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10	11/3 - 11/7	(VIII) MathScript, Data Acquisition (LV2)	E: Ch. 3 - 4	LV Assignment 1 due*	
11	11/10 - 11/14	No Lecture	E: Ch. 5 - 8	LV Assignment 2 due*	
12	11/17 - 11/21	(IX) Data Files; Shift Reg.; Case & Sequence Structure (LV3)	E: Ch. 9 - 10		
13	11/24 - 11/26	(X) Curve Fitting and FFT; Digital Thermometer (LV4)		Wed.: LV Assignment 3 due#; Makeup Lab	Thu. Thanksgiving
14	12/1 - 12/5	(XI) PID Temperature Control (LV5)	E: Ch. 12 E: Appendix I	LV Assignment 4 due#	
15	12/8 - 12/10	Last Lecture		LV Assignment 5 due$ Lab open during reading/final week	
				regular time	Thu. lab meets on **Tuesday**

* The **reports** are due 11:00 (11 AM) on the **day of your lab**.
# The **LV assignmen**t write-ups are due on **Friday** at 11 AM (assignment 3 & 5 are exceptions).
$ The **Final Project (LV 5)** is has to be turned in by **12/19**, 12/10 is recommended.
- The lab tickets are due at the beginning of your lab, i.e. 13:10.
- The next week's assignment will be given out in lab lecture the week of the lab.

S: R. E. Simpson
E: John Essick

II) This week's assignment

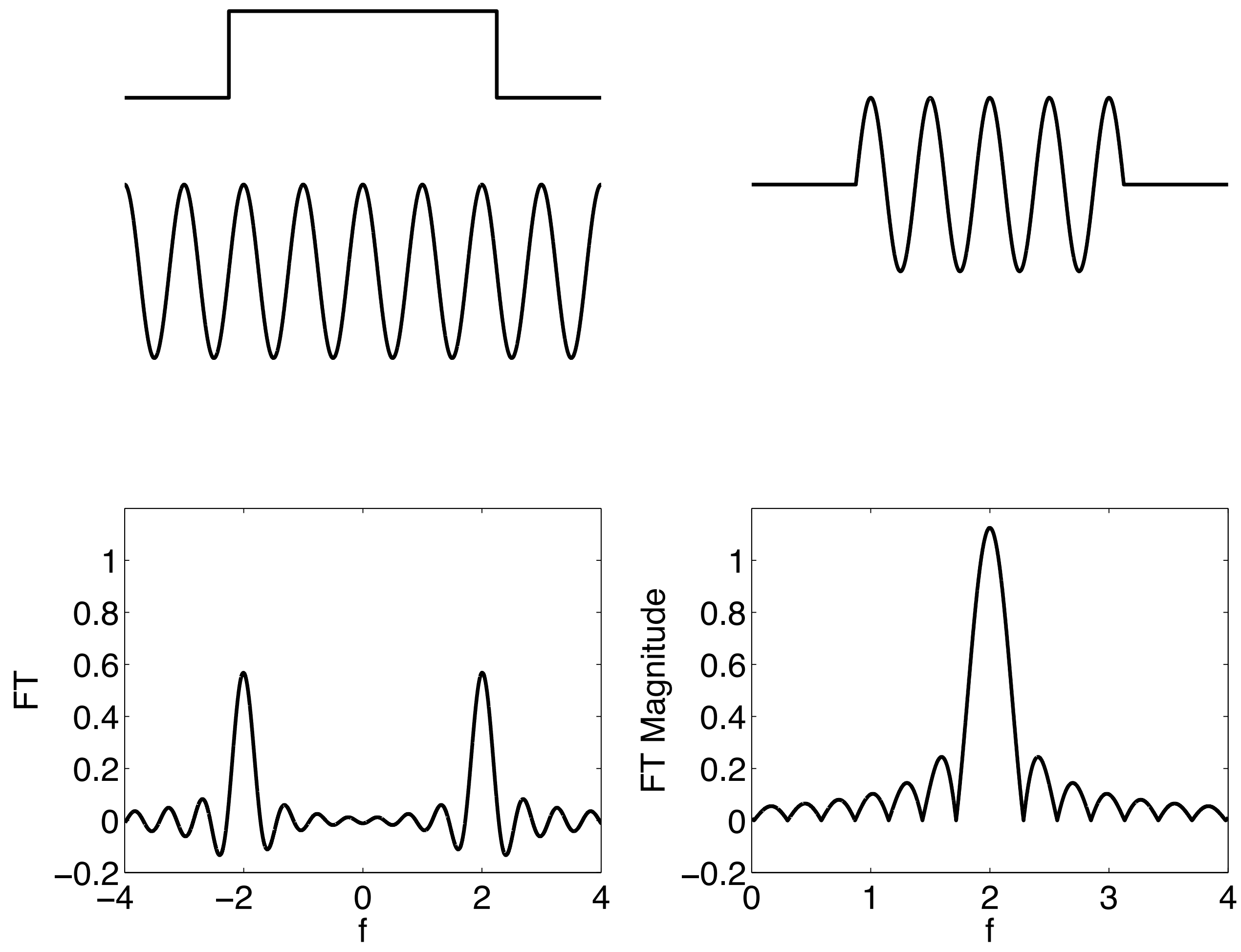
FFT

Curve Fitting

Temperature Measurement using a Thermistor

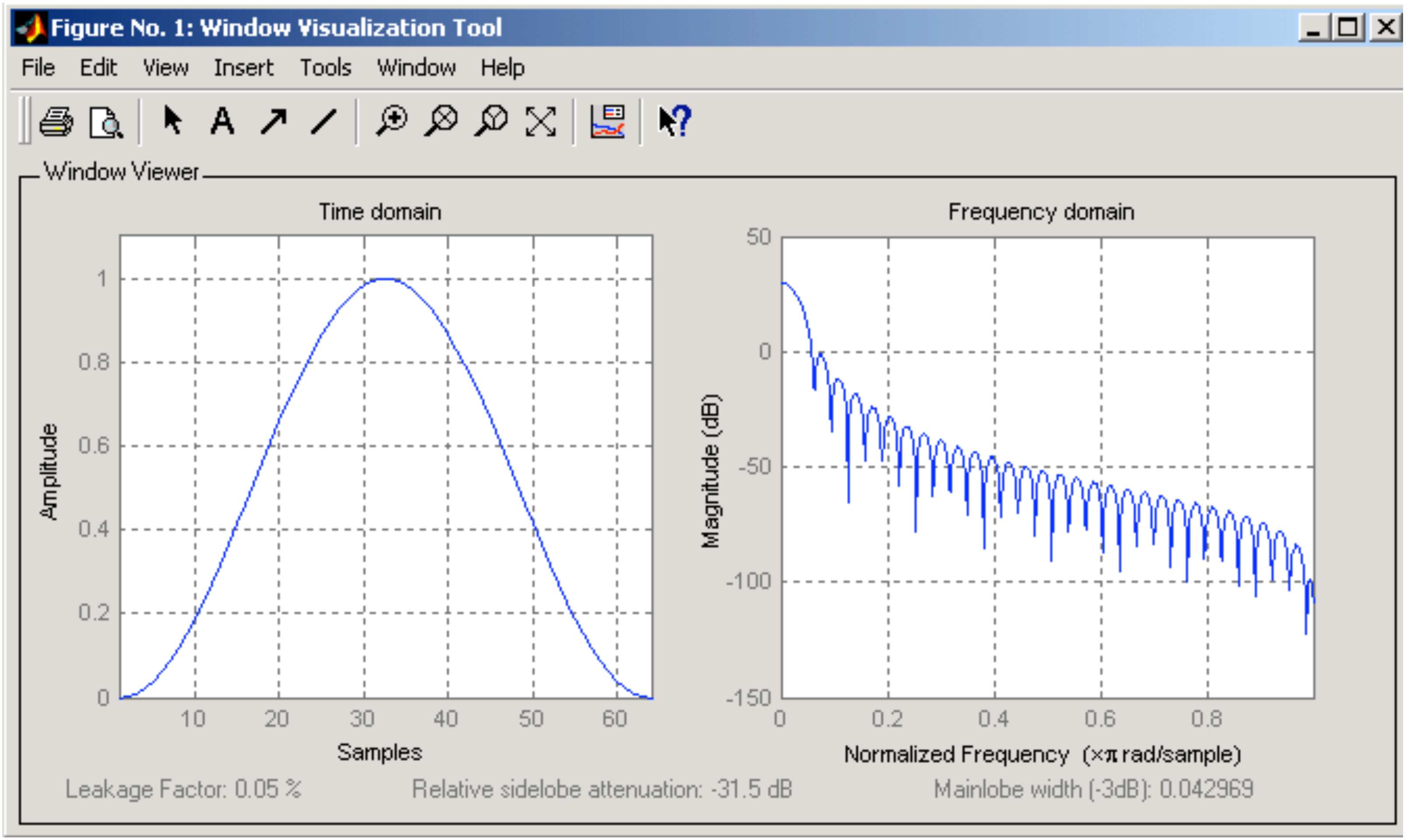
Fourier Analysis - Part 3

Reality I: Finite Time Series ⇒ Spectral Leakage



High Resolution
Low Dynamic Range

Homework - Hann Window:



$$\textbf{FT} \quad \hat{x}(f) \overset{\text{def}}{=} \int_{-\infty}^{\infty} x(t)\, e^{-i\,2\pi f\,t}\, dt$$

Reality II: Discrete Data ⇒ Periodic Spectrum

Sampling Rate: $f_s = 1/\Delta t \qquad t_j = j\Delta t \quad j = 0, 1, 2, \ldots, N-1$

Discrete Time Fourier Transform:

$$\textbf{DTFT} \quad \hat{X}(f) = \sum_{j=0}^{N-1} X(t_j)\, e^{-i\,2\pi f\,t_j}$$

