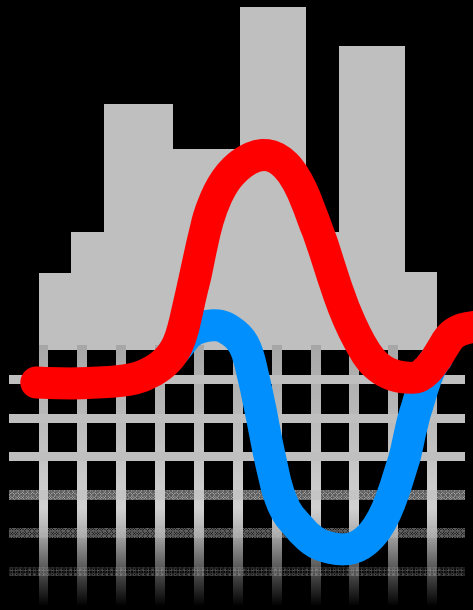


Facility Dynamics
ENGINEERING

Controlling Analog Processes

Proportional Control and Proportional plus Integral plus Derivative Control

Presented By:

David Sellers; Facility Dynamics Engineering

Senior Engineer

NAVFAC, San Diego

Control System Building Blocks

Automatically adjust a piece of machinery to give us what we want by comparing what is going on to what we want to go on and making appropriate adjustments to the process we want to control

Control System Building Blocks

Automatically adjust a piece of machinery to give us what we want by comparing what is going on to what we want to go on and making appropriate adjustments to the process we want to control

Inputs

Measure the process variable

Control System Building Blocks

Automatically adjust a piece of machinery to give us what we want by comparing what is going on to what we want to go on and making appropriate adjustments to the process we want to control

Inputs	Measure the process variable
Outputs	Adjust the controlled variable

Control System Building Blocks

Automatically adjust a piece of machinery to give us what we want by comparing what is going on to what we want to go on and making appropriate adjustments to the process we want to control

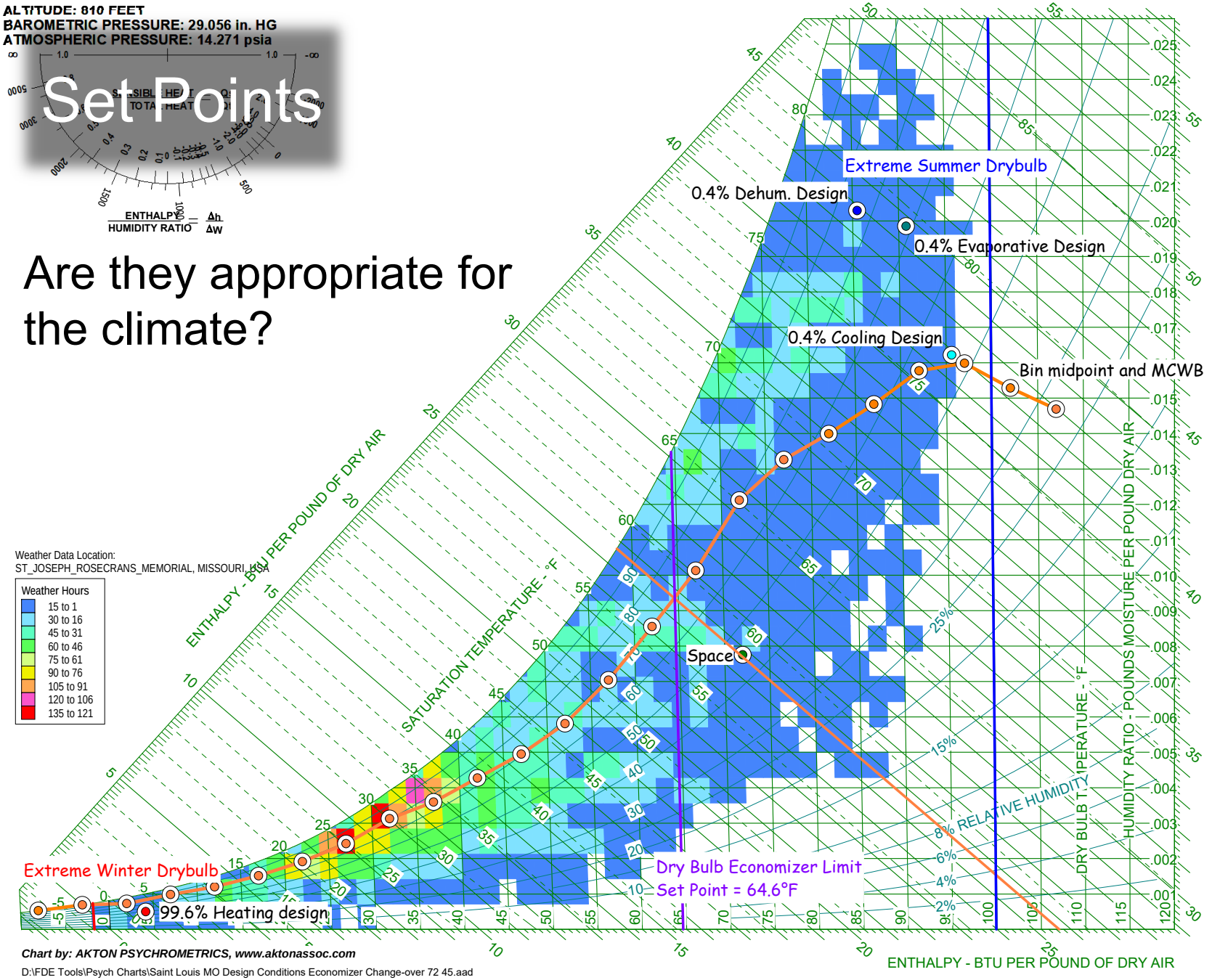
Inputs	Measure the process variable
Outputs	Adjust the controlled variable
Control Process	Logic and algorithms that tries to bring the controlled variable into agreement with the set point

Control System Building Blocks

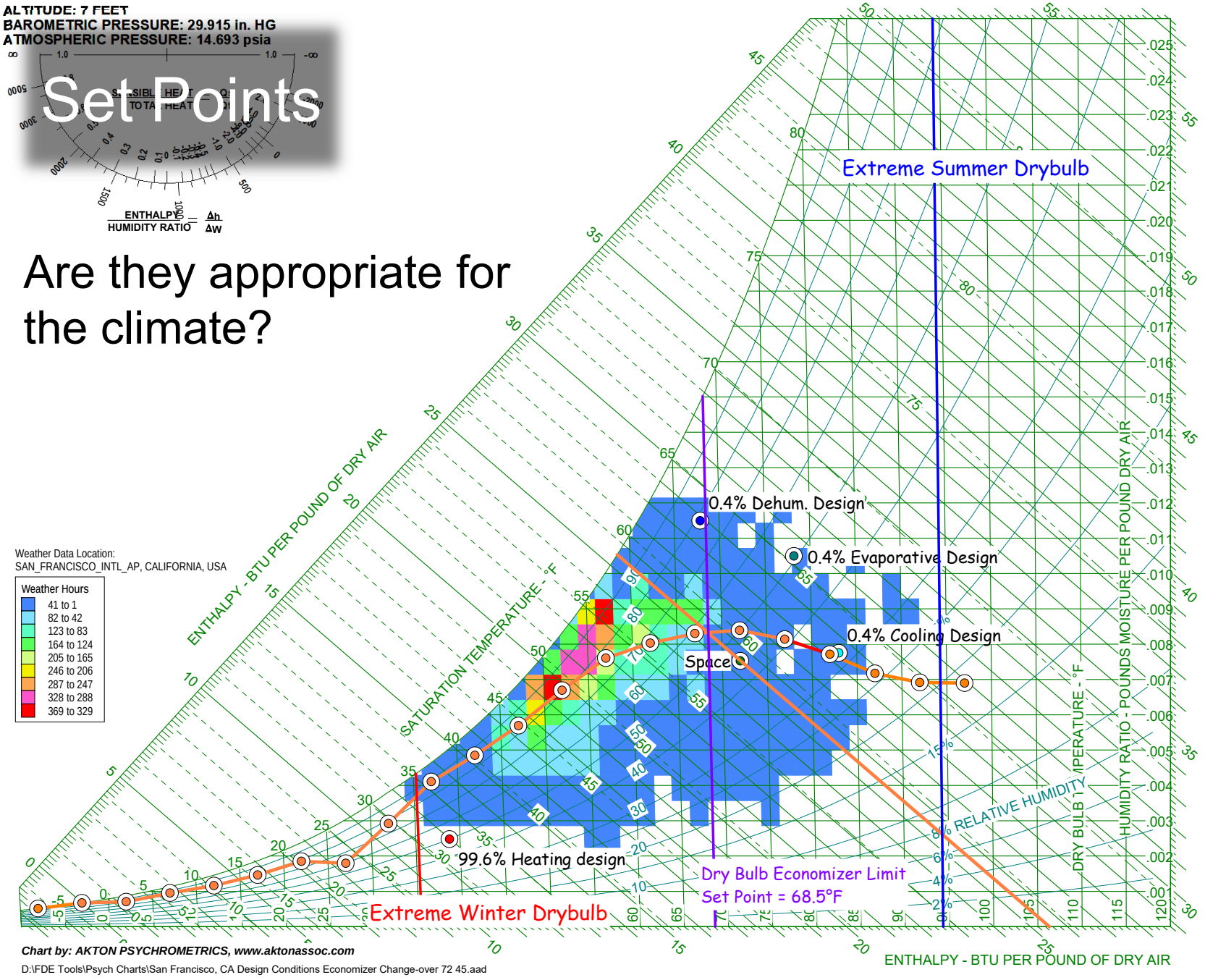
Automatically adjust a piece of machinery to give us what we want by comparing what is going on to what we want to go on and making appropriate adjustments to the process we want to control

Inputs	Measure the process variable
Outputs	Adjust the controlled variable
Control Process	Logic and algorithms that tries to bring the controlled variable into agreement with the set point
Set Point	Our requirements for the process that is under control, which can be fixed or variable

Set Points

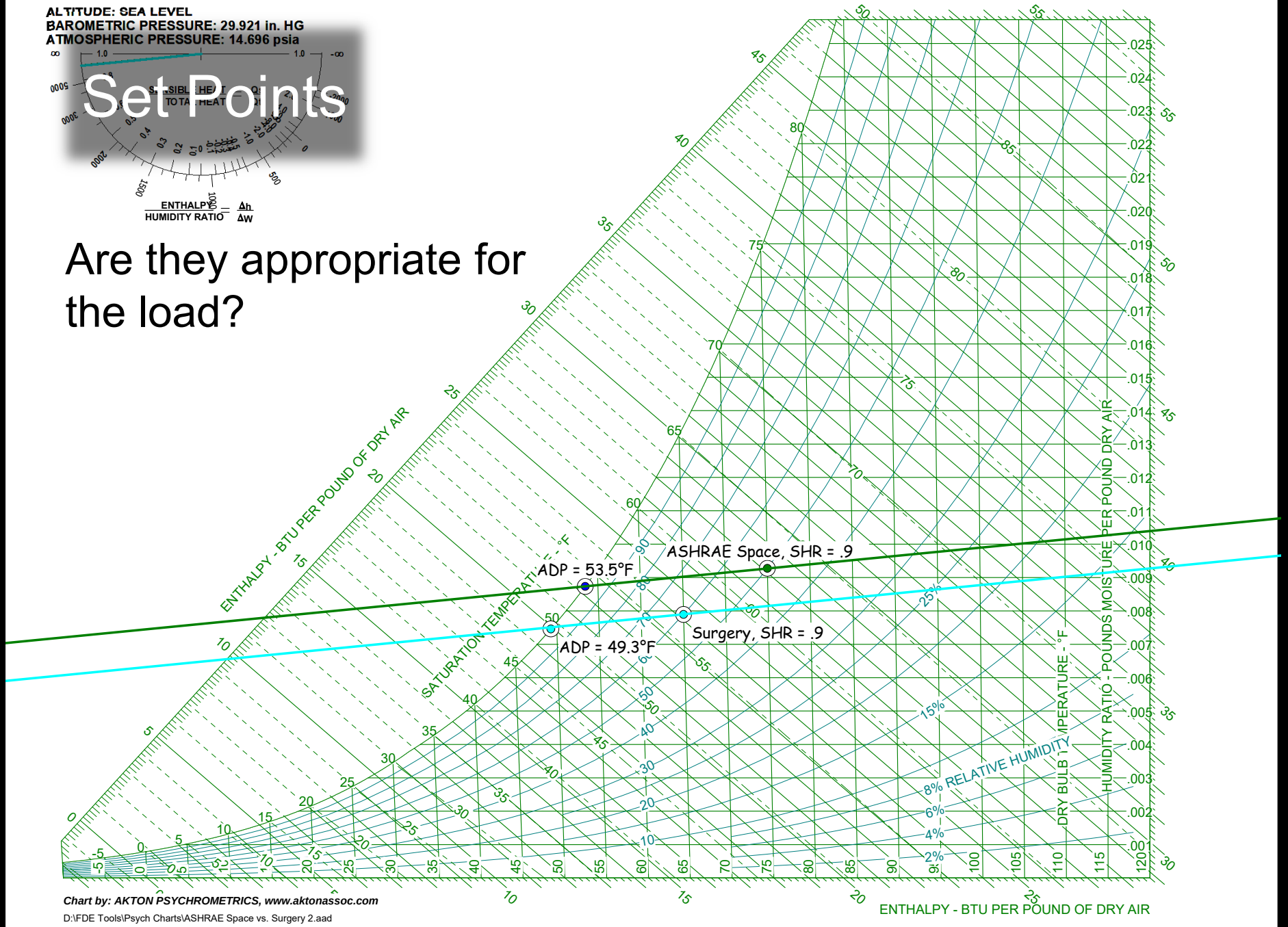

ALTITUDE: 810 FEET
BAROMETRIC PRESSURE: 29.056 in. HG
ATMOSPHERIC PRESSURE: 14.271 psia
ENTHALPY / HUMIDITY RATIO = Δh / Δw
Are they appropriate for the climate?
Extreme Summer Drybulb
0.4% Dehum. Design
0.4% Evaporative Design
0.4% Cooling Design
Bin midpoint and MCWB
Space
Extreme Winter Drybulb
99.6% Heating design
Dry Bulb Economizer Limit
Set Point = 64.6°F
Weather Data Location:
ST_JOSEPH_ROSECRANS_MEMORIAL, MISSOURI, USA
Weather Hours
15 to 1
30 to 16
45 to 31
60 to 46
75 to 61
90 to 76
105 to 91
120 to 106
135 to 121
ENTHALPY - BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - °F
DRY BULB TEMPERATURE - °F
HUMIDITY RATIO - POUNDS MOISTURE PER POUND DRY AIR
RELATIVE HUMIDITY
Chart by: AKTON PSYCHROMETRICS, www.aktonassoc.com
D:\FDE Tools\Psych Charts\Saint Louis MO Design Conditions Economizer Change-over 72 45.aad

Set Points


ALTITUDE: 7 FEET
BAROMETRIC PRESSURE: 29.915 in. HG
ATMOSPHERIC PRESSURE: 14.693 psia
ENTHALPY / HUMIDITY RATIO = Δh / Δw
Are they appropriate for the climate?
Weather Data Location:
SAN_FRANCISCO_INTL_AP, CALIFORNIA, USA
Weather Hours
41 to 1
82 to 42
123 to 83
164 to 124
205 to 165
246 to 206
287 to 247
328 to 288
369 to 329
Extreme Summer Drybulb
0.4% Dehum. Design
0.4% Evaporative Design
0.4% Cooling Design
Space
99.6% Heating design
Dry Bulb Economizer Limit
Set Point = 68.5°F
Extreme Winter Drybulb
ENTHALPY - BTU PER POUND OF DRY AIR
SATURATION TEMPERATURE - °F
DRY BULB TEMPERATURE - °F
HUMIDITY RATIO - POUNDS MOISTURE PER POUND DRY AIR
% RELATIVE HUMIDITY
Chart by: AKTON PSYCHROMETRICS, www.aktonassoc.com
D:\FDE Tools\Psych Charts\San Francisco, CA Design Conditions Economizer Change-over 72 45.aad

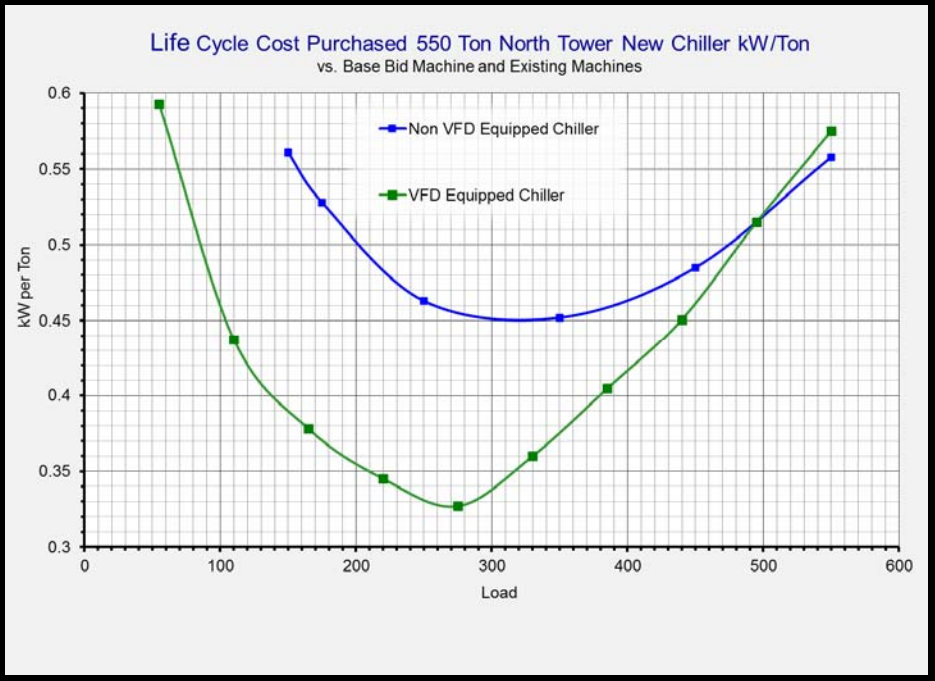
Set Points

Are they appropriate for the load?



Set Points

Do the resets provide the intended value?



Best Life Cycle Cost Towers								
t_{wb} = 72.9 °F (San Deigo Design Condition)								
Target CW Temp	Lowered CW Temp	Tower fan kW penalty	Tonnage at which colder water could be produced (Note 1)	Break Even Point; kW per ton improvement at different load conditions, tons				
				100	200	300	400	500
85	77.41	10.24	311	0.10	0.05	0.03		
t_{wb} = 60. °F								
85	67.74	10.92	389	0.11	0.05	0.04	0.03	
Best First Cost Towers								
t_{wb} = 72.9 °F (San Deigo Design Condition)								
Target CW Temp	Lowered CW Temp	Tower fan kW penalty	Tonnage at which colder water could be produced (Note 1)	Break Even Point; kW per ton improvement at different load conditions, tons				
				100	200	300	400	500
85	78.30	25.52	311	0.26	0.13	0.09		

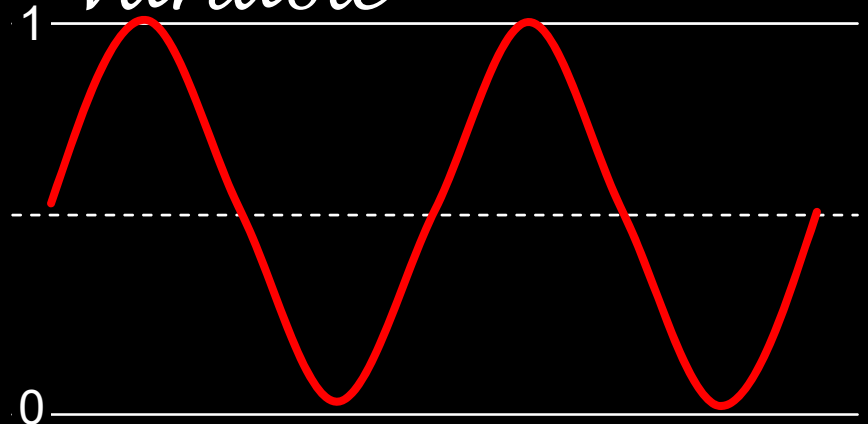
Note 1: Tonnage is based on a nominal 15,000 Btu/hr of heat rejection for every ton (12,000 Btu/hr of cooling.

