
Lab

Automatically-controlled process: *Questions 91 and 92*, **completed objectives due by the end of day 5**

Exam

Day 5 – **Complete mastery of these objectives due by the next exam date**

Specific objectives for the "mastery" exam:

- Electricity Review: Calculate voltages, currents, and phase shifts in an AC reactive circuit
- Perform numerical differentiation on a simple mathematical function (graphed)
- Perform numerical integration on a simple mathematical function (graphed)
- Identify the graphed response of a controller as being either P, I, or D; direct or reverse
- Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
- Determine the possibility of suggested faults in a 4-20 mA loop circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Calculate voltages and currents within balanced three-phase AC electrical circuits
- INST241 Review: Determine suitability of different flow-measuring technologies for a given process fluid type
- INST263 Review: Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process

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Recommended daily schedule

Day 1

Theory session topic: Derivative and PID control

Questions 1 through 20; answer questions 1-10 in preparation for discussion (remainder for practice)

Day 2

Theory session topic: Different PID control algorithms

Questions 21 through 40; answer questions 21-29 in preparation for discussion (remainder for practice)

Day 3

Theory session topic: Digital implementations of PID control

Questions 41 through 60; answer questions 41-49 in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Review for exam **or** Lab Day (instructor's choice)

Questions 61 through 80; answer questions 61-67 in preparation for discussion (remainder for practice)

Feedback questions *(81 through 90)* are optional and may be submitted for review at the end of the day

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Day 5

Exam

How To . . .

Access the worksheets and textbook: go to the *Socratic Instrumentation* website located at `http://www.ibiblio.org/kuphaldt/socratic/sinst` to find worksheets for every 2nd-year course section organized by quarter, as well as both the latest "stable" and "development" versions of the *Lessons In Industrial Instrumentation* textbook. Download and save these documents to your computer.

Maximize your learning: complete all homework *before* class starts, ready to be assessed as described in the "Inverted Session Formats" pages. Use every minute of class and lab time productively. Follow all the tips outlined in "Question 0" as well as your instructor's advice. Do not take constructive criticism personally. Make every reasonable effort to solve problems on your own before seeking help.

Identify upcoming assignments and deadlines: read the first page of each course worksheet.

Relate course days to calendar dates: reference the calendar spreadsheet file (`calendar.xlsx`), found on the BTC campus `Y:` network drive. A printed copy is posted in the Instrumentation classroom.

Locate industry documents assigned for reading: use the Instrumentation Reference provided by your instructor (on CD-ROM and on the BTC campus `Y:` network drive). There you will find a file named `00_index_OPEN_THIS_FILE.html` readable with any internet browser. Click on the "Quick-Start Links" to access assigned reading documents, organized per course, in the order they are assigned.

Study for the exams: Mastery exams assess specific skills critically important to your success, listed near the top of the front page of each course worksheet for your review. Familiarize yourself with this list and pay close attention when those topics appear in homework and practice problems. Proportional exams feature problems you haven't seen before that are solvable using general principles learned throughout the current and previous courses, for which the only adequate preparation is independent problem-solving practice every day. Answer the "feedback questions" (practice exams) in each course section to hone your problem-solving skills, as these are similar in scope and complexity to proportional exams. Answer these feedback independently (i.e. no help from classmates) in order to most accurately assess your readiness.

Calculate course grades: download the "Course Grading Spreadsheet" (`grades_template.xlsx`) from the Socratic Instrumentation website, or from the BTC campus `Y:` network drive. Enter your quiz scores, test scores, lab scores, and attendance data into this Excel spreadsheet and it will calculate your course grade. You may compare your calculated grades against your instructors' records at any time.

Identify courses to register for: read the "Sequence" page found in each worksheet.

Receive extra instructor help: ask during lab time, or during class time, or by appointment. Tony may be reached by email at `tony.kuphaldt@btc.edu` or by telephone at 360-752-8477.

Identify job openings: regularly monitor job-search websites. Set up informational interviews at workplaces you are interested in. Participate in jobshadows and internships. Apply to jobs long before graduation, as some employers take *months* to respond! Check your BTC email account daily for alerts.

Impress employers: sign the FERPA release form granting your instructors permission to share academic records, then make sure your performance is worth sharing. Document your project and problem-solving experiences for reference during interviews. Honor all your commitments.

Begin your career: participate in jobshadows and internships while in school to gain experience and references. Take the first Instrumentation job that pays the bills, and give that employer at least two years of good work to pay them back for the investment they have made in you. Employers look at delayed employment, as well as short employment spans, very negatively. Failure to pass a drug test is an immediate disqualifier, as is falsifying any information. Criminal records may also be a problem.

file `howto`

General Values, Expectations, and Standards

Success in this career requires professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. If you are ever in doubt as to the values you should embody, just ask yourself what kind of a person you would prefer to hire for your own enterprise. Those same values will be upheld within this program.

Learning is the purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here will be treated as a learning opportunity, every mistake as a "teachable moment". Every form of positive growth, not just academic ability, will be regarded as real learning.

Responsibility means *ensuring* the desired outcome, not just *trying* to achieve the outcome. To be a responsible person means you *own* the outcome of your decisions and actions.

Integrity means being honest and forthright in all your words and actions, doing your very best every time and never taking credit for the achievement of another.

Safety means doing every job correctly and ensuring others are not endangered. Lab safety standards include wearing closed-toed shoes and safety glasses in the lab room during lab hours, wearing ear protection around loud sounds, using ladders to reach high places, using proper lock-out/tag-out procedures, no energized electrical work above 30 volts without an instructor present in the lab room, and no power tool use without an instructor present in the lab room.

Diligence in study means exercising self-discipline and persistence, realizing that hard work is a necessary condition for success. This means, among other things, investing the necessary time and effort in studying, reading instructions, paying attention to details, utilizing the skills and tools you already possess, and avoiding shortcuts. Diligence in work means the job is not done until it is done *correctly*: all objectives achieved, all problems solved, all documentation complete, and no errors remaining.

Self-management means allocating your resources (time, equipment, labor) wisely, and not just focusing on the closest deadline.

Communication means clearly conveying your thoughts and paying attention to what others convey, across all forms of communication (e.g. oral, written, nonverbal).

Teamwork means working constructively with your classmates to complete the job at hand. Remember that here the first job is *learning*, and so teamwork means working to maximize everyone's learning (not just your own). The goal of learning is more important than the completion of any project or assignment.

Initiative means recognizing needs and taking action to meet those needs without encouragement or direction from others.

Representation means your actions reflect this program and not just yourself. Doors of opportunity for all BTC graduates may be opened or closed by your own conduct. Unprofessional behavior during tours, jobshadows, internships, and/or jobs reflects poorly on the program and will negatively bias employers.

Trustworthiness is the result of consistently exercising these values: people will recognize you as someone they can rely on to get the job done, and therefore someone they would want to employ.

Respect means acknowledging the intrinsic value, capabilities, and responsibilities of those around you. Respect is gained by consistent demonstration of valued behaviors, and it is lost through betrayal of trust.

<u>Punctuality and Attendance:</u> late arrivals are penalized at a rate of 1% grade deduction per incident. Absence is penalized at a rate of 1% per hour (rounded to the nearest hour) except when employment-related, school-related, weather-related, or required by law (e.g. court summons). Absences may be made up by directing the instructor to apply "sick hours" (12 hours of sick time available per quarter). Classmates may donate their unused sick hours. Sick hours may not be applied to unannounced absences, so be sure to alert your instructor and teammates as soon as you know you will be absent or late. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

<u>Mastery:</u> any assignment or objective labeled as "mastery" must be completed with 100% competence (with multiple opportunities to re-try). Failure to complete by the deadline date caps your grade at a C−. Failure to complete by the end of the *next* school day results in a failing (F) grade for that course.

<u>Time Management:</u> Use all available time wisely and productively. Work on other useful tasks (e.g. homework, feedback questions, job searching) while waiting for other activities or assessments to begin. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

<u>Orderliness:</u> Keep your work area clean and orderly, discarding trash, returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. Project wiring, especially in shared areas such as junction boxes, must not be left in disarray at the end of a lab shift. Label any failed equipment with a detailed description of its symptoms.

<u>Independent Study:</u> the "inverted" instructional model used in this program requires independent reading and problem-solving, where every student must demonstrate their learning at the start of the class session. Question 0 of every worksheet lists practical study tips. The "Inverted Session Formats" pages found in every worksheet outline the format and grading standards for inverted class sessions.

<u>Independent Problem-Solving:</u> make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given unless and until you run your own diagnostic tests.

<u>Teamwork:</u> inform your teammates if you need to leave the work area for any reason. Any student regularly compromising team performance through absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually. The same is true for students found inappropriately relying on teammates.

<u>Communication:</u> check your email daily for important messages. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly.

<u>Academic Progress:</u> your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers if you sign the FERPA release form. You may see these records at any time, and you should track your own academic progress using the grade spreadsheet template. Extra-credit projects will be tailored to your learning needs.

<u>Office Hours:</u> your instructor's office hours are by appointment, except in cases of emergency. Email is the preferred method for setting up an appointment with your instructor to discuss something in private.

<u>Grounds for Failure:</u> a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, or for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another's work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

file `expectations`

Program Outcomes for Instrumentation and Control Technology (BTC)

#1 | Communication

Communicate and express concepts and ideas across a variety of media (verbal, written, graphical) using industry-standard terms.

#2 | Time management

Arrives on time and prepared to work; Budgets time and meets deadlines when performing tasks and projects.

#3 | Safety

Complies with national, state, local, and college safety regulations when designing and performing work on systems.

#4 | Analysis and Diagnosis

Analyze, evaluate, and diagnose systems related to instrumentation and control including electrical and electronic circuits, fluid power and signaling systems, computer networks, and mechanisms; Select and apply correct mathematical techniques to these analytical and diagnostic problems; Select and correctly use appropriate test equipment to collect data.

#5 | Design and Commissioning

Select, design, construct, configure, and install components necessary for the proper function of systems related to instrumentation and control, applying industry standards and verifying correct system operation when complete.

#6 | System optimization

Improve technical system functions by collecting data and evaluating performance; Implement strategies to optimize the function of these systems.

#7 | Calibration

Assess instrument accuracy and correct inaccuracies using appropriate calibration procedures and test equipment; Select and apply correct mathematical techniques to these calibration tasks.

#8 | Documentation

Interpret and create technical documents (e.g. electronic schematics, loop diagrams, functional diagrams, P&IDs, graphs, narratives) according to industry standards.

#9 | Independent learning

Select and research information sources to learn new principles, technologies, and techniques.

#10 | Job searching

Develop a professional resume and research job openings in the field of industrial instrumentation.

file `outcomes_program`

Each and every outcome in this course is assessed at a mastery level (i.e. 100% competence)

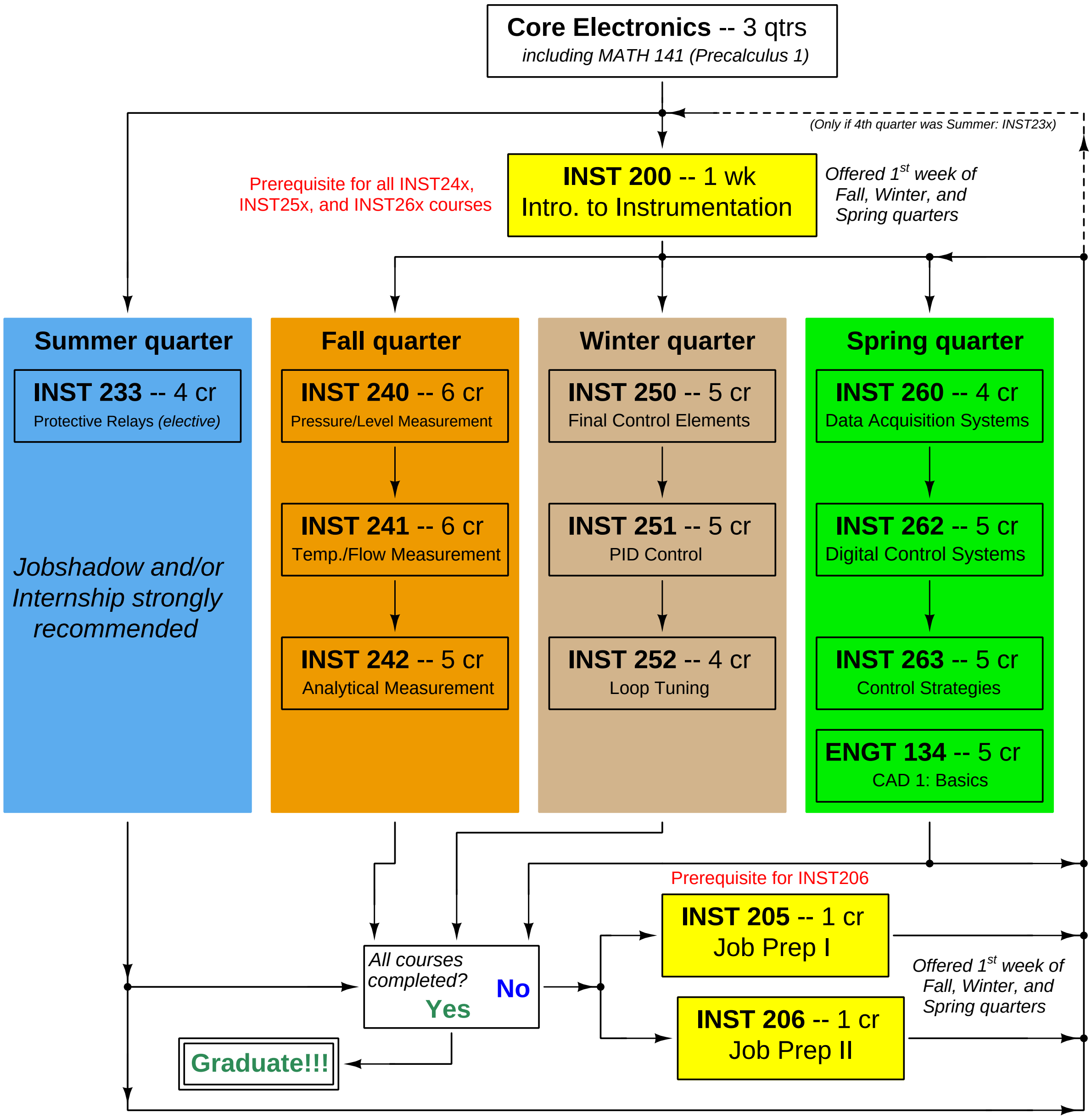
- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]
- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]
- Predict the response of an automatic control system to a component faults or process change, given pictorial and/or schematic illustrations. [Ref: Program Learning Outcome #4]
- Determine the effect of a component change on the gain of a pneumatic controller mechanism. [Ref: Program Learning Outcome #4]
- Compute the value of the numerical derivative at a single specified point on a graph. [Ref: Program Learning Outcome #4]
- Compute the value of the numerical integral over a specified interval on a graph. [Ref: Program Learning Outcome #4]
- Identify the response of a loop controller as being either P, I, or D based on a comparison of process variable, setpoint, and output trend graph recordings. [Ref: Program Learning Outcome #6]
- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]
- Determine the possibility of suggested faults in simple circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]
- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all lab work. [Ref: Program Learning Outcomes #1 and #2]
- Construct and commission a hand control loop using a pneumatic controller and pair of split-ranged pneumatic control valves. [Ref: Program Learning Outcome #5]
- Connect a loop controller to the electronic transmitter and final control element of a pre-constructed process, then commission all components to form a working feedback control loop. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team's control systems. [Ref: Program Learning Outcome #8]
- Adjust the PID settings of your team's control loop for stable operating behavior. [Ref: Program Learning Outcome #6]
- Wire and program a VFD (Variable Frequency motor Drive) for remote starting and stopping of an AC induction motor using pushbutton switches, measuring motor line current with a clamp-on ammeter. [Ref: Program Learning Outcome #5]
- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly

annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Diagnose a random fault simulated by computer in a 4-20 transmitter circuit, logically justifying your steps before an instructor. [Ref: Program Learning Outcome #4]

file `outcomes_INST251`

Sequence of second-year Instrumentation courses



The particular sequence of courses you take during the second year depends on when you complete all first-year courses and enter the second year. Since students enter the second year of Instrumentation at four different times (beginnings of Summer, Fall, Winter, and Spring quarters), the particular course sequence for any student will likely be different from the course sequence of classmates.

Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students, depending on when they first enter the second year of the program:

file sequence

General tool and supply list

Wrenches

- Combination (box- and open-end) wrench set, 1/4" to 3/4" – *the most important wrench sizes are 7/16", 1/2", 9/16", and 5/8"; get these immediately!*
- Adjustable wrench, 6" handle (sometimes called "Crescent" wrench)
- Hex wrench ("Allen" wrench) set, fractional – 1/16" to 3/8"
- *Optional:* Hex wrench ("Allen" wrench) set, metric – 1.5 mm to 10 mm
- *Optional:* Miniature combination wrench set, 3/32" to 1/4" (sometimes called an "ignition wrench" set)

Note: *always maximize surface engagement on a fastener's head to reduce stress on that fastener. (e.g. Using box-end wrenches instead of adjustable wrenches; using the proper size and type of screwdriver; never using any tool that mars the fastener such as pliers or vise-grips unless absolutely necessary.)*

Pliers

- Needle-nose pliers
- Diagonal wire cutters (sometimes called "dikes")

Screwdrivers

- Slotted, 1/8" and 1/4" shaft
- Phillips, #1 and #2
- Jeweler's screwdriver set
- *Optional:* Magnetic multi-bit screwdriver (e.g. Klein Tools model 70035)

Electrical

- Multimeter, Fluke model 87-IV or better
- Assortment of alligator-clip style jumper wires
- Soldering iron (10 to 40 watt) and rosin-core solder
- Resistor, potentiometer, diode assortments (from first-year lab kits)
- Package of insulated compression-style fork terminals (14 to 18 AWG wire size, #10 stud size)
- Wire strippers/terminal crimpers for 10 AWG to 18 AWG wire and insulated terminals
- *Optional:* ratcheting terminal crimp tool (e.g. Paladin 1305, Ferrules Direct FDT10011, or equivalent)

Safety

- Safety glasses or goggles (available at BTC bookstore)
- Earplugs (available at BTC bookstore)

Miscellaneous

- Simple scientific calculator (non-programmable, non-graphing, no conversions), TI-30Xa or TI-30XIIS recommended. Required for some exams!
- Portable personal computer capable of wired Ethernet connectivity, Wi-Fi connectivity, displaying PDF documents, creating text documents, creating and viewing spreadsheets, running PLC programming software (MS Windows only), and executing command-line utilities such as `ping`.
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

file `tools`

Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*. All "theory" sessions follow the *inverted* format and contain virtually no lecture.

Inverted theory sessions

The basic concept of an "inverted" learning environment is that the traditional allocations of student time are reversed: instead of students attending an instructor-led session to receive new information and then practicing the application of that information outside of the classroom in the form of homework, students in an inverted class encounter new information outside of the classroom via homework and apply that information in the classroom session under the instructor's tutelage.

A natural question for instructors, then, is what their precise role is in an inverted classroom and how to organize that time well. Here I will list alternate formats suitable for an inverted classroom session, each of them tested and proven to work.

Small sessions

Students meet with instructors in small groups for short time periods. Groups of 4 students meeting for 30 minutes works very well, but groups as large as 8 students apiece may be used if time is limited. Each of these sessions begins with a 5 to 10 minute graded inspection of homework with individual questioning, to keep students accountable for doing the homework. The remainder of the session is a dialogue focusing on the topics of the day, the instructor challenging each student on the subject matter in Socratic fashion, and also answering students' questions. A second grade measures each student's comprehension of the subject matter by the end of the session.

This format also works via teleconferencing, for students unable to attend a face-to-face session on campus.

Large sessions

Students meet with instructors in a standard classroom (normal class size and period length). Each of these sessions begins with a 10 minute graded quiz (closed-book) on the homework topic(s), to keep students accountable for doing the homework. Students may leave the session as soon as they "check off" with the instructor in a Socratic dialogue as described above (instructor challenging each student to assess their comprehension, answering questions, and grading the responses). Students sign up for check-off on the whiteboard when they are ready, typically in groups of no more than 4. Alternatively, the bulk of the class session may be spent answering student questions in small groups, followed by another graded quiz at the end.

Correspondence

This format works for students unable to attend a "face-to-face" session, and who must correspond with the instructor via email or other asynchronous medium. Each student submits a thorough presentation of their completed homework, which the instructor grades for completeness and accuracy. The instructor then replies back to the student with challenge questions, and also answers questions the student may have. As with the previous formats, the student receives another grade assessing their comprehension of the subject matter by the close of the correspondence dialogue.

In all formats, students are held accountable for completion of their homework, "completion" being defined as successfully interpreting the given information from source material (e.g. accurate outlines of reading or video assignments) and constructive effort to solve given problems. It must be understood in an inverted learning environment that students *will* have legitimate questions following a homework assignment, and that it is therefore unreasonable to expect mastery of the assigned subject matter. What is reasonable to expect from each and every student is a basic outline of the source material (reading or video assignments) complete with major terms defined and major concepts identified, plus a good-faith effort to solve every problem. Question 0 (contained in every worksheet) lists multiple strategies for effective study and problem-solving.

Sample rubric for pre-assessments

- **No credit** = Any homework question unattempted (i.e. no effort shown on one or more questions); incomprehensible writing; failure to follow clear instruction(s)
- **Half credit** = Misconception(s) on any major topic explained in the assigned reading; answers shown with no supporting work; verbatim copying of text rather than written in student's own words; outline missing important topic(s); unable to explain the outline or solution methods represented in written work
- **Full credit** = Every homework question answered, with any points of confusion clearly articulated; all important concepts from reading assignments accurately expressed in the outline and clearly articulated when called upon by the instructor to explain

The minimum expectation at the start of every student-instructor session is that all students have made a good-faith effort to complete 100% of their assigned homework. This does not necessarily mean all answers will be correct, or that all concepts are fully understood, because one of the purposes of the meeting between students and instructor is to correct remaining misconceptions and answer students' questions. However, experience has shown that without accountability for the homework, a substantial number of students will not put forth their best effort and that this compromises the whole learning process. Full credit is reserved for good-faith effort, where each student thoughtfully applies the study and problem-solving recommendations given to them (see Question 0).

Sample rubric for post-assessments

- **No credit** = Failure to comprehend one or more key concepts; failure to apply logical reasoning to the solution of problem(s); no contribution to the dialogue
- **Half credit** = Some misconceptions persist by the close of the session; problem-solving is inconsistent; limited contribution to the dialogue
- **Full credit** = Socratic queries answered thoughtfully; effective reasoning applied to problems; ideas communicated clearly and accurately; responds intelligently to questions and statements made by others in the session; adds new ideas and perspectives

The minimum expectation is that each and every student engages with the instructor and with fellow students during the Socratic session: posing intelligent questions of their own, explaining their reasoning when challenged, and otherwise positively contributing to the discussion. Passive observation and listening is not an option here – every student must be an active participant, contributing something original to every dialogue. If a student is confused about any concept or solution, it is their responsibility to ask questions and seek resolution.

Methods of instruction (continued)

If a student happens to be absent for a scheduled class session and is therefore unable to be assessed on that day's study, they may schedule a time with the instructor to demonstrate their comprehension at some later date (before the end of the quarter when grades must be submitted). These same standards of performance apply equally make-up assessments: either inspection of homework or a closed-book quiz for the pre-assessment, and either a Socratic dialogue with the instructor or another closed-book quiz for the post-assessment.

Methods of instruction (continued)

Lab sessions

In the lab portion of each course, students work in teams to install, configure, document, calibrate, and troubleshoot working instrument loop systems. Each lab exercise focuses on a different type of instrument, with a limited time period typically for completion. An ordinary lab session might look like this:

(1) Start of practical (lab) session: announcements and planning
  (a) The instructor makes general announcements to all students
  (b) The instructor works with team to plan that day's goals, making sure each team member has a clear idea of what they should accomplish
(2) Teams work on lab unit completion according to recommended schedule:
  (First day) Select and bench-test instrument(s), complete prototype sketch of project
  (One day) Connect instrument(s) into a complete loop
  (One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
  (One or two days) Each team member calibrates/configures the instrument(s)
  (Remaining days, up to last) Each team member troubleshoots the instrument loop
(3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

Troubleshooting assessments must meet the following guidelines:

- Troubleshooting must be performed *on a system the student did not build themselves.* This forces students to rely on another team's documentation rather than their own memory of how the system was built.
- Each student must individually demonstrate proper troubleshooting technique.
- Simply finding the fault is not good enough. Each student must consistently demonstrate sound reasoning while troubleshooting.
- If a student fails to properly diagnose the system fault, they must attempt (as many times as necessary) with different scenarios until they do, reviewing any mistakes with the instructor after each failed attempt.

Distance delivery methods

Sometimes the demands of life prevent students from attending college 6 hours per day. In such cases, there exist alternatives to the normal 8:00 AM to 3:00 PM class/lab schedule, allowing students to complete coursework in non-traditional ways, at a "distance" from the college campus proper.

For such "distance" students, the same worksheets, lab activities, exams, and academic standards still apply. Instead of working in small groups and in teams to complete theory and lab sections, though, students participating in an alternative fashion must do all the work themselves. Participation via teleconferencing, video- or audio-recorded small-group sessions, and such is encouraged and supported.

There is no recording of hours attended or tardiness for students participating in this manner. The pace of the course is likewise determined by the "distance" student. Experience has shown that it is a benefit for "distance" students to maintain the same pace as their on-campus classmates whenever possible.

In lieu of small-group activities and class discussions, comprehension of the theory portion of each course will be ensured by completing and submitting detailed answers for *all* worksheet questions, not just passing daily quizzes as is the standard for conventional students. The instructor will discuss any incomplete and/or incorrect worksheet answers with the student, and ask that those questions be re-answered by the student to correct any misunderstandings before moving on.

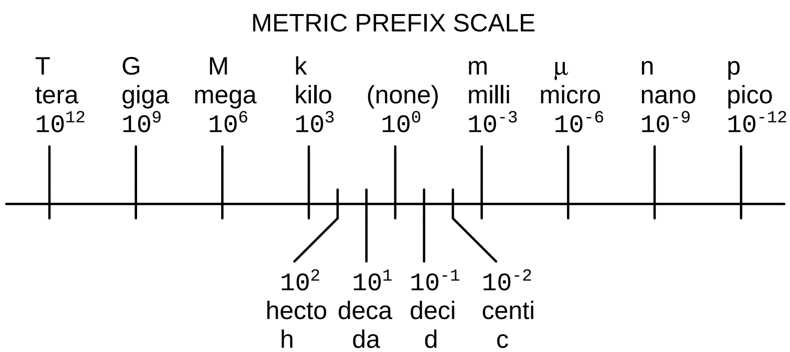
Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either by arranging time in the school lab facility and/or completing activities on equivalent equipment outside of school (e.g. at their place of employment, if applicable). Labwork completed outside of school must be validated by a supervisor and/or documented via photograph or videorecording.

Conventional students may opt to switch to "distance" mode at any time. This has proven to be a benefit to students whose lives are disrupted by catastrophic events. Likewise, "distance" students may switch back to conventional mode if and when their schedules permit. Although the existence of alternative modes of student participation is a great benefit for students with challenging schedules, it requires a greater investment of time and a greater level of self-discipline than the traditional mode where the student attends school for 6 hours every day. No student should consider the "distance" mode of learning a way to have more free time to themselves, because they will actually spend more time engaged in the coursework than if they attend school on a regular schedule. It exists merely for the sake of those who cannot attend during regular school hours, as an alternative to course withdrawal.

file `distance`

Metric prefixes and conversion constants

- **Metric prefixes**
- Yotta = 10^{24} Symbol: Y
- Zeta = 10^{21} Symbol: Z
- Exa = 10^{18} Symbol: E
- Peta = 10^{15} Symbol: P
- Tera = 10^{12} Symbol: T
- Giga = 10^{9} Symbol: G
- Mega = 10^{6} Symbol: M
- Kilo = 10^{3} Symbol: k
- Hecto = 10^{2} Symbol: h
- Deca = 10^{1} Symbol: da
- Deci = 10^{-1} Symbol: d
- Centi = 10^{-2} Symbol: c
- Milli = 10^{-3} Symbol: m
- Micro = 10^{-6} Symbol: μ
- Nano = 10^{-9} Symbol: n
- Pico = 10^{-12} Symbol: p
- Femto = 10^{-15} Symbol: f
- Atto = 10^{-18} Symbol: a
- Zepto = 10^{-21} Symbol: z
- Yocto = 10^{-24} Symbol: y



- **Conversion formulae for temperature**
- ^{o}F = (^{o}C)(9/5) + 32
- ^{o}C = (^{o}F - 32)(5/9)
- ^{o}R = ^{o}F + 459.67
- K = ^{o}C + 273.15

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

1 gallon (gal) = 231.0 cubic inches (in^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm^3)

Conversion equivalencies for velocity

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

Conversion equivalencies for mass

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

Conversion equivalencies for force

1 pound-force (lbf) = 4.44822 newton (N)

Conversion equivalencies for area

1 acre = 43560 square feet (ft^2) = 4840 square yards (yd^2) = 4046.86 square meters (m^2)

Conversion equivalencies for common pressure units (either all gauge or all absolute)

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

Conversion equivalencies for absolute pressure units (only)

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

Conversion equivalencies for energy or work

1 british thermal unit (Btu – "International Table") = 251.996 calories (cal – "International Table") = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10^{10} ergs (erg) = 778.169 foot-pound-force (ft-lbf)

Conversion equivalencies for power

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

Acceleration of gravity (free fall), Earth standard

9.806650 meters per second per second (m/s^2) = 32.1740 feet per second per second (ft/s^2)

Physical constants

Speed of light in a vacuum (c) = 2.9979 × 10^8 meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number (N_A) = 6.022 × 10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602 × 10^{-19} Coulomb (C)

Boltzmann's constant (k) = 1.38 × 10^{-23} Joules per Kelvin (J/K)

Stefan-Boltzmann constant (σ) = 5.67 × 10^{-8} Watts per square meter-Kelvin^4 ($W/m^2 \cdot K^4$)

Molar gas constant (R) = 8.314 Joules per mole-Kelvin (J/mol-K)

Properties of Water

Freezing point at sea level = 32^oF = 0^oC

Boiling point at sea level = 212^oF = 100^oC

Density of water at 4^oC = 1000 kg/m^3 = 1 g/cm^3 = 1 kg/liter = 62.428 lb/ft^3 = 1.94 slugs/ft^3

Specific heat of water at 14^oC = 1.00002 calories/g·^{o}C = 1 BTU/lb·^{o}F = 4.1869 Joules/g·^{o}C

Specific heat of ice ≈ 0.5 calories/g·^{o}C

Specific heat of steam ≈ 0.48 calories/g·^{o}C

Absolute viscosity of water at 20^oC = 1.0019 centipoise (cp) = 0.0010019 Pascal-seconds (Pa·s)

Surface tension of water (in contact with air) at 18^oC = 73.05 dynes/cm

pH of pure water at 25^o C = 7.0 (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20^oC and 760 torr = 1.204 mg/cm^3 = 1.204 kg/m^3 = 0.075 lb/ft^3 = 0.00235 slugs/ft^3

Absolute viscosity of dry air at 20^oC and 760 torr = 0.018 centipoise (cp) = 1.8 × 10^{-5} Pascal-seconds (Pa·s)

Question 0

How to get the most out of academic reading:

- Outline, don't highlight! Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.
- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Create your own questions based on what you read, as a teacher would to challenge students.

How to effectively problem-solve and troubleshoot:

- Rely on principles, not procedures. Don't be satisfied with memorizing steps – learn *why* those steps work. Each step should make logical sense and have real-world meaning to you.
- Sketch a diagram to help visualize the problem. Sketch a graph showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.
- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.
- Check for exceptions – does your solution work for *all* conditions and criteria?
- Work "backward" from a hypothetical solution to a new set of given conditions.

How to manage your time:

- Avoid procrastination. Work now and play later, every single day.
- Consider the place you're in when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).
- Eliminate distractions. Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.
- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

Above all, cultivate persistence, as this is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

file `question0`

Checklist when reading an instructional text

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

$\boxed{\surd}$ Briefly OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

$\boxed{\surd}$ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

$\boxed{\surd}$ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

$\boxed{\surd}$ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

$\boxed{\surd}$ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

$\boxed{\surd}$ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

General challenges following a tutorial reading assignment

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

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file `license`

Question 1

Read and outline the "Derivative (Rate) Control" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

Further exploration . . . (optional)

The now-famous paper on PID controller tuning written by Ziegler and Nichols in 1942 contains many useful insights into behavior of the basic PID control algrithm. Here is one of them:

> Pre-act response does not replace automatic reset response since it ceases to act when the pen becomes stationary. However, while reset increases period of oscillation and decreases stability, the effect of pre-act is just the opposite. On the debit side for pre-act lies only the increased difficulty of adjusting three responses instead of two, but the use of the basic unit, pre-act time, allows the setting to be determined from the period of oscillation.

Describe what this passage is saying, in your own words. Do you see any unfamiliar terms, which you may determine the meaning of from context? What insight(s) can you gather about the use of the integral control mode, as well as the derivative control mode?

file i04301

Question 2

Read and outline the "Summary of PID Control Terms" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

Suggestions for Socratic discussion

- Which of the three PID control actions (P, I, or D) acts *on the future*?
- Which of the three PID control actions (P, I, or D) acts *on the present*?
- Which of the three PID control actions (P, I, or D) acts *on the past*?

file i04299

Question 3

Read and outline the "P, I, and D responses graphed" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

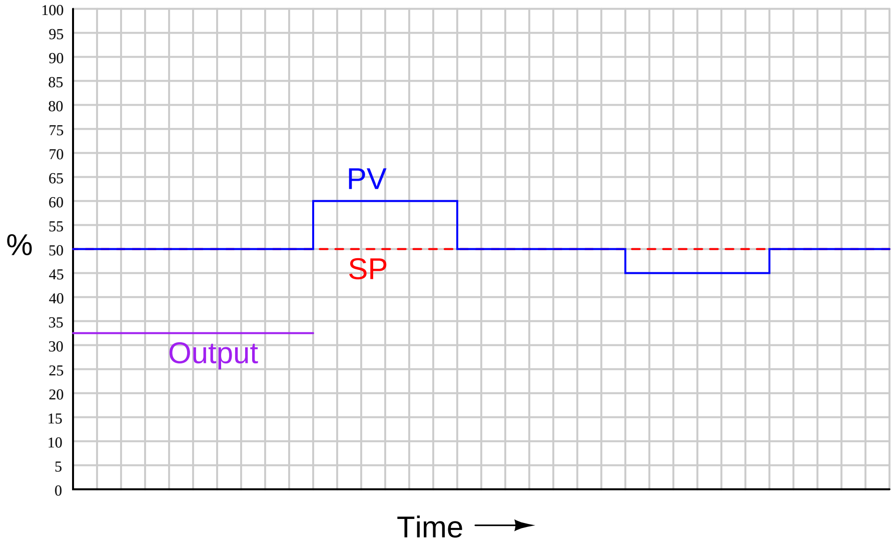
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

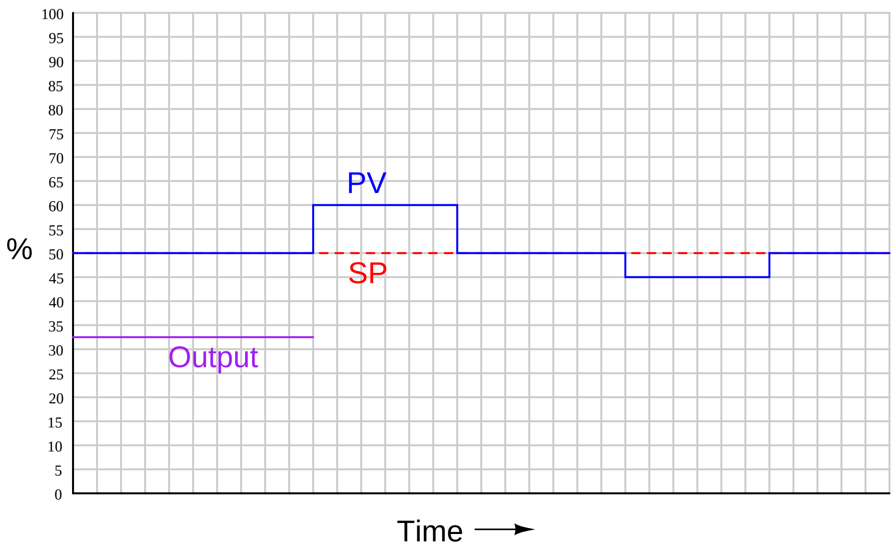
file i04300

Question 4

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller to the following input conditions, assuming *direct* controller action. Use a solid line for proportional, a dashed line for integral, and a dotted line for derivative:



Then, draw a final graph of the controller's output, showing how the P, I, and D terms would combine to form a composite waveform:



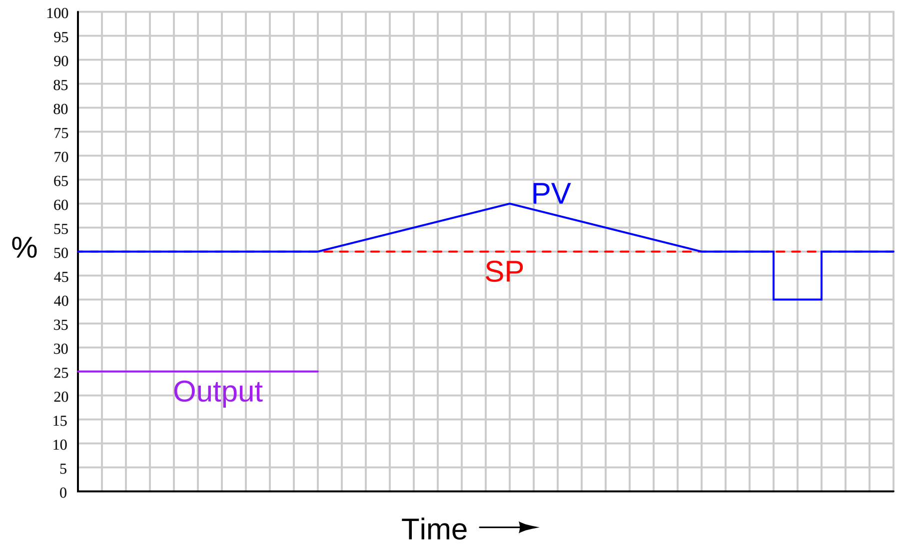
Suggestions for Socratic discussion

- Many students find the task of summing all three control actions together to be much more difficult than plotting any of the three responses separately. Devise a problem-solving strategy to ensure your summation will always be correct!

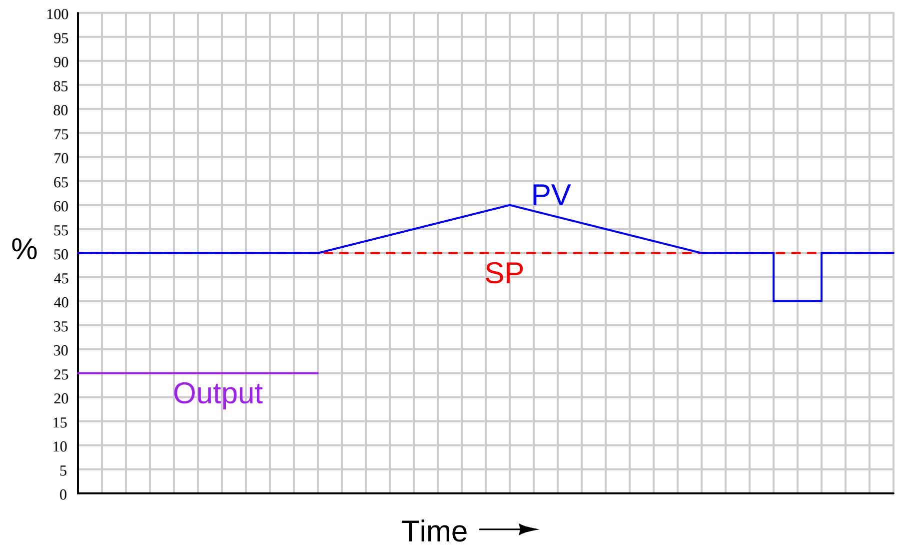
file i01637

Question 5

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller to the following input conditions, assuming *direct* controller action. Use a solid line for proportional, a dashed line for integral, and a dotted line for derivative:



Then, draw a final graph of the controller's output, showing how the P, I, and D terms would combine to form a composite waveform:



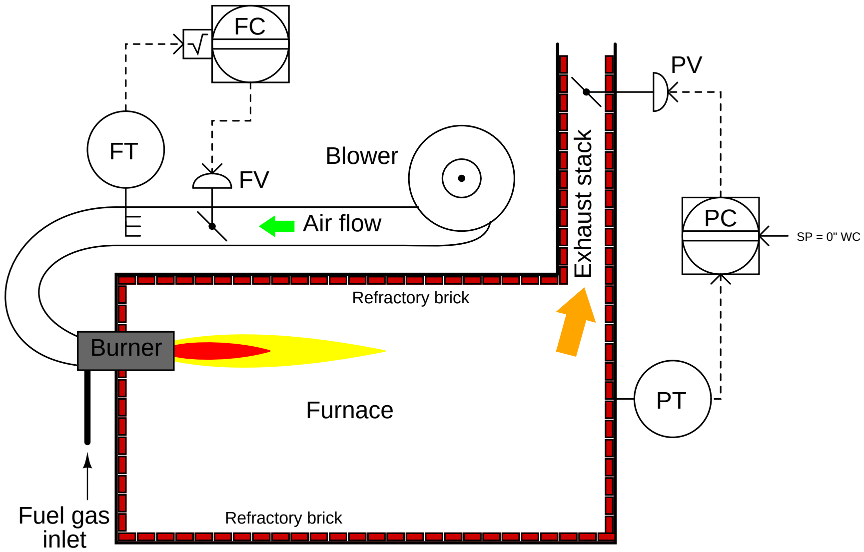
Suggestions for Socratic discussion

- Many students find the task of summing all three control actions together to be much more difficult than plotting any of the three responses separately. Devise a problem-solving strategy to ensure your summation will always be correct!

file i01638

Question 6

This combustion-heated furnace uses two controllers: one to control air flow entering the burner, and the other to control air pressure inside the furnace. Air flow control is important for proper heating, and air pressure control is important to prevent leakage around doorways and other openings in the furnace:



Suppose one day you are informed of a problem with this furnace: flames are seen escaping around the edges of the doors leading into the furnace while it is in operation.

Identify the likelihood of each specified fault for this process. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this process.

Fault	**Possible**	**Impossible**
Blower speed too high		
FC in manual mode		
PC in manual mode		
FT slightly mis-calibrated (registers too much flow)		
FT slightly mis-calibrated (registers too little flow)		
PT slightly mis-calibrated (registers too much pressure)		
PT slightly mis-calibrated (registers too little pressure)		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

Suggestions for Socratic discussion

- What do the ISA symbols indicate about design for both control valves?
- What do the ISA symbols indicate about the placement (location) of the two controllers?
- What kind of flowmeter is being used here to measure combustion air flow?

file i01554

Question 7

Desktop Process exercise

Configure your Desktop Process for proportional-only control, where there is negligible integral or derivative control action. Experiment with different "gain" values until reasonably good control is obtained from the process (i.e. fast response to setpoint changes with minimal "overshoot," good recovery from load changes). Record the "optimum" gain setting you find for your process, for future reference.

Identify and demonstrate some of the disadvantages of proportional-only control.

