Mechatronic Instrumentations

003.0

Introduction

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Basic Concepts of Actuators

An actuator is a device that actuates or moves an object within a system. More specifically, an actuator is a device that *coverts energy into motion* or mechanical energy. Therefore, an actuator is a specific type of a transducer

Thermal Actuators

One type of thermal actuator is a bimetallic strip. This device directly converts thermal energy into motion. This is accomplished by utilizing an effect called thermal expansion.

Kinetic Energy Increase Causes Atoms requiring bigger space than normal

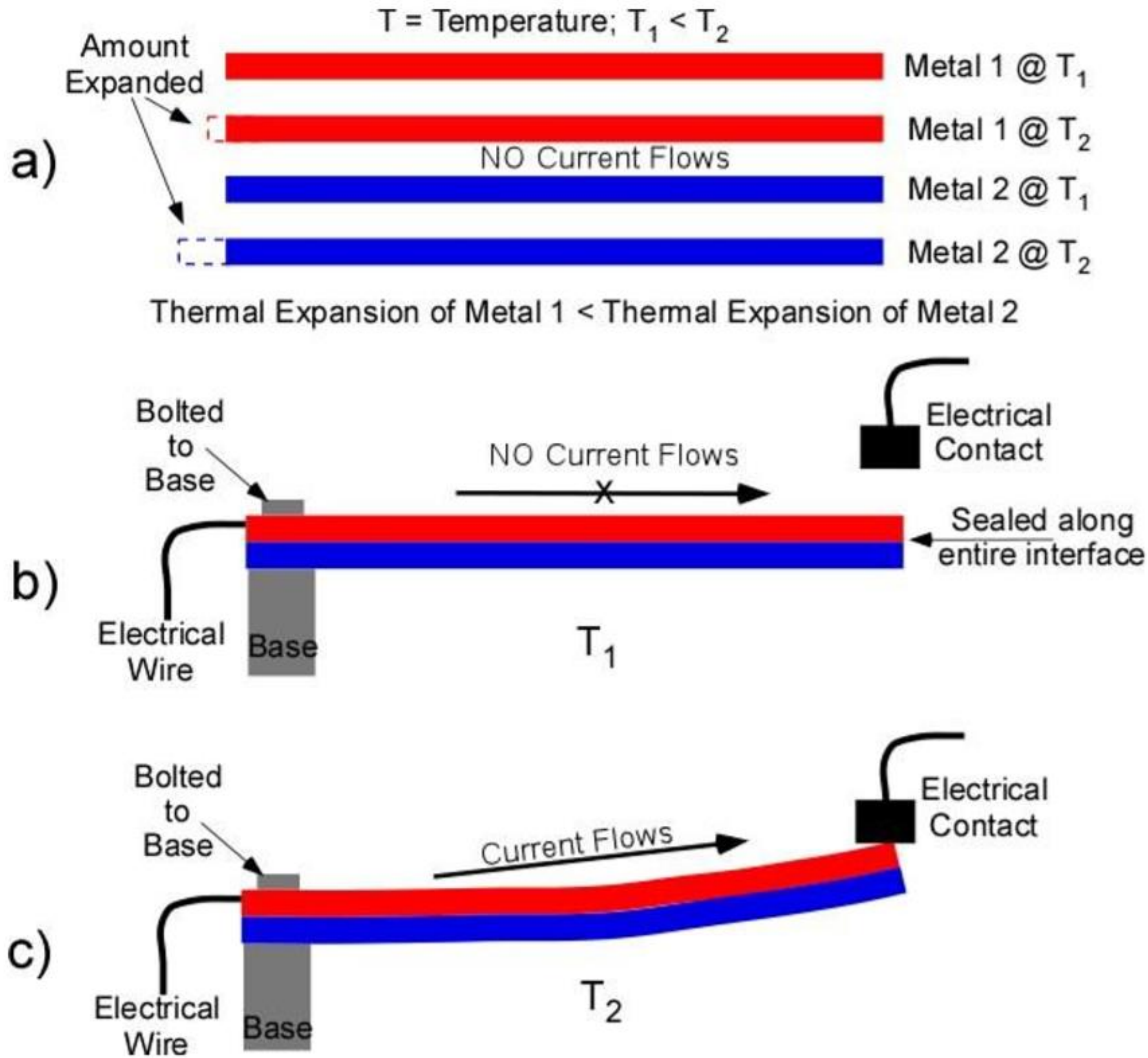
Thermal expansion is the manifestation of a change in thermal energy in a material. When a material is heated, the average distance between atoms (or molecules) increases. The amount of distance differs for different types of material. This microscopic increase in distance is unperceivable to the human eye. However, because of the huge numbers of atoms (or molecules) in a piece of material, the material expands considerably and, at times, is noticeable to the human eye.

Displacement due to temperature

- Consider a piece of steel 25 meters long. If the temperature of the steel increases by 36°C, (the difference between a cold winter day and a hot summer day), that piece of steel lengthens approximately 12 cm. This change in length is the thermal linear expansion. It is calculated by using the following formula:

$$\Delta L = a\, L_o\, \Delta T$$

- Where, ΔL is the change in length, a is the coefficient of linear expansion, L_o is the original length, and ΔT is the change in temperature in Celsius. If we are considering steel, the coefficient of linear expansion is $1.3\text{x}10^{-5}$, the original length is 25 meters, and of course the change of temperature is 36°C. This results in an expansion of 11mm

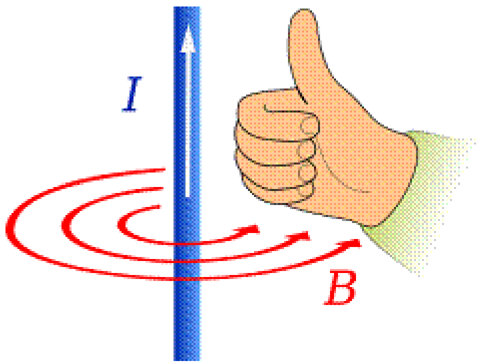

T = Temperature; $T_1 < T_2$
Amount Expanded
a)
Metal 1 @ T_1
Metal 1 @ T_2
NO Current Flows
Metal 2 @ T_1
Metal 2 @ T_2
Thermal Expansion of Metal 1 < Thermal Expansion of Metal 2
b)
Bolted to Base
NO Current Flows
Electrical Contact
Sealed along entire interface
Electrical Wire
Base
T_1
c)
Bolted to Base
Current Flows
Electrical Contact
Electrical Wire
Base
T_2

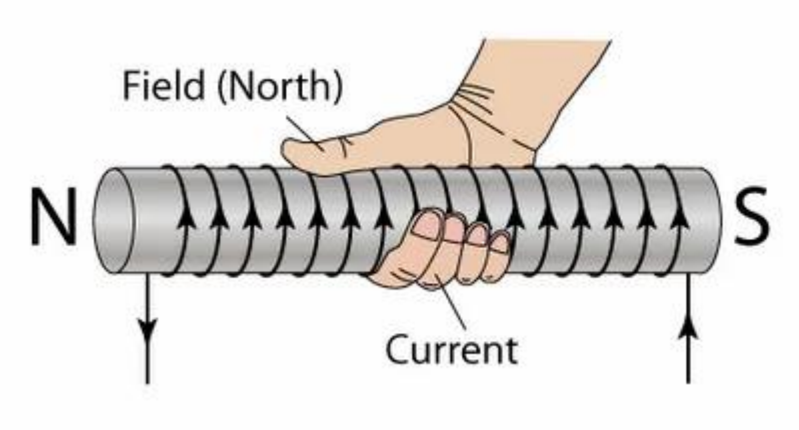
Mechanical Actuator

Mechanical actuators convert a mechanical input (usually rotary) into linear motion. A common example of a mechanical actuator is a screw jack. The figure below shows a screw jack in operation. Rotation of the screw causes the legs of the jack to move apart or move together. Inspecting the motion of the top point of the jack, this mechanical rotational input is clearly converted into linear mechanical motion.

