

Lab

Multiple loop tuning: *Question 91, completed objectives due by the end of day 5, section 3*

Exam

Day 6 of section 3

Capstone Assessment (see question 92)

Specific objectives for the optional “mastery” exam (worth +5% on the proportional exam score if passed the very first time):

- Electricity Review: Design a simple circuit to achieve a stated objective
 - Identify cause of poor loop performance from a trend graph
 - Identify problem in control loop based on faceplate display and field data
 - Calculate either the numerical derivative or the numerical integral from a graph
 - 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: Determine status of PLC output given input conditions and RLL program
 - INST240 Review: Determine suitability of different level-measuring technologies for a given process fluid type
 - INST263 Review: Determine the effect of a component fault or condition change in a selector or override control system
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Recommended daily schedule

Day 1

Theory session topic: Process characteristics

Questions 1 through 20; answer questions 1-8 in preparation for discussion (remainder for practice)

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 92*)

Day 2

Theory session topic: Process characteristics (continued)

Questions 21 through 40; answer questions 21-27 in preparation for discussion (remainder for practice)

Day 3

Theory session topic: Loop tuning methods and Troubleshooting

Questions 41 through 60; answer questions 41-50 in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Loop tuning practice

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

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.

General Values, Expectations, and Standards (continued)

Punctuality and Attendance: 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.

Mastery: 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.

Time Management: 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.

Orderliness: 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.

Independent Study: 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.

Independent Problem-Solving: 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.

Teamwork: 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.

Communication: 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.

Academic Progress: 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.

Office Hours: 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.

Grounds for Failure: 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.

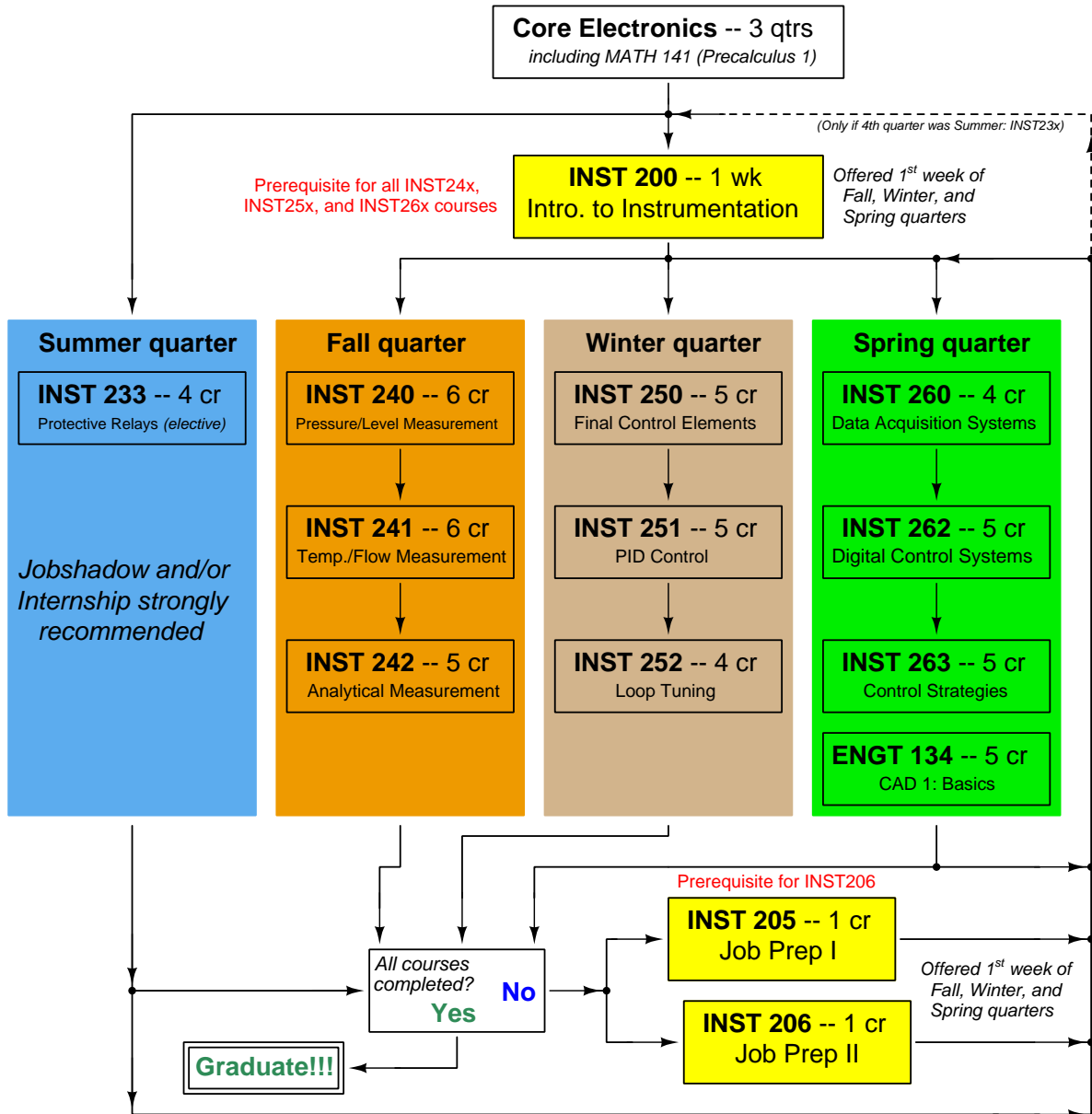
file outcomes_program

INST 252 Course Outcomes

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

- Tune multiple PID controllers for robust response to setpoint and process load changes. [Ref: Program Learning Outcome #6]
- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]
- Diagnose a random fault placed in another team's PID control system by the instructor within a limited time using no test equipment except a multimeter, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #5]
- Construct a working control loop consisting of a pre-made process unit with transmitter and final control element, properly connected to a controller, within a limited time. Both the process and the controller are randomly selected by the instructor, with PID tuning criteria (robust response to either setpoint or load changes) specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

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:

Possible course schedules depending on date of entry into 2nd year



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.

Methods of instruction (continued)

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.

file instructional

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.

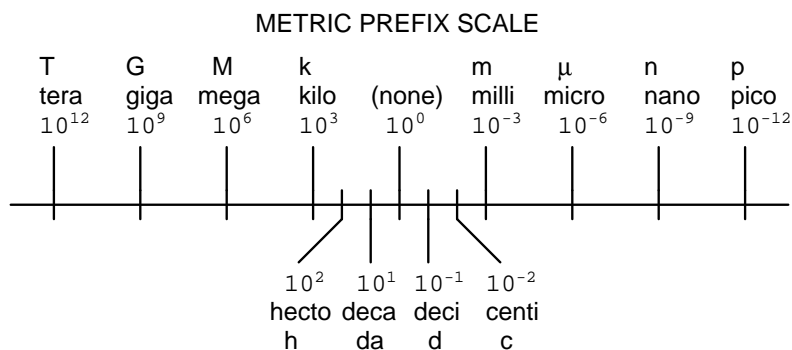
Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either 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.

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

- $^{\circ}\text{F} = (^{\circ}\text{C})(9/5) + 32$
- $^{\circ}\text{C} = (^{\circ}\text{F} - 32)(5/9)$
- $^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$
- $\text{K} = ^{\circ}\text{C} + 273.15$

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 (in³) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm³)

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 (ft²) = 4840 square yards (yd²) = 4046.86 square meters (m²)

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 10¹⁰ 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/s²) = 32.1740 feet per second per second (ft/s²)

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-Kelvin⁴ ($\text{W}/\text{m}^2 \cdot \text{K}^4$)

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

Properties of Water

Freezing point at sea level = $32^\circ\text{F} = 0^\circ\text{C}$

Boiling point at sea level = $212^\circ\text{F} = 100^\circ\text{C}$

Density of water at $4^\circ\text{C} = 1000 \text{ kg}/\text{m}^3 = 1 \text{ g}/\text{cm}^3 = 1 \text{ kg}/\text{liter} = 62.428 \text{ lb}/\text{ft}^3 = 1.94 \text{ slugs}/\text{ft}^3$

Specific heat of water at $14^\circ\text{C} = 1.00002 \text{ calories}/\text{g} \cdot ^\circ\text{C} = 1 \text{ BTU}/\text{lb} \cdot ^\circ\text{F} = 4.1869 \text{ Joules}/\text{g} \cdot ^\circ\text{C}$

Specific heat of ice $\approx 0.5 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Specific heat of steam $\approx 0.48 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Absolute viscosity of water at $20^\circ\text{C} = 1.0019 \text{ centipoise (cp)} = 0.0010019 \text{ Pascal-seconds (Pa}\cdot\text{s)}$

Surface tension of water (in contact with air) at $18^\circ\text{C} = 73.05 \text{ dynes}/\text{cm}$

pH of pure water at $25^\circ\text{C} = 7.0$ (*pH scale = 0 to 14*)

Properties of Dry Air at sea level

Density of dry air at 20°C and 760 torr = $1.204 \text{ mg}/\text{cm}^3 = 1.204 \text{ kg}/\text{m}^3 = 0.075 \text{ lb}/\text{ft}^3 = 0.00235 \text{ slugs}/\text{ft}^3$

Absolute viscosity of dry air at 20°C and 760 torr = $0.018 \text{ centipoise (cp)} = 1.8 \times 10^{-5} \text{ Pascal-seconds (Pa}\cdot\text{s)}$

file conversion_constants

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:

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.

