3 : ELEMEN DAN KARAKTERISTIK SENSOR

FI 365 – SISTEM INSTRUMENTASI

Program Studi Fisika

Waslaluddin, dkk

ISI KULIAH

- Elemen Sensor
- Karakteristik Dasar
- Identifikasi Karakteristik Sensor

ELEMEN SENSOR

Elemen Sensor

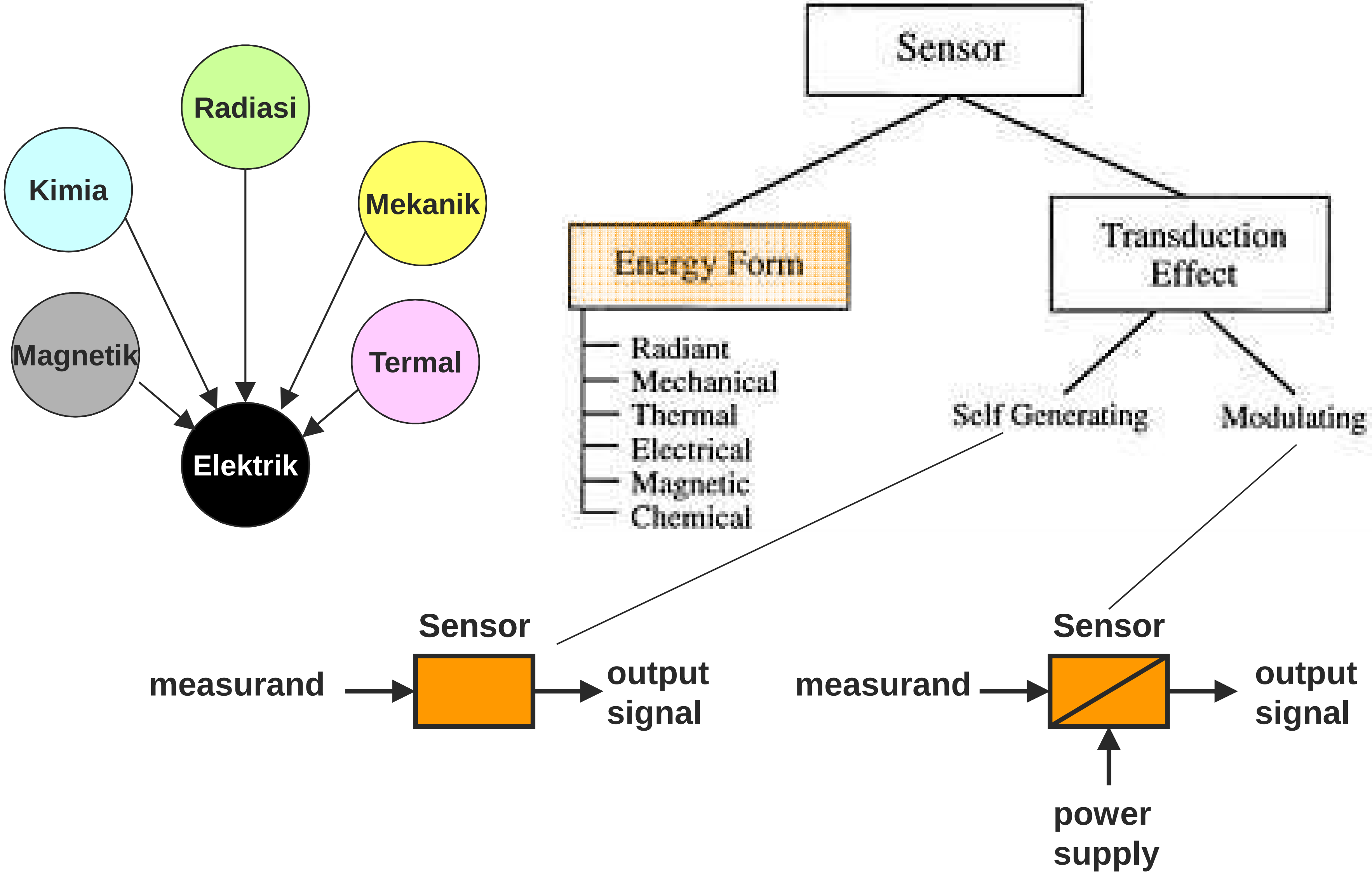
- Domain elemen sensor
  - material
  - energi

- Material
  - Silicon
  - Plastik
  - Metal
  - Keramik
  - Glass
  - Biological substance

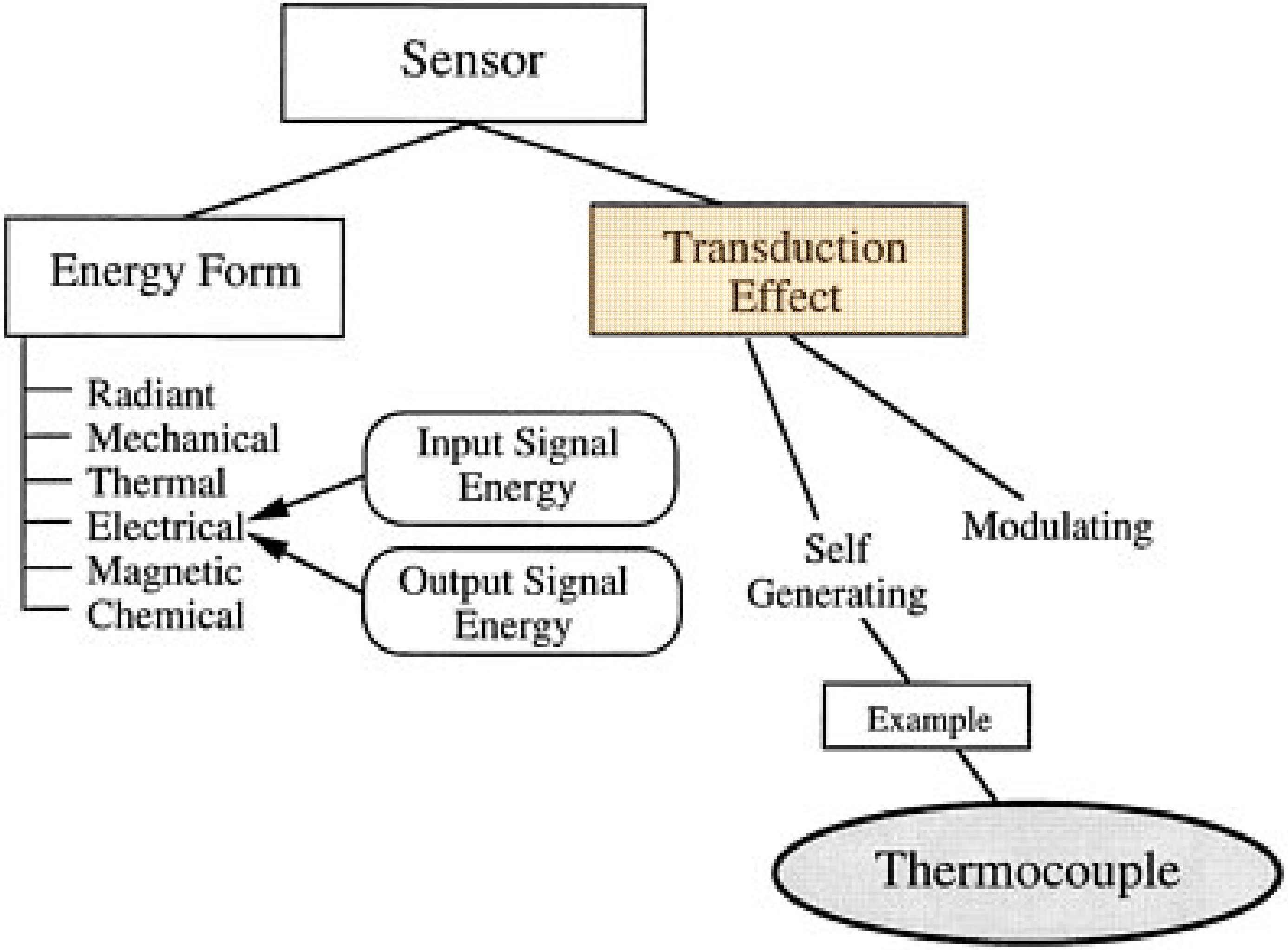
- Energi
  - Elektrik
  - Magnetik
  - Termal
  - Akustik
  - Optik

(lihat pembahasan prinsip transduksi)

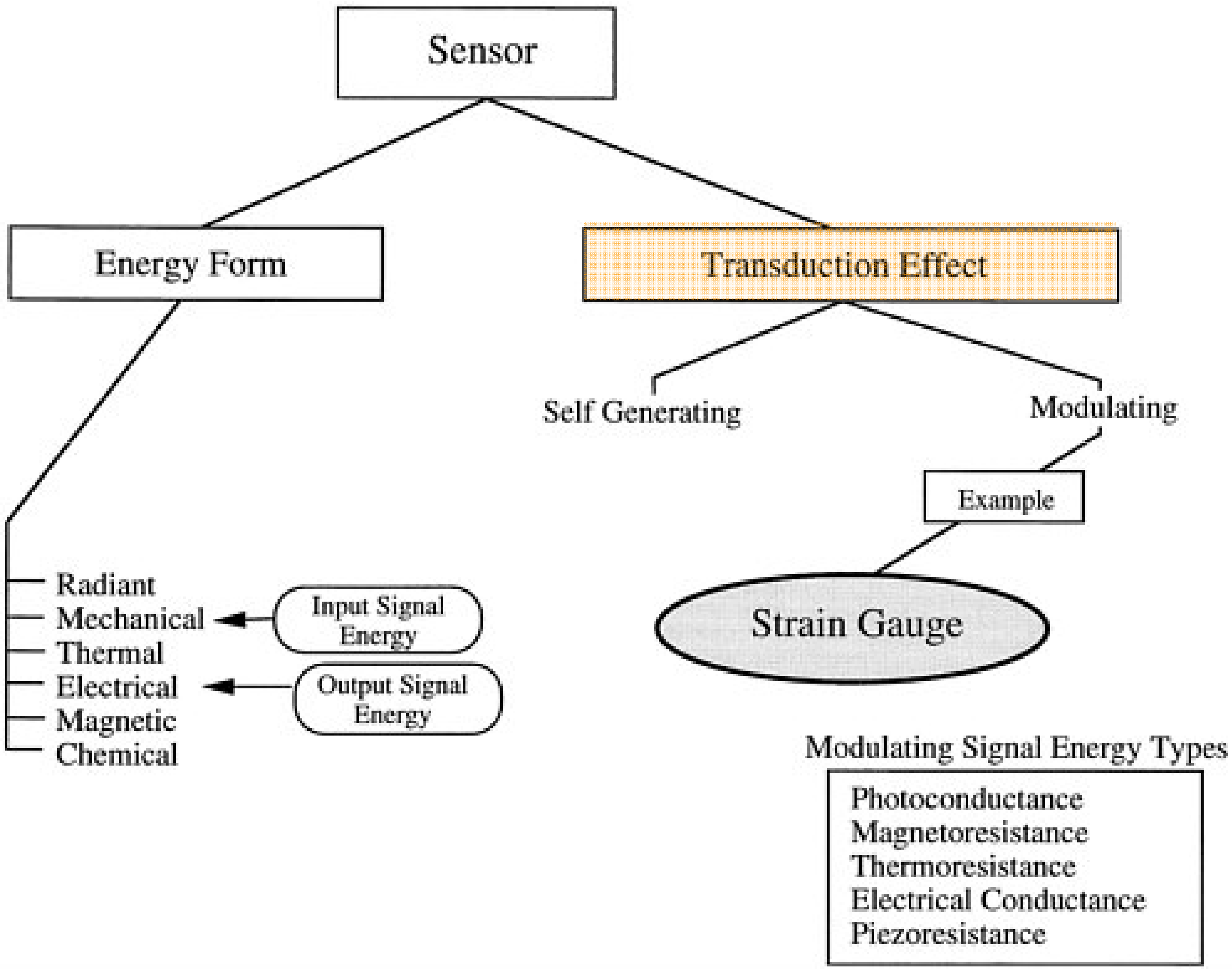
Stimulus


Radiasi
Kimia
Mekanik
Magnetik
Termal
Elektrik
Sensor
Energy Form
Radiant
Mechanical
Thermal
Electrical
Magnetic
Chemical
Transduction Effect
Self Generating
Modulating
Sensor
measurand
output signal
Sensor
measurand
output signal
power supply