Electric Actuator

Fleming's Hand Rule





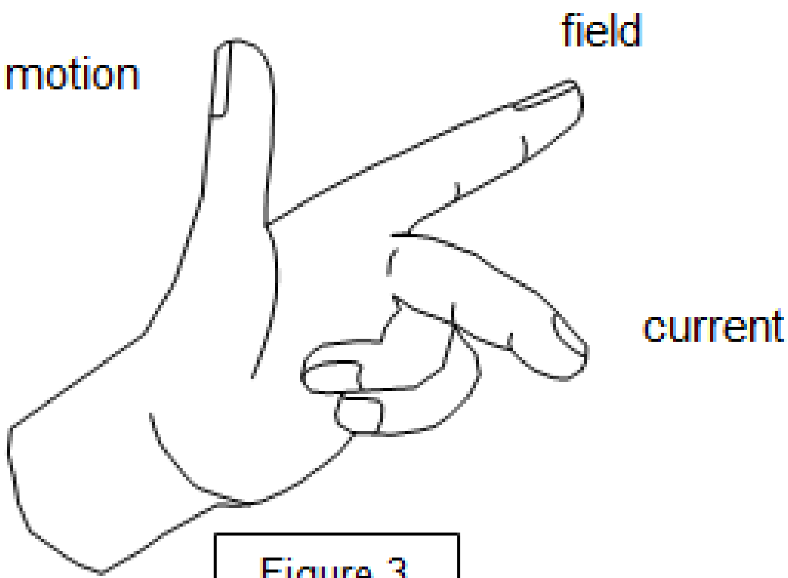


Figure 3

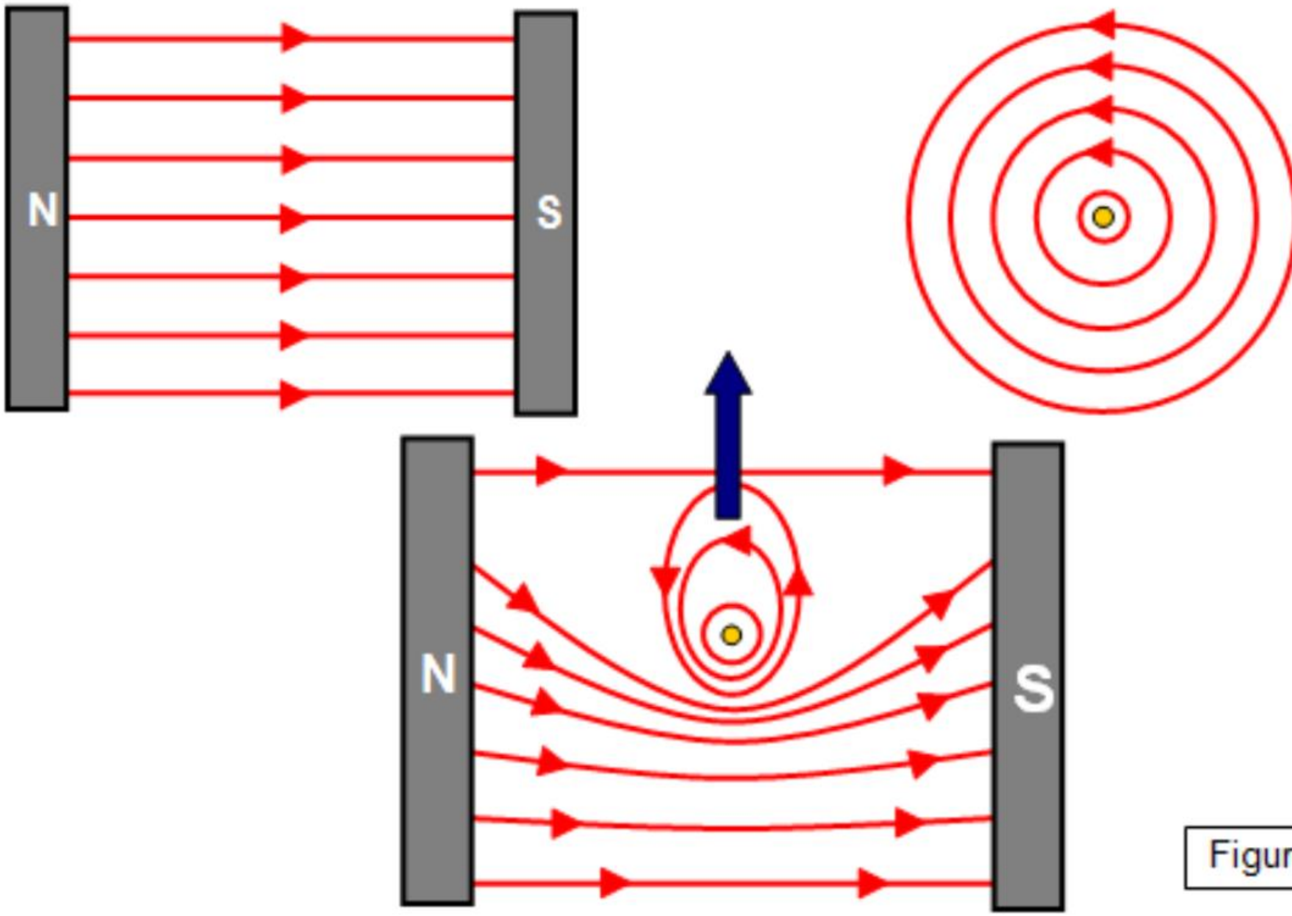
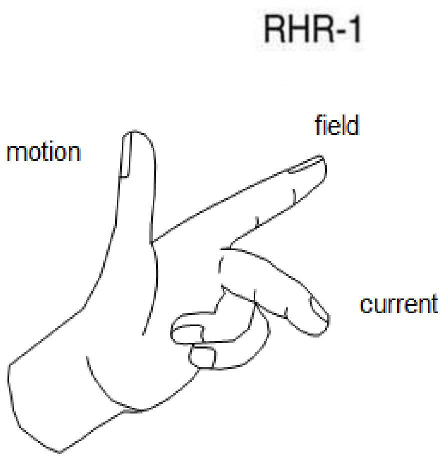
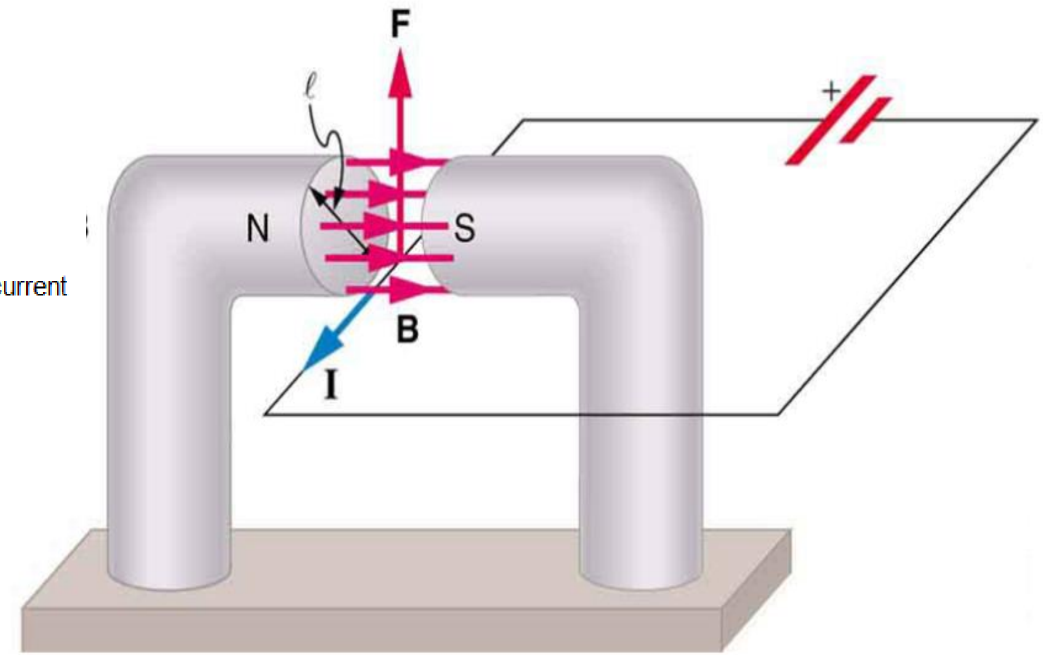


Figure 4

Current Carrying Conductor in Magnetic Field

Because charges ordinarily cannot escape a conductor, the magnetic force on charges moving in a conductor is transmitted to the conductor itself.





The magnetic field exerts a force on a current-carrying wire in a direction given by the right hand rule 1 (the same direction as that on the individual moving charges). This force can easily be large enough to move the wire, since typical currents consist of very large numbers of moving charges.

Principles of Electric motor (Electromechanical actuators)

$$\boldsymbol{F = IlB\sin\Theta}$$

Where:

- $\boldsymbol{F,\ is\ the\ force,}$
- $\boldsymbol{I, is\ the\ electric\ current}$
- $\boldsymbol{l, length\ of\ the\ conductor}$
- $\boldsymbol{B, is\ the\ magnetic\ flux\ density}$
- Θ, ***is the angle between the current and the flux***

Exercise

- **Calculate the force on the wire shown in the previous figure, given B = 1.50 [T], l = 5.00 [cm], and I = 20.0 [A].**