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.

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.

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.

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.

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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Questions

Question 1

Read and outline the introduction and the “Self-Regulating Processes” subsections of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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 i04316](#)

Question 2

Read and outline the “Integrating Processes” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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.).
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- (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 i04317](#)

Question 3

Read and outline the “Runaway Processes” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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 i04318](#)

Question 4

Read and outline the “Steady-State Process Gain” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” chapter in your *Lessons In Industrial Instrumentation* textbook.

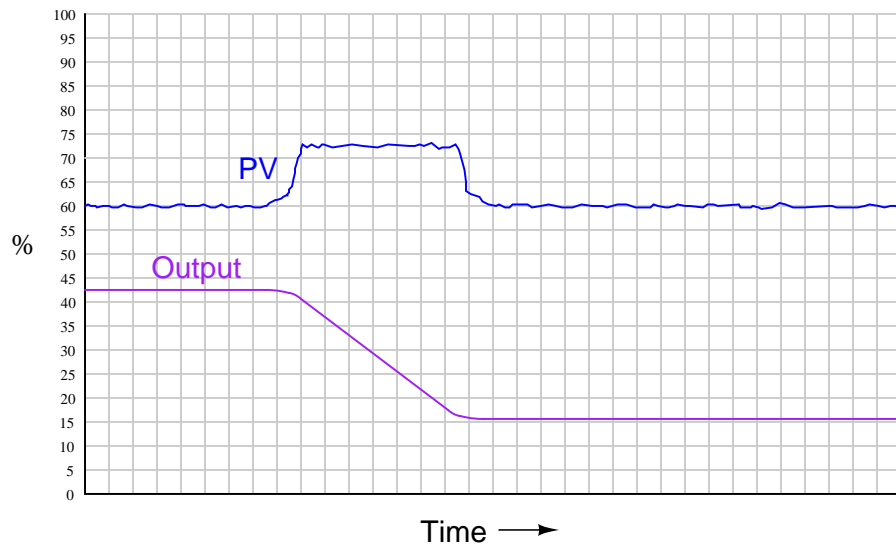
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (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.
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- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04319](#)

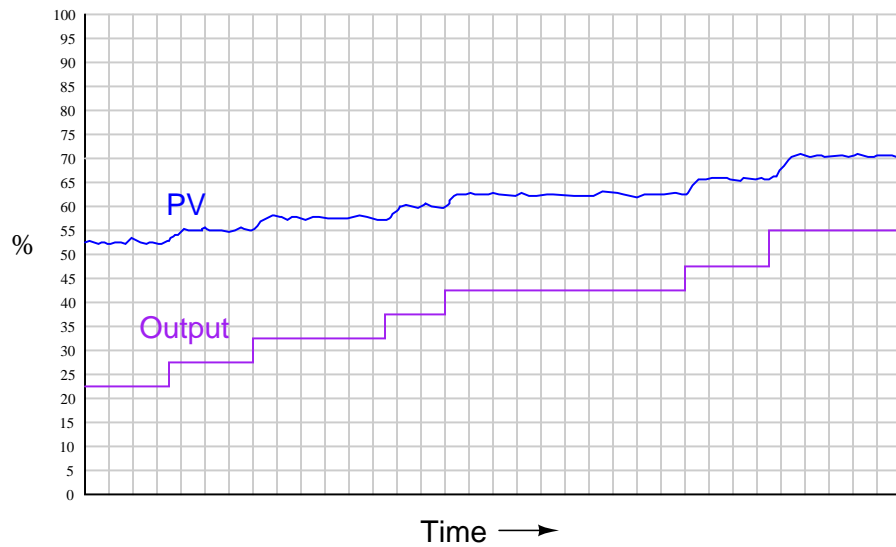
Question 5

Examine this trend graph showing a controller's PV and output signals as it controls a loop in automatic mode, and then answer the following questions about the loop based on data evident in the trend:



- Is the controller *direct-acting* or *reverse-acting*?
- Does the controller exhibit *P-only* action, *I-only* action, *PI* action, *ID* action, *PD* action, or full *PID* action?
- What value is the setpoint set at in this controller, or is there insufficient data to tell?

Now suppose this same controller is placed in manual mode, and an “open-loop” test is performed on the loop:



What exactly does this trend tell us about the *controller's action*, if anything? What does this trend tell us about the *process characteristics*, if anything? How could we tell just by examining this trend that the controller is in manual mode and not automatic mode?

[file i03508](#)

Question 6

In order to explore different process characteristics, it is useful to have access to loop simulation software you can run on your own personal computer. A “loop simulation” program mimics the behavior of a real process, allowing you to make tuning changes to a PID controller and see the results in a trend graph.

The caSCADA control system available in the BTC Instrumentation lab room offers loop simulation capability, in an application named `looptune`. In order to use this software, you must remotely log in to one of the caSCADA computers with the following instructions:

- Connect to the “Instrumentation” wireless network with your personal computer.
- Use SSH client software (e.g. BitVise) to log into any one of the caSCADA RTU computers listed below. The user name is `btc` and the password is `btc`.
 - 169.254.8.103 is the RTU-DCS02 node located in cabinet DCS-02
 - 169.254.8.133 is the RTU-JB15 node located in cabinet JB-15
 - 169.254.8.113 is the RTU-JB17 node located in cabinet JB-17
- Type `./looptune` at the terminal command prompt and press Enter.
- Follow the instructions as the program launches.
- After following the set-up instructions, you should see a trend graph and control screen that looks something like this:

```

PV = 34.9 percent = 34.940254 %
SP = 34.9 percent = 34.940254 %
OUT = 50.0 percent
PID scan rate = 5.0/sec
caSCADA PID version 3.3
Copyright (C) 2017
GNU GPL version 3
Man -- (adjust output)
K_P = 0.5 (gain)  FFG= 0.0
K_I = 0.0 r/min  DB = 0.0%
K_D = 0.0 sec    FFB= 0.0%
Reverse-acting,  Ideal
Trend interval = 5 scans

+-----+-----+
|                                     |HH|
|                                     |H |
|           p  ppp  pp  p  p         |  |
| ppppppppppppppppppppppppppppppp  |  |
|                                     |  |
|                                     |  |
|           p                         |  |
|                                     |LL|
+-----+-----+
Trend update rate = 1.0 ticks per second
F1 (M) Manual
F2 (A) Auto
F9 (pgup) + 10
F8 (up) + 1
F7 (right) + 0.1
F6 (left) - 0.1
F5 (down) - 1
F4 (pgdwn) - 10
F11 (S) Select
(Q) Exit
F12 (T) Capture
trend data
    
```

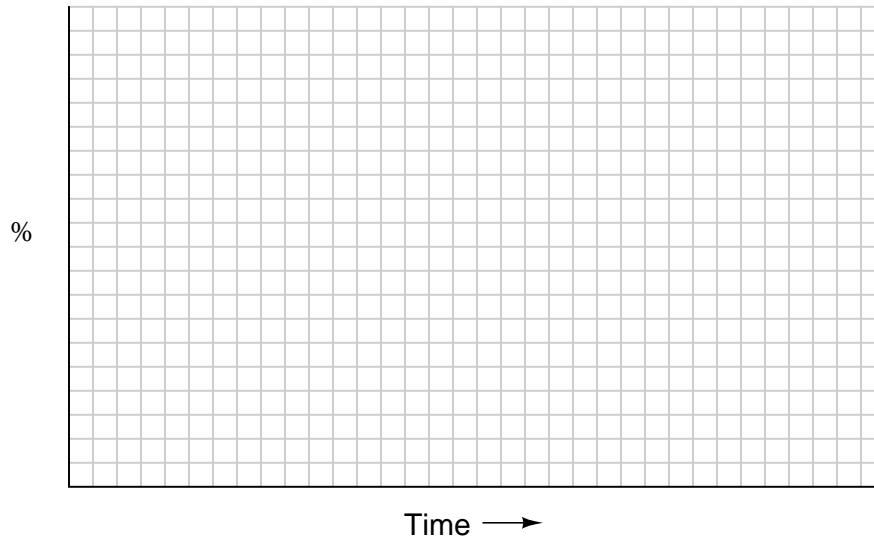
Control parameters are selected by pressing the “S” key as many times as necessary. The selected parameter is shown in white text, as opposed to the default text color black. Manual mode is selected by pressing “M” and automatic mode is selected by pressing “A”. In manual mode the default parameter selection is Output (OUT), while in automatic the default parameter becomes Setpoint (SP). Parameter values are adjusted by tenths using the left and right arrow keys, by ones using the up and down arrow keys, and by tens using the Page Up and Page Down keys.