Two Different Worlds

Where We Came From

Analog

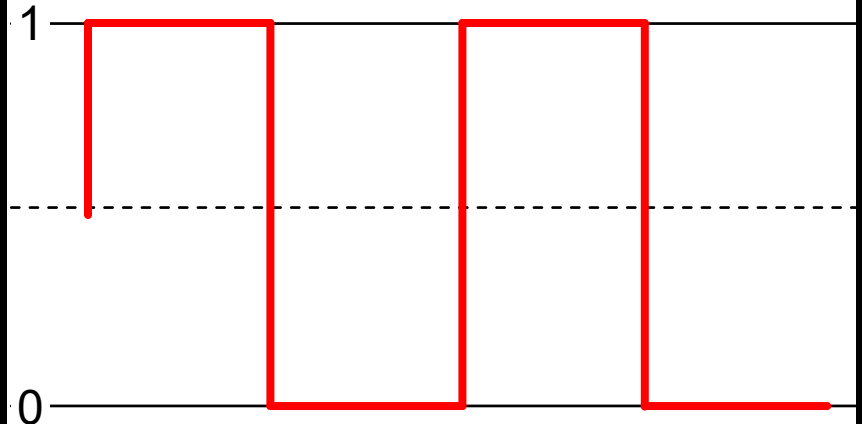
Continuously Variable



Where We Are

Digital

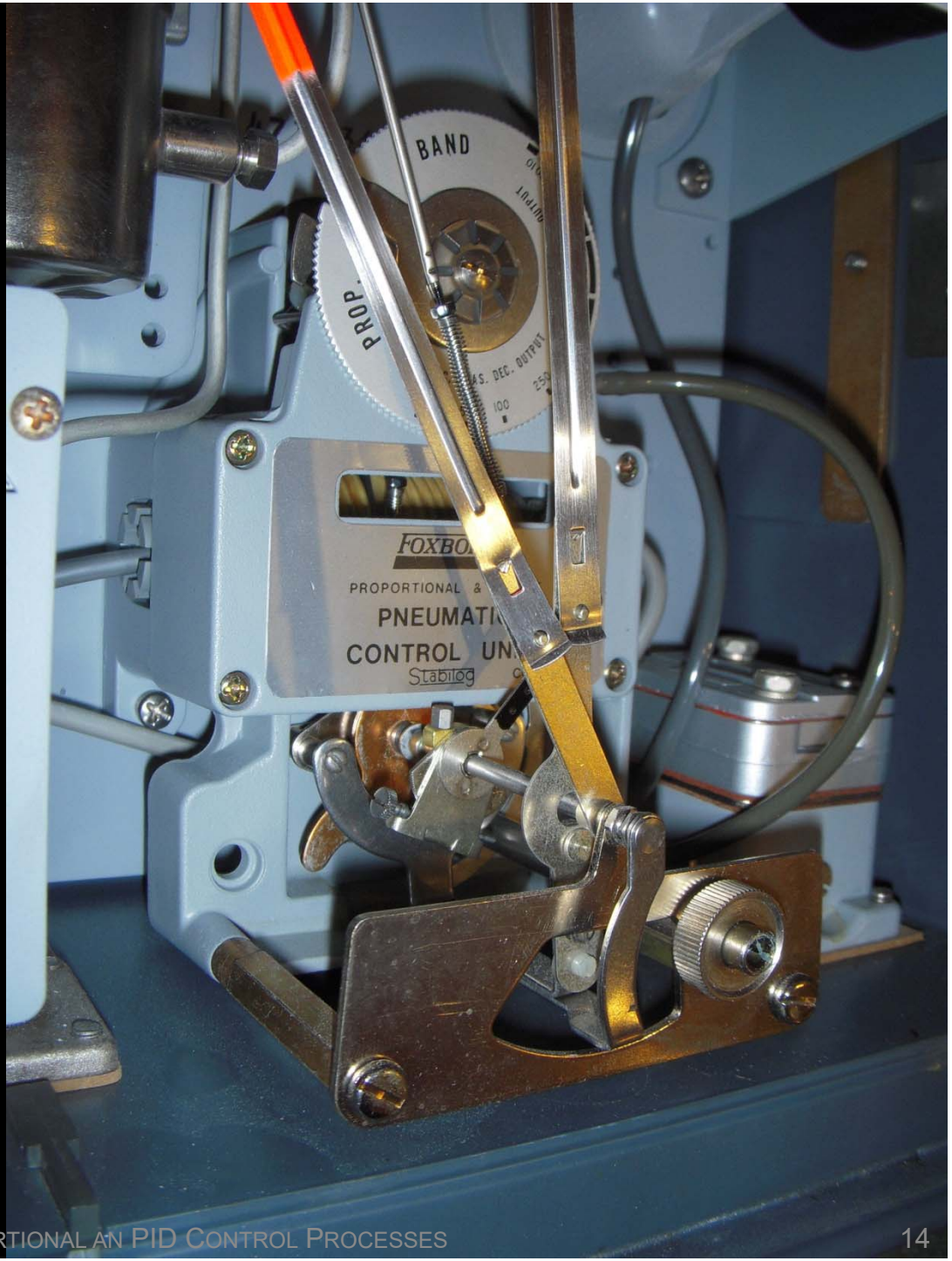
Discrete units



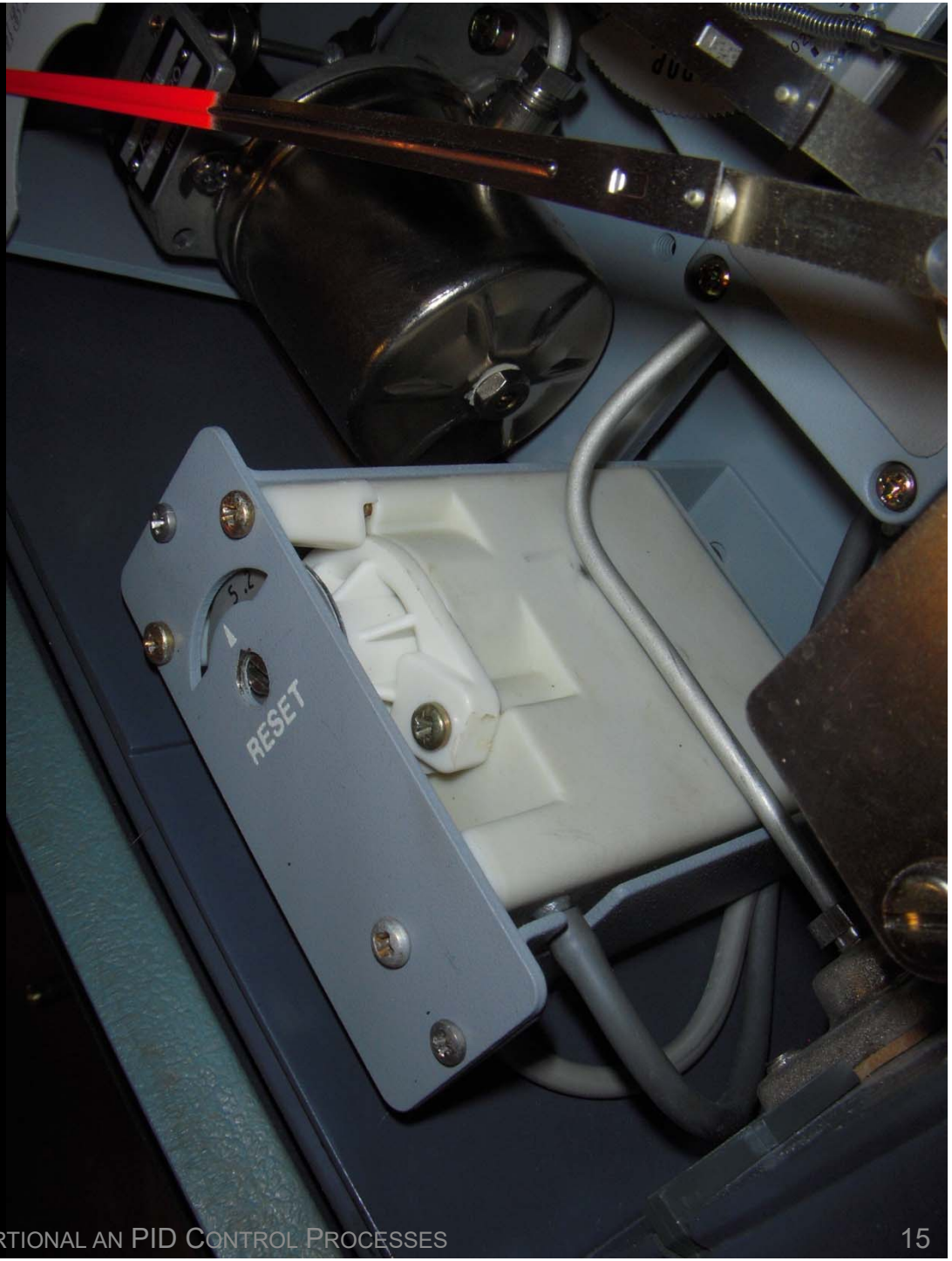
A 1950/60's Vintage Analog Controller

A 1950/60's Vintage Analog Controller

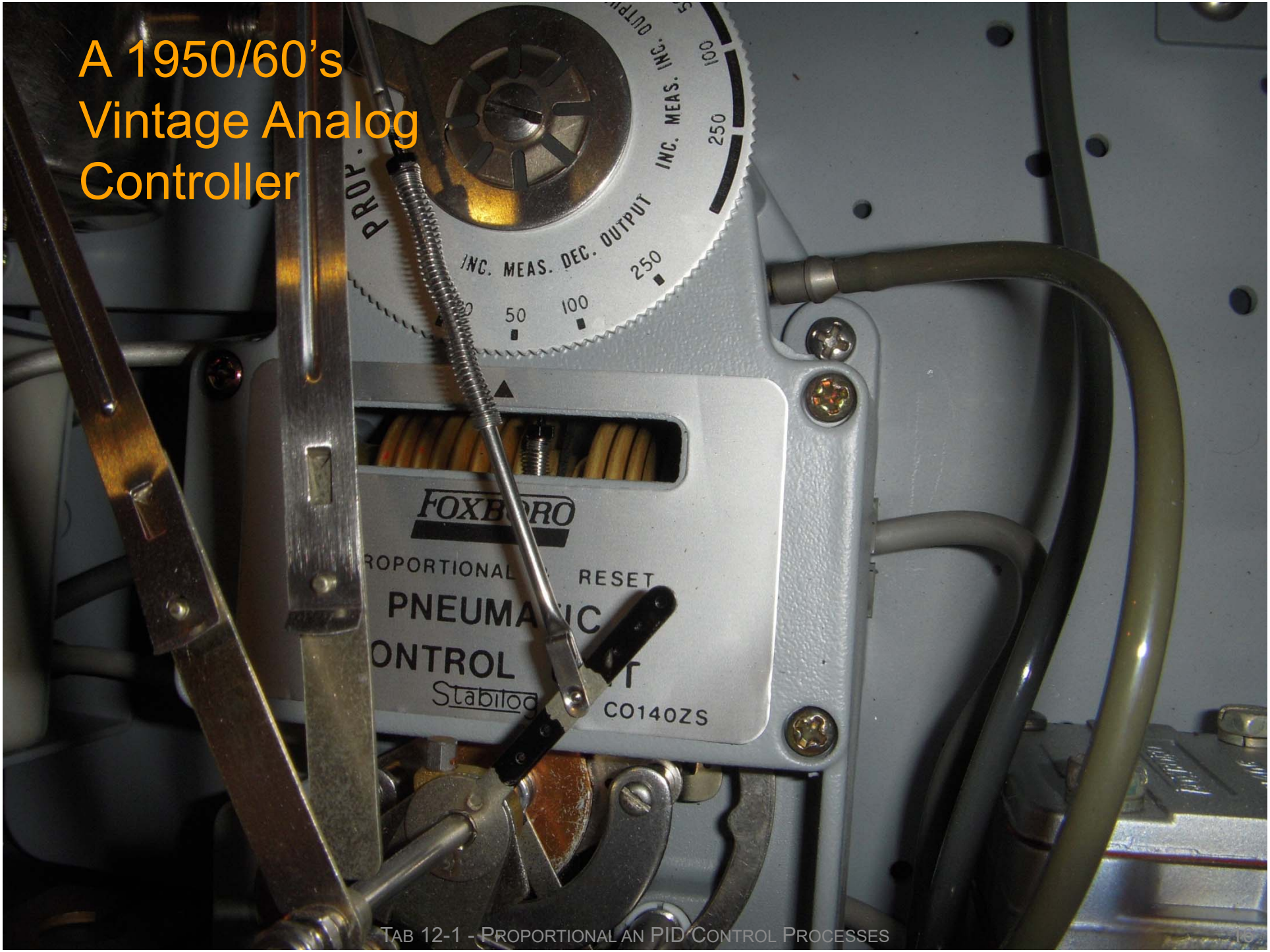
A 1950/60's Vintage Analog Controller



A 1950/60's Vintage Analog Controller

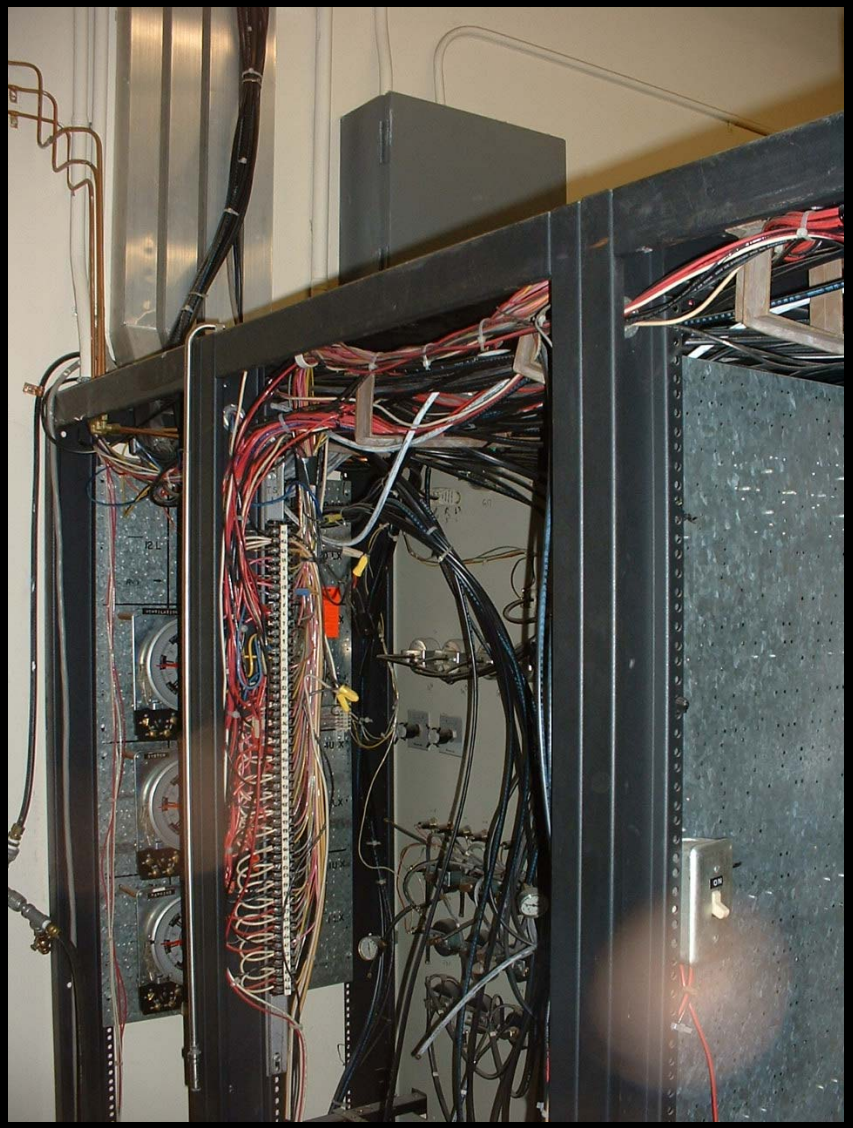


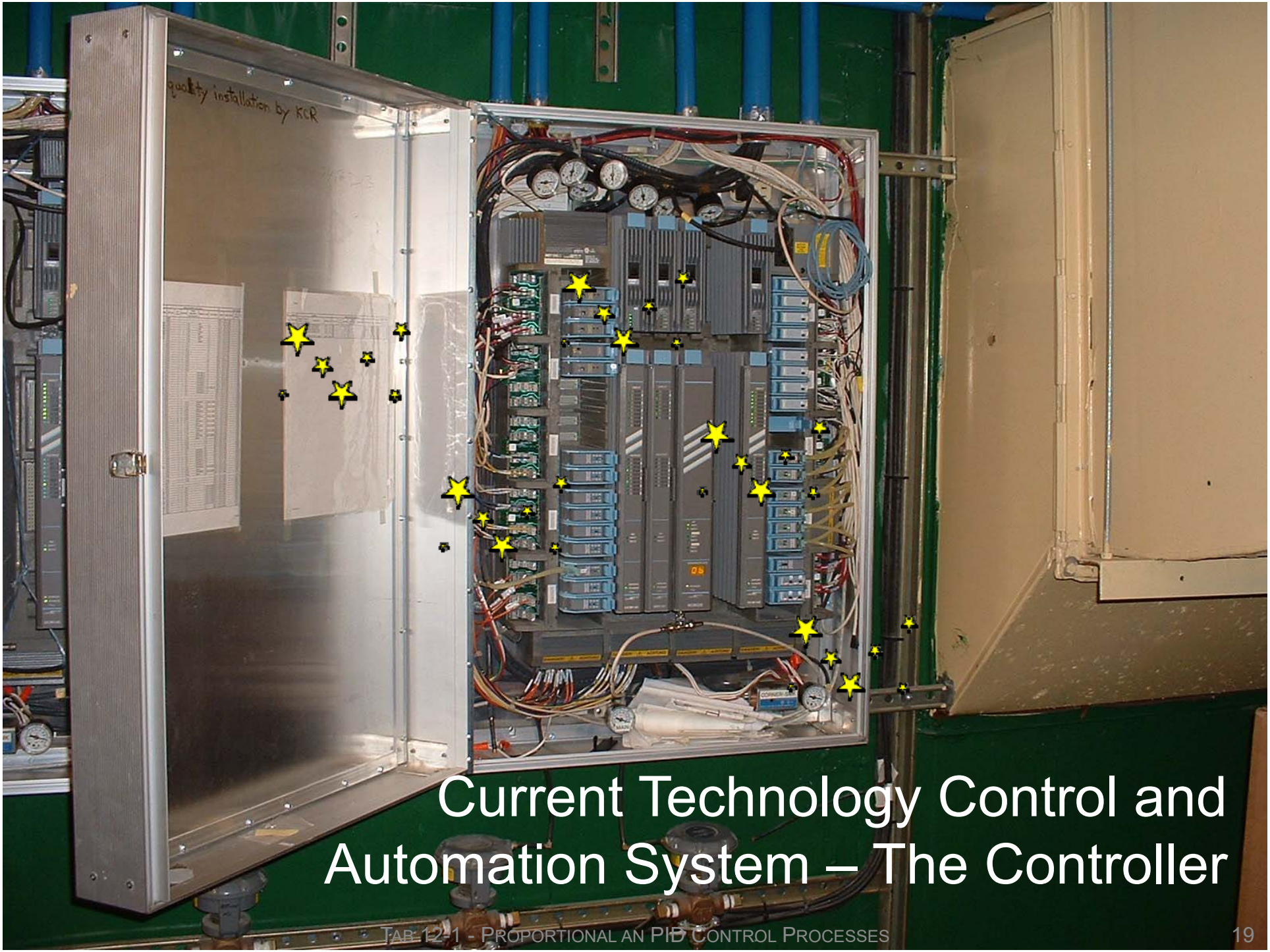
A 1950/60's Vintage Analog Controller



A 1970's Vintage Control and Automation System

A 1970's Vintage Control and Automation System

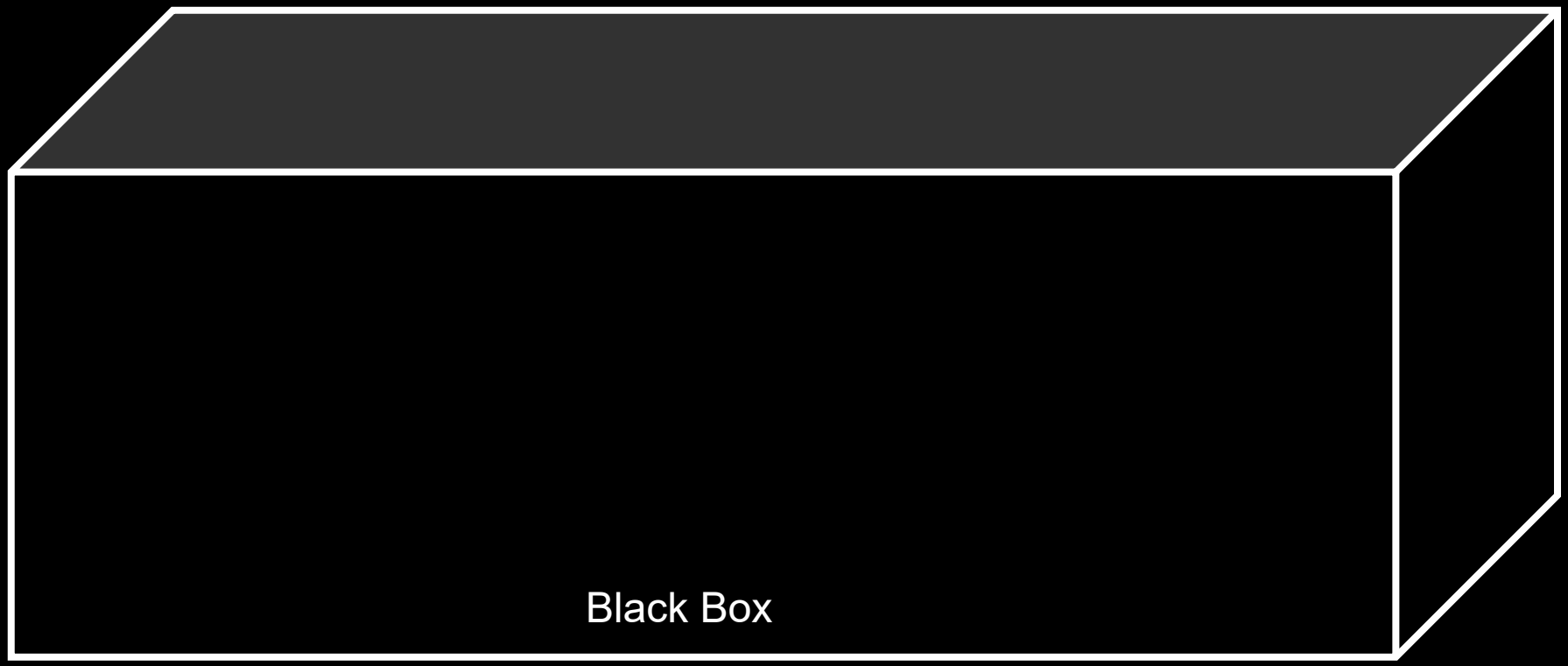




Current Technology Control and Automation System – The Controller

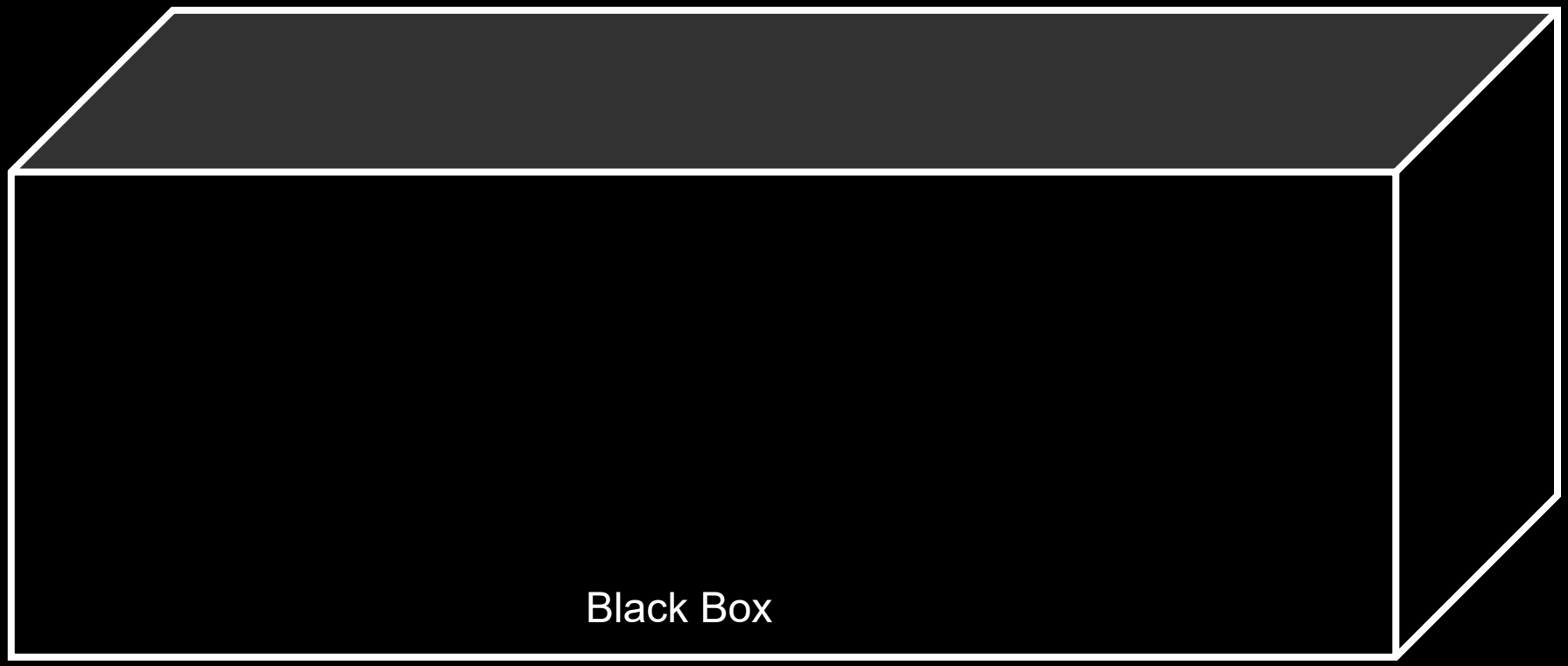
Not Being Able to See or Get Your Hands on What's Going On

… a down side to DDC



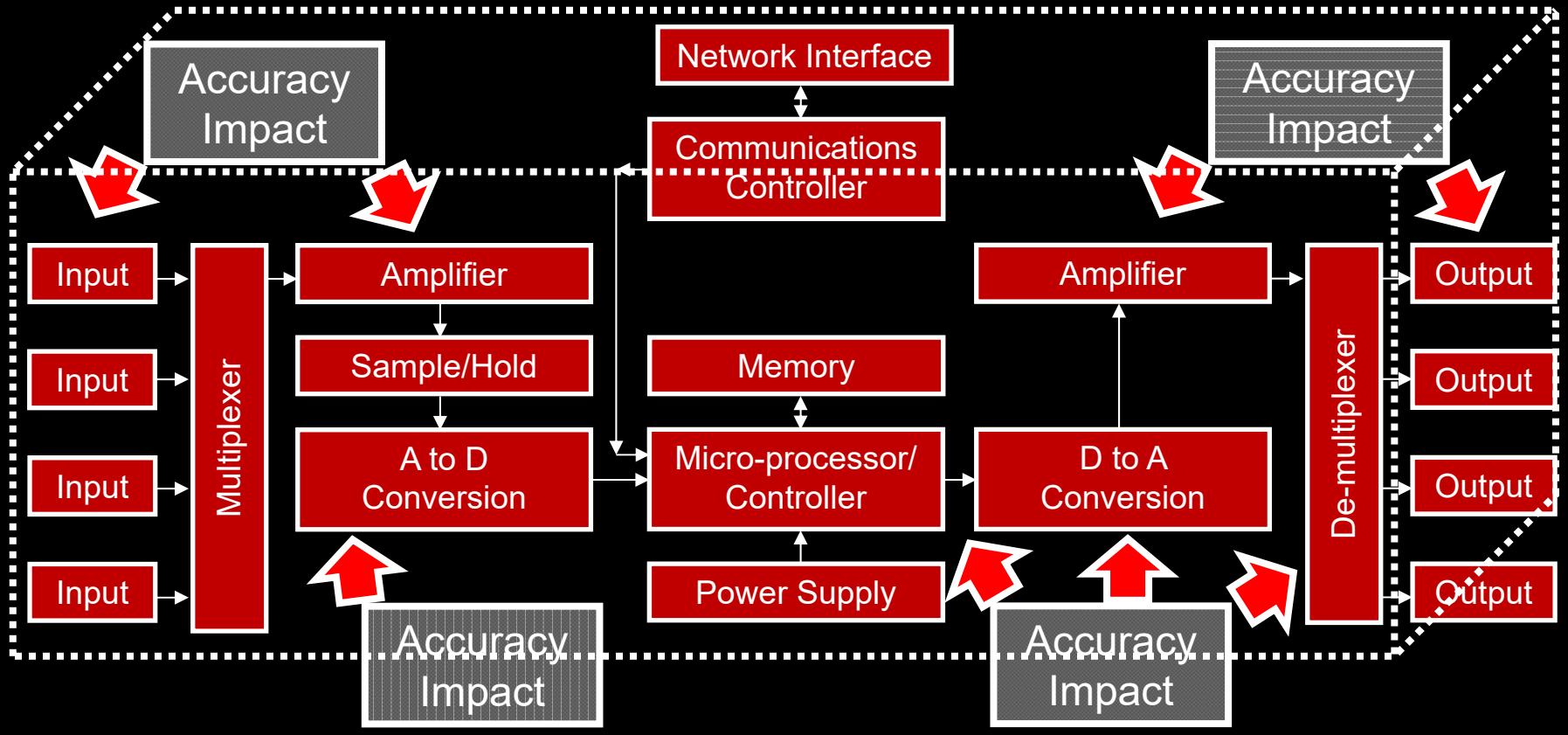
Even Though You Can't See Them …

… the inner workings and controlling software of a DDC controller are critical to success



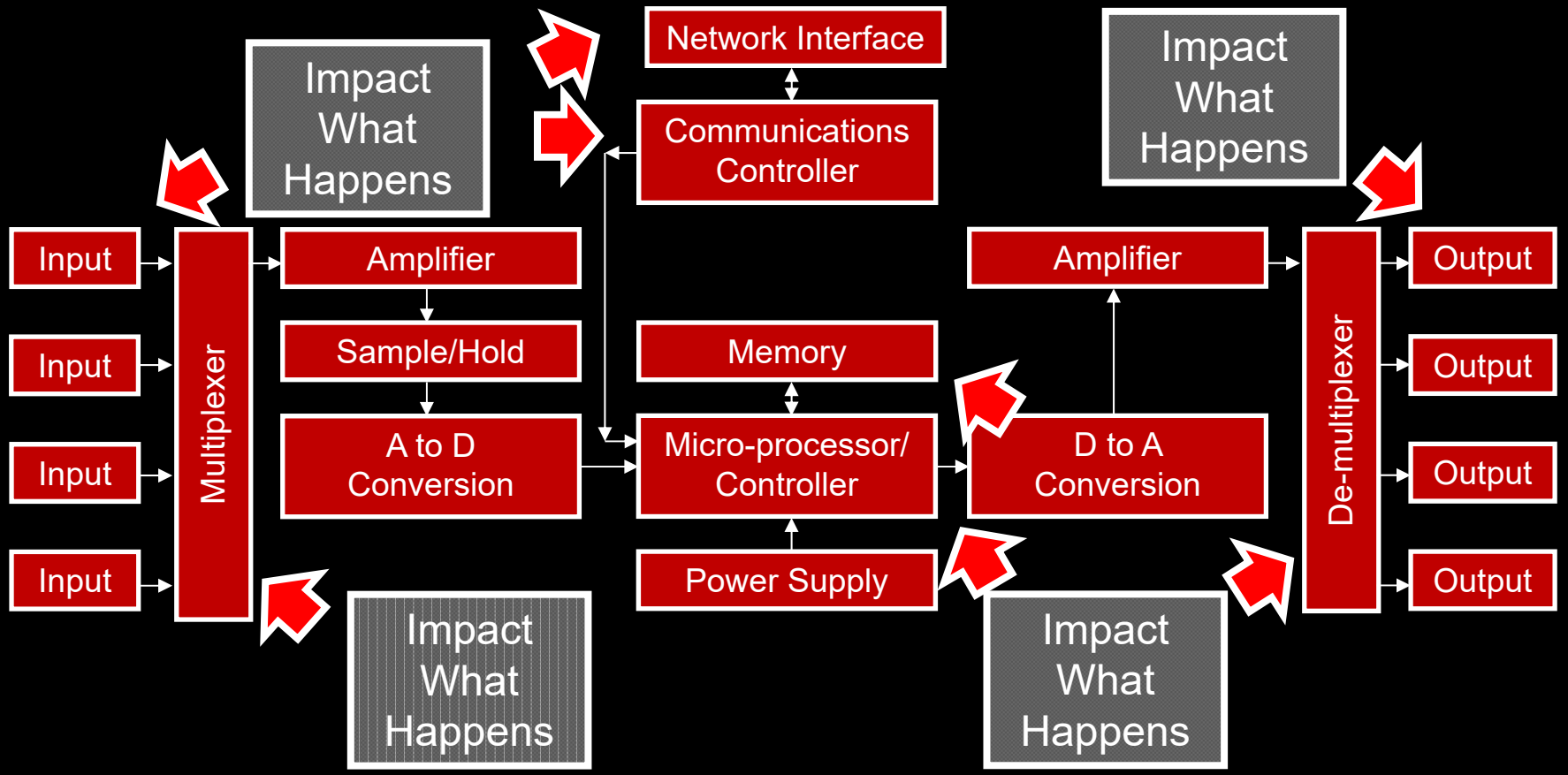
Even Though You Can't See Them …

… the inner workings and controlling software of a DDC controller are critical to success



