Pressure and Temperature Sensors

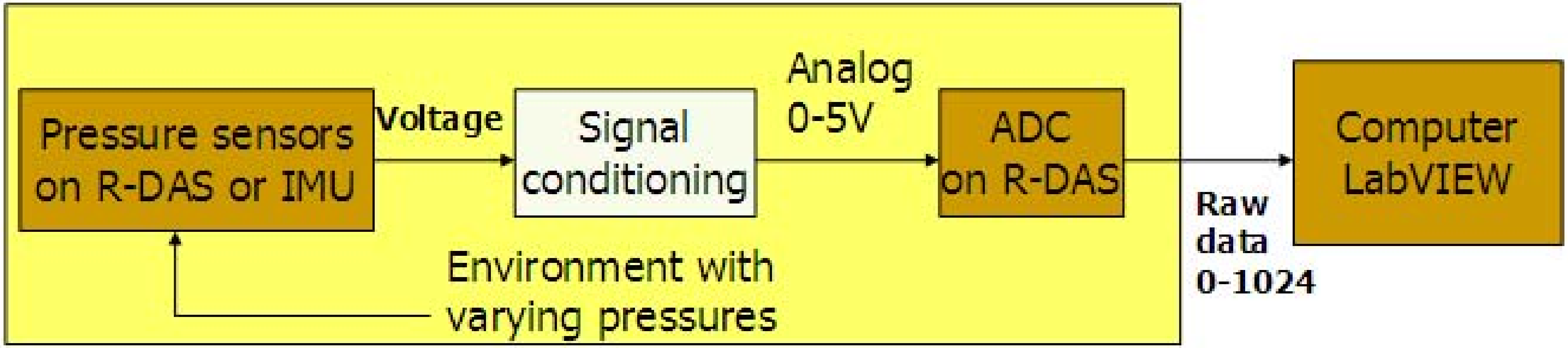
E80

Feb 17, 2009

Agenda

- Pressure sensors and calibration
- Relating pressure to altitude
- Temperature sensors and calibration (Steinhart-Hart constants)

Pressure Sensors

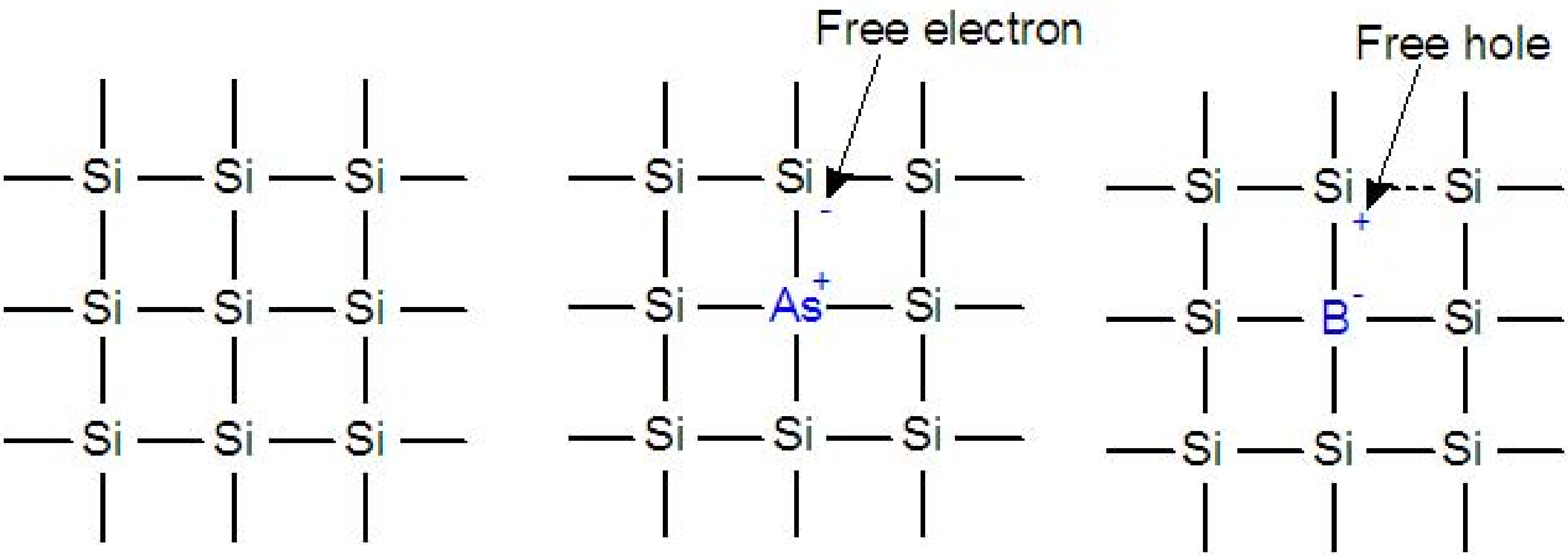


- Why use pressure sensors?

→ Can figure out altitude from Pressure

How Pressure Sensors Work

Made from semiconductors



Silicon Lattice

n-doped Silicon

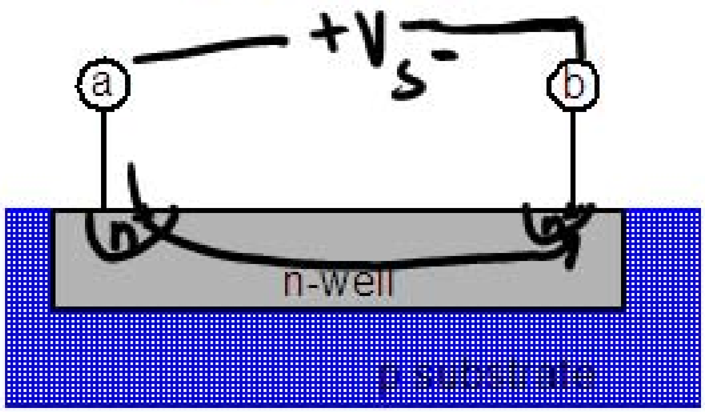
negative charges floating around

p-doped Silicon

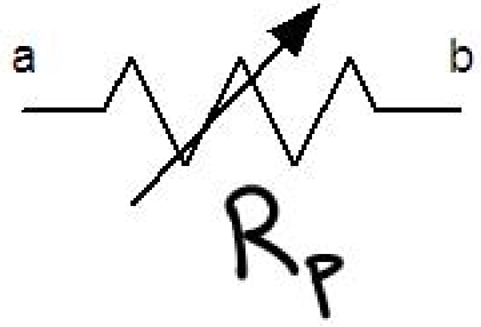
positive charges

How Pressure Sensors Work

Device

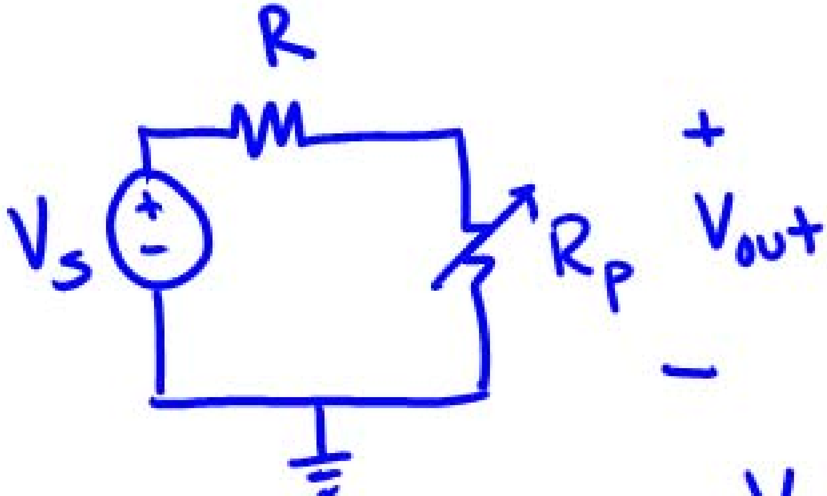


Symbol



How do we measure resistance?

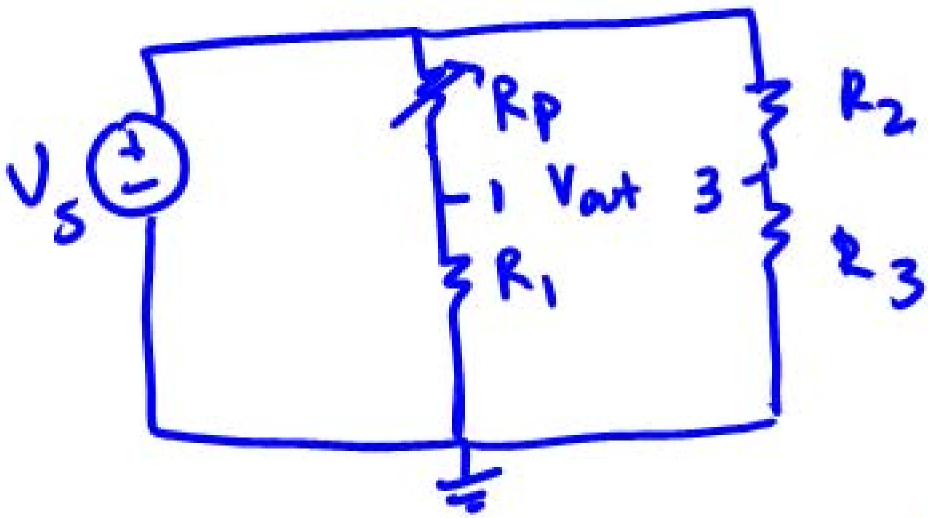
Voltage Divider:



$$V_{out} = \left[\frac{R_p}{R_p + R}\right] V_s$$

How do we measure resistance?