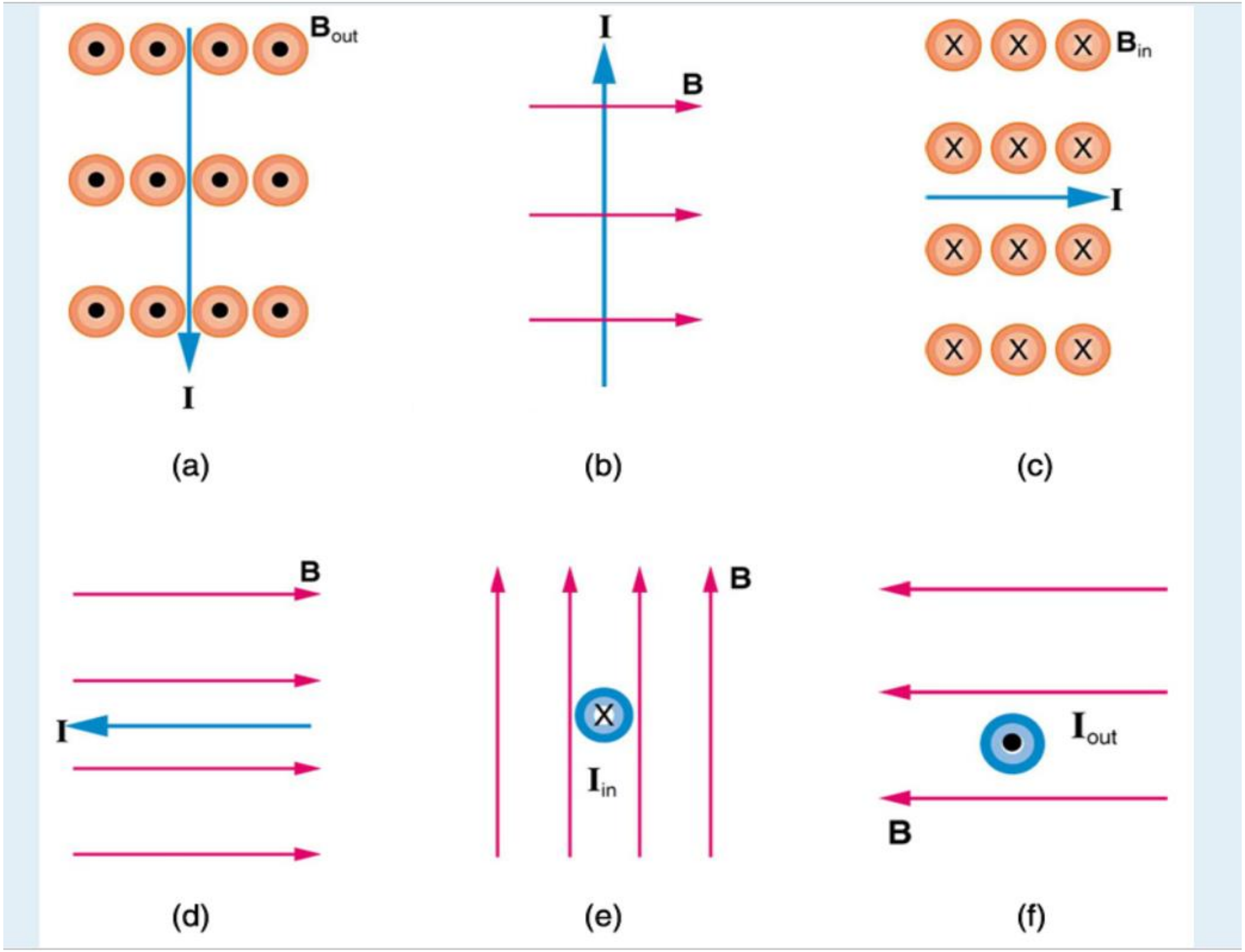
Solution

$$F = IlB\sin\Theta$$

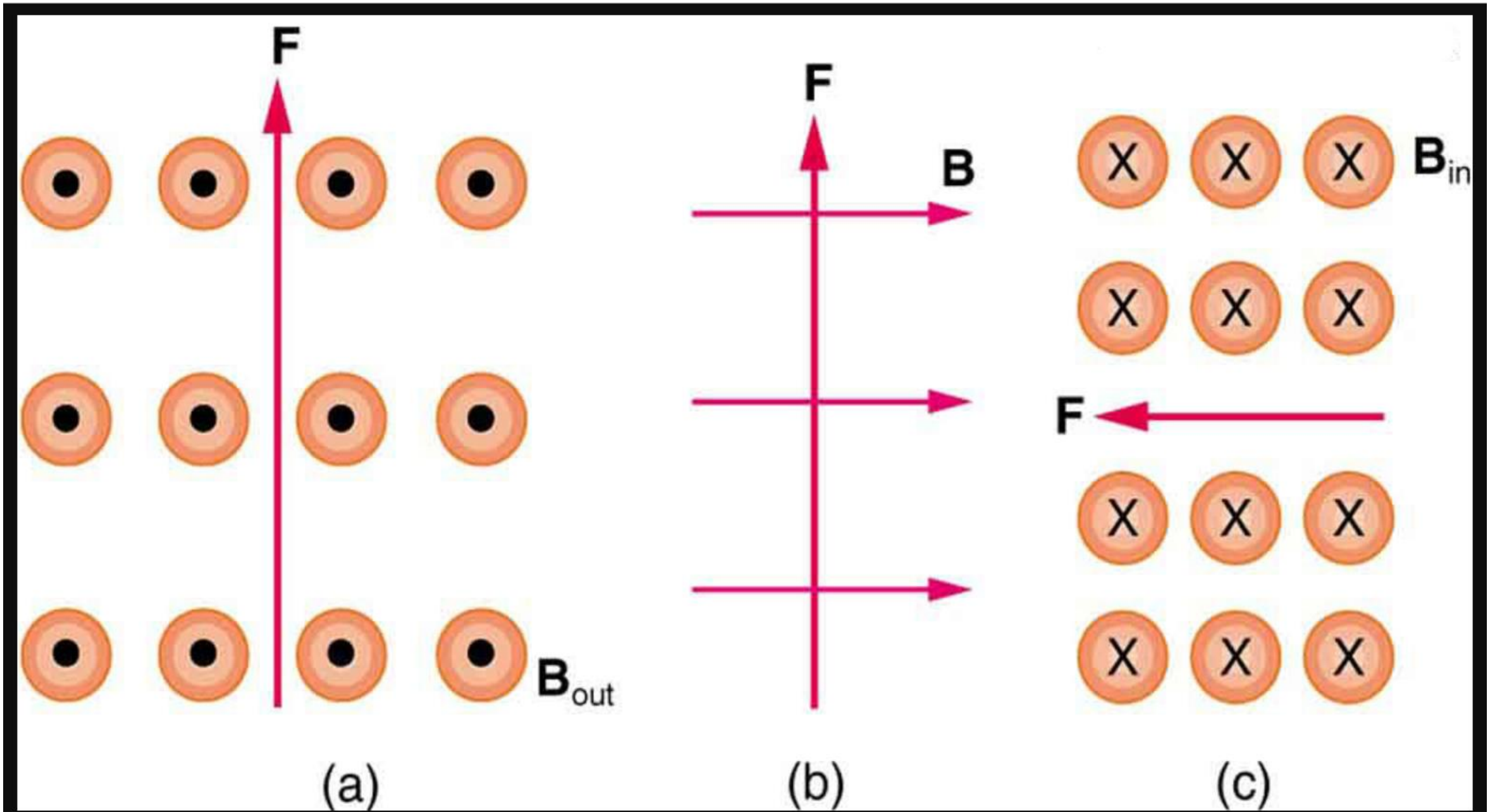
- Θ=90º
- $F[N] = 20\ x\ 0.05\ x\ 1.5\ x\ \sin(90)$
- $F[N] =$ **1.5 N**

- **Imagine you have a coil of n turns placed in side a magnetic flux B ?**

Question: Determine the direction of the force in the following cases



<u>Question</u>: What is the direction of the electric current that experienced these forces inside the magnetic field shown

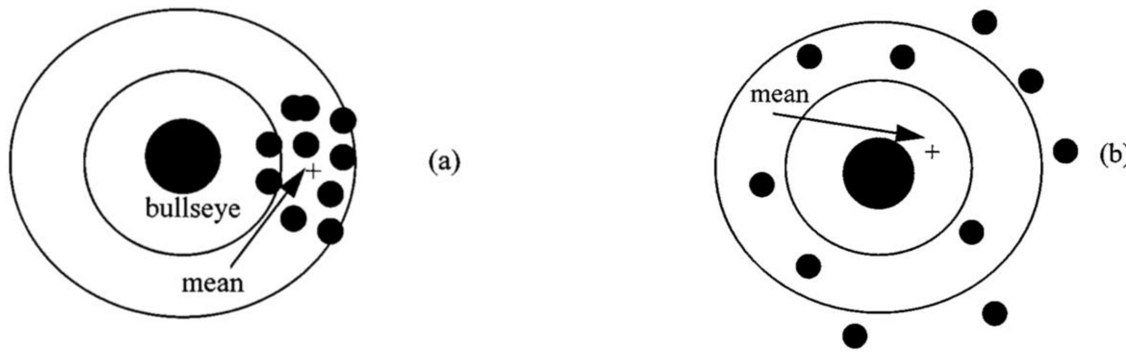


Characteristics of instruments

Measurement is a process of mapping actually occurring variables into equivalent values. Deviations from perfect measurement mappings are called errors:

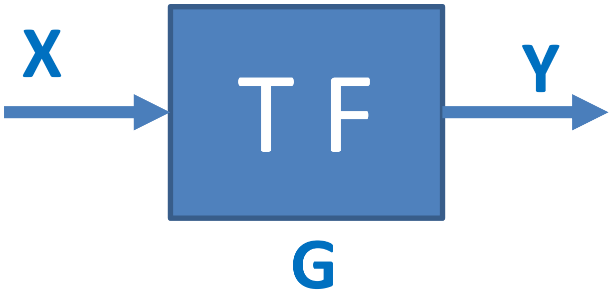
Characteristics of Instrument

- Static Characteristics of Instrument Systems Output/Input Relationship
- Drift
- Hysteresis and Backlash
- Saturation
- Bias
- Error of Nonlinearity


bullseye
mean
(a)
mean
(b)