Transduction effect

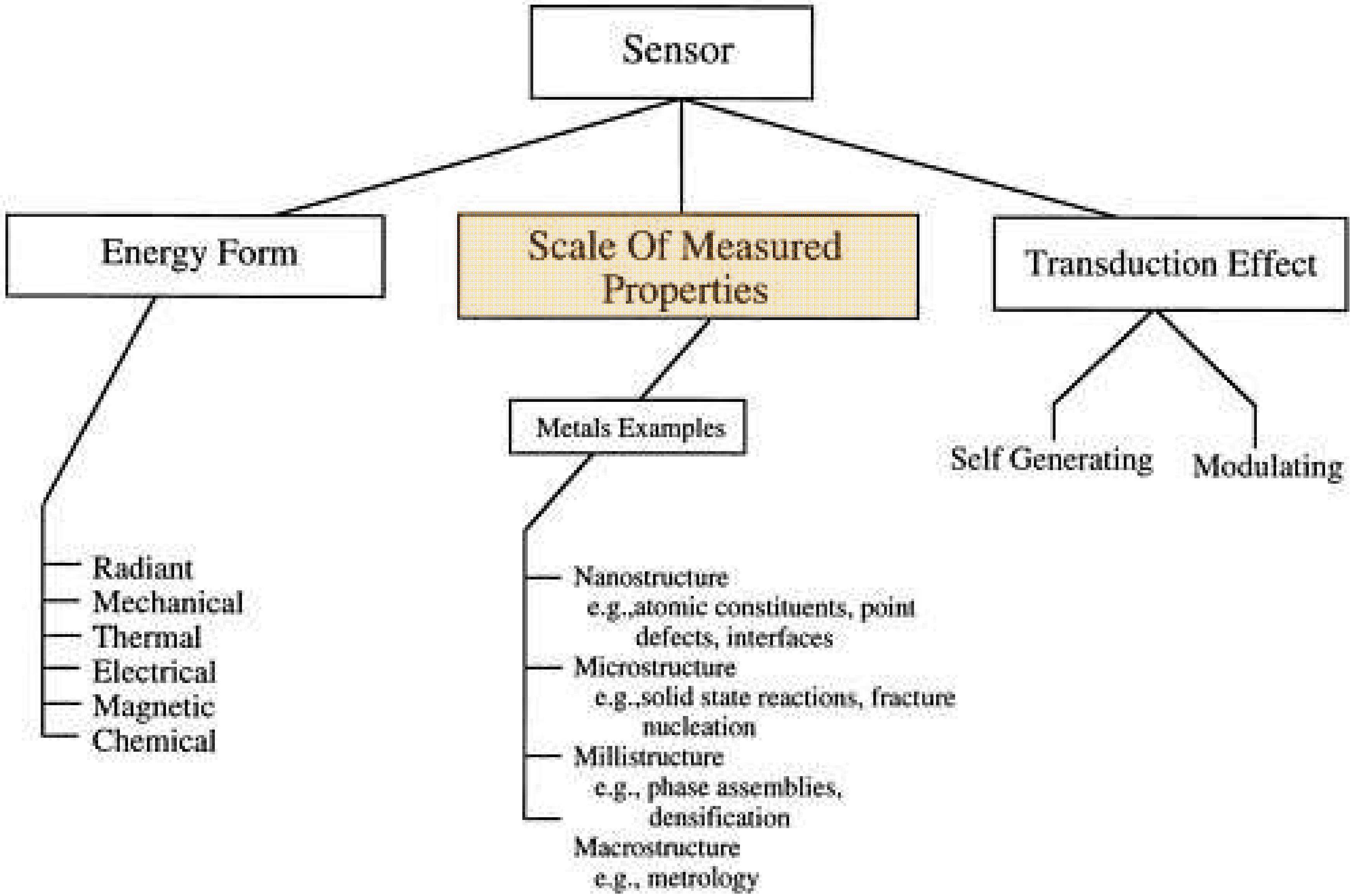


Transduction effect

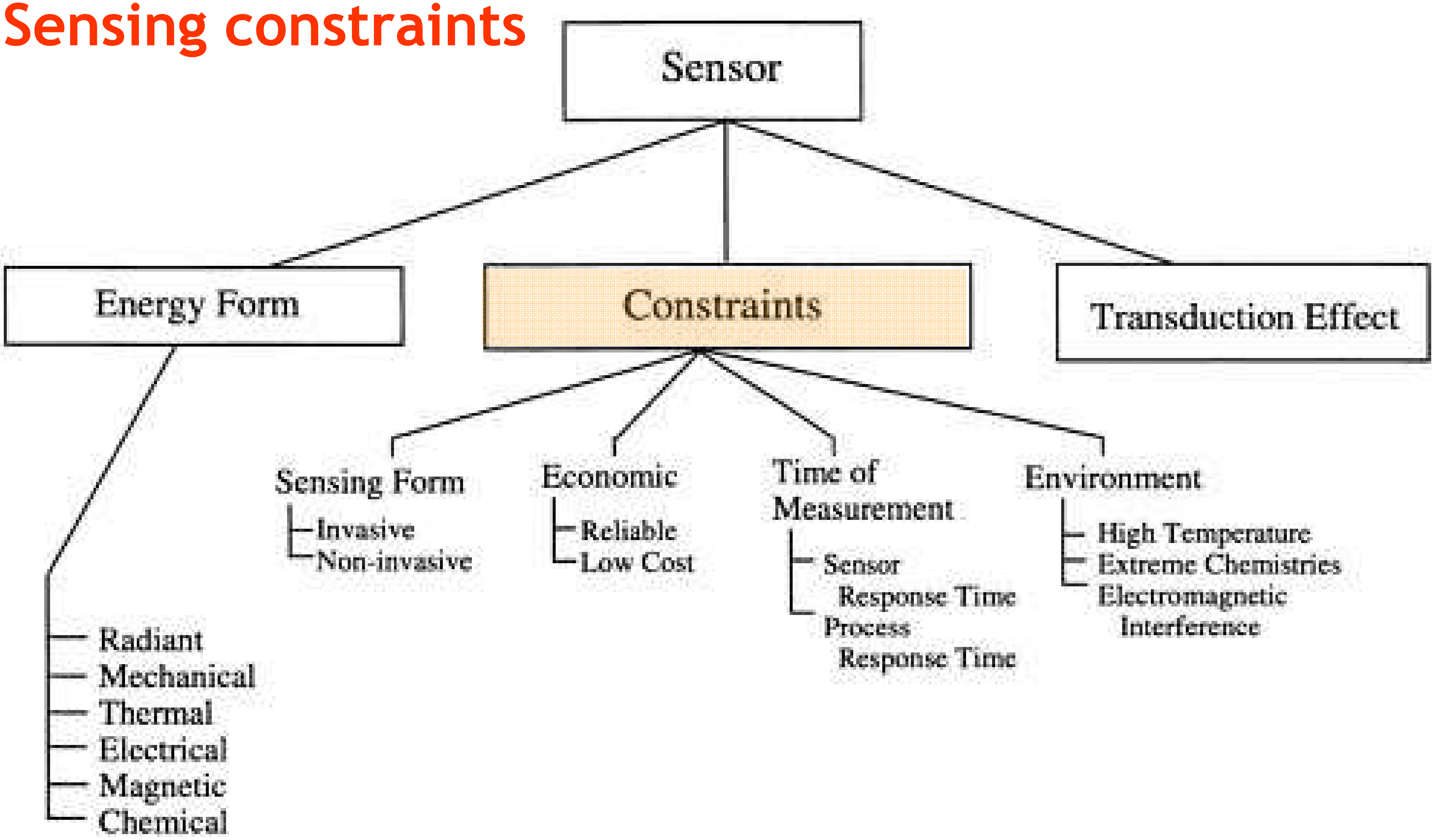


FI 365 SISTEM INSTRUMENTASI

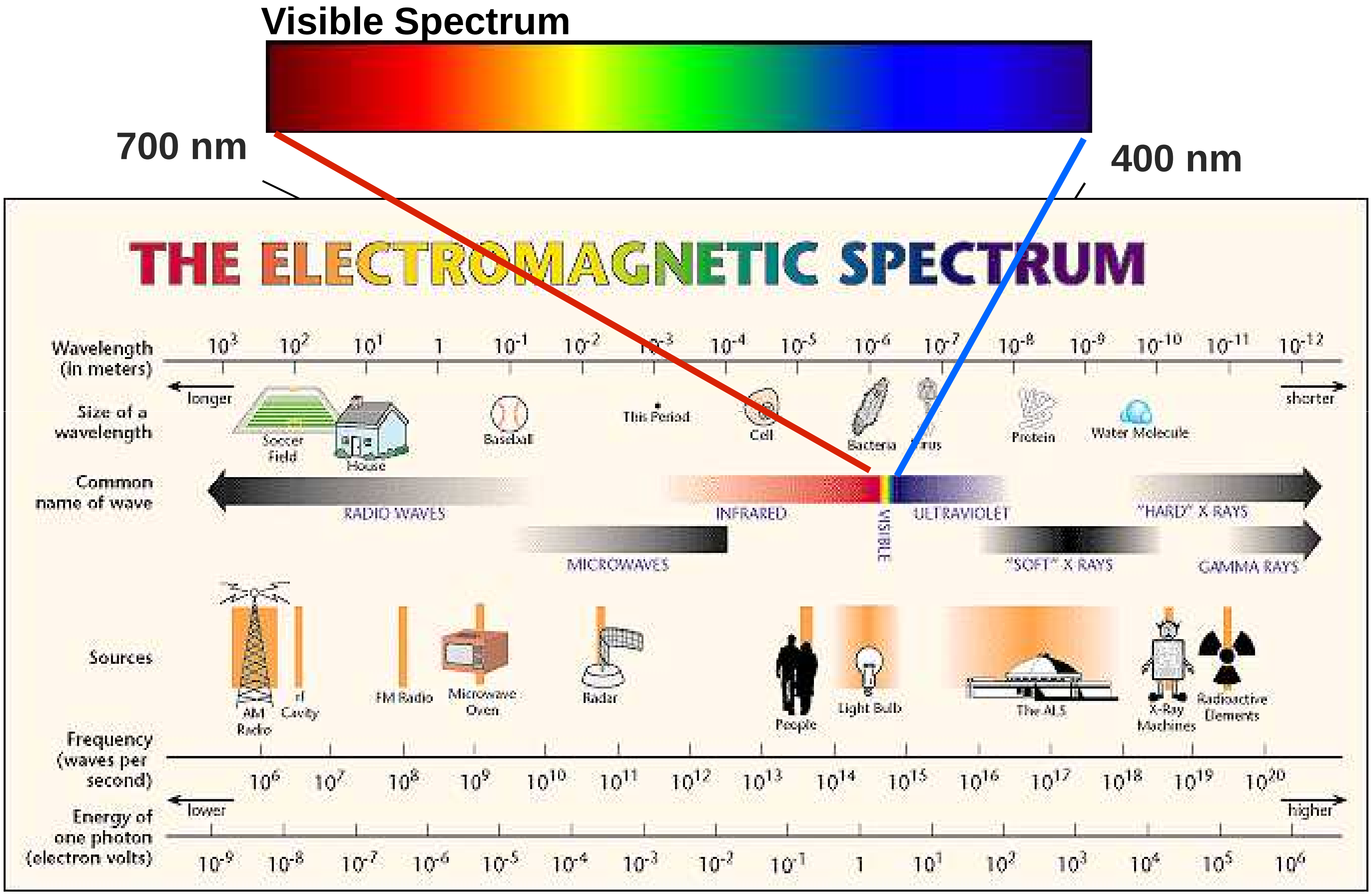
Scale of measurands



Sensing constraints



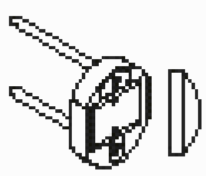
Radiant Sensors → Electromagnetic Spectrum