Wheatstone Bridge ckt



If all R's equal,

$V_{out} = 0$

If $R_2 = R_3$

$$V_{out} = \left[\frac{R_1}{R_1 + R_p} - \frac{R_3}{2R_3} \right] V_s$$

$$R_p = R_1 \left[\frac{V_s - 2V_{out}}{V_s + 2V_{out}} \right]$$

$$V_{out} = V_1 - V_3$$

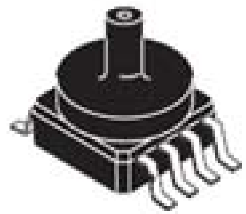
$$= \left(\frac{R_1}{R_1 + R_p} \right) V_s - \left(\frac{R_3}{R_3 + R_2} \right) V_s$$

$$= \left[\left(\frac{R_1}{R_1 + R_p} \right) - \left(\frac{R_3}{R_3 + R_2} \right) \right] V_s$$

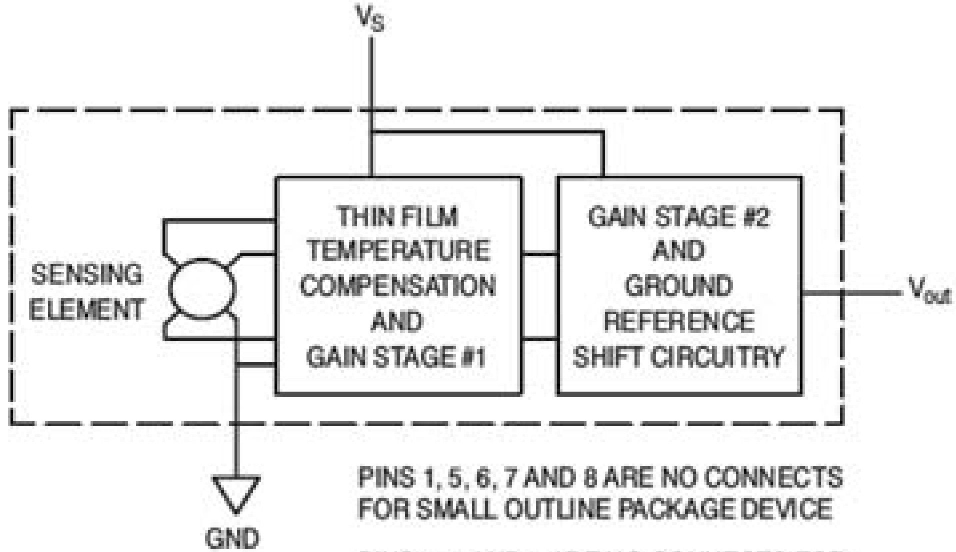
Pressure sensors
MPX4115A(IMU) / MPXA6115A (R-DAS)

SMALL OUTLINE PACKAGE

MPXA4115A6U
CASE 482



MPXA4115AC6U
CASE 482A



PINS 1, 5, 6, 7 AND 8 ARE NO CONNECTS FOR SMALL OUTLINE PACKAGE DEVICE

PINS 4, 5 AND 6 ARE NO CONNECTS FOR UNIBODY DEVICE

Figure 1. Fully Integrated Pressure Sensor Schematic

Features

- 1.5% Maximum Error over 0° to 85°C
- Ideally suited for Microprocessor or Microcontroller–Based Systems
- Temperature Compensated from –40° to +125°C
- Durable Epoxy Unibody Element or Thermoplastic (PPS) Surface Mount Package

http://www.freescale.com/files/sensors/doc/data_sheet/MPX4115A.pdf?pspll=1
http://www.eng.hmc.edu/NewE80/PDFs/MPXA6115A.pdf

Pressure sensors-MPX4115A

- **Pressure range:** 15-115 kPa
- **Sensitivity:** 45.9mV/kPa
- **Supply voltage:** 5V
- **Output analog voltage:**
  - Offset voltage (V_{off}): output voltage at minimum rated pressure (Typical@ 0.204V)
  - Full scale output (Vfso): output voltage at maximum rated pressure (Typical@ 4.794 V)
- **Pressure units**
  - Pascal (Pa)=N/m^2: standard atmosphere P_0=101325=101.325kPa
  - Psi= (Force) pound per square inch: 1 Psi=6.89465 KPa

http://www.freescale.com/files/sensors/doc/data_sheet/MPX4115A.pdf?pspll=1

How does voltage correlate to pressure?

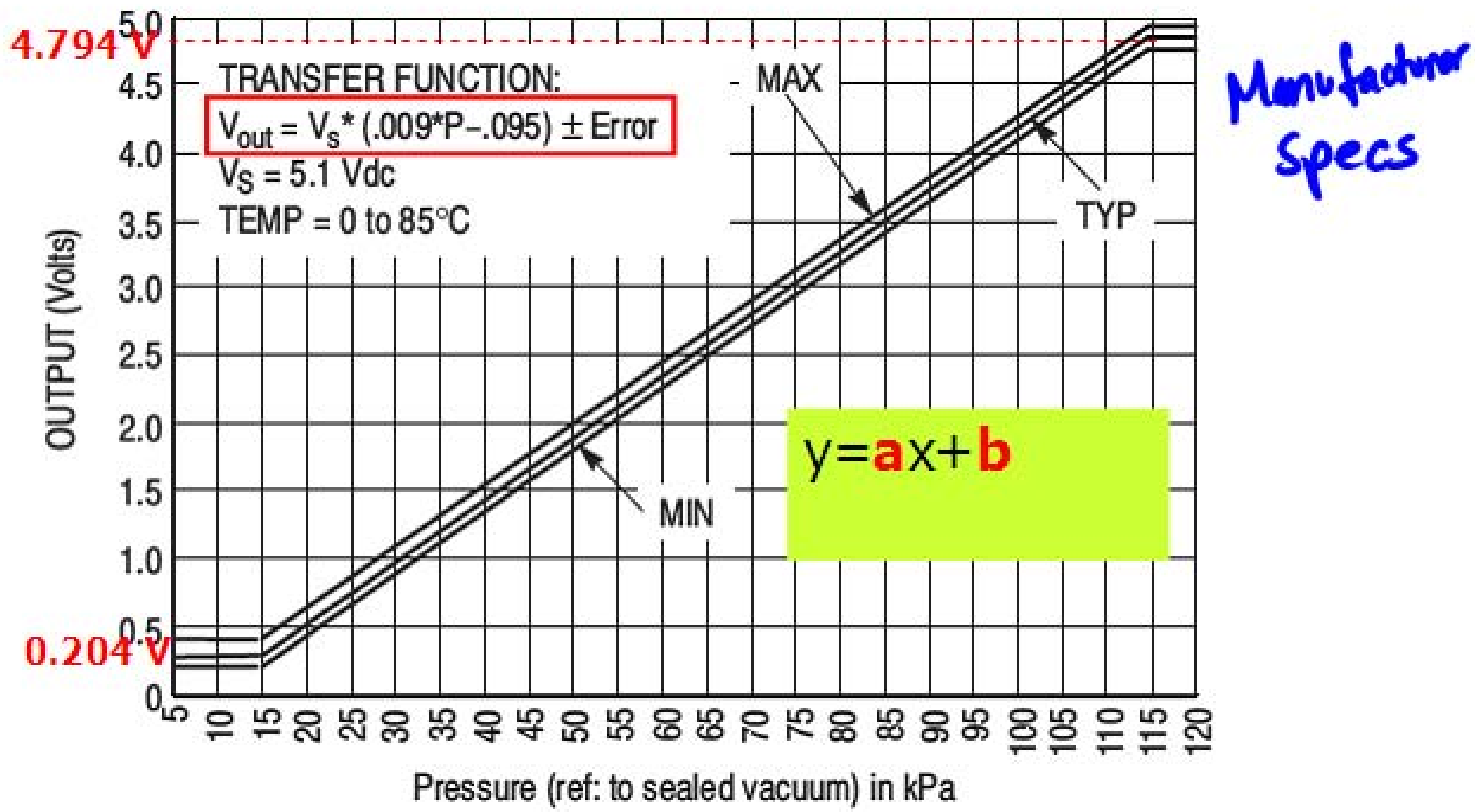
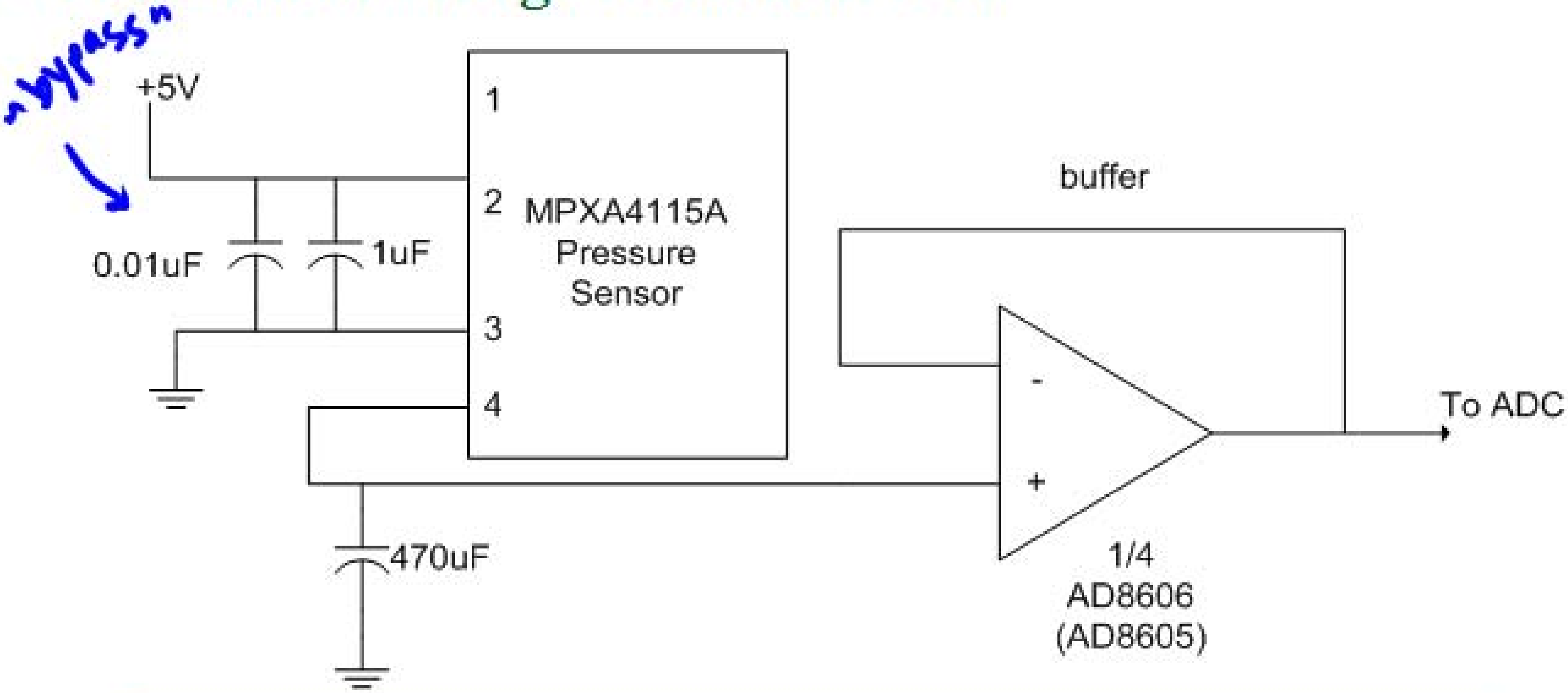


