Setting the Standard for Automation™

“The Six"

Fundamental Control Strategies Every Process Control Developer Must Know

Standards
Certification
Education & Training
Publishing
Conferences & Exhibits

About the Presentation

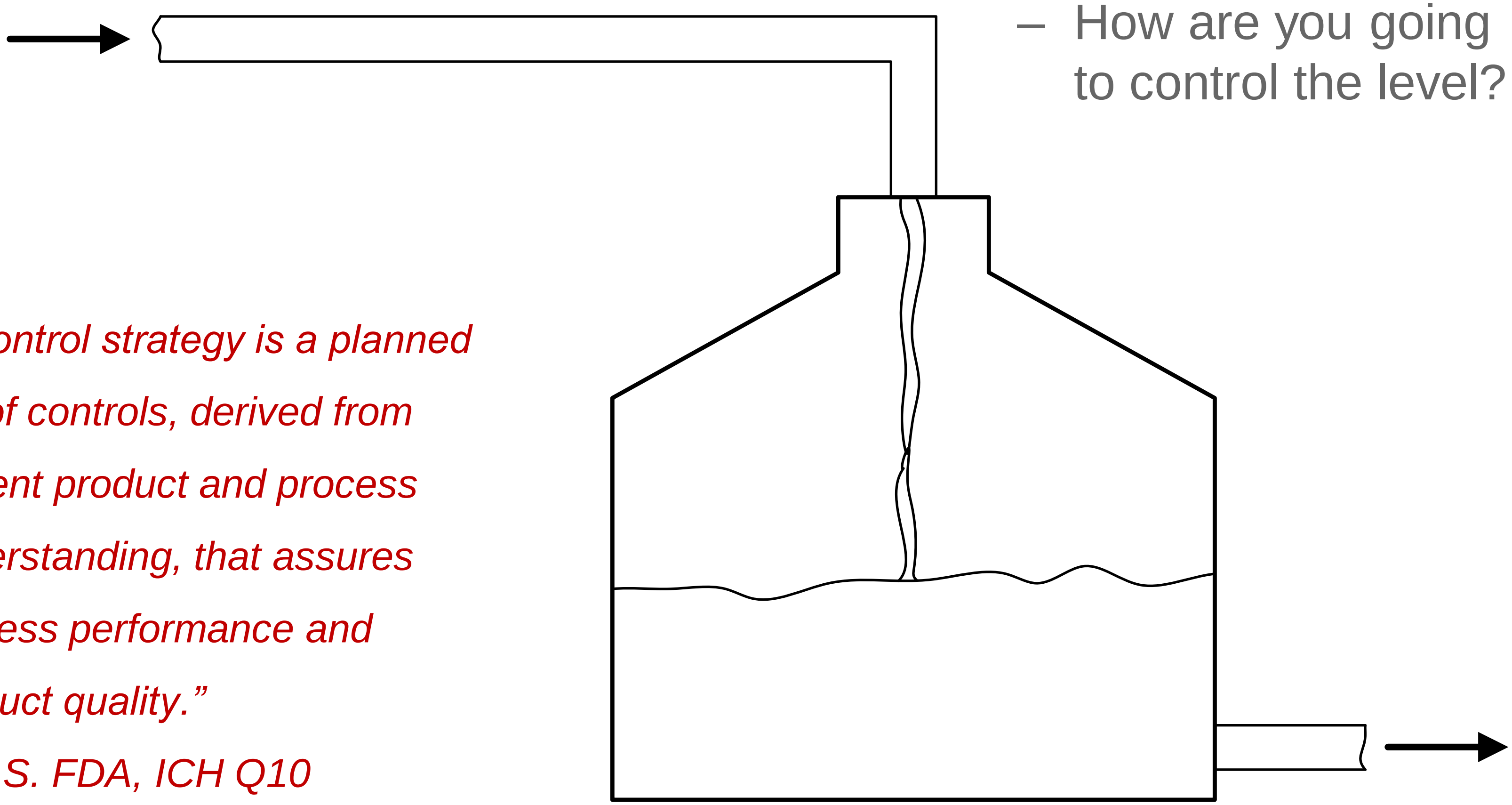
- About the Presenter
- What do we mean by “Control Strategies”?
- Six Fundamental Control Strategies
  - PID Feedback Control
  - Feedforward Control
  - Cascade Control
  - Split-Range Control
  - Ratio Control
  - Override Select Control
- Going beyond these strategies

About the Presenter

- Dale E. Reed, CAP
  - B.S. Chem. Eng., Rensselaer Polytechnic Institute, 1980.
  - Current Position: Principal Engineer, PlantPAx System Engineering, at Rockwell Automation in Mayfield Heights, Ohio
  - With Allen-Bradley Company / Rockwell Automation since 1984.
- ISA / Cleveland Section Member since August 1980
  - Currently serve as Delegate and Standards and Practices Chair
  - Section Secretary, 2013-2014; Section President, 2015-2016
  - Serve on ISA18, ISA101, ISA106 standards committees
  - ISA S&P Board of Directors since January 2016
- ISA Certified Automation Professional since July 2005

What Do We Mean by "Control Strategy"?

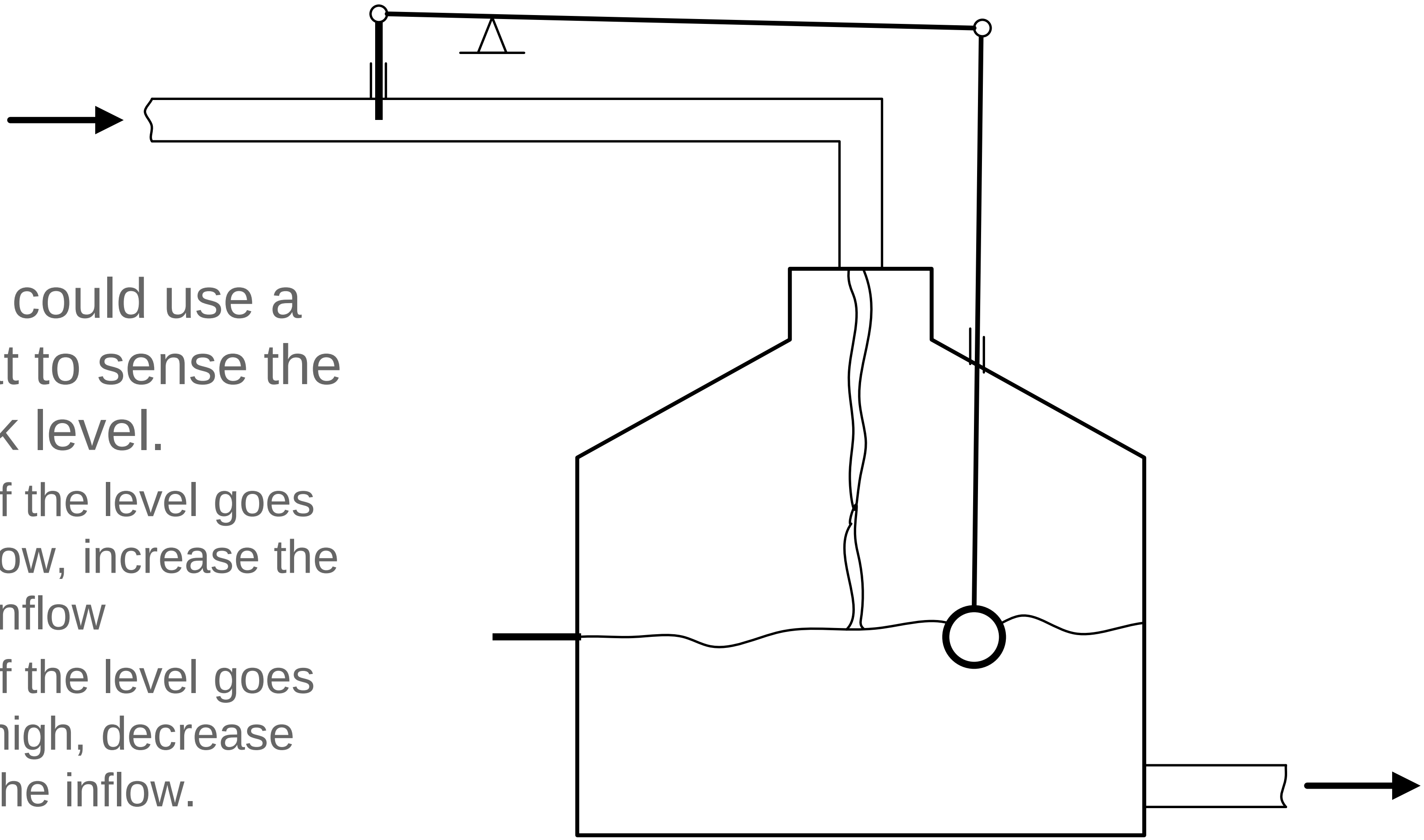
- Here's a process!
  - How are you going to control the level?



"A control strategy is a planned set of controls, derived from current product and process understanding, that assures process performance and product quality."

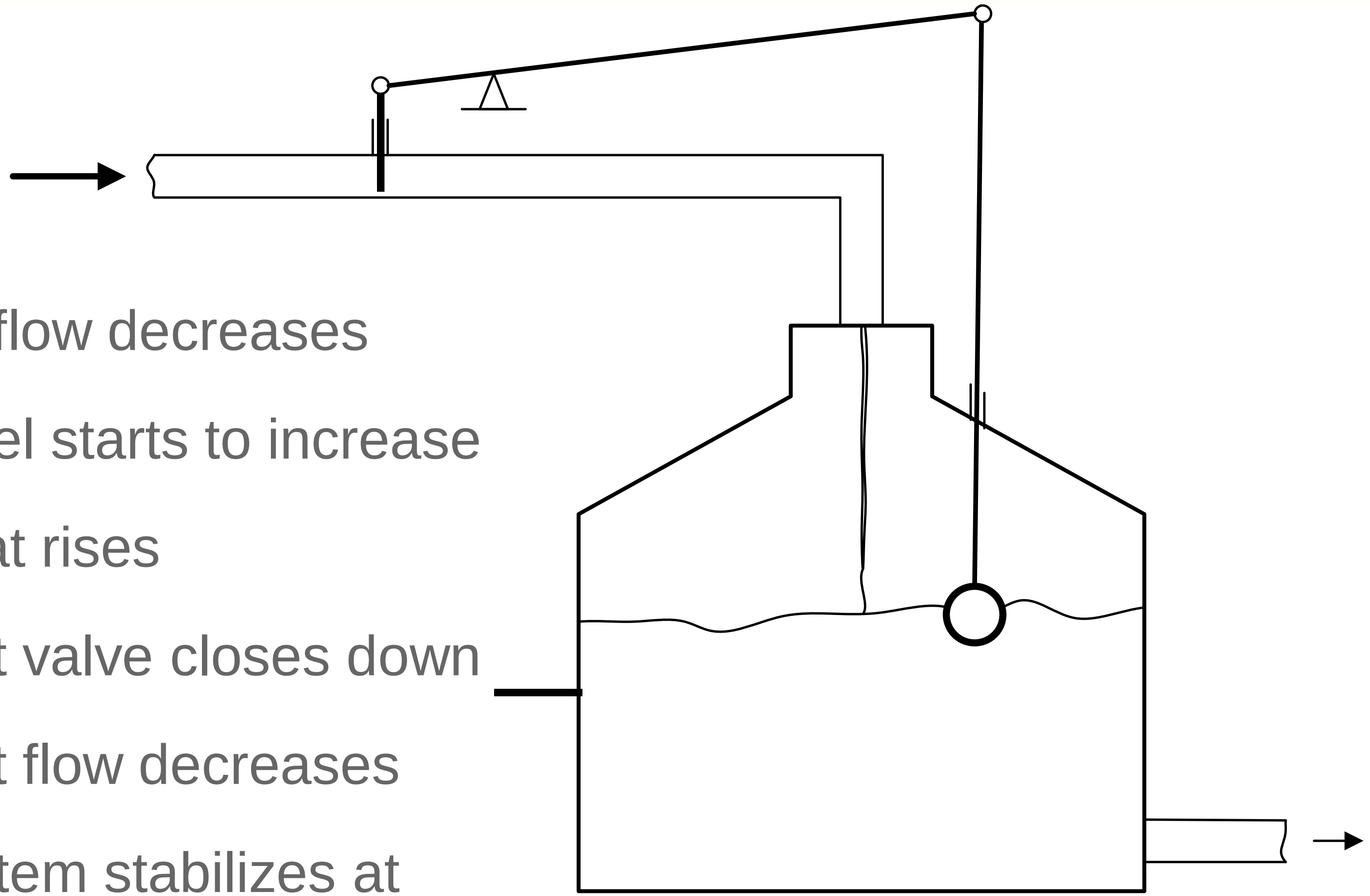
U.S. FDA, ICH Q10

Adjust the Inflow to Maintain Tank Level



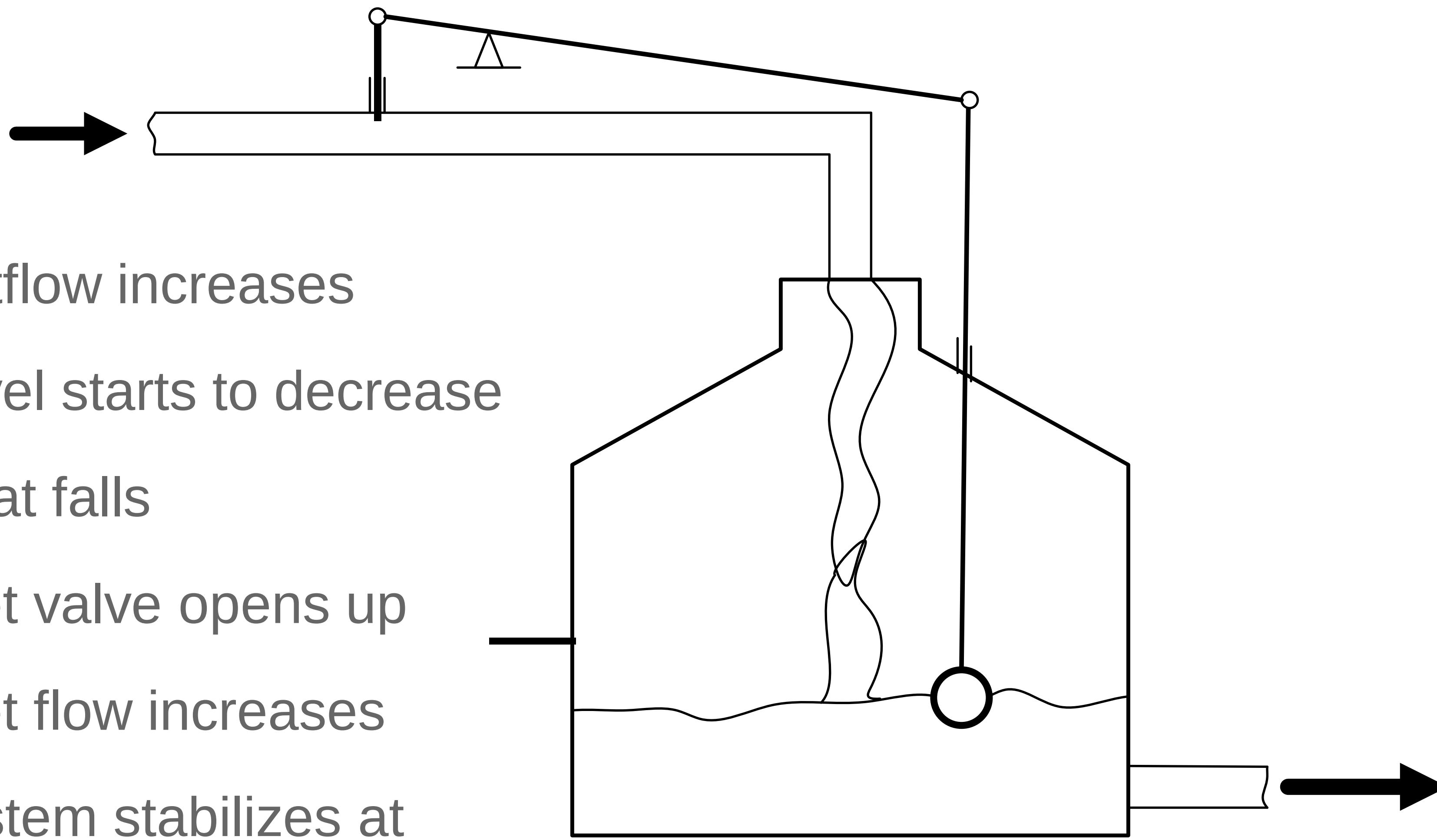
- We could use a float to sense the tank level.
  - If the level goes low, increase the inflow
  - If the level goes high, decrease the inflow.

