\sigma + jw} F(s) e^{st} ds$$

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

The Unit Step Function

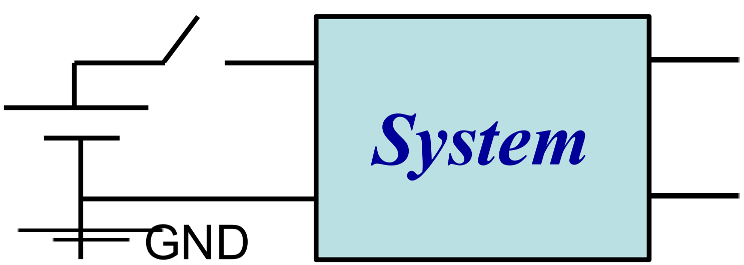


$u(t) = 0,\ t < 0$

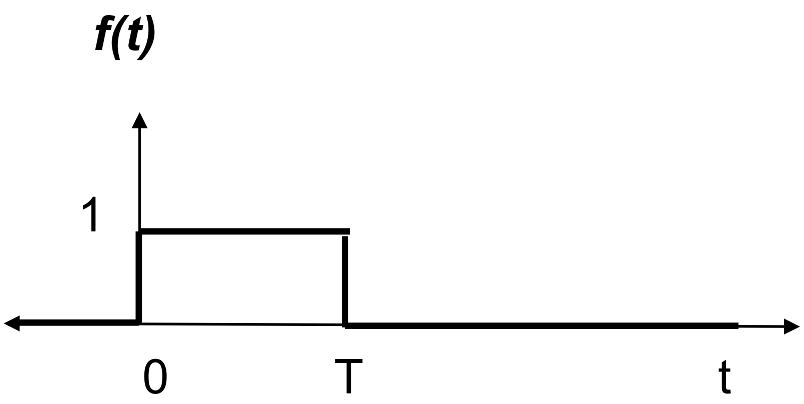
$u(t) = 1,\ t \geq 0$

$$L\{u(t)\} = \int_0^\infty e^{-st} u(t) dt = \int_0^\infty 1 e^{-st} dt = -\frac{1}{s}[e^{-st}]_0^\infty = \frac{1}{s}$$

$$L\{u(t)\} = U(s) = \frac{1}{s}$$

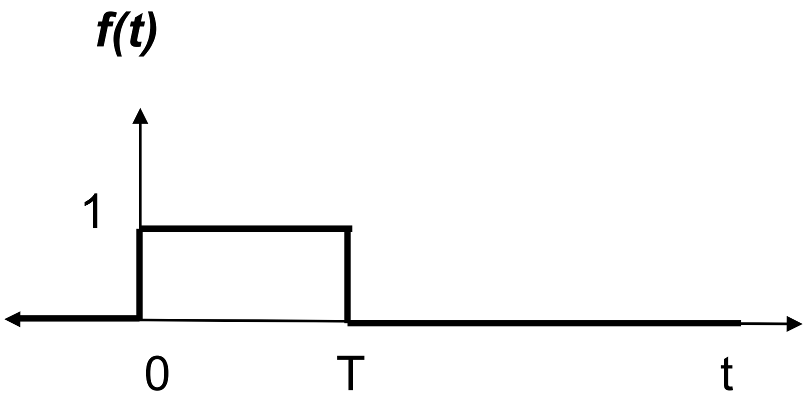


Digital Signal



Find the Laplace transform of this signal using LT definition integral

Solution



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

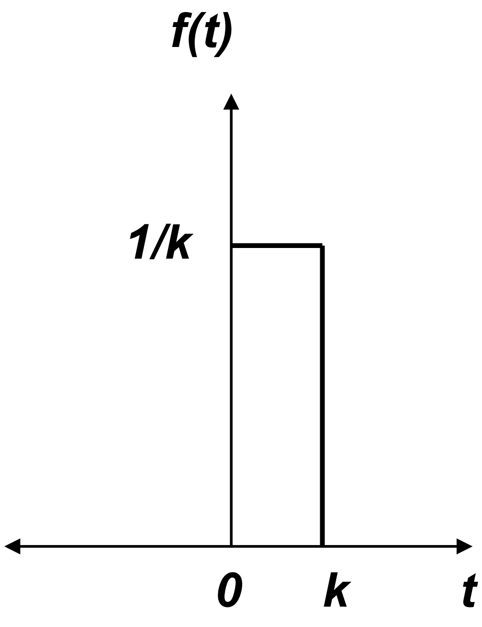
$$\int_0^T e^{-st} f(t)dt + \int_T^\infty e^{-st} f(t)dt =$$

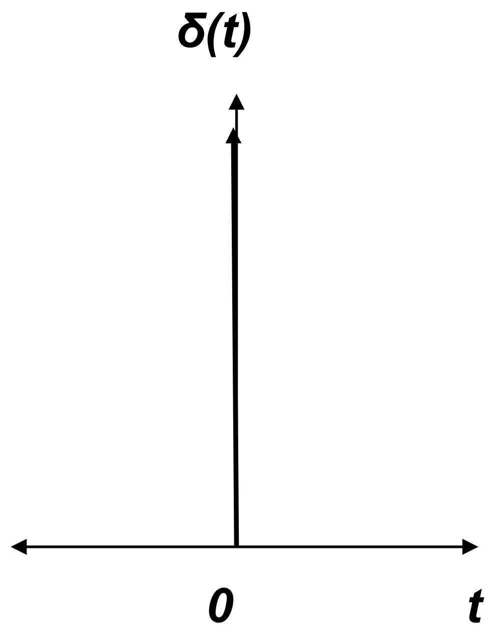
f(t) = 0, t < 0
f(t) = 1, 0 ≤ t ≤ T
f(t) = 0, t > T

$$\int_0^T e^{-st} * 1dt + 0 = \frac{1}{-s}\left[e^{-st}\right]_0^T$$

$$L = \frac{1}{s}(1 - e^{-sT})$$

Impulse Function





$$f(t) = \frac{1}{k} \; for\; 0 \le t < k$$

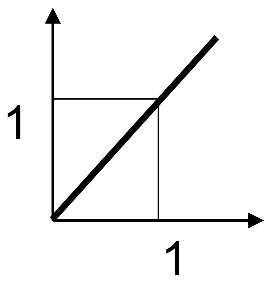
$$f(t) = 0 \; for\; t > k$$

$$F(s) = 1$$

Laplace Transform of Some Common Functions

$\delta(t)$, *unit impulse*	1
$\delta(t-T)$, *delayed unit impulse*	e^{-sT}
$u(t)$, *a unit step*	$\dfrac{1}{s}$
$u(t-T)$, *a delayed unit step*	$\dfrac{e^{-sT}}{s}$

Laplace Transform of Some Common Functions



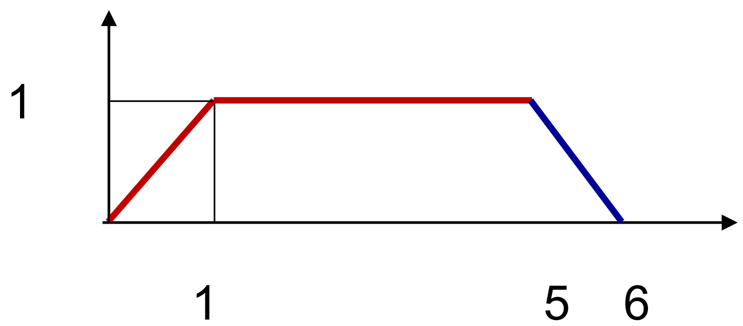
$t,\ a\ unit\ ramp$ $\quad F(s)=\int_0^\infty te^{-st}dt=\left[\frac{te^{-st}}{-s}\right]_0^\infty+\frac{1}{s}\int_0^\infty e^{-st}dt=\frac{1}{s^2}$

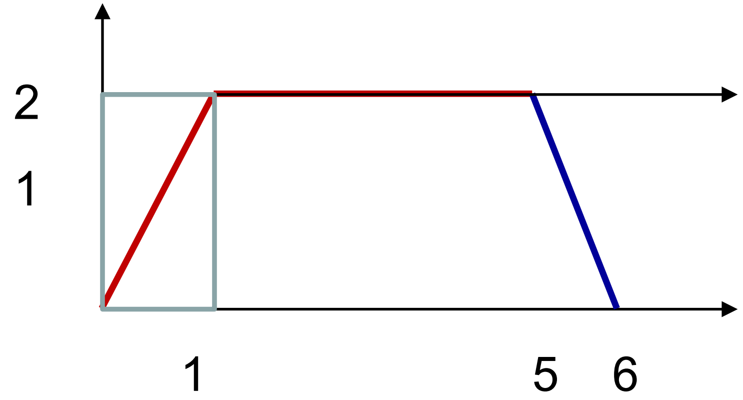
$t^n,\ n-th\ order\ ramp$ $\quad \frac{n!}{s^{n+1}}$

e^{-at}, exponential decay $\quad \frac{1}{s+a}$

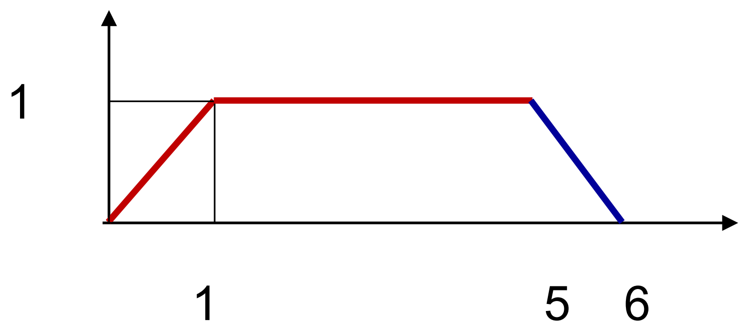
$1-e^{-at}$, exponential growth $\quad \frac{a}{s(s+a)}$