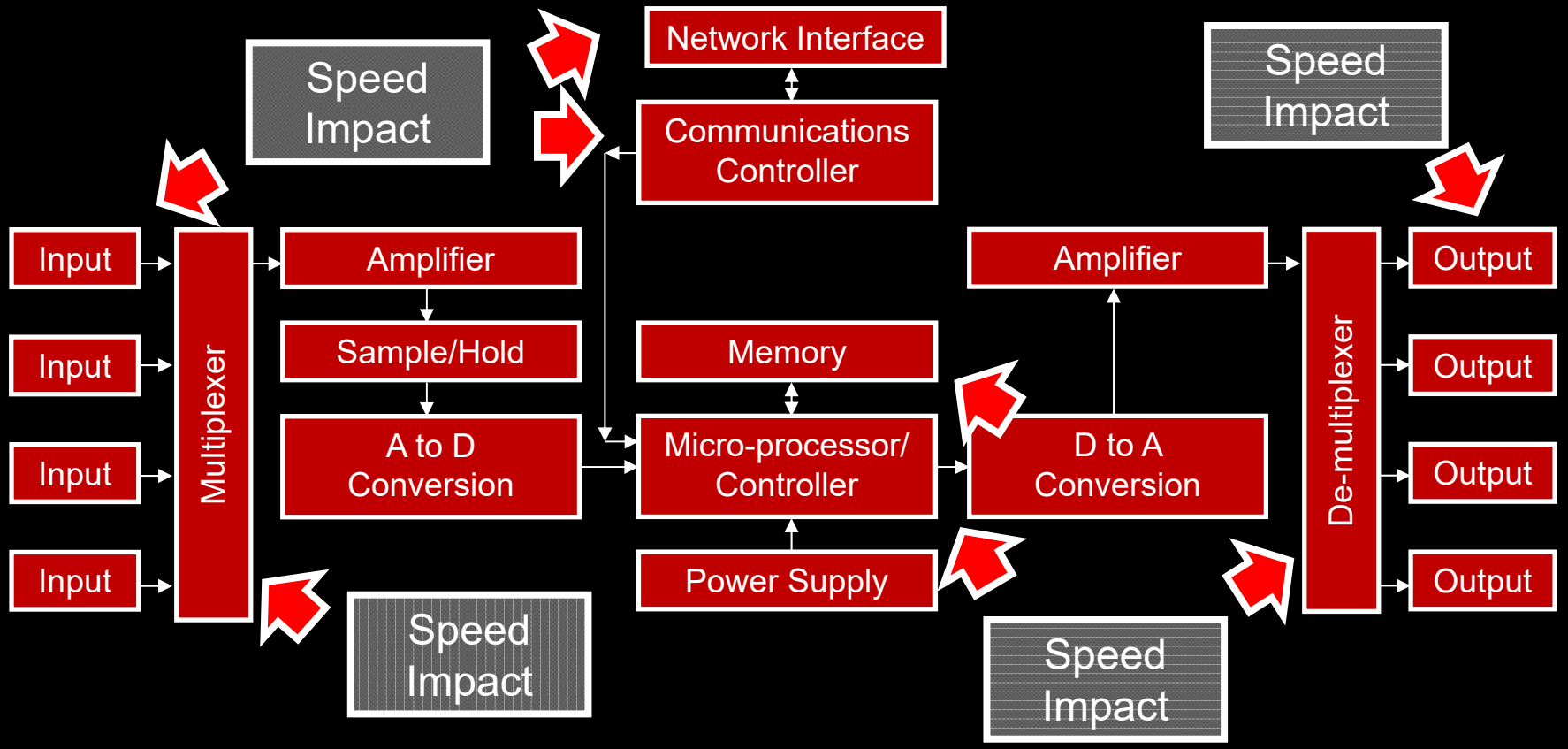
Even Though You Can't See Them …

… the inner workings and controlling software of a DDC controller are critical to success

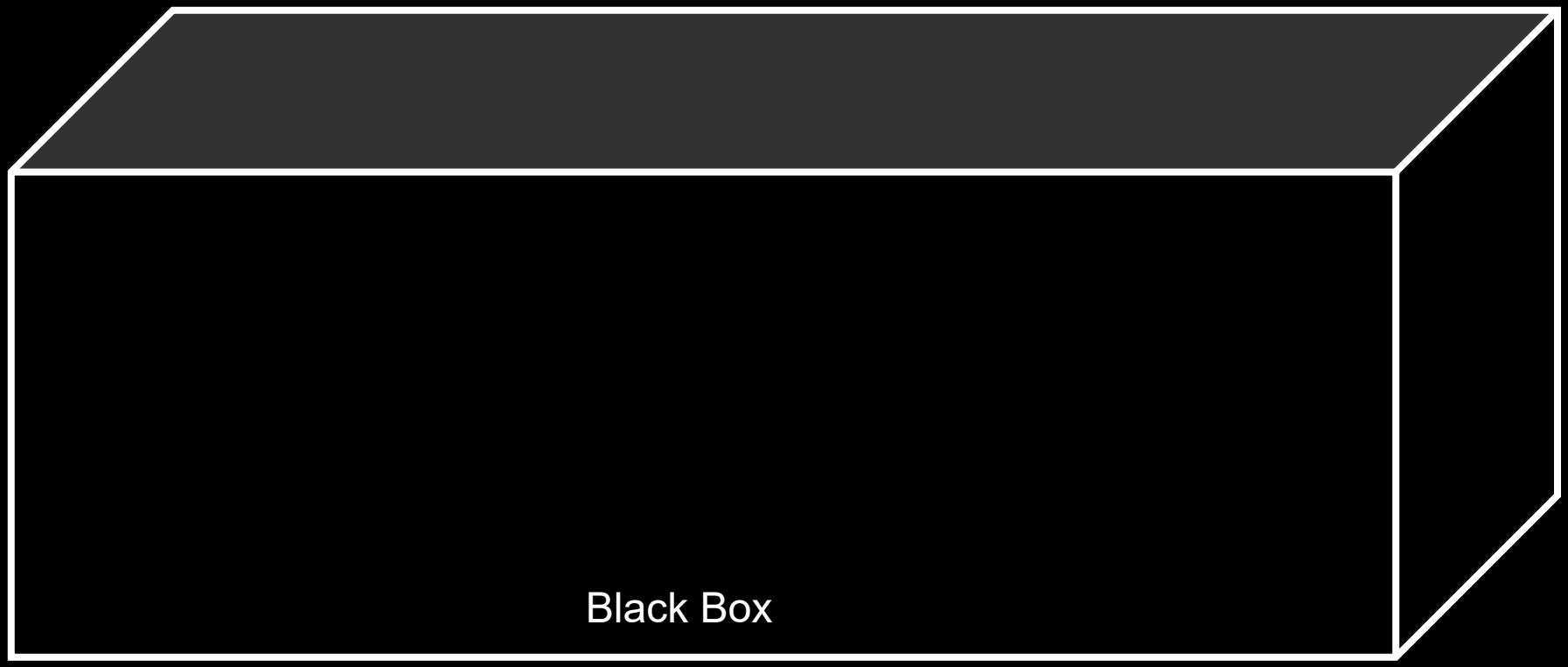


Even Though You Can't See Them …

… the inner workings and controlling software of a DDC controller are critical to success



Step Outside the Black Box and its Still and Analog World



Generally, there's Good News and Bad News

Good News

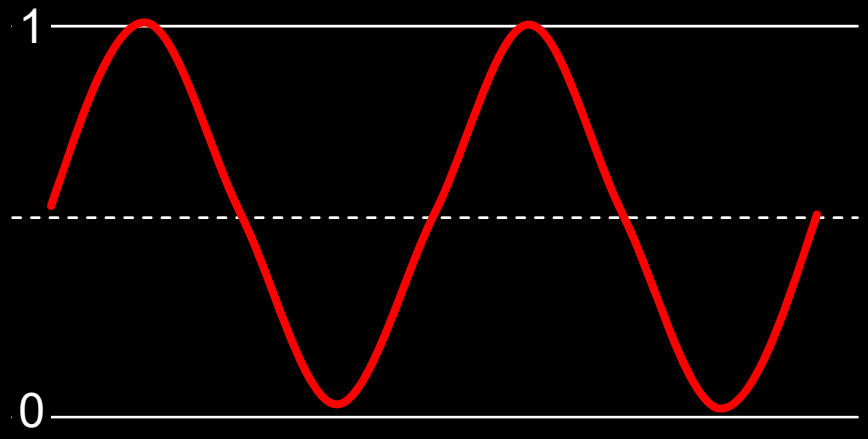
- No moving parts in the controller
- More information
- Fast response
- Precision
- Modifications made by typing things in stead of wiring or piping things
- Infinitely flexible
- Cost effective
- Out of this world capabilities

Bad News

- The controller is a black box
- The information may not be correct
- Capable of doing dumb things very quickly
- Capable of doing dumb things very precisely
- Not everyone took the high school typing elective
- Can implement misapplication of fundamentals
- Flexibility sacrificed by poorly defined designs in competitive bid environments
- Still have to deal with the real world

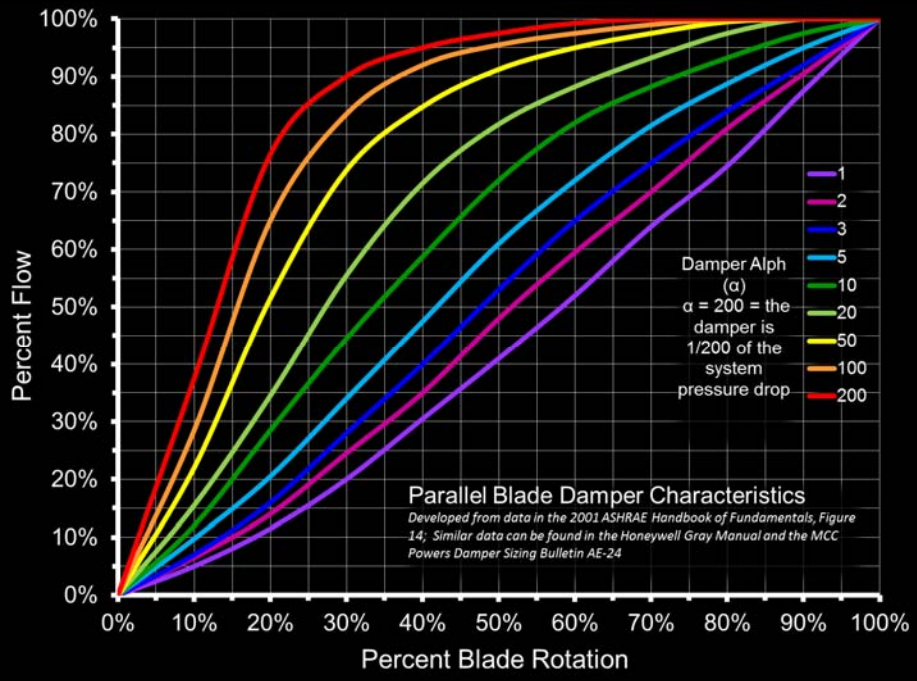
By Definition, a Lot of HVAC Processes are *Continuously Variable*

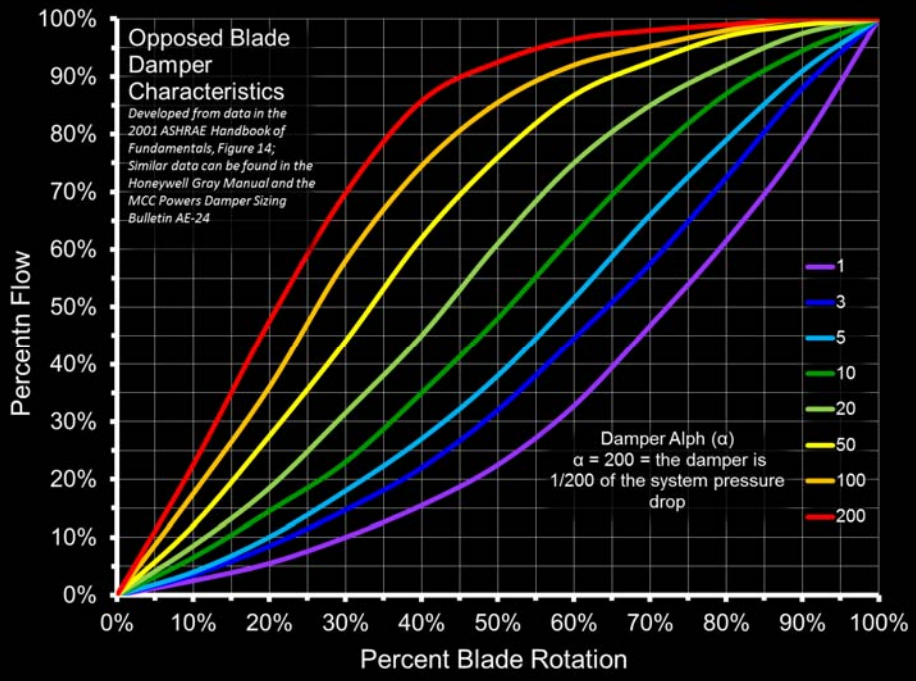
Analog



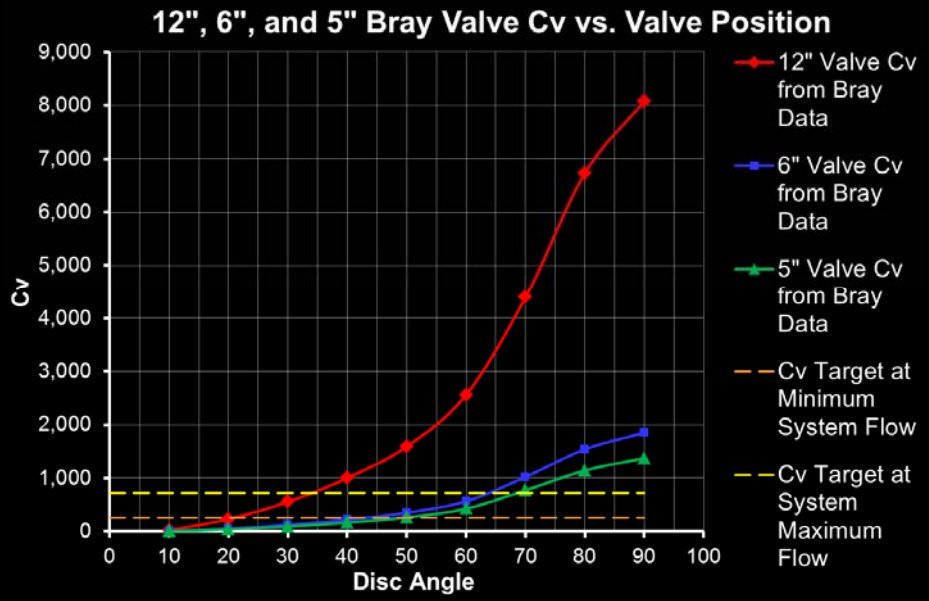
- Variable Air Volume
- Variable Flow Pumping
- Variable Speed Drives
- Variable Pitch Inlet Vanes
- Variable Pitch Fans
- Variable Flow Refrigeration

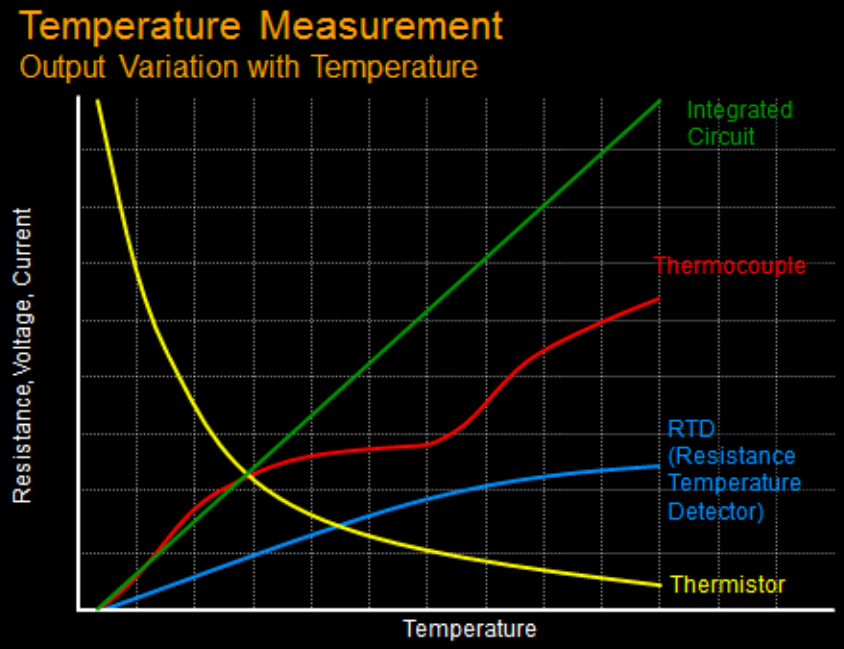
By Nature, Most HVAC Components Have Analog, Non-linear Characteristics



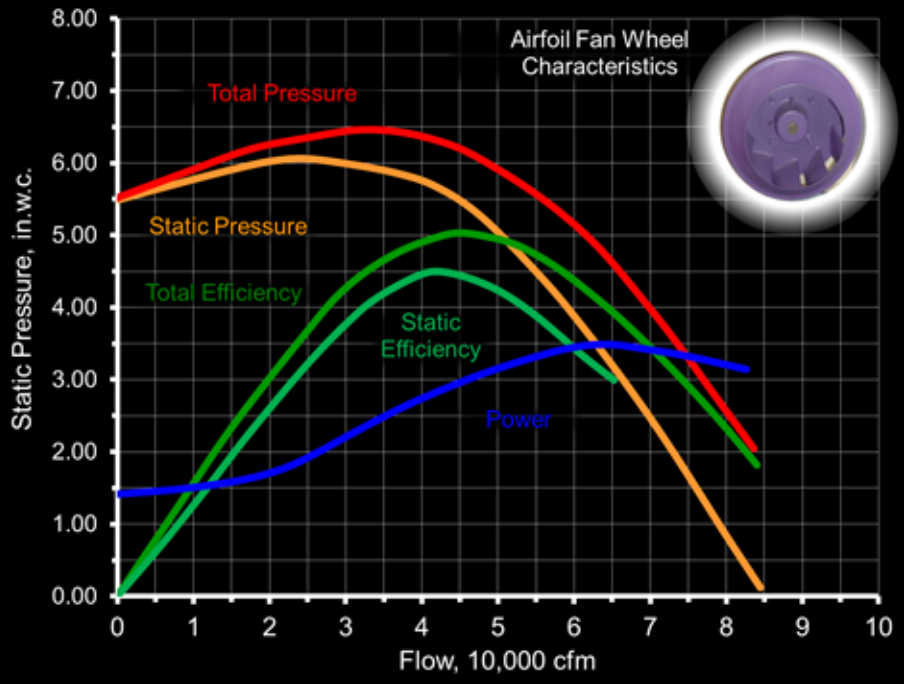


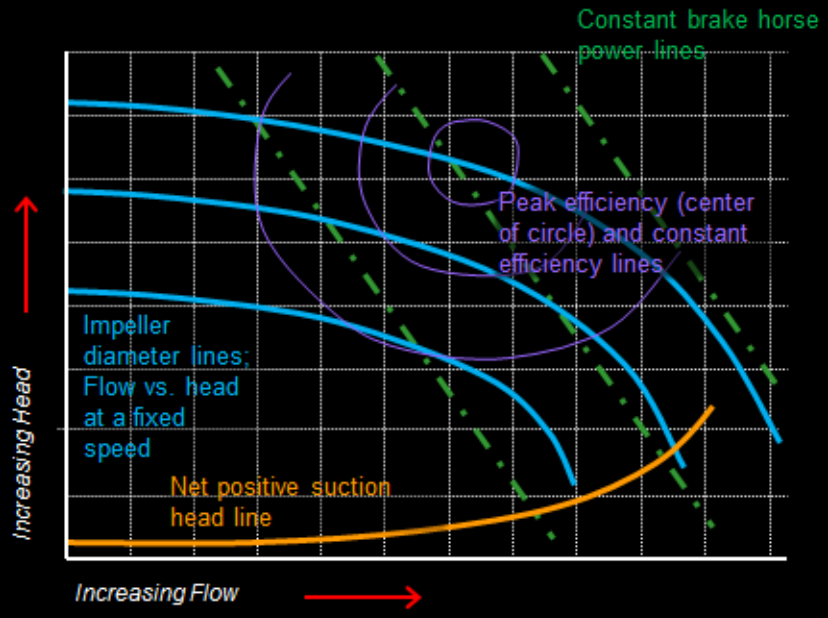
By Nature, Most HVAC Components Have Analog, Non-linear Characteristics





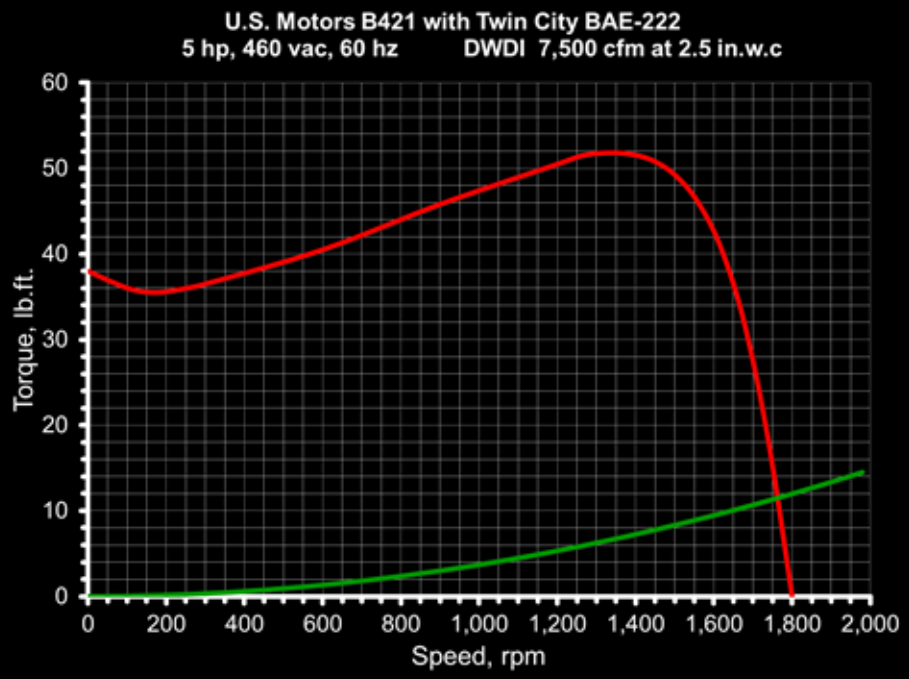
By Nature, Most HVAC Components Have Analog, Non-linear Characteristics

