

Control System Toolbox for transfer functions!

Working with:

1. Introduction Presentation 3
2. TCLab temperature response (includes a video)

Why is Control Necessary?

There are two main reasons for control.

The first reason for control is to maintain the controlled variable at its desired value when disturbances occur.

The second reason for control is to respond to changes in the “desired value”.

What does a control system do?

Maintain desired conditions in a physical system by adjusting selected variables.

- A specific value or range is used as a **desired value** for the **controlled variable**.
- The conditions of the system are **measured**.
- Each system has a **control calculation or algorithm**.
- The results of calculation are implemented by **final control elements**.

Control Objectives

1. Safety
2. Environmental Protection
3. Equipment Protection
4. Smooth Operation and Production Rate
5. Product Quality
6. Profit
7. Monitoring and Diagnosis

1 Control objective:

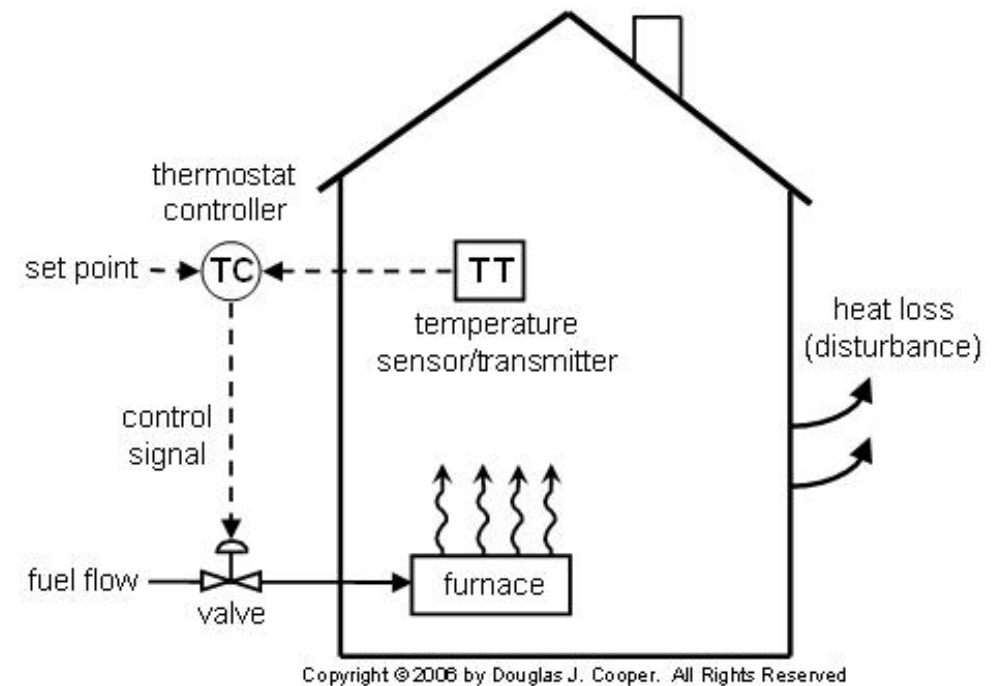
Consider a house in a cold climate which is to be maintained near a desired temperature by circulating hot water through a heat exchanger.

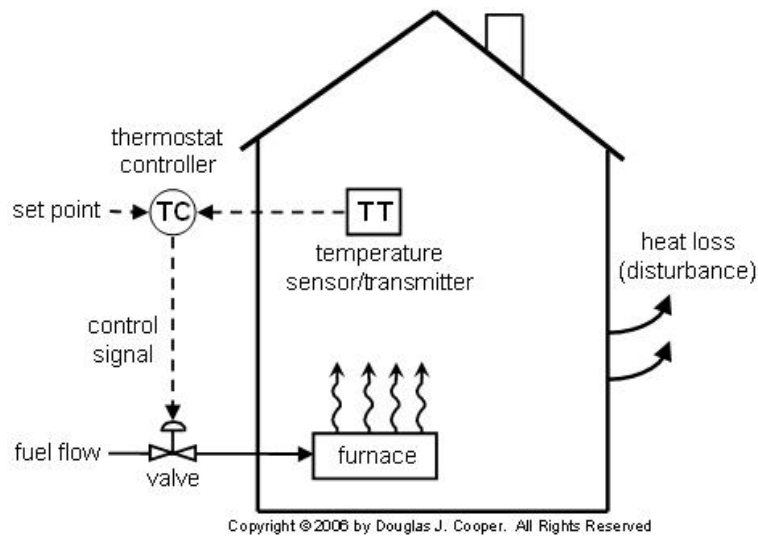
2 Input and output variables:

Heated room example: input: fuel to the furnace
 output: room temperature

3 Constraints:

We assume, for example, that the valve operates between the extremes of **fully closed** or **fully open**, and that the system operates continuously.





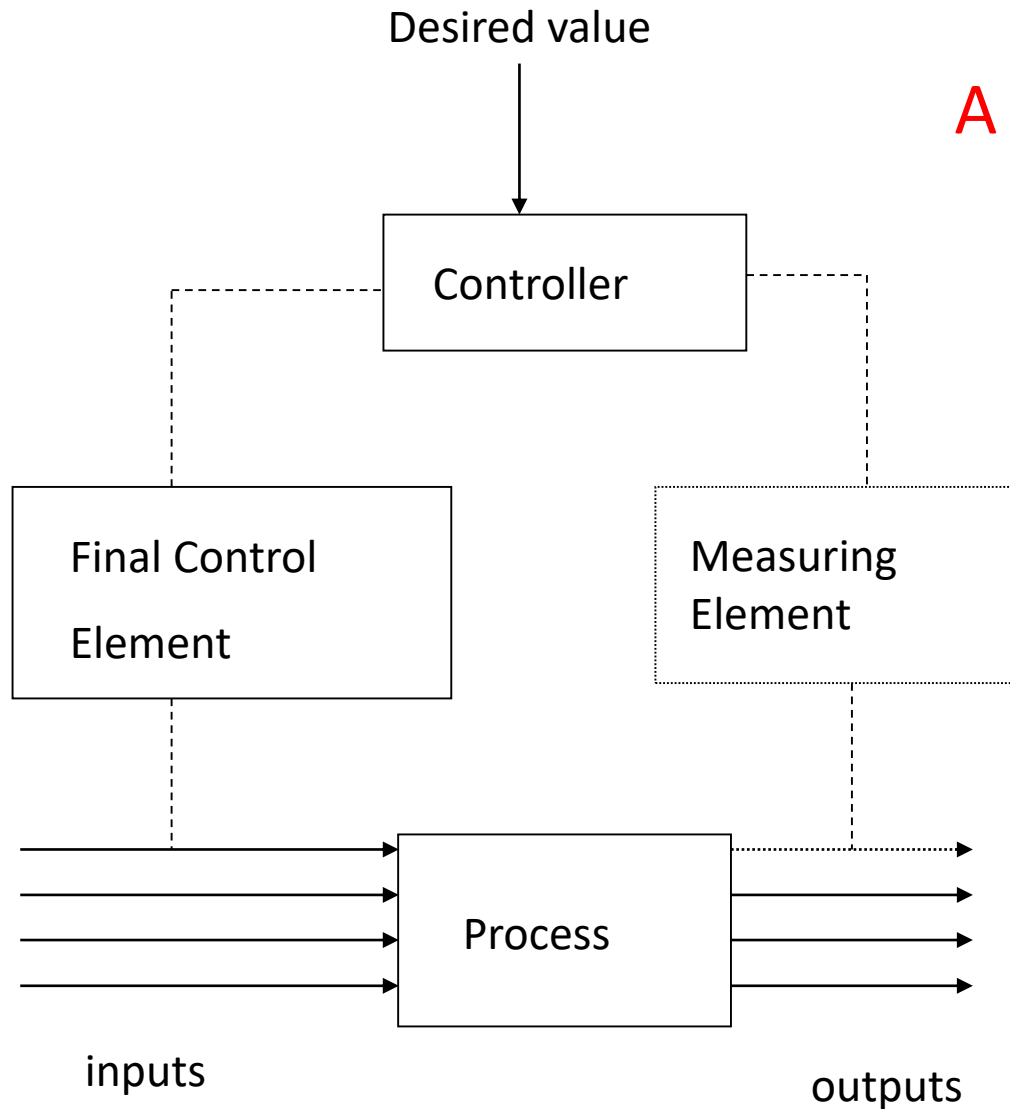
4 Safety:

Environmental and economic considerations

5 Control structure:

- A thermostat determines the temperature of the room.
- This temperature is compared with the desired temperature or range of temperatures.
- If the temperature is below the desired value, the furnace and the pump are turned on. If the temperature is above, the furnace and pump are turned off.

A Control Engineering “Engineer” is in charge of



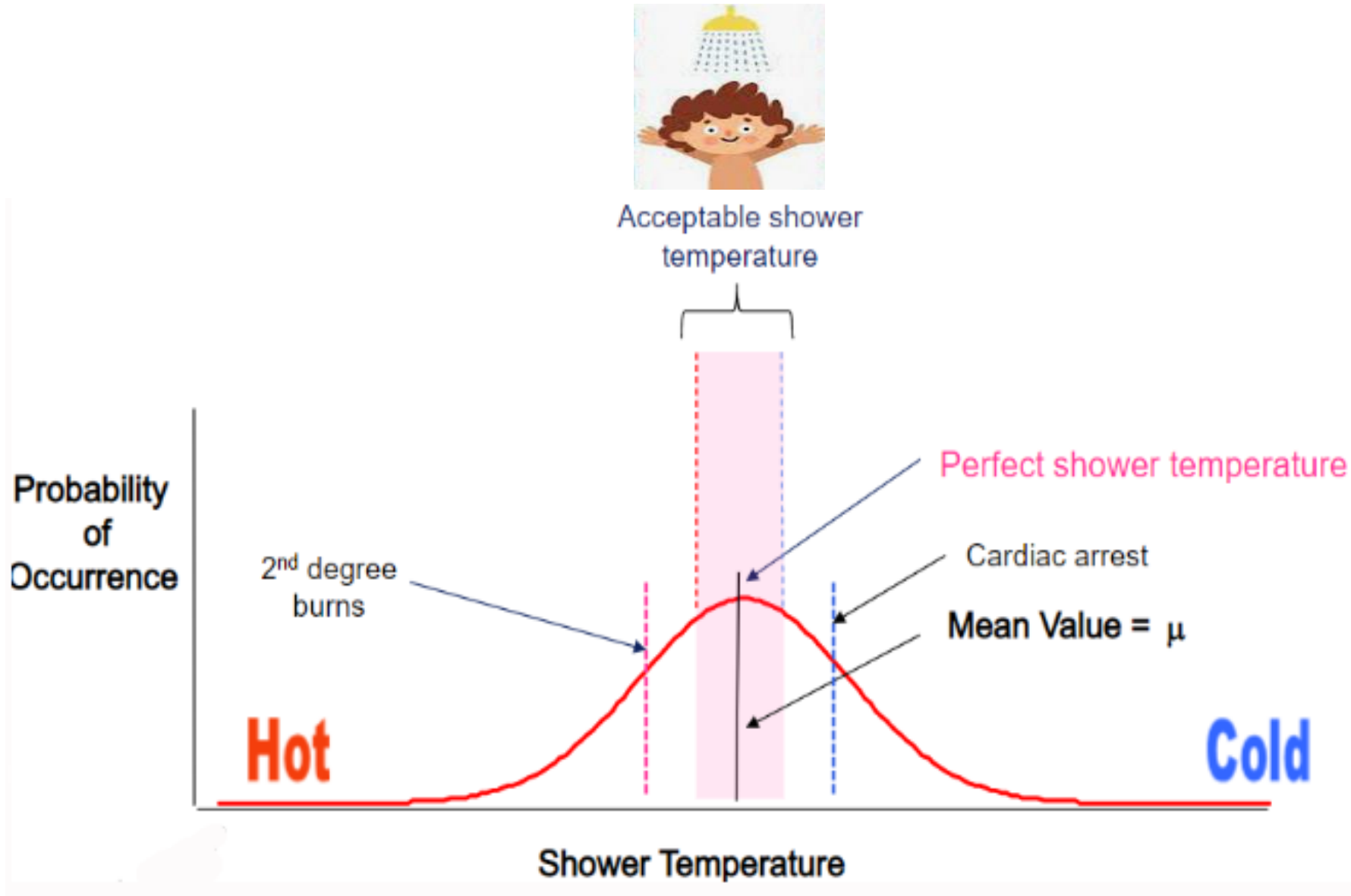
1. Process Design
2. Measurements
3. Final Control Elements
4. Control Structure
5. Control Calculations

