Process Instrumentation and Control

Process Instrumentation & Control

- Control valves make a significant contribution to pressure drop (see later lecture on hydraulics)
- Control valve location can create a need for additional pumps and compressors, and must be decided in order to size the pumps and compressors
- It is therefore necessary for the design engineer to understand the plant control philosophy even at the PFD stage and the PFD usually shows the location of control valves
- More details of process control are usually included in the piping and instrumentation diagram (P&ID) – see Ch 5
- This lecture is a very brief overview of control for design purposes – more will come in your process control class

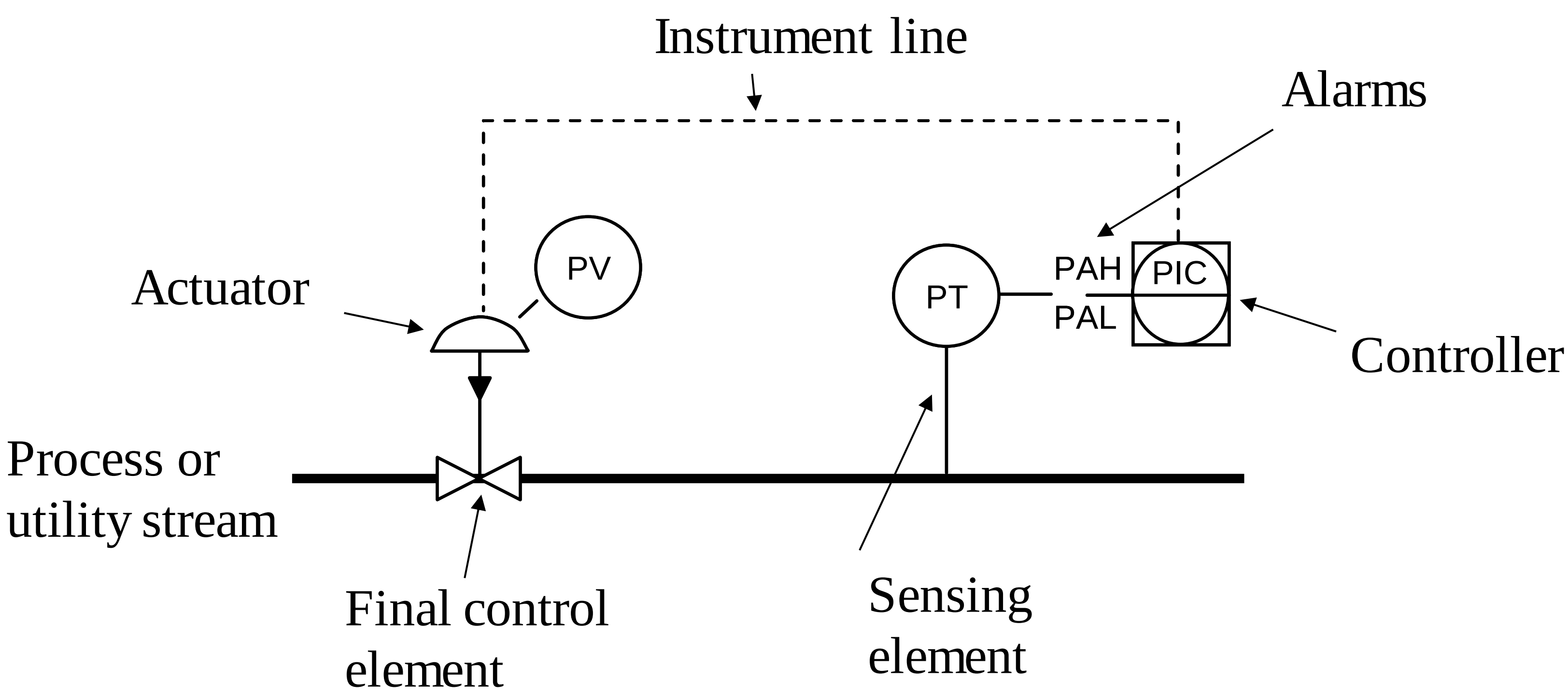
Process Instrumentation & Control

- **Basics of process control**
- Process instrumentation
- Reading a P&ID
- Control of unit operations
- Process safety instrumentation
- Plant-wide control and optimization

Objectives of Process Control

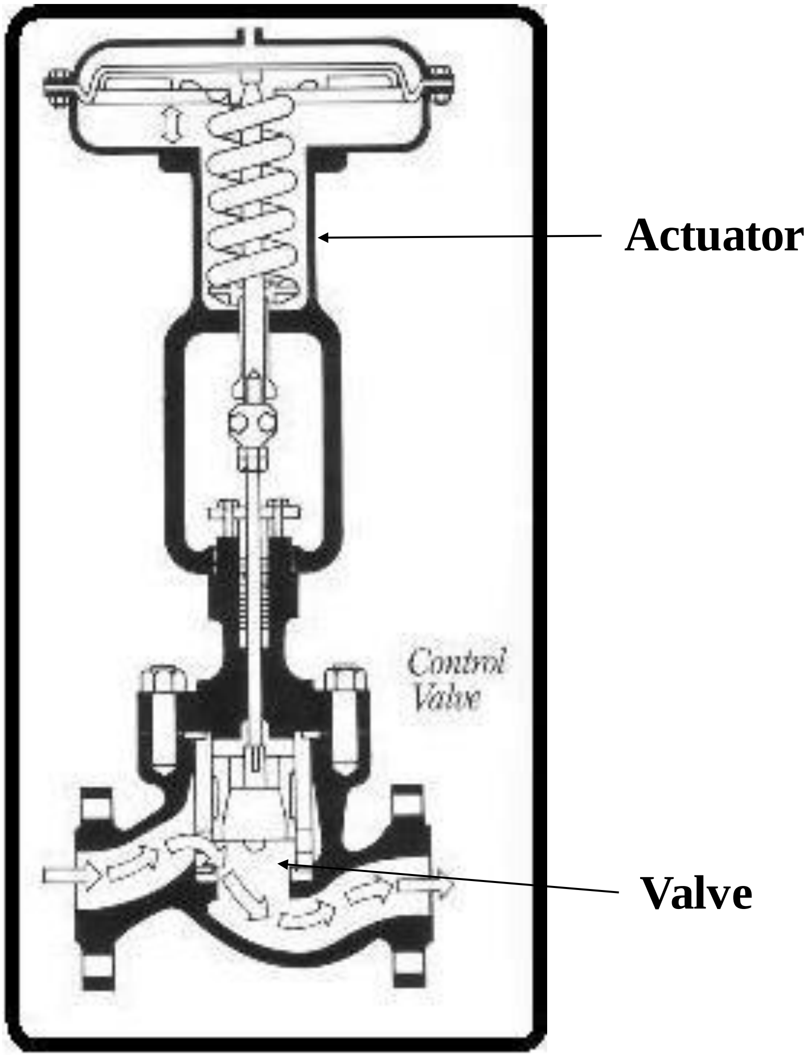
- Ensure stable process operation
  - Particularly, keep the plant operating under safe conditions
  - Minimize damage to equipment due to variation in plant conditions
- Ensure operation meets product specifications
- Minimize impact of external disturbances
  - Example: change in ambient temperature
- Optimize process performance
  - Maintain process throughput
  - Minimize operating costs

Control Loop Components



- The sensing *instrument* detects the *measured variable* and sends a signal to a *controller*, which signals the *actuator* to close or open a control valve and adjust the *manipulated variable* (usually a flow rate)

Control Valves



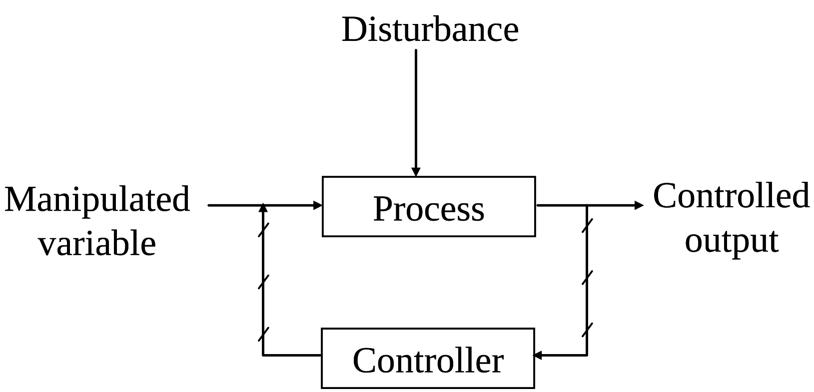
Source: Valve Manufacturer’s Association, www.vma.org

- The final control element is usually a control valve
  - Exceptions: electric heaters, mixers, variable speed drives
- The actuator is either a motor or a bellows that opens or closes the valve in response to the signal

Types of Control Loop

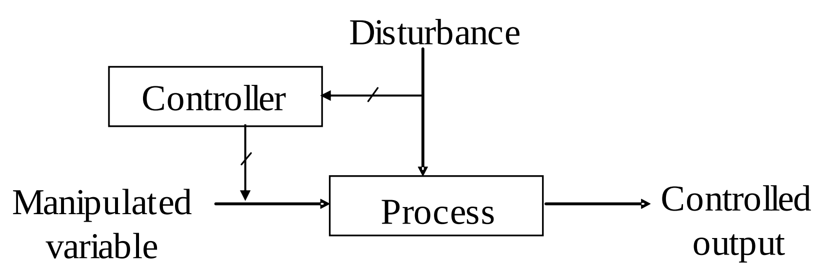
Feedback

- Control system measures changes in a process output and then adjusts manipulated variable to return output to set point
- Can be slow if process response time is long

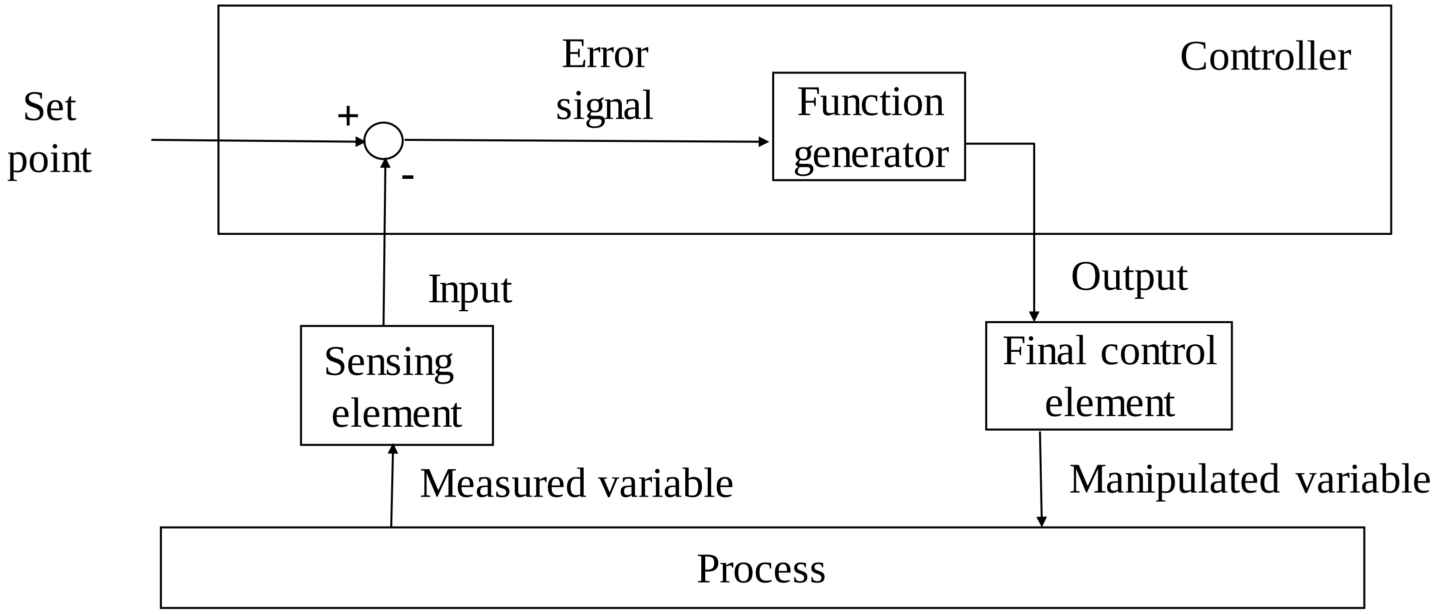


Feed Forward

- Control system measures disturbance and adjusts manipulated variable to compensate for it so that controlled output is not affected
- Requires greater knowledge of system response



