Control Systems: Design, Performance and Commissioning Issues

Control Processes

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

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A Historical Perspective and A Look at Pneumatic Controls

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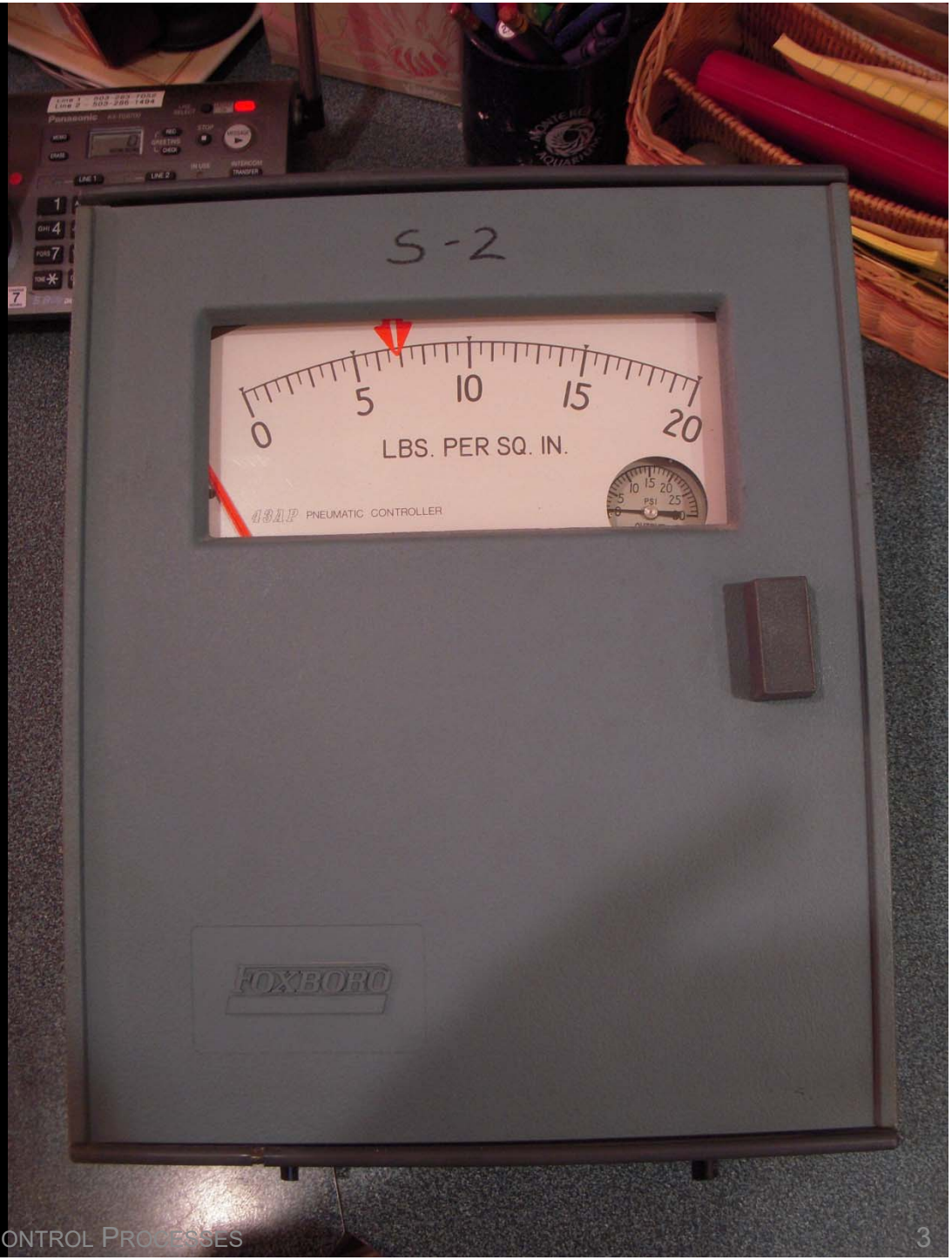
A 1950/60's Vintage Analog Controller



A 1950/60's Vintage Analog Controller

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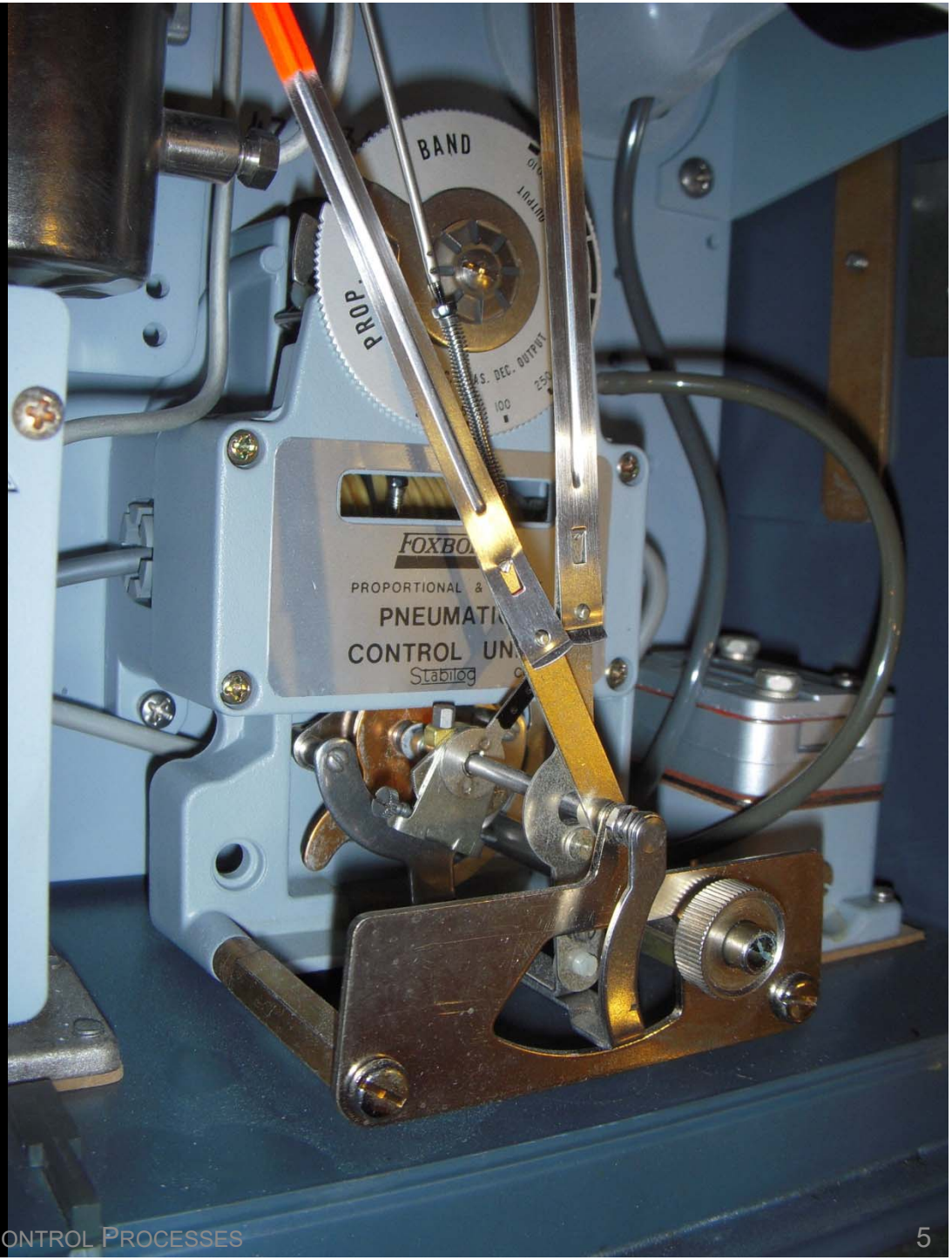

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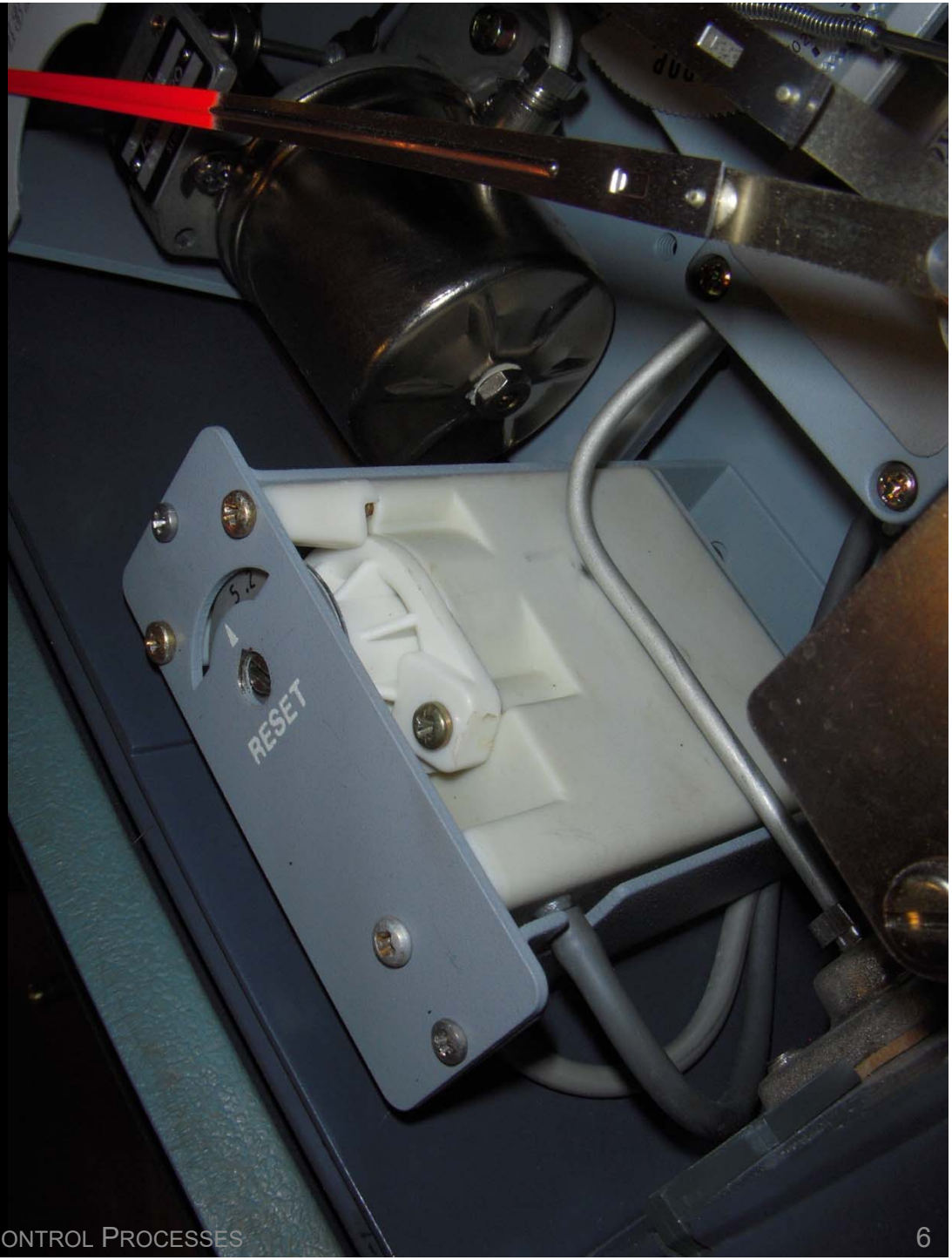

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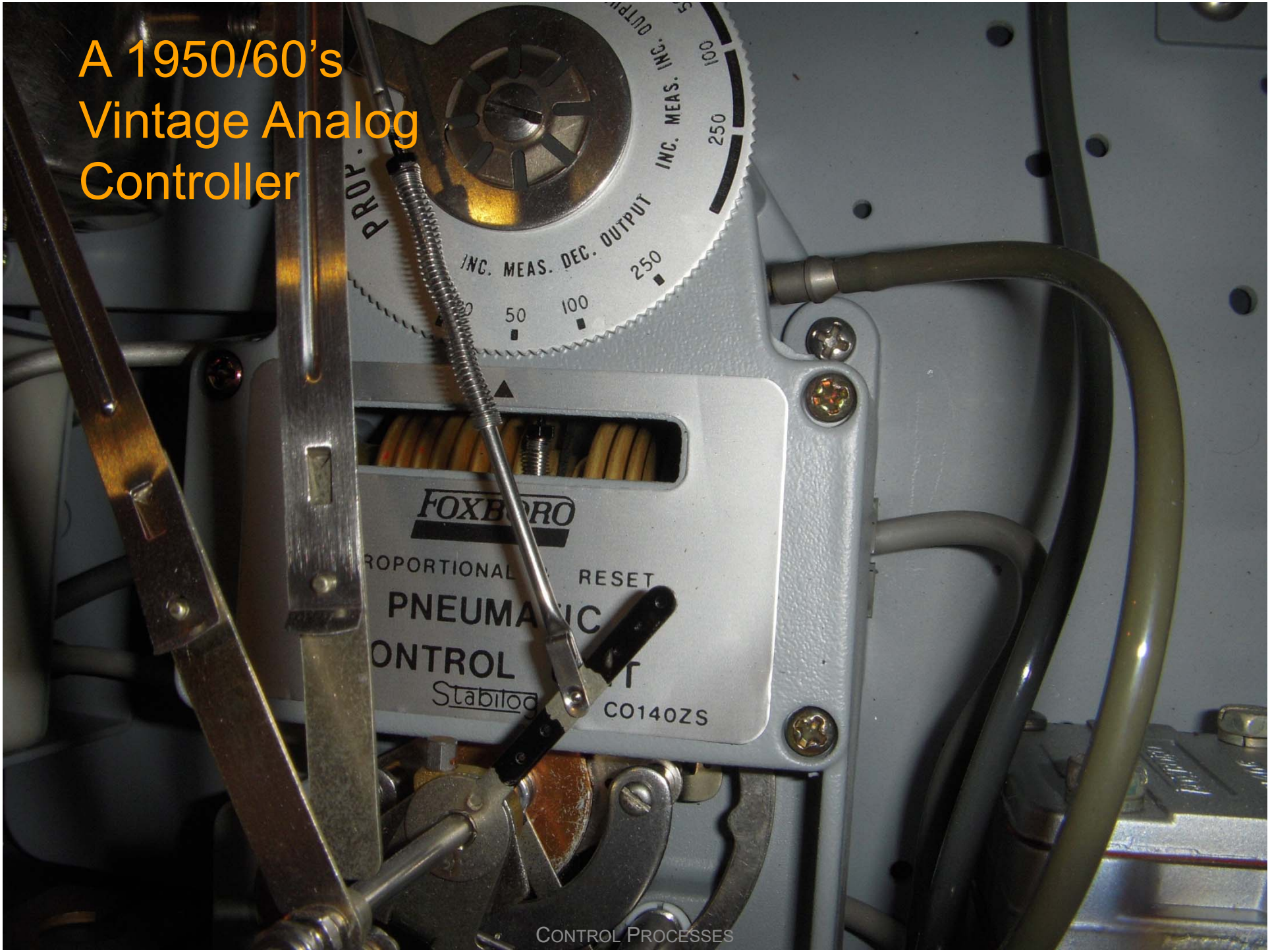

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Pneumatic Controllers in Action

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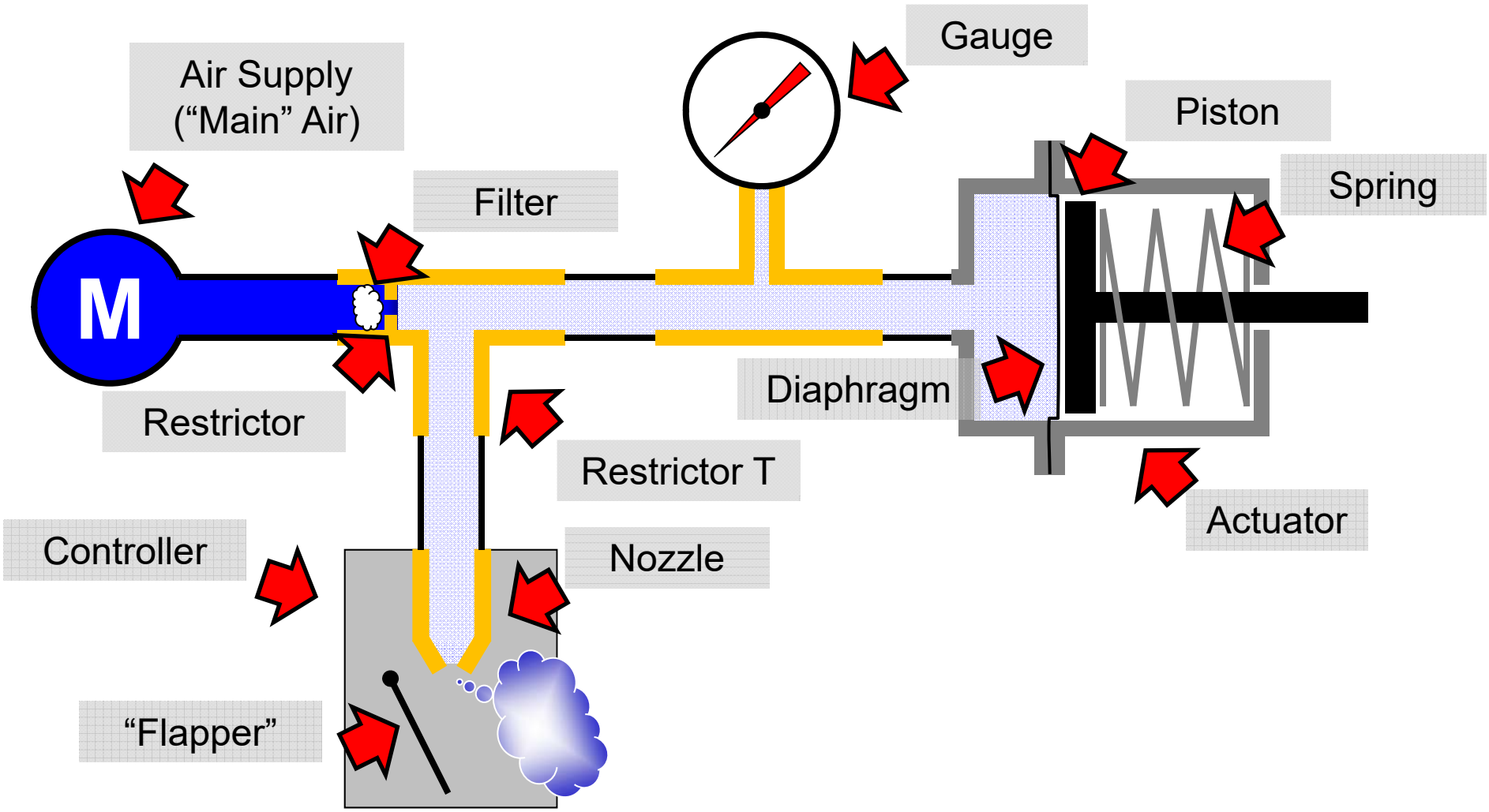
A Typical One Pipe Pneumatic Control System



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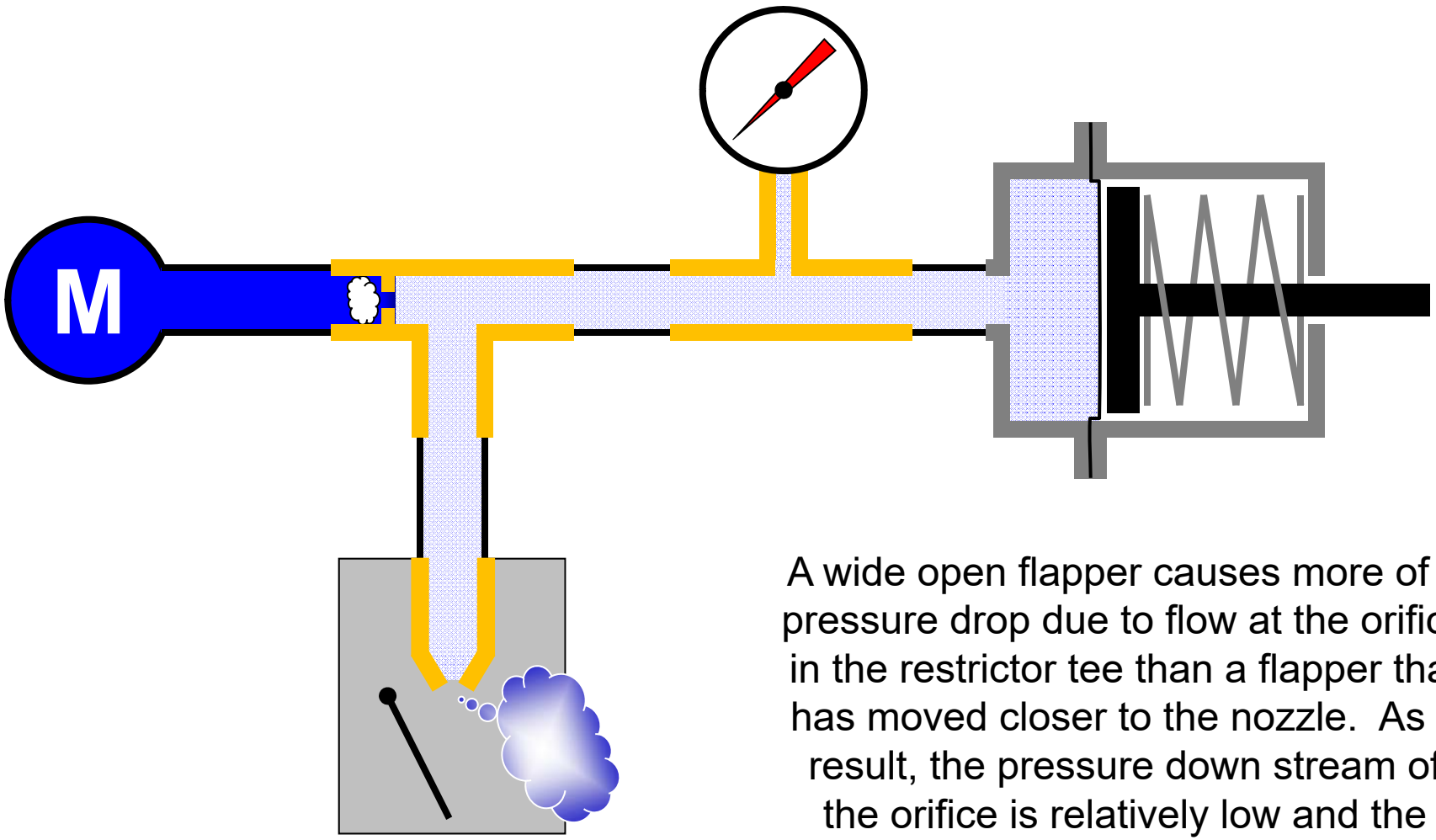
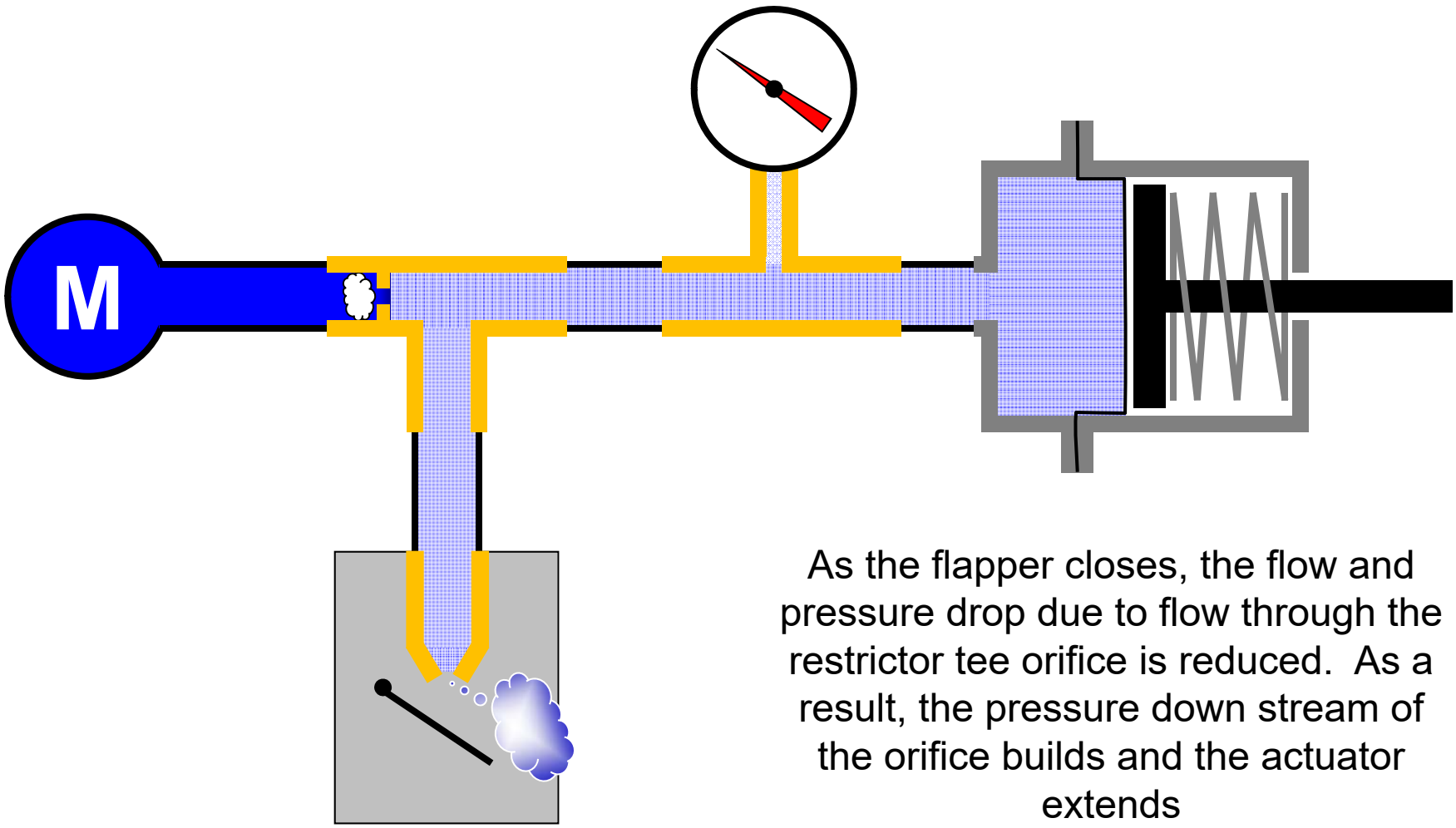


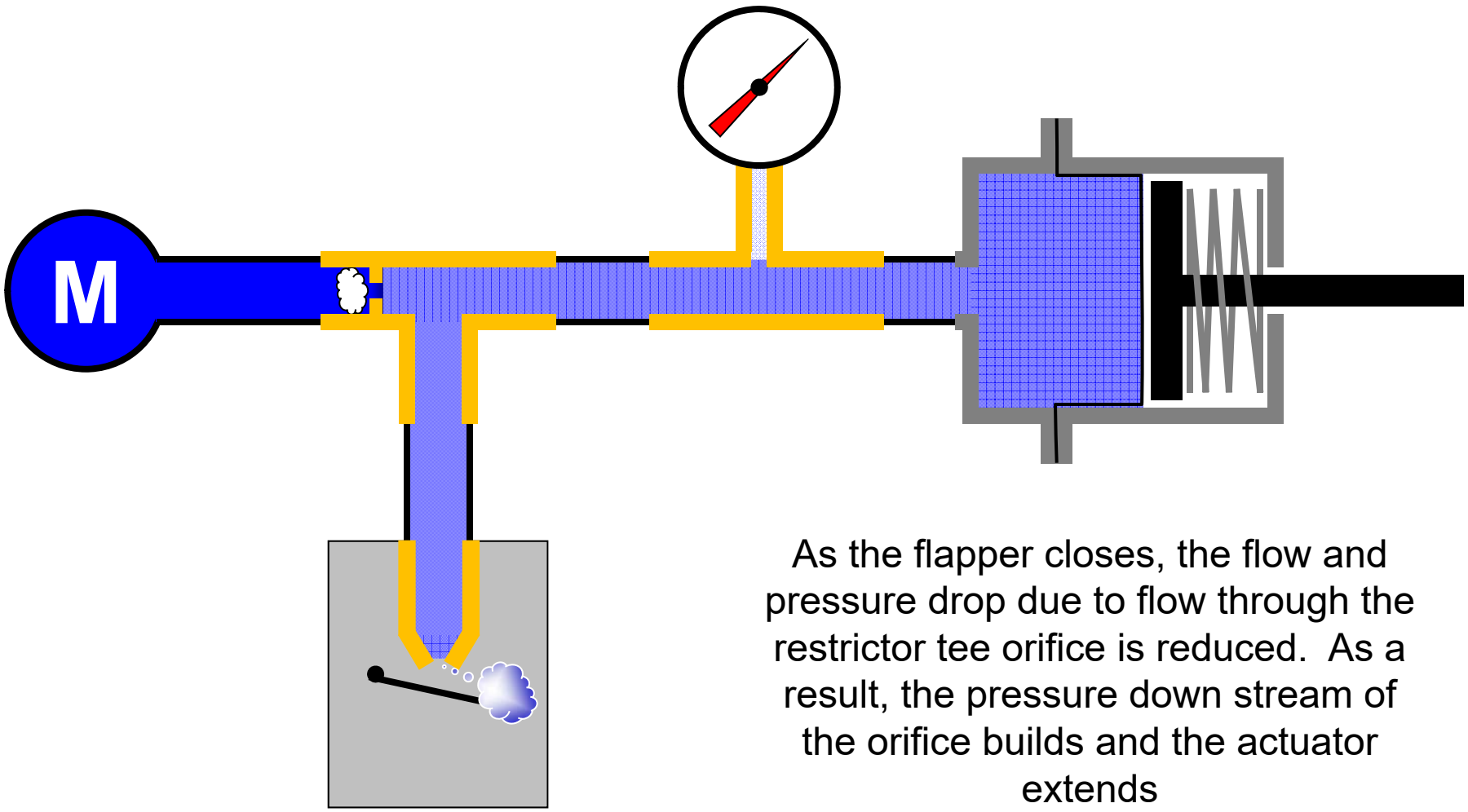
A wide open flapper causes more of a pressure drop due to flow at the orifice in the restrictor tee than a flapper that has moved closer to the nozzle. As a result, the pressure down stream of the orifice is relatively low and the actuator retracts

A Typical One Pipe Pneumatic Control System



As the flapper closes, the flow and pressure drop due to flow through the restrictor tee orifice is reduced. As a result, the pressure down stream of the orifice builds and the actuator extends

A Typical One Pipe Pneumatic Control System



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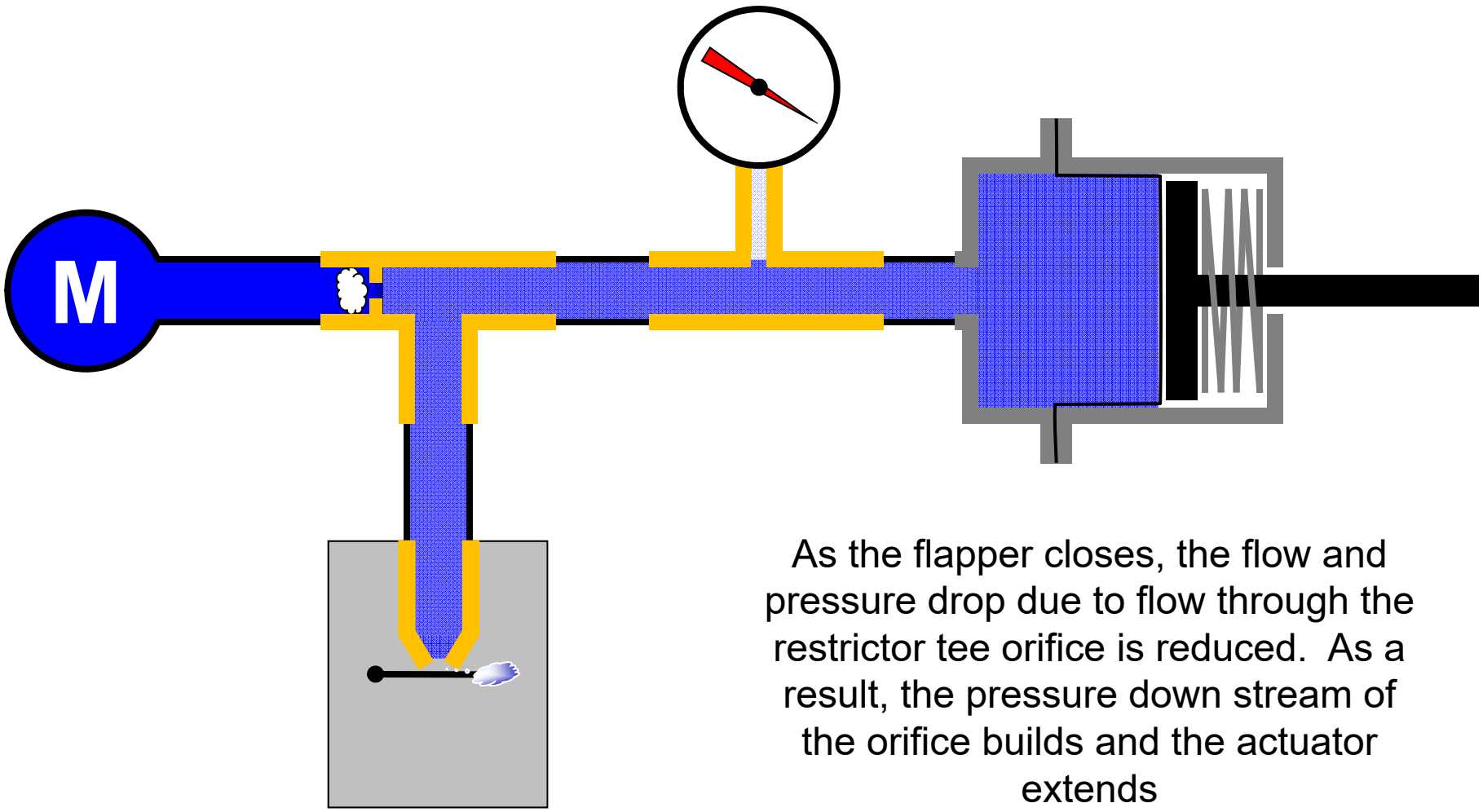

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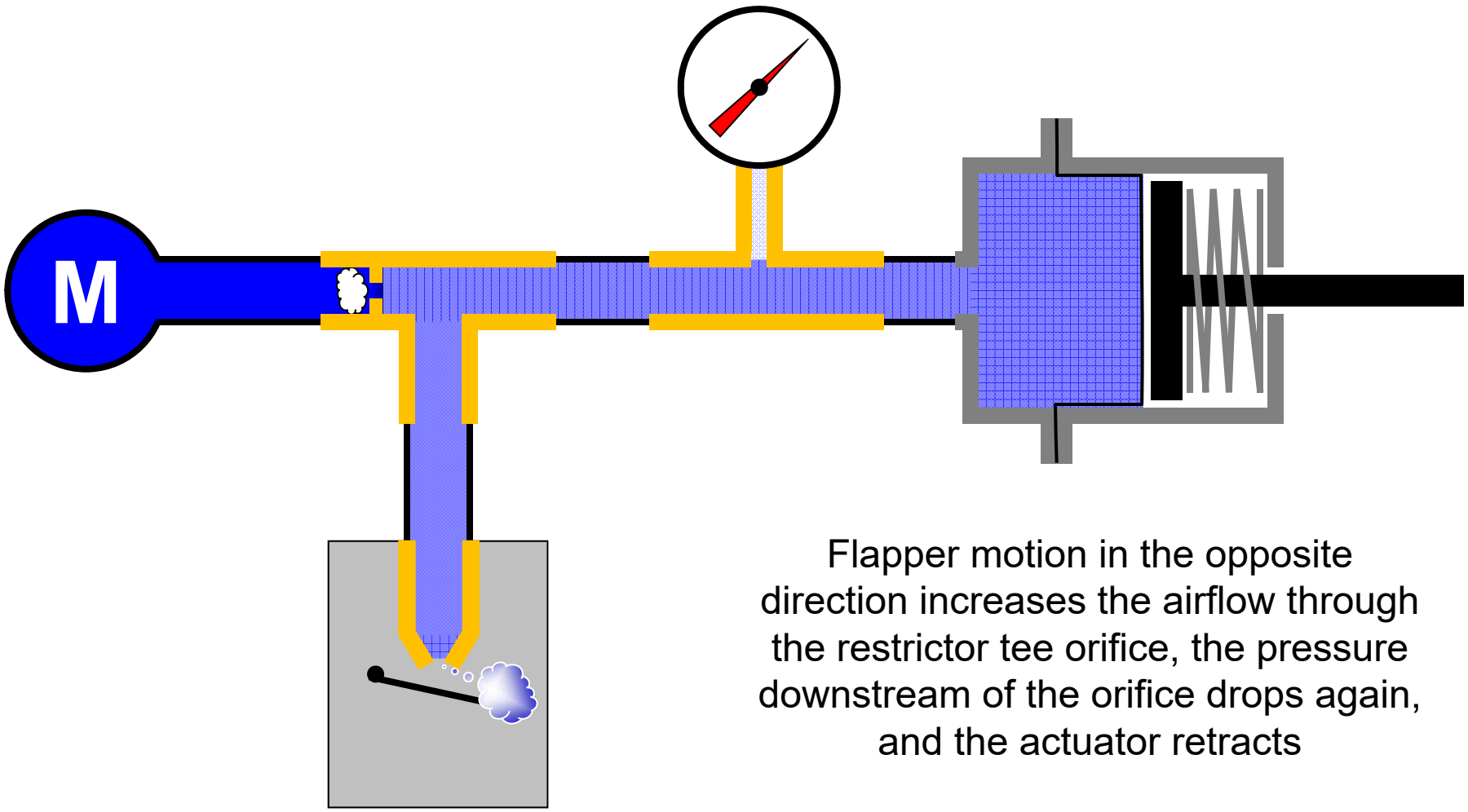

Flapper motion in the opposite direction increases the airflow through the restrictor tee orifice, the pressure downstream of the orifice drops again, and the actuator retracts

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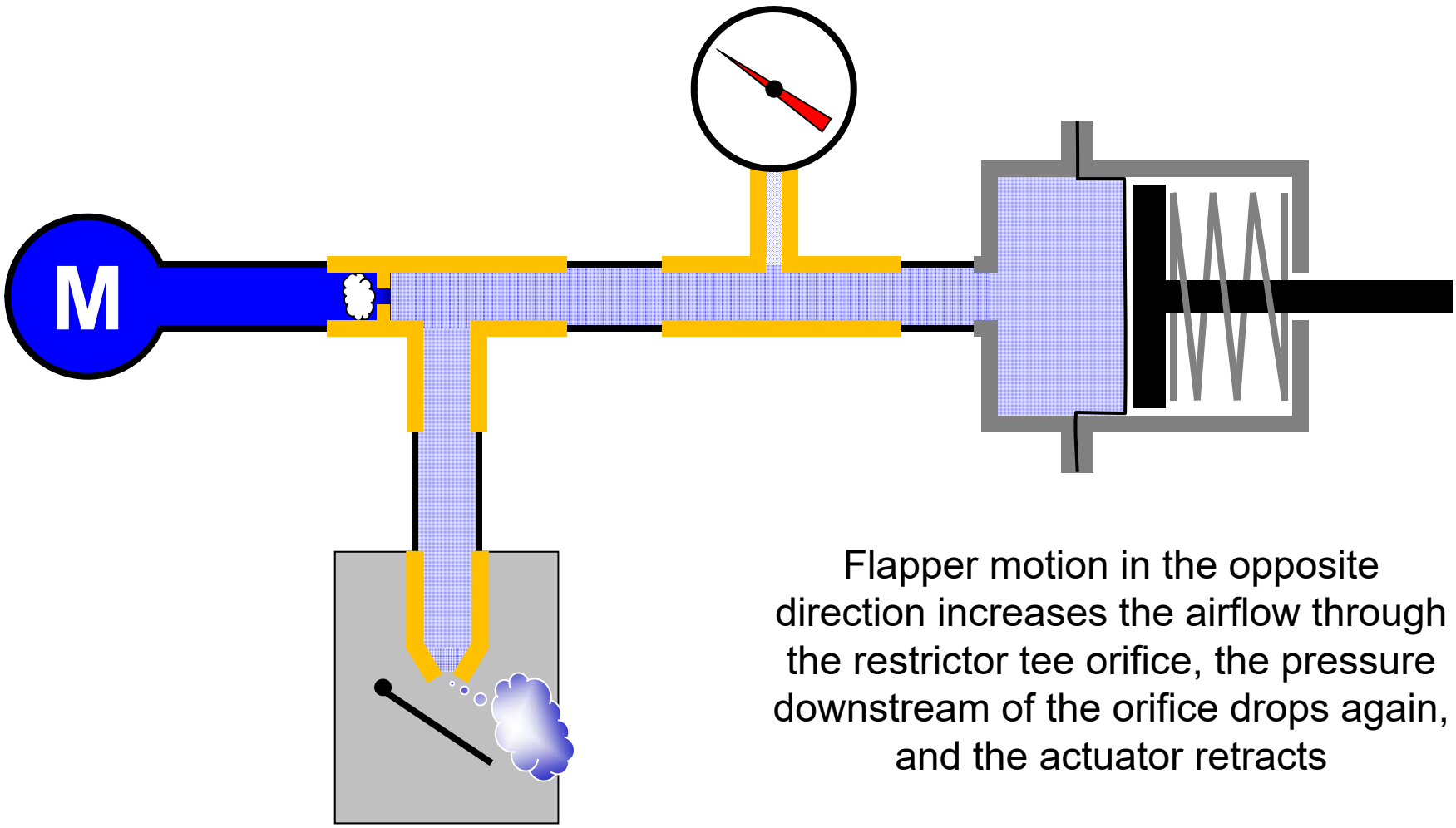

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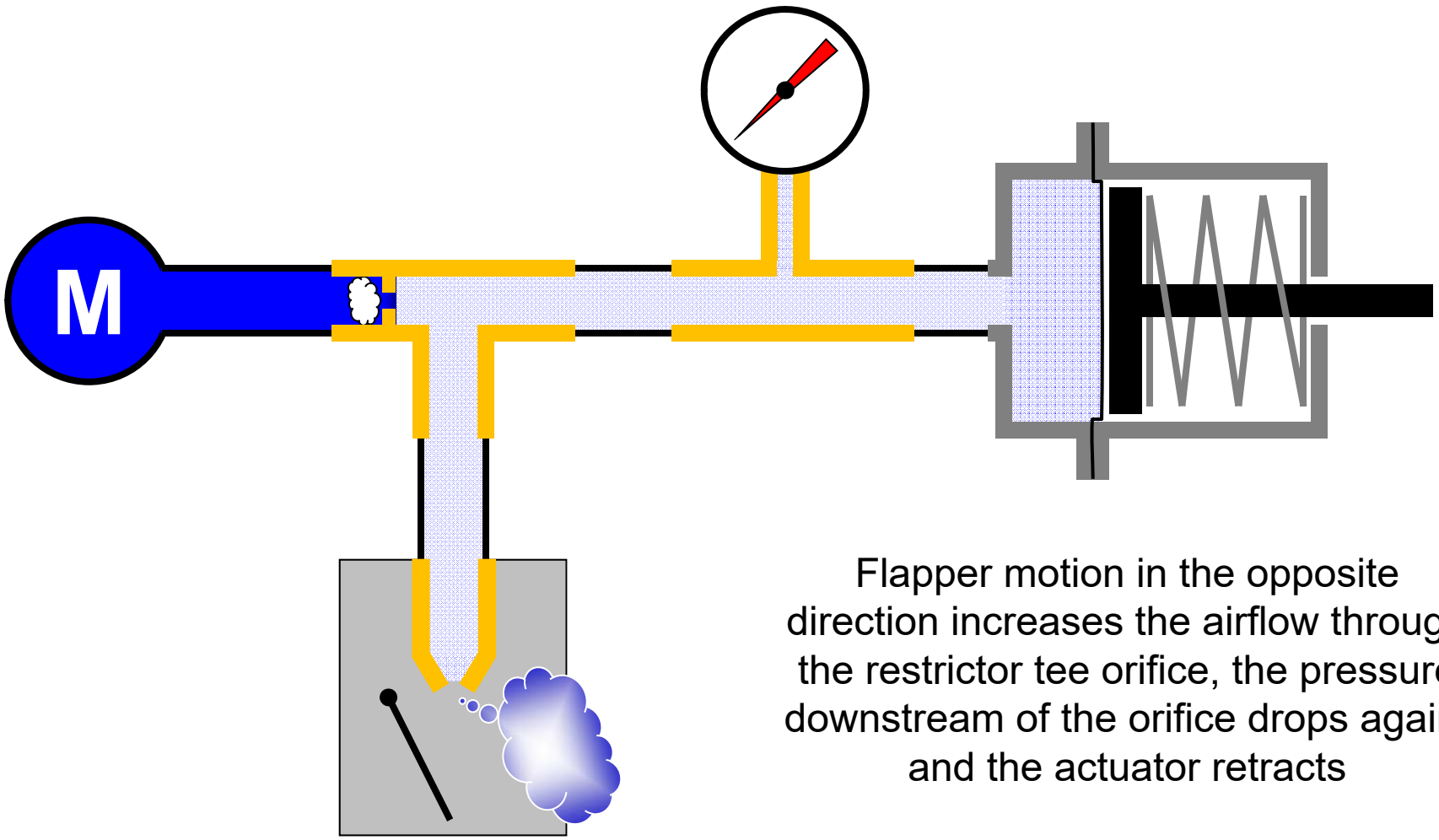