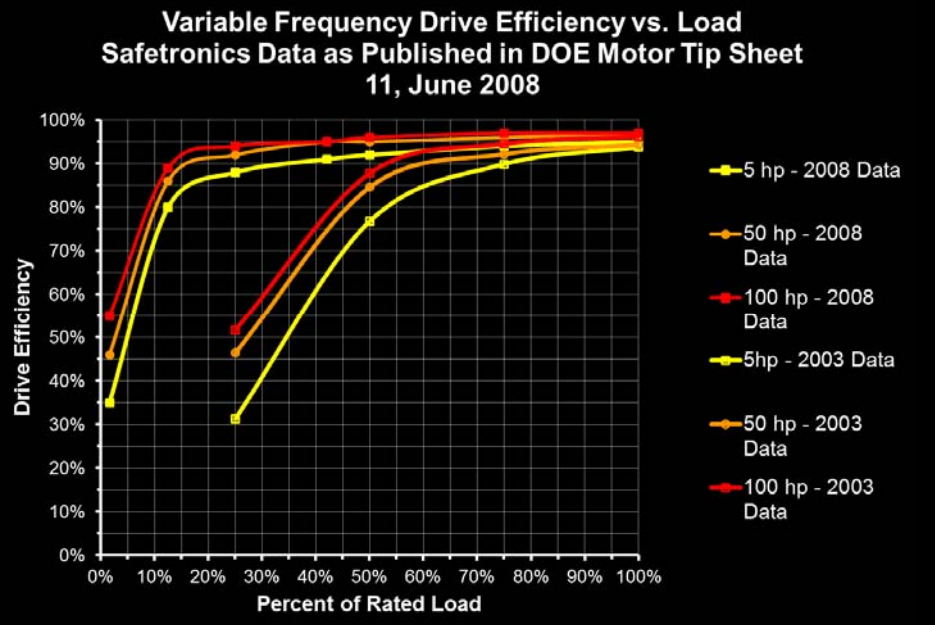




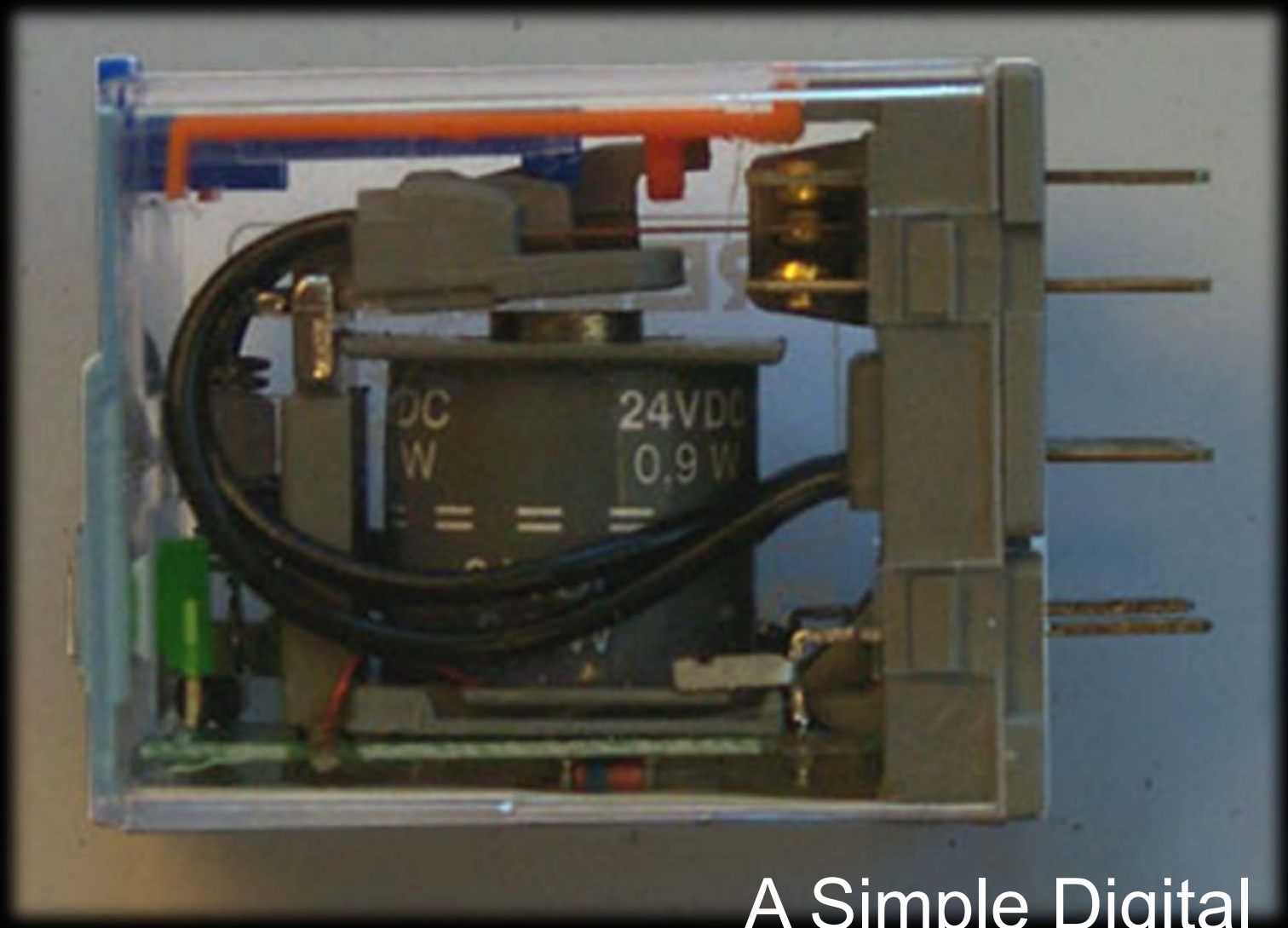
Tab 3-3 - Pumps and Fans 6

By Nature, Most HVAC Components Have Analog, Non-linear Characteristics

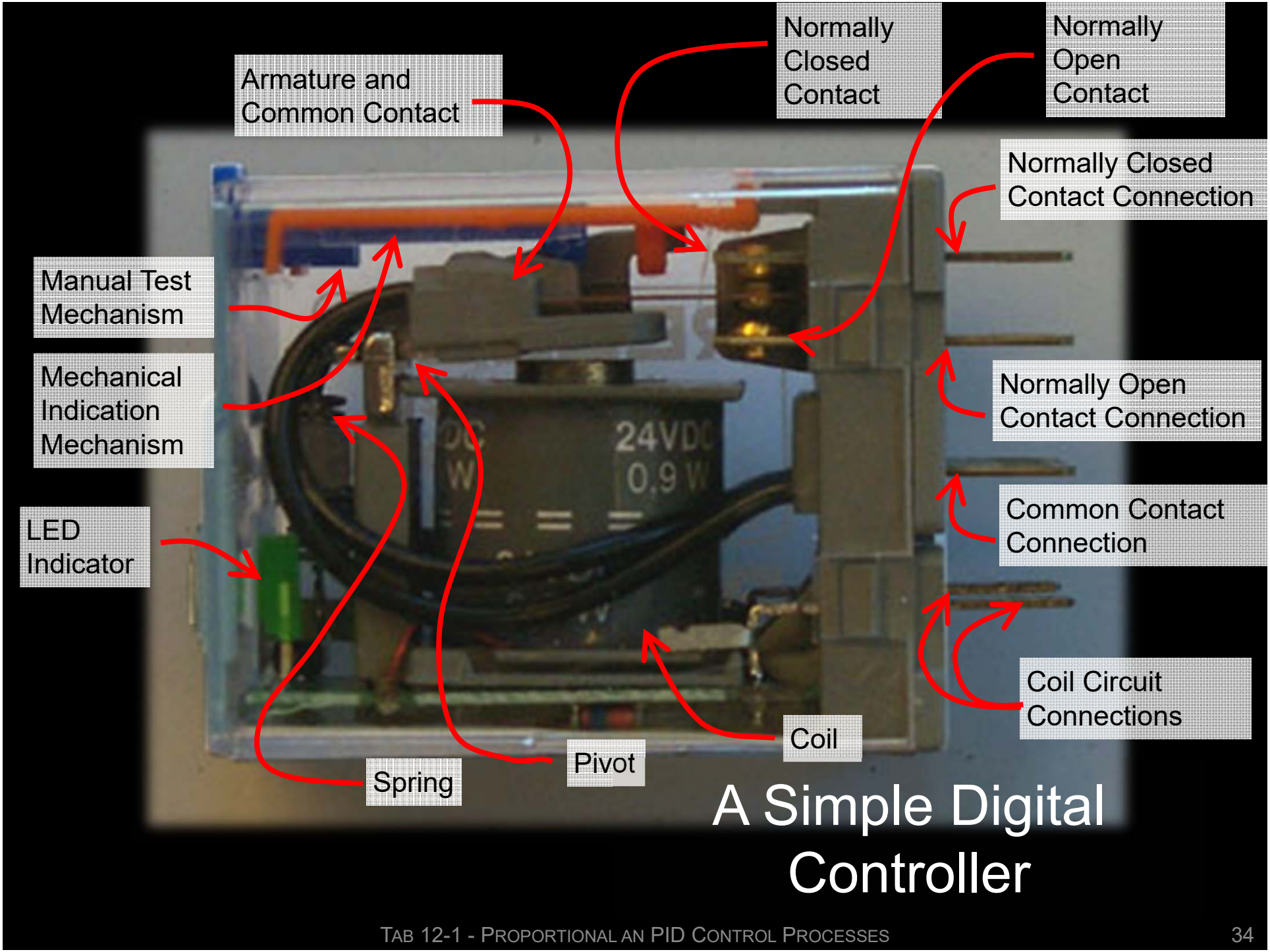




A Simple Digital Control Process



A Simple Digital Controller

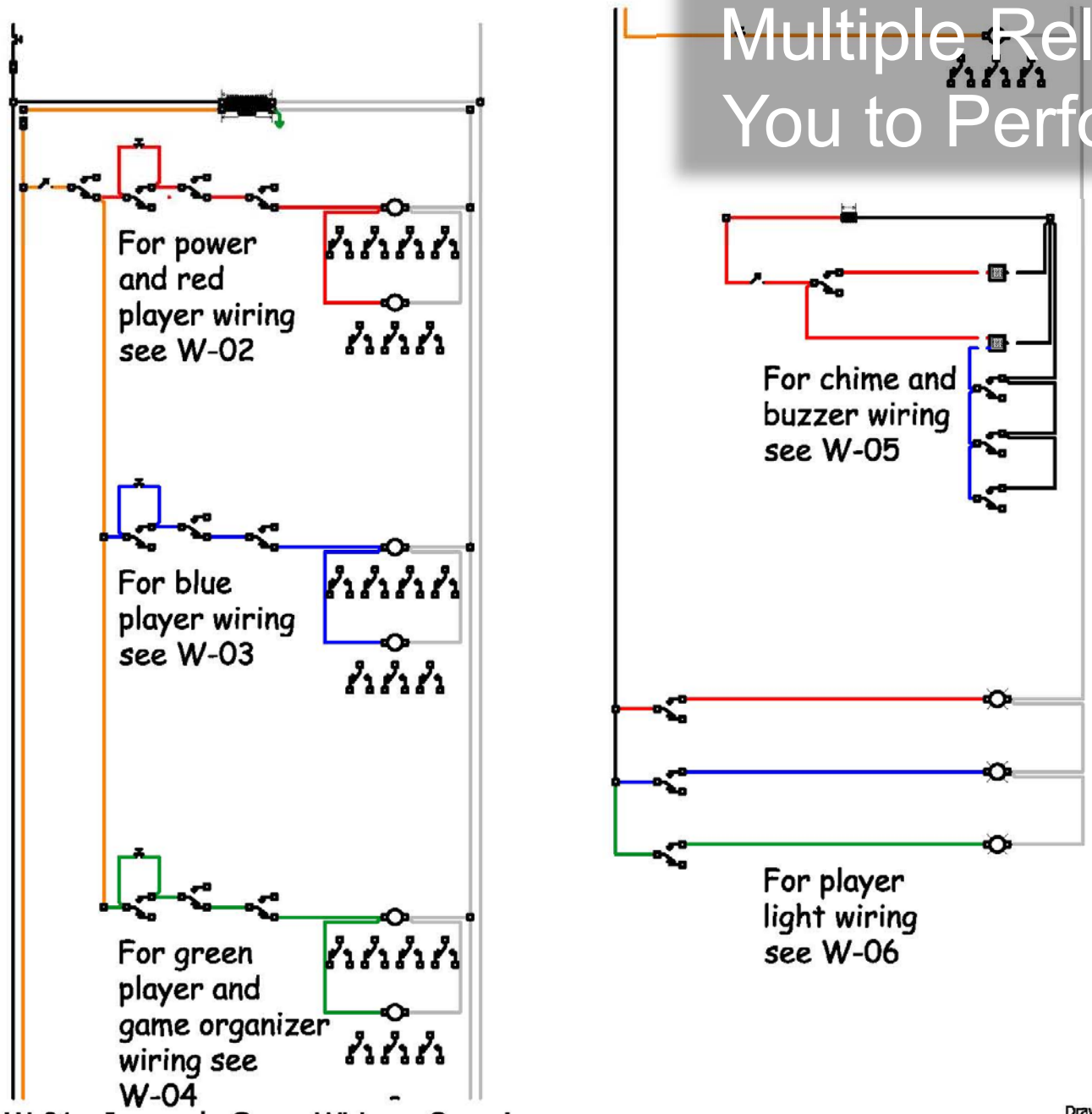


A Simple Digital Controller

A Fun Digital Control Process


Multiple Relays Allow
You to Perform Logic

Multiple Relays Allow You to Perform Logic

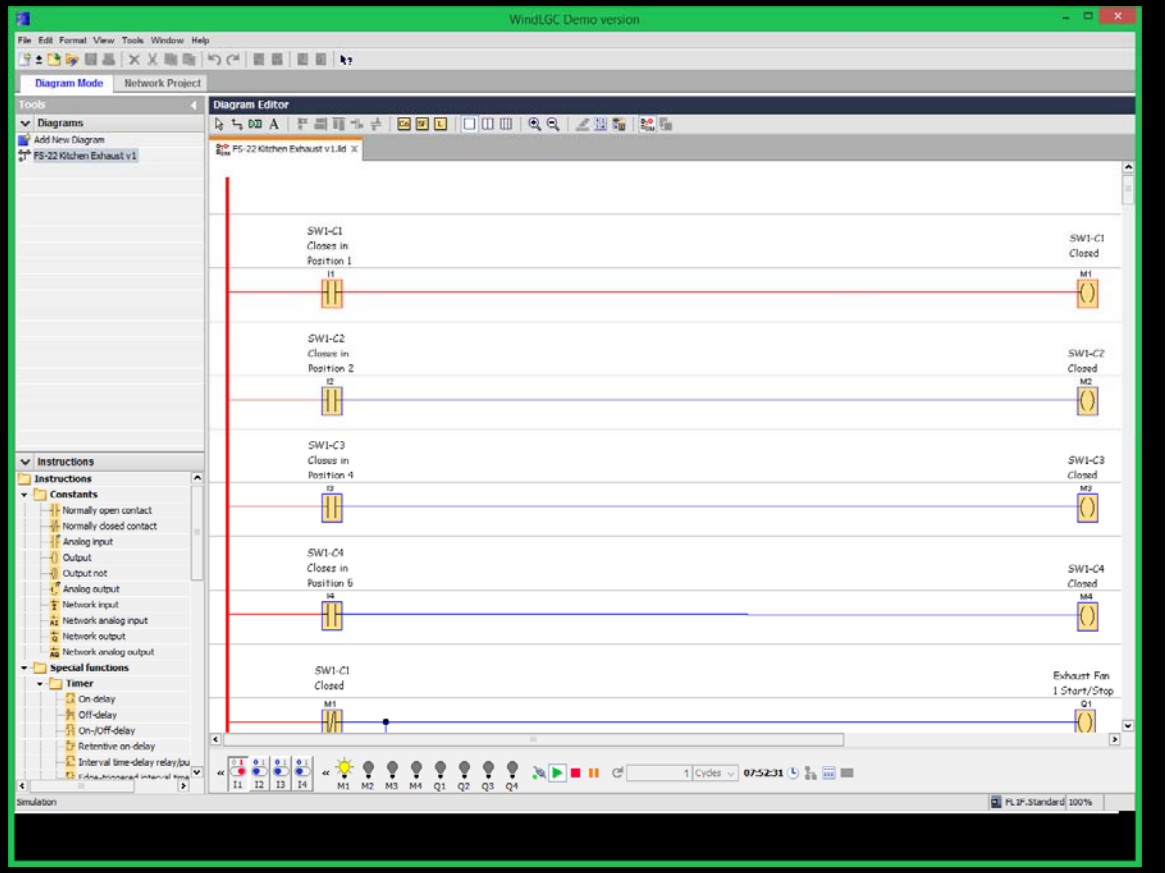


Simple Things are Sometimes Complex

Fan Truth Table					
Switch Position	60° Left	30° Left	Centered	30° Right	60° Right
Fan 1	Off	On	On	On	On
Fan 2	Off	Off	On	On	On
Fan 3	Off	Off	Off	On	On
Fan 4	Off	Off	Off	Off	On

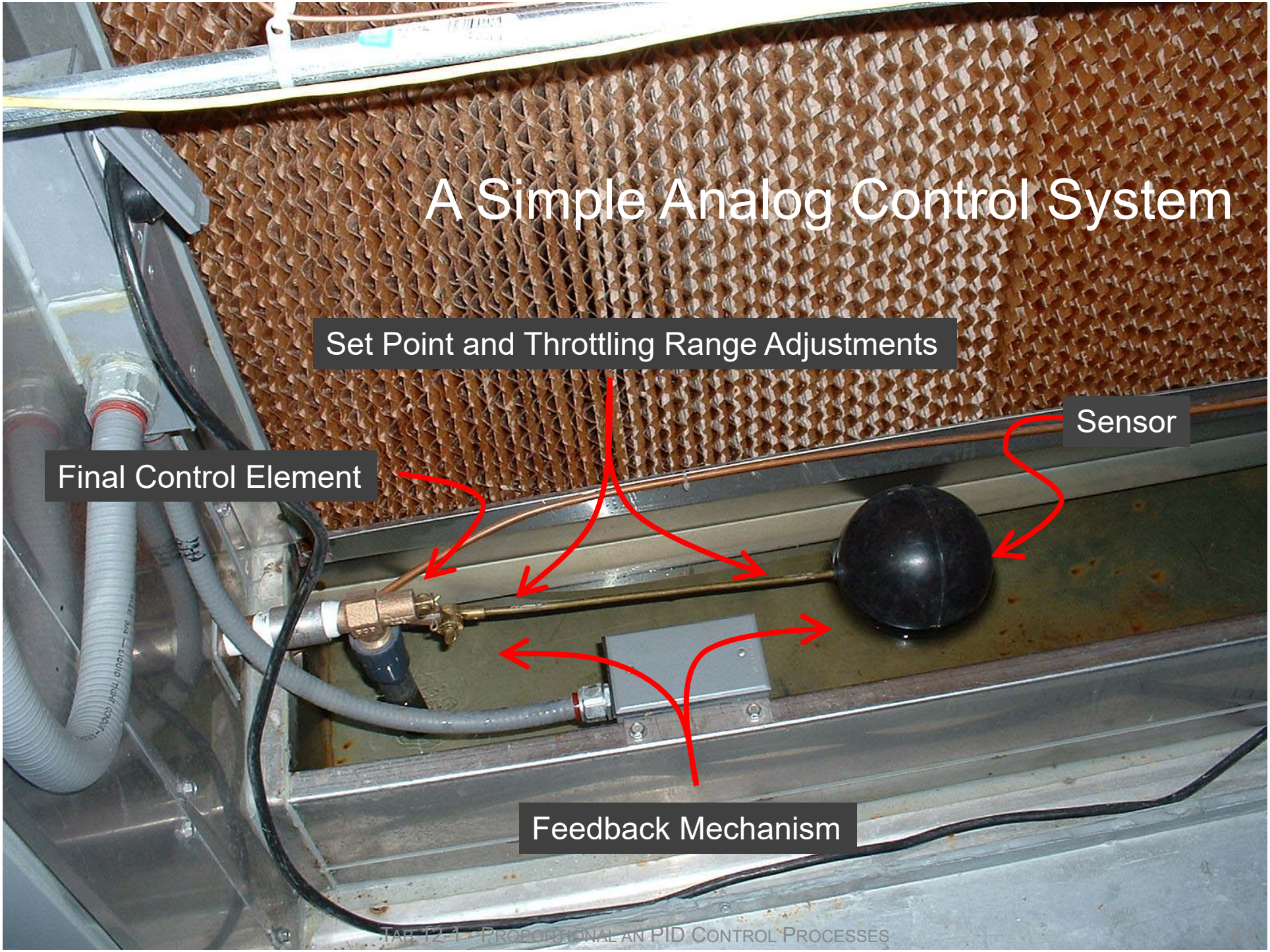
Simple Things are Sometimes Complex

Fan Truth Table					
Switch Position	60° Left	30° Left	Centered	30° Right	60° Right
Fan 1	Off	On	On	On	On
Fan 2	Off	Off	On	On	On
Fan 3	Off	Off	Off	On	On
Fan 4	Off	Off	Off	Off	On
Selector Switch Truth Table					
Desired Function	All Fans Off	Fan 1 Runs	Fans 1 and 2 Run	Fans 1, 2, and 3 Run	Fans 1, 2, 3, and 4 Run
Switch Position	60° Left	30° Left	Centered	30° Right	60° Right
Contact 1	Closed	Open	Open	Open	Open
Contact 2	Open	Closed	Open	Open	Open
Constact 3	Open	Open	Open	Closed	Open
Constact 4	Open	Open	Open	Open	Closed



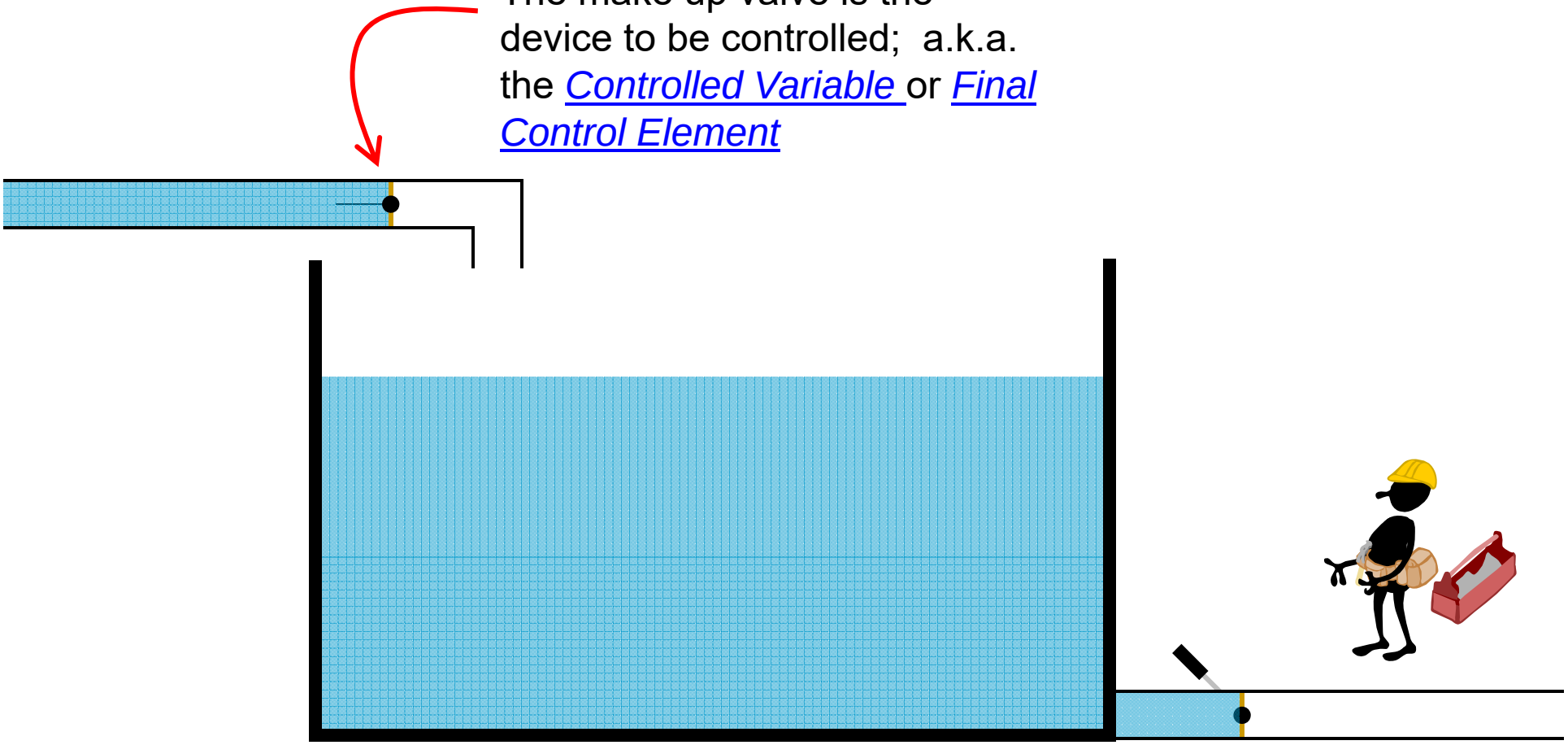
Multiple Relays Allow You to Perform Logic

For more about how to make your own Jeopardy game, see Learning about Relay Logic; Build Your Very Own Jeopardy Game and Making a Jeopardy Game Board in PowerPoint to Supplement Your Light and Buzzer System (and Learning a Bit About PowerPoint Templates)

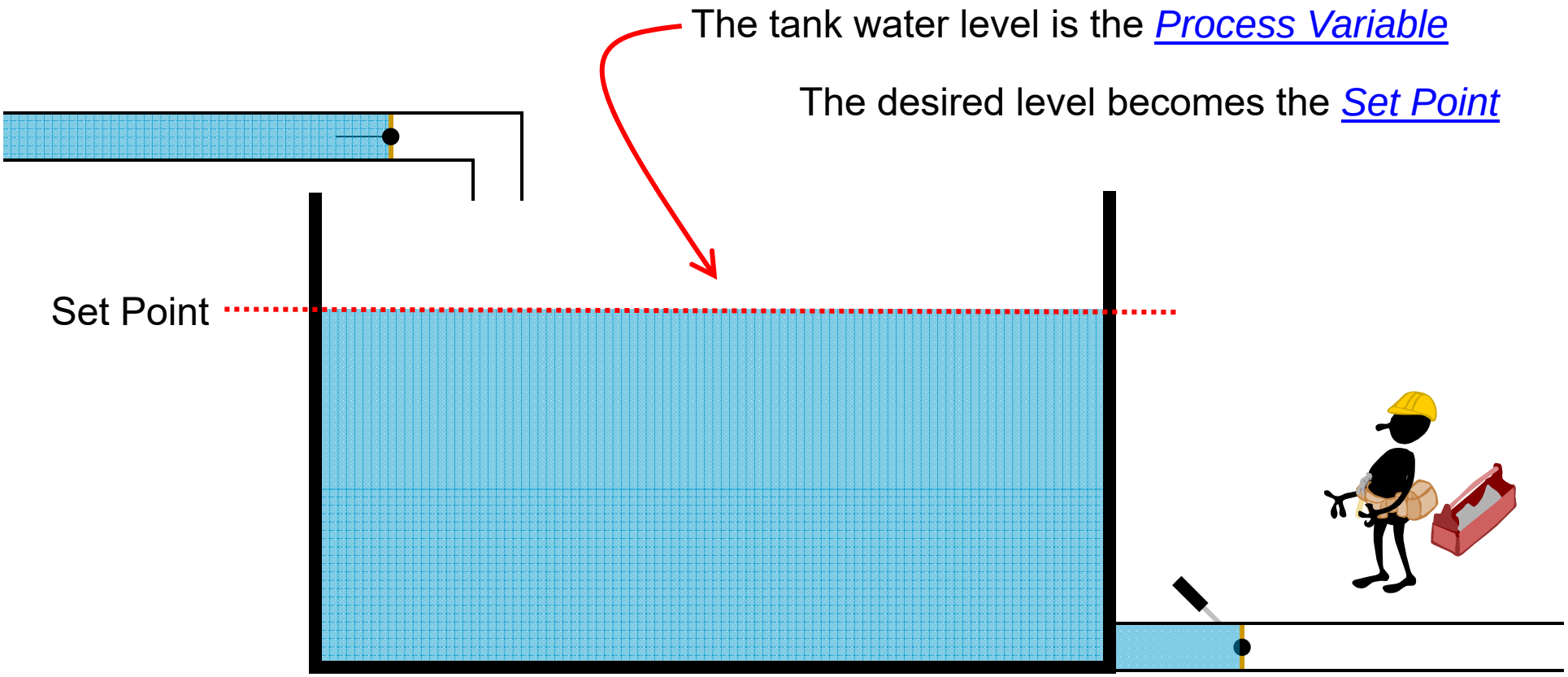

A Simple Analog Control System
Set Point and Throttling Range Adjustments
Sensor
Final Control Element
Feedback Mechanism