Behavior of System Variables

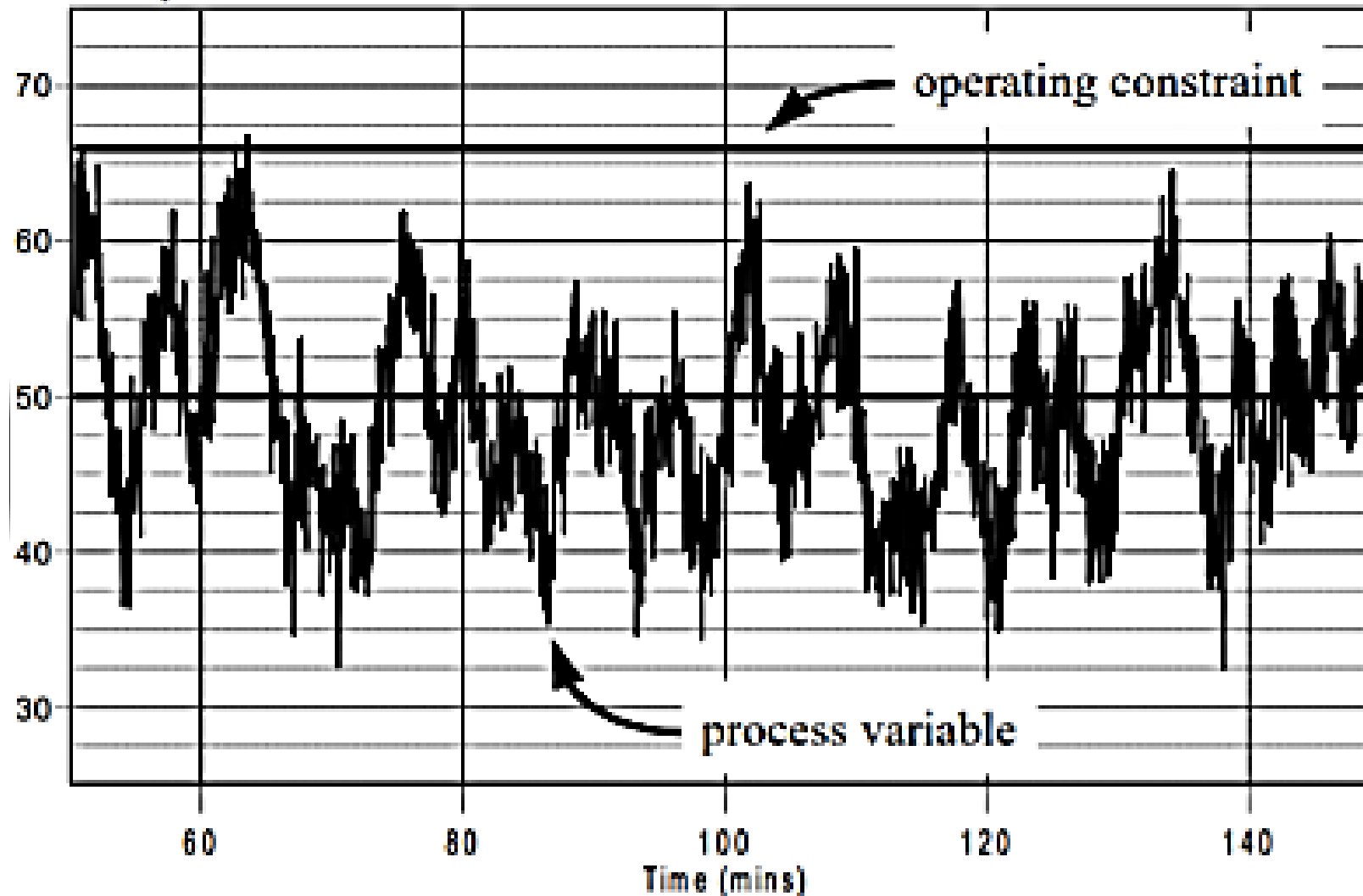
1. In process control, two types of variables exist:
 - Manipulated variables, which can be adjusted
 - Controlled variables, which are affected by the adjustments.
2. There is a specified range for the variables.
3. The effectiveness of control to maintain the process at desired conditions depends on:
 - Sign and magnitude of response
 - Speed of response
 - Shape of response
4. The analysis of the system's possible variations and sensitivity of the dynamic behaviour to those variations are important in the modelling.

Steady-State System Response

Objective: to reduce variability in the control loop

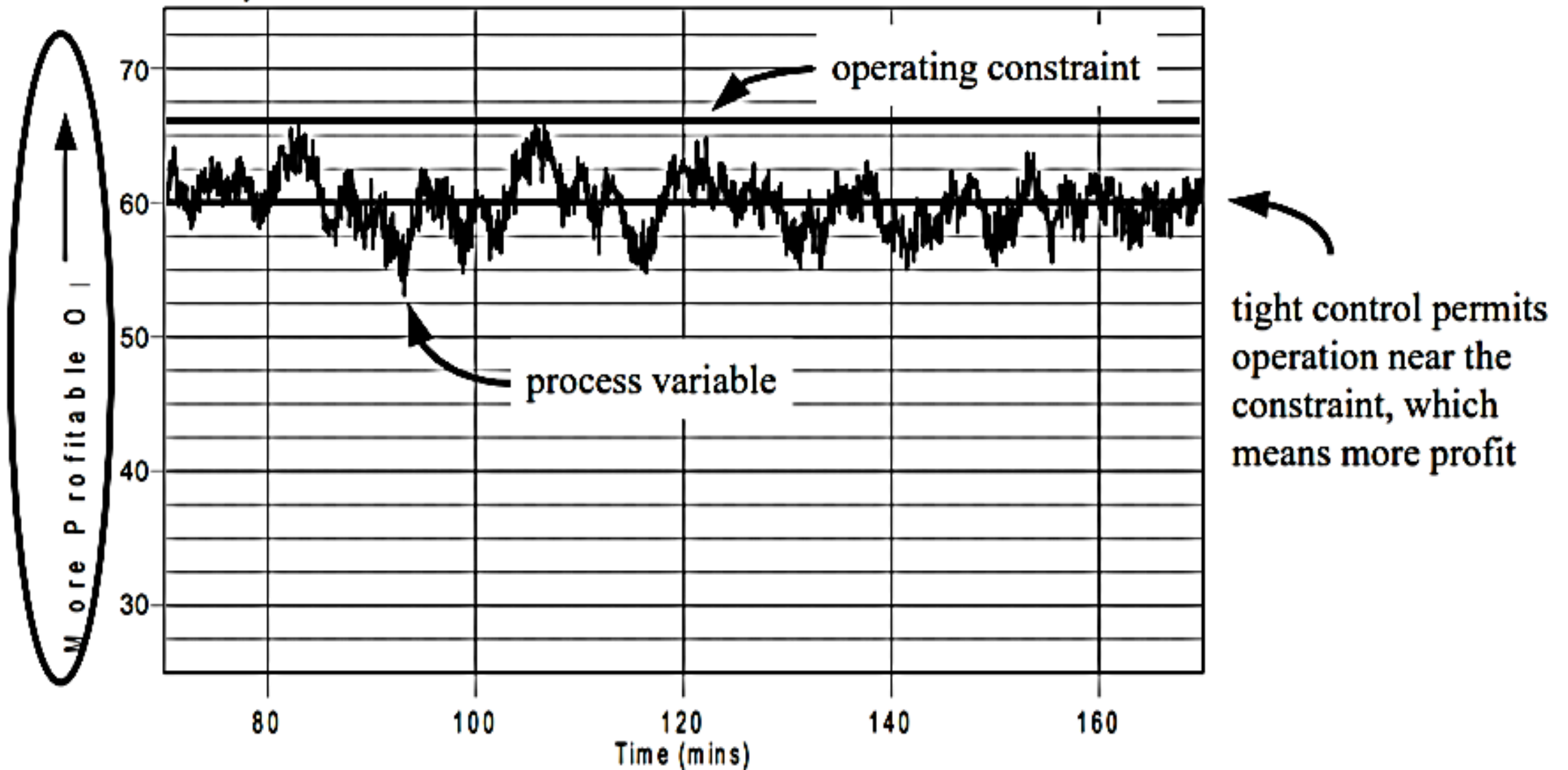


Poor Control-large variability

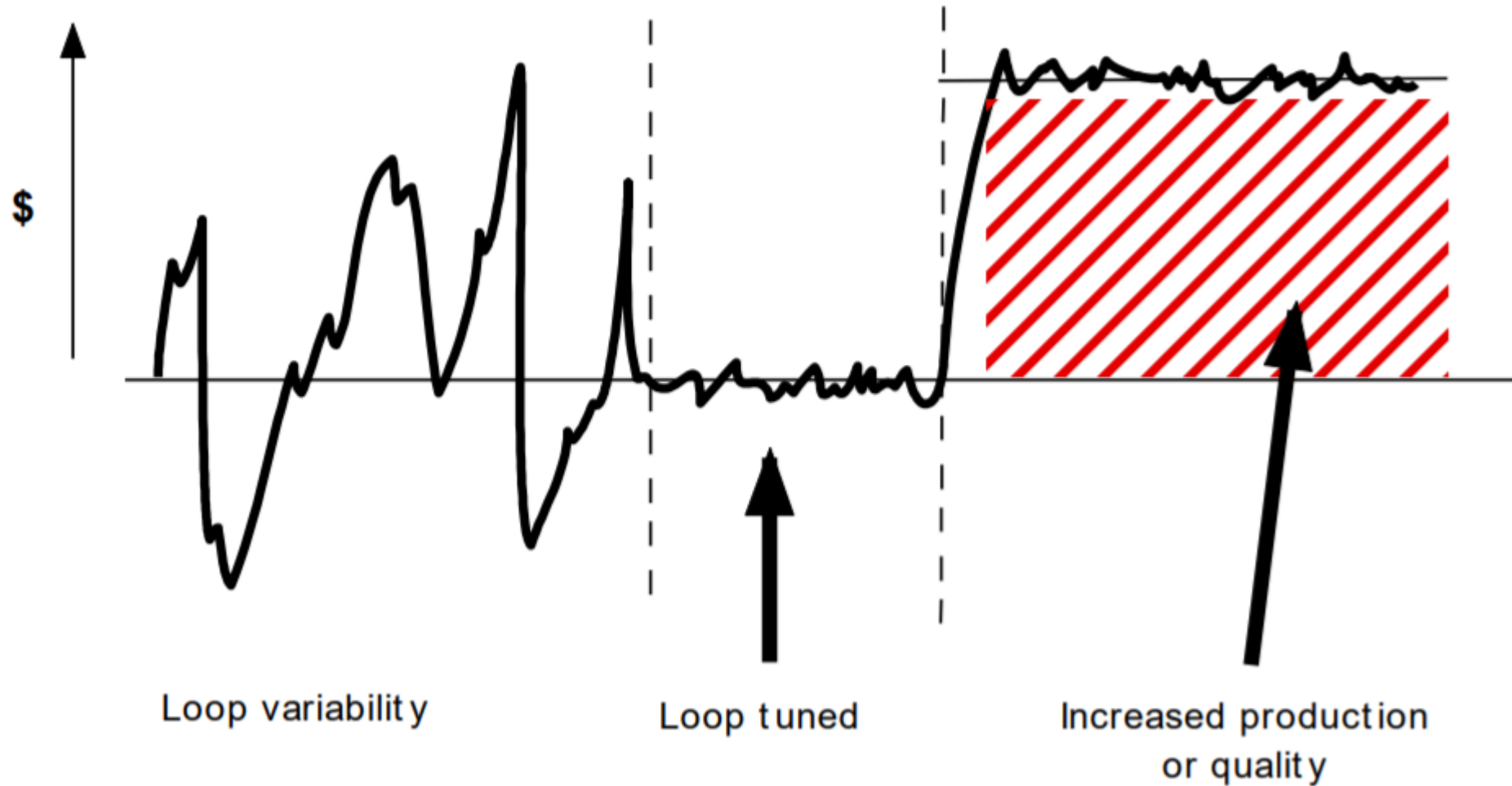


poor control means large variability, so the process must be operated in a less profitable region

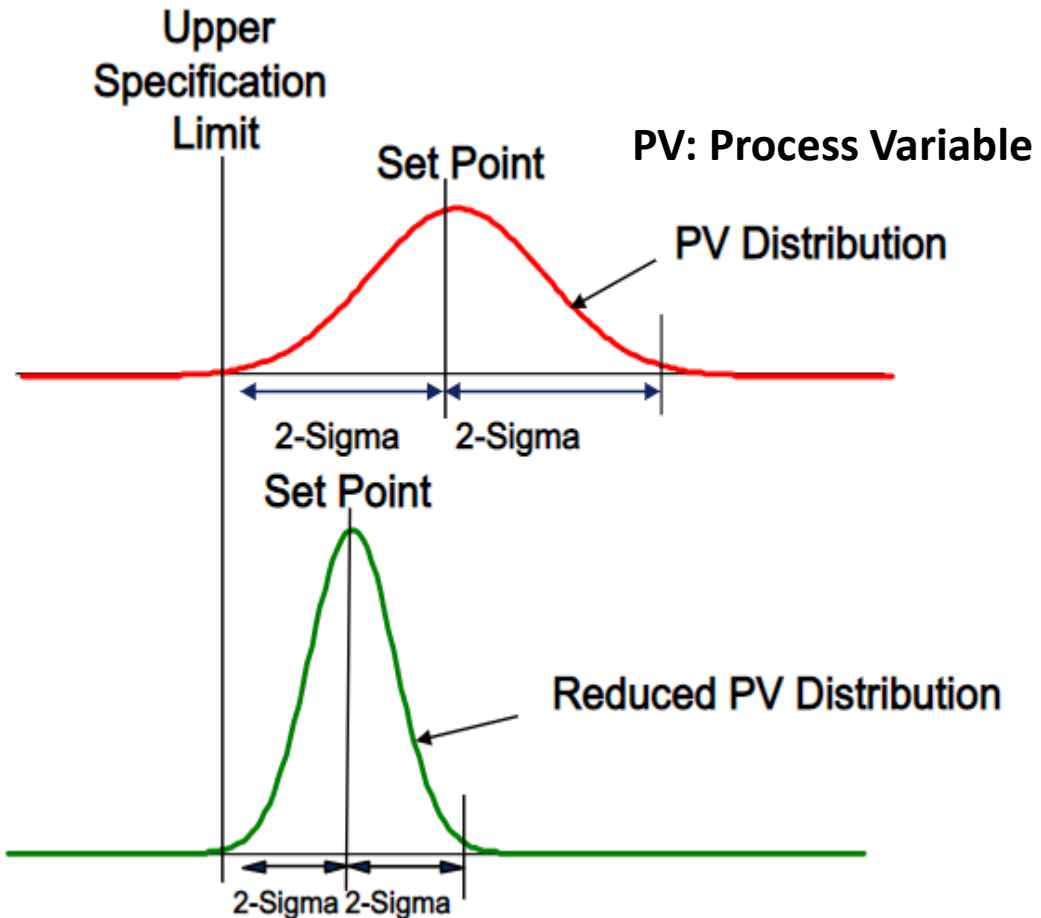
Tight control – less waste-more profit



Objective: to reduce variability in the control loop



Objective: to reduce variability in the control loop



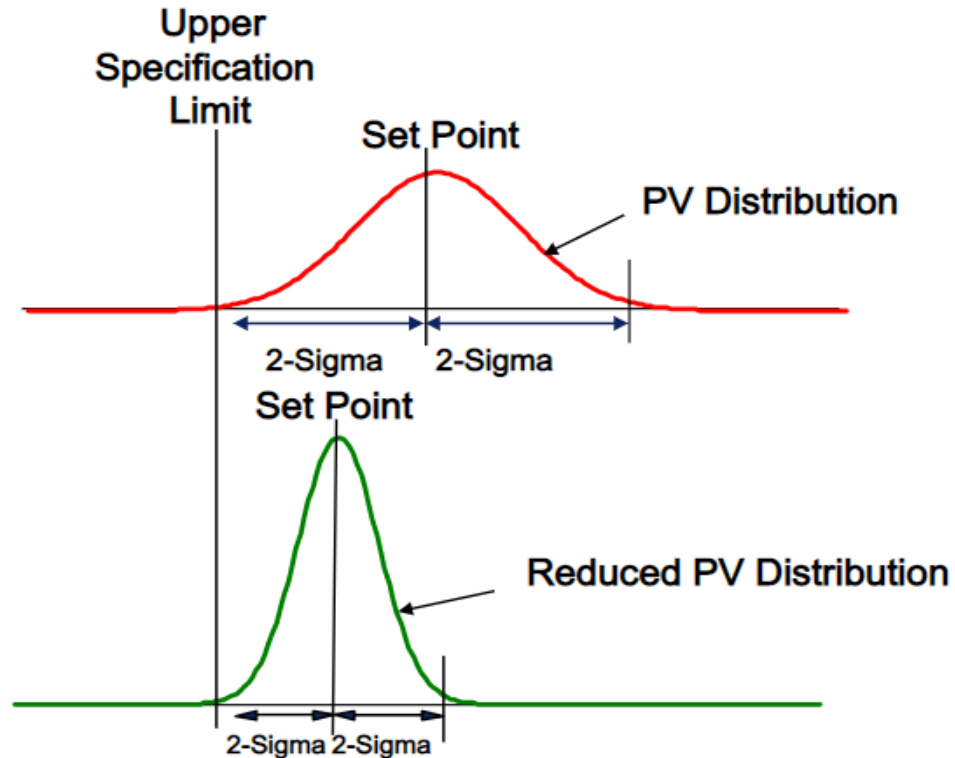
The normal distribution or Gaussian distribution

The usual justification for using the normal distribution for modeling is the **Central Limit theorem**, which states (roughly) that the sum of independent samples from any distribution with finite mean and variance converges to the normal distribution as the sample size goes to infinity.