Figure 4. Output versus Absolute Pressure

http://www.freescale.com/files/sensors/doc/data_sheet/MPX4115A.pdf?pspll=1

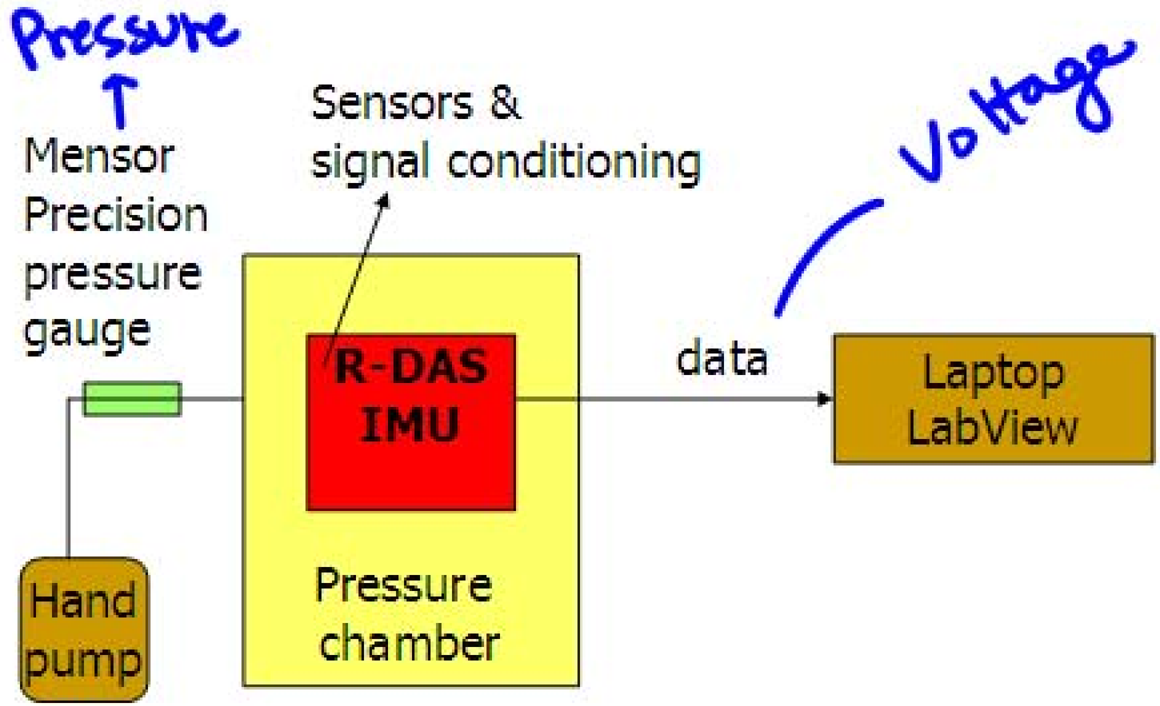
Signal Conditioning Circuitry

- From sensor voltage to ADC on IMU



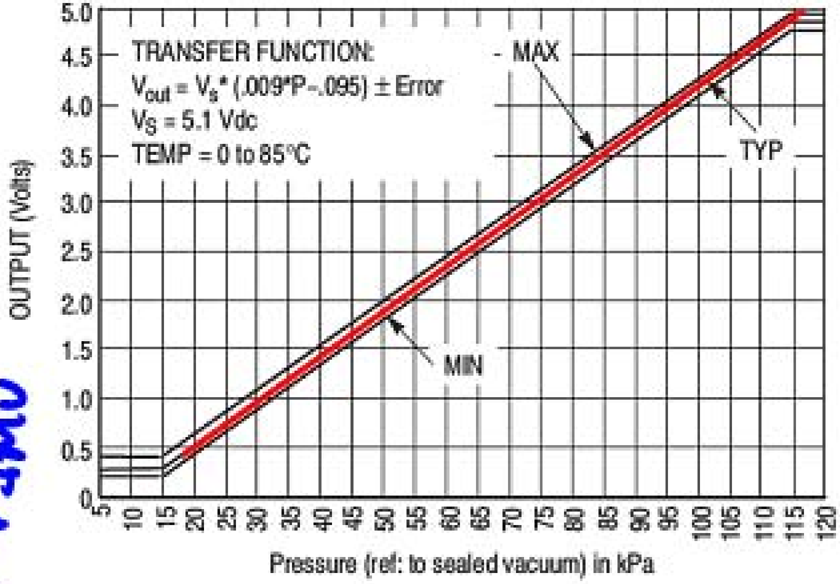
- 0.2-4.8V
- IMU Rin=1kΩ, so unity gain buffer for loading
- Low pass filter before ADC
- All power supplies bypassed to reduce noises