The rather crude trend graph shows process variable with letter “p” characters, Output with letter “o” characters, and Setpoint with letter “s” characters. If you wish to capture a trend display, you may do so at any time by pressing the “T” key – a comma-separated variable file will be written (`0_pid_trend.csv`) which may be opened in any spreadsheet program (e.g. Microsoft Excel) and used to draw a nice trend graph with colored traces.

[file i04320](#)

Question 7

Use loop simulation software on a personal computer (e.g. the `looptune` application that is part of the caSCADA software suite) to simulate the effects of an “open loop” test. This means placing the loop controller in manual mode and moving the control valve by 5% or 10%. Try this on a simulated process and sketch the results below. *Answer this question for a process you have not done an open loop test on yet.* If you are using caSCADA `looptune`, choose the “Surprise me!” option for process type, and the “Perfect valve” option for the control valve type.



Determine whether the process is self-regulating or integrating. If it is self-regulating, determine its steady-state gain by dividing the change in PV by the change in output ($\frac{\Delta PV}{\Delta m}$):

Steady-state gain = _____ with valve step-change from _____% to _____%

Steady-state gain = _____ with valve step-change from _____% to _____%

Steady-state gain = _____ with valve step-change from _____% to _____%

Suggestions for Socratic discussion

- Why should an *open-loop* test be one of the first things you do when attempting to optimize a control loop?

[file i04321](#)

Question 8

Read and outline Case History #53 (“Another Valve with Weird Characteristics”) from Michael Brown’s collection of control loop optimization tutorials.

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.

Be sure to answer the following questions:

- Identify the type of test performed on this valve prior to placing the loop controller in automatic and noting problems.
- Explain what feature(s) of the second valve test revealed the problem.
- Instead of repairing the valve, the refinery personnel decided they would rather fix the problem through PID tuning. Explain how they were able to do this, even though it was not the ideal solution.
- Note the parameters appearing underneath “Loop Signature” in the screen-capture of the Protuner software. What parameters does Protuner measure about the process, and how might this save a lot of time for the technician or engineer optimizing a control system?

[file i01673](#)

Question 9

For a moving fluid passing through any *heat exchanger*, the rate of heat transfer ($\frac{dQ}{dt}$) required to change the temperature (ΔT) of the fluid flowing at a known mass flow rate ($\frac{dm}{dt}$) having a fixed specific heat value (c) is predicted by this formula:

$$\frac{dQ}{dt} = \frac{dm}{dt} c \Delta T$$

Where,

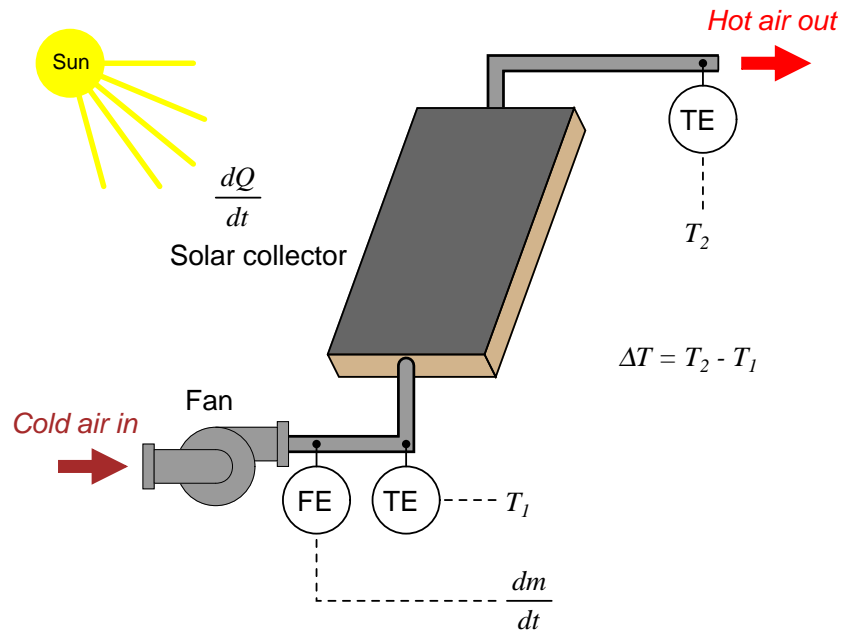
$\frac{dQ}{dt}$ = Heat transfer rate (metric calories per second or British BTUs per second)

$\frac{dm}{dt}$ = Mass flow rate of fluid (metric grams per second or British pounds per second)

c = Specific heat of substance (typically a constant value for that substance, in BTU per pound-degree F or calories per gram-degree C)

ΔT = Temperature change (metric degrees Celsius or British degrees Fahrenheit)

We may apply this formula to the application of a solar air heater, using the sun's radiant energy ($\frac{dQ}{dt}$) to raise the temperature (ΔT) of air flowing ($\frac{dm}{dt}$) from the inlet to the outlet of the collector:



Based on this equation, determine whether the temperature rise (ΔT) for any given intensity of sunlight ($\frac{dQ}{dt}$) will be a self-regulating, integrating, or runaway process variable with respect to the air's mass flow rate ($\frac{dm}{dt}$). For example, if we were to suddenly increase the fan's speed to cause a greater mass flow rate of air to go through the collector, would the temperature difference settle at some new stable value (self-regulating), would it continue to change steadily over time (integrating), or would it change faster and faster over time (runaway)?

Suggestions for Socratic discussion

- Why would anyone care what this solar collector's characteristic response to a change in air flow would be?
- This problem is one lending itself well to a *thought experiment*. Describe the thought experiment you would "perform" on this system to explore its characteristics, and how you would apply the experiment to the equation relating heat and temperature.

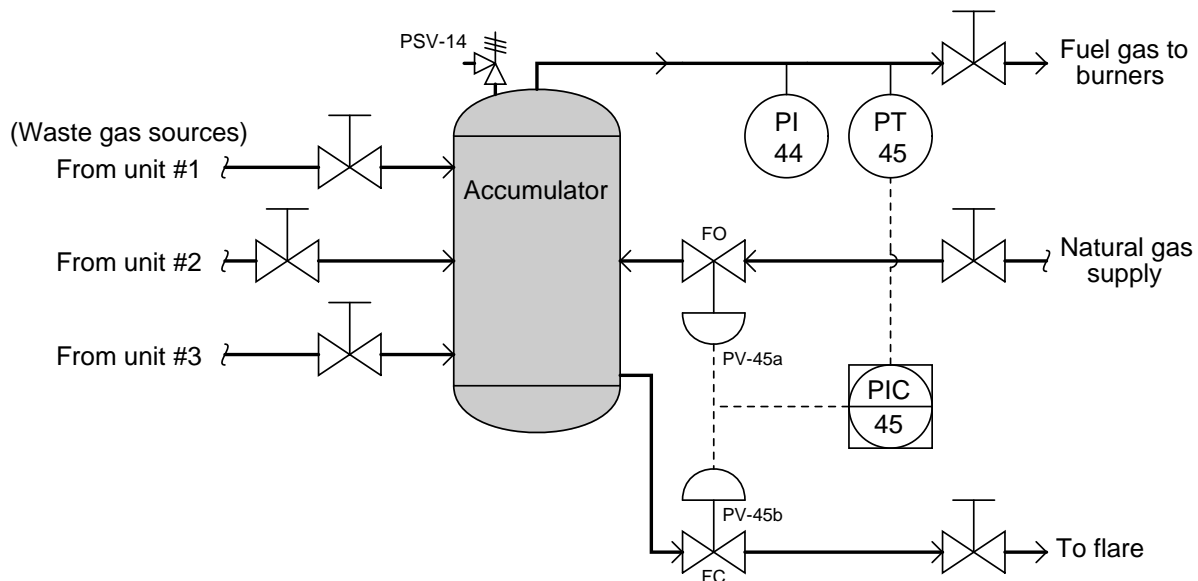
- For those students who have studied flow measurement technologies, identify any appropriate flowmeters for this process application.