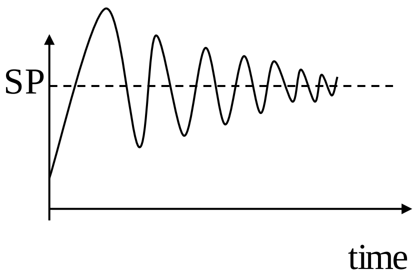
Feedback Control



- Controller computes error between input and set point and adjusts output based on a control algorithm

Typical Control Algorithms

- P: Proportional
  - Controller output is proportional to error
  - The proportionality constant is called the controller gain
  - High gain gives fast response, but can lead to instability
  - Low gain can cause offsets



- I: Integral
  - Output is proportional to integral of error
  - Eliminates offsets from P control, but makes response more sluggish
- D: Derivative
  - Output is proportional to rate of change of error
  - Damps out instability and allows higher gain to be used
- Other functions such as summation, multipliers, and advanced models can be easily coded in digital controllers

PID Controller Response

- For a PID Controller,

$$\text{Controller Output} = G\left[e + (1/T_i)\int_o^t e\,dt - T_d\left(\frac{de}{dt}\right)\right]$$

where: G = Controller gain

e = Error (set point minus measured variable)

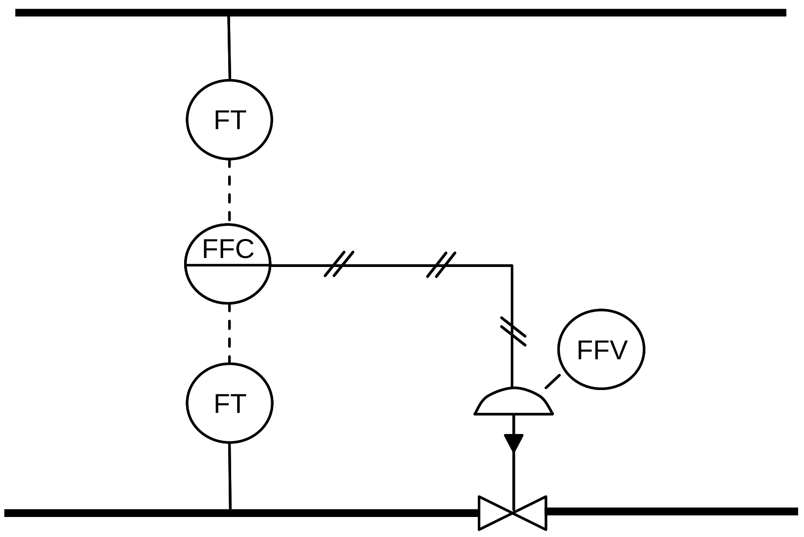
T_i = Integral time constant

T_d = Derivative time constant

- The controller output is proportional to the error, the time integral of the error, and the rate of change of the error. G, T_i and T_d are the controller tuning parameters.
- Much more of this in control class

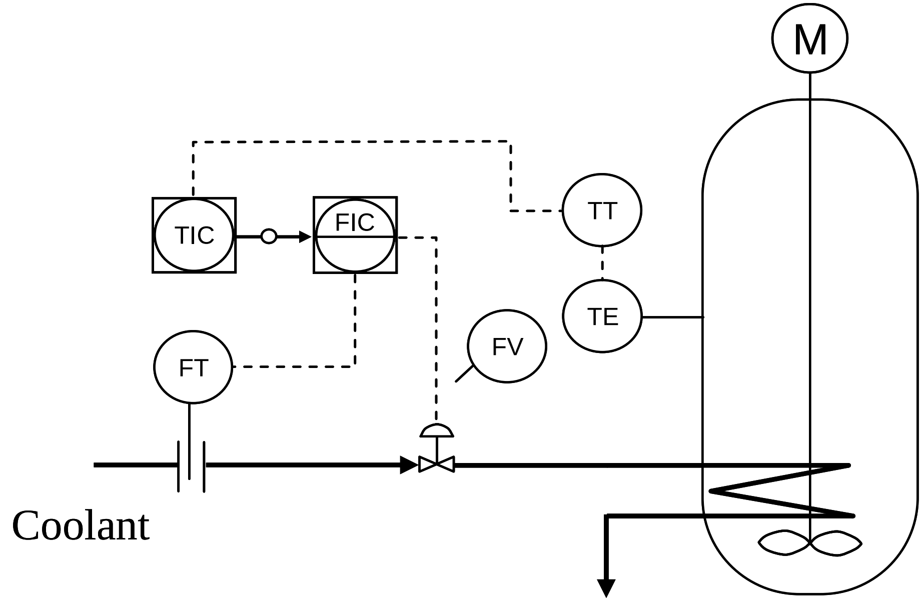
Ratio Control

- One stream is controlled in ratio to another
- Often used for controlling feed rates to try to maintain stoichiometry
- Also used in some types of distillation column control to set reflux or boil-up ratios



Cascade Control

- One *primary* controller is used to adjust the set point of a second *secondary* controller
- Used to minimize outside load variations and increase process stability
- Example: reactor temperature (primary controller) cascades onto coolant flow controller (secondary) to control reactor temperature



Process Instrumentation & Control

- Basics of process control
- **Process instrumentation**
- Reading a P&ID
- Control of unit operations
- Process safety instrumentation
- Plant-wide control and optimization

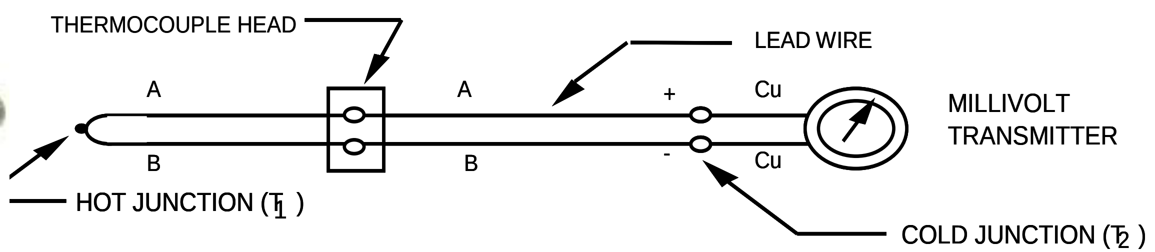
What Can Be Measured?
(& How Easily)

Easy | Difficult

- Easy means cheap, reliable instrument with fast response time and accurate measurement

Temperature Measurement: Thermocouples

- When a junction between dissimilar wires is heated, an EMF (voltage) is developed, which can be read by a millivolt transmitter
- The junction is usually housed in a thermowell



ISA TYPE	A (+)	B (-)	
E	CHROMEL	CONSTANTAN	← Typical
J	IRON	CONSTANTAN	
K	CHROMEL	ALUMEL	← High T
T	COPPER	CONSTANTAN	

Temperature Measurement: Thermocouples

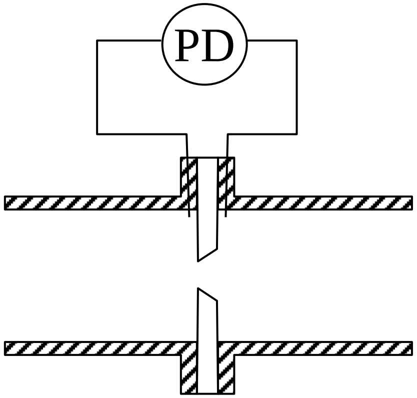
- Response depends on thermowell location and heat transfer
  - Instrument error is usually ± 3 to 4 F
  - There may be additional offsets if the thermowell is incorrectly located
- Response is fast if located in a flowing stream
- Sometimes thermocouples are also strapped to walls of vessels
  - For high temperature processes or processes with large exotherms

Pressure Measurement

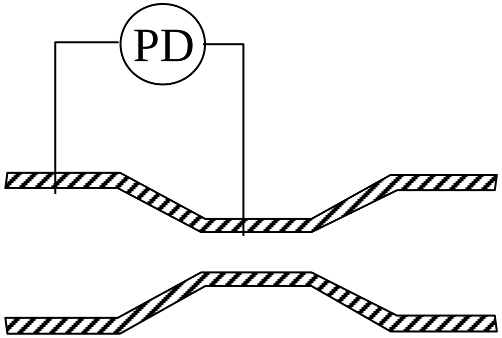
- Pressure instruments usually measure differential pressure
- If one side is atmospheric pressure then the difference is the process *gauge* pressure (usually written barg or psig), not *absolute* pressure (bara, psia)
- Several possible methods:
  - Mechanical: measure displacement of a bellows or Bourdon tube
  - Electrical: attach a strain gauge to a bellows
  - Capacitance: diaphragm moves capacitor plate (most common type)
  - Piezoelectric: measures change in semiconductor conductivity
- Pressure measurement devices respond quickly and accurately
- Differential pressure measurement is used as the basis for flow and level measurement

Flow Rate Measurement

- Place a restriction in the flow path and measure the resulting pressure drop using a differential pressure (PD) cell
- If fluid properties are known, results can be calibrated to flow rates



Orifice Meter

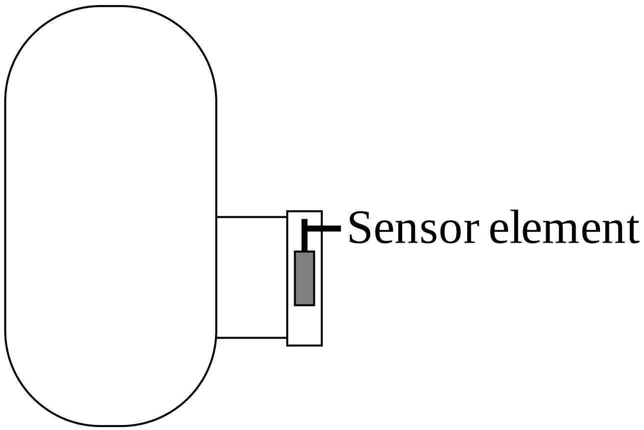


Venturi Meter

Level Measurement

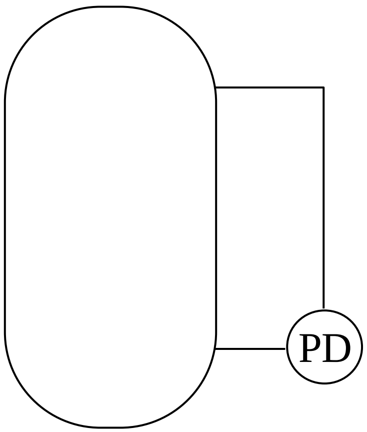
Displacement

- *Displacer* moves up and down with level due to bouyancy
- Displacer movement is detected via mechanical or magnetic linkage



Differential Pressure

- Measures static head of liquid using a differential pressure cell
- Density of the liquid and vapor must be known and constant



Composition Measurement

- Some components can be detected at low concentrations using sensors that have been designed to pick up that component
  - Examples: O_2, CO, H_2S, H_2
  - Component sensors are often sensitive to other components, so check carefully with vendor to make sure the device is rated for the application
- More detailed composition can be measured by on-line GC methods
  - TCD: thermal conductivity detector
  - FID: flame ionization detector
  - Response can be slow (5 to 30 minutes), particularly if a long column is used
- Online NIR can be used in some cases
- Composition is often inferred from other properties
  - Boiling point
  - Conductivity

Process Instrumentation & Control

- Basics of process control
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Piping and Instrument Diagrams

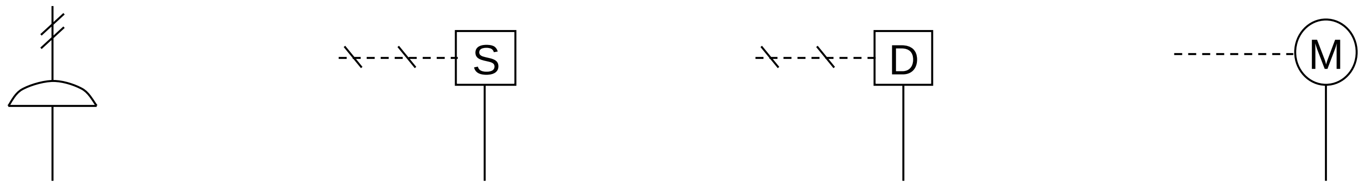
- The P&ID shows all the instruments and valves in the process
  - Not just control loops
  - Vents, drains, sample points, relief valves, steam traps, isolation valves, etc.
- The P&ID usually also indicates line sizes and pipe metallurgy
- Companies occasionally use their own symbols, but U.S. standard is ISA-5.1-1984 (R1992) from the International Society for Automation
- The P&ID is usually produced in consultation with a specialist controls engineer
- Example of real P&ID: see Ch5