Statistics and Machine Learning Toolbox™ offers several ways to work with the normal distribution.

https://www.mathworks.com/help/stats/normal-distribution.html?searchHighlight=normal%20distribution&s_tid=srchtitle_support_results_1_normal%20distribution

Objective: to reduce variability in the control loop



The standard normal distribution has zero mean μ and unit standard deviation.

If z is standard normal, then $\sigma z + \mu$ is also normal with mean μ and standard deviation σ .

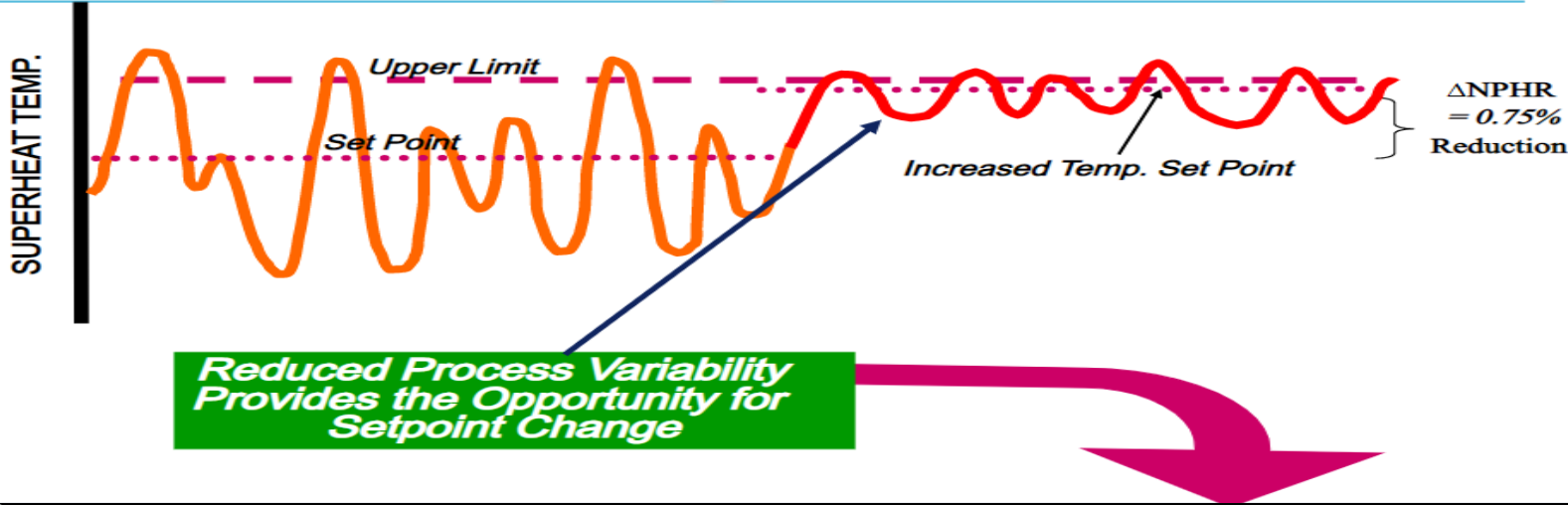
Parameters

The normal distribution uses these parameters.

Parameter	Description	Support
μ (μ)	Mean	$-\infty < \mu < \infty$
σ (σ)	Standard deviation	$\sigma \geq 0$

Main Steam Temperature Control

Decreased Variability = Increased Profit



$\Delta NPHR$ reduction of the set point variability

$$\text{Savings} = \underbrace{\left(\frac{0.75}{100}\right)}_{\text{Reduction}} \underbrace{\left(11000 \frac{\text{BTU}}{\text{KW} \cdot \text{HR}}\right)}_{\text{gas cost}} \underbrace{\left(\frac{\$6.563}{\text{MM BTU}}\right)}_{\text{consumption}} \underbrace{(8760 \frac{\text{HR}}{\text{Year}})}_{\text{time}}$$

BTU = British gas units

MM = 1000000

$$\text{Savings} = 1'517.785 \frac{\$}{\text{year}}$$

Main Steam Temperature Control

Decreased Variability = Increased Profit

10-15,000 Btu/kWh
approximate range of
heat rates of natural
gas-fired steam turbines

Henry Hub Natural Gas Spot Price (Dollars per Million Btu)

Week Of	Mon	Tue	Wed	Thu	Fri
2022 Nov-14 to Nov-18	6.24	5.90	5.88	6.20	6.10
2022 Nov-21 to Nov-25	6.23	6.27	6.57		6.57

$$\text{Savings} = \underbrace{\left(\frac{0.75}{100}\right)}_{\text{Reduction}} \underbrace{\left(11000 \frac{\text{BTU}}{\text{KW} \cdot \text{HR}}\right)}_{\text{gas cost}} \underbrace{\left(\frac{\$6.563}{\text{MM BTU}}\right)}_{\text{consumption}} \underbrace{\left(320000 \text{ KW}\right)}_{\text{time}} \underbrace{\left(8760 \frac{\text{HR}}{\text{Year}}\right)}$$

BTU = British
gas units

MM = 1000000

$$\text{Savings} = 1'517.785 \frac{\$}{\text{year}}$$

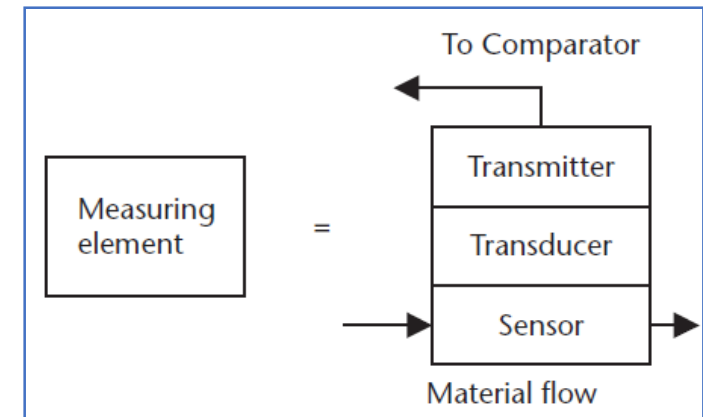
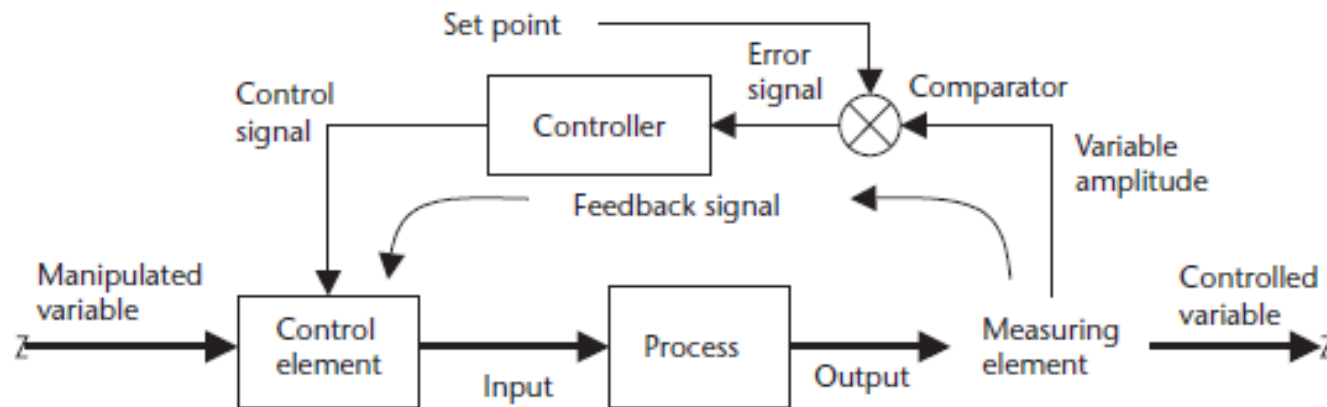
Elements in a Control Loop

Measurements

“One can control only what is measured”

Measurement is the determination of the physical amplitude; the measurement value must be consistent and repeatable.

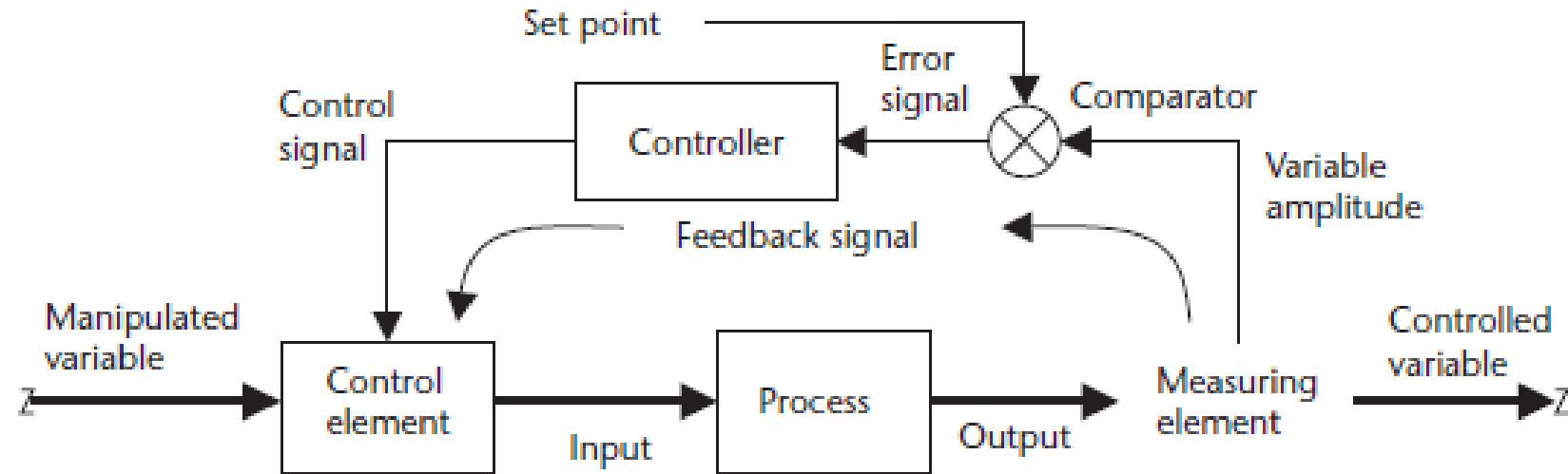
The engineer should select sensors that measure important variables rapidly, reliably and with sufficient accuracy.