Periodic Spectrum: $\hat{X}(f + k f_s) = \hat{X}(f)$

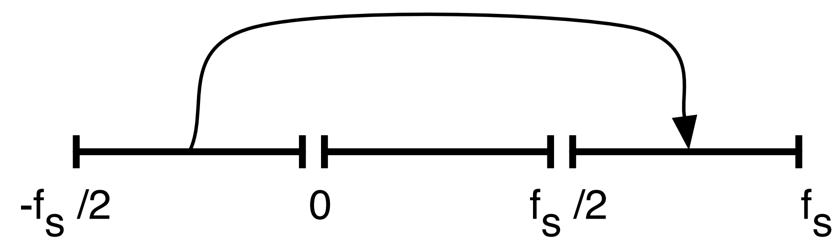
$$e^{-i2\pi(f+kf_s)t_j} = e^{-i(2\pi f t_j + 2\pi k f_s\, j/f_s)} = e^{-i2\pi f t_j}\, e^{-i2\pi k j} = e^{-i2\pi f t_j}$$

Discrete Fourier Transform (Fast Fourier Transform)

DFT (FFT)

$$\hat{X}(f_k) = \sum_{j=0}^{N-1} X(t_j)\, e^{-i\, 2\pi f_k\, t_j} \qquad k = 0, \ldots, N-1$$

$$f_k = k\, \Delta f = k\, \frac{1}{N \Delta t}$$



FFT

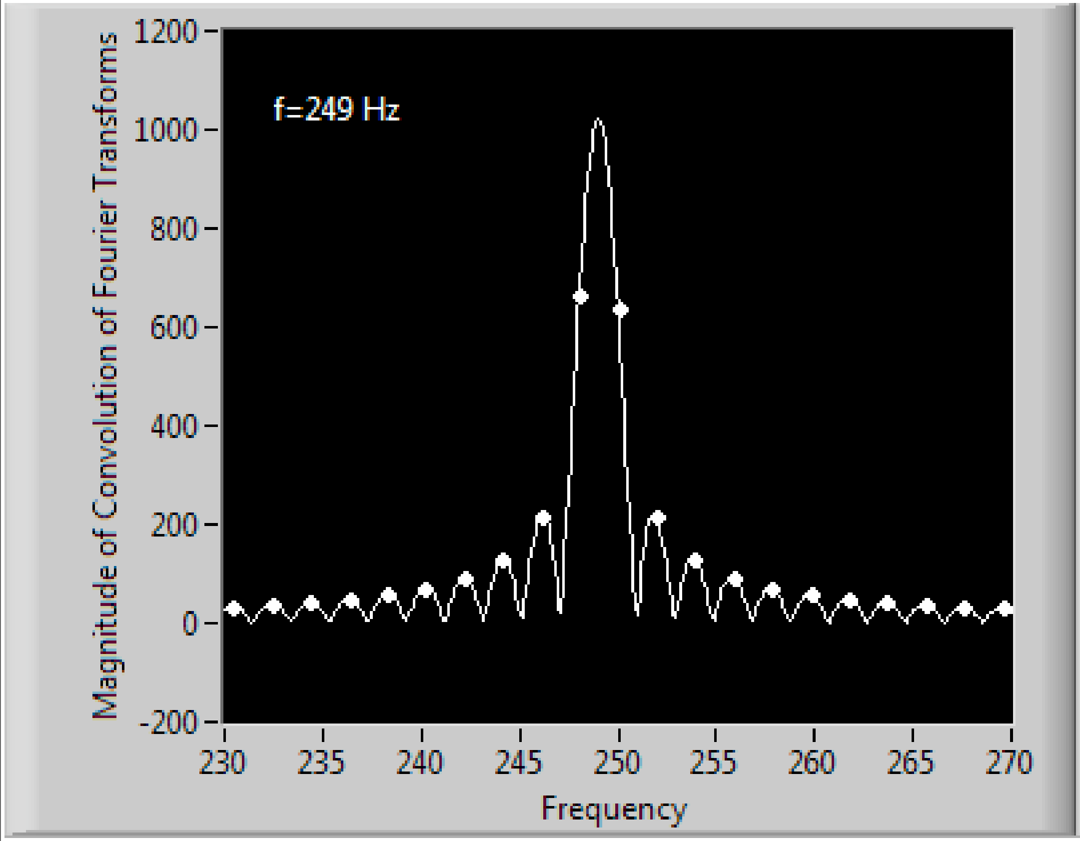
$$N \log_2 N \ (\text{vs. } N^2) \text{ for } N = 2^m \text{ with } m \text{ integer}$$

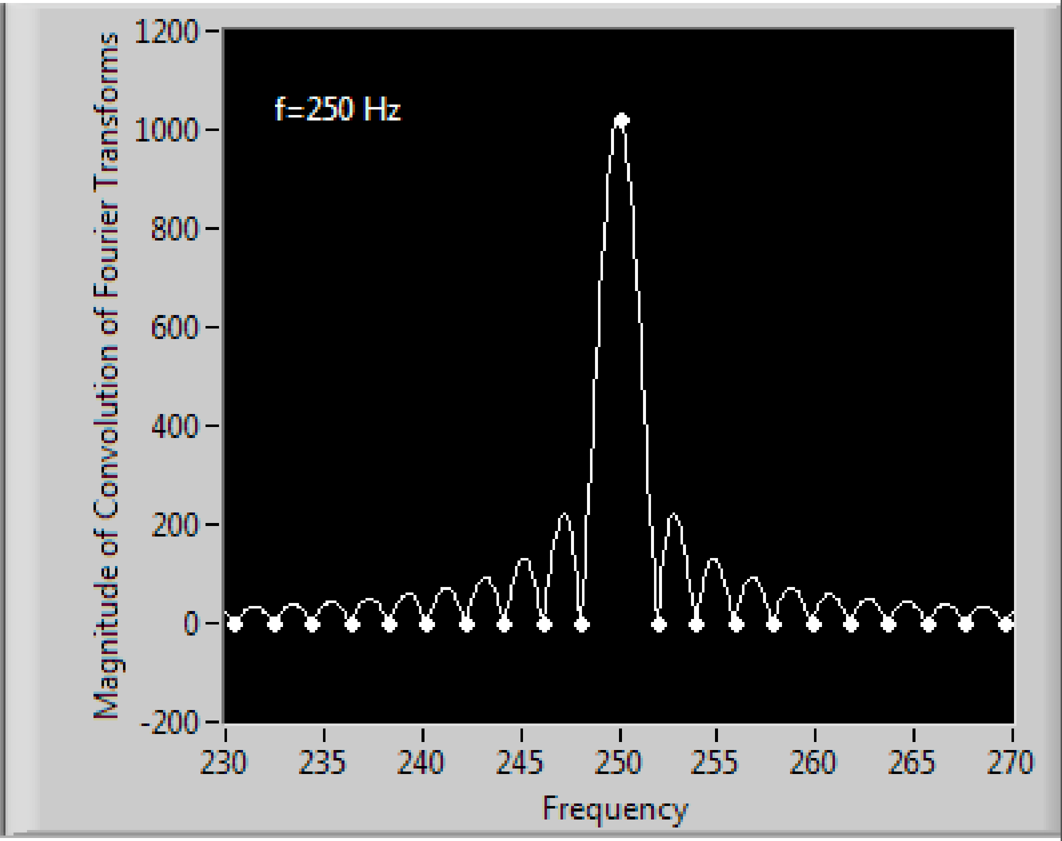
one kilosample	2^{10}	$\longrightarrow$	$100\,\times$
one Megasample	2^{20}	$\longrightarrow$	$50000\,\times$
one hundret Megasample	2^{27}	$\longrightarrow$	5 Million $\times$

Discrete Fourier Transform (Fast Fourier Transform)