ISA 5.1 P&ID Symbols

Control Valves

General | Three-way | Globe | Diaphragm

Actuators

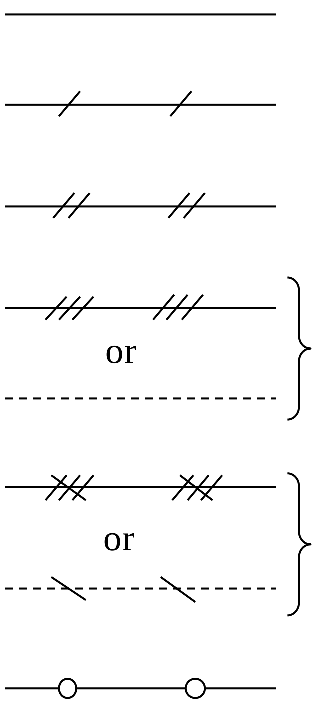


Diaphragm or unspecified actuator | Solenoid | Digital | Rotary motor

Valve Failure Positions

- It is important to specify what happens to a control valve if the signal fails
- The final valve position has an impact on process safety and pressure relief scenarios and may affect other instrumentation

ISA 5.1 Instrument Lines



Instrument supply or connection to process

Undefined signal

Pneumatic (instrument air) signal

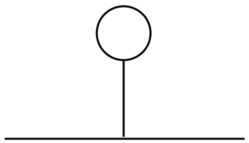
Electric signal (4 to 20 mA)

Electric binary (on-off) signal

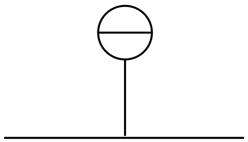
Internal system link (software or data link)

- Most newer plants use electric signals
- Pneumatic signals are found in older plants and locations where electric signals would be unsafe
- Binary signals are used for digital signals and for solenoids and other on-off devices
- Instrument lines are always drawn lighter than process lines on the P&ID

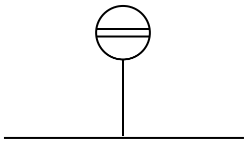
ISA 5.1 Controller Symbols



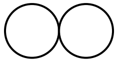
Field mounted



Panel mounted in primary location

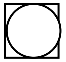


Panel mounted in auxiliary location (local panel)

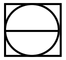


Dual function instrument

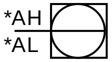
Distributed Control Shared Display Symbols



Field mounted shared display device with limited access to adjustments



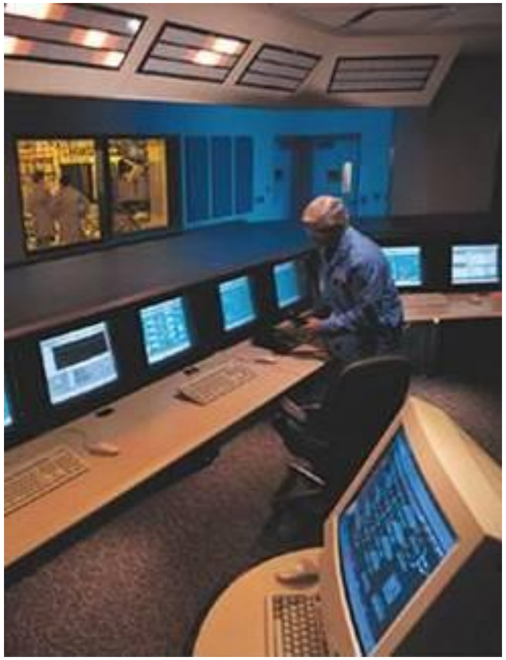
Shared display device with operator access to adjustments



Shared display device with software alarms (* is measured variable)

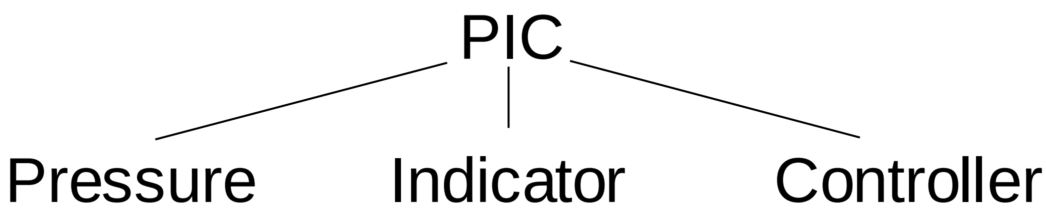
Shared Display Devices

- Most plant control rooms now use shared display devices that show the outputs of multiple instruments on a VDU screen
- Operator can see a flow diagram that identifies where the instrument is and can enter set points
- Software also allows data to be plotted as trends
- Data can be accessed remotely
- Data is collected and logged for process records



Source: UOP

ISA 5.1 Nomenclature



- Two- to four-letter codes are used to identify the instrument or controller
- First letter always indicates the initiating or measured variable
- Subsequent letters I = indicator, R = recorder, C = controller, T = transmitter, V = valve, Z = other final control element, S = switch, Y = compute function, AH = high alarm, AL = low alarm

ISA 5.1 Nomenclature: First Letters

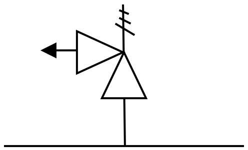
- A Analysis (composition)
- F Flow
- FF Flow ratio
- J Power
- L Level
- P Pressure (or vacuum)
- PD Pressure differential
- Q Quantity
- R Radiation
- T Temperature
- TD Temperature differential
- W Weight
- C, D, G, M, N, O can be user-defined variables

Exercise: Identify The Instrument

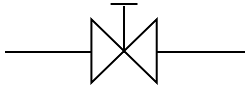
- Can you figure out what each of these ISA 5.1 codes means and what the instrument does?
  - TRC
  - AR
  - PAH
  - PAHH
  - LI
  - PC
  - TSH
  - FFY
  - PT
  - JIAL

ISA 5.1 Other Common Symbols

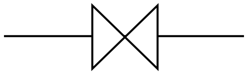
Restriction orifice



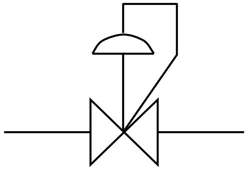
Pressure relief or safety valve



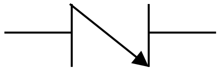
Hand control valve



Gate valve or isolation valve



Self-contained backpressure regulator



Stop check (non-return) valve

Process Instrumentation & Control

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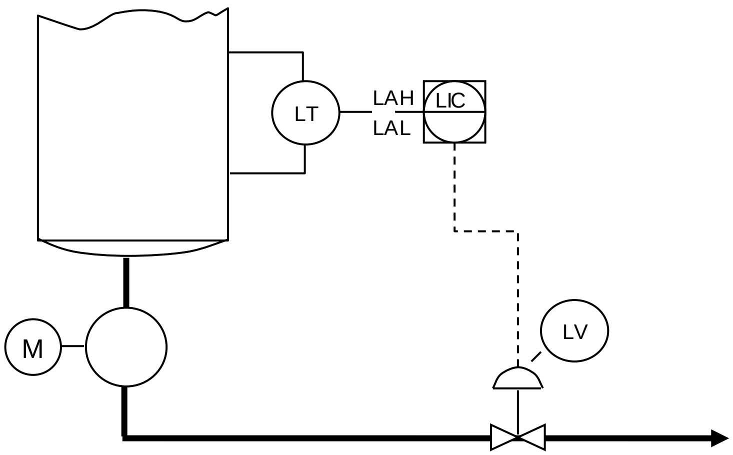
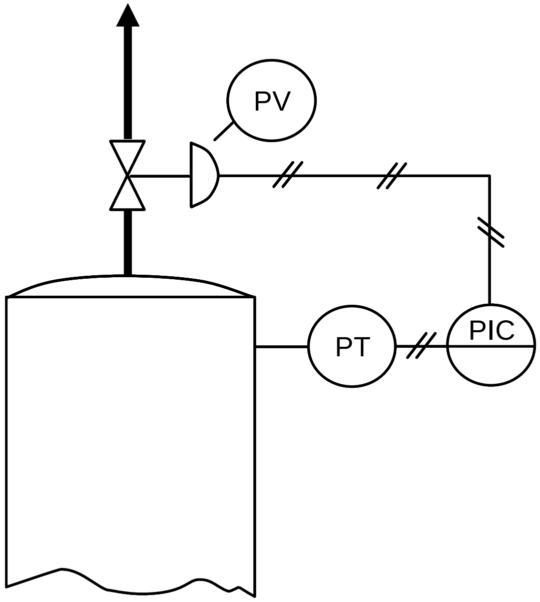
Level Control



- A level control is needed whenever there is a V/L or L/L interface
- Level control sets inventories in process equipment
- Many smaller vessels are sized based on level control response time

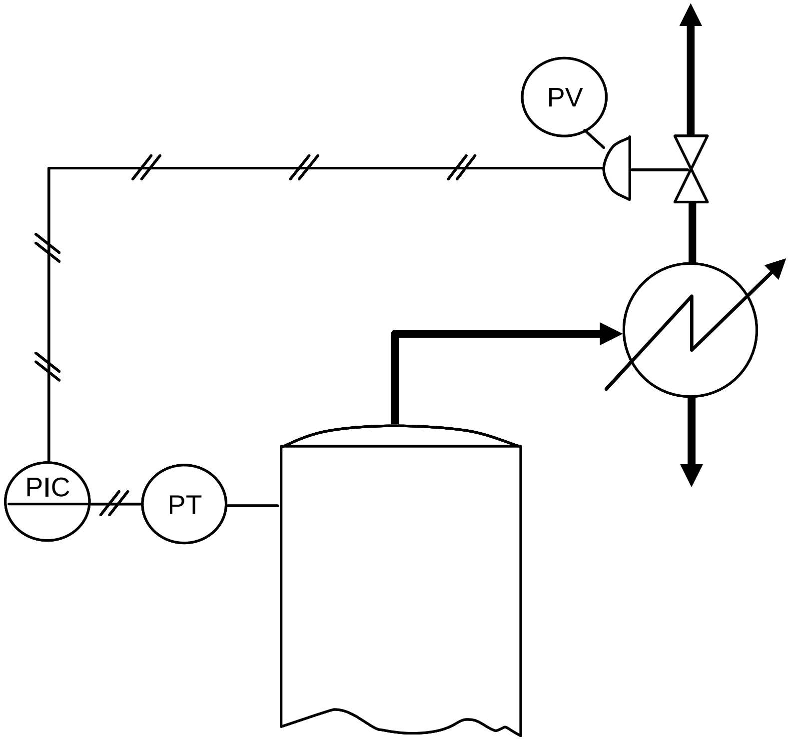
Pressure Control

- Pressure control is usually by venting a gas or vapor
- In hydrocarbon processes, off-gas is often vented to fuel
- In other processes, nitrogen may be brought in to maintain pressure and vented via scrubbers
- Most common arrangement is direct venting (shown)
- Several vessels that are connected together may have a single pressure controller

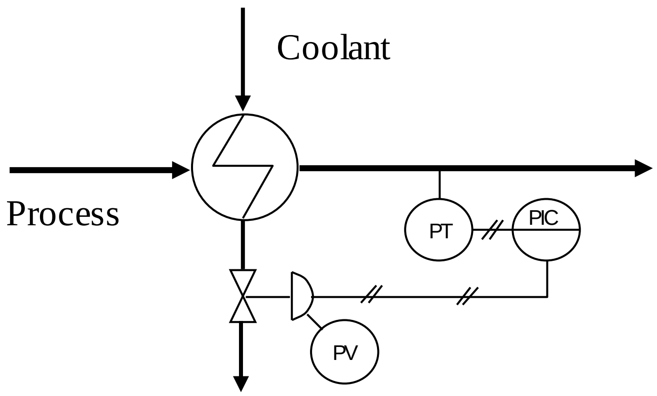


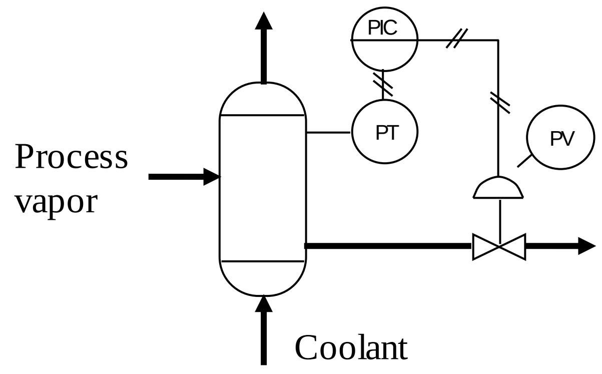
Pressure Control

- If vapor has a high loading of condensable material, then pressure control is on the vent gas stream from the condenser