A Simple Control Requirement

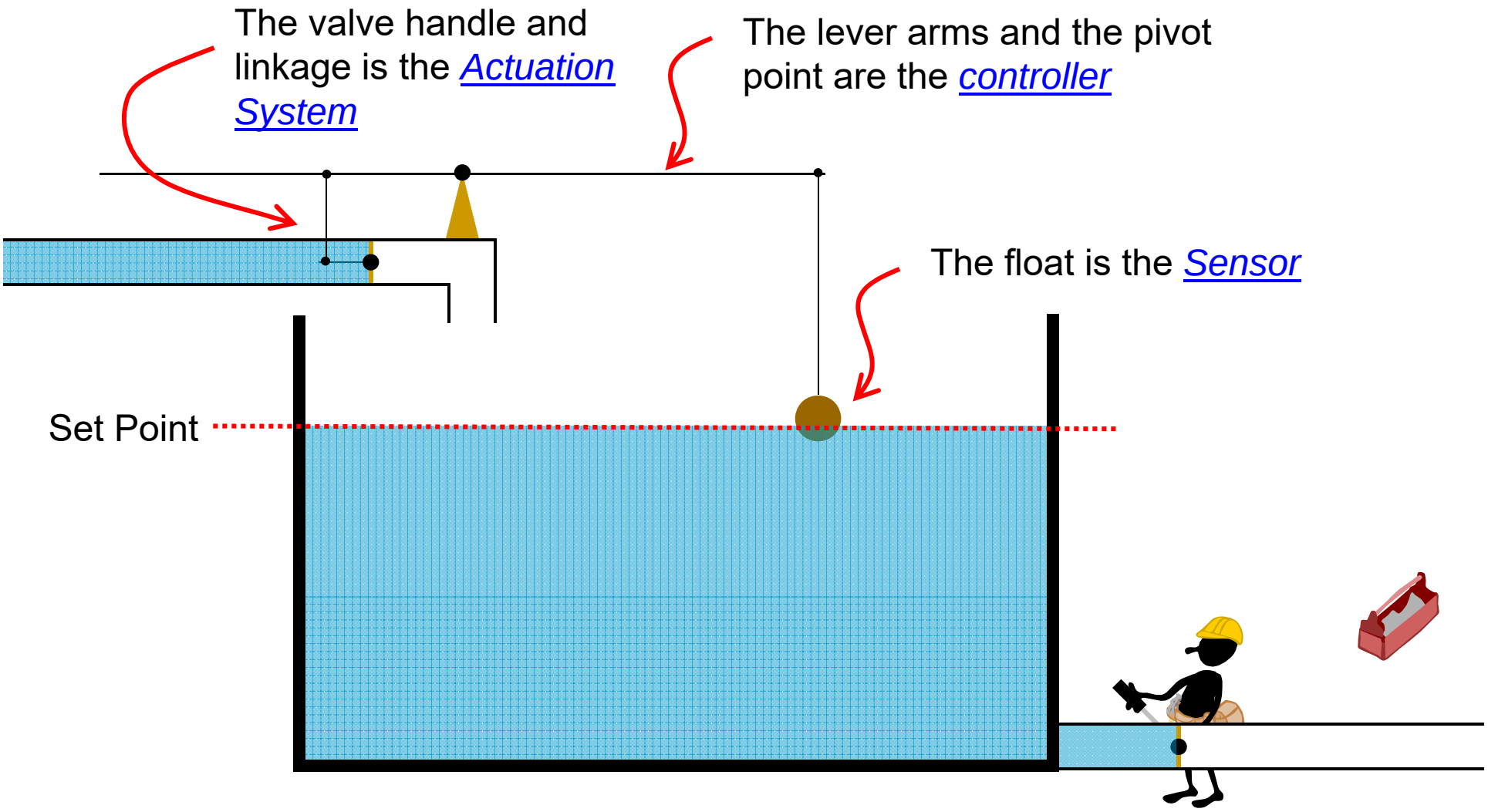
The make up valve is the device to be controlled; a.k.a. the *Controlled Variable* or *Final Control Element*



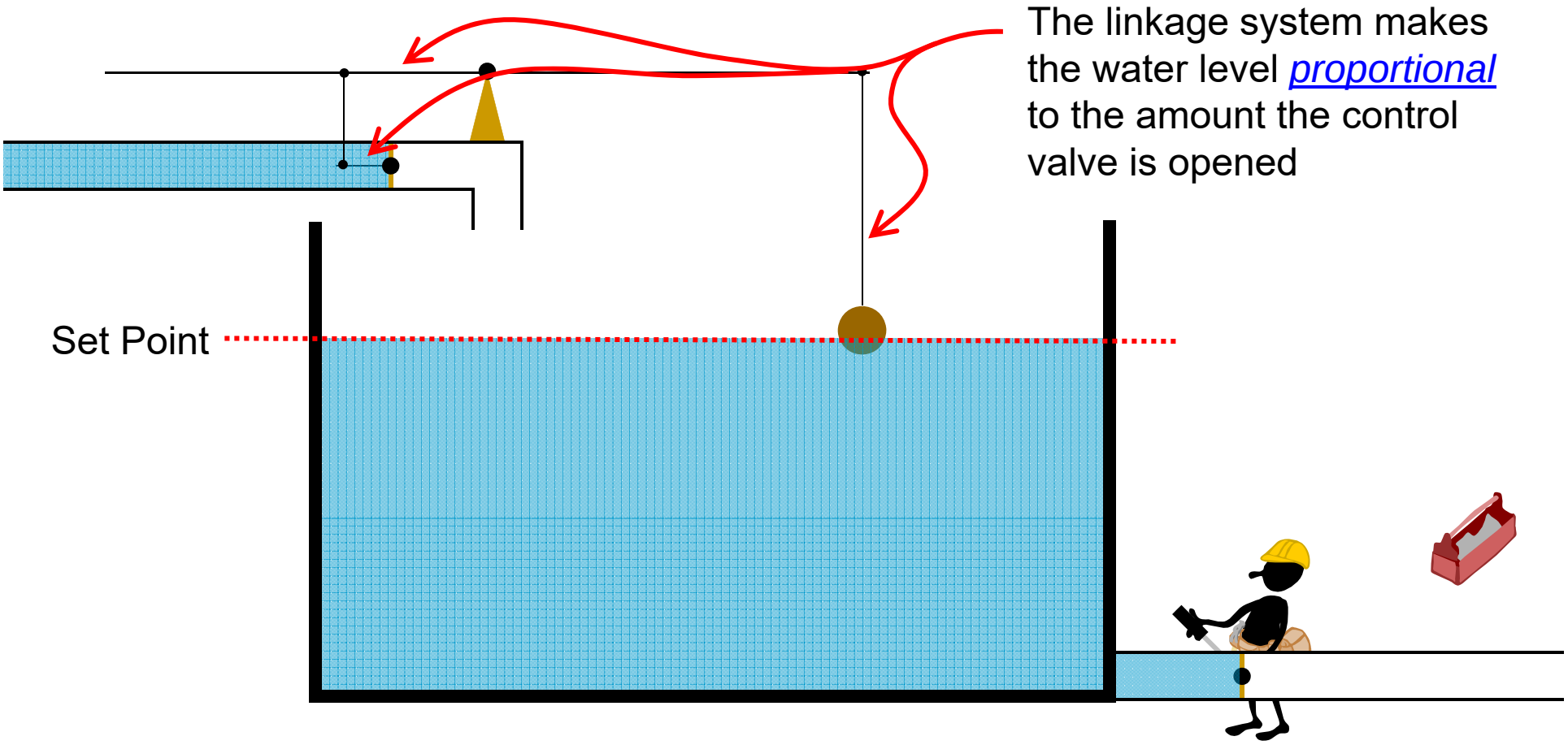
A Simple Control Requirement



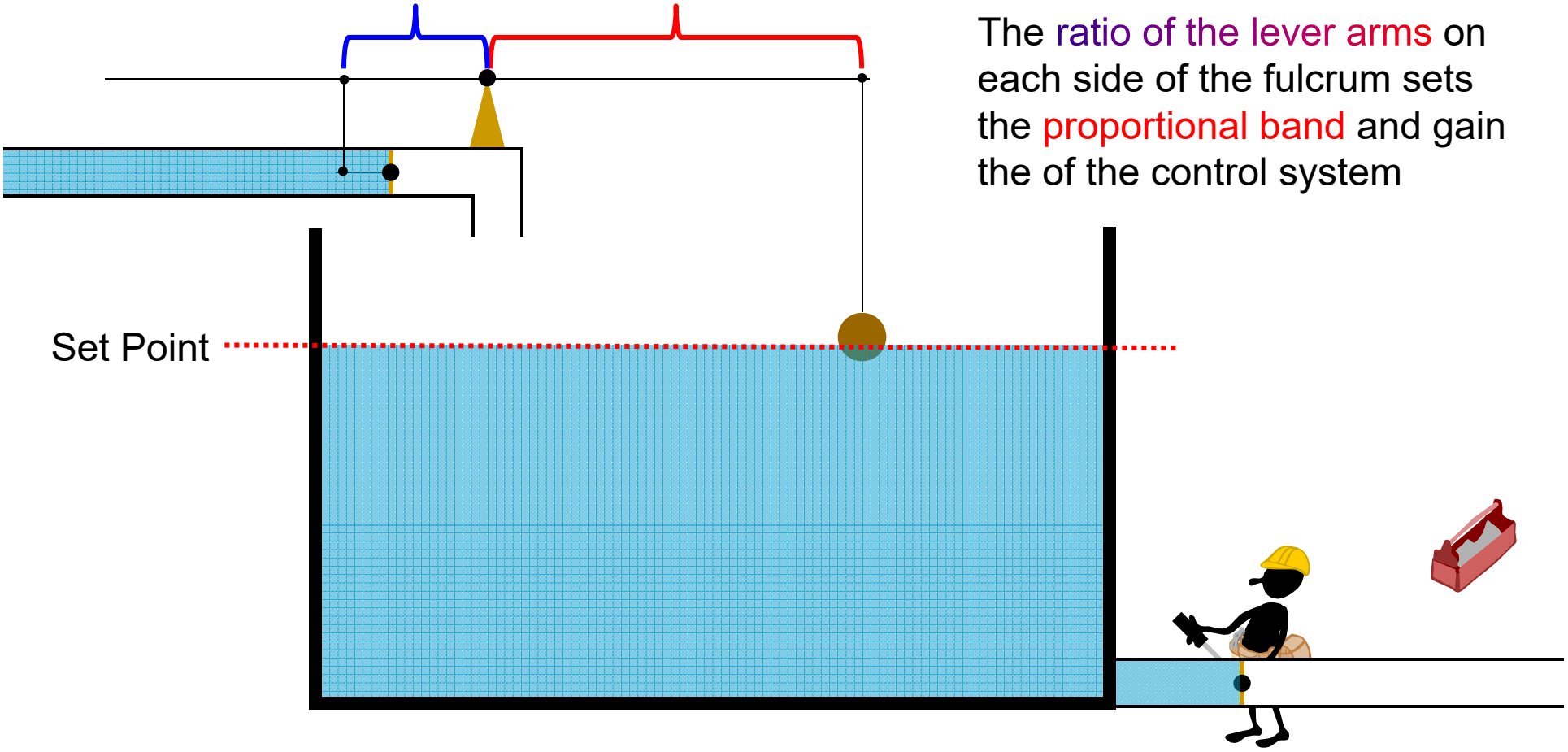
A Simple Proportional Control System



A Simple Proportional Control System

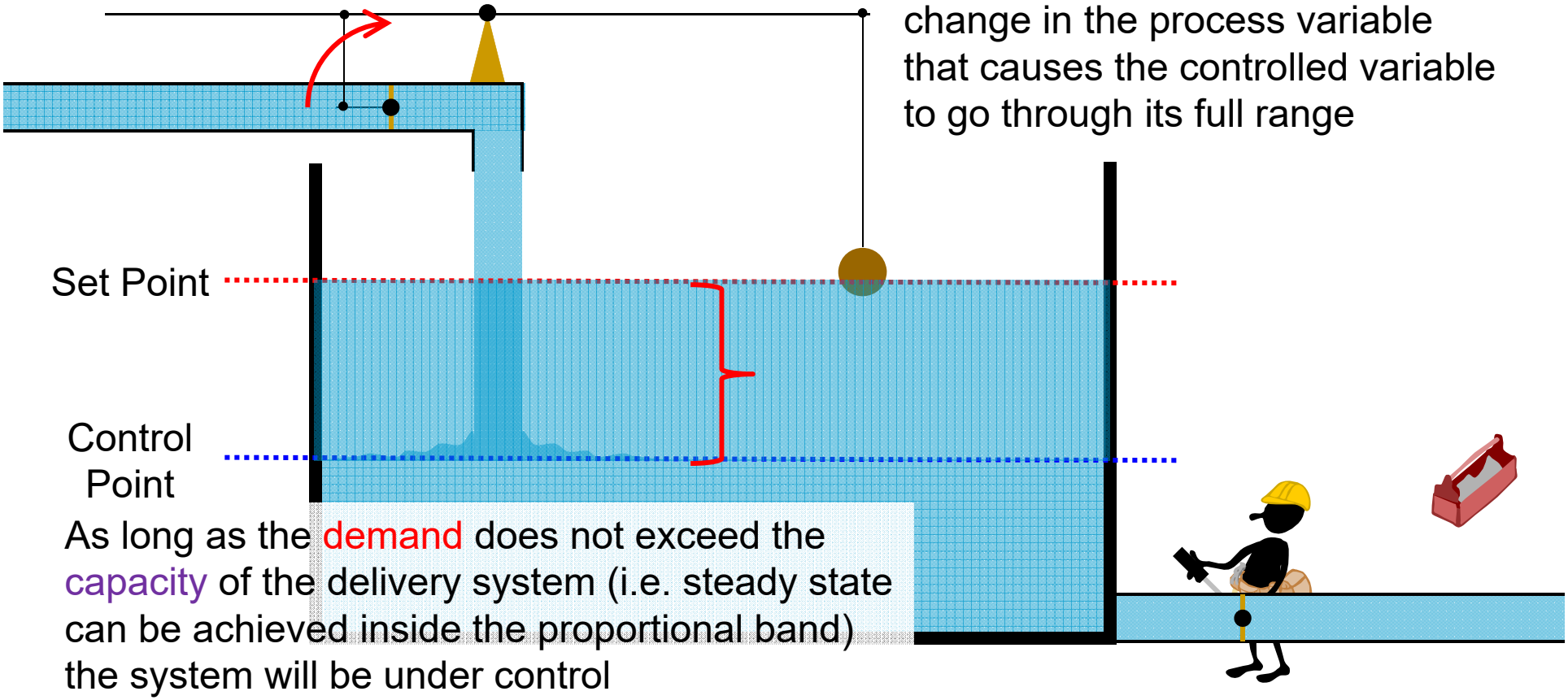


A Simple Proportional Control System



The ratio of the lever arms on each side of the fulcrum sets the proportional band and gain the of the control system

A Simple Proportional Control System

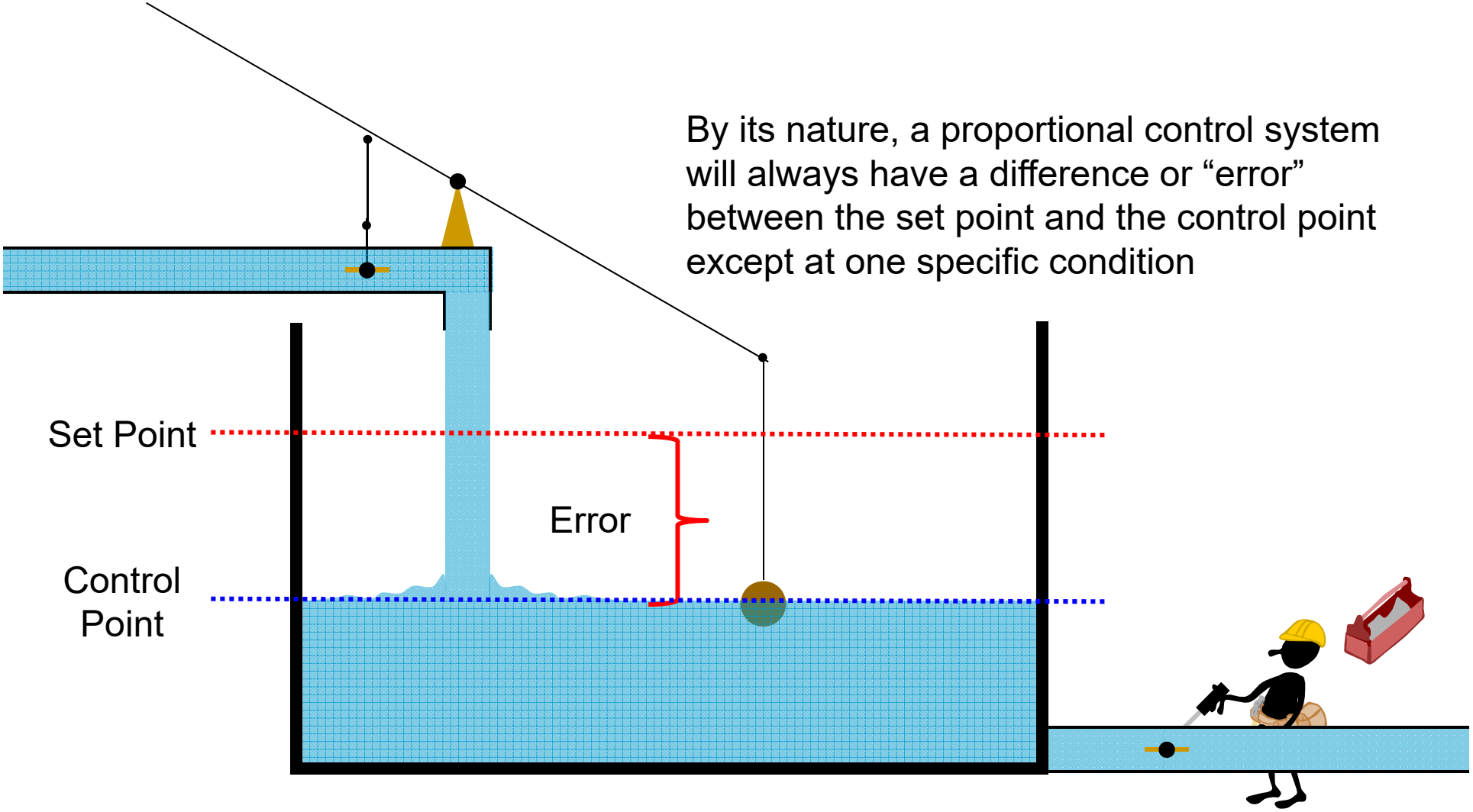


The proportional band is the change in the process variable that causes the controlled variable to go through its full range

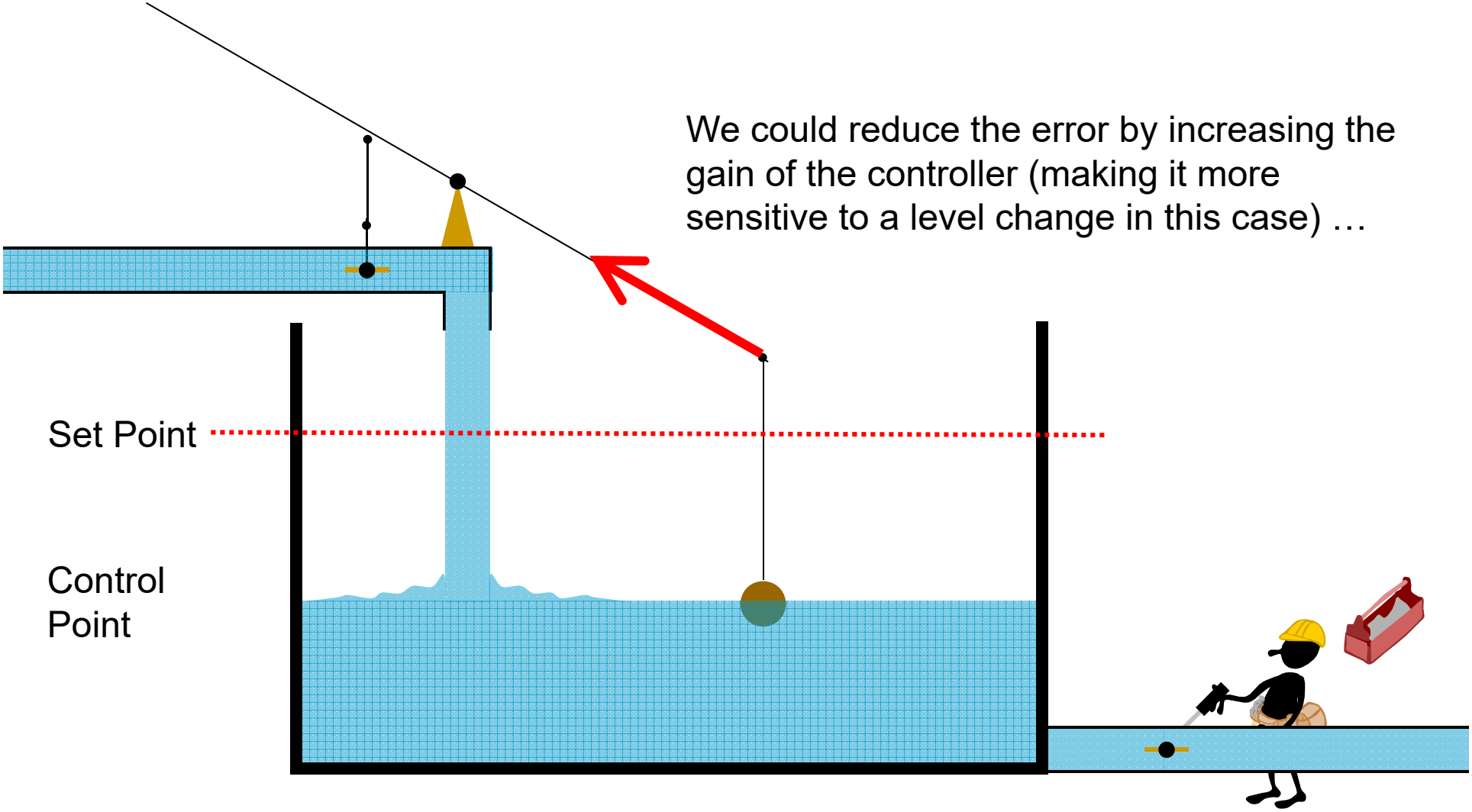
As long as the demand does not exceed the capacity of the delivery system (i.e. steady state can be achieved inside the proportional band) the system will be under control

A Simple Proportional Control System

By its nature, a proportional control system will always have a difference or “error” between the set point and the control point except at one specific condition

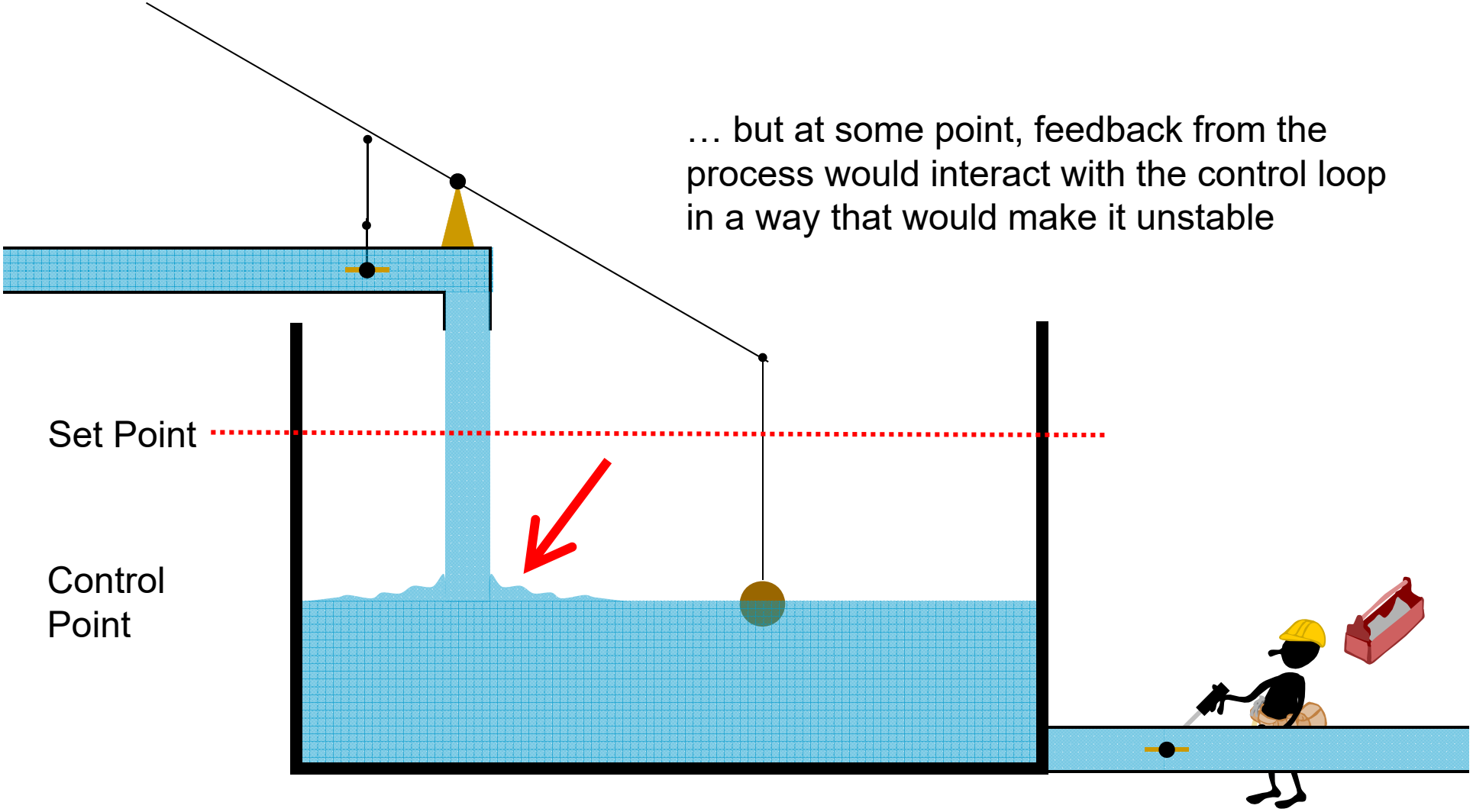


A Simple Proportional Control System



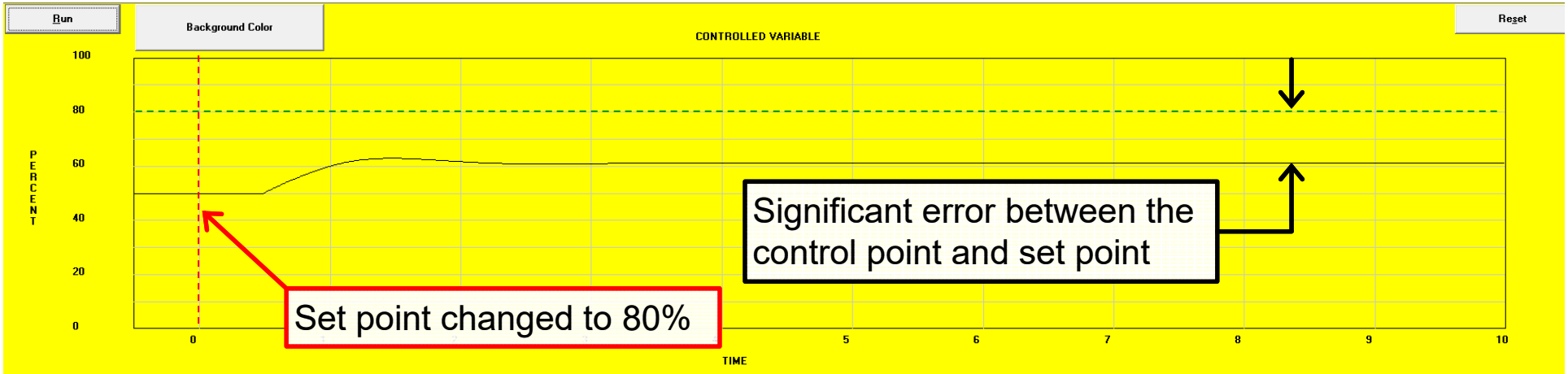
A Simple Proportional Control System

… but at some point, feedback from the process would interact with the control loop in a way that would make it unstable