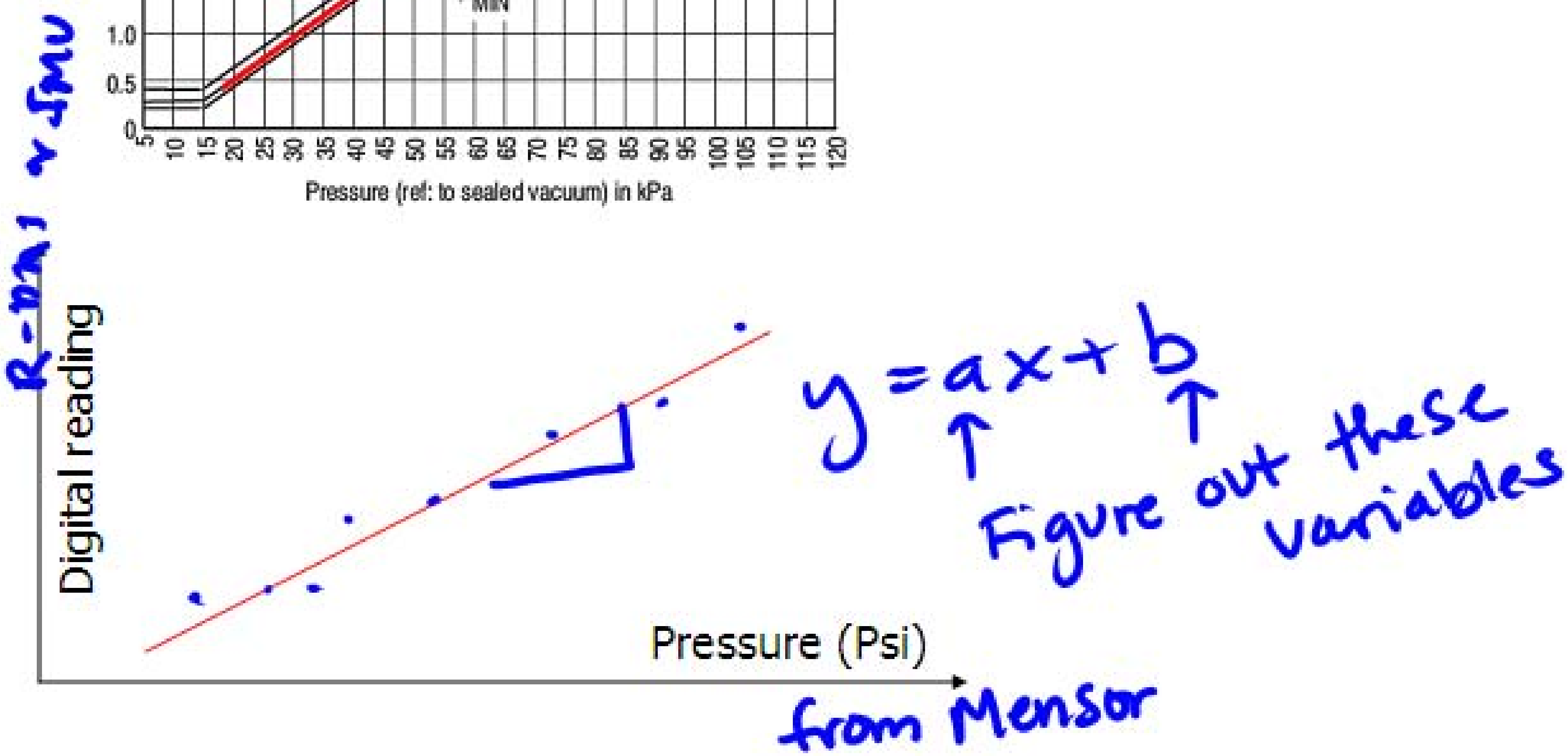
Calibrate in the lab



- Data (0-1024)→(0-5V)
- Pressure reading of Mensor is in units of psi

Calibration curve options





Error

Manufacturer

- Voltage Error = Pressure Error x Temperature Error Factor x 0.009 x Vs
- Temperature Error Factor=1 (0^oC - 85^oC)
- Pressure Error: +/- 1.5kPa

http://www.freescale.com/files/sensors/doc/data_sheet/MPX4115A.pdf?pspll=1

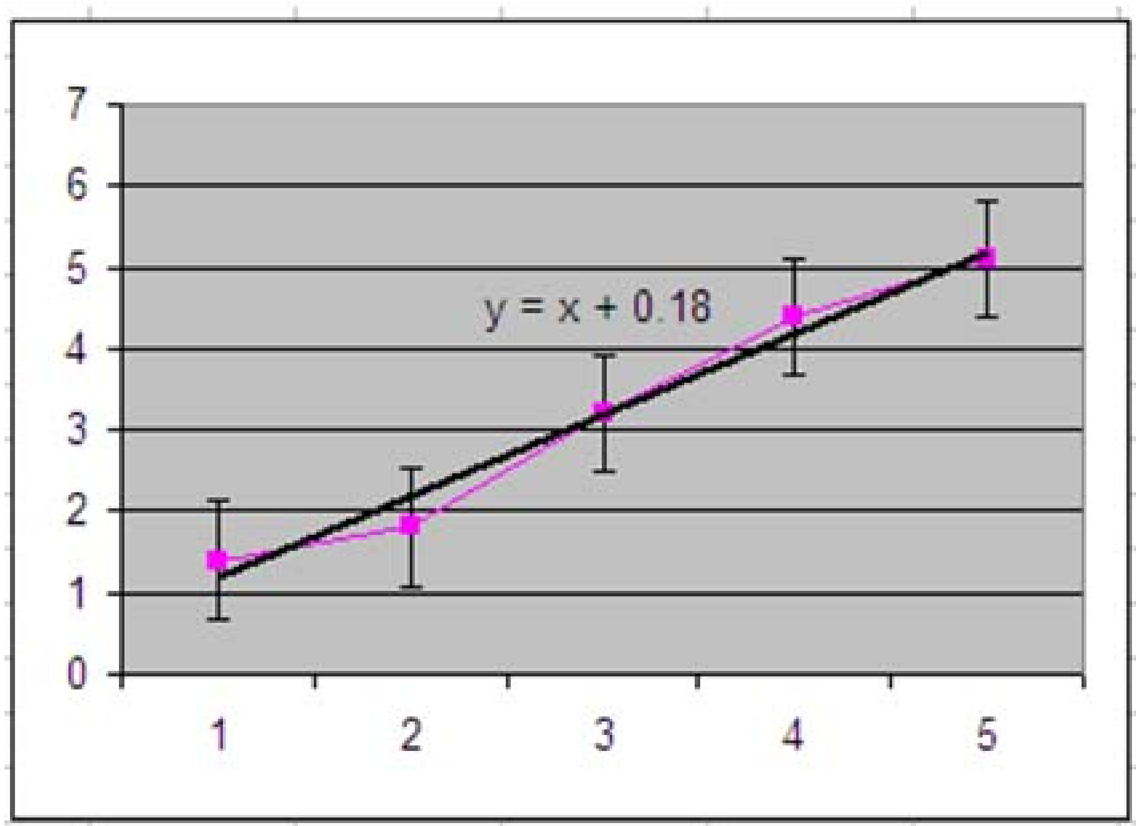
Find a and b in calibration curve

$y=ax+b$

- Collect data sets (x_1,y_1) (x_2, y_2)……(x_n, y_n), $n>2$
- Best fit (regression or least square) line
- Excel, Matlab, KlaidaGraph, LabView

Excel Example

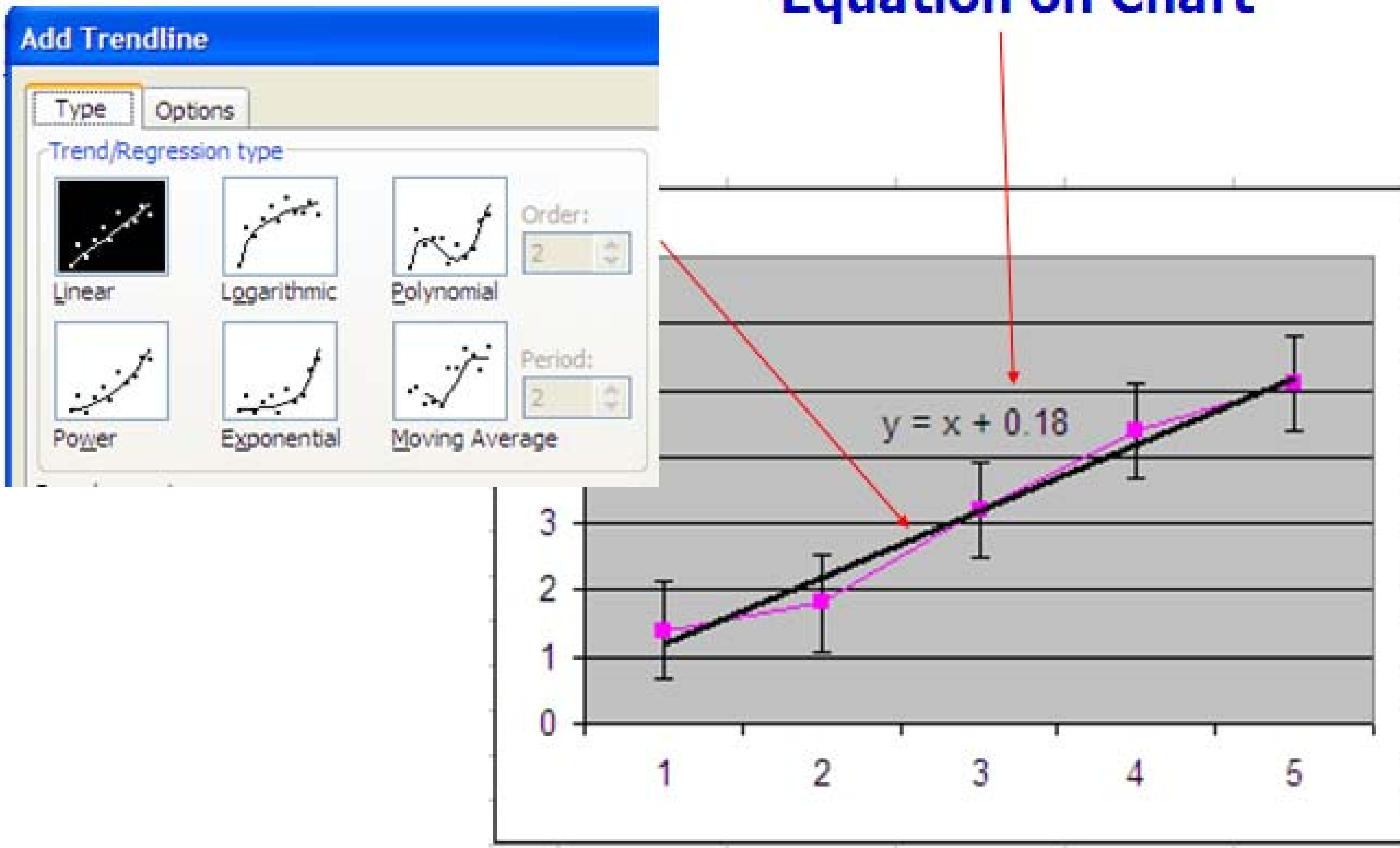
	A	B
1		
2		
3		
4	1	1.4
5	2	1.8
6	3	3.2
7	4	4.4
8	5	5.1
9		