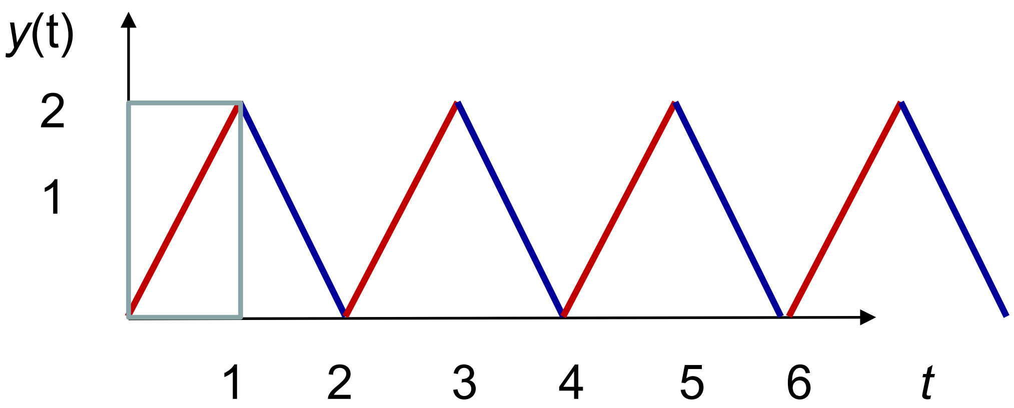
Laplace Transform of Some Common Functions



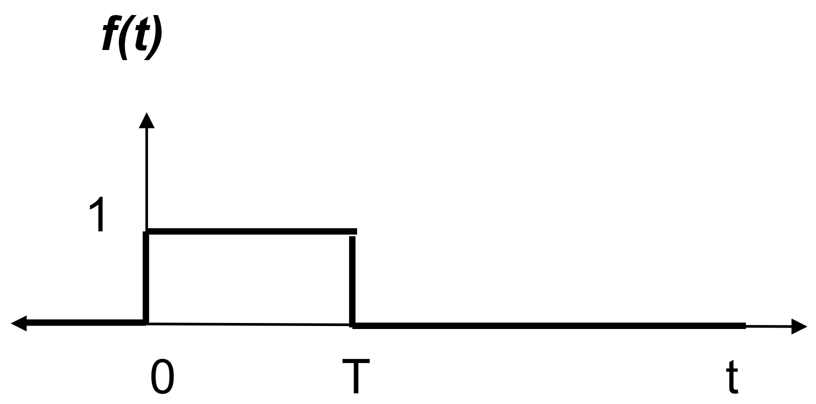


Laplace Transform of Some Common Functions



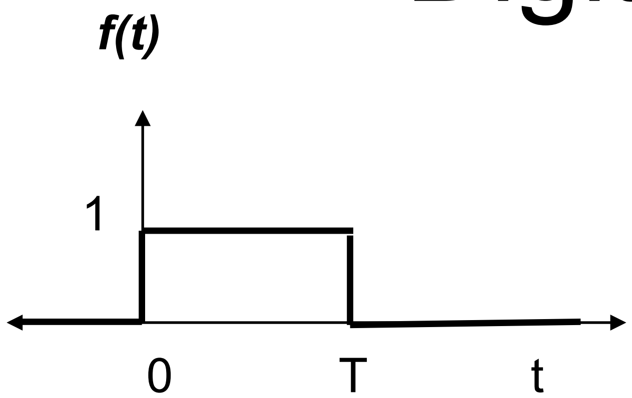


Digital Signal



Find the Laplace transform using common signals

Digital Signal Again



$u(t)$, a unit step $\qquad \dfrac{1}{s}$

$u(t-T)$, a delayed unit step $\qquad \dfrac{e^{-sT}}{s}$

$u(t)-u(t-T) \Rightarrow \qquad \Delta U(s)=\dfrac{1}{s}(1-e^{-sT})$

Laplace Transform Properties

- Linearity

$$L\{af(t)+bg(t)\}=aLf(t)+bLg(t)$$

- Shifting in s – domain

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

- Time domain shifting

$$L\{f(t-T)u(t-T)\}=e^{-sT}F(s)$$

- Periodic functions

$$f(t)=f(t+T), \quad Lf(t)=\frac{1}{1-e^{-sT}}F_1(s)$$

F_1 is Laplace transform for the first period only

Laplace Transform Properties

- Initial and final values
- Derivatives
- Integrals

First Order System

$$a_1 \frac{dx}{dt} + a_0 x = b_0 y$$

$\mathrm{a}_1\ \mathrm{a}_0\ \mathrm{b}_0$ are constants, y *and* x are input and output

Laplace transform with all initial conditions zero is

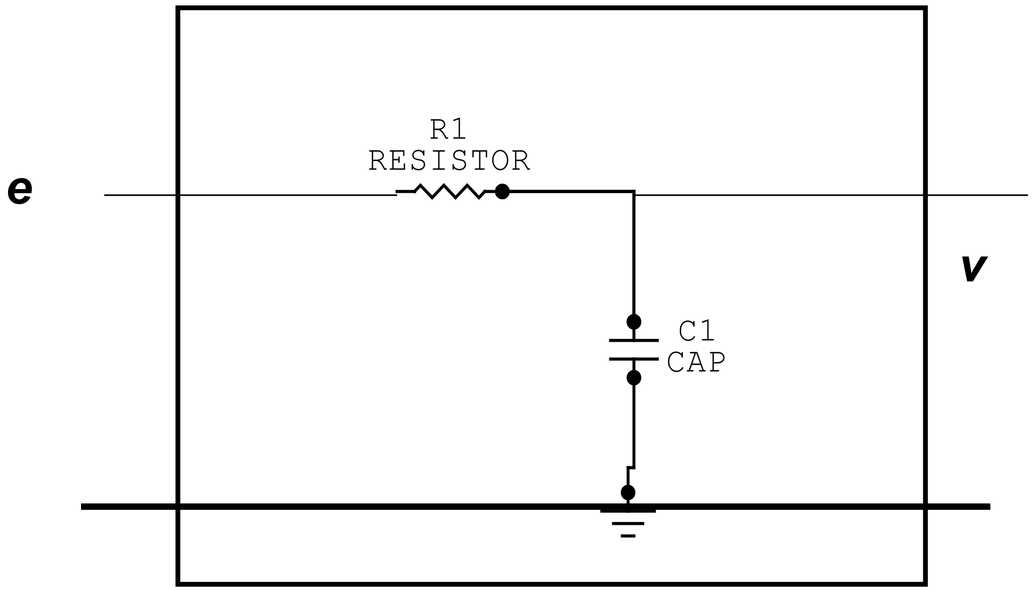
$$\mathrm{a}_1 sX(s) + \mathrm{a}_0 X(s) = \mathrm{b}_0 Y(s)$$