Radiant Sensors ➔ Electromagnetic Spectrum

Light Sensors

- Photodiodes
- Phototransistor
- Photoresistors
- Cooled Detectors
- Thermal Detectors
  - Golay Cells
  - Thermopile Sensors
  - Pyroelectric Sensors
  - Bolometers
  - Active Far-Infrared Sensors
  - Gas Flame Detectors



Radiation Sensors

- **Scintillating Detectors**
- **Ionization Detectors**
  - **Ionization Chambers**
  - **Proportional Chambers**
  - **Geiger–Müller Counters**
  - **Semiconductor Detectors**

Mechanical Sensors

Occupancy and Motion Detectors

- Ultrasonic Sensors
- Microwave Motion Detectors
- Capacitive Occupancy Detectors
- Triboelectric Detectors
- Optoelectronic Motion Detectors
    - Visible and Near-Infrared Light Motion Detectors & Far-IR Motion Detectors

Position, Displacement, and Level

- Potentiometric Sensors
- Gravitational Sensors
- Capacitive Sensors
- Inductive and Magnetic Sensors
    - LVDT and RVDT
    - Eddy Current Sensors & Transverse Inductive Sensor
    - Hall Effect Sensors & Magnetoresistive Sensors
- Optical Sensors
    - Optical Bridge & Proximity Detector with Polarized Light
    - Fiber-Optic Sensors & Fabry–Perot Sensors
    - Grating Sensors & Linear Optical Sensors (PSD)
- Ultrasonic Sensors
- Radar Sensors : Micropower Impulse Radar & Ground-Penetrating Radar
- Thickness and Level Sensors : Ablation & Thin-Film & Liquid-Level Sensors

Mechanical Sensors

Velocity and Acceleration

- Capacitive Accelerometers
- Piezoresistive Accelerometers
- Piezoelectric Accelerometers
- Thermal Accelerometers
  - Heated-Plate Accelerometer
  - Heated-Gas Accelerometer
- Gyroscopes
  - Rotor Gyroscope
  - Monolithic Silicon Gyroscopes
  - Optical Gyroscopes

Pressure Sensors

- Mercury Pressure Sensor
- Piezoresistive Sensors
- Capacitive Sensors .
- VRP Sensors
- Optoelectronic Sensors
- Vacuum Sensors
  - Pirani Gauge
  - Ionization Gauges
  - Gas Drag Gauge

Force, Strain, and Tactile Sensors

- Strain Gauges
- Tactile Sensors .
- Piezoelectric Force Sensors

Mechanical Sensors

Flow Sensors

- Thermal Transport Sensors
- Ultrasonic Sensors
- Electromagnetic Sensors
- Microflow Sensors
- Breeze Sensor
- Coriolis Mass Flow Sensors
- Drag Force Flow Sensors

Acoustic Sensors

- Resistive Microphones
- Condenser Microphones
- Fiber-Optic Microphone
- Piezoelectric Microphones
- Electret Microphones
- Solid-State Acoustic Detectors

Temperature Sensors

- Thermoresistive Sensors
  - Resistance Temperature
  - Silicon Resistive Sensors
  - Thermistors
    - NTC Thermistors
    - Self-Heating Effect in NTC Thermistors
    - PTC Thermistors

- Thermoelectric Contact Sensors
- Semiconductor P-N Junction Sensors
- Optical Temperature Sensors
  - Fluoroptic Sensors
  - Interferometric Sensors
  - Thermochromic Solution Sensor

- Acoustic Temperature Sensor
- Piezoelectric Temperature Sensors

Magnetic Sensors

Direct Sensors

- Metal-Oxide Chemical Sensors
- ChemFET
- Electrochemical Sensors
- Potentiometric Sensors
- Conductometric Sensors
- Amperometric Sensors
- Enhanced Catalytic Gas Sensors
- Elastomer Chemiresistors

Complex Sensors

- Thermal Sensors
- Pellister Catalytic Sensors
- Optical Chemical Sensors
- Mass Detector
- Biochemical Sensors
- Enzyme Sensors

Humidity and Moisture Sensors

- Capacitive Sensors
- Electrical Conductivity Sensors
- Thermal Conductivity Sensor
- Optical Hygrometer
- Oscillating Hygrometer

Chemical Sensors

Direct Sensors
- Metal-Oxide Chemical Sensors
- ChemFET
- Electrochemical Sensors
- Potentiometric Sensors
- Conductometric Sensors
- Amperometric Sensors
- Enhanced Catalytic Gas Sensors
- Elastomer Chemiresistors

Complex Sensors
- Thermal Sensors
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- Enzyme Sensors

Humidity and Moisture Sensors
- Capacitive Sensors
- Electrical Conductivity Sensors
- Thermal Conductivity Sensor
- Optical Hygrometer
- Oscillating Hygrometer

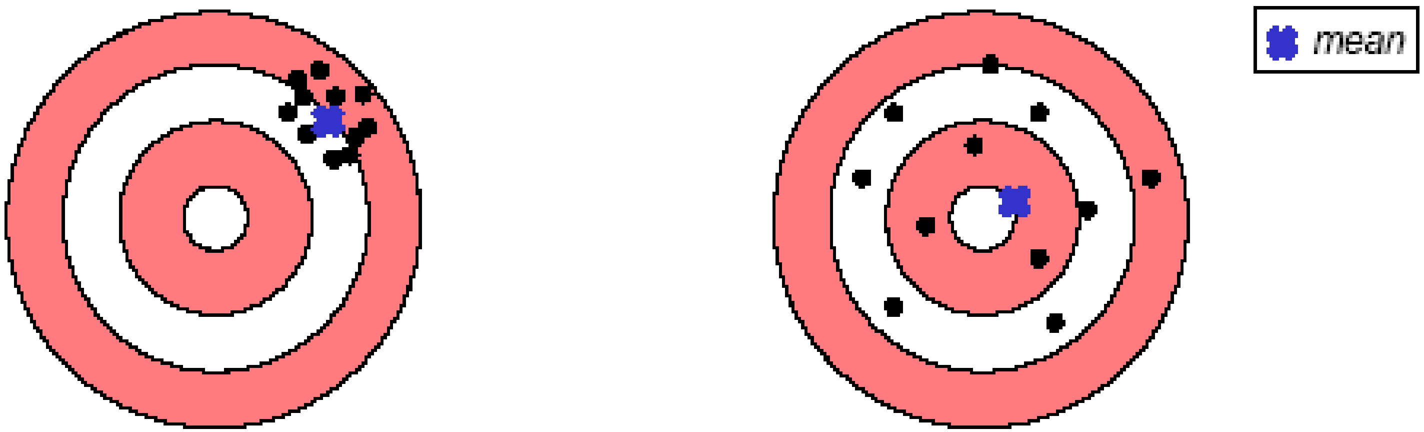
KARAKTERISTIK SENSOR

- Karakteristik **STATIK**
- Karakteristik **DINAMIK**

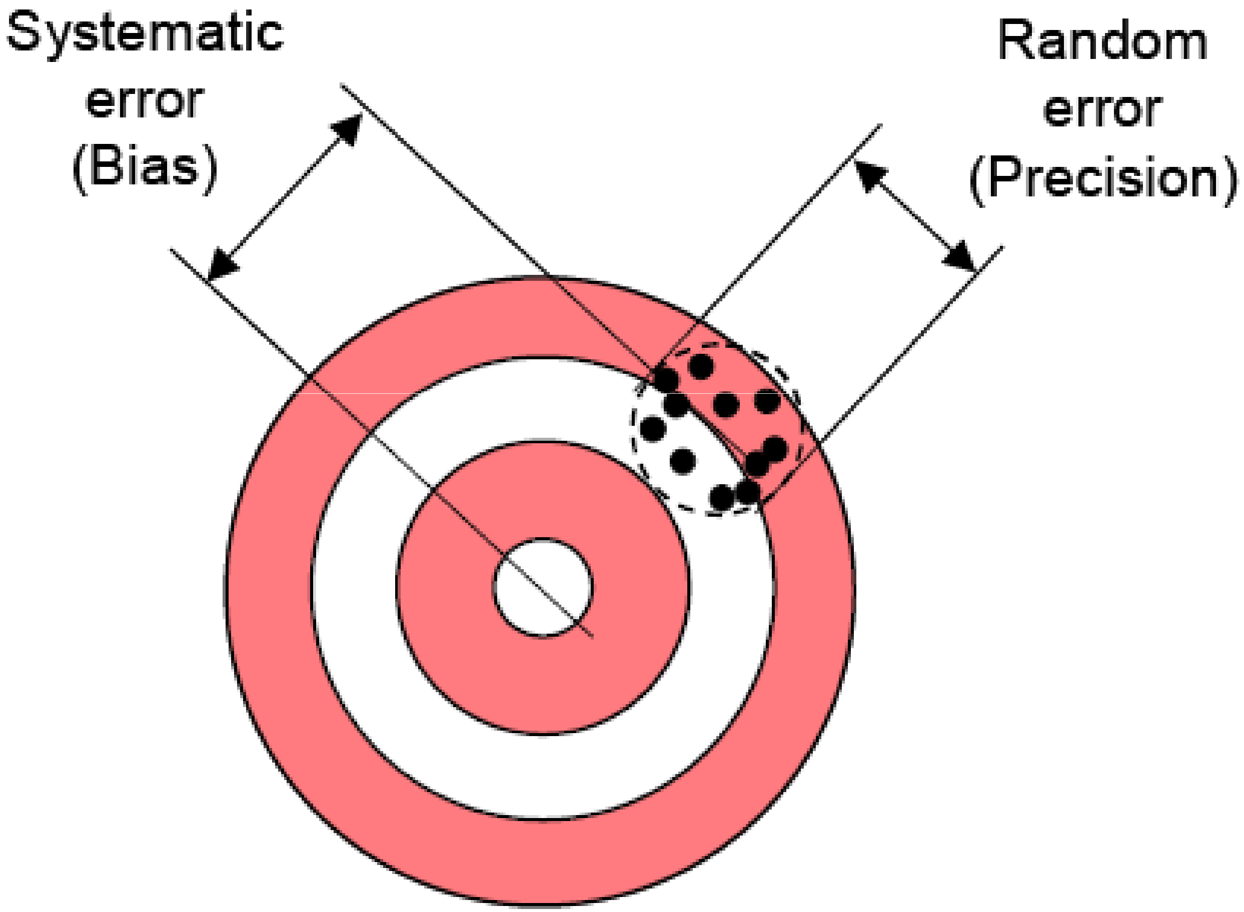
Karakteristik : Pendahuluan

Shooting darts

- Discrimination
  - The size of the hole produced by a dart
- Which shooter is more accurate?
- Which shooter is more precise?