What If the Demand Decreases?



- Outflow decreases
- Level starts to increase
- Float rises
- Inlet valve closes down
- Inlet flow decreases
- System stabilizes at a reduced flow rate

What If the Demand Increases?



- Outflow increases
- Level starts to decrease
- Float falls
- Inlet valve opens up
- Inlet flow increases
- System stabilizes at an increased flow rate

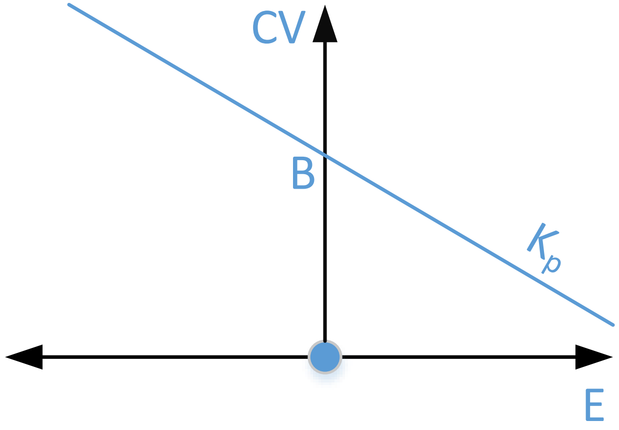
The Essence of Feedback Control

- The *Process Variable* (*PV*), in this case the level, has to deviate from its target value, the *Setpoint* (*SP*), for any control action to take place.
- The difference between the PV and SP is called the *Error* (*E*).
- The sign of the Error depends on which way we have to move the valve when the level is too high or too low:

$$E=PV-SP \quad \text{-or-} \quad E=SP-PV$$

Proportional-Only Control

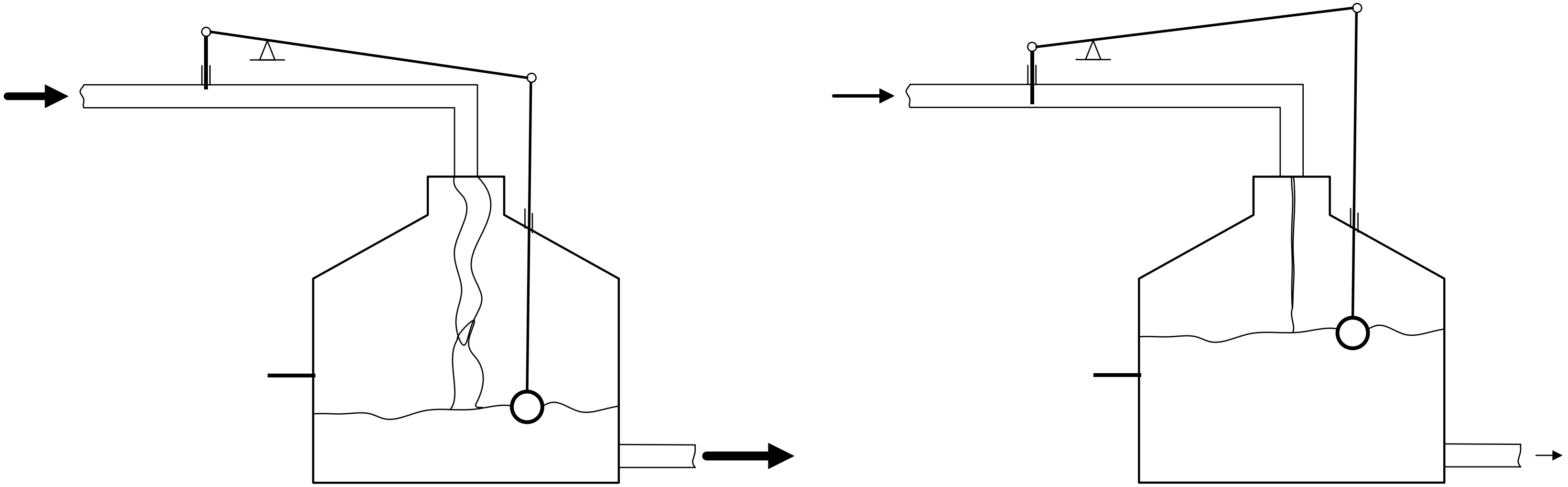
- The control implemented on the tank level is called Proportional-Only Control, or, simply, *Proportional Control.*
- The *Controlled Variable* (*CV*), in this case, the valve position, is directly proportional to the error.
- Slope is the *Proportional Gain* (K_p).
- There is also a *Bias* – because the valve position (and thus the flow) is not zero when the error is zero.



$$CV = K_p\, E + B$$

Offset

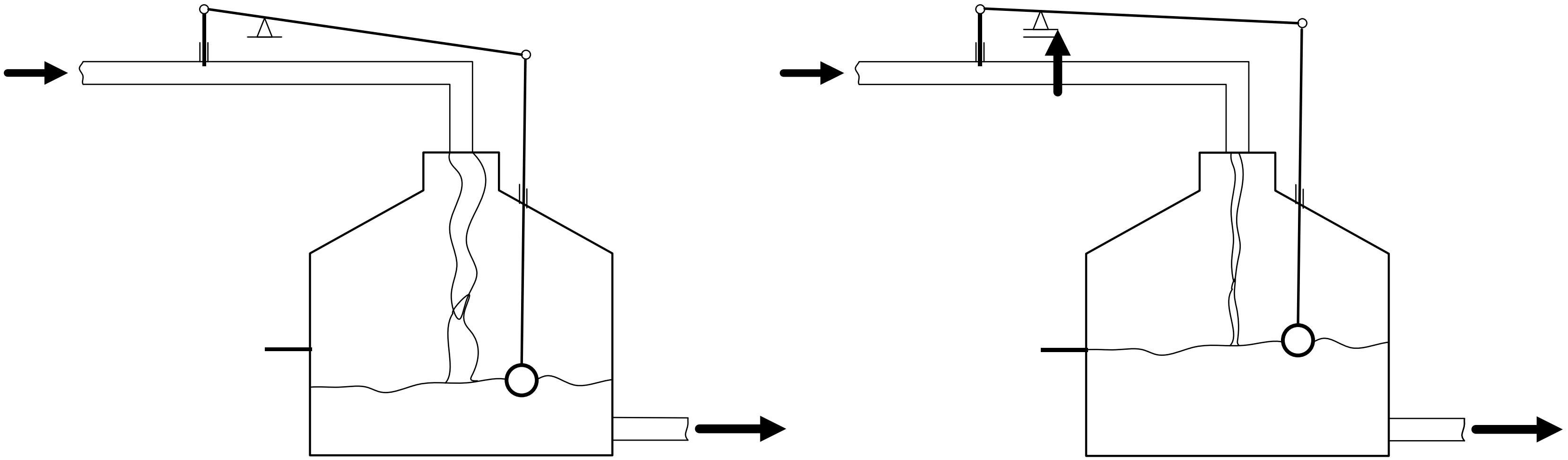
- Notice the final levels at high demand and at low demand:



- Proportional Control **does not result in zero error** (except at one specific demand)! In general, there is an *Offset*, an error value at which the loop stabilizes.

How Can We Eliminate the Offset?

- For this mechanical example, we could move the fulcrum of the lever up or down (adjust the Bias):



- If there is a sustained error, slide the fulcrum (Bias) up or down to “mop up the error”.

Proportional-Plus-Integral Control

- Determining the “sustained error” is done by integrating (summing) *E* with respect to time.
- How quickly we move the bias (fulcrum) for a given sustained error is the *Integral Gain* (K_i).
- Simply replace the Bias in the Proportional-Only equation with the integrated error:

$$CV = K_p\, E + \boldsymbol{K_i} \int_{\boldsymbol{t=0}}^{\boldsymbol{t}} \boldsymbol{E\, dt}$$

- For convenience in tuning, we sometimes use this form:

$$CV = K_c \left(E + \frac{1}{t_i} \int_{t=0}^{t} E\, dt \right)$$

What Puts the "D" in PID?

- What if the level starts rising (or falling) too fast?
  - If the level is rising fast, start closing the valve…
  - …even if the level is still below the setpoint!
- How fast is the level rising or falling?
  - Take the derivative with respect to time (rate of change).

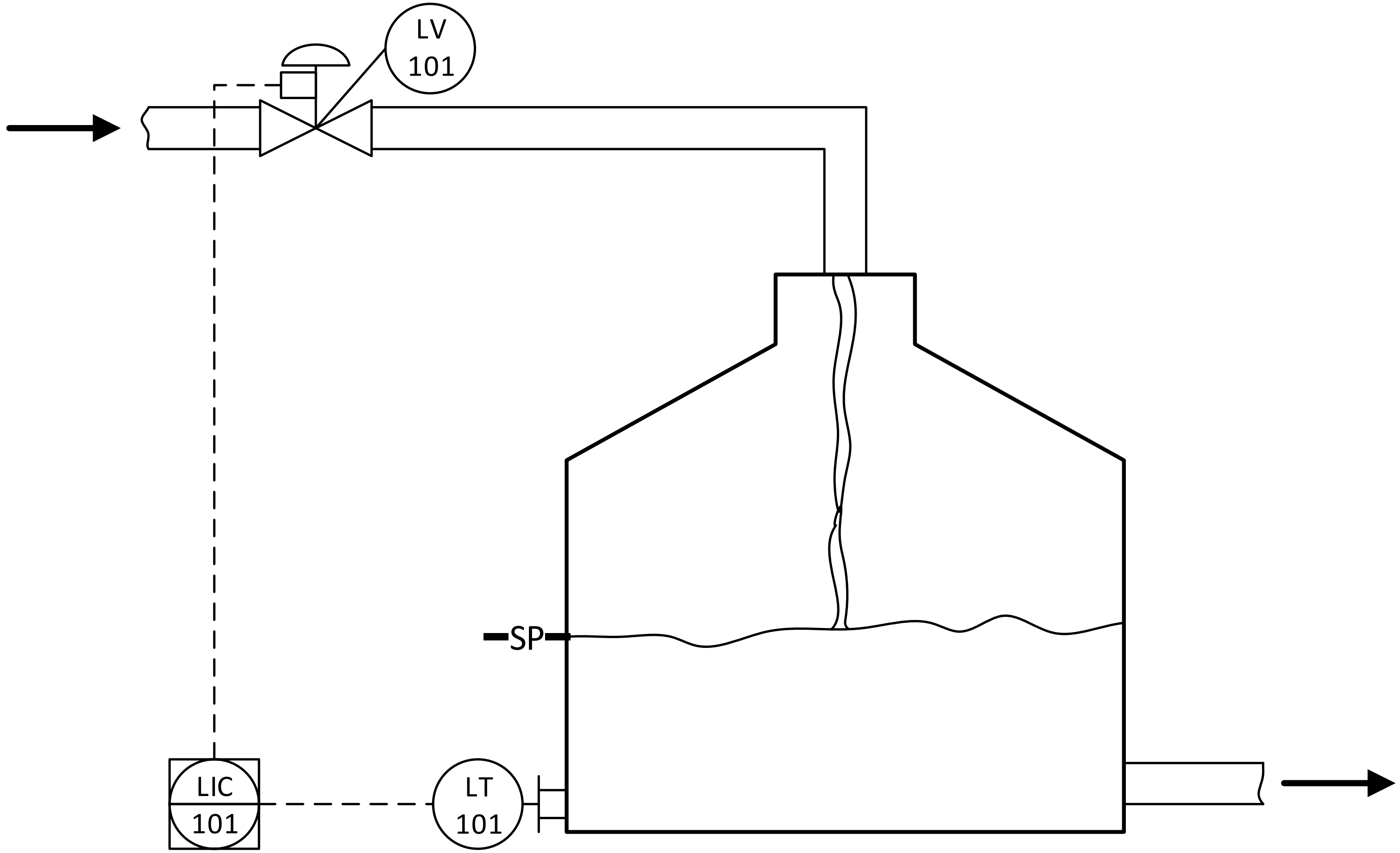
$$CV = K_p\,E + K_i \int_{t=0}^{t} E\,dt + \boldsymbol{K_d \frac{dE}{dT}}$$

  - or

$$CV = K_c\left(E + \frac{1}{t_i} \int_{t=0}^{t} E\,dt + t_d \frac{dE}{dt}\right)$$

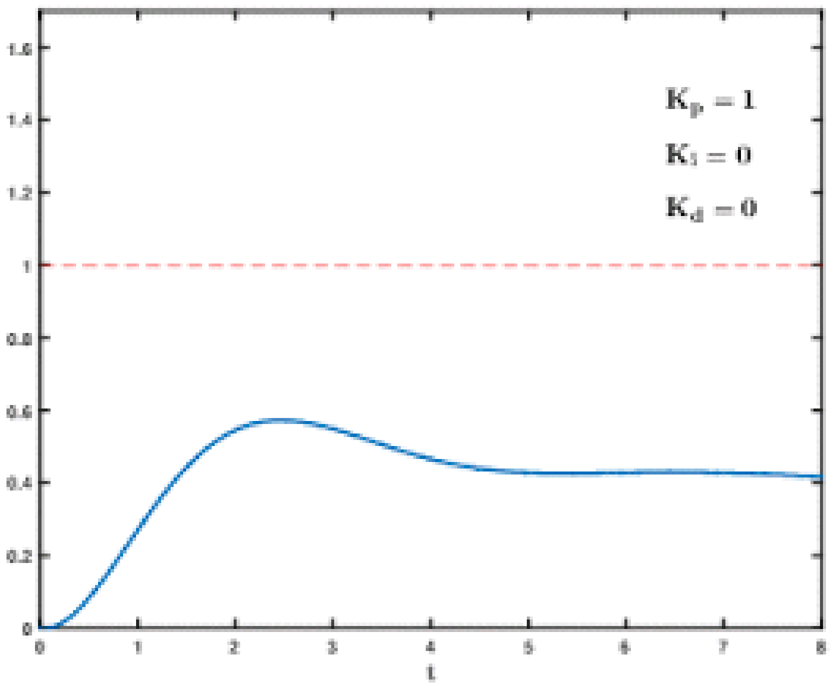
- Sorry, I couldn't think of a mechanical analogue!