Suggestions for Socratic discussion

- Does your controller use *gain* or *proportional band* as the unit for Proportional action?
- Does your controller use *repeats per minute*, *repeats per second*, *minutes per repeat*, or *seconds per repeat* as the unit for Integral action? In each case, what would be considered a suitable value to yield "negligible" action?
- Does your controller use *minutes* or *seconds* as the unit for Derivative action? In each case, what would be considered a suitable value to yield "negligible" action?

file i04306

Question 8

Desktop Process exercise

Configure your Desktop Process for proportional-plus-integral (P+I) control, where there is negligible derivative control action. Experiment with different "gain" and "reset" tuning parameter values until reasonably good control is obtained from the process (i.e. fast response to setpoint changes with minimal "overshoot," good recovery from load changes). Record the "optimum" P and I settings you find for your process, for future reference.

Identify and demonstrate how the addition of integral control action to proportional control action overcomes some of the limitations of proportional-only control.

Suggestions for Socratic discussion

- Does your controller use *repeats per time* or *time per repeat* as the unit for Integral action? What is the specific unit of time used (minutes, seconds)?
- Calculate the number of seconds per repeat of integral action you ended up using for good P+I control of the Desktop Process motor speed. How does this amount of time compare with the amount of time the motor physically takes to achieve a new speed value following a manual step-change in the controller's output?

file i04307

Question 9

Desktop Process exercise

Configure your Desktop Process for proportional-plus-derivative (P+D) control, where there is negligible integral control action. Experiment with different "gain" and "rate" tuning parameter values until reasonably good control is obtained from the process (i.e. fast response to setpoint changes with minimal "overshoot," good recovery from load changes). Record the "optimum" P and D settings you find for your process, for future reference.

Identify and demonstrate how the addition of derivative control action to proportional control action overcomes some of the limitations of proportional-only control.

Suggestions for Socratic discussion

- Does your controller use *minutes* or *seconds* as the unit for Derivative action?
- What happens when you configure a loop controller with too much derivative action? How is this effect different from (or similar to) what happens when a controller has too much gain, or too much integral action?
- Does derivative control action work to eliminate offset like integral action does? How can you tell?

file i04308

Question 10

Desktop Process exercise

Configure your Desktop Process for full proportional-plus-integral-plus-derivative (PID) control. Experiment with different "gain," "reset," and "rate" tuning parameter values until reasonably good control is obtained from the process (i.e. fast response to setpoint changes with minimal "overshoot," good recovery from load changes). Record the "optimum" P, I, and D settings you find for your process, for future reference. If you are using PID simulation software instead of a real physical process, select a process that is self-regulating with minimal noise or load changes.

Compare the optimum PID tuning parameter values you arrived at compared to those of your classmates.

Suggestions for Socratic discussion

- How do the P, I, and D settings (when all used together to achieve optimum control) compare to the P setting by itself found to yield optimum proportional-only control, or the P and I settings found to yield optimum PI control, or the P and D settings found to yield optimum PD control?

file i04309

Question 11

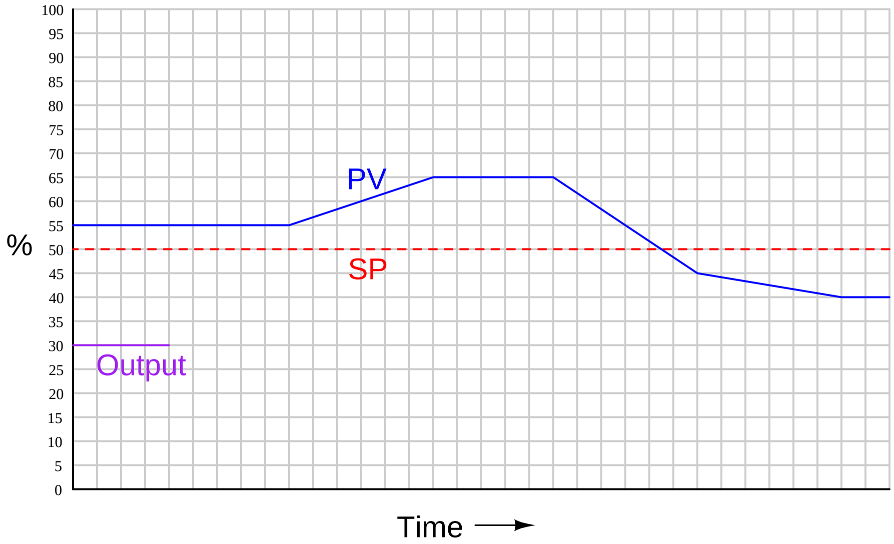
It is sometimes said that in a PID controller, proportional action works on the *present*, while integral action works on the *past* and derivative action works on the *future*. Explain what this means.

file i01639

Question 12

Derivative control action is where the output signal of a controller shifts in direct proportion to the rate that *error* (the difference between process variable and setpoint) changes.

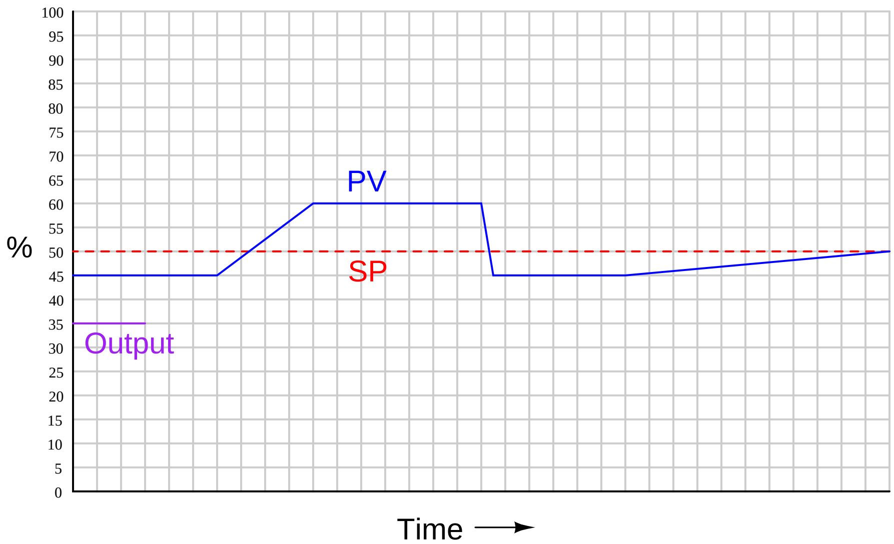
Given this definition, identify how a derivative-acting controller would respond to the following process variable (PV) and setpoint (SP) values over time:



Assume *direct* control action.
file i02419

Question 13

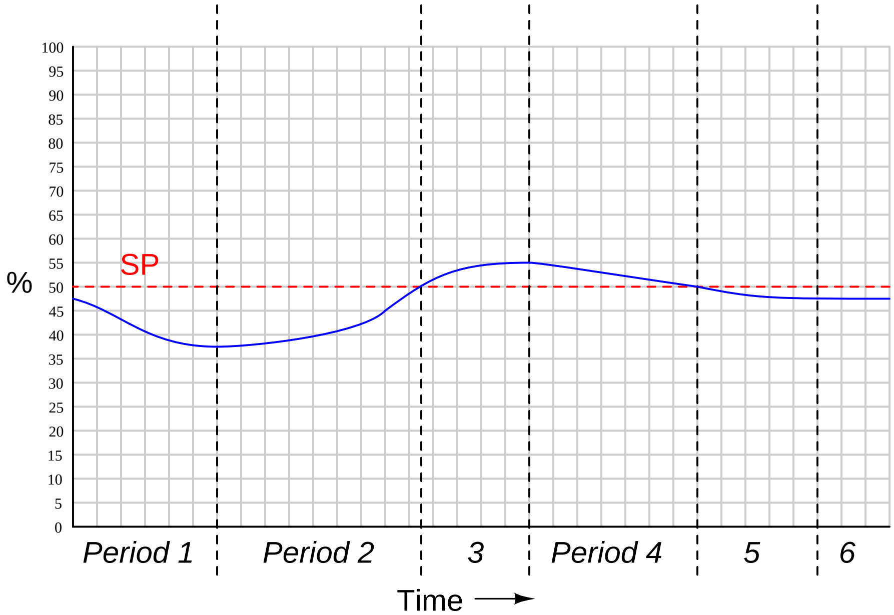
Qualitatively graph the response of an hypothetical derivative-only controller over time to the following changes in process variable:



Assume *reverse* control action.
file i03279

Question 14

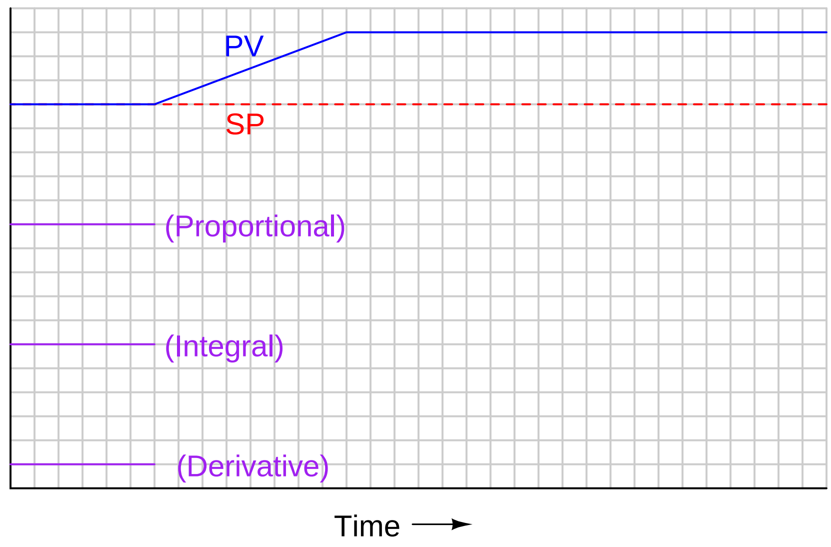
Determine how each control action (P, I, and D) would react during the periods marked on this process trend by using the symbols ↑ (driving up), ↓ (driving down), + (positive), − (negative) or 0 (zero), compared to the actions of each at the beginning of the trend. Do this for P, as well as for I and D. Assume *direct action* for the controller.



file i01641

Question 15

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller as it experiences a ramp in process variable (PV):

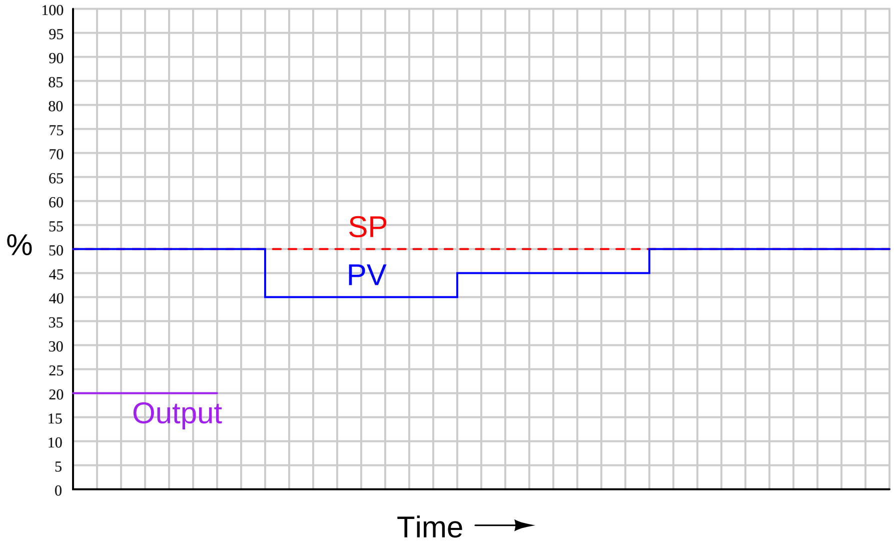


Assume *direct* controller action.

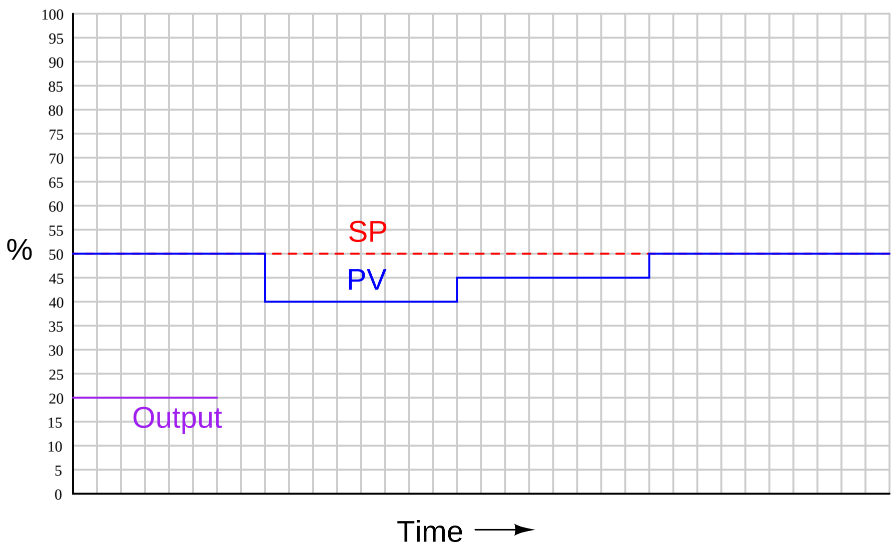
file i03371

Question 16

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller to the following input conditions, assuming *reverse* controller action. Use a solid line for proportional, a dashed line for integral, and a dotted line for derivative:



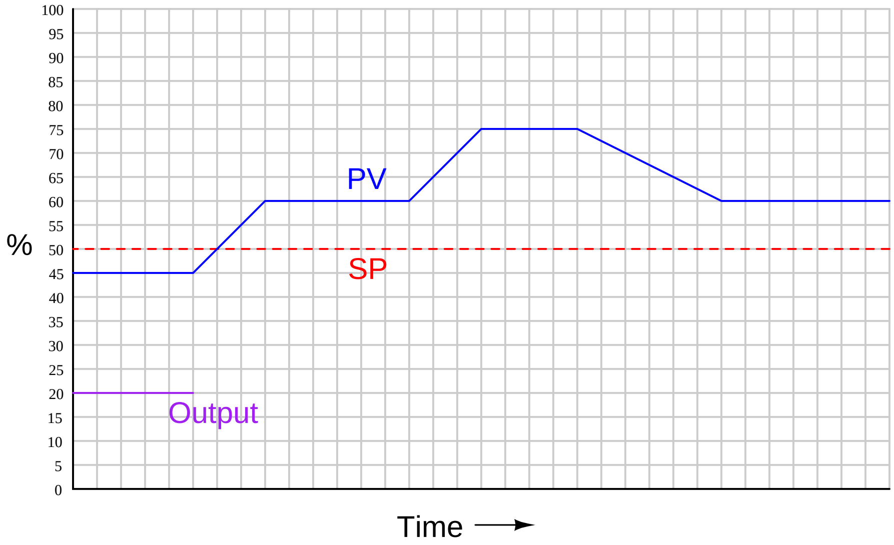
Then, draw a final graph of the controller's output, showing how the P, I, and D terms would combine to form a composite waveform:



file i03303

Question 17

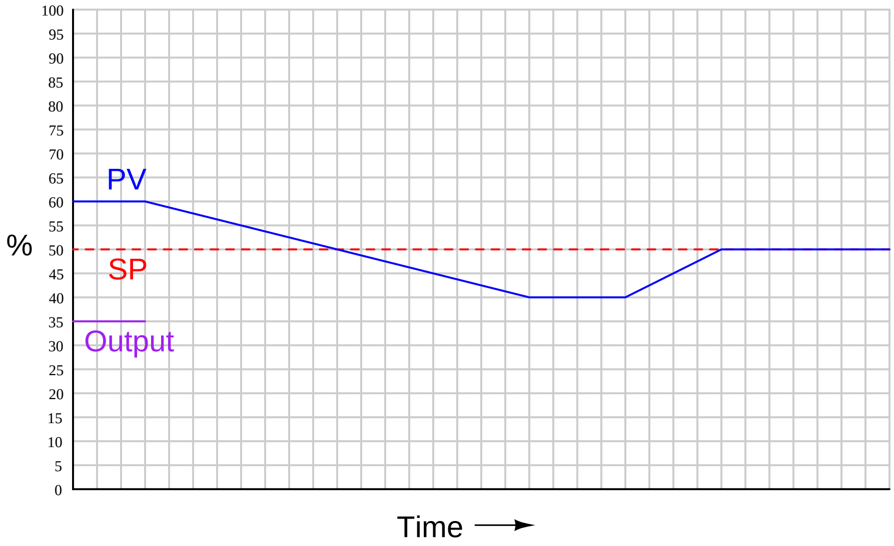
Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:



Assume *direct* control action.
file i03275

Question 18

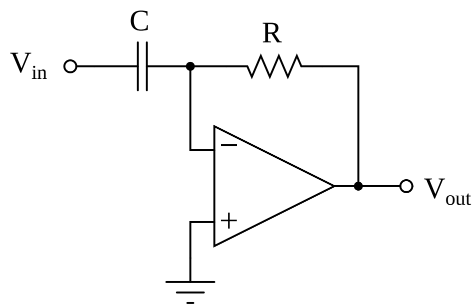
Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:



Assume *direct* control action.
file i03276

Question 19

Determine a pair of standard capacitor and resistor values for this op-amp circuit that will produce a 5 volt output voltage signal for an input voltage signal changing at a steady *rate* of 5 volts per second.



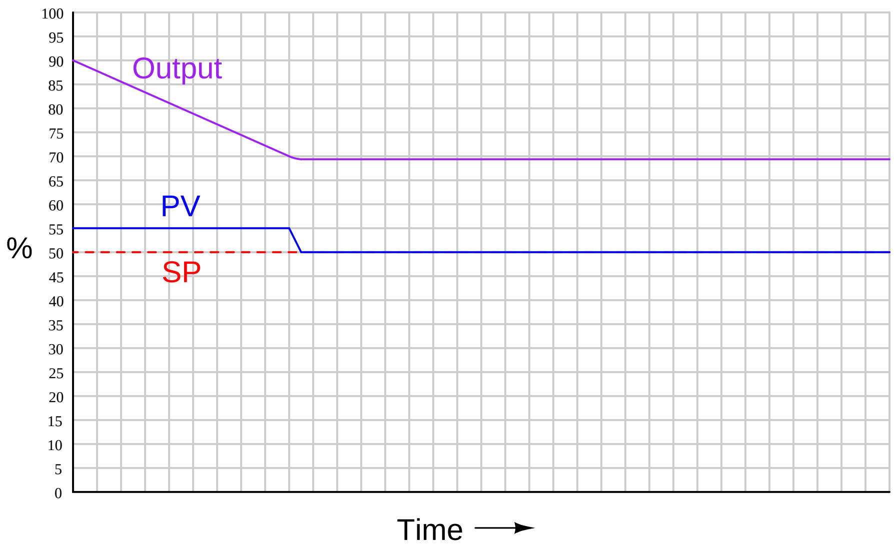
In other words, design this differentiator circuit to have a *time constant* of exactly 1 second.

file i01525

Question 20

Question 21

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



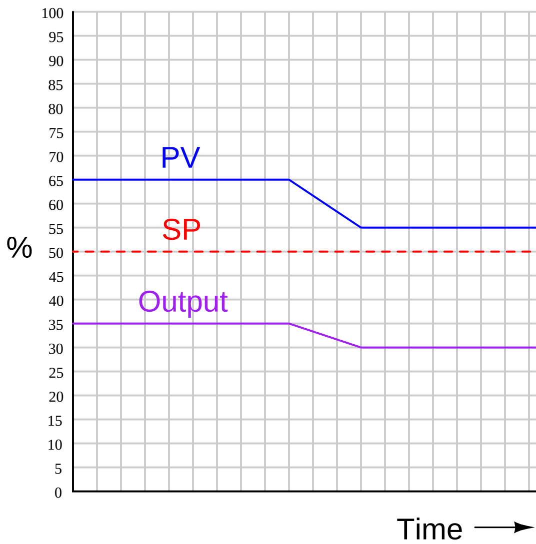
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03306

Question 22

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



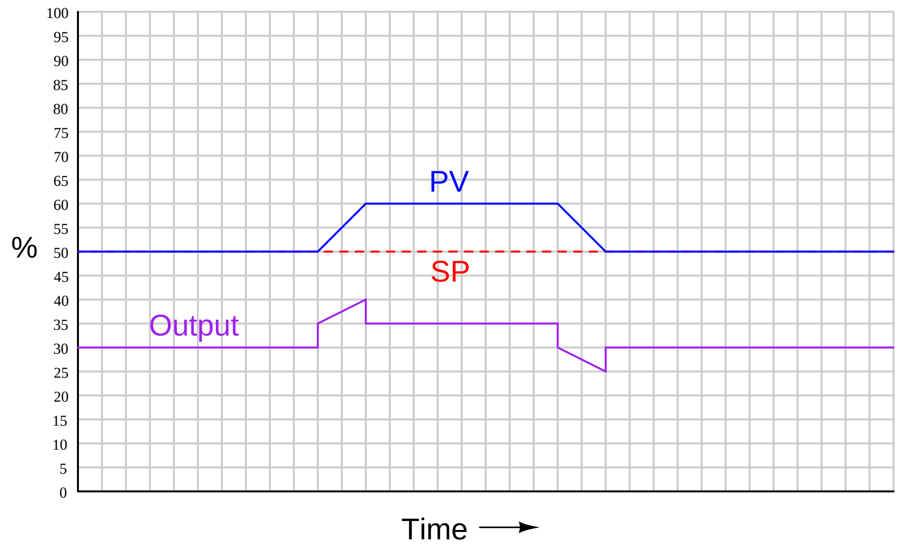
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03305

Question 23

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



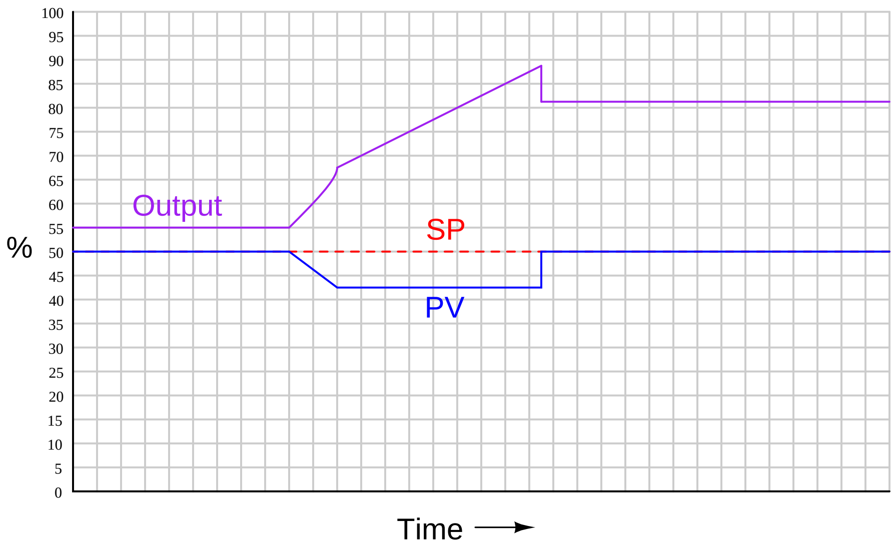
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if this controller implemented a full PID algorithm.

  file i03307

Question 24

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03309

Question 25

Read and outline the "Derivative and Integral Control Actions" subsection of the "Analog Electronic PID Controllers" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

file i04310

Question 26

Read and outline the "Different PID Equations" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

file i01642

Question 27

Read and outline the "Full-PID Circuit Design" subsection of the "Analog Electronic PID Controllers" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

file i04311

Question 28

Read and outline the "Derivative Control Action" subsection of the "Pneumatic PID Controllers" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

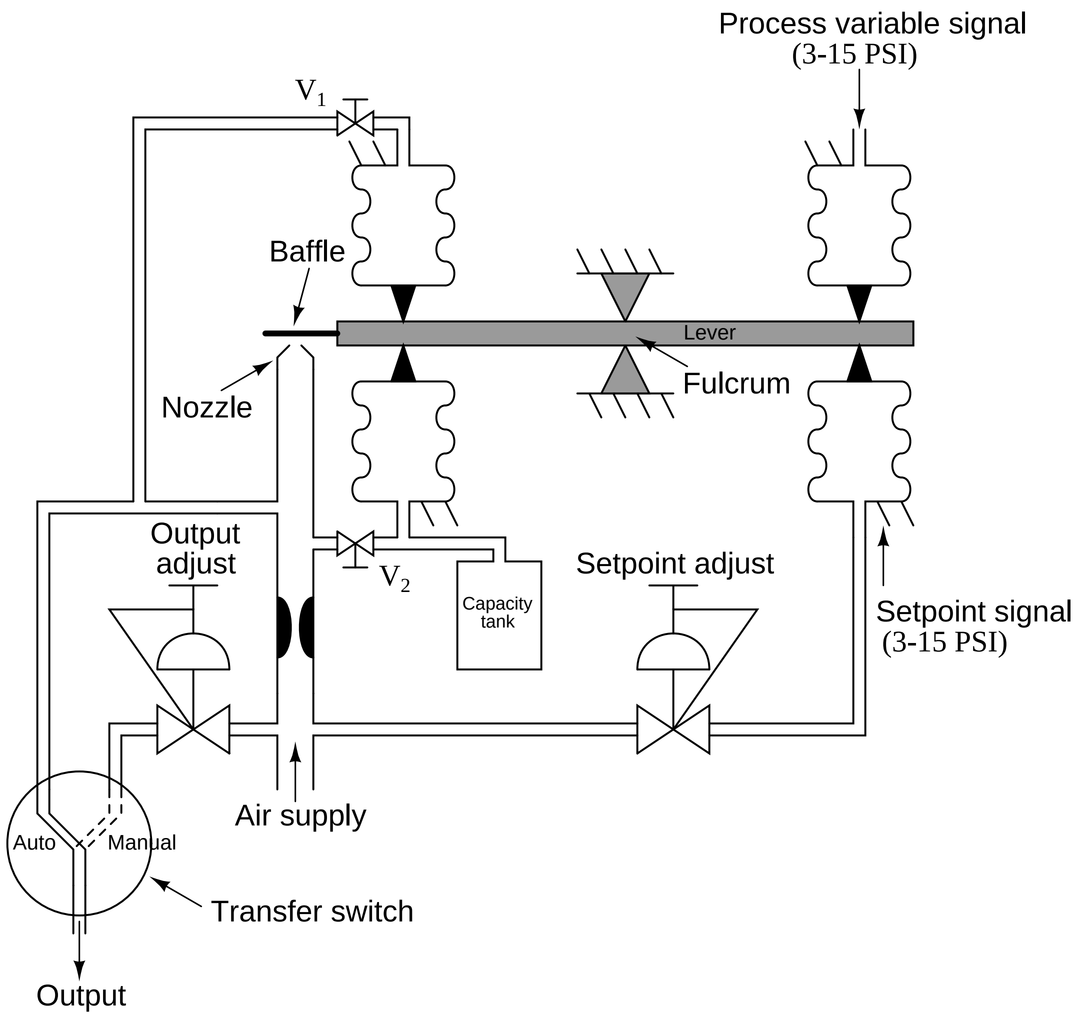
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

file i04313

Question 29

Shown here is the schematic diagram of a full "PID" analog pneumatic controller. Although it lacks the features of output and setpoint tracking, it does possess all three control terms: Proportional, Integral, and Derivative.



Based on your analysis of this mechanism, answer the following questions:

- Is this controller reverse or direct acting?
- Which valve adjusts the integral constant (τ_i)?
- Which valve adjusts the derivative constant (τ_d)?
- What will a change in the capacity tank's volume affect?
- Will adjustment of the proportional constant affect either the integral or derivative responses?
- What would happen if valve V_2 were fully shut?

Suggestions for Socratic discussion

- A powerful problem-solving technique is performing a *thought experiment* where you mentally simulate the response of a system to some imagined set of conditions. Describe a useful "thought experiment" for this system, and how the results of that thought experiment are helpful to answering these questions.

file i01636

Question 30

On some PID controllers, an option is given to allow derivative action to act on process variable (PV) changes only, or act on error (PV − SP) changes like integral action always does. What benefit would it be to have derivative action working on PV changes only and not SP changes?

file i01644

Question 31

A computer spreadsheet program may be used as a simulator for a PID controller. By entering sets of values for Process Variable (PV), Setpoint (SP), Gain (K_P), Integral time constant (tau_I), Derivative time constant (tau_D), and Bias (B), we may program a spreadsheet to calculate the controller output values and even graph them.

Begin creating your own spreadsheet by following the format shown below:

	A	B	C	D	E	F	G	H	I
1	**Time (min)**	**PV**	**SP**	**Error**	**Derivative**	**Integral**	**Output**	**K_P -->**	2
2	0	50	50					**tau_I -->**	0.5
3	1	53	50					**tau_D -->**	5
4	2	56	50					**Bias -->**	50
5	3	59	50						
6	4	59	50						
7	5	57	50						
8	6	55	50						
9	7	53	50						

Assume a controller implementing the following P+D equation (note that our spreadsheet will calculate discrete steps rather than continuous change, hence the Δ notation instead of the more customary d notation, and the summation symbol Σ instead of the integration symbol $\int$):

$$\text{Output} = K_p e + \frac{1}{\tau_i}\Sigma(e\,\Delta t) + \tau_d \frac{\Delta e}{\Delta t} + b$$

Write equations for spreadsheet cells in columns `D`, `E`, `F`, and `G` so that the error term, derivative term ($\tau_d \frac{\Delta e}{\Delta t}$), integral term ($\frac{1}{\tau_i}\Sigma(e\,\Delta t)$), and total output values will be automatically calculated for any PV and SP values entered in columns `B` and `C`. Assume *direct action* for the controller.

- Formula for cell `D3`:
- Formula for cell `E3`:
- Formula for cell `F3`:
- Formula for cell `G3`:

Note: your first formula begins on row 3 rather than row 2 because you need to compare two points in time (e.g. row 3 versus row 2) in order to calculate rates of change and accumulated error-time products. Simply enter zero (0) for the derivative term value in cell `E2` as well as for the integral term value in cell `F2`.

file i03632

Question 32

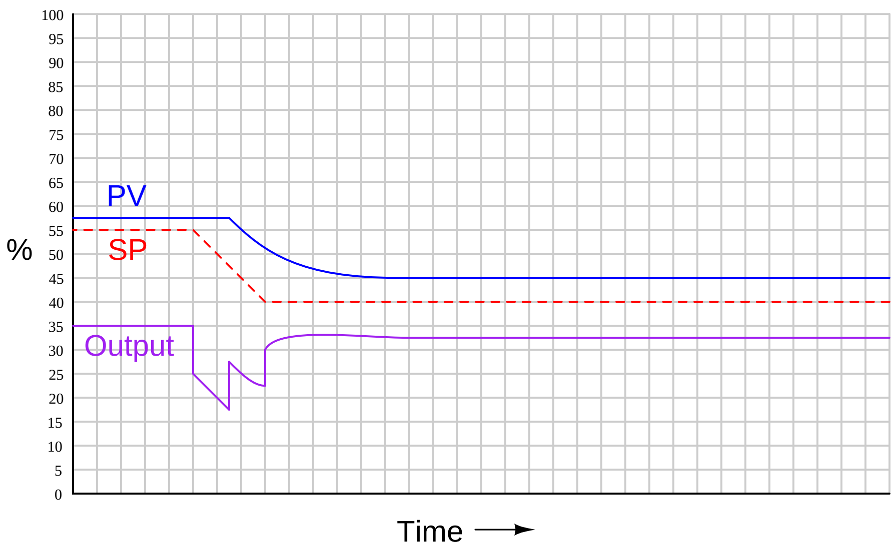
Suppose you were configuring a PID controller in preparation for tuning the PID constants, and desired to set the gain to a value of 1 and the other control actions (I and D) to minimum effect. Identify appropriate numerical values to enter for each of these constants, assuming the following units:

- Proportional = __________ % proportional band
- Reset = __________ minutes per repeat
- Rate = __________ minutes

file i01653

Question 33

Examine this graphic trend of a proportional-plus-derivative controller's response to input changes over time:



Identify which of the following algorithms is being used in this P+D controller, and how you can tell:

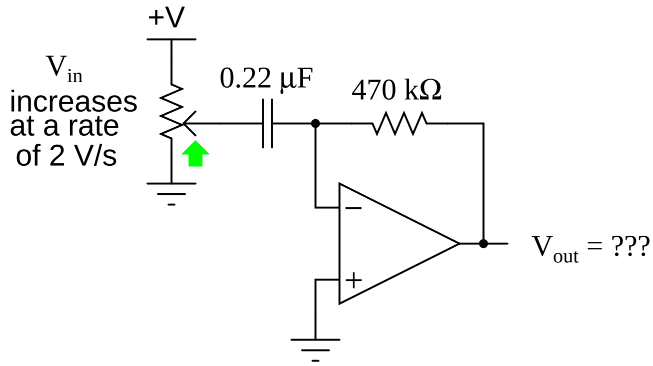
$$m = K_p \left(e + \tau_d \frac{de}{dt} \right) + b$$

$$m = K_p \left(e + \tau_d \frac{d(\mathrm{PV})}{dt} \right) + b$$

file i03277

Question 34

Calculate the output voltage of this op-amp circuit as the input voltage increases at a steady rate of 2 volts per second:

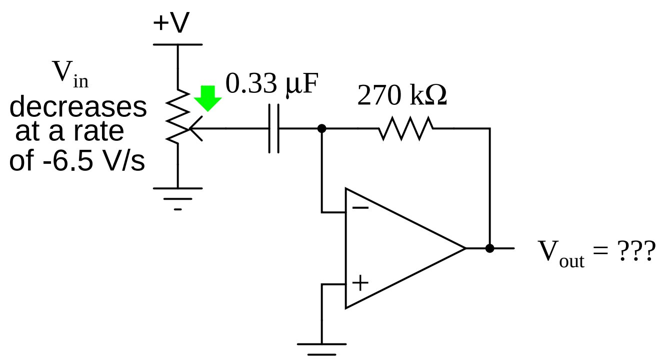


Then, calculate the "time constant" of this differentiator circuit (i.e. the factor relating output voltage to input rate-of-change).

file i01523

Question 35

Calculate the output voltage of this op-amp circuit as the input voltage decreases (goes in a negative direction) at a steady rate of -6.5 volts per second:

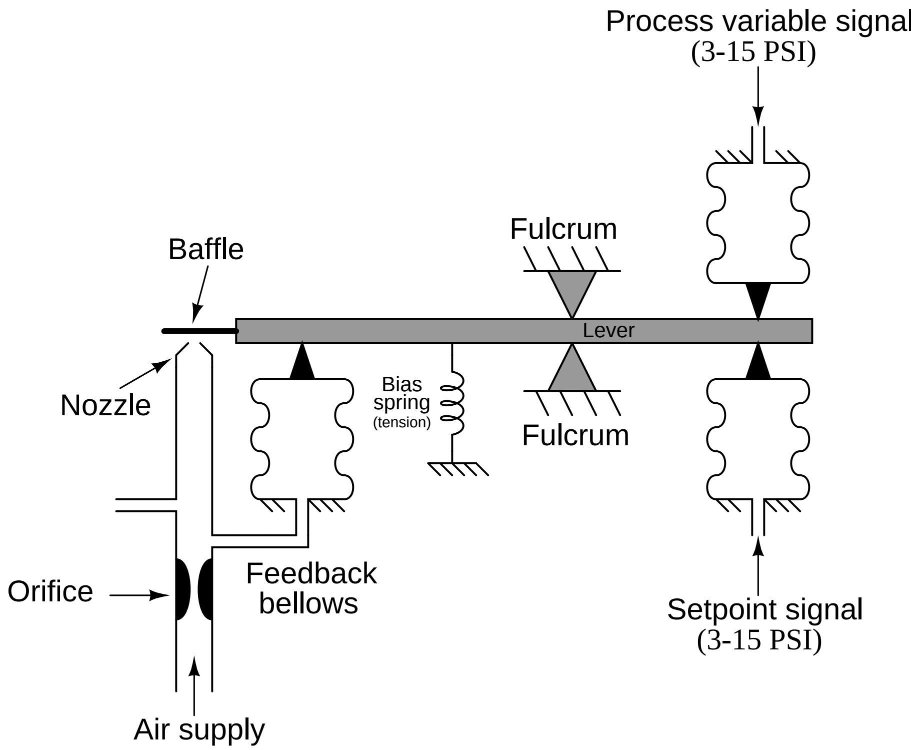


Then, calculate the "time constant" of this differentiator circuit (i.e. the factor relating output voltage to input rate-of-change).

file i01524

Question 36

Suppose the feedback bellows in this pneumatic controller were replaced with one significantly smaller (having a much smaller surface area for air pressure to act upon, and also a much smaller internal volume):



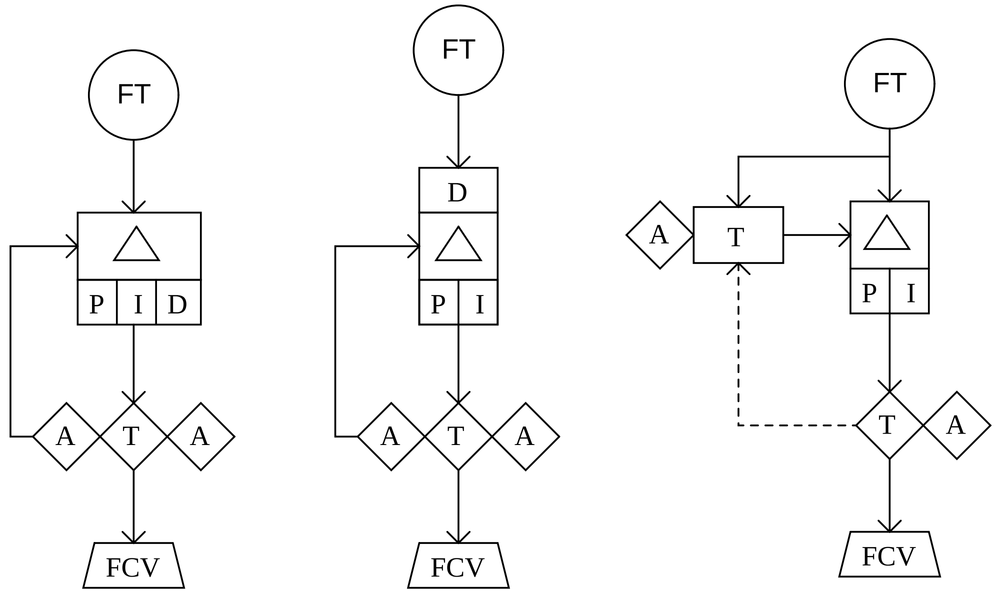
Identify the effects this component change would have on the controller, and on the process being controlled:

- Will this alteration *increase*, *decrease*, or *not affect* the proportional band of the controller?
- Will this alteration *increase*, *decrease*, or *not affect* the bias value in the controller's equation?
- Will this alteration *increase*, *decrease*, or *not affect* the time it takes for the controller's output to fully respond to a sudden change in PV or SP signal?
- Assuming the controller did a fine job controlling the process before this component change, describe how this alteration will affect the quality of control:

  file i01768

Question 37

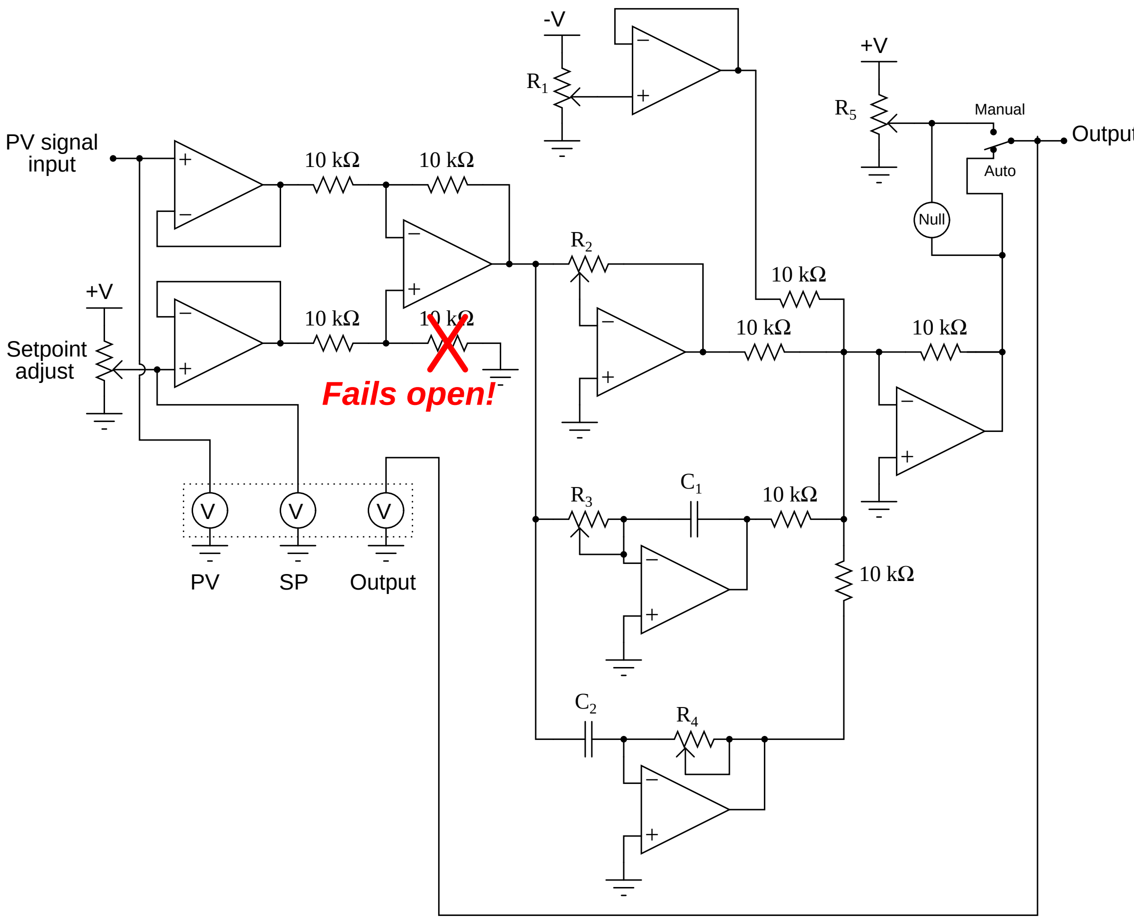
The following functional diagrams represent different controller options in a flow control loop. Identify each of the features:



file i01792

Question 38

An electronic PID controller is controlling a process at a setpoint of 50%. The output signal happens to be 67% at the time, and the process variable is holding at setpoint:



Then suddenly the resistor shown below the subtracting opamp fails open, due to a bad solder joint. Determine how the controller will drive the output signal as a result of this fault. Specifically, determine:

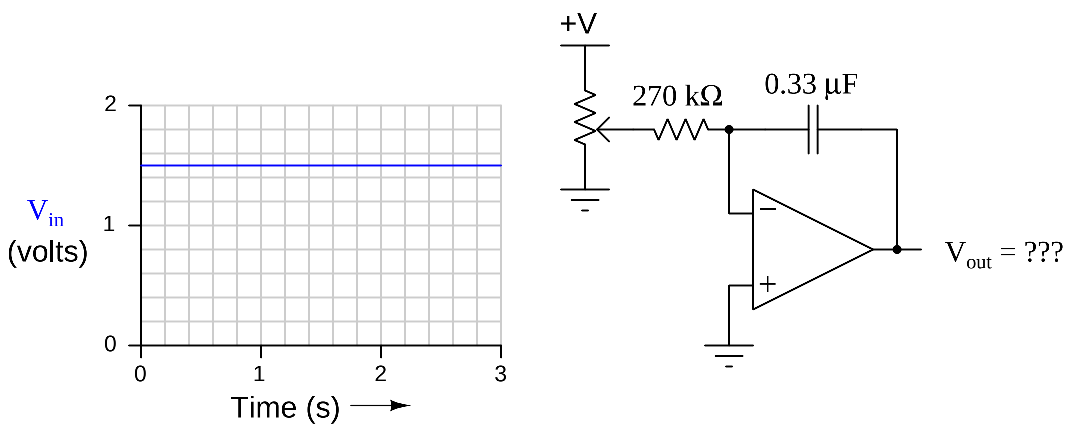
- The effect on the output signal immediately after the fault:

- The effect on the output signal a few seconds after the fault (but before the process itself has had time to react to the change in output):

  file i01852

Question 39

Calculate the output voltage of this opamp circuit assuming a constant input voltage of +1.5 volts applied for 0.5 seconds. Assume the capacitor begins in a state of zero charge ($V_0 = 0$ volts):

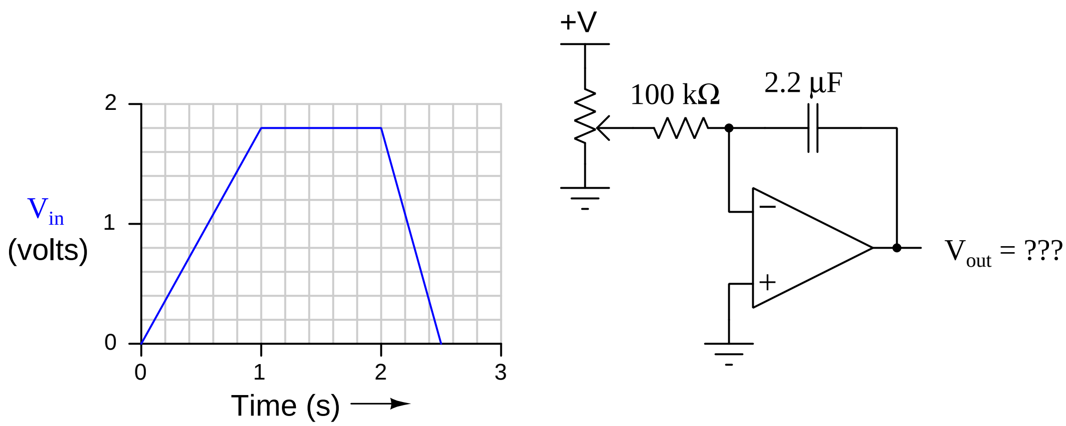


Also, calculate the "time constant" of this integrator circuit (i.e. the factor relating output voltage rate-of-change to input voltage).

file i01026

Question 40

Calculate the output voltage of this opamp circuit given the input voltage profile shown in the graph. Assume the capacitor begins with a charge (V_0) of +8 volts:

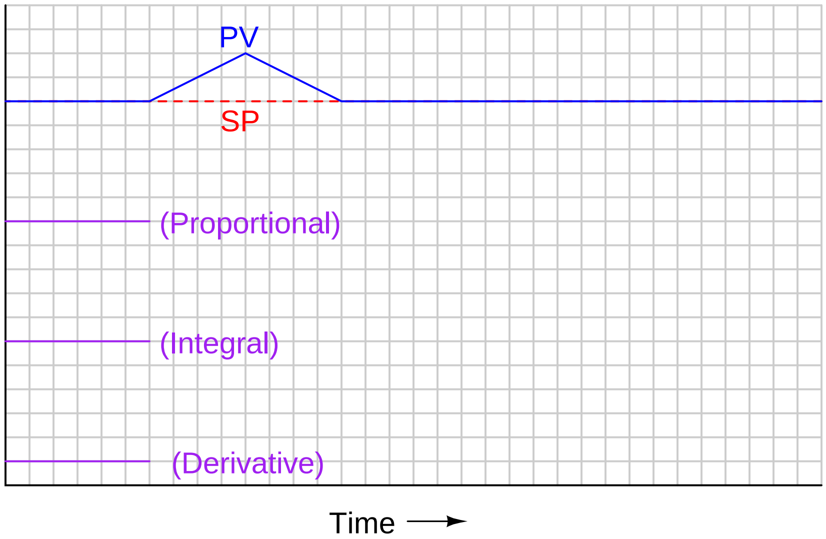


Also, calculate the "time constant" of this integrator circuit (i.e. the factor relating output voltage rate-of-change to input voltage).

file i01027

Question 41

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller as it experiences a triangular "step" in process variable (PV):



Assume *direct* controller action.