Typically:
Leakage + Sampling

Exact for periodic functions with period $T = N\Delta t$

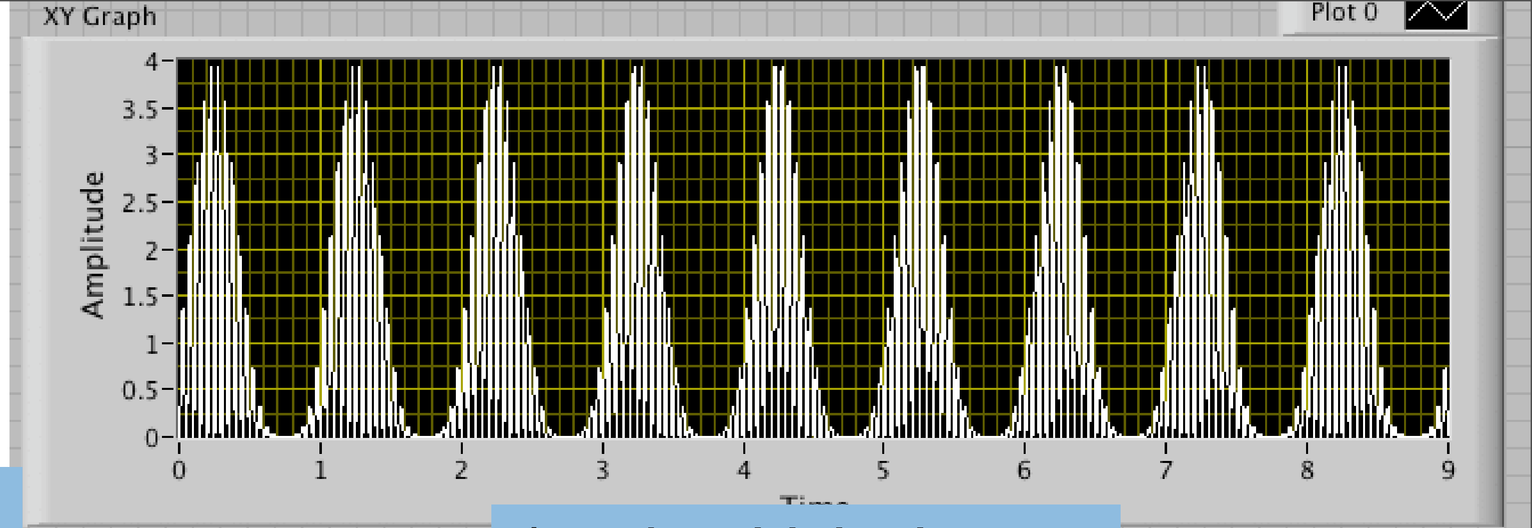




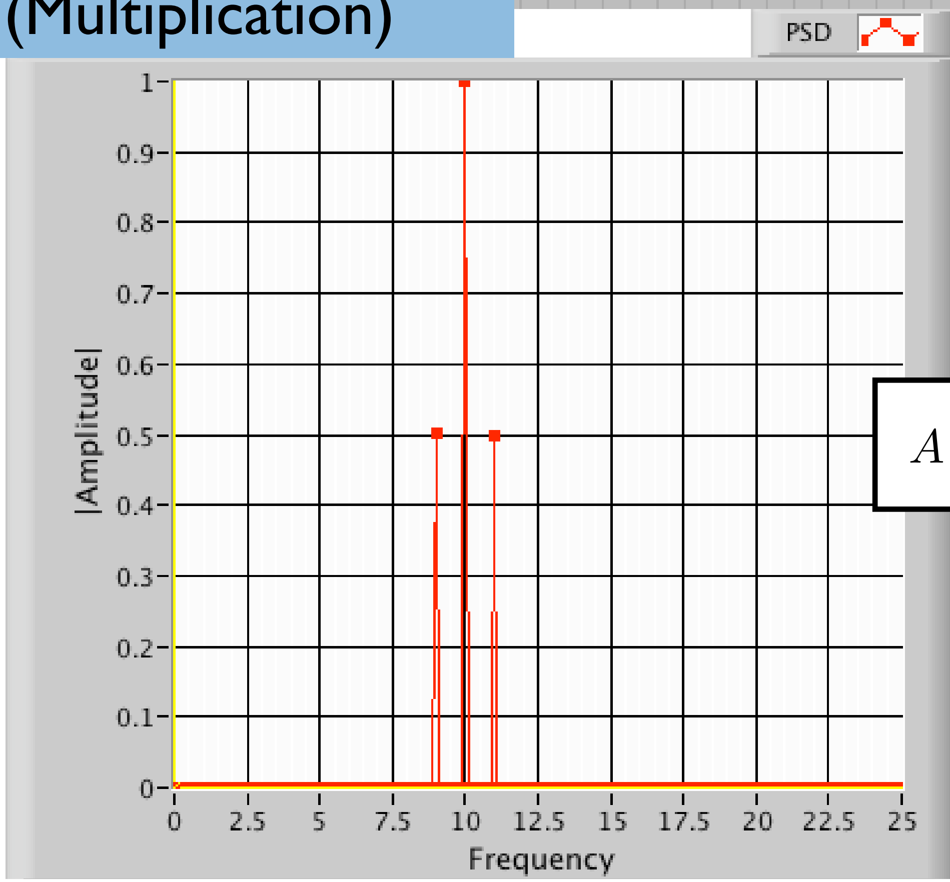
Fourier Analysis

Time Domain	Transform Type	Frequency Domain
$x(t)$ continuous, non-periodic	Fourier Transform	$\hat{x}(f)$ continuous, non-periodic
$x(t)$ continuous, periodic	Fourier Series	$\hat{x}(f_k)$ discrete, non-periodic
$x(t_j)$ discrete, non-periodic	Discrete Time Fourier Transform	$\hat{x}(f)$ continuous, periodic
$x(t_j)$ discrete, periodic	Discrete Fourier Transform (Fast Fourier Transform)	$\hat{x}(f_k)$ discrete, periodic

Homework:

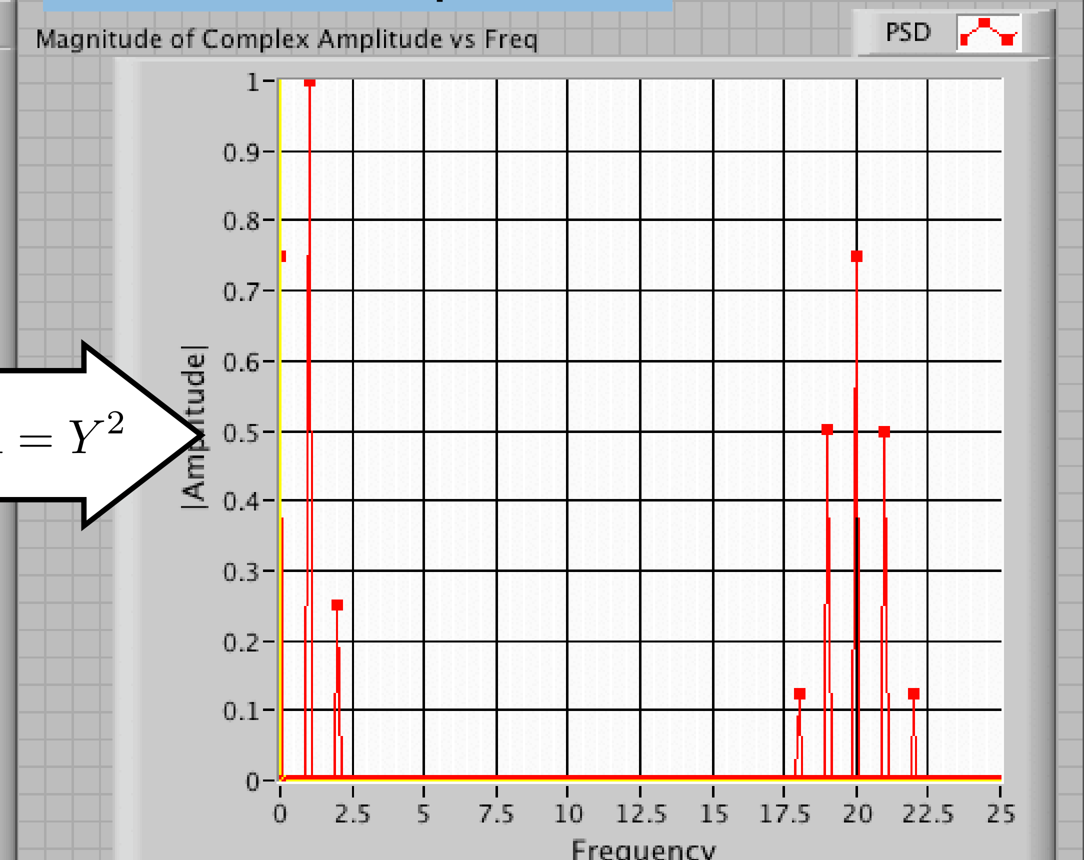


Amplitude Modulation (Multiplication)

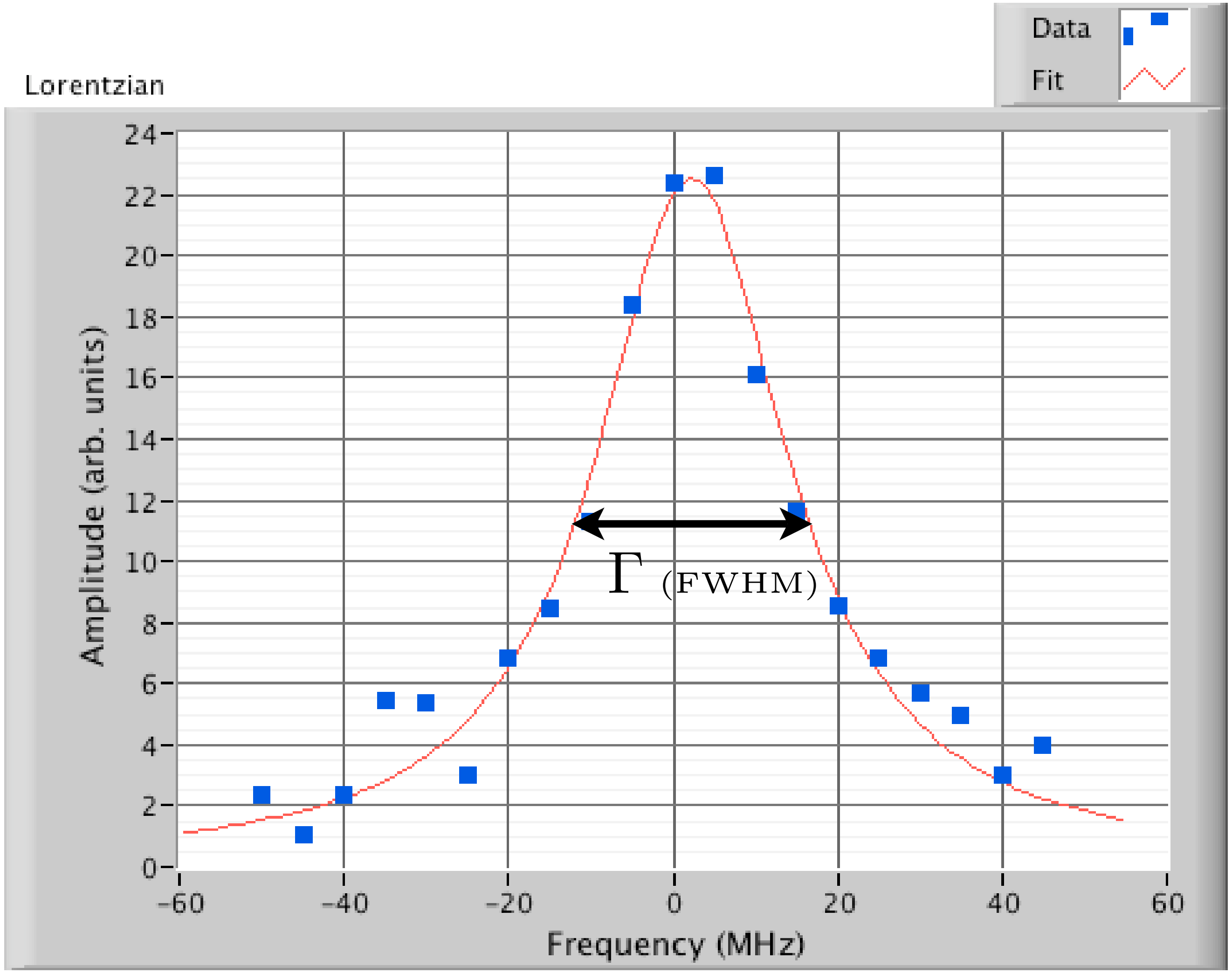


$$A = Y^2$$

Another Multiplication



Lorentzian: $L(f) = \frac{A}{\pi} \frac{\Gamma/2}{(f - f_0)^2 + (\Gamma/2)^2}$



$^{87}\mathrm{Rb}\ \mathrm{D}_2\ (5^2\mathrm{S}_{1/2} \rightarrow 5^2\mathrm{P}_{3/2})$