How It Looks in a Modern Control System



Effects of Gain on PID Terms

- This animation shows the effects of increasing the gain for each of the three terms of the PID algorithm.
  - Note the offset before Integral is applied!
  - Note the overshoot with increasing P and I gain!



- These are "ideal" models – YMMV!
  - In my experience, Derivative makes a less marked improvement!

Courtesy: Automation Forum (automationforum.co, automationforum.in), see:
http://www.automationforum.co/2016/01/basics-of-pid-controller-proportional.html

Some Problems with PID Control

- The underlying math depends on some assumptions about “linear” variables.
  - Things like pH are decidedly NON-linear!
- The CV has limits in what it can do.
  - Can’t open a valve 120% open!

But the biggest problem:

- The PV must move away from the SP in order for control action to be initiated.
  - A disturbance must move the process from optimum to less-than-optimum before the controller does anything!

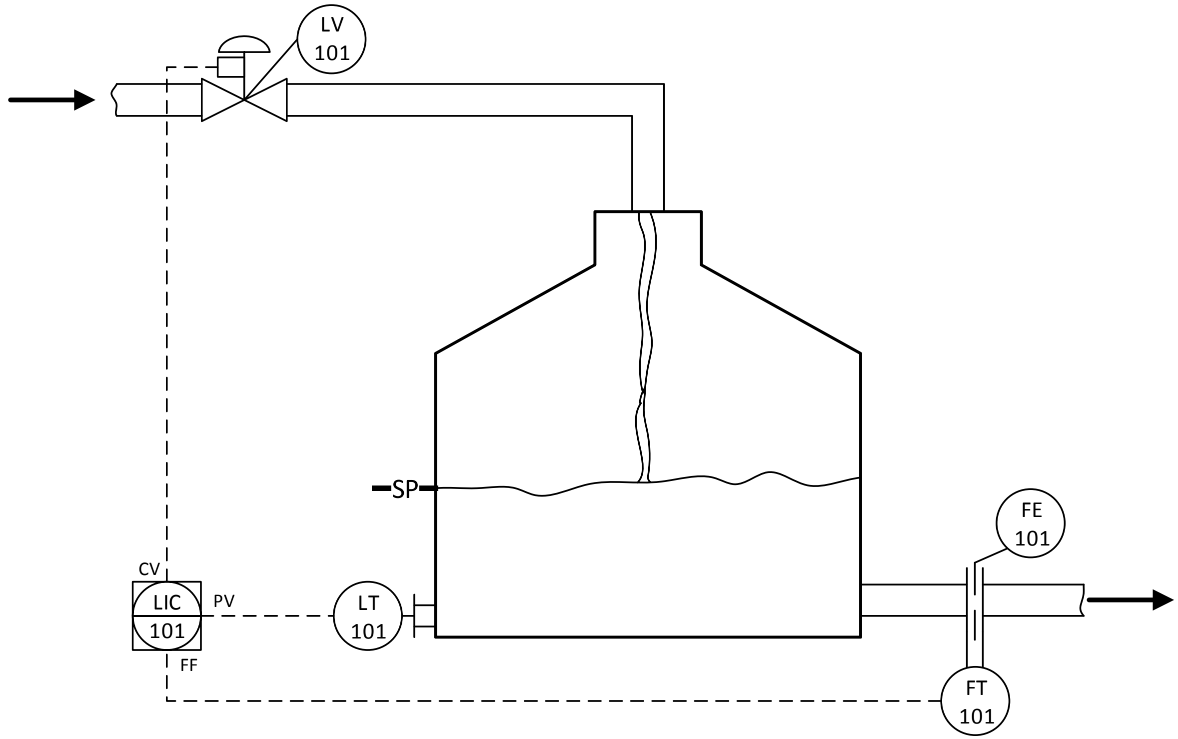
What If…

- … you could measure the disturbance…
- … then account for it by changing the CV…
- … BEFORE the PV moves off setpoint?

Yes, you can!

Feedforward Control

- Suppose we measure the outflow from the tank…



- If we set the valve based on the outflow, we can adjust inflow to the new demand BEFORE the level changes!

Feedforward Control

- The outflow is now a Measured Disturbance, or a *Disturbance Variable* (DV).
  - There's usually some kind of Feedforward Model for how the DV affects the process.
  - The math goes between the DV measurement and the Feedforward (FF) input to the controller.
- Here, the model is trivial: adjust the inflow to match the outflow.
  - The FF signal bumps the CV (output) directly, without going through the PID (feedback) controller.

$$CV = K_p E + K_i \int_{t=0}^{t} E \, dt + K_d \frac{dE}{dT} + \boldsymbol{F}$$

When to Use Feedforward Control

- When you can measure the disturbance
  - If you can't measure it, you can't account for it!
- When it's important that the PV not change
  - In our tank example, the tank might exist for the purpose of letting the level vary! No big deal if it changes!
- When the disturbance dynamics have an impact
  - Integral will "mop up" an unchanging FF input to zero the Error.
- When the disturbance has a non-linear impact
  - Feedforward can "remove" a non-linear disturbance from the PID feedback control (which works best if linear).

Damn the Distrubances! I Can Control Everything!

- Nope! You need enough “degrees of freedom”.
  - Controlling one variable means creating disturbances in another.
  - Here, controlling tank level means disturbing the inflow.
    - The disturbance in the level caused by changes in outflow is **transferred** from the tank level to the inflow stream.
- The level example I’m using is a VERY BAD example!

A tank’s purpose is often to buffer disturbances in flow!

The level can float (within the capacity of the tank) to absorb changes and differences in flow!

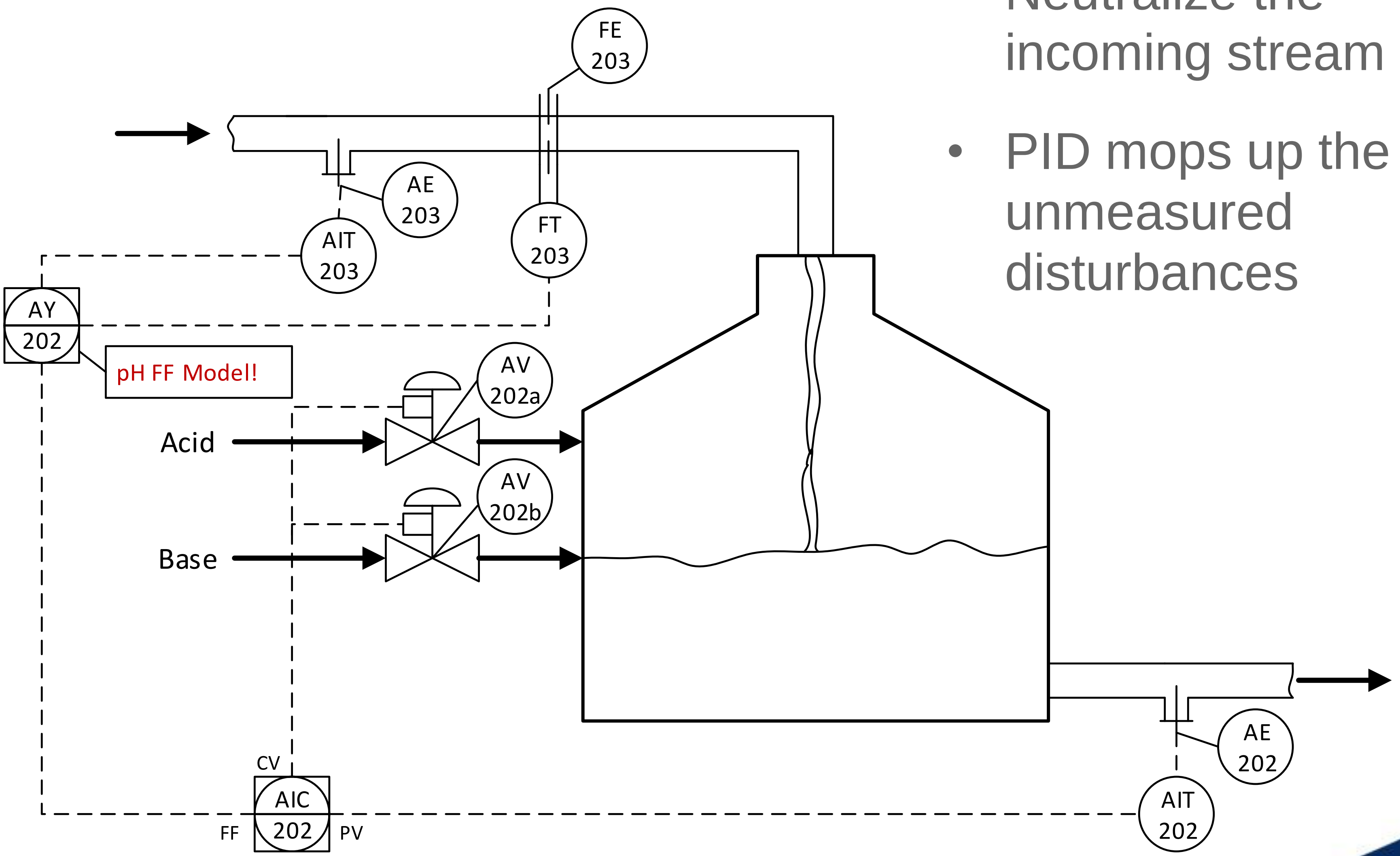
*You cannot control both flows PLUS the level – Disturbances can be transferred but not destroyed!**

** ”Rothenberg’s Law of Conservation of Disturbances”*

When to Use Feedforward Control

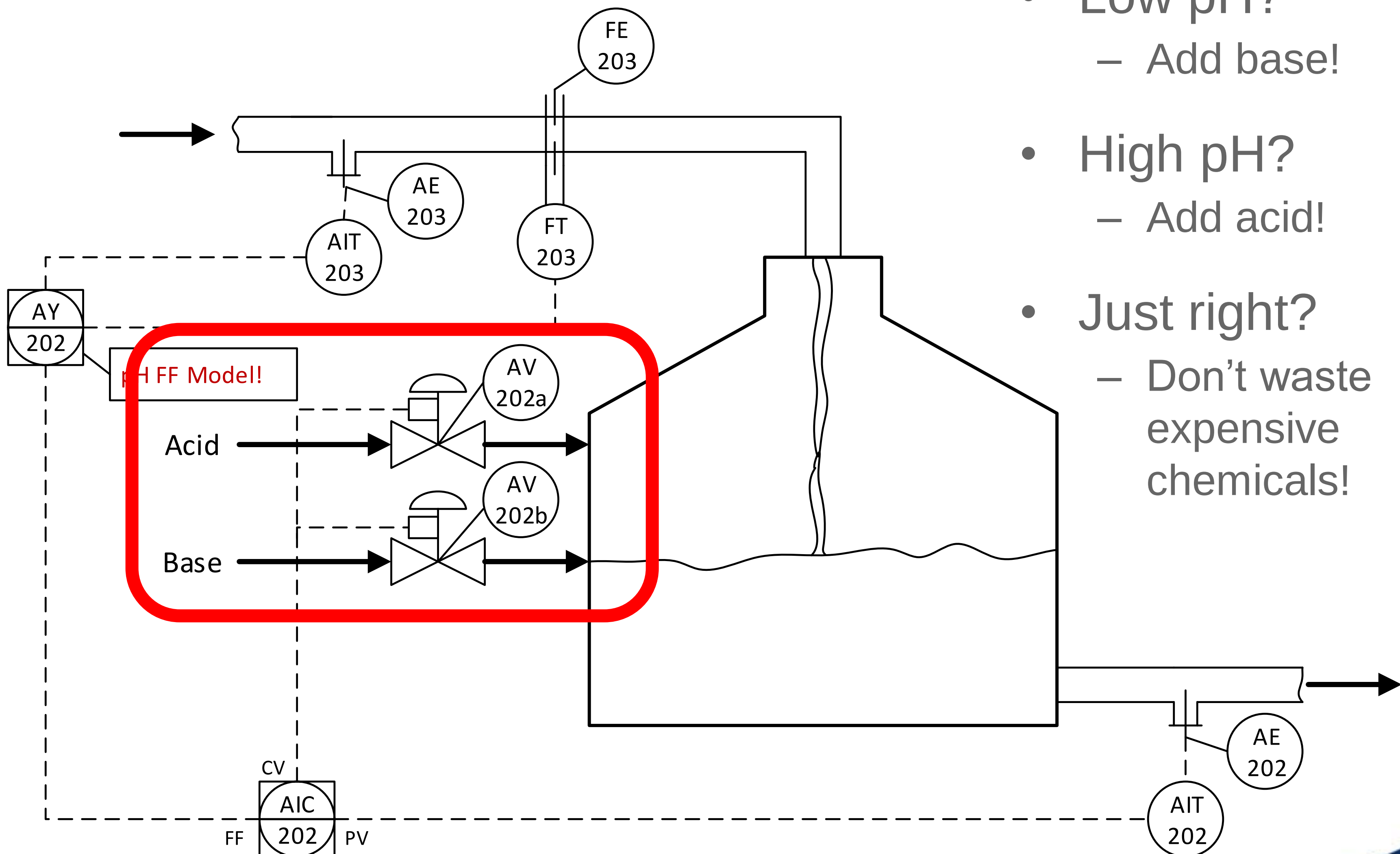
- More on "When the disturbance has a non-linear impact"
  - PID works best for processes with a linear process response to changes in the CV.
  - Sometimes the PV **measurement** is non-linear – for example, pH is a logarithm of a concentration.
    - You learned the math for pH in high school chemistry! (Didn't you?)
  - Even if you can't come up with an exact model:
    - You can create a good enough model by approximation.
    - You can create a good dynamic model based on recorded trends.
  - Feedback control is there to mop up the unmeasured disturbances…
    - … but also to mop up leftover error in the model

Feedforward: pH Control Example



- Neutralize the incoming stream
- PID mops up the unmeasured disturbances

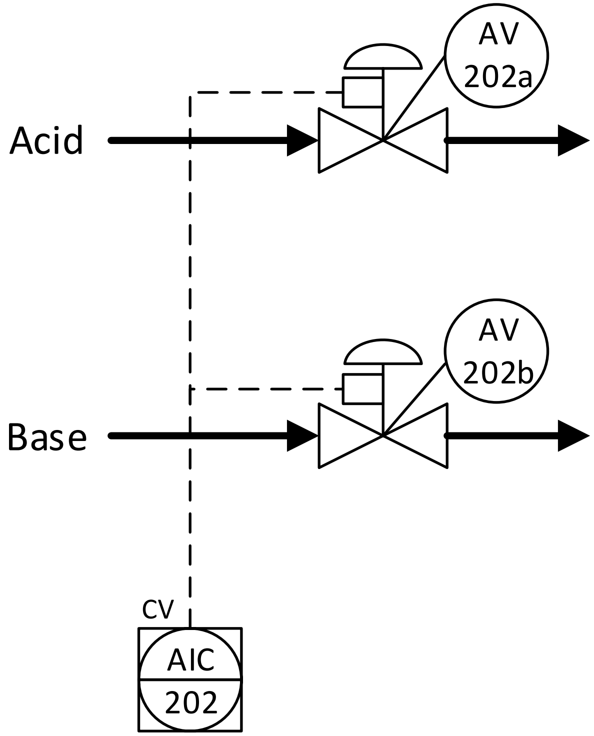
What's With Those Two Valves?