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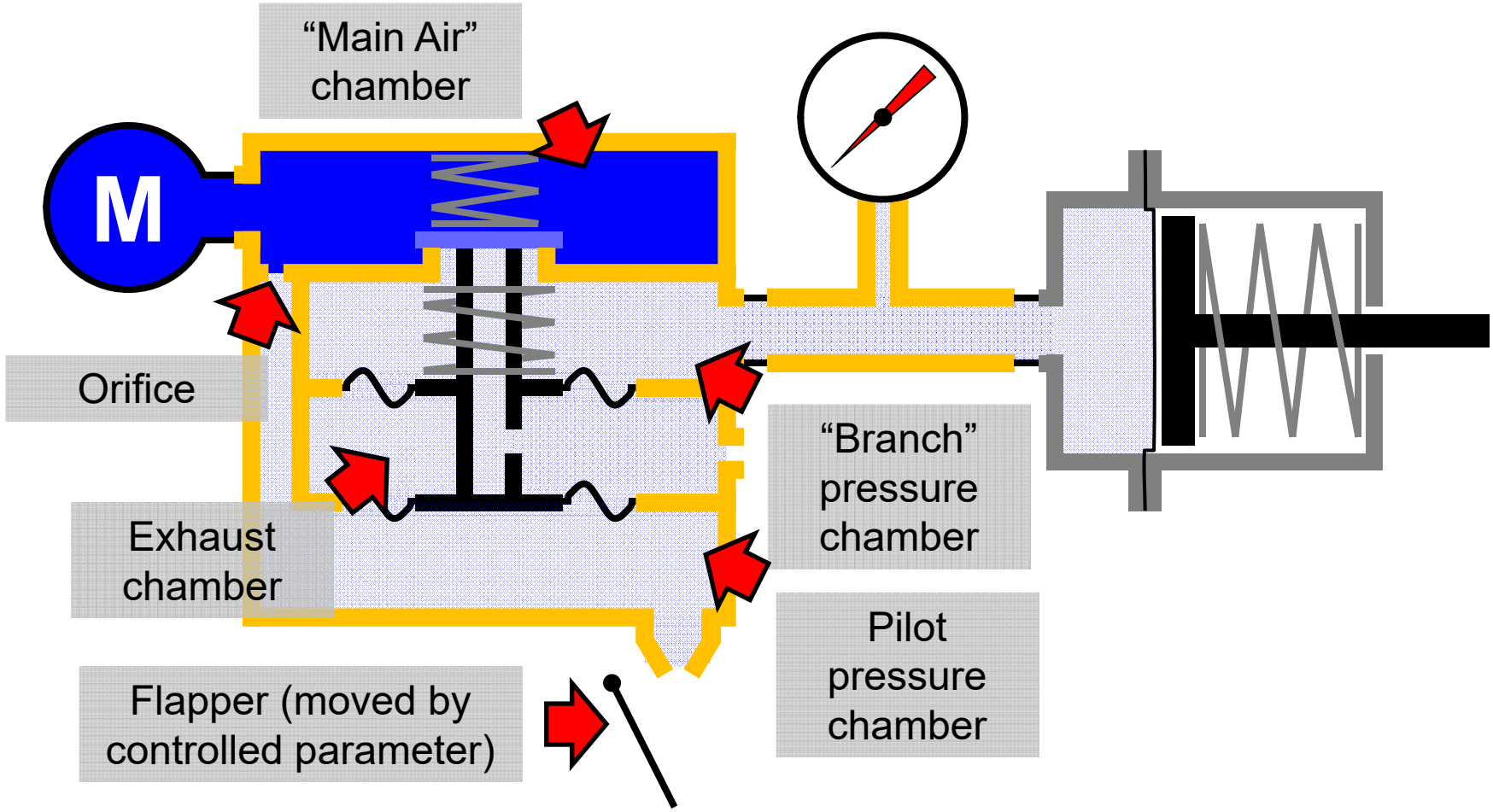
A Typical Two Pipe Pneumatic Control System



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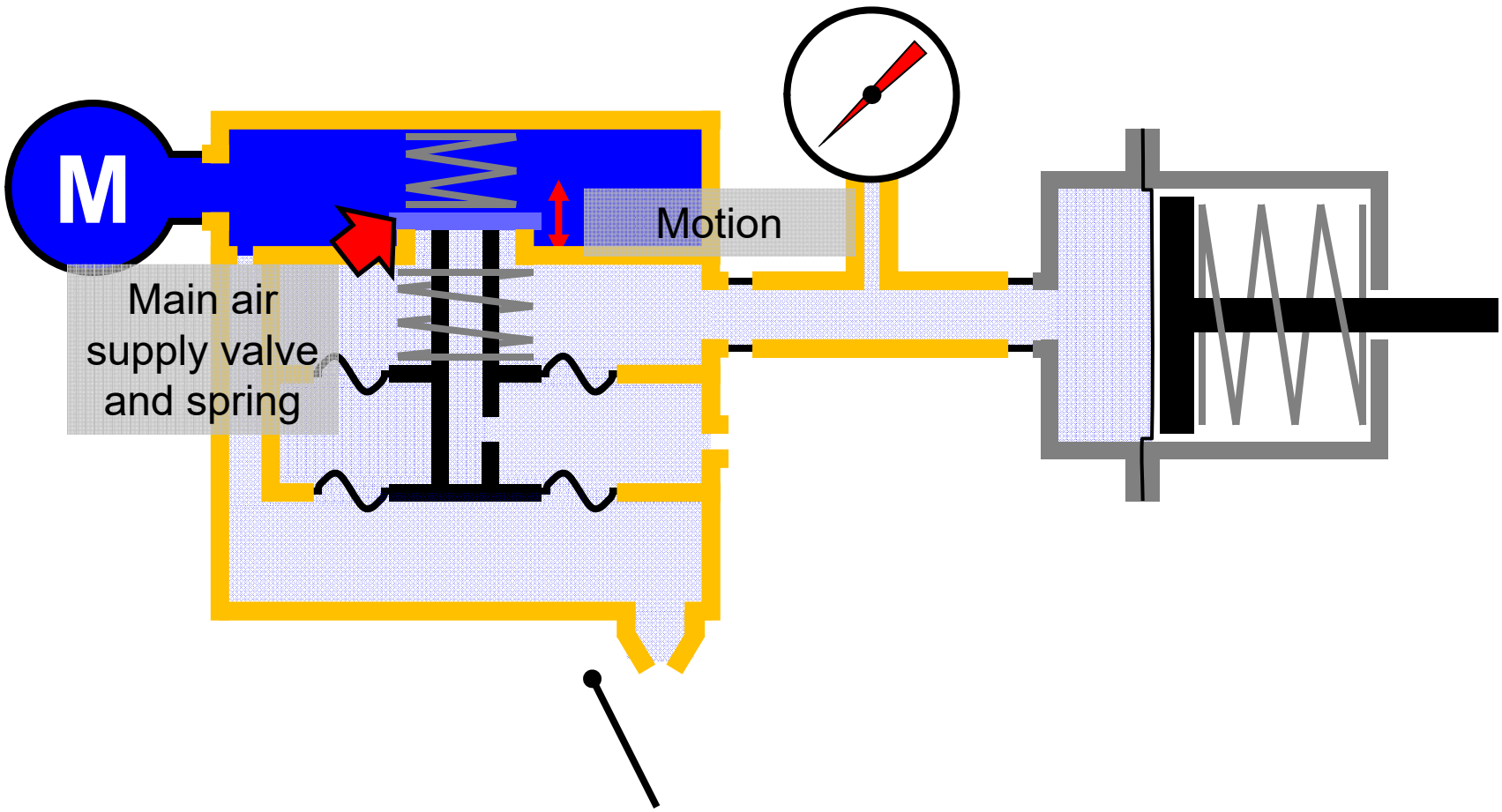

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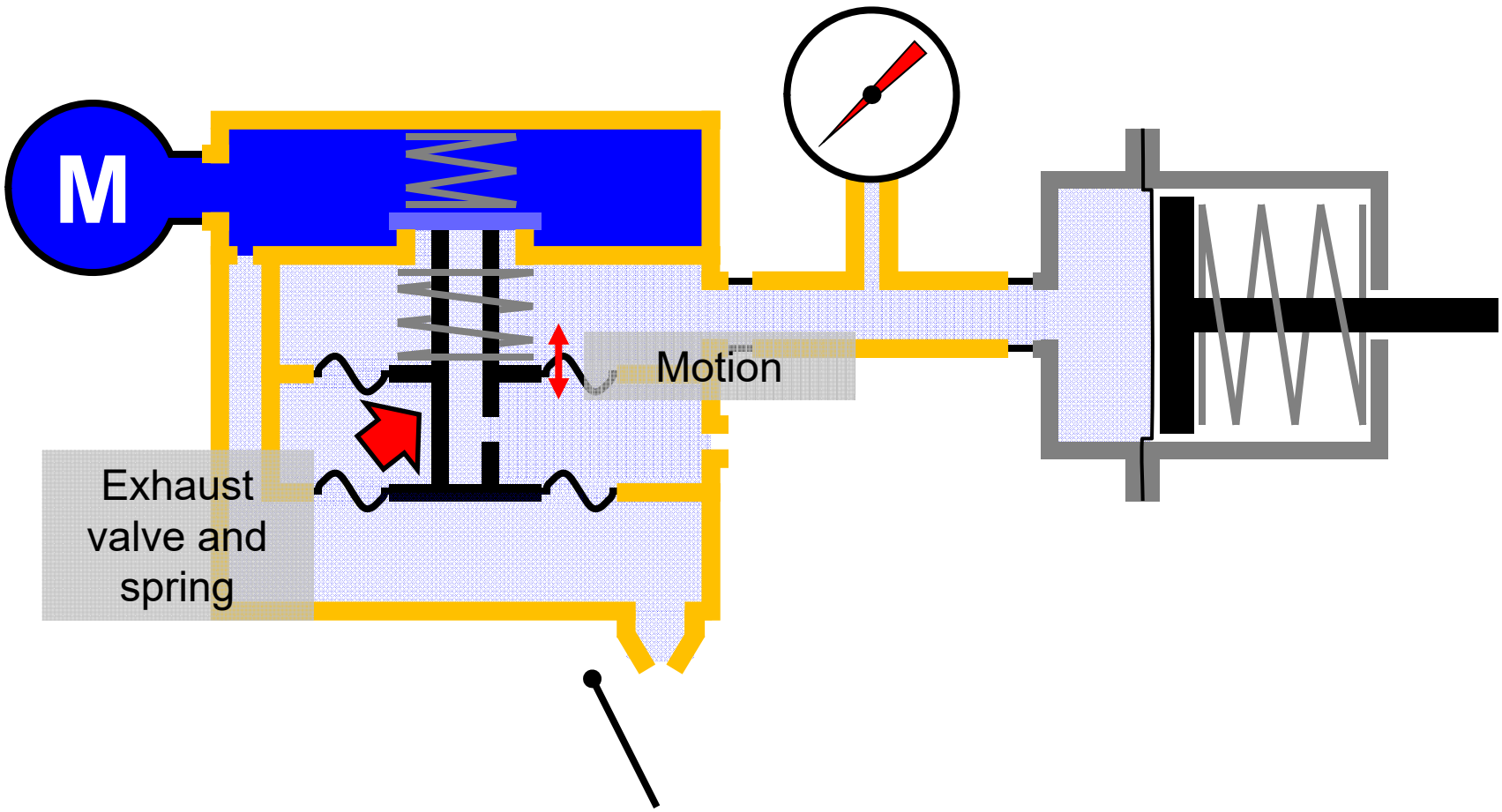

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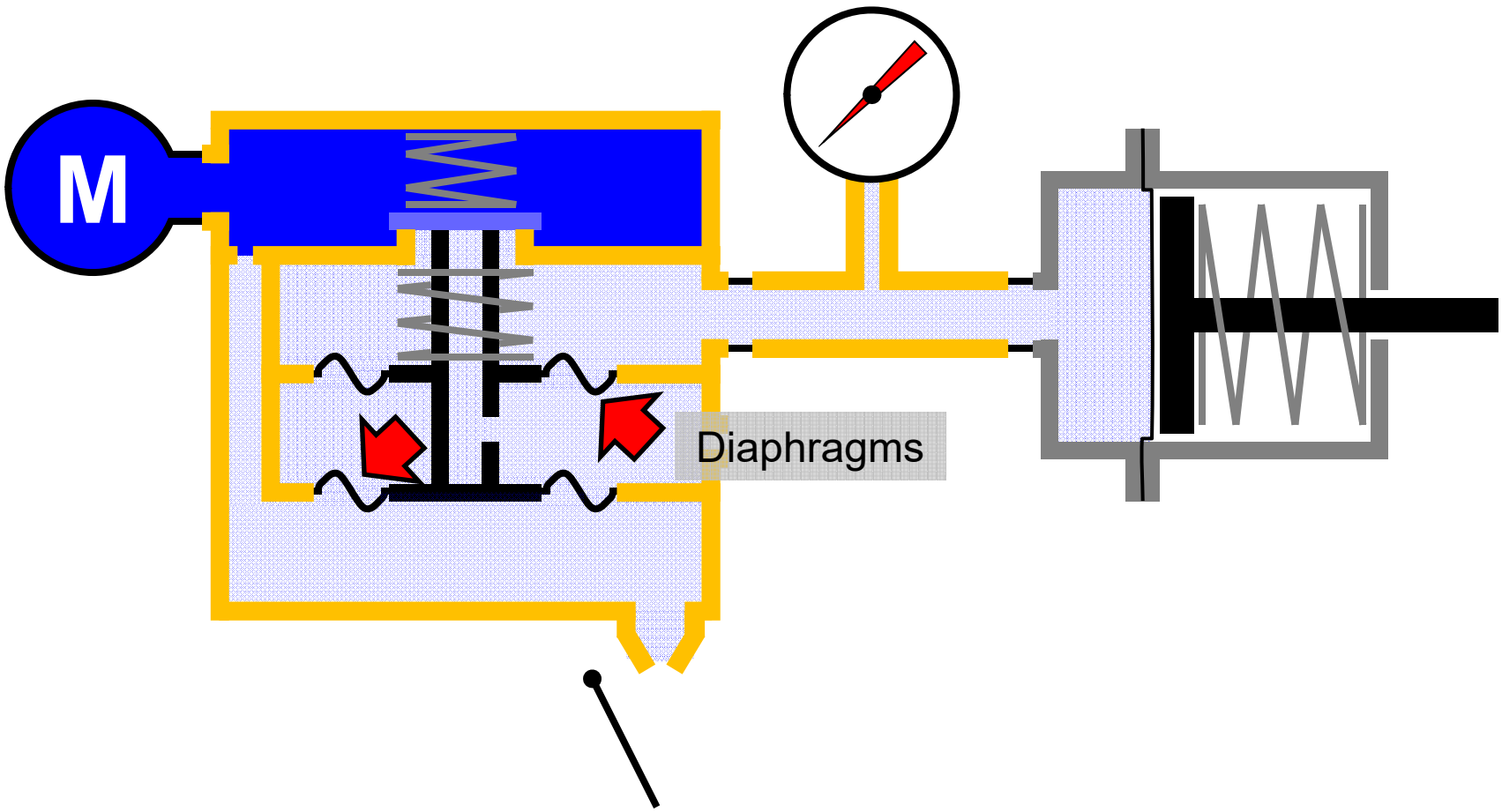

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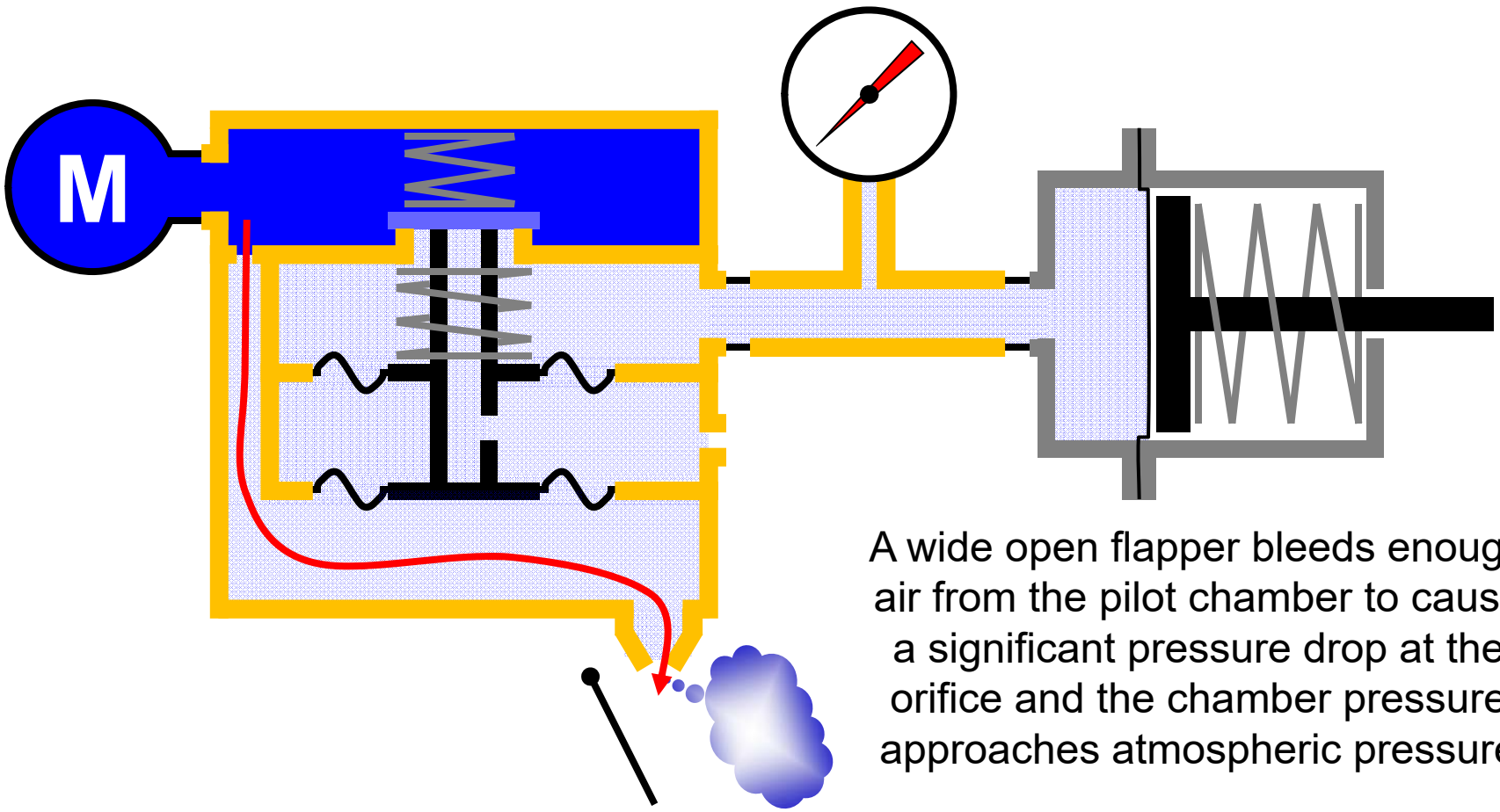
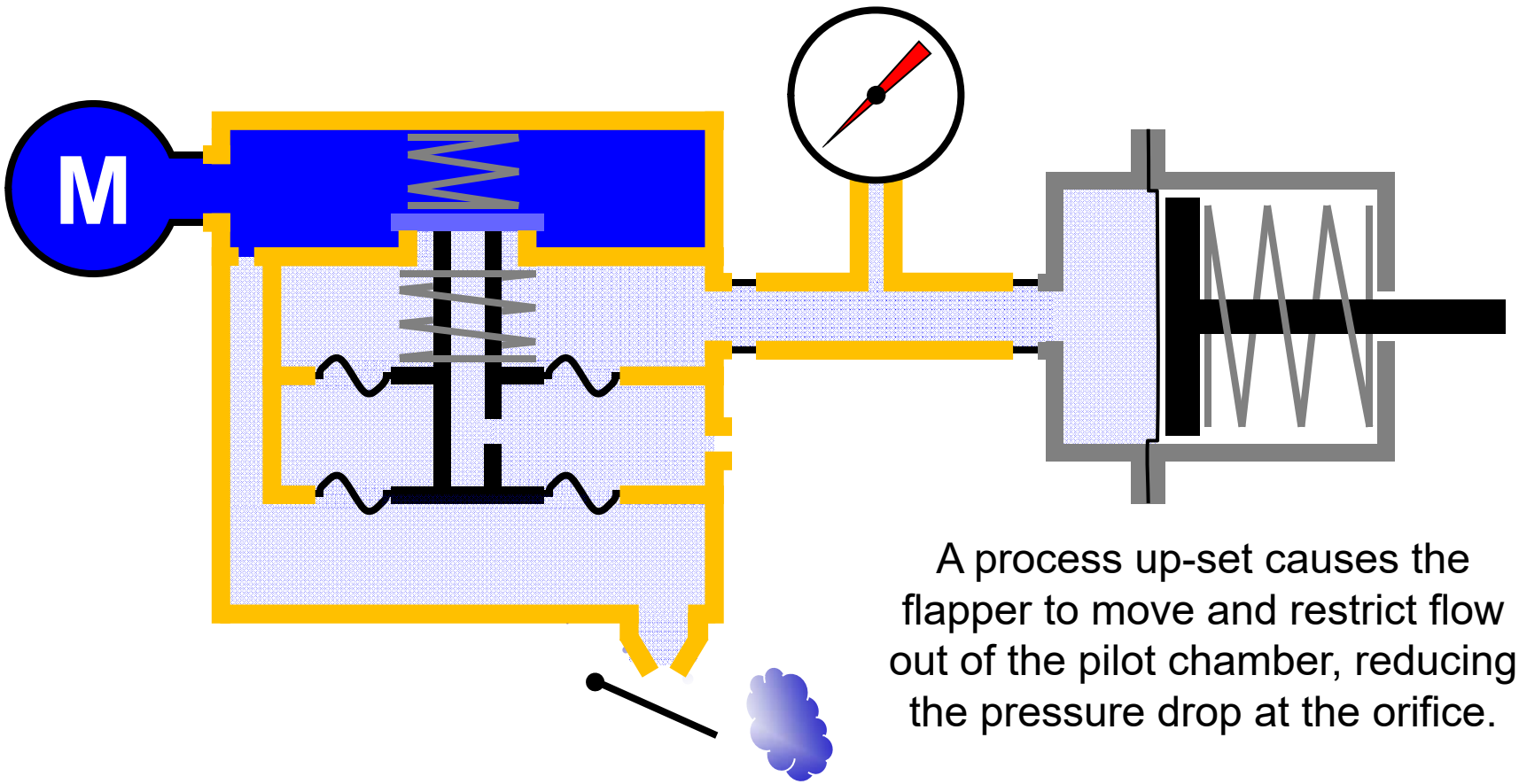


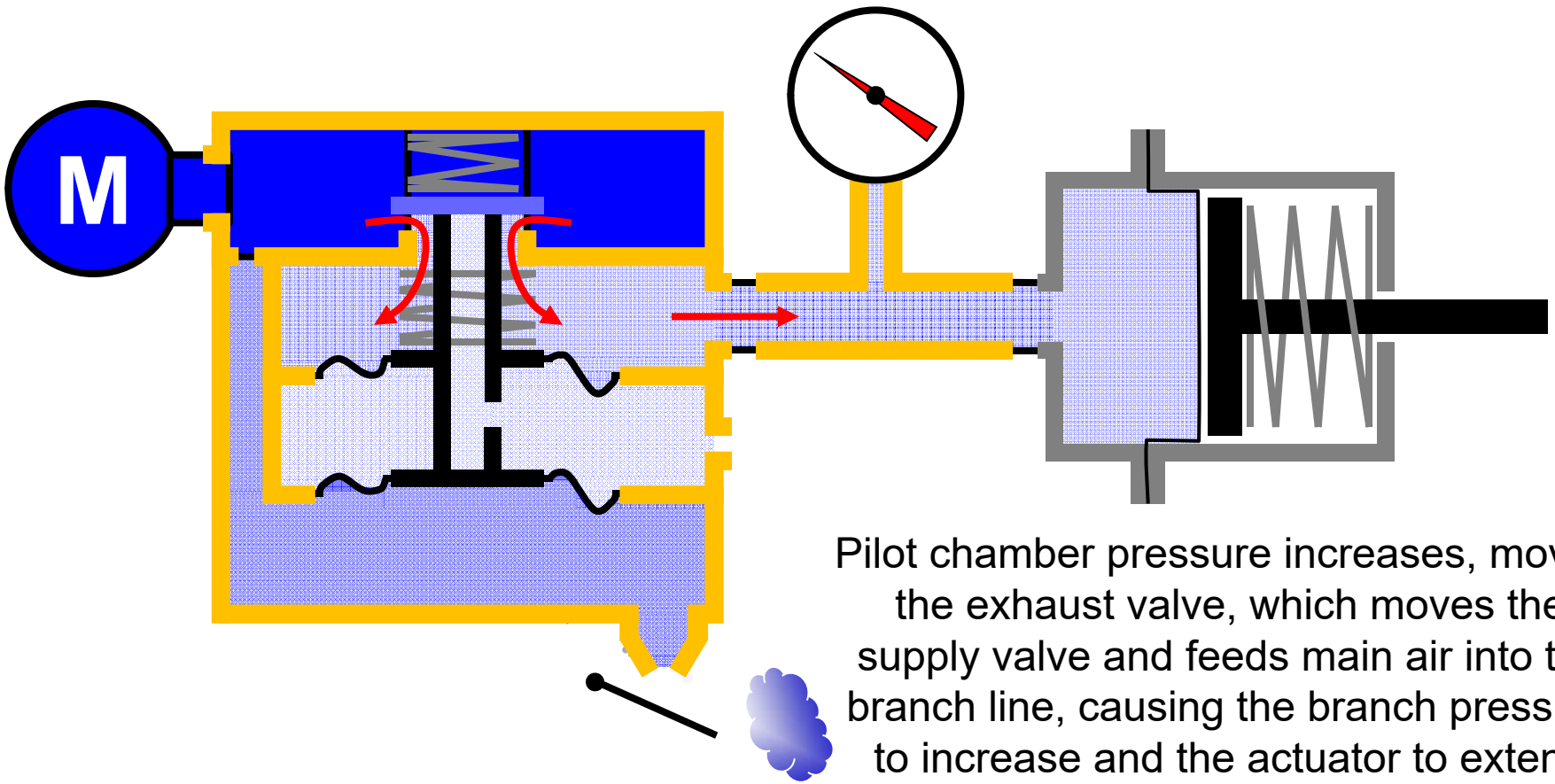
A wide open flapper bleeds enough air from the pilot chamber to cause a significant pressure drop at the orifice and the chamber pressure approaches atmospheric pressure

A Typical Two Pipe Pneumatic Control System



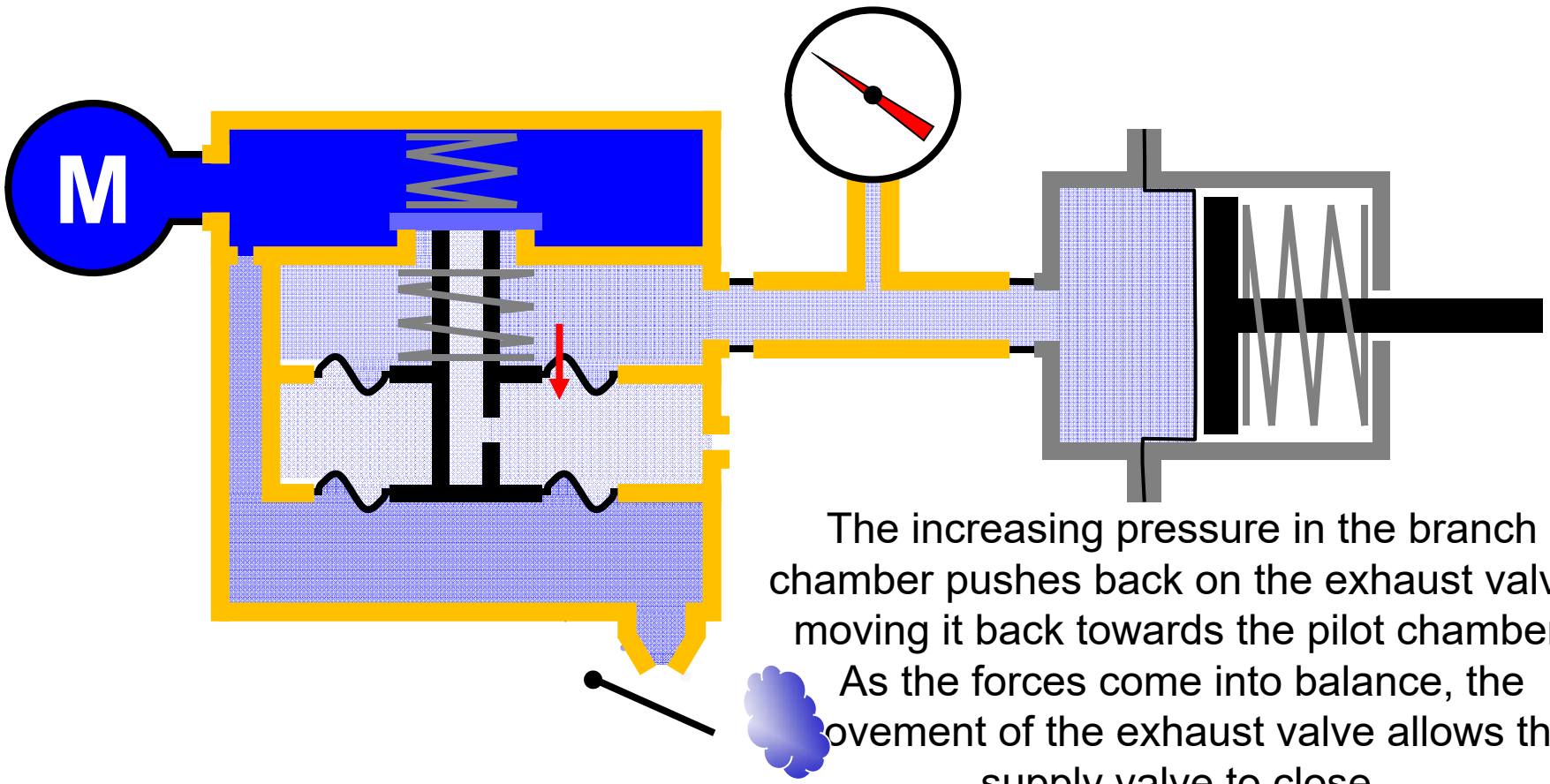
A process up-set causes the flapper to move and restrict flow out of the pilot chamber, reducing the pressure drop at the orifice.

A Typical Two Pipe Pneumatic Control System



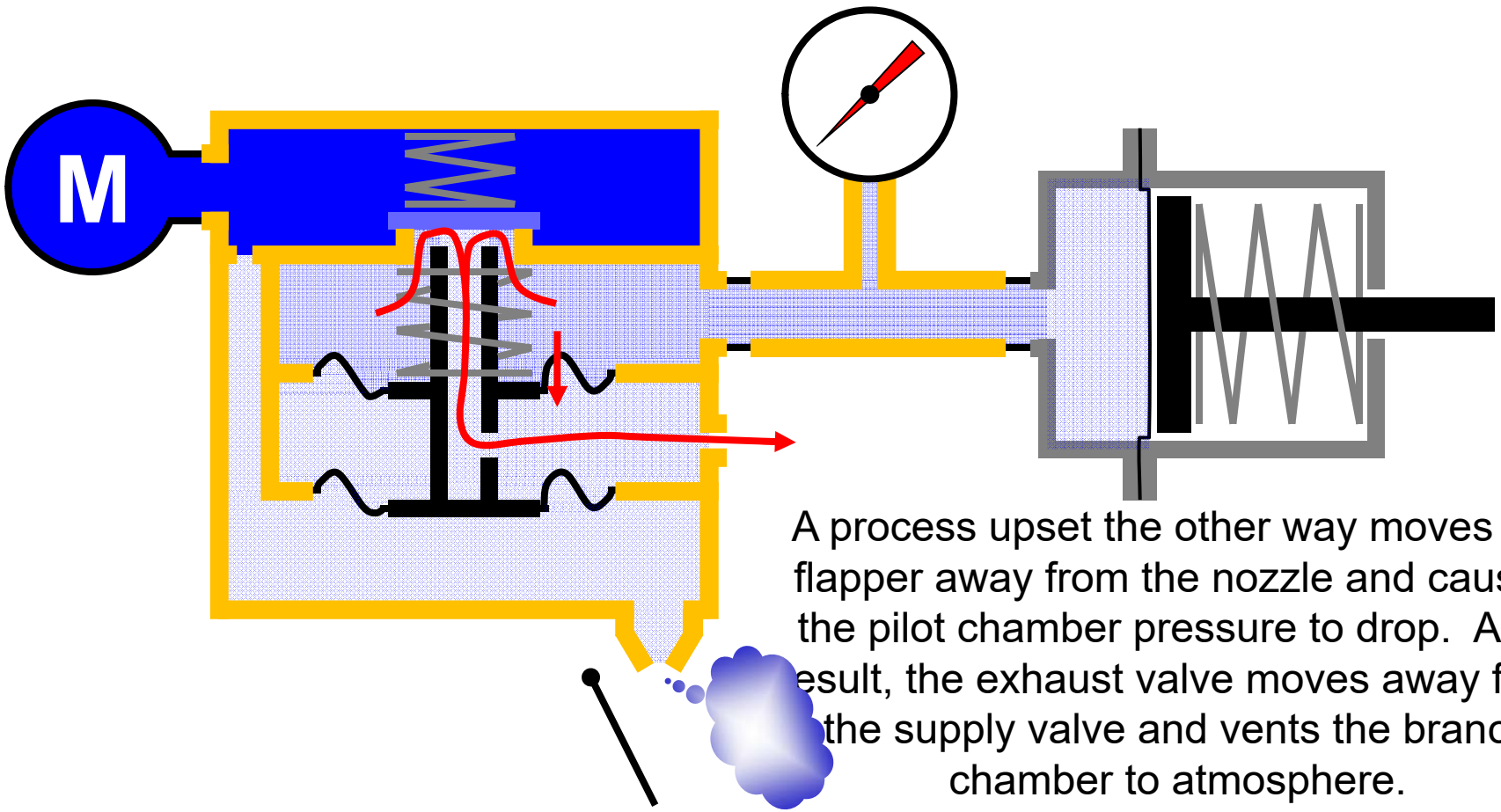
Pilot chamber pressure increases, moving the exhaust valve, which moves the supply valve and feeds main air into the branch line, causing the branch pressure to increase and the actuator to extend

A Typical Two Pipe Pneumatic Control System



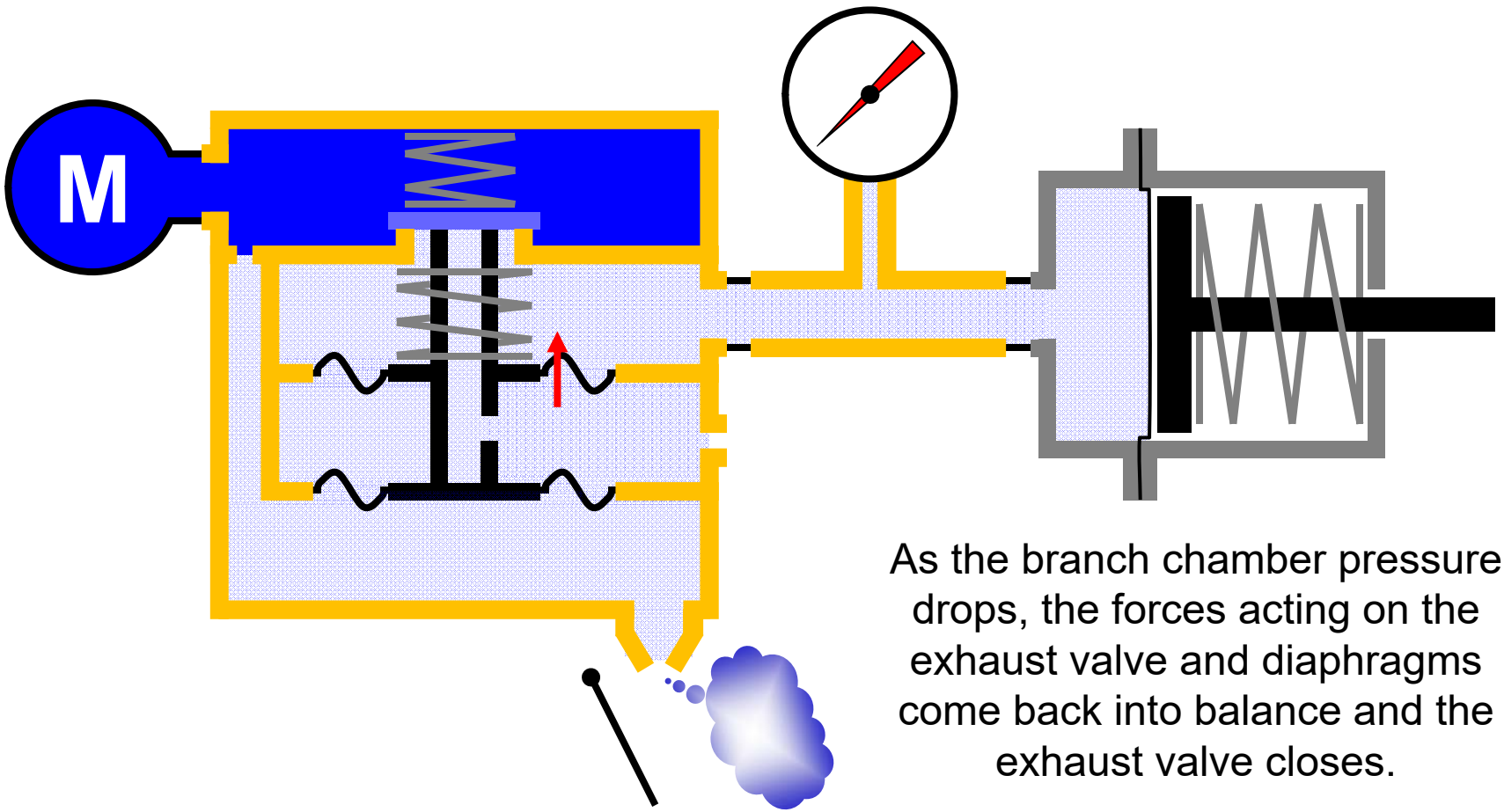
The increasing pressure in the branch chamber pushes back on the exhaust valve, moving it back towards the pilot chamber. As the forces come into balance, the movement of the exhaust valve allows the supply valve to close.

A Typical Two Pipe Pneumatic Control System



A process upset the other way moves the flapper away from the nozzle and causes the pilot chamber pressure to drop. As a result, the exhaust valve moves away from the supply valve and vents the branch chamber to atmosphere.

A Typical Two Pipe Pneumatic Control System



As the branch chamber pressure drops, the forces acting on the exhaust valve and diaphragms come back into balance and the exhaust valve closes.