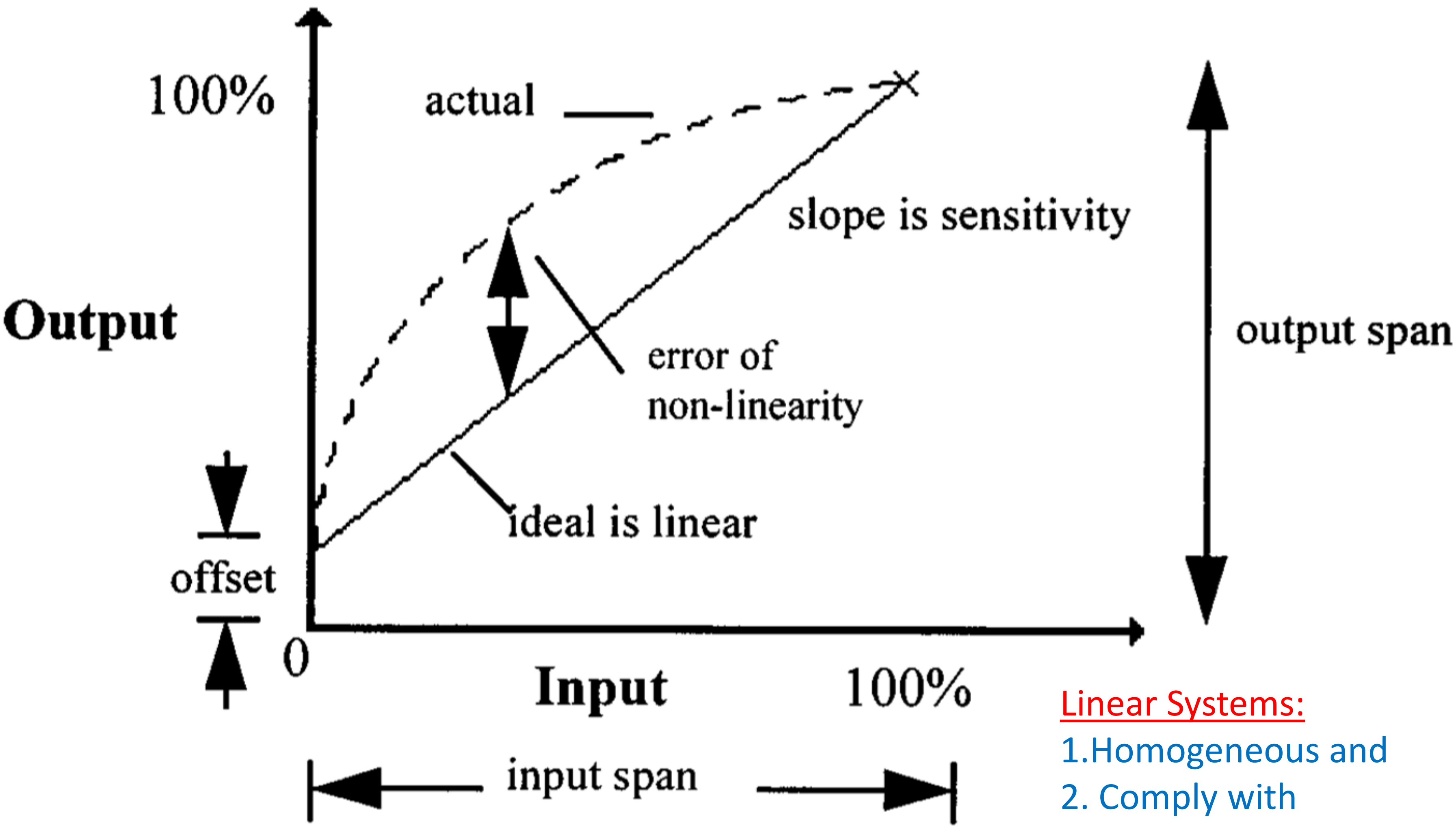
Transfer Function

- T F = Ratio of Output to Input
- $TF = \frac{Output}{Input} = \frac{Y}{X} = G$



- Systems that are consisting of subsystems $TF_{total} = G_1 x G_2 x G_3 \cdots$

Typical input-output characteristic curve of an instrument



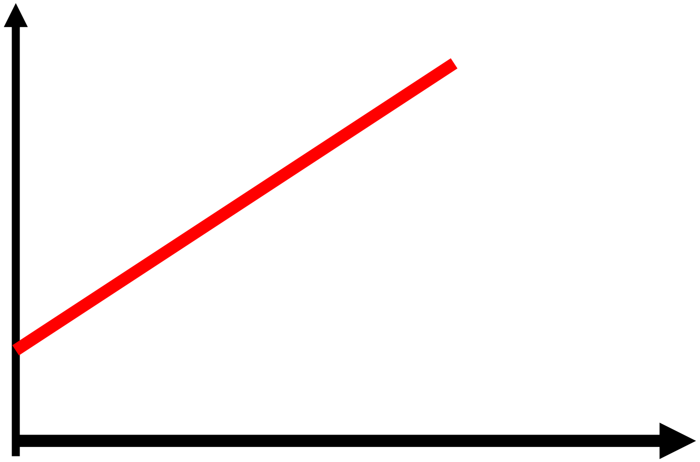
<u>Linear Systems:</u>

1.Homogeneous and

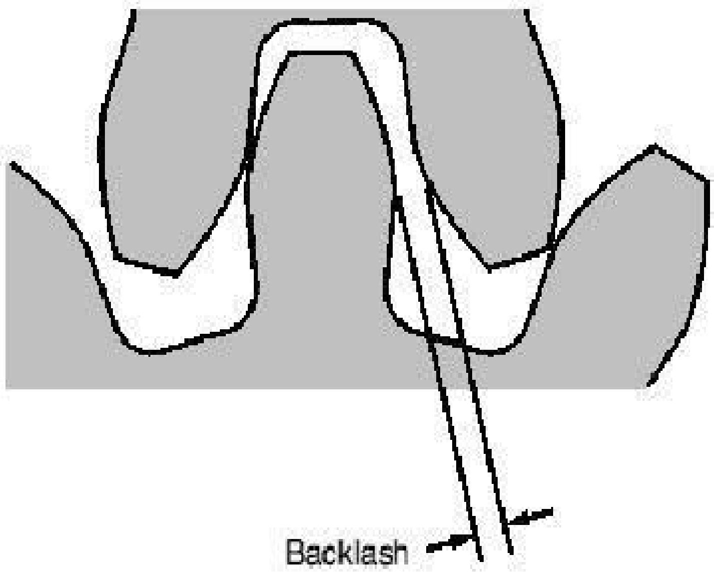
2. Comply with Superposition

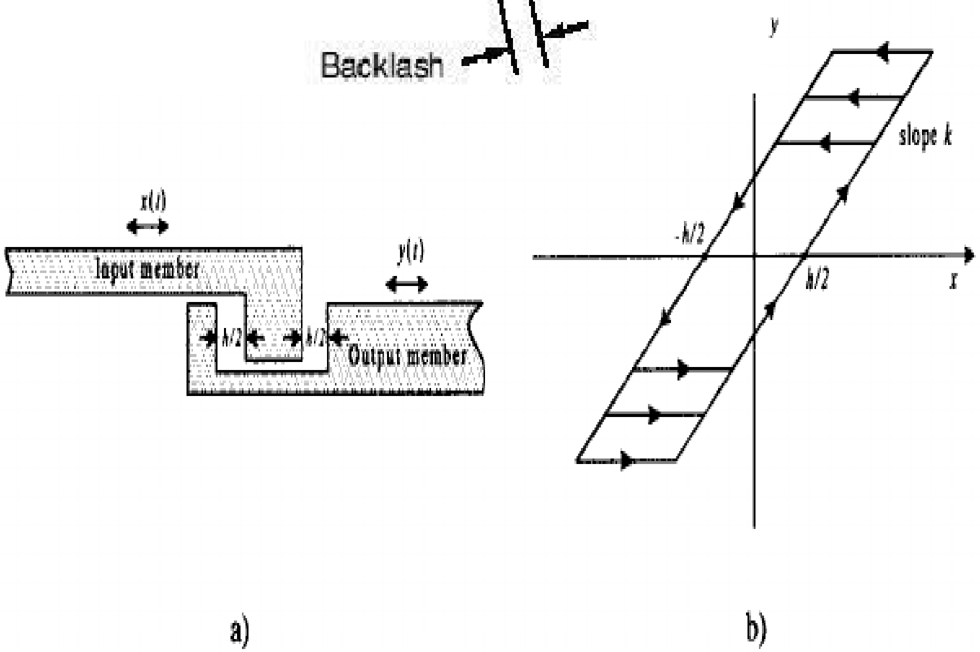
Drift

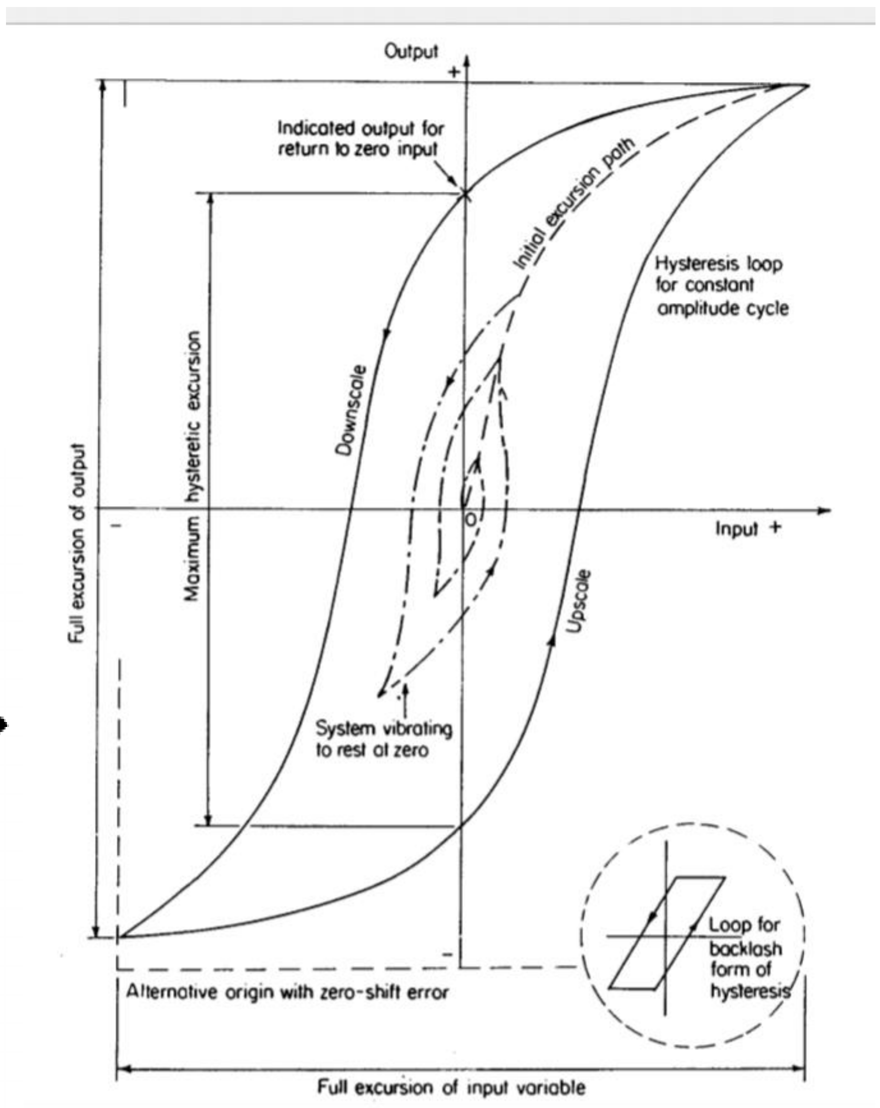
- Slackening of spring and stretchir
- DC voltage drift in amplifier