[file i01777](#)

Question 10

Many flammable gases are produced in chemical processing and oil refineries as “waste” products. These “waste” gases may be used as fuel for steam boilers and combustion heaters in other parts of the refinery. The problem is, “waste” fuel gas production is often unsteady, and the demand for fuel gas in boilers and heaters is unsteady as well. There are times when there will be a surplus of waste gas (more than can be used), and times when there will not be enough.

The following pressure control system works to maintain constant fuel gas pressure in the accumulator vessel despite changes in waste gas flows and fuel gas demands:



Control valves PV-45a and PV-45b are split-ranged, electrically connected in series to operate off the same 4-20 mA signal from PIC-45. The controller itself is direct-acting, and the valves’ split-range calibrations are as follows:

Valve	Fully closed at	Fully open at
PV-45a	12 mA	4 mA
PV-45b	12 mA	20 mA

An operator happens to notice a low pressure indication registered on PI-44: 23 PSI. The controller setpoint is 30 PSI, and the operator calls the control room on her radio to verify the setpoint is still at 30 PSI. Worried, she then calls you over to investigate the problem with her. Your first diagnostic test is to call the control operator on your radio and ask what the pressure indication reads for PIC-45. The control room operator calls back to tell you PIC-45 reads 22.8 PSI.

Explain how you would proceed troubleshooting this problem. What are some likely causes for the low pressure, and what would your next diagnostic step(s) be? Do you think PSV-14 could be at fault? If your next step was to take an electrical measurement somewhere in the signal wiring of this system, what measurement would you take and what might that measurement tell you about the nature of the problem?

[file i00077](#)

Question 11

Processes are sometimes classified according to the types of electrical component that behave similarly: *resistive* or *capacitive*. What exactly is a “resistive” process (sometimes called a *self-regulating* process), and a “capacitive” process (sometimes called an *integrating* or *ramping* process)? Give one example of each type of process.

[file i01676](#)

Question 12

In a simple resistor-capacitor circuit, what is the definition of the term *time constant*? For example, what does it mean to say that an RC circuit has a “time constant” of 3 seconds?

[file i01677](#)

Question 13

What does it mean for a process (such as a temperature-controlled cookie oven) to have a *time constant*? I am referring here to the process itself (oven, heating element, and cookies), not the control system.

[file i01678](#)

Question 14

Most processes may be characterized as either *integrating*, *self-regulating*, or some combination of the two. However, there are processes whose characteristic is better described as *runaway*. Describe what a “runaway” process is, and give an example of it if you can.

[file i01683](#)

Question 15

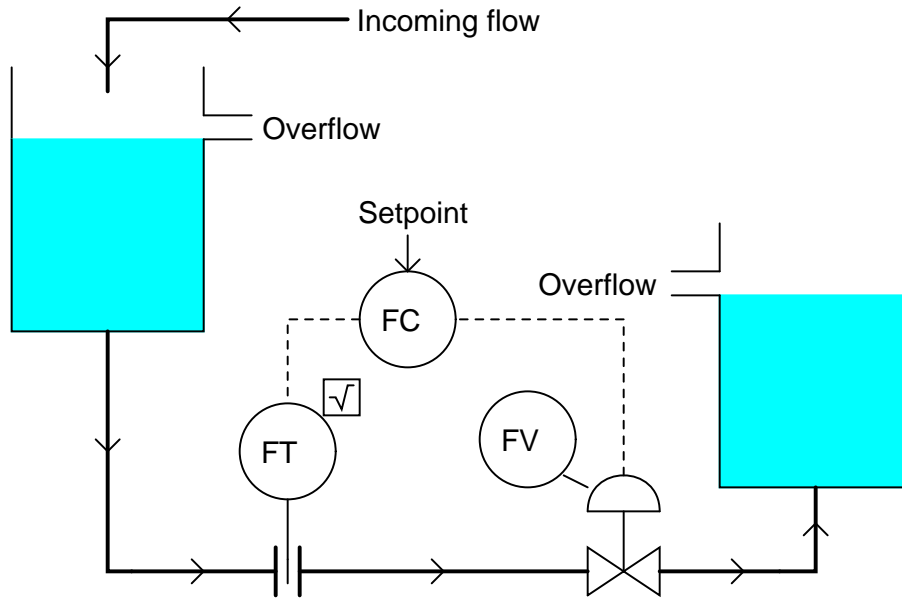
Imagine driving an automobile with very sensitive steering: just a few degrees of steering wheel motion at highway speeds is sufficient to quickly change lanes. Now imagine driving an automobile having significantly less sensitive steering: a whole quarter-turn of the steering wheel is needed to generate the same response as a few degrees of rotation in the first vehicle.

An important process quantity is its *gain*. How would you qualify the two automobile steering systems just described in terms of process gain, from the perspective of lane position as the process variable, steering wheel angle as the manipulated variable, and you (the driver) as the proportional controller? Which automobile has a high process gain, and which has a low process gain?

[file i01457](#)

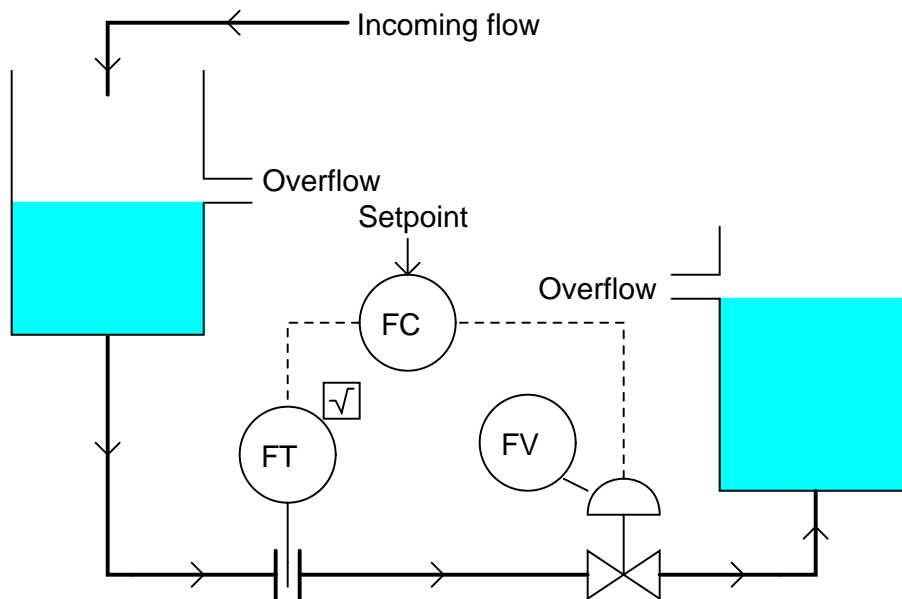
Question 16

Examine this flow control system, where a valve controls the flow rate of liquid between two vessels:



Since each vessel has its liquid level controlled by an overflow pipe, the head pressure at the bottom of each will be constant. This means that the differential pressure across the valve will be constant as well.

Suppose now that the higher vessel has its overflow pipe moved to a lower location, thus reducing the controlled level in that vessel, and consequently the head pressure generated at the bottom:



This change in head pressure, of course, reduces the amount of differential pressure across the valve. How will this affect the process gain, as it relates to flow control? In other words, will the flow rate become more or less sensitive to changes in valve position as a result of decreasing the pressure drop across the valve?

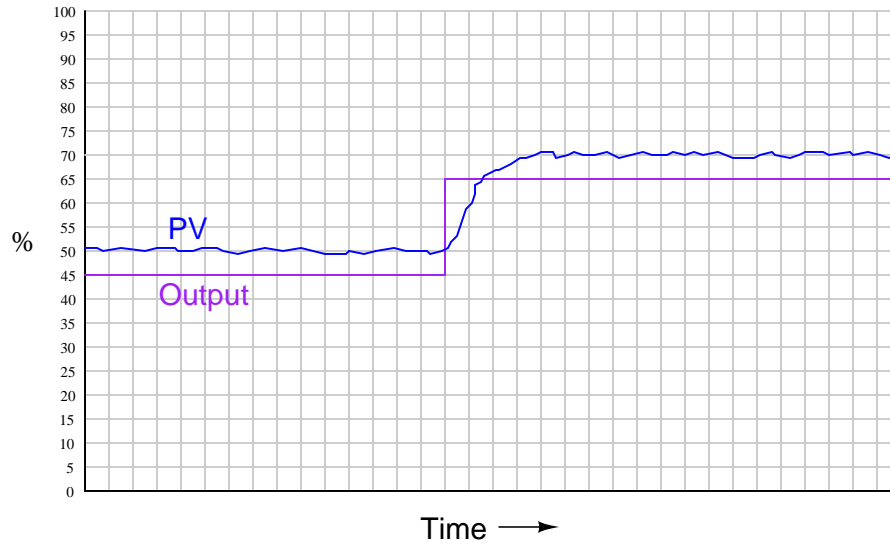
What will happen to the process gain if we then replace the control valve with one having a larger C_v value (a larger opening for fluid flow when fully open)?