$f_0 = 384.230484\ \mathrm{THz}$

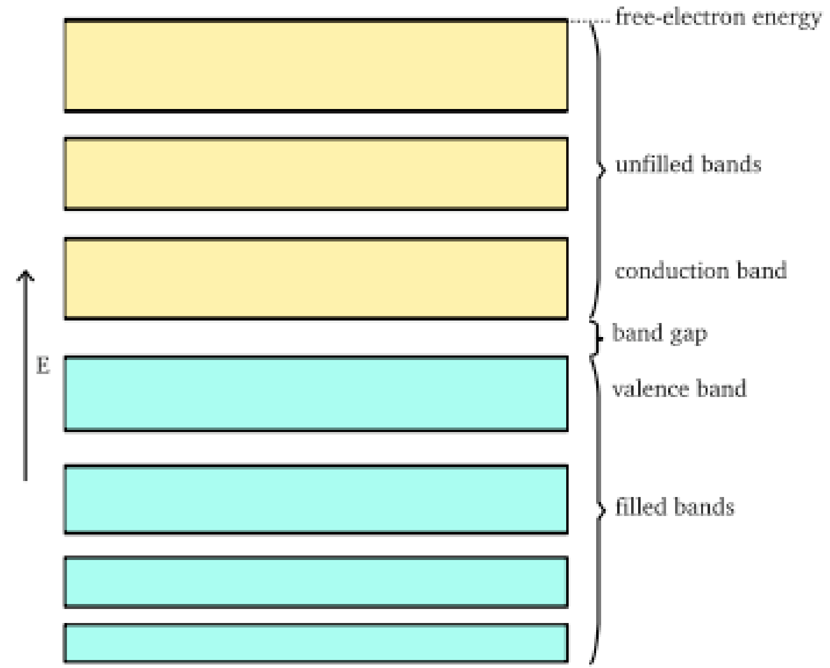
$\lambda = 780.2412\ \mathrm{nm}$

$\tau = ?$

$$\mathcal{F}^{-1}_{f,t}\left[\frac{A}{\pi} \frac{\Gamma/2}{(f - f_0)^2 + (\Gamma/2)^2}\right] = A\, e^{-i(2\pi f_0 t) - \Gamma\pi|t|}$$

Thermistor - Physics

Semiconductor Band Structure



Thermal activation:

$$n = n_0 \, \exp\left[-\frac{\Delta E}{kT}\right]$$

-> resistance decreases with Temp.

Lorentz force: $\mathbf{F} = q\left(\mathbf{E} + \mathbf{v} \times \mathbf{B}\right)$

Drude model: $$m\frac{d\langle \mathbf{v} \rangle}{dt} = q\mathbf{E} - \frac{m}{\tau}\langle \mathbf{v} \rangle \qquad \frac{d\langle \mathbf{v} \rangle}{dt} = 0 \;\Rightarrow\; \langle \mathbf{v} \rangle = \frac{q\tau}{m}\,\mathbf{E}$$

Current density: $$\mathbf{j} = \sigma \mathbf{E} = nq\langle \mathbf{v} \rangle = \frac{nq^2\tau}{m}\,\mathbf{E}$$

Resistivity: $$\rho = \frac{1}{\sigma} = \frac{m}{ne^2\tau} \qquad \rho = \frac{m}{n_0 e^2 \tau}\, e^{\frac{\Delta E}{kT}} = \rho_0\, e^{\frac{\Delta E}{kT}}$$

Resistance: $$R = \rho \frac{L}{A} = R_0\, e^{\frac{\Delta E}{kT}}$$

Thermistor - Physics

$$R = \rho \frac{L}{A} = R_0 \, e^{\frac{\Delta E}{kT}}$$

$$\ln(R) = \ln(R_0) + \frac{\Delta E}{kT}$$

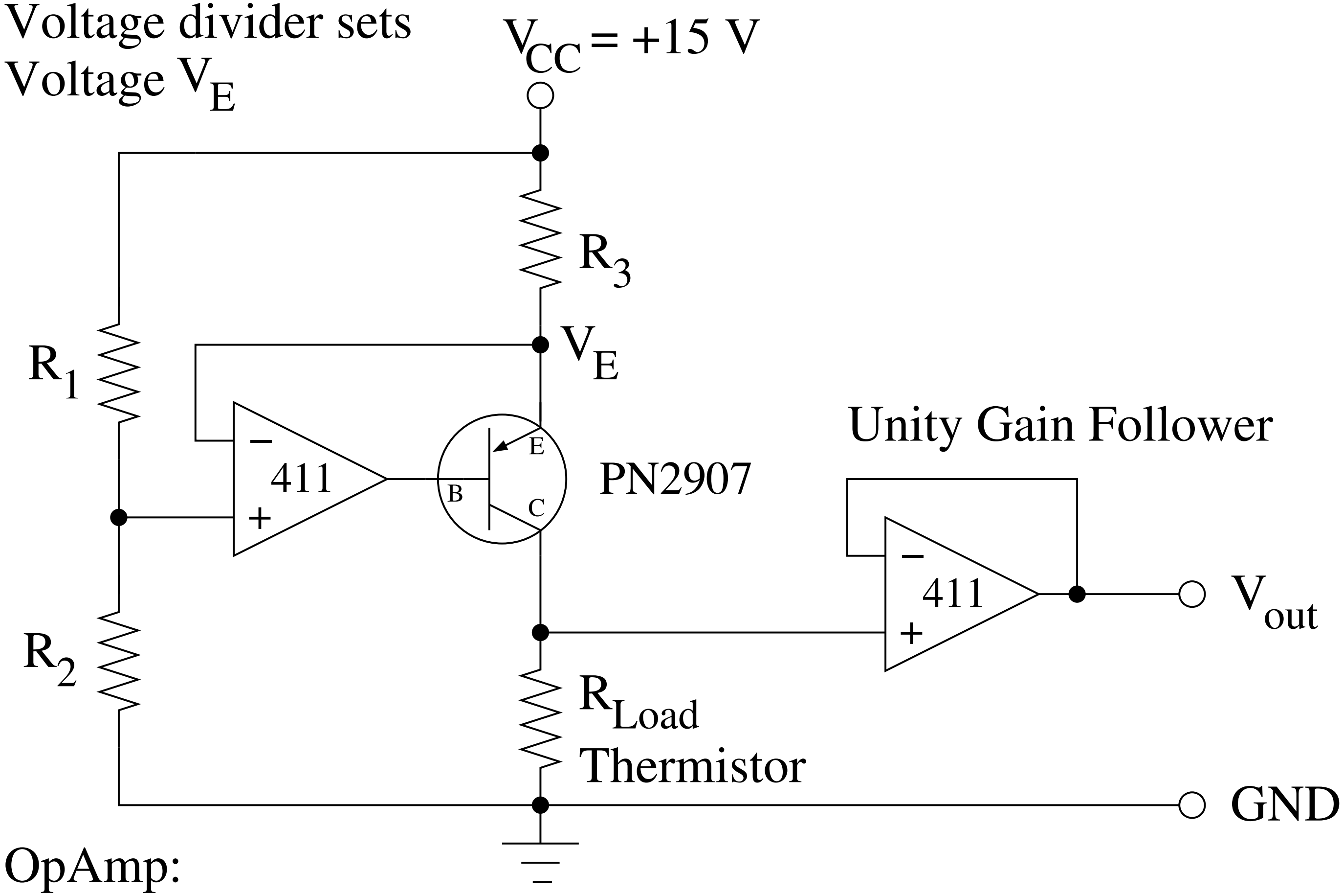
Beta Formula:

$$\frac{1}{T} = A + B \ln(R) \qquad A = \frac{-k}{\Delta E} \ln\left(\frac{mL}{A n_0 e^2 \tau}\right) \qquad B = \frac{k}{\Delta E}$$

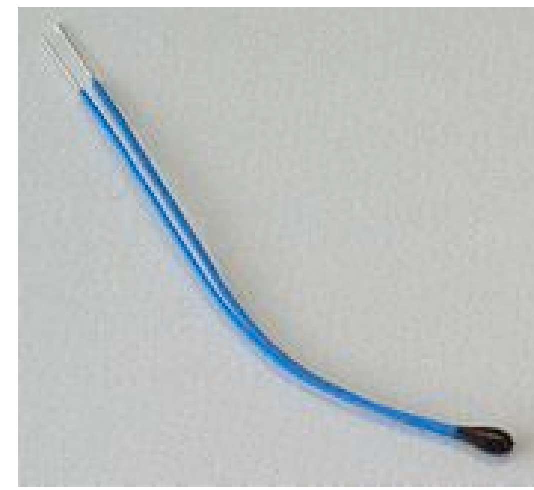
Steinhart - Hart Equation:

$$\frac{1}{T} = A + B \ln(R) + D \ln(R)^3$$

Voltage divider sets
Voltage V_E



OpAmp:
Decouples Voltage Divider
Sets base voltage such that emitter voltage is constant



$$I = 0.1 \text{ mA, e.g. } R_1 = R_2 = 10\text{k}\Omega \quad R_3 = 75\text{k}\Omega$$

Report the measured current through the thermistor

Fit Thermistor Data to get coefficients of Steinhart-Hart equation.