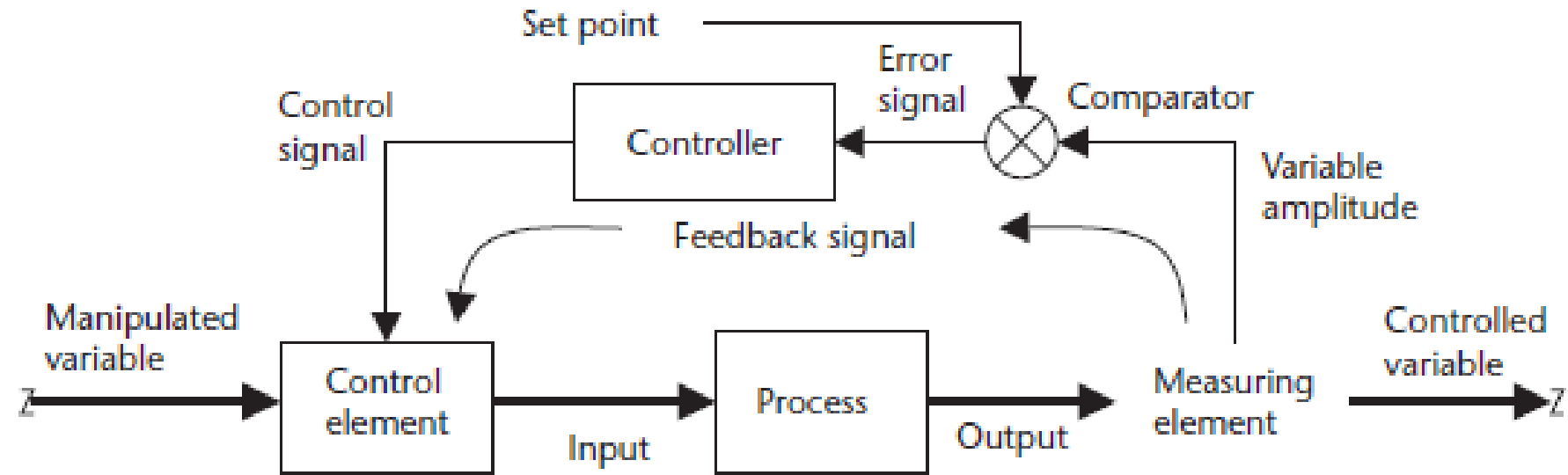
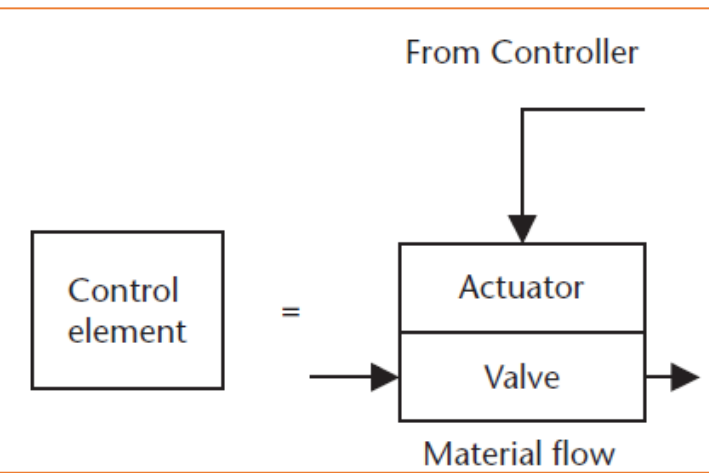


A sensor converts a physical parameter into a form **that can be used or understood** - converting temperature, pressure, force, or flow into an electrical signal, measurable motion, or a gauge reading.

Controller is a microprocessor-based system that determines the next step to be taken in a sequential process or evaluate the error signal in continuous control to determine what action is to be taken.

The controller can condition the signal, such as correcting the signal for temperature effects or nonlinearity in the sensor.





Control Element is the device that controls the incoming material to the process (e.g., the valve). The element is typically a flow control element and can have an On/Off characteristic or can provide linear control.

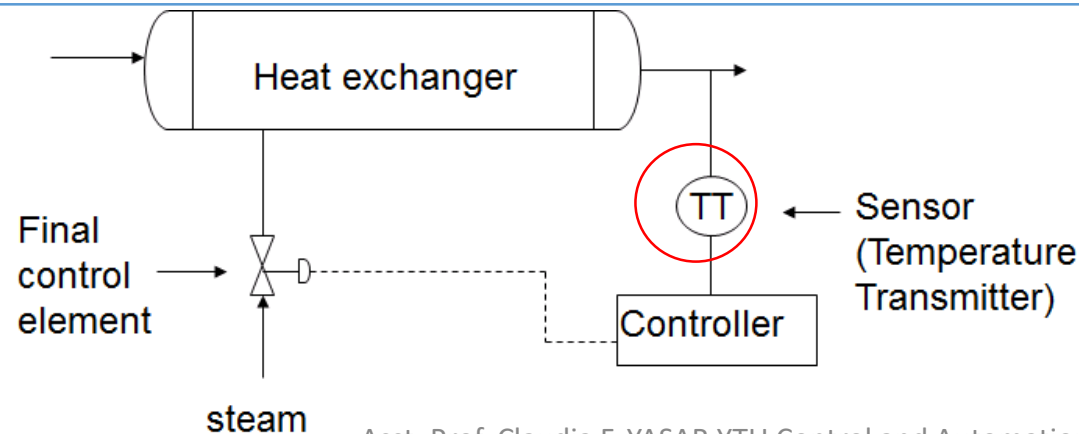
The control element is used to adjust the input to the process, bringing the output variable to the value of the set point.

How is Process Control Documented?

In standard Drawing:

- ❑ process equipment is drawn in solid lines ———
- ❑ sensors are designated by a circle connected to the point in the process where they are located ○
- ❑ process control loops are shown by dashed lines. - - - - -

- The first letter in the instrumentation symbol indicates the type of variable measured.
- The subsequent letter(s) give information about the function performed.

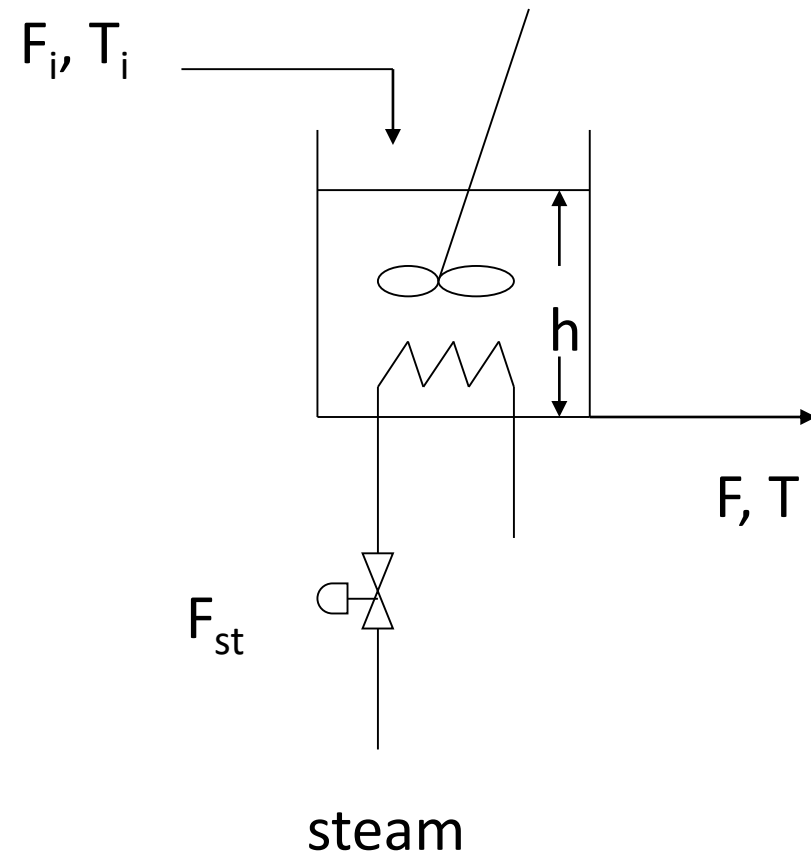


A	analyzer
F	Flow rate
L	Level of liquid or solid
P	Pressure
T	temperature

- ❑ In order to avoid misunderstanding, standard symbols developed by Instrument Society of America (ISA) are used.

Thank heating system

A liquid enters to the tank with a **flow rate F_i (ft³/min)** and a **temperature of T_i (°F)**, where it is heated with steam having a **flow rate of F_{st} (lb/min)**. Let **F and T** be the **flow rate and temperature** of the stream leaving the tank.



The tank is considered to be **well stirred**, (the temperature of the effluent is equal to the temperature of the liquid in the tank).

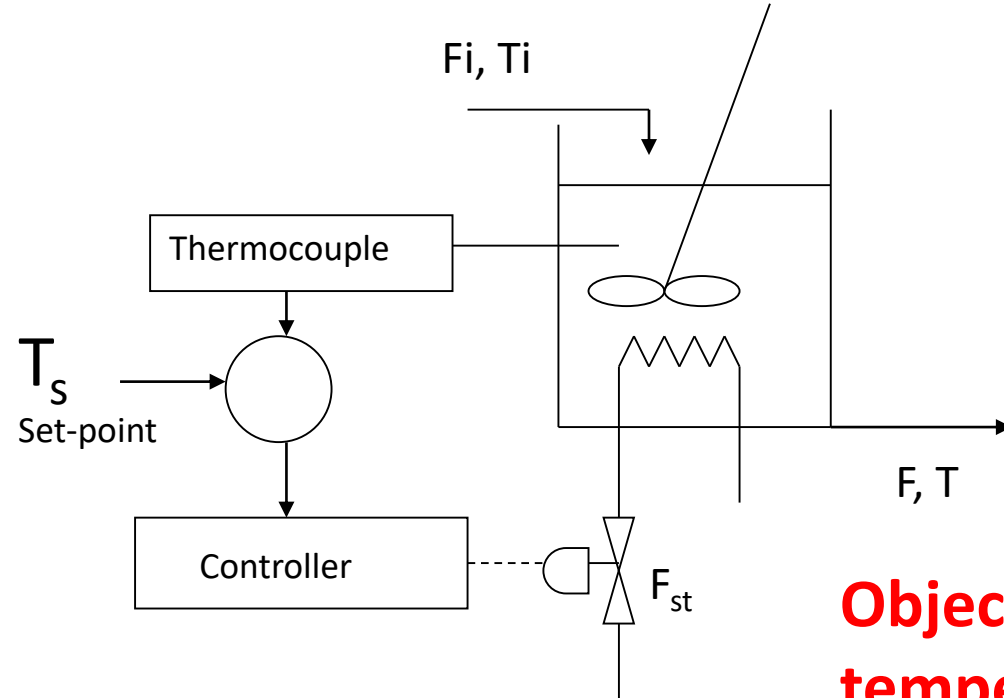
The control objectives of the heater are:

1. To keep the **effluent temperature T** at the desired value T_s .
2. To **keep the volume of the liquid** in the tank at a desired value V_s .

Disturbed by external factors such as changes in the feed flow rate F_i and temperature T_i .

Feedback control

A thermocouple measures the temperature of the fluid in the tank. Then this temperature is compared with the desired value yielding a deviation $\varepsilon = T_s - T$

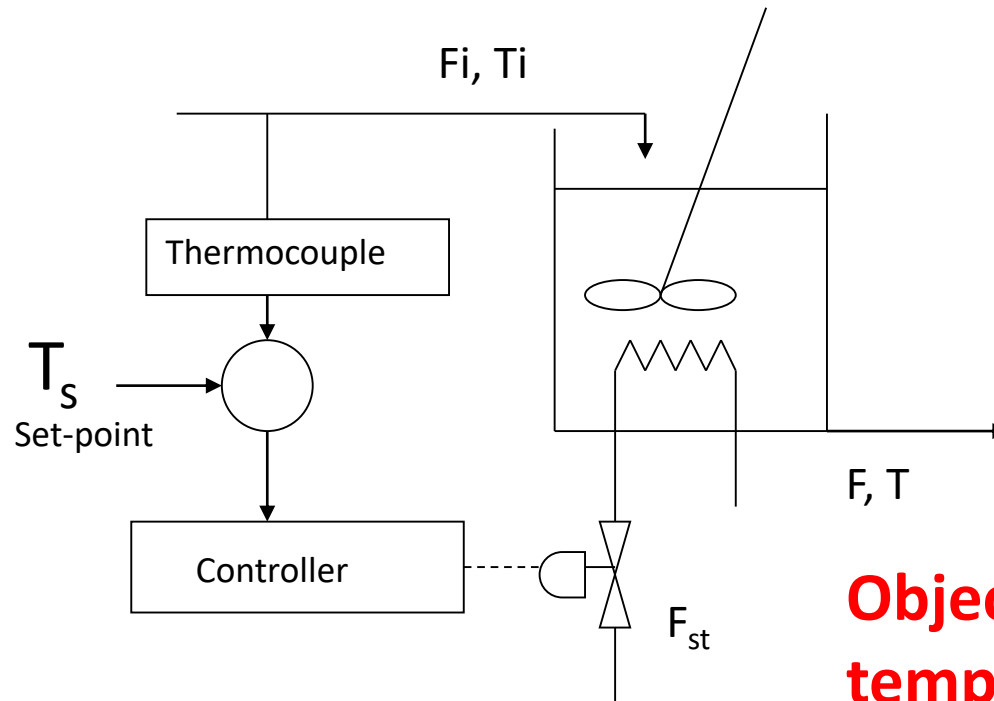


The value of deviation ε is sent to a control mechanism which decides what must be done to turn back to the desired value T_s .

Objective: to keep the effluent temperature T at the desired value T_s .

Feedforward control

This controller does not wait until the effects of the disturbances has been felt by the system, but acts appropriately before the external disturbance affects the system anticipating what its effect will be.

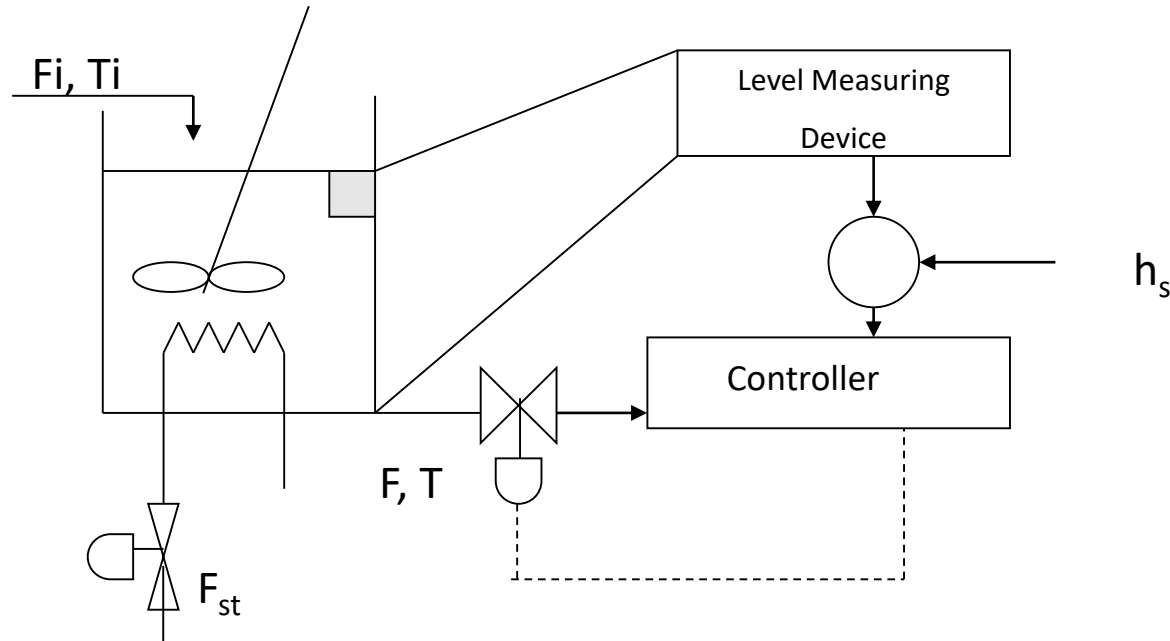


Objective: to keep the effluent temperature T at the desired value T_s .