$$G(s) = \frac{X(s)}{Y(s)} = \frac{b_0}{a_1 s + a_0}$$

$$G(s) = \frac{b_0 / a_0}{(a_1 / a_0)s + 1} = \frac{G}{\tau s + 1}$$

A First Order System

Filter Example



$$e = iR + v; \quad i = C\frac{dv}{dt}$$

$$e = C\frac{dv}{dt}R + v$$

$$E(s) = RCsV(s) + V(s)$$

$$\frac{V(s)}{E(s)} = \frac{V(s)}{sRCV(s) + V(s)}$$

$$\frac{V(s)}{E(s)} = \frac{1}{sRC + 1} = \frac{1}{\tau s + 1}$$

$$\tau = RC = \text{time constant}$$

Second Order System

$$a_2 \frac{d^2x}{dt^2} + a_1 \frac{dx}{dt} + a_0 x = b_0 y$$

$$G(s) = ?$$

Second Order System

$$a_2 \frac{d^2x}{dt^2} + a_1 \frac{dx}{dt} + a_0 x = b_0 y$$

$a_2\ a_1\ a_0\ b_0$ are constants y is the input, x is the output

Laplace transform with all initial conditions zero is

$$a_2 s^2 X(s) + a_1 s X(s) + a_0 X(s) = b_0 Y(s)$$

$$G(s) = \frac{X(s)}{Y(s)} = \frac{b_0}{a_2 s^2 + a_1 s + a_0}$$

Second Order System

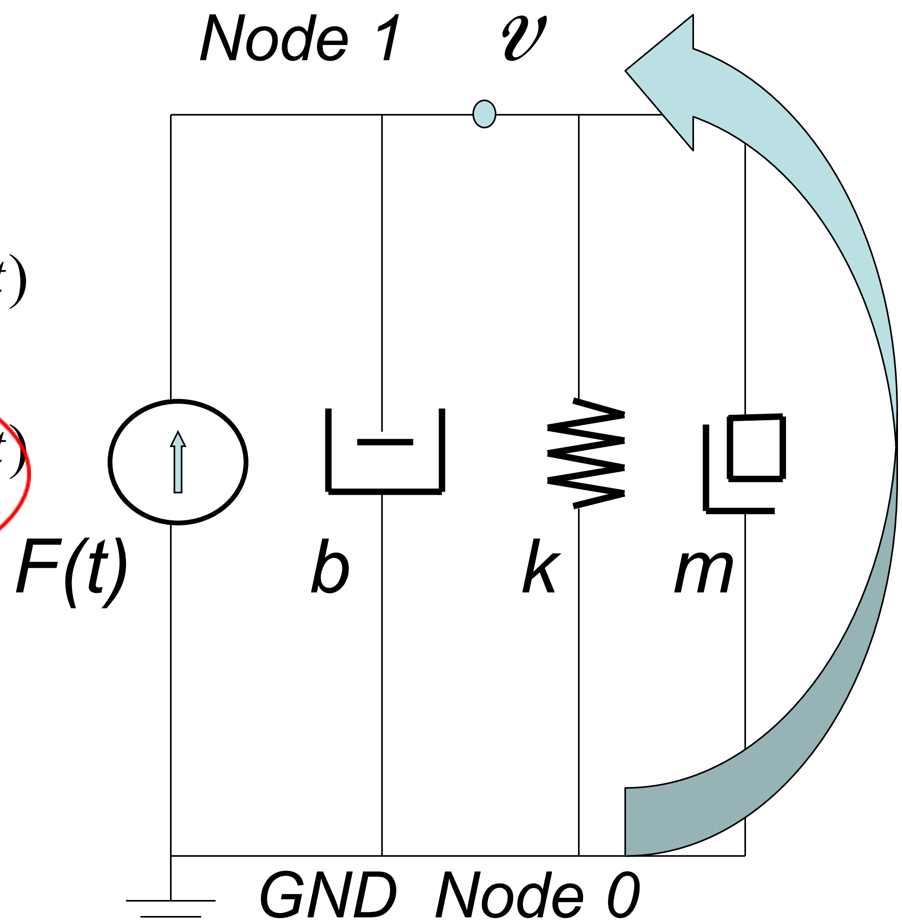
Basic Mechanical Network 1

$$Bv + m\frac{dv}{dt} + k\int v dt = F$$

$$b\frac{dy(t)}{dt} + m\frac{d^2y(t)}{dt} + ky(t) = F(t)$$

$$m\frac{d^2y(t)}{dt} + b\frac{dy(t)}{dt} + ky(t) = F(t)$$

$$(b + m\frac{d}{dt} + k\int dt)v = F$$

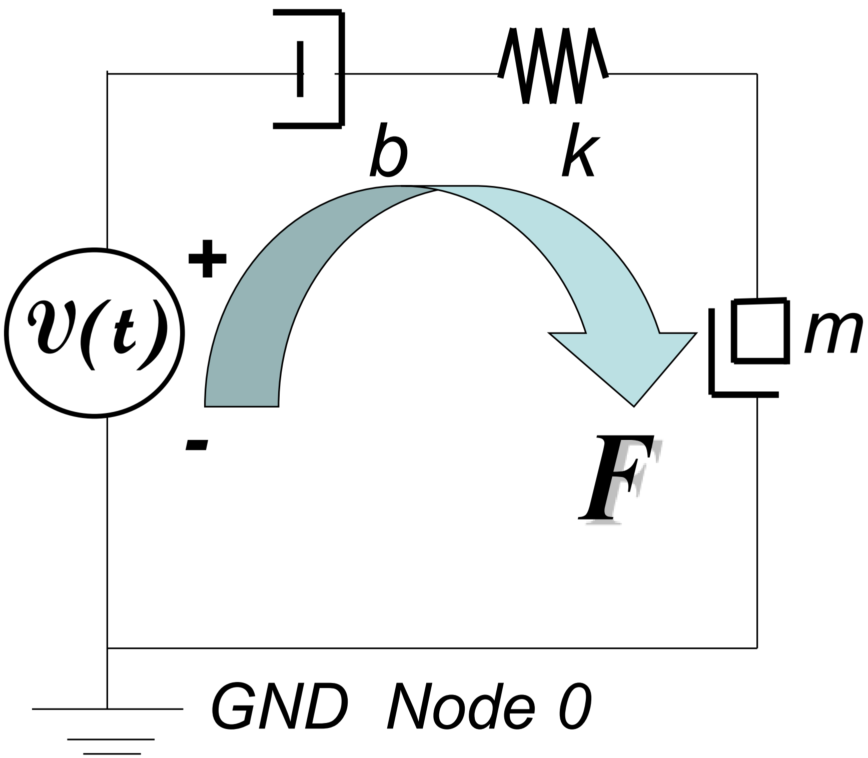


Second Order System

Basic Mechanical Network 2

$$\frac{F}{b}+\frac{1}{k}\frac{dF}{dt}+\frac{1}{m}\int Fdt=v$$

$$(\frac{1}{b}+\frac{1}{k}\frac{d}{dt}+\frac{1}{m}\int dt)F=v$$



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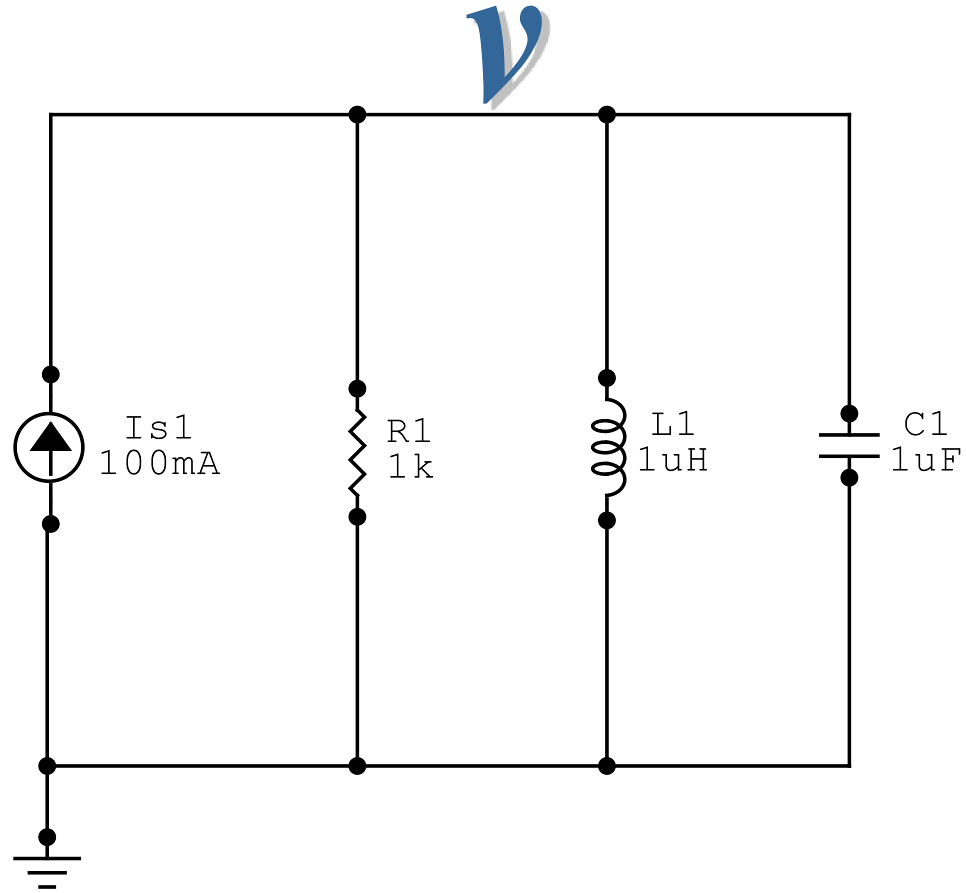
Second Order System

Basic Electrical Network 1

$$\frac{v}{R}+C\frac{dv}{dt}+\frac{1}{L}\int v dt=i$$

$$\left(\frac{1}{R}+C\frac{d}{dt}+\frac{1}{L}\int dt\right)v=i$$



Second Order System

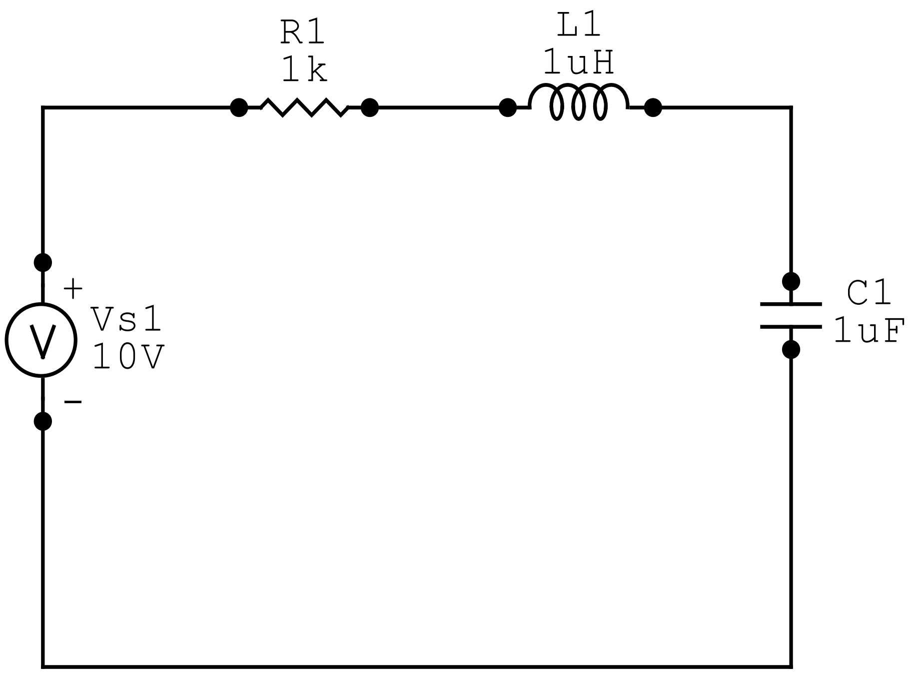
Basic Electrical Network 2

$$Ri + L\frac{di}{dt} + \frac{1}{C}\int idt = v$$

$$R\frac{di}{dt} + L\frac{d^2i}{dt} + \frac{i}{C} = \frac{dv}{dt}$$

$$L\frac{d^2i}{dt} + R\frac{di}{dt} + \frac{i}{C} = \frac{dv}{dt}$$

$$(R + L\frac{d}{dt} + \frac{1}{C}\int dt)i = v$$

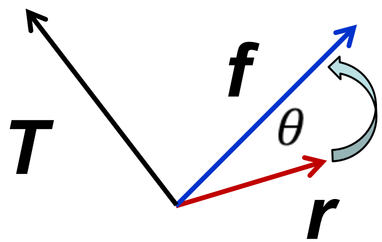


Mechanical System Elements Rotation

- Torque = Moment = Moment of Force T
- Angular Velocity w
  - Moment of Inertia $I = J = \int r^2 dm$