Hysteresis and Backlash

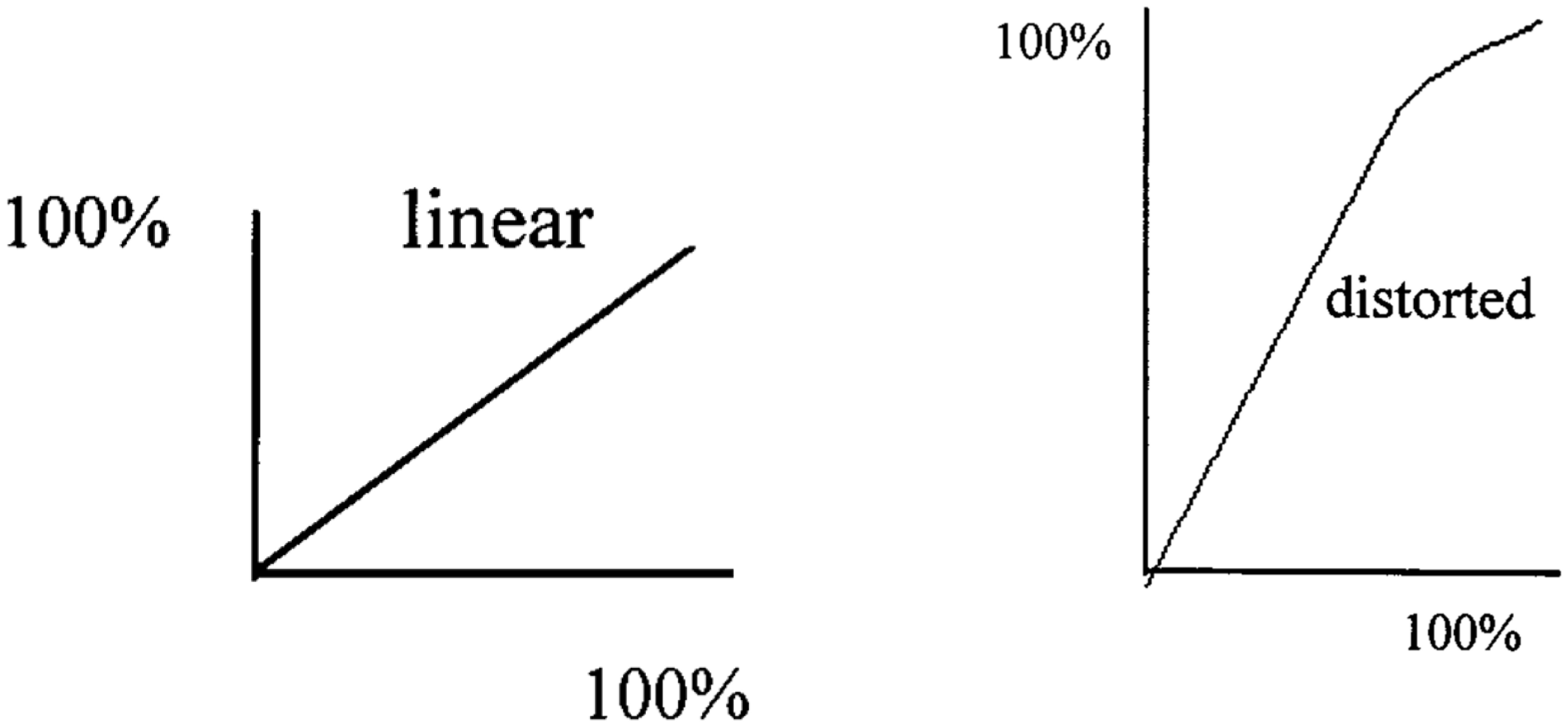






Saturation

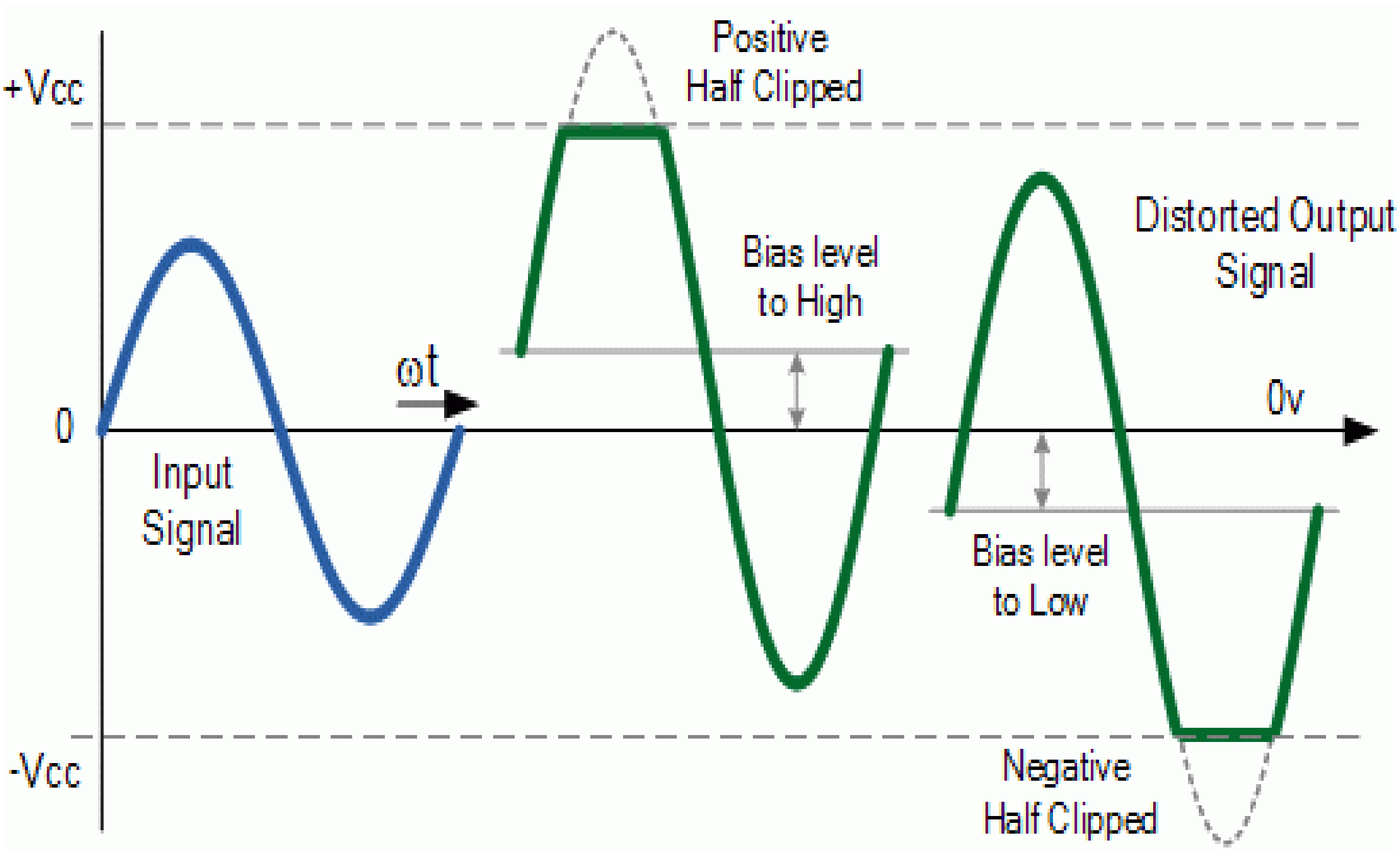
Measurements are linear over certain part of the characteristic curve. (compression at top end)



Bias

- **Sometimes, the electronic signal processing situation calls for the input signal to be processed at a higher average voltage or current than arises normally. Here a dc value is added to the input signal to raise the level to a higher state as shown in Figure 3.10. A need for this is met where only one polarity of signal can be amplified by a single semiconductor element. This is usually done to overcome noise.**

Error due to nonlinearity



Dynamic Characteristics of Instrumentation Systems

- Due to high nonlinearity in characteristic of most instrumentation systems, finding a precise mathematical formula is not always an easy task. However generic formulas can be developed for limited spans of input variables. This way the characteristic curve can then be divided into zones each having its own formula (Transfer Function), this is called linearization.
- Lookup Tables in computers and other digital systems can provide good solution, but these remains: non-mathematical; experimental; and/or numerically obtained (usually iterative) models.

- $\boldsymbol{a_2 \frac{d^2y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)}$
- Laplace Transform Form

$$a_2 Y(s) + a_1 Y(s) + a_0 Y(s) = X(s)$$

$$T.F. = \frac{Y(s)}{X(s)} = \frac{1}{a_2 s^2 + a_1 s + a_0}$$

Laplace Transform

Item no.	$f(t)$	$F(s)$
1.	$\delta(t)$	1
2.	$u(t)$	$\frac{1}{s}$
3.	$tu(t)$	$\frac{1}{s^2}$
4.	$t^n u(t)$	$\frac{n!}{s^n + 1}$
5.	$e^{-at}u(t)$	$\frac{1}{s+a}$
6.	$\sin \omega t u(t)$	$\frac{\omega}{s^2+\omega^2}$
7.	$\cos \omega t u(t)$	$\frac{s}{s^2+\omega^2}$

$$a_n \frac{d^n c(t)}{dt^n} + a_{n-1} \frac{d^{n-1} c(t)}{dt^{n-1}} + \cdots + a_0 c(t) = b_m \frac{d^m r(t)}{dt^m} + b_{m-1} \frac{d^{m-1} r(t)}{dt^{m-1}} + \cdots + b_0 r(t)$$

$$\frac{C(s)}{R(s)} = G(s) = \frac{(b_m s^m + b_{m-1} s^{m-1} + \cdots + b_0)}{(a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0)}$$

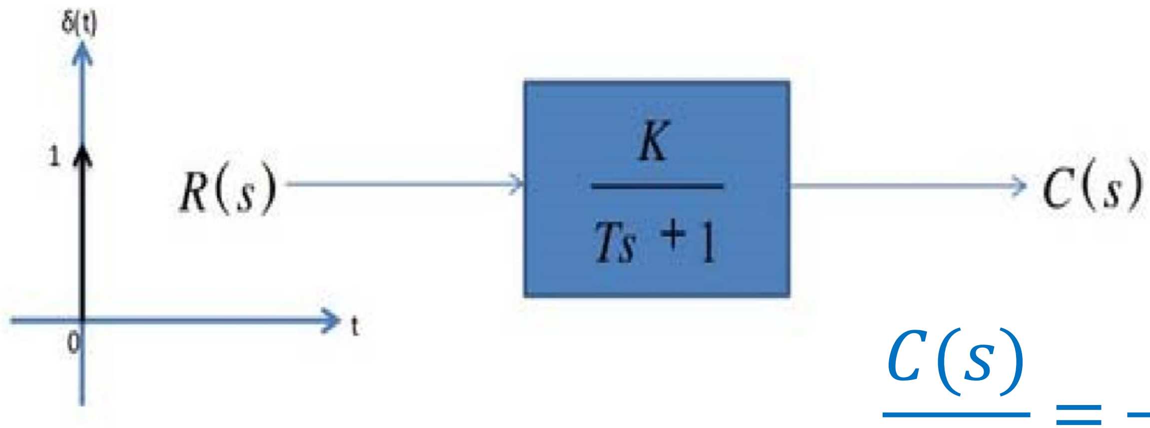
$$R(s) \longrightarrow \boxed{\frac{(b_m s^m + b_{m-1} s^{m-1} + \cdots + b_0)}{(a_n s^n + a_{n-1} s^{n-1} + \cdots + a_0)}} \longrightarrow C(s)$$