Objective: to keep the volume of the liquid in the tank at a desired value V_s .

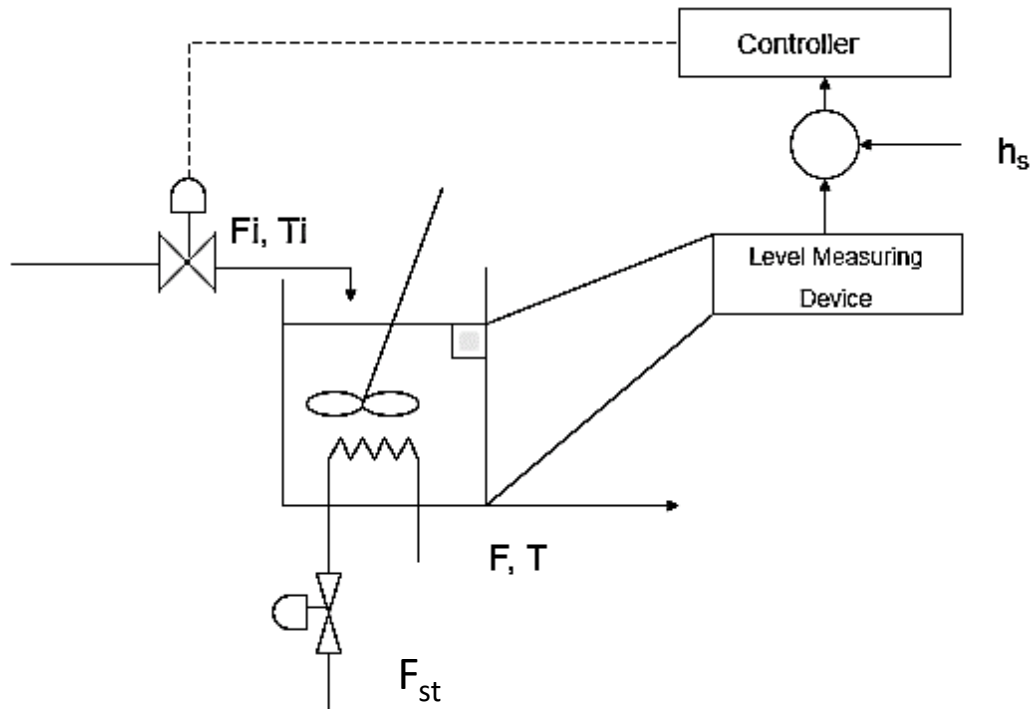
Keep the volume at its set point or keep the liquid level h_s .

We measure the level of the liquid in the tank and we open or close the effluent flow rate.



Feedback control

Objective: to keep the volume of the liquid in the tank at a desired value V_s .



Input variables are: F_i , T_i and F_{st} (which denote the effect of surroundings on the process)

Output variables are: F , V and T (which denote the effect of process on the surroundings)

Feedback control

The input variables can be further classified as:

1. Manipulated (or adjustable) variables, if their values can be adjusted freely by the human operator or a control mechanism.
2. Disturbances, if their values are not the result of adjustment by an operator or a control system.

The output variables are also classified as:

1. Measured output variables, if their values are known by directly measuring them.
2. Unmeasured output variables, if they are not or cannot be measured directly.

Note:

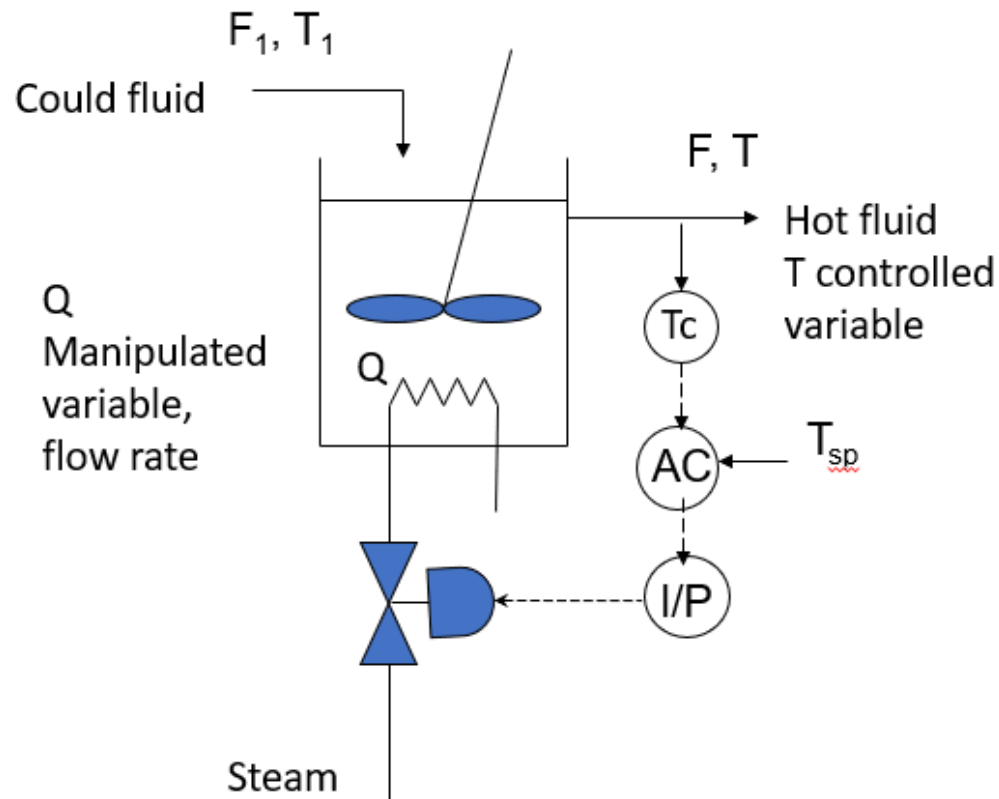
- Understand your process, as well as your control objectives
What needs to be controlled? Which variables effect each other (and how)?
Where does variability hurt you most? Etc.
- Remember there's a dynamic component.
- Think about control early in design phase.

MODEL-BASED DESIGN THERMAL PROCESS

Transfer functions

Example: Heating process: modelling, control and instrumentation

Consider a Stirred-Tank heating process with constant Holdup and the following assumptions: perfect mixing, thus, the exit temperature T is also the temperature of the tank contents; the density ρ and heat capacity C_p of the liquid are assumed to be constant, thus, their temperature dependence is neglected; heat losses are negligible.



$$F_1 = 2 \times 10^{-5} \frac{m^3}{min}$$

$$\rho = 10^6 \frac{g}{m^3}$$

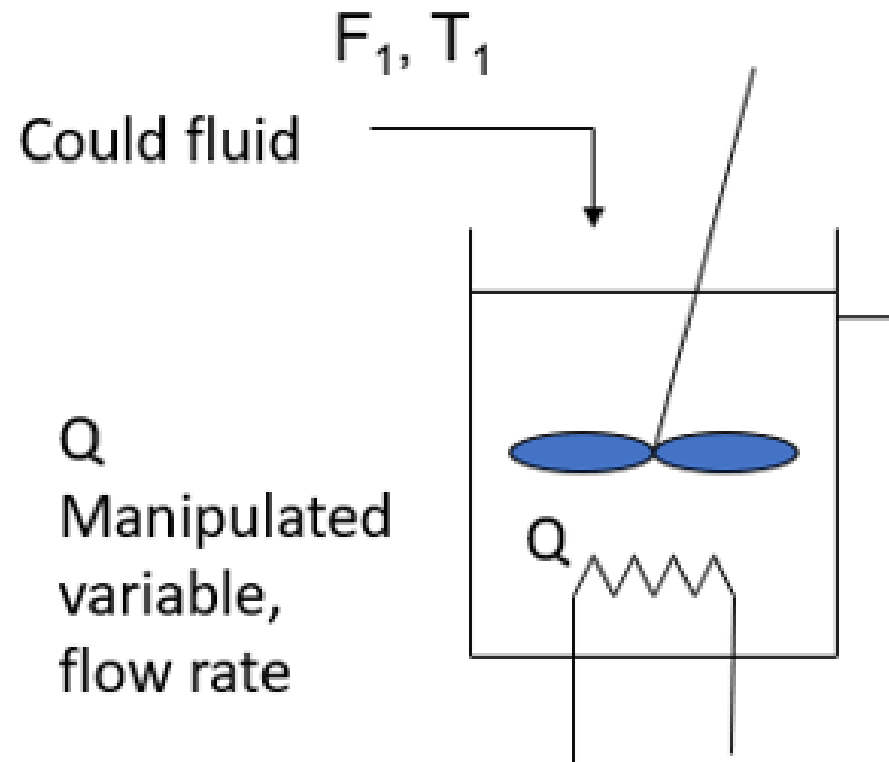
$$C_p = 1 \frac{K cal}{g ^\circ C}$$

$$V = 1 m^3$$

$$T_1 = 30 ^\circ C$$

$$Q = 1200 \frac{K cal}{min}$$

- Determine the total and energy balance to obtain dT/dt .
- Use the given parameters and calculate the nominal steady-state temperature, T .