Pressure Control: Condensers

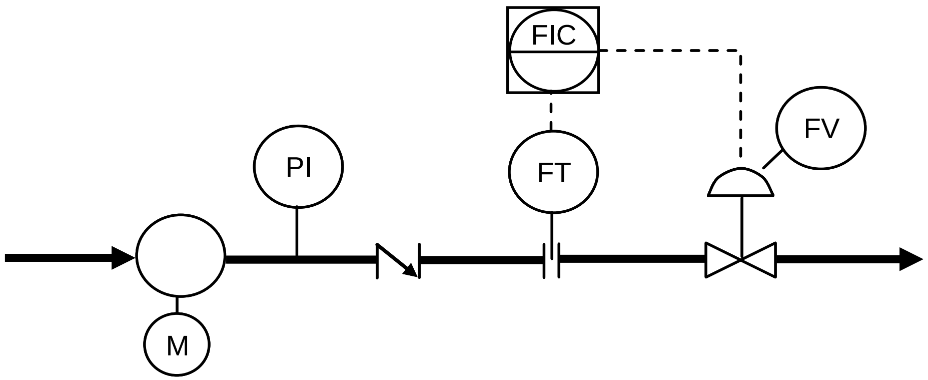


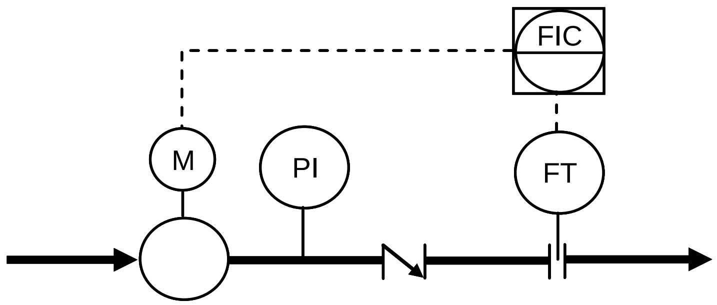


- Alternatively, for a condenser, we can control the coolant supply or the heat transfer surface (by varying the liquid level)
- These methods control pressure by changing the rate of condensation

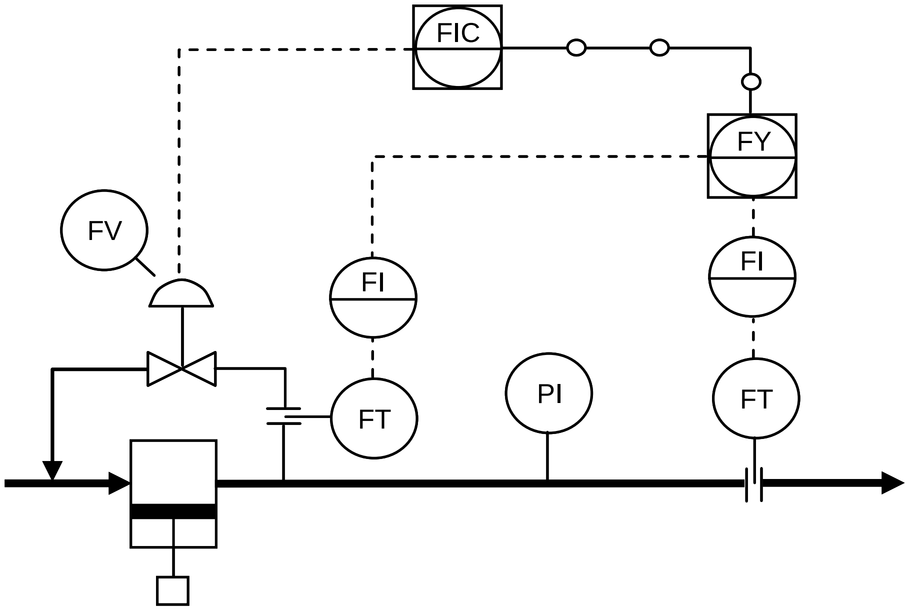
Flow Control

- Most common arrangement is a control valve downstream of a pump or compressor
- Using a variable speed drive is a more efficient method, but higher capital cost



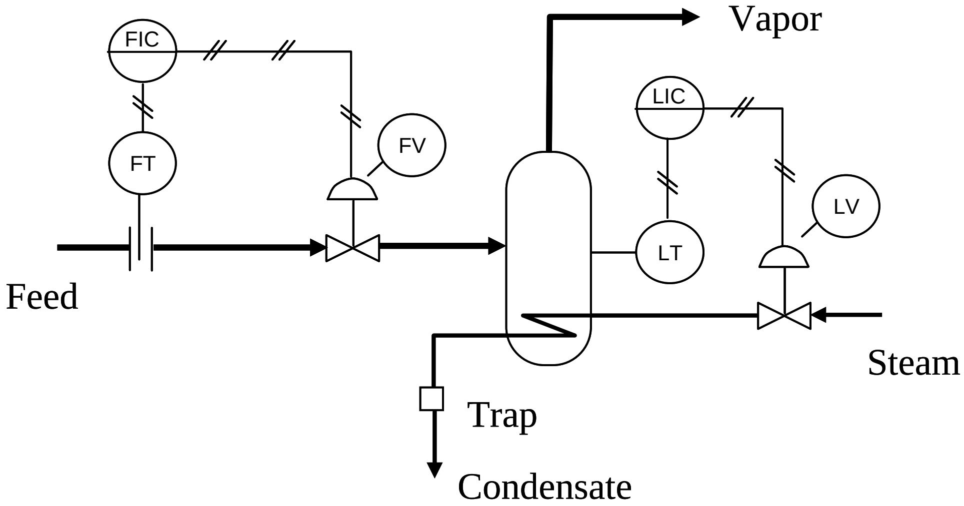


Flow Control: Reciprocating Pump



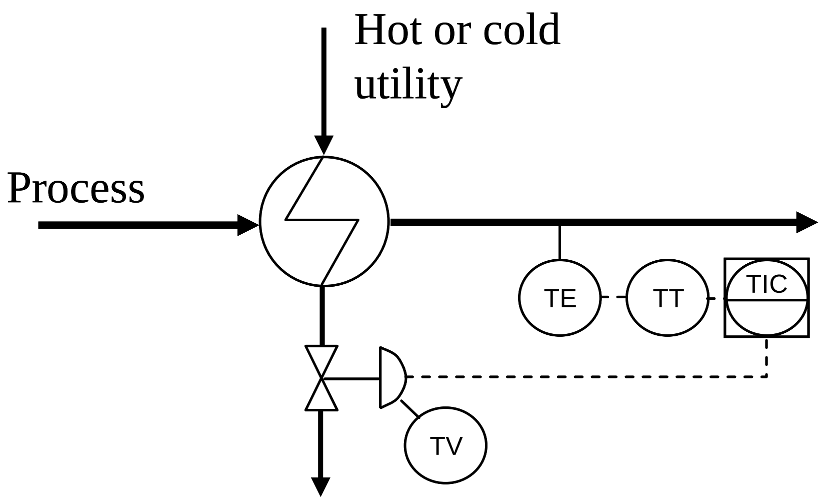
- Reciprocating pumps and compressors and other positive displacement devices deliver constant flow rate
- Flow can be controlled by manipulating a spill-back to the pump feed

Flow Control: Vaporizer



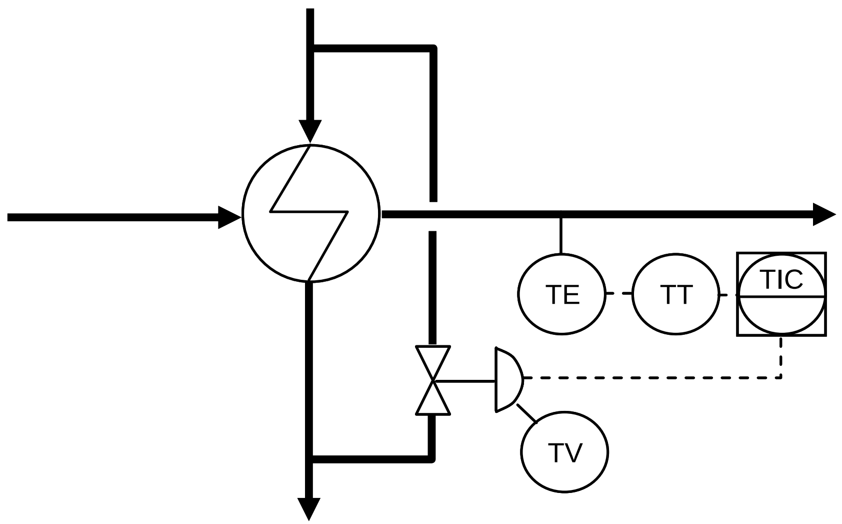
- Vaporizer flow control needs to prevent liquid accumulation
- Hence use level controller to actuate heat input to the vaporizer and maintain a constant inventory
- Control of liquid flow in is easier than control of vapor flow out

Temperature Control: Single Stream



- Heaters and coolers are usually controlled by manipulating the flow rate of the hot or cold utility stream
- Final control element can be on inlet or outlet of utility side

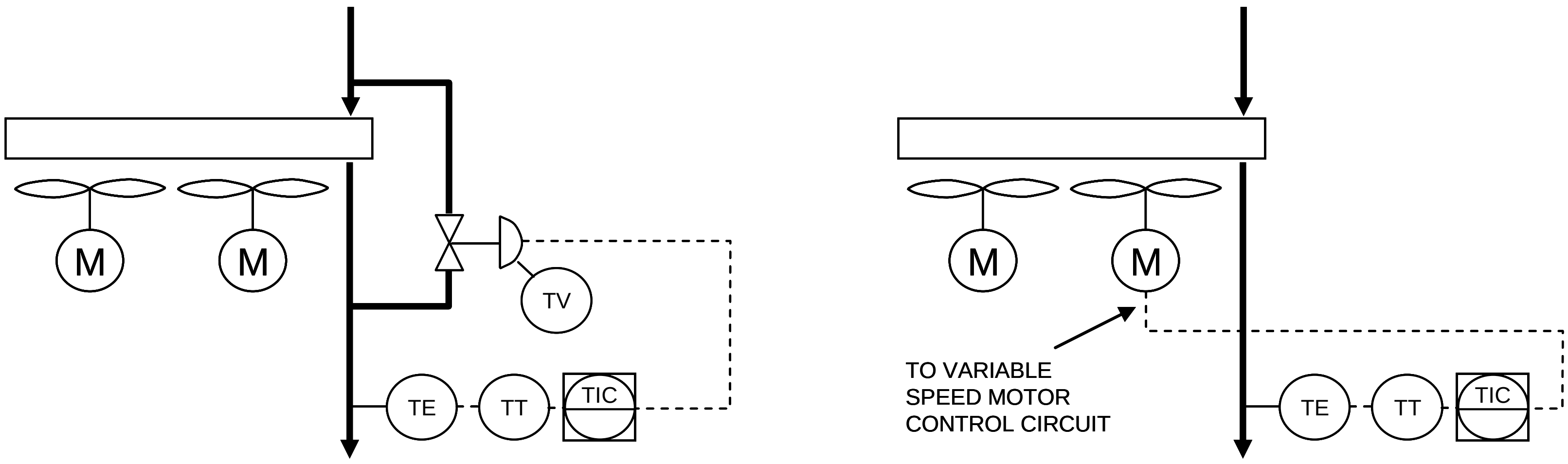
Temperature Control: Heat Exchangers



- Temperature control for an exchanger is usually by manipulating the flow through a bypass
- Only one side of an exchanger can be temperature controlled

- It is also common to see exchangers with no temperature control and have temperature control on the downstream heater and cooler

Temperature Control: Air Coolers

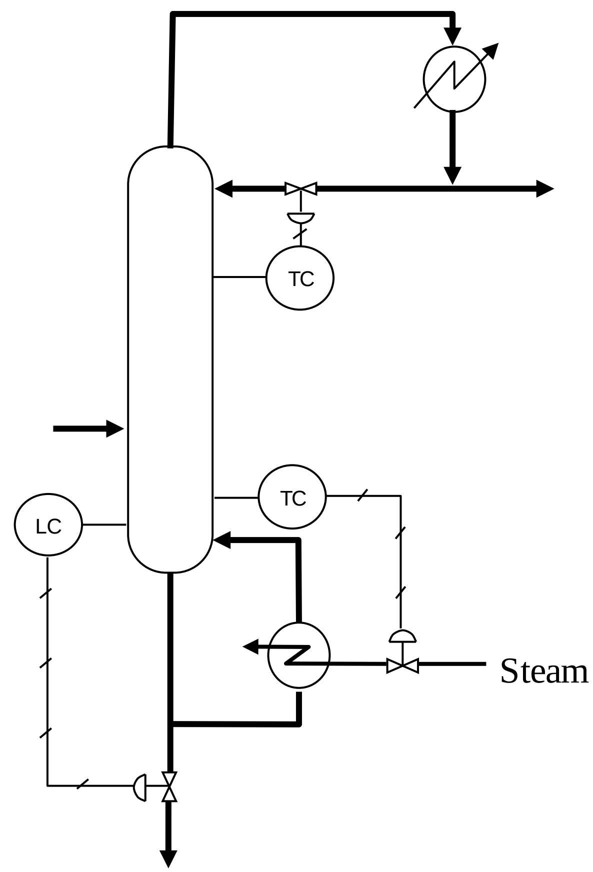


- Ambient air temperature varies, so air coolers are oversized and controlled by manipulating a bypass
- Alternatively, air cooler can use a variable speed motor, louvers or variable pitch fans – see lectures on heat exchange equipment