Rotation:
Torque and Angular Velocity

$$\mathbf{T} = \mathbf{r} \times \mathbf{f} \qquad [Nm]$$



$$\omega = \frac{d\theta}{dt} \qquad \left[\frac{1}{s}\right]$$

$$T = rf\sin(\theta) \quad [Nm] = \left[mkgm / s^2 = kgm^2 / s^2\right]$$

$$Energy[J] = Torque[Nm] * Angle[radian] = T * \theta$$

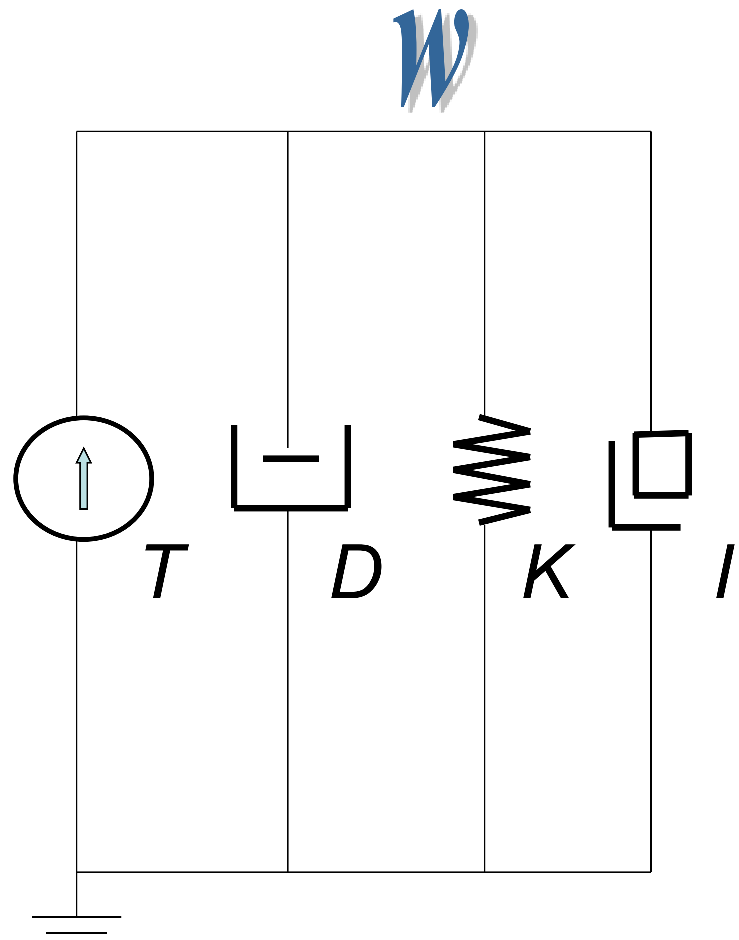
Rotational Kinetic Energy = E_{Krot}=1/2*Iw^2

*Power [W]= Torque [Nm]*Angular Speed [radian/s]*

Basic Mechanical Rotation Network 1r

$$Dw + I\frac{dw}{dt} + K\int wdt = T$$

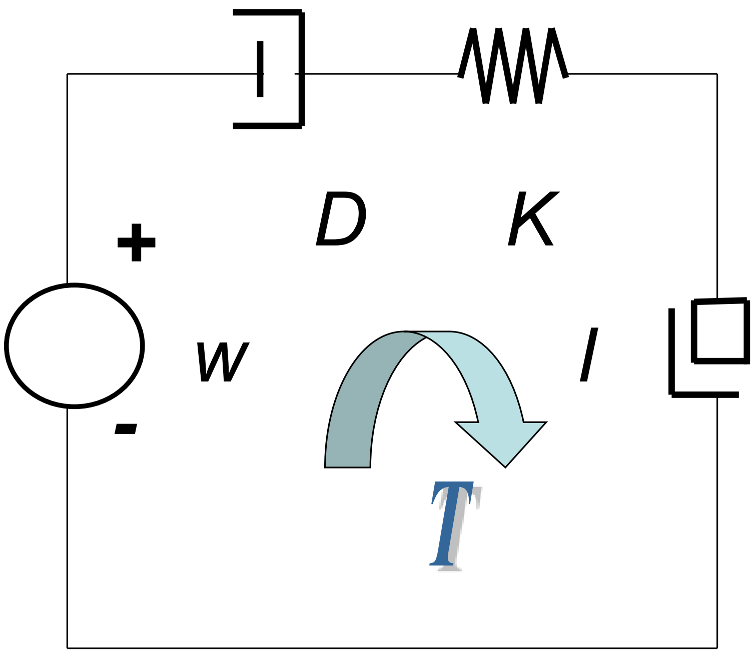
$$(D + I\frac{d}{dt} + K\int dt)w = T$$



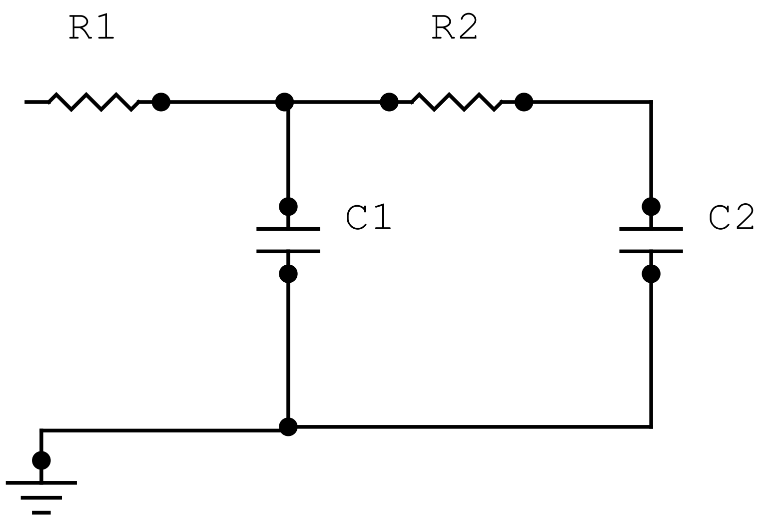
Basic Mechanical Rotation Network 2r

$$\frac{T}{D}+\frac{1}{K}\frac{dT}{dt}+\frac{1}{I}\int Tdt = w$$

$$\left(\frac{1}{D}+\frac{1}{K}\frac{d}{dt}+\frac{1}{I}\int dt\right)T = w$$



A Second Order System



$$\frac{V(s)}{E(s)} = \frac{1}{(1+\tau_1 s)(1+\tau_2 s)}$$

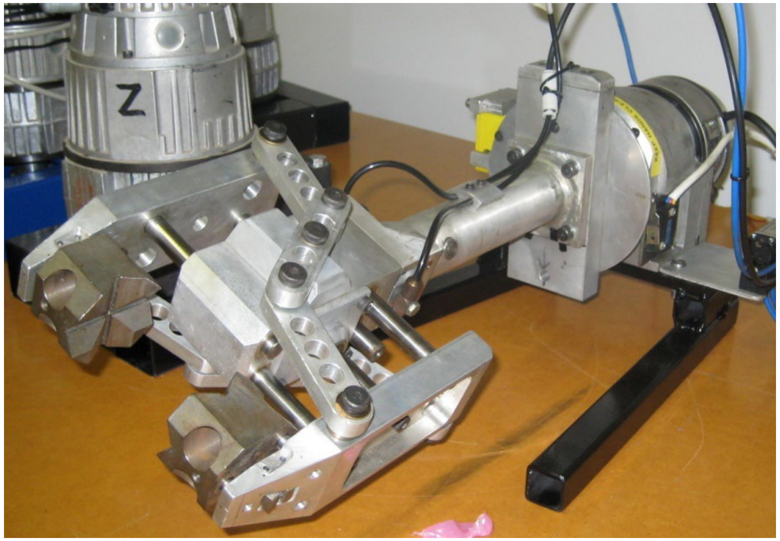
$$\frac{V(s)}{E(s)} = \frac{A}{1+\tau_1 s} + \frac{B}{1+\tau_2 s}$$

A Second Order System Example

A robot arm has following transfer function:

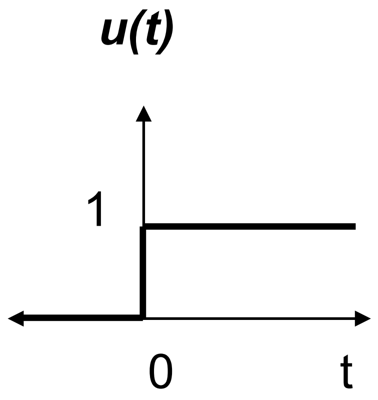
$$G(s) = \frac{K}{(s+3)^2}$$

If an unit step input is applied, what will be the output?



A Second Order System
Exam Question Example

$$X(s) = G(s)Y(s) = \frac{K}{(s+3)^2} \times ?$$



Find the response in time domain and draw the output function

Solution

$$X(s) = G(s)Y(s) = \frac{K}{(s+3)^2} \times \frac{1}{s}$$

Using partial fractions we can get

$$X(s) = \frac{K}{9s} - \frac{K}{9(s+3)} - \frac{K}{3(s+3)^2}$$

The inverse transform is

$$x(t) = \frac{1}{9}K - \frac{1}{9}Ke^{-3t} - \frac{1}{3}Kte^{-3t}$$

Solution - Explained

$$X(s) = \frac{K}{(s+3)^2} \times \frac{1}{s} = \frac{A}{s} + \frac{Bs + C}{(s+3)^2} = \frac{A}{s} + \frac{C}{(s+3)} + \frac{D}{(s+3)^2}$$

$$\frac{K}{(s+3)^2} \times \frac{1}{s} = \frac{A}{s} + \frac{C}{(s+3)} + \frac{D}{(s+3)^2}$$

$$K = A(s+3)^2 + Cs(s+3) + Ds$$

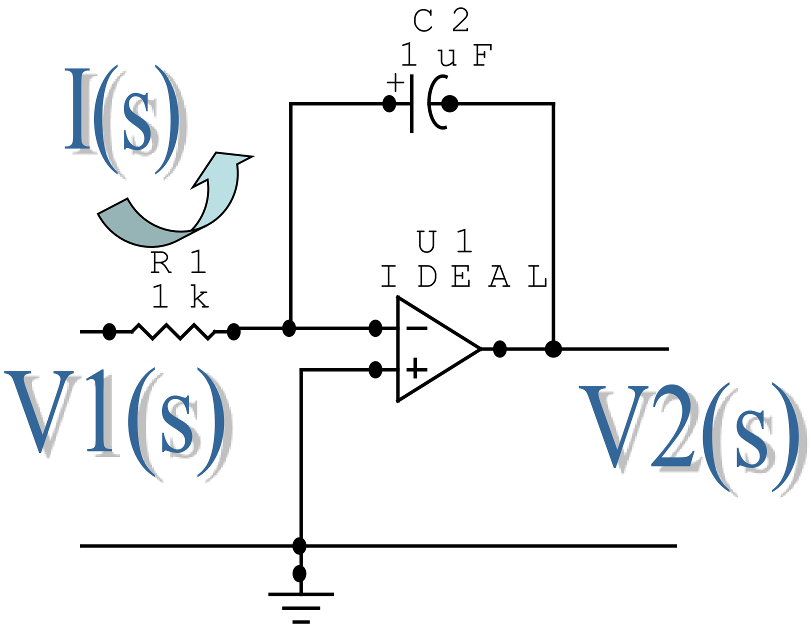
$$A = \frac{K}{9}; \qquad C = -\frac{K}{9}; \quad D = -\frac{K}{3}$$