Contoh : Kesalahan sistematik dan random



Karakteristik Sensor

- **Static characteristics**
  - The properties of the system after all transient effects have settled to their final or steady state
    - **Accuracy**
    - **Discrimination**
    - **Precision**
    - Errors
    - Drift
    - Sensitivity
    - Linearity
    - Hystheresis (backslash)
- **Dynamic characteristics**
  - The properties of the system transient response to an input
    - Zero order systems
    - First order systems
    - Second order systems

Akurasi, Diskriminasi dan Presisi

- **Accuracy is the capacity of a measuring instrument to give RESULTS close to the TRUE VALUE of the measured quantity**
  - Accuracy is related to the bias of a set of measurements
  - (IN)Accuracy is measured by the absolute and relative errors

$$\text{ABSOLUTE ERROR} = \text{RESULT} - \text{TRUE VALUE}$$

$$\text{RELATIVE ERROR} = \frac{\text{ABSOLUTE ERROR}}{\text{TRUE VALUE}}$$

  - More on errors in a later slide
- **Discrimination is the minimal change of the input necessary to produce a detectable change at the output**
  - Discrimination is also known as RESOLUTION
  - When the increment is from zero, it is called THRESHOLD

Presisi

- **The capacity of a measuring instrument to give the same reading when repetitively measuring the same quantity under the same prescribed conditions**
  - Precision implies agreement between successive readings, NOT closeness to the true value
    - Precision is related to the variance of a set of measurements
  - Precision is a necessary but not sufficient condition for accuracy
- **Two terms closely related to precision**
  - Repeatability
    - The precision of a set of measurements taken over a short time interval
  - Reproducibility
    - The precision of a set of measurements BUT
      - taken over a long time interval or
      - Performed by different operators or
      - with different instruments or
      - in different laboratories

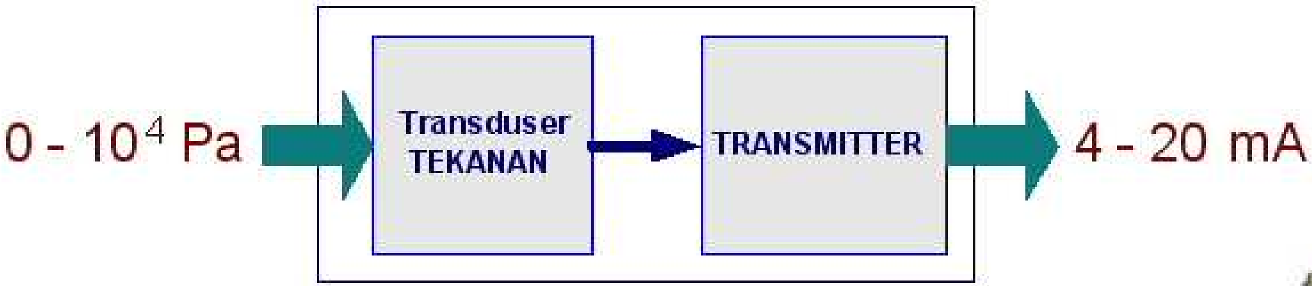
Akurasi dan Errror

- **Systematic errors**
  - Result from a variety of factors
    - Interfering or modifying variables (i.e., temperature)
    - Drift (i.e., changes in chemical structure or mechanical stresses)
    - The measurement process changes the measurand (i.e., loading errors)
    - The transmission process changes the signal (i.e., attenuation)
    - Human observers (i.e., parallax errors)
  - Systematic errors can be corrected with COMPENSATION methods (i.e., feedback, filtering)
- **Random errors**
  - Also called NOISE: a signal that carries no information
  - True random errors (white noise) follow a Gaussian distribution
  - Sources of randomness:
    - Repeatability of the measurand itself (i.e., height of a rough surface)
    - Environmental noise (i.e., background noise picked by a microphone)
    - Transmission noise (i.e., 60Hz hum)
  - Signal to noise ratio (SNR) should be >>1
    - With knowledge of the signal characteristics it may be possible to interpret a signal with a low SNR (i.e., understanding speech in a loud environment)

Rentang Input & Output

RANGE

- **Input Range**
  - Rentang nilai antara input minimum dan input maksimum
  - Misal : Input range suatu transduser tekanan **0 s/d 10^4 Pa**
- **Output Range**
  - Rentang nilai antara output minimum dan output maksimum
  - Misal : Output range suatu transmitter **4 s/d 20 mA**



pressure transmitter

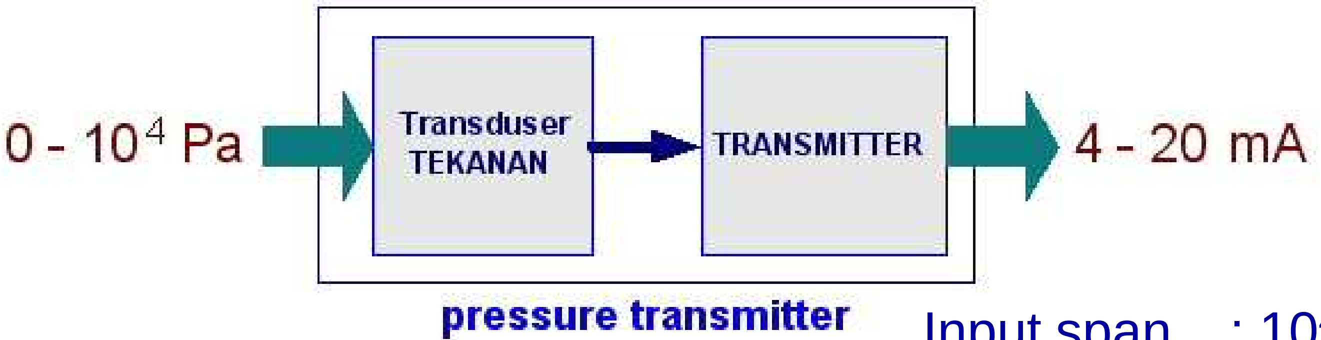
Input range : 0 s/d 10^4 Pa
Output range : 4 s/d 20 mA

Span

SPAN

- **Variasi maksimum input atau output suatu sistem pengukuran**
  - Input Span = $Input_{max} - Input_{min}$
  - Output Span = $Output_{max} - Output_{min}$

- **Contoh**
  - Suatu *Pressure Transmitter* memiliki span sebagai berikut
    - Input Span = 10^4 Pa
    - Output Span = 16 mA



Input span : 10^4 Pa
Output span : 16 mA

Linieritas

LINIERITAS

- **Suatu sistem dikatakan linier jika hubungan input dan output merupakan suatu garis lurus**
- Nilai output suatu sistem linier dinyatakan sbb

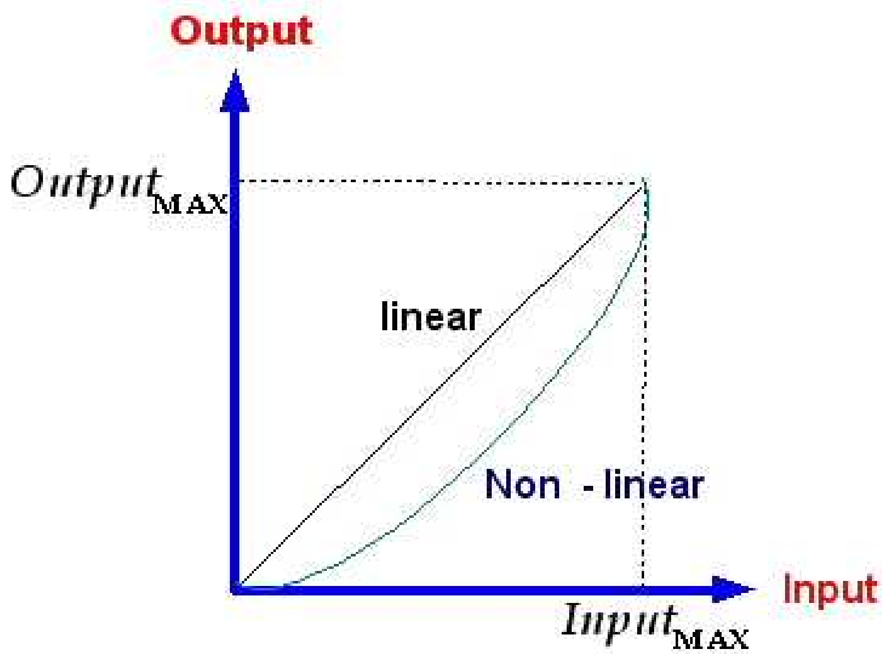
$$Output_{\mathrm{ideal}} = K \times Input + a$$

$$K = \text{Kemiringan Garis Lurus} = \frac{Output_{\mathrm{MAX}} - Output_{\mathrm{MIN}}}{Input_{\mathrm{MAX}} - Input_{\mathrm{MIN}}}$$

Non-linieritas

NON-LINIERITAS

- **Suatu sistem dikatakan non-linier jika hubungan input dan output bukan merupakan suatu garis lurus**
- Contoh kurva **linier** dan **non-linier :**



Persamaan Output

- **Secara umum, *Output* suatu sistem merupakan fungsi *Input* dengan bentuk persamaan polinomial berikut**

$$Out(In) = a_0 + a_1 In + a_2 In^2 + \ldots + a_m In^m$$
$$= \sum_{k=0}^{k=m} a_i In^k$$

Contoh

Tegangan keluaran suatu termokopel **copper-constantan** (type T), diekspresikan dengan persamaan polinom berikut,

$$E(T) = 38.74T + 3.319 \cdot 10^{-2} T^2 + 2.071 \cdot 10^{-4} T^3 + \ldots + f(T^4)$$

Untuk rentang 0 s/d 400 ^oC, tegangan keluaran $E(T{=}0) = 0\ \mu V$ & $E(T{=}400^oC) = 20869\ \mu V$. Persamaan linier untuk rentang tsb,

$$E_{linear} = 52.17\, T$$

Kesalahan linierisasi adalah,

$$error(T) = -13.43T + 3.319 \cdot 10^{-2} T^2 + 2.071 \cdot 10^{-4} T^3 + \ldots + f(T^4)$$

Sensitivitas

SENSITIVITAS

- Perbandingan perubahan keluaran sistem terhadap perubahan masukan sistem

$$\text{Sensitivity} = \frac{d(Out)}{d(In)}$$

Contoh : Sensitivitas Termokopel Cooper - Constantant

$$\text{Sensitivity} = \frac{dE}{dT} = 38.74 + 6.638 \cdot 10^{-2} T + 6.213 \cdot 10^{-4} T^2 + ...$$