One Pipe vs. Two Pipe Pneumatic Thermostats

One Pipe Thermostats

1. Inexpensive and simple
2. High air consumption
3. Sensitive to leaks
4. Restrictor tees that can:
    1. Plug
    2. Require periodic replacement
    3. Are difficult to find
5. Branch line length to the sensor can impact accuracy
6. Branch line length impacts lags
7. Mechanical devices
8. Operate on very small force differentials
9. Pivot points, linkages and diaphragms that can wear

Two Pipe Thermostats

1. More expensive and complex
2. Lower air consumption
3. Tolerate leaks
4. No restrictor tees
5. Branch line length has no accuracy impact
6. Branch line length impacts lags
7. Mechanical devices
8. Operate on very small force differentials
9. Pivot points, linkages and diaphragms that can wear

Pneumatic Controls vs. Pneumatic Actuation

Pneumatic Controls

1. Complex
2. Operate on very small force differentials
3. Potentially slow reaction times due to orifices
4. Pivot points, linkages and diaphragms that can wear
5. Consume air continuously due to pilot valves and bleed orifices
6. Dirty air leads to system wide failures
7. Mechanical devices

Pneumatic Actuation

1. Simple
2. Can generate large forces
3. Can move very quickly
4. Very few moving parts and moving parts are simple
5. Only consume air (energy) when they move
6. Tolerate dirty air
7. Mechanical devices
8. Require a separate air system and signal convertors when applied when with DDC technology

Electric Actuators vs. Pneumatic Actuators

Electric Actuation

1. Complex
2. Use small, low power motors to allow wiring without conduit
3. Slow because of gear trains required by small motors
4. Many moving parts; gears, clutches end switches etc.
5. Consume power continuously if they are holding against a spring
6. Mechanical devices
7. No air system required (but power distribution panels required for zones to comply with NEC article 725 requirements for the energy limited required for wiring with out conduit

Pneumatic Actuation

1. Simple
2. Can generate large forces
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7. Require a separate air system and signal convertors when applied when with DDC technology

Electric Actuators vs. Pneumatic Actuators

Electric Actuation

1. Complex
2. Motors are small/not powerful to allow low-voltage wiring (no conduit)
3. Small motors require
4. Consume power continuously if they are holding against a spring
5. Dirty air leads to system wide failures
6. Mechanical devices

Pneumatic Actuation

1. Simple
2. Can generate large forces and move very quickly
3. Very few moving parts and moving parts are simple
4. Only consume air (energy) when they move
5. Tolerate dirty air
6. Mechanical devices
7. Require a separate air system when applied with DDC technology
8. Require a signal converted when applied with DDC technology

Pneumatic Control Resources

Blog posts on www.Av8rDAS.Wordpress.com

- Pneumatic Controls Resources
- Pneumatic Controls, First Cost Advantages, and Retrocommissioning Opportunities
- Retrocommissioning Findings: Make Up Air Handling System Simultaneous Heating and Cooling – The Clues – #2 – The Controls May be Pneumatic
- Resources for the Resourceful: The Honeywell "Gray Manual'
- Control Technology; A Glimpse Backward and Some Thoughts on the Future

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Control Processes

Moving to DDC (Direct Digital Control or Distributed Digital Control)

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A 1970's Vintage Control and Automation System

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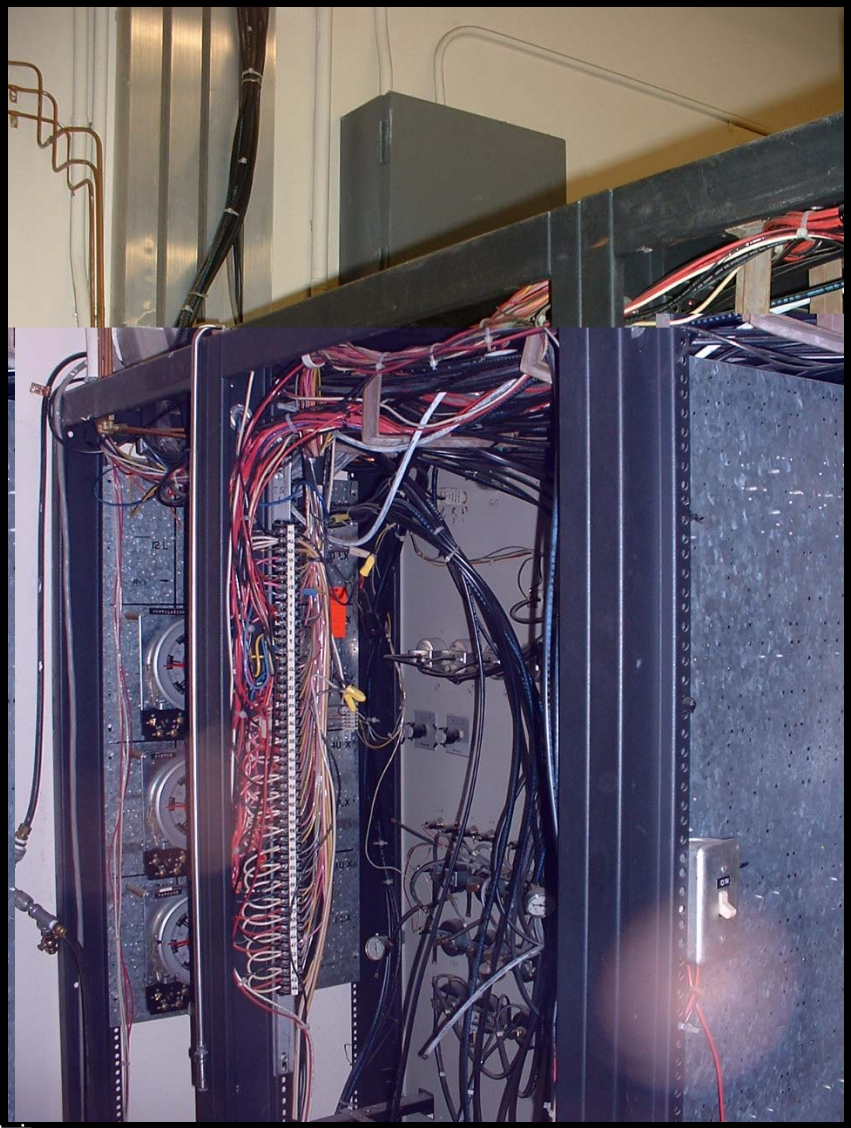
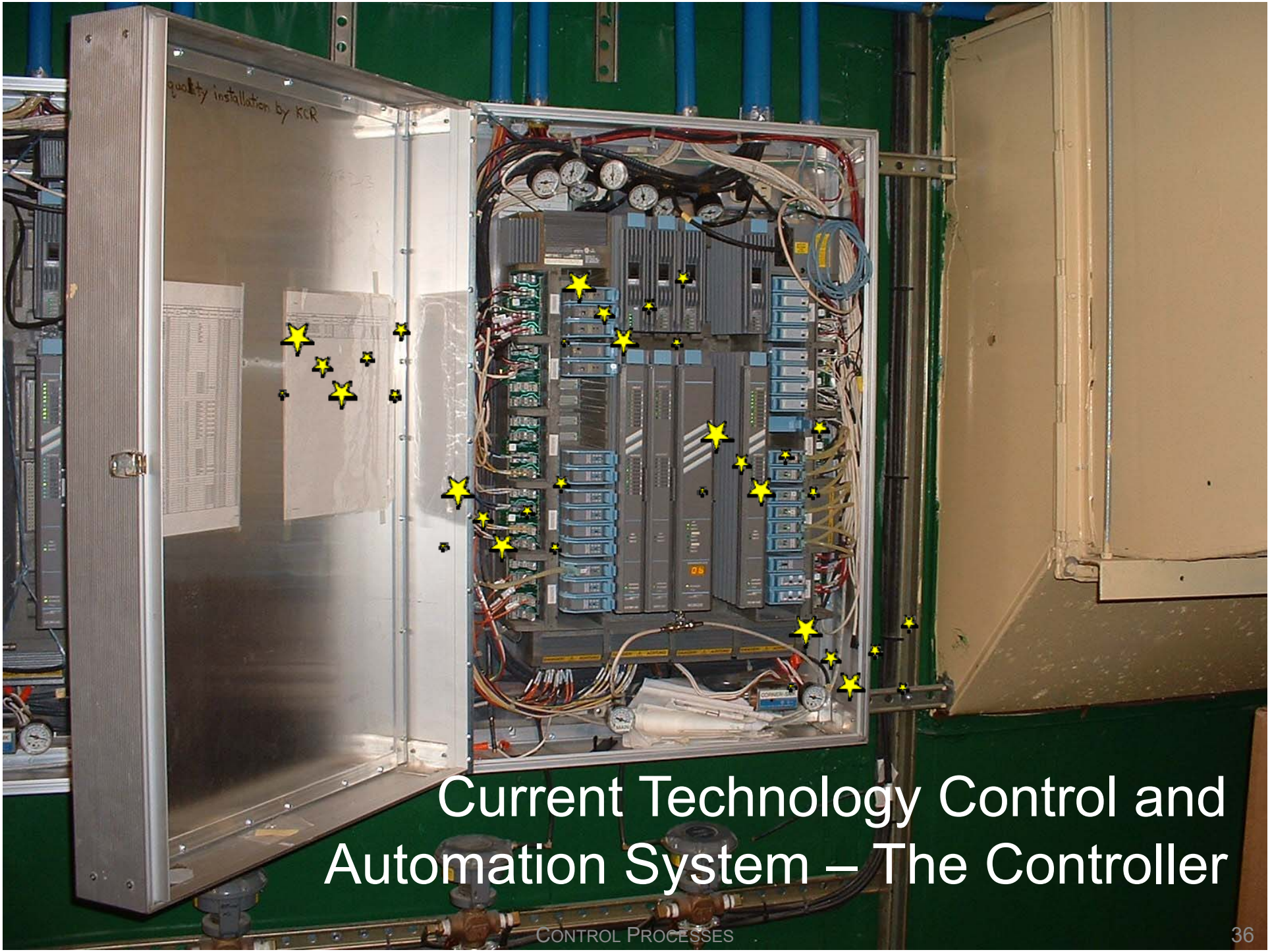
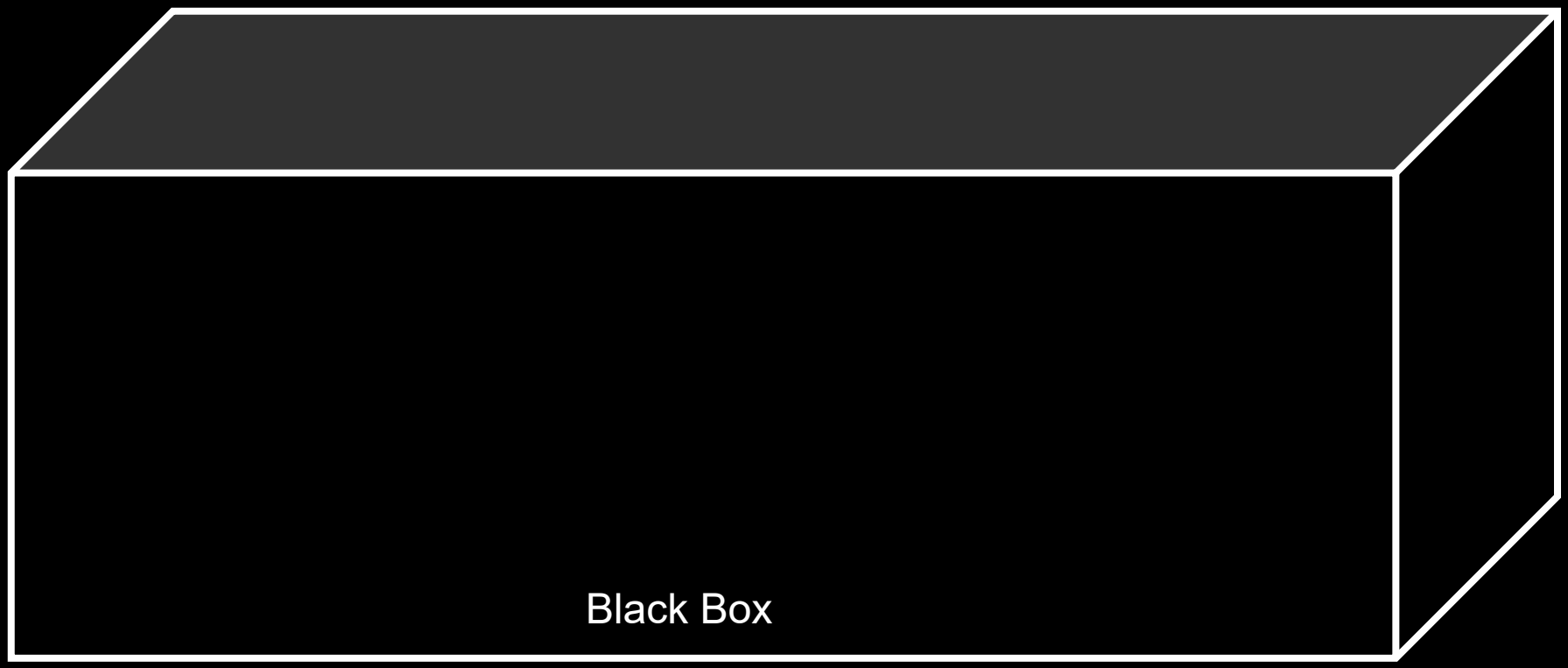




Current Technology Control and Automation System – The Controller

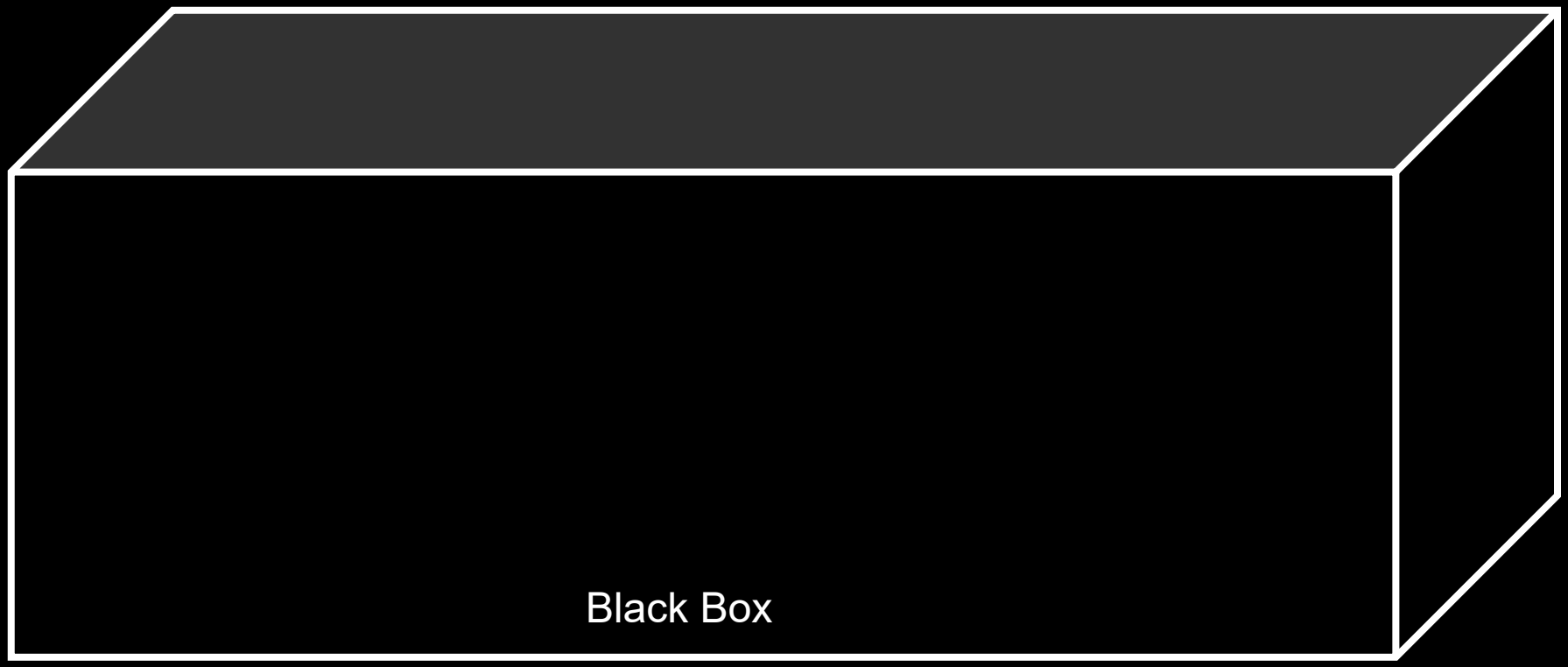
Not Being Able to See or Get Your Hands on What's Going On

… 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



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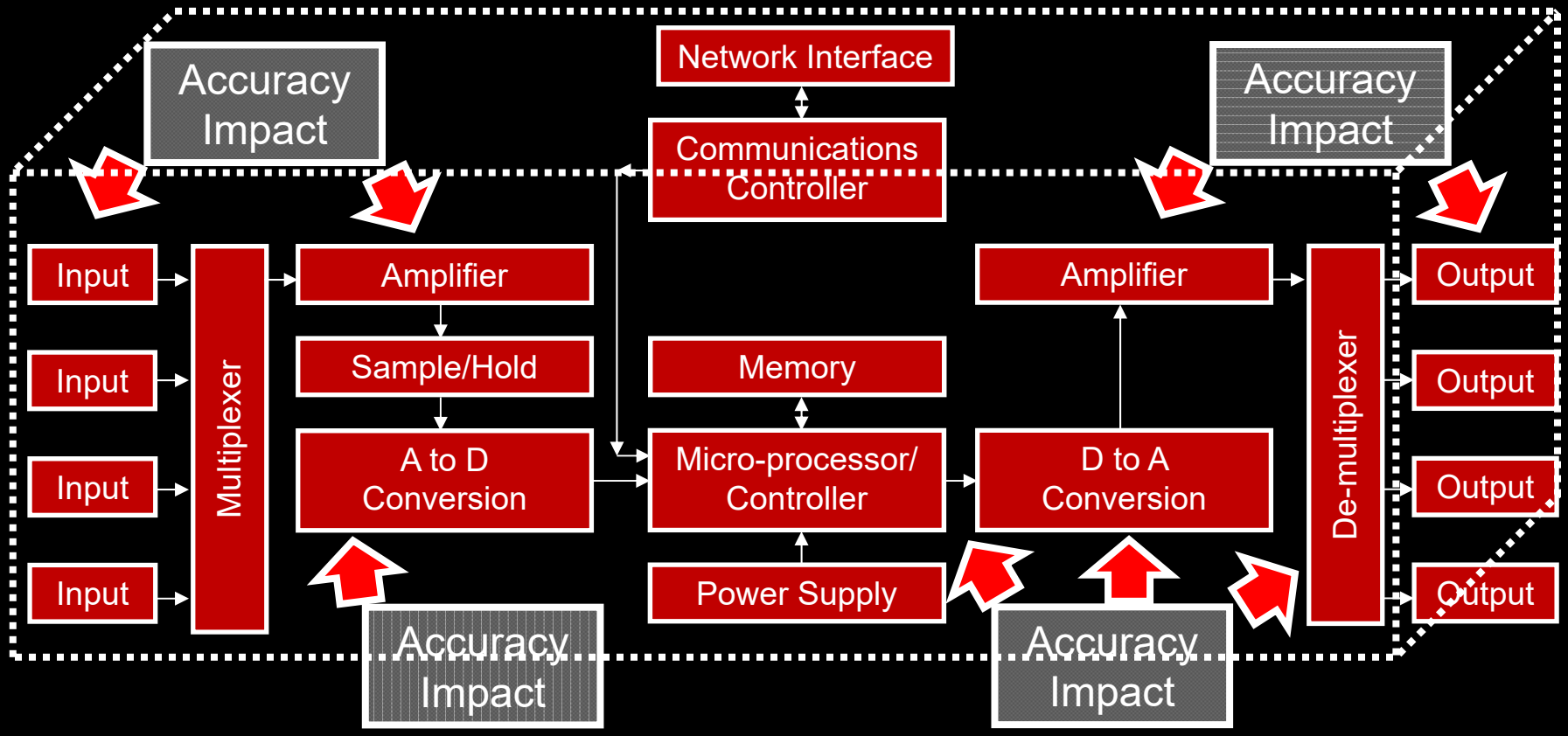

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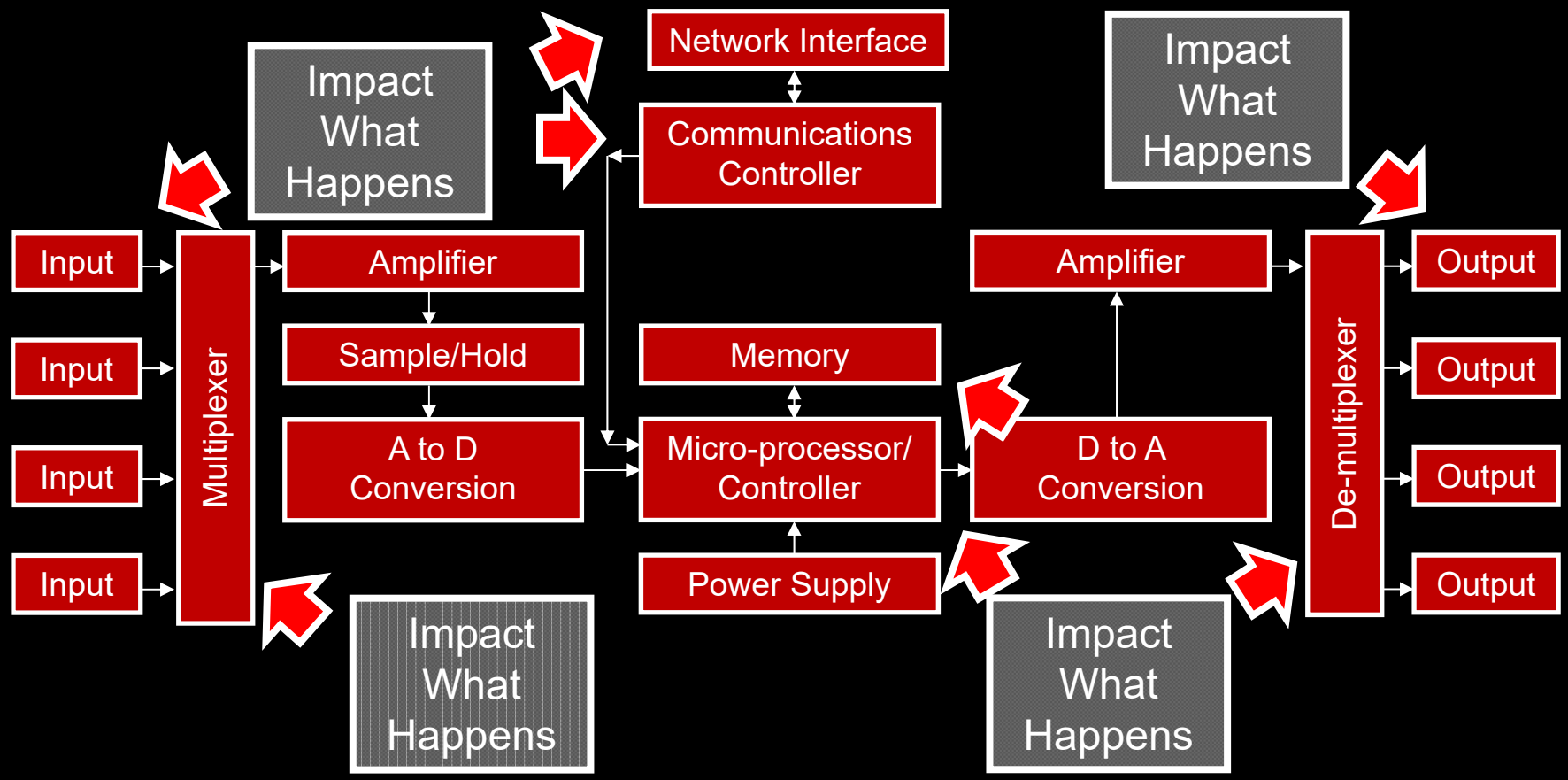

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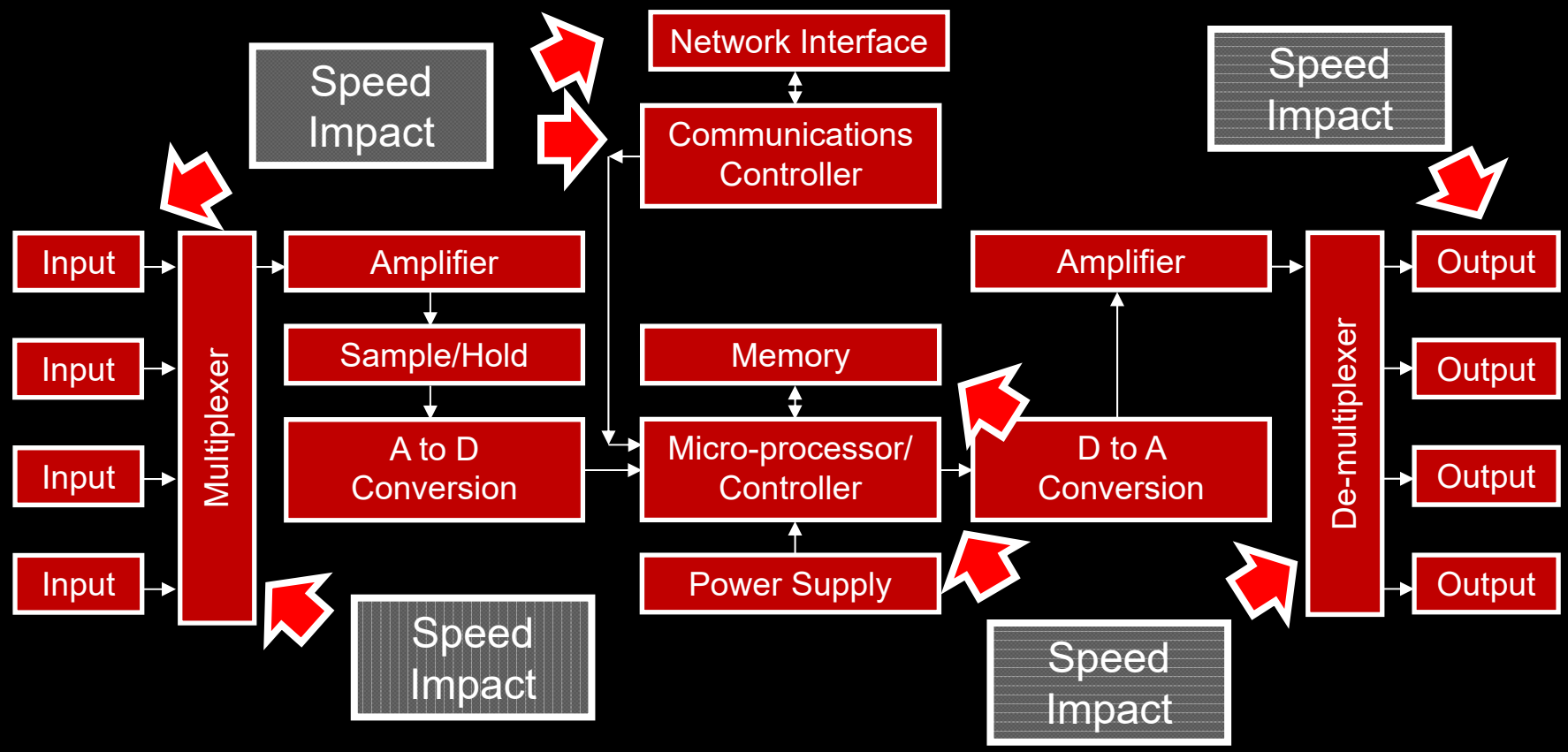
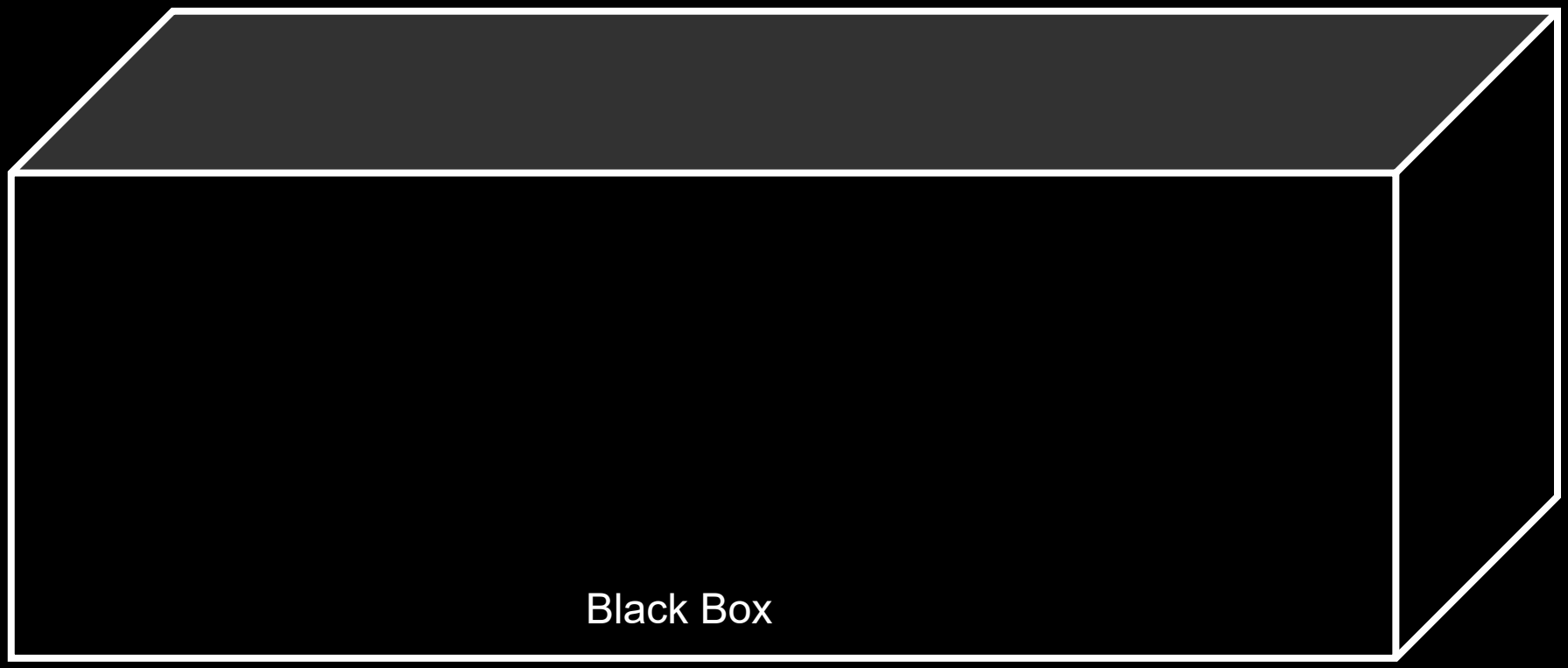


Step Outside the Black Box and its Still and Analog World



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

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Control Processes

Digital Control Processes

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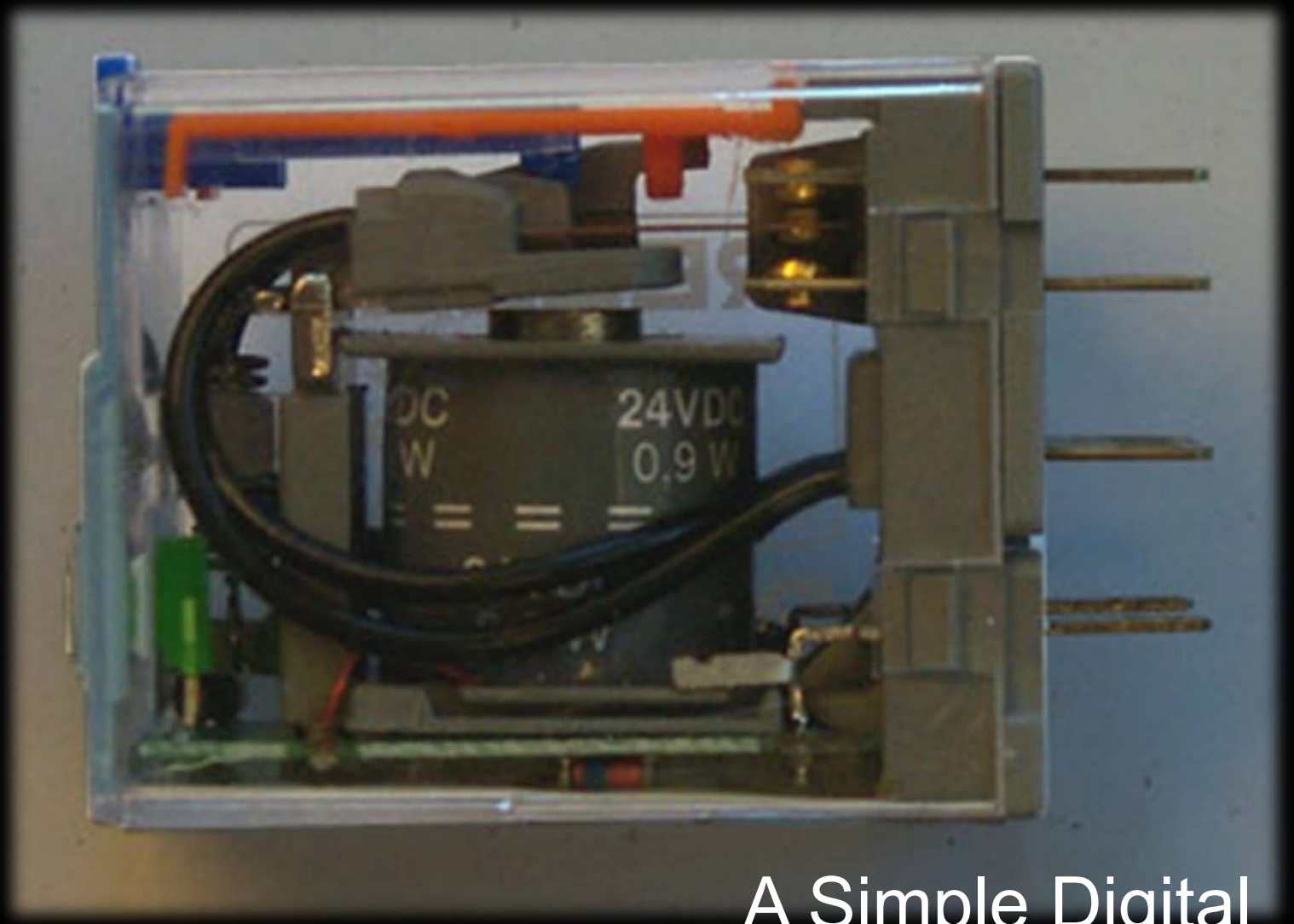
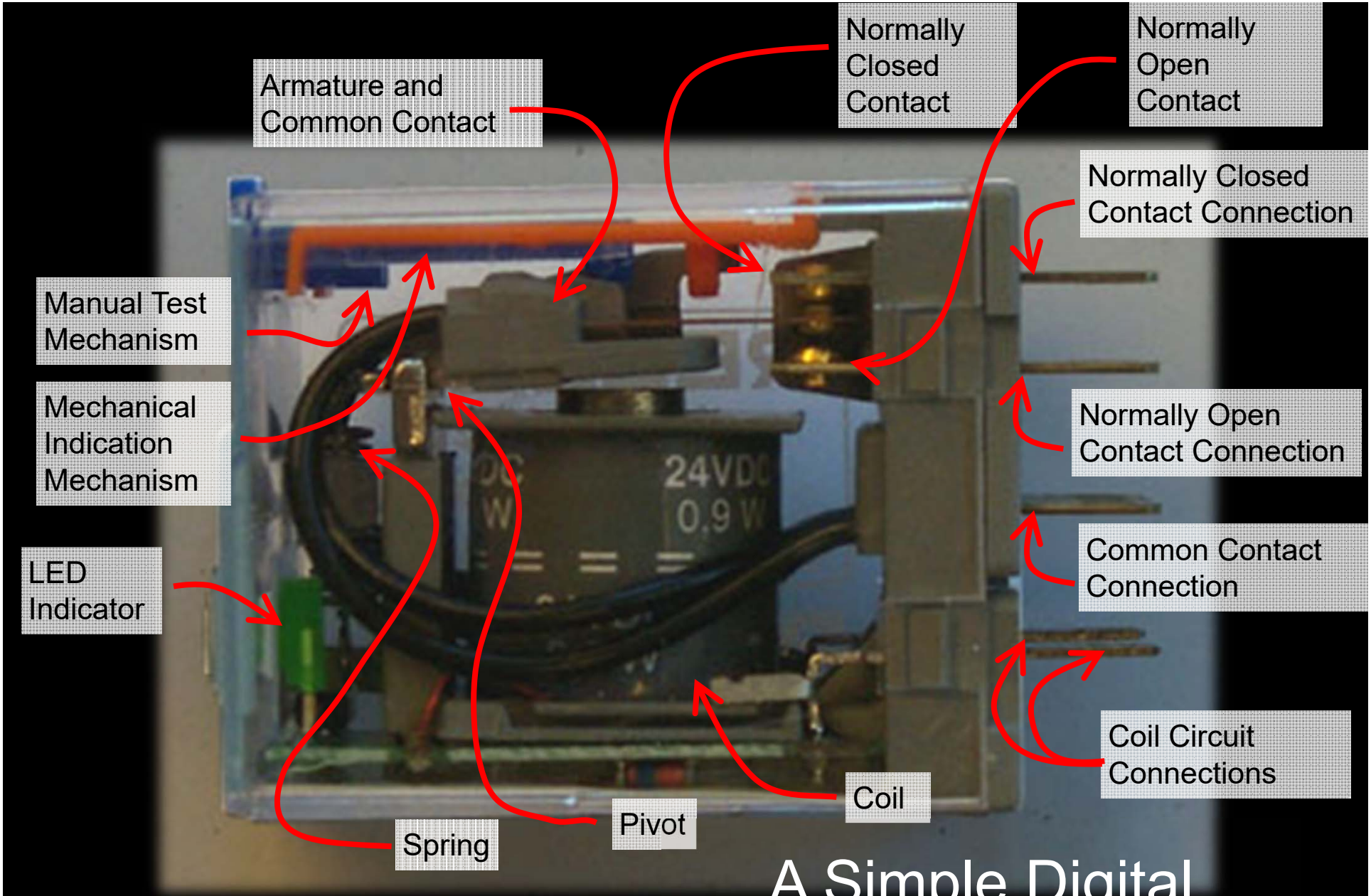
A Simple Digital Control Process



A Simple Digital Controller



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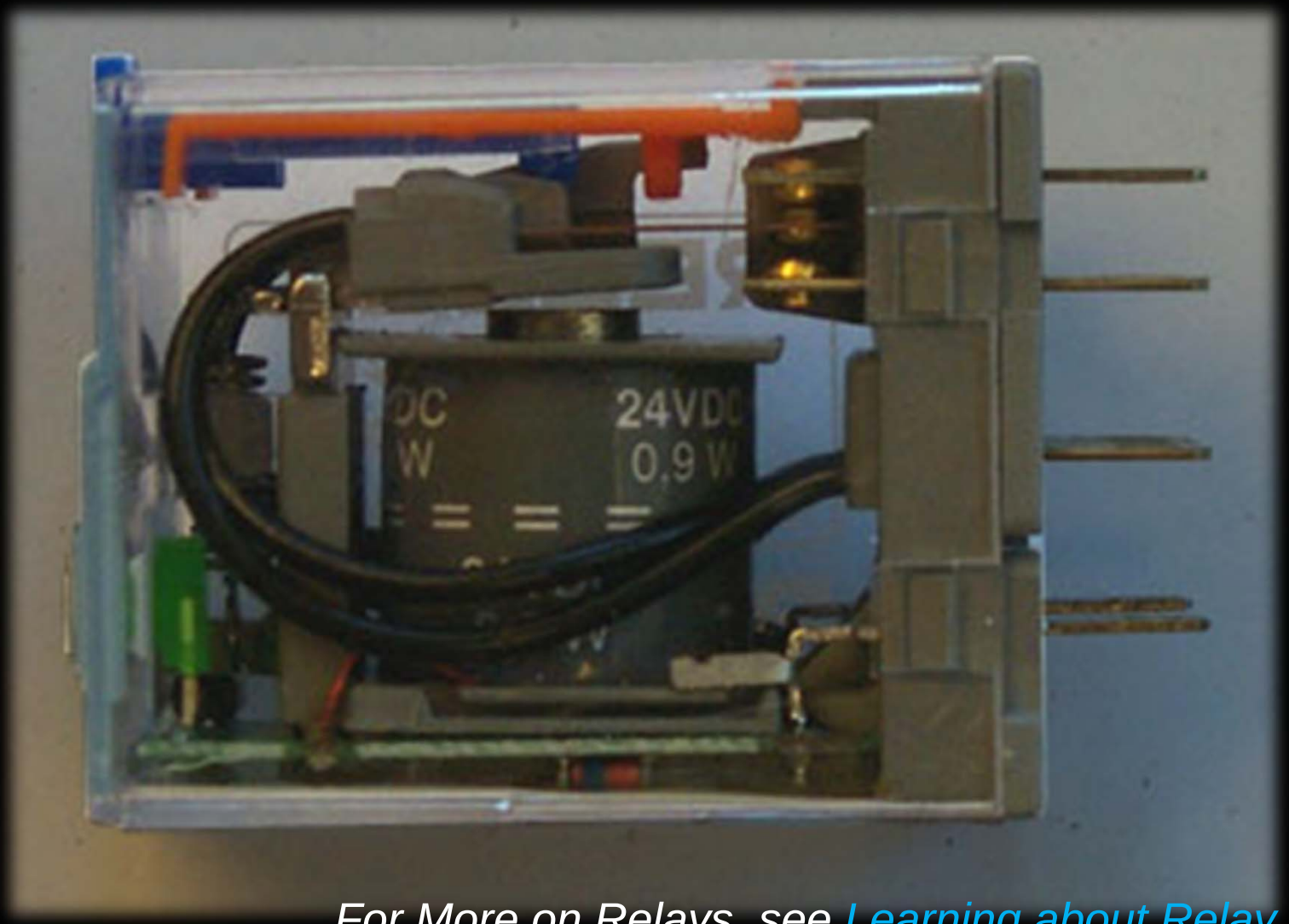
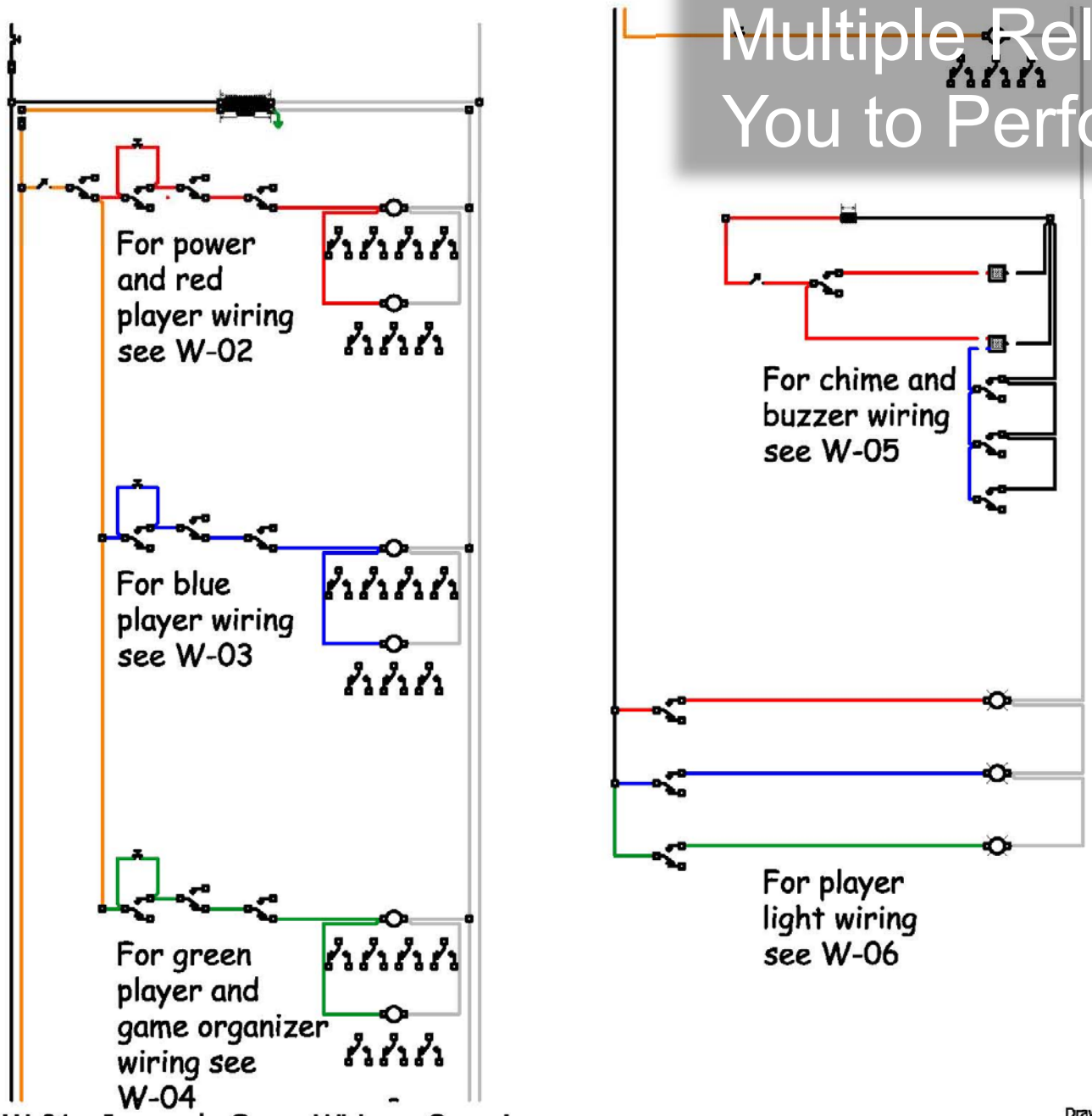


For More on Relays, see [Learning about Relay Logic; What's a Relay?](www.Av8rDAS.Wordpress.com) at www.Av8rDAS.Wordpress.com

A Fun Digital Control Process

Multiple Relays Allow You to Perform Logic

Multiple Relays Allow You to Perform Logic



W-01 - Jeopardy Game Wiring - Overview

Drawn by: DAS Checked by: DAS
December 26, 2005, Rev 1 12-29-05

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)

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Floating and Proportional Control

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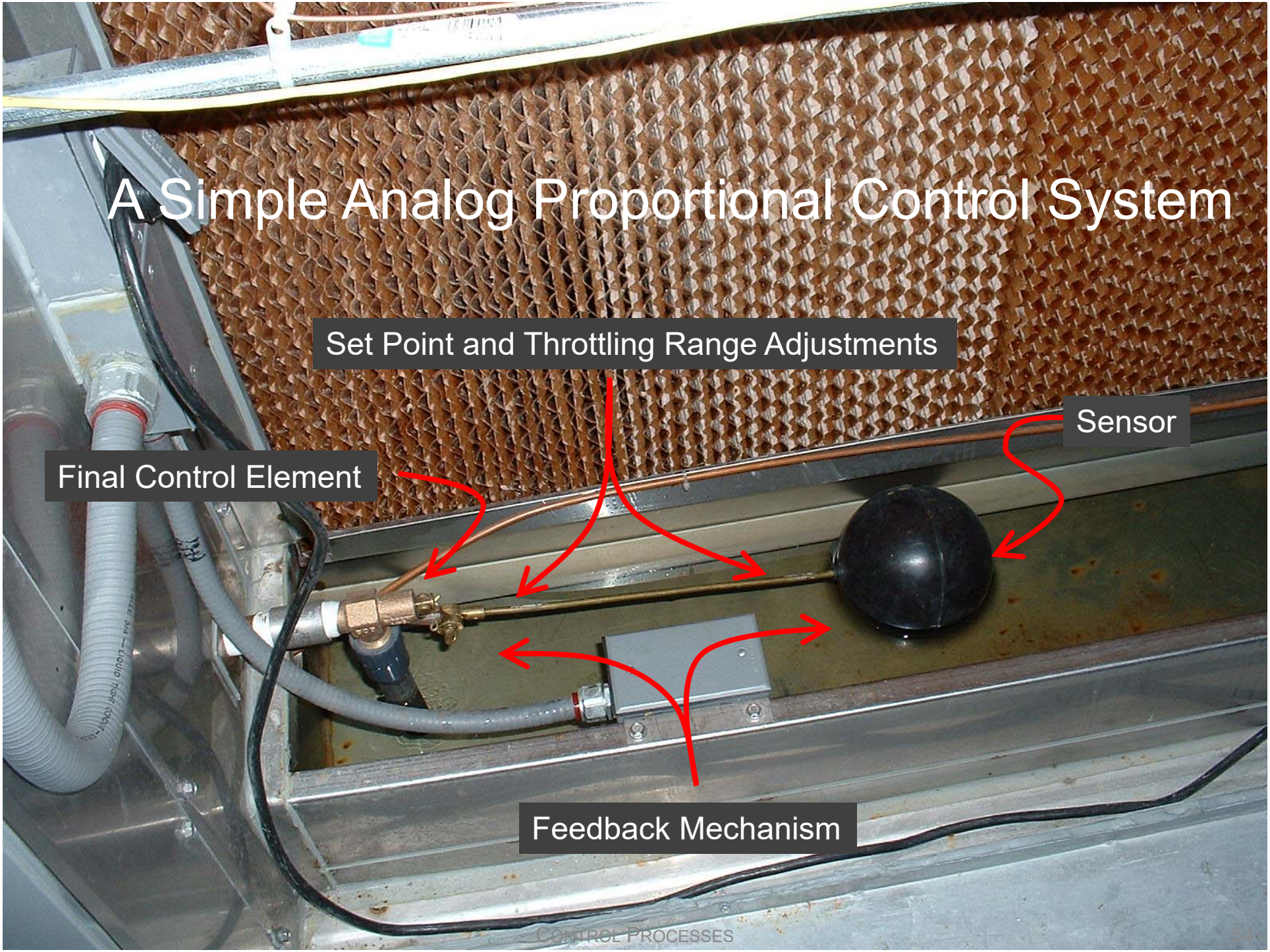
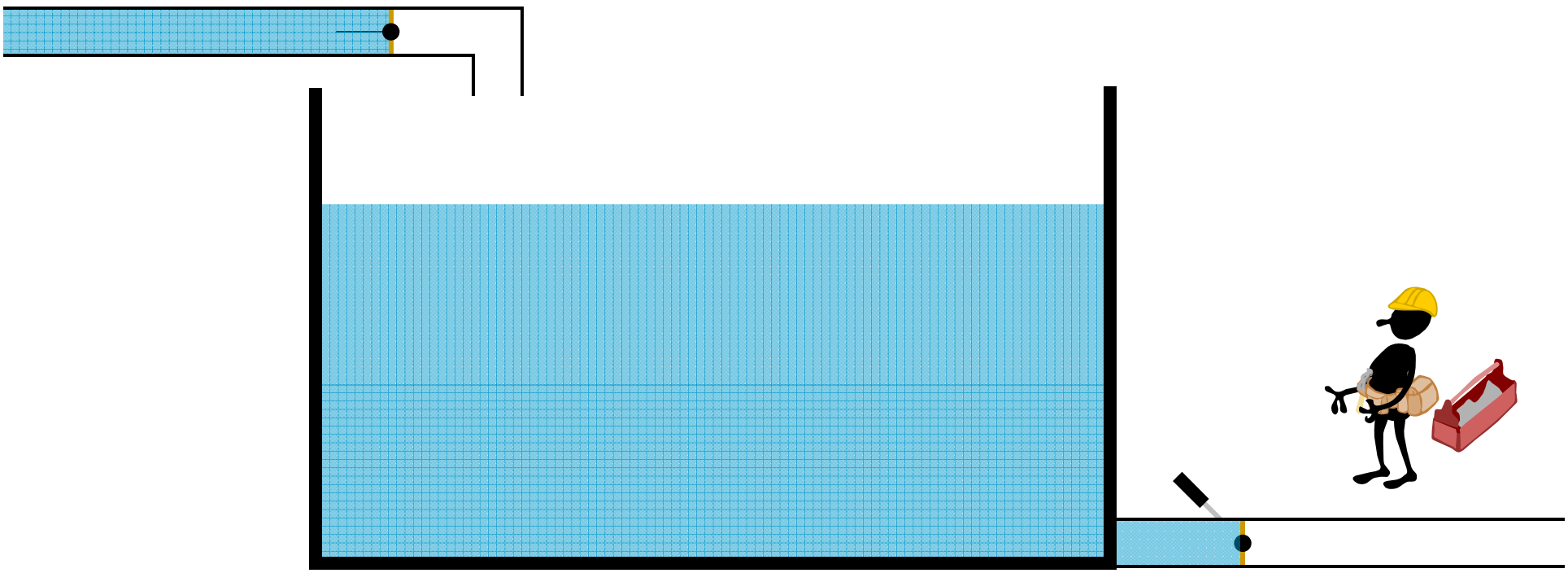
A Simple Analog Proportional Control System