Suggestions for Socratic discussion

- Do your best to describe each action (P, I, and D) *verbally*, as though you are explaining each one to someone for the first time. Keep your explanations as simple as you can without sacrificing technical accuracy.

file i03373

Question 42

Read and outline the "Introduction to Pseudocode" subsection of the "Digital PID Algorithms" section of the "Closed-Loop Control" chapter in your *Lessons In Industrial Instrumentation* textbook.

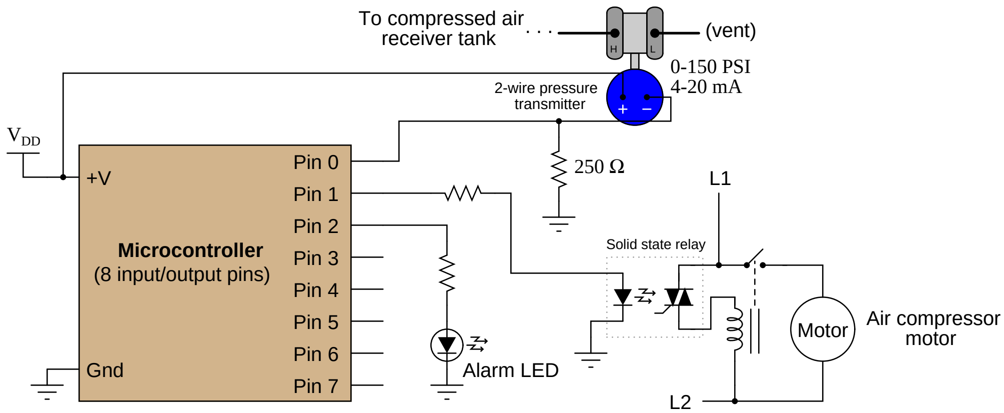
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.
(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).
(3) General principles, especially physical laws, referenced in the text.
(4) Questions of your own you would pose to another reader, to challenge their understanding.
(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
(6) Any points of confusion, and precisely why you found the text confusing.

Feel free to skip past the portions of this subsection discussing *branching* and *functions*.
file i02920

Question 43

A *microcontroller* is a single-chip digital computer with onboard I/O capable of receiving and transmitting different types of electrical signals, and a processor capable of executing a series of written instructions. This one is being used to control an air compressor:



Examine the following program (written in an informal programming language called "pseudocode") and explain how the microcontroller decides when to turn the motor on and off. Also determine the pressures at which the microcontroller turns on and shuts off the compressor:

Pseudocode listing

```
Declare Pin0 as an analog input (scale 0 to 5 volts = 0 to 1023)
Declare Pin1 as a discrete output
Declare Pin2 as a discrete output
Declare A as a constant = 805
Declare B as a constant = 750
Declare C as a constant = 700

LOOP
  // (Comment: Motor control points)
  IF Pin0 > A, SET Pin1 LOW
  ELSEIF Pin0 < B, SET Pin1 HIGH
  ENDIF

  // (Comment: Alarm LED control points)
  IF Pin0 < C, SET Pin2 HIGH
  ELSE SET Pin2 LOW
  ENDIF
ENDLOOP
```

Suggestions for Socratic discussion

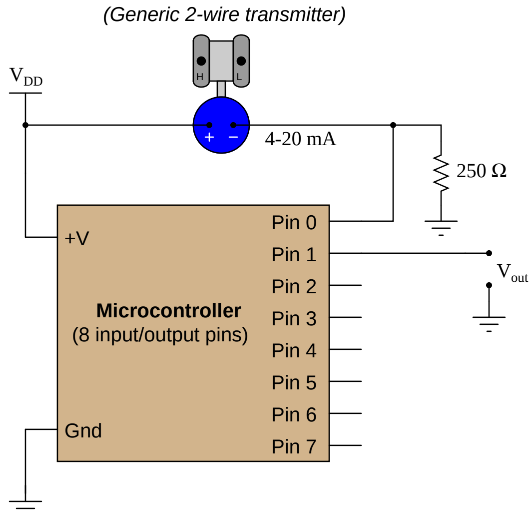
- Which sections of the pseudocode program listing are executed repeatedly, and which sections are executed only once?
- How many bits of resolution does this microcontroller have for the analog input on pin #0, assuming that 0 to 1023 is the full range of the converter?
- Explain how the *solid state relay* device works to help control the compressor motor.
- Explain what would happen if you deleted the `LOOP` and `ENDLOOP` statements in the microcontroller program.

- Modify the pseudocode so that the alarm LED comes on if the pressure gets too high.
- Modify the pseudocode so that the alarm LED comes on if the pressure gets too high *or* too low.

file i01454

Question 44

Examine this microcontroller circuit and program, designed to act as a general-purpose proportional controller:



Pseudocode listing

```
Declare Pin0 as an analog input (scale 0 to 5 volts = 0 to 1023)
Declare Pin1 as an analog output (scale 0 to 5 volts = 0 to 1023)
Declare SP as a variable, initially set to a value of 614
Declare GAIN as a variable, initially set to a value of 1.0
Declare ERROR as a variable
Declare BIAS as a constant = 614

LOOP
  SET ERROR = Pin0 - SP
  SET Pin1 = (GAIN * ERROR) + BIAS
ENDLOOP
```

Is this controller *direct* or *reverse* acting? What edit(s) to the program listing would be required to change the direction of the controller's action?

Suggestions for Socratic discussion

- Which sections of the pseudocode program listing are executed repeatedly, and which sections are executed only once?
- How many bits of resolution does this microcontroller have for the analog input on pin #1, assuming that 0 to 1023 is the full range of the converter?
- Does the speed of program execution (i.e. how fast the loop repeats itself) affect the controller's ability to control a process?
- Could all the "Declare" instructions be placed within the loop of this program? Why or why not?
- Explain what would happen if you deleted the `LOOP` and `ENDLOOP` statements in the microcontroller program.
- Modify this program to include a PV alarm, turning on an LED alarm lamp if the PV exceeds a certain value, and turning it back off when the PV drops below another value.

file i01486

Question 45

Digital controllers calculate the time-derivative of an input signal by sampling that signal (analog-to-digital conversion) repeatedly and performing mathematical analysis on it between samples. Here is a "pseudocode" algorithm that a digital computer might use in computing an input signal's rate-of-change over time:

Pseudocode listing

```
LOOP
  SET x = input    // (Sample input signal and set 'x' equal to that value)
  SET t = system_time    // (Sample system clock and set 't' equal to that value)

  SET delta_x = x - last_x
  SET delta_t = t - last_t

  SET rate = delta_x ÷ delta_t    // (Calculate the rate of change Δx/Δt)

  SET last_x = x    // (Set 'last_x' equal to the current value of 'x')
  SET last_t = t    // (Set 'last_t' equal to the current value of 't')
ENDLOOP
```

Explain how this algorithm works, calculating rate of change based on successive samples of the input variable and of the system clock (time).

Suggestions for Socratic discussion

- Suppose the order of the last two SET instructions were reversed. How will this change affect the operation of the program, if at all?
- Suppose the "t = system_time" SET instruction is deleted from the program. How will this change affect the operation of the program, if at all?
- Suppose the microprocessor were upgraded such that this program executed at twice its normal speed (i.e. it would "loop" through the algorithm twice as frequently as before). How will this change affect the calculation of rates of change, if at all?

file i01557

Question 46

Research the PID equations available for use in the Rockwell (Allen-Bradley) Logix5000 PLC control system. You will find the "General Instructions" programming reference manual (publication 1756-RM0031-EN-P) to be most useful for this purpose.

How many different PID equations are available to use in the PID instruction? How do their operations differ from one another?

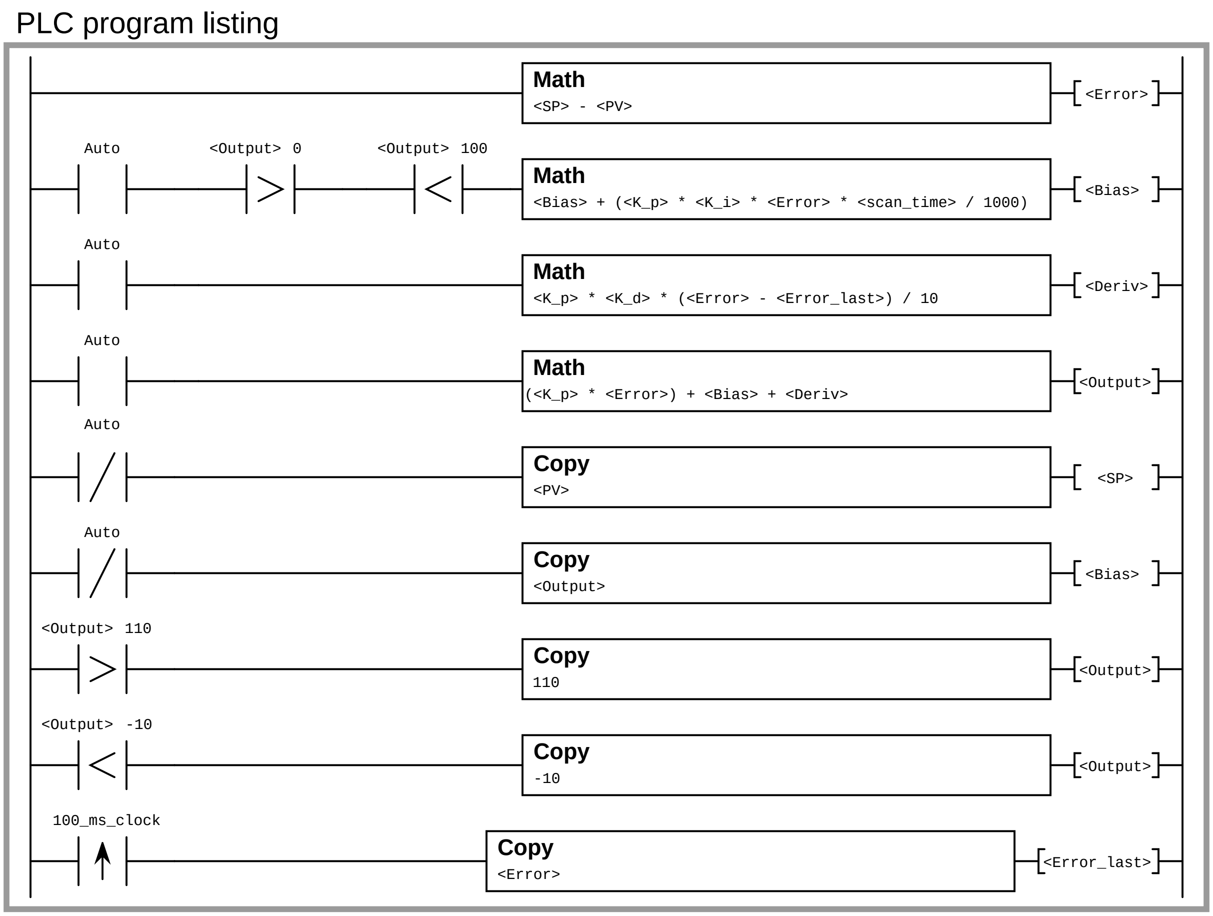
Suggestions for Socratic discussion

- Identify the unit(s) of measurement used by the Logix5000 PLC for the *proportional* term of the PID equation.
- Identify the unit(s) of measurement used by the Logix5000 PLC for the *integral* term of the PID equation.
- Identify the unit(s) of measurement used by the Logix5000 PLC for the *derivative* term of the PID equation.
- Suppose we were using a Logix5000 PLC to control a process with a large first-order lag time, and we needed fast response to setpoint changes. Would you suggest using the PID equation(s) where derivative is calculated on error, or using the PID equation(s) where derivative is calculated on PV only?
- Examine the structured text routine shown on page 513 of this manual, showing how to set up a 1000 ms timer to execute the PID instruction once every second. Identify variable assignments, function calls, and conditional statements in this snippet of ST code. Compare and contrast the structured text example against the ladder-logic programming example of the same algorithm.
- Examine the structured text routine shown on page 515 of this manual, showing how to set up a PID instruction to be executed as soon as the analog input card completes a scan. Identify variable assignments, function calls, and conditional statements in this snippet of ST code. Compare and contrast the structured text example against the ladder-logic programming example of the same algorithm.
- Can you spot the typographical error(s) in the equation section of this manual, comparing different equation options for the PID instruction?

file i01600

Question 47

Some programmable logic controllers (PLCs) do not have a built-in PID instruction, and so to implement PID control in one of these PLCs the technician or engineer must build their own PID algorithm from math statements. Examine this ladder-logic program for a PLC implementing full PID control:



- Is this a *direct-acting* or a *reverse-acting* algorithm? Which instruction(s) in the program indicate this?
- Does this program implement the *Parallel*, *Ideal*, or *Series* PID equation? Which instruction(s) in the program indicate this?
- Where does the program implement the feature of *setpoint tracking*?
- Where does the program implement the feature of *output tracking*?
- Where is integral action (I) calculated in this program?

Suggestions for Socratic discussion

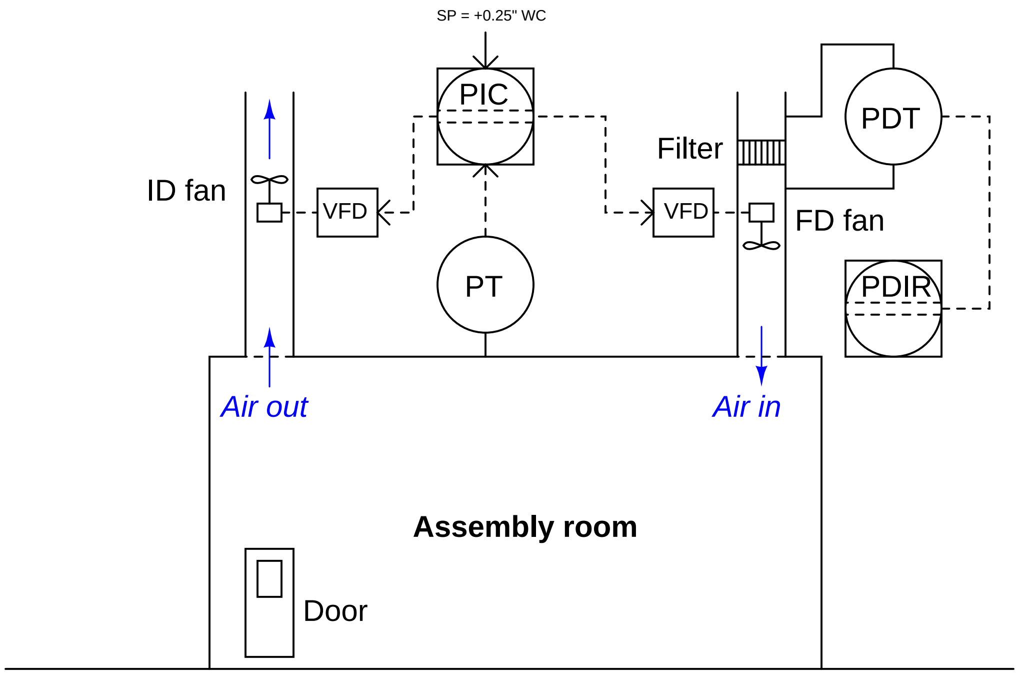
- Modify this PLC program so that it implements the *other* direction of action (i.e. reverse-action instead of direct-action, or vice-versa).
- Modify this PLC program so that it implements a different PID equation from the one it implements now.
- Modify this PLC program so that it implements a P+I equation (no derivative).

- Modify this PLC program so that it implements a P+D equation (no integral).
- Modify this PLC program so that it implements an I+D equation (no proportional).
- What is the significance of the "↑" symbol inside the 100_ms_clock contact?
- What is the significance of each "<" and ">" symbol inside some of the contacts?
- Where does this program implement *reset windup limiting*?
- Would it make any difference if the Error_last "copy" instruction were placed at the beginning of the program instead of the very end of the program? Hint: consider when a PLC typically scans its I/O to update any discrete and analog values – in the portion of the execution cycle *outside* the program scan.

file i02674

Question 48

This room pressure control system maintains a slightly positive pressure in a precision electronic assembly room to prevent dust from entering from the outside, while always ensuring a rapid flow rate of air through the room. It regulates pressure by modulating two variable-speed fans: one introducing air to the room (the "forced draft" fan) and one venting air from the room (the "induced draft" fan). A pressure transmitter outputs 4 mA at 0 "W.C room pressure and 20 mA at 2 "W.C. room pressure:



Suppose you are called to troubleshoot a problem in this system: the room air pressure is holding steady at +0.17 inches WC (according to the display on the DDC control system) with the FD fan running at 100% speed and the ID fan running at 0% speed. Based on this data, identify the most likely cause of the problem, and also how you would confirm your diagnosis *before* making any repairs.

Next, calculate the amount of force exerted on a walk-in door from the room's positive pressure (at setpoint) assuming the door is 30 inches wide and 84 inches tall.

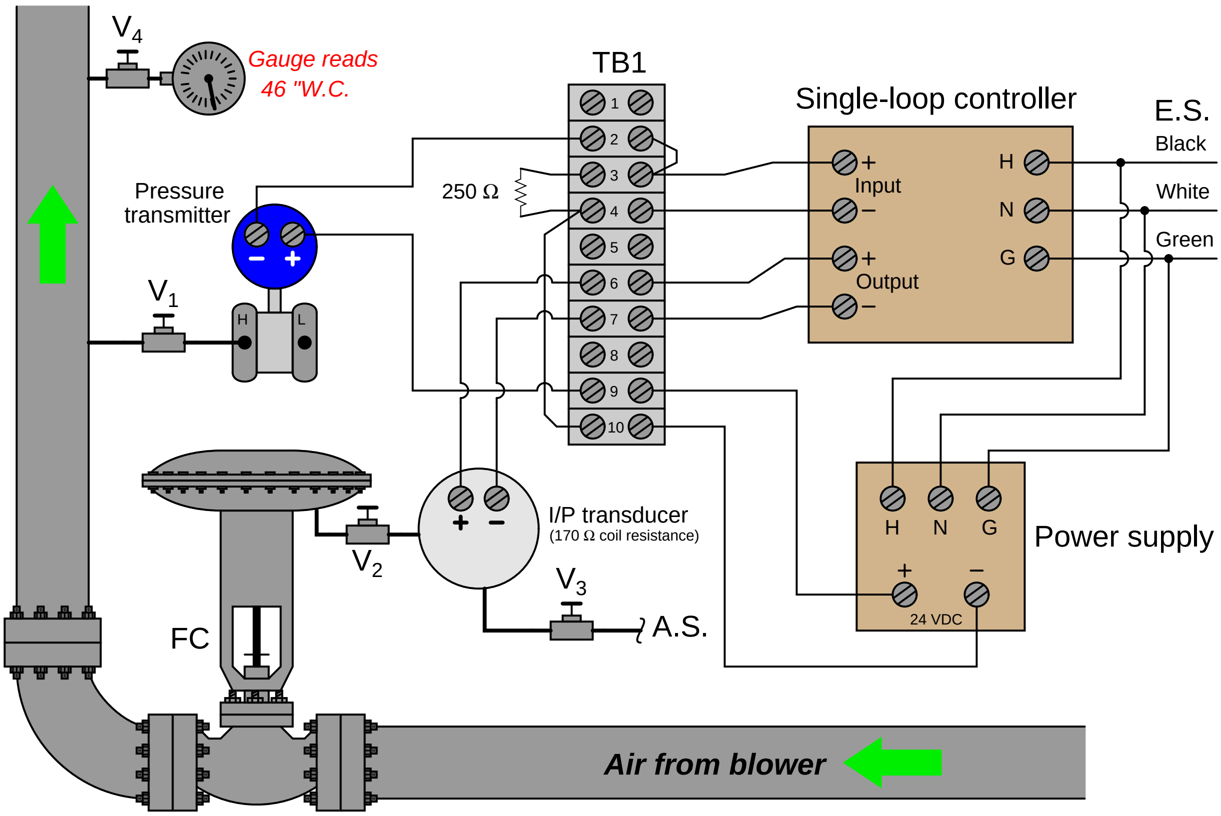
Suggestions for Socratic discussion

- What does "VFD" stand for, and what exactly do the "VFD" boxes do to exert control over the speed of the two fan motors?
- Determine the most likely combination of split-ranges for the two controller outputs (0 to 10 volts DC each, with each VFD calibrated for 0% speed at 0 volts and 100% speed at 10 volts).
- Determine the effect a failed PT (high output signal) will have on room pressure.
- Determine the effect a failed FD VFD (motor dead) will have on room pressure.
- Determine the effect a failed ID VFD (motor dead) will have on room pressure.

file i01566

Question 49

This single-loop control system has a problem: the pressure indicated on the controller's faceplate only shows 45 inches W.C. despite the setpoint's value of 95 inches W.C. (measurement range = 0 to 120 inches W.C.). The operator has already attempted to correct the problem by placing the controller in manual and setting the output at 100%, to no avail:



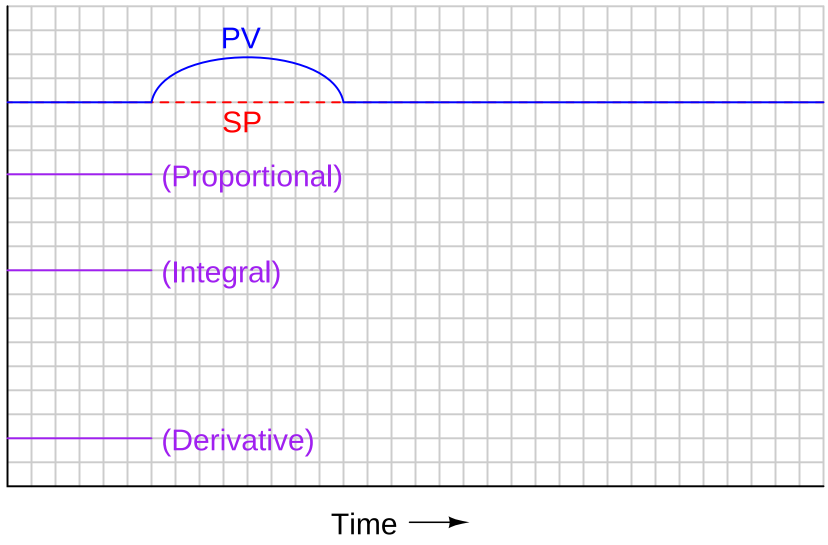
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure AC line voltage		
Measure DC power supply output voltage		
Inspect PID tuning parameters in controller		
Inspect PV range values (LRV, URV) in controller		
Push flapper toward nozzle in I/P		
Pull flapper away from nozzle in I/P		
Measure DC voltage between TB1-3 and TB1-4		
Measure DC voltage between TB1-6 and TB1-7		

file i01590

Question 50

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller as it experiences a rounded "step" in process variable (PV):



Assume *reverse* controller action.

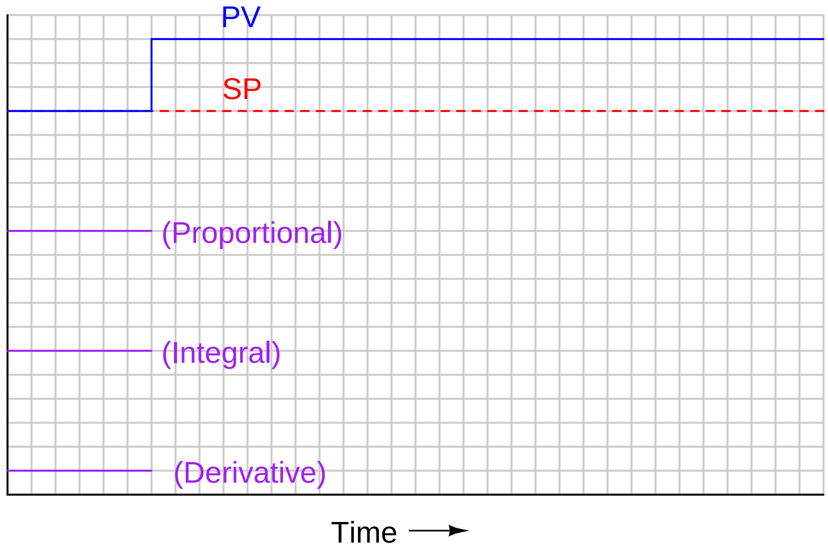
Suggestions for Socratic discussion

- Do your best to describe each action (P, I, and D) *verbally*, as though you are explaining each one to someone for the first time. Keep your explanations as simple as you can without sacrificing technical accuracy.

file i03372

Question 51

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller as it experiences a step-change in process variable (PV):



Assume *direct* controller action.

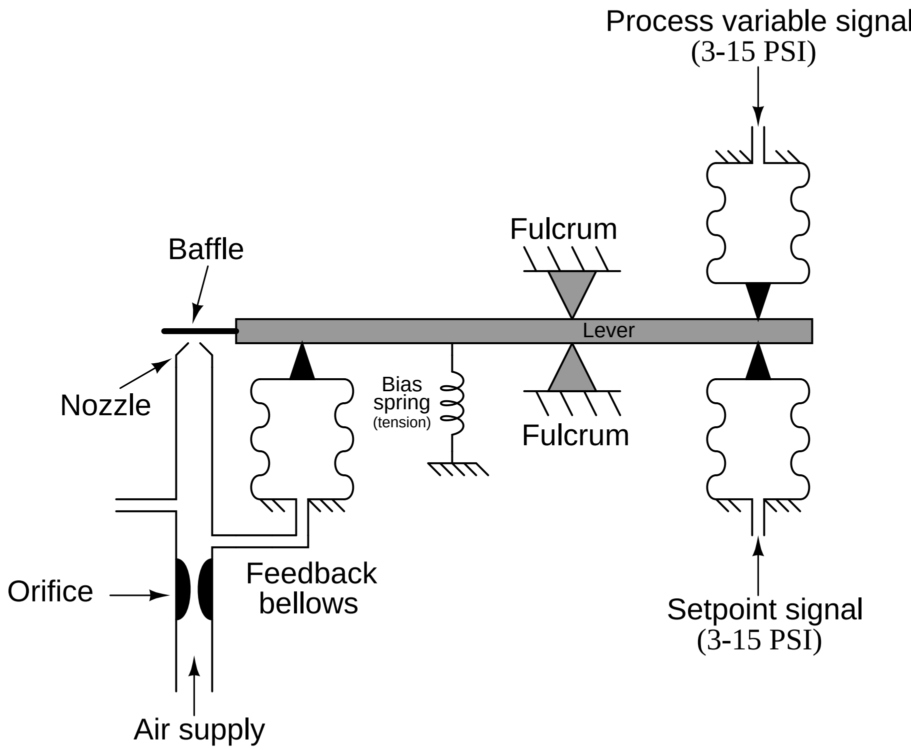
Suggestions for Socratic discussion

- Do your best to describe each action (P, I, and D) *verbally*, as though you are explaining each one to someone for the first time. Keep your explanations as simple as you can without sacrificing technical accuracy.

file i03370

Question 52

Suppose the feedback bellows in this pneumatic controller were replaced with one significantly larger (having a much larger surface area for air pressure to act upon, and also a much larger internal volume):



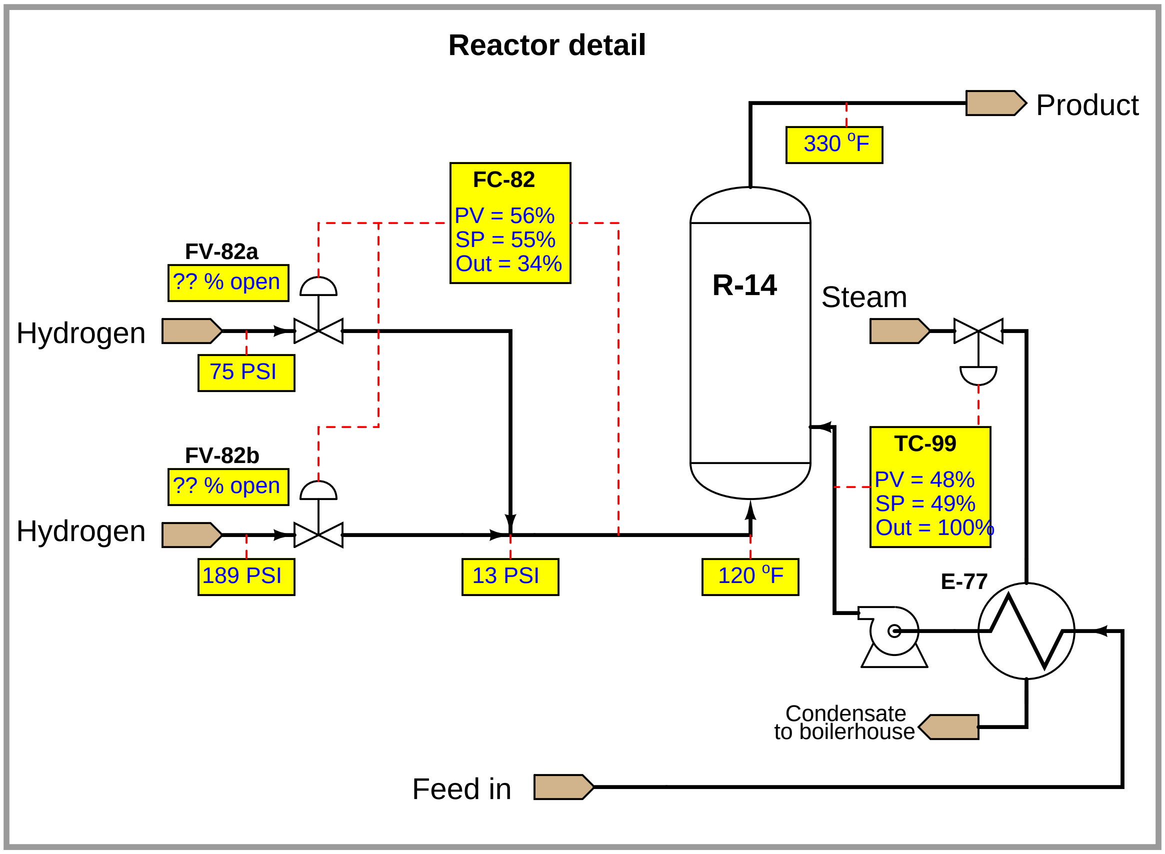
Identify the effects this component change would have on the controller, and on the process being controlled:

- Will this alteration *increase*, *decrease*, or *not affect* the proportional band of the controller?
- Will this alteration *increase*, *decrease*, or *not affect* the bias value in the controller's equation?
- Will this alteration *increase*, *decrease*, or *not affect* the time it takes for the controller's output to fully respond to a sudden change in PV or SP signal?
- Assuming the controller did a fine job controlling the process before this component change, describe how this alteration will affect the quality of control:

  file i01767

Question 53

A process uses two split-ranged control valves (FV-82a and FV-82b, with "progressive" ranges) to control the flow of hydrogen gas entering a chemical reactor. Valve (FV-82a) is the first of the two hydrogen valves to open (wide-open when FC-82's output is 50%), while valve FV-82b is the last to open (just beginning to open when FC-82's output is 50%). The graphic display on the DCS is supposed to provide operators with a visual indication of the process, the proportion controller, and both valve positions:



This graphic display, however, is not complete. The engineer forgot to program it to display the individual positions of valves FV-82a and FV-82b. The way it stands right now, the operator can see the controller's output signal (shown here at 34%), but cannot tell what the individual stem positions are for each of the two split-ranged valves. This task has been left to you!

Write a formula for calculating each valve's position based on the output value from controller FC-82. These formulae will be entered into the DCS to provide a display to the operator of each valve's stem position. You may refer to the controller's output signal value as x in each formula if you prefer:

Position of valve FV-82a =

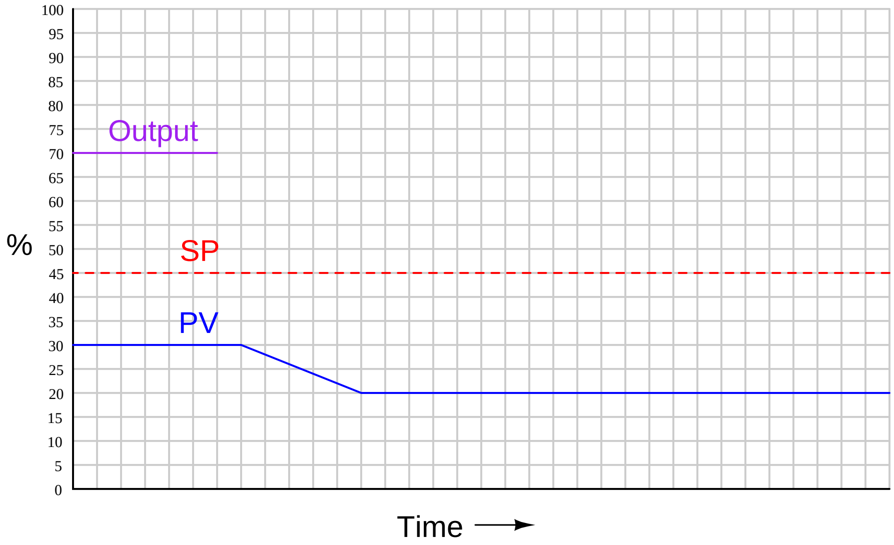
Position of valve FV-82b =

Don't worry about limiting these calculated values to prevent nonsense numbers like $< 0\%$ and $> 100\%$, because this value-limiting can be easily programmed into the DCS display software. Just write mathematical formulae to properly predict the two valve positions within their normal ranges.

file i01521

Question 54

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

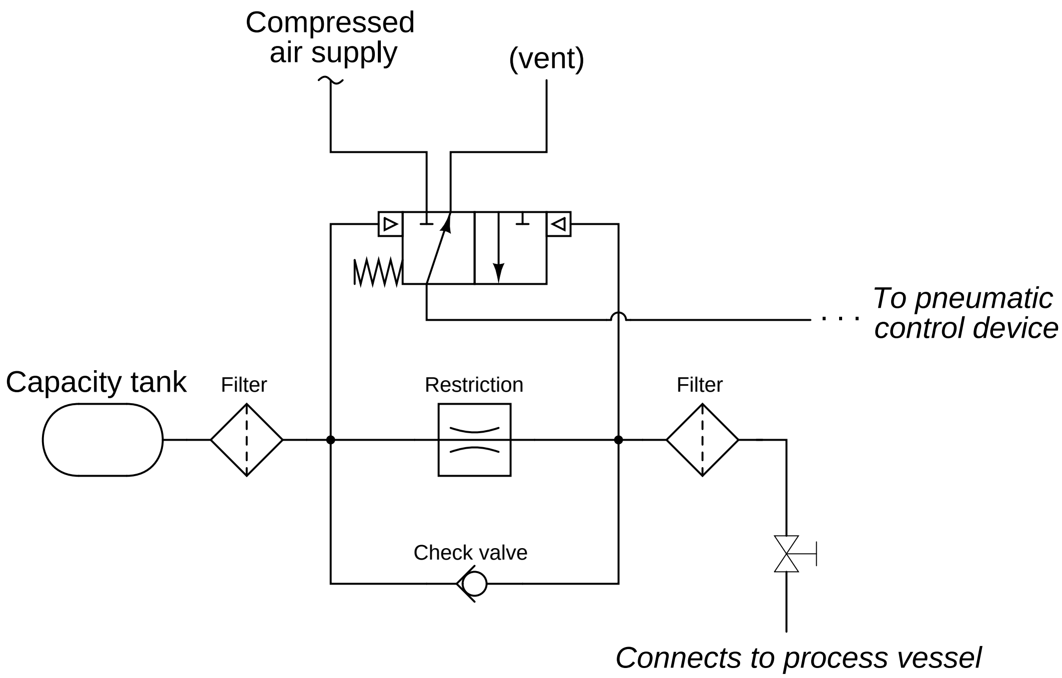


Assume *reverse* control action.

file i03755

Question 55

This schematic diagram shows a pneumatic sensing mechanism (based loosely on the Bettis DeltaMatic pipeline valve shutoff system) designed to take action when the gas pressure inside of a process vessel begins to change at a sufficient *rate* over time:



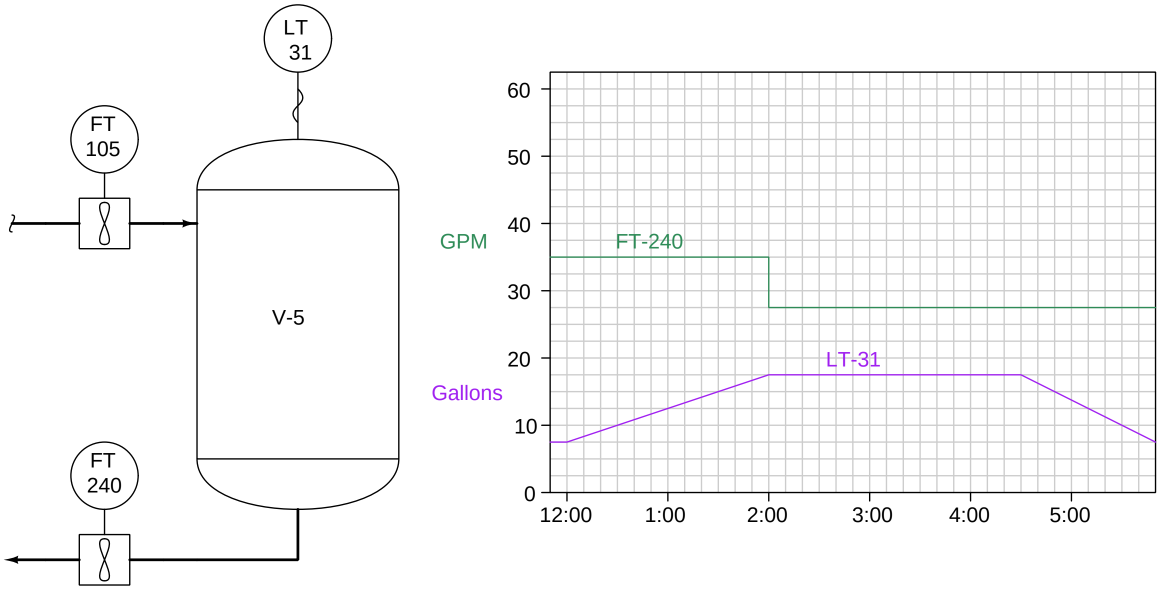
Analyze this diagram, then answer the following questions:

- Does this mechanism activate (i.e. switch out of its "normal" state) when the process pressure's rate of change *rises* quickly over time, *falls* quickly over time, or rapidly changes in *either* direction?
- Identify what would have to be altered in this mechanism to make the previous answer different (i.e. make the mechanism respond to a different direction of process pressure change).
- Identify the direction of air flow through the line leading to the "pneumatic control device" when the process pressure is not changing at all.
- Identify one component that would have to be altered in this mechanism to make it *less sensitive* to rates of process gas pressure change over time, and also identify how that component would have to be altered (e.g. size, shape, etc.).

file i04429

Question 56

Calculate the rate of liquid flow coming into process vessel V-5 at 1:30 PM, and also at 3:45 PM, based on the information shown here:



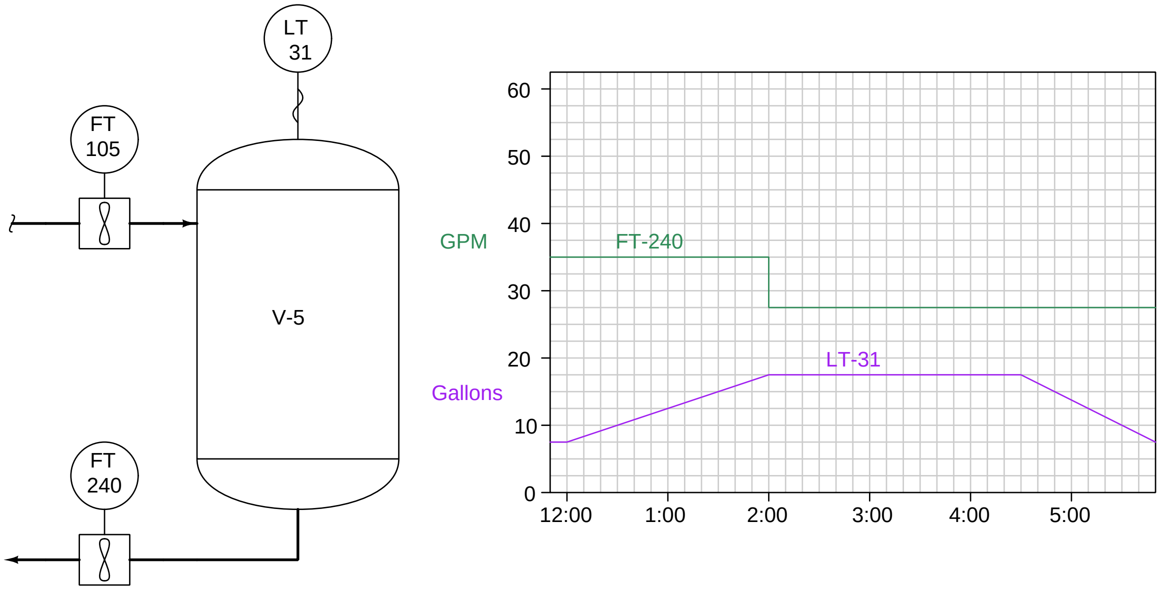
Q_{in} @ 1:30 PM = __________ GPM

Q_{in} @ 3:45 PM = __________ GPM

file i02890

Question 57

Calculate the volume of liquid discharged from this vessel between 1:00 PM and 4:00 PM based on the information shown here:

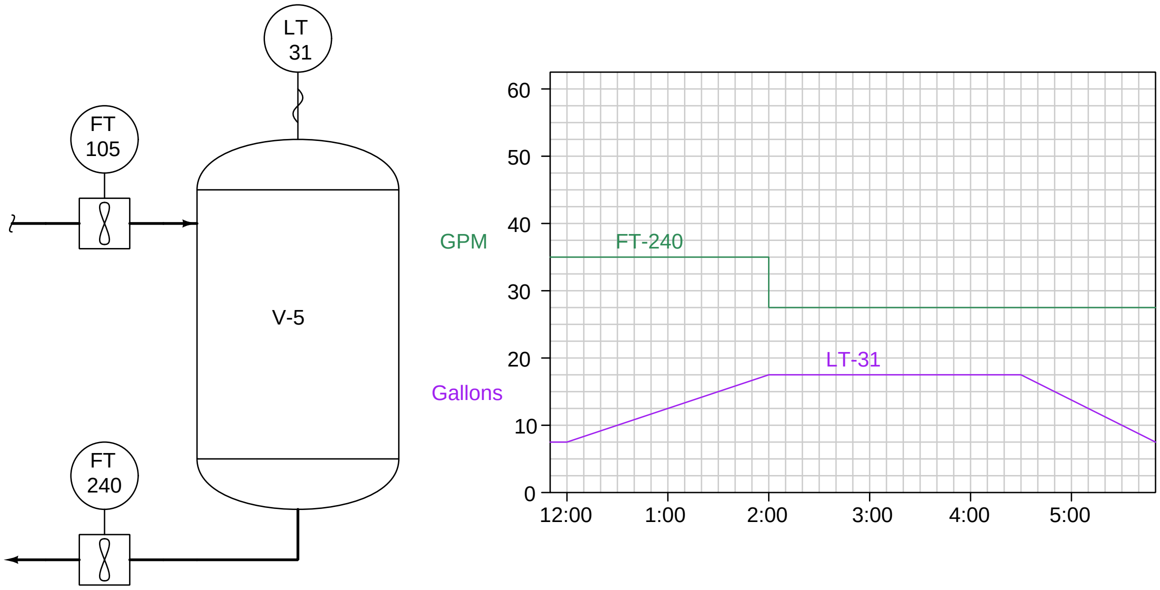


$V_{discharged}$ between 1:00 PM and 4:00 PM = ___________ gallons

file i02889

Question 58

Calculate the amount of liquid lost from the vessel between 4:30 PM and 5:30 PM based on the information shown here:

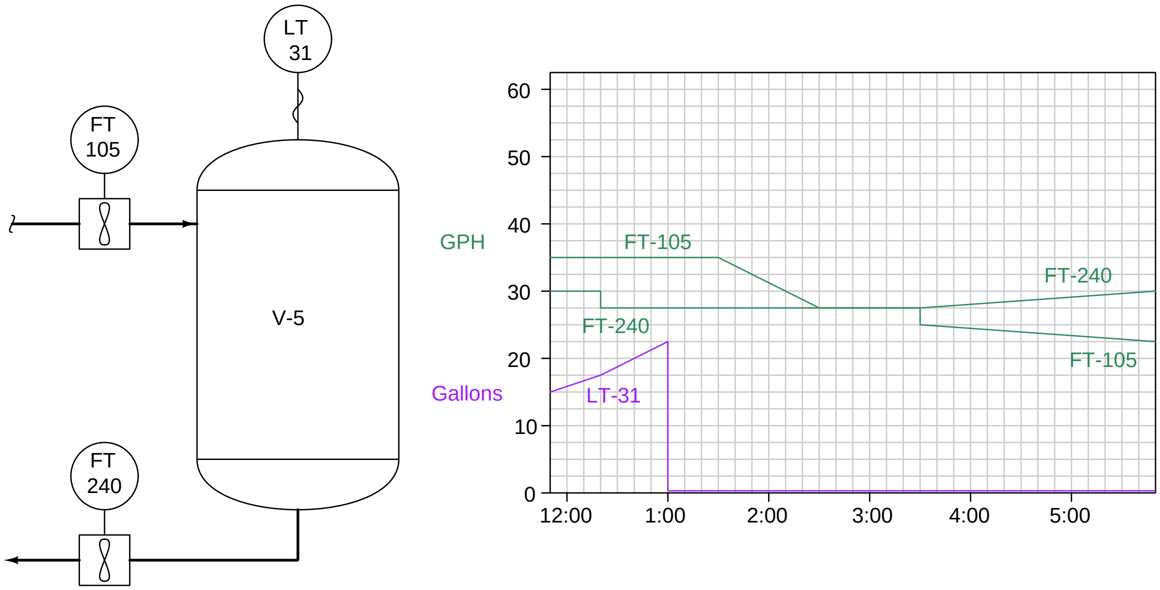


V_{lost} between 4:30 PM and 5:30 PM = __________ gallons

file i02888

Question 59

The level transmitter (LT-31) on vessel V-5 failed at 1:00 PM today, its signal going all the way to zero even though there was still liquid inside the vessel. You are asked to calculate the amount of liquid in the vessel at 3:00 PM based on the flow trends shown (in units of gallons per *hour*):



V @ 3:00 PM = __________ gallons

file i02886

Question 60

Question 61

Describe your recent learning experiences succinctly enough to be included as a line-item in your résumé. Identify how this learning has made you more marketable in this career field. Be as specific as you can, and feel free to include non-technical as well as technical learning in your description (e.g. project management, organization, independent research, troubleshooting, design, software applications, electric circuit analysis, control theory, etc.)!

Identify any knowledge and/or skill areas in which you would like to become stronger, and describe practical steps you can take to achieve that goal. Don't limit yourself to just technical knowledge and skills, but consider behavioral habits (e.g. patience, attention to detail, time management) and general academic abilities (e.g. reading, writing, mathematics) as well. If you find yourself struggling to achieve a goal, don't just say "I'll work harder" as your plan of action – identify something *different* you can do to achieve that goal.

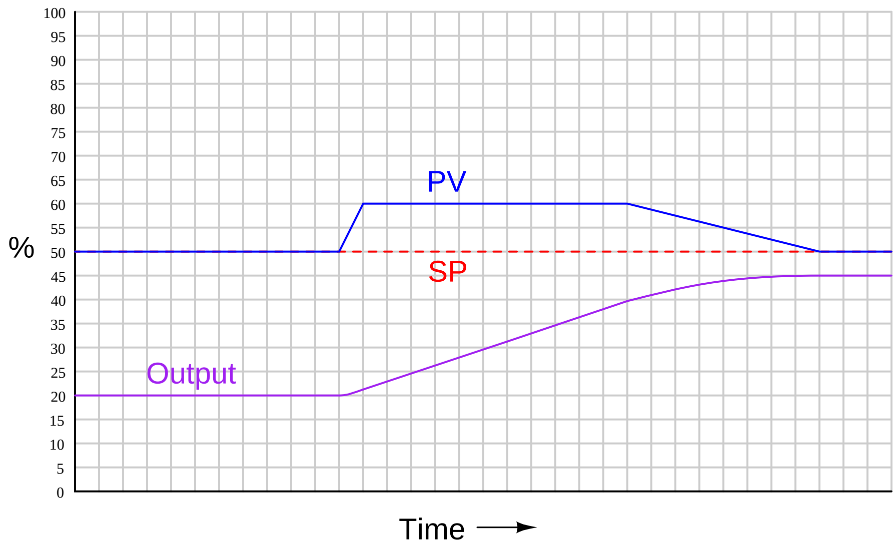
Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

A helpful guide to traits and skills valued by employers are the "General Values, Expectations, and Standards" pages near the beginning of this worksheet. Another is the "So You Want To Be An Instrument Technician?" career guide.

file i00999

Question 62

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



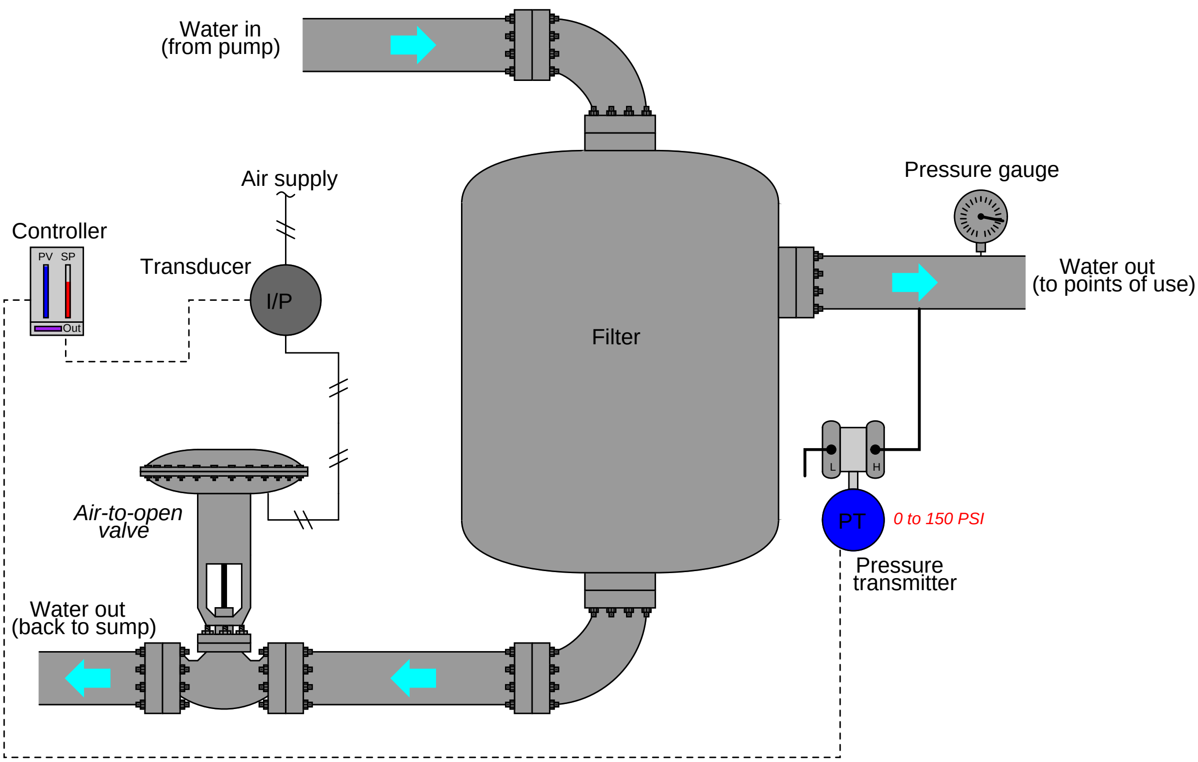
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if the PV had only deviated by 5% from the setpoint rather than a full 10% (for the same duration in time).
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03308

Question 63

This water filter's discharge pressure is controlled by a PID controller, throttling the amount of water returned to the sump:



An operator tells you there is a problem with this system, though: the controller faceplate registers 146 PSI of water pressure, with a setpoint at 100 PSI. You happen to notice that the bargraph on the controller faceplate showing output is at 100%. Another operator in the field (near the exchanger) reports via radio that the control valve stem is at the "closed" position, and that the pressure gauge mounted on the filter's discharge line registers 143 PSI.

Another instrument technician happens to be with you, and recommends you connect a multimeter to the transmitter's signal wiring to measure the 4-20 mA signal. Explain why this test would be a waste of time, and propose a better test for helping to pinpoint the location of the fault.

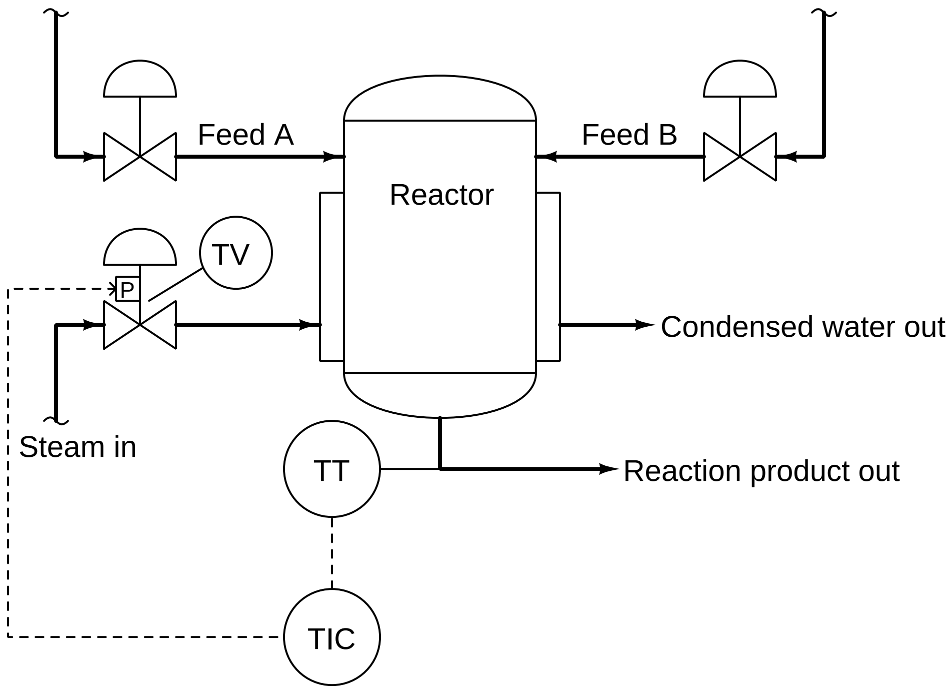
Suggestions for Socratic discussion

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which field variables correspond with their respective controller faceplate displays, and which do not. Apply this comparative test to the scenario described, and use it to explain why the technician's proposed test was probably not the best first step.
- Determine the proper action for this loop controller (direct or reverse).
- For those who have studied PID tuning, qualitatively determine appropriate P, I, and D parameters for the loop controller based on how you would expect this process to respond.

file i00434

Question 64

In this process, two chemical streams are mixed together in a reactor vessel. The ensuing chemical reaction is endothermic (heat-absorbing) and must be heated by steam to ensure the solution is at the necessary temperature to thoroughly react. A temperature transmitter (TT) senses the reaction product temperature and sends a 4-20 mA signal to a temperature indicating controller (TIC). The controller then sends a 4-20 mA control signal to the temperature valve (TV) to throttle steam flow:



First, identify the proper *action* of the temperature controller (either direct or reverse) assuming the temperature transmitter is direct-acting, the control valve is fail-open (air-to-close), and the positioner is configured for signal-to-close.

Then explain what would happen if the controller were improperly set for the *other* control action.

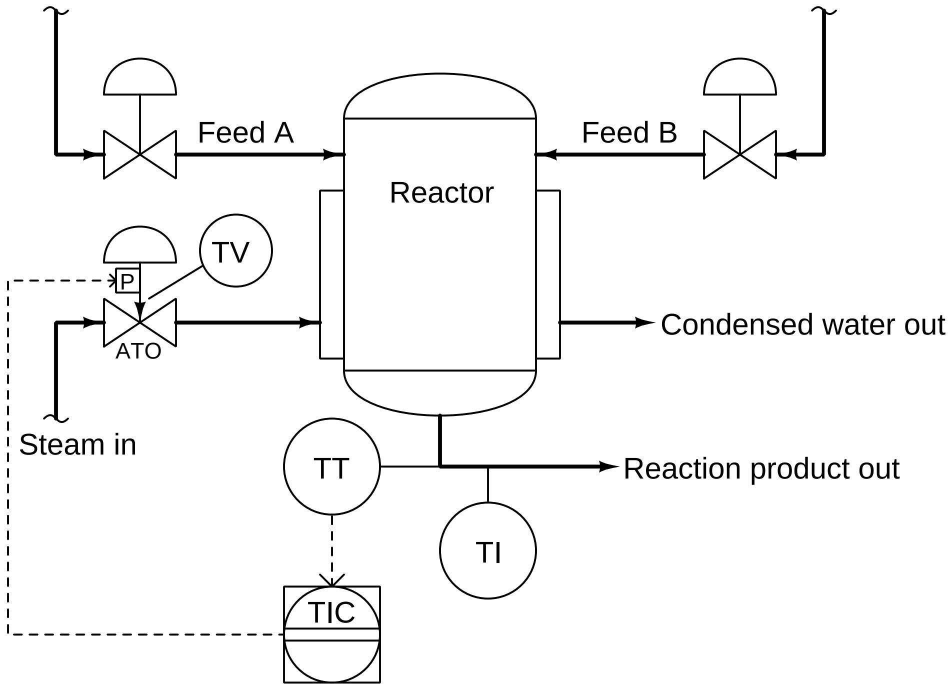
Suggestions for Socratic discussion

- What is the opposite of *endothermic*, and how might that type of process reactor temperature control be designed differently from this one?
- What would happen to the process temperature if the instrument air supply failed?
- What would happen to the process temperature if the temperature transmitter failed with a low signal?
- What would happen to the process temperature if the positioner's nozzle were to plug?
- How would the controller respond if the steam supply failed?
- How would the controller respond if the condensed water line were to plug?

file i04387

Question 65

In this process, two chemical streams are mixed together in a reactor vessel. The ensuing chemical reaction is endothermic (heat-absorbing) and must be heated by steam to ensure the solution is at the necessary temperature to thoroughly react. A temperature transmitter (TT) senses the reaction product temperature and sends a 4-20 mA signal to a temperature indicating controller (TIC). The controller then sends a 4-20 mA control signal to the temperature valve (TV) to throttle steam flow:



Suppose the last instrument technician to calibrate the temperature transmitter made a mistake, and the transmitter consistently reads 15^o too hot. For example, if the reaction product temperature is actually 275^o F, the transmitter outputs a current signal corresponding to 290^o F.

Describe in detail the effect this mis-calibration will have on the performance of the heating system.

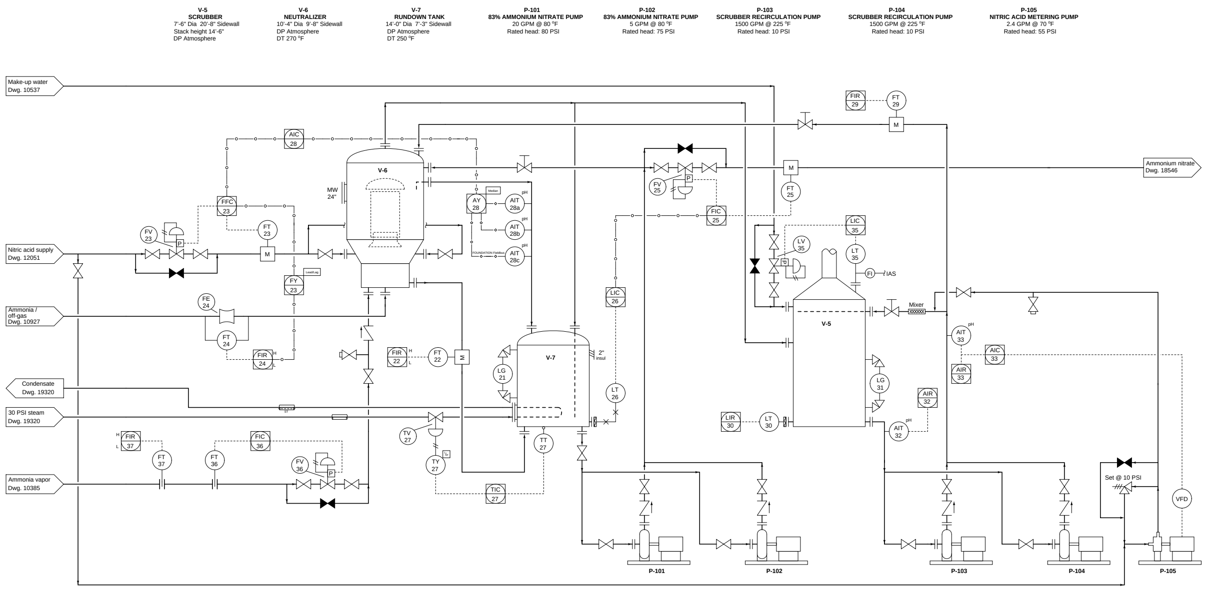
Suggestions for Socratic discussion

- Would this calibration error be apparent on the faceplate of the controller (i.e. an offset of 15 ^{o}F between PV and SP)? Why or why not?
- Explain how you could use your multimeter to discern whether the calibration error was in the controller's analog input (its ADC), or actually in the transmitter itself.
- Identify the proper controller action (i.e. either *direct* or *reverse*) for this process, and explain your method of analysis to make this determination.
- Identify some component alteration that would demand the *opposite* controller action (i.e. either *direct* now instead of *reverse*, or vice-versa).
- What would happen if Feed A valve suddenly failed closed?

file i04386

Question 66

In this process, ammonia vapor and nitric acid are combined in a chemical reactor vessel to form ammonium nitrate, one of the principal ingredients of synthetic fertilizer. A flow controller (FIC-36) regulates the flow of ammonia vapor into the reactor:



Suppose the last instrument technician to calibrate flow control valve FV-36 made a mistake, such that the valve stem position is 5% further open than it should be at all signal values. For example, if the controller sends a 25% (8 mA) signal to the control valve, it actually opens up to a stem position of 30%.

Describe in detail the effect this mis-calibration will have on the regulation of ammonia vapor flow.

Suggestions for Socratic discussion

- Perform a "thought experiment" where someone attaches a wooden block to the accelerator pedal of your car without your knowledge, so that the accelerator pedal will be pressed down further than you think it is for any given foot position. How will this affect your actual driving speed as you attempt to obey the speed limit?
- Why would a *regulated* flow rate of ammonia vapor be important in a process such as this?
- Explain why three pH transmitters (AIT-28a, AIT-28b, AIT-28c) are used to measure the neutralizer's effluent pH instead of just using one transmitter.
- Suppose the positioner on FV-25 fails so that the valve opens wide. How will this fault affect the liquid level in V-7 (the rundown tank)?
- Suppose the circuit breaker feeding electrical power to the VFD on pump P-105 trips. How will this fault affect variables in this process? Will any loop controllers attempt to compensate for the fault by responding with changes in output signal?
- LT-35 is a "bubbler" style of level sensor, slowly bubbling compressed air out the end of a submerged tube. The more liquid inside scrubber V-5, the more compressed air "backpressure" builds up inside the bubble tube, causing the pressure-sensing transmitter to register a greater liquid level. Suppose this "bubble tube" plugs at its very end (submerged inside the tank). How will this fault affect the actual level inside the scrubber?

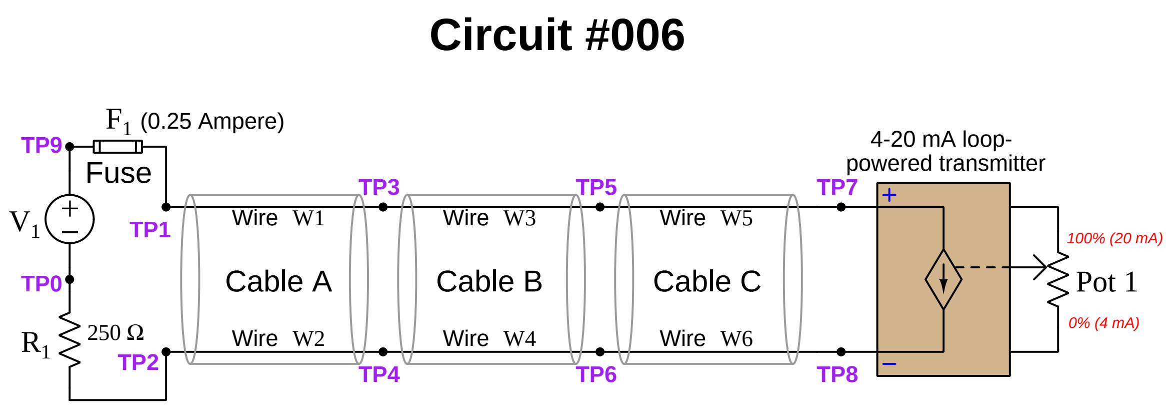
file i04388

Question 67

Simulated troubleshooting exercise

During today's session your instructor will have a computer set up to run an electric circuit troubleshooting simulation program called `TROUBLESHOOT`, so that you can practice your troubleshooting skills on a simulated 4-20 mA loop-powered transmitter circuit.

The circuit we will be simulating today is a loop-powered 4-20 mA transmitter with a DC voltage source as the power supply. This is circuit number `006` selectable within the `TROUBLESHOOT` simulating program:



Nominal component values:

V_1 = _______ Volts +/- _____ %

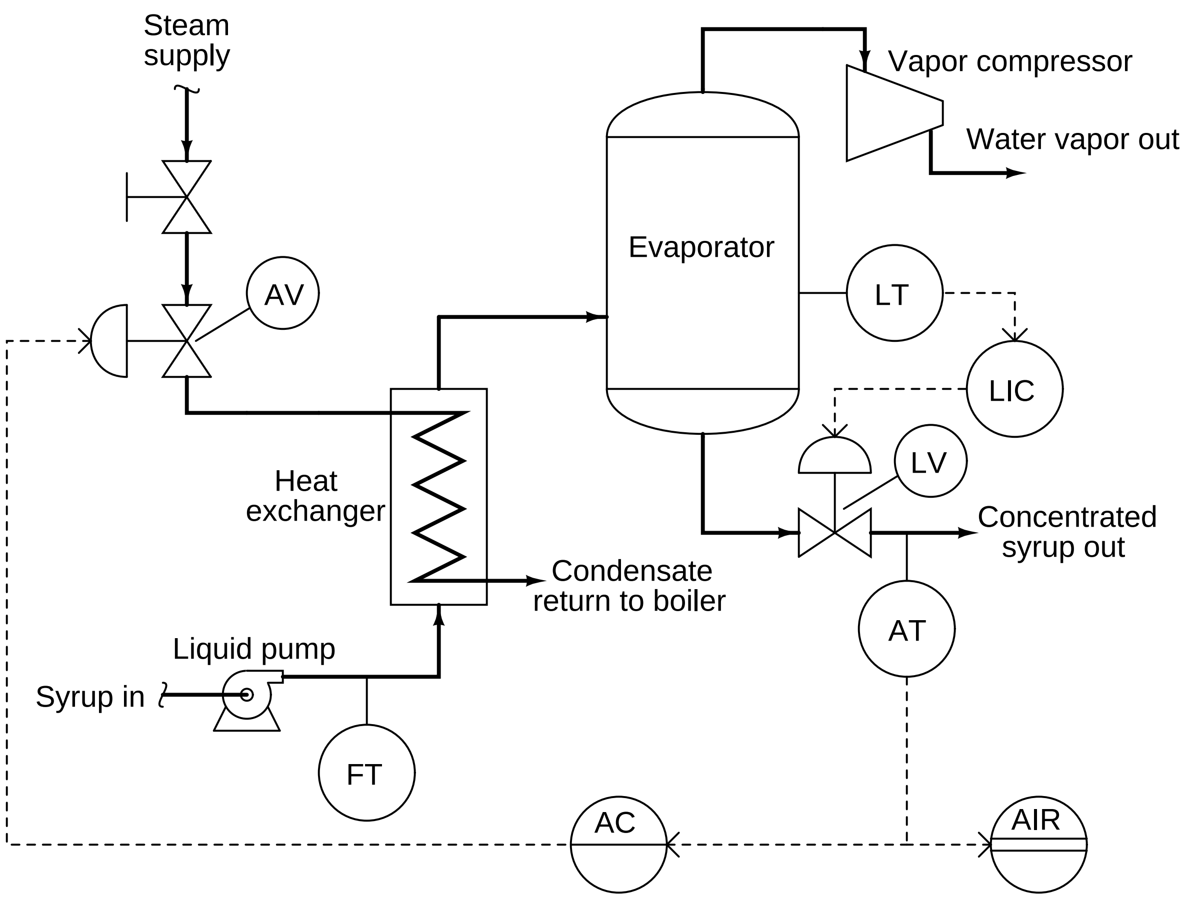
R_{pot1} = _______ Ohms +/- _____ %

Be ready to annotate measured values on this schematic diagram as you troubleshoot! You may find it convenient to bring a printed copy of this schematic diagram with you to the session for this purpose.

file i02850

Question 68

In this process, maple syrup is heated as it passes through a steam heat exchanger, then enters an evaporator where the water boils off. The purpose of this is to raise the sugar concentration of the syrup, making it suitable for use as a food topping. A level control system (LT, LIC, and LV) maintains constant syrup level inside the evaporator, while an analytical control system (AT, AIR, AC, and AV) monitors the sugar concentration of the syrup and adjusts steam flow to the heat exchanger accordingly.



Suppose the steam boiler is having problems, causing the steam supply temperature to be less than what it normally is. Describe in detail the effect this boiler system problem will have on the performance of the analytical control system.

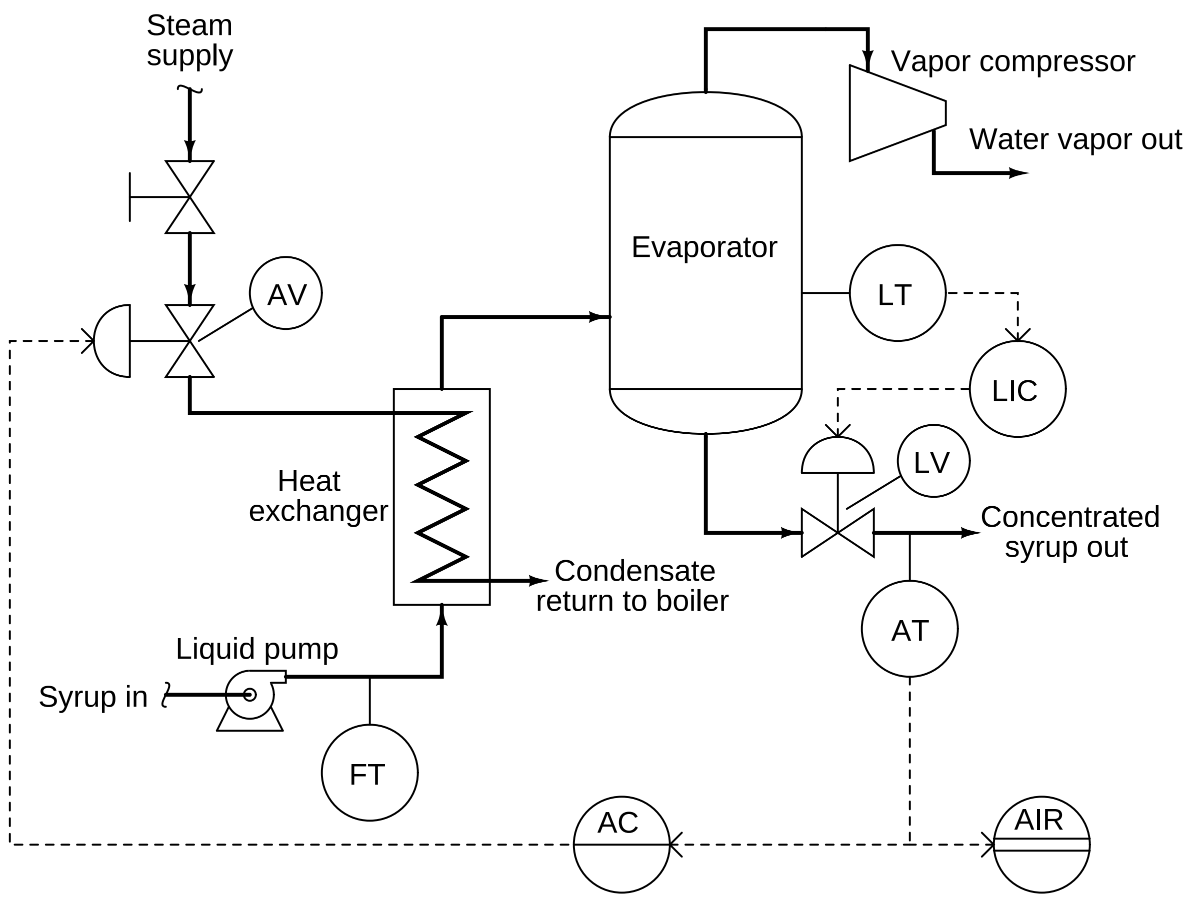
Suggestions for Socratic discussion

- Identify as many *loads* in this process as you can, determining the direction of influence each one has on each controlled variable.
- Suppose the heat exchanger begins to "foul" with solid deposits from the raw syrup, impeding the tranfer of thermal energy from the steam to the syrup. How would the control system respond to this process change? How could this problem be diagnosed without disassembling the exchanger?

file i04390

Question 69

In this process, maple syrup is heated as it passes through a steam heat exchanger, then enters an evaporator where the water boils off. The purpose of this is to raise the sugar concentration of the syrup, making it suitable for use as a food topping. A level control system (LT, LIC, and LV) maintains constant syrup level inside the evaporator, while an analytical control system (AT, AIR, AC, and AV) monitors the sugar concentration of the syrup and adjusts steam flow to the heat exchanger accordingly.



Suppose the level control valve (LV) fails completely open. Determine the effect this failure will have on the sugar concentration of the outgoing syrup.

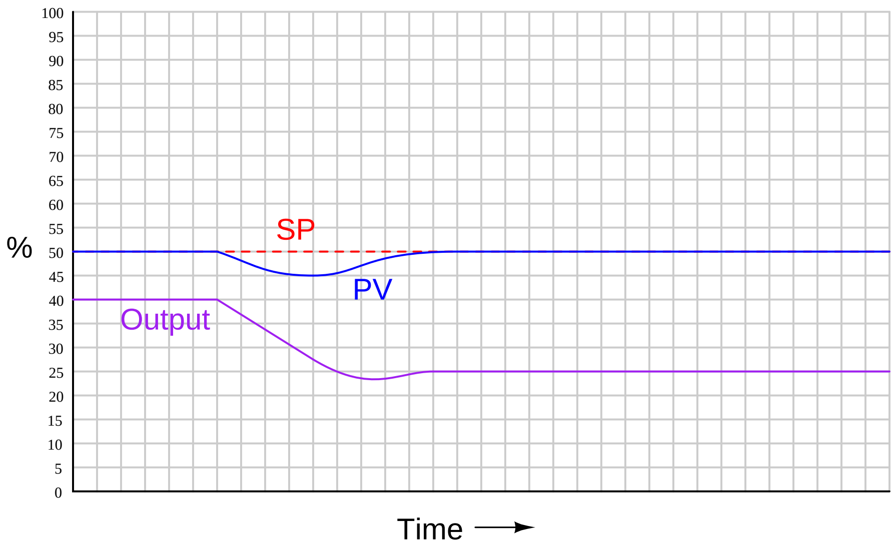
Suggestions for Socratic discussion

- Identify a few realistic reasons why the level control valve might fail all the way open in a process such as this.
- Suppose the compressor speed is suddenly reduced. What effect will this have on the control systems in this process, as well as syrup quality?

file i04389

Question 70

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



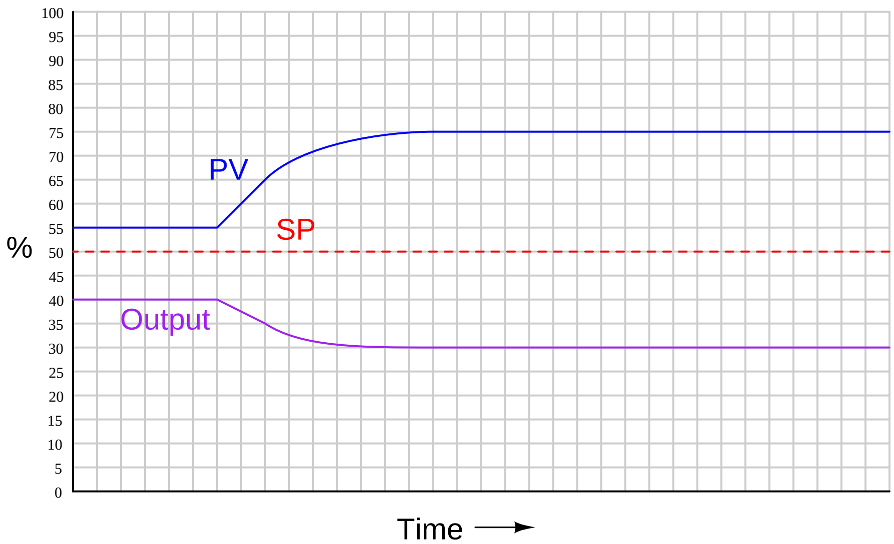
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- The output trend exhibits a slight "reversal" of motion just as the PV returns to equal SP. Explain why integral action *cannot* be responsible for the output signal's reversal in direction.
- Integral and Derivative control actions are often discernible from the *phase shift* they introduce between the output and PV "waves". Do you see any evidence of such phase shift in this trend? If so, which action (I or D) does that phase shift suggest?
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03769

Question 71

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



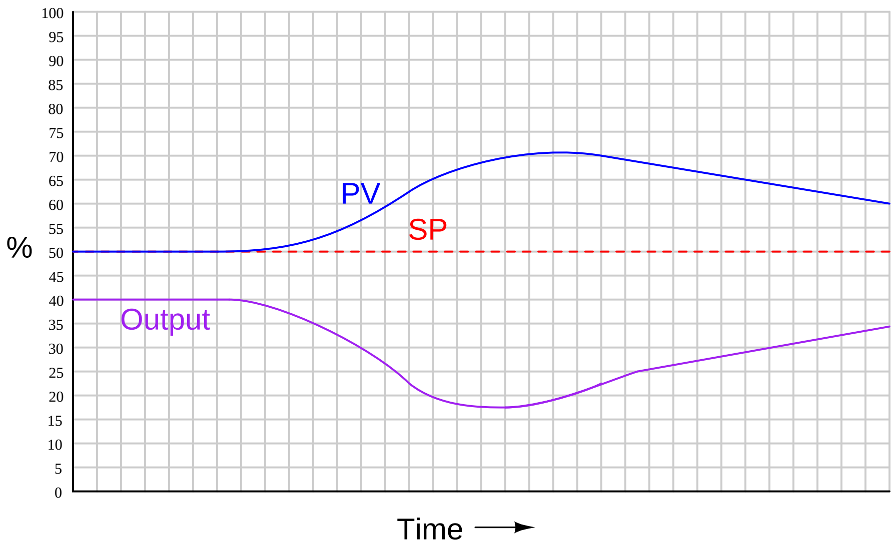
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask yourself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Re-draw the output trend if this controller implemented a full PID algorithm.

file i03768

Question 72

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. Based on what you see in this trend, determine whether the controller is direct or reverse acting, and also whether it implements a P-only, I-only, P+I, I+D, or P+D control algorithm.