The Method of Partial Fractions With Laplace Transform

http://www.math.oregonstate.edu/home/programs/undergrad/CalculusQuestStudyGuides/ode/laplace/pf/pf.html

More Transfer Functions

Filter, Integrating Circuit



$$v1(t) = R \times i(t)$$

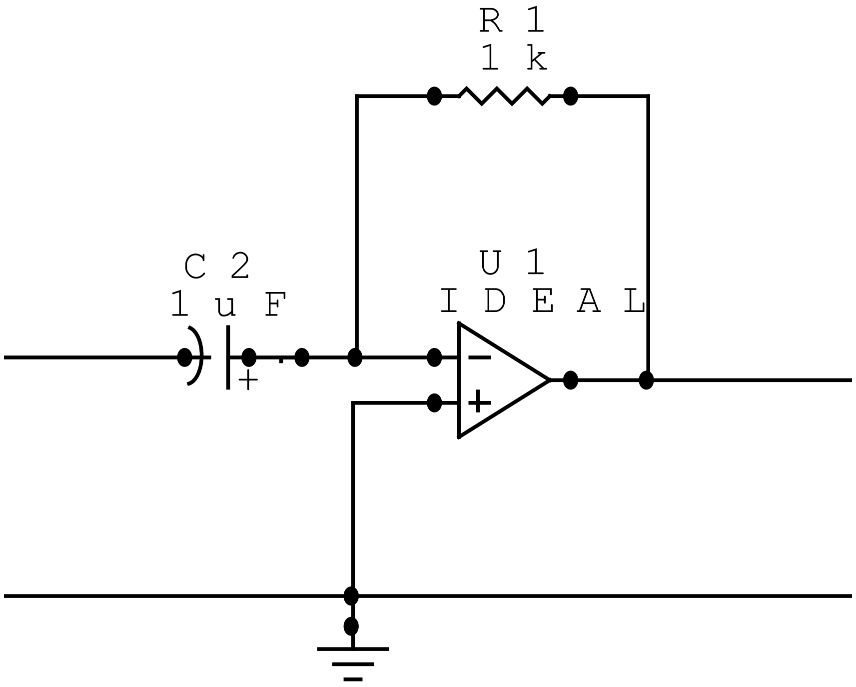
$$V1(s) = R \times I(s)$$

$$v2(t) = -\frac{1}{C}\int i(t)dt$$

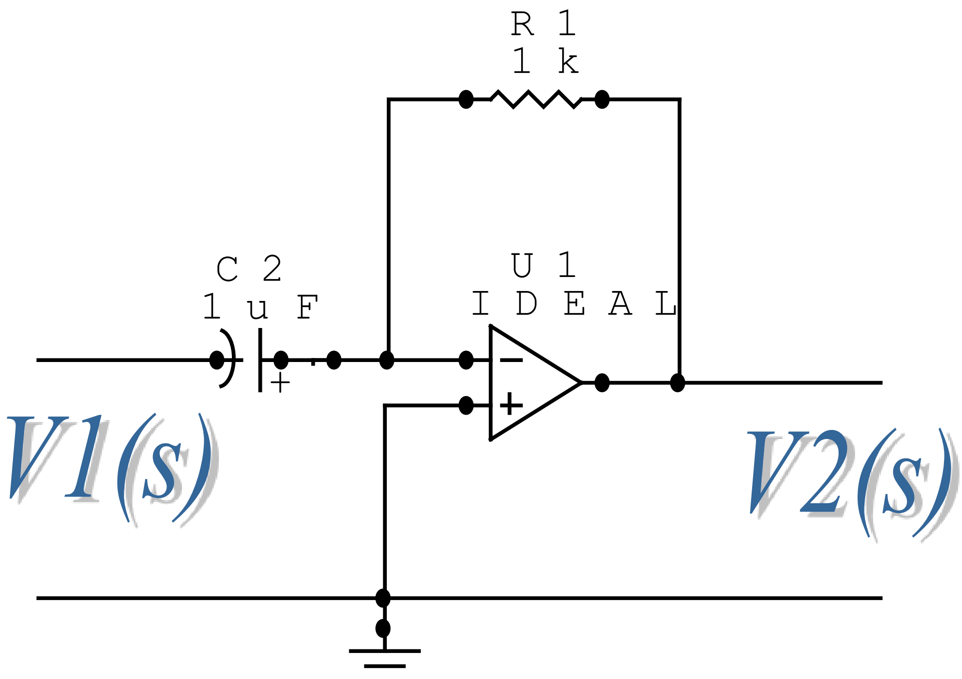
$$V2(s) = -\frac{1}{sC} \times I(s)$$

$$\frac{V_2(s)}{V_1(s)} = -\frac{1}{RCs}$$

Differentiating Circuit



Differentiating Circuit

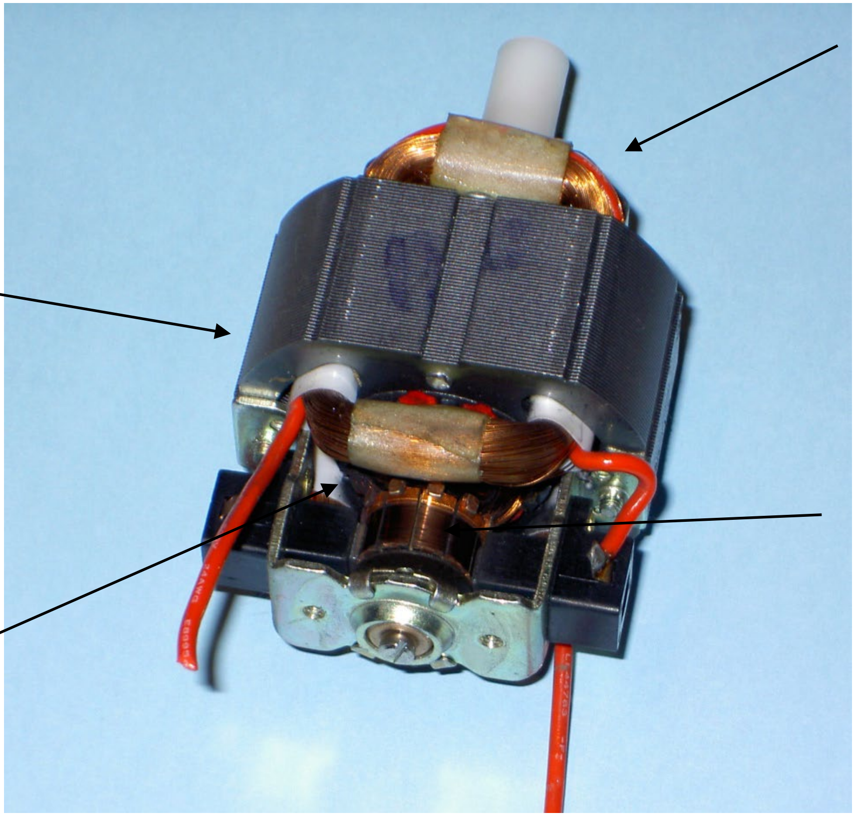