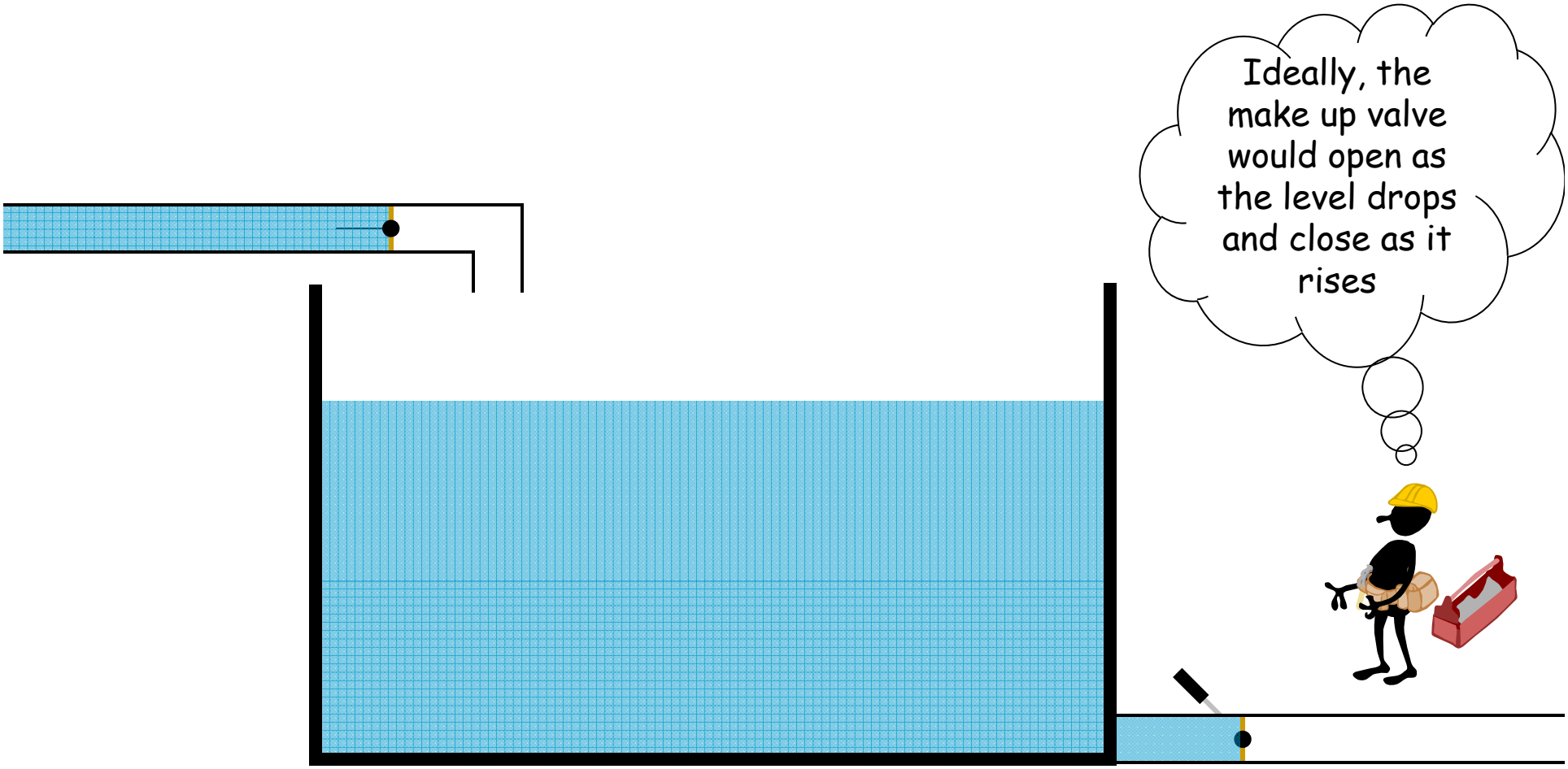


A Simple Control System

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



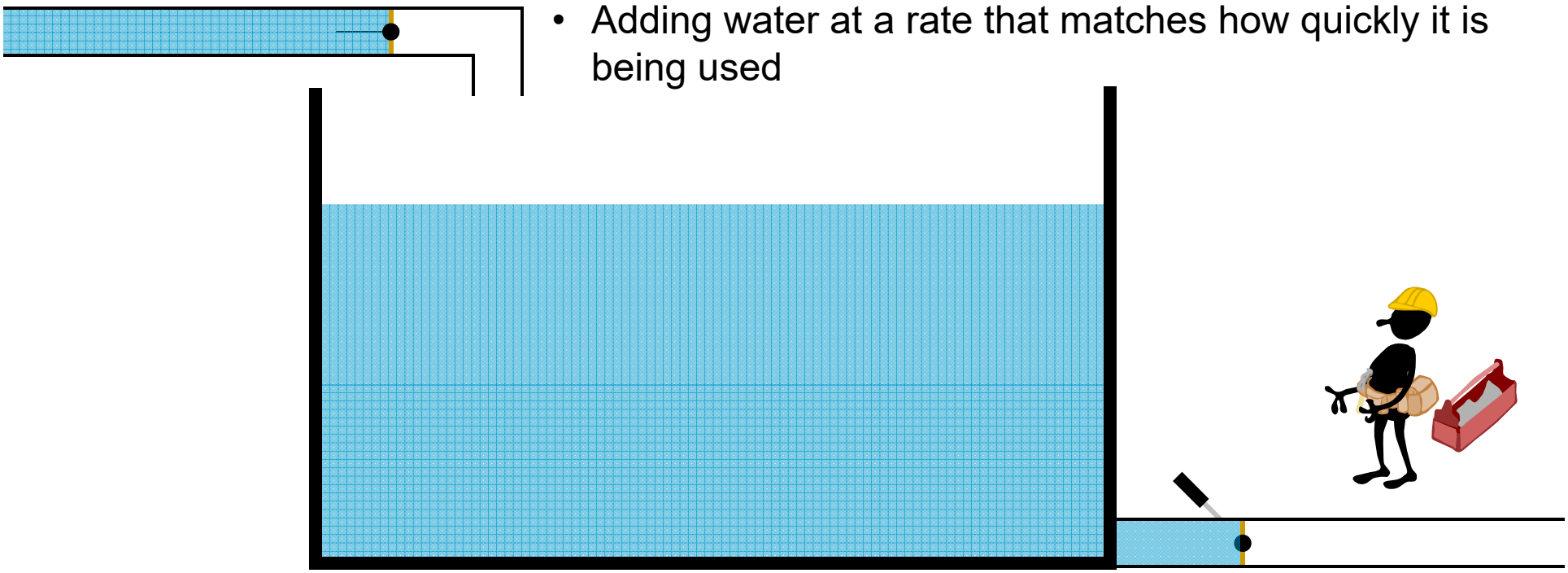
A Simple Control System



A Simple Control System

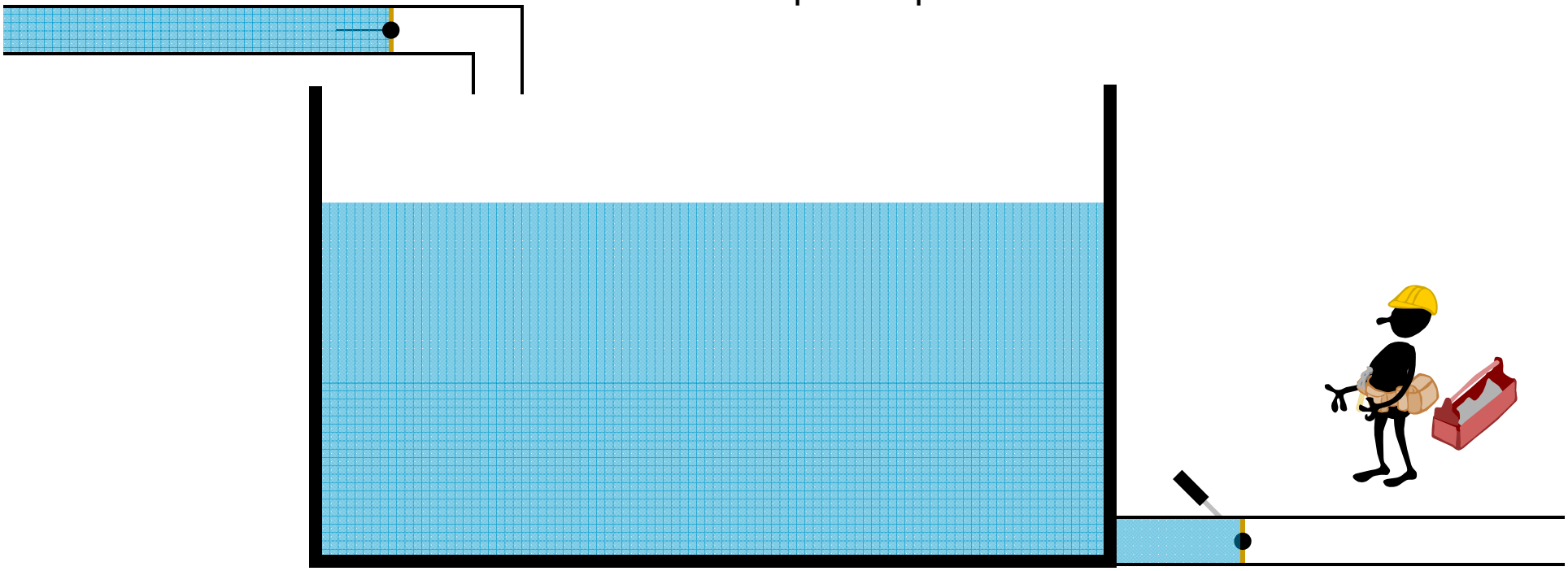
Because the tank acts as a flywheel in the system, it would be possible to serve the load by:

- Adding water when the level drops to a certain point
- Adding water at a rate that matches how quickly it is being used



A Simple Control System

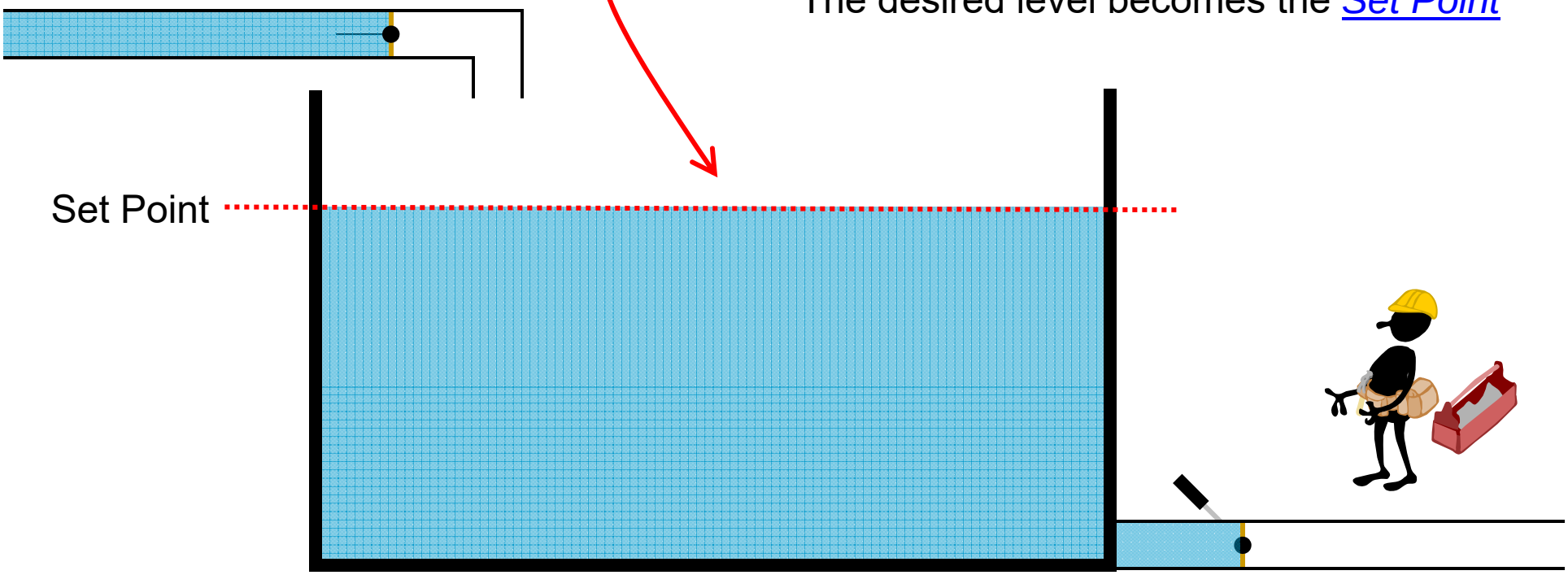
Monitoring the tank water level will allow us to gauge how much make up we need to add as demand picks up



A Simple Control System

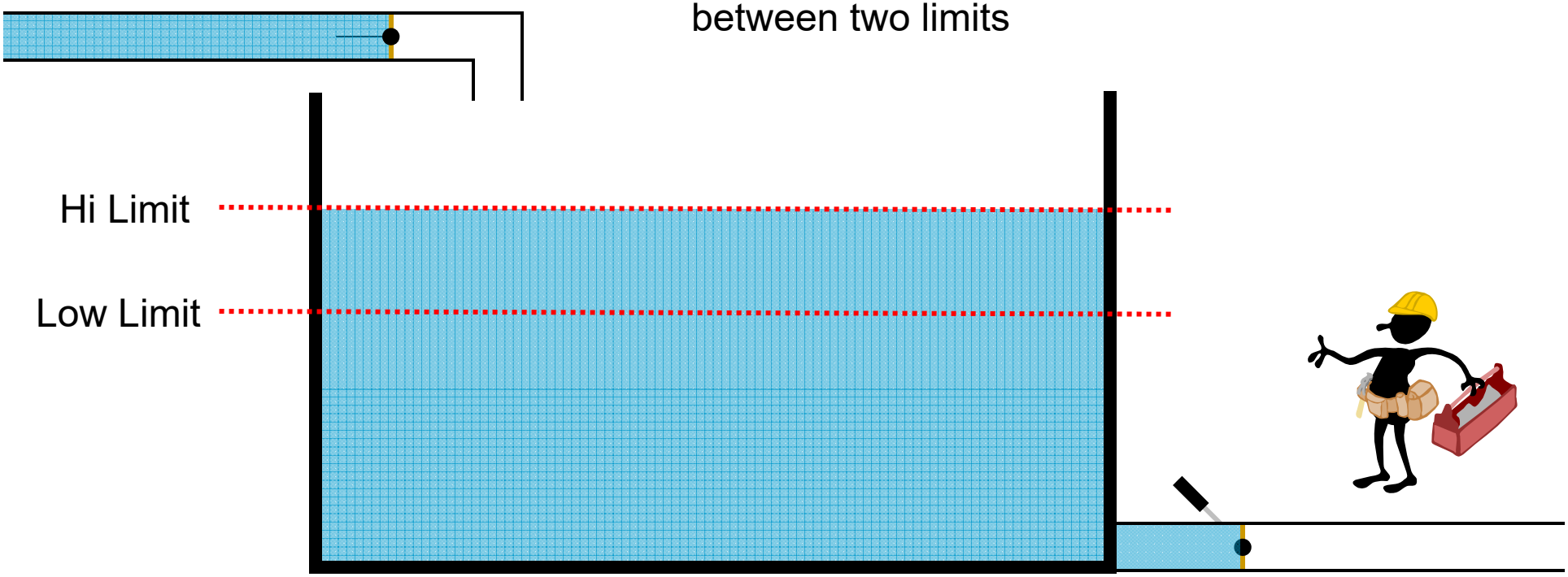
The tank water level is the *Process Variable*

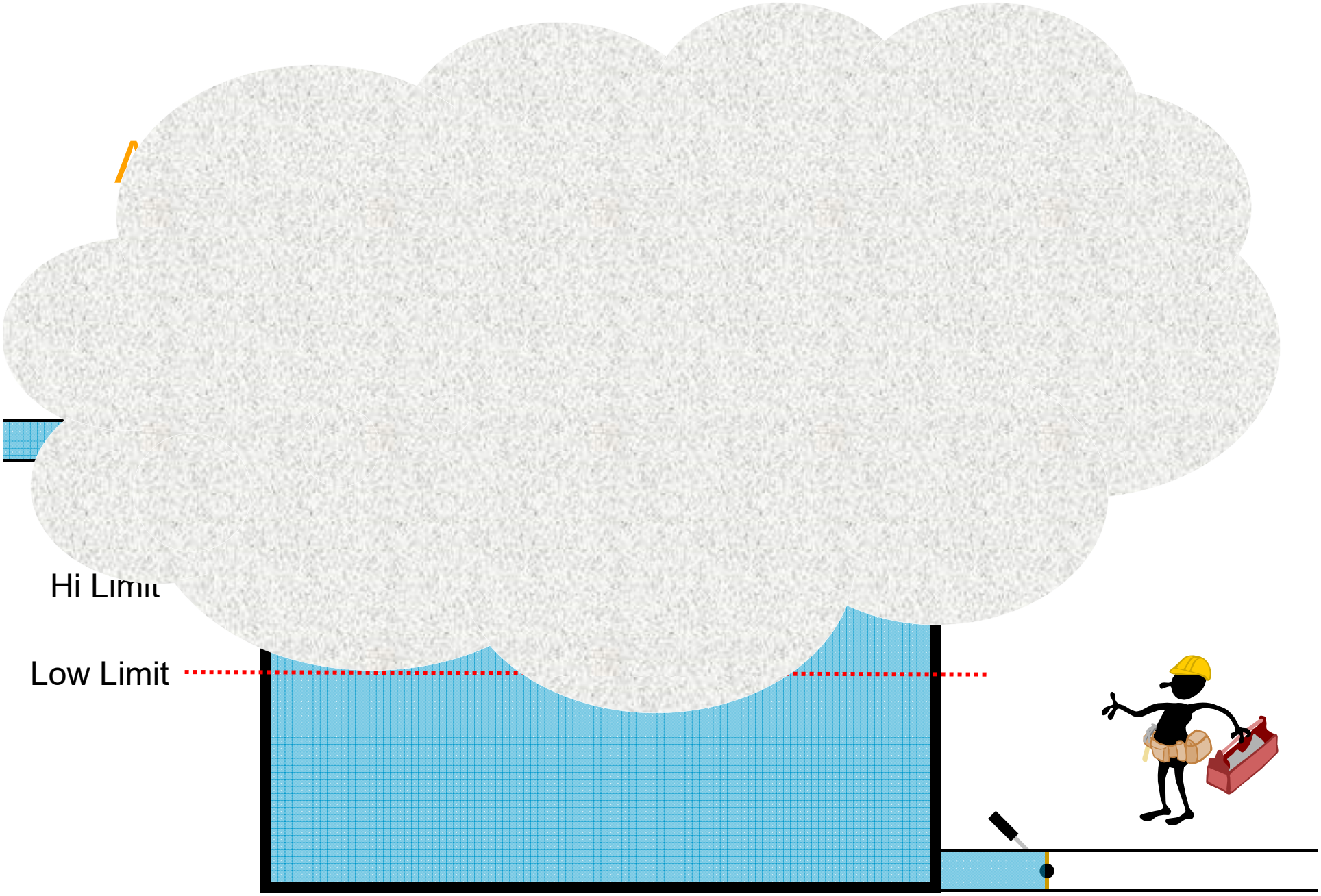
The desired level becomes the *Set Point*

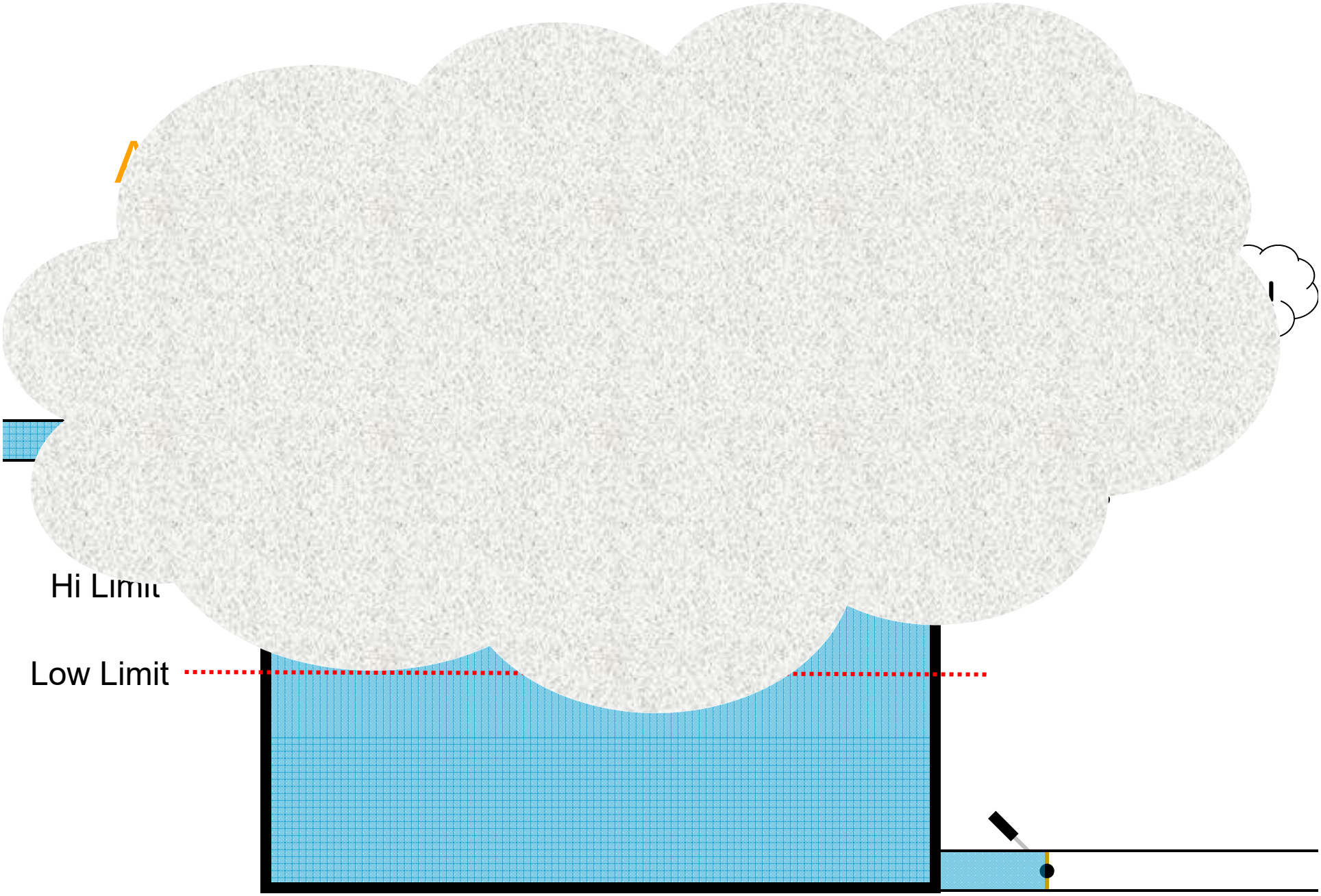


A Simple Control System

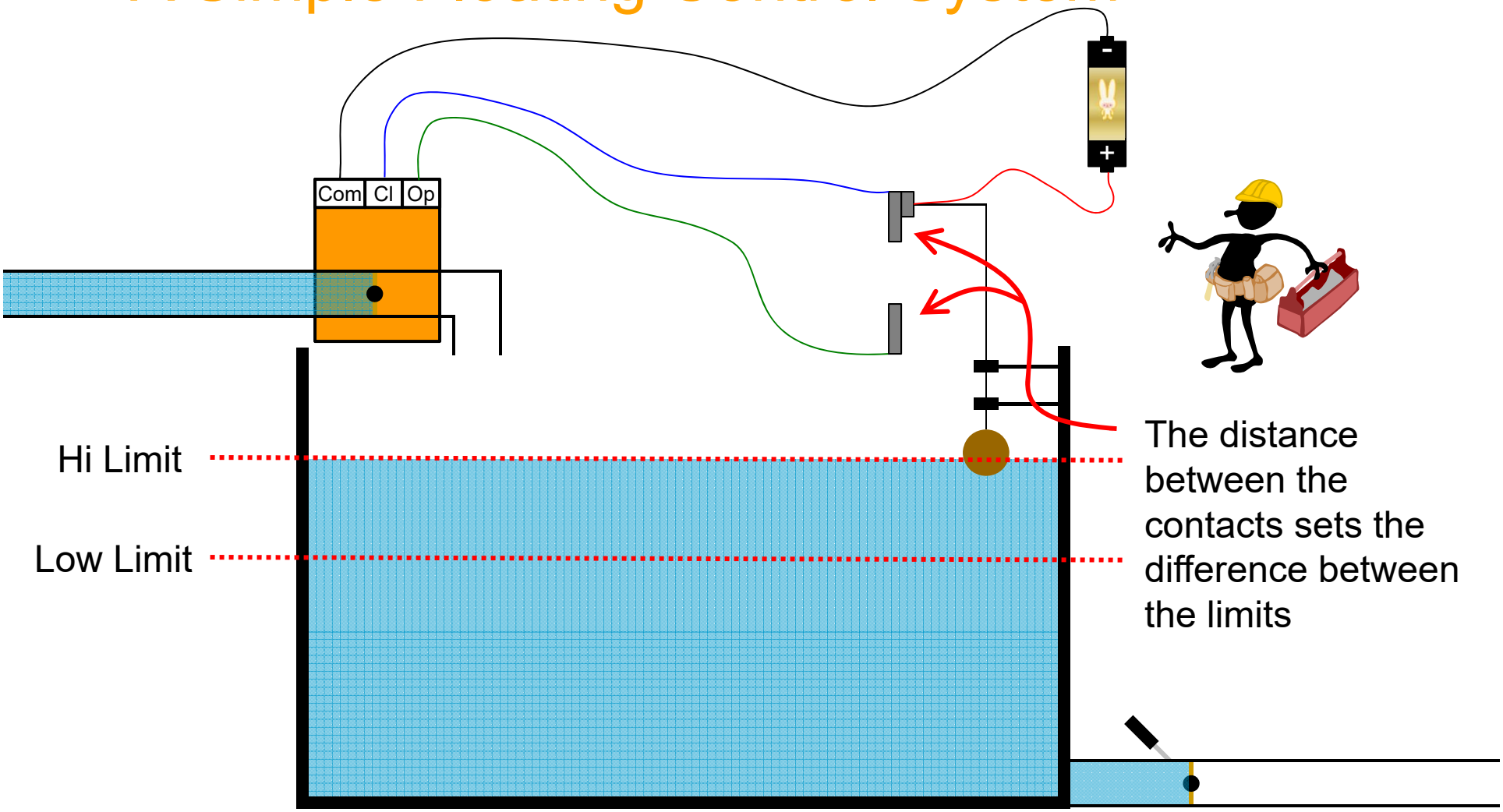
It may be possible to achieve satisfactory control by simply keeping the tank level between two limits



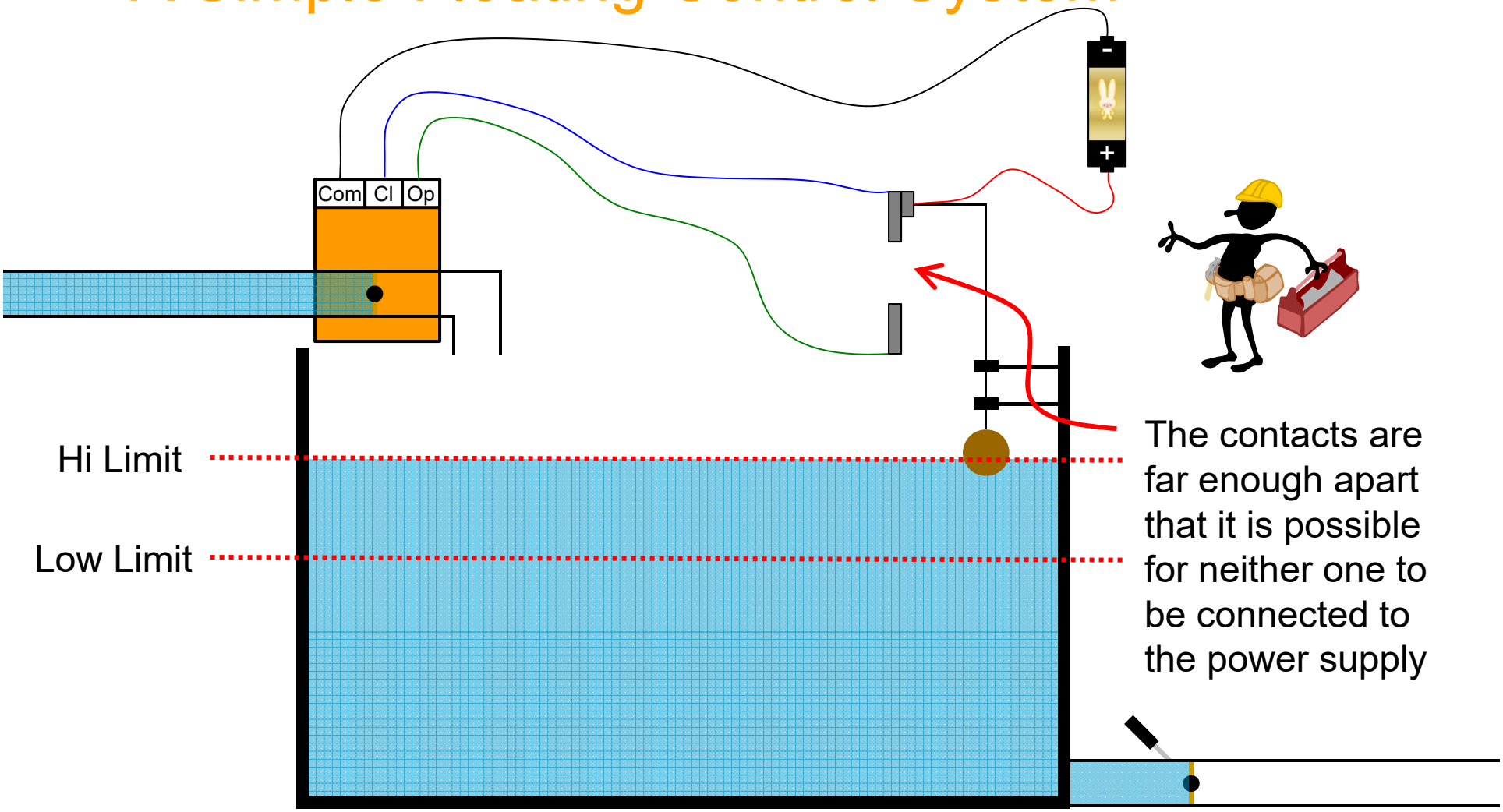

Hi Limit
Low Limit


Hi Limit
Low Limit

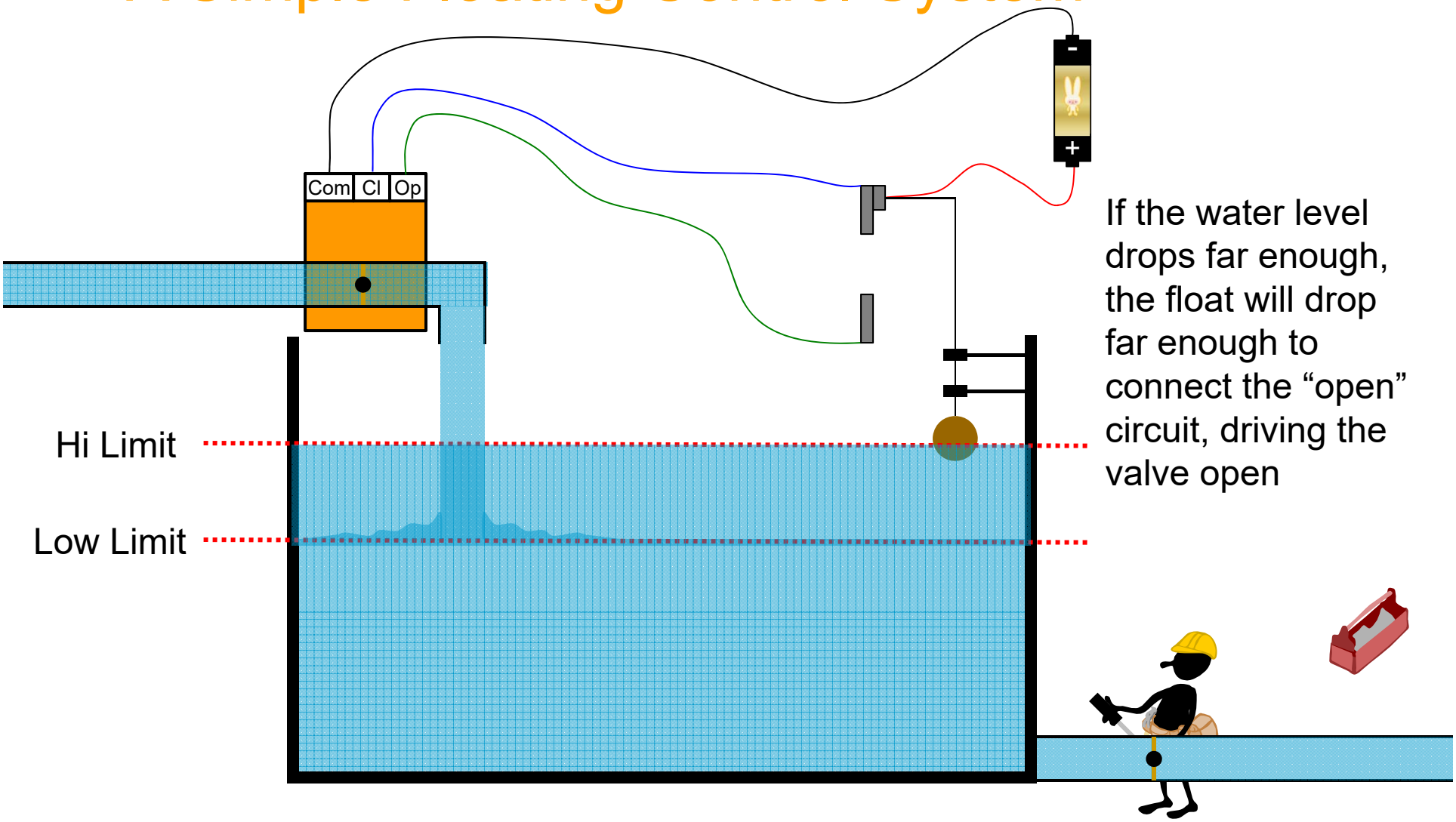
A Simple Floating Control System



A Simple Floating Control System

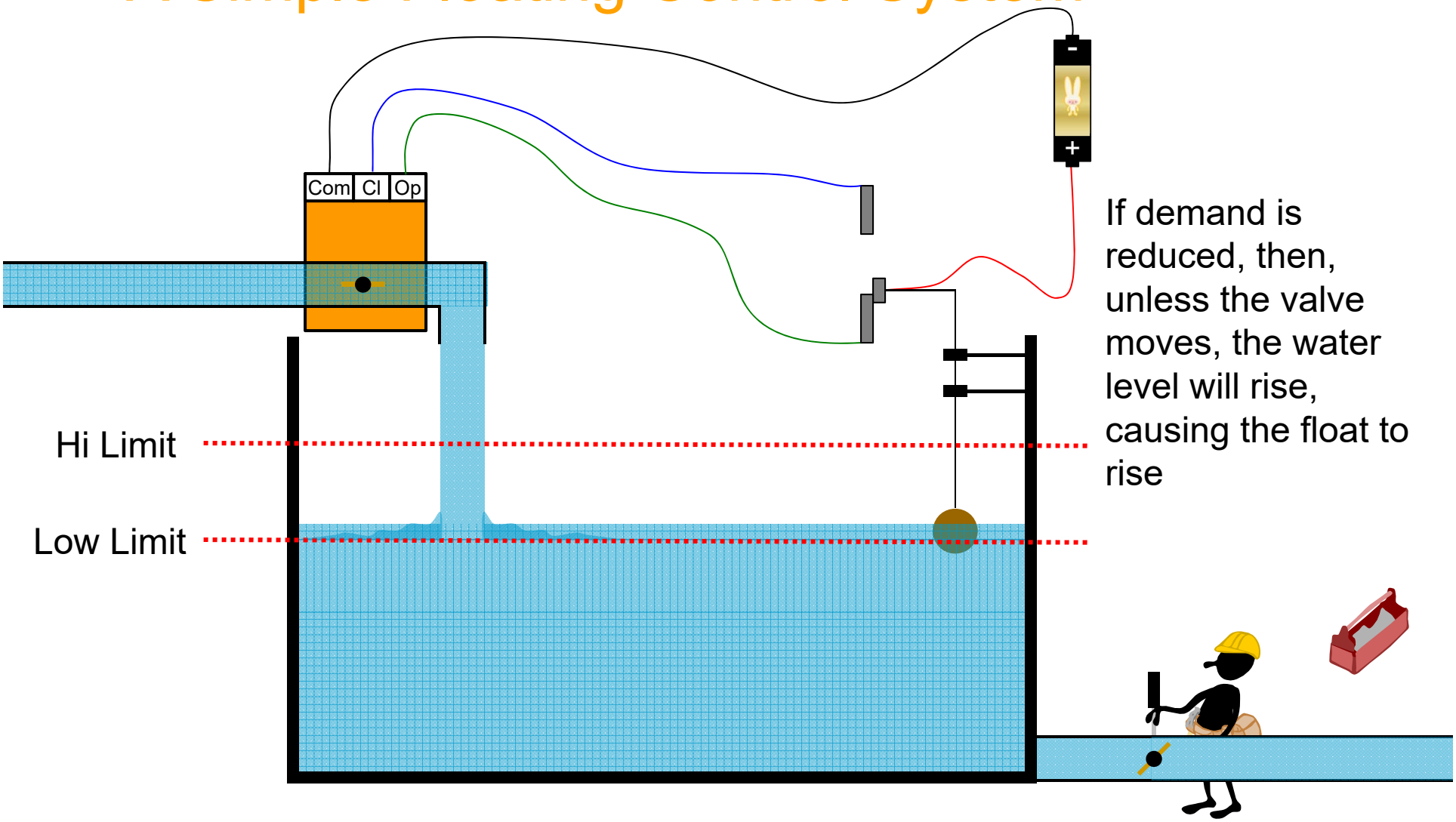


A Simple Floating Control System



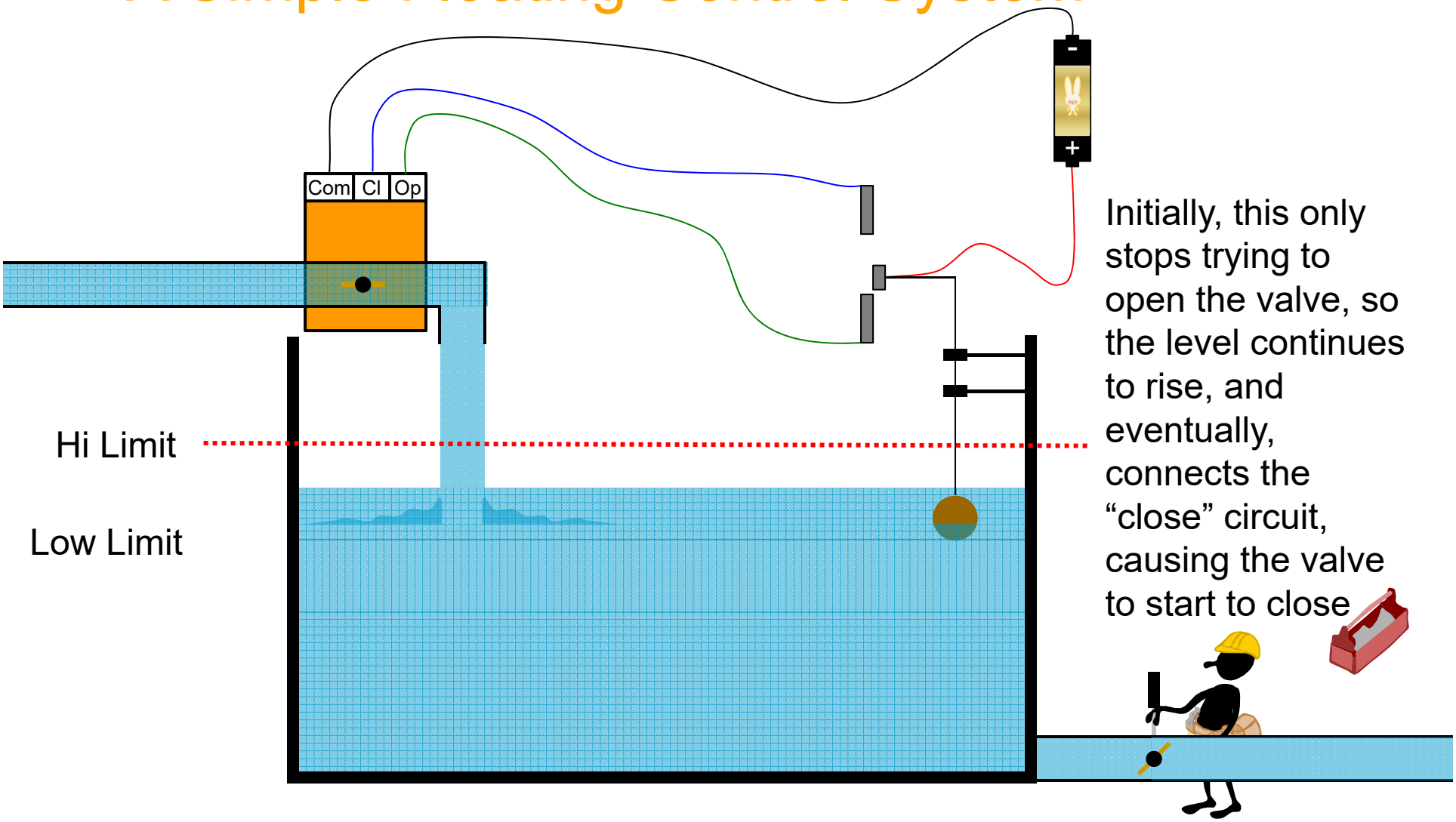
If the water level drops far enough, the float will drop far enough to connect the “open” circuit, driving the valve open

A Simple Floating Control System



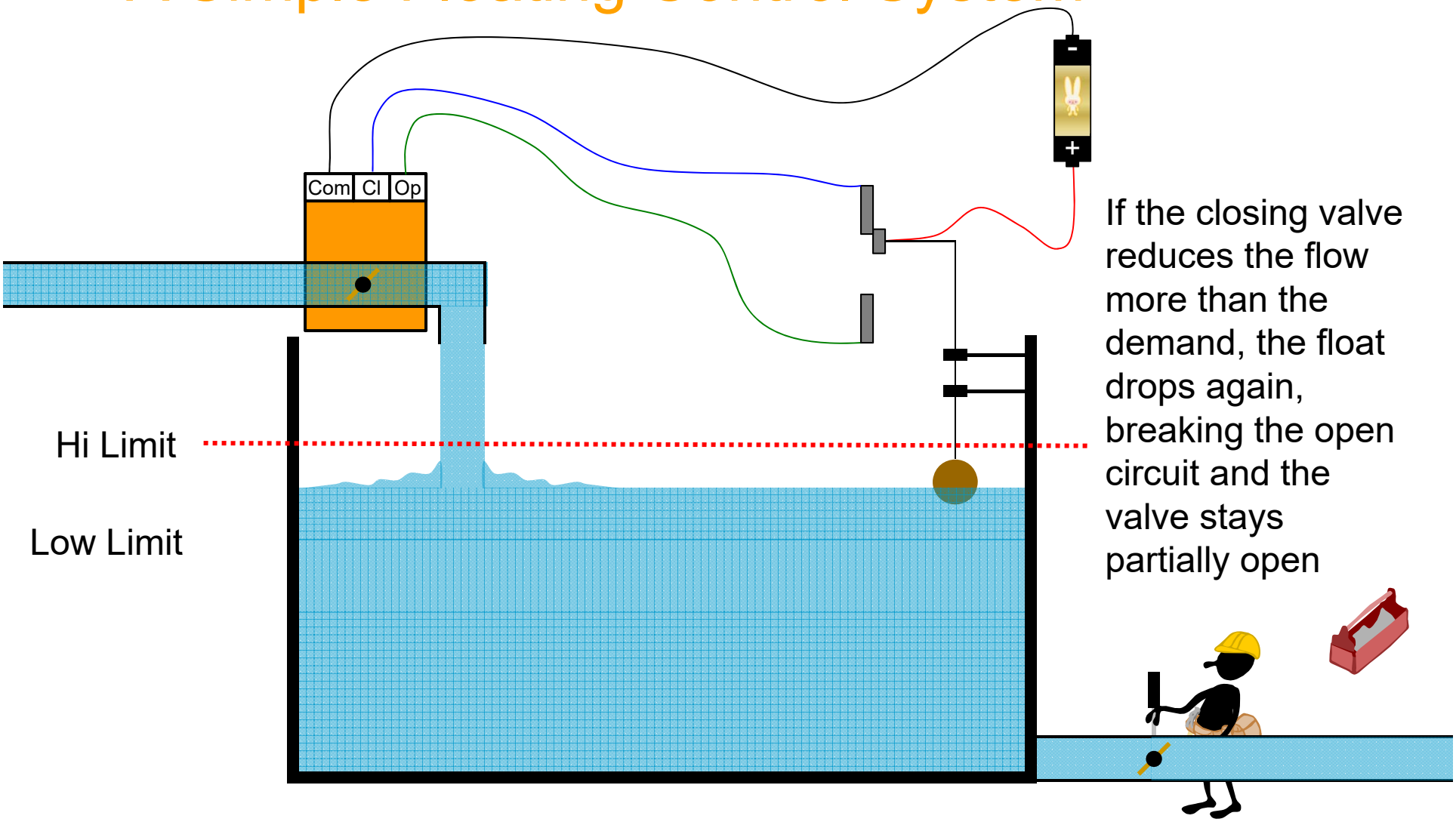
If demand is reduced, then, unless the valve moves, the water level will rise, causing the float to rise