Finally, what will happen to the process gain if we re-calibrated the flow transmitter for a smaller span (for example, from 0-120 GPM to 0-75 GPM)?

[file i01458](#)

Question 17

Suppose you see this process response following a manual “step-change” in the output (final control element):

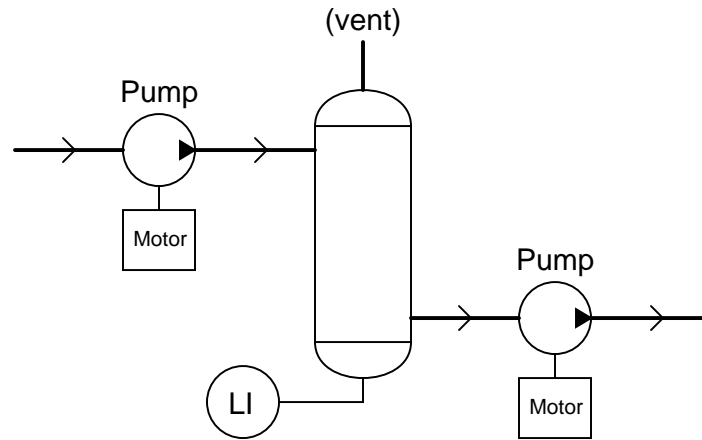


Is this process inherently *self-regulating*, or *integrating*? Explain your answer.

[file i01662](#)

Question 18

Examine this P&ID:



Each pump is of the “reciprocating” type, a form of positive displacement machine. In essence, each rotation of the motor shaft causes the pump to move a measured quantity of liquid from its inlet to its outlet.

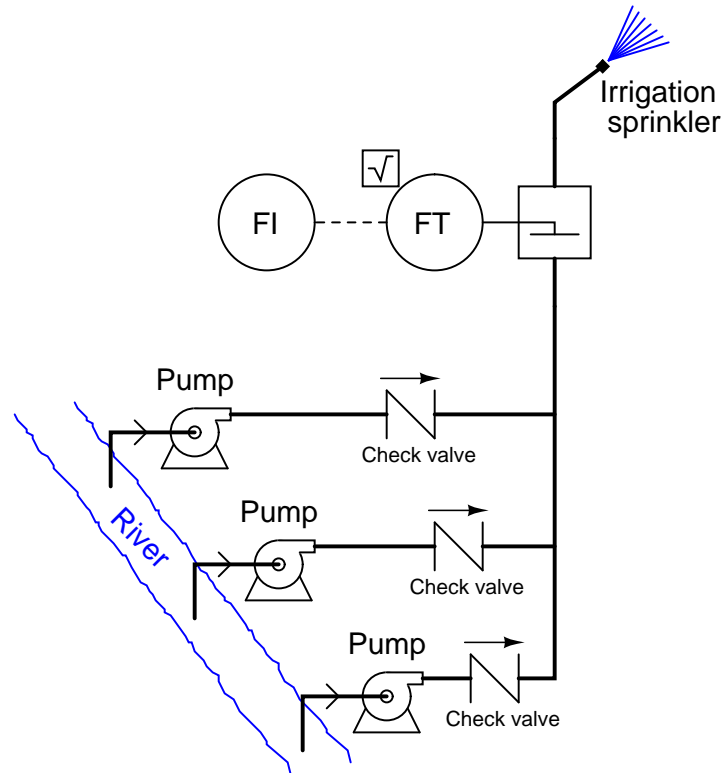
What will happen to the liquid level inside the vessel over time if one pump is moving more liquid flow?

Would you characterize this process as inherently *self-regulating* or inherently *integrating*?

[file i01658](#)

Question 19

Examine this P&ID:

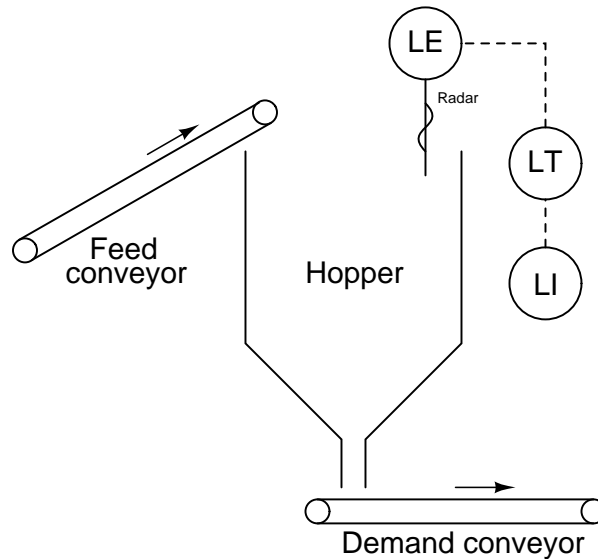


Three water pumps draw water from a river and deliver it to an irrigation sprinkler. What will happen to the water flow rate over time if one of the pumps is turned off (the other two pumps left running)?

Would you characterize this process as inherently *self-regulating* or inherently *integrating*?
[file i01661](#)

Question 20

Examine this P&ID:



The “feed conveyor” introduces granular material into the hopper, where the pile’s height is measured by a guided-wave radar level transmitter. The “demand conveyor” draws material from the bottom of the hopper as needed to supply another process.

What will happen to the level inside the hopper over time if one conveyor moves more material than the other?

Would you characterize this process as inherently *self-regulating* or inherently *integrating*?
[file i01660](#)

Question 21

Read and outline the “Lag Time” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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 i04322](#)

Question 22

Read and outline the “Multiple Lags (Orders)” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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.
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- (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 i04323](#)

Question 23

Read and outline the “Dead Time” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” 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 i04324](#)

Question 24

Read and outline the “Hysteresis” subsection of the “Process Characteristics” section of the “Process Dynamics and PID Controller Tuning” chapter in your *Lessons In Industrial Instrumentation* textbook.

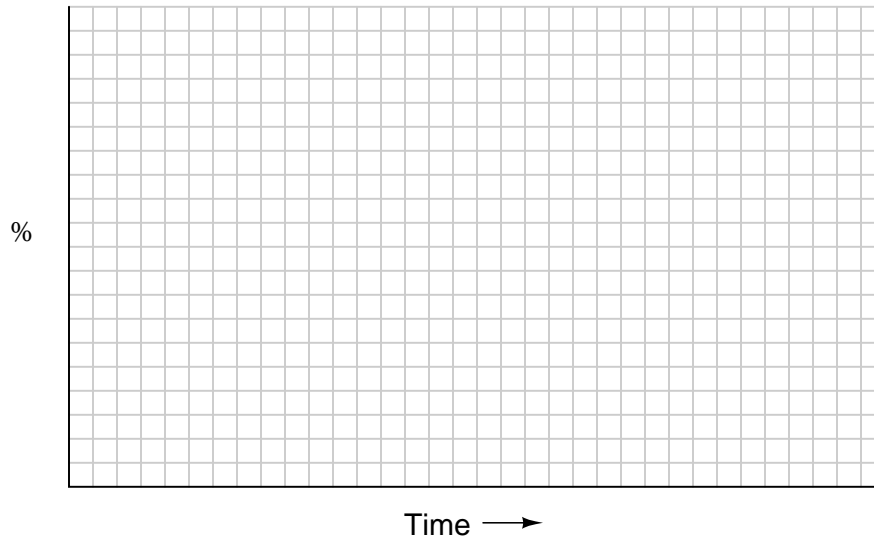
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

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- (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 i04325](#)

Question 25

Use loop simulation software on a personal computer (e.g. the `looptune` application that is part of the caSCADA software suite) to simulate the effects of an “open loop” test. This means placing the loop controller in manual mode and moving the control valve by 5% or 10%. Try this on a simulated process and sketch the results below. *Answer this question for a process you have not done an open loop test on yet.* If you are using caSCADA `looptune`, choose the “Surprise me!” option for process type, and the “Perfect valve” option for the control valve type.



Determine whether the process possesses one or more orders of *lag*, and estimate both the time constant of the process and the dead time of the process.