$$\frac{V_2(s)}{V_1(s)} = -RCs$$

DC Motor Physical Structure

Field coils

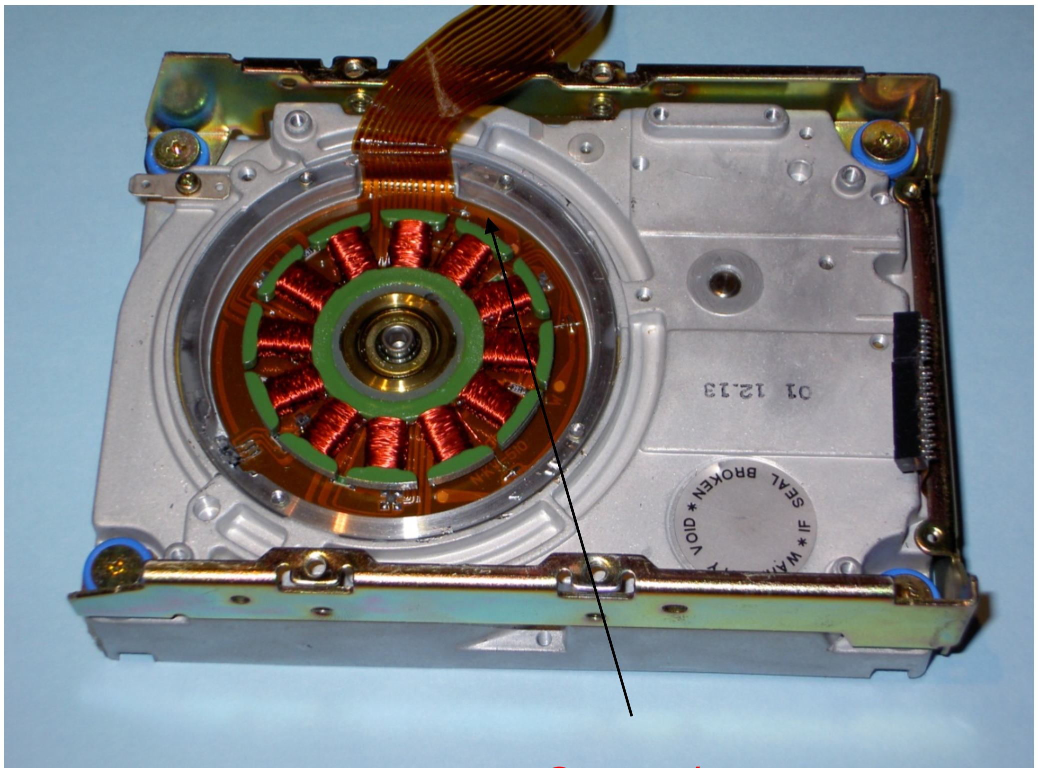
Stator
Field Frame
or yoke,
Field Pole



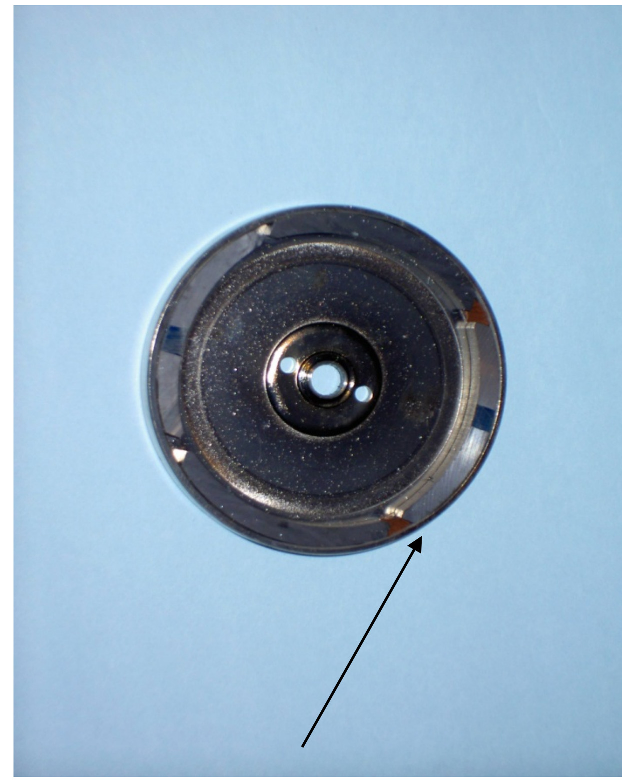
Commutator

Rotor
Armature and
Commutator

BLDC -Hard Disk Spindle Motor



Stator /
Field Pole



Permanent Magnet
Rotor

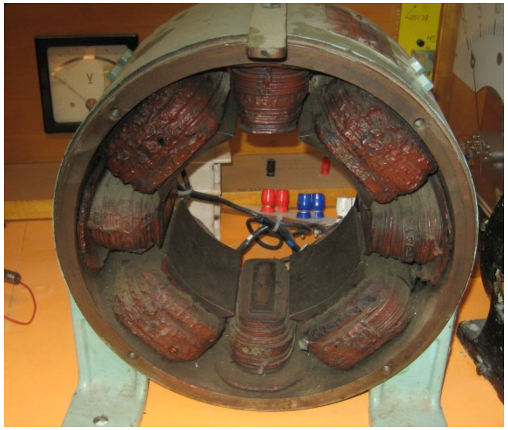
A DC Motor Components: Armature / Rotor and Stator

1

Rotor

2

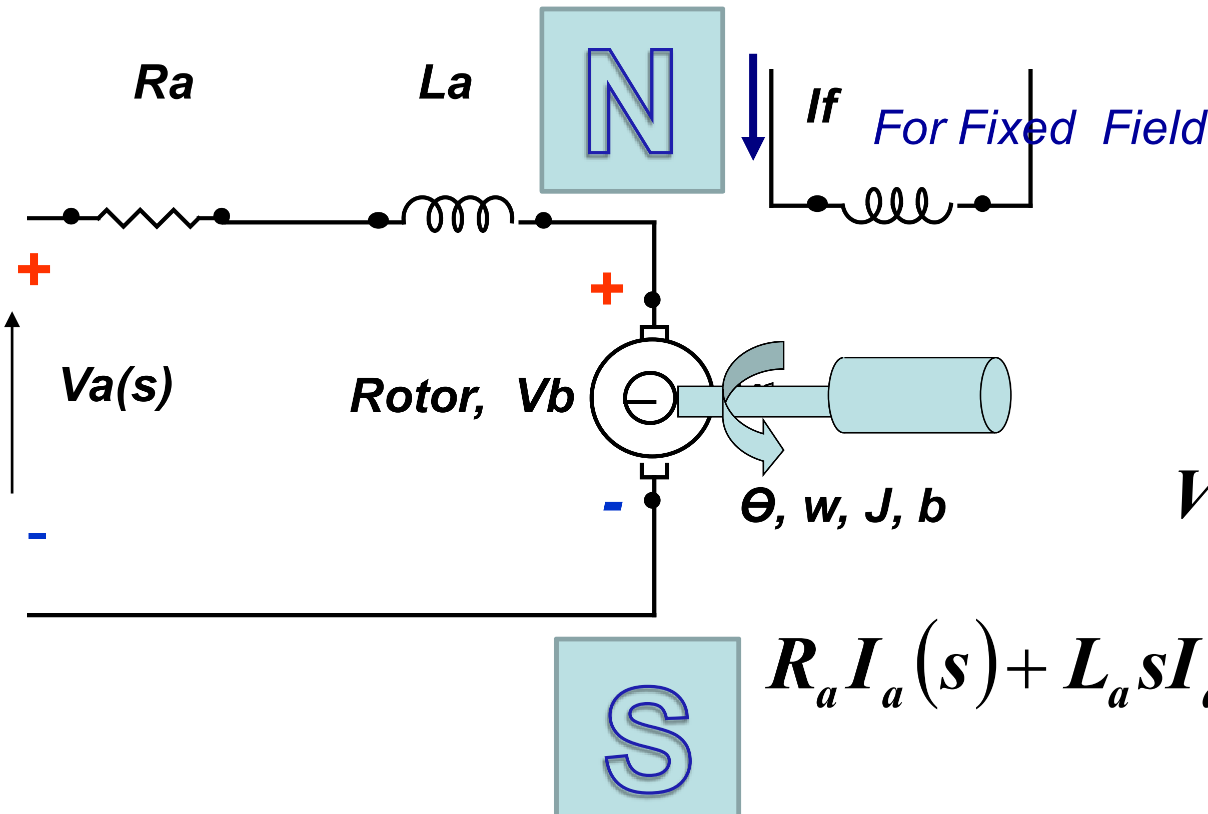
Stator Permanent Magnet,
or Electromagnet like this one