Adding Trendlines

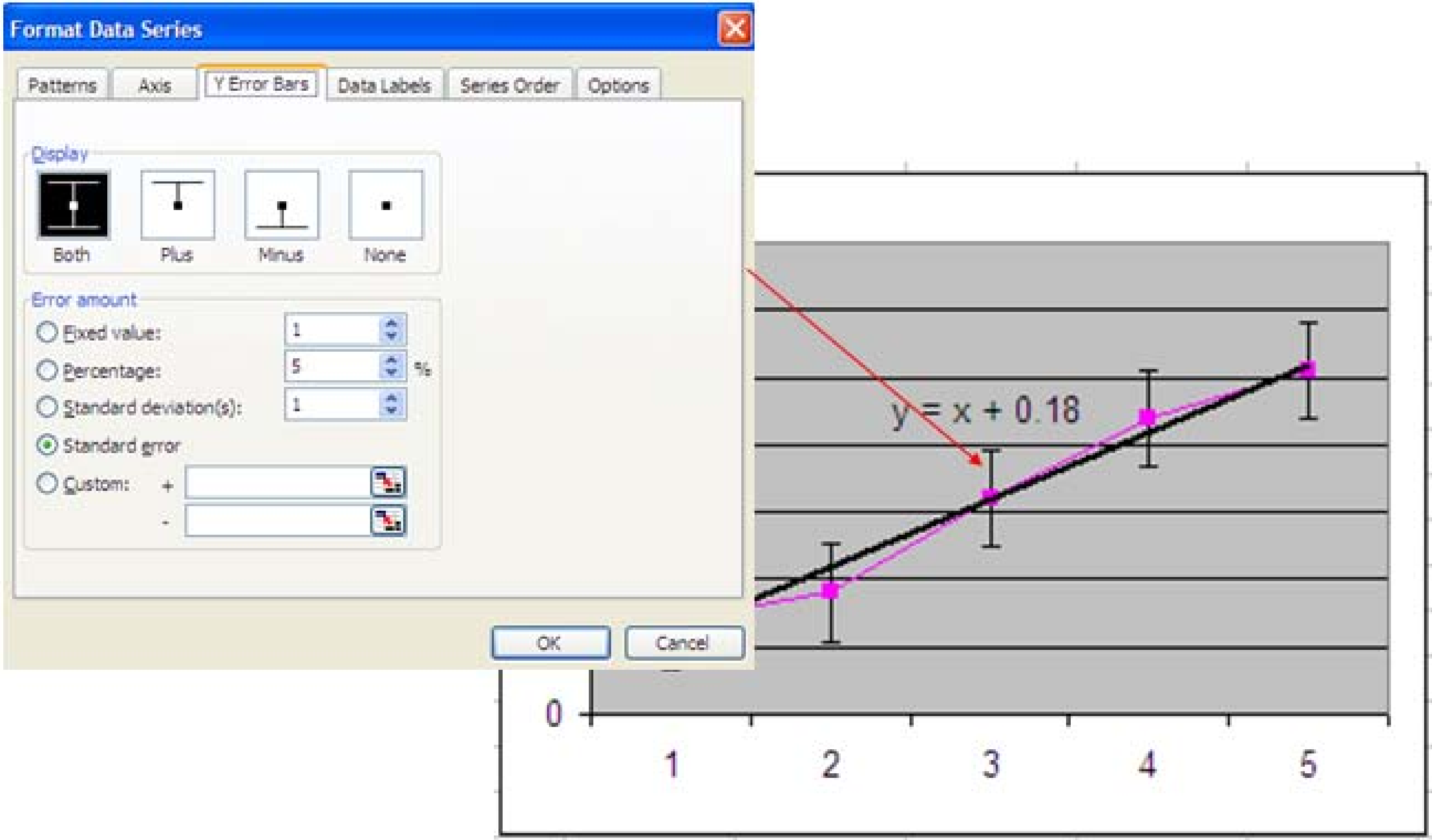
Chart -> Add Trendline

Options -> Display Equation on Chart



Adding Standard Error

Double-click on data series



Can also find a and b by hand

$$\text{Slope}: \quad a = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (\beta_1)$$

$$\text{Intercept}: \quad b = \bar{y} - a\bar{x} \quad (\beta_0)$$

Can also find error bars by hand

$$S_\varepsilon = \sqrt{\frac{\sum_{i=1}^{n} \varepsilon_i^2}{N-2}}$$

$$S_b = S_\varepsilon \sqrt{\frac{1}{N} + \frac{\bar{x}^2}{\sum_{i=1}^{N} (x_i - \bar{x})^2}}$$

$$S_a = S_\varepsilon \sqrt{\frac{1}{\sum_{i=1}^{N} (x_i - \bar{x})^2}}$$

$$\lambda_b = tS_b$$

$$\lambda_a = tS_a$$

Example

	A	B
1		
2		
3		
4	1	1.4
5	2	1.8
6	3	3.2
7	4	4.4
8	5	5.1
9		

$$a = 1$$

$$b = 0.18$$

$$S_\varepsilon = 0.29$$

$$S_a = 0.09$$

$$S_b = 0.3$$

$$\lambda_a = 0.3 \quad (95\% \; confidence)$$

$$\lambda_b = 0.97 \quad (95\% \; confidence)$$

Example using Matlab

```
% matrix of x values
x = [1 2 3 4 5]';

% matrix of y (observed outputs)
Y = [1.4 1.8 3.2 4.4 5.1]';

X = [ones(size(x)) x];  % the first column of this matrix must be 1's

% Perform linear reqression using least squares
% B: a matrix of the coefficients, B0 and B1 (b and a in previous example)
% BINT: a matrix of the confidence intervals for each coefficient
% R: a matrix of the residuals
% RINT: a matrix of the confidence intervals of the residuals, centered
% around each residual
[B, BINT, R, RINT] = regress(Y,X);
```

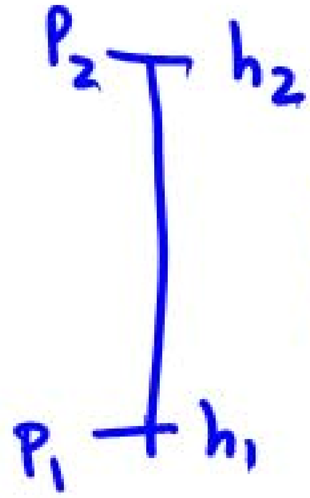
How does pressure (P) relate to altitude (h)?

$$P = \frac{F}{A} = \frac{mg}{A} = \frac{m}{V/h} \cdot g = \rho g h$$

Assume ρ is constant.

$$\Delta P = -\rho g \Delta h$$

$$P_2 - P_1 = -\rho g (h_2 - h_1)$$



$h_2 > h_1$

$P_2 < P_1$

How does pressure (P) relate to altitude (h)?

ρ isn't constant. ✓

$n = \#$ moles

$M =$ molar mass (kg/mol)

$$\rho = \frac{\text{Mass}}{\text{Volume}} = \frac{nM}{nRT/P}$$

$pV = nRT$

$$= \frac{MP}{RT}$$

$$\Delta P = -\rho g \Delta h$$

$$= -\frac{MP}{RT} g \Delta h$$

$$\frac{\Delta P}{\Delta h} = -\underbrace{\frac{Mg}{RT}}_{A} P(h)$$

$$\frac{dP(h)}{dh} = -A\,P(h)$$

$$P(h) = Ce^{-Ah}$$

@ $h=0$ $P(h) = C = P_0$

$$\boxed{P(h) = P_0 e^{-\frac{Mg}{RT}h}}$$ ✓

How does pressure (P) relate to altitude (h)?

$$h = \frac{T_0}{-\left(dT/dh\right)} \cdot \left[1 - \left(\frac{P_0}{P}\right)^{\frac{\left(dT/dh\right)R}{gM}}\right]$$

where

- h = altitude (above sea level) **(in meters)**
- P_0 = standard atmosphere pressure= 101.325kPa
- T_0 = 288.15K (+15°C)
- dT/dh= - 0.0065 K/m: thermal gradient or standard temperature lapse rate
- R = gas constant (8.31432 N*m/mol*K)
- g = (9.80665 m/s²)
- M = molar mass of earth's air (0.0289644 kg/mol)

Reference: (1976 US standard atmosphere)

How does pressure (P) relate to altitude (h)?

Plug in all the constants

$$h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325\text{kPa}}{P}\right)^{-0.1902}\right) \qquad \textbf{(1)}$$

- h is measured **in meters.**
- Equation calibrated up to 36,090 feet (11,000m).
- Reference: http://en.wikipedia.org/wiki/Atmospheric_pressure
- Different values of dT/dh for different layers of the atmosphere

How does pressure (P) relate to altitude (h)?