Read thermistor voltage N times

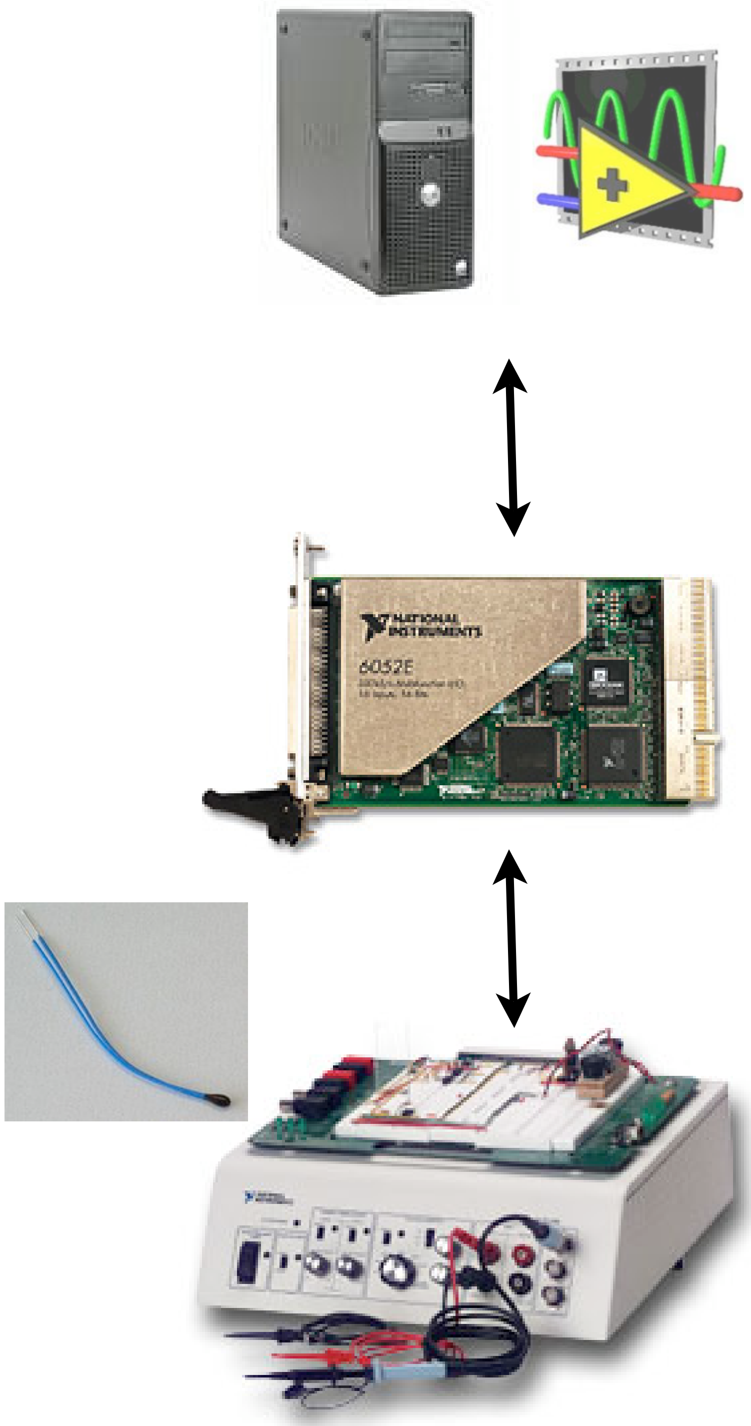
Find average voltage V

Calculate thermistor resistance R = V/I

Calculate temperature via Steinhart-Hart Equation

Display temperature in ^{o}C

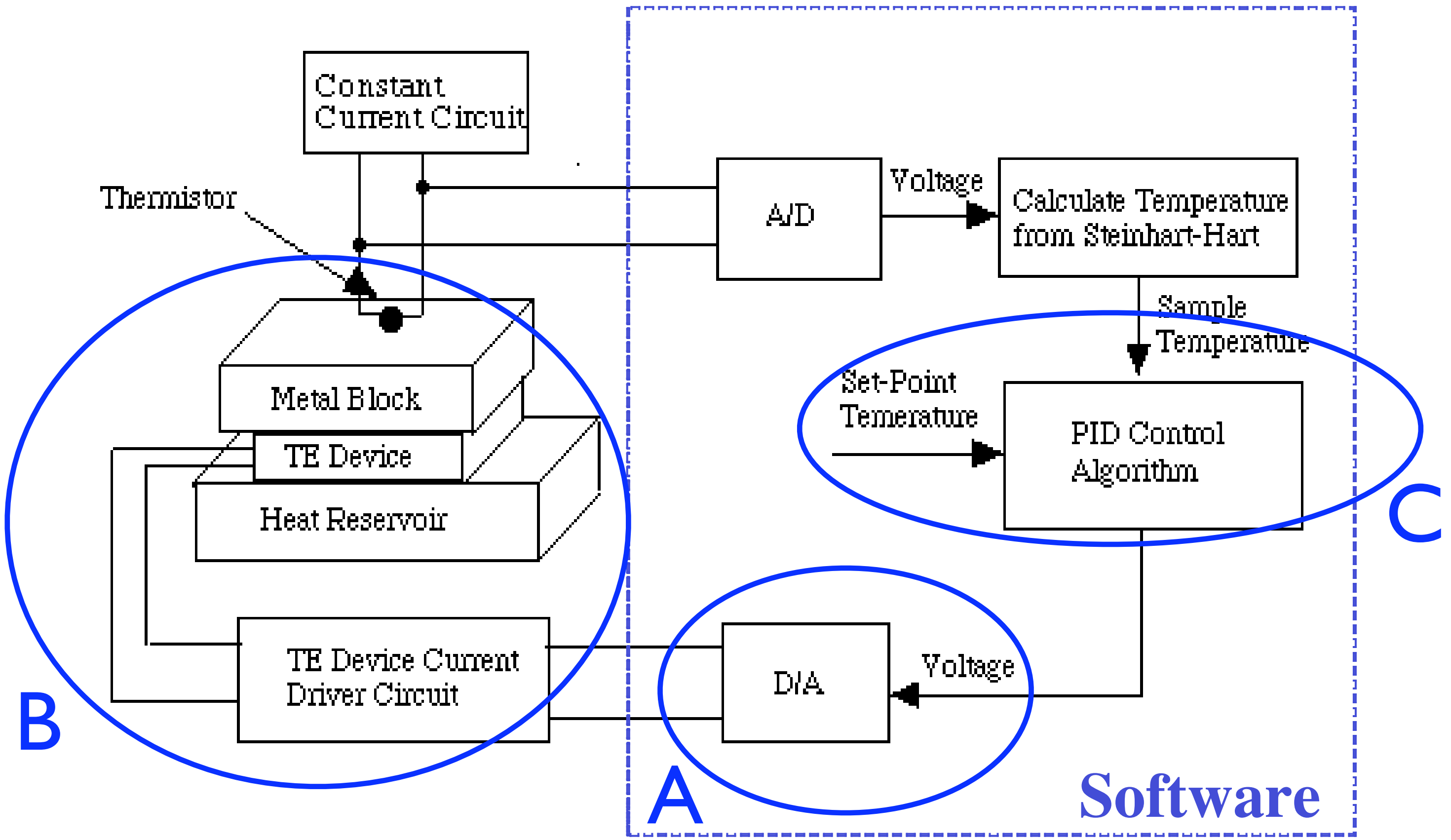
Wait, then repeat



III) Final Project

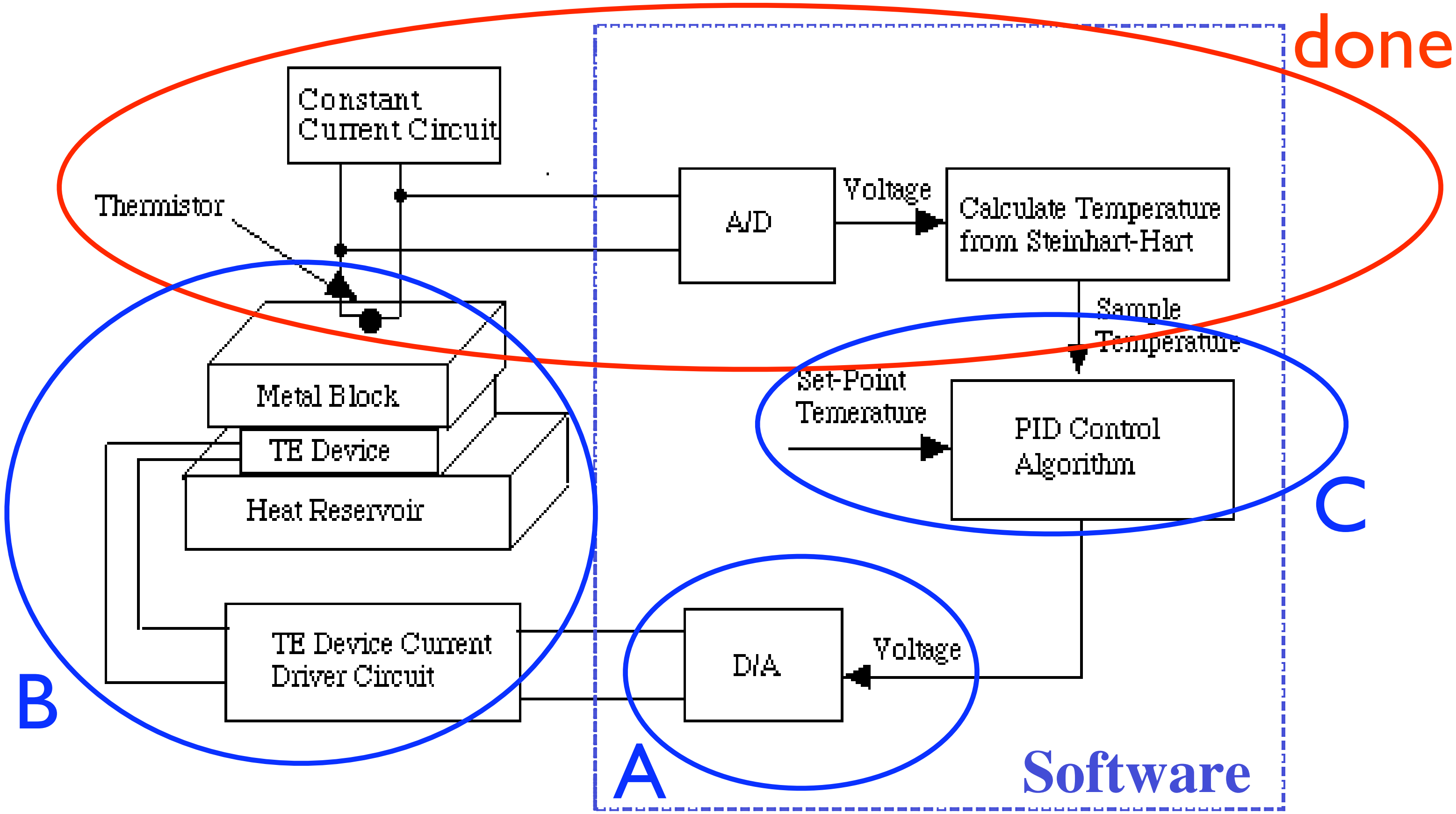
PID-Temperature Controller

TEMPERATURE CONTROL PROJECT



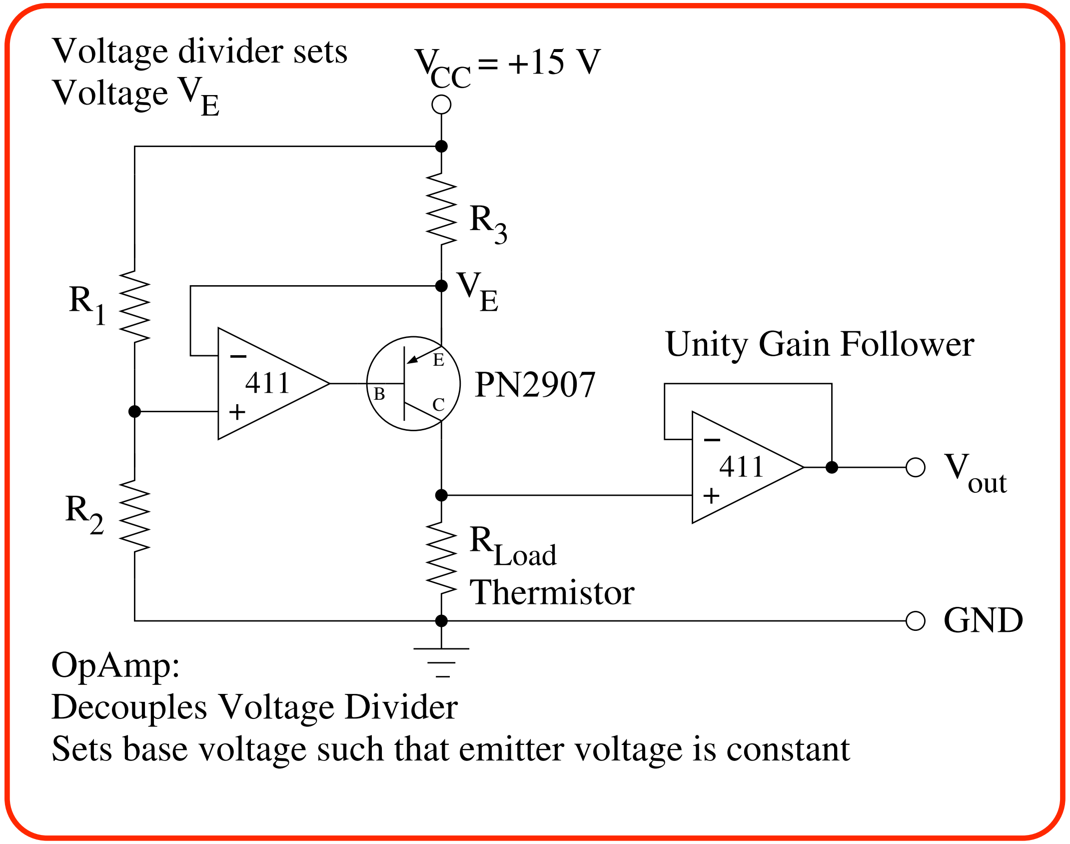
A) Use DAQ Assistant

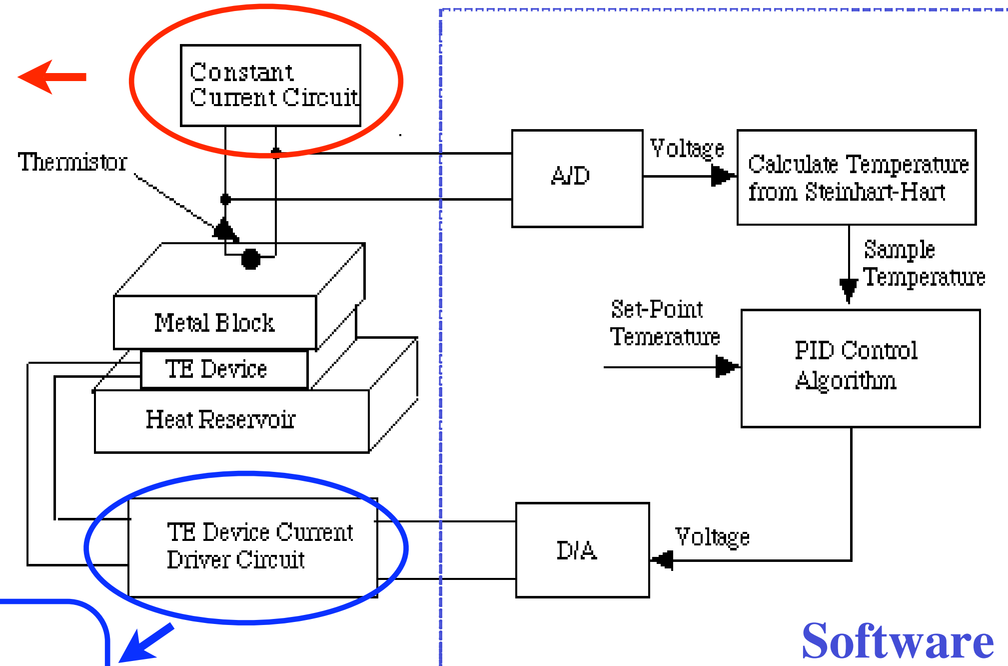
TEMPERATURE CONTROL PROJECT

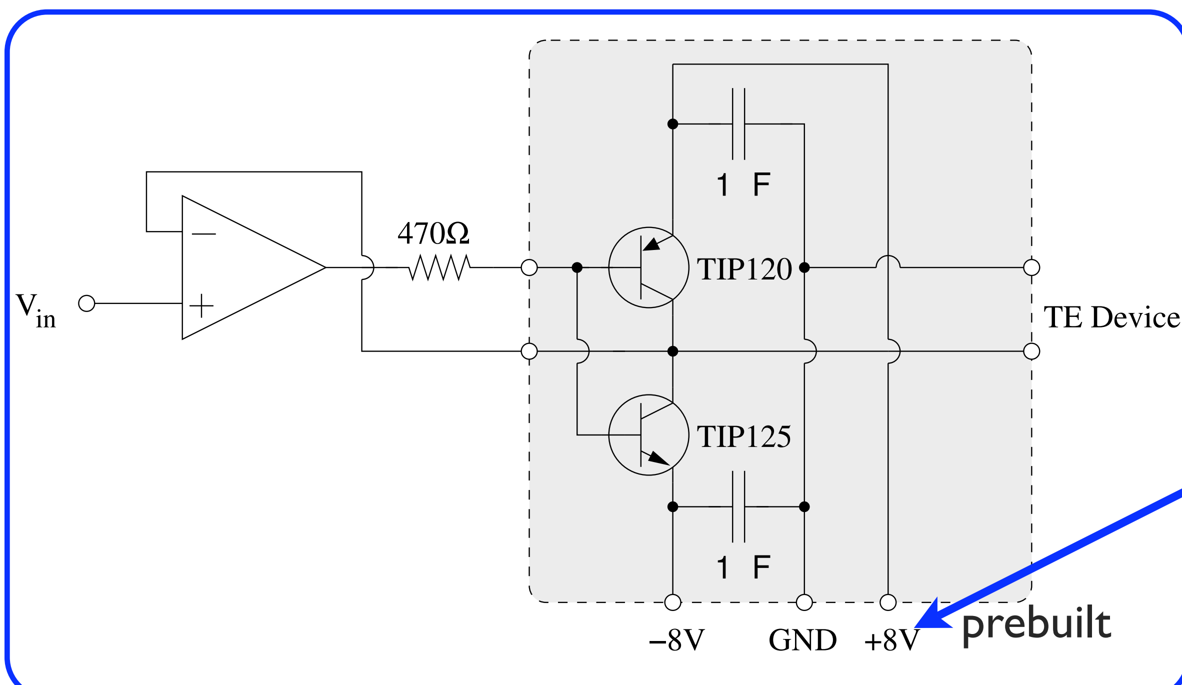


A) Use DAQ Assistant

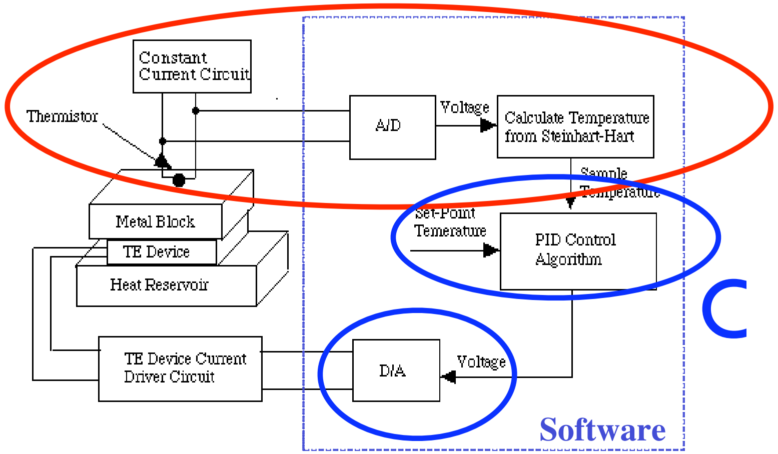
B) Analog Hardware



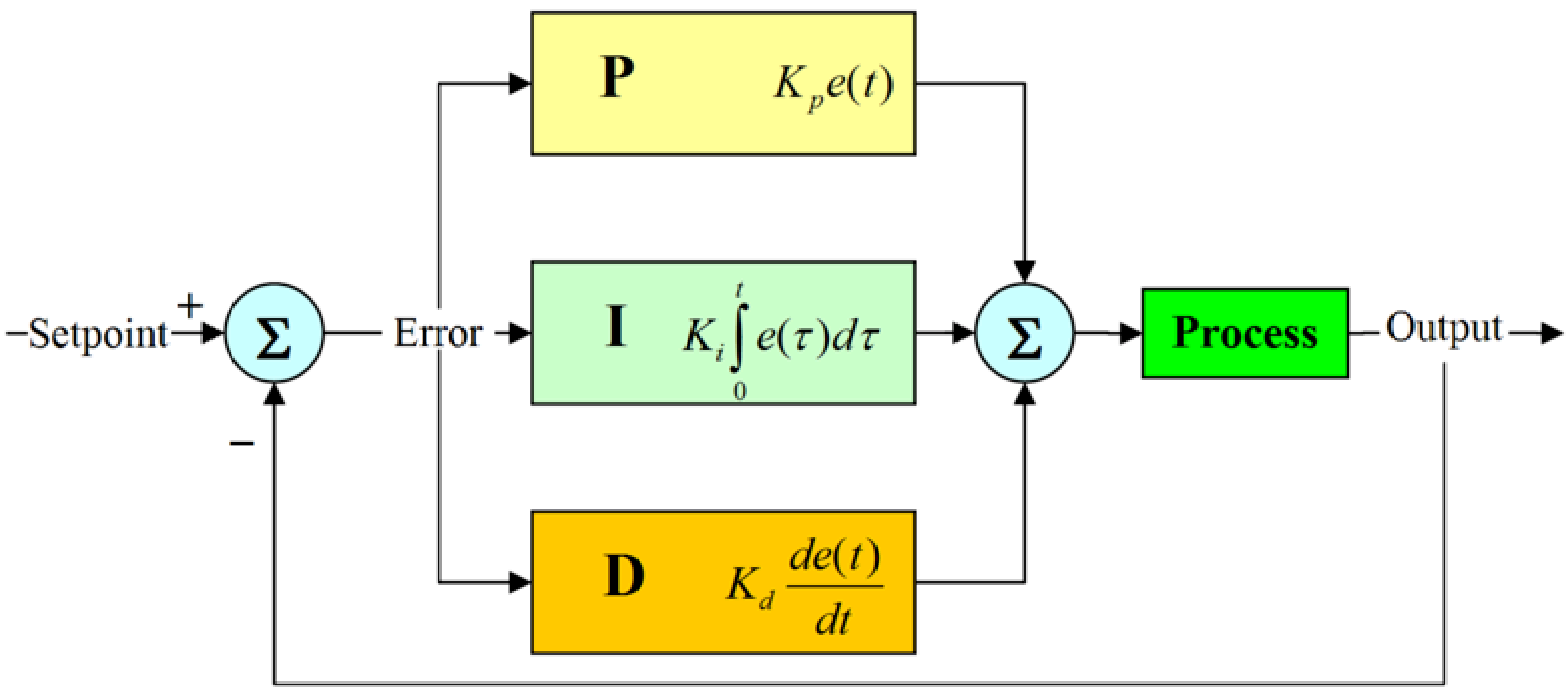




PS280 Power supply



C) PID Control



http://en.wikipedia.org/wiki/PID_controller

Example: A very very simple model

$$\frac{d\Theta}{dt} = -\gamma\,\Theta + u(t) \qquad \Theta(t) = T_{plate} - T_{air} \qquad u(t) = control$$

Consider constant control

If $u(t) = K\,\Theta_0$=const. $\quad \Theta(t) = \frac{K\,\Theta_0}{\gamma}\left(1 - e^{-\gamma t}\right) \quad \Theta(\infty) = \frac{K}{\gamma}\,\Theta_0$