A Simple Floating Control System



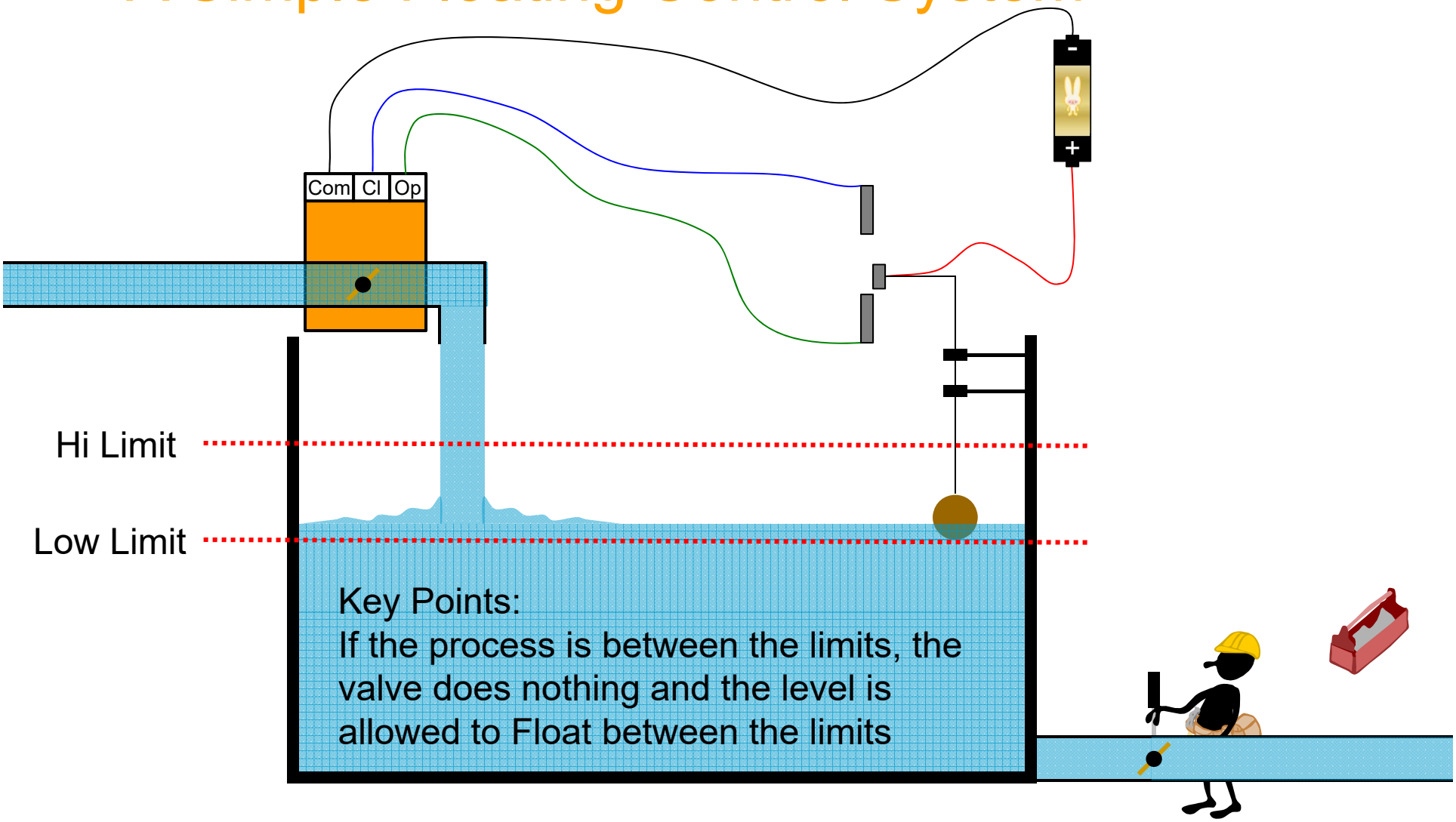
Initially, this only stops trying to open the valve, so the level continues to rise, and eventually, connects the “close” circuit, causing the valve to start to close

A Simple Floating Control System

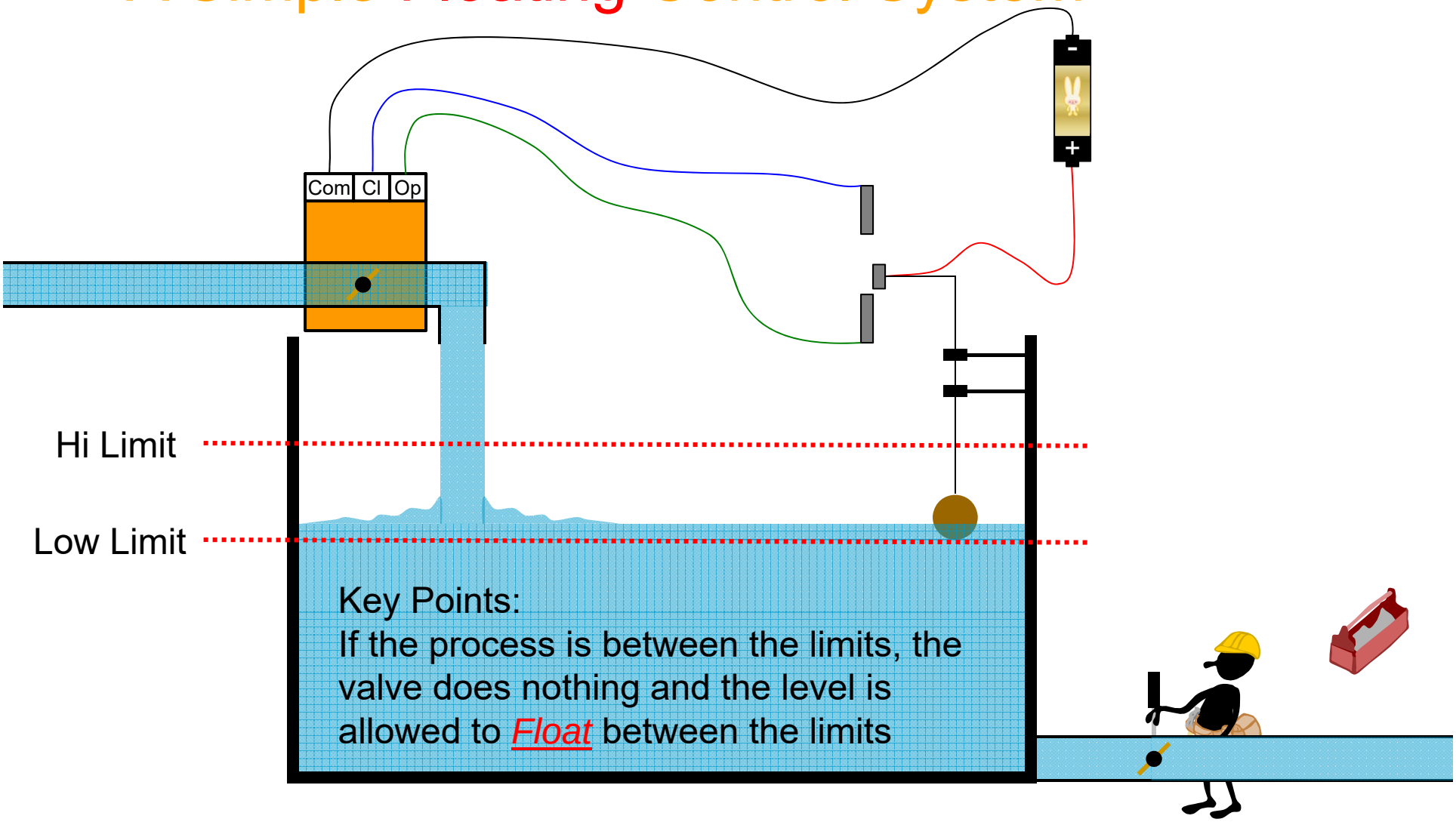


If the closing valve reduces the flow more than the demand, the float drops again, breaking the open circuit and the valve stays partially open

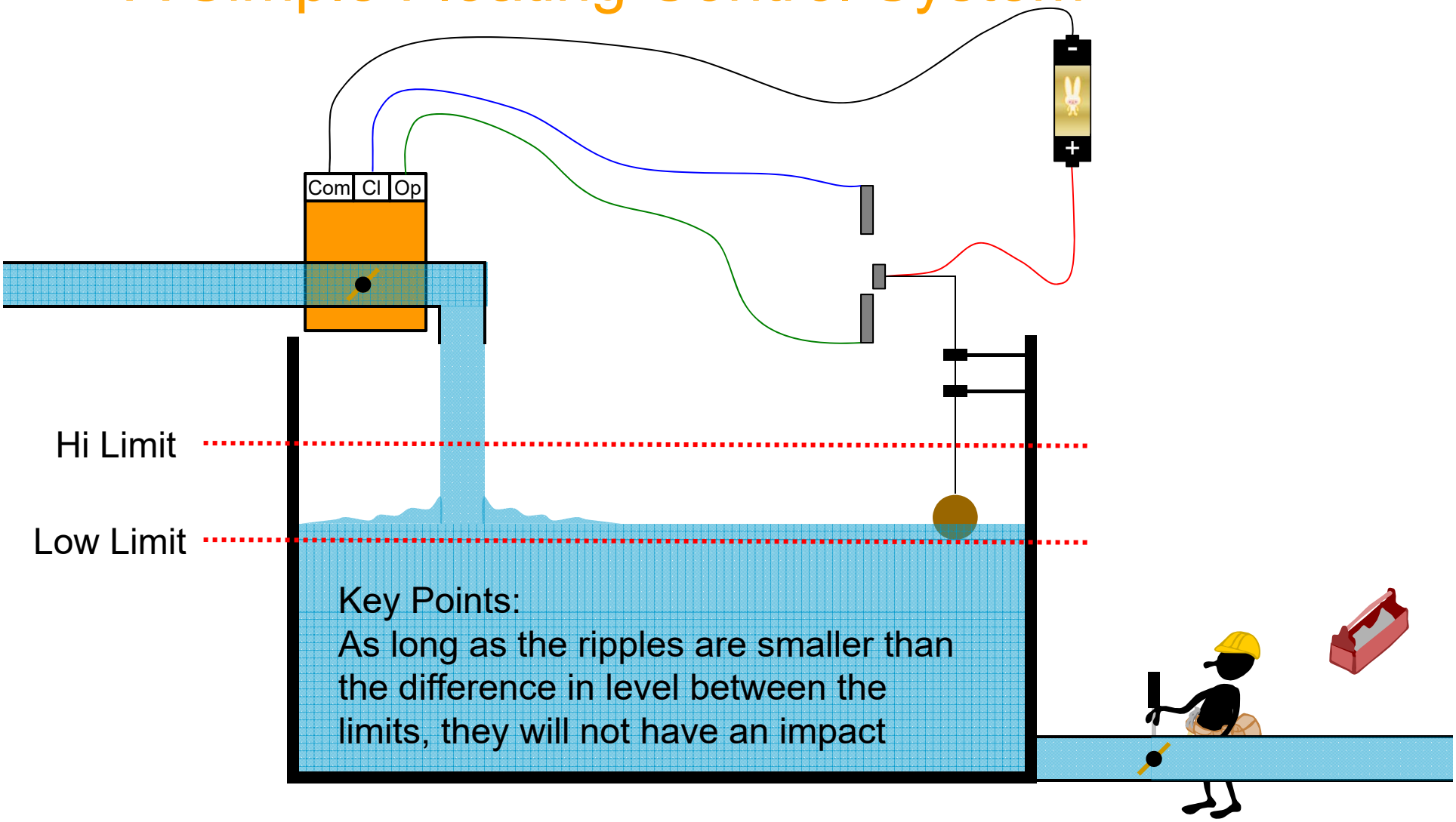
A Simple Floating Control System



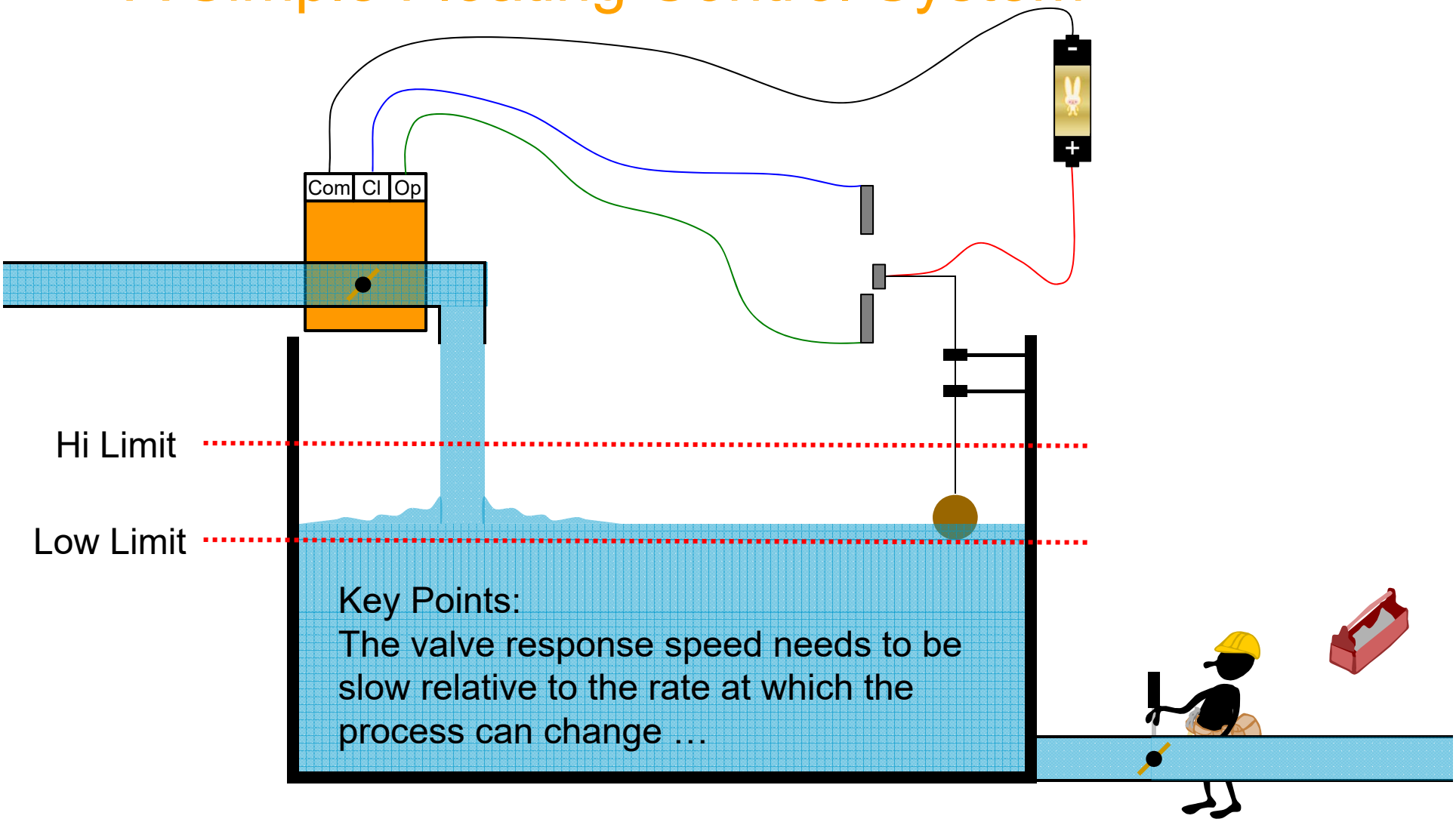
A Simple Floating Control System



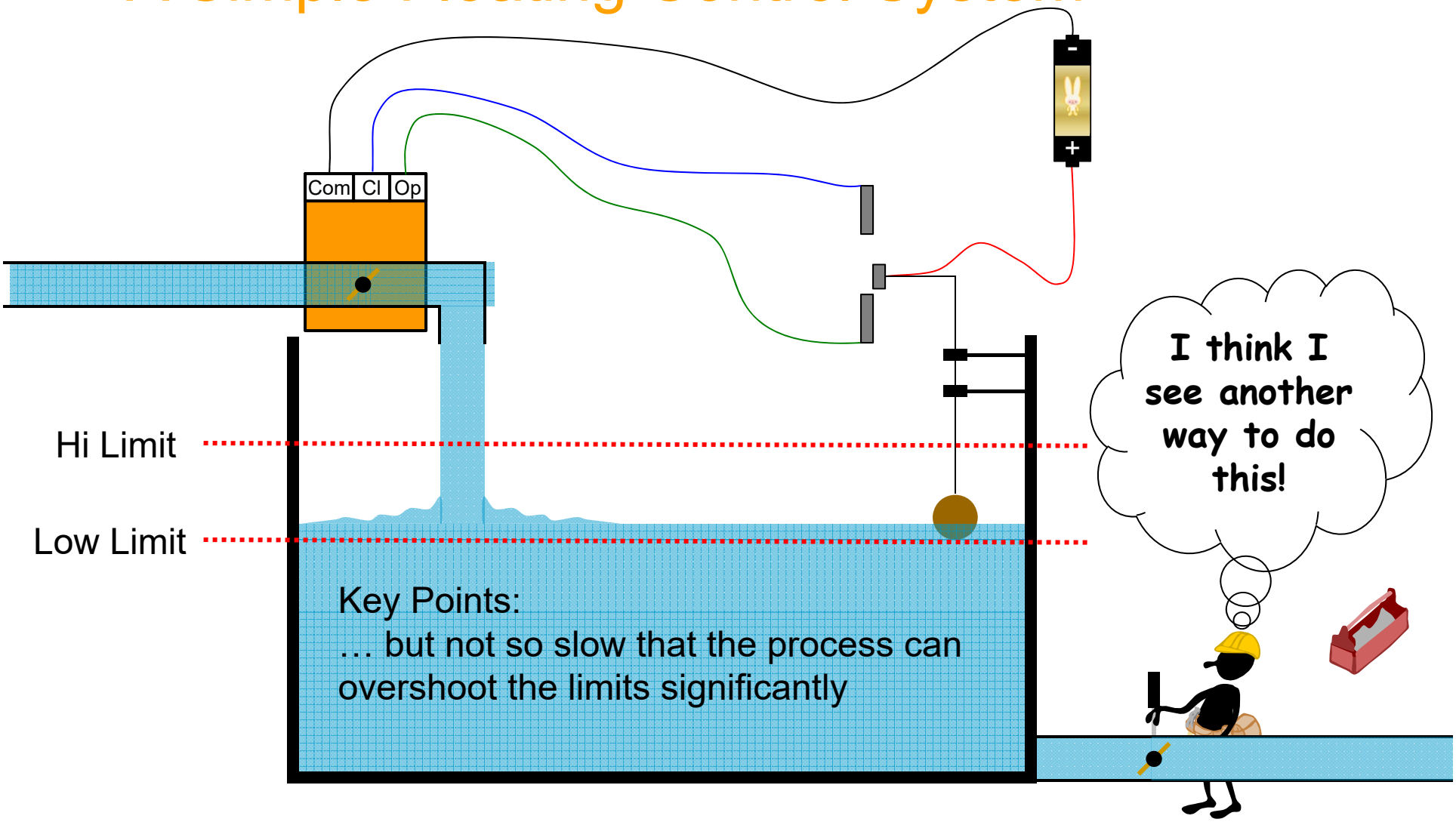
A Simple Floating Control System

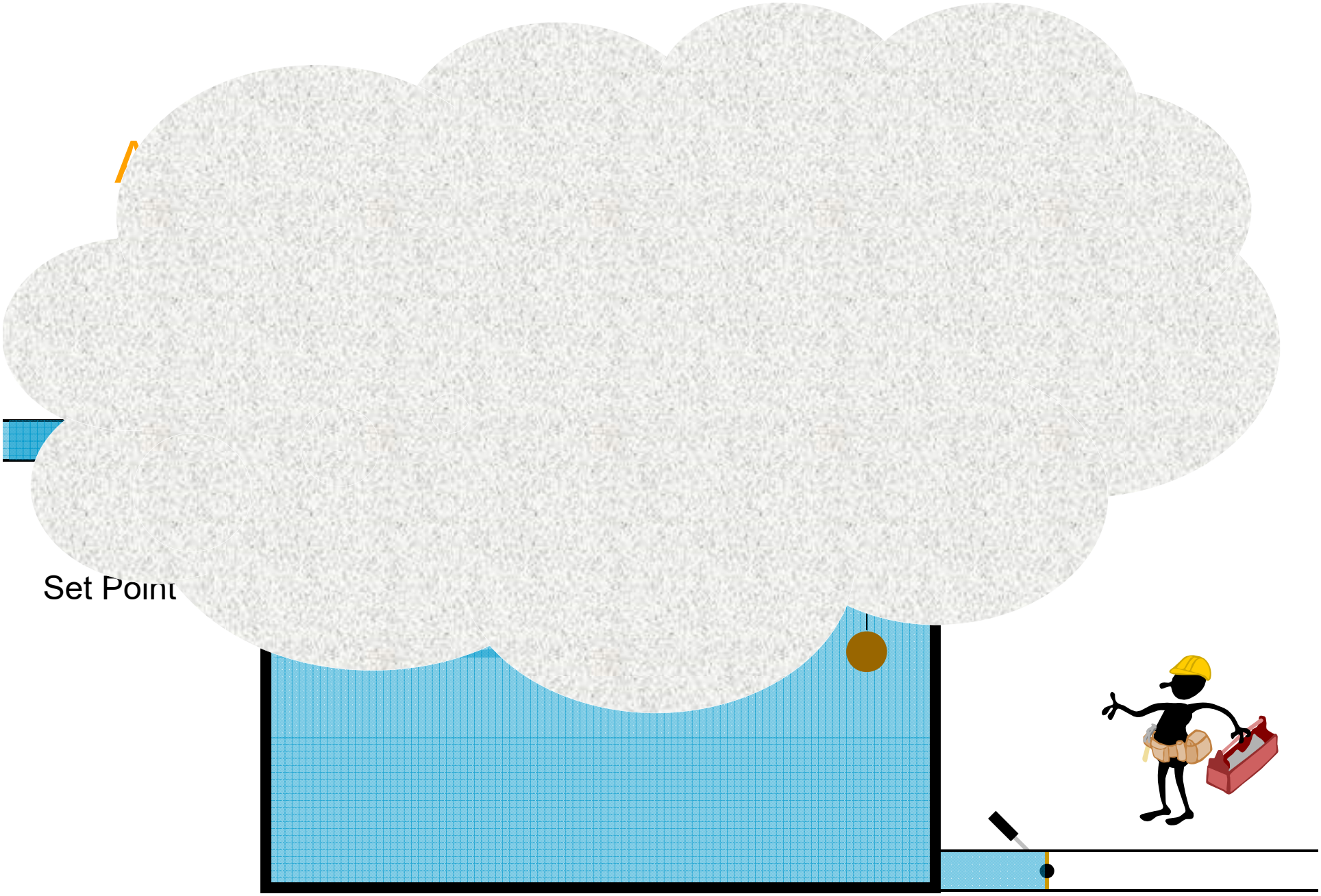


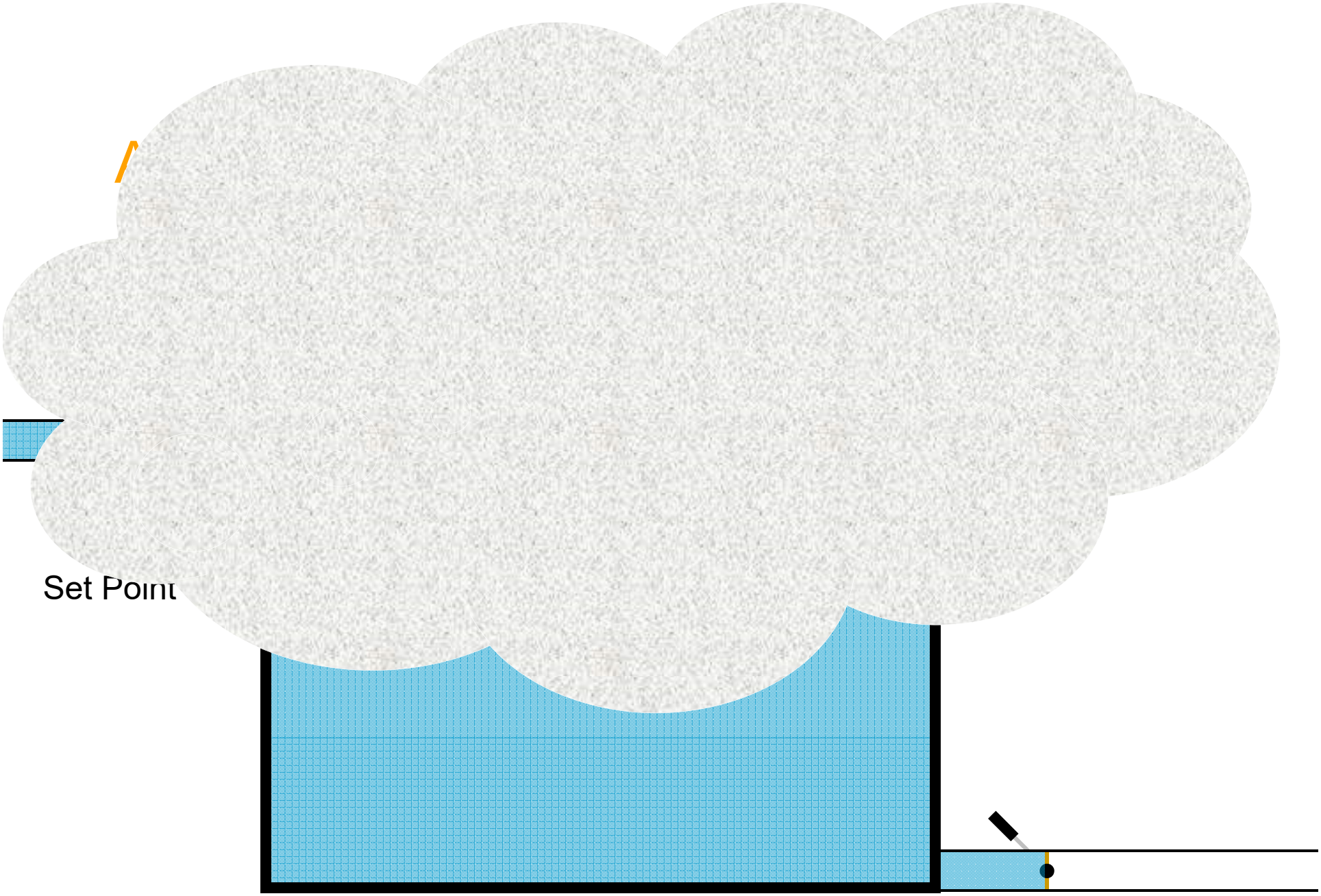
A Simple Floating Control System



A Simple Floating Control System

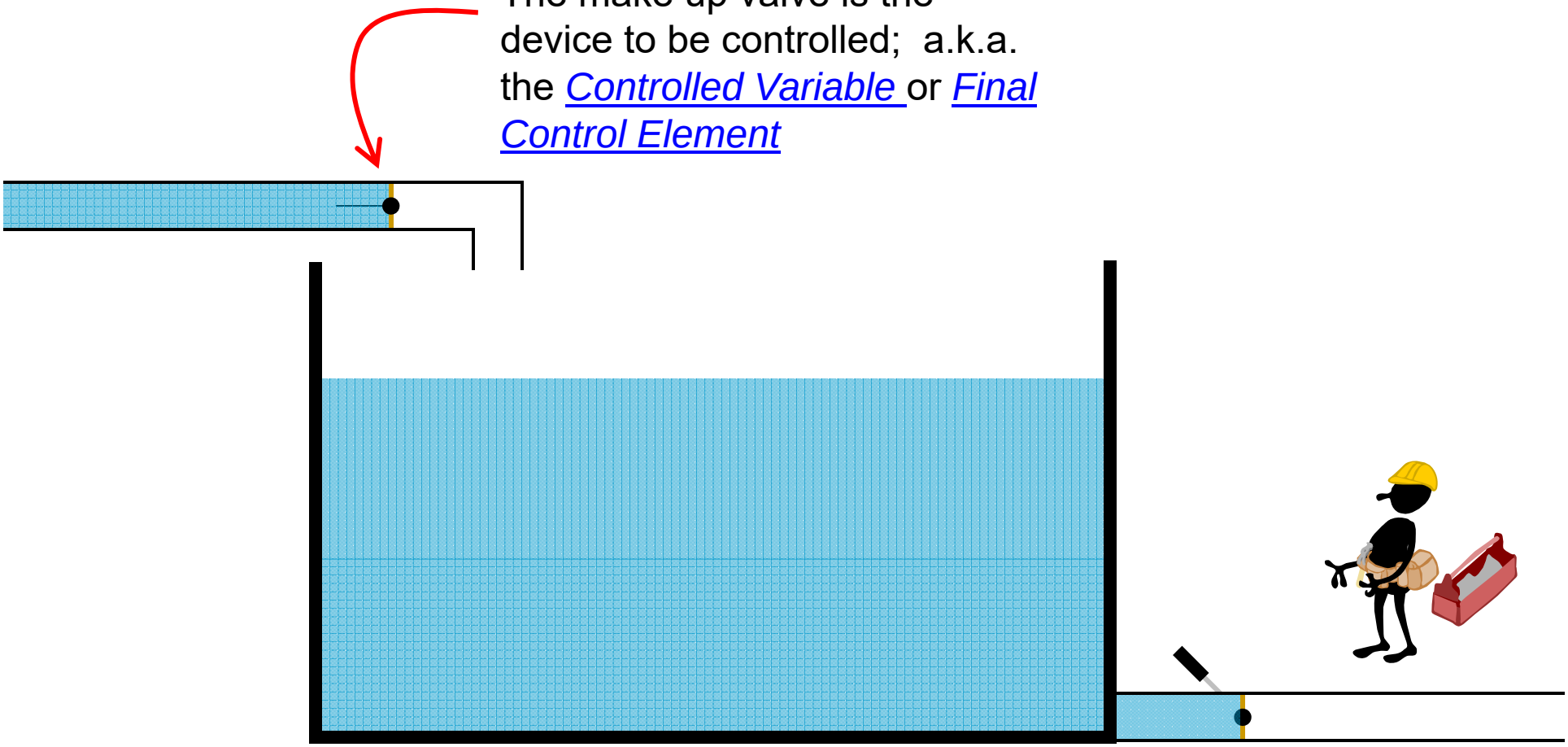



Set Point


Set Point

A Simple Control Requirement

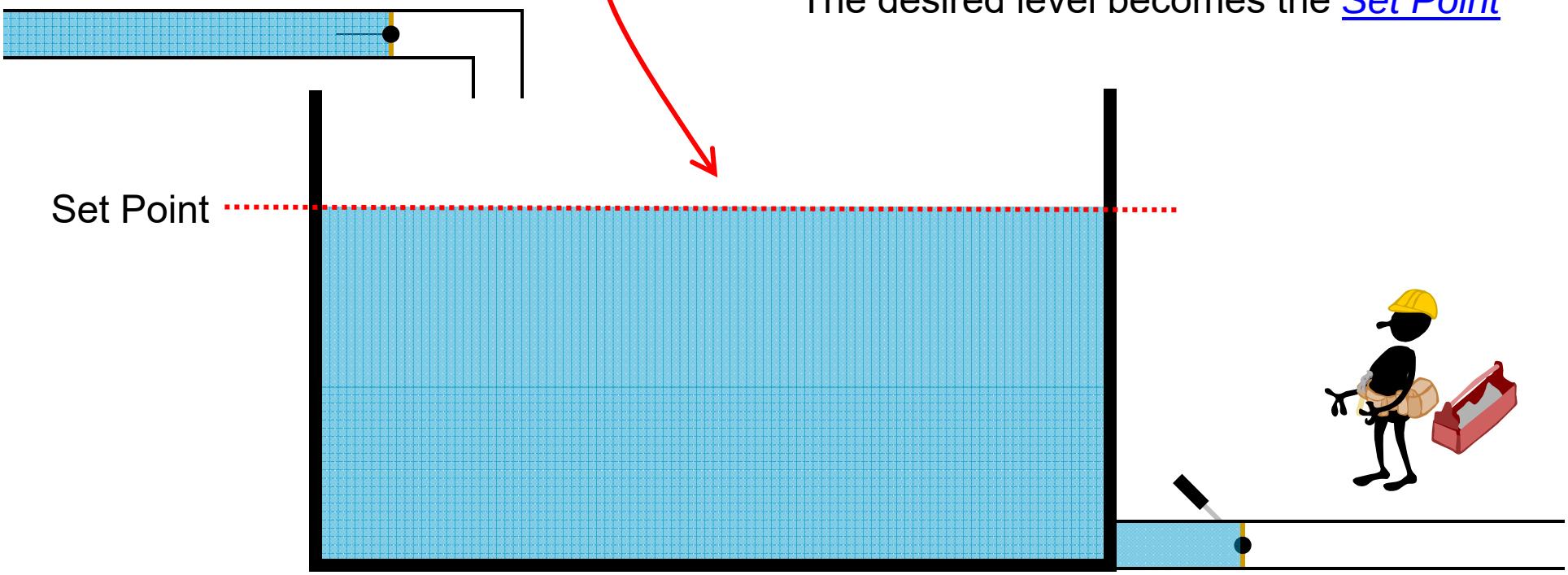
The make up valve is the device to be controlled; a.k.a. the *Controlled Variable* or *Final Control Element*



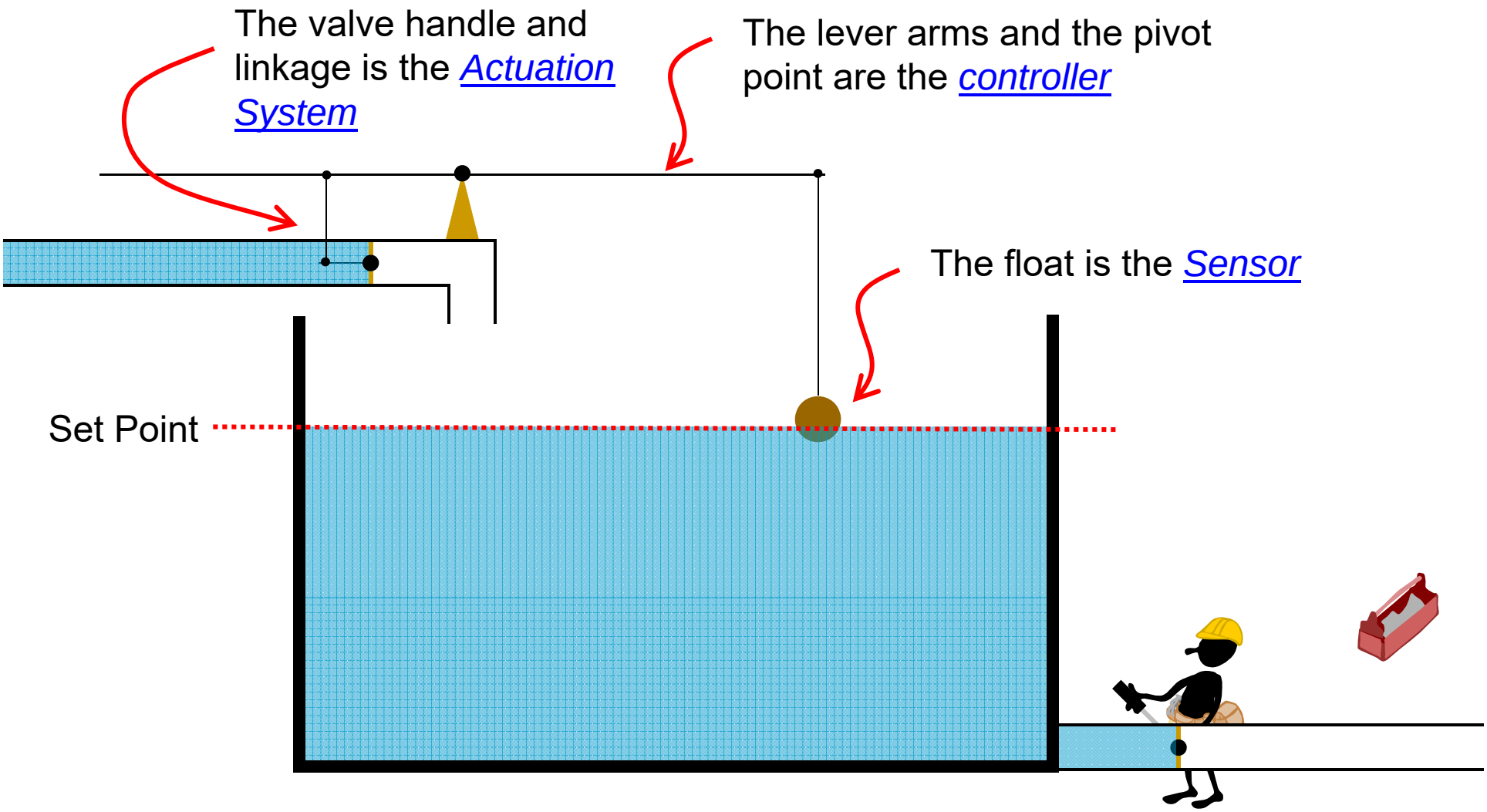
A Simple Control Requirement

The tank water level is the *Process Variable*

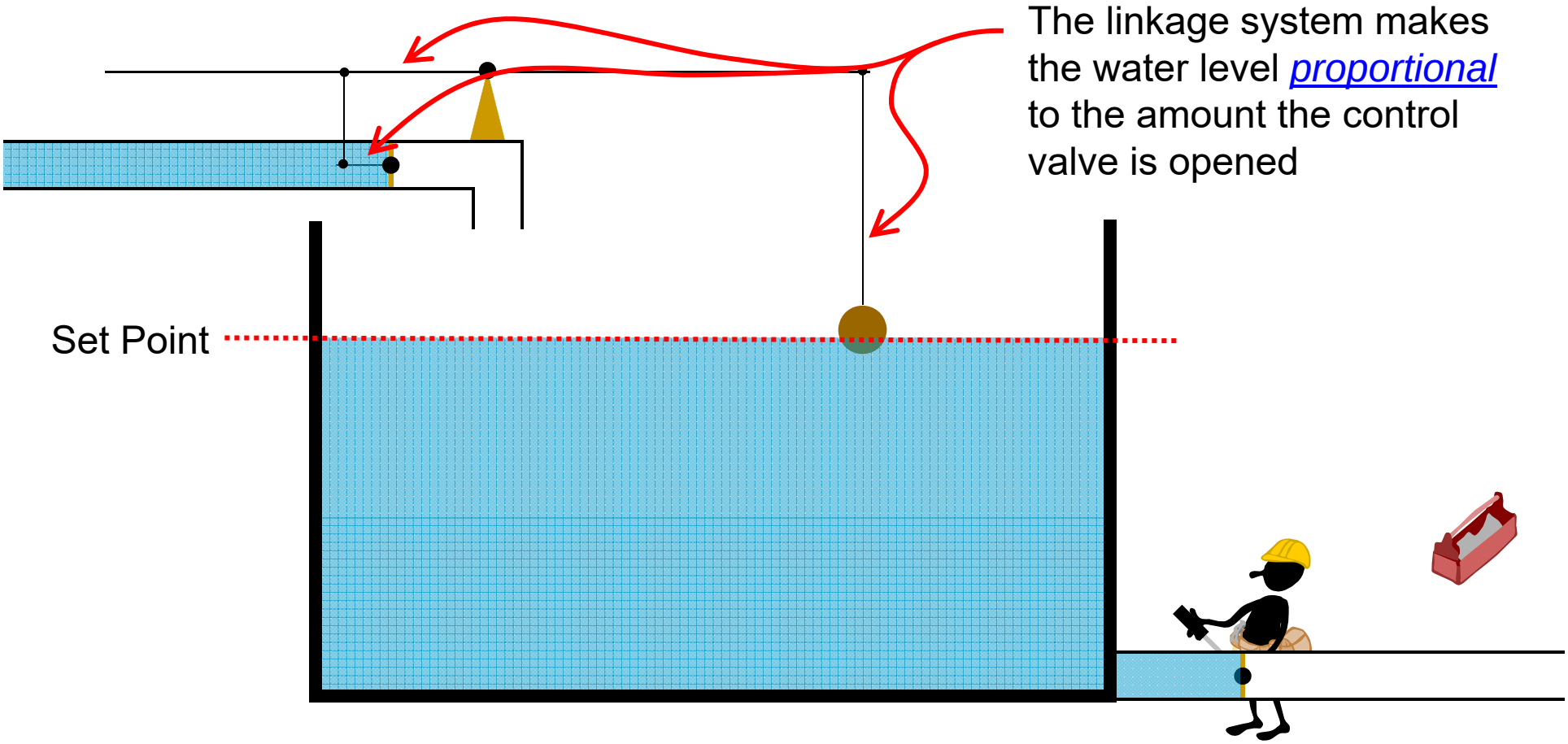
The desired level becomes the *Set Point*