Exercise:

- Find the transfer function of the measuring instrument that have the following differential equation for its input/output characteristics

$$\frac{dc(t)}{dt} + 2c(t) = r(t)$$

Impulse Response of First Order System



$$\frac{C(s)}{R(s)} = \frac{K}{Ts+1}$$

$$for\ impulse\ response\ C(s) = \delta(s) = 1$$

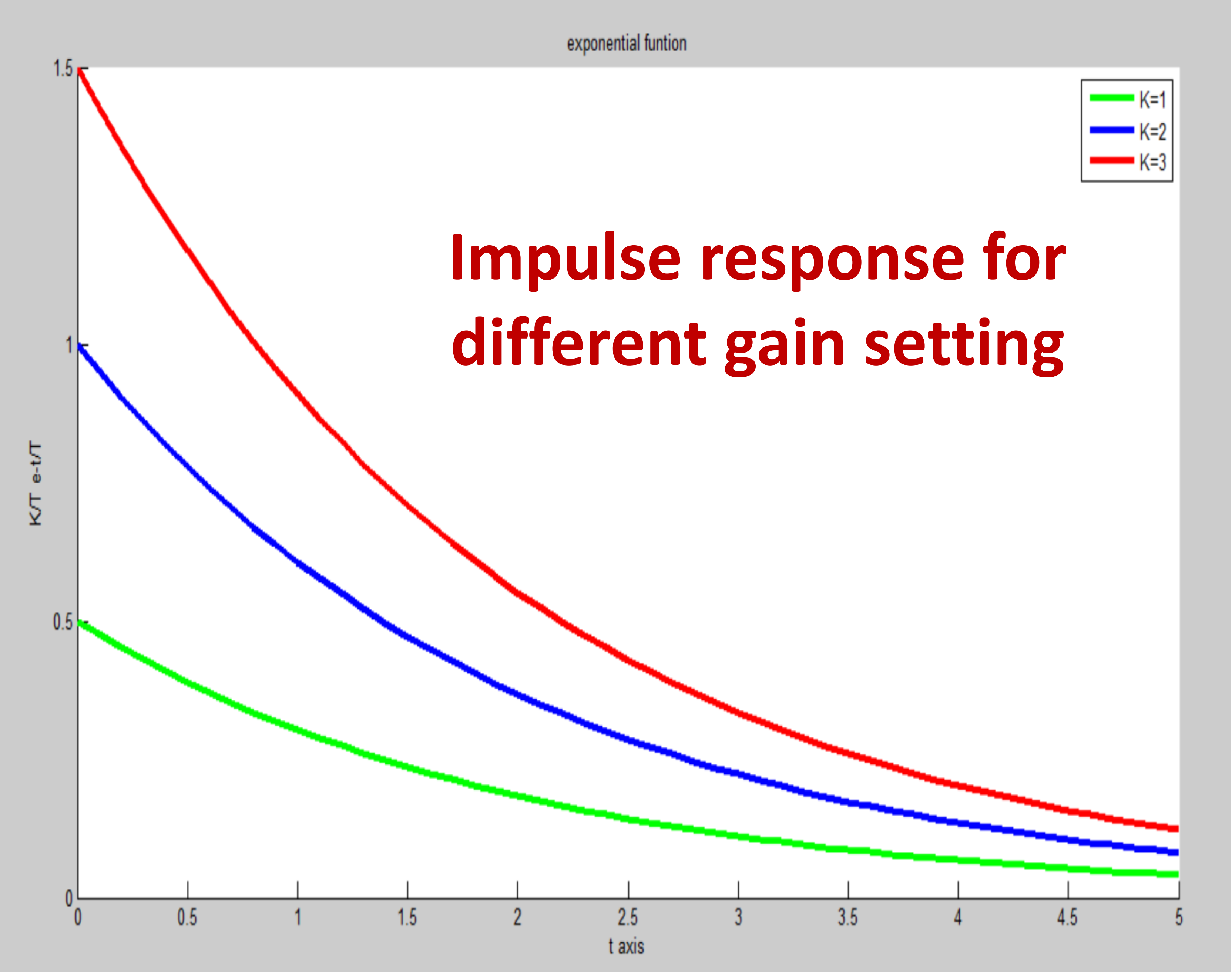
Hence, $C(s) = \frac{K}{Ts+1}$ $\quad$ $c(t) = \frac{K}{T}e^{-\frac{t}{T}}$

Effect of Gain on impulse response

$$c(t) = \frac{K}{T} e^{-\frac{t}{T}}$$

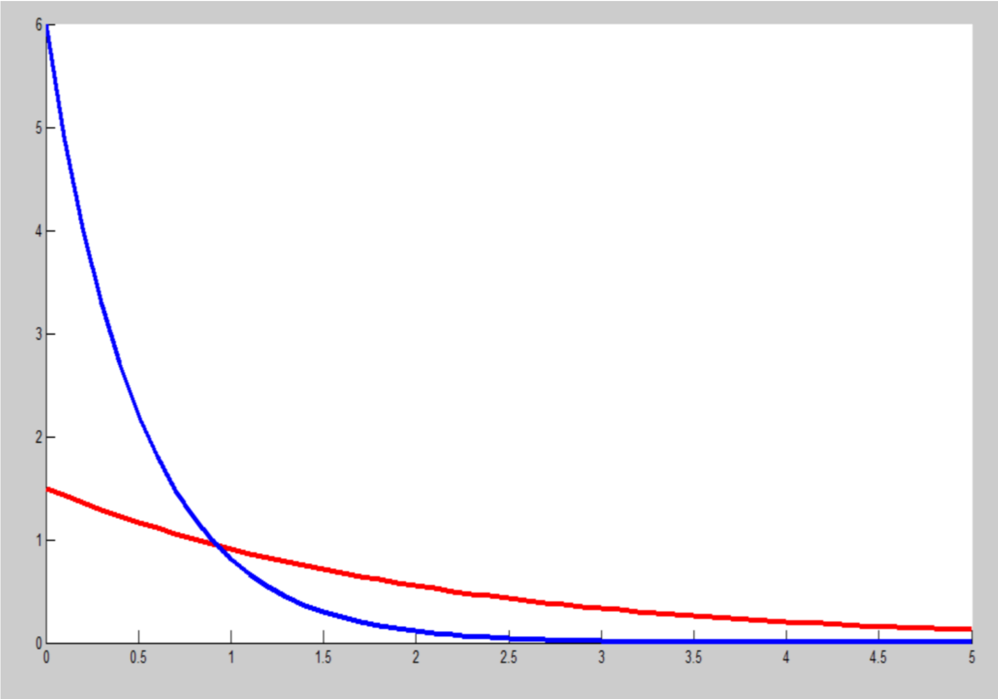
```
>>T=2;
>>t=[0:0.1:5];
>> plot(t,(1/T)*exp(-t/T),'r','LineWidth',3)
>> hold on
>> plot(t,(2/T)*exp(-t/T),'b','LineWidth',3)
>> plot(t,(3/T)*exp(-t/T),'g','LineWidth',3)
```