Consider ***P*** **-** proportional control

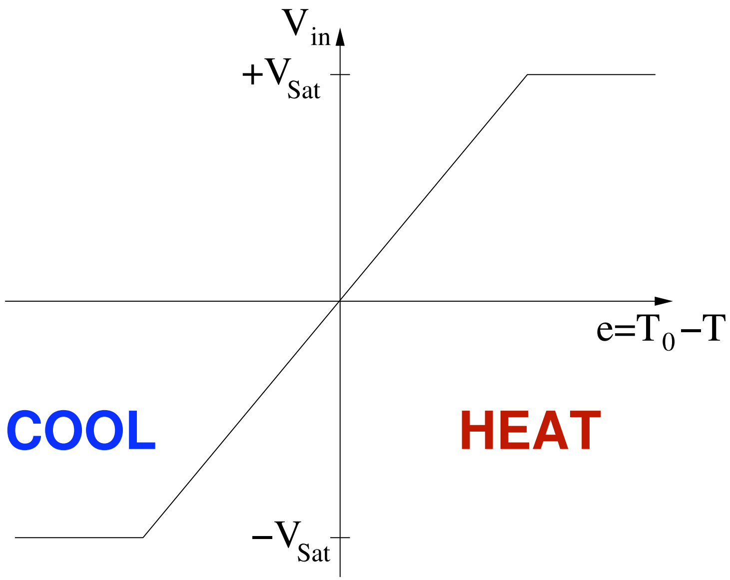
If $u(t) = K_P\,(\Theta_0 - \Theta)$

$$\begin{aligned} \frac{d\Theta}{dt} &= -\gamma\,\Theta + K_P\,(\Theta_0 - \Theta) \\ &= -(\gamma + K_P)\,\Theta + K_P\,\Theta_0 \end{aligned}$$

$$\Theta(\infty) = \frac{K_P}{\gamma + K_P}\,\Theta_0 \neq \Theta_0$$

P - proportional control

- Proportional to deviation from setpoint
- Considers only present value
- Big K_P - rapid control, potentially unstable
- Overshoot typical
- Always has offset (small for K_P big)
- Saturation of feedback



Consider ***I* -** integral control

$$\frac{d\Theta}{dt} = -\gamma\,\Theta + u(t) \qquad \Theta(t) = T_{plate} - T_{air} \qquad u(t) = K_i \int_0^t (\Theta_0 - \Theta)\,dt$$

Differentiate:

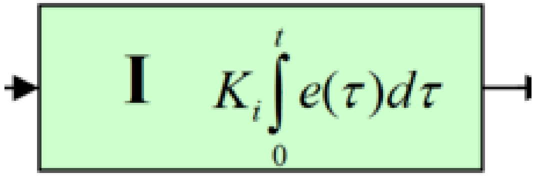
$$\frac{d^2\Theta}{dt^2} + \gamma\frac{d\Theta}{dt} + K_i\Theta = K_i\Theta_0$$

$$\Theta(\infty) = \Theta_0$$

Same for ***PI* -** proportional-integral control

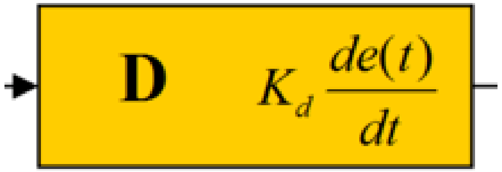
$$\frac{d\Theta}{dt} = -\gamma\,\Theta + u(t) \qquad u(t) = K_p(\Theta_0 - \Theta) + K_i \int_0^t (\Theta_0 - \Theta)\,dt$$