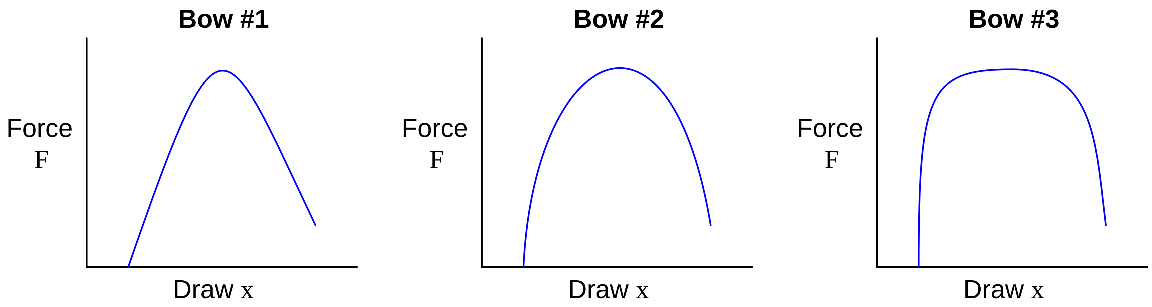
Suggestions for Socratic discussion

- A useful problem-solving technique to apply here is working the problem *backwards*: ask youself what the output trend would look like for each action (P, I, D) and then see what the given output trend most resembles.
- Integral and Derivative control actions are often discernible from the *phase shift* they introduce between the output and PV "waves". Do you see any evidence of such phase shift in this trend? If so, which action (I or D) does that phase shift suggest?

file i03770

Question 73

Compare the three force-draw curves for compound archery bows shown here:



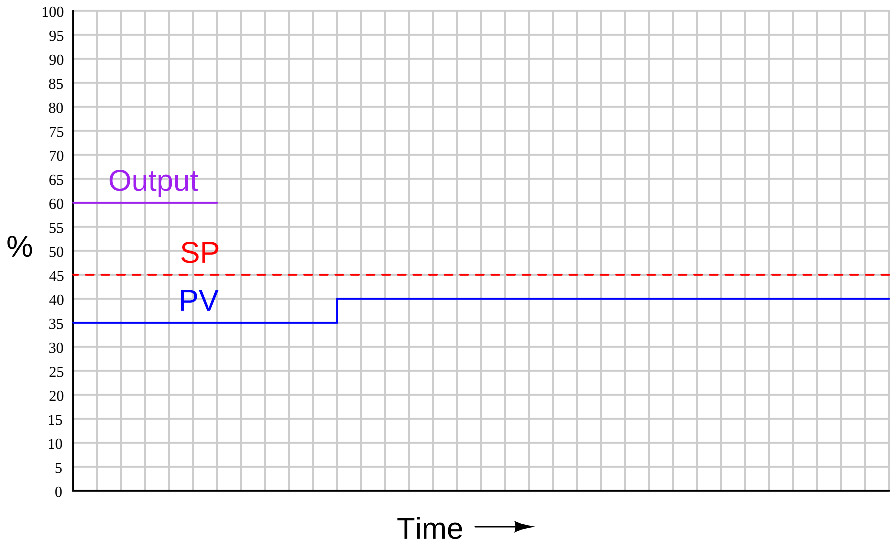
Each bow exhibits the exact same peak force, holding force, and draw length. The difference is in the shape of the cam mechanisms used to characterize each bow's draw. Examine the three force-draw curves shown here, then answer the following questions:

- Which bow will be the more tiring (fatiguing the archer) one to shoot, all other factors being equal?
- Which bow will accelerate the arrow most rapidly, all other factors being equal?
- Which bow will store more energy, all other factors being equal?
- Which bow will result in the greatest arrow velocity, all other factors being equal?
- Which bow will be easier for a novice archer to draw, all other factors being equal?

file i04432

Question 74

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

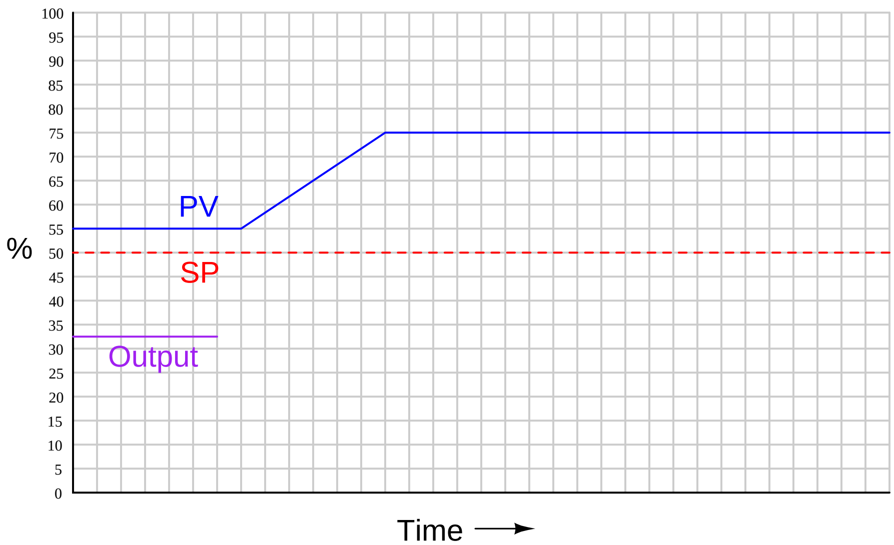


Assume *direct* control action.

file i03754

Question 75

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

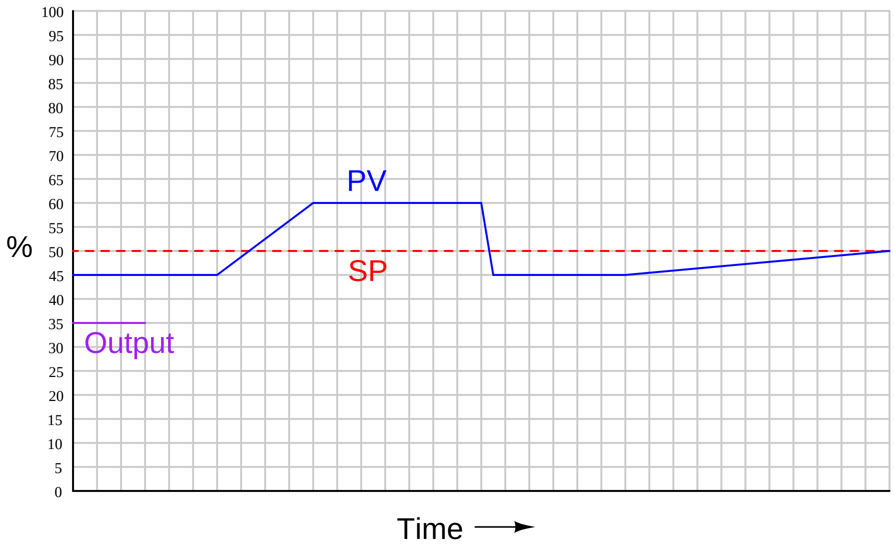


Assume *direct* control action.

file i03749

Question 76

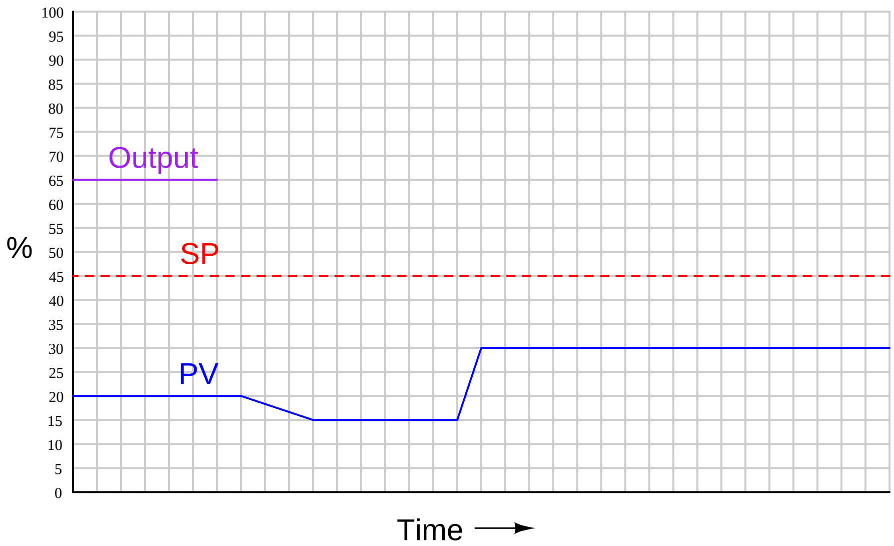
Qualitatively graph the response of a proportional-only controller over time to the following changes in process variable:



Assume *reverse* control action.
file i03278

Question 77

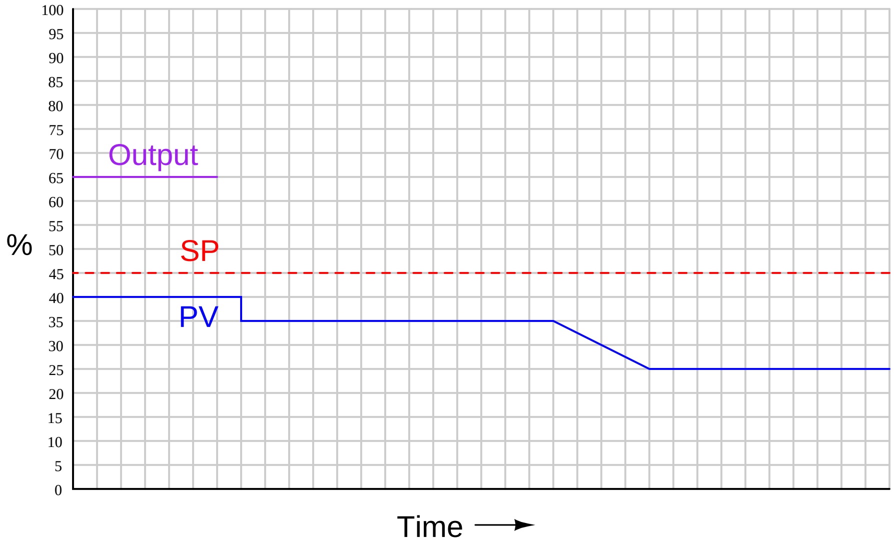
Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:



Assume *direct* control action.
file i03750

Question 78

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

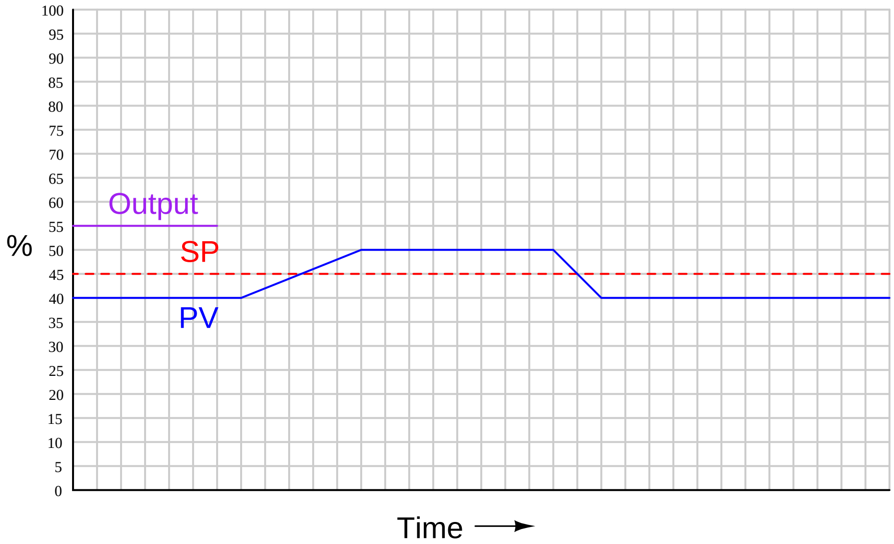


Assume *reverse* control action.

file i03751

Question 79

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

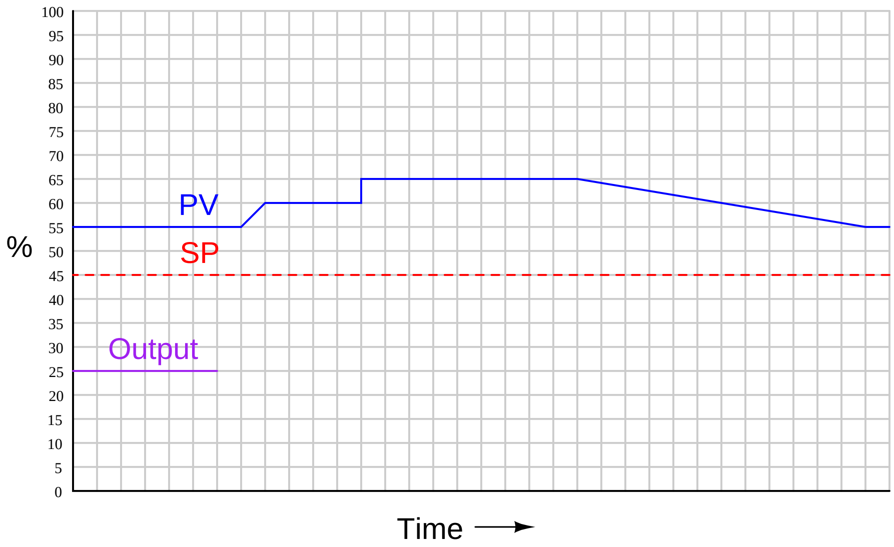


Assume *direct* control action.

file i03752

Question 80

Qualitatively graph the response of a proportional-plus-derivative controller over time to the following changes in process variable:

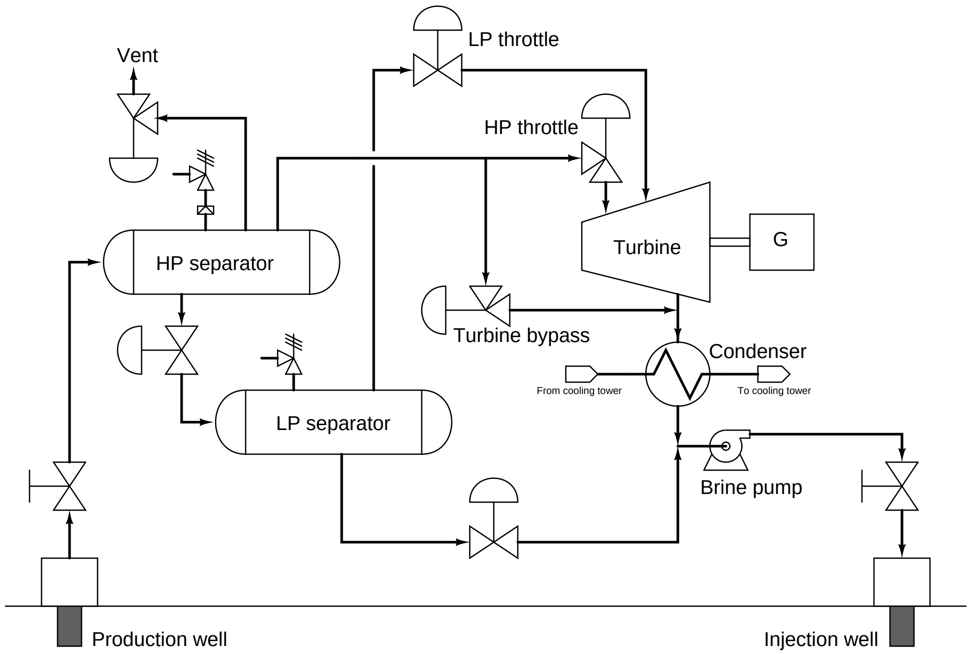


Assume *reverse* control action.

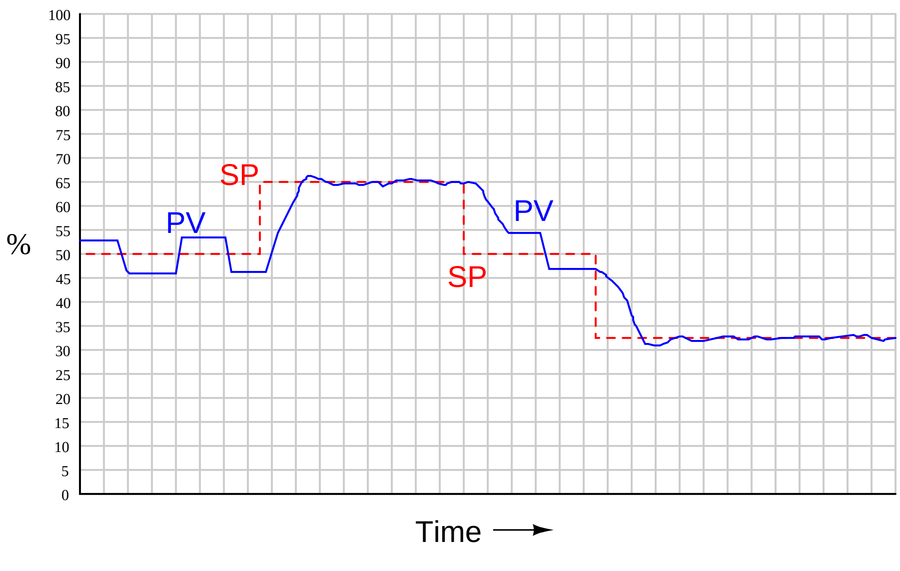
file i03753

Question 81

This is a PFD for a simple geothermal power plant, drawing a mixture of superheated steam and entrained minerals from a "production well" drilled deep into the earth, and injecting the condensed water and minerals into a second "injection well" to be re-heated by geothermal heat:



One day an operator notices something strange on the trend graph for the HP separator: the brine level in that separator seems to oscillate in a square-wave manner around the usual setpoint value, but stabilizes at any other setpoint value:

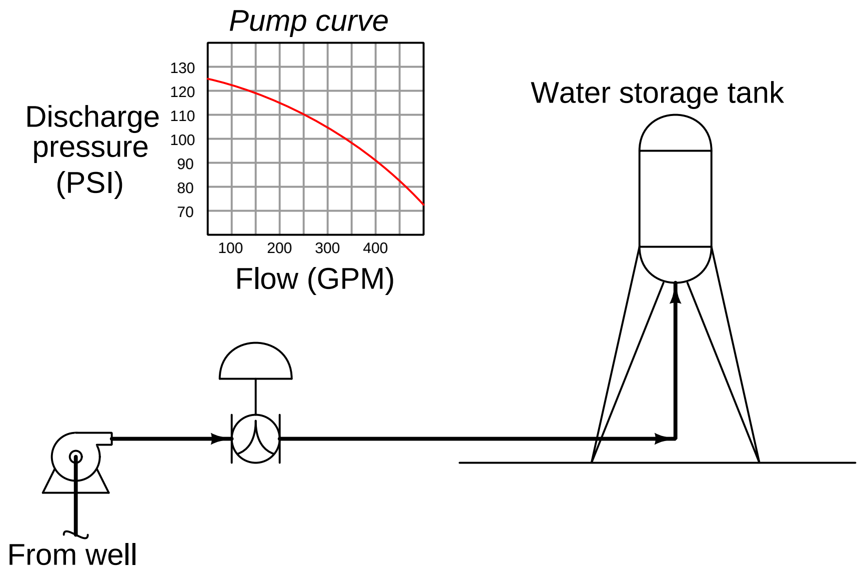


Identify a realistic cause for this strange level-control behavior, and then identify the next step you would take to diagnose and rectify the problem.

file i00070

Question 82

Calculate an appropriate control valve size (C_v and nominal pipe size) for this water flow control application, assuming a maximum flow rate of 300 GPM:

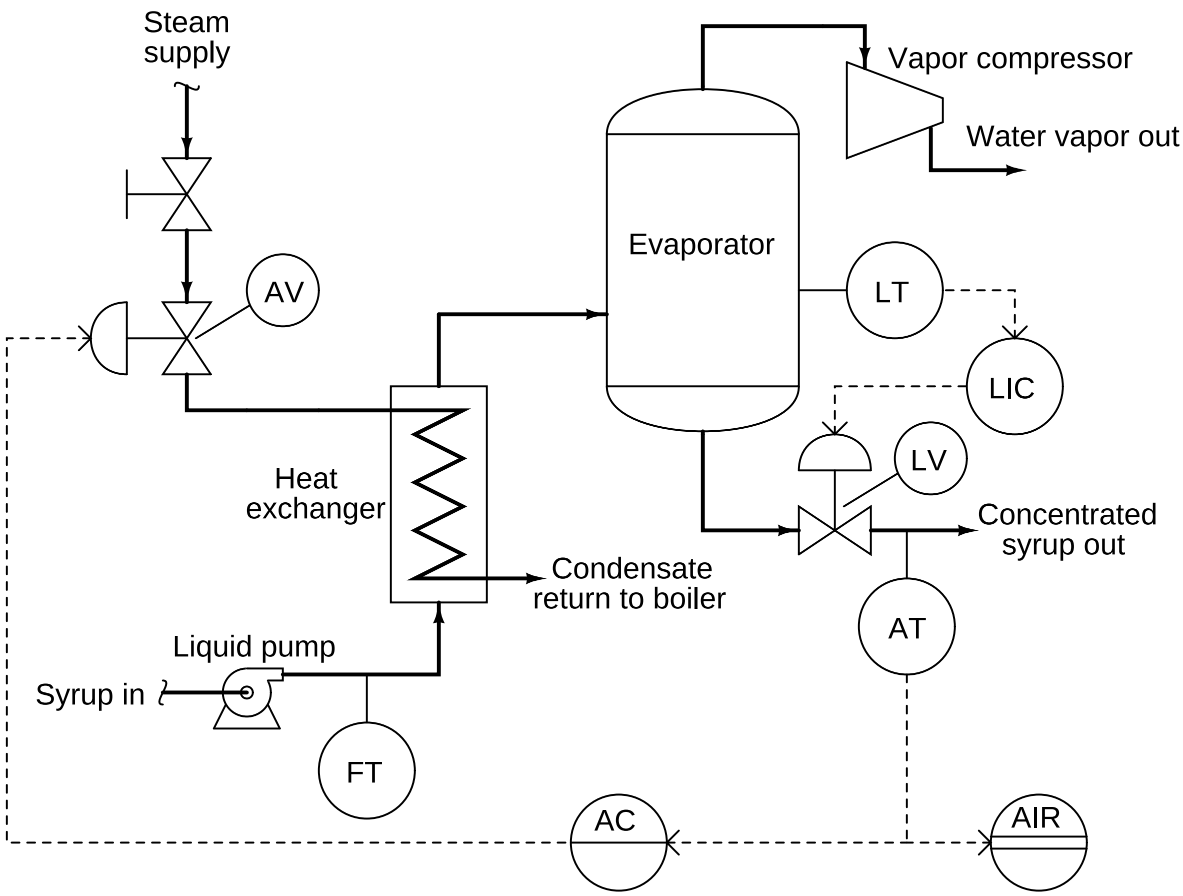


Assume a vertical distance of 195 feet from the pump discharge to the average water level in the storage tank.

file i01823

Question 83

In this process, maple syrup is heated as it passes through a steam heat exchanger, then enters an evaporator where the water boils off. The purpose of this is to raise the sugar concentration of the syrup, making it suitable for use as a food topping. A level control system (LT, LIC, and LV) maintains constant syrup level inside the evaporator, while an analytical control system (AT, AIR, AC, and AV) monitors the sugar concentration of the syrup and adjusts steam flow to the heat exchanger accordingly.



Suppose the analytical control loop has been optimally tuned, with the sugar concentration of the evaporated syrup holding precisely at setpoint. Now suppose the steam supplied to this process by the boiler suddenly increases in temperature. Explain what will happen to the syrup's sugar concentration over time, assuming two different control algorithms, all other factors being equal:

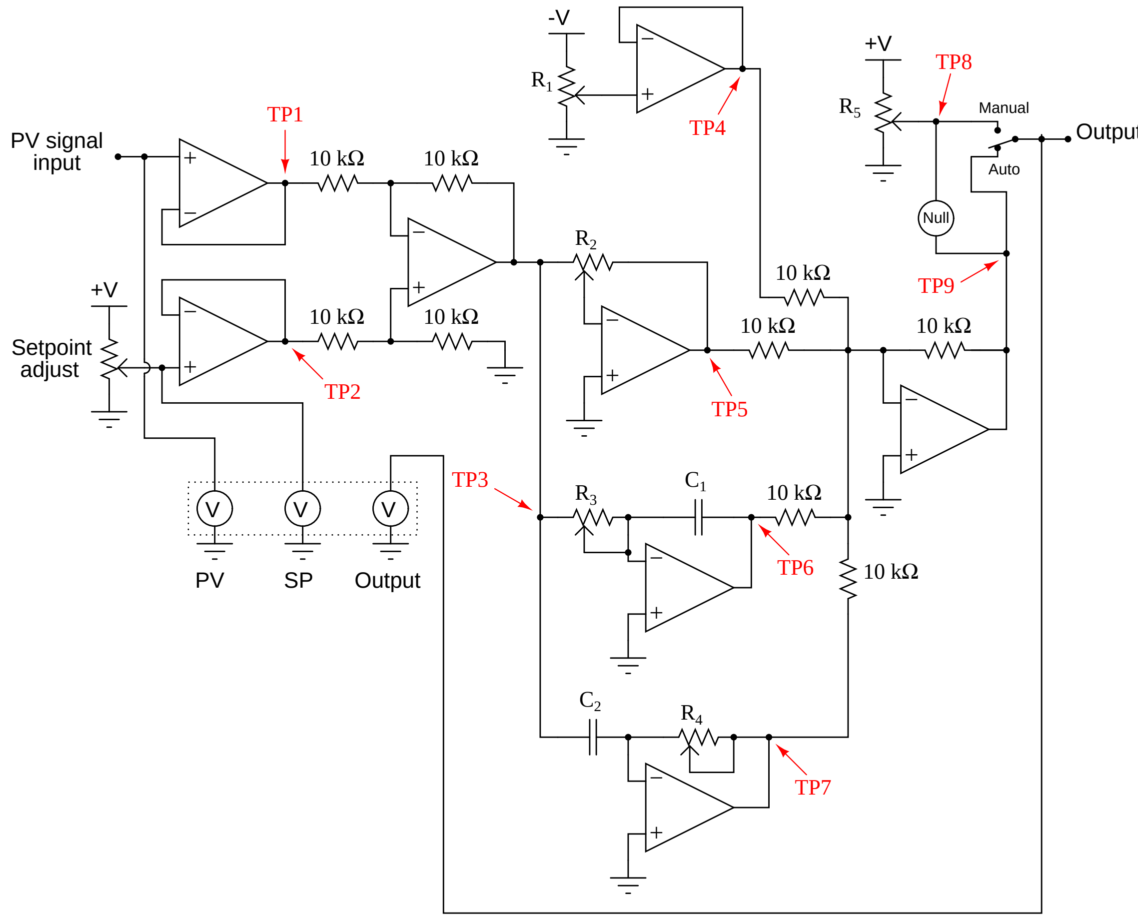
Analytical controller is proportional-only:

Analytical controller is proportional-plus-integral (P+I):

file i04314

Question 84

Shown here is the schematic diagram of a full "PID" analog electronic controller. Although it lacks the features of output and setpoint tracking, it does possess all three control terms: Proportional, Integral, and Derivative.



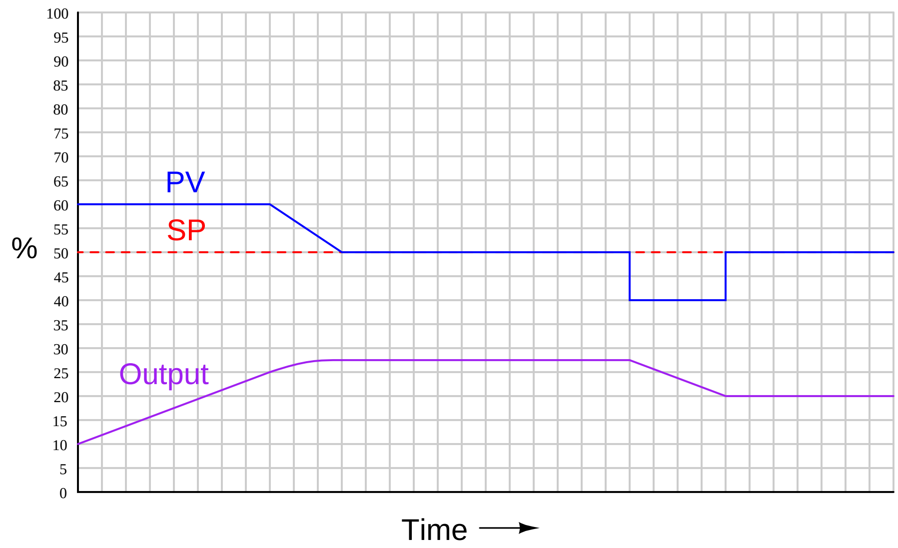
Based on your analysis of this circuit, answer the following questions:

- At what test point would you measure the controller's derivative term signal?
- At what test point would you measure the controller's error signal?
- At what test point would you measure the controller's setpoint signal?
- Which potentiometer adjusts the integral constant (τ_i)?
- Which potentiometer adjusts the derivative constant (τ_d)?
- Which capacitor is used to calculate the integral term?
- Will adjustment of the proportional constant affect either the integral or derivative responses?

file i01635

Question 85

The process trend shown below reveals a controller's response to the process variable signal and the setpoint. The controller implements a full PID algorithm of the "parallel" type (equation shown below):



$$m = K_p e + \frac{1}{\tau_i} \int e \, dt + \tau_d \frac{de}{dt}$$

Assuming each horizontal division is equal to 1 minute of time, determine the following tuning parameter values. Be sure to show all your mathematical work!

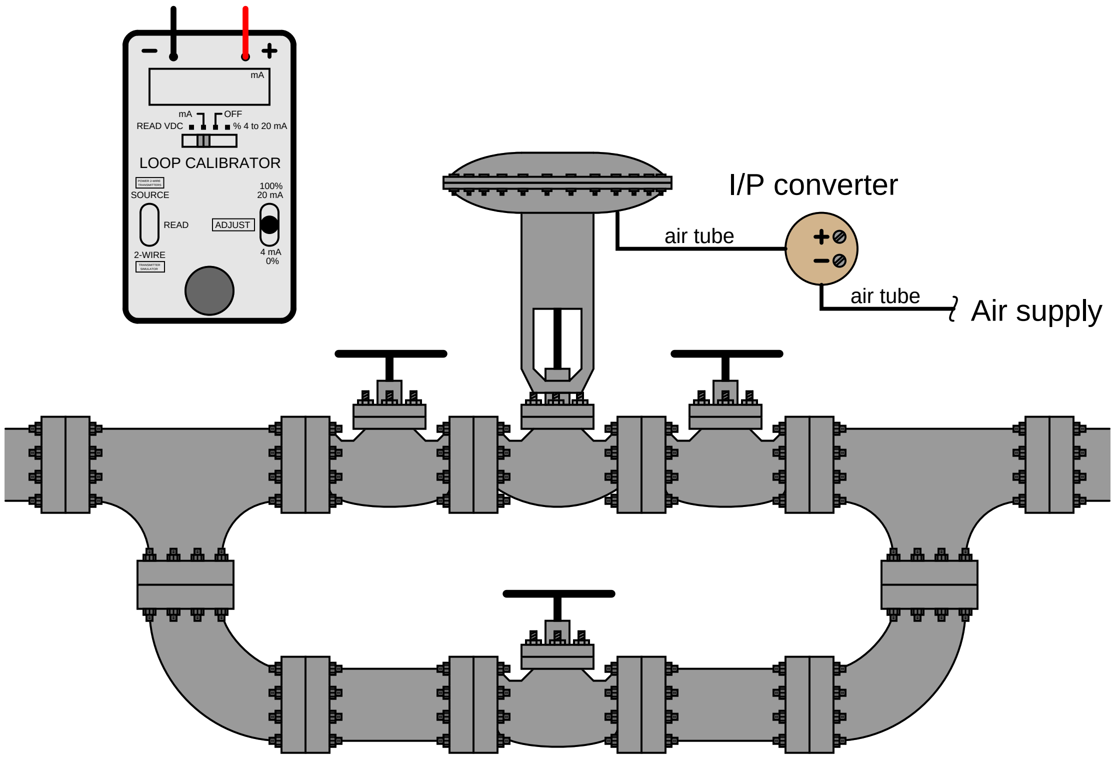
- *Direct* or *Reverse* control action
- $K_p =$ __________ (unitless gain)
- $\tau_i =$ __________ minutes
- $\tau_d =$ __________ minutes

Finally, explain how we can tell this controller is *not* implementing either the "Ideal" (ISA) or "Interactive" (Series) PID equation, based solely on the trend graph.

file i04315

Question 86

Suppose you are asked to check the calibration of a control valve before wires have been pulled to that location from a controller output. Process fluid is flowing through the pipe, bypassing the control valve until such time it is ready to be placed into service. The only piece of calibrated test equipment you have with you, though, is a 4-20 mA loop calibrator with an inoperative "Source" mode. The calibrator can measure and simulate 4-20 mA just fine, but it cannot *source* 4-20 mA.



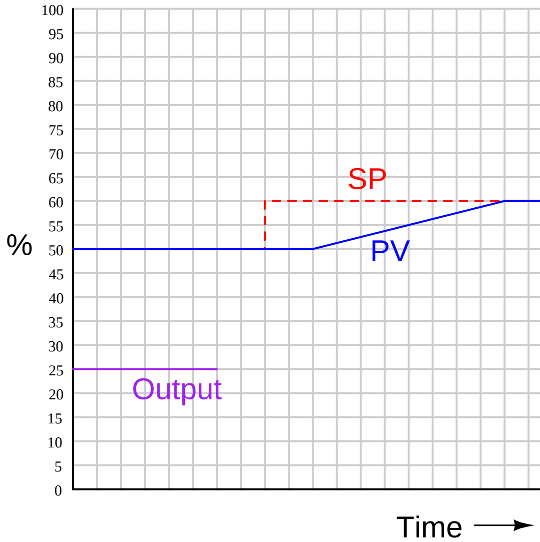
Show how you could still (creatively) use the loop calibrator to stroke the valve despite its lacking functionality – feel free to add any other electronic component(s) as necessary to make it work. Then, calculate the necessary current to send to the valve to make it open to 75%, assuming a split-range calibration of 12 mA (closed) to 20 mA (open).

Also, determine the necessary hand-valve settings (fully shut, fully open, or partially open) in order to bypass flow around the control valve but maintain operator (manual) control over the flow rate, and determine which (if any) of these manual valves must be *locked* and *tagged* for safety while the control valve remains unfit for service.

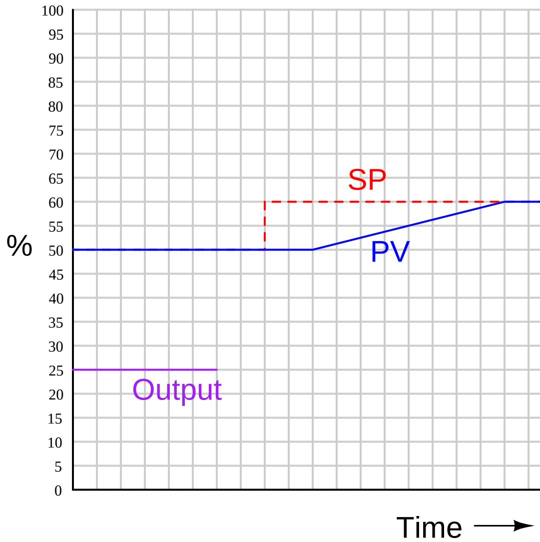
file i03617

Question 87

Qualitatively graph the individual proportional, integral, and derivative responses of a PID controller to the following input conditions, assuming *reverse* controller action. Use a solid line for proportional, a dashed line for integral, and a dotted line for derivative:



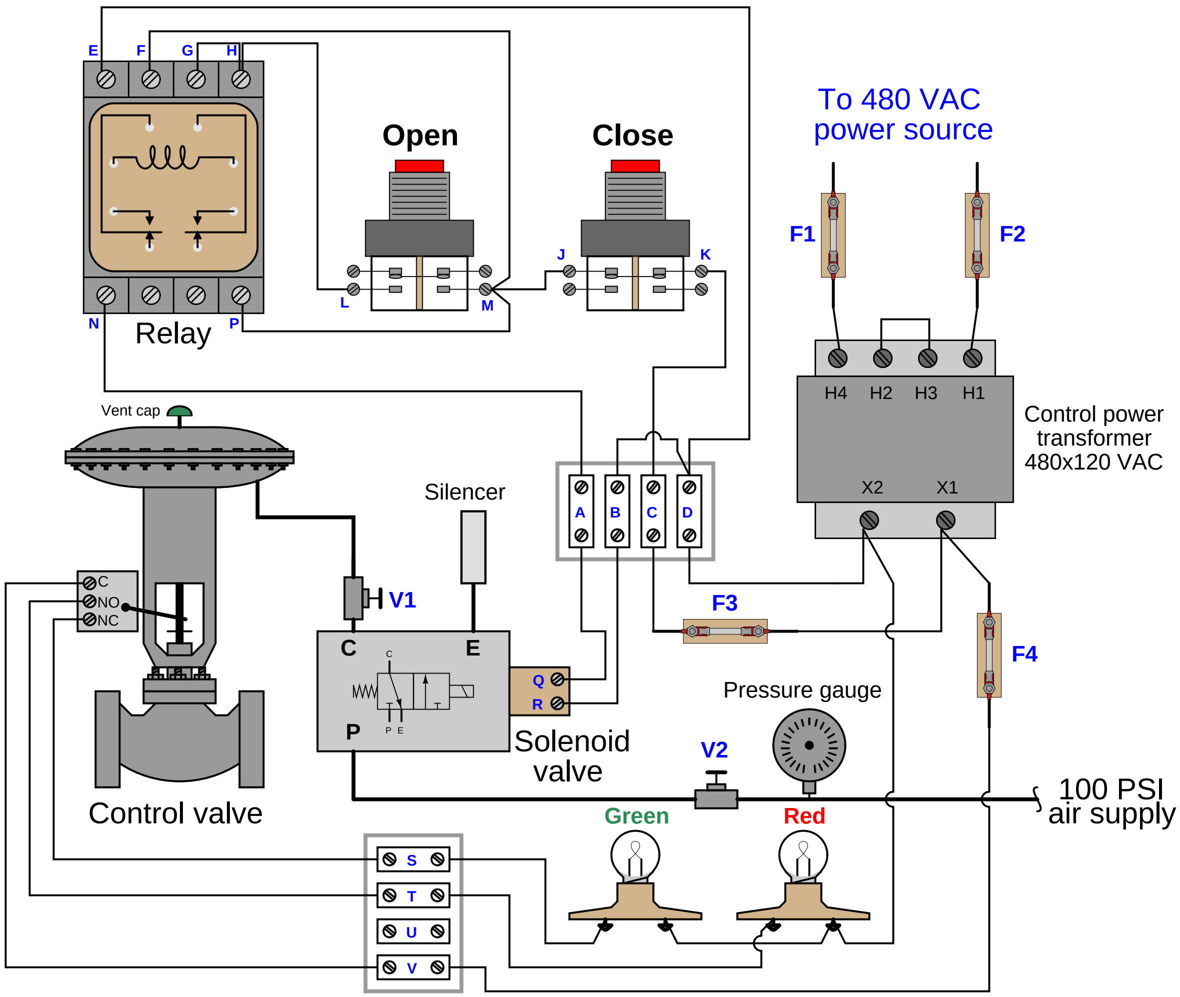
Then, draw a final graph of the controller's output, showing how the P, I, and D terms would combine to form a composite waveform:



file i03304

Question 88

Something is wrong with this valve control circuit. When the operator presses the "open" pushbutton, the valve position indicating lights still show it to be closed (green light on, red light off):



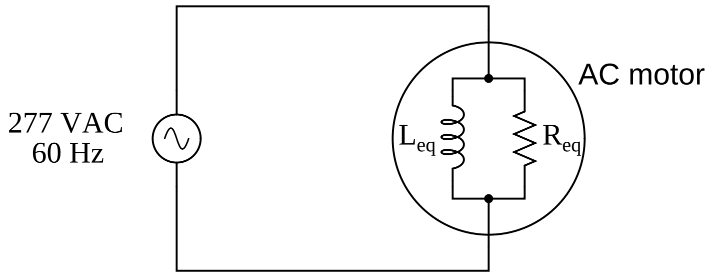
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure AC voltage across Fuse F1 with "Close" button pressed		
Measure AC voltage across Fuse F3 with "Close" button pressed		
Measure AC voltage across solenoid coil with "Open" button pressed		
Measure AC voltage across solenoid coil with "Closed" button pressed		
Measure AC voltage between terminals X2 and T with "Open" button pressed		
Measure AC voltage between terminals L and D with "Open" button pressed		
Check air supply pressure (look at pressure gauge)		

file i01564

Question 89

An AC electric motor under load can be considered as a parallel combination of resistance and inductance:

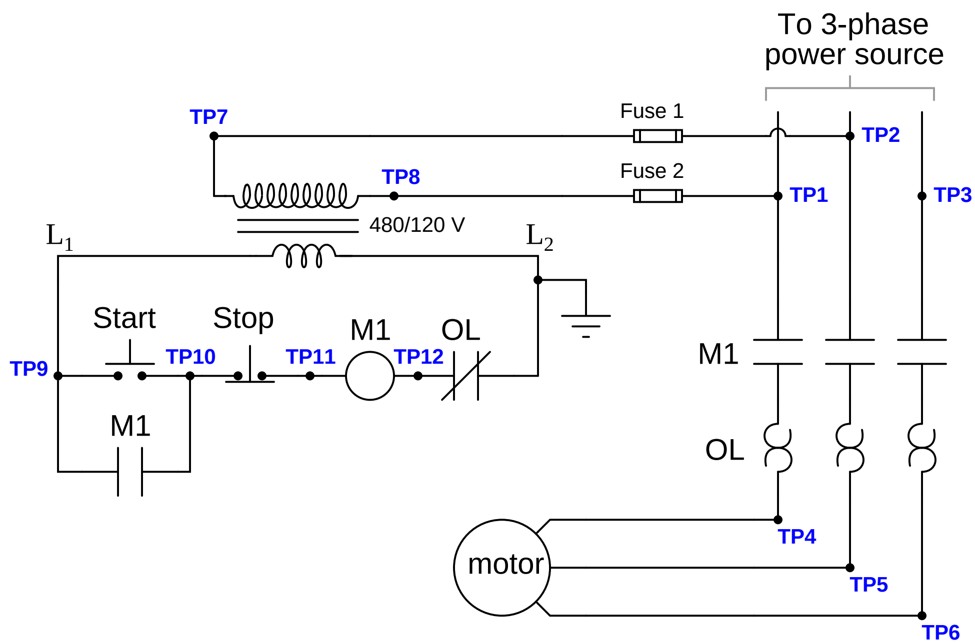


Calculate the equivalent inductance (L_{eq}) if the measured source current is 27.5 amps and the motor's equivalent resistance (R_{eq}) is 11.2 Ω.

file i01059

Question 90

The following motor control "bucket" has a problem. When the "Start" button is pressed, the motor refuses to start, although an audible "clunk" may be heard from the contactor when the "Start" switch is pressed, and again when the "Stop" switch is pressed:



Using your digital voltmeter, you measure 480 volts AC between TP2 and TP3 with the "Start" switch pressed. From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted). The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted

1.
2.

- Circuit elements that must be functioning properly

1.
2.

file i03201

Question 91

Lab Exercise

Your task is to commission, document, and successfully operate a process controlled by a recording PID controller. Several alternative process types exist and are documented in subsequent pages. The working process you commission will be used in future lab exercises this quarter to meet other learning objectives, which means you will *not* disassemble this project at the completion of these lab objectives as you normally would.

The following table of objectives show what you and your team must complete within the scheduled time for this lab exercise. Note how some of these objectives are individual, while others are for the team as a whole:

Objective completion table:

Performance objective	**Grading**	**1**	**2**	**3**	**4**	**Team**
Team meeting and prototype sketch	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Simulated troubleshooting of 4-20 mA circuit	mastery					– – – –
Trend graph displays PV and Output	mastery	–	–	–	–	
PV alarms defined and enabled	mastery	–	–	–	–	
Process exhibits good control behavior	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –

The "proportional" score for this activity is based on the number of attempts require to master each objective. Every failed attempt is marked by a 0, and every pass by a 1. The total number of 1 marks divided by the total number of marks (both 1's and 0's) yields a percentage value. Team objectives count as part of every team member's individual score. The *Safety and professionalism* deduction is a flat −10% per instance, levied on occasions of unprofessional or unsafe conduct.

It is essential that your team plans ahead what to accomplish each day. A short (10 minute) team meeting at the beginning of each lab session is a good way to do this, reviewing what's already been done, what's left to do, and what assessments you should be ready for. There is a lot of work involved with building, documenting, and troubleshooting these working instrument systems!

As you and your team work on this system, you will invariably encounter problems. You should always attempt to solve these problems as a team before requesting instructor assistance. If you still require instructor assistance, write your team's color on the lab whiteboard with a brief description of what you need help on. The instructor will meet with each team in order they appear on the whiteboard to address these problems.

Lab Exercise – objectives and expectations

Each objective is assessed at the *mastery* level, which means it is not complete until it meets *all* expectations. Re-tries are allowed, but failed attempts will be recorded and factored into your score for this lab exercise.

Team meeting and prototype sketch

Read the lab exercise documentation and discuss with your teammates the objectives to be achieved and the time allotted to do so. Formulate a plan to achieve these objectives and draft a prototype design for the system you intend to build. Then, meet with your instructor to present your team's action plan and prototype design. *This prototype sketch should be annotated with all expected physical parameters (e.g. voltage polarities, current directions, fluid pressures, etc.).* Be prepared to answer all manner of questions about your team's goals, planned schedule of work, available resources, and prototype design, including analysis of the design for specific faults and condition changes. Do not begin construction until your design has been analyzed and approved! Note that multiple meetings may be required if the instructor's assistance is needed to select components influencing your design.

Circuit design challenge

Sketch a correct circuit for a 4-20 mA instrument "loop" based on random instrument selections by the instructor and reference manuals for each instrument.

Final loop diagram and system inspection

Create a complete loop diagram of your team's completed system according to the ISA 5.1 standard, then show that the constructed system meets or exceed all standards described in the lab exercise documentation.

Troubleshooting simulation

Logically diagnose the nature and location of a fault simulated by computer in a 4-20 mA transmitter circuit (either loop-powered or externally-powered), using the `TROUBLESHOOT` simulation program. Successful completion of this objective consists of identifying the simulated fault at or below "par" in all measures and logically defending each and every step taken.