Field Winding /

Field Magnet

DC Motor Armature Controlled with Permanent Magnet, or Fixed Field



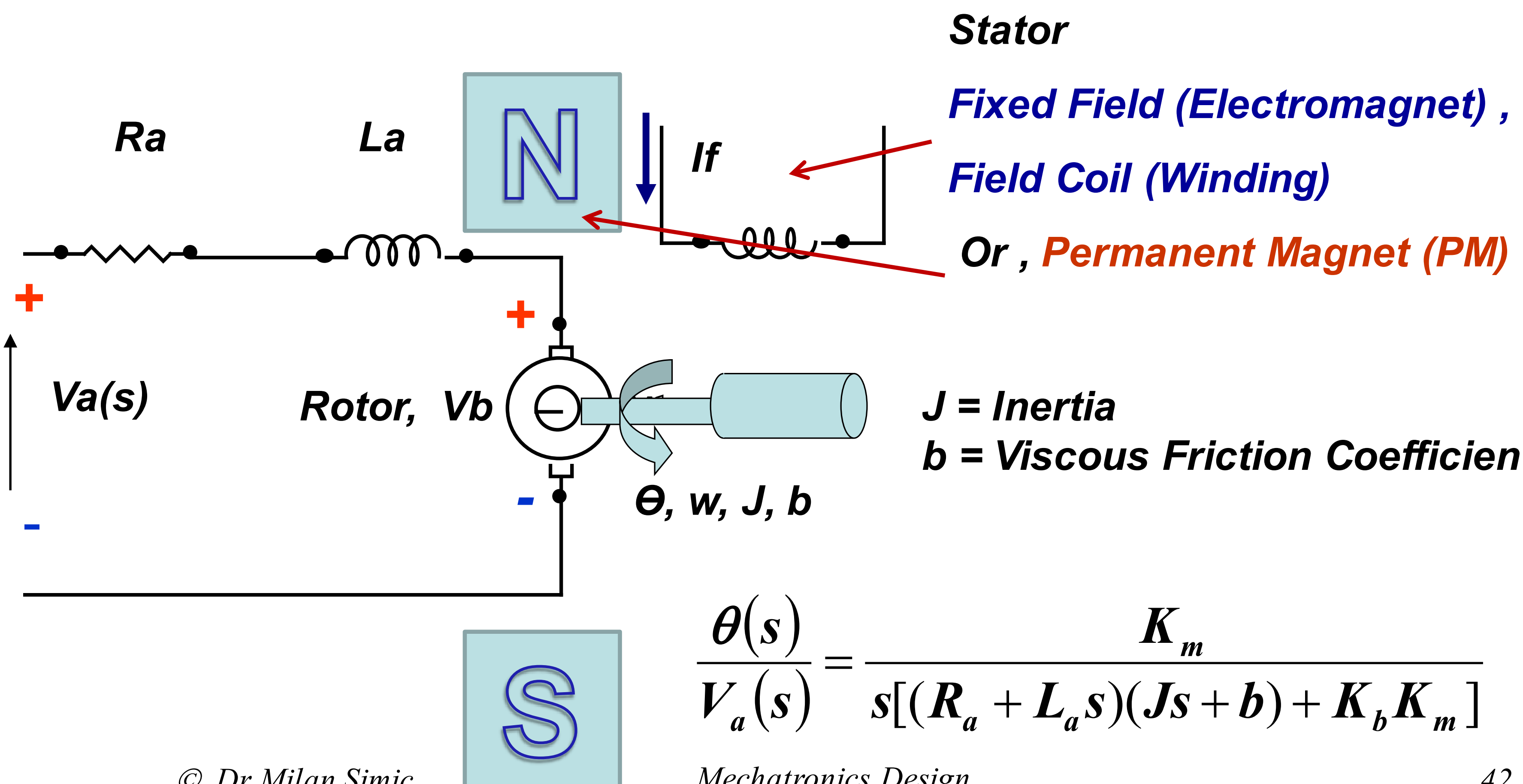
$$e = -\frac{d\phi(t)}{dt}$$

$$v_b(t) = K_b \frac{d\theta(t)}{dt}$$

$$V_b(s) = K_b s\theta(s)$$

$$R_a I_a(s) + L_a s I_a(s) - V_b(s) = V_a(s)$$

DC Motor Armature Controlled with Permanent Magnet, or Fixed Field

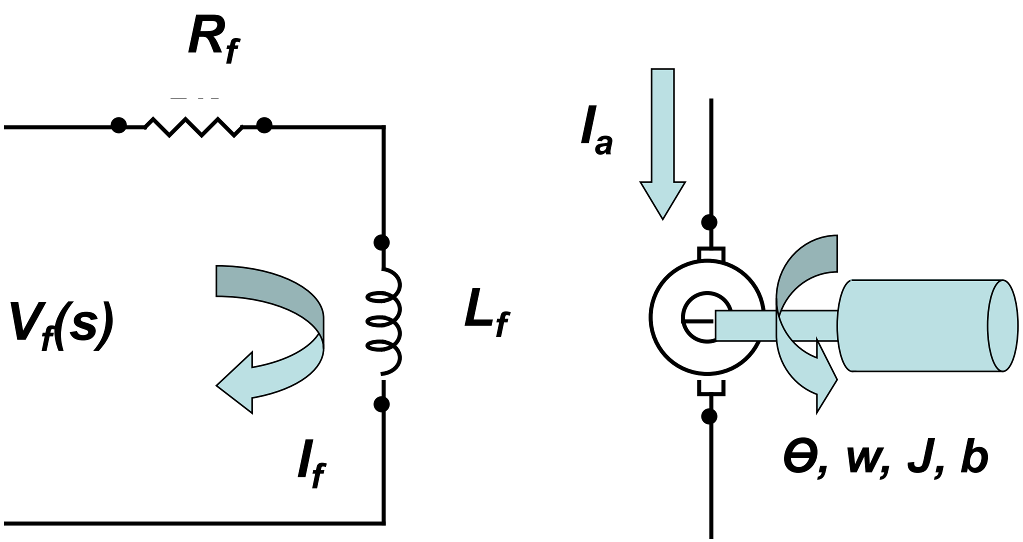


J = Inertia

b = Viscous Friction Coefficient

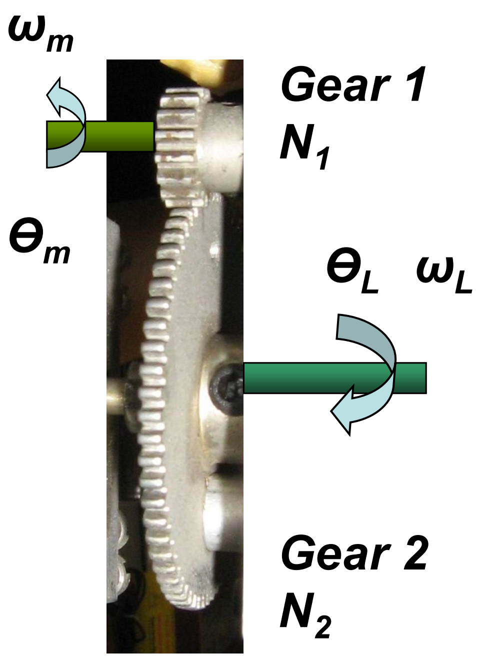
$$\frac{\theta(s)}{V_a(s)} = \frac{K_m}{s[(R_a + L_a s)(Js + b) + K_b K_m]}$$

DC Motor Field Controlled



$$\frac{\theta(s)}{V_f(s)} = \frac{K_m}{s(Js+b)(L_f s + R_f)}$$

Gear Train, Rotational Transformer



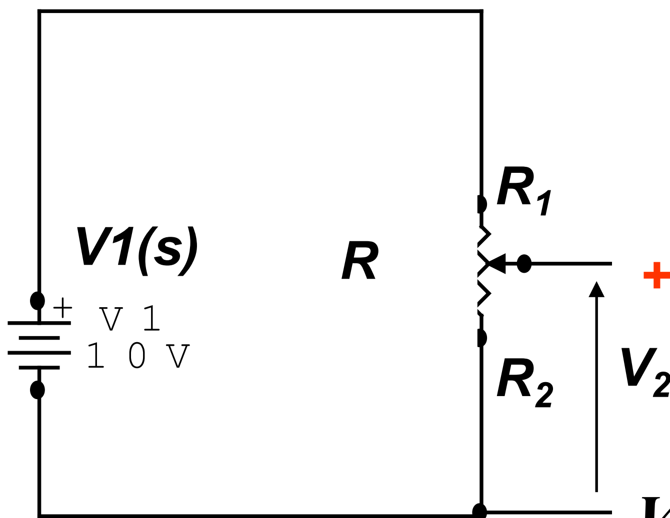
$$\text{Gear Ratio} = \boldsymbol{n} = \frac{N_1}{N_2}$$

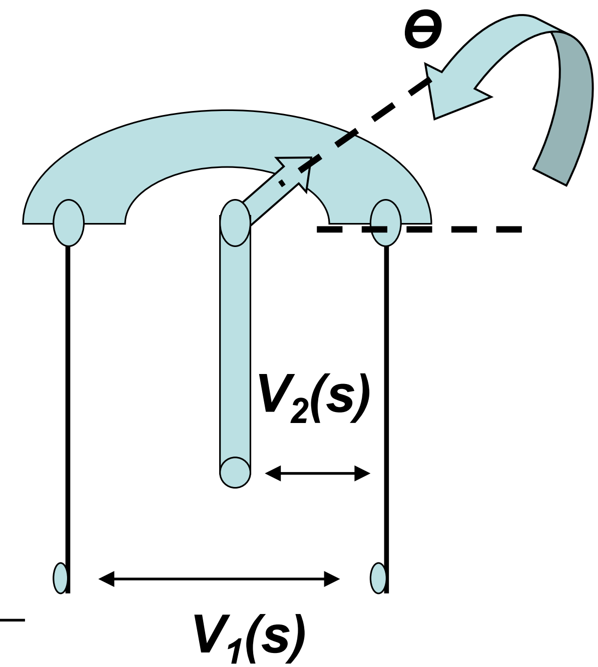
$$N_2\theta_L = N_1\theta_m$$

$$\theta_L = n\theta_m$$

$$\omega_L = n\omega_m$$

Potentiometer, Voltage Control





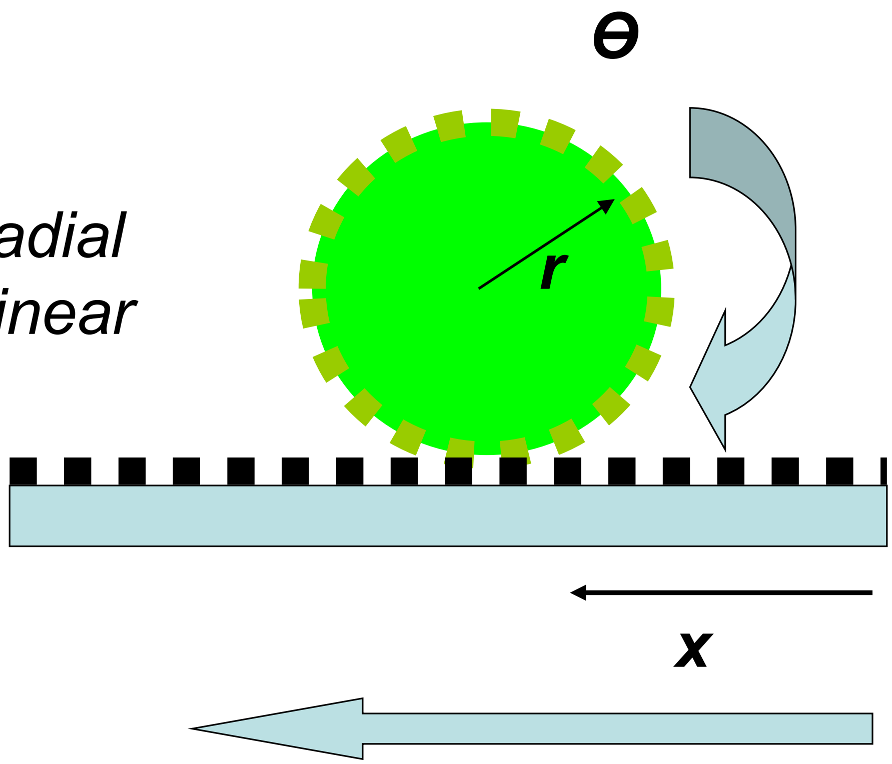
$$\frac{V_2(s)}{V_1(s)} = \frac{R_2}{R} = \frac{R_2}{R_1 + R_2}$$