Plug in all the constants

$$h = 4.43\times10^{4}\times\left(1-\left(\frac{101.325\text{kPa}}{P}\right)^{-0.1902}\right) \quad \textbf{(1)}$$

Example

Suppose, **P = 85 kPa** (from Pressure sensor)

Method 1:

$$\Delta h = -\frac{\Delta P}{\rho g} = -\frac{(85 - 101)kPa}{(1.2\frac{kg}{m^3} * 9.8\frac{m}{s^2})} = 1.36\ km$$

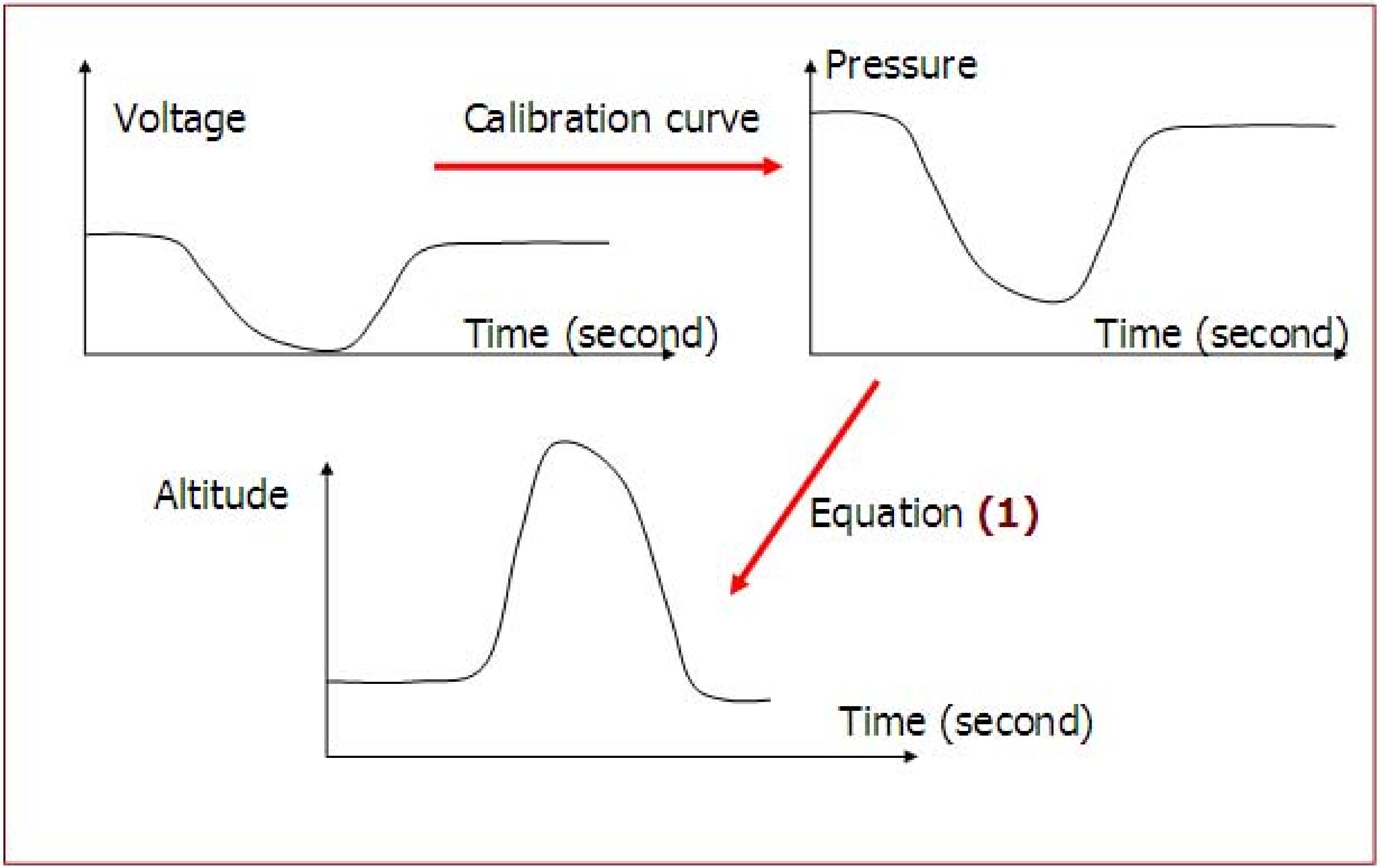
Method 2:

$$h = -\frac{RT}{Mg}\ln(\frac{P}{P_0}) = -8440\ln(\frac{85kPa}{101kPa}) = 1.46km$$

Method 3:

$$h = 4.43 \times 10^4 \times \left(1 - \left(\frac{101.325kPa}{85kPa}\right)^{-0.1902}\right) = 1.43km$$

Calibration process



How do we measure temperature?

- Thermometer
- Thermister : resistance changes w/ temp.
- Galileo thermometer

Temperature measuring devices

- Thermocouples
  - Metals generate a small voltage under a temperature difference
  - Measure voltage, know temperature difference
  - Largest temperature range (-200 ˚C – 1000 ˚C), low accuracy
- Resistance Temperature Detectors (RTDs)
  - Usually made from platinum
  - Resistance varies linearly with temperature
  - Large temperature range (-200 ˚C – 500 ˚C), medium accuracy
- Thermistors
  - Usually made of ceramic or polymer
  - Smaller temperature range (-40 ˚C – 125 ˚C), medium-high accuracy

Thermistors

- Sensitive, accurate, reliable, inexpensive $3
- Temperature dependent resistors
- Most common: Negative-Temperature Coefficient (NTC) thermistors T↑ R↓
- NTC themistors have nonlinear R-T characteristics
- Steinhart-Hart equation models the R-T relationship.

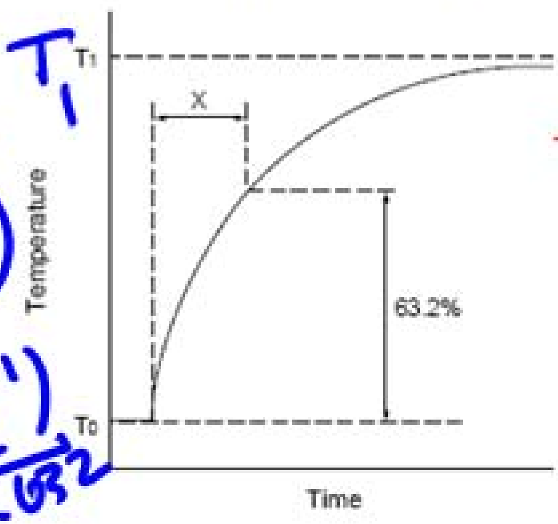
More background: http://www.thermometrics.com/assets/images/ntcnotes.pdf

Examples: thermistors in your car

- **Air conditioning**
- **Seat temperature controls**
- **Electronic fuel injection** air/fuel mixture and cooling water temperatures are monitored to help determine the fuel concentration for optimum injection
- **Warning indicators** oil and fluid temperatures, oil level and turbo-charger switch off
- **Fan motor control** based on cooling water temperature
- **Frost sensors** outside temperature measurement

Basic characteristics of thermistors

- Temperature range   −40°C to 125°C
- Resistance:
  - $R=R_0e^{B(1/T-1/T0)}$
  - $B=\ln(R/R_0)/(1/T-1/T_0)$
- Power dissipation
  - $P=C(T_2-T_1)$
  - C is the thermal dissipation constant (mW/°C).
- Thermal time constant