Trend graph displays PV and Output

Use the trend graph provided by your controller to show both the process variable and output signals graphed in real time. If your controller does not provide this function, you must connect a data acquisition unit (DAQ) or a digital oscilloscope to the proper circuit points to graph representative voltage signals.

PV alarms defined and enabled

Activate and set process variable high and low values to serve as warnings for anyone operating the control system, alerting them when the PV has drifted too high or too low.

Process exhibits good control behavior

Adjust the P, I, and/or D parameters in your loop's controller to achieve stable automatic-mode control for both varying setpoint values and varying process loads.

Lab percentage score

Successful completion of the lab exercise requires demonstrated mastery of all objectives. A percentage value is based on the number of attempts required to achieve mastery on these objectives: the number of objectives divided by the number of total attempts equals the percentage. Thus, a perfect lab percentage score is possible only by completing all objectives on the first attempt. Marks given for team objectives factor into each individual's score. If one or more members of a team repeatedly compromise team performance, they may be removed from the team and required to complete remaining lab exercises alone.

Deductions from this percentage value will be levied for instances of unsafe or unprofessional conduct (see below), the final result being the lab percentage score.

Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, formulating a plan to complete the lab project in the allotted time, and productively managing time. As with the other objectives, chronic patterns of poor performance in this domain may result in the offending student being removed from the team. Deductions to the lab percentage score will *not* be made for performance already graded such as tardiness and attendance.

General format and philosophy

This lab exercise is *project-based:* the instructor serves as the project engineer, while each student's role is to implement the standards set for the project while budgeting time and resources to complete it by the deadline date. Students perform real work as part of the lab exercise, managing their work day and functioning much the same as they will on the job. The tools and equipment and materials used are all industry-standard, and the problems encountered are realistic. This instructional design is intentional, as it is proven effective in teaching project management skills and independent working habits.

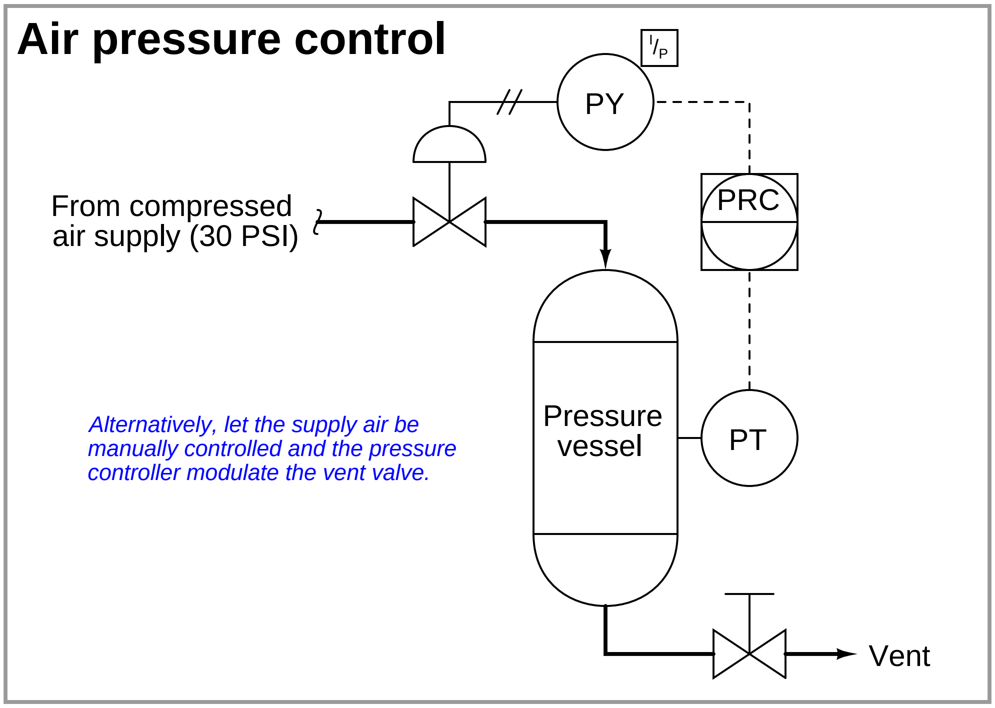
When you require the instructor's assistance to answer a question or to check off an objective, write your name (or your team's name) on the lab room whiteboard. Questions take priority over checkoffs, so please distinguish questions from other requests (e.g. writing a question-mark symbol "?" after your name makes this clear). **There will be times when you must wait for extended periods** while the instructor is busy elsewhere – instant service is an impossibility. Adequate time *does* exist to complete the lab exercise if you follow all instructions, communicate well, and work productively. Use all "down time" wisely: filling it with tasks not requiring the instructor's assistance such as other lab objectives, homework, feedback questions, and job searches.

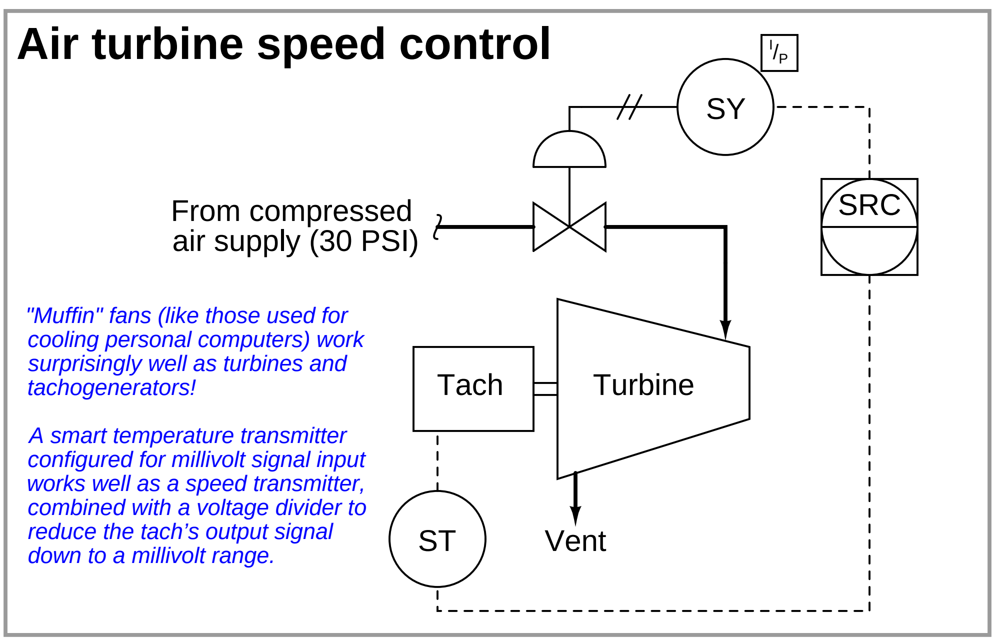
Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's presence so long as that work does not disturb the learning environment for other students.

DO NOT TAKE SHORTCUTS when completing tasks! Learning requires focused attention and time on task, which means that most 'shortcuts" actually circumvent the learning process. Read the lab exercise instructions, follow all instructions documented in equipment manuals, and follow all advice given to you by your instructor. Make a good-faith effort to solve all problems on your own *before* seeking the help of others. Always remember that this lab exercise is just a means to an end: no one *needs* you to build this project; it is an activity designed to develop marketable knowledge, skills, and self-discipline. In the end it is your *professional development* that matters most, not the finished project!

Lab Exercise – choosing a process to commission

There are a number of process types to choose from when selecting the one you will commission with your team. The only non-negotiable limitations is that the process must be safe, legal, and possible to complete in the time allotted for this lab. A number of process units have already been constructed on 2' × 2' plywood boards, but you are welcome to construct your own. Your instructor may assign new process units to be constructed or modified, time permitting. What follows are some examples of physical processes (documented in P&ID form) that work well for the purpose of exploring closed-loop control in the lab:

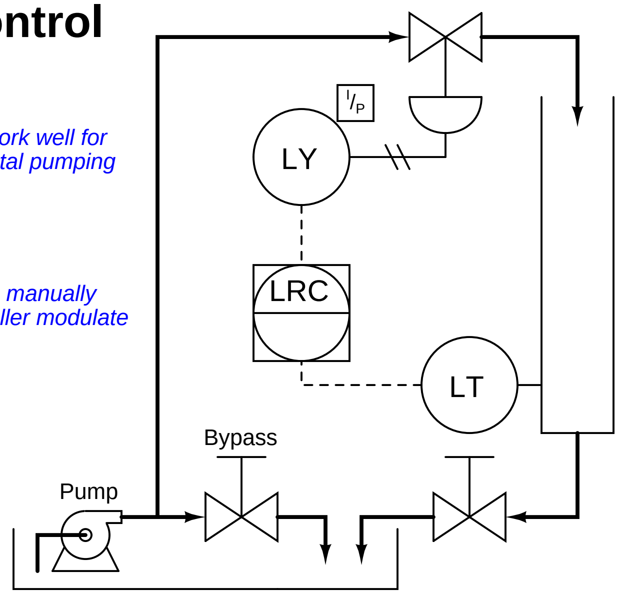




Water level control

Fountain-style water pumps work well for this purpose, so long as the total pumping height (head) is not too great.

Alternatively, let the in-flow be manually controlled and the level controller modulate the drain valve.

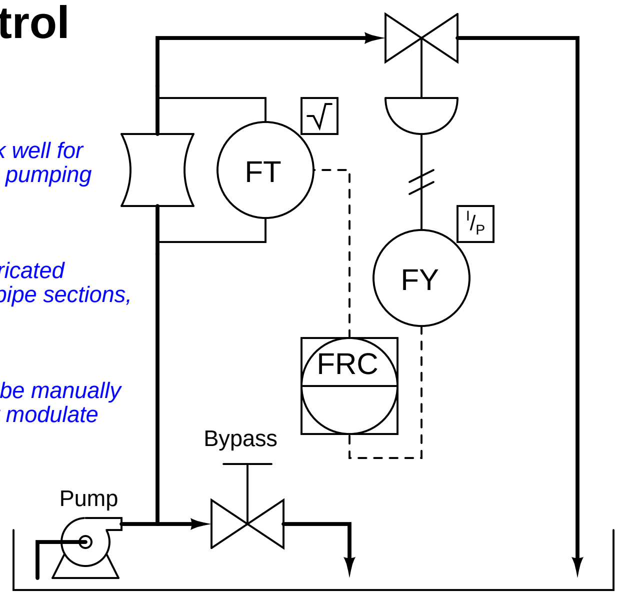


Water flow control

Fountain-style water pumps work well for this purpose, so long as the total pumping height (head) is not too great.

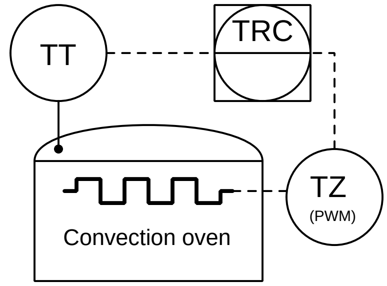
Simple venturi tubes may be fabricated using bell reducers and straight pipe sections, in either plastic or metal.

Alternatively, let the venturi flow be manually controlled and the flow controller modulate the bypass valve.



Oven temperature control

A cheap electric toaster oven or convection oven works well for this purpose. The only "hard-to-find" part is the power controller (JC) which modulates AC power to the heating element in accordance with the temperature controller's 4-20 mA output signal.

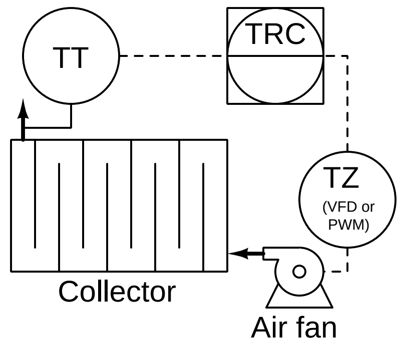


Solar air heater control

For the purposes of this lab exercise, the solar collector may be made out of cardboard with clear plastic food wrap as the cover material.

Paint the inside of the collector flat black for maximum heat absorption capability.

Use a variable-frequency motor drive (VFD) if the fan is turned by an AC motor. If using a DC fan (e.g. computer cooling fan), you may use a simpler PWM power controller.



Other process ideas include:

- Soldering iron temperature control (blowing air over tip with variable-speed fan).
- Draft pressure control (controlling very low air pressure inside of a box).
- Pneumatic piston height control (using lengths of PVC pipe to build a simple piston/cylinder which may be used to lift small weights using modest air pressures). A good way to control air pressure to the piston is to route the I/P transducer's output to a *volume booster* relay and let the relay's output directly drive the piston. Piston height may be sensed using a flexible water tube attached to the piston rod, running to a stationary pressure transmitter.
- Sterno-fired air heat exchanger.
- Miniature steam boiler. *Note: this is an advanced project!*
- Air/Fuel ratio burner control. *Note: this is an advanced project!*
- Servomechanism position control. *Note: this is an advanced project!*
- Inverted pendulum balance. *Note: this is a <u>very</u> advanced project!*

Lab Exercise – team meeting, prototype sketch, and instrument selection

An important first step in completing this lab exercise is to **meet with your instructor** as a team to discuss safety concerns, team performance, and specific roles for team members. If you would like to emphasize exposure to certain equipment (e.g. use a particular type of control system, certain power tools), techniques (e.g. fabrication), or tasks to improve your skill set, this is the time to make requests of your team so that your learning during this project will be maximized.

An absolutely essential step in completing this lab exercise is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This usually takes the form of a simple electrical schematic and/or loop diagram showing all electrical connections between components, as well as any tubing or piping for fluids. This prototype sketch need not be exhaustive in detail, but it does need to show enough detail for the instructor to determine if all components will be correctly connected for their safe function.

You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of electric current, voltage polarities, and identifying electrical sources/loads. Use this task as an opportunity to strengthen your analytical skills! Remember that you will be challenged in this program to do all of this on your own (during "capstone" assessments), so do not make the mistake of relying on your teammates to figure this out for you – instead, treat this as a problem *you* must solve and compare your results with those of your teammates.

Your team's prototype sketch is so important that the instructor will demand you provide this plan before any construction on your team's working system begins. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!* Similarly, you should not deviate from the prototype design without instructor approval, to ensure nothing will be done to harm equipment by way of incorrect connections. Each member on the team should have ready access to this plan (ideally possessing their own copy of the plan) throughout the construction process. Prototype design sketching is a skill and a habit you should cultivate in school and take with you in your new career.

When selecting field instruments for this lab exercise, choose a *transmitter* suitable for measuring your process variable, and likely an *I/P converter* used to convert the controller's 4-20 mA output signal into an air pressure that a control valve may operate on. Electronic process controllers are in several locations throughout the lab, ready to be used for controlling processes. Your instructor will help you select appropriate instruments for the process you have chosen.

You may also need a *data acquisition unit* (*DAQ*) or a digital oscilloscope set to a very slow timebase value to function as a trend recorder. When used with a personal computer and connected properly to the loop circuit, either device will provide graphical displays of loop variables over time. Students usually find the connection of a DAQ unit or oscilloscope to their loop controller to be the trickiest part of their loop wiring. You will need to consult the manufacturer documentation on the DAQ/scope as well as the field instruments and controller in order to figure out how to wire them together. Even if your process controller already provides trending capability, you may find connection of a DAQ or oscilloscope to your loop circuits a useful exercise because the ability to quickly connect and use these tools to monitor electrical parameters in a system is a valuable diagnostic skill in this career.

You will find your teammates who have already taken the Measurement course series (INST24X) will be very helpful in showing you how to check, configure, calibrate, and install the measuring instrument(s) you will need for your process!

Planning a functioning system should take no more than an hour if the team is working efficiently, and will save you hours of frustration (and possible component destruction!).

Lab Exercise – circuit design challenge

Your instructor will choose one 4-20 mA field instrument and one control system from the lists shown below, for which you must sketch and annotate an accurate circuit diagram showing how the two instruments would connect to each other. If this interconnection between controller and field instrument requires additional electrical components to function (e.g. DC or AC power source, precision 250 Ω resistor, diode, relay, etc.), those must be incorporated into your diagram as well. The required annotation will consist of denoting all expected directions of current (marked by arrows pointing in the direction of conventional flow) and all expected voltage polarities (marked by + and − symbols), as well as identifying all electrical sources and loads as such. Instruction manuals for all instrument listed are available on the electronic Instrumentation Reference for your convenience. When your sketch is complete, you must show the relevant manual pages to your instructor for verification of correct connections.

This exercise tests your ability to locate appropriate information in technical manuals, to sketch a correct 4-20 mA loop circuit for a given pair of instruments, and to correctly annotate all voltages and currents. The electronic Instrumentation Reference will be available to you in order to answer this question.

Since all 4-20 mA "loops" are basically series DC circuits, it is highly recommended that you approach their design the same as for any other DC circuit: carefully identify all *sources* and *loads* in the circuit, trace directions of all currents, and mark the polarities of all voltages. Most of the mistakes made in this type of circuit design challenge may be remedied by careful consideration of these specific circuit-analysis details.

4-20 mA transmitter options

- Pressure
  - → Rosemount 1151 Alphaline (analog), 1151 HART, or 3051 HART
  - → Yokogawa DPharp EJX110A or EJX910
  - → Honeywell ST3000
- Level
  - → Rosemount APEX non-contact radar, 3300 GWR, or 5300 GWR
- Temperature
  - → Rosemount 444, 644, 3044, or 3144
  - → Foxboro RTT15 or RTT30
  - → Moore Industries SPT with sourcing (4-wire) 4-20 mA output
  - → Moore Industries SPT with sinking (2-wire) 4-20 mA output
  - → Moore Industries TRX or TDY
- Flow
  - → Foxboro CFT50 coriolis
- Analytical
  - → Rosemount 5081-P (pH)
  - → Daniel 700 gas chromatograph (4 analog output channels)
  - → Foxboro 876PH (pH/ORP/ISE)

Controller options

- Monolithic
  - → Siemens 352P
  - → Siemens 353
  - → Foxboro 716C
  - → Foxboro 718TC
  - → Foxboro 762CNA
  - → Moore Industries 535
  - → Honeywell UDC2300
  - → Honeywell UDC3500
- Modular – *you choose the appropriate I/O module*
  - → Siemens 353R
  - → Emerson ROC800 SCADA/RTU
- Distributed Control System (DCS) – *you choose the appropriate I/O module*
  - → Emerson DeltaV with M-series I/O
  - → Emerson DeltaV with S-series I/O
  - → Honeywell Experion with 2MLF series I/O
- Programmable Logic Controller (PLC) – *you choose the appropriate I/O module*
  - → Automation Direct "CLICK"
  - → Siemens S7-300
  - → Rockwell ControlLogix (catalog number 1756)
  - → Rockwell CompactLogix (catalog number 1769)

4-20 mA Final Control Element options

- Pneumatic control valve positioners
  - → Fisher 3582i positioner
  - → Fisher DVC6000 positioner
- Electrically actuated valves (MOV)
  - → Limitorque actuator with Modutronic-20 II controller
  - → Rotork AQ with Folomatic controller
- AC motor drives (VFD)
  - → Rockwell PowerFlex 4
  - → Automation Direct GS1

Correct circuit sketch (instructor verifies): ____

Correct voltage annotations (instructor verifies): ____ (+ and − symbols)

Correct current annotations (instructor verifies): ____ (arrows showing conventional flow)

Correct source/load identifications (instructor verifies): ____

Study reference: the "Analog Electronic Instrumentation" chapter of *Lessons In Industrial Instrumentation*, particularly the section on HART.

Lab Exercise – building the system

The Instrumentation lab is set up to facilitate the construction of working instrument "loops," with over a dozen junction boxes, pre-pulled signal cables, and "racks" set up with 2-inch vertical pipes for mounting instruments. These racks also provide structure for building physical processes, with more than enough weight-bearing capacity to hold any process vessels and equipment. The only wires you should need to install to build a working system are those connecting the field instrument to the nearest junction box, and then small "jumper" cables connecting different pre-installed cables together within intermediate junction boxes.

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. Instruments attach to 2-inch pipes using special brackets and U-bolts. These brackets and U-bolts are located in the instrument storage area.

Select a specific loop controller for your system. Your instructor may choose the controller for your team, to ensure you learn more than one type of controller during the course of a quarter.

Finally, your process control system needs to have a loop number, so all instruments may be properly labeled. This loop number needs to be unique, so that another team does not label their instruments and cables the same as yours. One way to make your loop number unique is to use the equivalent resistor color-code value for your team's color in the loop number. For example, if you are the "Red" team, your loop number could be "2".

Common mistakes:

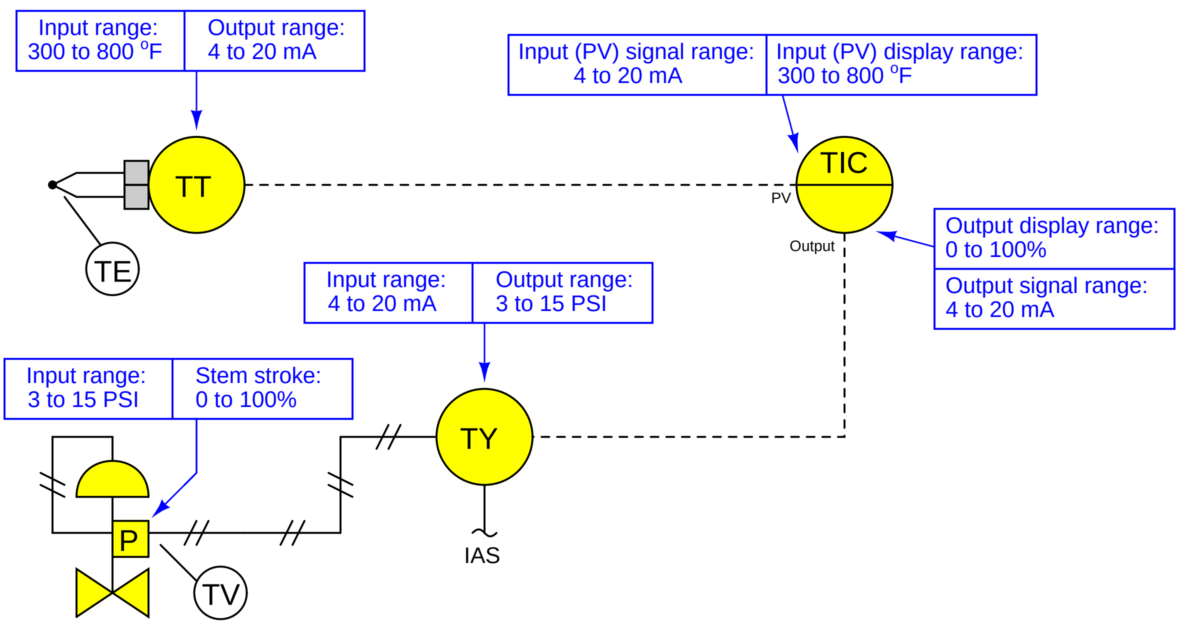
- Neglecting to consult the manufacturer's documentation for field instruments (e.g. how to wire them, how to calibrate them).
- Mounting the field instrument(s) in awkward positions, making it difficult to reach connection terminals or to remove covers when installed.
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).
- Failing to tug on each and every wire where it terminates to ensure a mechanically sound connection.
- Students working on portions of the system in isolation, not sharing with their teammates what they did and how. It is important that the whole team learns all aspects of their system!

Building a functioning process complete with instrumentation for control typically takes one or two sessions (3 hours each) if all components are readily available and the team is working efficiently!

Notes on instrument ranging

An important configuration parameter for any practical measurement or control system is *process variable ranging*. This entails setting both the transmitter and indicator/controller to a specified measurement range, with the controller indicating the process variable in real "engineering units" (e.g. PSI or degrees F rather than just percent). The following tutorial describes how this works and which configuration parameters to modify in a variety of different control systems found in the Instrumentation lab room.

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don't "know" what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 ^{o}F and output 20 mA when sensing 800 ^{o}F, but the controller must display an indication of 300 ^{o}F when it receives a 4 mA signal from the transmitter, and display an indication of 800 ^{o}F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 ^{o}F input (and 4-20 mA output) as well as range the controller to display 300-800 ^{o}F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:



Analog (non-"smart") transmitters, I/P transducers, and valve positioners are ranged using "zero" and "span" adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital ("smart") transmitters and valve positioners are ranged by setting LRV and URV parameters using a "communicator" device or a personal computer equipped with the appropriate interface and software. This too is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

Digital electronic loop controllers contain parameters specifying the process variable (PV) ranges. The following page lists examples of PV range configuration parameters for several different makes and models of loop controllers.

- Siemens/Moore 352 controller: process variable range parameters are located in the "Operator's Display" function block (FB15):
  → LRV = *Process Lo*
  → URV = *Process Hi*

- Siemens/Moore 352P and 353 controller: process variable range parameters are located in the "Analog Input" function block (AIN):
  → LRV = *Minscale*
  → URV = *Maxscale*

- Emerson DeltaV DCS: process variable range parameters are located in the "Analog Input" function block (AI) and "PID" function block (PID):
  → (AI block) = the *OUT_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. The *L_Type* parameter needs to be set to "indirect" to allow scaling to occur ("direct" mode prohibits scaling), and the *XD_Scale* parameter needs to be ranged 0 to 100%. Note that the "direct" and "indirect" options for *L_Type* have absolutely nothing to do with "direct" and "reverse" PID controller action, which is configured elsewhere.
  → (PID block) = the *PV_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. Note: the PID block's *PV_SCALE* range must exactly match the *OUT_SCALE* range of the AI block!

- Honeywell UDC 2500 controller: process variable input #1 range parameters are located in the "Input 1" set-up group of parameters:
  → LRV = *IN1 LO*
  → URV = *IN1 HI*

- Automation Direct "SOLO" controller: process variable range parameters are located in the following registers:
  → LRV = *P3-4 Input Range Low*
  → URV = *P3-3 Input Range High*

- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a "Scale" instruction (SCL) or a "Scale with Parameters" instruction (SCP). In either case, the instruction takes the raw count value from the input channel's analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you <u>not</u> save or download the PLC program, because doing so may alter the PLC's network address and lead to communication problems. Just make the changes while the PLC is in "Run" mode and then exit the program*:
  → (SCL instruction) = *Rate* and *Offset* values scale the signal according to the slope-intercept formula $y = mx + b$, where *Rate* is $10000m$ and *Offset* is b
  → (SCP instruction LRV) = *Scaled Min.*
  → (SCP instruction URV) = *Scaled Max.*

- Allen-Bradley Logix5000 controller: process variable scaling parameters are located in the "PID" instruction (PID):
  → LRV = *.MINS*
  → URV = *.MAXS*

- caSCADA "`pid`" control program: process variable scaling parameters are located in one of the source code files which must be modified using a text editor program, then recompiling the `pid` program so the new parameters may take effect. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key, after which a set of instructions will appear on the screen showing the default LRV and URV range values, and which file to find these parameters within. After editing and saving this file, you will need to type `make` at the Linux command line and press Enter to recompile the program. Finally, type `./pid` and press Enter to initiate the recompiled program.
  → LRV = *pid[0].LRV*
  → URV = *pid[0].URV*

file `ranging`

Notes on controller action

An important set of configuration parameters for any control system are *controller action* and *PID tuning*. Proper controller action means that the control system reacts to setpoint changes and process variable disturbances in the correct direction (e.g. a temperature control system that acts to reduce heat input when the process variable is above setpoint). Proper PID tuning means that the control system reacts to setpoint changes and process variable disturbances to an appropriate degree over time (e.g. a temperature control system that applies the right amount of additional heat input when the process variable goes below setpoint). A controller with the wrong action will cause a process to "run away" to one extreme value or the other. A controller with poor PID tuning will fail to achieve setpoint, and/or oscillate needlessly. The following is a list of configuration parameters to modify in a variety of different control systems found in the Instrumentation lab room.

If the controller happens to be programmed using function blocks, these important parameters will be found in the "PID" function block. For other controller models, there will be a menu option with action (direct/reverse) and tuning (P/I/D) parameters. Note that some controllers provide a quick-access feature to edit the PID tuning parameters, but generally not for changing the direction of action. Here are some examples:

- Siemens/Moore 352 controller: control action parameters are located in the "PID" function block (FB13). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the "Tune" button rather than by entering the PID function block edit menu:
  → Direction (Direct/Reverse)= *SA1*
  → Proportional (P) = *SPG1* as a unitless gain value
  → Integral (I) = *STI1* in units of minutes per repeat
  → Derivative (D) = *STD1* in units of minutes

- Siemens/Moore 352P and 353 controller: control action parameters are located in the "PID" function block (PID). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the "Tune" button rather than by entering the PID function block edit menu:
  → Direction (Direct/Reverse)= *DIR ACT*
  → Proportional (P) = *PG* as a unitless gain value
  → Integral (I) = *TI* in units of minutes per repeat
  → Derivative (D) = *TD* in units of minutes

- Emerson DeltaV DCS: control action parameters are located in the "PID" function block (PID) conforming to the FOUNDATION Fieldbus standard:
  → Direction (Direct/Reverse)= Found in the *CONTROL_OPTS* set of parameters as a "check-box" where a checked box sets direct action and an unchecked box sets reverse action.
  → Proportional (P) = *GAIN* as a unitless gain value
  → Integral (I) = *RESET* in units of seconds per repeat
  → Derivative (D) = *RATE* in units of seconds

- Honeywell UDC 2500 controller: control direction is located in the "CONTRL" set-up group of parameters, while the PID tuning coefficients are located in the "TUNING" set-up group of parameters:
  → Direction (Direct/Reverse)= *Action*
  → Proportional (P) = *PB* or *Gain* as a proportional band percentage or as a unitless gain value, respectively
  → Integral (I) = *I Min* or *I RPM* in units of minutes or repeats per minute, respectively
  → Derivative (D) = *Rate T* in units of minutes

- Automation Direct "SOLO" controller: process variable range parameters are located in the following registers:
  → Direction (Direct/Reverse)= *P3-7 Heating/Cooling*
  → Proportional (P) = *P1-4 Proportional band* as a proportional band percentage
  → Integral (I) = *P1-5 Integral time* in units of seconds
  → Derivative (D) = *P1-6 Derivative time* in units of seconds

- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: control action parameters are located in the "PID" instruction. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab (reading the PV on the first analog input and sending the output to the first analog output of the I/O card):
  → Direction (Direct/Reverse)= Found in the *Control Mode* field where E=PV−SP represents direct action and E=SP−PV represents reverse action.
  → Proportional (P) = *Controller Gain* K_c as a unitless gain value
  → Integral (I) = *Reset* T_i in units of minutes per repeat
  → Derivative (D) = *Rate* T_d in units of minutes

- Allen-Bradley Logix5000 controller: control action parameters are located in the "PID" instruction (PID):
  → Direction (Direct/Reverse)= E where PV−SP represents direct action and SP−PV represents reverse action.
  → Proportional (P) = K_p or K_c as a unitless gain value
  → Integral (I) = K_i in units of seconds per repeat
  → Derivative (D) = K_d in units of minutes

- caSCADA "`pid`" control program: control action parameters are located on the operator interface screen, above the trend graph. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key. Once the `pid` control program is running (reading the PV on analog input AIN0 and sending the output to analog output DAC0 of the LabJack DAQ), each parameter may be selected by pressing the `S` key as often as needed, and the parameter values changed by pressing the arrow and page up/down keys. Note that the control direction may only be switched while the controller is in manual mode. Tuning parameters may be altered in either manual or automatic modes.
  → Direction (Direct/Reverse)= will either show "`Direct-acting`" or "`Reverse-acting`"
  → Proportional (P) = `K_P` as a unitless gain value
  → Integral (I) = `K_I` in units of repeats per minute
  → Derivative (D) = `K_D` in units of seconds

Notes on controller tuning

For those who have never tuned a controller before but need to set the PID parameters for basic loop stability in automatic mode, here are some tips for setting the P, I, and D parameter values. Every PID controller provides means to alter the tuning coefficients named *proportional* (also called *gain*), *integral* (also called *reset*), and *derivative* (also called *rate or pre-act*). Settings which are virtually assured to yield stable control are as follows:

- **P** – a "gain" value of less than one (i.e. a "proportional band" value of at least 100%).
- **I** – a "reset" value of zero repeats per minute, or the largest value possible for minutes per repeat.
- **D** – a "rate" value of zero.

Mind you, these parameters will not yield *good* control, but merely *stable* control. In other words, these tuning parameter values will make the controller fairly unresponsive, but at least it won't oscillate out of control. Also bear in mind that having an integral (reset) value set for minimum action (i.e. zero repeats per minute, or very high minutes per repeat) will result in a controller that never quite makes the process variable value reach setpoint – instead, there will be a persistent "offset" between PV and SP with integral action essentially turned off.

file `control`

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous with inspection of each team member's loop diagram. Team members will exchange diagrams with each other and then verify from those diagrams what the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and −, black and white for AC "hot" and "neutral", green for earth ground).
- All metallic electrical enclosures must be bonded to earth ground for safety.
- Proper wire types and attachment to terminals (e.g. appropriate wire gauge for the expected current, use of stranded wire wherever possible, correct terminals crimped to ends of wires, no stray wire strands at any point).
- Attached wires must withstand being lightly pulled with fingers.
- Wire insulation must be intact (i.e. no bare wires anywhere).
- Panel wiring must be neat in appearance (e.g. all cables run directly from terminal block to nearest wire duct, with all excess wire length tucked inside wire duct).
- Wiring outside of panels should be run through conduit wherever possible.
- Correct tools must be used at all times. This includes the use of fixed-size wrenches rather than adjustable wrenches whenever possible, box-end over open-end wrenches whenever possible, and the correct type and size of screwdriver used to turn screw heads.
- All electrical components must be located to avoid exposure to liquids.
- All tube and pipe connections must be properly made (e.g. correct "swaging" of tube ends, no over- or under-tightened fittings, Teflon tape or pipe sealant used on all NPT threads).
- All manual controls (e.g. buttons, handles, knobs) must be accessible and function without undue effort.

Documentation Standards

- Loop diagrams must be drawn in accordance with ISA standard 5.1.
- Each instrument must have an appropriate ISA-standard tag name, and this tag name must be visible on the actual instrument (e.g. written on masking tape and attached to the instrument).
- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
- All instrument symbols must be appropriate to the device, function, and location. The large white-colored control panel and the DCS operator stations constitute the *main control room*. All electrical enclosures in the lab room are *auxiliary* locations, and everything else is considered a *field* location.
- Instrument functions shared within a common device must be represented by the "shared" symbol on the diagram (e.g. a controller that is part of a multi-loop control system such as a DCS). Shared controllers must have their identifying loop noted on the diagram (e.g. DCS South Loop #23).
- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

- Each location (e.g. field, junction box, control room) must be clearly delineated with vertical seperation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. *"Where is the controller for this loop?"*) or determining important configuration parameters (e.g. range settings).

Sample diagrams are provided in this worksheet (immediately following the lab exercise documentation), and each student is urged to use these sample diagrams as references when drafting their own. The "Lessons In Industrial Instrumentation" textbook also describes ISA-standard documentation practices.

Common mistakes:

- Incorrect tag name format, using letters that do not conform to the ISA 5.1 standard (e.g. including "PLC" or "DCS" in a controller's tag name).
- Forgetting that every instrument's tag name in a loop must begin with the same letter, and that this first letter represents the process variable being measured/controlled.
- Forgetting to label all field instruments with their own tag names (e.g. AT-83).
- Failing to label termination points (e.g. terminal block screws) *exactly* as they are labeled in real life.
- Poor use of space on the diagram paper, causing some portions of the diagram to become "crowded" rather than all components being evenly spaced. *Hint: begin your diagram by sketching the field instrument at the far left of the paper and the control room instrument at the far right of the paper, then draw all other instruments and connections in between!*
- Forgetting to label all signal wires (see example loop diagrams).
- Forgetting to note all wire colors.
- Forgetting to put your name on the loop diagram!
- Leaving junction box cables outside of wire duct, looking messy.
- Leaving wire duct covers off.
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.
- Not placing loop sheet instruments in the correct orientation (field instruments on the left, control room instruments on the right).

Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

Lab Exercise – troubleshooting

An important aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a fault in a simulated circuit. You will use the open-source software called `TROUBLESHOOT` for this objective, which natively runs on the Linux operating system and is already installed on the caSCADA nodes in the main lab room (under the `/tshoot` directory). You may also compile and run this free software natively on an Apple personal computer, or if running Windows you may install the free `Cygwin` emulator complete with development tools and use that to compile and run `TROUBLESHOOT`.

The `TROUBLESHOOT` software offers multiple simulated circuits to select, *the particular circuit for this lab exercise being specified earlier in this outline*. The software tracks every step you take, and the amount of time taken for each step. Scores are given at the end for such metrics as number of steps taken, total "cost" incurred (with different cost values associated with different actions), and total time taken. The software also provides reasonable "par" scores for each of the randomly-selected faults.

Included with every installation of `TROUBLESHOOT` is a set of PDF files, each one depicting the schematic diagram for a simulated circuit. It is advisable for you to print a paper copy of this schematic so that you can easily annotate measurements you take during the simulation.

In order to successfully pass this objective, you must start up the simulation in the instructor's presence, document the randomly-selected circuit values on paper (in order to later verify it is the exact same simulation scenario), complete the simulation on your own, and then logically defend each of your steps (recounted by the software after your declaration of the fault). You must meet or improve upon *all* of the "par" values given by the software. Like all mastery objectives, multiple re-tries will be permitted. You are also welcome to practice using this software on your own before committing to a graded demonstration.

Failure to achieve all par scores, or failure to apply logical reasoning to the defense of every step take, or simple failure to identify the random fault will disqualify the effort, in which case you must re-try with a different (random) fault.

The instructor will review each troubleshooting effort after completion, highlighting good and bad points for the purpose of learning. Troubleshooting is a skill born of practice and failure, so do not be disappointed in yourself if you must make multiple attempts to pass! One of the important life-lessons embedded in this activity is how to deal with failure, because it *will* eventually happen to you on the job! There is no dishonor in failing to properly diagnose a fault after doing your level best. The only dishonor is in taking shortcuts or in giving up.

Common mistakes:

- Not practicing the use of the `TROUBLESHOOT` software.
- Relying on voltage measurement across a suspected open wire to confirm that it has failed open. This test only works if there are no other opens (e.g. "off" switch, blown fuse, etc.) in that circuit!

The purpose of every troubleshooting exercise is to foster and assess your ability to intelligently diagnose a complex system. Finding the fault by luck, or by trial-and-error inspection, is no demonstration of skill. Competence is only revealed by your demonstrated ability to logically analyze and isolate the problem, correctly explaining all your steps!

Lab Exercise – PV alarms

Most loop controllers have built-in *alarm* capability to signal whenever the process variable (PV) goes outside of prescribed bounds. In this lab exercise you will configure your controller's "high" and "low" PV alarm points to serve as warnings to the operator. A good general recommendation is to set the PV high alarm to 90% and the PV low alarm to 10%, unless specified otherwise by the project engineer (i.e. your instructor). While "tuning" your process for optimal performance, you may determine it to be most stable within a certain range of PV values, in which case you are free to set the high and low alarm limits to the boundary values for that stable range.

The procedure for setting alarm point values is documented in the manufacturer's manual for the control system, and is typically a setting available to operations personnel (i.e. not requiring engineering-level privileges on the control system to change). You will need to research how to do this.

Alarm settings are especially important when *tuning* a controller, to delineate how far the PV is allowed to stray without adversely affecting the process. This will become an important performance criteria in the *next* lab exercise when students individually tune PID controllers for different processes.

Lab Exercise – operating the system

All networked loop controllers in the lab (DCS, DDC, PLC, single-loop networked) provide graphing functionality so that you may plot your process variable (PV) and output values over time. This graphical data is essential for tuning PID-controlled loops. If you happen to be using a controller that does not provide graphing capability, your team must attach a trend recorder and/or a data acquisition unit (plus a personal computer) to the necessary signal cables so that these values are recorded over time.

PID tuning is a subject worthy of its own course, and so you will not be expected to achieve perfect control on your process. You will find, however, that one of the best ways to learn PID tuning is by "playing" with your process as it responds to different tuning parameters entered into the loop controller. The expectation for "good control behavior" in the context of this lab exercise is for the loop to exhibit response that is no less stable following large setpoint changes than the classic "quarter-wave damping" described by Ziegler and Nichols in their 1942 paper.

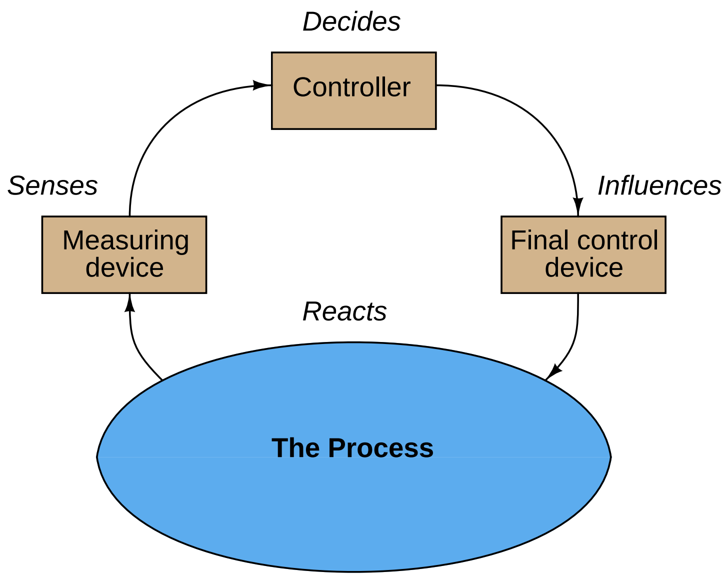
Most student-built processes are quite safe to operate. However, if your process harbors any unique hazards (e.g. overflowing water may present a slip hazard, overheated oven may cause materials to smoke or burn), you must be aware of these hazards and limit everyones' exposure to them. All team members for each process must be familiar with the inherent hazards of their process and how to mitigate them. One operational step to help avoid problems is to configure the controller for *setpoint limits* preventing the setpoint value from being placed at "dangerous" values in automatic mode. Just what these setpoint limit values should be set to varies with the process and the team's experience operating it.

As your time with the process builds, you will no doubt arrive at ideas for improving it. Feel free to work with your team to optimize the process in any way you see fit. The goal is to have your process as robust and "problem-free" as possible for other teams to use it in later coursework!

A tendency of students when they first learn to tune PID control loops is to proceed carelessly because they know the "toy" processes they are learning to tune aren't going to harm anything if their PVs go out of bounds. While this assumption might be true for your team's process, it is not good to form or reinforce bad habits. Thus, the inclusion of alarm point(s) on your process PV – especially if connected to some form of signaling device that is annoying and/or embarrassing to trip such as a loud buzzer – makes for a better teaching tool for others learning PID tuning!

Notes on troubleshooting feedback control loops

Recall that every feedback control loop consists of four basic elements: an element that *senses* the process variable (e.g. primary sensing element, transmitter), an element that *decides* what how to regulate this process variable (e.g. a PID controller), an element that *influences* the process variable (e.g. a control valve, motor drive, or some other final control device), and finally the process itself which *reacts* to the final control device's actions:



You can check each element of your feedback control loop by comparing its input with its output to see if each element is doing what it should:

(1) **Decision-making:** Carefully examine the controller faceplate, looking at the values of PV, SP, and Output. Is the controller taking appropriate action to force PV equal to SP? In other words, is the Output signal at a value you would expect if the controller were functioning properly to regulate the process variable at setpoint? If so, then the controller's action and tuning are most likely not at fault. If not, then the problem definitely lies with the controller.

(2) **Sensing:** Compare the controller's displayed value for PV with the actual process variable value as indicated by local gauges, by feel, or by any other means of detection. If there is good correspondence between the controller's PV display and the real process variable, then there probably isn't anything wrong with the measurement portion of the control loop (e.g. transmitter, impulse lines, PV signal wiring, analog input of controller, etc.). If the displayed PV disagrees with the actual process variable value, then something is definitely wrong here.