Distillation Control

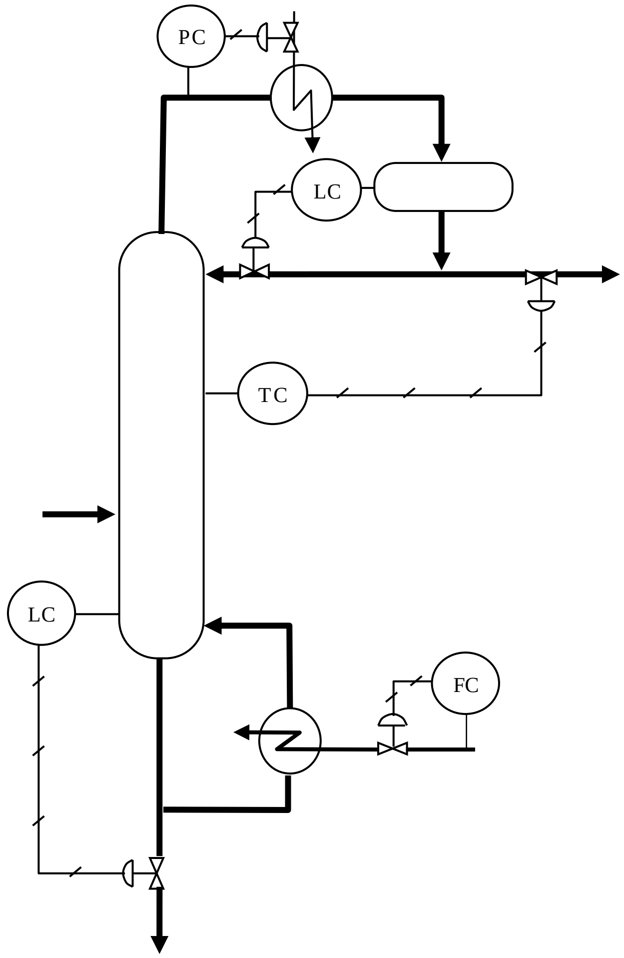
- Distillation control is a specialized subject in its own right
- In addition to controlling condenser pressure and level in the sump, a simple distillation column has two degrees of freedom
  - Material balance (split) and energy balance (heat input or removed)
  - Therefore needs two controllers
  - Therefore has the possibility that the controllers will interact and “fight” each other
- Side streams, intermediate condensers & reboilers, pump-arounds, etc. all add extra complexity and degrees of freedom
- There are several good books on this subject
  - Kister, H.Z., 1989, *Distillation Operation*, McGraw-Hill
  - Luyben, W.L. 2006, *Distillation Design and Control Using Aspen Simulation*, Wiley

Distillation: Temperature Pattern Control



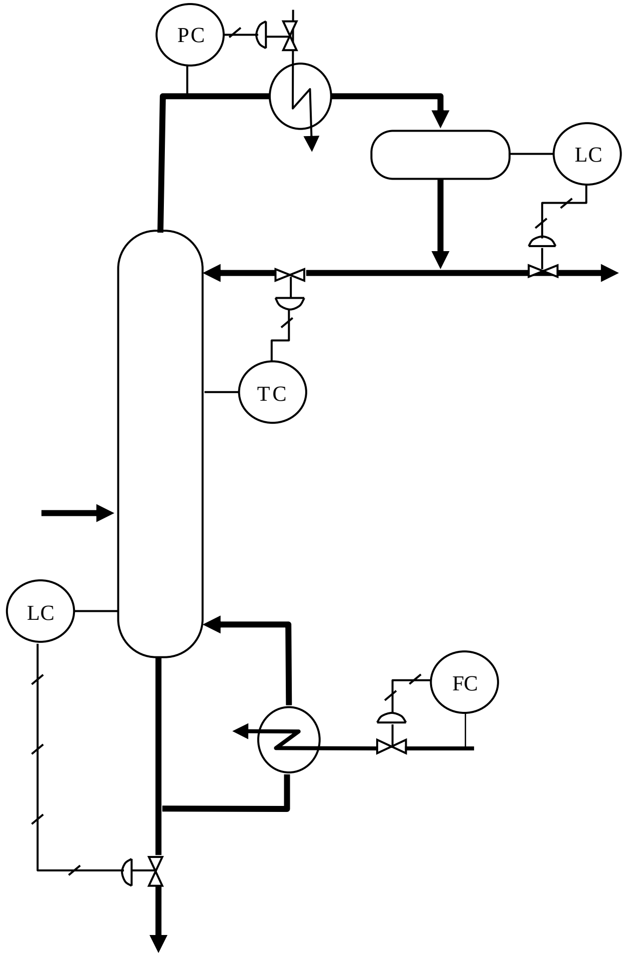
- Tray temperature is used to infer composition
- Composition is used to adjust reflux rate and reboiler heat input
- Tray locations for temperature detectors need to be chosen carefully
- Controllers can fight each other – not a good scheme
- Material balance control schemes are more robust

Distillation: Material Balance Control



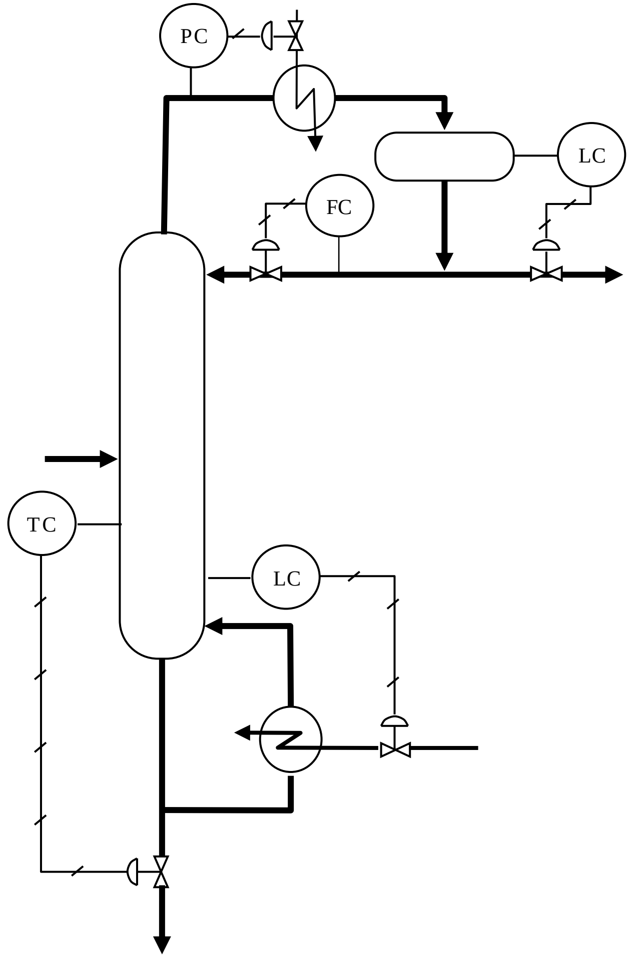
- Direct control of distillate composition by using tray temperature to infer composition and control distillate flow rate
- Flow control on (constant) boil-up rate could be set in ratio to feed if feed flow rate was highly variable

Distillation: Material Balance Control



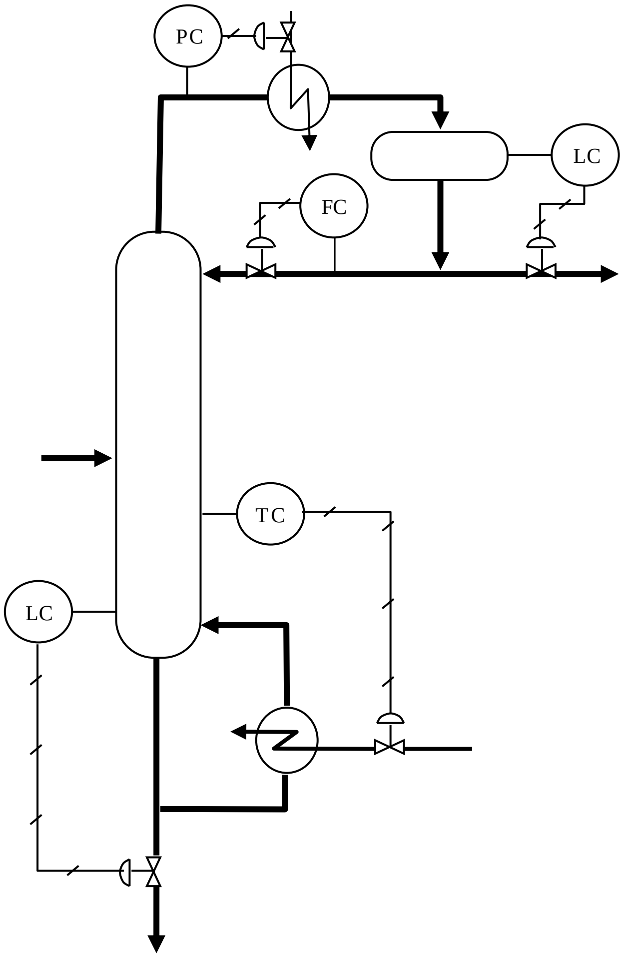
- Indirect control of distillate composition by using tray temperature to infer composition and control reflux rate
- Flow control on (constant) boil-up rate could be set in ratio to feed if feed flow rate varies

Distillation: Material Balance Control



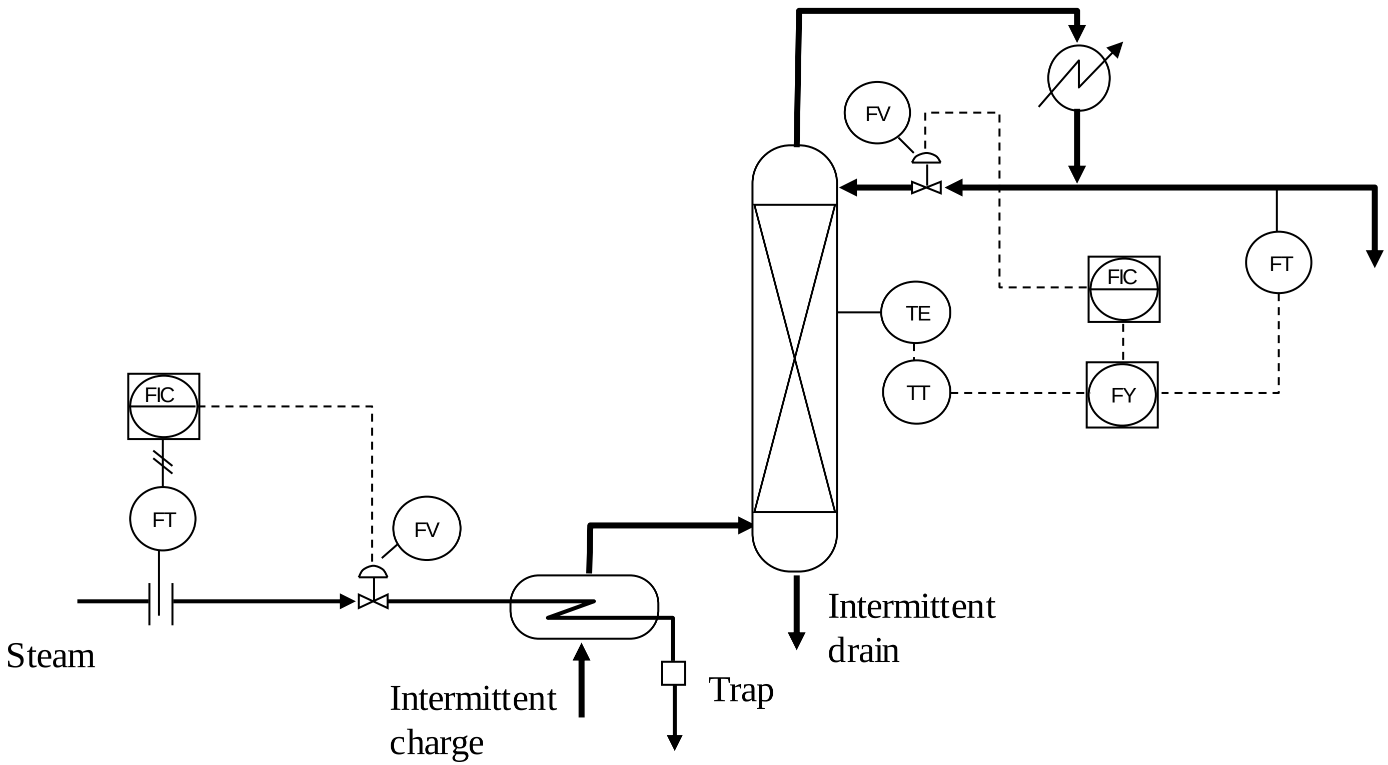
- Direct control of bottoms composition by using tray temperature to infer composition and control bottoms flow rate
- Flow control on (constant) reflux rate could be set in ratio to feed if feed flow rate varies