$$\frac{d^2\Theta}{dt^2} + (K_p + \gamma)\frac{d\Theta}{dt} + K_i\Theta = K_i\Theta_0 \quad \rightarrow \quad \Theta(\infty) = \Theta_0$$



I - integal control

- Proportional to integral of deviation from setpoint
- Eliminates offset error of P-control
- Considers past values
- Big K_i - rapid rise time, increased overshoot



D - differential control

- Proportional to derivative of deviation from setpoint
- Reduces overshoot of PI controller
- Predicts future values

PID - control for our very very simple model

$$\frac{d\Theta}{dt} = -\gamma\,\Theta + u(t) \qquad \Theta(t) = T_{plate} - T_{air} \qquad u(t) = control$$

No control $\quad \dfrac{d\Theta}{dt} + \gamma\Theta = 0$

PID control

$$\frac{d\Theta}{dt} + \gamma\Theta = K_p(\Theta_0 - \Theta) + K_i \int_0^t (\Theta_0 - \Theta)\, dt + K_d \frac{d(\Theta_0 - \Theta)}{dt}$$

$$E = \Theta_0 - \Theta = (T_{plate}^{goal} - T_{air}) - (T_{plate} - T_{air}) = T_{plate}^{goal} - T_{plate}$$

iteration n

Thermistor SubVI

Read and find average thermistor voltage $V_{thermistor}$

Calculate thermistor resistance $R_{thermistor}$

Calculate temperature T_n via Steinhart-Hart Equation (A=? B=? D(or C)=?)