Impulse response for different gain setting

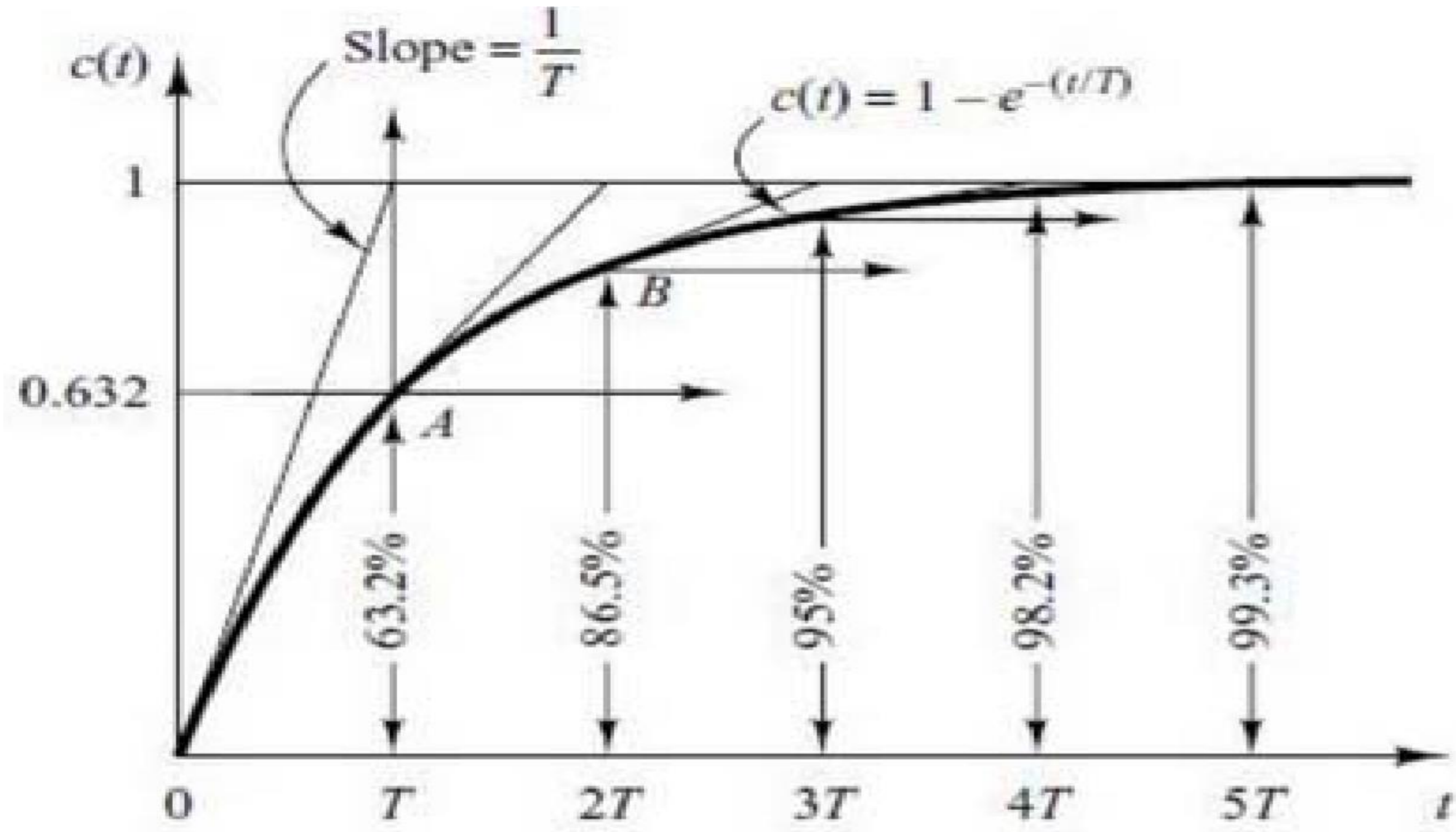


Effect of Time Constant

- >> hold on
- >> T =2;
- >> t = [0:0.1:5];
- >> plot(t,(3/T)*exp(-t/T),'r','LineWidth',3)
- >> T=0.5;
- >> plot(t,(3/T)*exp(-t/T),'b','LineWidth',3)



Step Response of First Order System



$$R(s) = \frac{1}{s}$$

$$C(s) = \frac{K}{Ts+1}\frac{1}{s}$$

$$c(t) = Ku(t) - e^{-\frac{t}{T}}$$

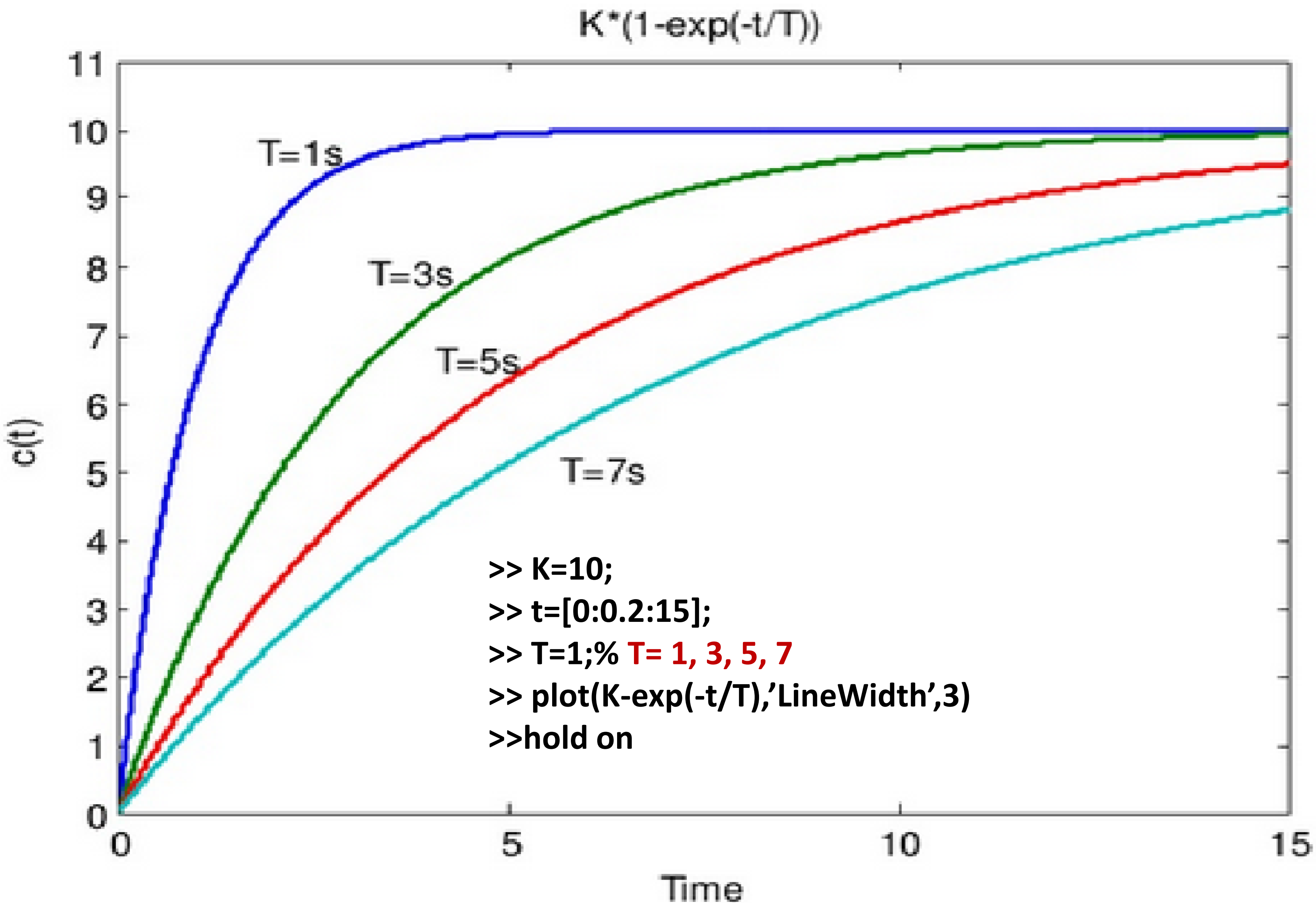
1) Where $u(t) = 1$

$$c(t) = K - e^{-\frac{t}{T}}$$

2) Where $t = T$

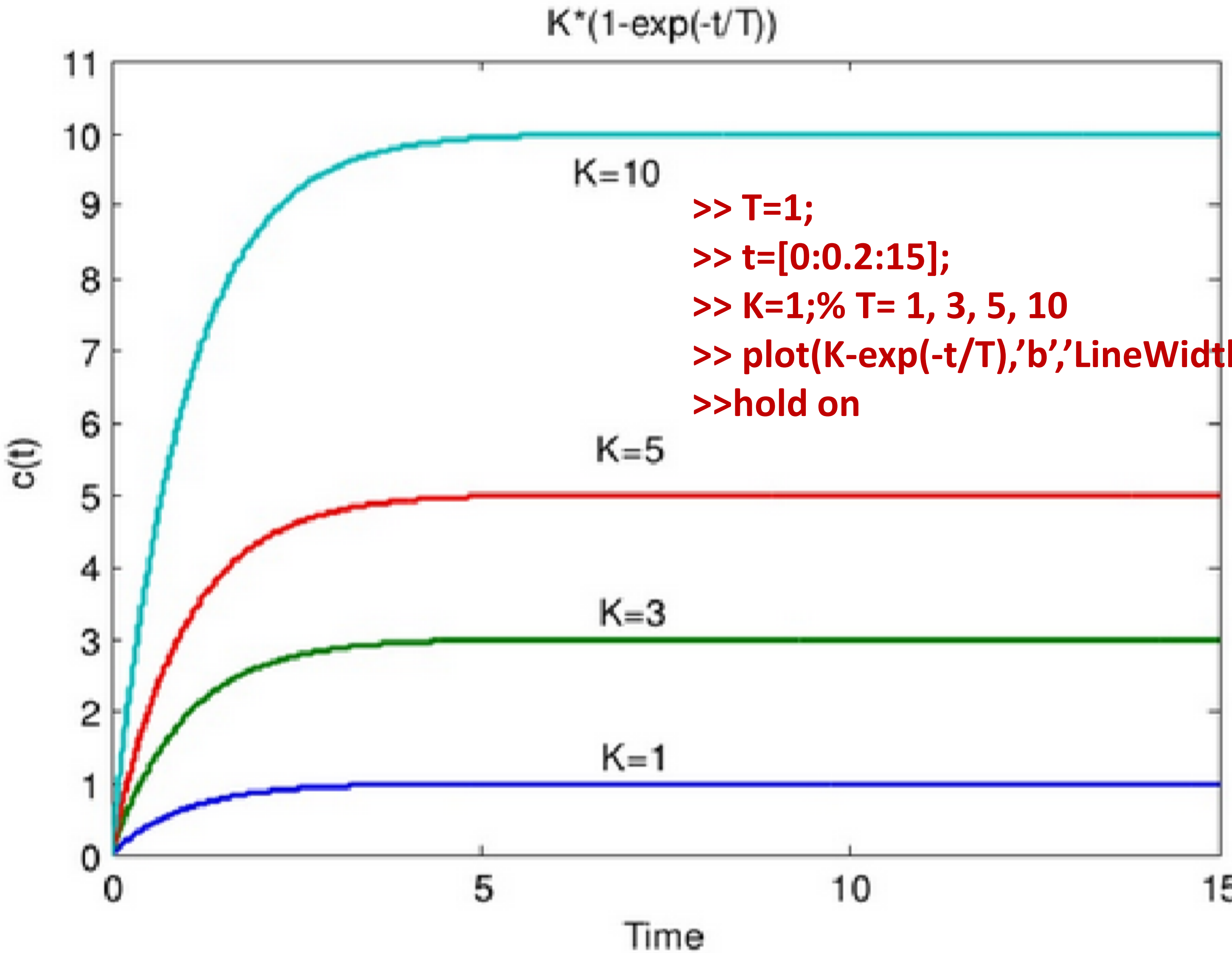
$$c(t) = K - e^{-1} = 0.632K$$

Step Response with different Time




```
>> K=10;
>> t=[0:0.2:15];
>> T=1;% T= 1, 3, 5, 7
>> plot(K-exp(-t/T),'LineWidth',3)
>>hold on
```