Distillation: Material Balance Control



- Indirect control of bottoms composition by using tray temperature to infer composition and control boil-up rate
- Flow control on (constant) reflux rate could be set in ratio to feed if feed flow rate varies

Batch Distillation

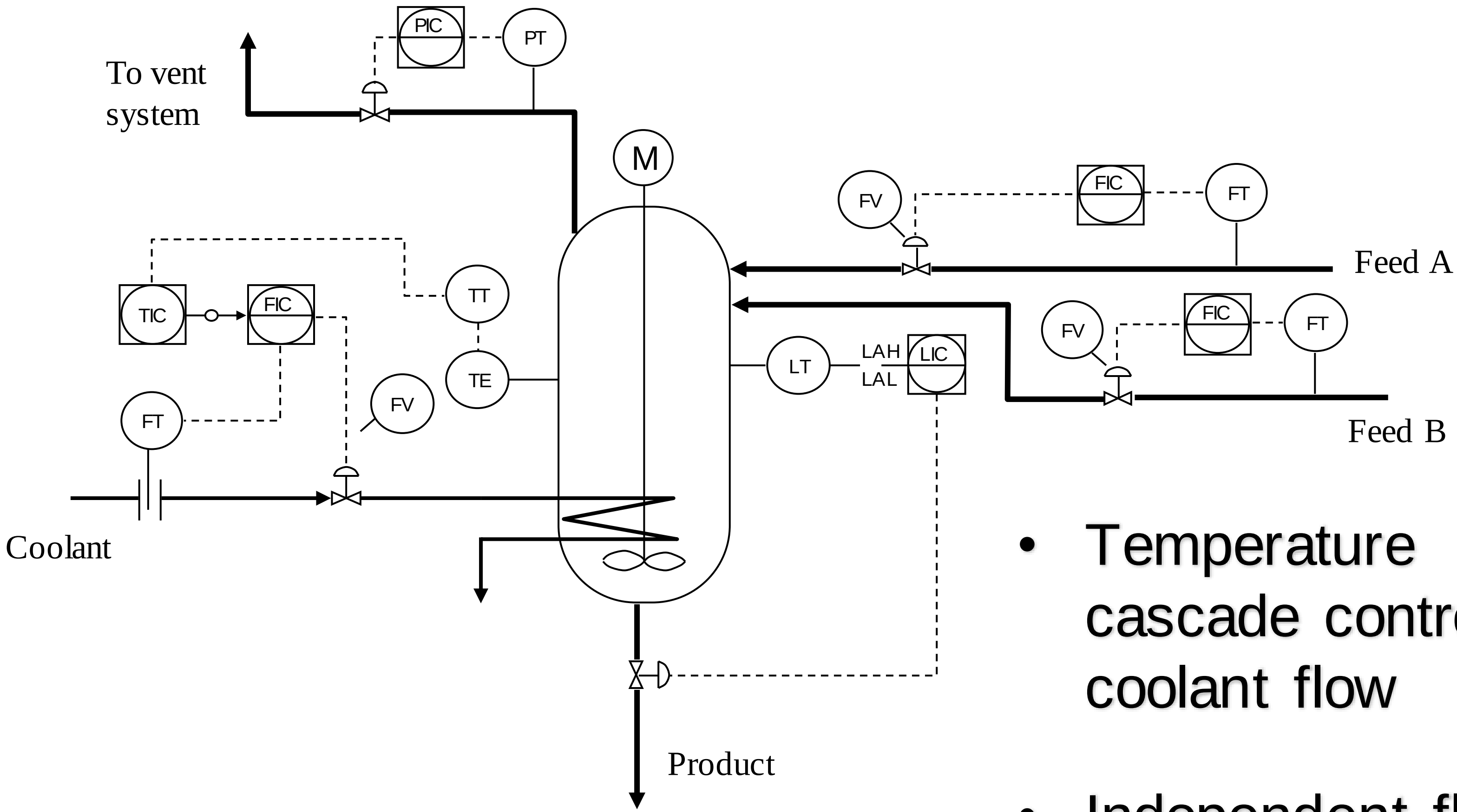


- Reflux flow control adjusted based on temperature (used to infer composition)

Reactor Control

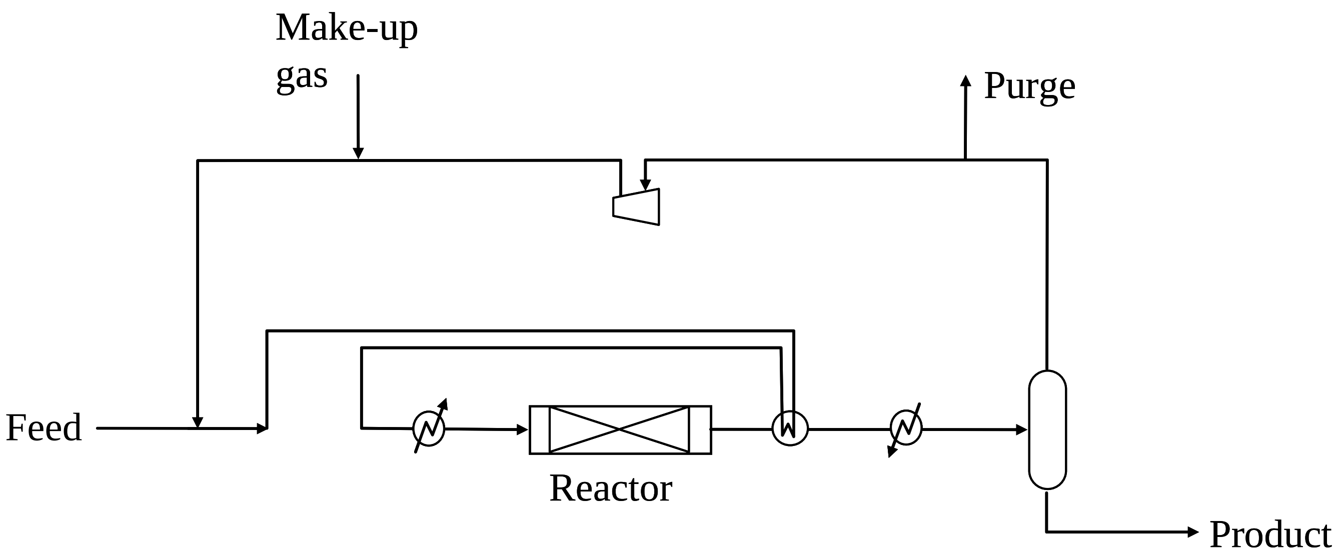
- Control of flow is usually carried out on cold reactor feeds
  - Flows are often ratio controlled to get close to desired stoichiometry or maintain desired excess of one feed
- Pressure control is on reactor vapor outlet or on vent space
- Level control maintains inventory for liquid phase reactors
- Temperature control can be
  - On feeds
  - On heating or cooling jacket
  - On recirculation through external heaters or cooler
  - By controlling flow of quench/reheat streams

Typical Stirred Tank Reactor Control Scheme



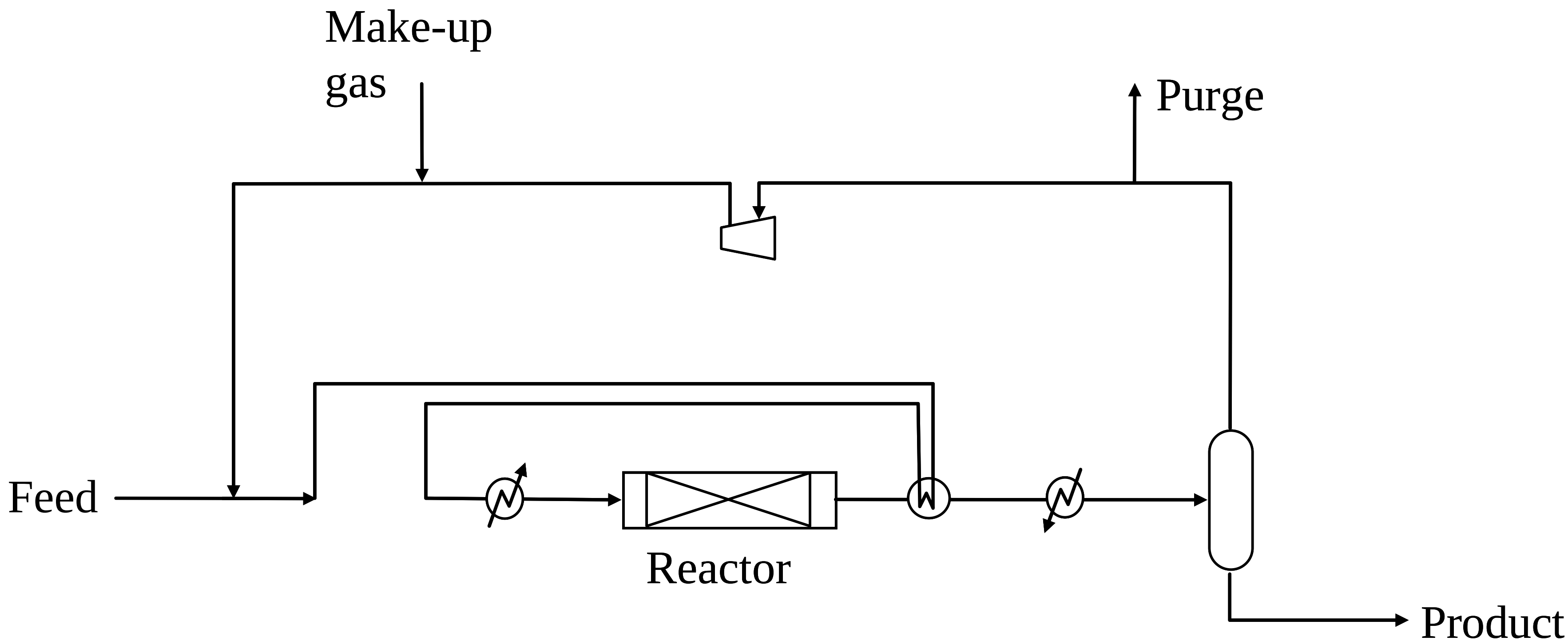
- Temperature cascade control of coolant flow
- Independent flow control of feeds

Exercise: Gas Recycle Process



- Remember the simple flowsheet introduced in the lecture on simulation?
- Liquid feed is mixed with recycle gas, heat exchanged against reactor effluent, heated to reactor temperature then passed over fixed bed of catalyst. Product is cooled and liquid product is recovered. Unconverted gas is recycled with purge to prevent accumulation of inerts

Exercise: Gas Recycle Process



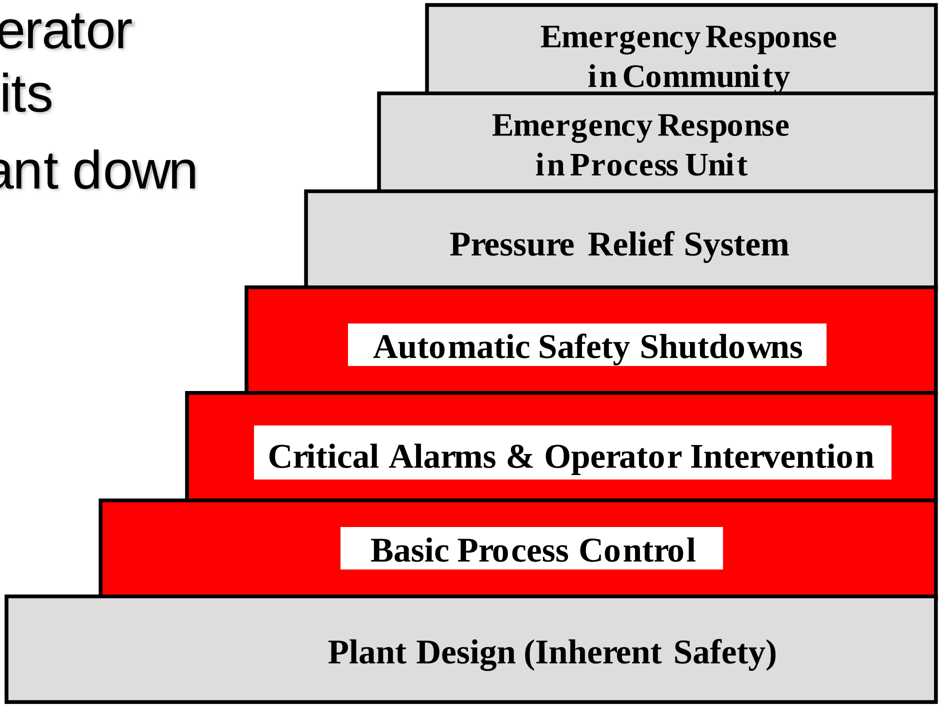
- What controllers would you use?
- Where would you place them?