$$F_1 = 2 \times 10^{-5} \frac{m^3}{min}$$

$$\rho = 10^6 \frac{g}{m^3}$$

$$C_p = 1 \frac{K cal}{g ^\circ C}$$

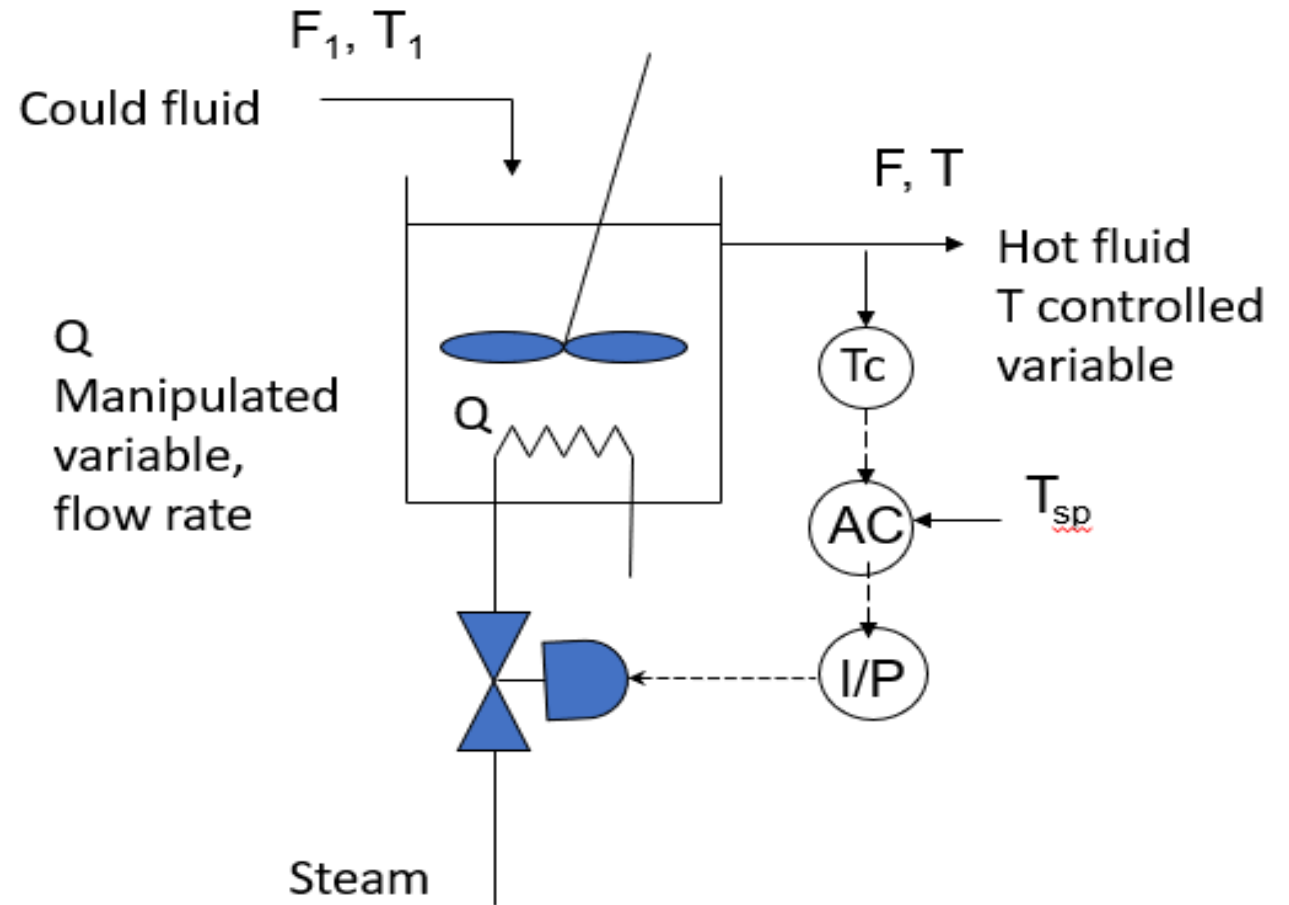
$$V = 1 m^3$$

$$T_1 = 30 \quad ^\circ C$$

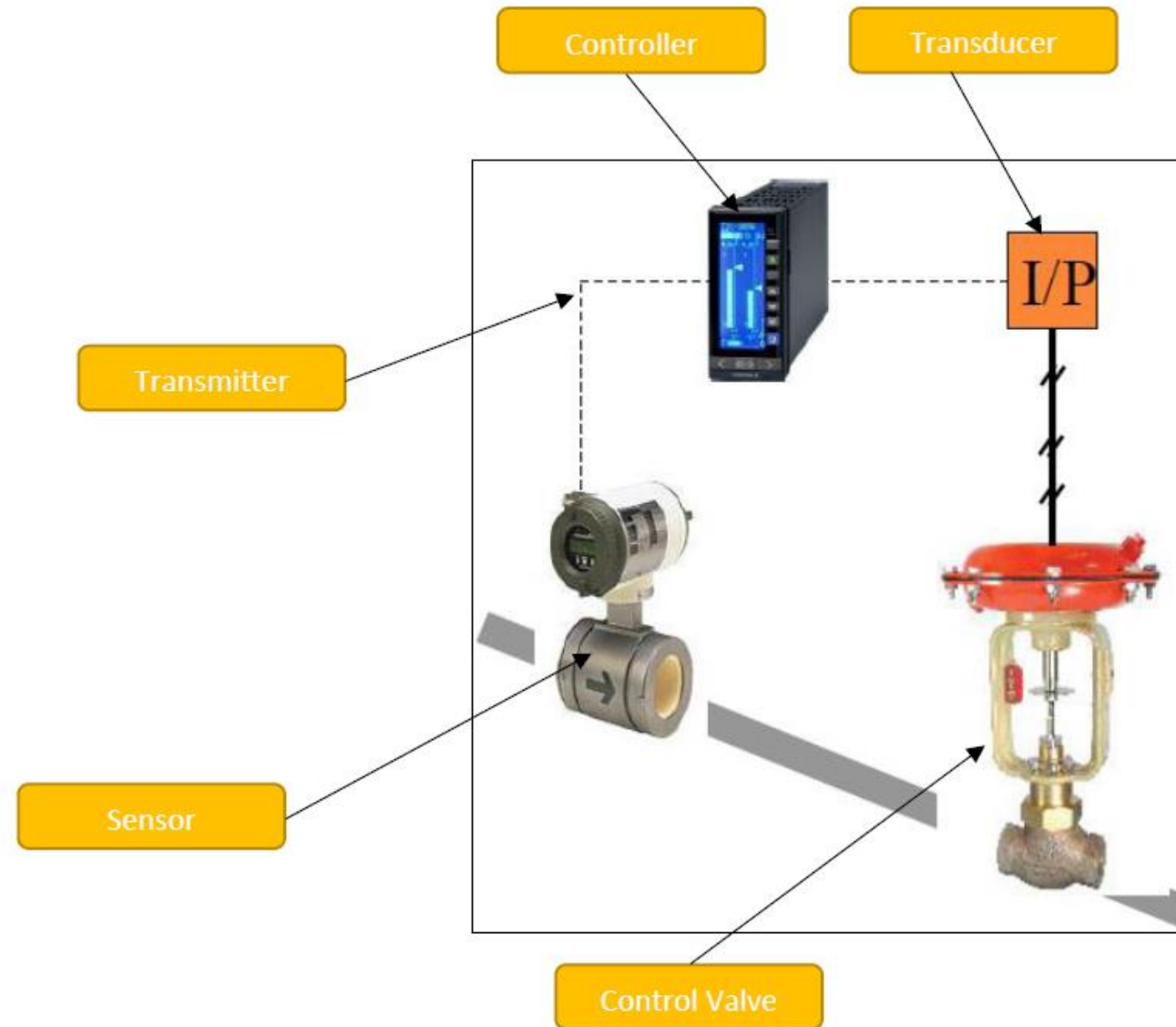
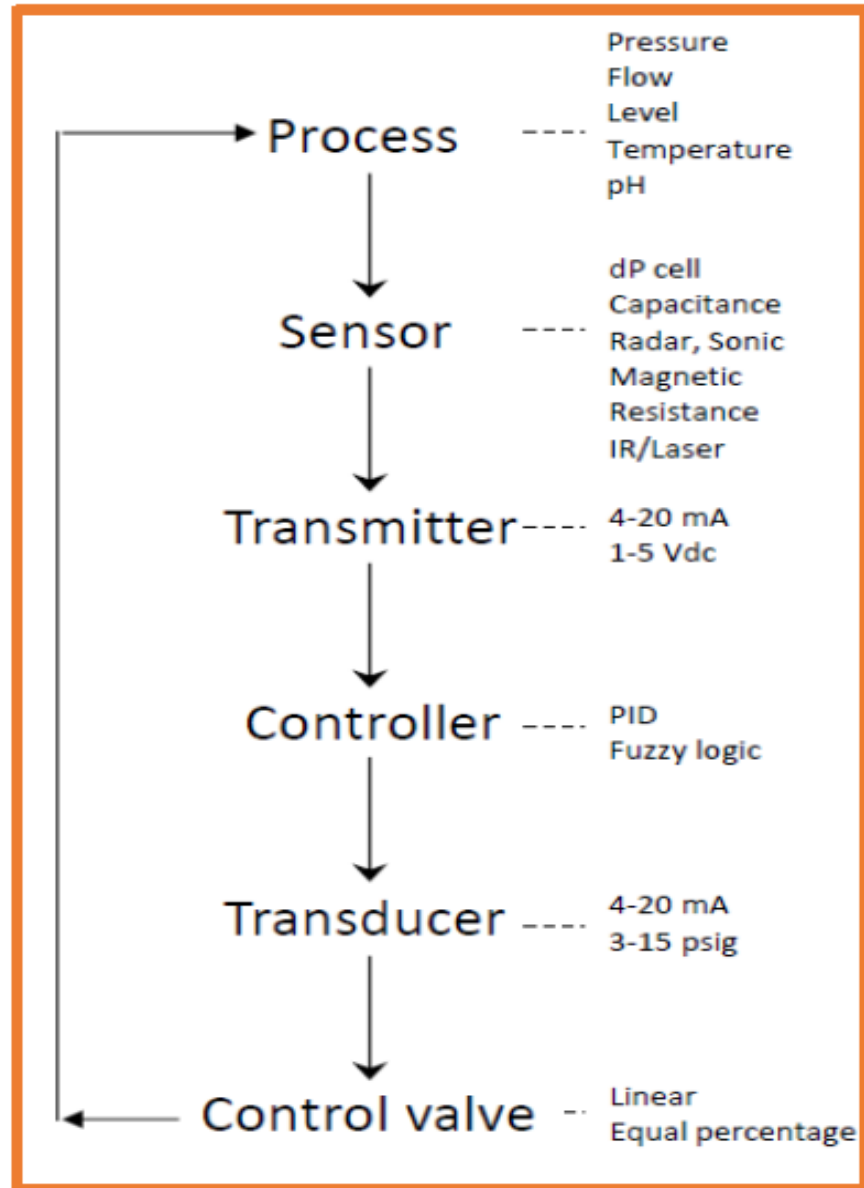
$$Q = 1200 \frac{K cal}{min}$$

- Propose a block diagram to control the liquid temperature $T=T_{sp}$. The controller consist of a single feedback control loop to keep an T_{sp} output temperature. Include all the required instrumentation blocks, transfer functions, and choose a regulator.

- Describe each of the transfer functions, and calculate transfer function parameters, when possible, by using the given values.