Step Response with different gain settings




```
>> T=1;
>> t=[0:0.2:15];
>> K=1;% T= 1, 3, 5, 10
>> plot(K-exp(-t/T),'b','LineWidth',3)
>>hold on
```

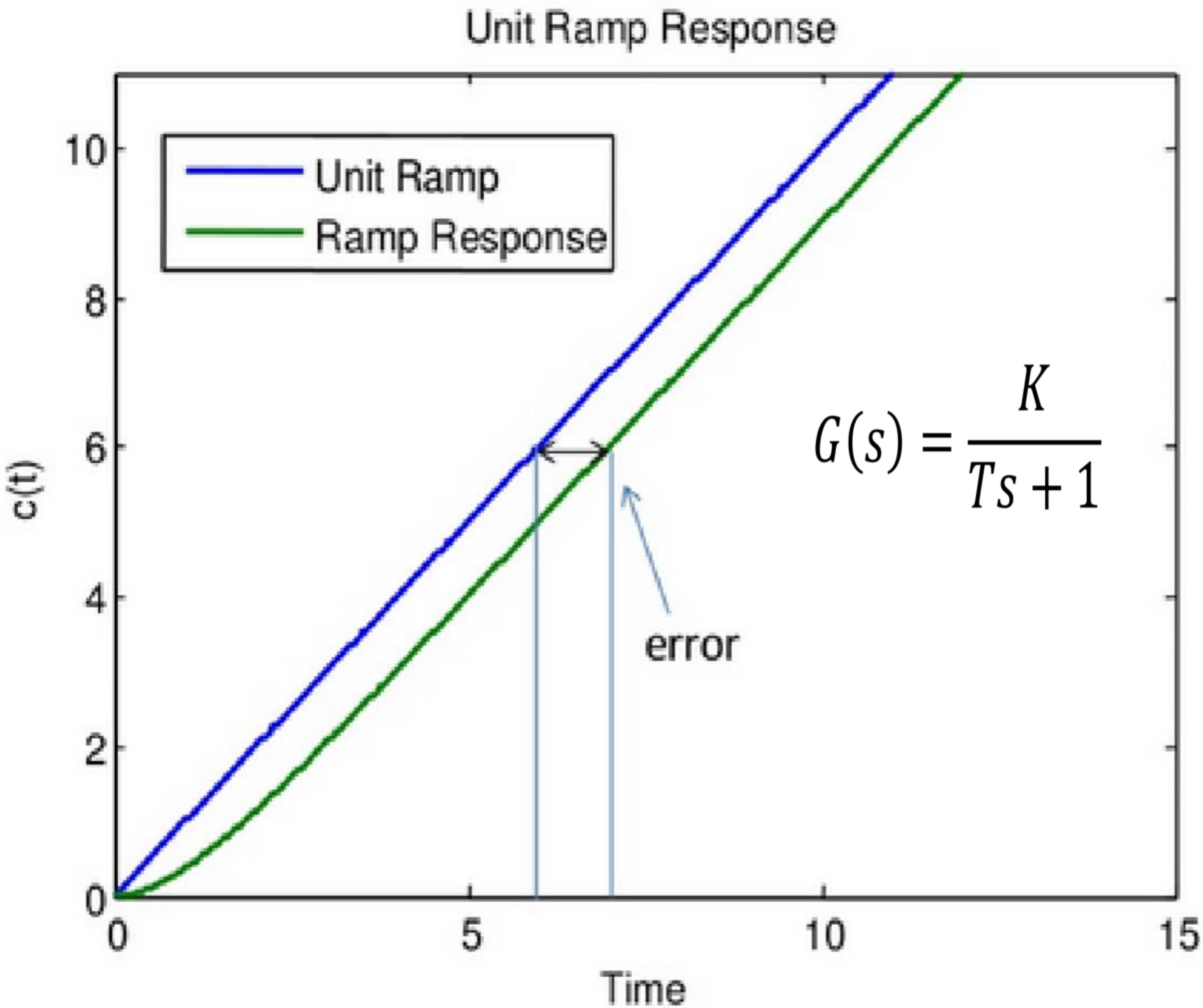
Ramp Response of First Order System

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

$$C(s) = \frac{K}{Ts+1}\frac{1}{s^2}$$

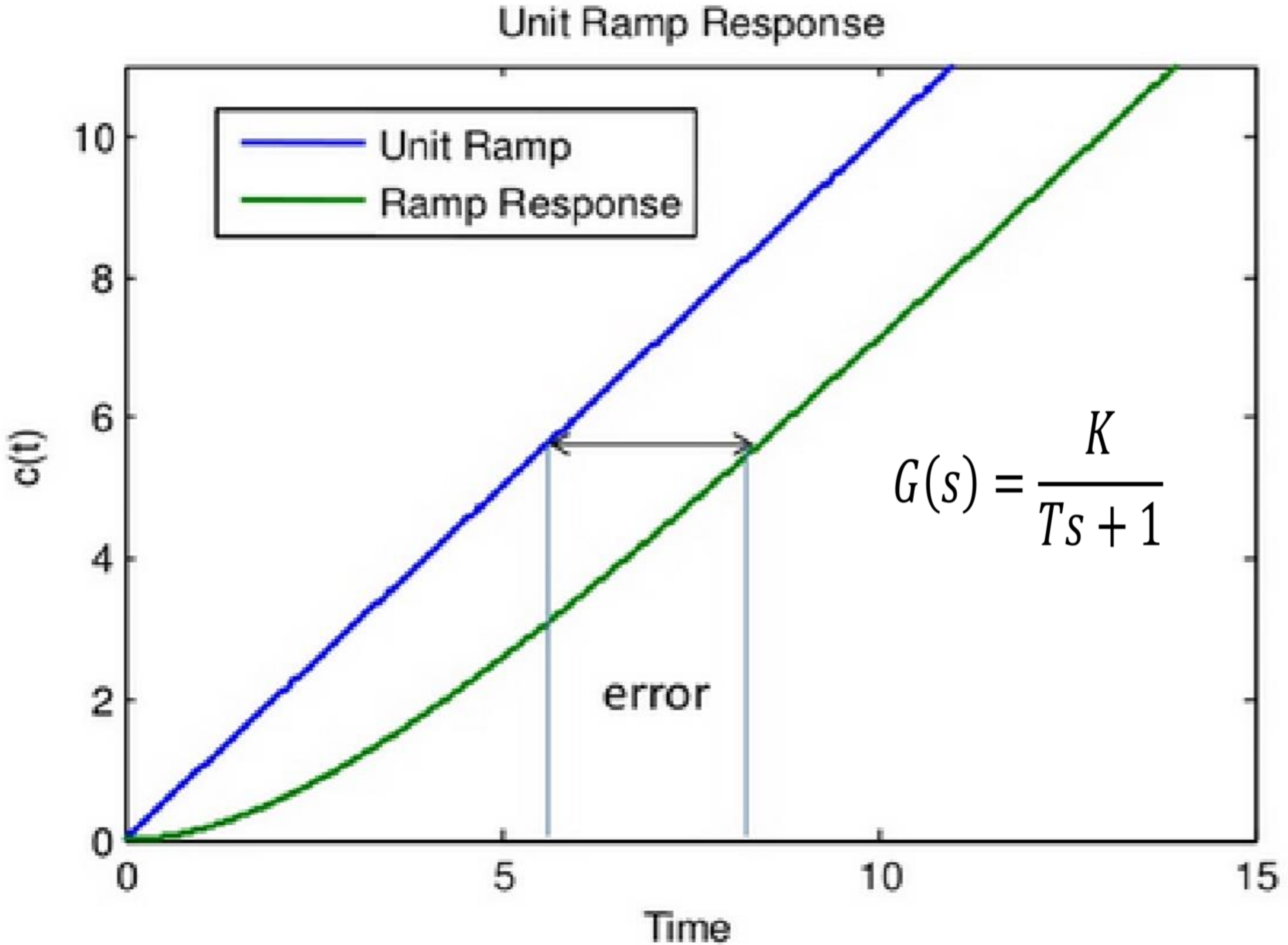
$$c(t) = Kt - T + Te^{-\frac{t}{T}}$$

K=1 and T=1



$$G(s) = \frac{K}{Ts + 1}$$

K=1 and T=3



$$G(s) = \frac{K}{Ts+1}$$

Effects of Feedback

1 Gain, What is gain?

We have seen that the open loop gain is G but the overall gain of a negative feedback control system is: $\dfrac{G}{1+GH}$

It is obvious that if $GH > 0$ then the overall gain will reduce. However, if $GH < 0$, then this could lead to an increase in the overall gain.

② Sensitivity (S)

$$S = \frac{\%\ \text{change in T.F.}}{\%\ \text{Change in } G} = \frac{\frac{dT}{T}}{\frac{dG}{G}} = \frac{dT}{dG} \cdot \frac{G}{T}$$

$$\frac{dT}{dG} = \frac{d}{dG}\left(\frac{G}{1+GH}\right) = \frac{d}{dG}\left\{G(1+GH)^{-1}\right\}$$

$$\frac{dT}{dG} = G\left(-(1+GH)^{-2}H\right) + (1+GH)^{-1}$$

$$= \frac{-GH}{(1+GH)^2} + \frac{1}{1+GH} = \frac{-GH+1+GH}{(1+GH)^2}$$

$$\frac{dT}{dG} = \frac{1}{(1+GH)^2} \quad \Bigg| \quad S = \frac{1}{(1+GH)^2} \cdot \frac{G(1+GH)}{G}$$

$$\boxed{S_G^T = \frac{1}{1+GH}}$$

if $GH > 0$, sensitivity reduces

③ Stability

In the system that we are considering, the open loop gain is G , the closed loop is $T.F. = \dfrac{G}{1+GH}$,

The system is stable if its output is under control.

What happens if $GH = -1$?

Hence, feedback needs to be chosen sensibly