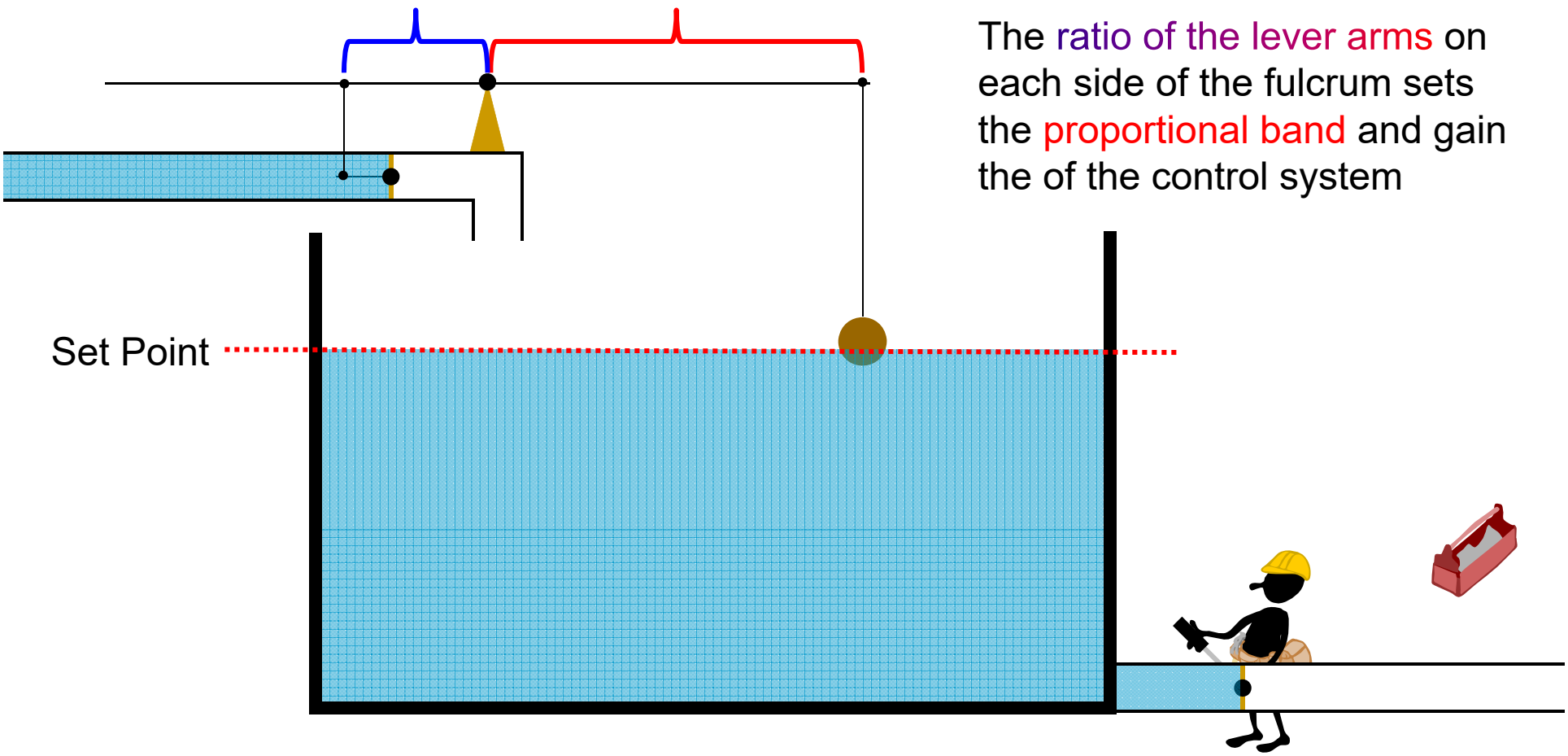
A Simple Proportional Control System



A Simple Proportional Control System



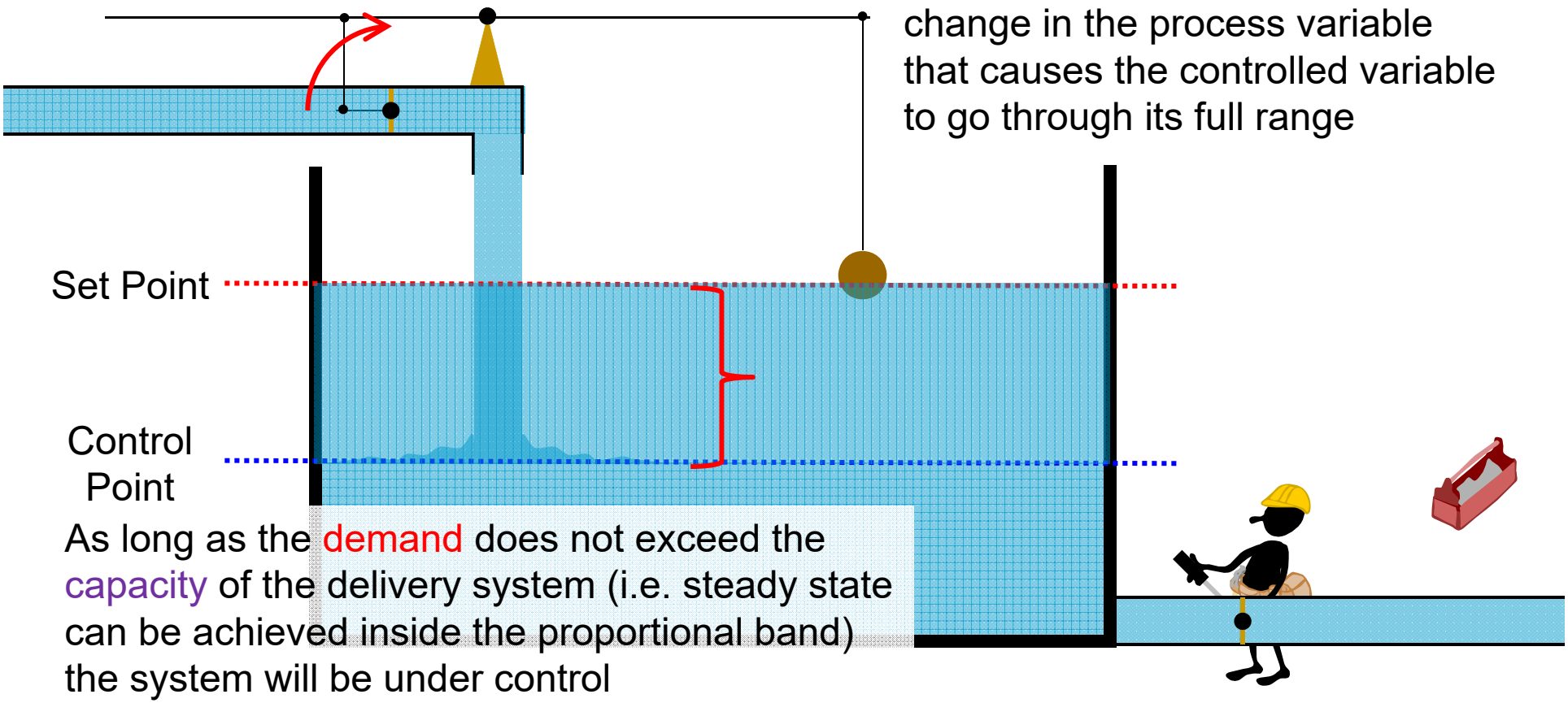
A Simple Proportional Control System



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

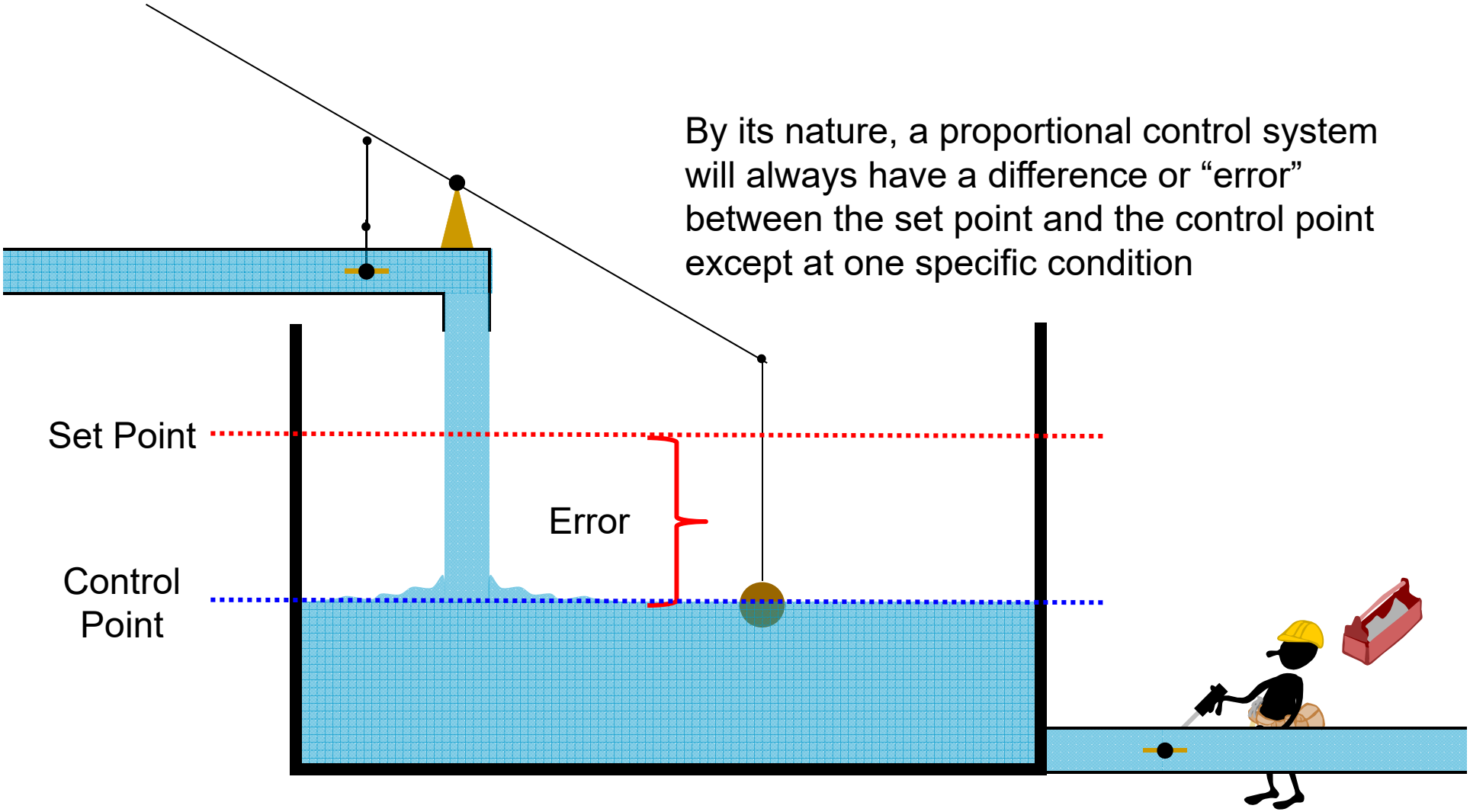
The proportional band is the change in the process variable that causes the controlled variable to go through its full range



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

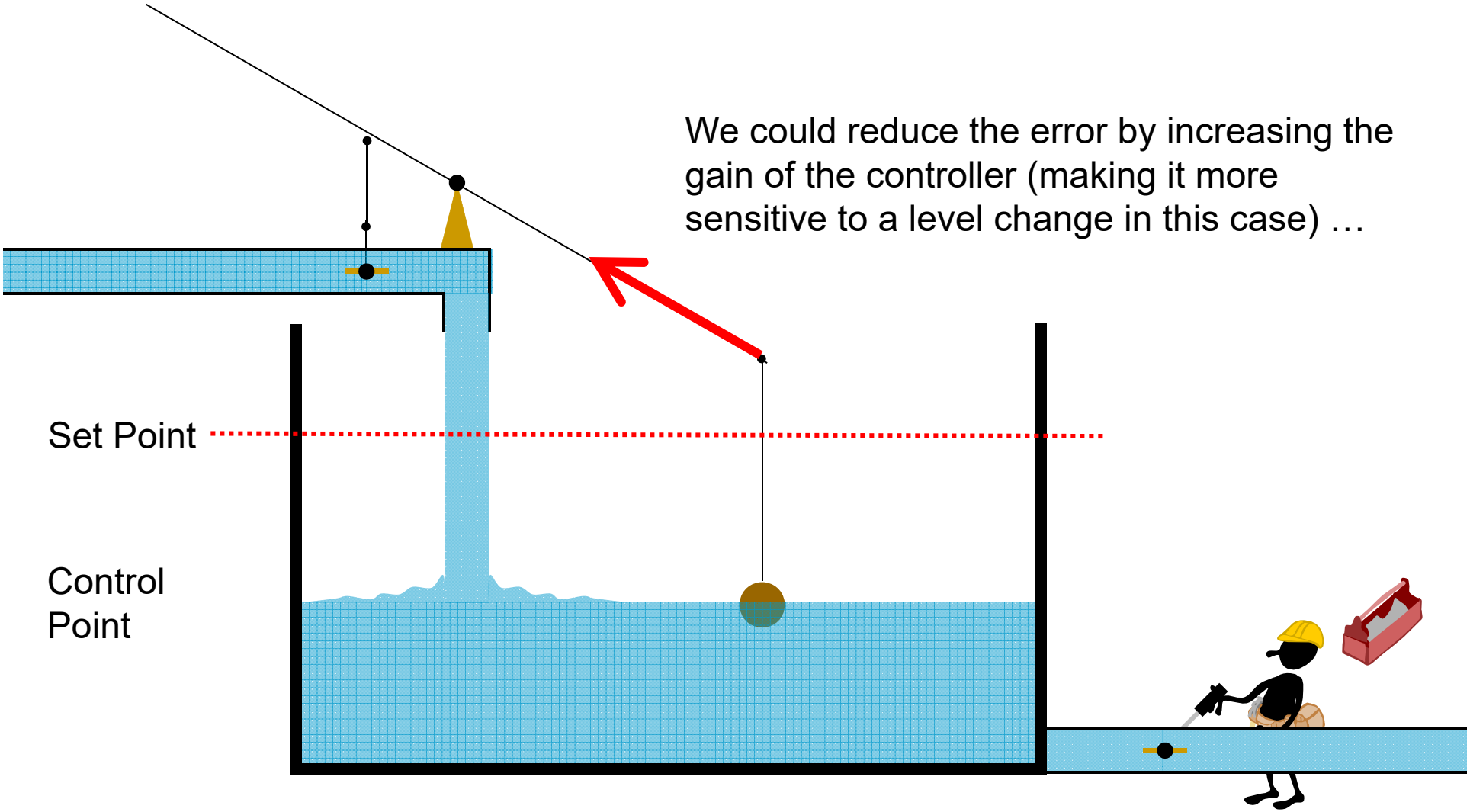
A Simple Proportional Control System

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



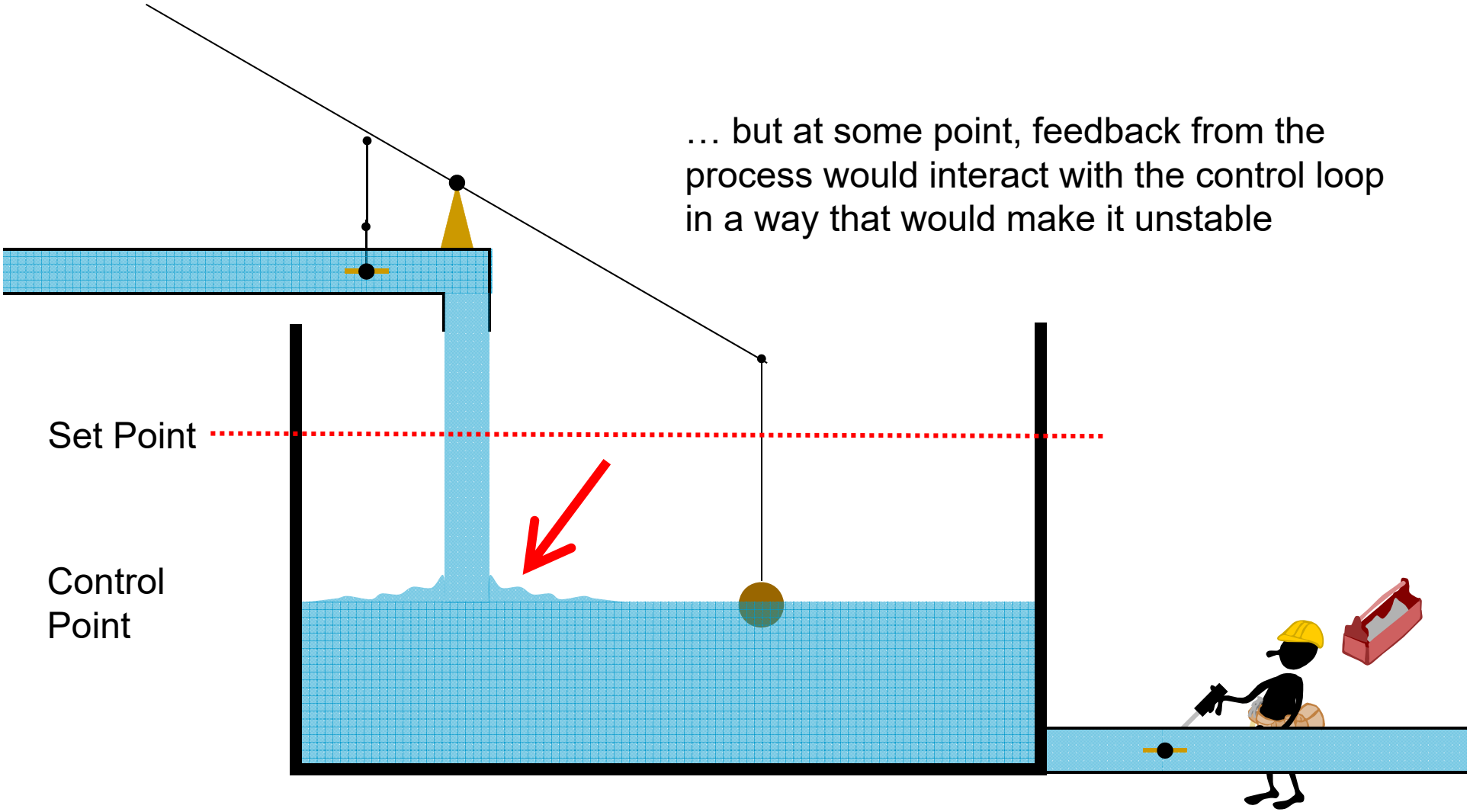
A Simple Proportional Control System

We could reduce the error by increasing the gain of the controller (making it more sensitive to a level change in this case) …



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



Control Systems: Design, Performance and Commissioning Issues

Control Processes

The Impact of Narrowing the Throttling Range in a Proportional Control Process

Instructor:

David Sellers

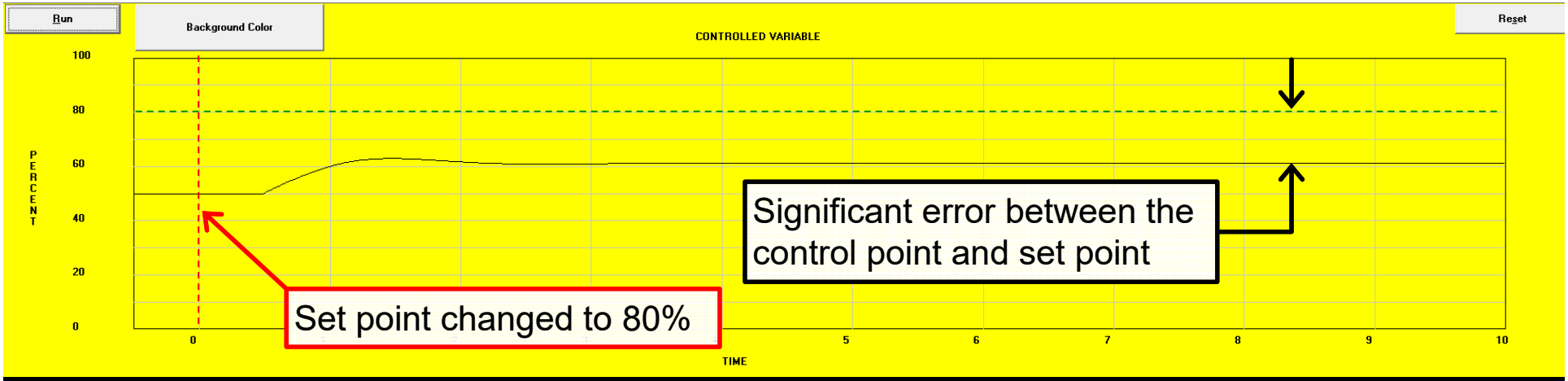
Senior Engineer

Facility Dynamics Engineering

October 23, 2017

The Impact of Narrowing Throttling Range

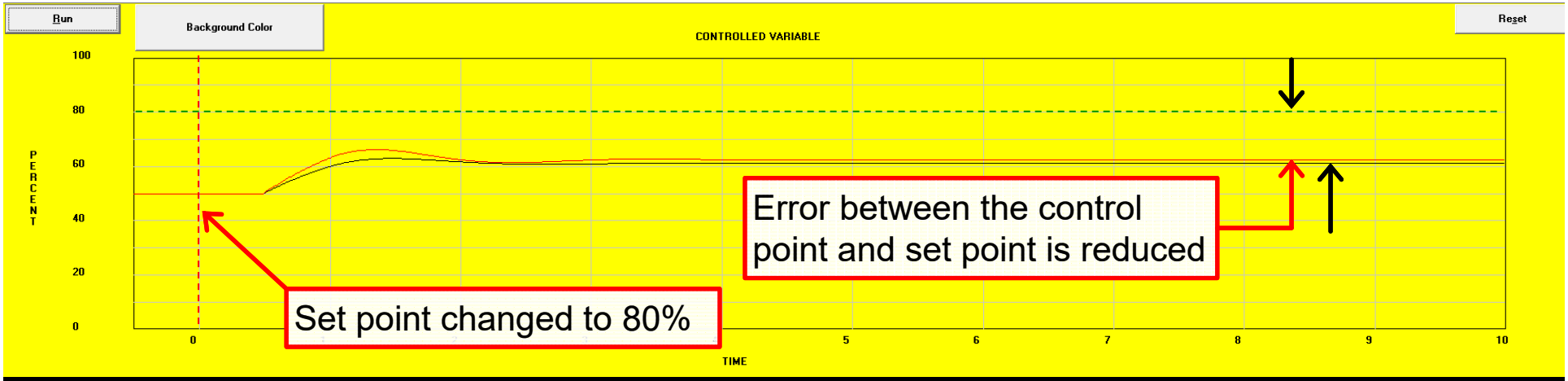
Proportional band =400% and set point changed to 80% (black line)



The Impact of Narrowing Throttling Range

Proportional band =400% (black line)

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

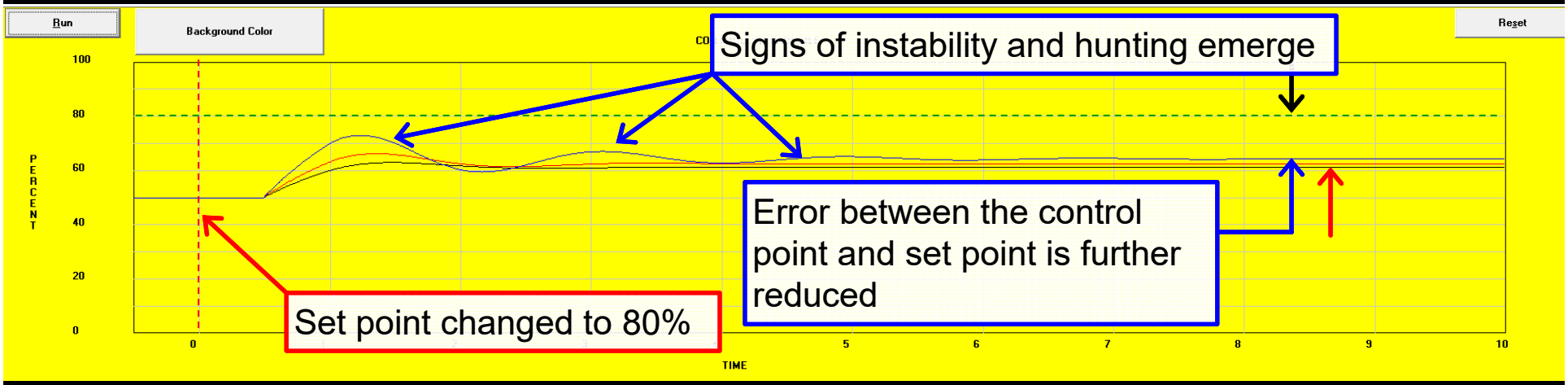


The Impact of Narrowing Throttling Range

Proportional band =400% (black line)

Proportional band =300% (red line)

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



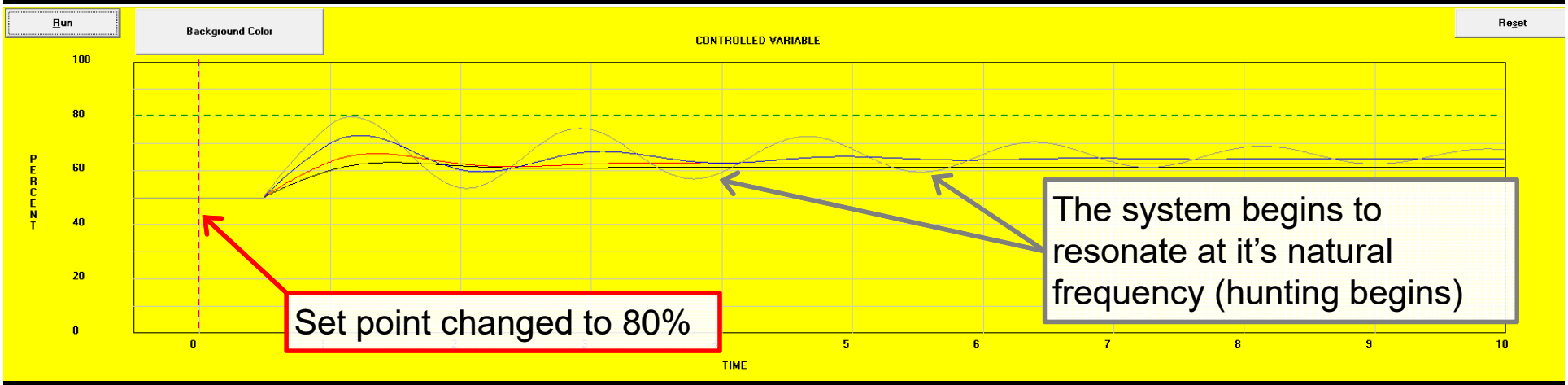
The Impact of Narrowing Throttling Range

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

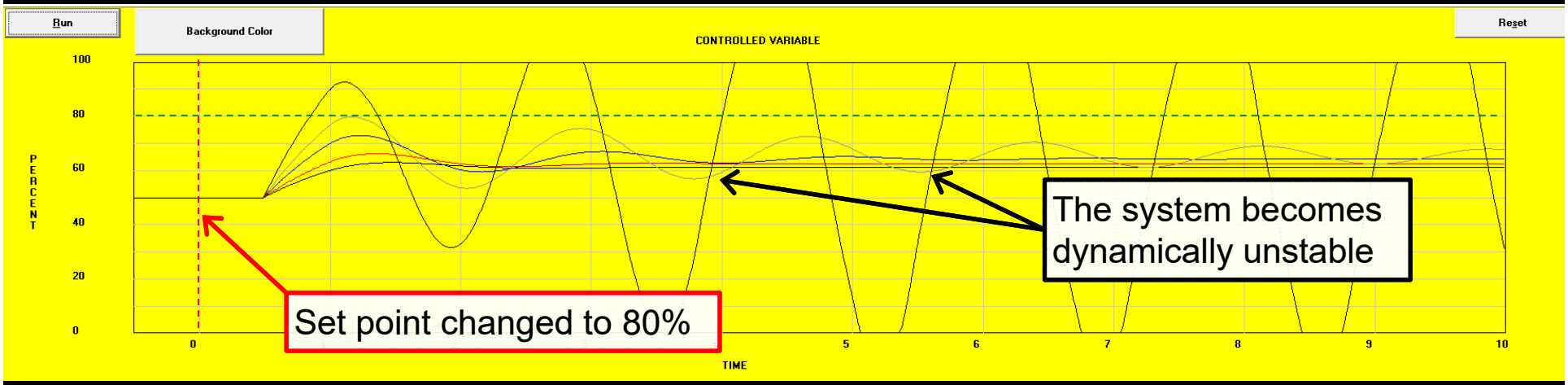
Proportional band =400% (black line)

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)



Control Systems: Design, Performance and Commissioning Issues

Control Processes

Proportional plus Integral plus Derivation (PID) Control Processes

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

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

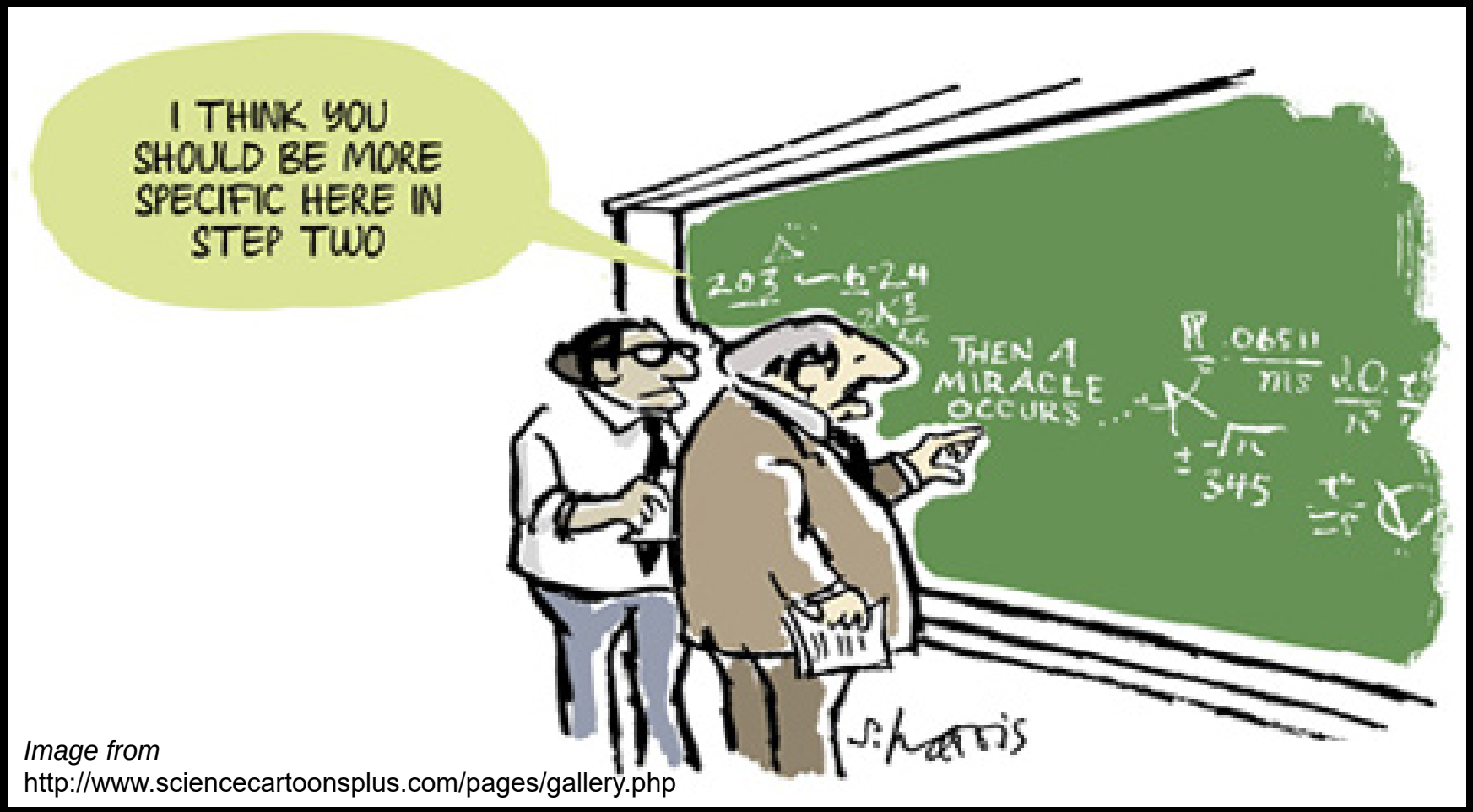


Image from
http://www.sciencecartoonsplus.com/pages/gallery.php

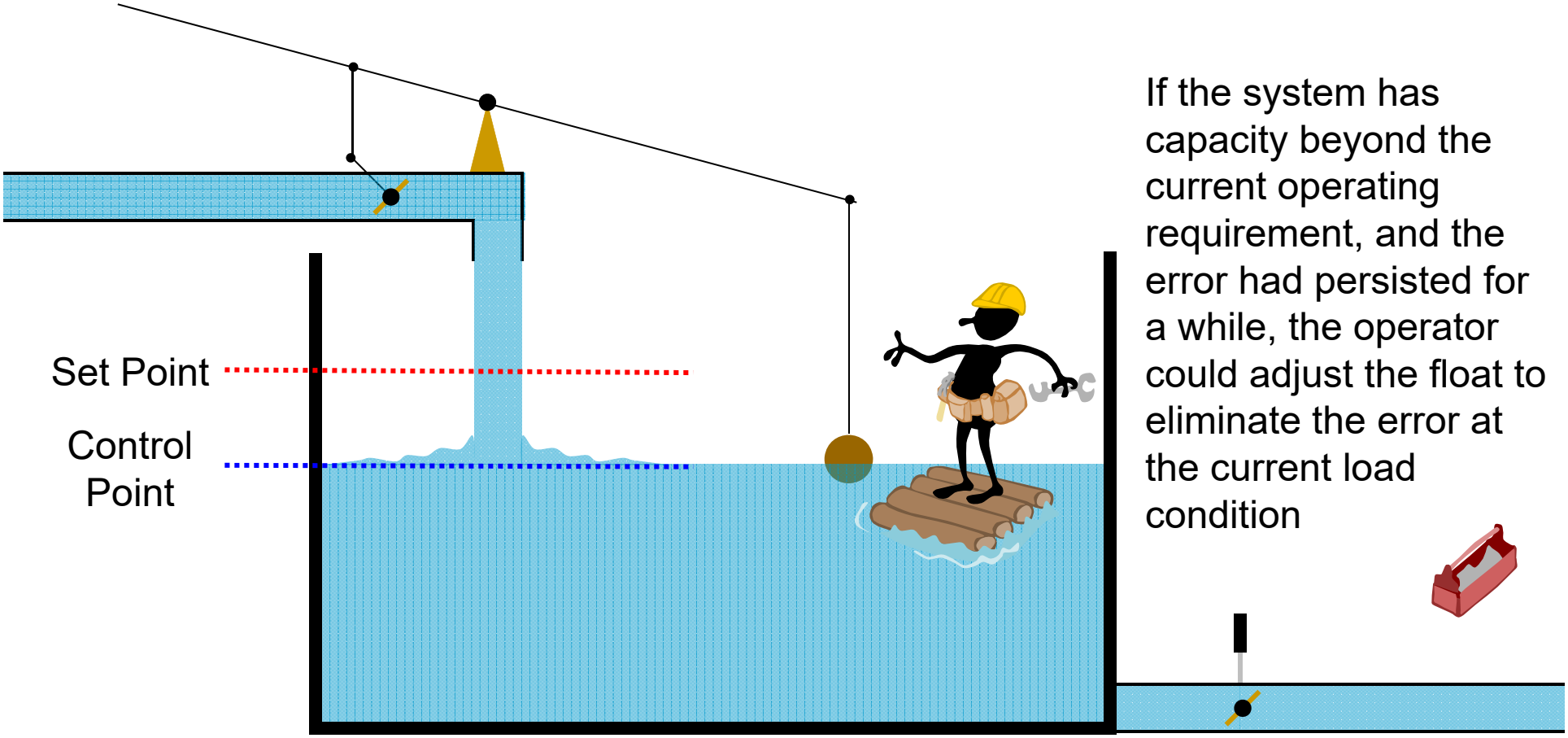
Proportional plus Integral plus Derivative Control (PID)

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

A Simple Proportional Control System;

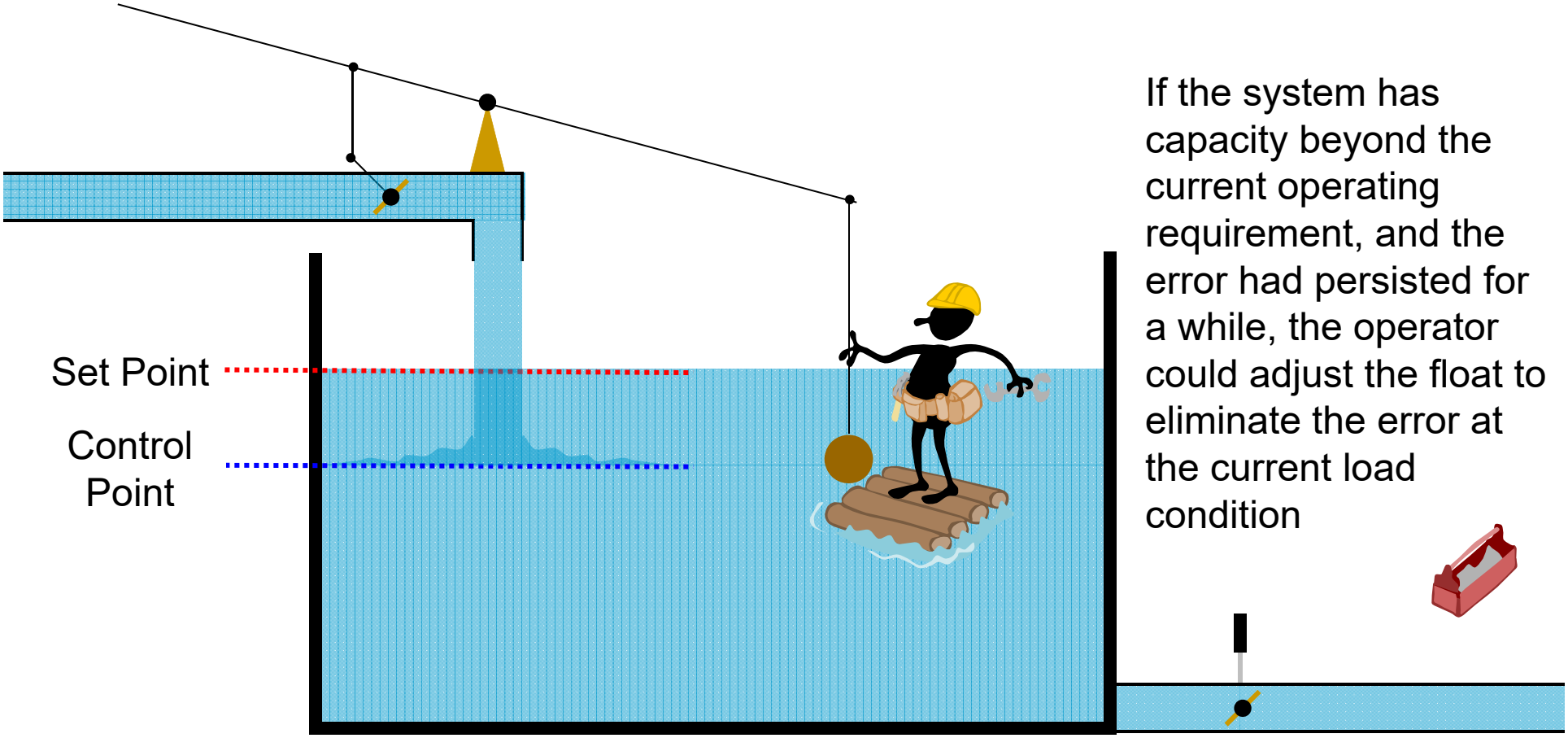
Adding Integral Control



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

A Simple Proportional Control System;

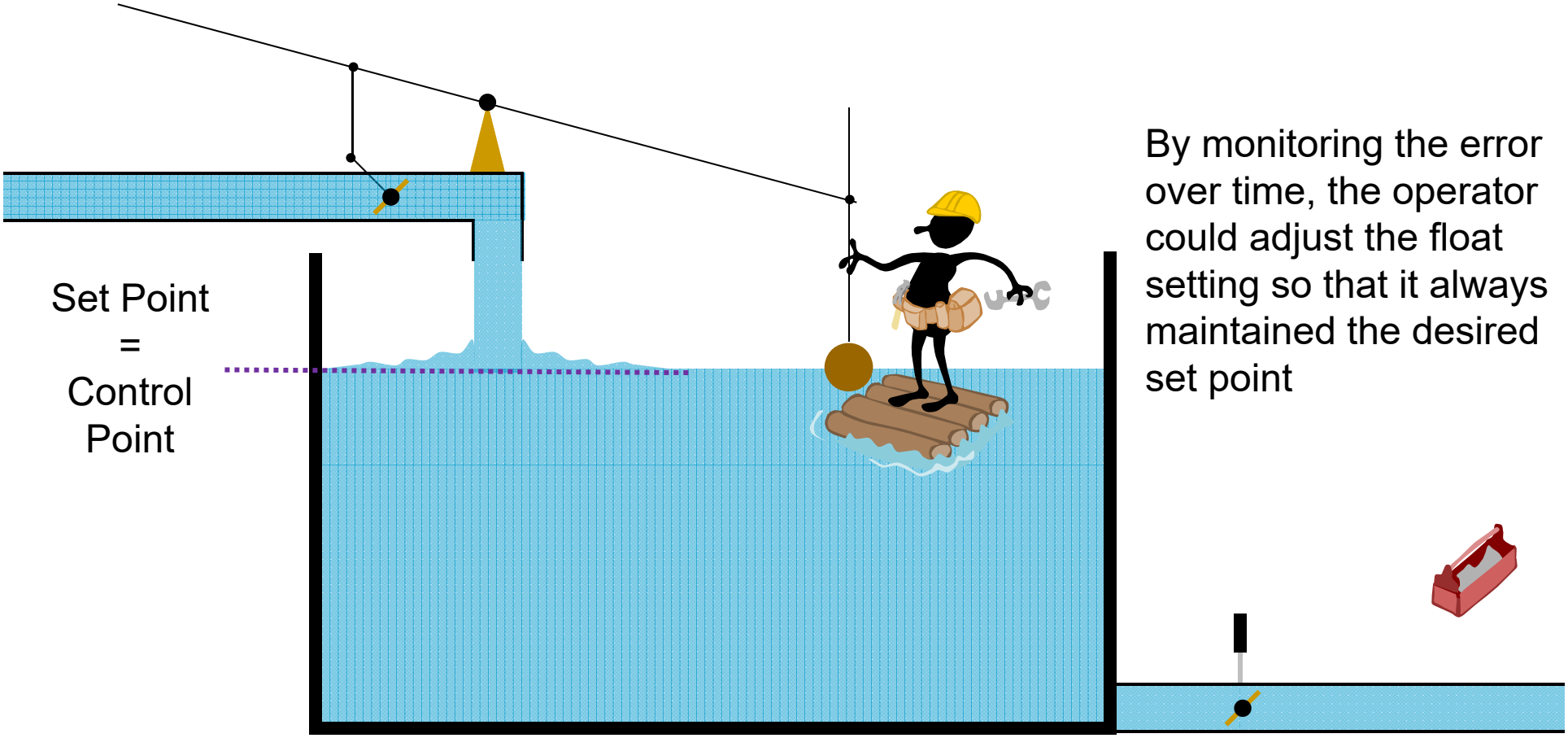
Adding Integral Control



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

A Simple Proportional Control System;

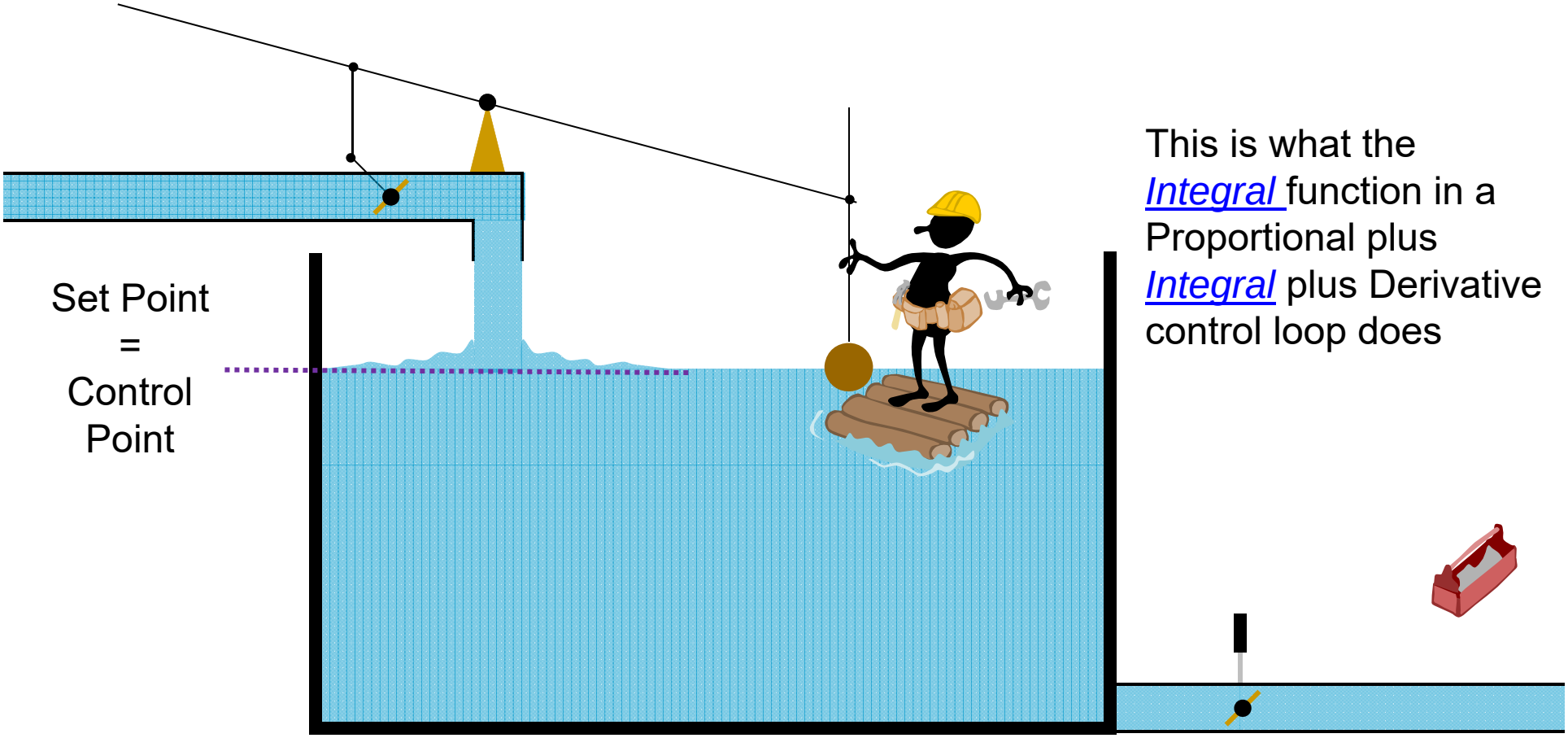
Adding Integral Control



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

A Simple Proportional Control System;