- Low pH?
  - Add base!
- High pH?
  - Add acid!
- Just right?
  - Don't waste expensive chemicals!

Split-Ranged Valves

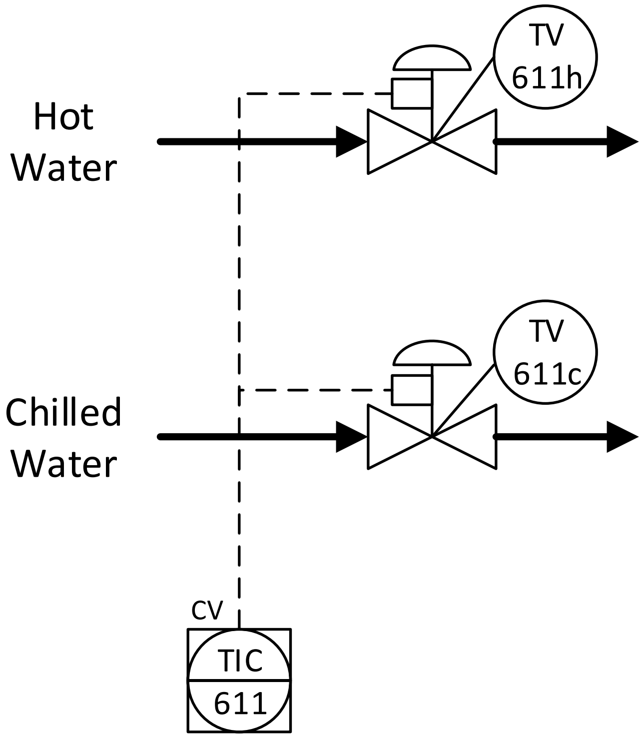
- When the CV is less than 50%
  - Open one valve (let's say Base)
  - Close the other valve (Acid)
  - At 0% CV Base is wide open
- When the CV is more than 50%
  - Open the other valve (Acid)
  - Close the other (Base)
  - At 100% CV, Acid is wide open
- At 50% CV, both are closed



What should the CV do on a loop failure (e.g., pH transmitter fail)?

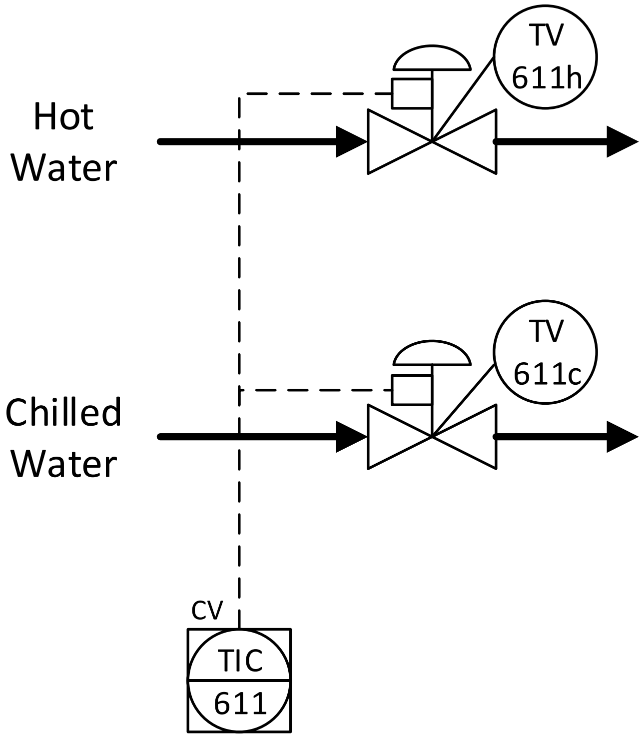
Split-Range Use Cases

- Temperature Control
  - Heating when CV is more than 50%
  - Cooling when CV is less than 50%
- Others in your experience?
- Important considerations:
  - Be very careful about what to do on system failures
  - Be very careful about what to do near the switchover point



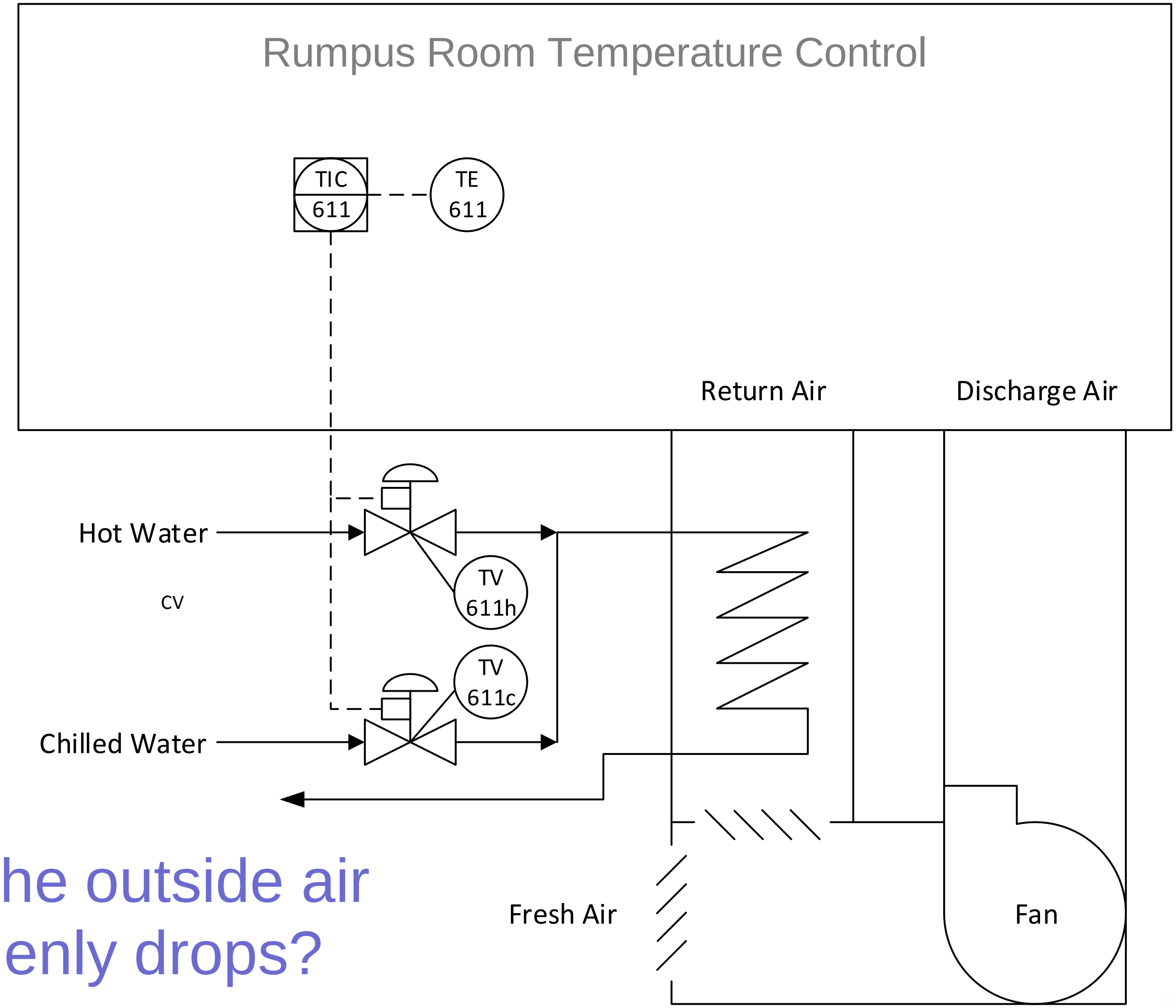
Split-Range Considerations

- If you can, size the valves so the loop gain doesn't change at switchover
  - The switchover point doesn't have to be at 50% CV!
  - The design may have more heat capacity than cooling, so the switchover might be, say, 30%
  - Or use adaptive gains
- Deadband or overlap
  - May need to sequence devices during switchover, for example: switching chilled water and steam



Another Example

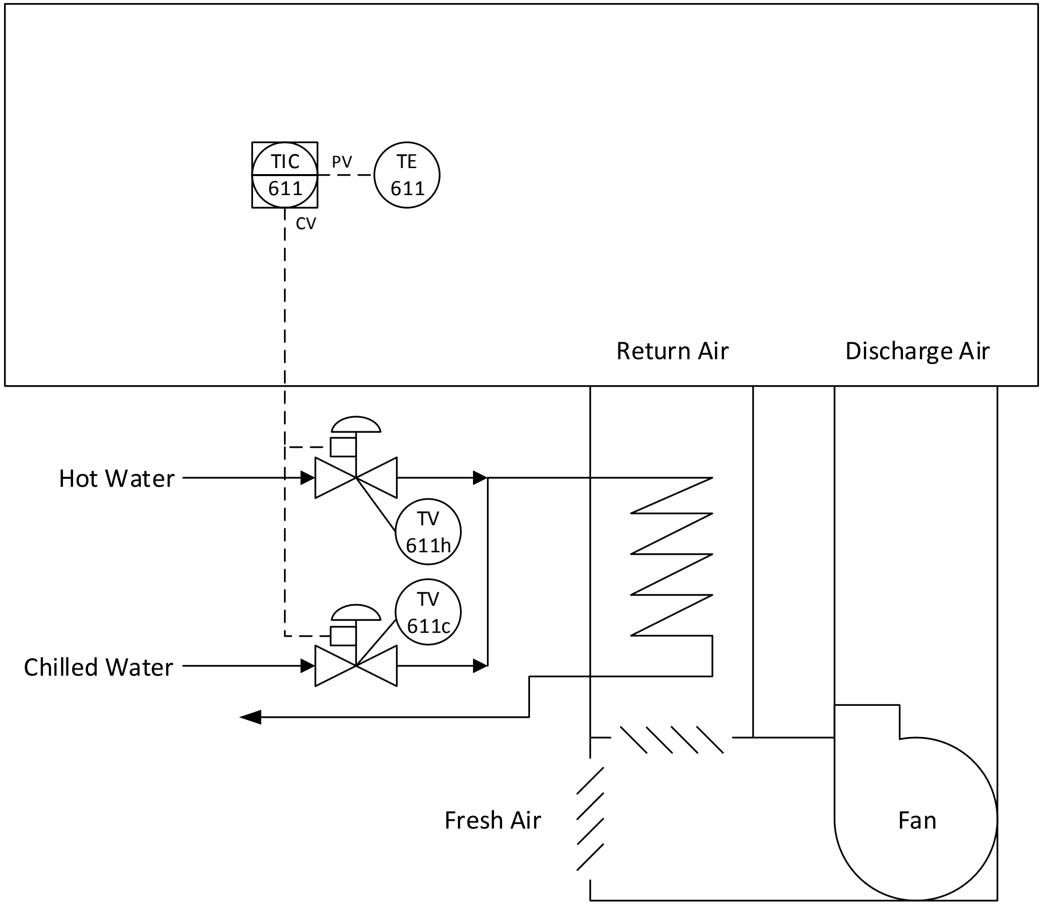
- Consider this temperature control strategy
  - NOTE: this is a closed-loop full analog control, NOT an on-off thermostat!



- What happens if the outside air temperature suddenly drops?