PID VI

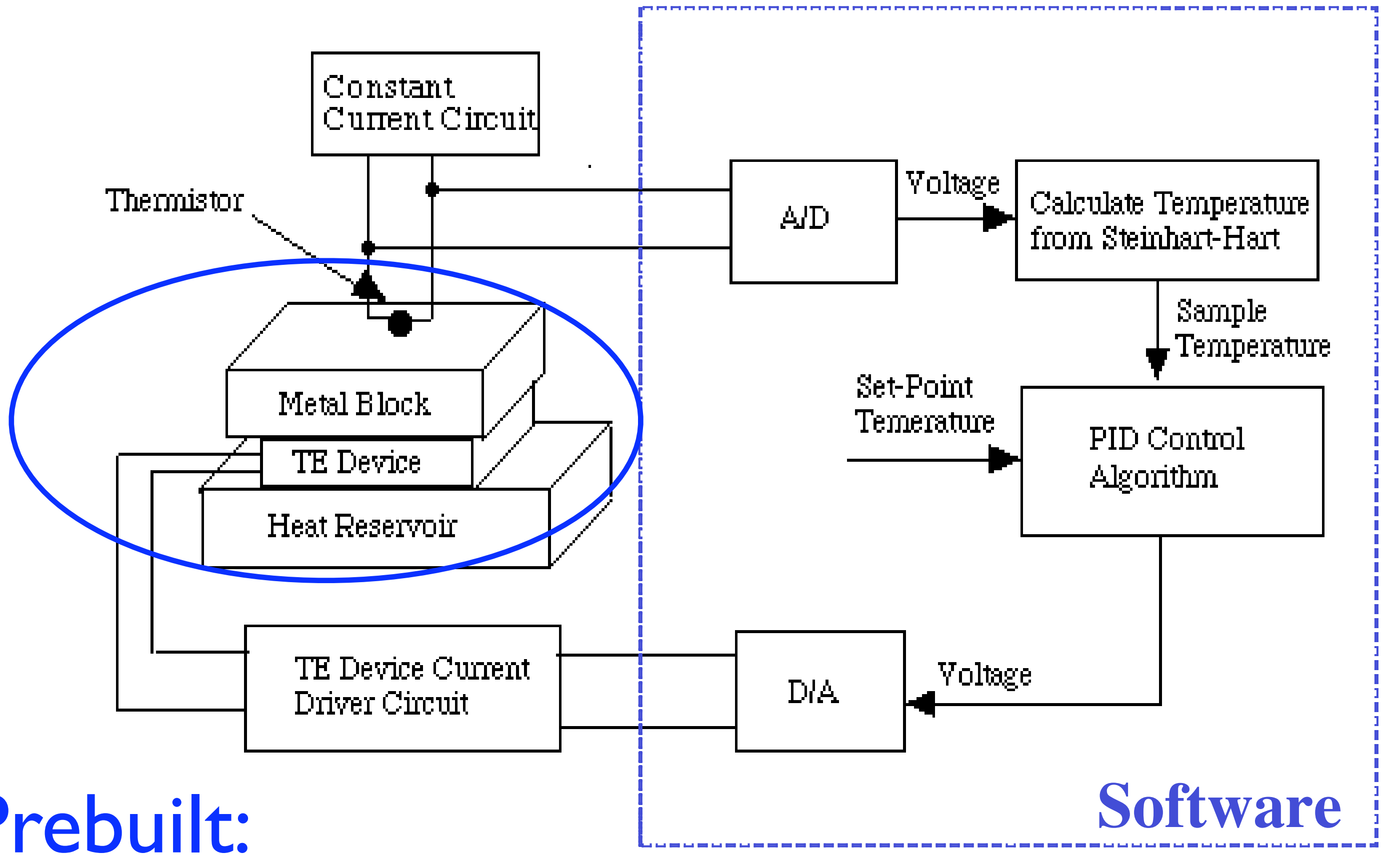
Calculate error : $E_n = T_{set} - T_n$

Calculate PID Control Voltage:

$$V_{PID} = K_p E_n + K_i \Delta t \sum_{m=0}^{n} E_m + K_d \frac{1}{\Delta t} (E_n - E_{n-1})$$

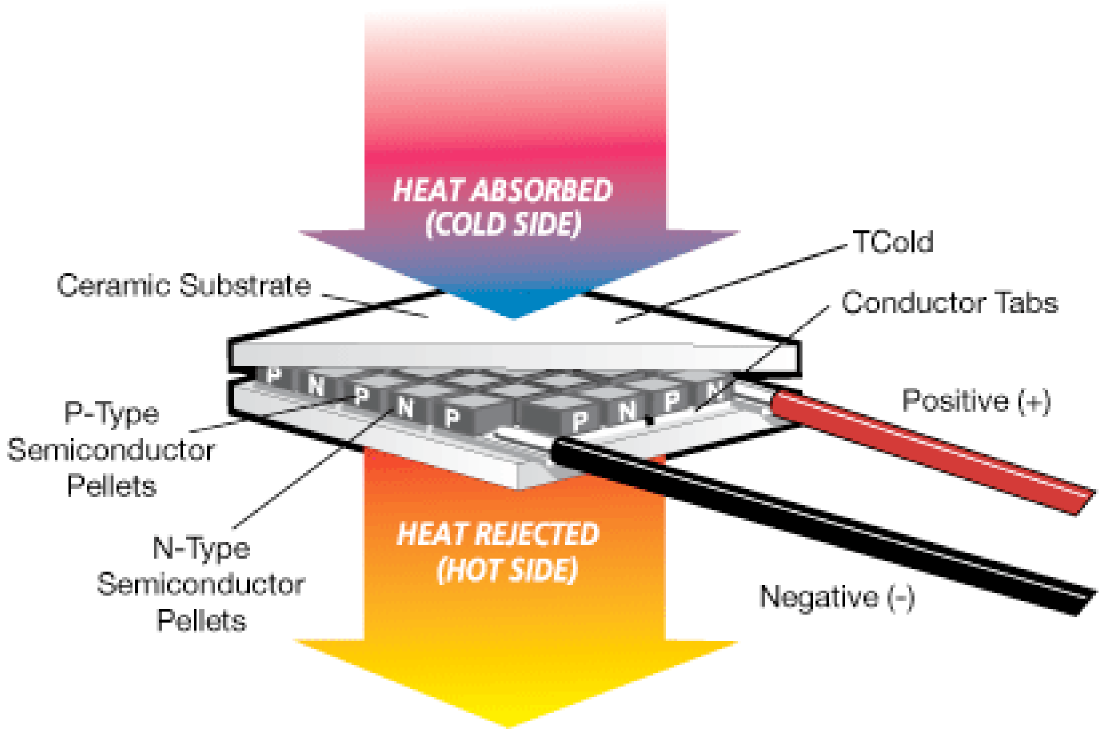
Write V_{PID}

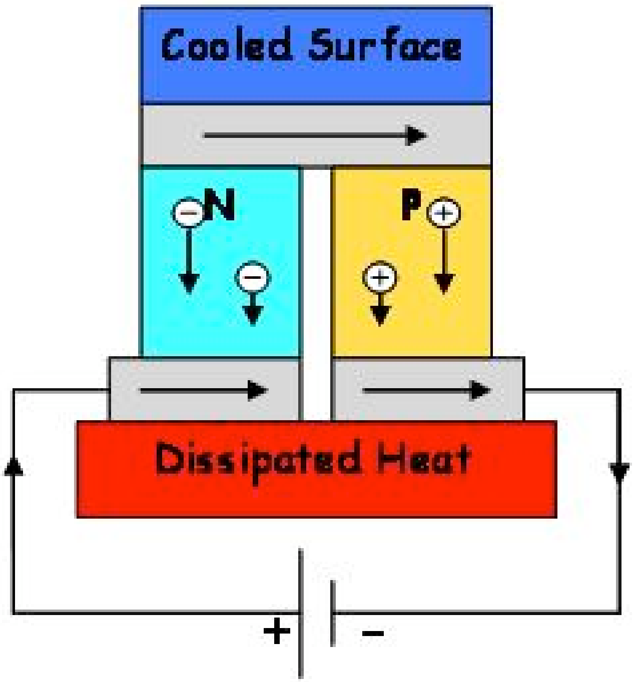
TEMPERATURE CONTROL PROJECT

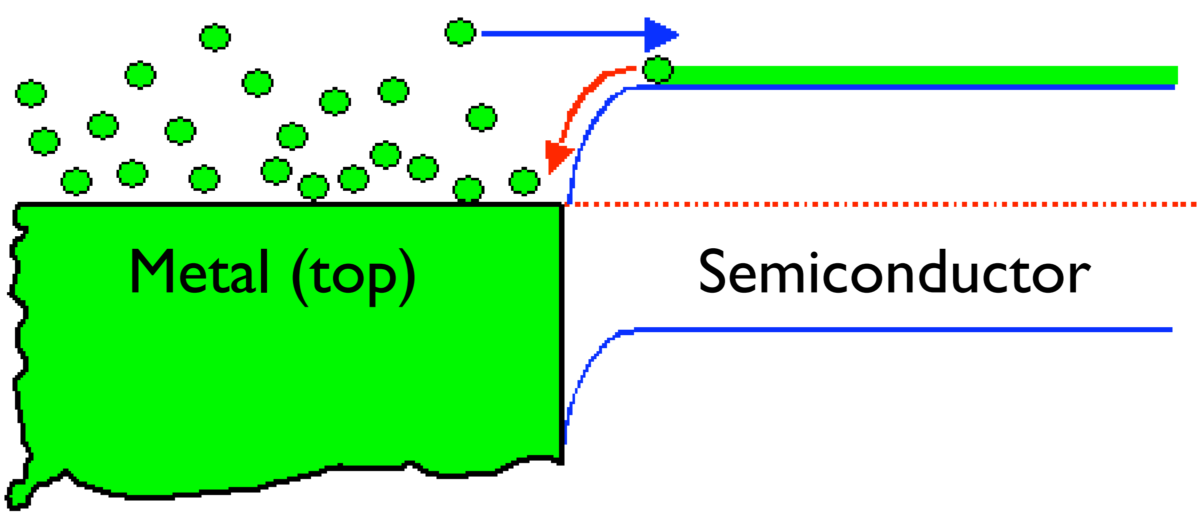


D - Prebuilt: Thermoelectric Element

D) Thermoelectric Device







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