The Impact of Narrowing Throttling Range

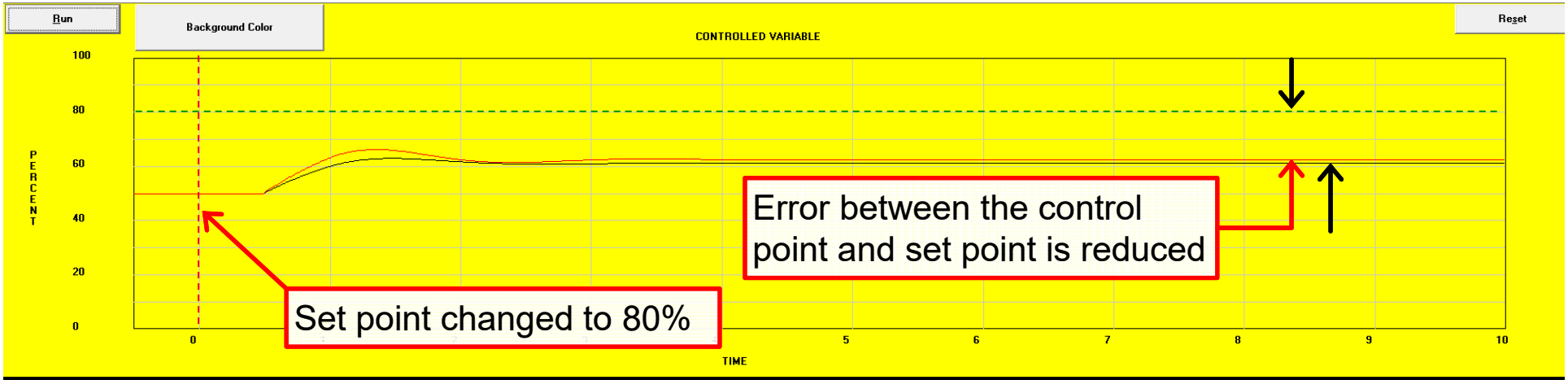
Proportional band =400% and set point changed to 80% (black line)



The Impact of Narrowing Throttling Range

Proportional band =400% (black line)

Proportional band =300% and set point changed to 80% (red line)

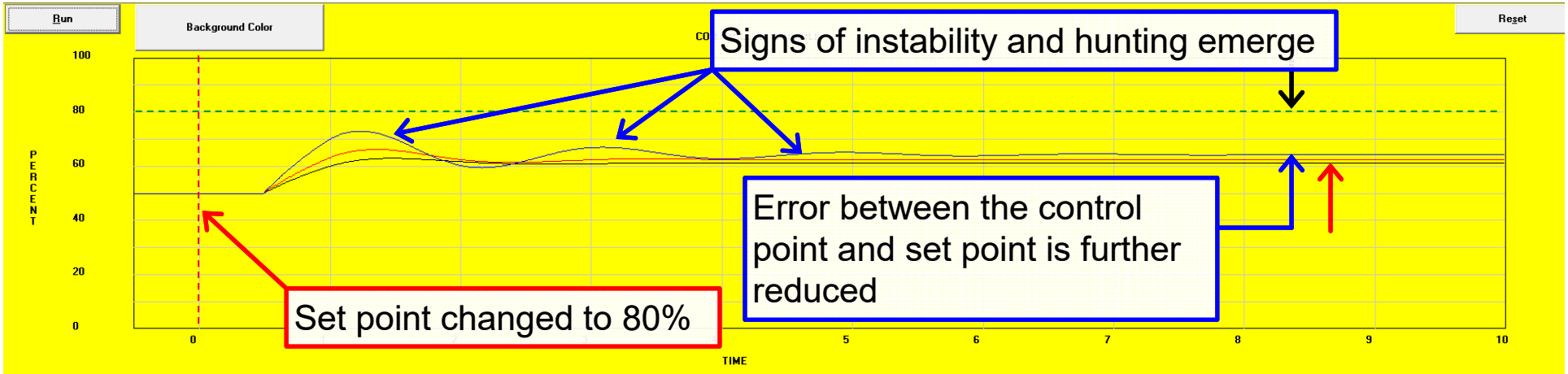


The Impact of Narrowing Throttling Range

Proportional band =400% (black line)

Proportional band =300% (red line)

Proportional band =200% and set point changed to 80% (blue line)



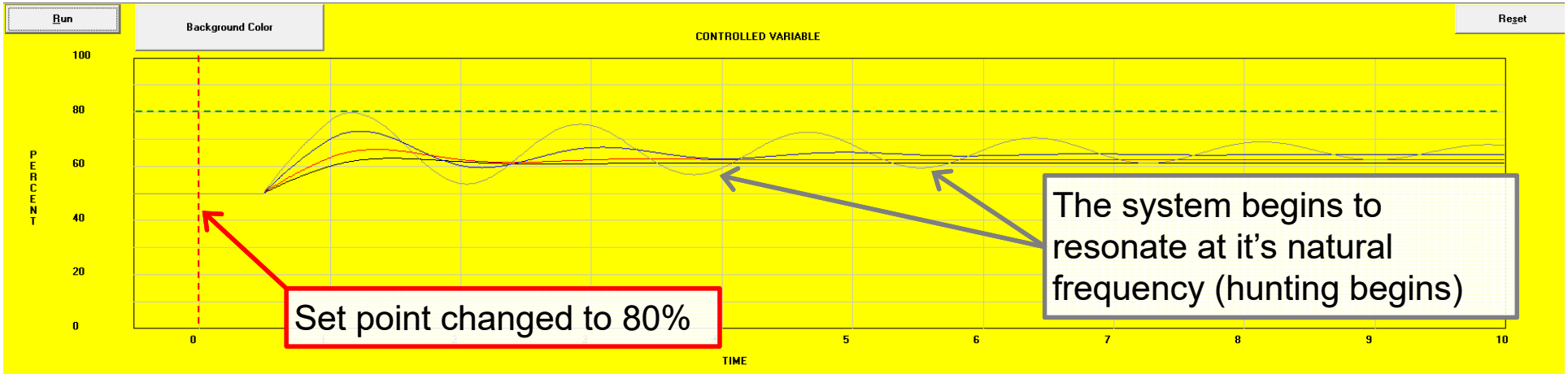
The Impact of Narrowing Throttling Range

Proportional band =400% (black line)

Proportional band =300% (red line)

Proportional band =200% (blue line)

Proportional band =150% and set point changed to 80% (gray line)



The Impact of Narrowing Throttling Range

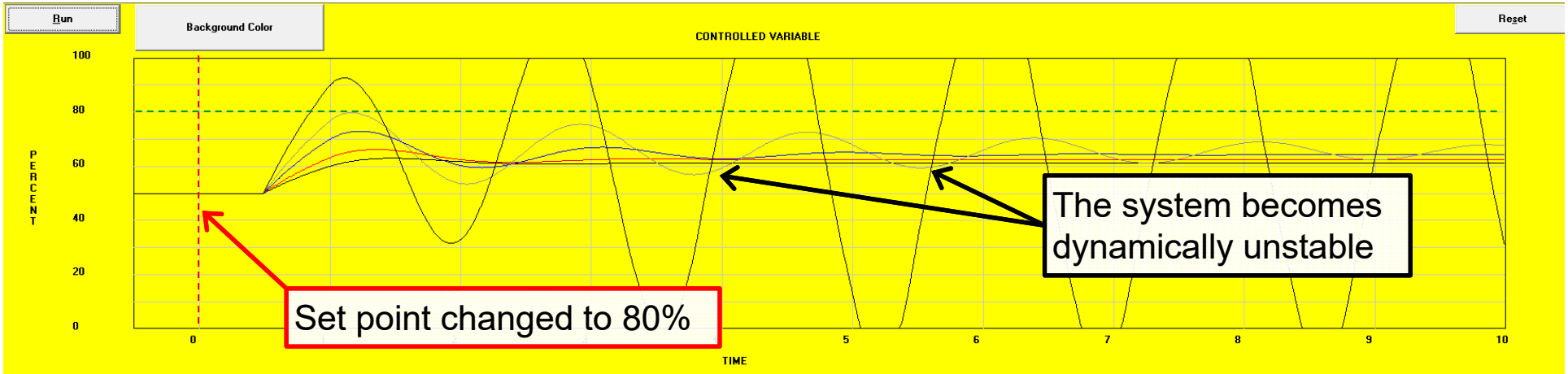
Proportional band =400% (black line)

Proportional band =300% (red line)

Proportional band =200% (blue line)

Proportional band =150% (gray line)

Proportional band =100% and set point changed to 80% (second black line)



Bottom Lines On Proportional Control

1. All proportional control processes will show a difference between set point and control point (a.k.a. error) under all operating conditions other than one very specific condition
2. The error can be reduced by narrowing down the throttling range
3. There is a limit to how much you can narrow the throttling range with out hunting
4. The limit is a function of the physics of the control system; things like lags, play in the linkage system, the nature of the process, etc.

Then a Miracle Occurs

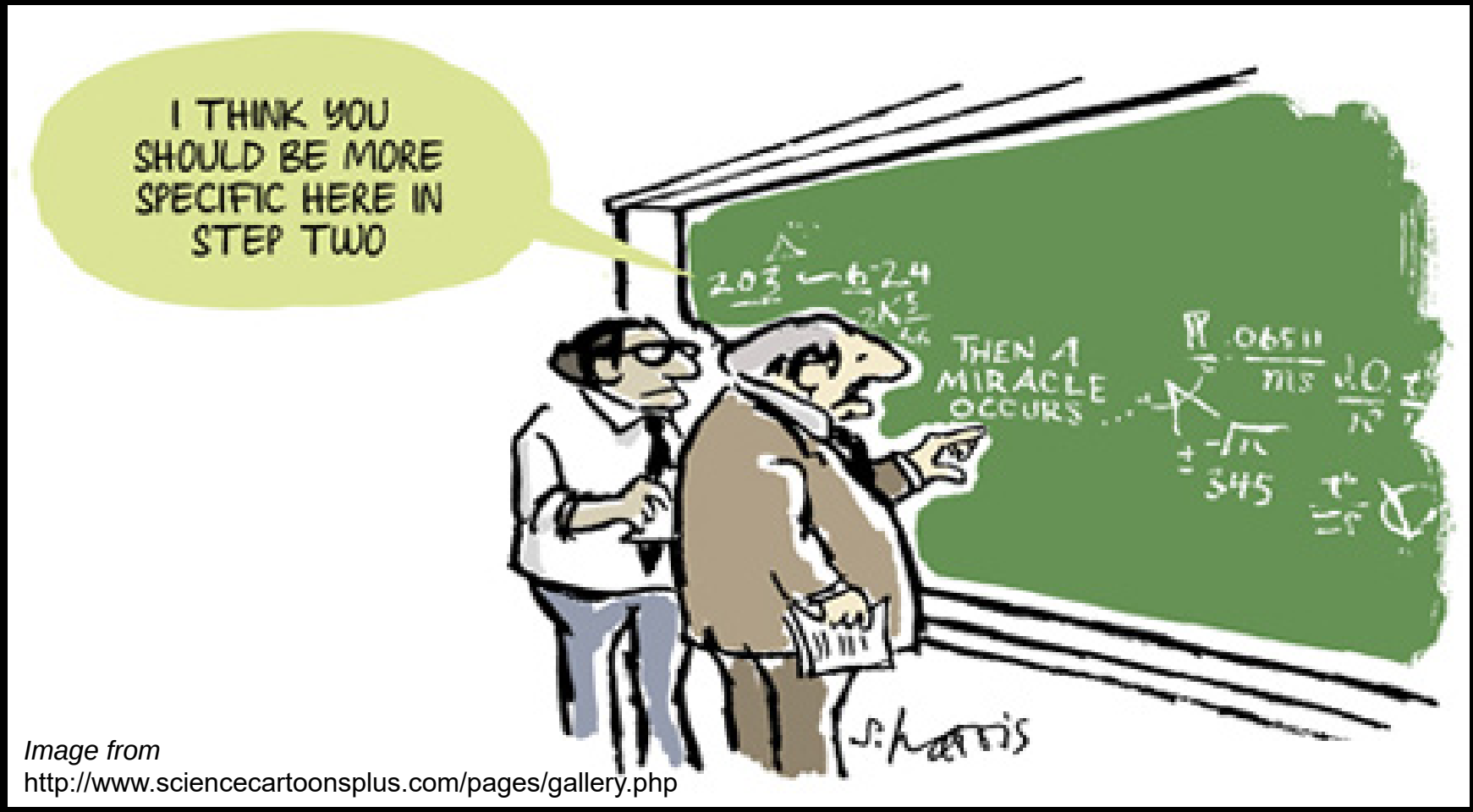


Image from
http://www.sciencecartoonsplus.com/pages/gallery.php

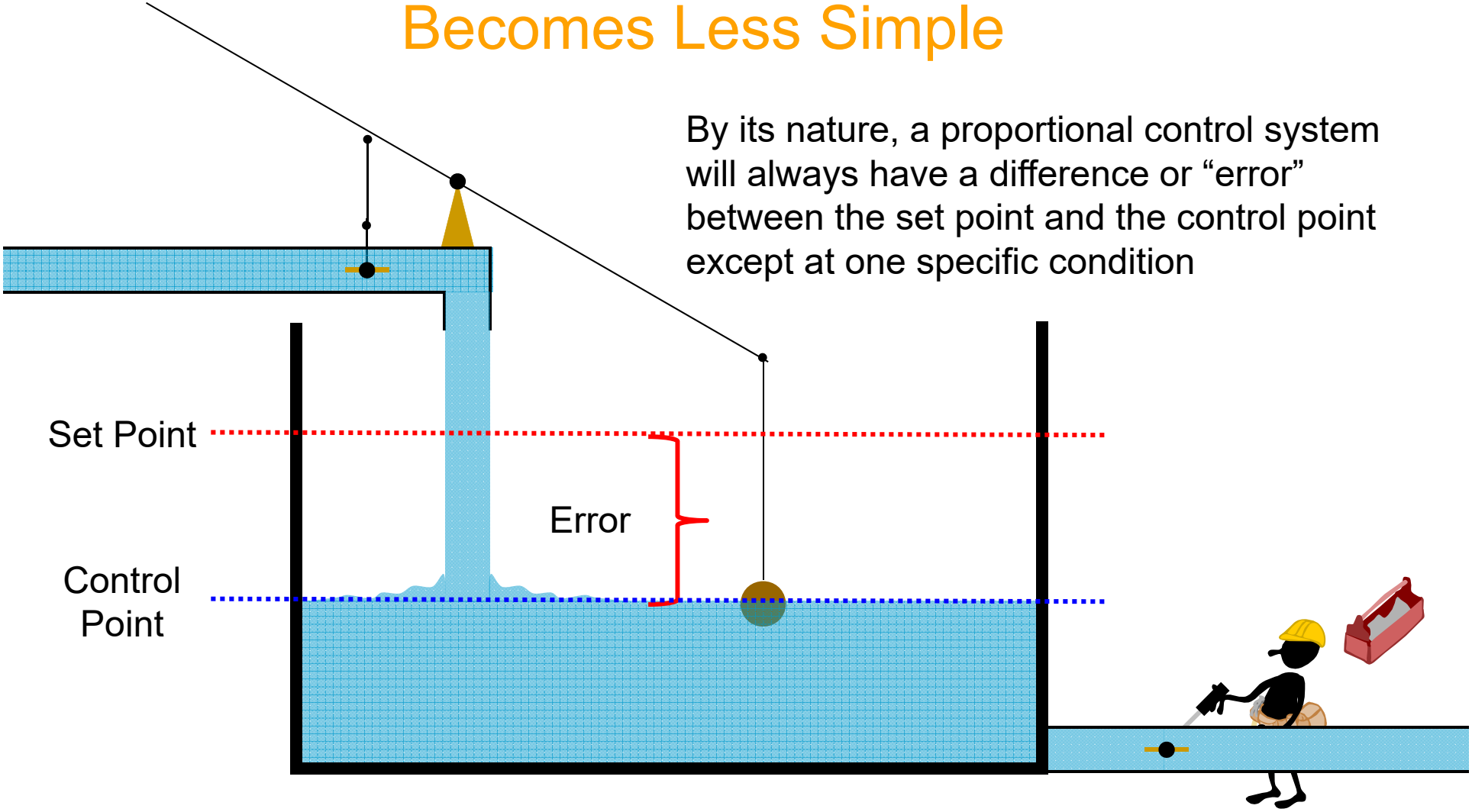
Proportional plus Integral plus Derivative Control (PID)

PID is the Miracle that can:

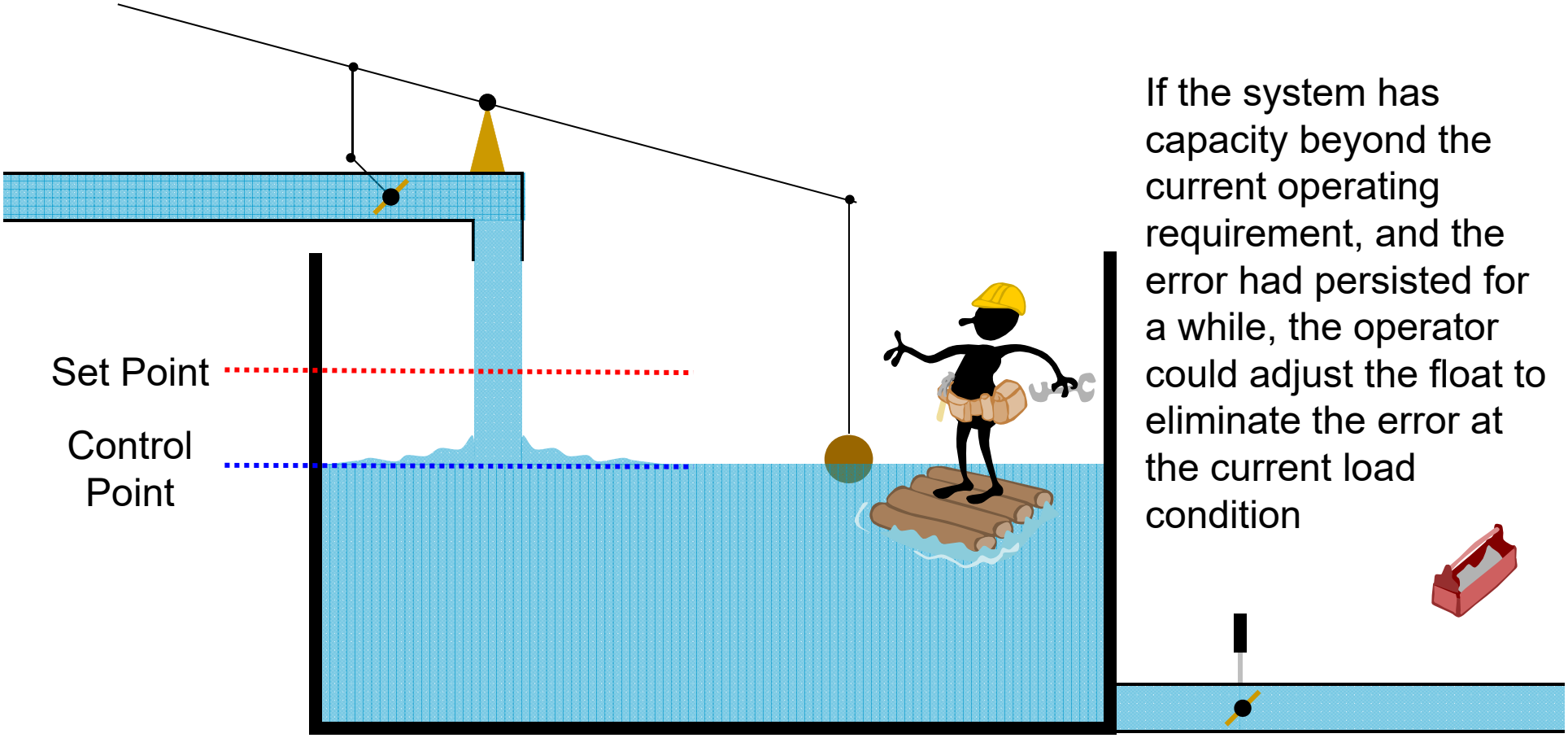
- Eliminate error
- Reduce the magnitude of a spike when a system is upset
- Reduce the settling time after an upset

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple

By its nature, a proportional control system will always have a difference or “error” between the set point and the control point except at one specific condition

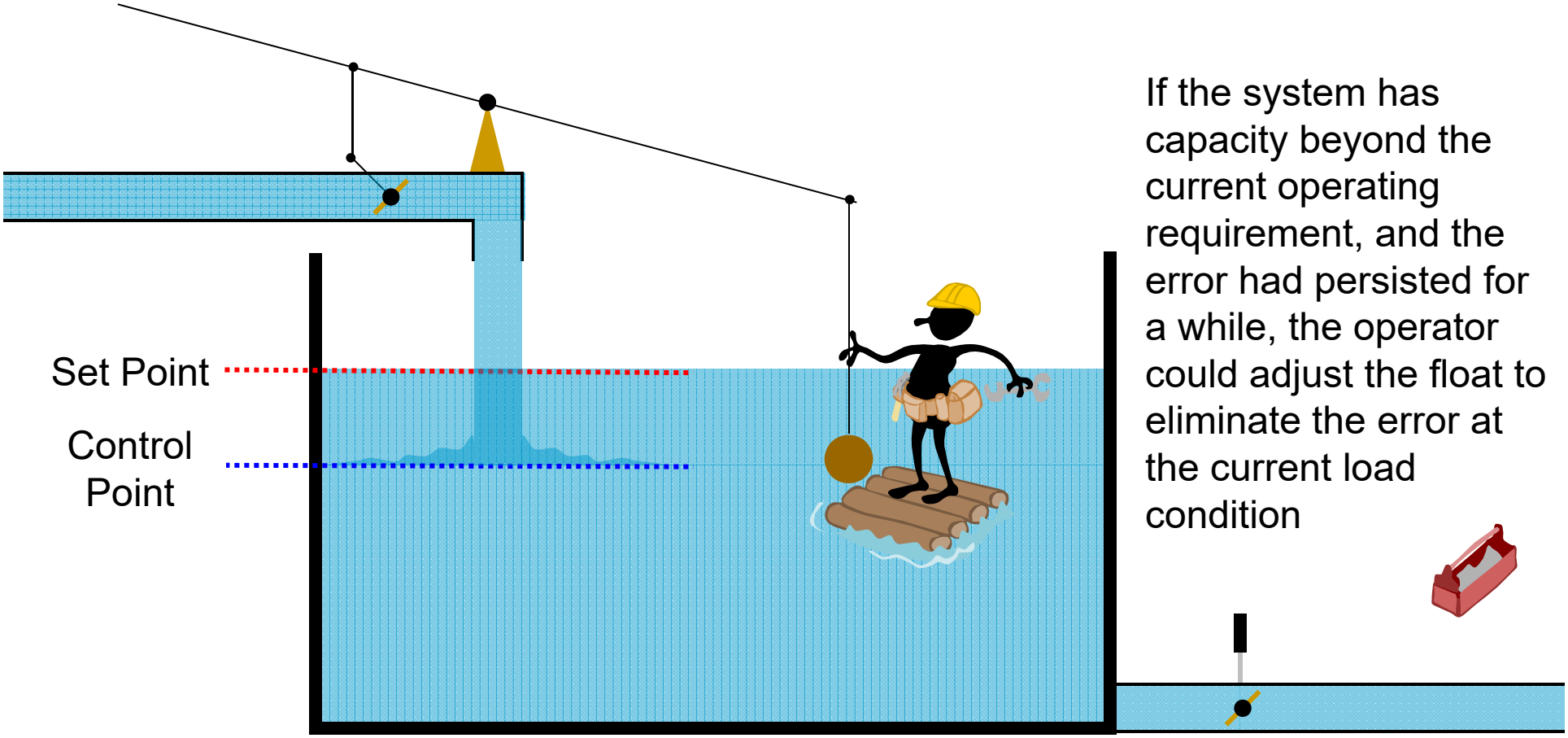


Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



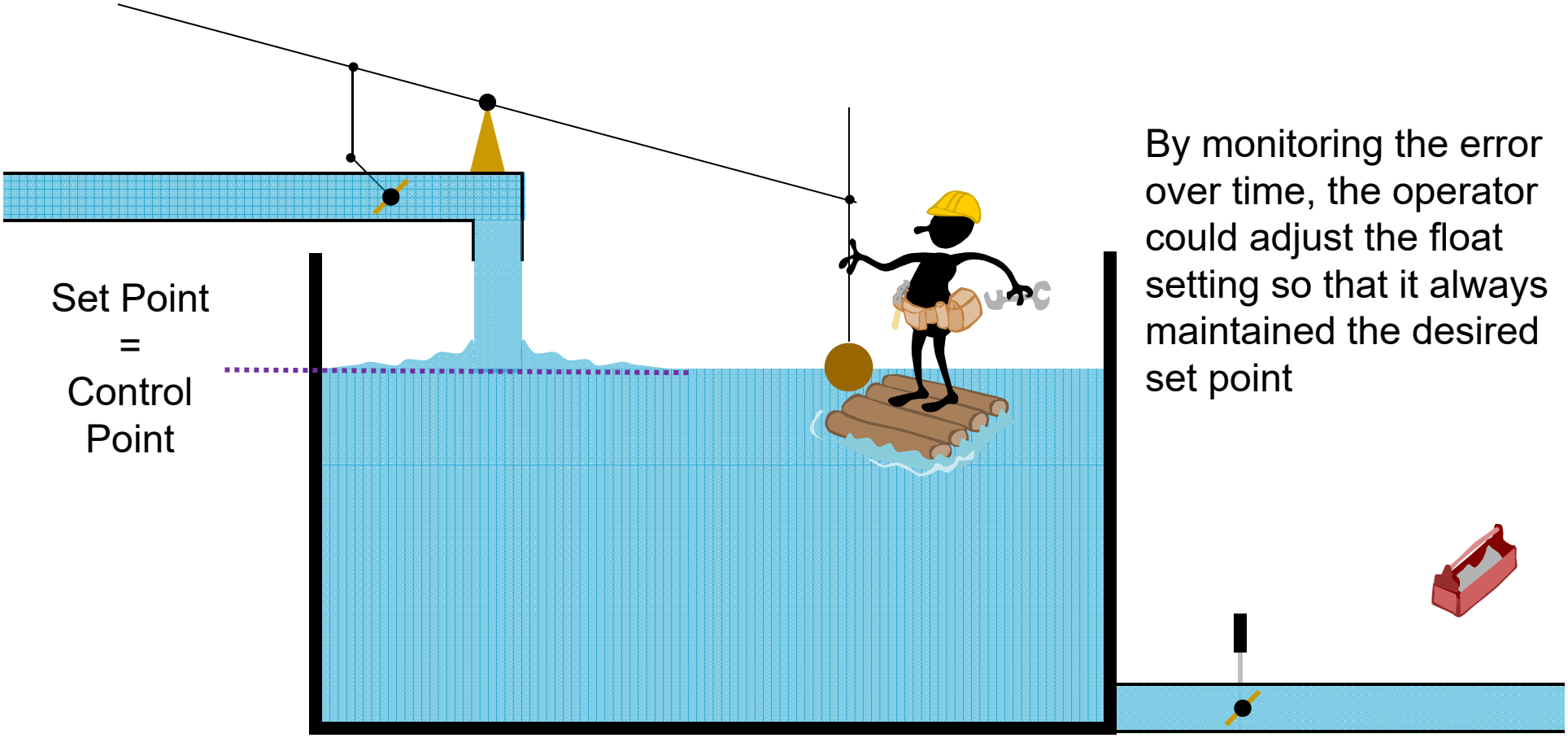
If the system has capacity beyond the current operating requirement, and the error had persisted for a while, the operator could adjust the float to eliminate the error at the current load condition