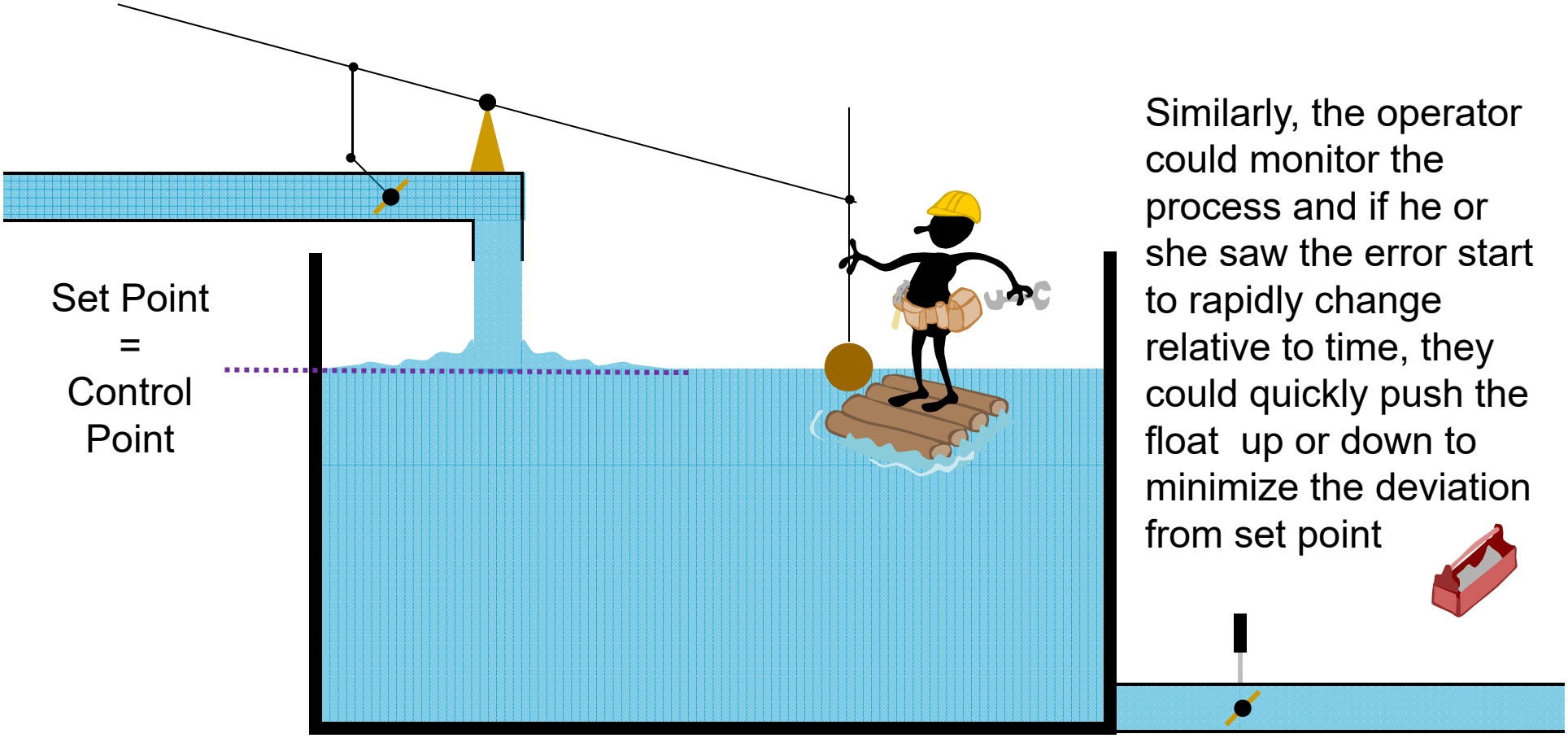
Adding Integral Control



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

A Simple Proportional Control System;

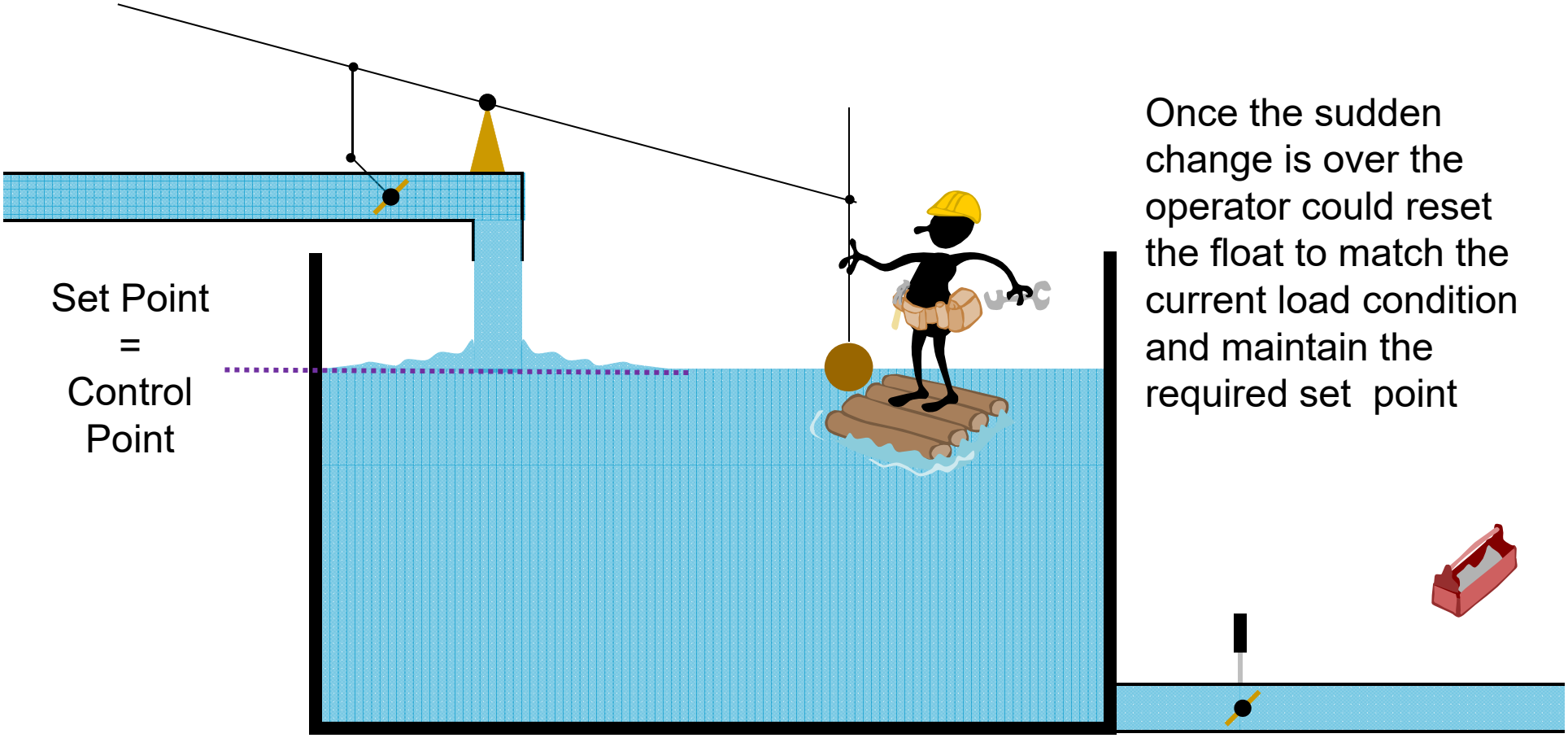
Adding Derivative Control



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

A Simple Proportional Control System;

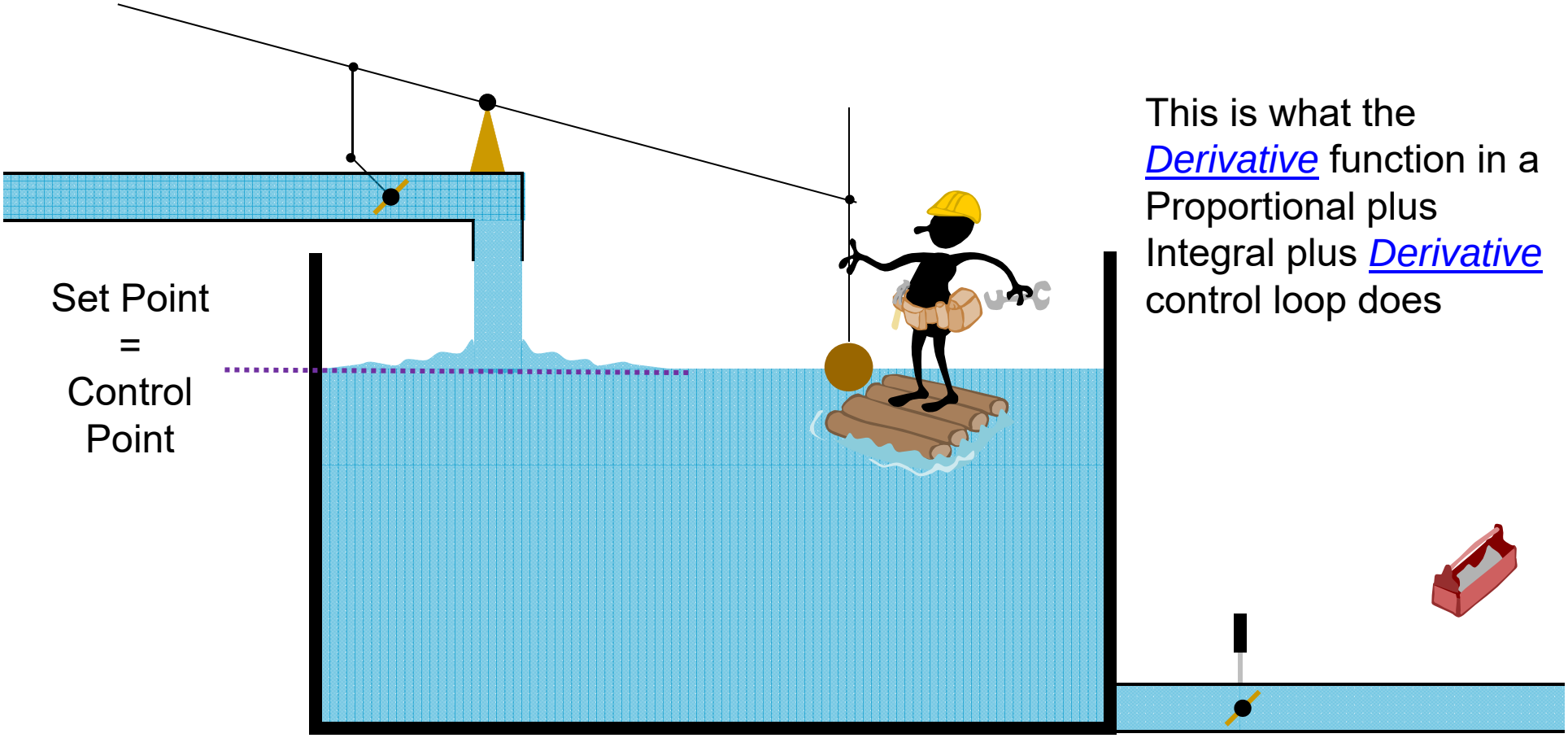
Adding Derivative Control



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

A Simple Proportional Control System;

Adding Derivative Control



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

Control Systems: Design, Performance and Commissioning Issues

Control Processes

The Impact of Adding Integral and Derivative Gain to a Proportional Control Process

Instructor:

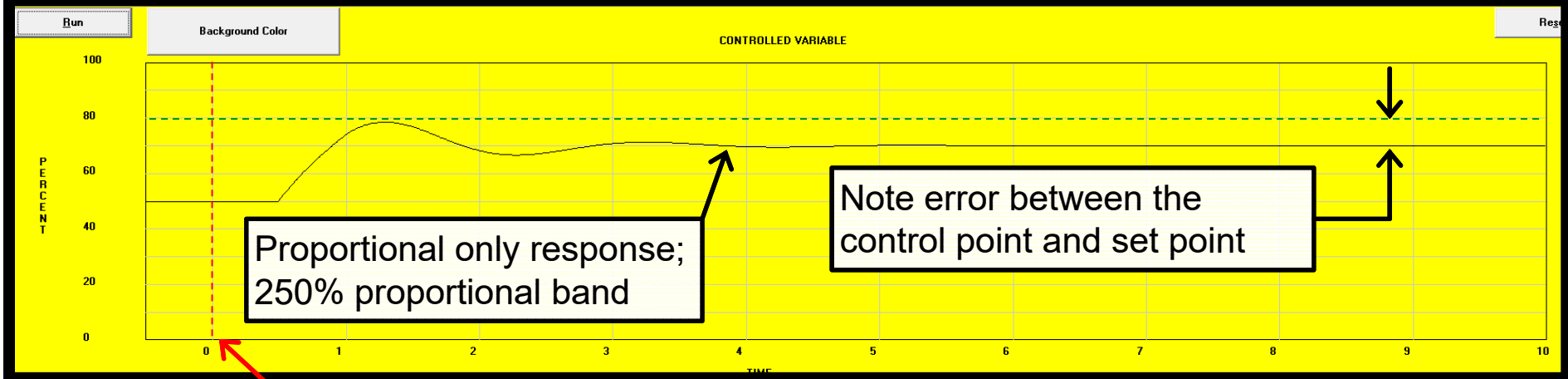
David Sellers

Senior Engineer

Facility Dynamics Engineering

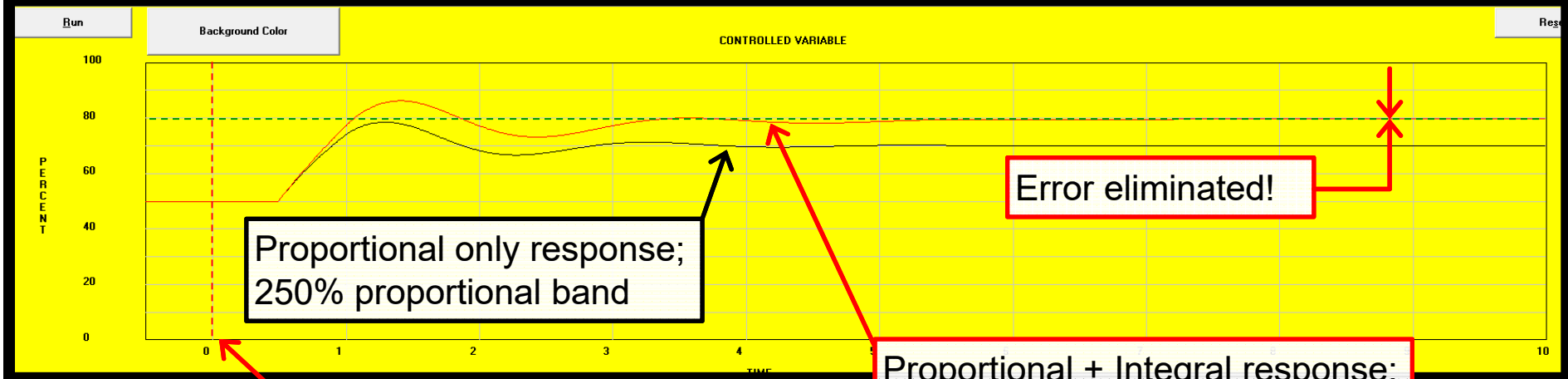
October 23, 2017

The Impact of Adding Integral Gain



Set point changed to 80%

The Impact of Adding Integral Gain



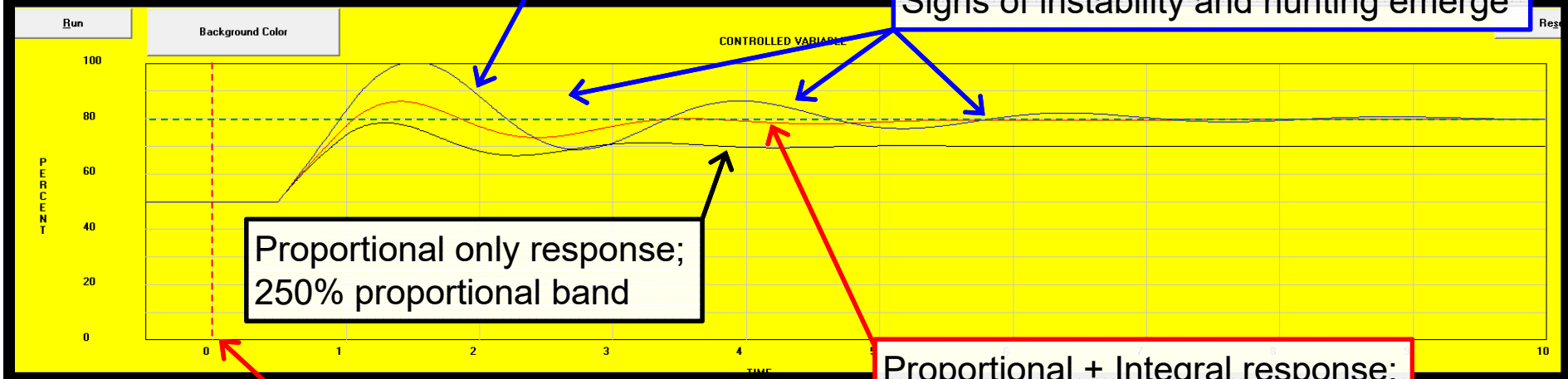
Set point changed to 80%

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

The Impact of Adding Integral Gain

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

Signs of instability and hunting emerge



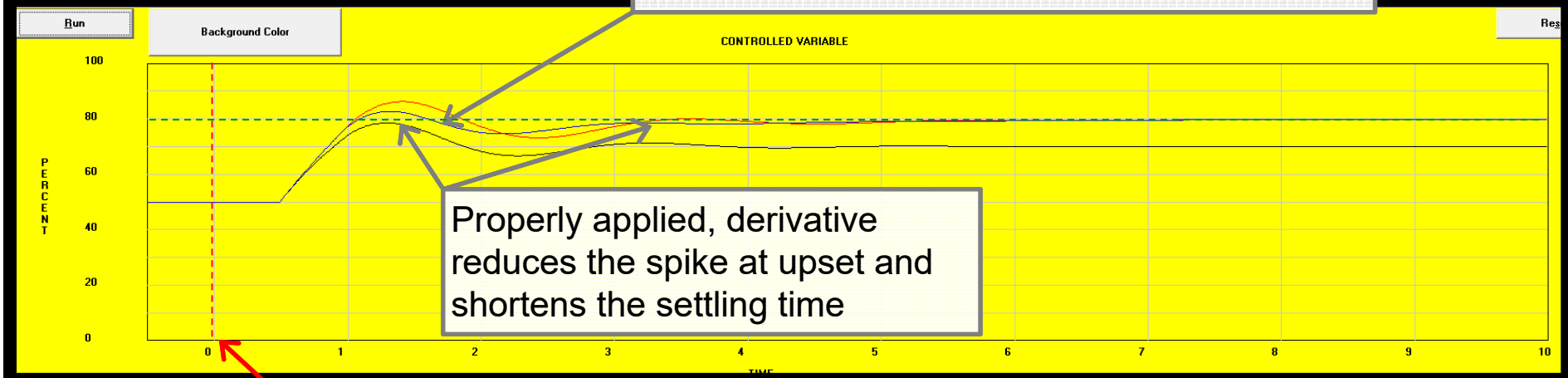
Proportional only response; 250% proportional band

Set point changed to 80%

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

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*

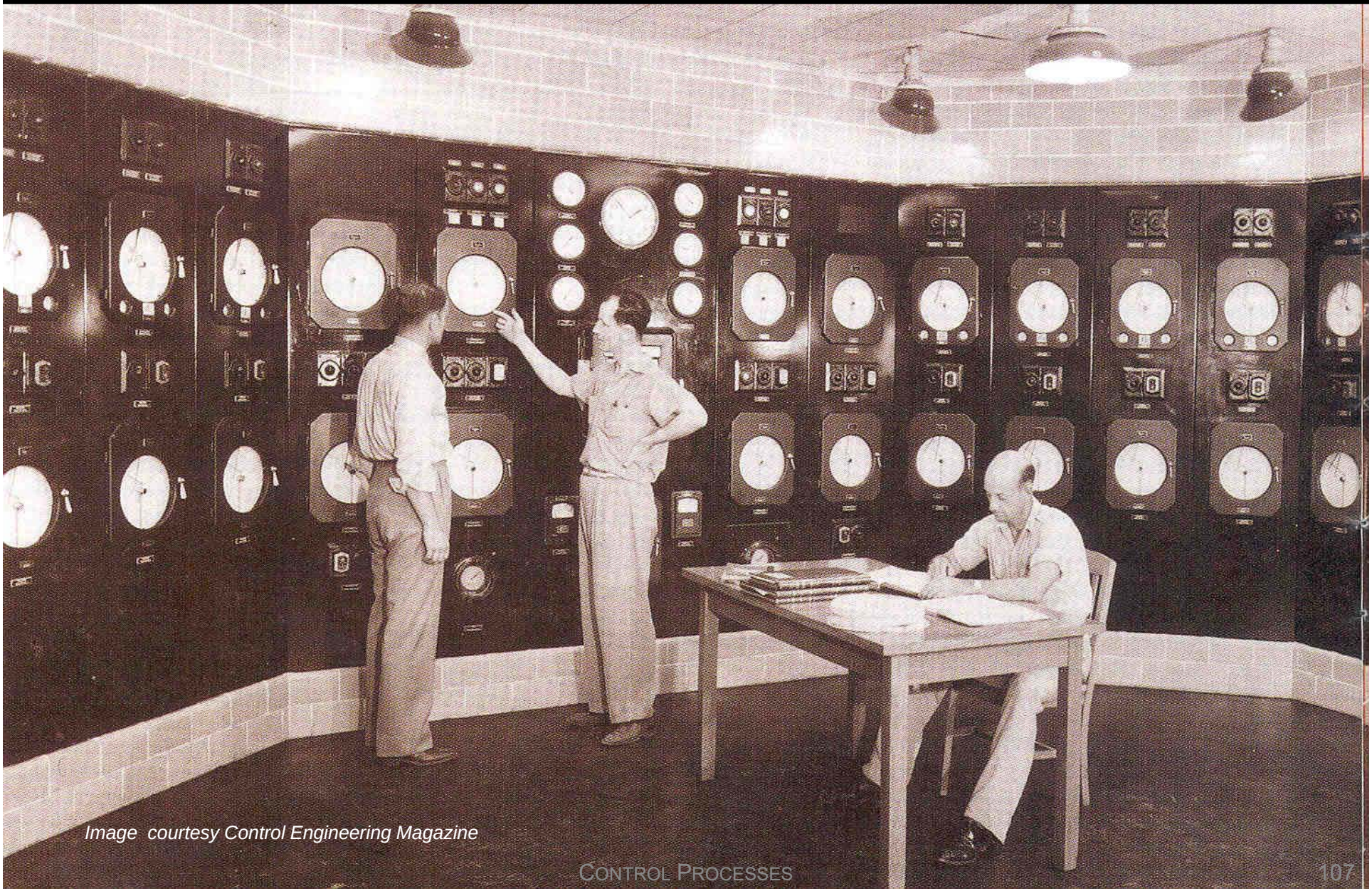


Image courtesy Control Engineering Magazine

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

Control Systems: Design, Performance and Commissioning Issues

Control Processes

Integral and Derivative Gain Units of Measure

Instructor:

David Sellers

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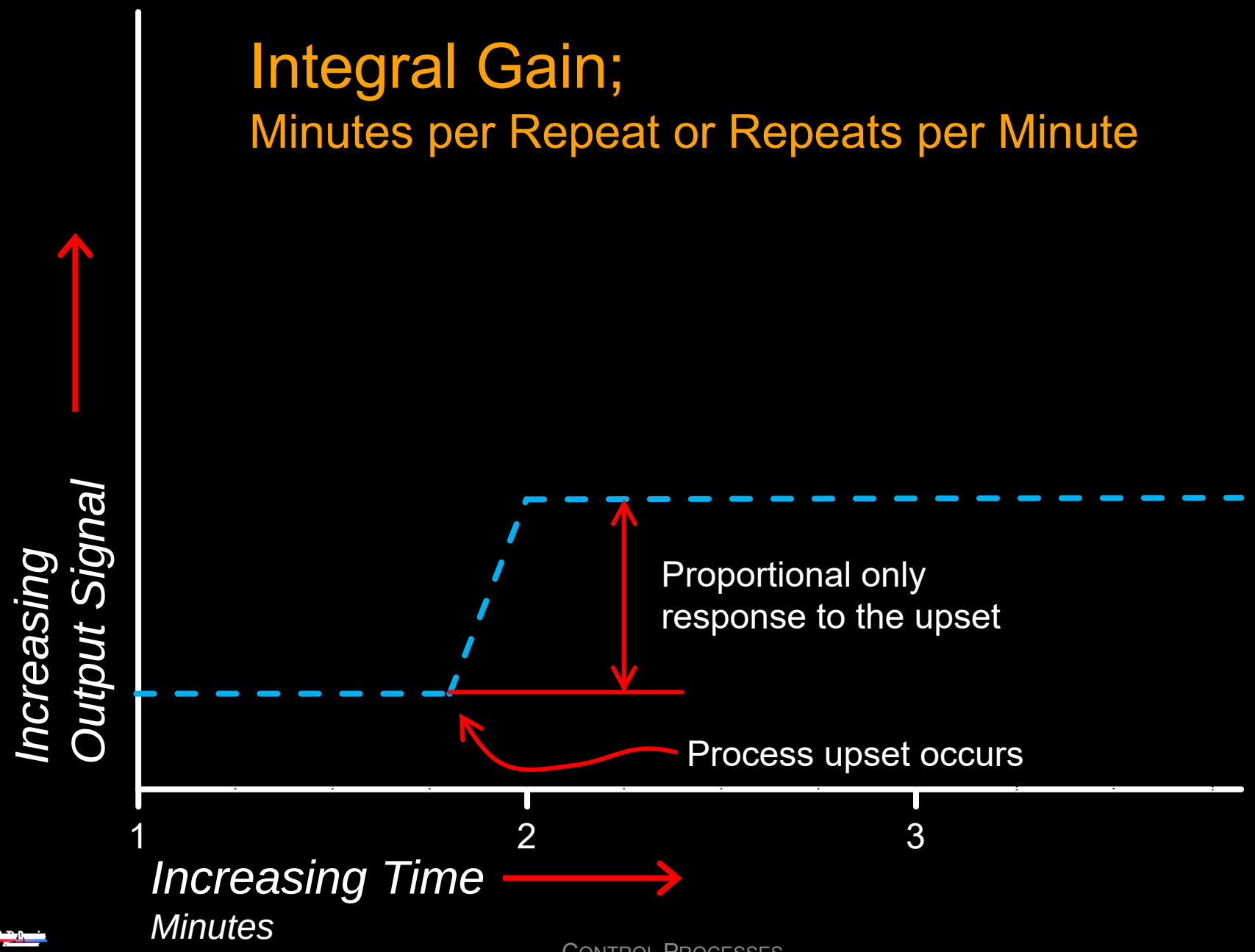
October 23, 2017

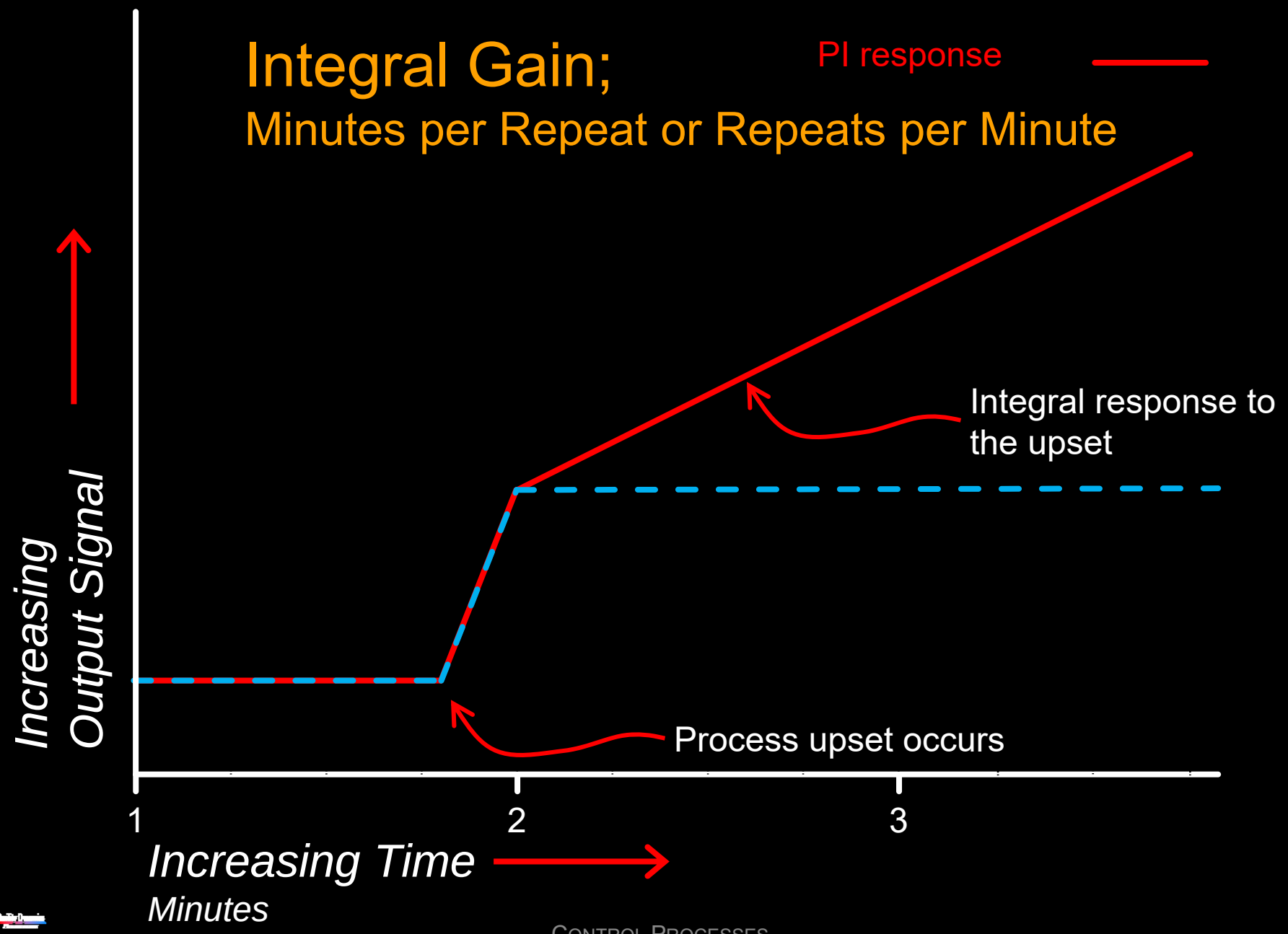
Integral Gain;

Minutes per Repeat or Repeats per Minute



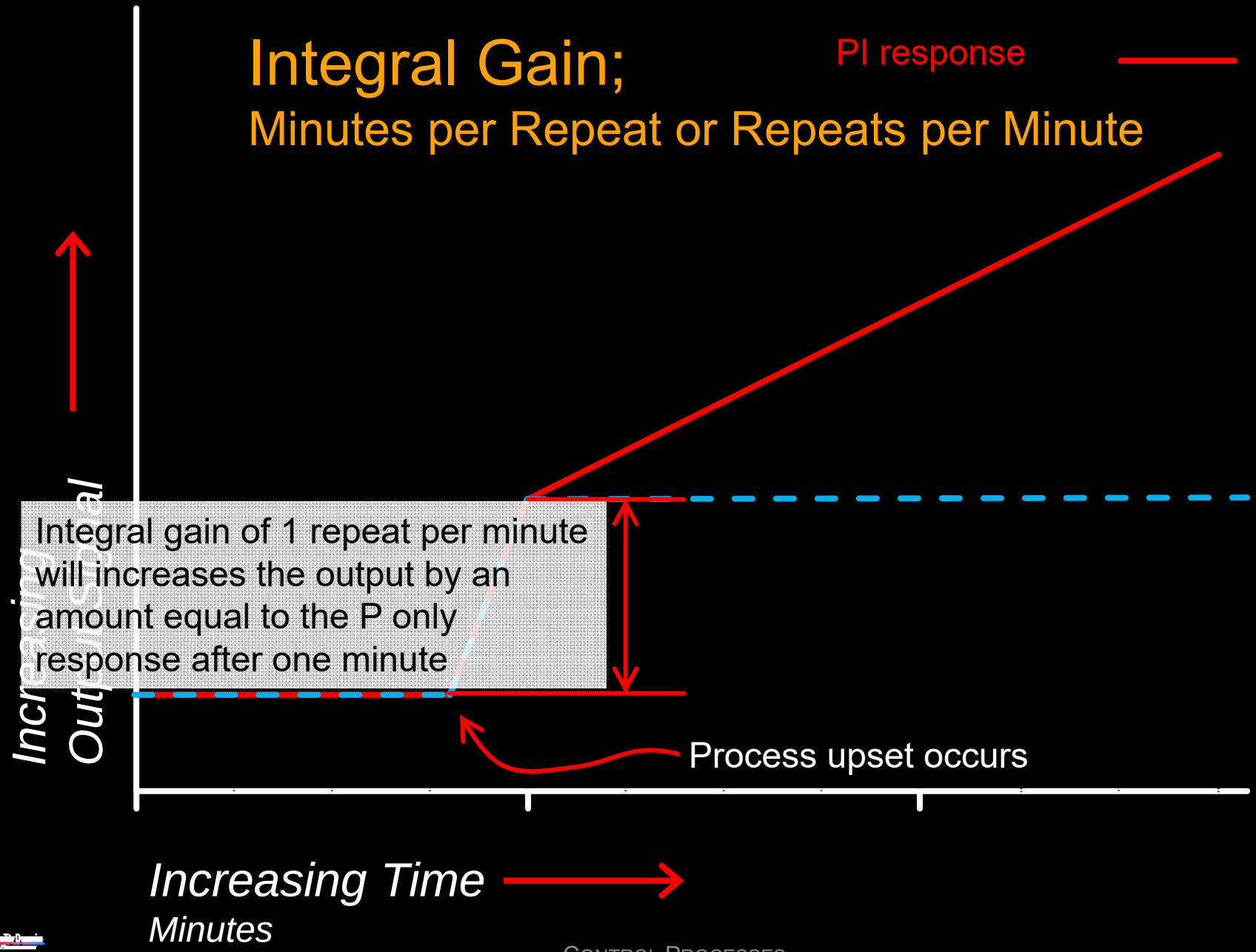
Integral Gain;

Minutes per Repeat or Repeats per Minute



Integral Gain;

Minutes per Repeat or Repeats per Minute



Potential Problems when Adding Integral Action

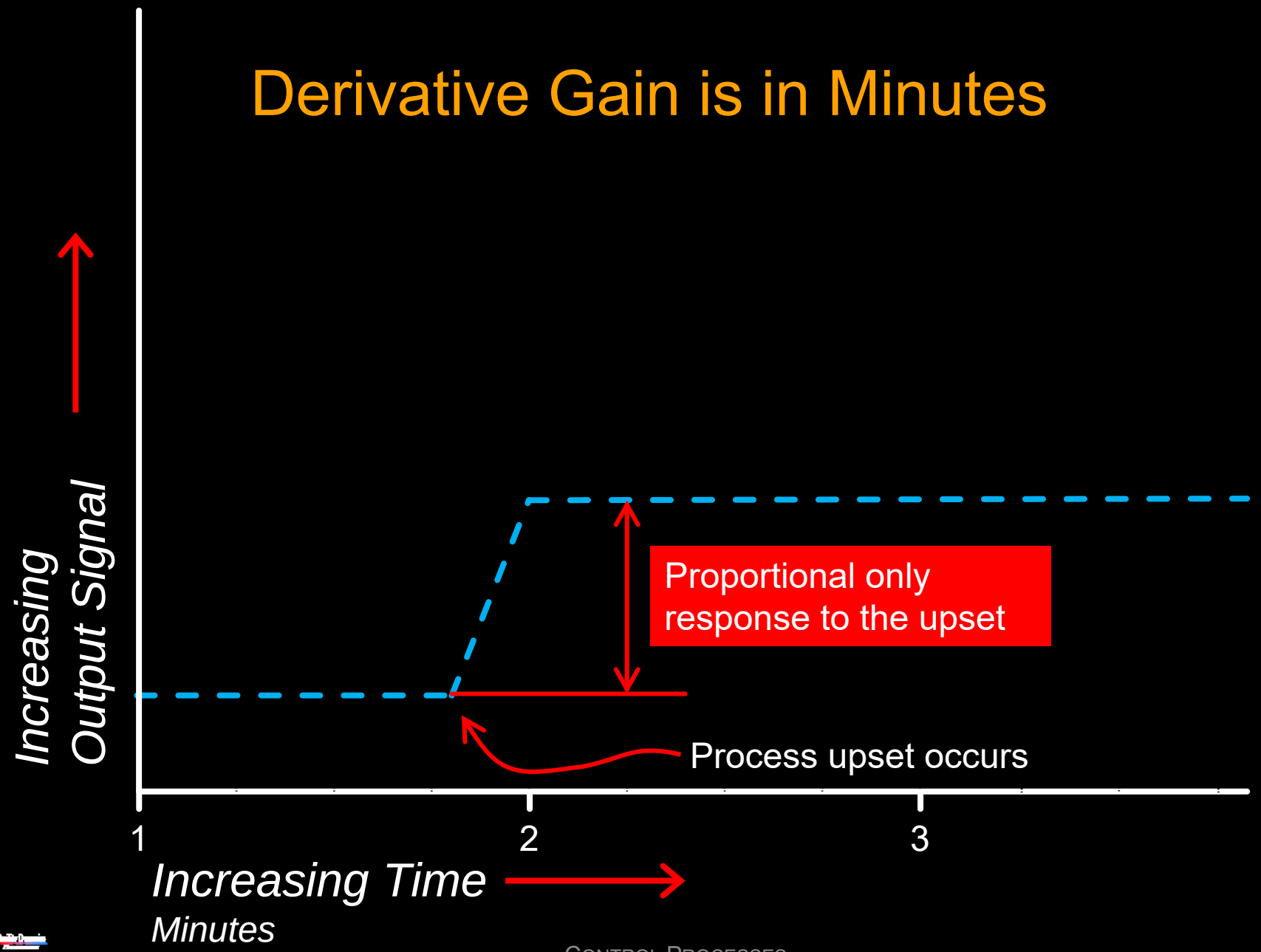
Loop instability unless a commensurate reduction in proportional gain is made

Tuning and maintenance become more complex, time consuming and difficult

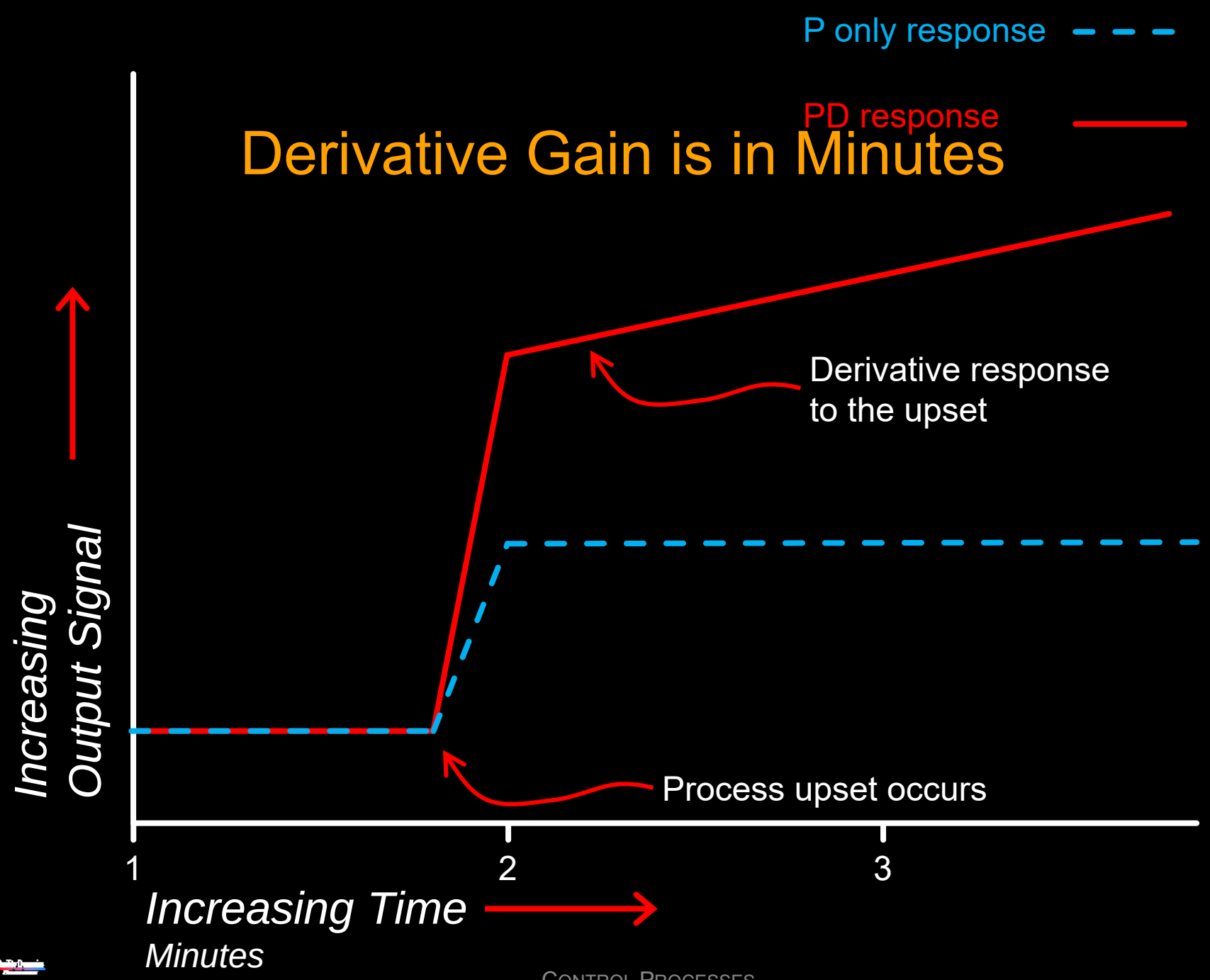
"Wind-up" can occur

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

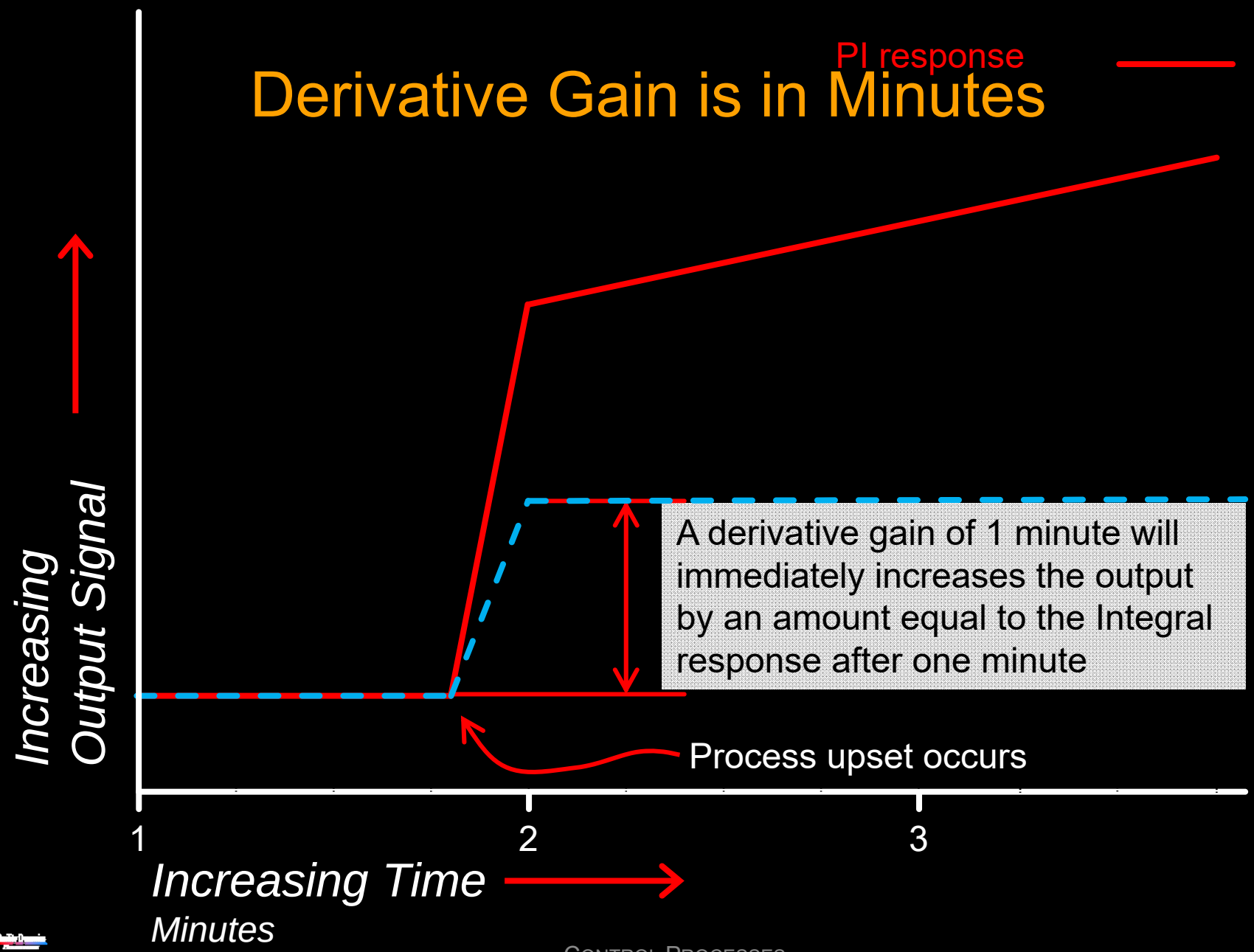
Derivative Gain is in Minutes



Derivative Gain is in Minutes



Derivative Gain is in 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!