Input Gangguan

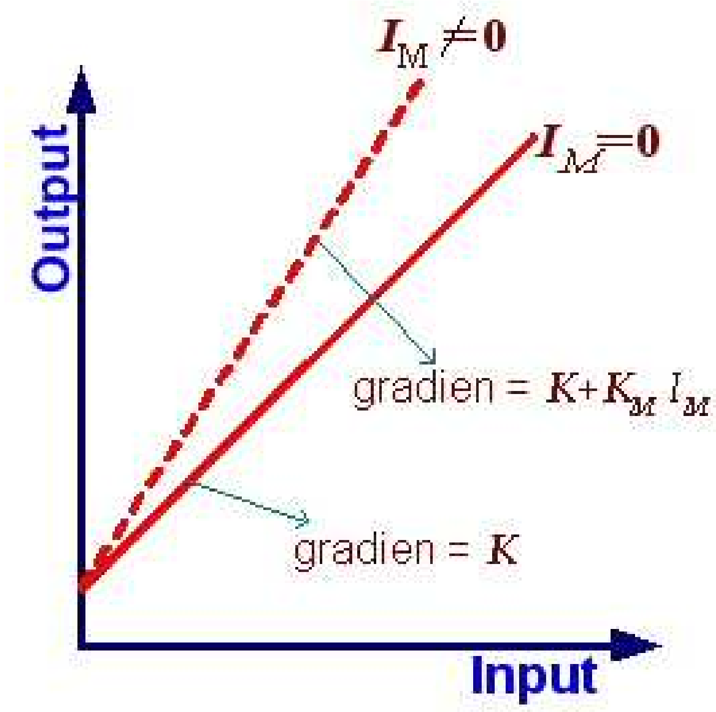
EFEK LINGKUNGAN (*environmental effect*)

- Secara umum, output pengukuran tidak hanya fungsi input pengukuran, tetapi juga fungsi input lingkungan seperti temperatur lingkungan, tekanan atmosfir, kelembaban relatif, suplai tegangan dsb.

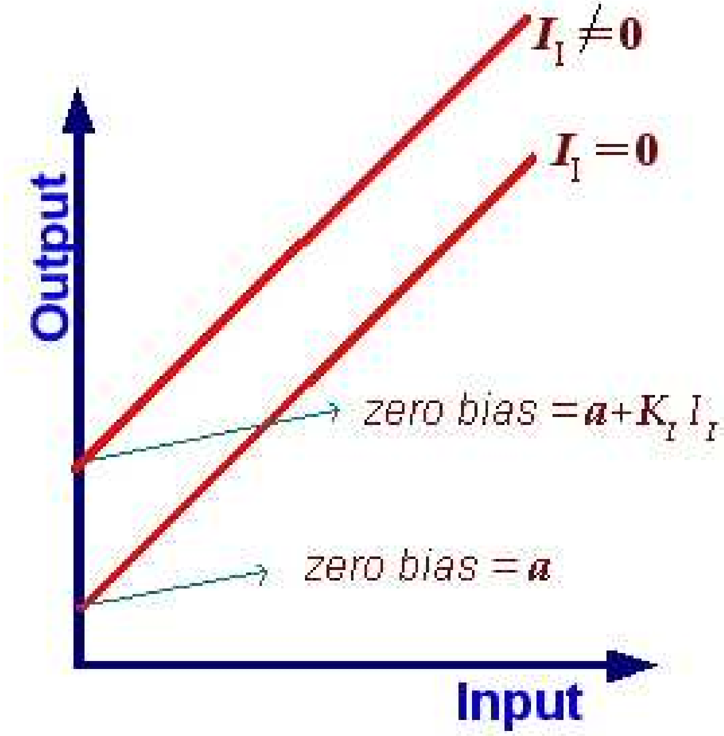
- Terdapat 2 jenis input lingkungan
  - Modifying Input
    - Menyebabkan sensitivitas linier sistem pengukuran berubah
  - Interfering Input
    - Menyebabkan intersepsi atau *zero bias* sistem pengukuran berubah

Input Gangguan

Efek lingkungan



Efek Modifying Input



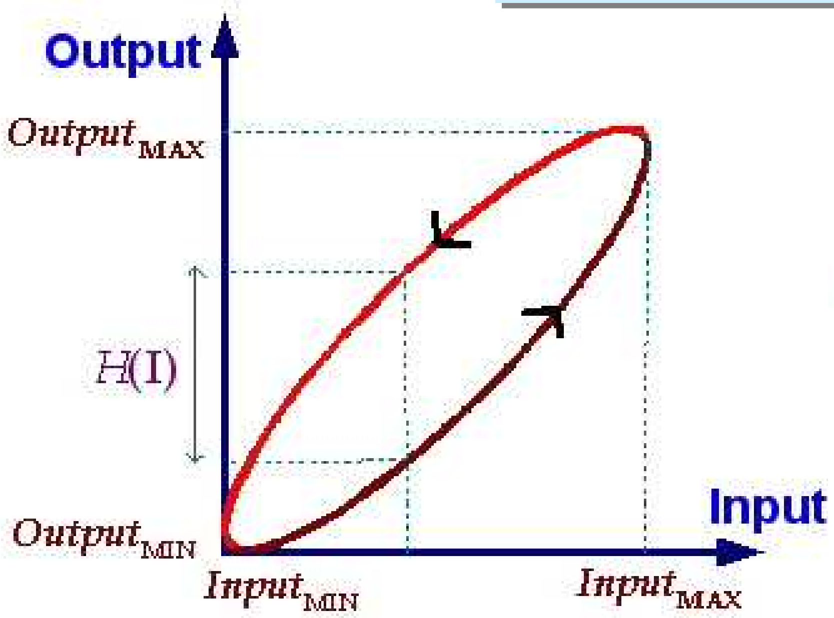
Efek Interfering Input

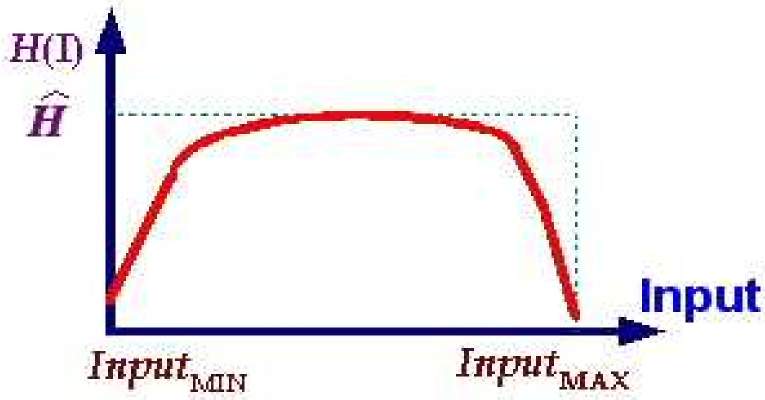
Histeresis

HYSTERESIS

- Histeresis adalah perbedaan nilai *Output* pengukuran pada saat nilai *Input* pengukuran membesar (naik) dan mengecil (turun).

$$Hysteresis(I) = Out(In)_{\uparrow} - Out(In)_{\downarrow}$$

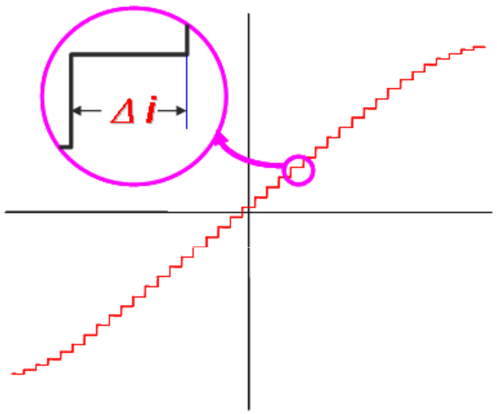


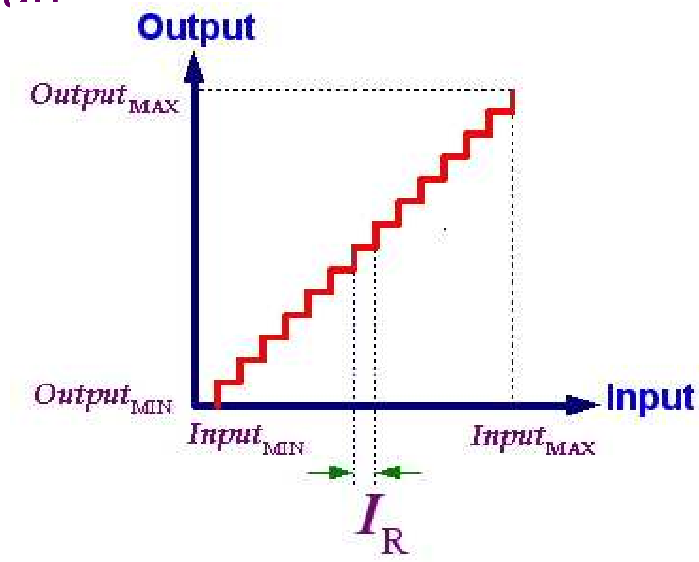


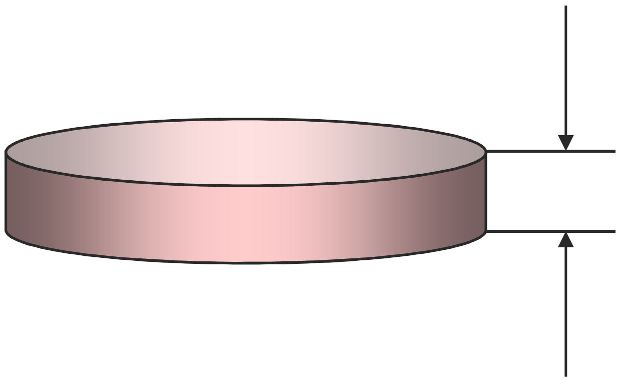
Resolusi

RESOLUSI

- Perubahan nilai terkecil *Input* pengukuran yang memberikan respon pada *Output* pengukuran







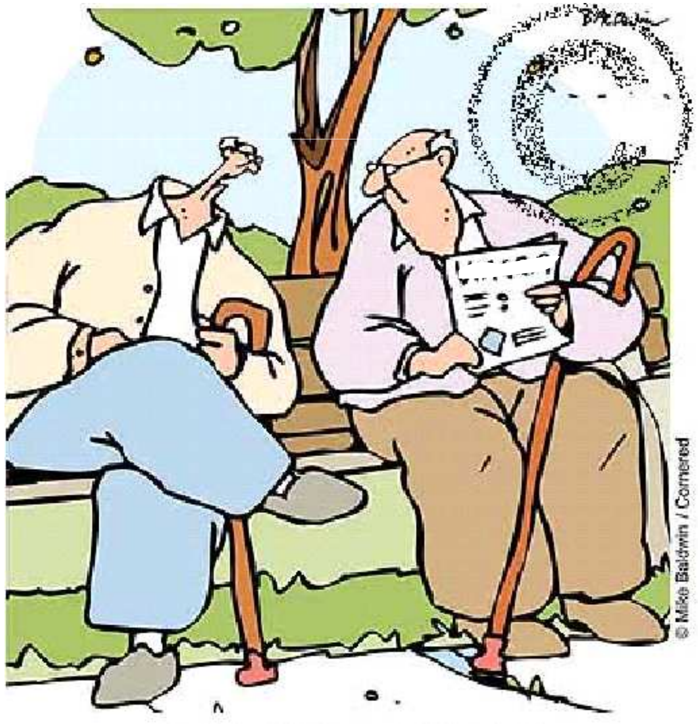
Hasil pengukuran:
- 4,235 mm
- 4,240 mm
- 4,236 mm
- 4,235 mm
- 4,237 mm

Resolusi ?