$T(t)=T_1(1-e^{-t/\tau})$

@ $t=\tau$ $T(\tau)=T_1(1-e^{-1})$ .632

http://www.murata.com

R-T characteristics of thermistor

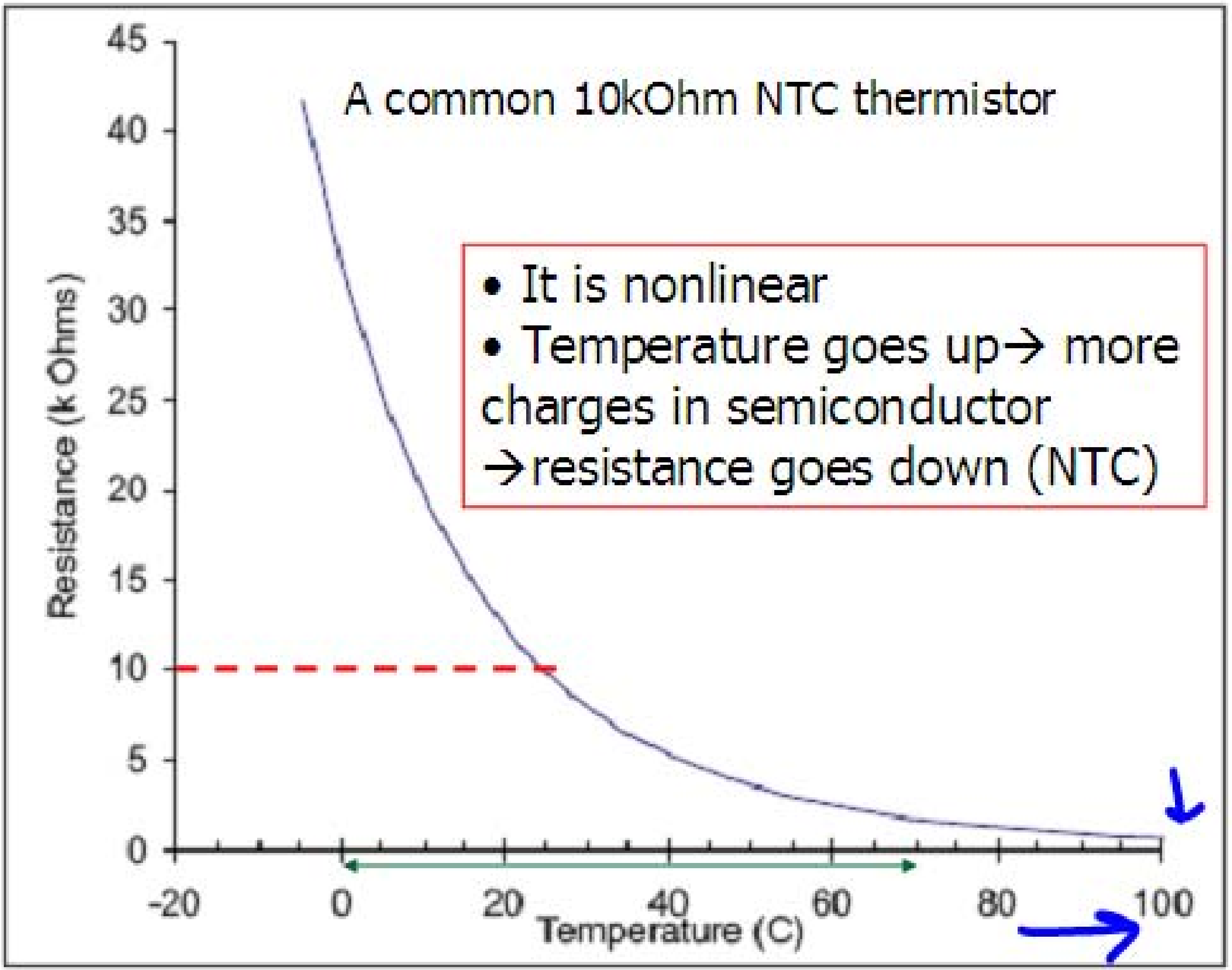
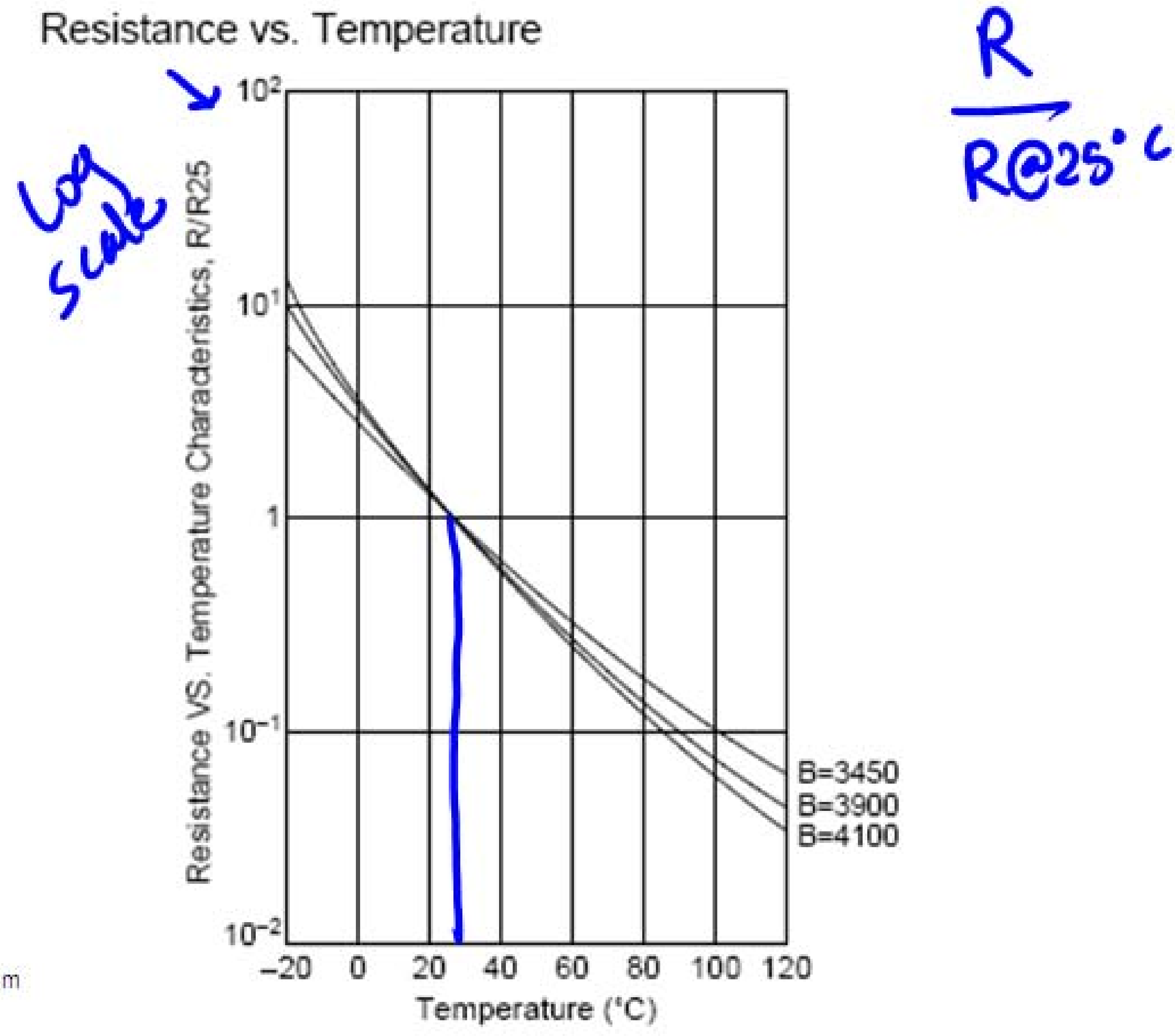


Figure 1. NTC R-T response curve.

R-T characteristics of thermistor



http://www.murata.com

Relating T to R: Steinhart-Hart (S-H) Equations

- **<u>3 term form:</u>**

$$\frac{1}{T} = C_1 + C_2 \ln(R) + C_3 (\ln(R))^3$$

- 2 term form:

$$\frac{1}{T} = C_1' + C_2' \cdot \ln(R)$$

Note $C_1' \neq C_1, C_2' \neq C_2$

- T, in Kelvin.
- How do we measure thermistor resistance? Voltage Divider
- How do we figure out C_1, C_2 and C_3?

How do we measure thermistor resistance?

– Voltage divider

How do we figure out C_1, C_2, and C_3?

$$\frac{1}{T} = C_1 + C_2 \ln(R) + C_3 \ln(R)^3$$

External sensor → T; thermistor → R

① – Need at least 3 ⇒ 3 equations, 3 unknowns

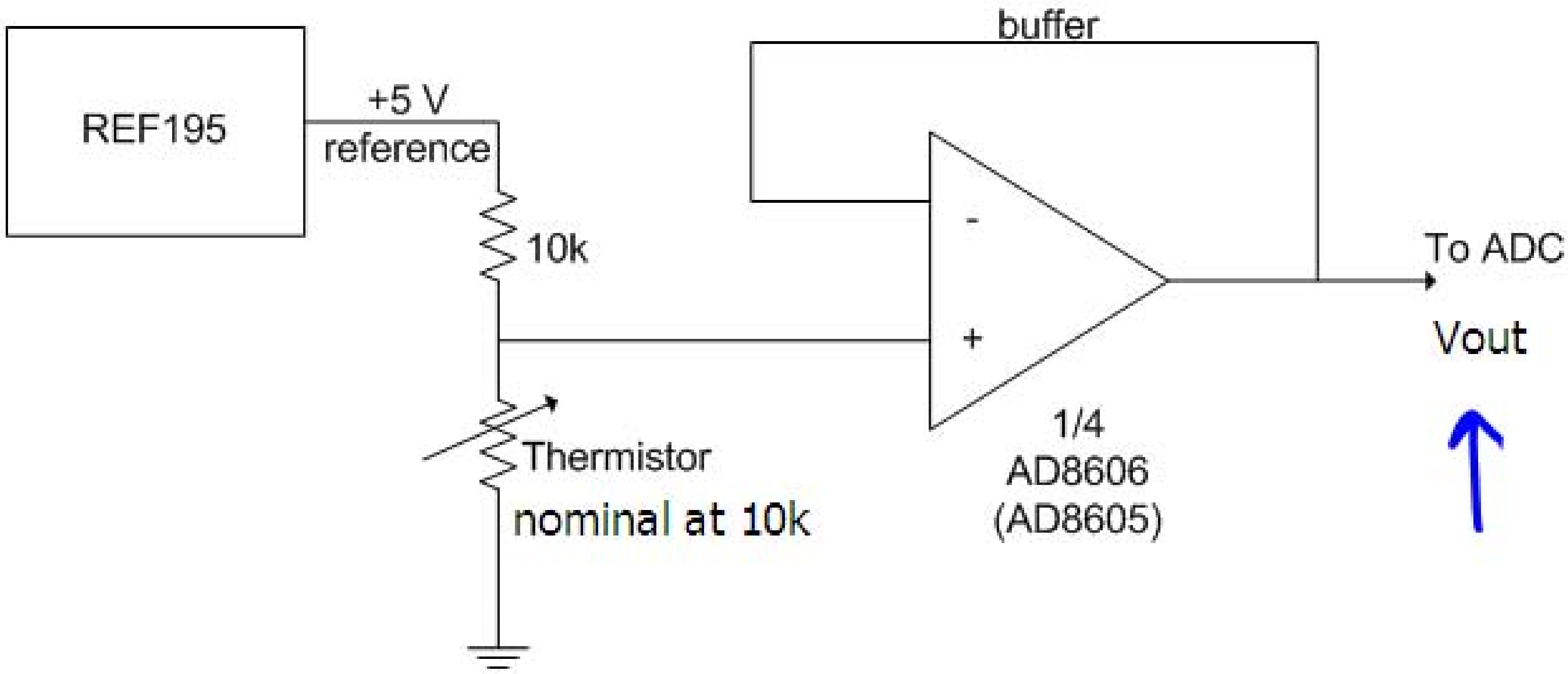
② – Take more samples:

– linear regression fit: Wikipedia.org ⇒ Linear Regression Example

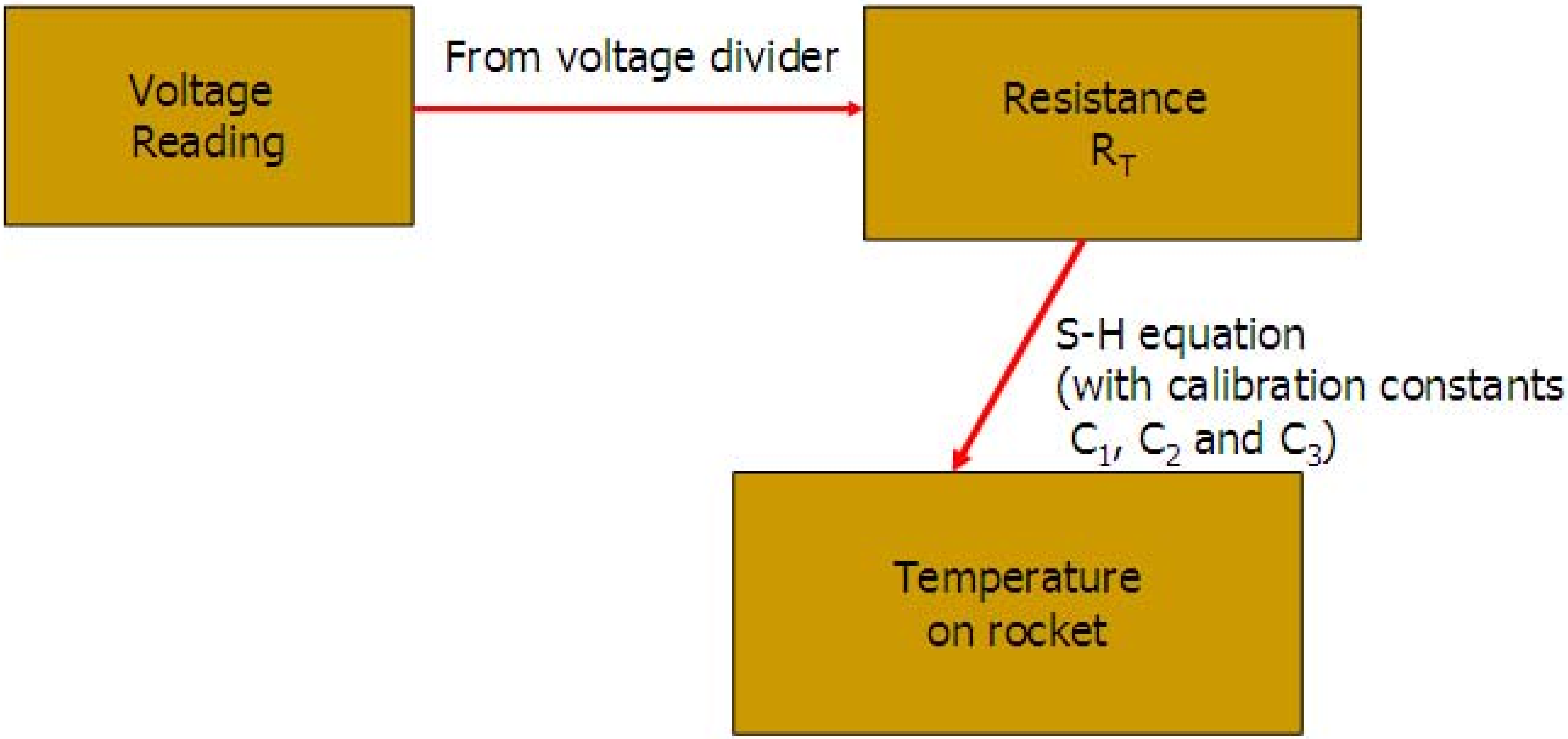
How do we figure out C_1, C_2, and C_3?

```
% Measured Resistance values
R = [37e3 20e3 10e3 5e3 4e3 2e3]';

% Observed temperatures, corresponding to resistance
  matrix
T = [0 10 25 38 50 80]';

% Convert temperatures to Kelvin and create Y = 1/T
Y = 1./(T + 273.15);

X = [ones(size(R)) log(R) (log(R).^3)];

[B, BINT, R, RINT] = regress(Y,X);
```

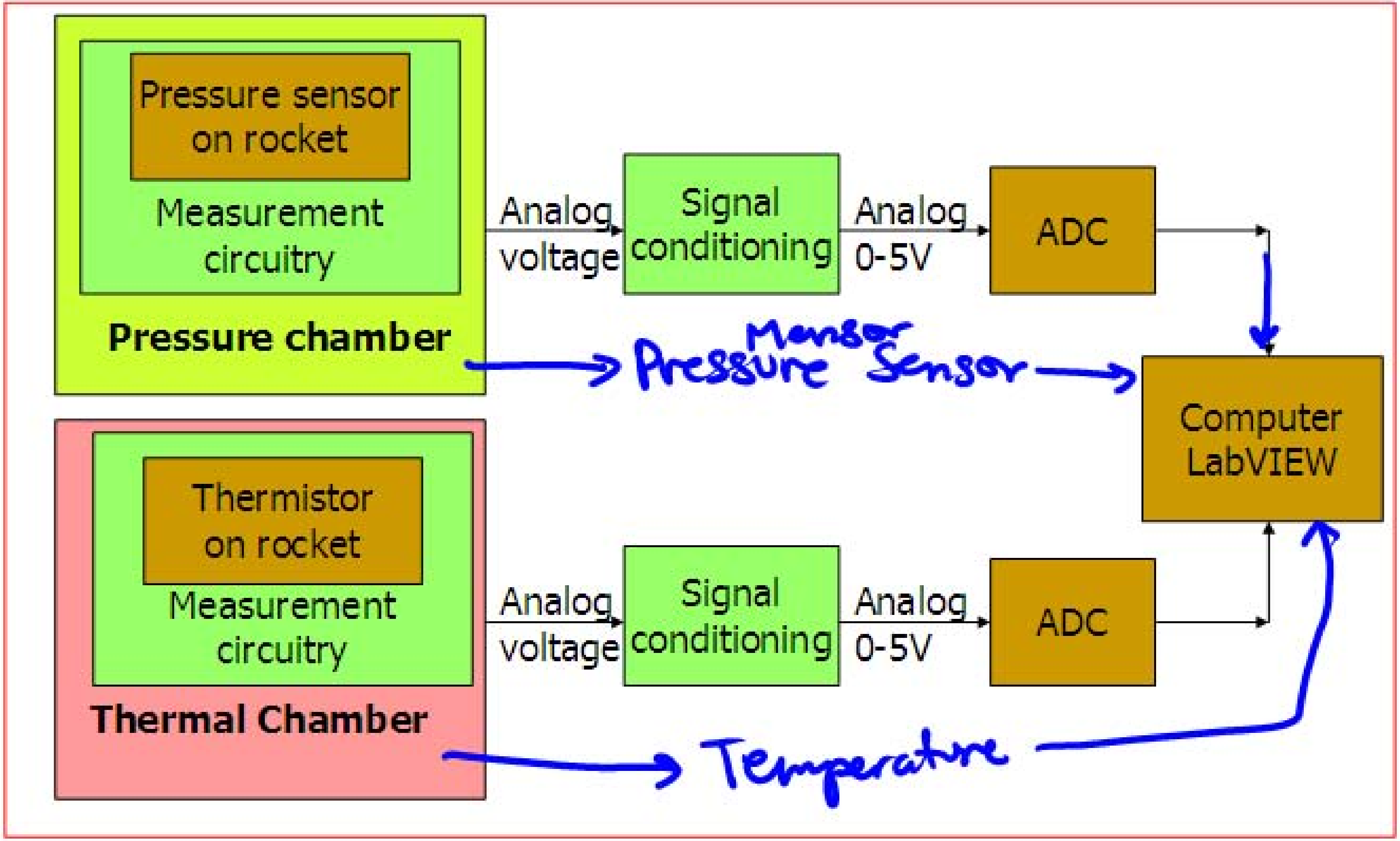
Thermistor signal conditioning circuits



Thermistor on the rocket



Summary


Pressure sensor on rocket
Measurement circuitry
Pressure chamber
Analog voltage
Signal conditioning
Analog 0-5V
ADC
Mensor
Pressure Sensor
Computer LabVIEW
Thermistor on rocket
Measurement circuitry
Thermal Chamber
Analog voltage
Signal conditioning
Analog 0-5V
ADC
Temperatre