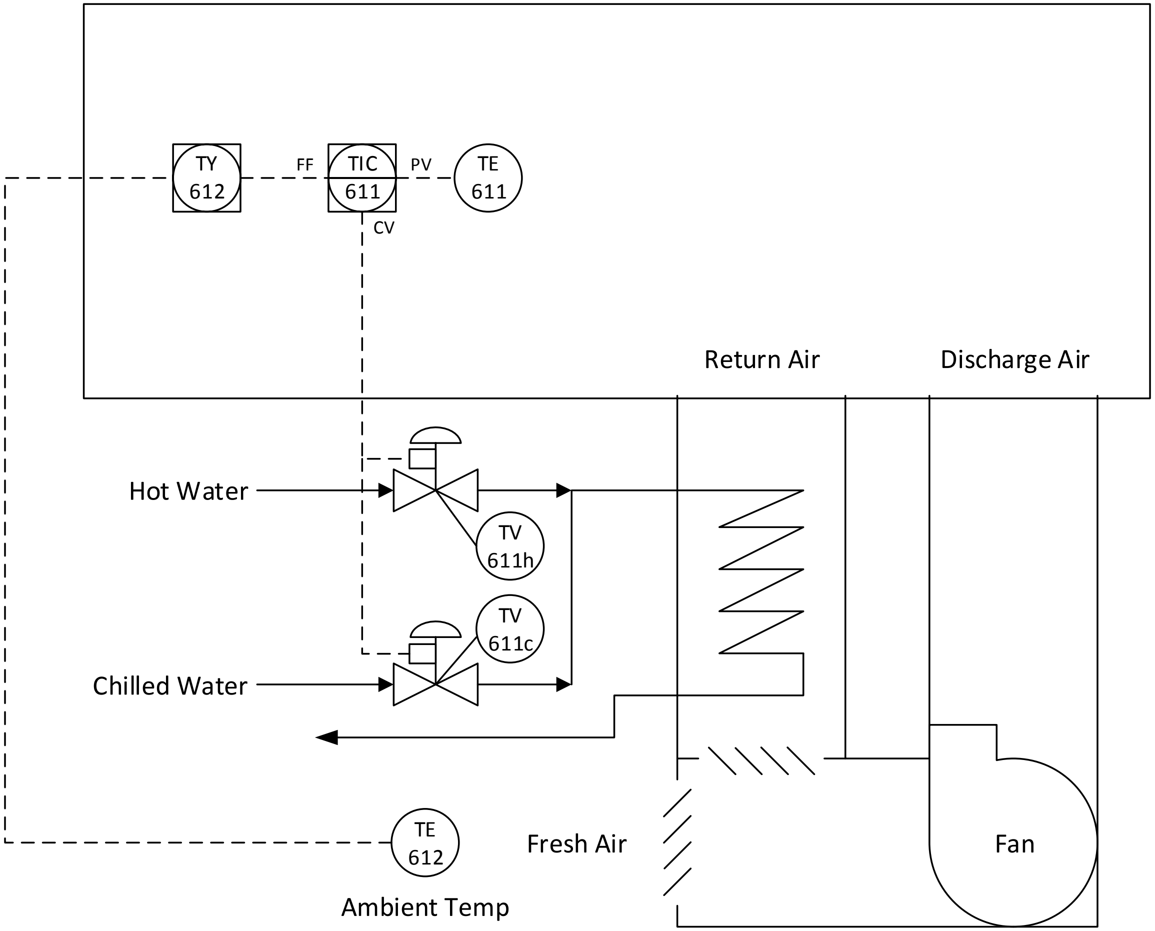
What Are the Effects of This Disturbance?

- The incoming Fresh Air temperature falls.
- This results in cooler Discharge Air into the room.
- The room cools as a result of thermal loss through the walls.
- The controller calls for more hot water to compensate.



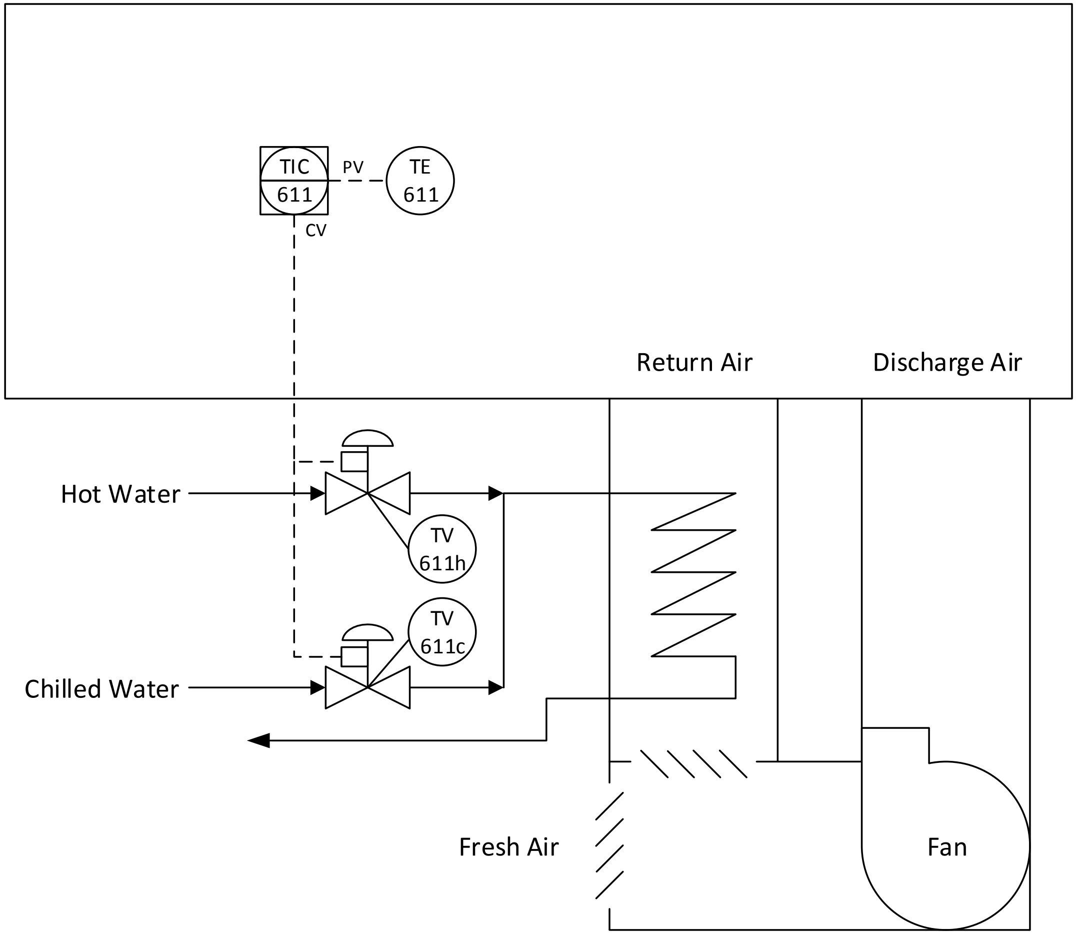
So? We Can Measure This Disturbance!

- We can compensate with a Feedforward Model…
- But what about OTHER disturbances?



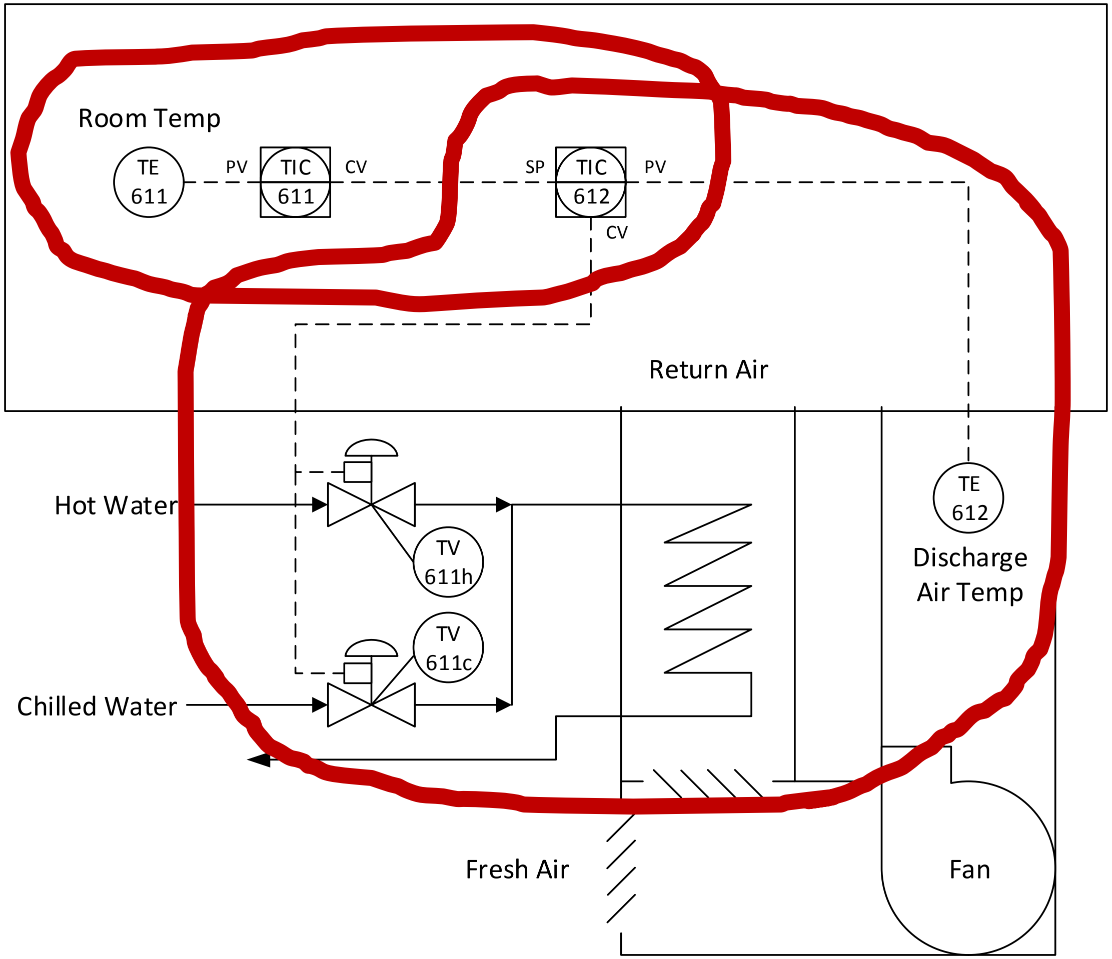
What About Other Disturbances?

- The hot water (or chilled water or steam) supply temperature or pressure could change.
- The damper positions could change the mix of fresh air.
- The fresh air filter (not shown) clogs over time.



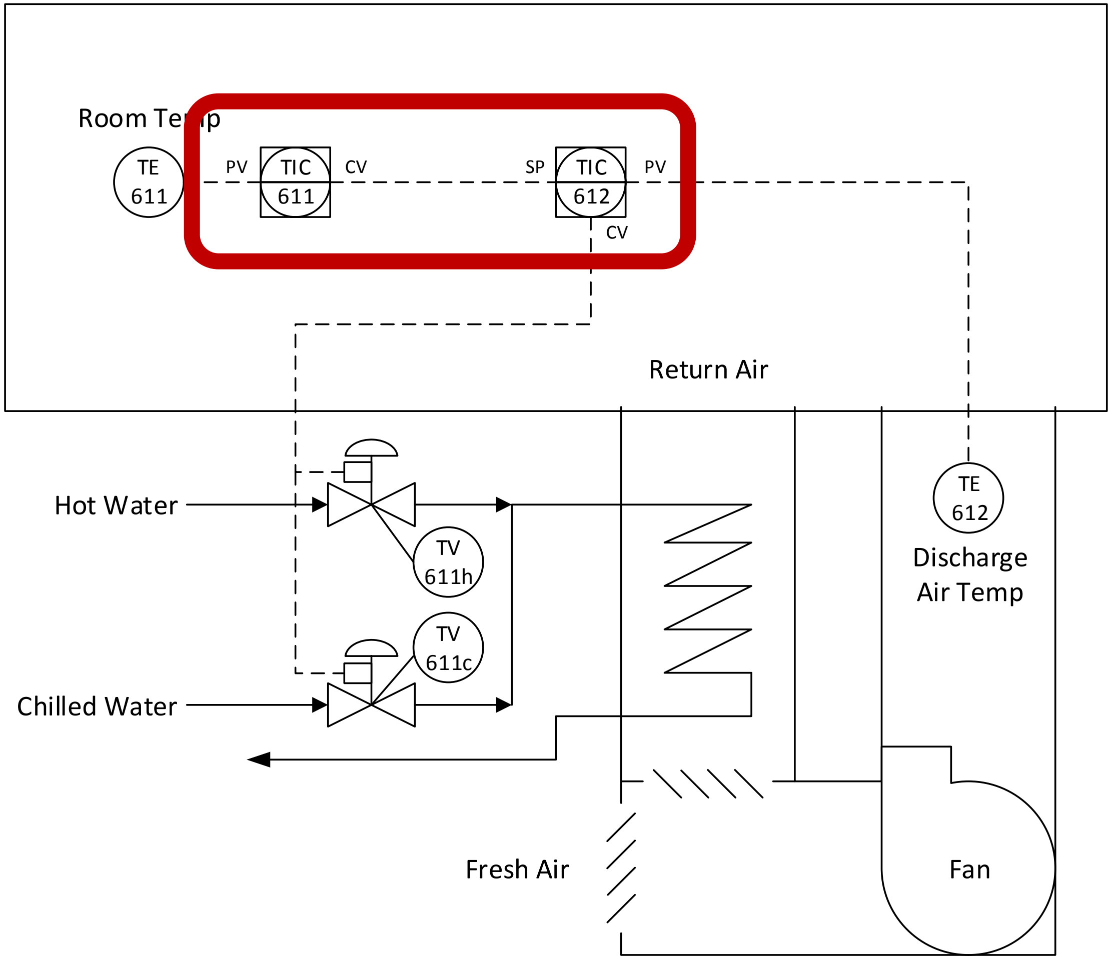
A Simple Way to Deal with MOST of These Disturbances

- Consider two PID loops, one stacked on top of the other:
  - The Discharge Air Temp loop responds quickly to disturbances like supply variances, incoming fresh air temp changes.
  - The Room Temp loop controls room temperature by requesting a discharge air temperature.



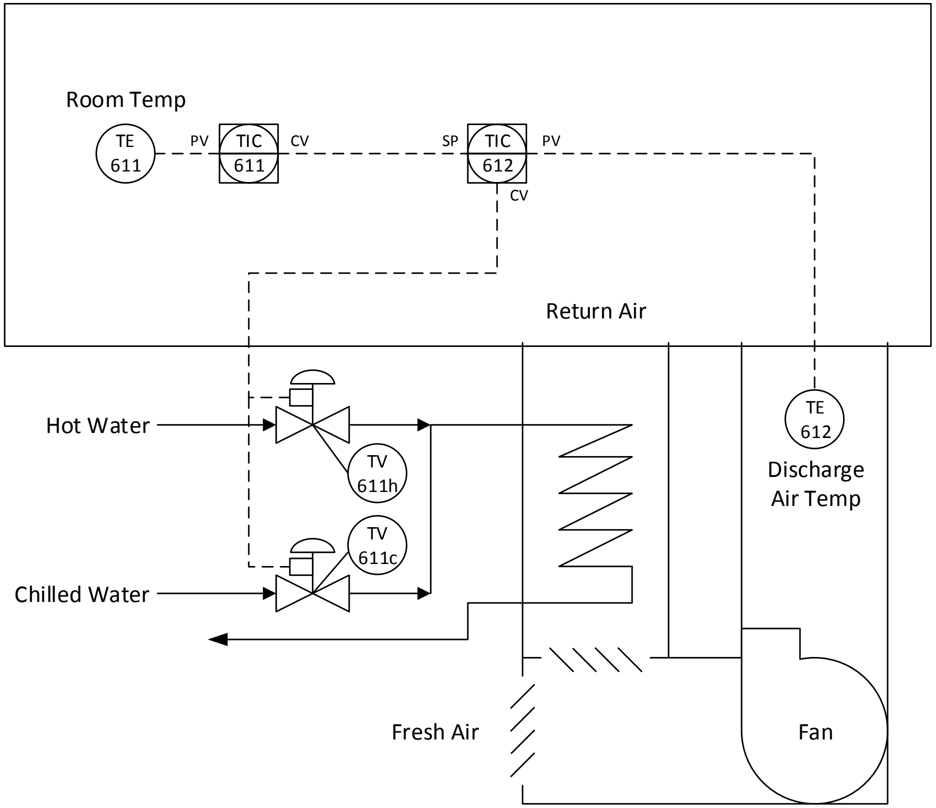
Cascade Control

- When the output of one loop becomes the setpoint of another loop, the loops are said to be “cascaded”.
  - The loop being driven (SP set) is the *“secondary”* or “inner” loop.
  - The loop driving (CV sent to inner loop) is the *“primary”* or “outer” loop.