Aging

WEAR & AGING

- Efek ini mengakibatkan karakteristik sistem pengukuran seperti konstanta pengukuran ***K*** dan *zero bias* ***a*** berubah secara perlahan-lahan selama masa pakai



Kesalahan

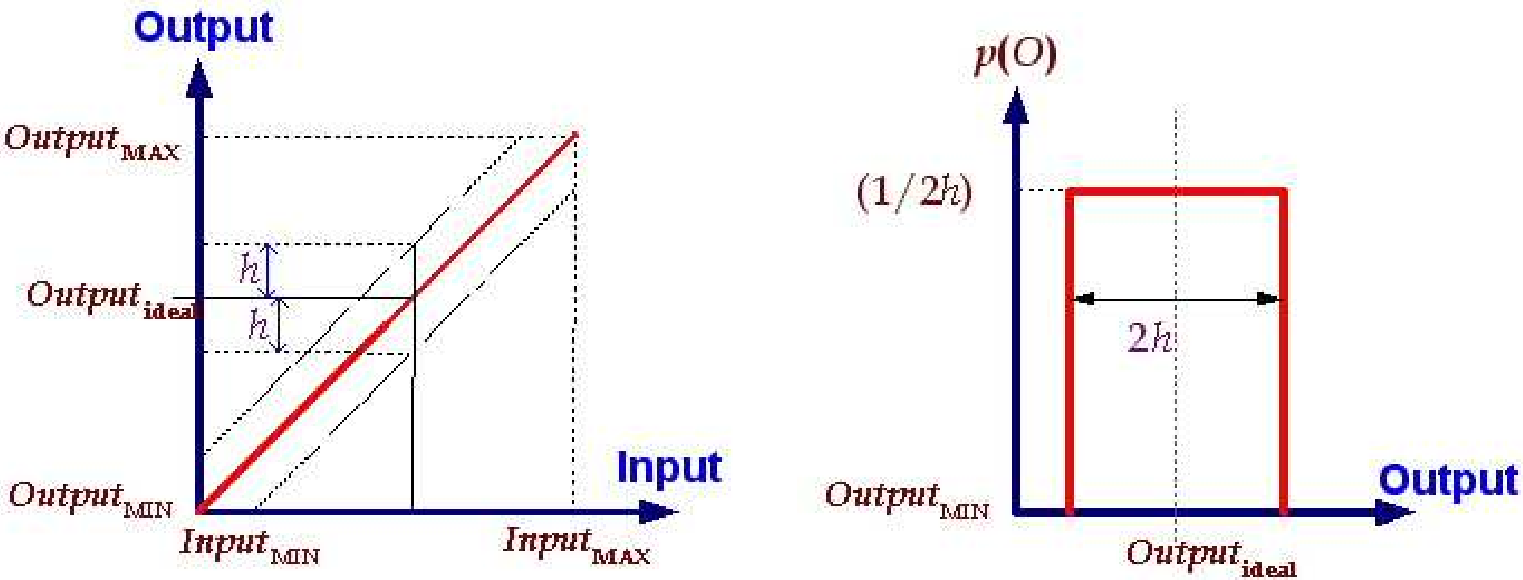
ERROR BANDS (pita *error*)

- Efek non-linieritas, histeresis dan resolusi, pada sistem pengukuran relatif sulit untuk dikuantifikasi secara tepat.
- Kinerja suatu sistem pengukuran dinyatakan dalam ***error bands***
- Kinerja sistem pengukuran dinyatakan dalam fungsi ***probability density*** *p*(*O*)

$$p(O)\begin{cases} = \dfrac{1}{2h} & Out_{ideal} - h \le Out \le Out_{ideal} + h \\ = 0 & 0 > Out_{ideal} + h \\ = 0 & Out_{ideal} - h > 0 \end{cases}$$

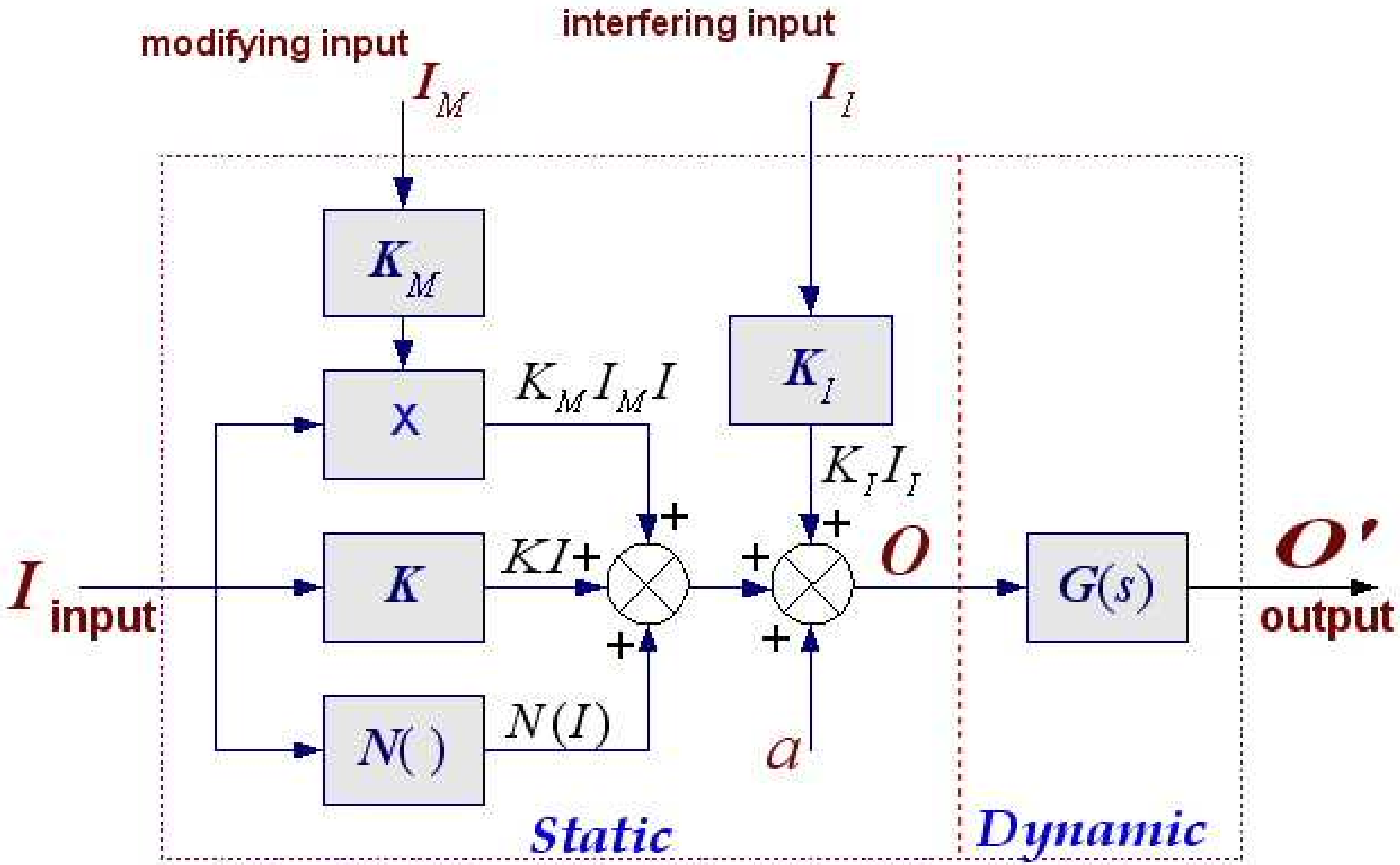
Kesalahan

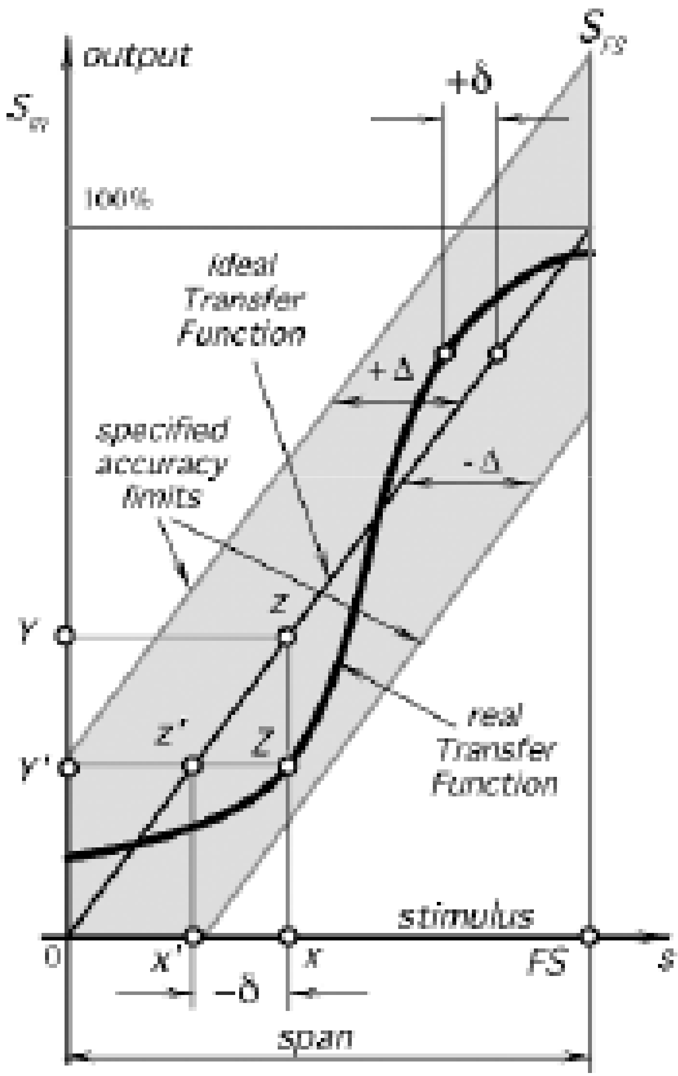
ERROR BANDS (pita *error*)