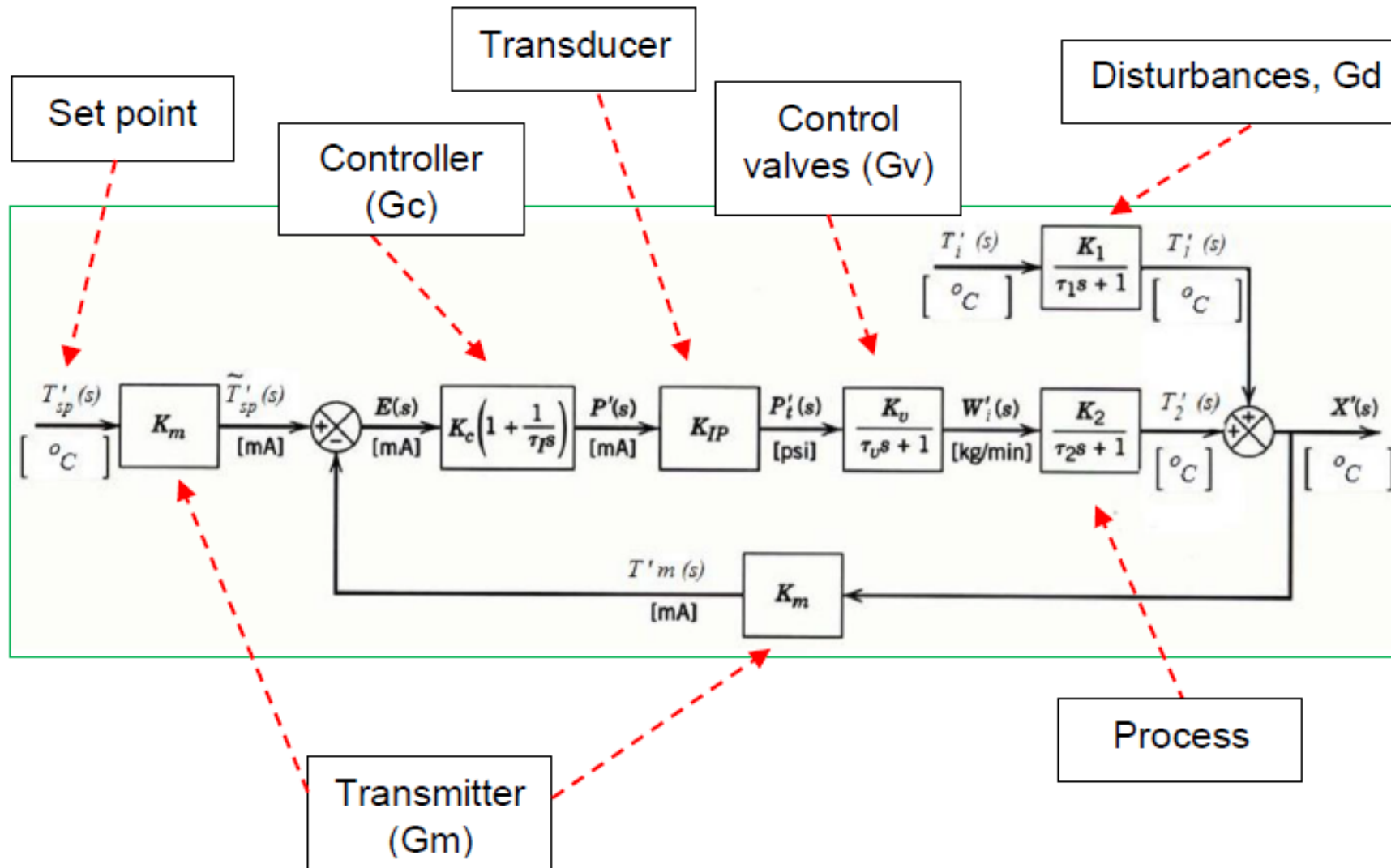


Process Control Loop



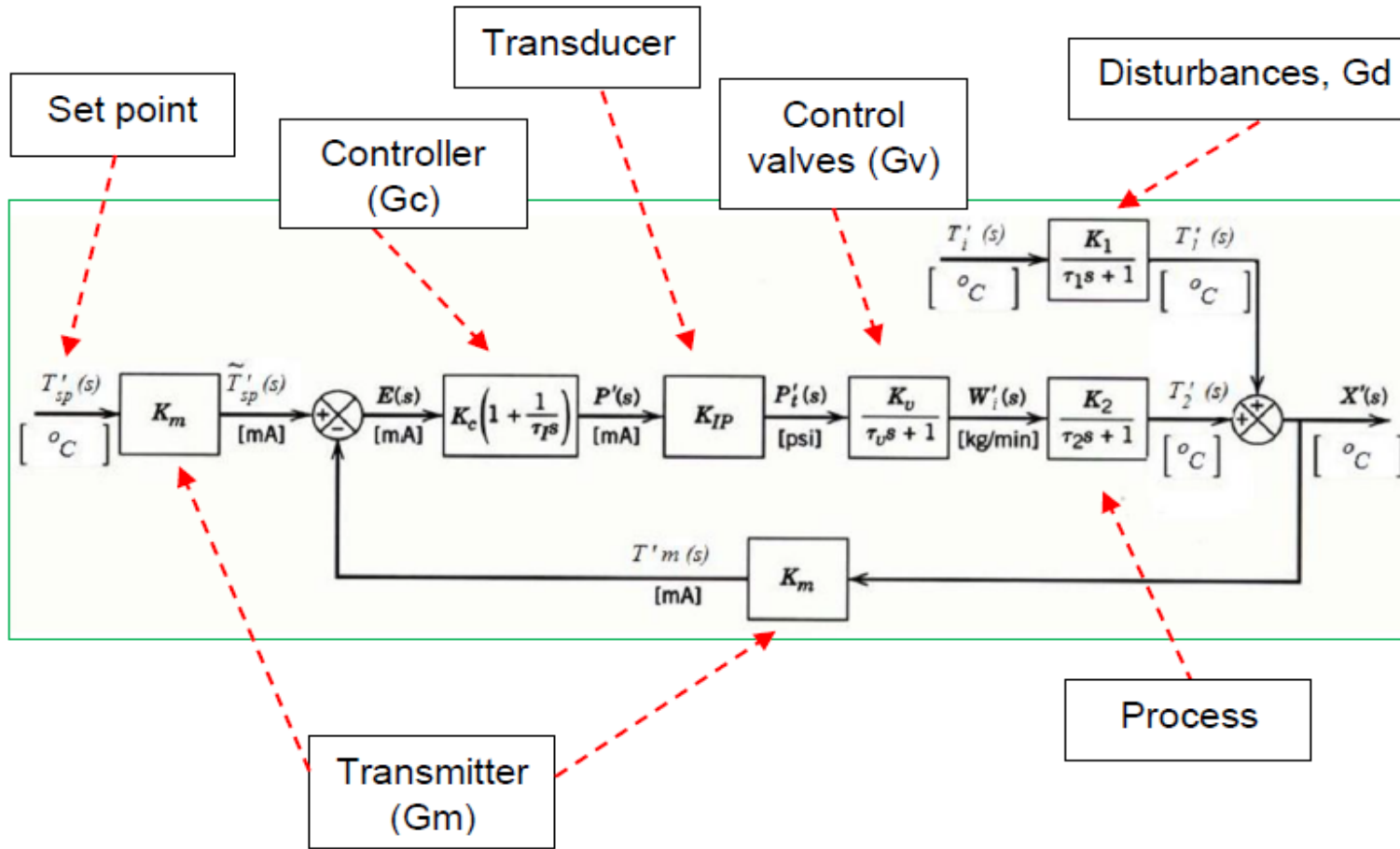
Thermal Process Control

➤ Overall



Components of a Control Loop

➤ Overall

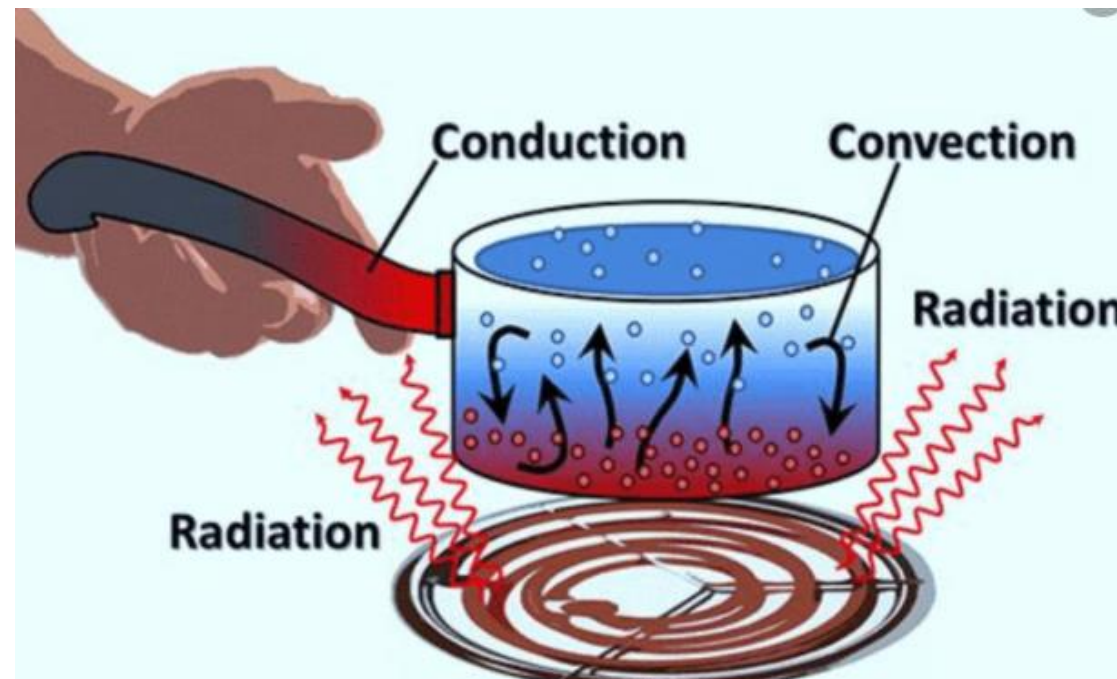


Control Objective = Set Point (T_{sp})

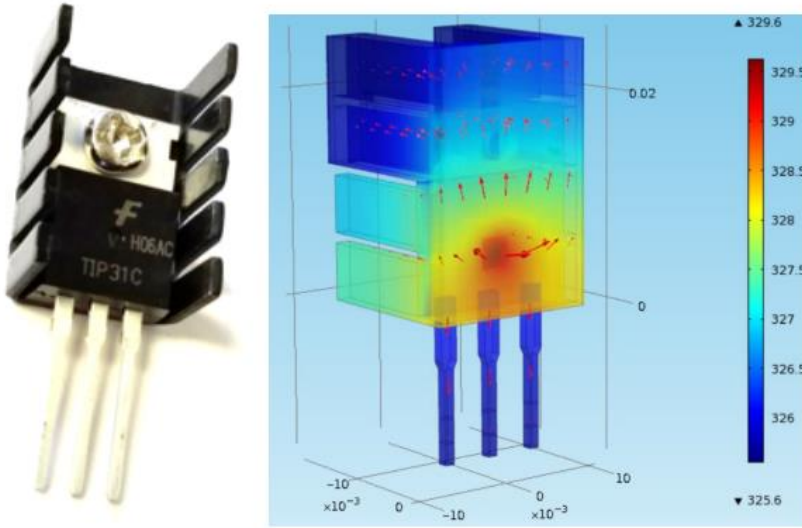
- System Output $X'(s)$
- Measured Process Variable $X'(s)$
- Controlled Variable $X'(s)$
- System reference $T'_{sp}(s)$
- PID: Controller Output $P'(s)$
- Manipulated Variable $W'_i(s)$
- Disturbances $T'_i(s)$

Heat energy transfer

Heat energy is transferred from one point to another using any of three basic methods: conduction, convection, and radiation. These modes of transfer can be considered separately, but in practice two or more of them can be present simultaneously.



Temperature Modelling



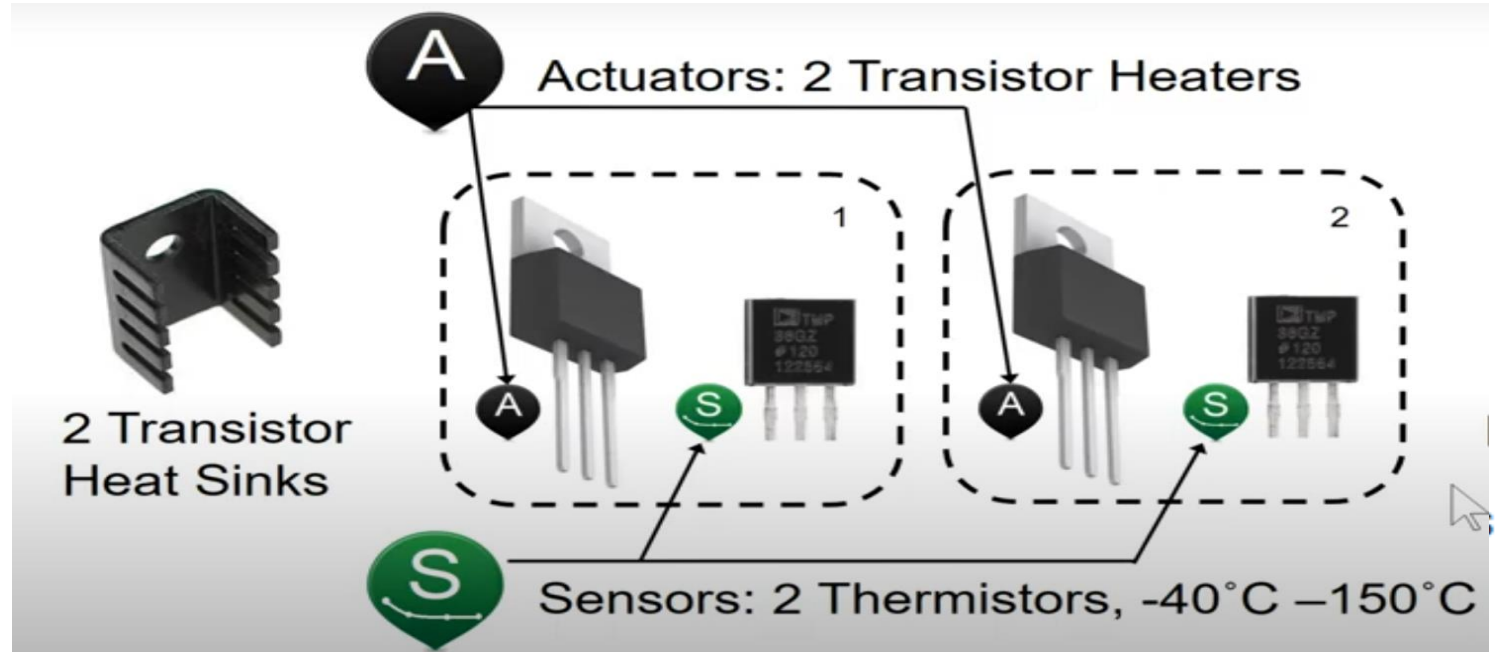
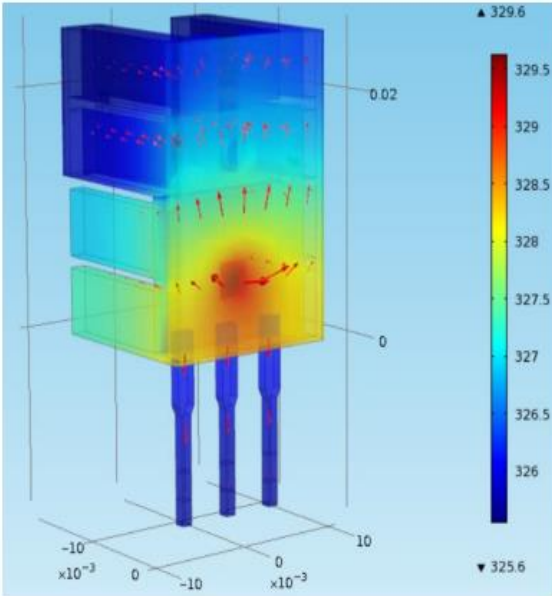
More information

<https://apmonitor.com/pdc/index.php/Main/ArduinoModeling>

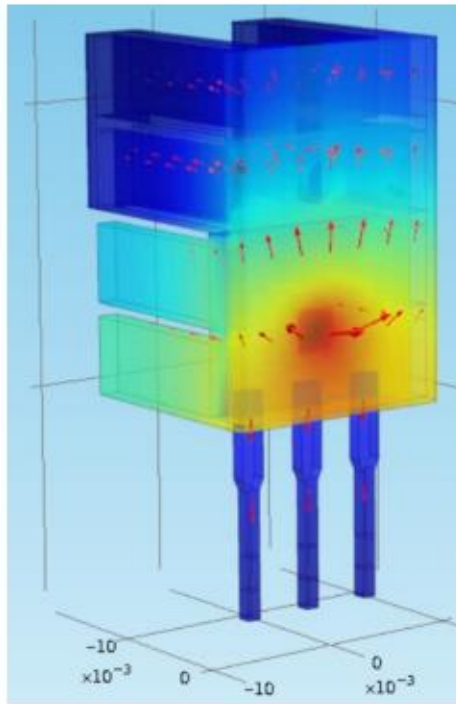
Where to buy the TC-lab

<https://www.amazon.com/TCLab-Temperature-Control-Lab/dp/B07GMFWMRY>

Use the energy balance to create a dynamic model of the dynamic response between input power to the transistor and the temperature sensed by a thermistor. **The full energy balance includes convection and radiation terms.**



the device primarily by convection but radiative heat transfer may also be a contributing factor. The radiative heat transfer can be included in the model to determine what fraction of heat is lost by convection and heat radiation. Heat transfer is improved with a thermal coupling (white epoxy) that connects the two components.



Quantity
Initial temperature (T_0)
Ambient temperature (T_∞)
Heater output (Q)
Heater factor (α)
Heat capacity (C_p)
Surface Area (A)
Mass (m)
Overall Heat Transfer Coefficient (U)
Emissivity (ϵ)
Stefan Boltzmann Constant (σ)

$$m c_p \frac{dT}{dt} = \sum \dot{h}_{in} - \sum \dot{h}_{out} + Q$$

Q is the rate of heat transfer

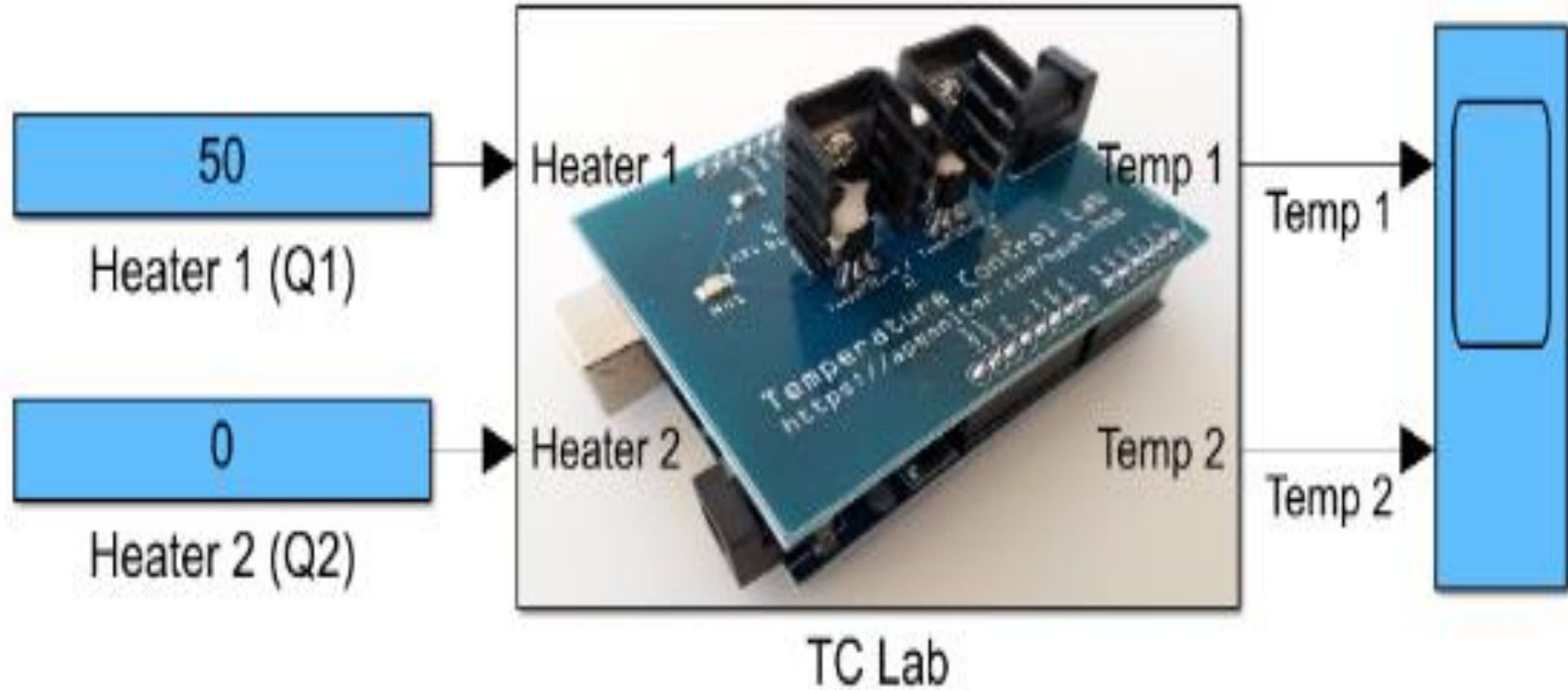
$$m c_p \frac{dT}{dt} = U A (T_\infty - T) + \epsilon \sigma A (T_\infty^4 - T^4) + \alpha Q$$