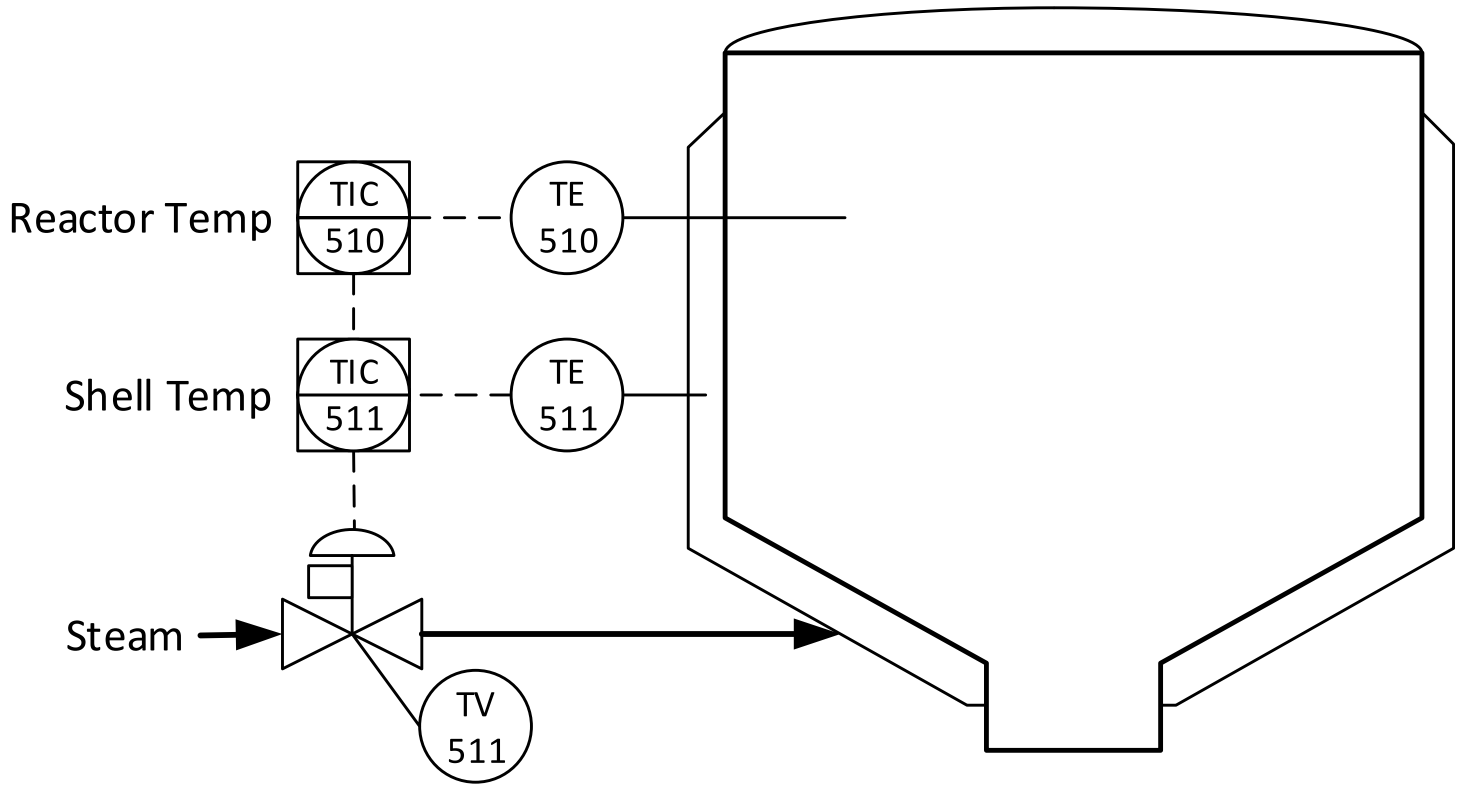


Cascade Control Considerations

- Generally, the inner loop must be "much" faster than the outer loop.
  - About 3x faster or more
- Here, the discharge air temperature loop responds "much" faster than the overall room temperature
  - Consider the thermal mass of the room, plus its insulation



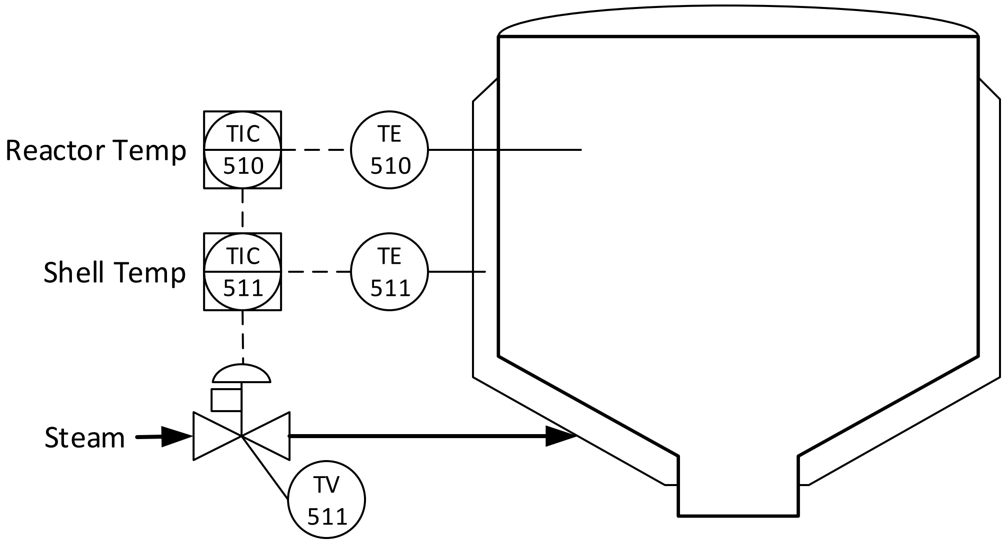
Other Examples of Cascade Control



- Reactor temperature (big, slow), over reactor shell temperature (much less volume, faster)

When to Use Cascade Control

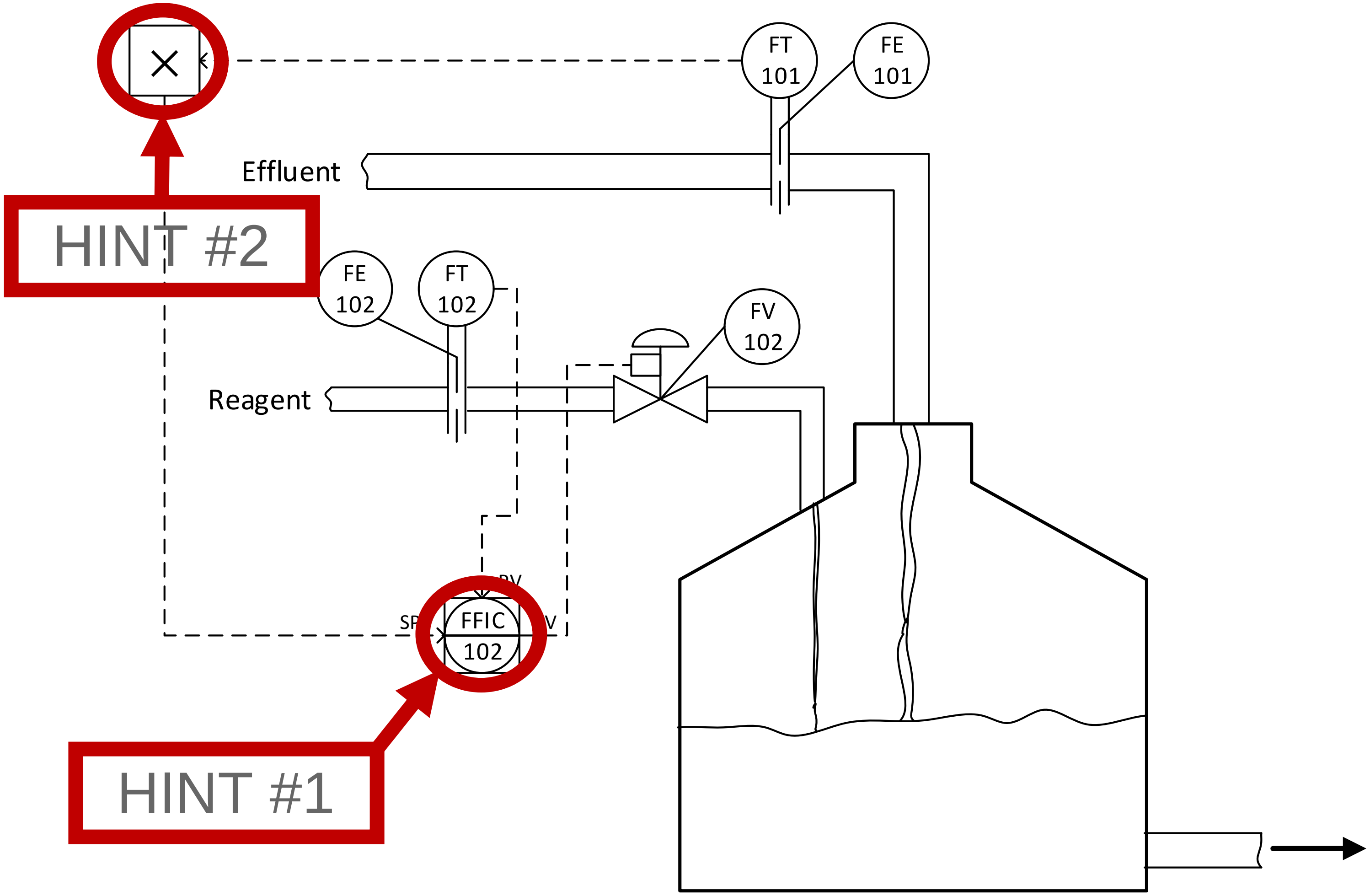
- There are disturbances that **cause** measurable changes that you can handle with this separate loop.
  - Suppose the steam valve has lots of "sticktion"…
  - The inner loop keeps this or other non-linearity from affecting the outer loop.



- That inner loop responds "faster" than the overall control.
- Useful: You can apply constraints on the inner loop…
  - … such as Setpoint clamping, to prevent undesirable excursions.

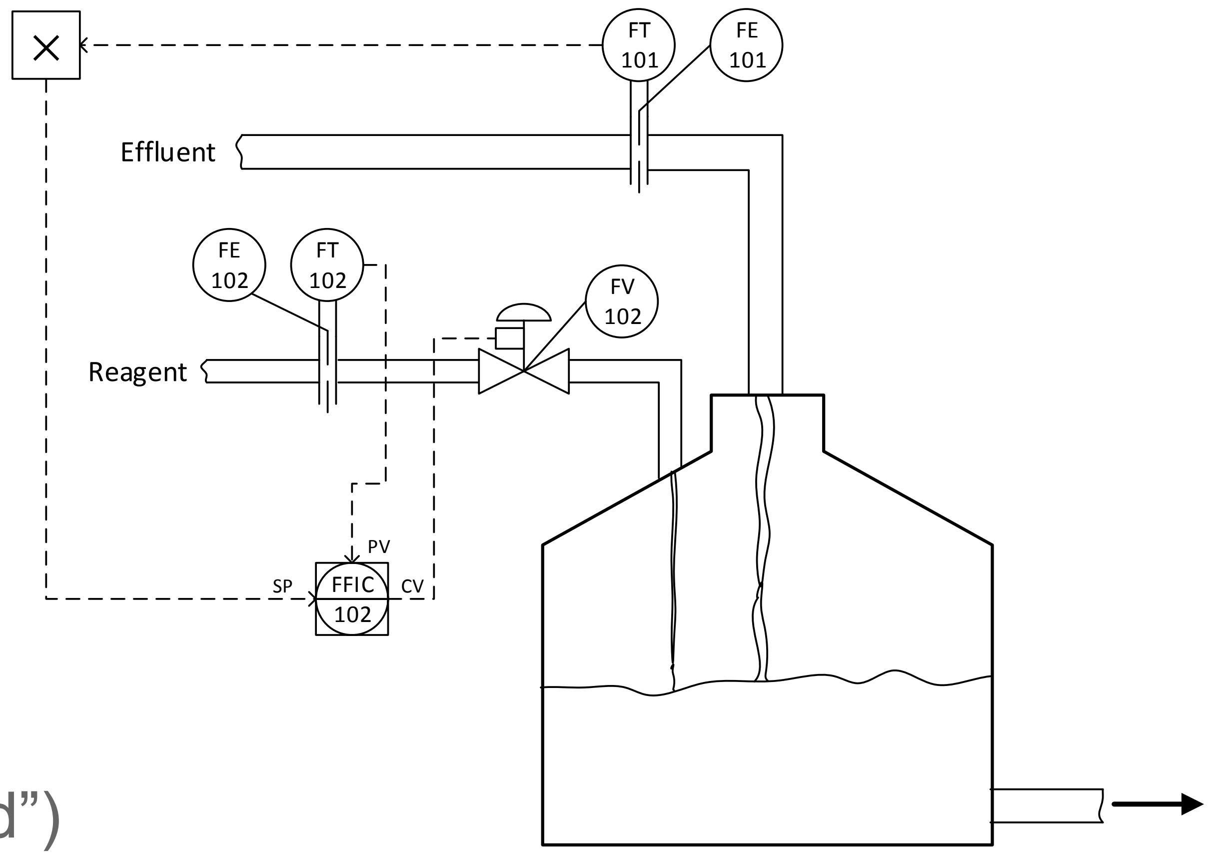
Test Your Knowledge!

- Is this an example of Cascade Control?