Multiple lags? Yes or No Time constant = _____ Dead time = _____

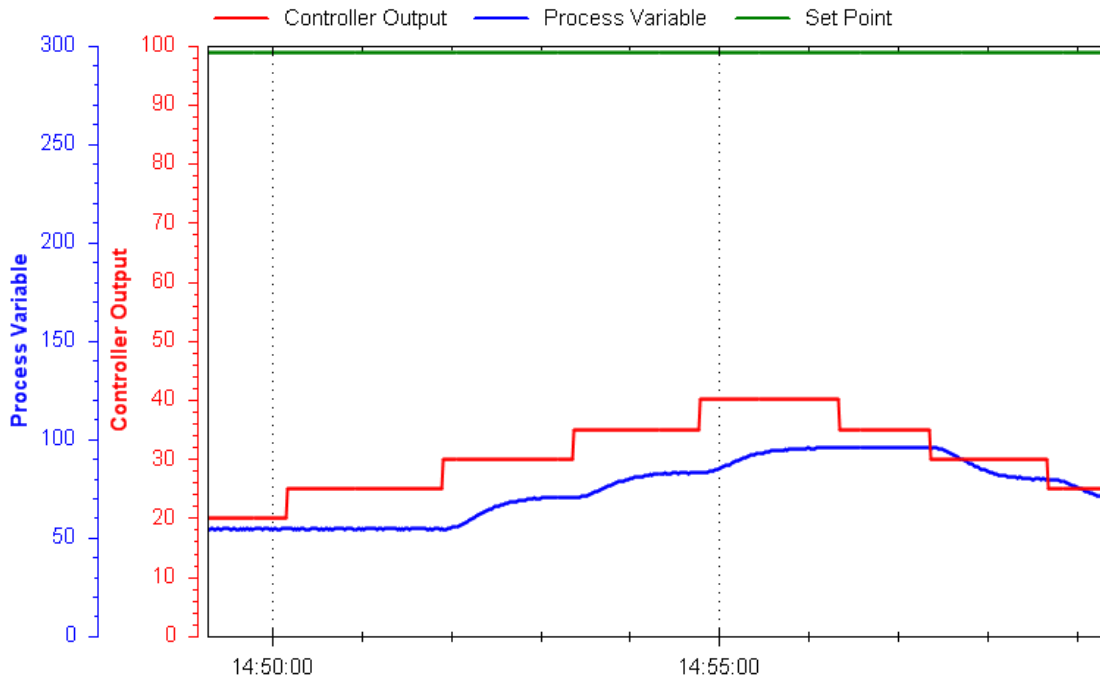
Suggestions for Socratic discussion

- What characteristics of the open-loop trend would you inspect to determine whether or not a process has *multiple* lags?
- Explain the significance of multiple lags in a process. How does this impact our ability to control the process using negative feedback (a loop controller)?
- Explain the significance of dead time in a process. How does this impact our ability to control the process using negative feedback (a loop controller)?
- Generally speaking, which is worse for feedback control: a relatively large *lag* time or a relatively large *dead* time? Explain your reasoning.

[file i04326](#)

Question 26

Examine this process trend showing the PV, SP, and Output of a loop controller:



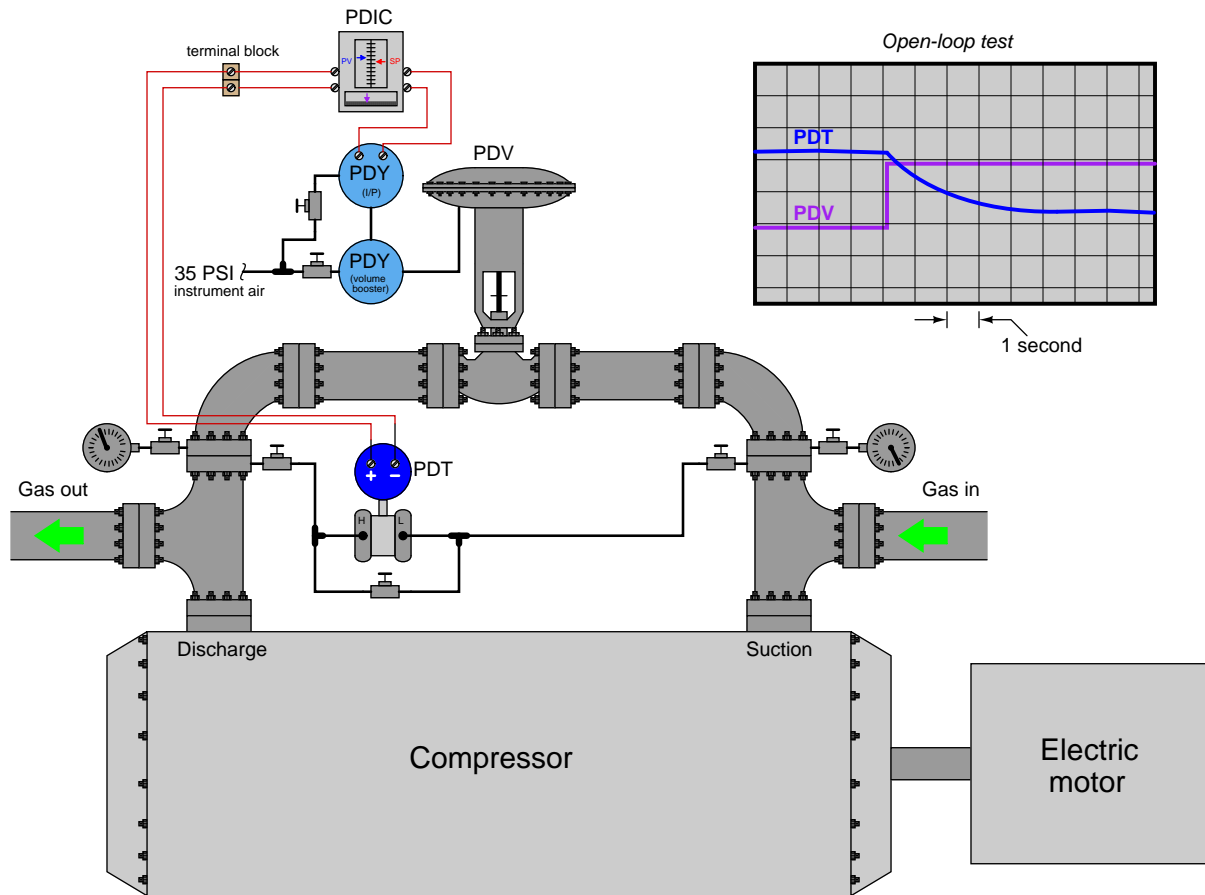
Based on what you see here, determine the following:

- Whether this is an open-loop or a closed-loop response
- Whether the controller is (or needs to be) *direct-acting* or *reverse-acting*
- If possible, identify any problems with the field instrumentation
- If possible, identify any problems with the controller PID tuning
- Qualitatively identify the kind of PID tuning we will need for robust control

file i01924

Question 27

This control system measures and regulates the amount of differential pressure across a gas compressor, by opening a *recirculation* valve to let high-pressure discharge gas go back to the low-pressure “suction” of the compressor. This control system needs to be very fast-acting, and currently it is anything but that, as revealed by the open-loop trend shown in the upper-right of this illustration:



After inspecting the trend graph, you decide to walk out of the control room and over to the compressor where you can observe the valve stem move. You then call the control room operator on your two-way radio and ask him to move the control valve (in manual) back to its starting position. What you see is a very quick, crisp motion from the control valve: no hesitation and no overshoot. The PDT trend still takes several seconds to stabilize, though.

Identify what type of problem you think you are dealing with here, as the compressor’s differential pressure should *not* take several seconds to stabilize following a sudden move by the recirculation valve. Also suggest a next diagnostic test or measurement to take, explaining how the result(s) of that test helps further identify the location and/or nature of the fault.

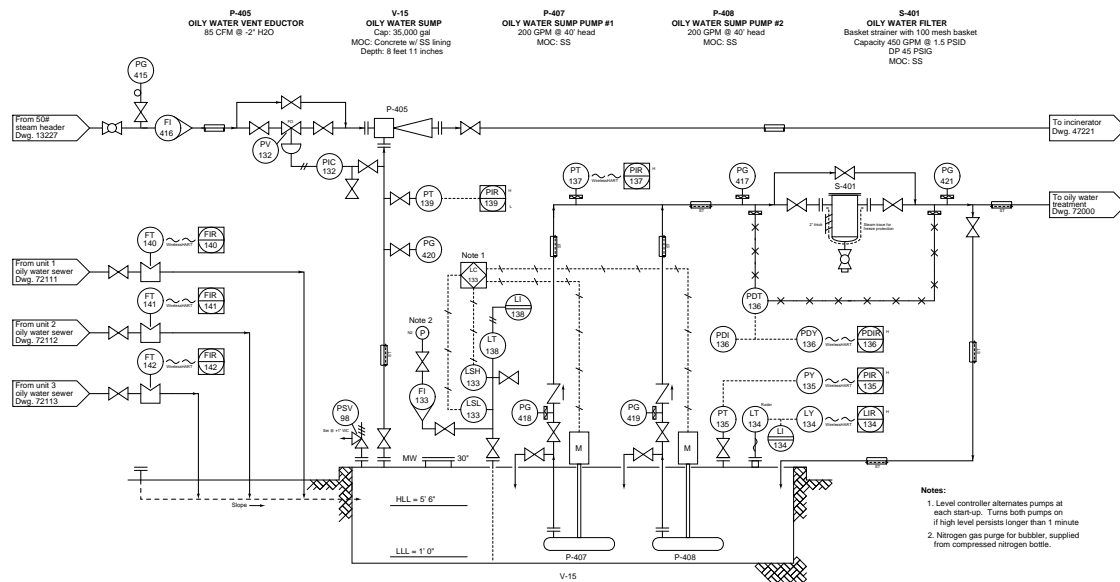
Suggestions for Socratic discussion

- Explain why the first test of observing valve motion was a very good decision. What specifically did the result of that test tell you about the nature and/or location of the fault?