Process Instrumentation & Control

- Basics of process control
- Process instrumentation
- Reading a P&ID
- Control of unit operations
- **Process safety instrumentation**
- Plant-wide control and optimization

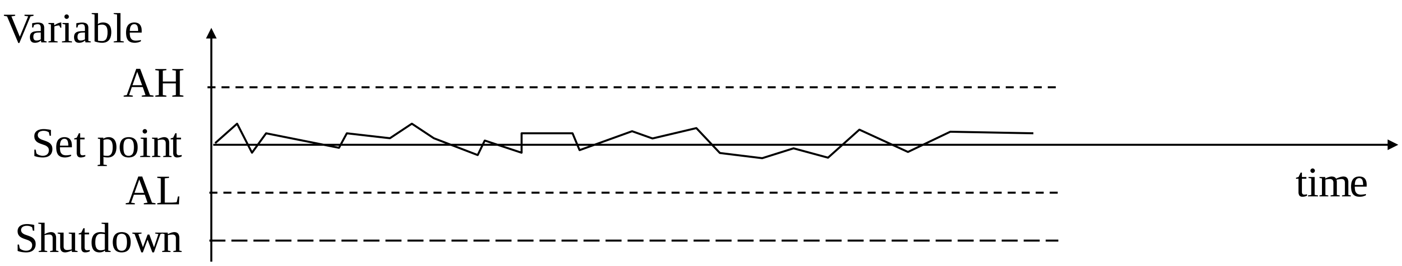
Role of Controls in Process Safety

- Control system is involved in three levels of process safety
  - Keeping plant operation steady
  - Sounding alarms to notify operator when variables are out of limits
  - Automatically shutting the plant down when necessary



Process Control, Alarms and Shutdowns

- Controlled parameters naturally fluctuate around set point



- If the measured variable exceeds a preset limit an alarm should alert the operator to take appropriate action
    - Alarm limits should be set far enough from normal process variation to avoid nuisance alarms
- If the measured variable exceeds a safe operating limit then an automatic plant shutdown may be necessary
    - Shutdown limit should be set far enough from alarm limit that the operator has a chance to respond to the alarm
    - But not so far that no time is left to safely shut the plant down

Standards for Safety Instrumentation

- ISA S84.01 Safety Instrumented Systems
  - U.S. standard for emergency shutdown systems
  - Primary goal is to protect people, not plant or profits
  - ISA S84.01 = IEC 61511
- IEC 61508 & 61511
  - IEC = International Electrotechnical Commission
  - International standards for safety instrumented systems
- Standards define requirements for sensors, solvers (logic), and final elements (valves, switches)
- Consult most recent version of standards for current best practices
- Other standards also recommend best practices for alarm levels, vessel sizing to allow adequate control, etc.

Safety Integrity Levels

- ISA S84.01 defines three levels of safety integrity depending on the availability of the SIS
- Availability = time the system is available / total time
- Safety Integrity Levels

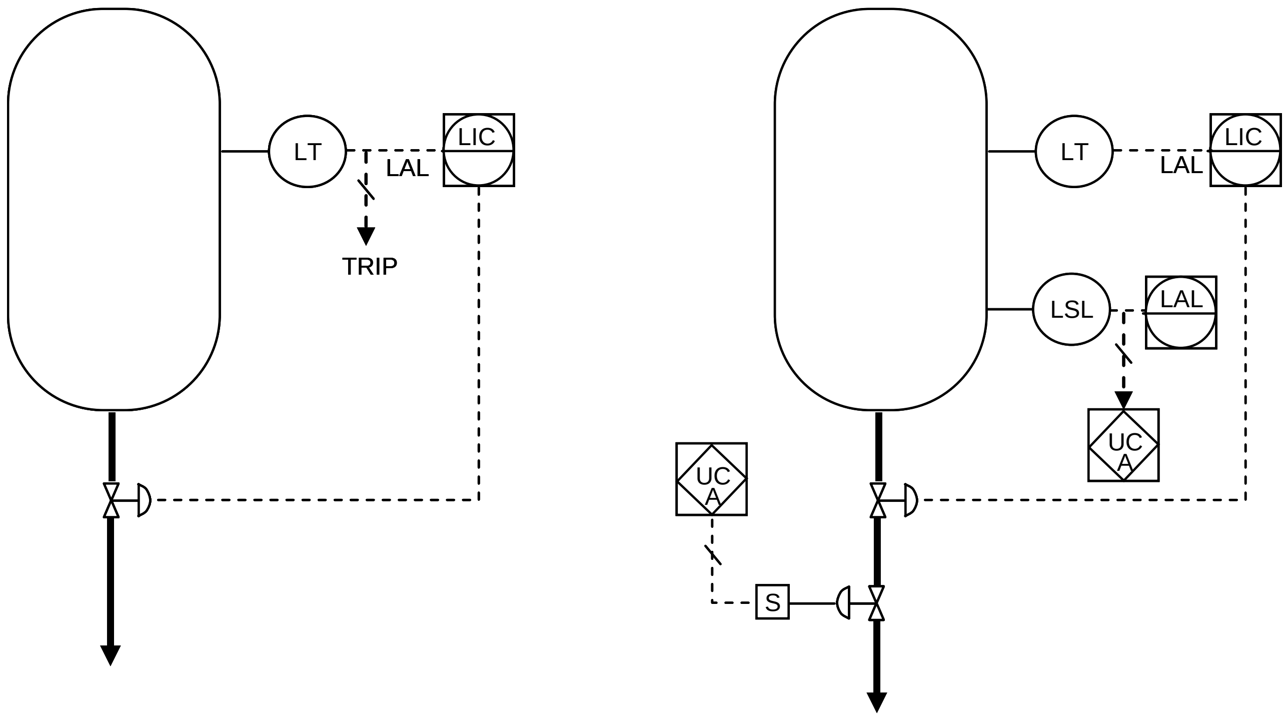
SIL	Availability	System redudancy
– SIL 1	90 – 99%	Non-redundant
– SIL 2	99 – 99.9%	Partially redundant
– SIL 3	99.9 – 99.99%	Totally redundant

- Redundant system means instrumentation is duplicated

Safety Integrity Level

- SIL should be determined during a process hazard analysis (see Ch10 and lectures on process safety)
- SIL required depends on risk of operator exposure and injury
  - Can be calculated using fault trees
  - See Ch10 and later lecture
- SIL determines the type of instrumentation that should be used

Process Alarms and Shutdown Trips



- Software alarms can be set on instruments and controllers through the digital control system and show up on shared displays
- Separate alarm and shutdown instrumentation can also be used, for higher redundancy

Caution on Software Alarms

- There is a temptation to put lots of software alarms in digital control systems
- If there are too many alarms then they can become a distraction to the operators
  - Increasing the chance of human error
  - Increasing the chance that the operator will ignore the alarm, switch it off, or acknowledge it without taking action
  - Increased chance of an "alarm flood"
- Alarms should be carefully placed and calibrated to make sure that they serve the purpose of the designer
- Operators should be trained to understand the importance of every alarm on the plant

Process Instrumentation & Control

- Basics of process control
- Process instrumentation
- Reading a P&ID
- Control of unit operations
- Process safety instrumentation
- **Plant-wide control and optimization**

Plant-Wide Control
(Advanced Process Control, APC)

All new plants and most older plants have the instruments and controllers connected to a plant-wide digital control system (DCS). Using the DCS:

- Operators can update individual controller set points via shared displays
- Plant information systems can log data
- Feedforward and multivariable predictive control can be implemented more easily
- Plant real-time optimization can be implemented through the control system

Most controllers now have microprocessors built into them, so the computational capacity that is needed is not necessarily located in the control room

Plant-Wide Control Issues

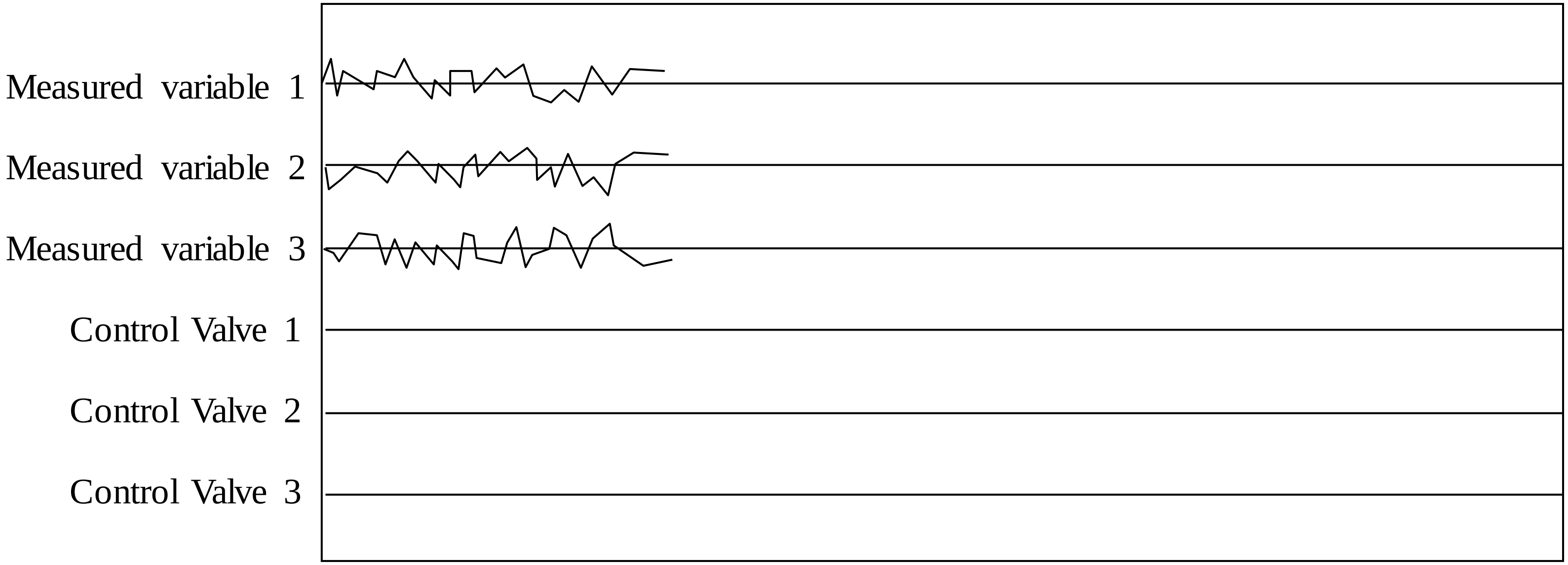
- Where do we control inventories?
  - All vessels that have a liquid level
  - Do we need extra surge volume to keep operations steady?
- Where is the best place to control pressure?
  - Single PC setting plant back-pressure?
  - Need for different pressure levels?
- Where is best place to control material balance?
  - Can only control flow in one place per feed stream
  - Control after removing contaminants?
  - Ratio control?
  - What about recycles?

Plant-Wide Control Issues

- Where is best place to control temperatures?
  - Heaters and coolers only?
  - Control of heat exchanger networks?
- How do we meet product specifications?
  - Use of on-line analytical instruments?
  - Inference through bubble point?
  - Sampling of product storage tank?
- How do we optimize the process?
  - Maximize throughput and product yield while staying on spec?
  - Minimize cost of production?
  - Maximize time on stream between shutdowns?

Multivariable Predictive Control

- What if we have three manipulated variables that interact with each other through non-linear equations?