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



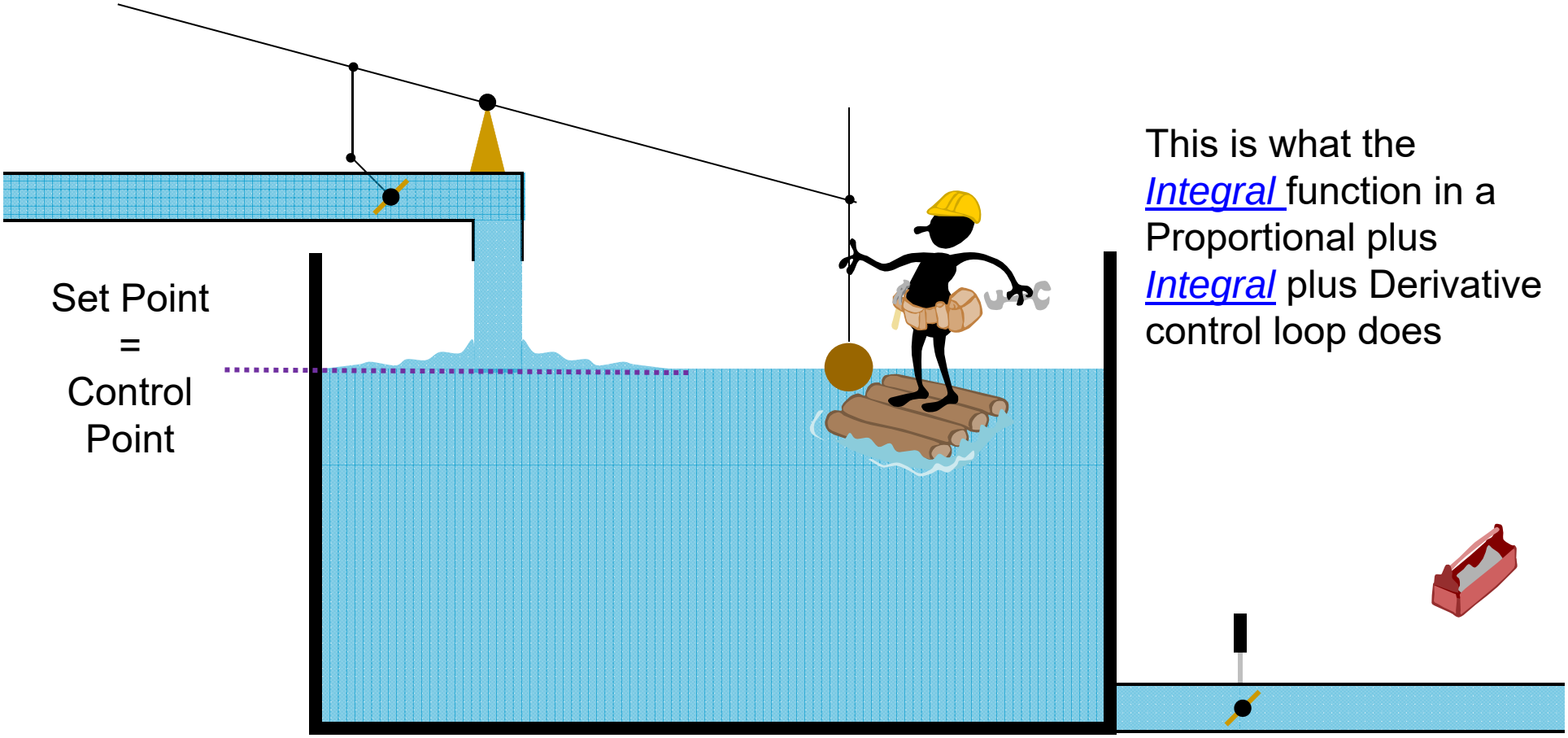
If the system has capacity beyond the current operating requirement, and the error had persisted for a while, the operator could adjust the float to eliminate the error at the current load condition

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



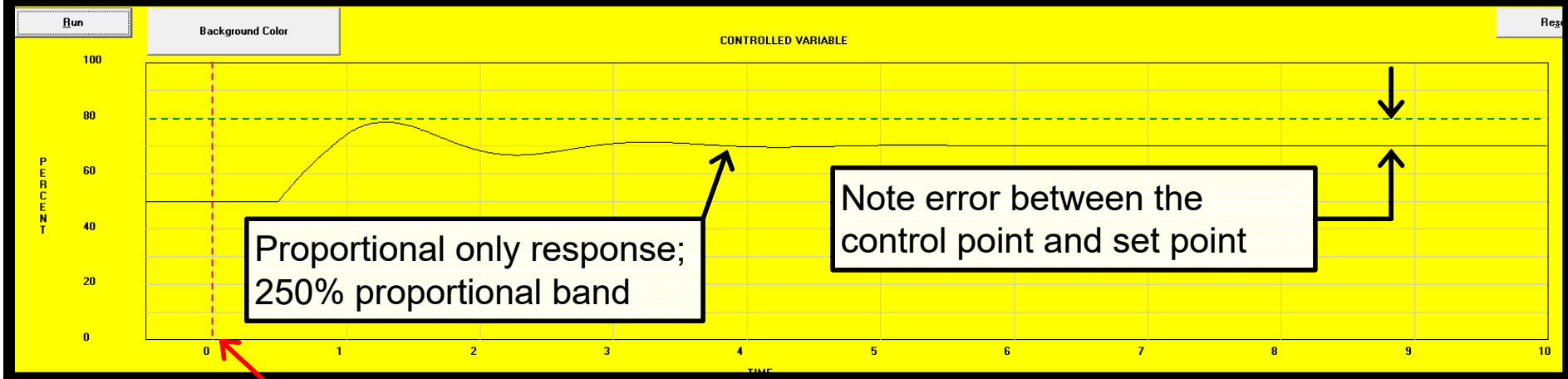
By monitoring the error over time, the operator could adjust the float setting so that it always maintained the desired set point

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple

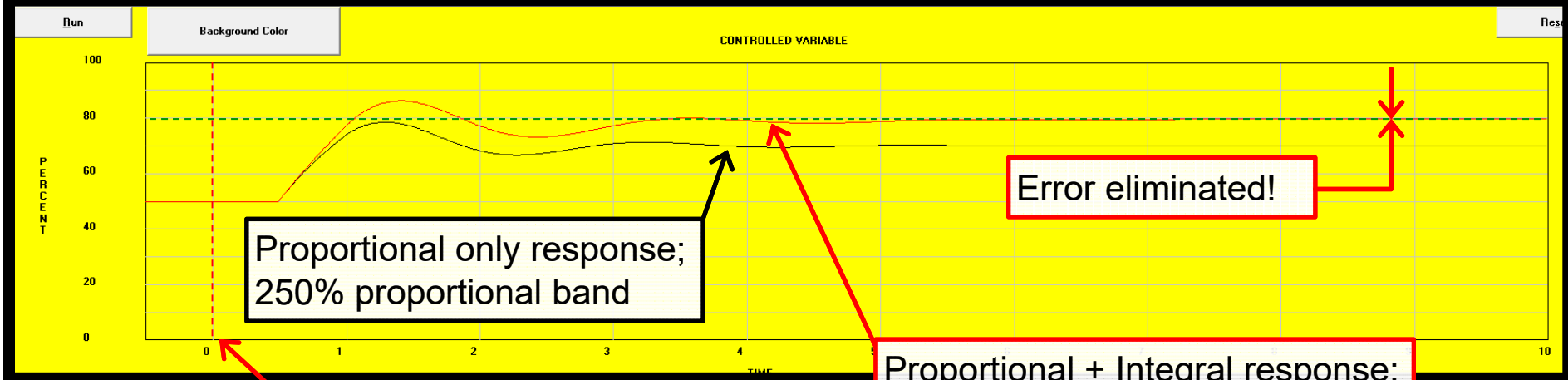


This is what the *Integral* function in a Proportional plus *Integral* plus Derivative control loop does

The Impact of Adding Integral Gain



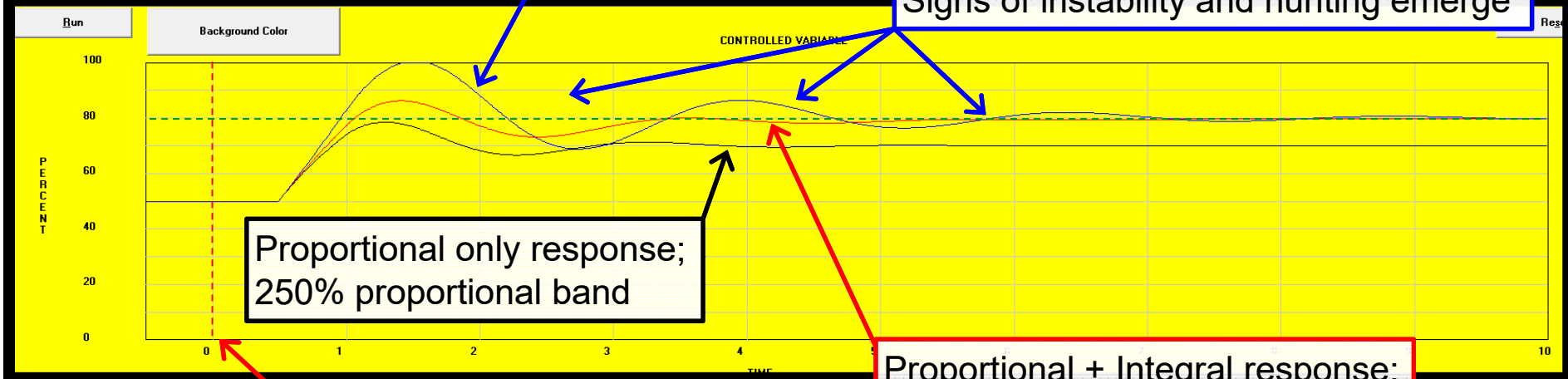
The Impact of Adding Integral Gain



The Impact of Adding Integral Gain

Proportional + Integral response; 250% proportional band, Integral time = 0.75 minutes

Signs of instability and hunting emerge

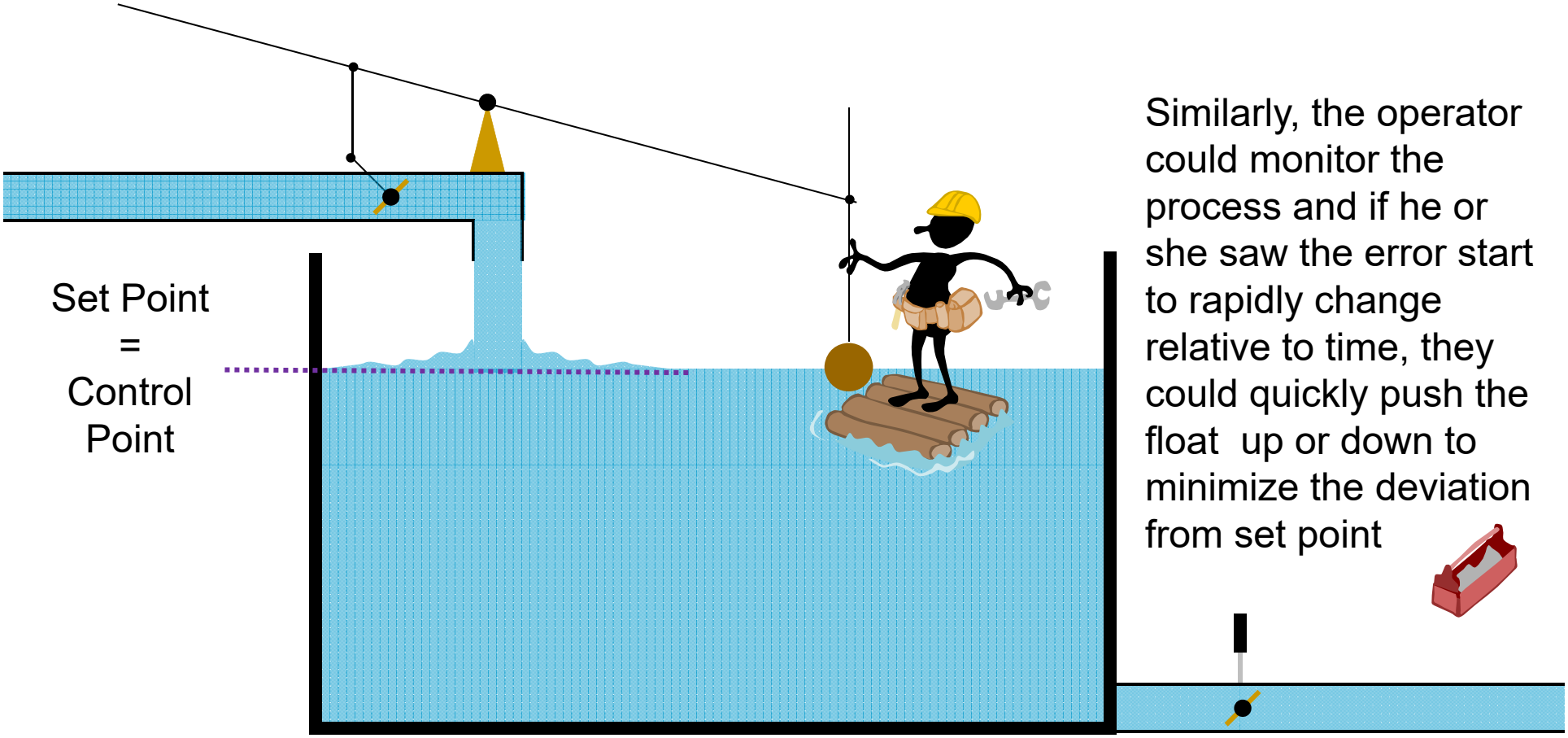


Proportional only response; 250% proportional band

Set point changed to 80%

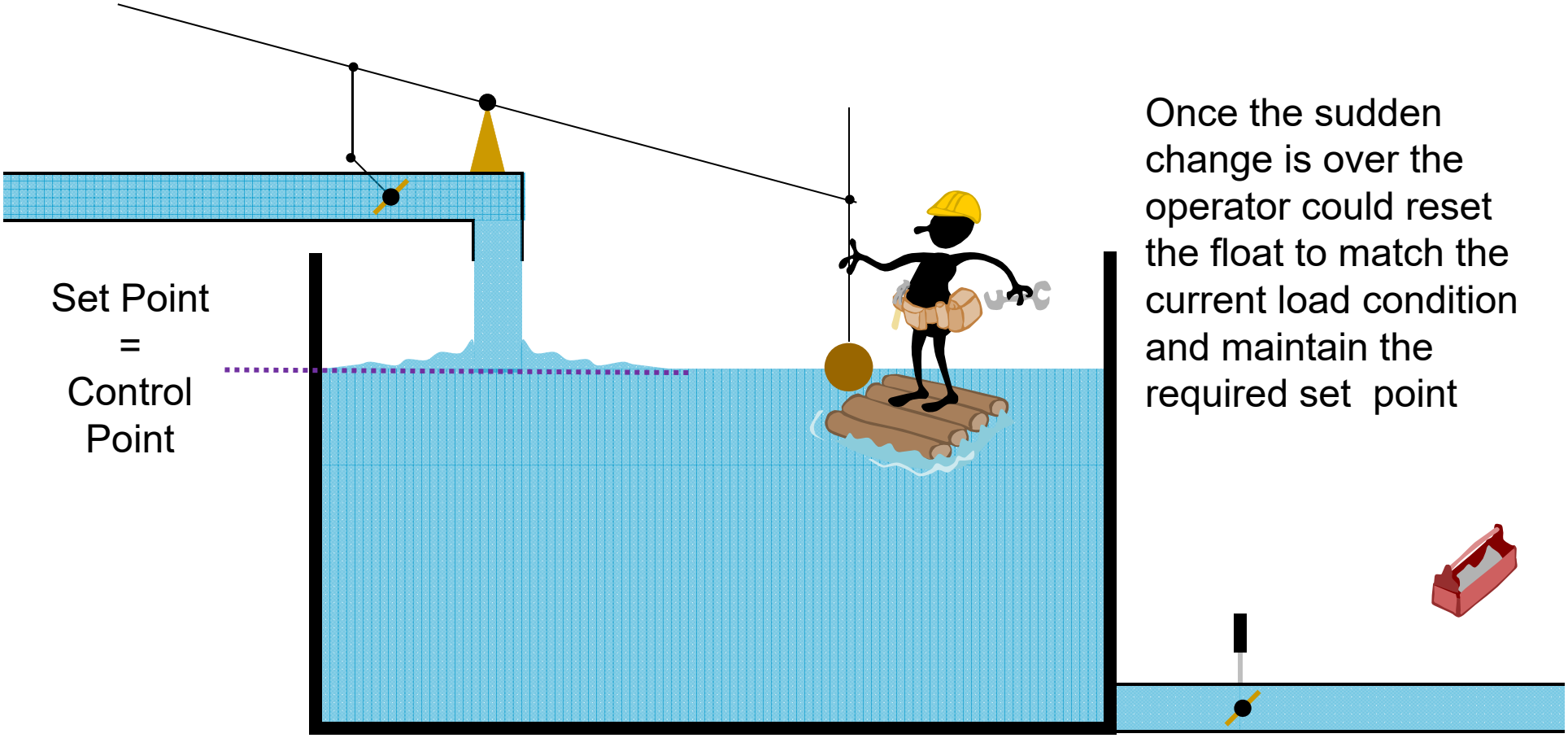
Proportional + Integral response; 250% proportional band, Integral time = 2 minutes

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



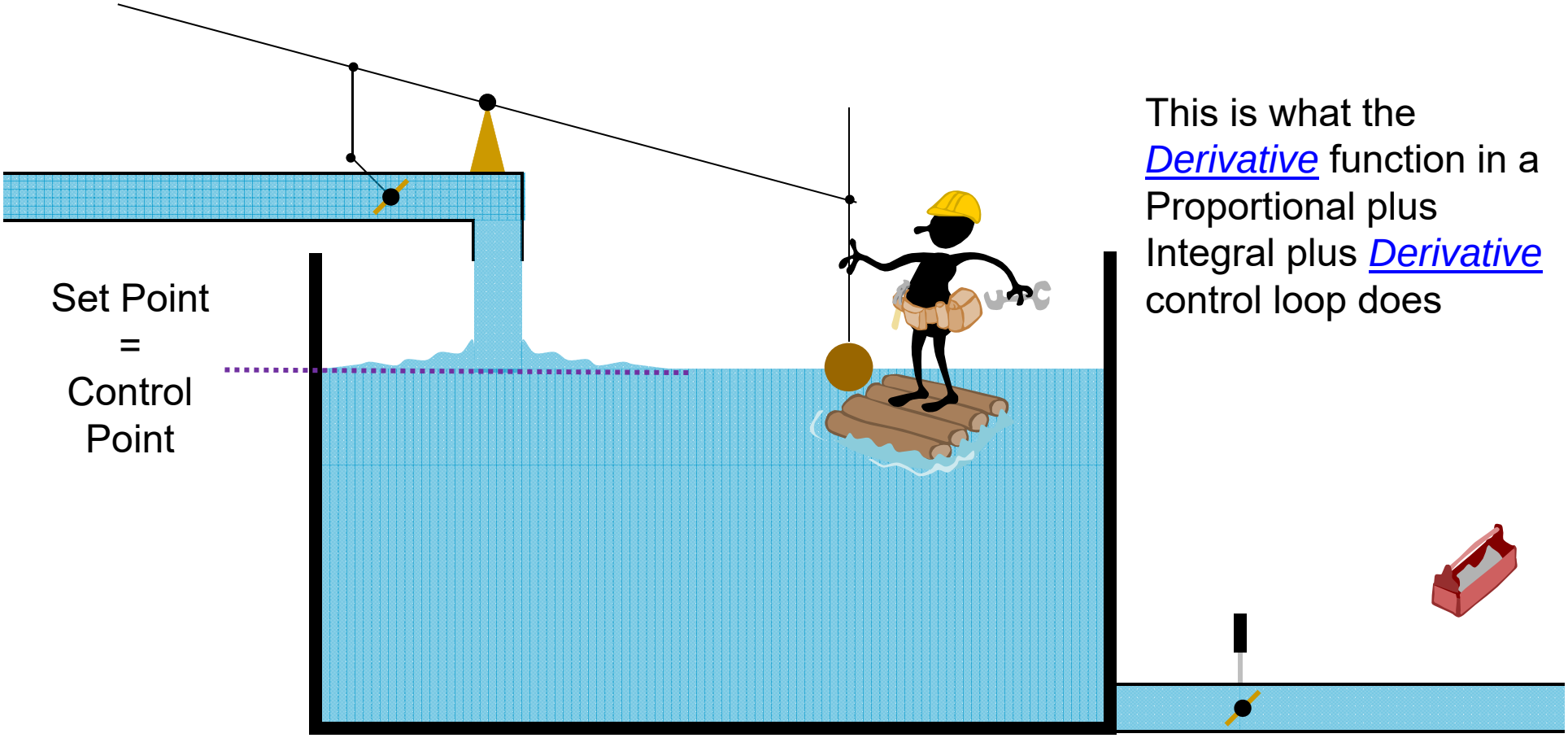
Similarly, the operator could monitor the process and if he or she saw the error start to rapidly change relative to time, they could quickly push the float up or down to minimize the deviation from set point

Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



Once the sudden change is over the operator could reset the float to match the current load condition and maintain the required set point

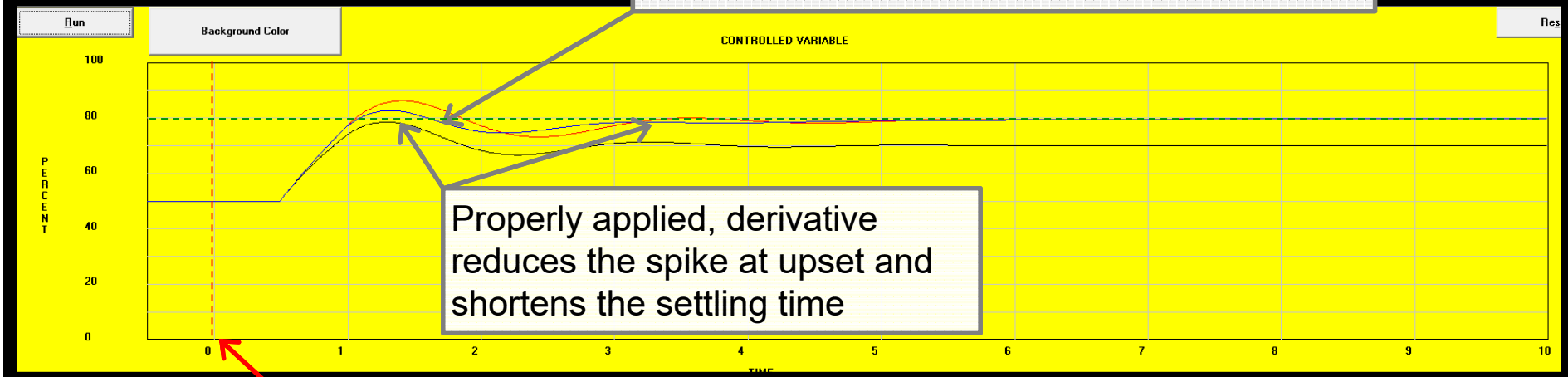
Eliminating Proportional Error; A Simple Proportional Control System Becomes Less Simple



This is what the *Derivative* function in a Proportional plus Integral plus *Derivative* control loop does

The Impact of Adding Derivative Gain

Proportional + Integral + Derivative response; 250% proportional band, Integral time = 0.75 minutes, Derivative time = 0.1 minutes



Properly applied, derivative reduces the spike at upset and shortens the settling time