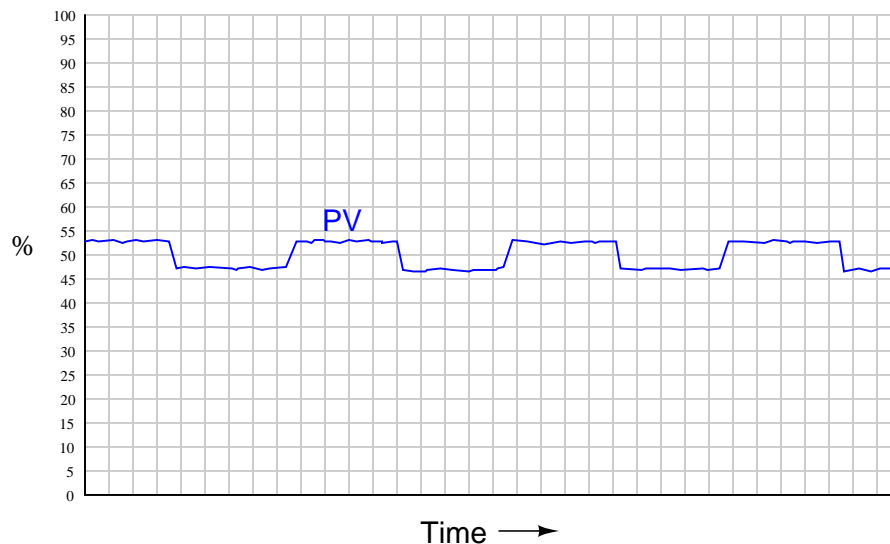
[file i02324](#)

Question 28

Suppose a pressure controller predominantly using integral action is used to control the amount of vacuum produced by steam eductor P-405 by throttling steam at its inlet. The high-velocity flow of steam through the narrow throat of the eductor causes a drop in pressure (the “venturi effect”). This vacuum is then used to evacuate hazardous gases from oily water sump V-15:



Inspecting the pressure trend shown by PIR-139, you see the following pattern:



What do you suppose is wrong with this system? Do you suspect this to be a serious problem, or not?

Suppose a fellow instrument technician decides to “de-tune” controller PIC-132 to fix the problem, changing the integral action from 4 repeats per minute to 2 repeats per minute. Will this solution work? Why or why not?

Suggestions for Socratic discussion

- How would this trend be affected if PIC-132 were placed into manual mode?
- Suppose a fellow instrument technician suggests this unusual trend could be caused by mechanical vibration near the transmitter. What would you say to this suggestion? How could you prove or disprove this hypothesis?
- Suppose a fellow instrument technician suggests this unusual trend could be caused by a very slow update time in PT-139 (which is a digital transmitter). What would you say to this suggestion? How could you prove or disprove this hypothesis?
- How would this trend be affected if the block valve between the sump and the eductor were shut?

[file i01682](#)

Question 29

Explain what a *first-order* process is.

[file i01679](#)

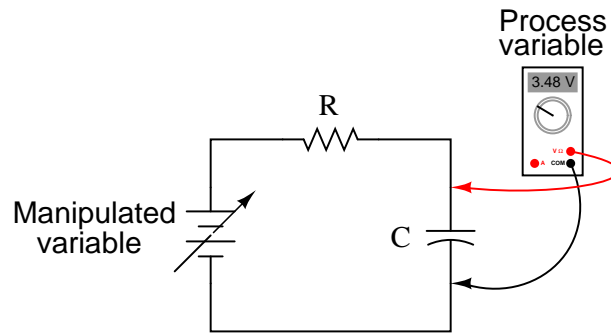
Question 30

What is a *second-order* process, and how does it differ from a first-order process?

[file i01680](#)

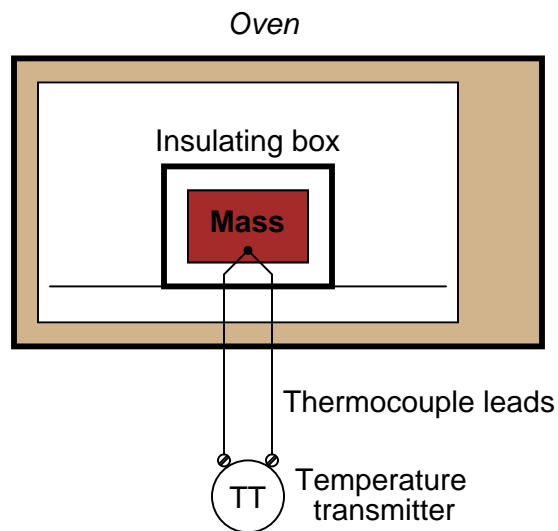
Question 31

We know that a simple one-resistor, one-capacitor circuit mimics the behavior of a single-order process:



Modify this resistor-capacitor circuit to have a *second-order* response, in order to mimic a second-order process.

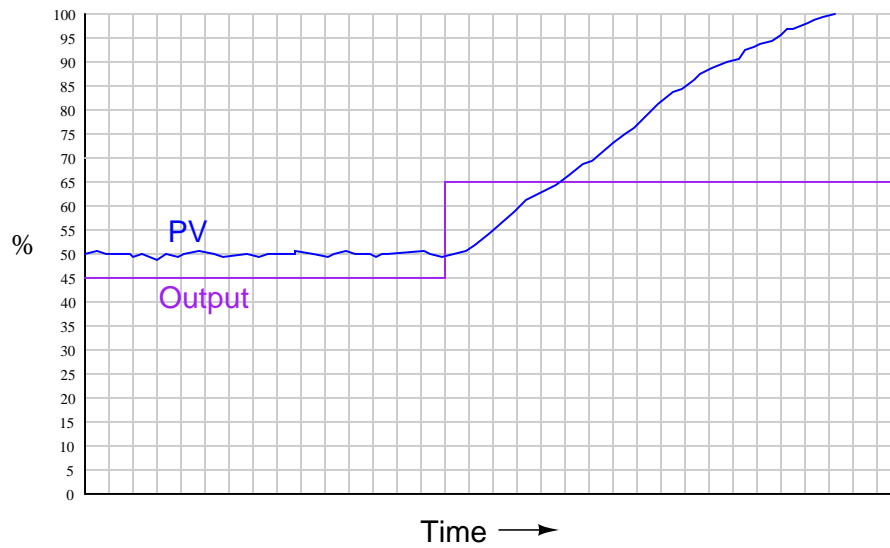
Now, explain what it is about this process that makes it second-order:



[file i01681](#)

Question 32

Suppose you see this process response following a manual “step-change” in the output (final control element):



Is this process inherently *self-regulating*, or *integrating*? Explain your answer.
[file i01663](#)

Question 33

Which type of process (self-regulating or integrating) is naturally stable when the controller is left in “manual” mode, and which type of process is not? Explain why.

Which type of process (self-regulating or integrating) is theoretically controllable by proportional action alone? Explain why.
[file i01664](#)

Question 34

Question 35

Question 36

Question 37

Question 38

Question 39

Question 40

Question 41

Read and outline the “Ziegler-Nichols Closed-Loop (‘Ultimate Gain’)” subsection of the “Quantitative PID Tuning Procedures” section of the “Process Dynamics and PID Controller Tuning” 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:

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- (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.

In particular, you should write your own step-by-step instructions for implementing the Ziegler-Nichols “closed-loop” tuning method, so you will have a concise reference to apply to later loop tuning challenges:

-
-
-
-

[file i04328](#)

Question 42

Read and outline the “Ziegler-Nichols Open-Loop” subsection of the “Quantitative PID Tuning Procedures” section of the “Process Dynamics and PID Controller Tuning” 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:

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- (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.