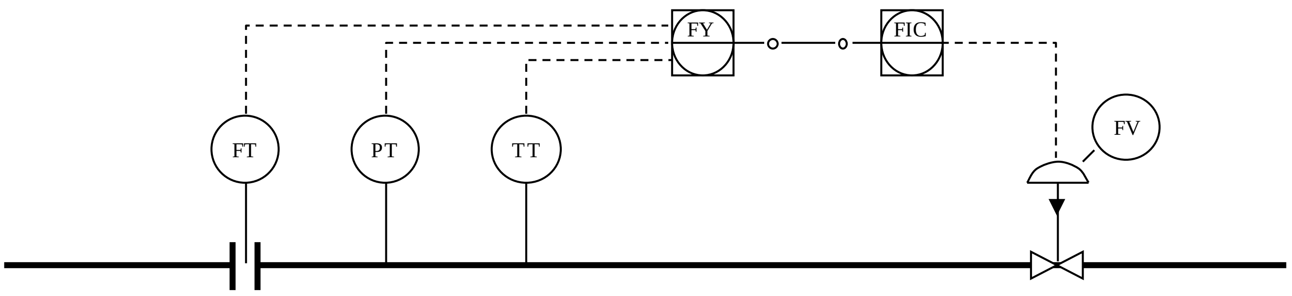


- Single Input Single Output (SISO) controllers will have a hard time responding and will tend to have strong interactions with each other (tendency to fight)

Multivariable Predictive Control

- In this situation, instead of SISO controllers we need a Multiple Input Multiple Output (MIMO) controller
- The controller algorithm is a model that captures the non-linear interaction between the manipulated variables
  - Does **not** have to be a "fundamental" model
  - **Does** have to capture dynamic response
  - Can be tuned from plant operation
- Hence another name for multivariable predictive control is model-based predictive control
- With MIMO devices, there is no longer a direct pairing of measured and manipulated variables as in the earlier unit operations examples

MIMO Example: Gas Mass Flow Controller



- Gas mass flow cannot be measured or controlled directly
- By measuring volume flow, temperature and pressure we can compute mass flow as long as composition is known and steady
    - This is actually MISO, not MIMO, but the FY could talk to another device such as a ratio controller

Device Communication Standards

- Now that individual controllers (and even instruments) contain microprocessors, the computational power of the DCS is distributed
- To make best use of this distributed computation power, the devices need to be able to communicate with each other
- Communication standards are set by ISA, IEC and the controller manufacturers and are currently evolving rapidly

Evolution of Controller Communication Standards

Manual Control
↓
Pneumatic Analog
↓
Electronic Analog
↓
Digital
↓
Fieldbus (ISA SP50)
↓
Wireless (ISA SP100)
↓
?!?!?!?

Source: UOP

Fieldbus (ISA SP50)

- Digital device communication protocol that allows "plug and play" connection of devices
- Requires less wiring and gives greater reliability through redundancy
- Different control companies have variations on the standard, so system compatibility and interoperability are issues

Source: UOP

Wireless Communication (SP100)

Advantages

- No cable runs
- Quicker and cheaper to set up
- Portable control room
- Improved safety (electric cables are easily damaged by fires)

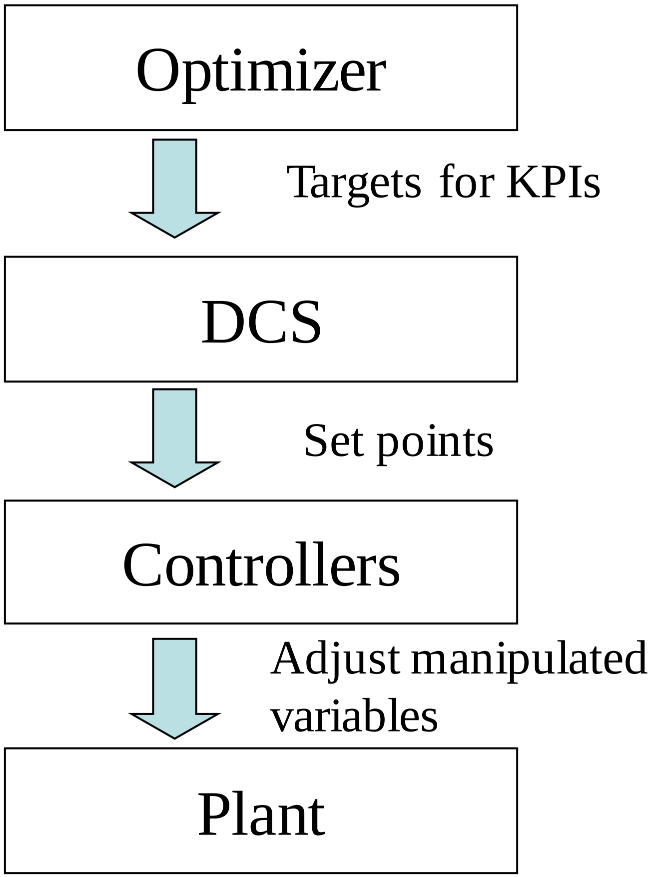
Problems

- Interference from other wireless devices
- Signal blocking due to steelwork
- Signal loss creates need for greater redundancy

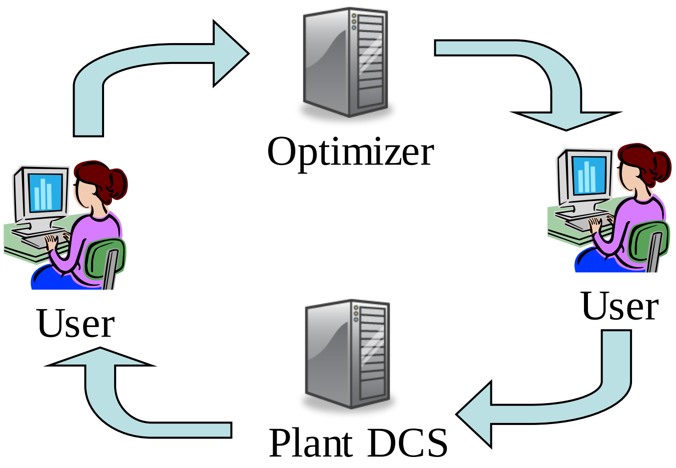
The controls companies are currently putting a lot of effort into developing the devices and standards for implementing wireless control

Real Time Optimization

- A DCS can be programmed to carry out optimization of plant performance by updating controller set points and MPC algorithms
- The optimizer is usually a higher level program that runs less frequently and is used to adjust set points periodically by computing target values for key performance indicators (KPIs)
- The optimizers used for RTO are often not very sophisticated – typically LP, MILP or simple NLP models



Types of Real-time Optimization

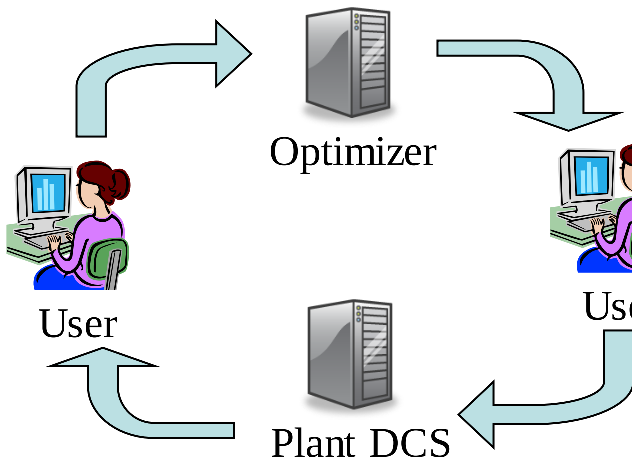


Off-line Optimization

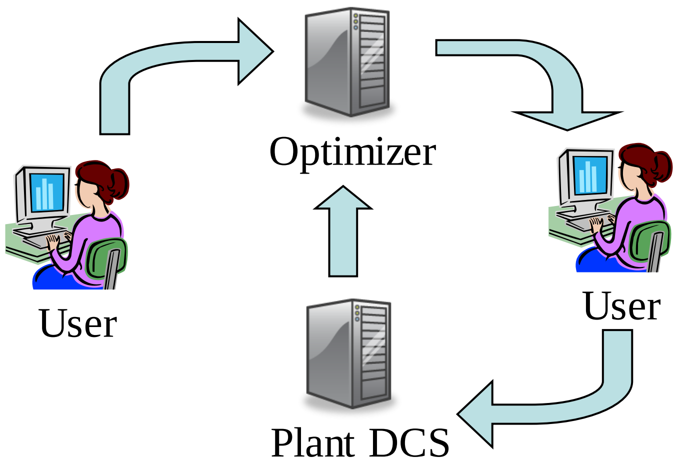
- Users take plant data and run the optimizer then send instructions to the plant operators to update the DCS settings

- Labor intensive and difficult to update more than daily

Types of Real-time Optimization



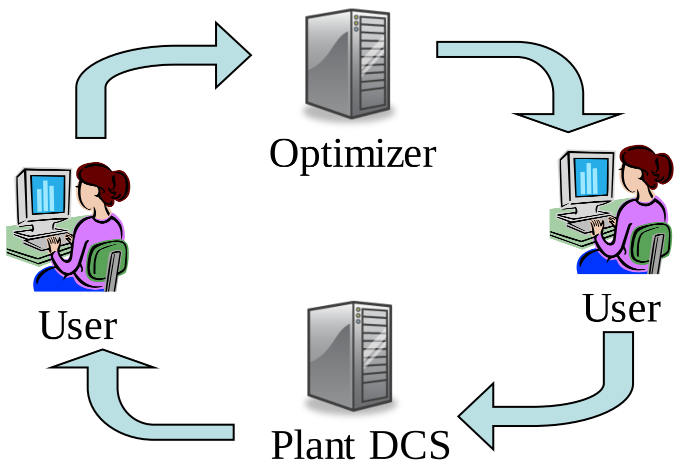
Off-line Optimization



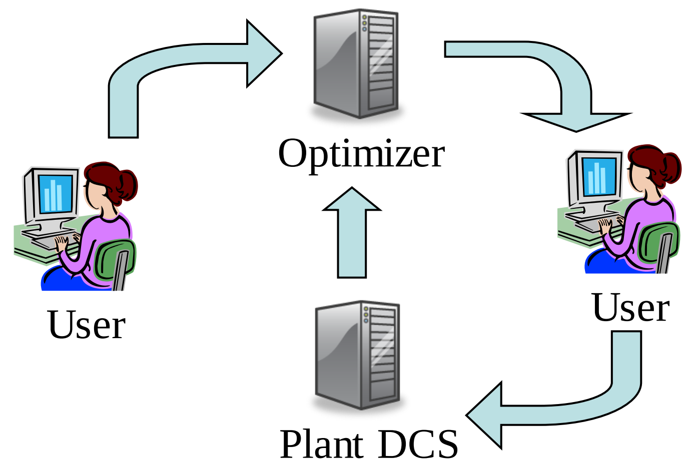
Open Loop On-line Optimization

- Users provide input to optimizer, DCS updates optimizer directly with plant settings and user updates DCS with new targets

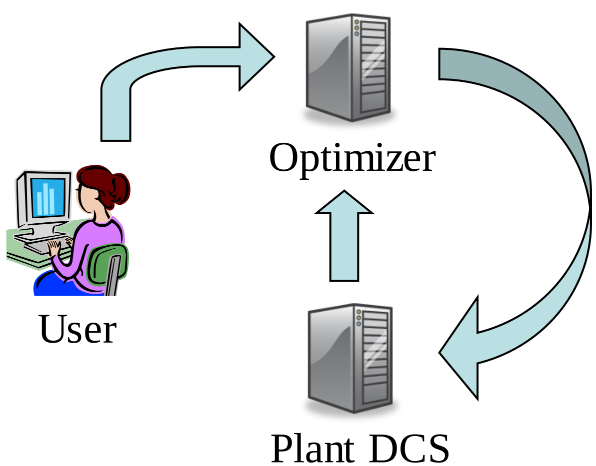
Types of Real-time Optimization



Off-line Optimization



Open Loop On-line Optimization



Closed Loop On-line Optimization

- Users only provide input to the optimizer and the DCS is updated directly by the optimizer

Real Time Optimization Models

- Models and algorithms for RTO have very tough requirements
  - Must be robust, i.e., always find a solution
  - Must solve quickly
  - Must converge to same solution whatever the starting point
  - Must allow for model error
  - Must reconcile data and filter out bad data
  - Must capture plant constraints
  - Must give reasonably good description of plant performance

- Hence frequent use of simple LP models

- Controls companies spend a lot of time setting up and tuning models

Benefits of Advanced Process Control

- See web sites, technical papers or presentations from the major controls vendors
  - Emerson Process Management www.EmersonProcess.com
  - Foxboro www.Foxboro.com
  - Honeywell Automation and Control Systems www.Honeywell.com
  - Yokogawa www.Yokogawa.com/us
- The controls vendors give lots of good examples of recent industrial projects that they have carried out
- Paybacks for installing APC systems are often very good

Questions ?