(3) **Influencing:** Compare the controller's displayed value for Output with the actual status of the final control element. If there is good correspondence between the controller's Output display and the FCE's status, then there probably isn't anything wrong with the output portion of the control loop (e.g. FCE, output signal wiring, analog output of controller, etc.). If the controller Output value differs from the FCE's state, then something is definitely wrong here.

(3) **Reacting:** Compare the process variable value with the final control element's state. Is the process doing what you would expect it to? If so, the problem is most likely not within the process (e.g. manual valves, relief valves, pumps, compressors, motors, and other process equipment). If, however, the process is not reacting the way you would expect it to given the final control element's state, then something is definitely awry with the process itself.

A crude closed-loop PID tuning procedure

Tuning a PID controller is something of an art, and can be quite daunting to the novice. What follows is a primitive (oversimplified for some situations!) procedure you can apply to many processes.

Step 1

Understand the process you are trying to control. If you do not have a fundamental grasp on the nature of the process you're controlling, it is pointless – even dangerous – to change controller settings. Here is a simple checklist to cover before touching the controller:

- What is the process variable and how is it measured?
- What is the final control element, and how does it exert control over the process variable?
- What safety hazards exist in this process related to control (e.g. danger of explosion, solidification, production of dangerous byproducts, etc.)?
- How far am I allowed to "bump" the process while I tune the controller and monitor the response?
- How is the controller mode switched to "manual," just in case I need to take over control?
- In the event of a dangerous condition caused by the controller, how do you shut the process down?

Step 2

Understand what the settings on the controller do. Is your controller configured for gain or proportional band? Minutes per repeat or repeats per minute? Does it use reset windup limits? Does rate respond to error or PV alone? You had better understand what the PID values do to the controller's action if you are going to decide which way (and how much) to adjust them! Back in the days of analog electronic and pneumatic controllers, I would recommend to technicians that they draw little arrow symbols next to each adjustment knob showing which way to turn for more aggressive action – this way they wouldn't get mixed up figuring out gain vs PB, rep/min vs min/rep, etc.: all they had to think of is "more" or "less" of each action.

Step 3

Manually "bump" the manipulated variable (final control element) to learn how the process responds. In manual mode, *you* are the controller! What you need to do is adjust the process to learn how it responds: is it an integrating process, a self-regulating process, or a runaway process? Is there significant dead time or hysteresis? Is the response linear and consistent? Many process control problems are caused by factors other than the controller, and this "manual test" step is a key diagnostic technique for assessing these other factors.

Step 4

Set the PID constants to "minimal" settings and switch to automatic mode. This means gain less than 1, no integral action (0 rep/min or maximum min/rep), no derivative action, and no filtering (i.e. damping).

Step 5

"Bump" the setpoint and watch the controller's response. This tests the controller's ability to manage the process on its own. What you want is a response that is reasonably fast without overshooting or undershooting too much, and without undue cycling. The nature of the process and the constraints of quality standards will dictate what is "too much" response time, over/undershoot, and cycling.

Step 6

Increase or decrease the control action aggressiveness according to the results of Step 5.

Step 7

Repeat steps 5 and 6 for P, I, and D, one at a time, in that order. In other words, tune the controller first to act as a P-only controller, then add integral (PI control), then derivative (PID), each as needed.

Step 8

"Bump" a load in the process and watch the controller's response. This tests the controller's ability to manage variations in process load over time. A controller's response to load changes will often differ from its response to setpoint changes. You still want controller response that is reasonably fast without overshooting or undershooting too much, and without undue cycling. However, you may have to find some compromise in tuning between good setpoint response and good load response. How you decide that compromise depends on whether the controller really needs to respond mostly to setpoint changes (e.g. the slave controller of a cascade loop) or to load changes.

Step 9

Increase or decrease the control action aggressiveness according to the results of Step 8.

Step 10

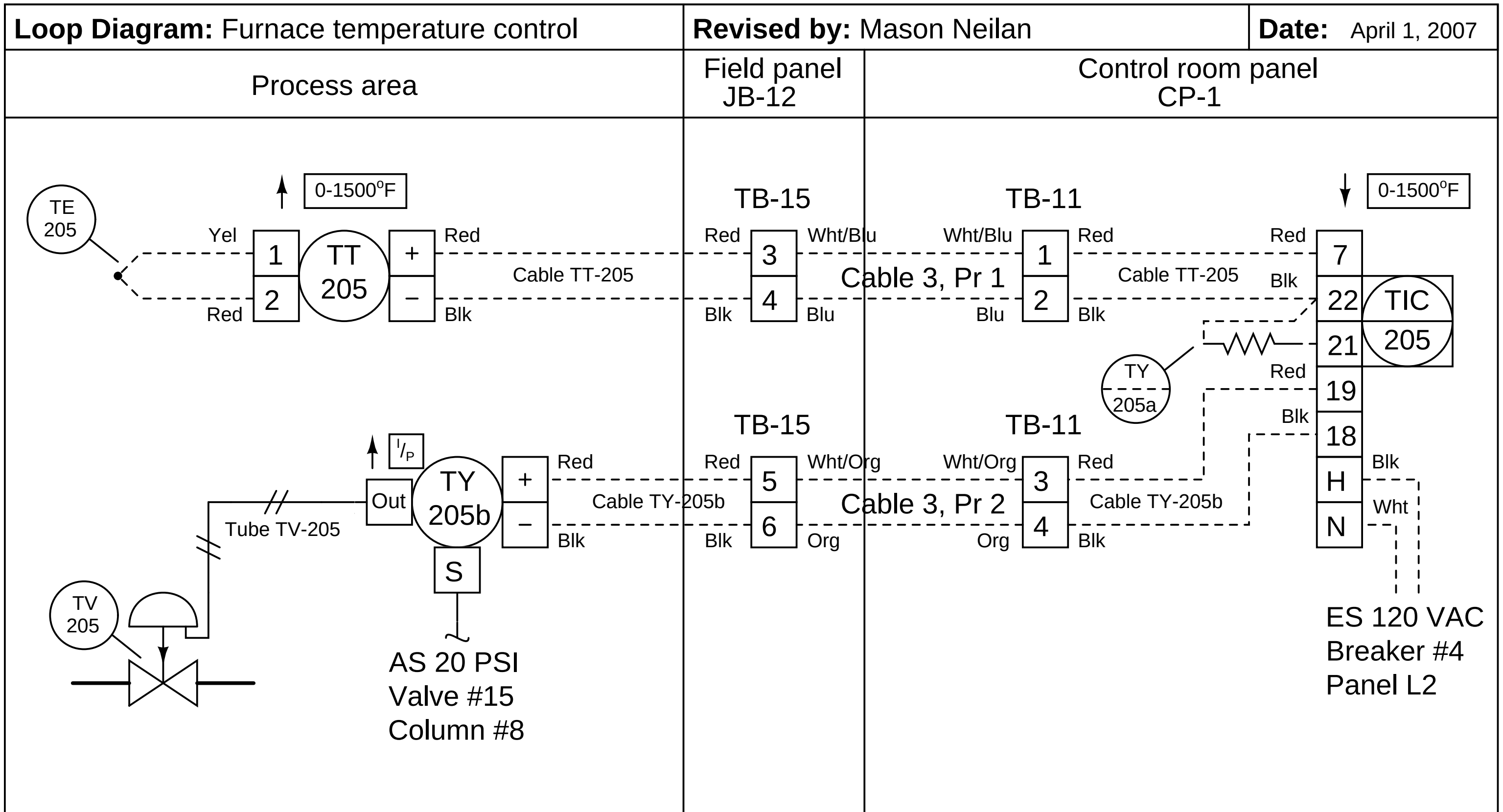
Repeat steps 8 and 9 for P, I, and D, one at a time, in that order. In other words, tune the controller first to act as a P-only controller, then add integral (PI control), then derivative (PID), each as needed.

Caveats

The procedure described here is *very* crude, and should only be applied as a student's first foray into PID tuning, on a safe "demonstration" process. It assumes that the process responds predominantly to proportional (P-only) action, which may not be true for some processes. It also gives no specific advice for tuning based on the results of step 3, which is the mark of an experienced PID tuner. With study, practice, and time, you will learn what types of processes respond best to P, I, and D actions, and then you will be able to intelligently choose what parameters to adjust, and what closed-loop behaviors to look for.

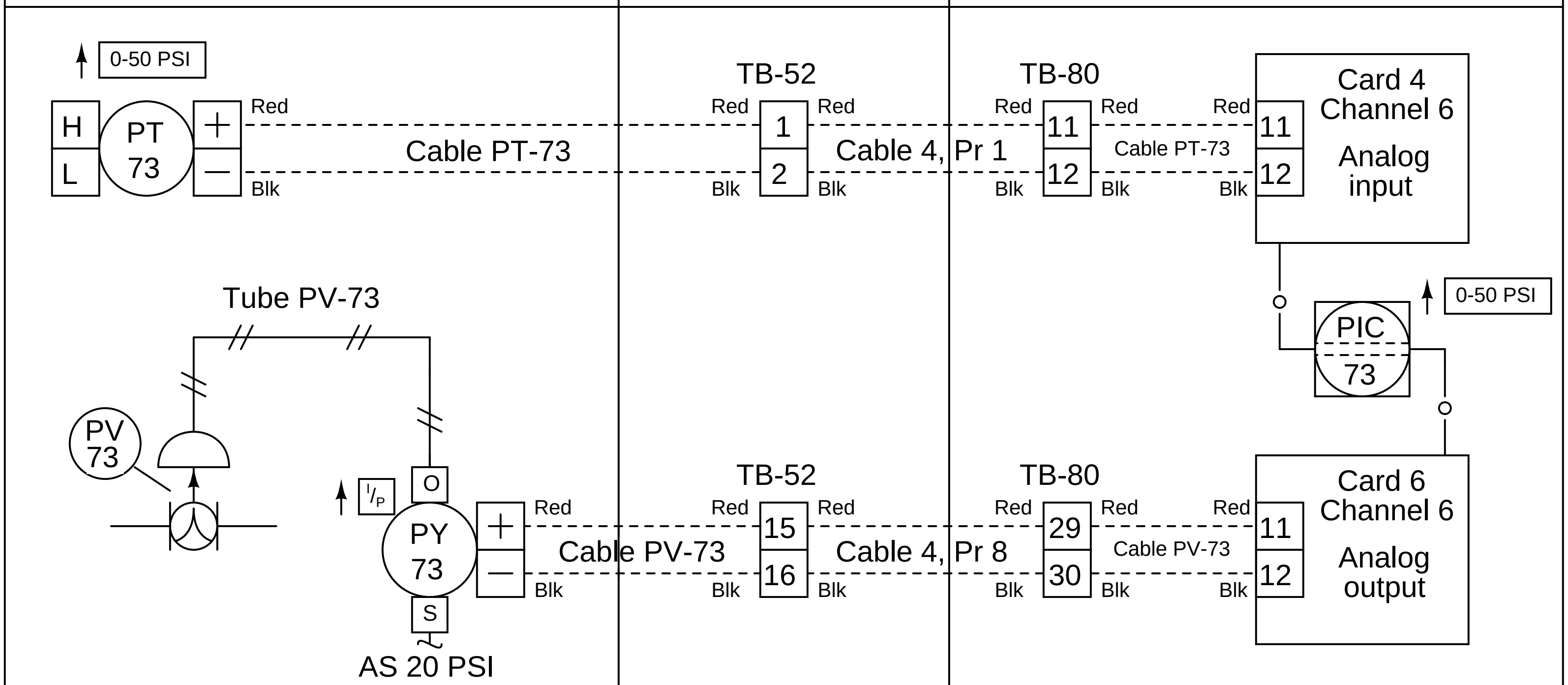
file i01558

Sample Loop Diagram (using a single-loop controller)



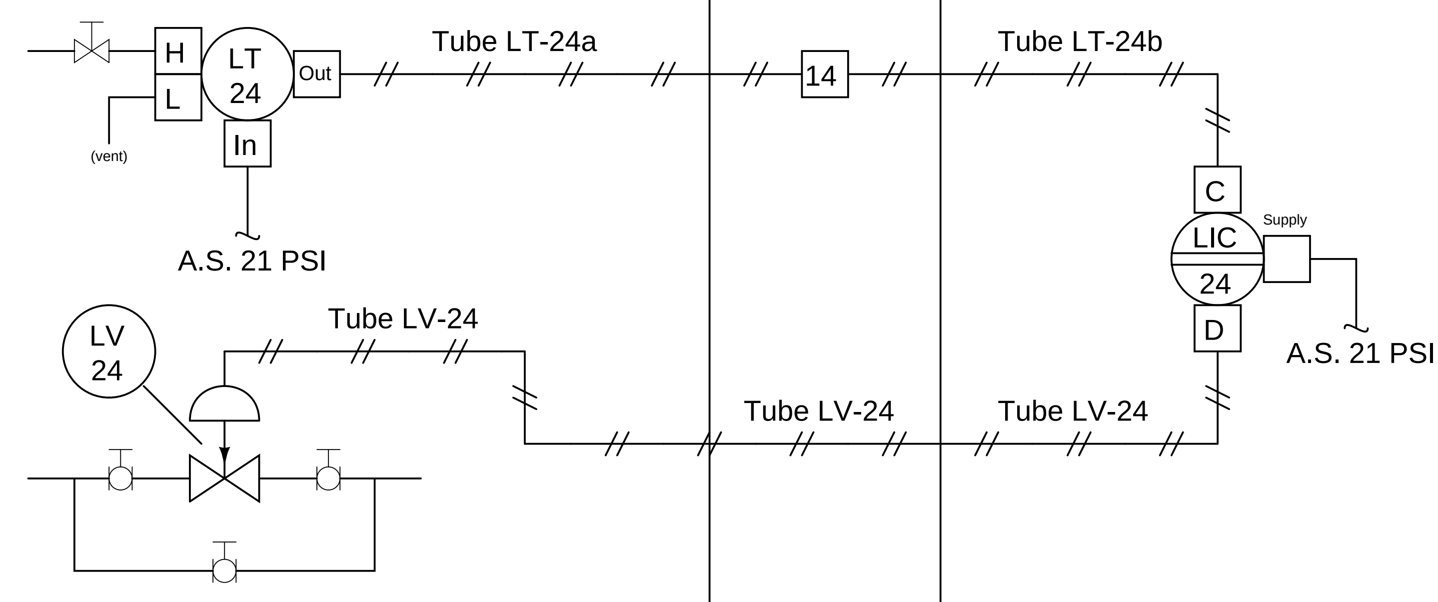
Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
TE-205	Thermocouple	Omega			Type K	Ungrounded tip
TT-205	Temperature transmitter	Rosemount	444	0-1500° F	4-20 mA	Upscale burnout
TY-205a	Resistor	Vishay			250 Ω	
TIC-205	Controller	Siemens	PAC 353	1-5 V	0-1500° F	Reverse-acting control
TY-205b	I/P transducer	Fisher	546	4-20 mA	3-15 PSI	
TV-205	Control valve	Fisher	Easy-E	3-15 PSI	0-100%	Fail-closed

Loop Diagram: Blue team pressure loop	**Revised by:** Duncan D.V.	**Date:** April 1, 2009
Field process area	Field panel JB-25	DCS cabinet



Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
PT-73	Pressure transmitter	Rosemount	3051CD	0-50 PSI	4-20 mA	
PIC-73	Controller	Emerson	DeltaV	4-20 mA	4-20 mA	HART-enabled input Direct-acting control
PY-73	I/P transducer	Fisher	846	4-20 mA	3-15 PSI	
PV-73	Control valve	Fisher	Vee-ball	3-15 PSI	0-100%	Fail-open

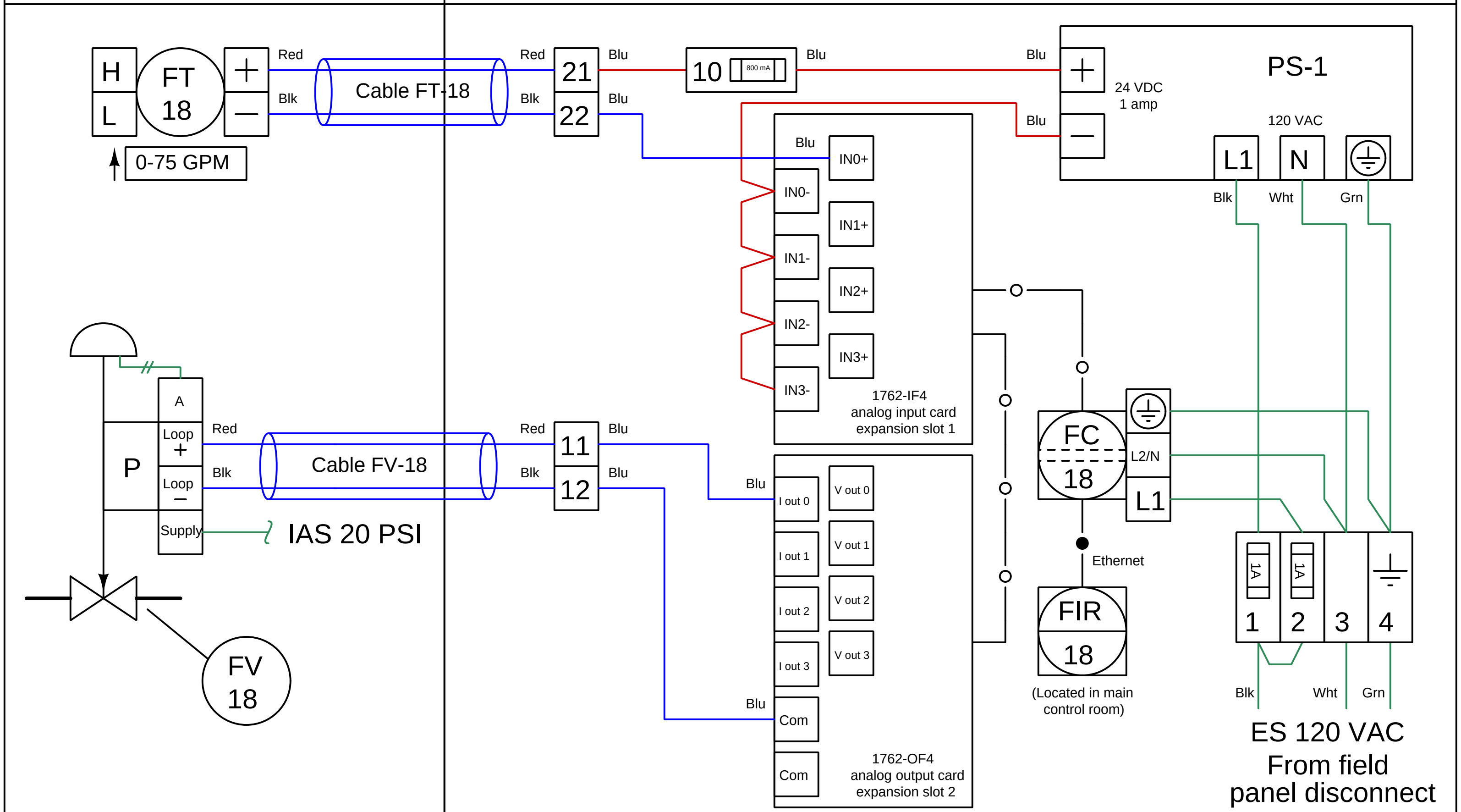
Loop Diagram: Sludge tank level control	**Revised by:** I. Leaky	**Date:** April 1, 2008
Process area	Bulkhead panel B-104	Control panel CP-11



Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
LT-24	Level transmitter	Foxboro	13A	25-150 "H_2O	3-15 PSI	
LIC-24	Controller	Foxboro	130	3-15 PSI	3-15 PSI	
LV-24	Control valve	Fisher	Easy-E / 667	3-15 PSI	0-100%	Fail closed

Loop Diagram: Unit feed flow control	**Revised by:** A. Bradley	**Date:** April 1, 2013

Process area	Field panel FP-25



Tag number	Description	Manufacturer	Model	Calibration	Notes
FT-18	Flow transmitter	Rosemount	3051S	0-100" WC input 4-20 mA output	Square-root characterization
FC-18	PLC	Allen-Bradley	ML1100	1762-IF4 input 4-20 mA 1762-OF4 output 4-20 mA	IP = 169.254.10.9 Mask = 255.255.0.0
FIR-18	HMI touch-panel	AutomationDirect	C-More		
FV-18	Flow valve with positioner	Fisher	ED / 667 DVC6010	4 mA = fully closed 20 mA = fully open	Fail-closed

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous with inspection of each team member's loop diagram. Team members will exchange diagrams with each other and then verify from those diagrams what the instructor sees when inspecting each and every panel and connection. *Please note that the "Lessons In Industrial Instrumentation" textbook describes good practices for construction and documentation.*

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and −, black and white for AC "hot" and "neutral", green for earth ground).
- All metallic electrical enclosures must be bonded to earth ground for safety.
- Proper wire types and attachment to terminals (e.g. appropriate wire gauge for the expected current, use of stranded wire wherever possible, correct terminals crimped to ends of wires, no stray wire strands at any point).
- Attached wires must withstand being lightly pulled with fingers.
- Wire insulation must be intact (i.e. no bare wires anywhere).
- Panel wiring must be neat in appearance (e.g. all cables run directly from terminal block to nearest wire duct, with all excess wire length tucked inside wire duct).
- Wiring outside of panels should be run through conduit wherever possible.
- Correct tools must be used at all times. This includes the use of fixed-size wrenches rather than adjustable wrenches whenever possible, box-end over open-end wrenches whenever possible, and the correct type and size of screwdriver used to turn screw heads.
- All electrical components must be located to avoid exposure to liquids.
- All tube and pipe connections must be properly made (e.g. correct "swaging" of tube ends, no over- or under-tightened fittings, Teflon tape or pipe sealant used on all NPT threads).
- All manual controls (e.g. buttons, handles, knobs) must be accessible and function without undue effort.

Documentation Standards

- Loop diagrams must be drawn in accordance with ISA standard 5.1.
- Each instrument must have an appropriate ISA-standard tag name, and this tag name must be visible on the actual instrument (e.g. written on masking tape and attached to the instrument).
- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
- All instrument symbols must be appropriate to the device, function, and location. The large white-colored control panel and the DCS operator stations constitute the *main control room*. All electrical enclosures in the lab room are *auxiliary* locations, and everything else is considered a *field* location.
- Instrument functions shared within a common device must be represented by the "shared" symbol on the diagram (e.g. a controller that is part of a multi-loop control system such as a DCS). Shared controllers must have their identifying loop noted on the diagram (e.g. DCS South Loop #23).
- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

- Each location (e.g. field, junction box, control room) must be clearly delineated with vertical seperation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. *"Where is the controller for this loop?"*) or determining important configuration parameters (e.g. range settings).

Sample diagrams are provided in this worksheet (immediately following the lab exercise documentation), and each student is urged to use these sample diagrams as references when drafting their own. The "Lessons In Industrial Instrumentation" textbook also describes ISA-standard documentation practices.

Common mistakes:

- Incorrect tag name format, using letters that do not conform to the ISA 5.1 standard (e.g. including "PLC" or "DCS" in a controller's tag name).
- Forgetting that every instrument's tag name in a loop must begin with the same letter, and that this first letter represents the process variable being measured/controlled.
- Forgetting to label all field instruments with their own tag names (e.g. AT-83).
- Failing to label termination points (e.g. terminal block screws) *exactly* as they are labeled in real life.
- Poor use of space on the diagram paper, causing some portions of the diagram to become "crowded" rather than all components being evenly spaced. *Hint: begin your diagram by sketching the field instrument at the far left of the paper and the control room instrument at the far right of the paper, then draw all other instruments and connections in between!*
- Forgetting to label all signal wires (see example loop diagrams).
- Forgetting to note all wire colors.
- Forgetting to put your name on the loop diagram!
- Leaving junction box cables outside of wire duct, looking messy.
- Leaving wire duct covers off.
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.
- Not placing loop sheet instruments in the correct orientation (field instruments on the left, control room instruments on the right).

Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!

file i00654

Answer 1

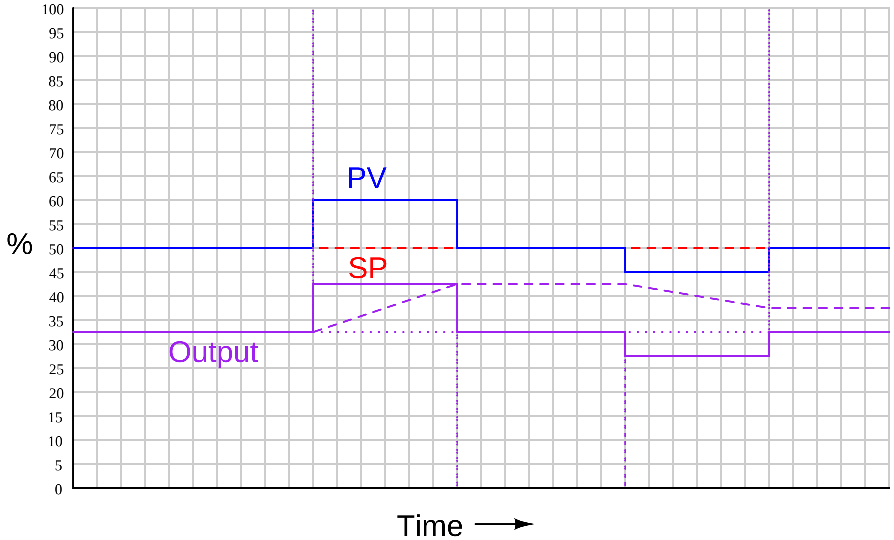
Answer 2

Answer 3

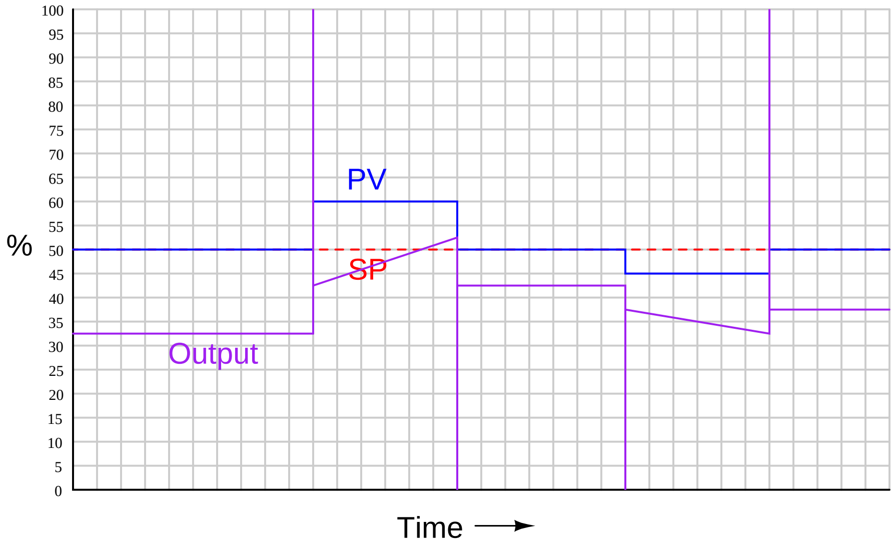
Answer 4

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:

Individual P, I, and D responses graphed:



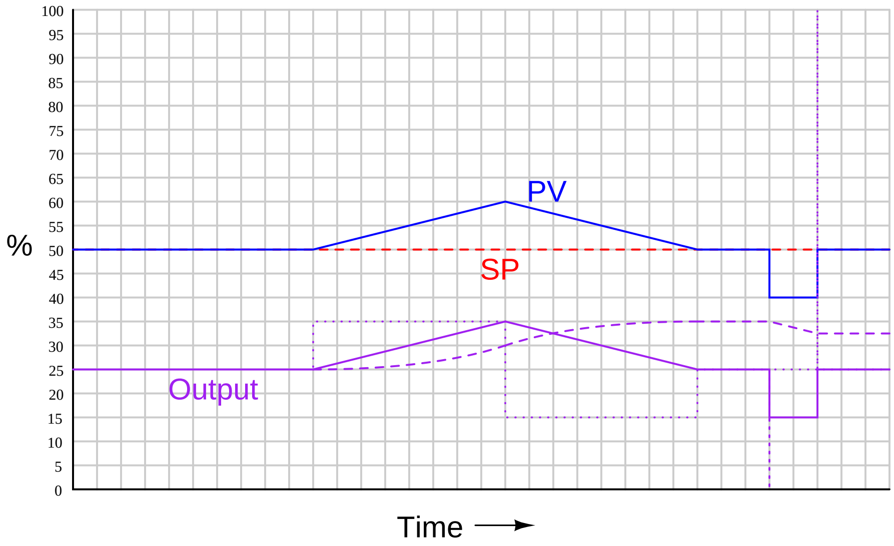
Final output signal graph:



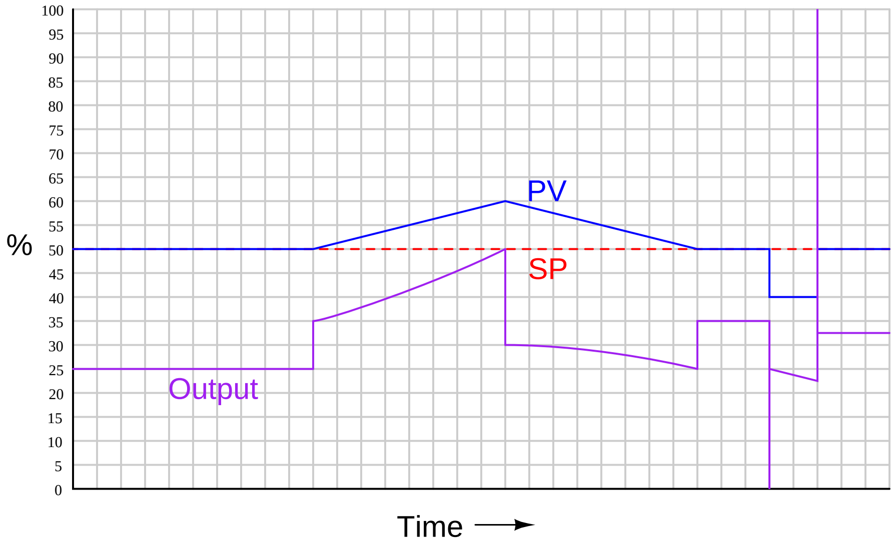
Answer 5

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:

Individual P, I, and D responses graphed:



Final output signal graph:



Answer 6

Fault	**Possible**	**Impossible**
Blower speed too high		$\surd$
FC in manual mode	(depends)	
PC in manual mode	$\surd$	
FT slightly mis-calibrated (registers too much flow)		$\surd$
FT slightly mis-calibrated (registers too little flow)		$\surd$
PT slightly mis-calibrated (registers too much pressure)		$\surd$
PT slightly mis-calibrated (registers too little pressure)	$\surd$	

Whether or not the FC being in manual mode could account for this furnace's problem depends on whether or not the exhaust damper has the capacity to vent enough exhaust to maintain setpoint even with the incoming air flow at some excessive rate. If so, then the FC being in manual mode would *not* account for the problem. If not, then the FC being in manual mode *could* account for the problem.

Answer 7

Answer 8

Answer 9

Answer 10

Answer 11

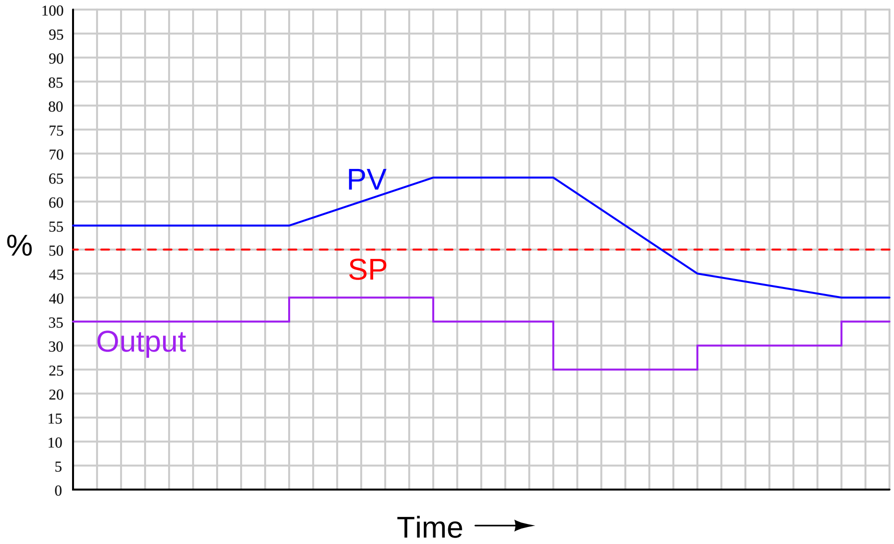
Proportional action is said to work on the present because its action is instantaneous and does not depend on time. The value of the proportional term in a PID controller is strictly a function of PV, SP, and gain, without any reference to time.

Integral action is said to work on the past, because its action is based on the amount of error (PV − SP) *accumulated over time*. Thus, the value of a PID controller's integral term is a function of past (accumulated) error.

Derivative action is said to work on the future, because its action is based on the rate-of-change over time of the PV, which is a good predictor of overshoot. This is why derivative action is sometimes called *preact*, because it preemptively acts to avoid overshoot of setpoint. This is analogous to a passenger in a fast-moving automobile, who can "predict" that the car's high speed will likely lead to "overshoot" of an intersection.

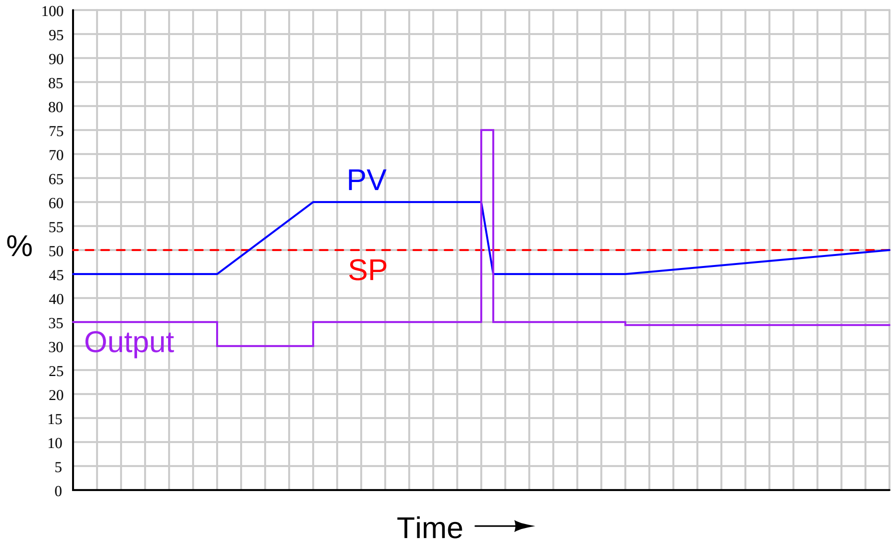
Answer 12

With derivative action, the **rate** at which error moves tells the output how **far** to go:

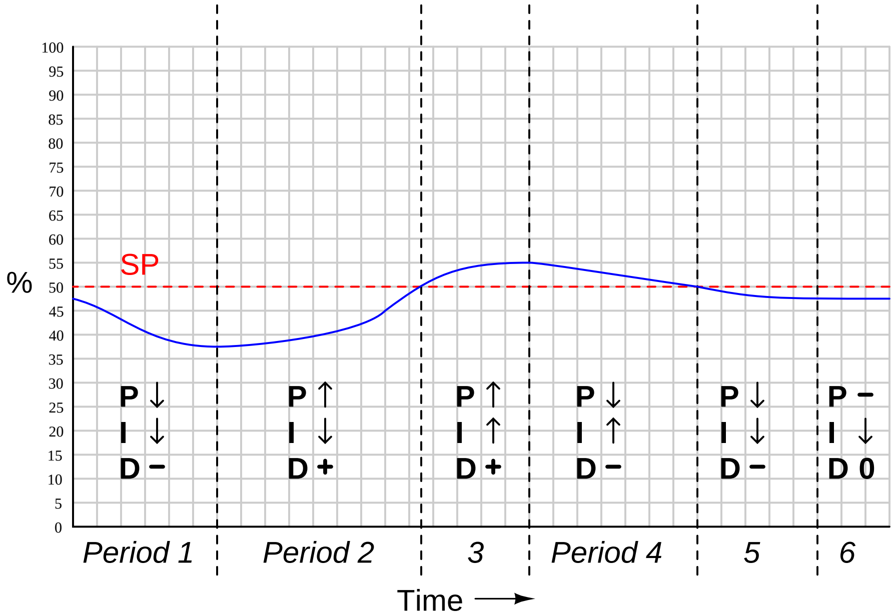


Answer 13

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:

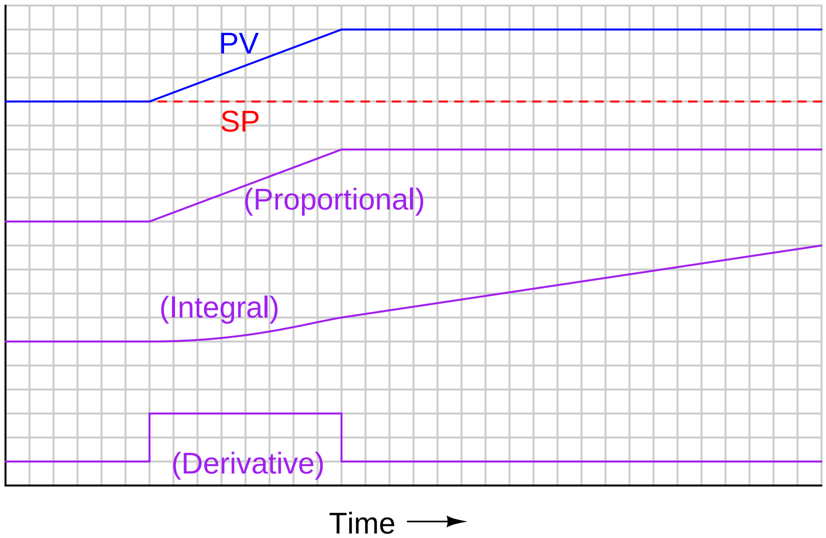


Answer 14



Answer 15

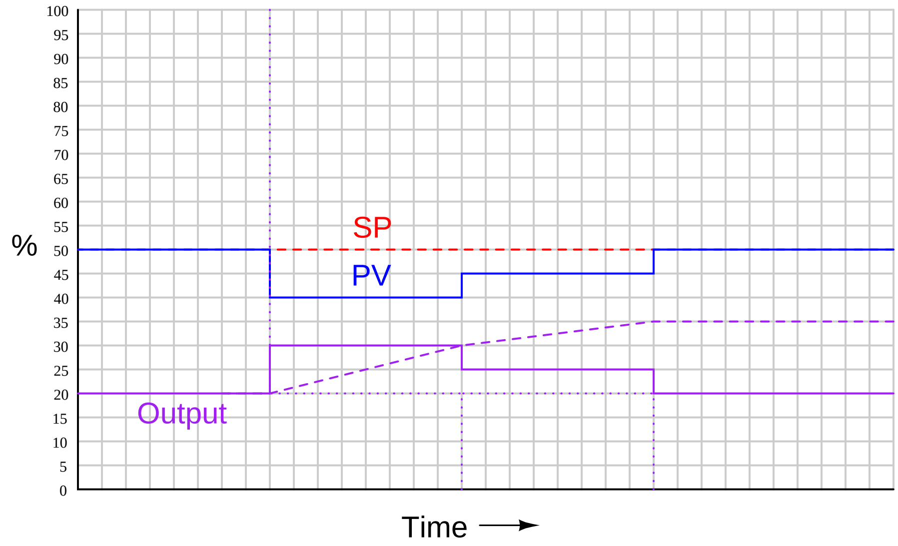
The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



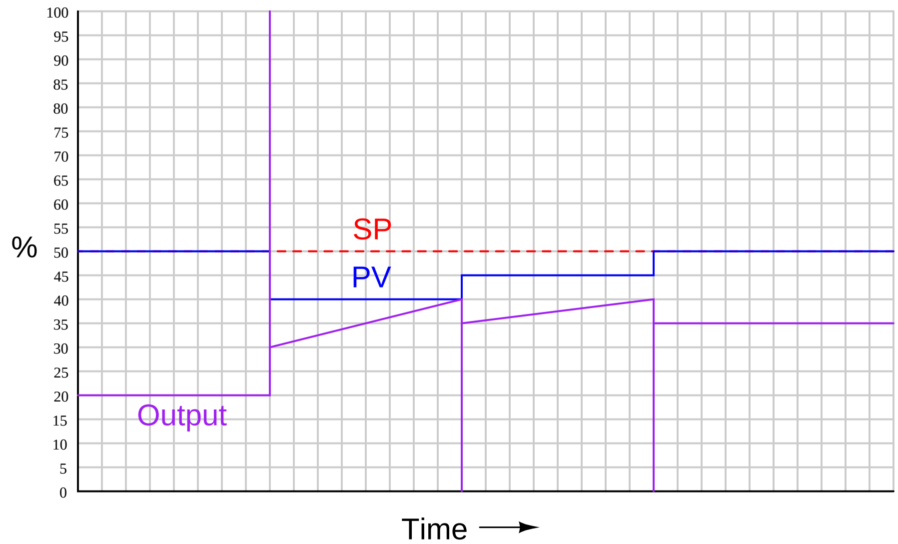
Answer 16

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:

Individual P, I, and D responses graphed:

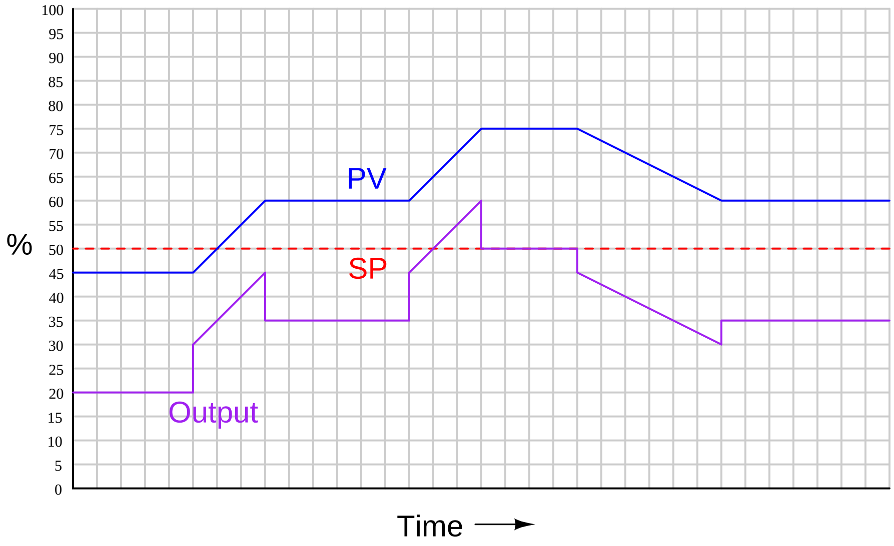


Final output signal graph:



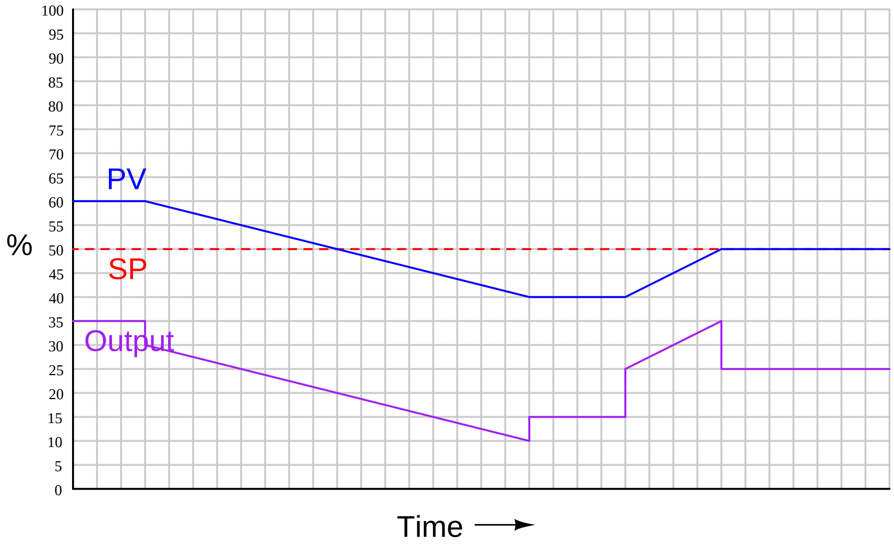
Answer 17

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 18

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 19

I'll let you figure out a pair of component values on your own! There is no single "correct" answer, as an infinite number of RC combinations will yield a time constant $\tau_d = 1$ second.