$$\frac{R_2}{R} = \frac{\theta}{\theta_{\max}}$$

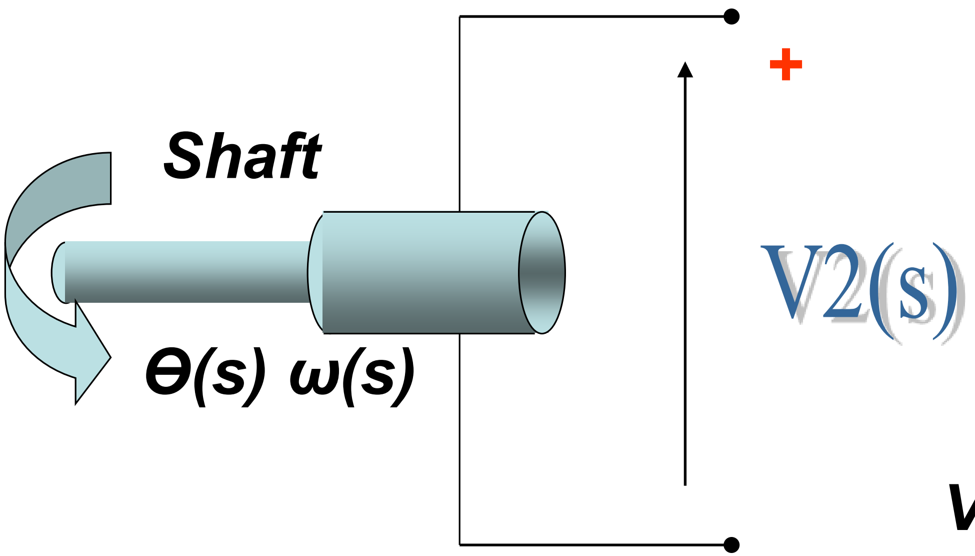
Rack and Pion

$x = r\theta$

Converts radial motion to linear motion



Tachometer, Velocity Sensor



$V2(s) = K_t w(s) = K_t s\Theta(s)$

K_t = constant

Block Diagram Models

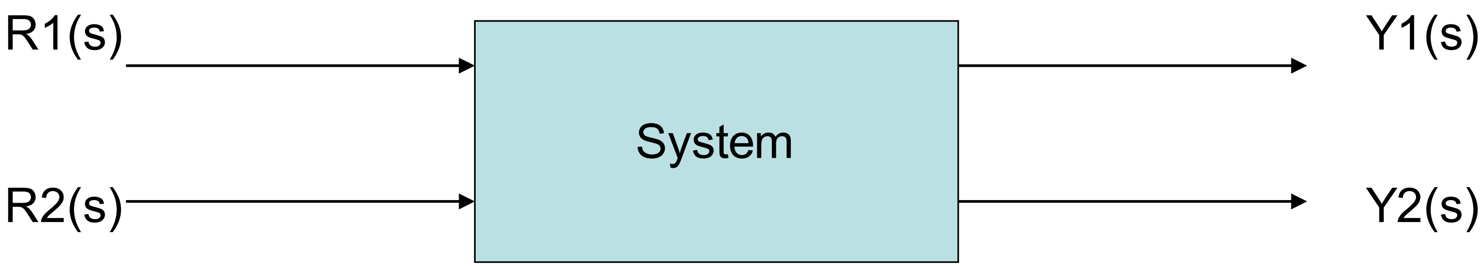
- Dynamic systems that contain automatic control sub-systems can mathematically be represented by a set of simultaneous differential equations.
- Application of Laplace transform simplifies solutions to the domain of linear algebraic equations.
- The block diagram representation of the control system is widely used in the system design.

Block Diagram

- Block diagram consists of unidirectional operational blocks that represent transfer functions of the variables involved.
- A block diagram of previously analysed DC motor (field controlled) is shown below.

$$V_f(s) \longrightarrow \boxed{G(s) = \frac{K_m}{s(Js+b)(L_f + R_f)}} \longrightarrow \Theta(s)$$

Complex System

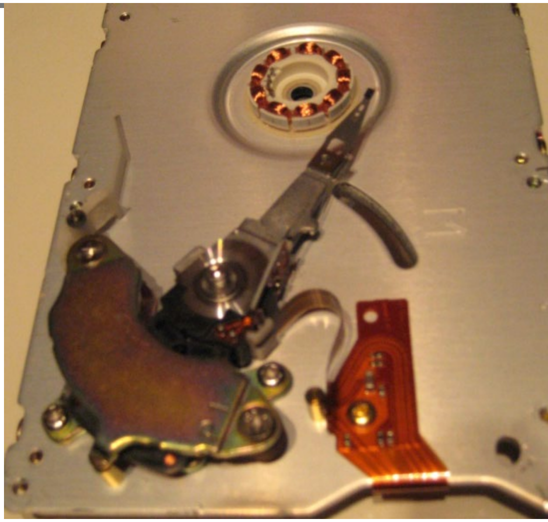


Y1(s)=G11(s)R1(s)+G12(s)R2(s)
Y2(s)=G21(s)R1(s)+G22(s)R2(s)

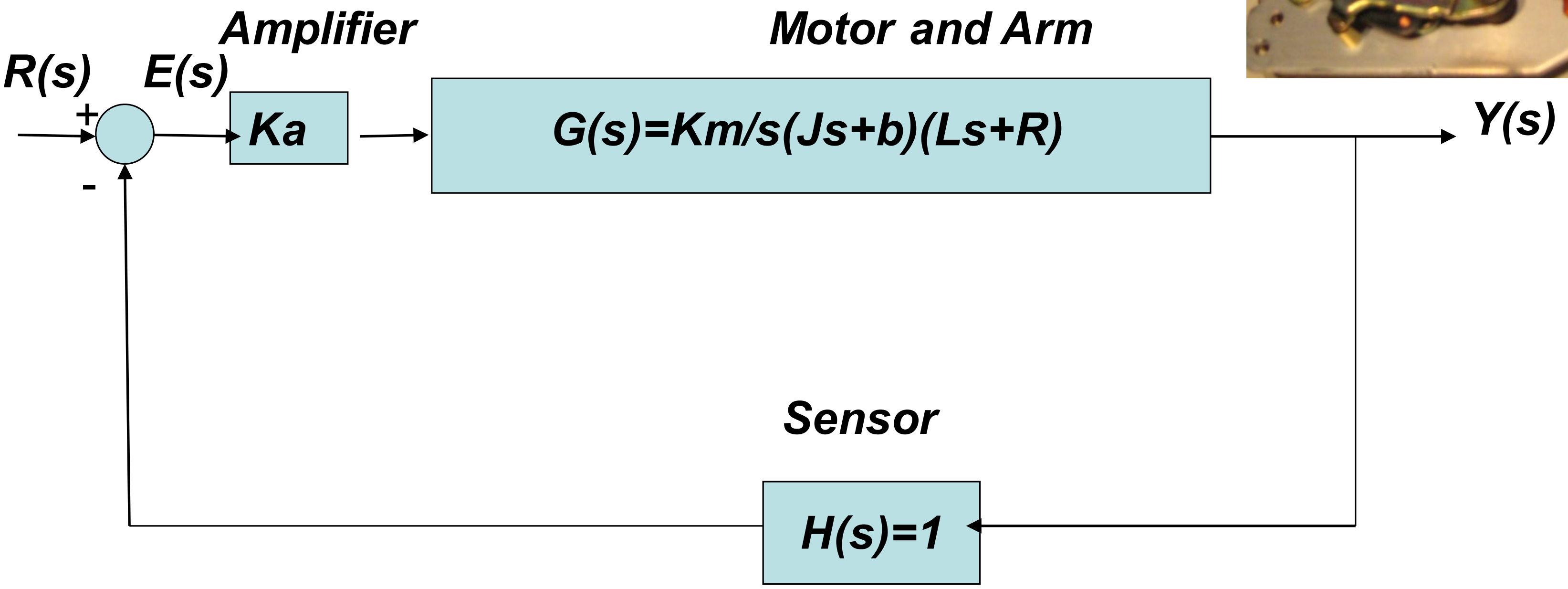
We can have ***m*** inputs and ***n*** outputs

Y=GR
where *G* is a *mxn transfer function* matrix and
Y and **R** are column matrices

Example



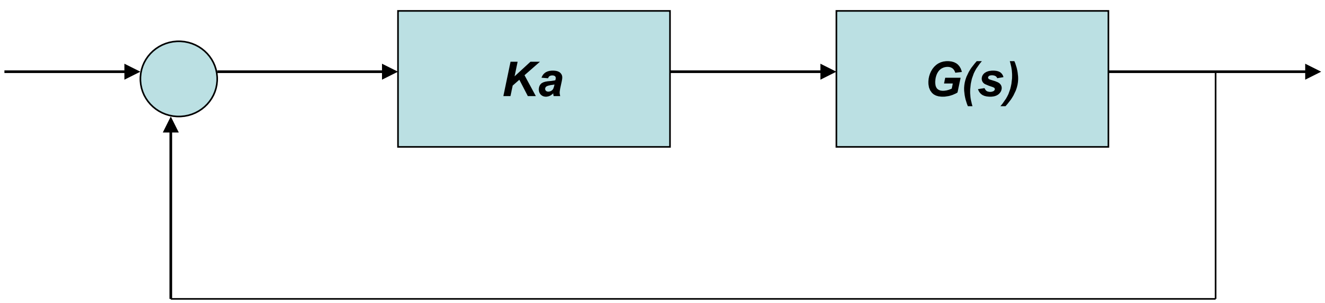
Disk drive R/W system block diagram



Find transfer function of this system

Solution

$$\frac{Y(s)}{R(s)} = \frac{K_a G(s)}{1 + K_a G(s)}$$



Resources

- De Silva, C. W. *Mechatronics: an integrated approach*, CRC Press, 2005.
- Necsulescu, D. *Mechatronics*, Prentice-Hall, 2007.
- Bishop, R.H. *LabVIEW 8, Student Edition*, Pearson Prentice-Hall, 2007.
- **Online@RMIT (Learning Hub)** **http://www.rmit.edu.au/online**
  - Lecture Notes, Labs, Project, Assessment
- Engineering Journal (You will create it during the course)

Thank you,
Questions