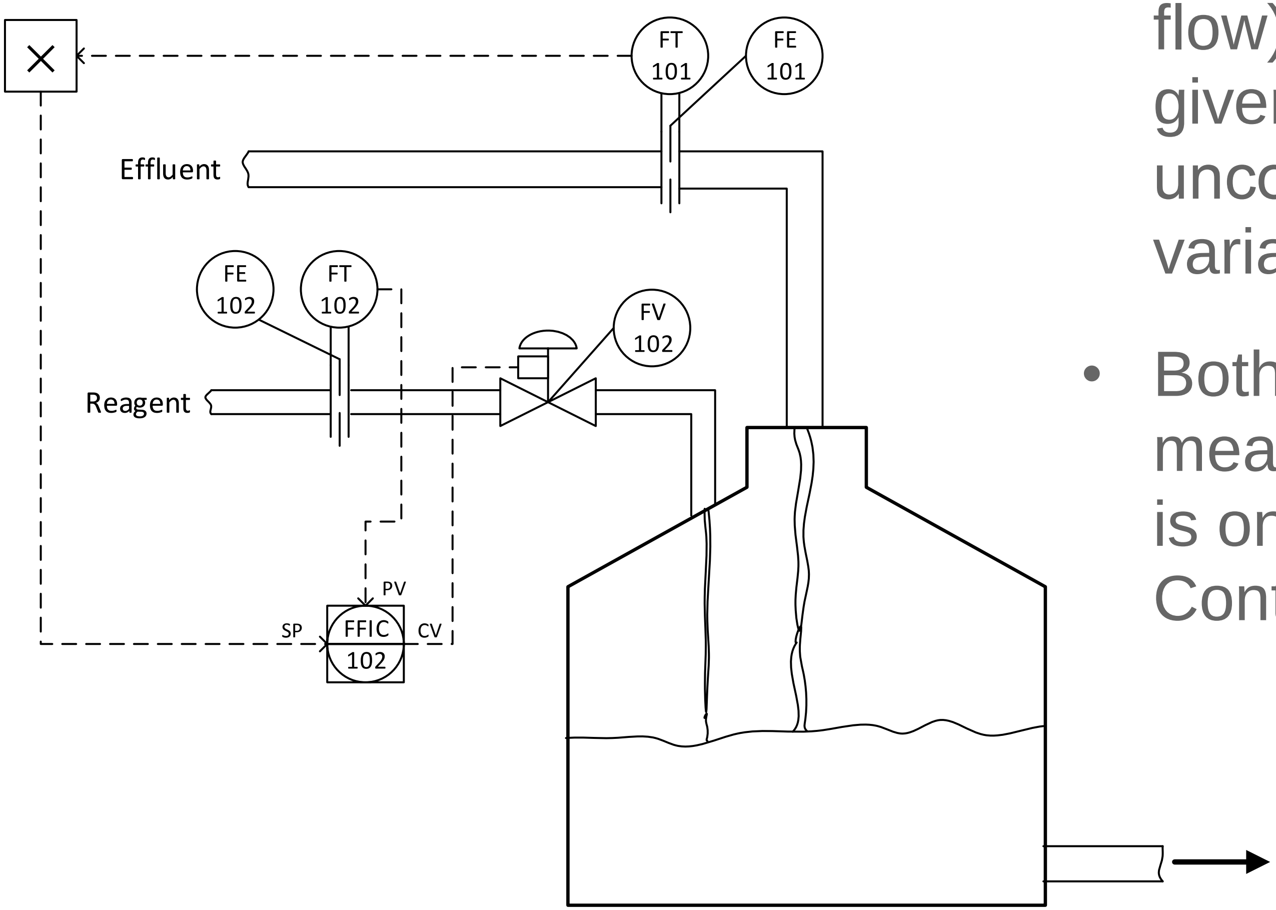


Where's the Loop?

- NO! There's not an outer control loop!
- Effluent flow is measured, but not controlled
- The two flows have similar time response
- Reagent flow is controlled at a *ratio* to the uncontrolled ("wild") effluent flow

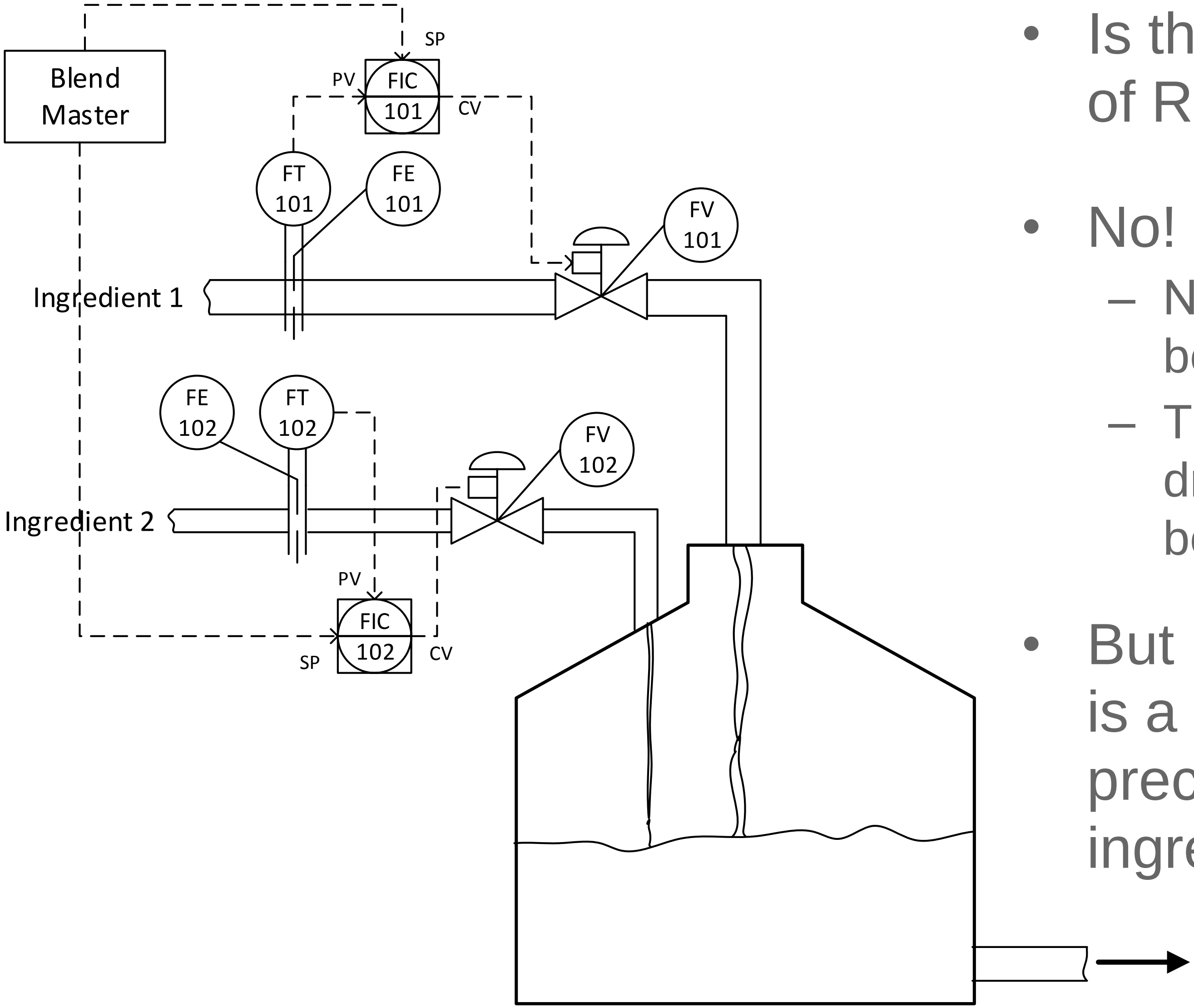


Ratio Control



- One variable (typically flow) is controlled at a given ratio to an uncontrolled ("wild") variable.
- Both variables are measured, but there is only one Final Control Element

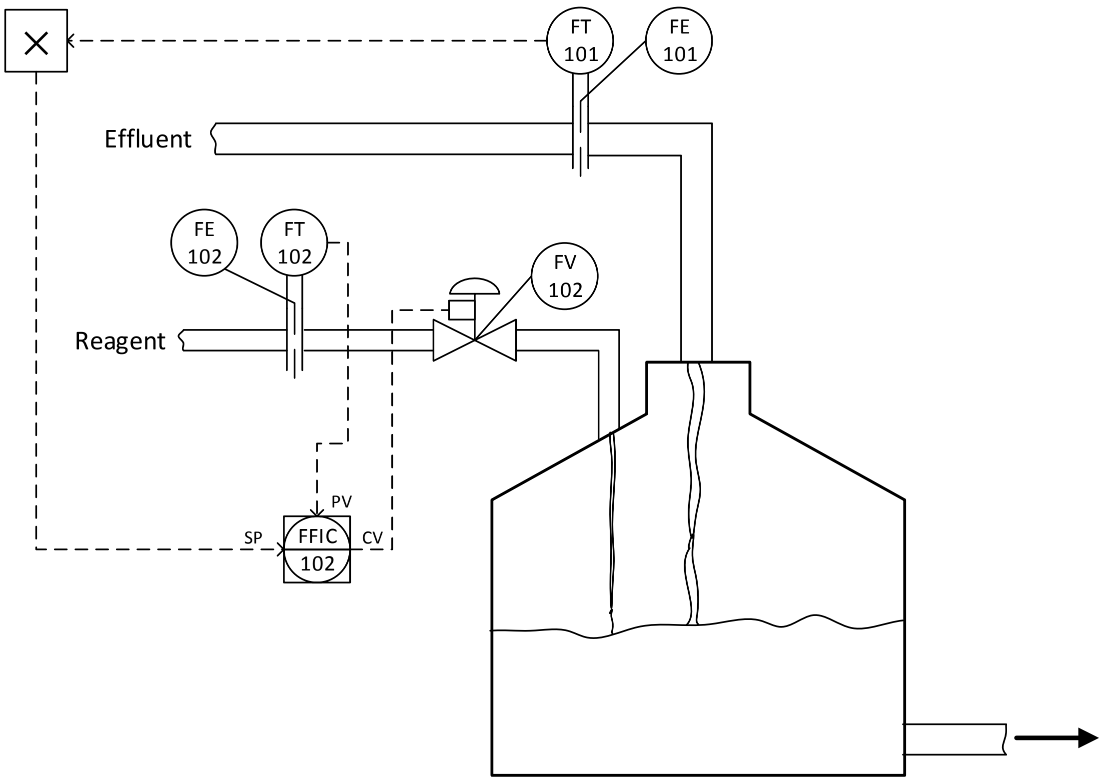
Test Your Knowledge (#2)



- Is this an example of Ratio Control?
- No!
  - Neither flow is "wild", both are controlled
  - The Blend Master drives setpoints to both flow loops
- But Digital Blending is a great way to precision blend ingredients!

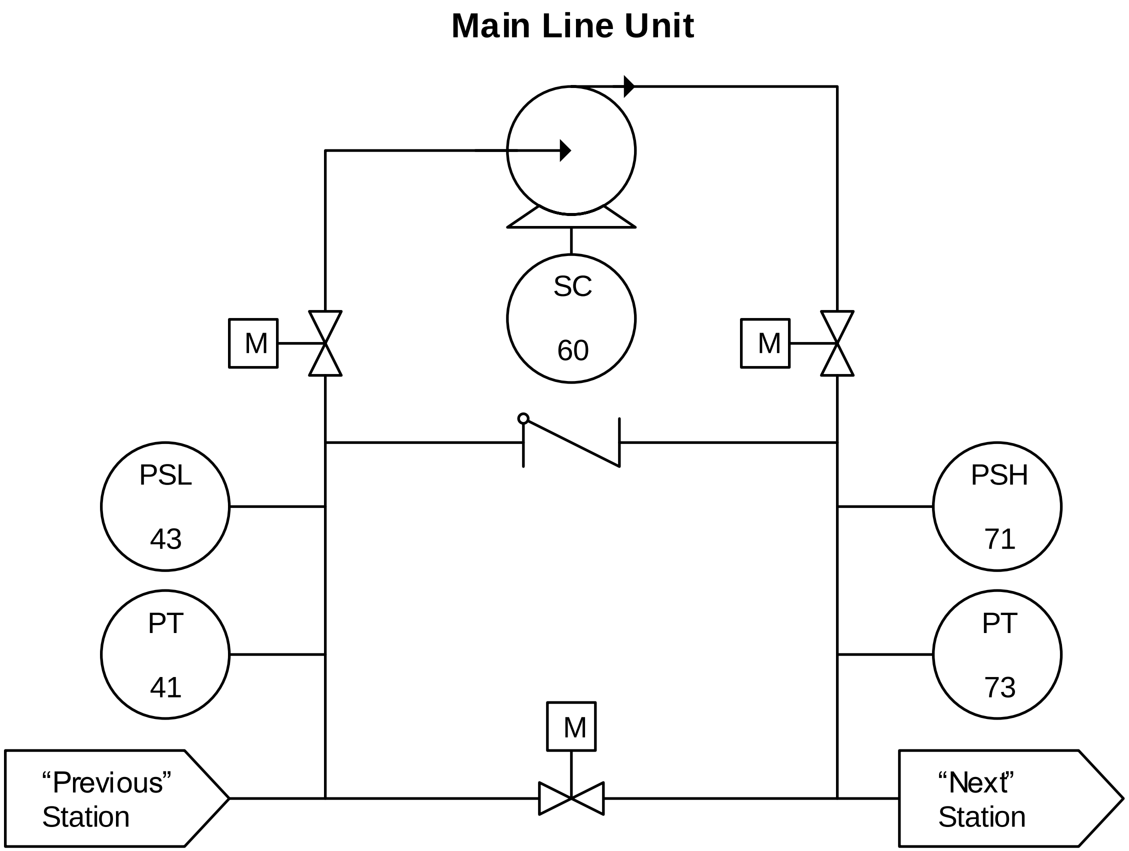
Ratio Control Considerations

- The controlled flow naturally lags
  - Measurement lag
  - Loop processing time
- Ratio control cannot make up for "historical" inaccuracy
  - It is an "instantaneous" ratio
  - Digital Blending uses the flow rates AND the accumulated flow totals to "integrate out" any accumulated variance from the target ratio