Answer 20

Answer 21

This is a *reverse-acting*, *integral-only* controller.

Answer 22

This is a *direct-acting*, *proportional-only* controller.

Answer 23

This is a *direct-acting*, *proportional + derivative* controller.

Answer 24

This is a *reverse-acting*, *proportional + integral* controller.

Answer 25

Answer 26

Answer 27

Answer 28

Answer 29

Partial answer:

- Which valve adjusts the derivative constant (τ_d)? $\mathbf{V}_2$
- Will adjustment of the proportional constant affect either the integral or derivative responses? **Yes!**

Answer 30

When derivative action works on the *error* signal, it responds to changes in setpoint (SP) and process variable (PV) equally. This will result in the controller output saturating (100% or 0%) upon step changes in setpoint, which can be a bad thing. That is why some controllers provide the option of having derivative action work only on PV changes only and not SP changes.

Answer 31

Partial answer:

- Formula for cell `D3`: `= B3 - C3`
- Formula for cell `E3`: `= $I$3 * (D3 - D2) / (A3 - A2)`
- Formula for cell `F3`: `= (D3 * (A3 - A2) / $I$2) + F2`

Answer 32

- Proportional = <u>100</u> % proportional band
- Reset = <u>(largest possible value)</u> minutes per repeat
- Rate = <u>0</u> minutes

Answer 33

This P+D controller calculates derivative on error (e), not just the value of the process variable (PV), so it uses the following algorithm:

$$m = K_p \left(e + \tau_d \frac{de}{dt} \right) + b$$

Answer 34

Since negative feedback from the op-amp's output holds the right-hand terminal of the capacitor at ground potential, the input voltage rising at 2 V/s is impressed directly across that capacitor. We know that the current through a capacitor is described by this equation:

$$i_C = C \frac{dv_C}{dt}$$

$$i_C = (0.22\ \mu\text{F})(2\ \text{V/s})$$

$$i_C = 0.44\ \mu\text{A}$$

This small current, going through the 470 kΩ resistor, produces a voltage drop of:

$$V = IR$$

$$V = (0.44\ \mu\text{A})(470\ \text{k}\Omega)$$

$$V = 0.2068\ \text{volts}$$

Since the direction of the current (conventional flow notation) is from left to right, this voltage drop across the resistor will be positive on the left and negative on the right. With the left-hand terminal of the resistor also at ground potential (0 volts), the output voltage becomes a *negative* 0.2068 volts.

The concept of time constant may make more sense when viewed from the perspective of *dimensional analysis*. If the input rate-of-change is measured in units of *volts per second*, and the output (which is proportional to the input rate-of-change) is measured in the unit of *volts*, then the constant of proportionality must be measured in the unit of *seconds*:

$$\text{Out} = k\ \text{In}$$

$$[\text{V}] = k \left(\frac{[\text{V}]}{[\text{s}]} \right)$$

$$[\text{V}] = [\text{s}] \left(\frac{[\text{V}]}{[\text{s}]} \right)$$

k must be expressed in units of time (the *second*).

$\tau_d = RC = 103.4$ ms

Answer 35

$V_{out} = 0.5792$ volts

$\tau_d = RC = 89.1$ ms

Answer 36

- This alteration will **decrease** the proportional band of the controller.
- This alteration will **increase** the bias value in the controller's equation.
- This alteration will **decrease** the response time of the controller to a sudden change in PV or SP signal.
- Assuming the controller did a fine job controlling the process before this component change, this alteration will cause the control quality to be over-reactive (oscillatory) and also develop less PV − SP offset than before.

Answer 37

Left diagram: Regular PID controller.

Center diagram: PID controller with derivative calculated on PV only (not error).

Right diagram: PI controller with setpoint tracking.

Answer 38

- The effect on the output signal immediately after the fault: *The output immediately steps up (most likely to saturation), as through the setpoint had suddenly increased.*
- The effect on the output signal a few seconds after the fault (but before the process itself has had time to react to the change in output): *The output signal will be winding up at a constant rate (assuming mild proportional action). It is also possible that proportional action is strong enough to simply drive the output to full saturation immediately after the fault, in which case no further changes in output will be seen.*

Answer 39

$$V_{out} = -\frac{1}{RC}\int_{t_0}^{t_f} V_{in}\, dt + V_0$$

$$V_{out} = -\left(\frac{1}{(270 \times 10^3\ \Omega)(0.33 \times 10^{-6}\ \text{F})}\right)\left(\int_0^{0.5} 1.5\, dt\right) + 0\ \text{V}$$

$$V_{out} = -\left(\frac{1}{0.0891\ \text{s}}\right)(0.75\ \text{V} \cdot \text{s}) + 0\ \text{V}$$

$$V_{out} = -8.418\ \text{V}$$

Calculating the time constant for this integrator circuit:

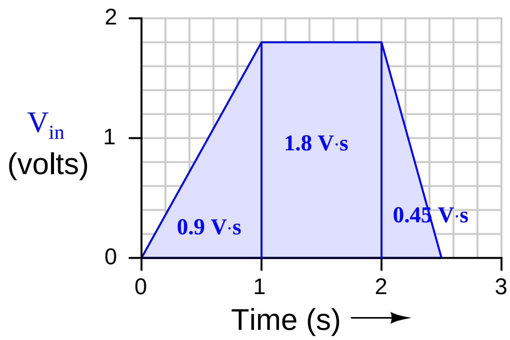
$\tau_i = RC = (270 \times 10^3\ \Omega)(0.33 \times 10^{-6}\ \text{F}) = 0.0891$ seconds

Answer 40

$$V_{out} = -\frac{1}{RC}\int_{t_0}^{t_f} V_{in}\,dt + V_0$$

$$V_{out} = -\left(\frac{1}{(100 \times 10^3\ \Omega)(2.2 \times 10^{-6}\ \mathrm{F})}\right)\left(\int_0^{2.5} V_{in}\,dt\right) + 8\ \mathrm{V}$$

At this point we need to evaluate the integral in order to proceed much further. Since V_{in} is not a constant, and we have no means to symbolically integrate the input voltage function, we must find the integral value graphically. Recalling that the graphical meaning of integration is the geometric *area* encompassed by the function, all we need to do is calculate the area of the trapezoid:



Total area under the curve =
0.9 + 1.8 + 0.45 = 3.15 volt-seconds

Note the units of measurement used to express the integral: *volt-seconds*, because the vertical dimension is expressed in units of *volts* and the horizontal dimension is expressed in units of *seconds* and integration involves *multiplication* of units.

$$V_{out} = -\left(\frac{1}{0.22\ \mathrm{s}}\right)(3.15\ \mathrm{V \cdot s}) + 8\ \mathrm{V}$$

$$V_{out} = -14.318\ \mathrm{V} + 8\ \mathrm{V}$$

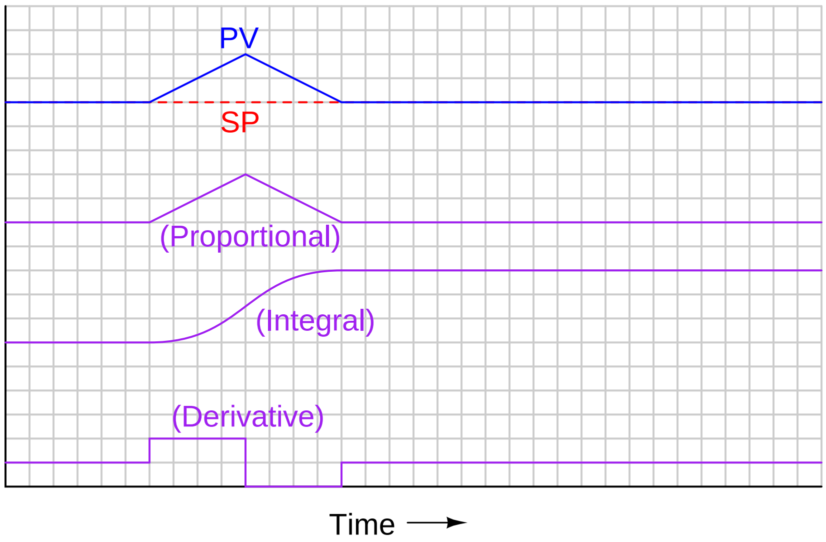
$$V_{out} = -6.318\ \mathrm{V}$$

Calculating the time constant for this integrator circuit:

$\tau_i = RC = (100 \times 10^3\ \Omega)(2.2 \times 10^{-6}\ \mathrm{F}) = 0.22$ seconds

Answer 41

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 42

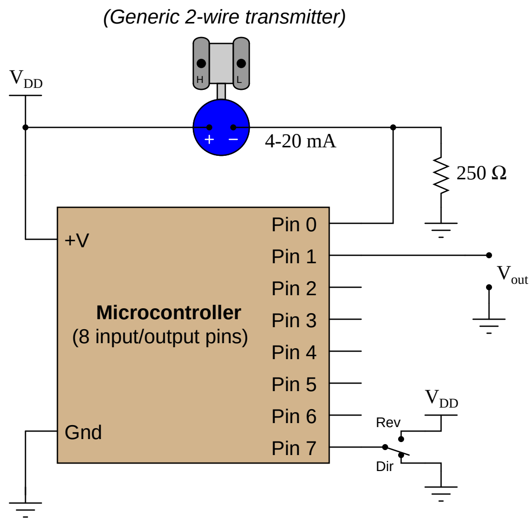
Answer 43

`A` = `805` = 110 PSI (motor stop point)
`B` = `750` = 100 PSI (motor start point)
`C` = `700` = 90.8 PSI (low air pressure alarm point)

Answer 44

The controller code as shown implements *direct* action, since the error is calculated as PV − SP.

The following additions give this controller the ability to switch between direct or reverse control action:



Pseudocode listing

```
Declare Pin0 as an analog input (scale 0 to 5 volts = 0 to 1023)
Declare Pin1 as an analog output (scale 0 to 5 volts = 0 to 1023)
Declare Pin7 as a discrete input
Declare SP as a variable, initially set to a value of 614
Declare GAIN as a variable, initially set to a value of 1.0
Declare ERROR as a variable
Declare BIAS as a constant = 614

LOOP
  IF Pin7 = 0, SET ERROR = Pin0 - SP
  ELSE, SET ERROR = SP - Pin0
  ENDIF

  SET Pin1 = (GAIN * ERROR) + BIAS
ENDLOOP
```

While a very slow program execution time could be bad for control, it actually could serve a useful purpose in some processes. In processes with large dead times (transport delays), one control strategy to apply is called *sample-and-hold*, which is precisely what this program would be if a purposeful and substantial delay time were inserted into the loop.

Answer 45

The trickiest part to understand is the relationship between `x` and `last_x`, and between `t` and `last_t`. This technique of declaring a variable pair and sequentially cascading a value from one variable to the next variable in each loop of execution, is commonly used in a lot of different algorithms. The point of this technique is to provide a means of measuring change in a variable (such as `x` and `t`) with every scan of the program. Once change in x and t are both known, the quotient (derivative) may be calculated by dividing one change by the other.

Answer 46

Answer 47

Answer 48

One possibility here is that the air filter is plugged.

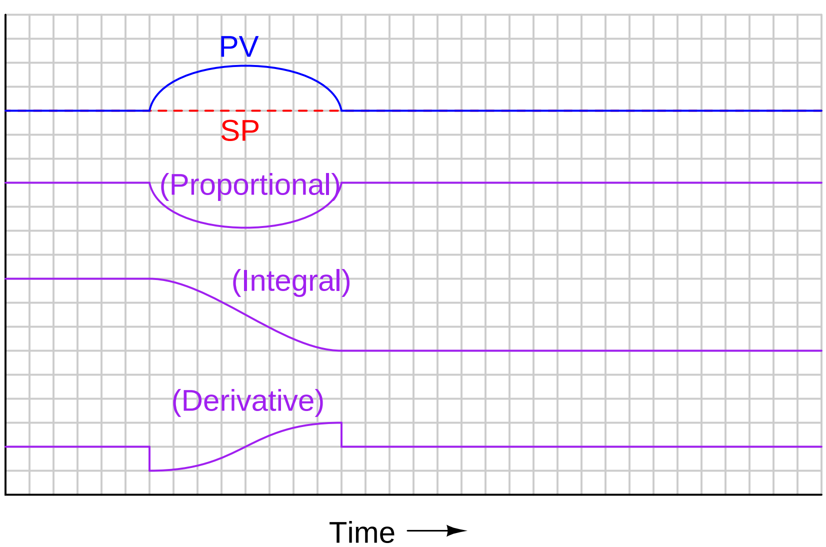
Answer 49

Partial answer:

Diagnostic test	**Yes**	**No**
Measure AC line voltage		
Measure DC power supply output voltage		$\surd$
Inspect PID tuning parameters in controller		
Inspect PV range values (LRV, URV) in controller		
Push flapper toward nozzle in I/P		
Pull flapper away from nozzle in I/P		
Measure DC voltage between TB1-3 and TB1-4		$\surd$
Measure DC voltage between TB1-6 and TB1-7		

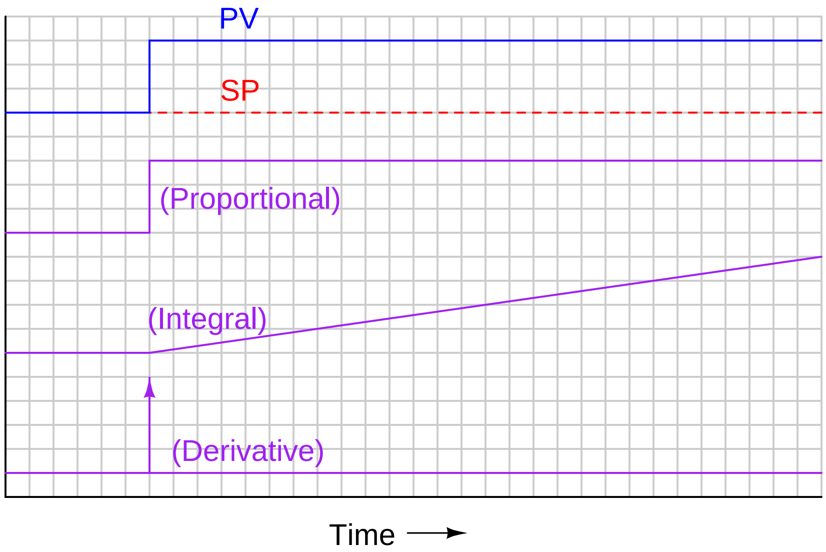
Answer 50

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 51

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 52

- This alteration will **increase** the proportional band of the controller.
- This alteration will **decrease** the bias value in the controller's equation.
- This alteration will **increase** the response time of the controller to a sudden change in PV or SP signal.
- Assuming the controller did a fine job controlling the process before this component change, this alteration will cause the control quality to be sluggish and also develop a larger PV − SP offset than before.

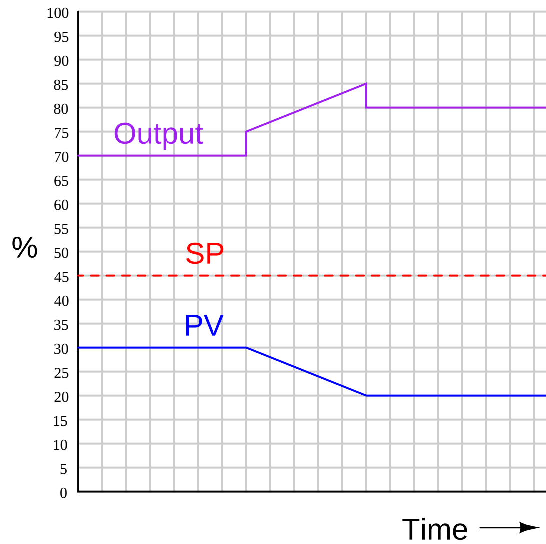
Answer 53

Position of valve FV-82a = `(FC-82 Output) * 2`

Position of valve FV-82b = `((FC-82 Output) * 2) - 100`

Answer 54

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 55

- This mechanism activates when the process pressure's rate of change **rises** quickly over time.
- To switch the direction of change, both the check valve and the spool valve's return spring would have to be reversed in direction.
- Identify the direction of air flow through the line leading to the "pneumatic control device" when the process pressure is not changing at all: **air flowing in from the pneumatic control device**.
- Identify one component that would have to be altered in this mechanism to make it *less sensitive* to rates of process gas pressure change over time, and precisely how that component would have to be altered (e.g. size, shape, etc.): either **enlarge the restriction**, **shrink the capacity tank**, and/or **replace the spool valve spring with one that is "stiffer"**.

Answer 56

At 1:30 PM, the level is increasing at a rate ($\frac{dV}{dt}$) of 5 gallons per hour, which is equivalent to 0.083 GPM. At that time the outgoing flow rate (FT-240) registers 35 GPM. Therefore, the incoming flow rate must be 0.083 GPM greater than FT-240, which is 35.083 GPM.

Q_{in} @ 3:45 PM must be equal to Q_{out} because the level (LT-31) is holding steady. Therefore, Q_{in} = 27.5 GPM at 3:45 PM.

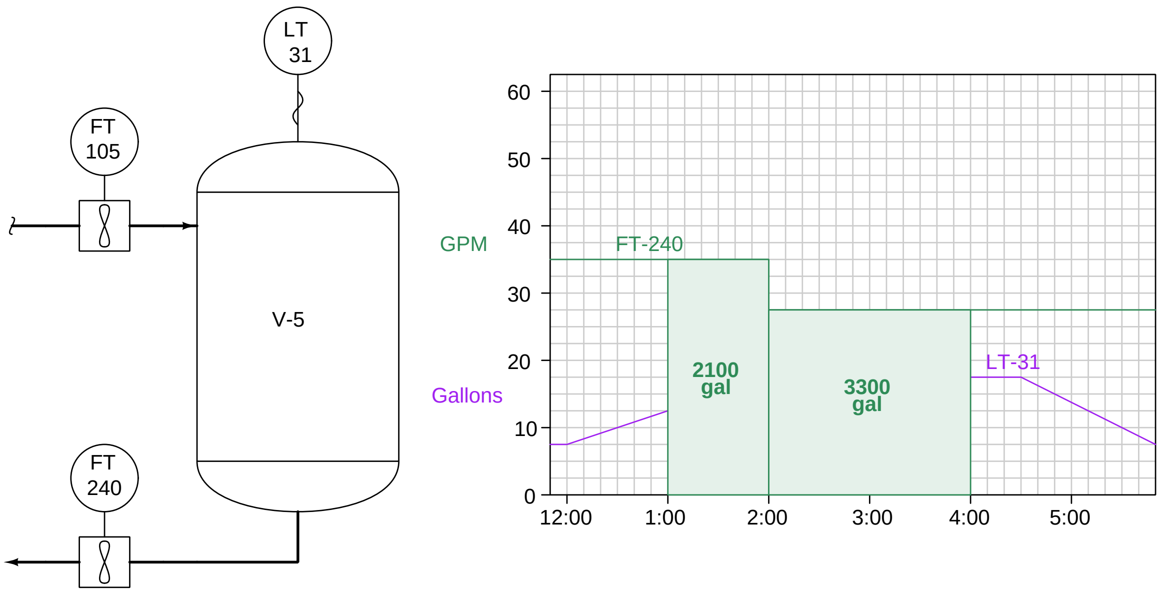
What this means is that the incoming flow decreased at the same time as the outgoing flow decreased (both at 2:00 PM). Between Noon and 2:00 PM Q_{in} was 35.083 GPM and Q_{out} was 35 GPM, but then both flow rates stepped down to 27.5 GPM at 2:00 PM.

Answer 57

Here we are asked to calculate a total volume given flow rate (in gallons per minute) and time. This involves multiplication (so that minutes of time will cancel out the "minutes" in GPM to yield an answer in gallons), which means the appropriate calculus function is *integration*. Specifically, we need to integrate the flow rate of FT-240 over the time interval of 1:00 PM to 4:00 PM:

$$V_{discharged} = \int_{1:00 \text{ PM}}^{4:00 \text{ PM}} Q_{FT-240} \, dt$$

This integral represents the area beneath the FT-240 flow function between 1:00 PM and 4:00 PM on the trend graph, represented by the two shaded rectangles below:



The first rectangle is 35 GPM high and 60 minutes wide, yielding an area of 2100 gallons:

$$\left(\frac{35 \text{ gal}}{\text{min}} \right) \left(\frac{60 \text{ min}}{1} \right) = 2100 \text{ gal}$$

The second rectangle is 27.5 GPM high and 120 minutes wide, yielding an area of 3300 gallons:

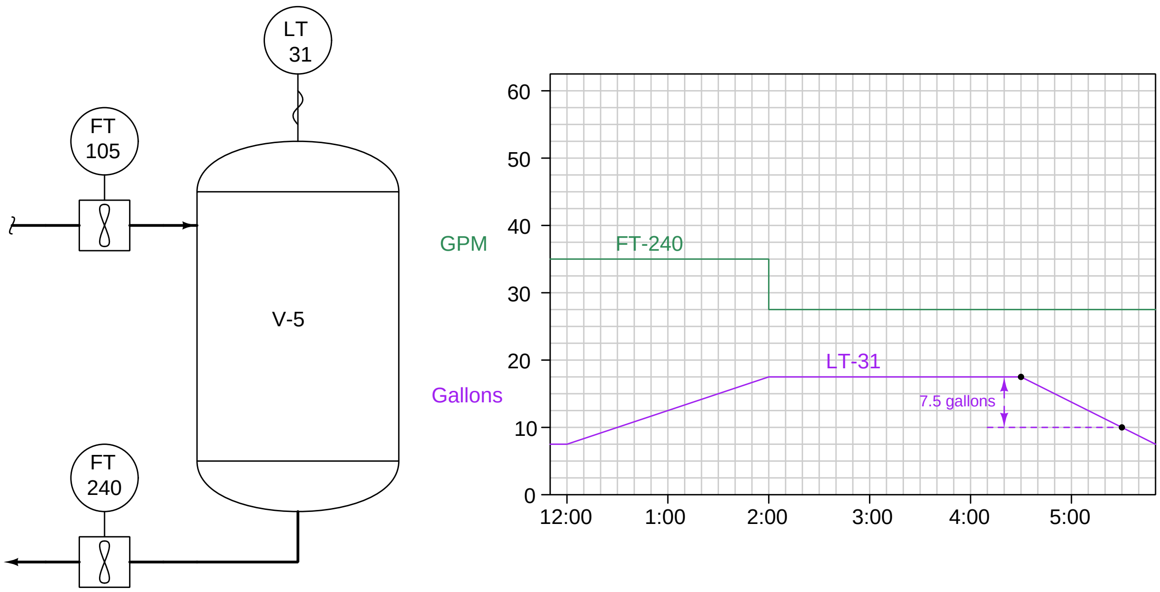
$$\left(\frac{27.5 \text{ gal}}{\text{min}} \right) \left(\frac{120 \text{ min}}{1} \right) = 3300 \text{ gal}$$

Together, the total area of these two rectangles is 5400 gallons, which is the value of our integral, and therefore the total quantity of liquid discharged from the vessel between 1:00 PM and 4:00 PM.

$V_{discharged}$ between 1:00 PM and 4:00 PM = **5400** gallons

Answer 58

This question is designed to probe your critical thinking, because there is absolutely no calculus involved in the answer! Level transmitter LT-31 already measures the amount of liquid stored in the vessel, so calculating volume lost between any two points in time is simply a matter of subtracting those LT-31 values at those times:



Since the vessel holds 17.5 gallons of liquid at 4:30 PM and holds 10 gallons of liquid at 5:30 PM, the amount of liquid lost from the vessel between those times is 7.5 gallons:

V_{lost} between 4:30 PM and 5:30 PM = $\underline{\mathbf{7.5}}$ gallons

Answer 59

We are asked to find the number of *gallons* inside the vessel given flow rates in *gallons per hour* and time in *hours*. Therefore, the mathematical operation we must employ is multiplication (so that "hours" cancels out to leave "gallons") and that means *integration*.

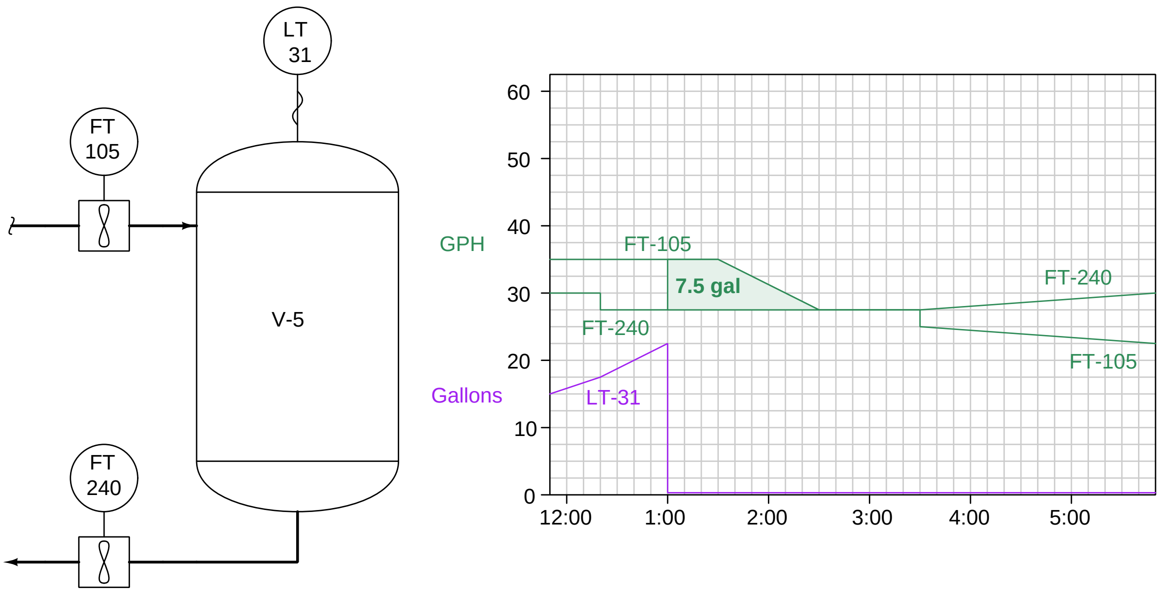
The vessel's accumulated volume rises or falls according to the difference between the incoming and outgoing flow rates over time. Mathematically we may express this by the following integral:

$$V = \int_{t_0}^{t_f} (Q_{in} - Q_{out}) \, dt + V_0$$

The level transmitter stopped working at 1:00 PM, so the last known volume of liquid inside the tank was measured then: 22.5 gallons. This must then be our initial volume (V_0), with 1:00 PM being the lower limit of our integration interval. The upper limit of our integration interval must be 3:00 PM which is the time when we're interested in the tank's liquid volume. Therefore:

$$V_{3:00} = \int_{1:00}^{3:00} (Q_{in} - Q_{out}) \, dt + 22.5 \text{ gal}$$

Evaluating this integral graphically, we end up with the following shaded area between the two flowmeter trendlines:



The area of this trapezoid (calculated as the area of a 3x3 square and a 3x6 triangle) is (7.5 gal/hr)(0.5 hr) + (0.5)(7.5 gal/hr)(1 hr) = 7.5 gallons. Thus:

$$V_{3:00} = \int_{1:00}^{3:00} (Q_{in} - Q_{out}) \, dt + 22.5 \text{ gal}$$

$$V_{3:00} = 7.5 \text{ gal} + 22.5 \text{ gal} = 30 \text{ gal}$$

Vessel V-5 therefore contains 30 gallons of liquid at 3:00 PM.

Answer 60

Answer 61

Answer 62

This is a *direct-acting*, *integral-only* controller.

Answer 63

The reason that the technician's proposed test would have been a waste of time is because the controller is already registering a reasonable pressure (approximately the same as the field-mounted gauge). In other words, the controller PV indication corresponds with the gauge, suggesting there is no problem in that (input) portion of the control system.

Answer 64

Answer 65

Answer 66

Answer 67

As of this date (2018), `TROUBLESHOOT` is a program written in the ANSI 'C' language for a Unix-based operating system such as Linux. It runs within a "terminal" (text-only) environment which is why a printed copy of the schematic diagram is necessary for the user to have. The program was written in this legacy format in order to be extremely compact, executable on the smallest of computers (e.g. Raspberry Pi or Beaglebone single-board PCs).

If you wish to run this circuit troubleshooting software on your own personal computer, you may do so in the following ways:

- Install free `Cygwin` software on your Windows-based PC, under which you may compile and run `TROUBLESHOOT`. `Cygwin` is a Unix emulation program providing a POSIX-compliant environment on any Windows operating system in which Unix software may be installed, compiled, and executed. *This is perhaps the easiest option for someone who wants to install* `TROUBLESHOOT` *on their Windows-based computer but who does not wish to purchase anything or alter the operating system.*
- Purchase your own single-board Linux-based PC such as a Raspberry Pi and run it natively on that platform.
- Install free *SSH* remote login software (such as `BitVise`) on your PC and then log into one of the Instrumentation lab's Raspberry Pi servers where `TROUBLESHOOT` is already installed. *This option is very easy, but its major disadvantage is the need to be in or near the Instrumentation lab in order to have wireless access to the servers – i.e. it's not an option for you to run this software at home.*
- Install and compile and run `TROUBLESHOOT` natively on an Apple PC with Unix-based operating system.
- Install the Linux operating system on your own PC, then install and compile and run `TROUBLESHOOT` natively.

`TROUBLESHOOT` is downloaded as a single "tar" file with a name such as `tshoot_1v3.tar`. The two numbers and the "v" represent the version of that software (e.g. `tshoot_1v3.tar` is version 1.3 of the `TROUBLESHOOT` software). Obtain the latest version of the software, download it to a directory on your computer accessible via a command-line "terminal" environment, and then enter the following commands to compile this software:

```
tar xvf tshoot*tar

make
```

After running these commands, `TROUBLESHOOT` should be ready to use. Simply enter the following command to begin execution:

```
./tshoot
```

Answer 68

The analytical control system should still be able to maintain sugar concentration at setpoint, unless the steam temperature is so low that even a wide-open steam valve does not heat the incoming syrup enough to sufficiently concentrate it.

Answer 69

Since there will no longer be a retention time for syrup in the evaporator, less water will evaporate from the heated syrup, resulting in a more "watery" (less concentrated) syrup exiting the evaporator.

Answer 70

This is a *direct-acting*, *proportional + integral* controller.

A significant clue to determining this controller possesses integral action is to note that the output settles at a very different value than where it started at (both times PV = SP). Only integral action can effectively shift the bias of the controller in this way.

Answer 71

This is a *reverse-acting*, *proportional-only* controller.

Follow-up question: estimate the proportional band of this controller.

Answer 72

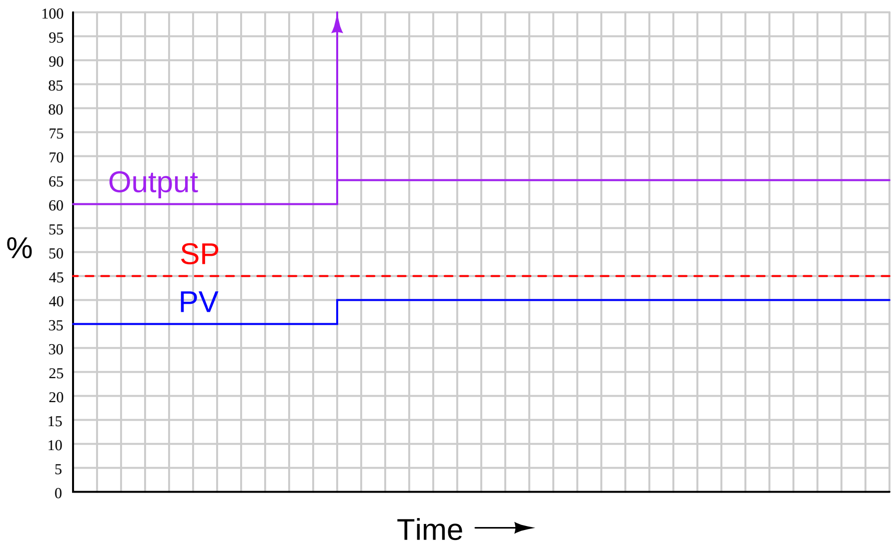
This is a *reverse-acting*, *proportional + derivative* controller.

Answer 73

The answer to all questions (except the last one) is bow #3. Bow #1 will be the easiest for a novice archer to draw.

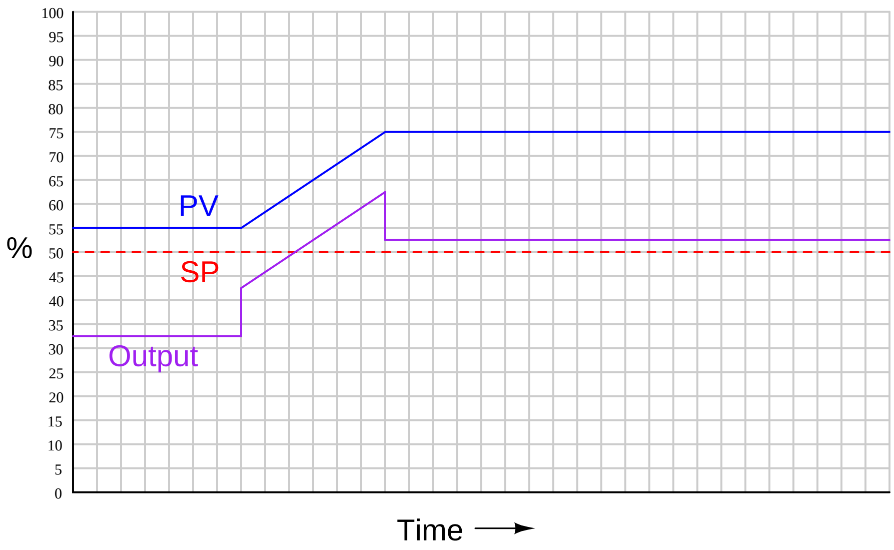
Answer 74

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



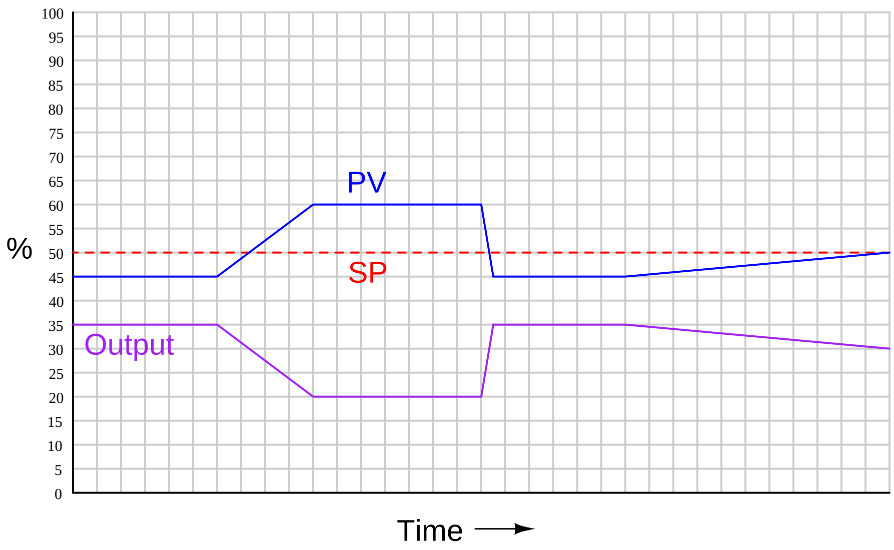
Answer 75

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



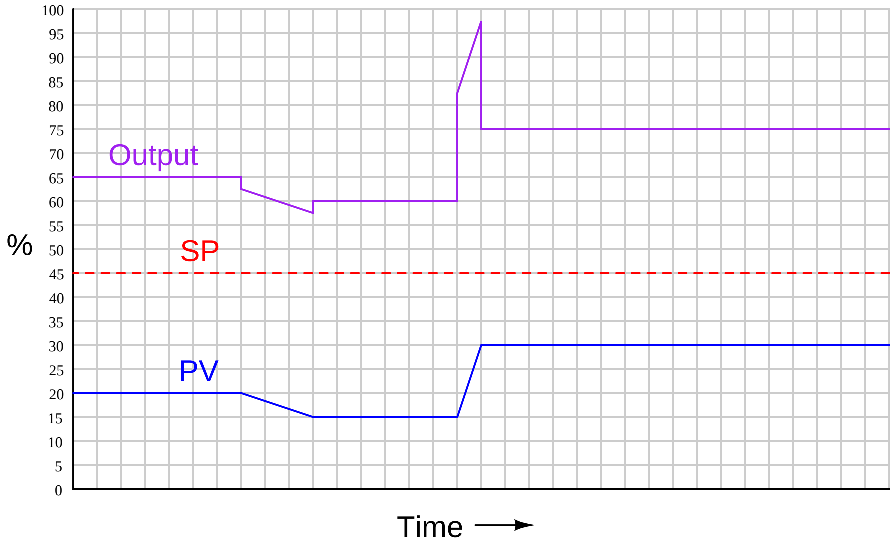
Answer 76

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



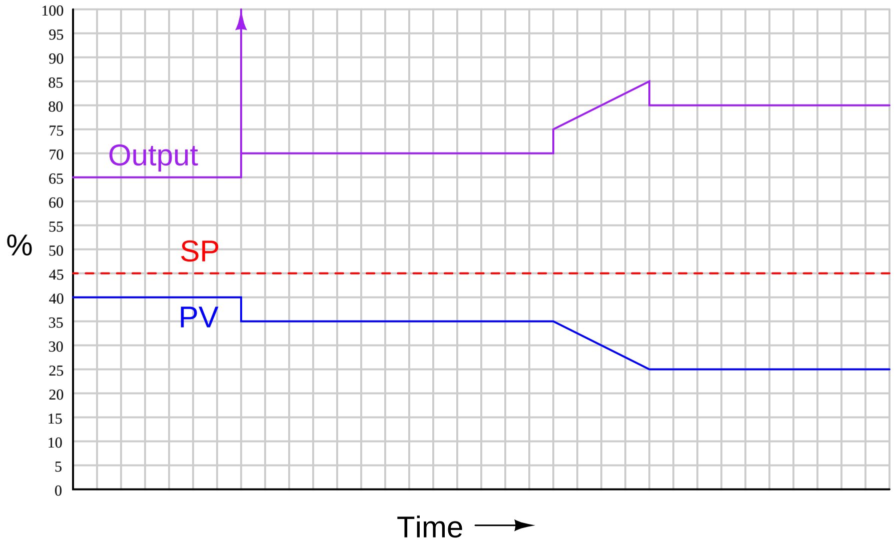
Answer 77

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 78

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 79

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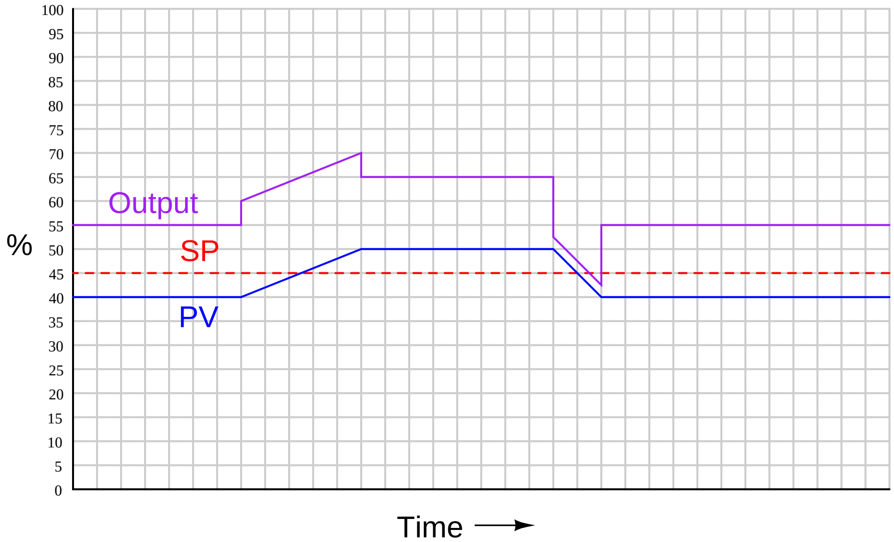
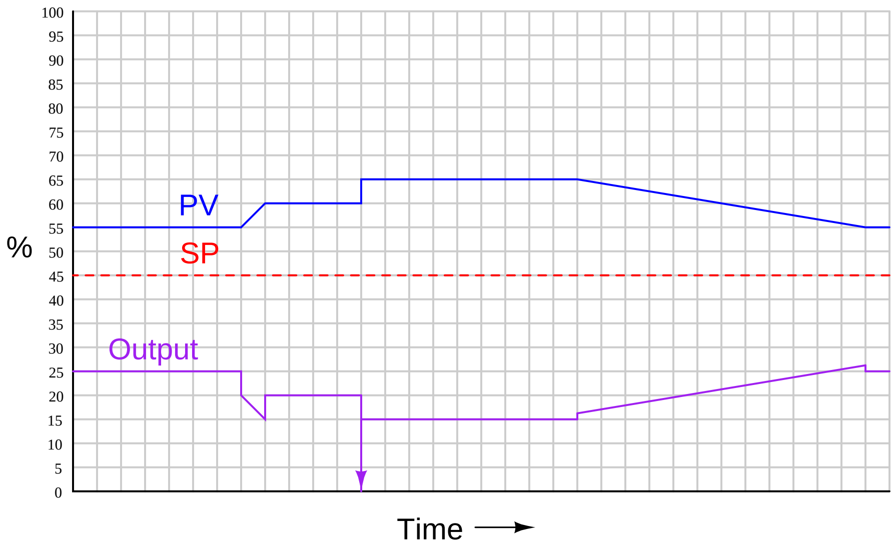


Answer 80

The controller output graph shown here is *qualitative* only. Although drawn to scale (i.e. all changes in the output are properly scaled relative to each other), the scale itself is arbitrary and therefore may not match the scale of your sketch:



Answer 81

This is a graded question – no answers or hints given!

Answer 82

This is a graded question – no answers or hints given!

Answer 83

This is a graded question – no answers or hints given!

Answer 84

This is a graded question – no answers or hints given!

Answer 85

This is a graded question – no answers or hints given!

Answer 86

This is a graded question – no answers or hints given!

Answer 87

This is a graded question – no answers or hints given!

Answer 88

This is a graded question – no answers or hints given!

Answer 89

This is a graded question – no answers or hints given!

Answer 90

This is a graded question – no answers or hints given!

Answer 91

Answer 92

Your loop diagram will be validated when the instructor inspects the loop with you and the rest of your team.