Convection

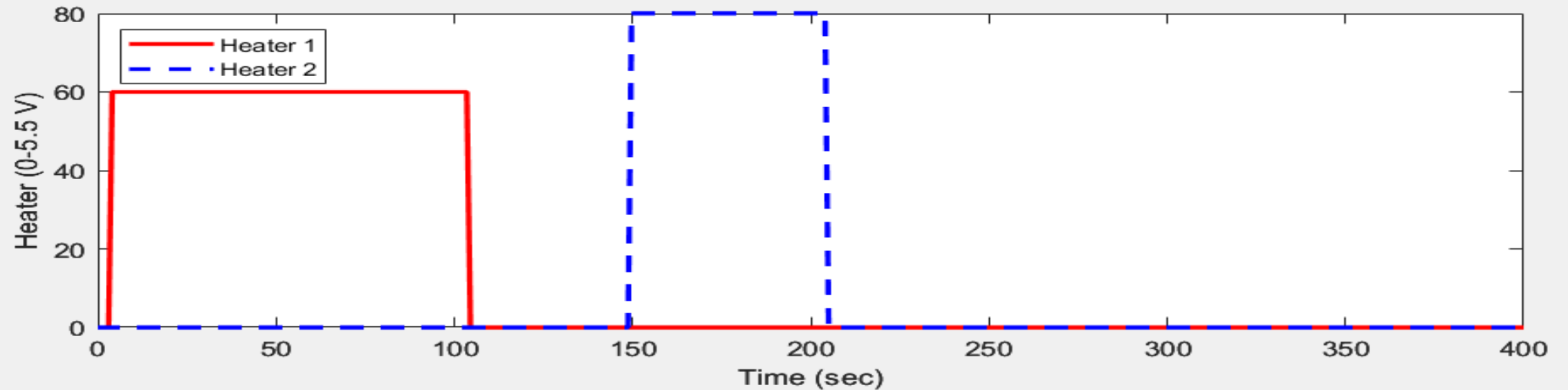
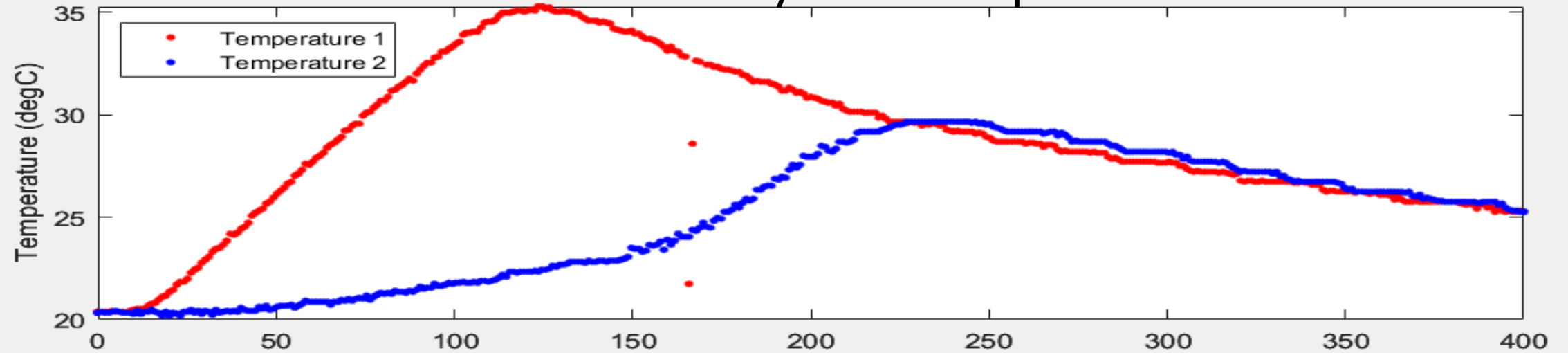
Radiation

Heater

REAL TIME EXPERIMENTS - TC Lab - Dynamic response for both heaters

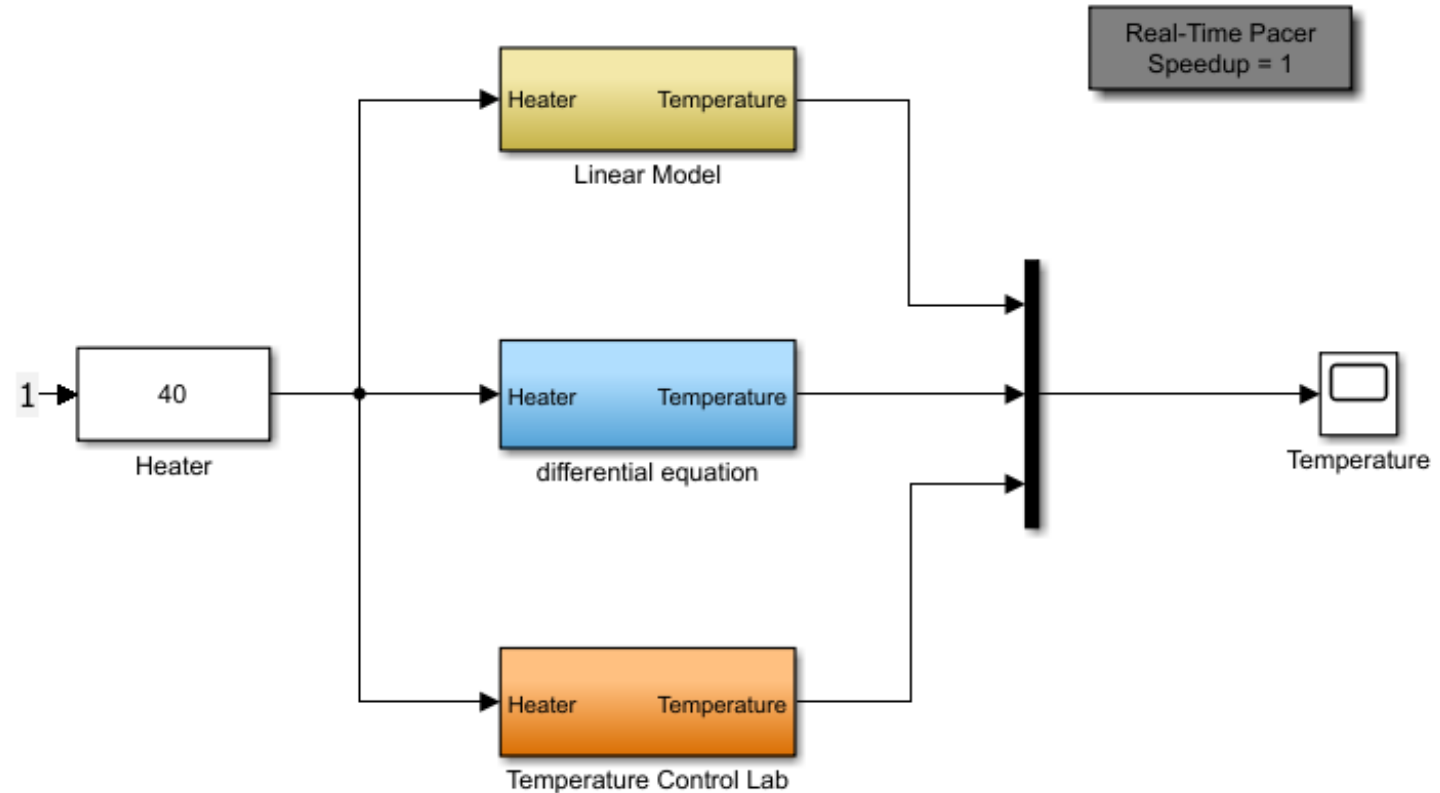
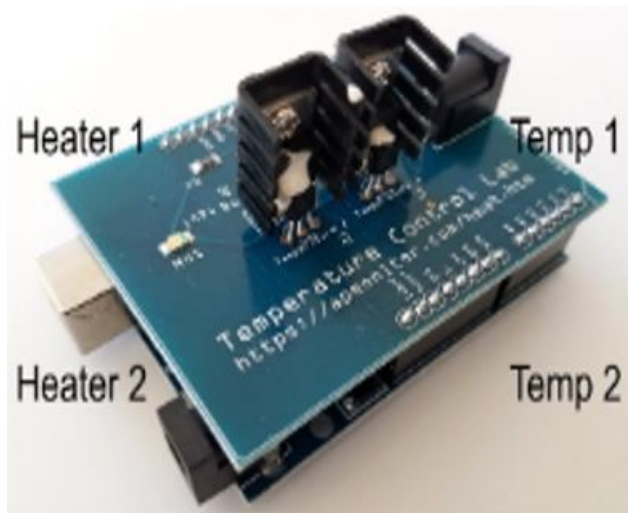


REAL-TIME EXPERIMENTS - TC Lab - Dynamic response for both heaters



REAL-TIME EXPERIMENTS - TC Lab – Dynamic model of a single heater

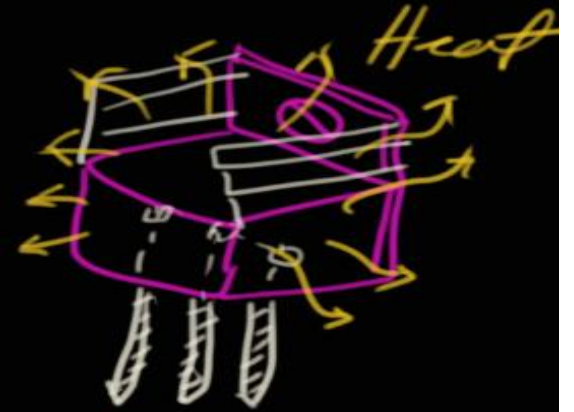
$m = 0.001$; % kg (1 gm)
% heat transfer coefficient
 $U = 200$; % W/m²-K
% surface area
 $A = 2 / 100^2$; % m²
% heat capacity
 $C_p = 4900.0$; % J/kg-K



REAL TIME EXPERIMENTS - TC Lab – Dynamic model of a single heater

Total Energy Balance

$$mC_p \frac{dT}{dt} = \underbrace{UA(T_{\infty} - T)}_{\text{Convection}} + \underbrace{\epsilon \sigma (T_{\infty}^4 - T^4)}_{\text{Radiation}} + \underbrace{\alpha Q}_{\text{heater}}$$



If we ignore Radiation components

* $mC_p \frac{dT}{dt} = UA(T_{\infty} - T) + \alpha Q$ First order differential equation

$$\left(\frac{mC_p}{UA} \right) \frac{dT}{dt} + T = T_{\infty} + \left(\frac{1}{UA} \right) \alpha Q$$

$$\tau_p \frac{dT}{dt} + T = T_{\infty} + k_p \alpha Q$$

$$\tau_p = \frac{mC_p}{UA}$$

$$k_p = \frac{1}{UA}$$

Using Laplace and assuming initial conditions 'zero'

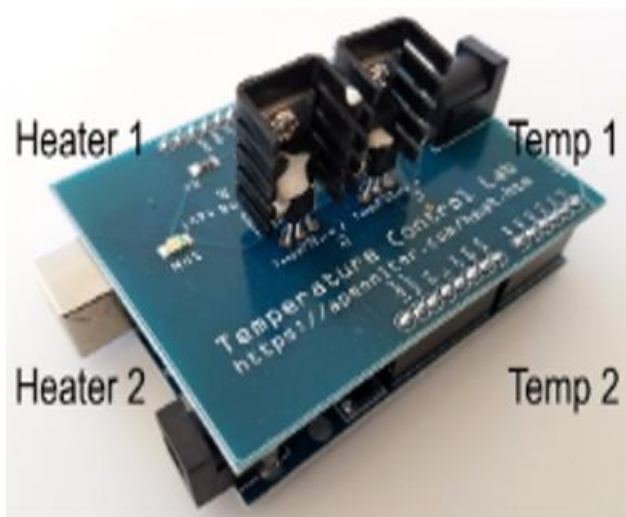
$$T(s) = \frac{1}{\tau_p s + 1} T_{\infty}(s) + \frac{k_p}{\tau_p s + 1} \alpha Q(s)$$

$$T(s) = T_{\infty} + \frac{k_p}{\tau_p s + 1} \alpha Q$$

Using * $\frac{dT}{dt} = \frac{UA(T_{\infty} - T) + \alpha Q}{mC_p}$

REAL TIME EXPERIMENTS - TC Lab – Dynamic model of a single heater

$m = 0.001$; % kg (1 gm)
% heat transfer coefficient
 $U = 200$; % $W/m^2 \cdot K$
% surface area
 $A = 2 / 100^2$; % m^2
% heat capacity
 $C_p = 4900.0$; % $J/kg \cdot K$



$$\begin{aligned} m &= 0.001 \text{ kg} \\ c_p &= 4900 \frac{J}{kg \cdot K} \\ U &= 200 \frac{W}{m^2 K} \\ A &= \frac{2}{100^2} m^2 \end{aligned} \quad \left. \begin{aligned} \tau_p &= \frac{(0.001 \text{ kg}) / (4900 \frac{J}{kg \cdot K})}{(200 \frac{W}{m^2 K}) (0.0002 m^2)} \\ \tau_p &= 122.5 \frac{J}{W} \\ \tau_p &= 122.5 s \end{aligned} \right\}$$

Video!

[TCLab Single Heater Response \(youtube.com\)](https://www.youtube.com/watch?v=...)

Dynamic Modeling of a Single Heater

Using The Energy Balance Equation

Use the Live Script
TCLab temperature response

This live script will teach you how to create a dynamic model of a single heater using energy balance.

Use the TCLab kit and Simulink to measure and validate the model of a single heater.

The main objectives are:

- To apply energy balance to a single heater system and obtain the system dynamics (a linear differential equation).
- To obtain the transfer function of the system.
- To conduct real-time experiments with the TCLab kit.
- Use Simulink to simulate a single heater differential equation and its transfer function.
- Visualize and compare both models' responses through real-time experiments.