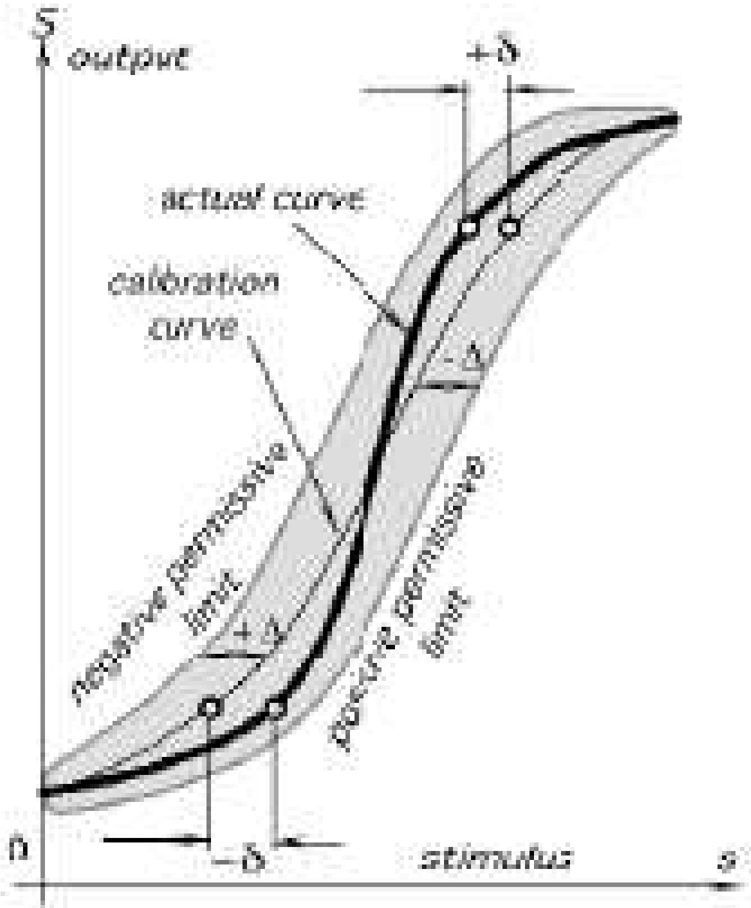


MODEL Umum Sensor

$$Out = K \cdot I + a + N(In) + K_M \cdot I_M \cdot I + K_I I_I$$

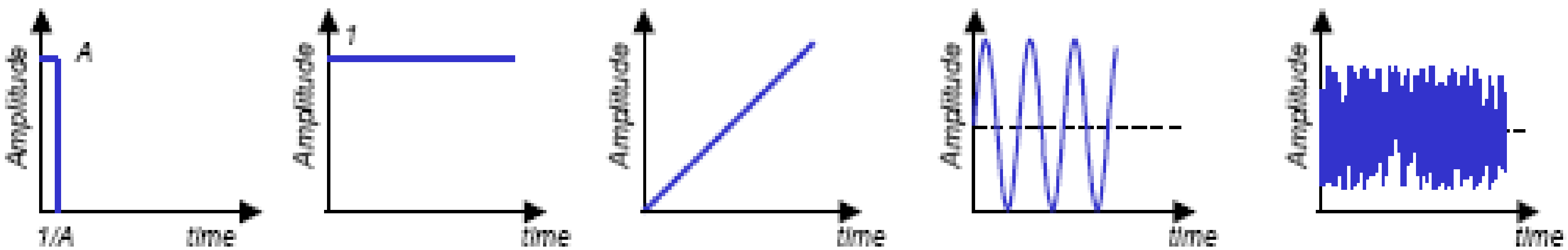



output
S_m
S_{FS}
+δ
100%
ideal Transfer Function
+Δ
-Δ
specified accuracy limits
Y
Z
Y'
z'
Z
real Transfer Function
stimulus
0
x'
x
-δ
FS
s
span


S
output
+δ
actual curve
calibration curve
-Δ
negative permissive limit
+Δ
positive permissive limit
-δ
stimulus
s

Karakteristik Dinamik

- The sensor response to a variable input is different from that exhibited when the input signals are constant (the latter is described by the static characteristics)
- The reason for dynamic characteristics is the presence of energy-storing elements
  - Inertial: masses, inductances
  - Capacitances: electrical, thermal
- Dynamic characteristics are determined by analyzing the response of the sensor to a family of variable input waveforms:
  - Impulse, step, ramp, sinusoidal, white noise…



Model Dinamika

- **The dynamic response of the sensor is (typically) assumed to be linear**
  - Therefore, it can be modeled by a constant-coefficient linear differential equation

$$a_k \frac{d^k y(t)}{dt^k} + \cdots a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = x(t)$$

  - In practice, these models are confined to zero, first and second order. Higher order models are rarely applied
- **These dynamic models are typically analyzed with the Laplace transform, which converts the differential equation into a polynomial expression**
  - Think of the Laplace domain as an extension of the Fourier transform
    - Fourier analysis is restricted to sinusoidal signals
      - $x(t) = \sin(\omega t) = e^{-j\omega t}$
    - Laplace analysis can also handle exponential behavior
      - $x(t) = e^{-\sigma t}\sin(\omega t) = e^{-(\sigma + j\omega)t}$

Review Transformasi LAPLACE

- The Laplace transform of a time signal y(t) is denoted by
  - L[y(t)] = Y(s)
    - The s variable is a complex number $s=\sigma+j\omega$
      - The real component σ defines the real exponential behavior
      - The imaginary component defines the frequency of oscillatory behavior
- The fundamental relationship is the one that concerns the transformation of differentiation

$$L\left[\frac{d}{dt}y(t)\right] = sY(s) - f(0)$$

- Other useful relationships are

Impulse: $L[\delta(t)] = 1$

Step: $L[u(t)] = \frac{1}{s}$

Ramp: $L[r(t)] = \frac{1}{s^2}$

Decay: $L[\exp(at)] = (s-a)^{-1}$

Sine: $L[\sin(\omega t)] = \frac{\omega}{s^2+\omega^2}$

Cosine: $L[\cos(\omega t)] = \frac{s}{s^2+\omega^2}$

Review Transformasi LAPLACE

- **Applying the Laplace transform to the sensor model yields**

$$L\left[a_k \frac{d^k y}{dt^k} + \cdots a_2 \frac{d^2 y}{dt^2} + a_1 \frac{dy}{dt} + a_o y(t) = x(t)\right]$$

$$\Downarrow$$

$$\left(a_k s^k + \cdots a_2 s^2 + a_1 s + a_o\right) Y(s) = X(s)$$

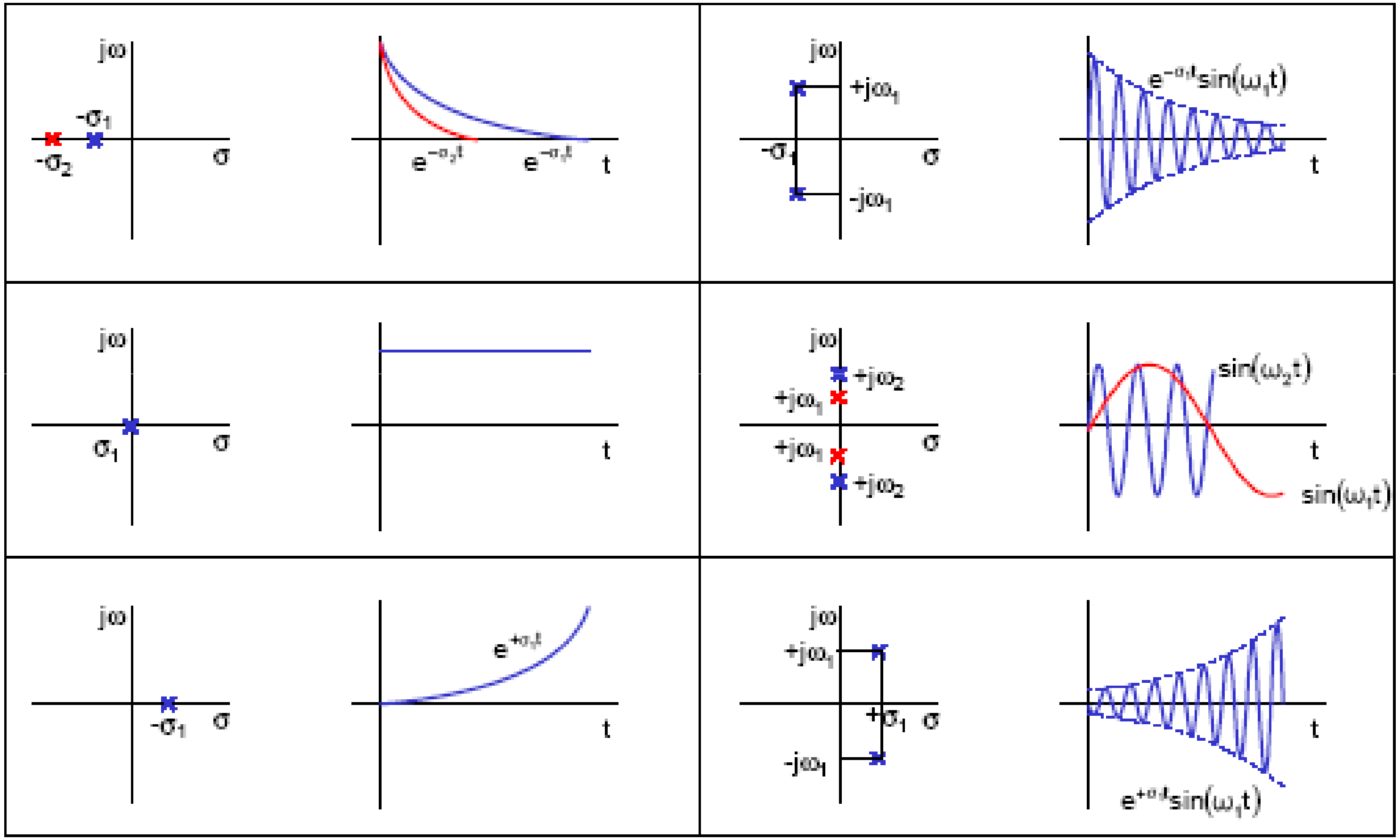
$$\Downarrow$$

$$G(s) = \frac{Y(s)}{X(s)} = \frac{1}{a_k s^k + \cdots a_2 s^2 + a_1 s + a_o}$$

  - G(s) is called the transfer function of the sensor

- **The position of the poles of G(s) -zeros of the denominator- in the s-plane determines the dynamic behavior of the sensor such as**
  - Oscillating components
  - Exponential decays
  - Instability

Lokasi *pole* dan perilaku dinamik

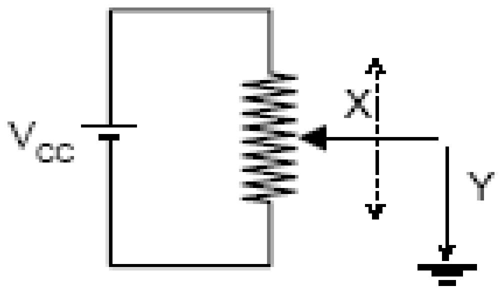


Sensor orde NOL

- Input and output are related by an equation of the type

$$y(t) = k \cdot x(t) \Rightarrow \frac{Y(s)}{X(s)} = k$$

- Zero-order is the desirable response of a sensor
  - No delays
  - Infinite bandwidth
  - The sensor only changes the amplitude of the input signal
- Zero-order systems do not include energy-storing elements
- Example of a zero-order sensor
  - A potentiometer used to measure linear and rotary displacements
    - This model would not work for fast-varying displacements



Sensor orde SATU

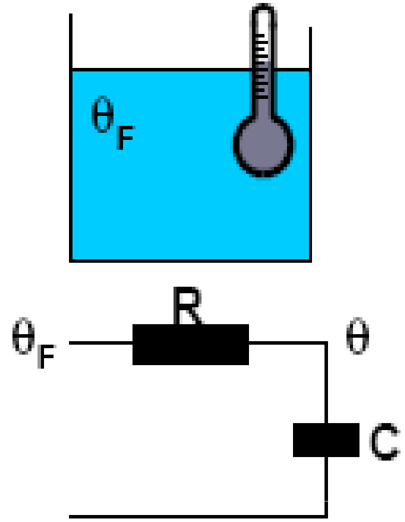
- Inputs and outputs related by a first-order differential equation

$$a_1 \frac{dy}{dt} + a_0 y(t) = x(t) \Rightarrow \frac{Y(s)}{X(s)} = \frac{1}{a_1 s + a_0} = \frac{k}{\tau s + 1}$$