Control Systems: Design, Performance and Commissioning Issues

Control Processes

Response to an Upset and PID Tuning Methods

Instructor:

David Sellers

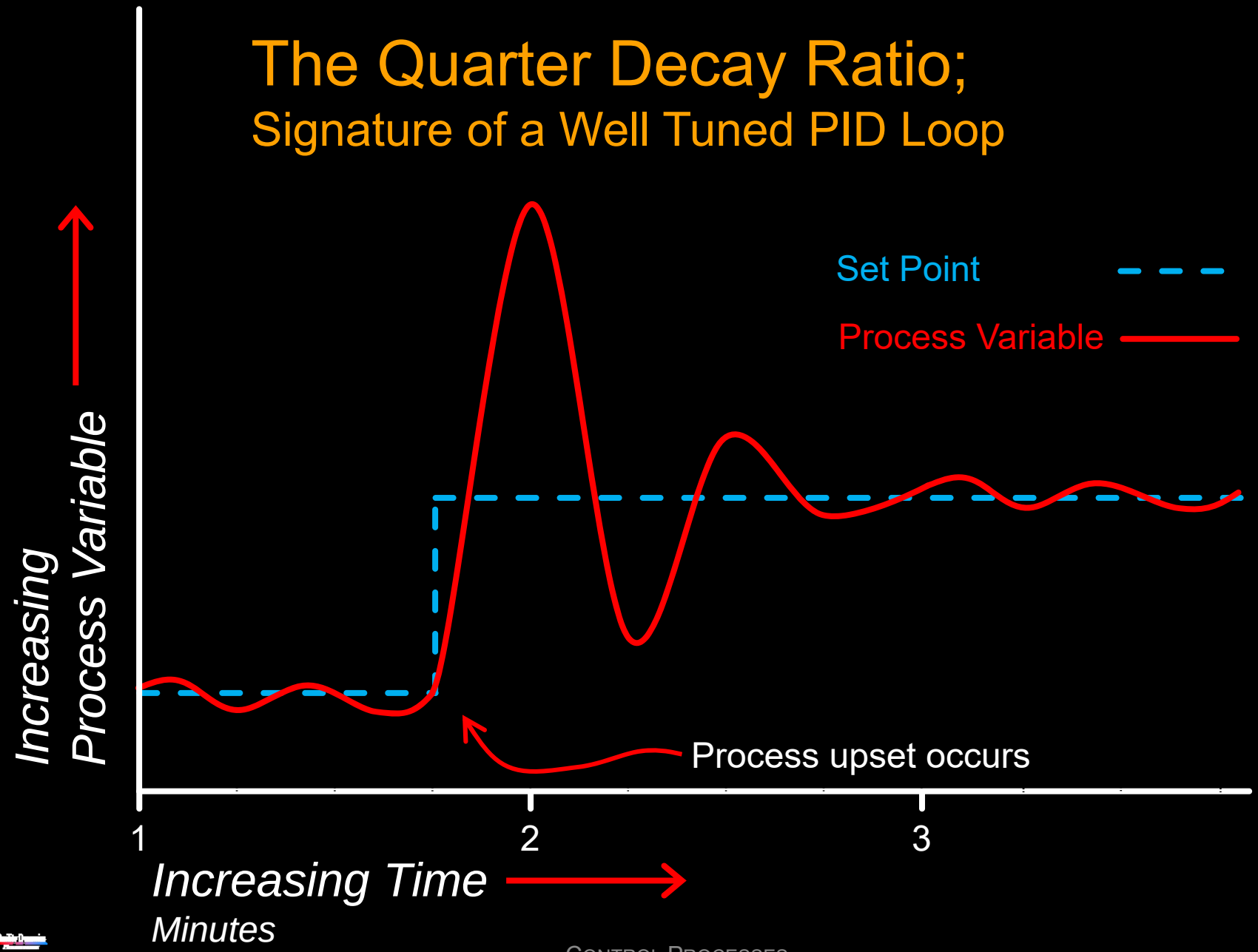
Senior Engineer

Facility Dynamics Engineering

October 23, 2017

The Quarter Decay Ratio;

Signature of a Well Tuned PID Loop



The Quarter Decay Ratio;

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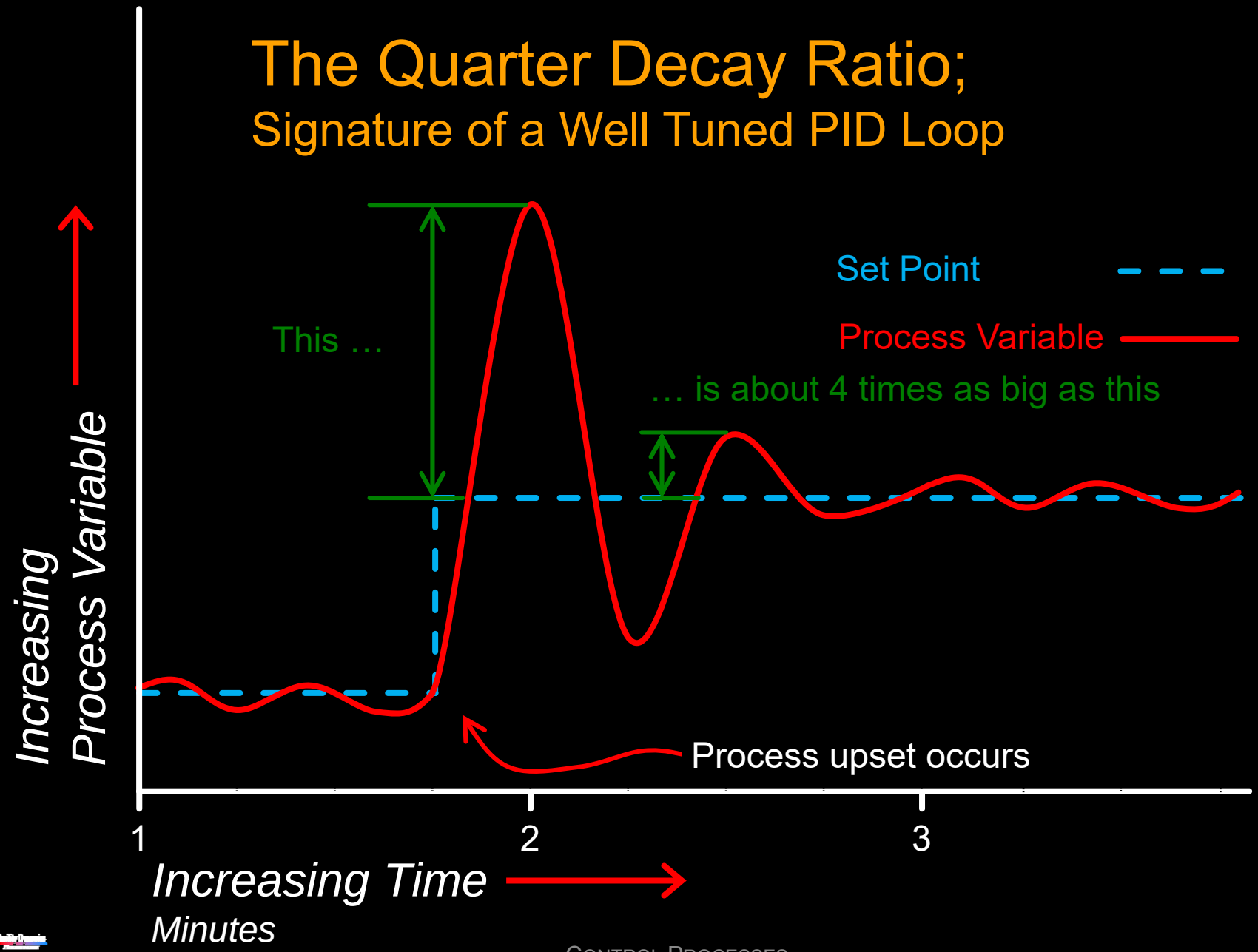
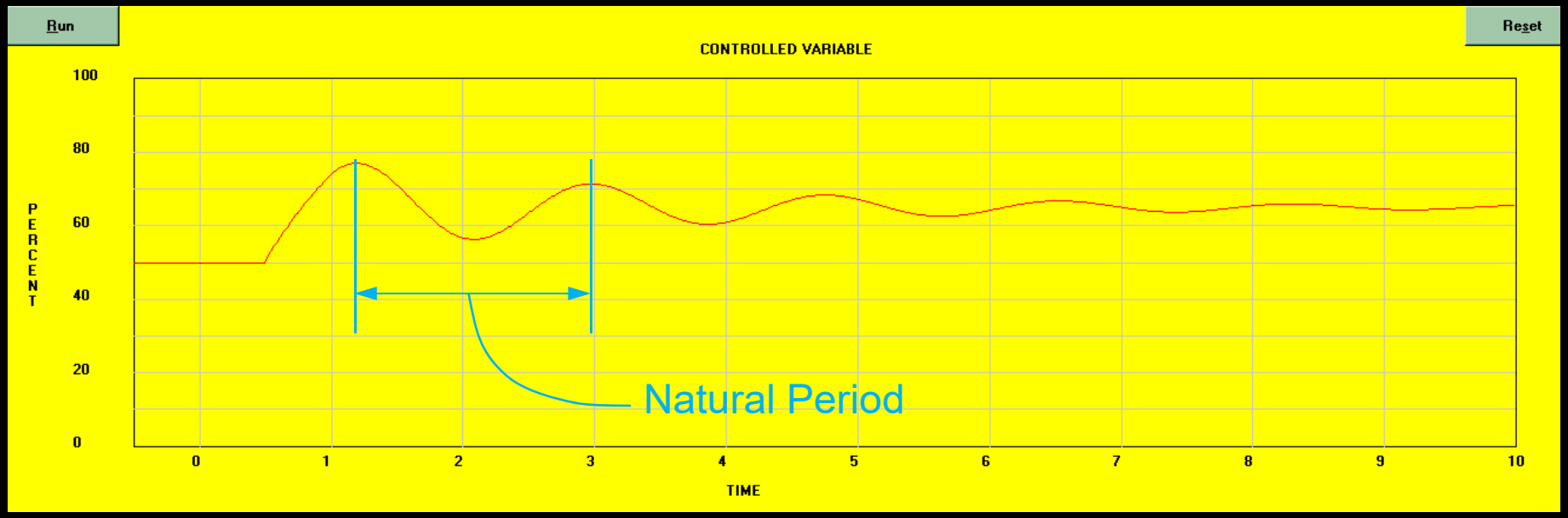


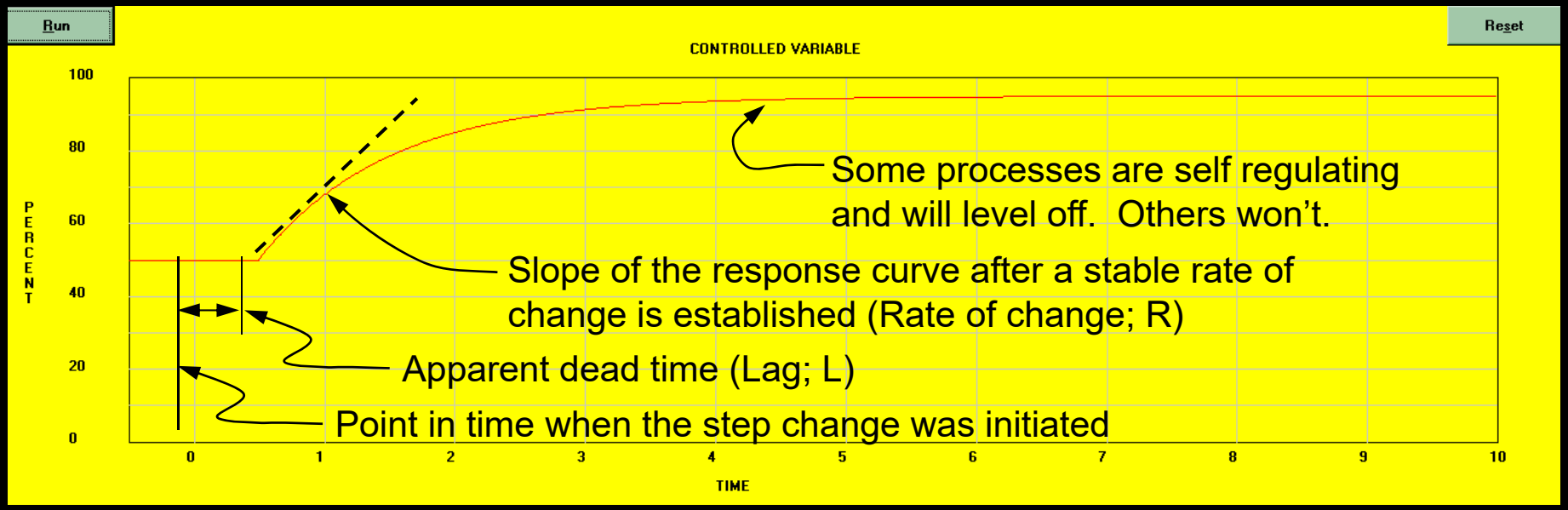
Closed Loop Tuning Method



With the system under automatic control, determine the Natural Period

- Proportional gain = ¼ to ½ of the ultimate gain producing the Natural Period
- Integral time in minutes per repeat = 1.2 times the Natural Period
- Derivative time in minutes = 1/8 of the Natural Period

Open Loop Tuning Method



Also useful for troubleshooting

With the system under manual control, insert a step change and observe the response curve. Set the controller as follows:

- Proportional gain = 1/(RL) to 1/(2 RL)
- Integral time in minutes per repeat = 5 times the apparent dead time
- Derivative time in minutes = ½ the apparent dead time.

Control Systems: Design, Performance and Commissioning Issues

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The Impact of Lags

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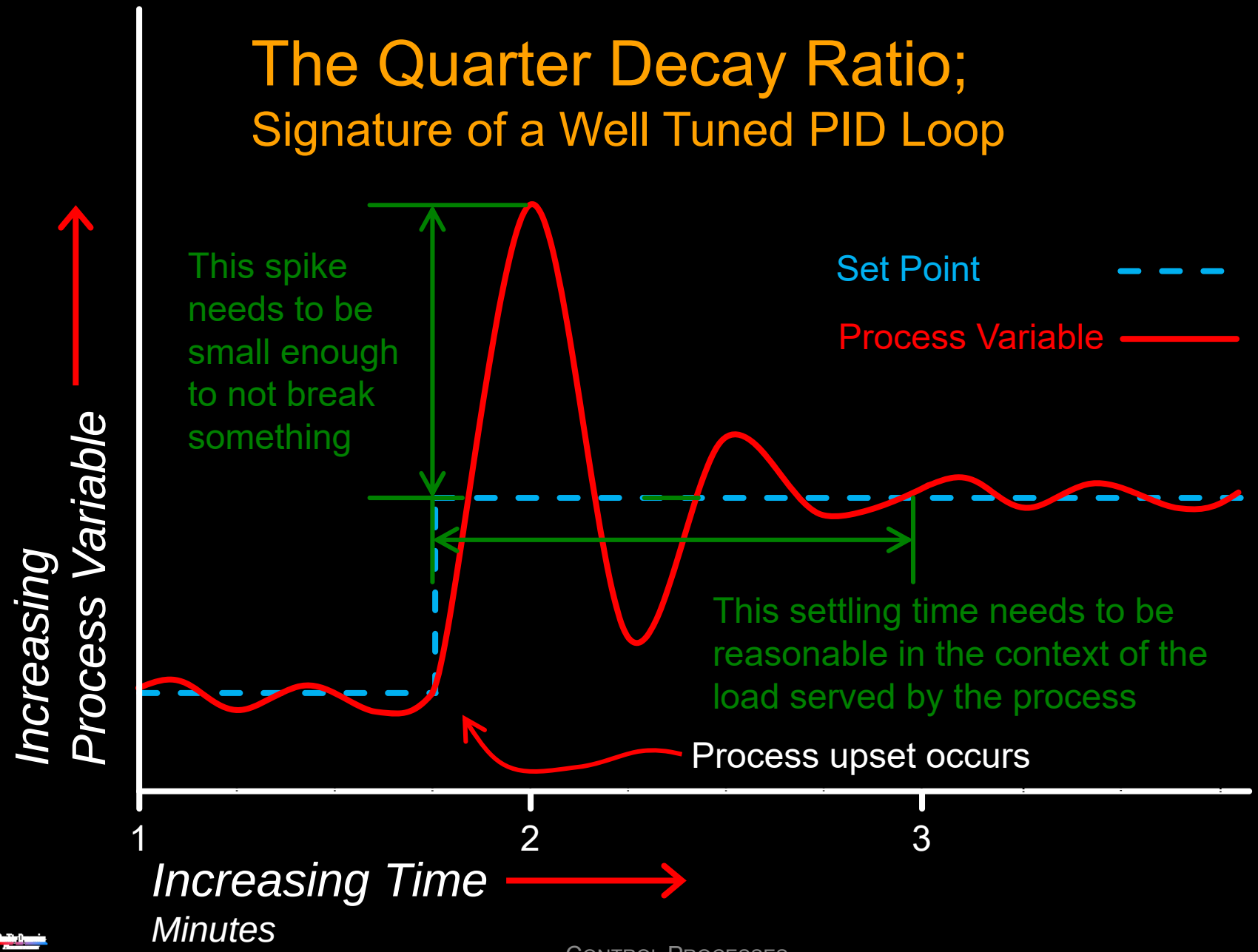
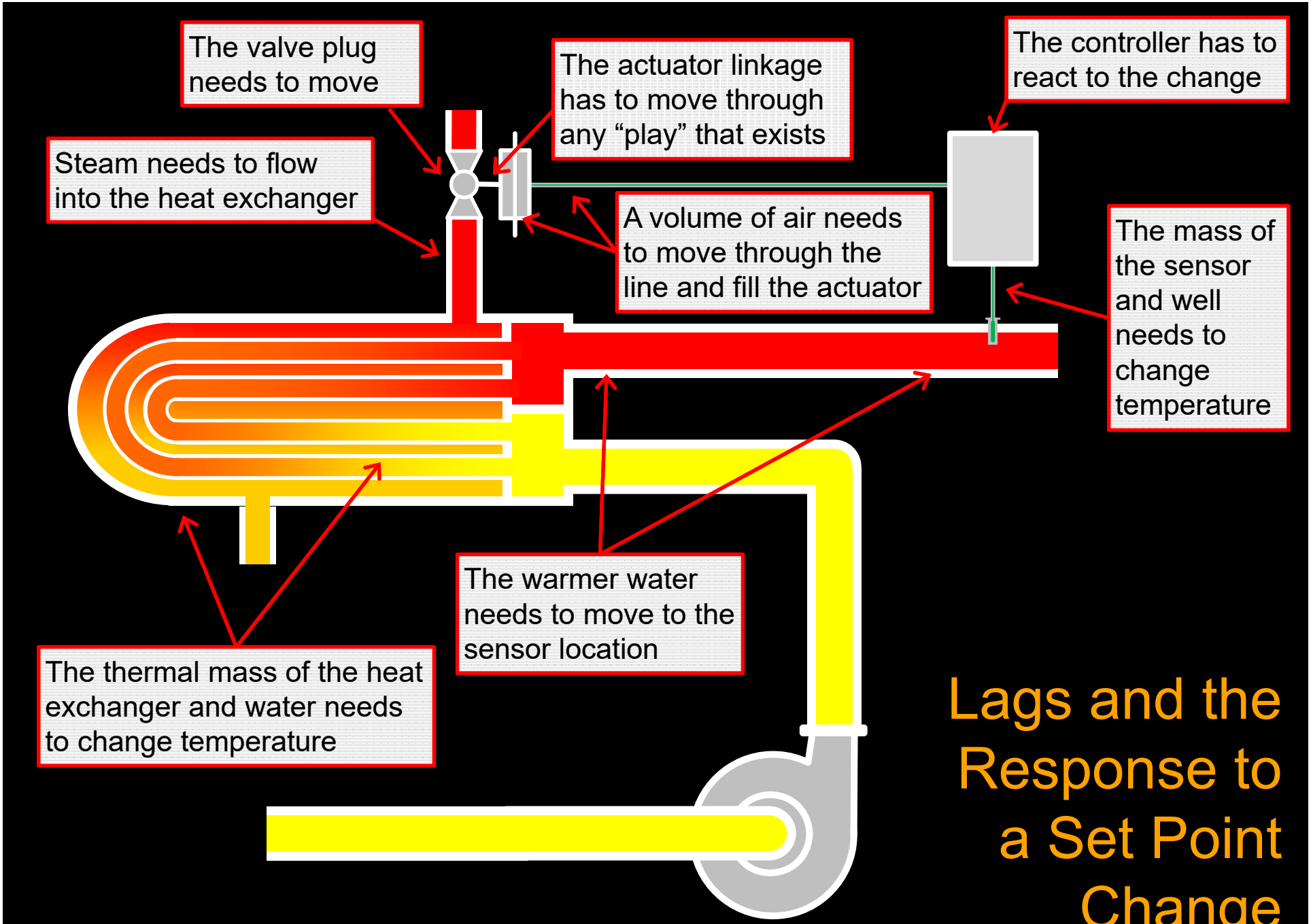
The Quarter Decay Ratio;

Signature of a Well Tuned PID Loop



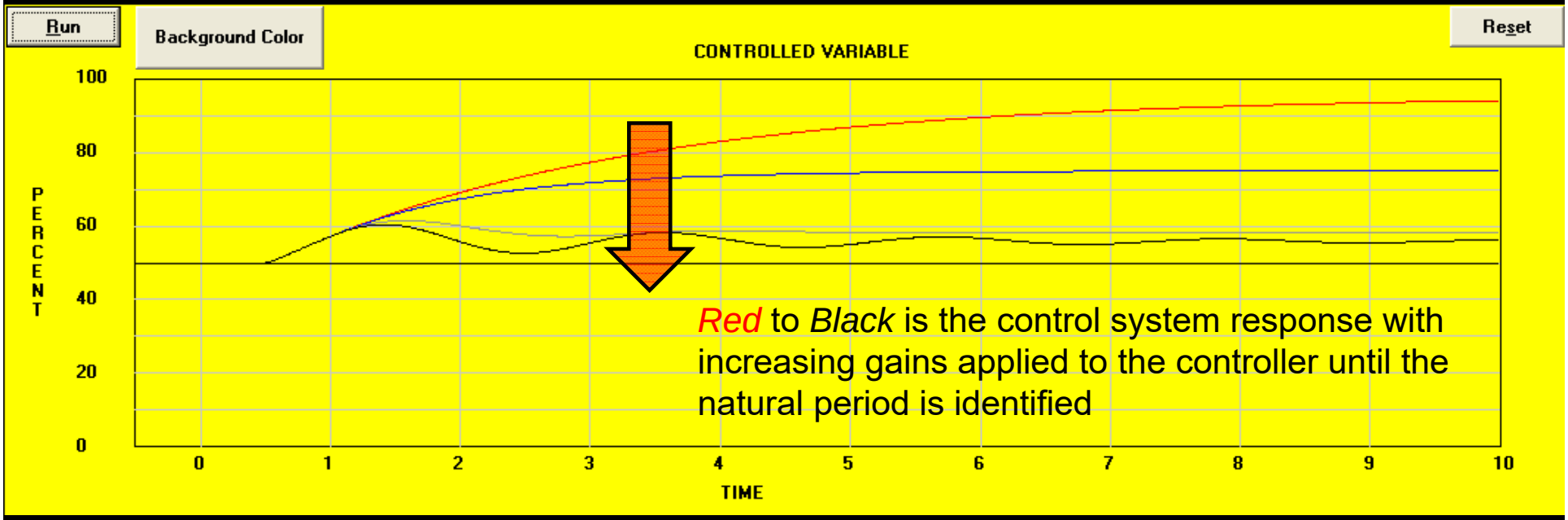
It All Depends on the Lags

David W. St. Clair



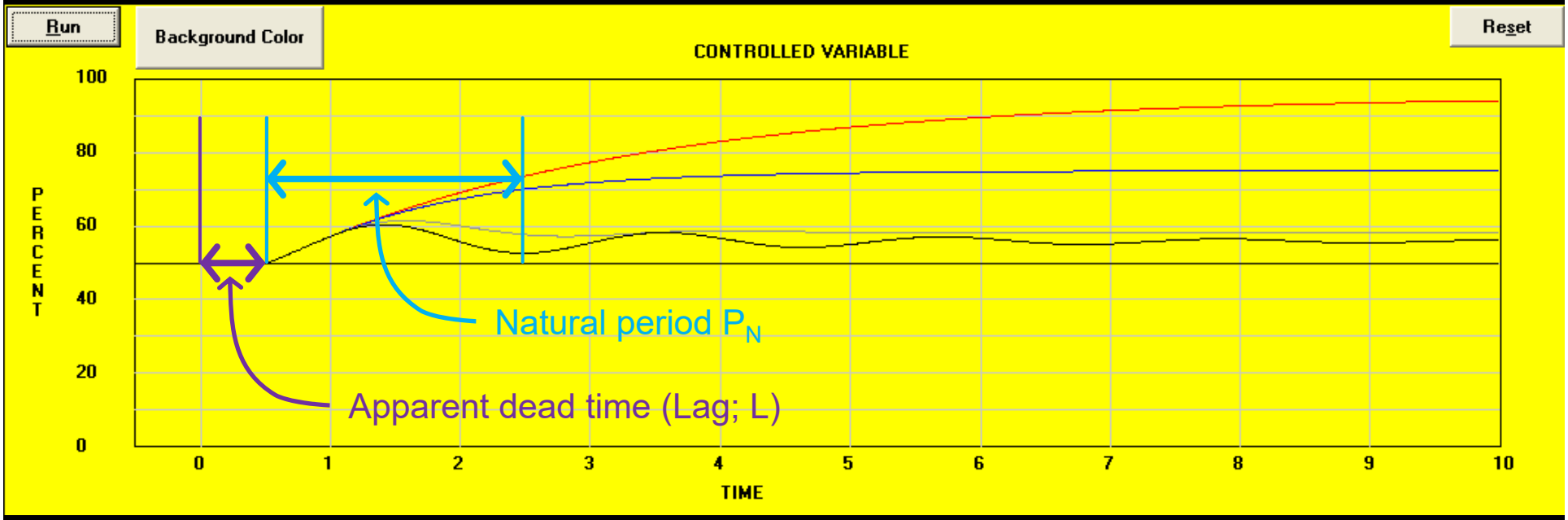
Lags and the Response to a Set Point Change

Some Observations

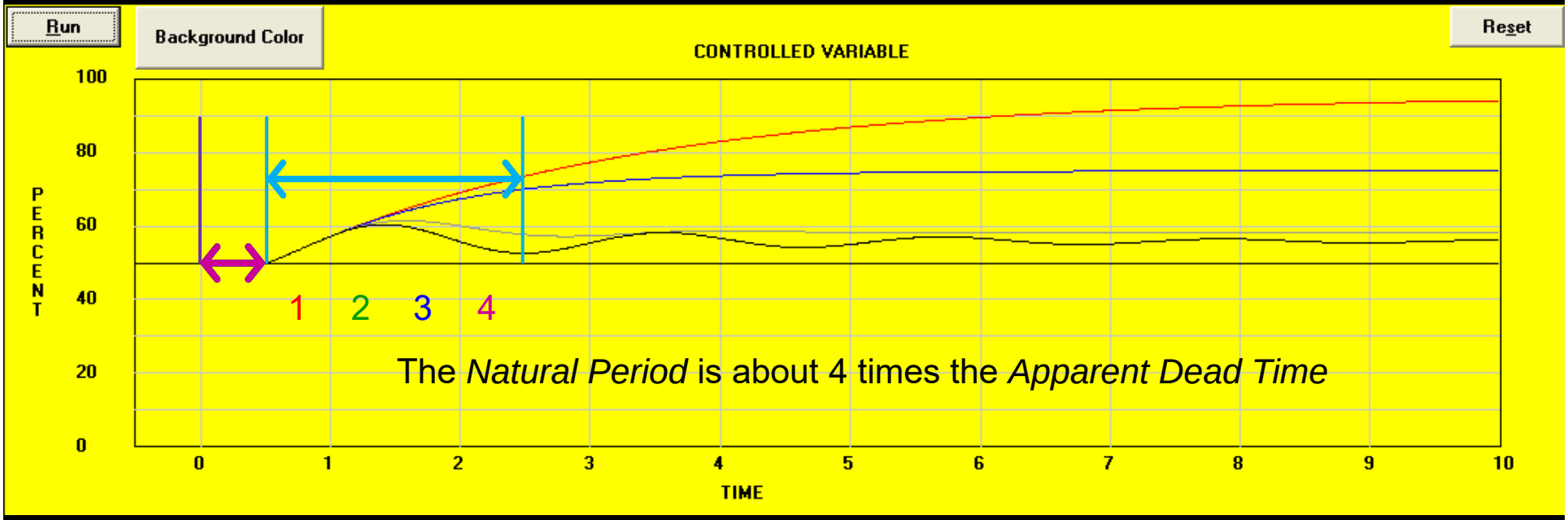


Red to *Black* is the control system response with increasing gains applied to the controller until the natural period is identified

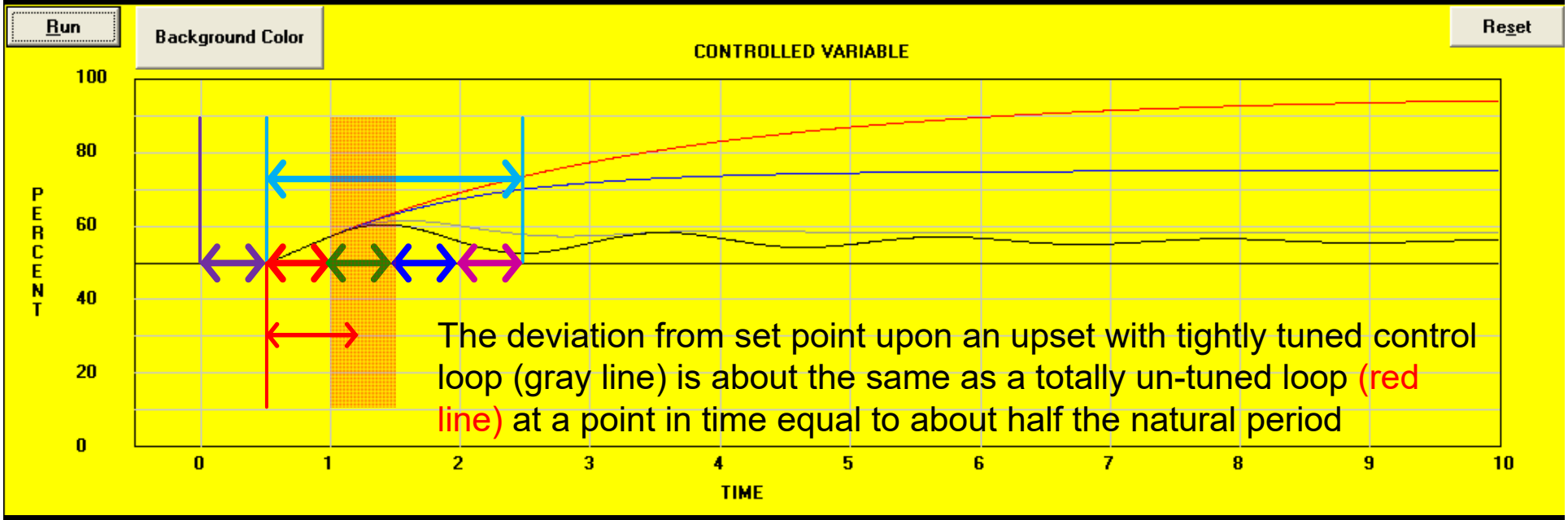
Some Observations



Some Observations

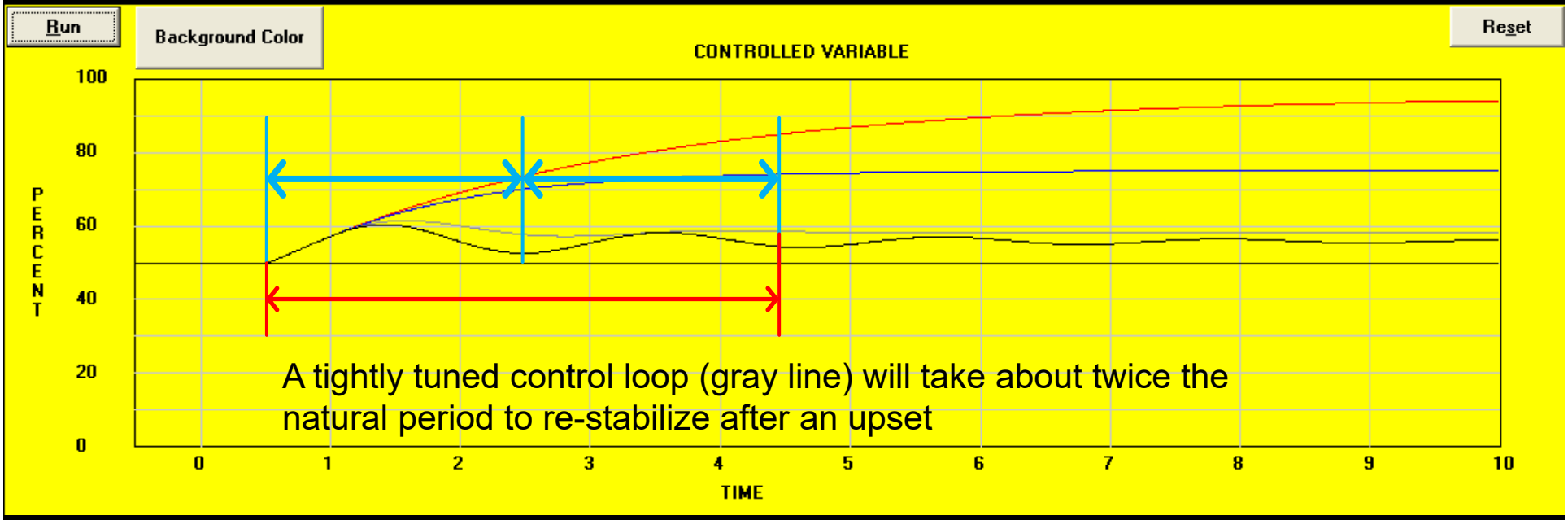


Some Observations

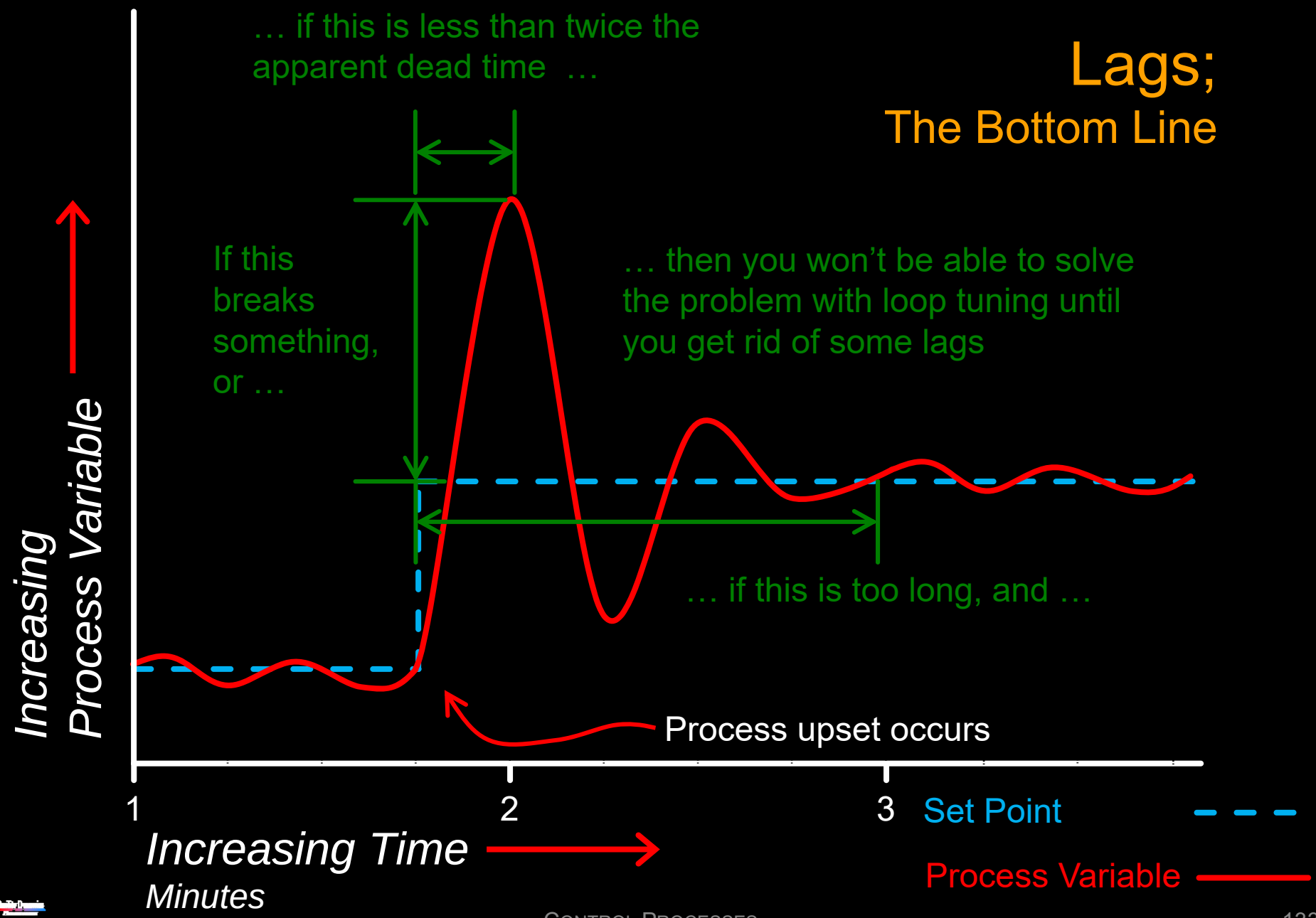


The deviation from set point upon an upset with tightly tuned control loop (gray line) is about the same as a totally un-tuned loop (red line) at a point in time equal to about half the natural period

Some Observations



Lags;
The Bottom Line



Getting Rid of Lags;
Sometimes It's Easier than Others

Easier

1. Add positioning relays to valve and damper actuators
2. Install faster actuators (particularly applicable to electric actuators)
3. Reduce the thermal lag associated with wells by not using them
4. Use tighter linkages to minimize hysteresis
5. Use ramps instead of acceleration and deceleration times in VFDs

Harder

1. Reducing transportation times
2. Reducing the thermal lags associated with the size of the machinery (mass of coils, fans, duct, pipe, etc.)

A Bit More About Ramps

Acceleration and Deceleration times

Apply all of the time, any time there is a change in the process

1. *An acceleration setting of, for example, 1hz/second will always apply regardless of if the difference between set point and control point was because of a start-up or step change in set point vs. minor variations in the control point relative to set point*
2. *This introduces a permanent lag into the control process with the associated implications for tuning the process*

Ramps

Only apply when the set point is outside some window relative to the control point

1. *Ramps will only apply if the difference between the set point and control point is large (outside of some predefined window)*
2. *If the set point and control point are inside the window, then the lag associated with the ramp drops out of the picture*
3. *As a result, the response to a minor variation in set point is much faster than the response to a step change (start up or set point change*

Control Systems: Design, Performance and Commissioning Issues

Control Processes

Rules for Tuning Control Loops (and Performing Functional Tests)

Instructor:

David Sellers

Senior Engineer

Facility Dynamics Engineering

October 23, 2017

General Rules for Tuning Control Loops

The Natural Period will be about 4 times the apparent dead time

Periodic disturbances can significantly impact a loop's ability to control

- Disturbance faster than the Natural Period – Control will not help
- Disturbance at or near the Natural Period – Resonance

For optimum performance, be just on the stable side of the ultimate gain point

The ultimate gain of the system will change as the characteristics of the system change

- Seasonal effects
- Aging and wear

General Rules for Tuning Control Loops

Be a little conservative

- HVAC systems see many variations in operating conditions
- First year is critical

Have an idea of what you expect to happen

- What you hope happens
- What you fear could happen

Know and agree about how far you will let things go

- How will you shut down the test in an emergency?
- Who will do what?
- Rehearse failure for critical systems

General Rules for Tuning Control Loops

Test and set all safety systems first

- Protect equipment
- Protect people

Schedule your testing

- Protect the load served from unnecessary disturbance
- Protect the load served from a crisis

Be available later

Document everything

Proceed slowly

Related Considerations

Non-linearity can influence ease of tuning.

- Input side
  - Thermistors
  - Differential pressure based flow sensors.
- Output side
  - Linkage arrangements
  - Velocity limiting

Loop interactions

- Very common in HVAC

Hysteresis and dead band effects

Auto tuning

- Not a panacea
- Not all algorithms will work the same

Just because you *CAN* do PID doesn't mean you *SHOULD* do PID

Use proportional only control in situations where high precision is not required or warranted by operational or economic concerns

- Space temperature control
- Limit functions
- Cascaded or highly interactive loops

Add integral action in situations where precision is required

Add integral action in situations where the proportional offset associated with a proportional only loop will result in significant energy waste

Think hard before adding derivative action to a control loop

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Control Processes

PID and Loop Tuning Resources

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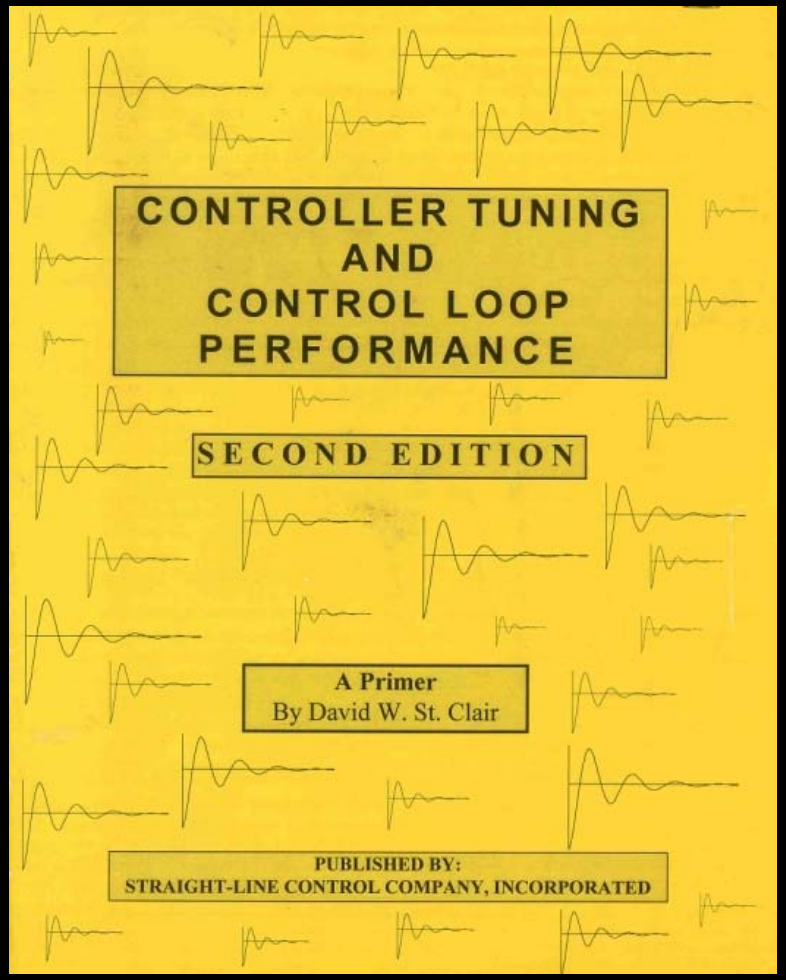
Tuning Resources

Controller Tuning and Control Loop Performance by David W. St. Clair

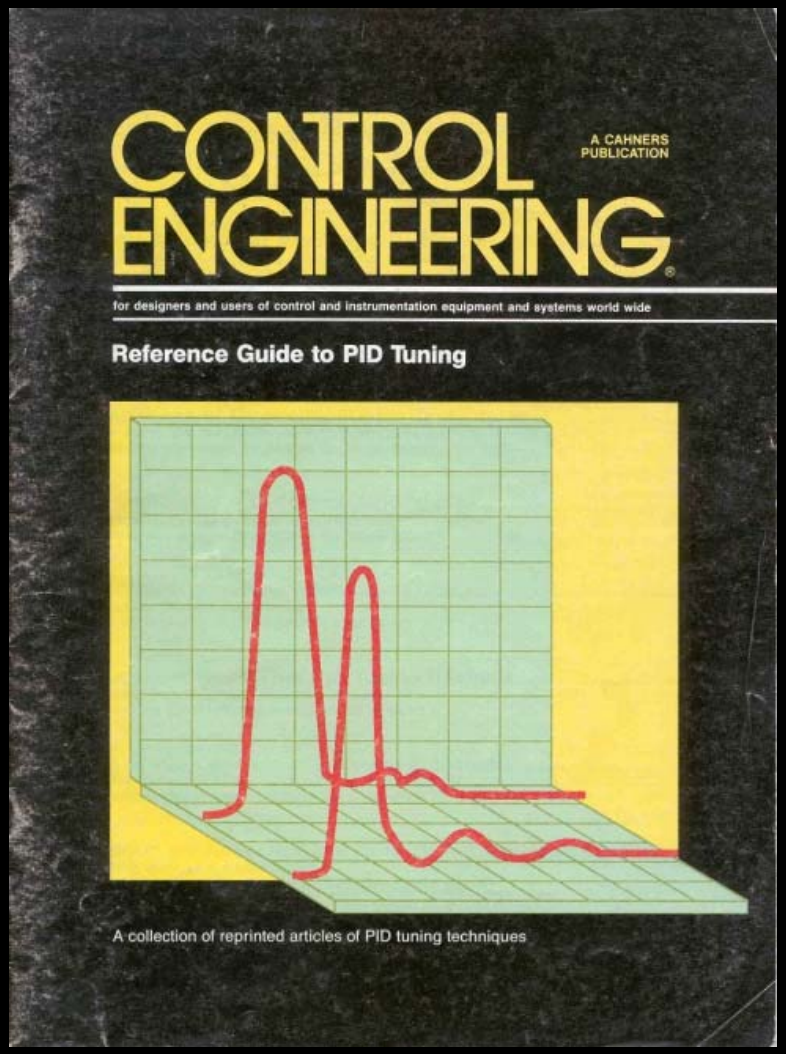
- Judy St. Clair
  Straight Line Control, LLC
  6326 4th Avenue South
  Richfield, MN 55423
  USA
  Phone:612-869-6814
  Fax: 612-869-2761
  jastclair@pro-ns.net
  http://www.straightlinecontrol.com



Tuning Resources

Reference Guide to PID Tuning

- Available from the publishers of Control Engineering
- See *A Field Perspective on Engineering Blog Post for Links*



Tuning Resources

See *An Overview of Proportional plus Integral plus Derivative Control and Suggestions for Its Successful Application and Implementation* from the proceedings of the 2001 International Conference on Enhanced Building Operations