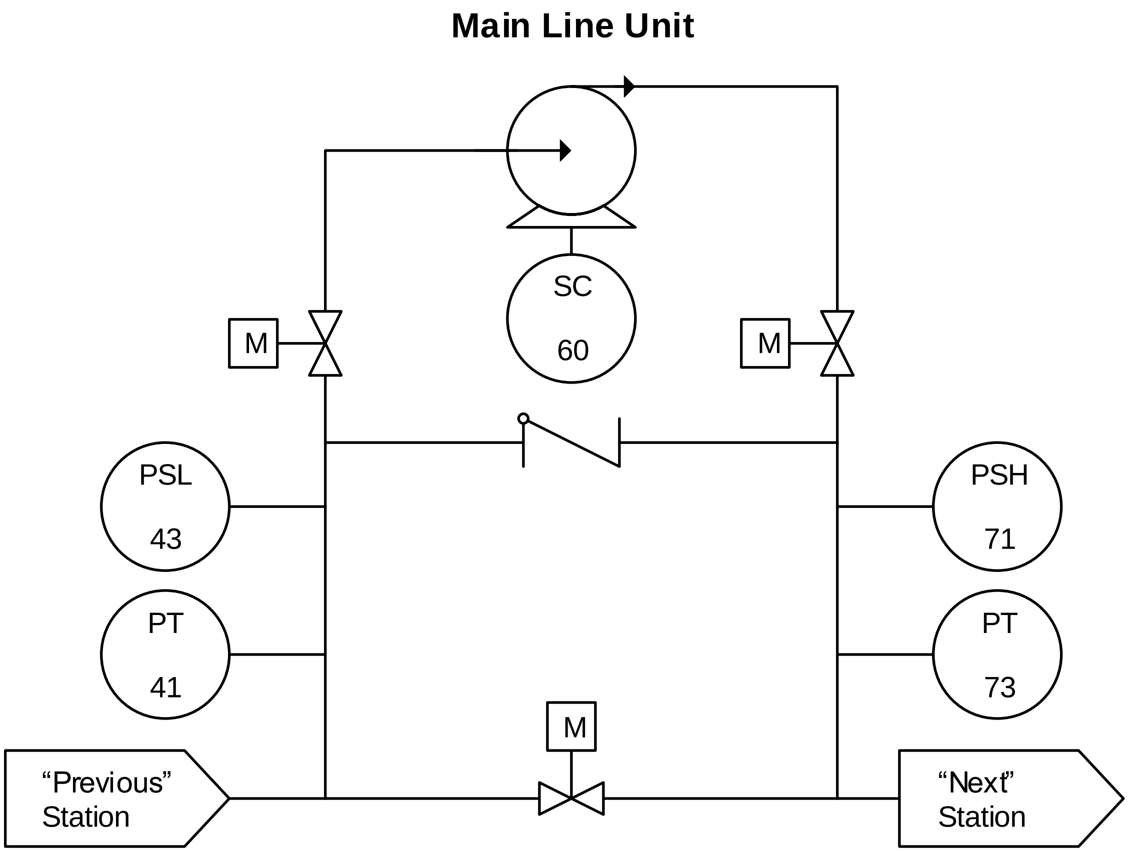
And Now Something Completely Different

- Consider this oil pipeline pump station
- We measure:
  - suction pressure
  - discharge pressure
  - motor current
- Let's control discharge pressure using the variable-speed drive on the pump!



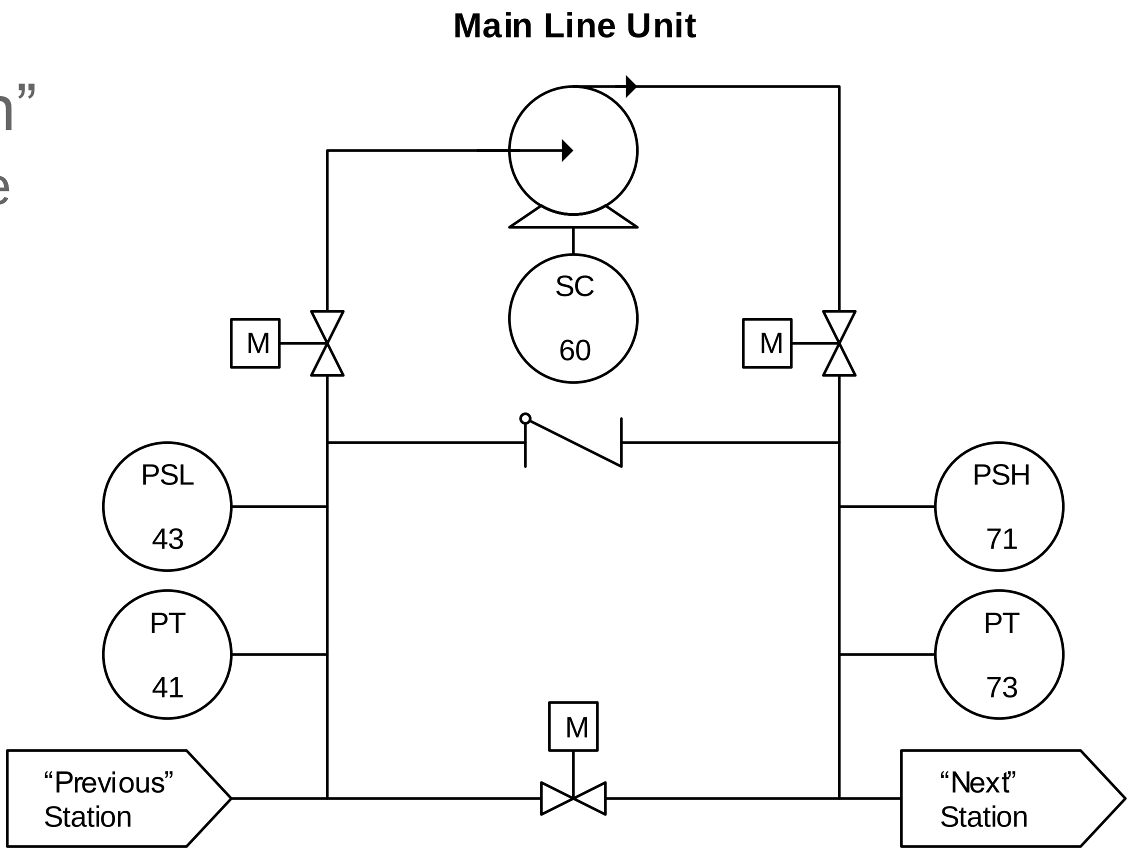
But There Are Constraints…

- We want to control the discharge pressure, but…
- If the suction pressure goes low, the pump cavitates
  - Big pump = big $$$!
- If the motor current goes too high, we trip the drive
  - Pressure upset gets sent down the line



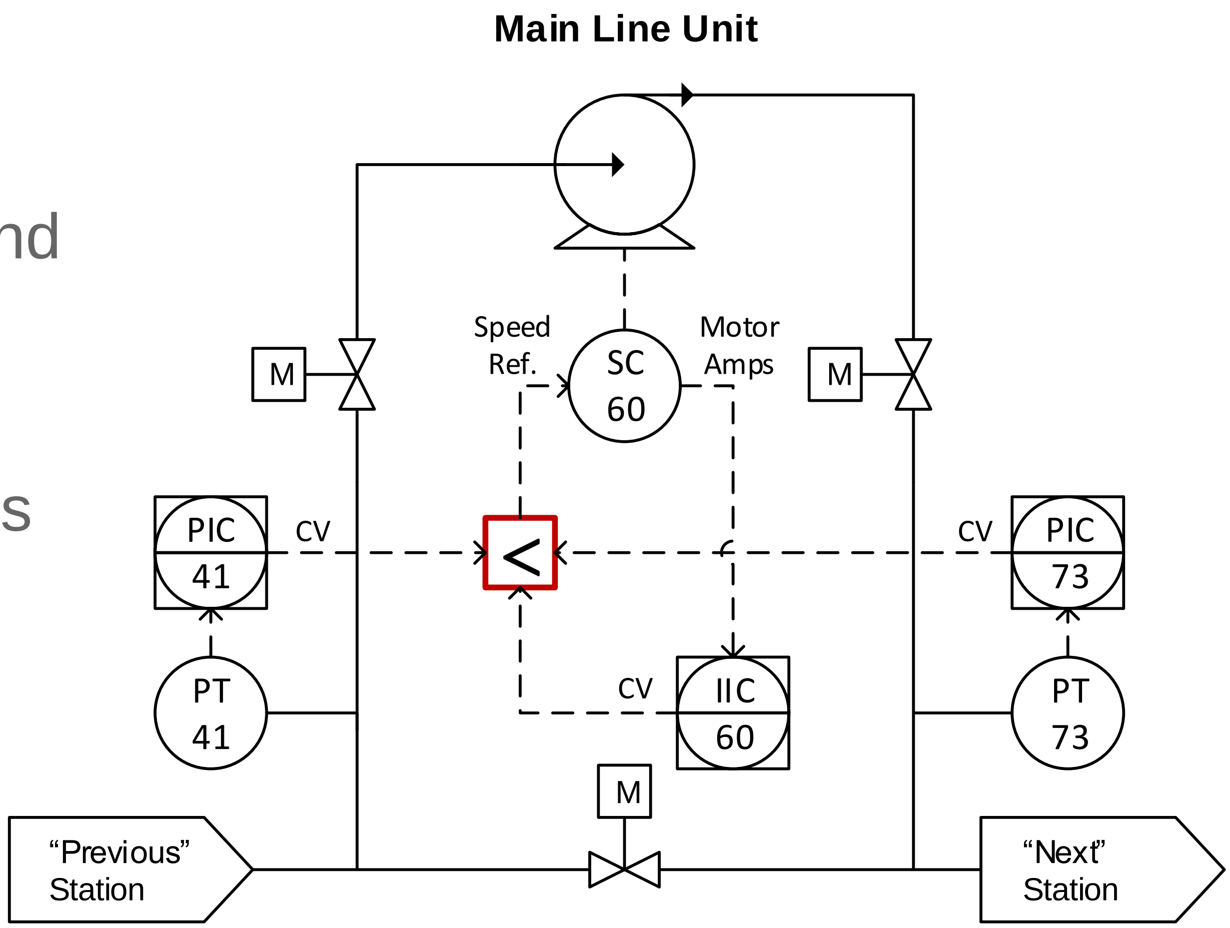
Lucky For Us!

- Both constraints act "in the same direction"
  - If the suction pressure goes low, slow down the pump until it recovers.
  - If the motor current goes high, slowing down the pump reduces the power, and so reduces the motor current.

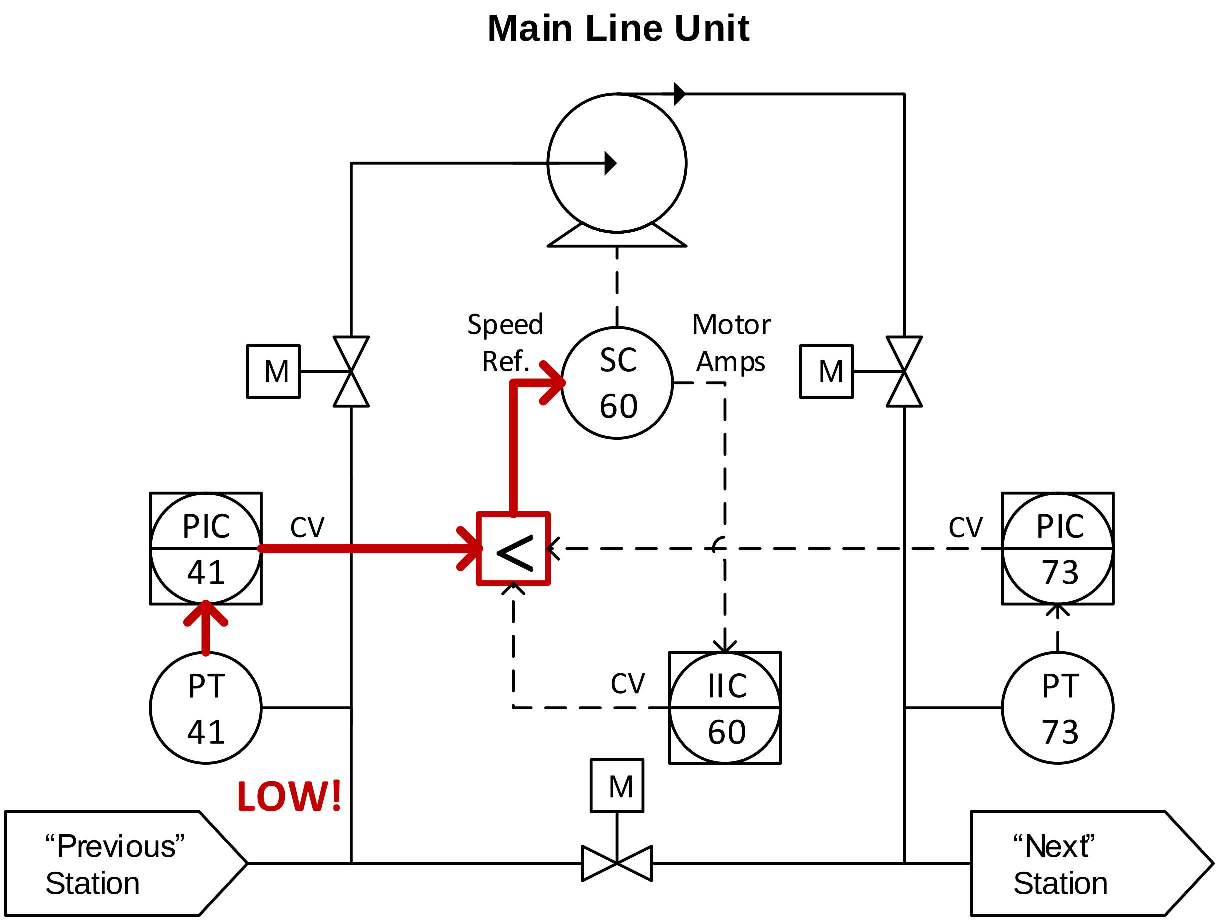


Override Select Control

- The *Primary* loop is the station discharge pressure.
- Suction pressure and motor current are *Override* loops.
- The low-select picks the lowest CV to send to the drive speed reference.



How Override Select Control Works (DEMO!)



- Suction pressure and motor current loops' setpoints are set to the constraint threshold (where to start acting)
- When a constraint is reached, that loop's error changes sign, its output drops, and it is selected.
- The selected CV is fed back to all three loops

Topics for Further Study

- Tuning
- Tuning! (what do K_p, K_i, and K_d MEAN anyway?)
- Tuning!!! (seriously, there are books just on tuning!)
- Control for interacting process variables
- Control for deadtime-dominant processes
  - Smith Predictor, among many
- Advanced process modeling and model-based control
  - Tuning of model based controllers MAKES SENSE! Lag time, dead time, process gain! Stuff you can read off a trend chart!

and so much more!

Questions?

- Ask now!
- Contact the presenter!
  - dereed@ra.rockwell.com
- Ask other experts at this meeting! (There are several!)
- Get a great book for more details:
  - Wade, Harold L., *Basic and Advanced Regulatory Control: System Design and Application* (2nd Edition), ISA, 2004.
  - ISBN: 978-1-55617-873-3
  - Many more topics: The ones covered here, plus extensive information on tuning, decoupling multiple variables, deadtime compensation, basics of model-based control, plus applying!