- First-order sensors have one element that stores energy and one that dissipates it
- Step response
  - $y(t) = Ak(1-e^{-t/\tau})$
    - A is the amplitude of the step
    - k ($=1/a_0$) is the static gain, which determines the static response
    - τ ($=a_1/a_0$) is the time constant, which determines the dynamic response
- Ramp response
  - $y(t) = Akt - Ak\tau u(t) + Ak\tau e^{-t/\tau}$
- Frequency response
  - Better described by the amplitude and phase shift plots

Contoh sensor orde SATU

- **A mercury thermometer immersed into a fluid**
  - What type of input was applied to the sensor?
  - Parameters
    - C: thermal capacitance of the mercury
    - R: thermal resistance of the glass to heat transfer
    - θ_F: temperature of the fluid
    - $\theta(t)$: temperature of the thermometer
  - The equivalent circuit is an RC network



- **Derivation**
  - Heat flow through the glass $(\theta_F - \theta(t))/R$
  - Temperature of the thermometer rises as $\frac{d\theta(t)}{dt} = \frac{\theta_F - \theta(t)}{RC}$
  - Taking the Laplace transform

$$s\,\theta(s) = \frac{\theta_F(s) - \theta(s)}{RC} \Rightarrow (RCs + 1)\theta(s) = \theta_F(s) \Rightarrow$$

$$\Rightarrow \theta(s) = \frac{\theta_F(s)}{(RCs+1)} \Rightarrow \theta(t) = \theta_F\left(1 - e^{-t/RC}\right)$$

Sensor orde DUA

- Inputs and outputs are related by a second-order differential equation

$$a_2\frac{d^2y}{dt^2}+a_1\frac{dy}{dt}+a_0y(t)=x(t)\Rightarrow\frac{Y(s)}{X(s)}=\frac{1}{a_2s^2+a_1s+a_0}$$

- We can express this second-order transfer function as

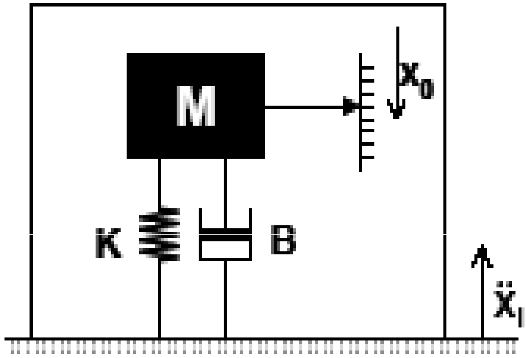
$$\frac{Y(s)}{X(s)}=\frac{k\omega_n^2}{s^2+2\zeta\omega_ns+\omega_n^2}$$

$$\text{with }k=\frac{1}{a_0},\ \zeta=\frac{a_1}{2\sqrt{a_0a_1}},\ \omega_n=\sqrt{\frac{a_0}{a_2}}$$

- Where
  - k is the static gain
  - ζ is known as the damping coefficient
  - ω_n is known as the natural frequency

Contoh sensor orde DUA

- **A thermometer covered for protection**
  - Adding the heat capacity and thermal resistance of the protection yields a second-order system with two real poles (overdamped)
- **Spring-mass-dampen accelerometer**
  - The armature suffers an acceleration
    - We will assume that this acceleration is orthogonal to the direction of gravity
  - x_0 is the displacement of the mass M with respect to the armature
  - The equilibrium equation is:



$$M(\ddot{x}_i - \ddot{x}_0) = Kx_0 + B\dot{x}_0$$

$$\Downarrow$$

$$Ms^2X_i(s) = X_0(s)\left[K + Bs + Ms^2\right]$$

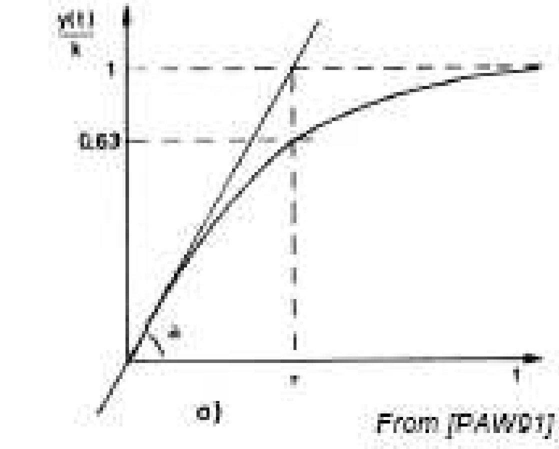
$$\Downarrow$$

$$\frac{X_0(s)}{s^2X_i(s)} = \frac{M}{K}\frac{K/M}{s^2 + s(B/M) + K/M}$$

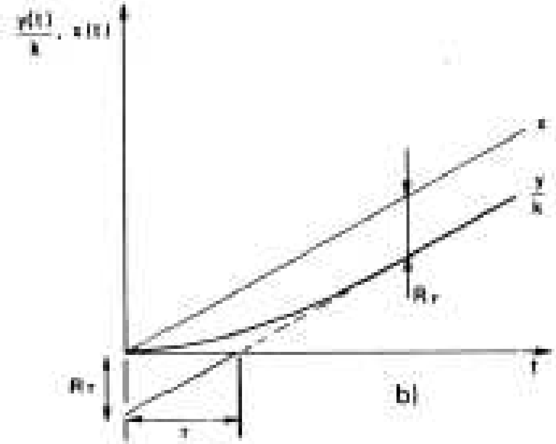
IDENTIFIKASI KARAKTERISTIK SENSOR

Respon sensor orde SATU

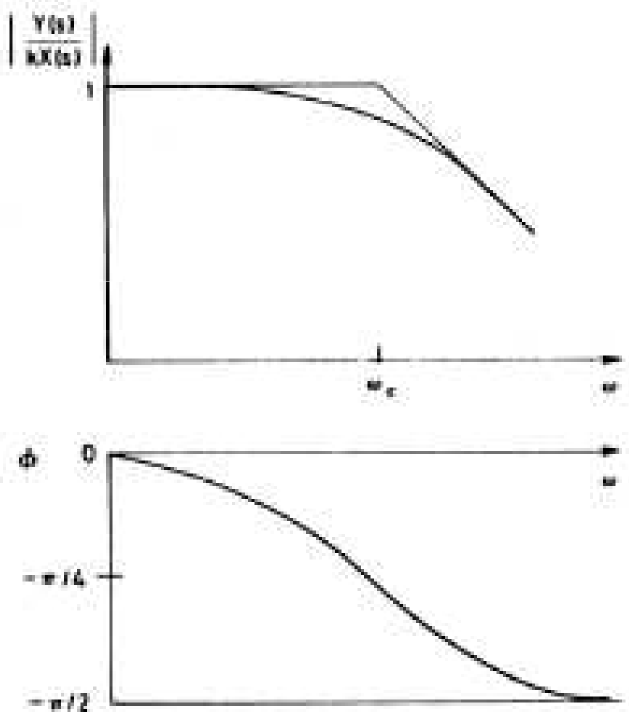
- Step response



- Ramp response

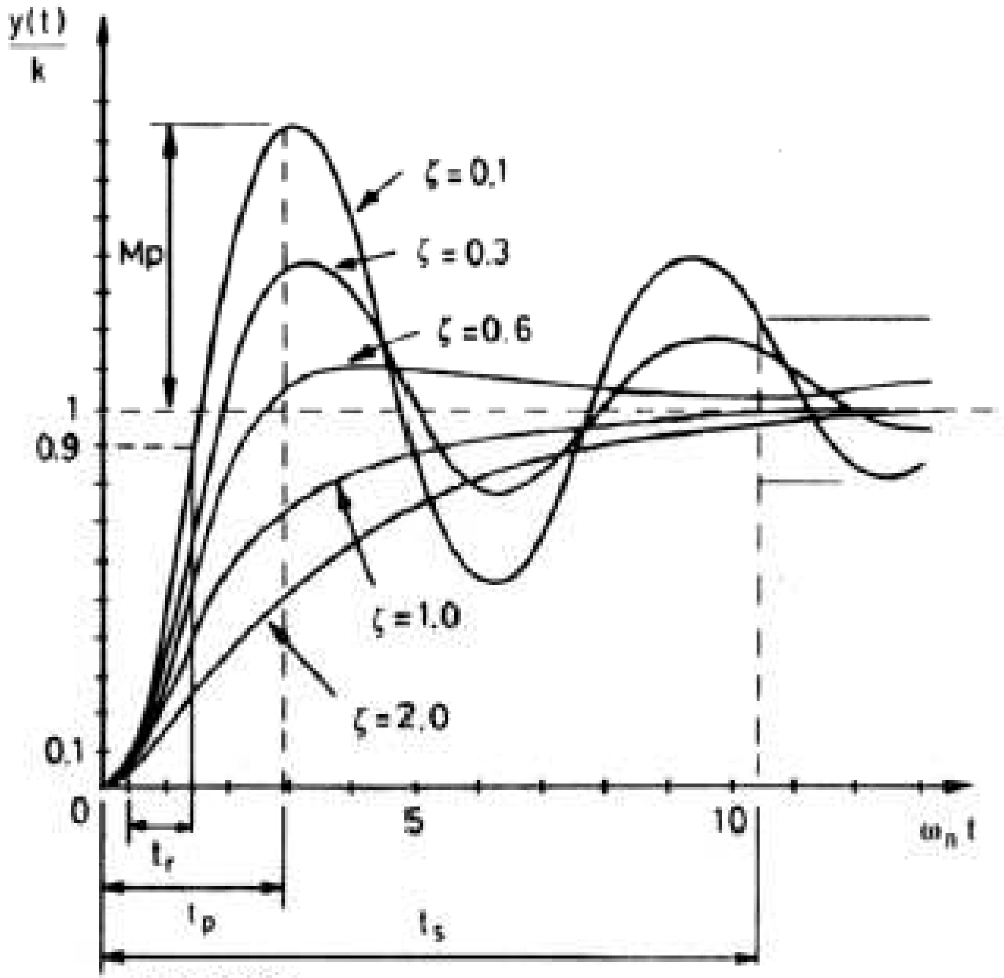


- Frequency response
  - Corner frequency $\omega_c=1/\tau$
  - Bandwidth



Respon STEP orde DUA

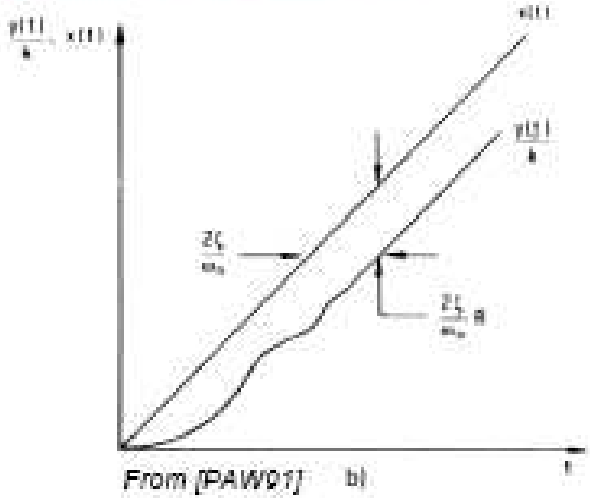
- **Response types**
  - Underdamped (ζ<1)
  - Critically damped (ζ=1)
  - Overdamped (ζ>1)
- **Response parameters**
  - Rise time (t_r)
  - Peak overshoot (M_p)
  - Time to peak (t_p)
  - Settling time (t_s)



From [PAW01]

Respon orde DUA

- Ramp response



- Frequency response