Set point changed to 80%

PID; *Its Been Around for a While*

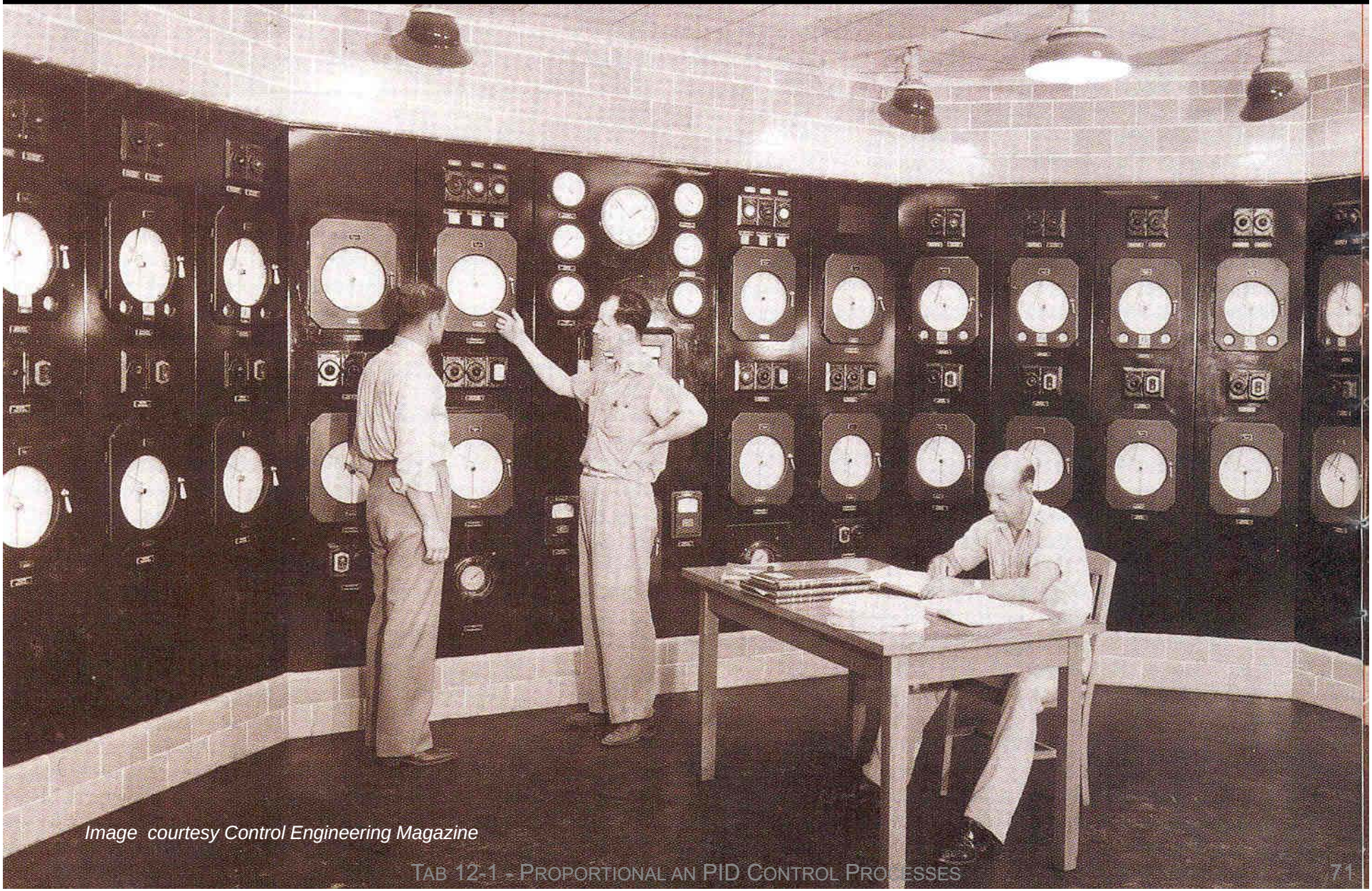


Image courtesy Control Engineering Magazine

PID Good News and Bad News

Good News

Eliminate offset

- Save energy
- Improve precision

Minimize process swings at start-up

Bad News

Not well understood by the HVAC industry

- More difficult to tune and adjust
- More difficult to maintain

Algorithm used varies with the manufacturer

- Tuning solution specifics are not portable
- Auto-tuning is not a panacea

Difficult to apply correctly

Often misapplied

PID; The Math Perspective

$$Output = K_P \times Proportional\ Offset + K_I \times \sum_{Time} Proportional\ Offset + K_D \times \frac{\partial Proportional\ Offset}{\partial Time}$$

Where :

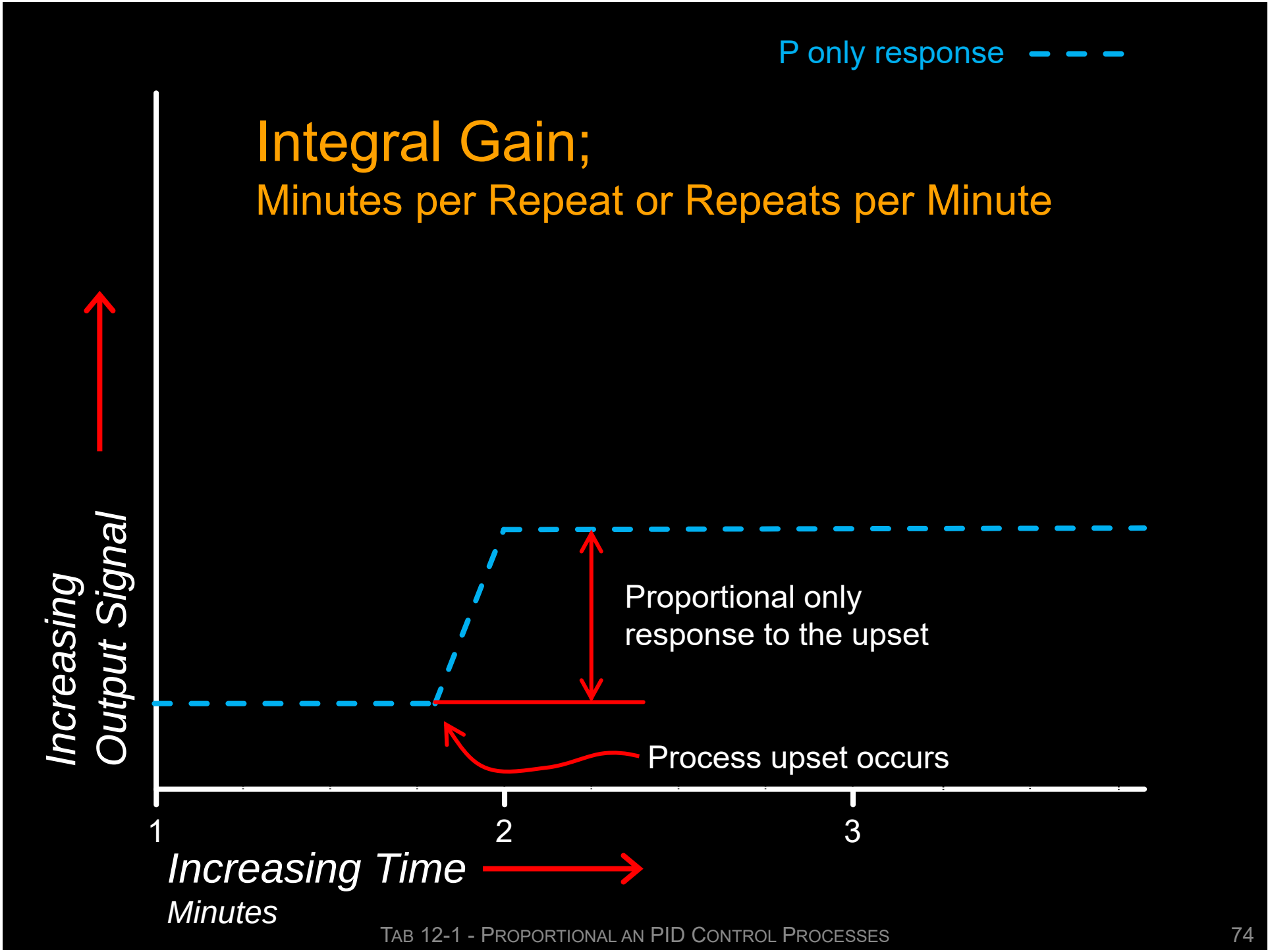
K_P = Proportional Gain

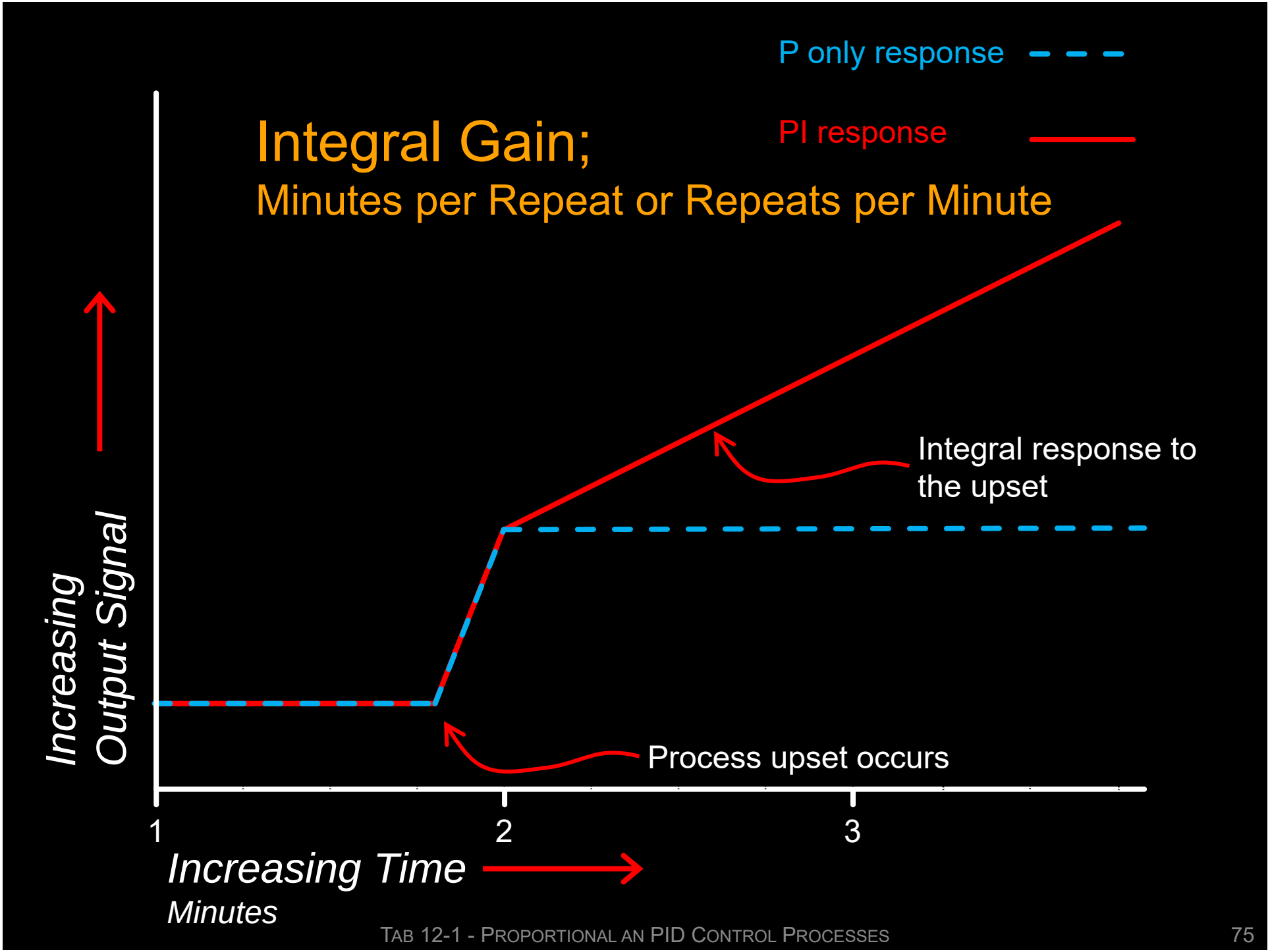
K_I = Integral Gain

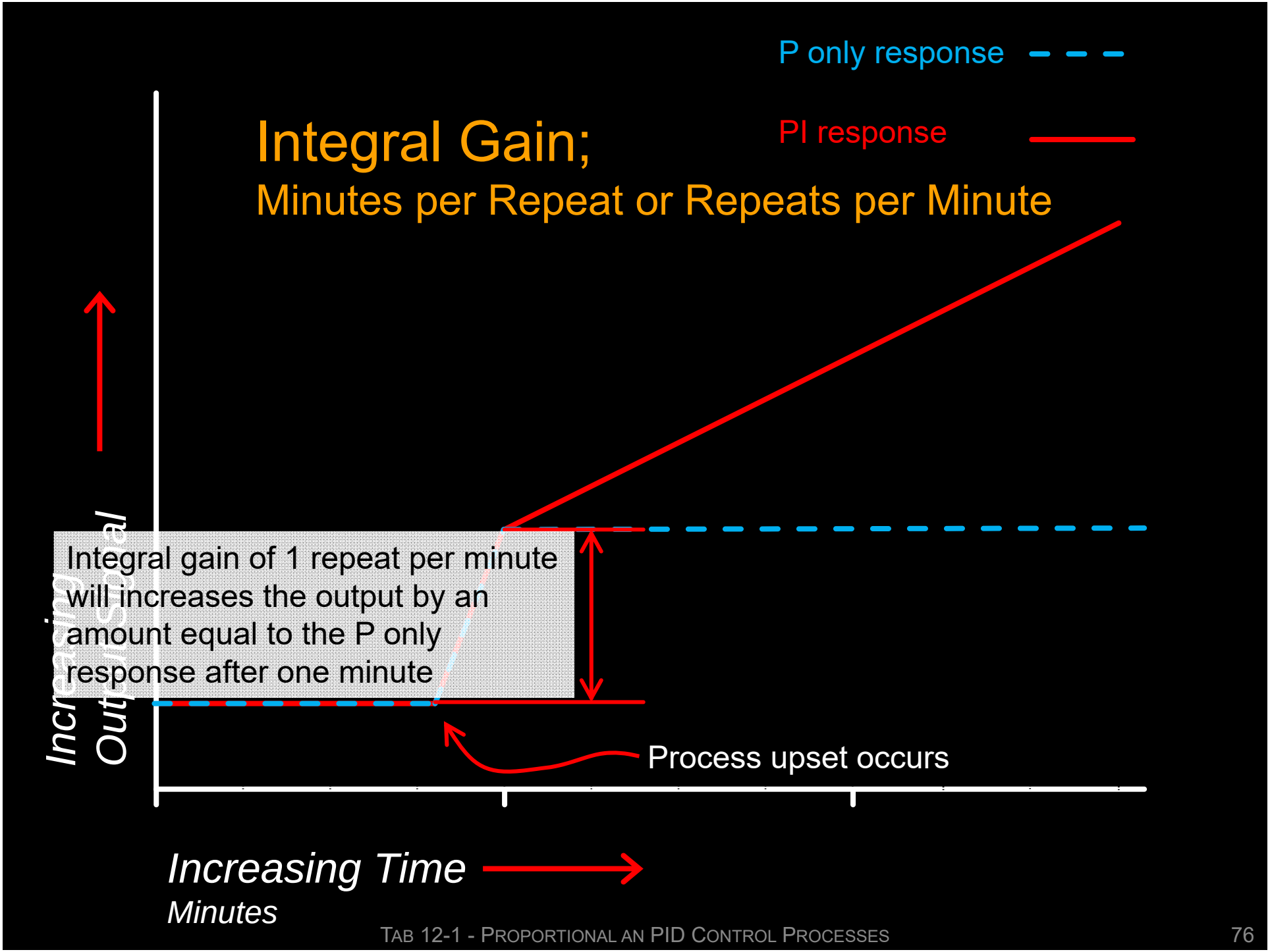
$\sum_{Time} Proportional\ Offset$ = Acumulated proportional offset over time

K_D = Derivative Gain

$\frac{\partial Proportional\ Offset}{\partial Time}$ = Rate of change of proportional offset over time


P only response
Integral Gain;
Minutes per Repeat or Repeats per Minute
Increasing
Output Signal
Proportional only
response to the upset
Process upset occurs
1
2
3
Increasing Time
Minutes


P only response
PI response
Integral Gain;
Minutes per Repeat or Repeats per Minute
Integral response to the upset
Process upset occurs
Increasing Output Signal
1
2
3
Increasing Time
Minutes


P only response
PI response
Integral Gain;
Minutes per Repeat or Repeats per Minute
Integral gain of 1 repeat per minute will increases the output by an amount equal to the P only response after one minute
Process upset occurs
Increasing Time
Minutes

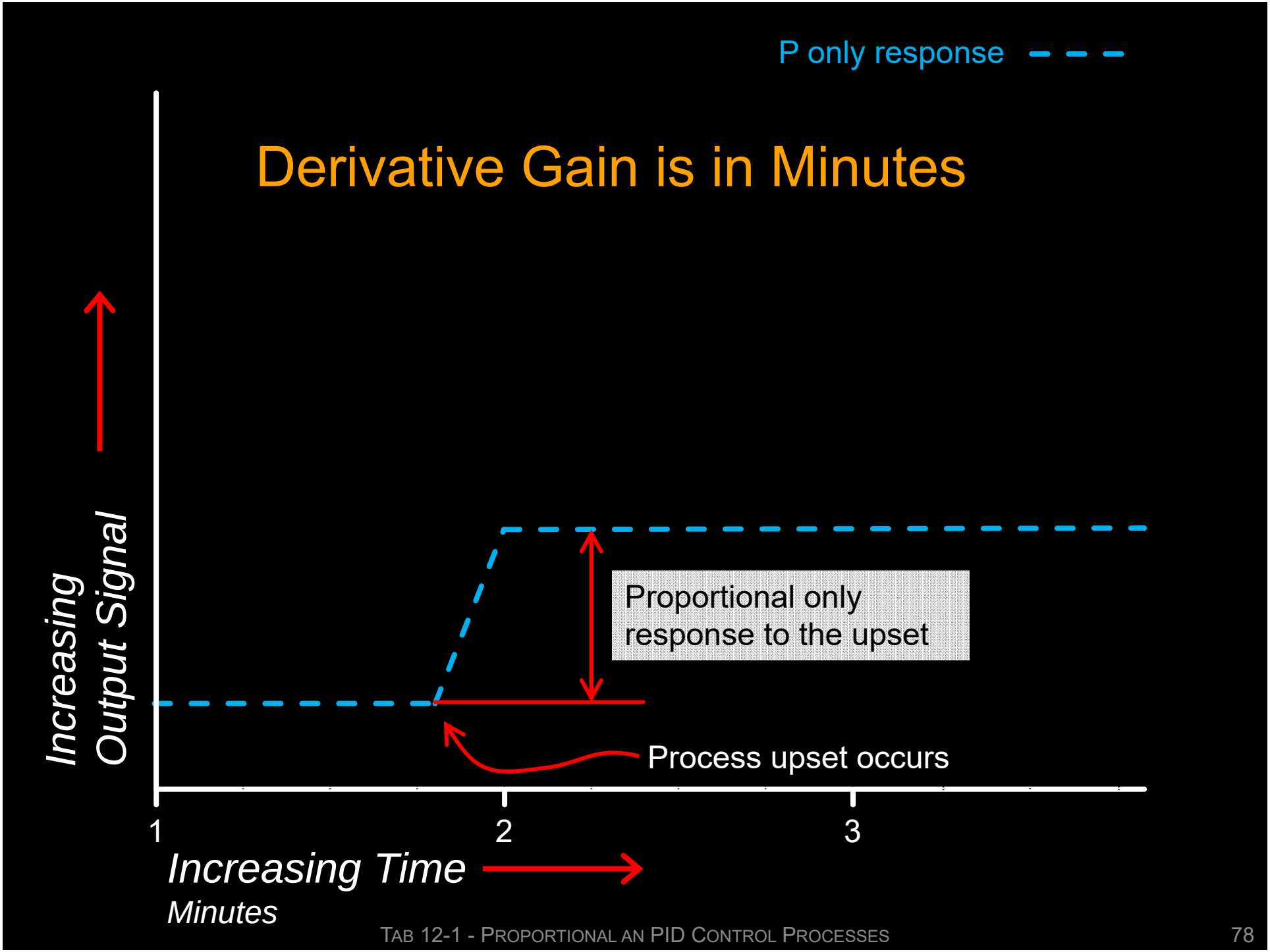
Potential Problems when Adding Integral Action

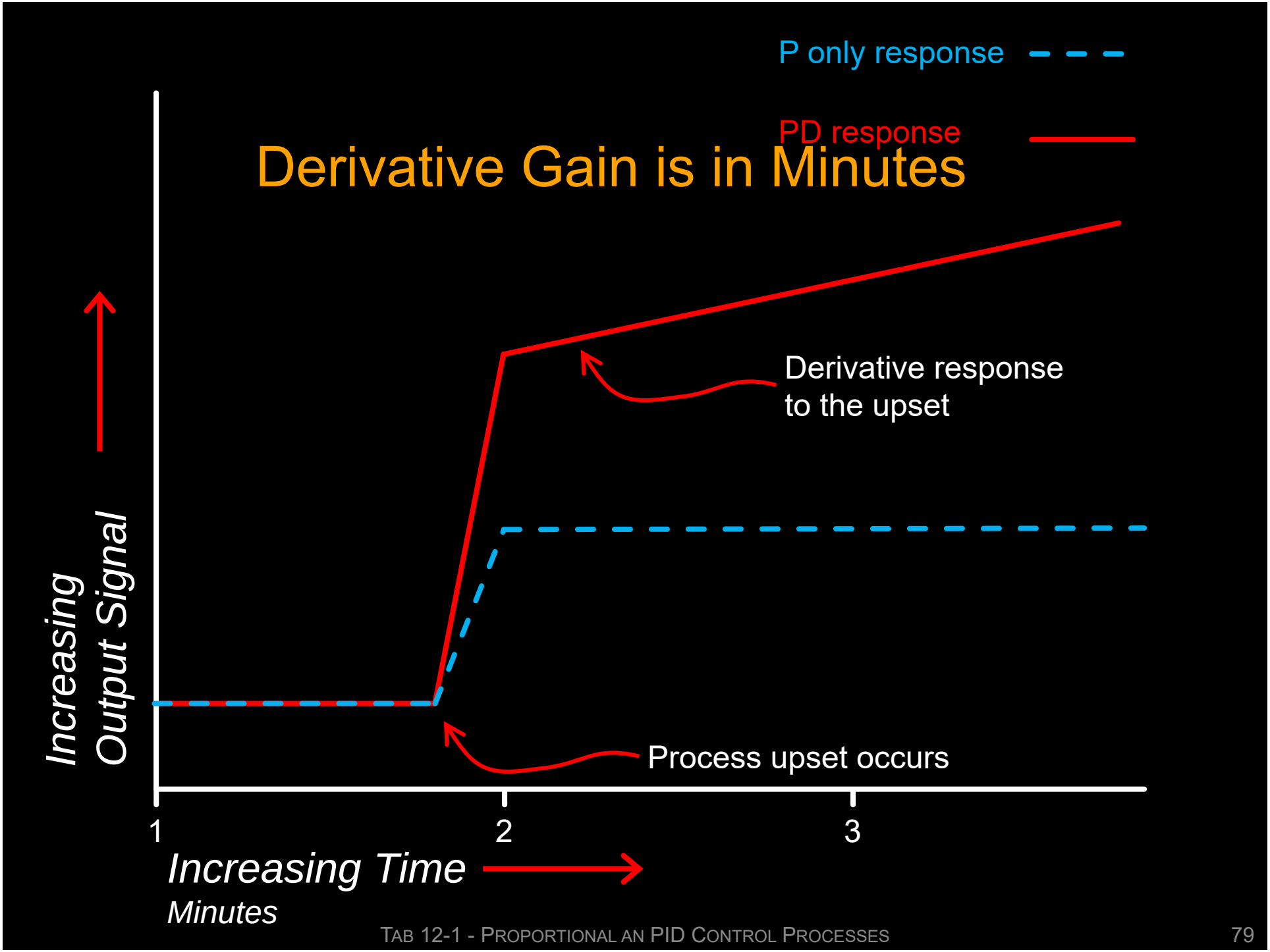
Loop instability unless a commensurate reduction in proportional gain is made

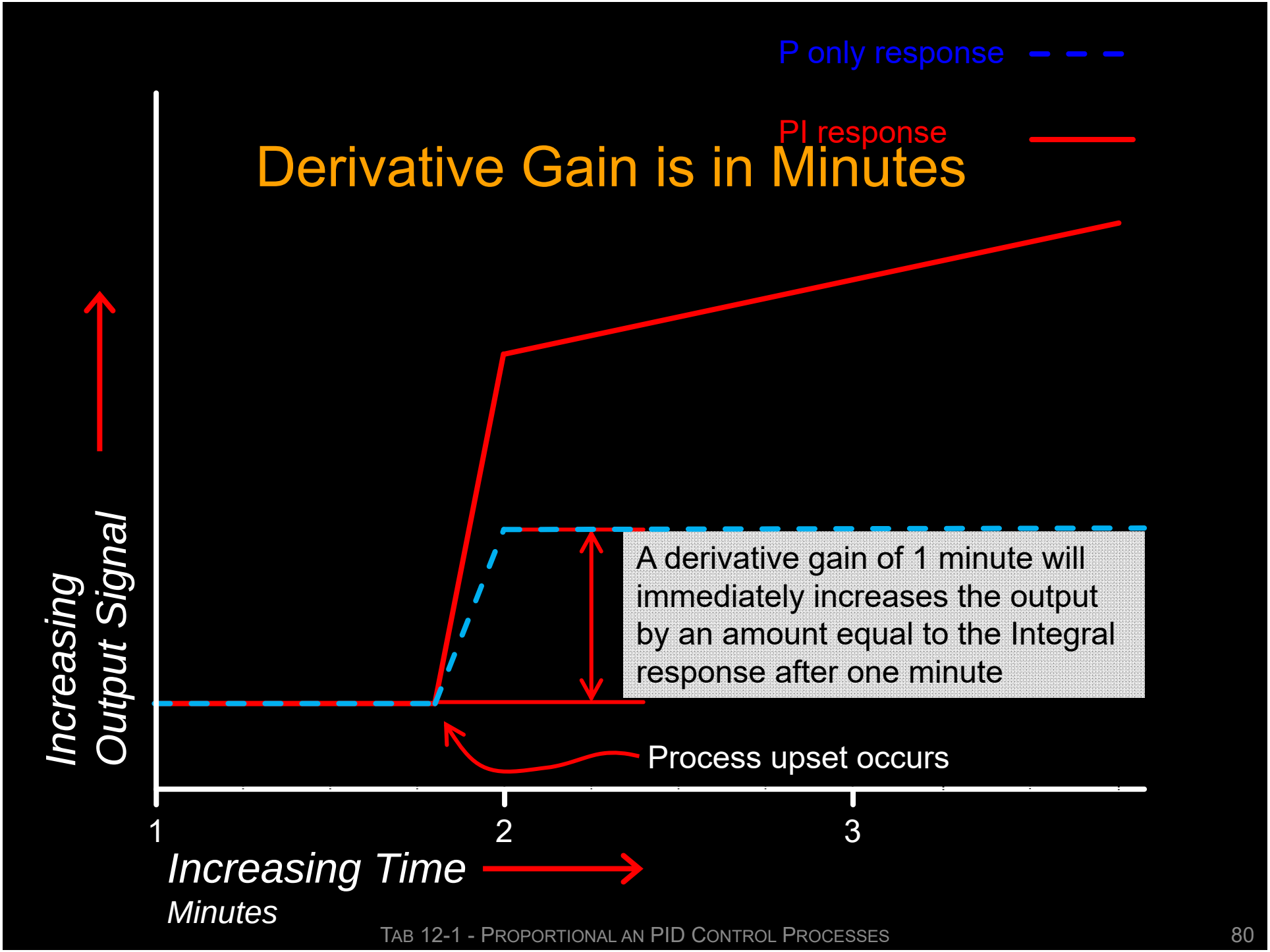
Tuning and maintenance become more complex, time consuming and difficult

“Wind-up” can occur

- During HVAC system overload conditions.
- During HVAC shut down if not handled appropriately


P only response
Derivative Gain is in Minutes
Increasing
Output Signal
Proportional only
response to the upset
Process upset occurs
1
2
3
Increasing Time
Minutes


P only response
PD response
Derivative Gain is in Minutes
Derivative response
to the upset
Process upset occurs
Increasing
Output Signal
1
2
3
Increasing Time
Minutes


P only response
PI response
Derivative Gain is in Minutes
Increasing Output Signal
A derivative gain of 1 minute will immediately increases the output by an amount equal to the Integral response after one minute
Process upset occurs
1
2
3
Increasing Time
Minutes

Derivative Action Is Difficult to Apply

Provides no benefit if there is not enough

Too much can cause many more problems than it is worth

Typically not necessary for HVAC applications

Use it with CAUTION!