In particular, you should write your own step-by-step instructions for implementing the Ziegler-Nichols “open-loop” tuning method, so you will have a concise reference to apply to later loop tuning challenges:

-
-
-
-

Further exploration . . . (optional)

A paper written by G.H. Cohen and G.A. Coon in 1953 entitled “Theoretical Consideration of Retarded Control” sought to improve on the techniques advanced by Ziegler and Nichols in 1942. An interesting passage is shown here, from the beginning of the Cohen-Coon paper:

The process can be characterized by its reaction curve which is the chart record obtained when the valve is given a sudden sustained disturbance with the controller disconnected. Such a record is shown in figure 1(a) for a unit change in pressure. There appears to be a period of time during which the pen moves but little and this dead time or lag L may be of some magnitude in comparison with the transfer lag (the lag due to the lumped capacity of the process). The dead time is due to the fact that the process is really a continuum where the parameters which describe the process are distributed. The lag due to the finite time of transport of the signal (for example, a long tube which carries a compressible fluid) is called a distance-velocity lag. If the continuum contains no inertia, it may be represented by a number of cascaded lumped resistance-capacity networks. Increasing the number of cascaded elements gives a better approximation to the continuum since the order of contact with the time axis increases with the number of elements in the lumped circuit approximation. However, the complexity of the problem increases with the number of elements.

Describe what this passage is saying, in your own words. Are Cohen and Coon describing a closed-loop tuning method or an open-loop tuning method? Are they regarding lag time and dead time as identical parameters, or as different qualities of the process? What do they mean by the term “capacity” and how does this relate to your existing knowledge of process dynamics?

[file i04329](#)

Question 43

Read and outline all subsections in the “Heuristic PID Tuning Procedures” section of the “Process Dynamics and PID Controller Tuning” 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:

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- (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.
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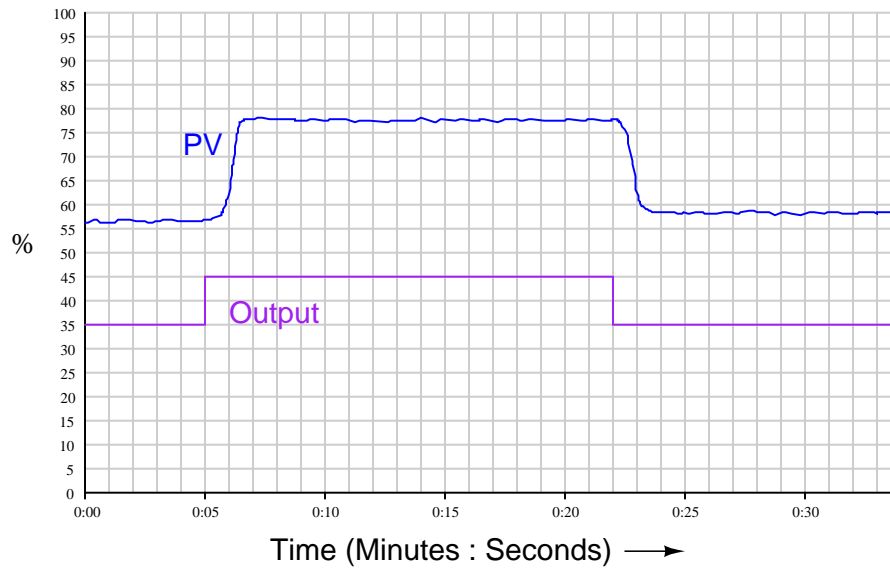
In particular, you should write your own step-by-step instructions for implementing a heuristic tuning method, so you will have a concise reference to apply to later loop tuning challenges:

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-

[file i04330](#)

Question 44

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, do you think the process might benefit from a controller with aggressive P, I, or D action? Explain why or why not for each action.

A very common misconception among students first learning how to analyze loop trend graphs is to mistakenly interpret the above trend as indication that the controller already has proportional action programmed into it. Explain why this is a misconception, and how we can avoid it.

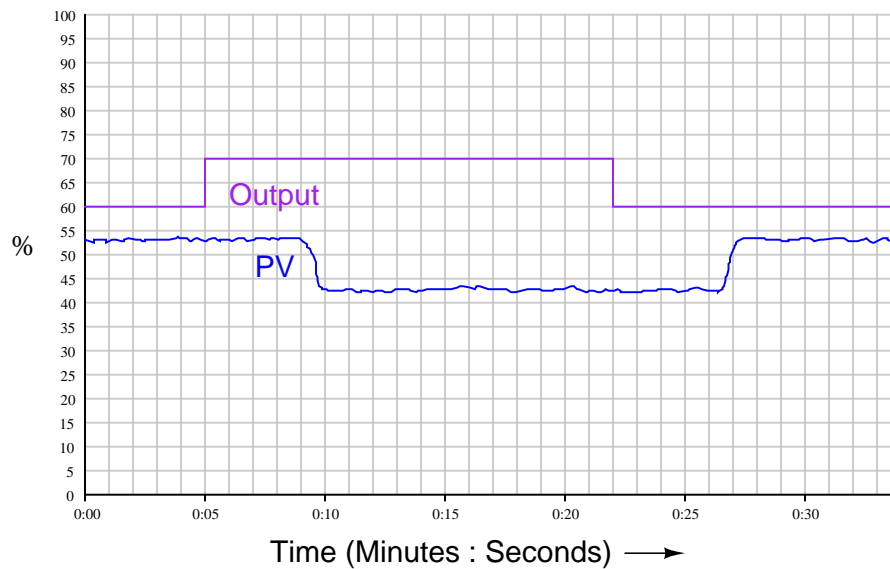
Suggestions for Socratic discussion

- One area of confusion for new students is whether any given trend graph reveals an *open-loop* test or a *closed-loop* test. Explain how it is possible to discern the kind of test done on this process just by looking at the trend lines.
- Explain why it is important to determine whether the trend graph reveals an *open-loop* test or a *closed-loop* test. What difference does this determination make?
- Based on what you see here, does the controller need to be configured for *direct* action or for *reverse* action?

[file i01718](#)

Question 45

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



Something about the process variable's response should worry you, if you were tasked with tuning this process for optimum control. Explain what is so worrisome about this trend, and identify some possible causes.

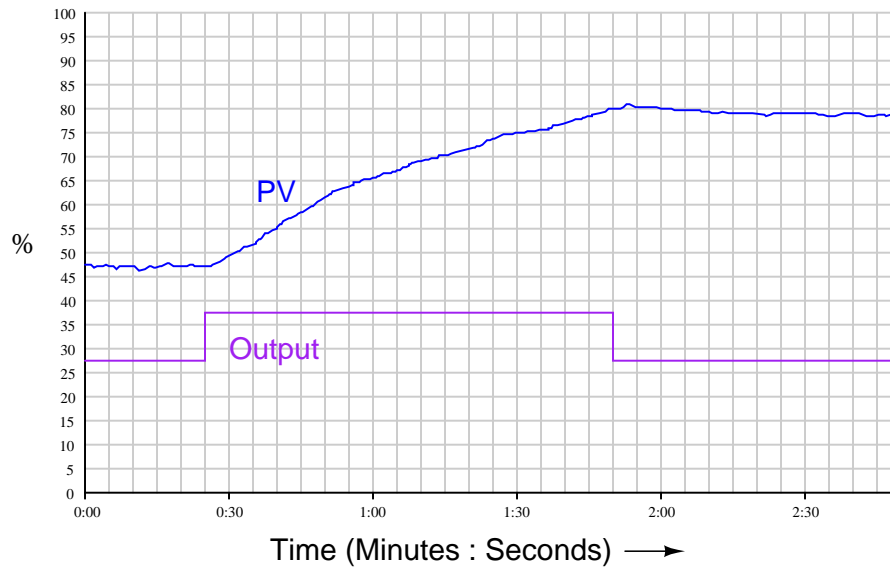
Suggestions for Socratic discussion

- One area of confusion for new students is whether any given trend graph reveals an *open-loop* test or a *closed-loop* test. Explain how it is possible to discern the kind of test done on this process just by looking at the trend lines.
- Explain why it is important to determine whether the trend graph reveals an *open-loop* test or a *closed-loop* test. What difference does this determination make?
- Determine at least *two different* potential causes for the PV trend you see here.
- Based on what you see here, does the controller need to be configured for *direct* action or for *reverse* action?

[file i01719](#)

Question 46

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, do you think the process might benefit from a controller with aggressive P, I, or D action? Explain why or why not for each action.

Suppose a fellow instrument technician looked over your shoulder at this trend graph and declared, “I see a lot of integral action in that controller!” What would you say to that comment? Is it helpful in determining how the controller *ought* to be tuned? Explain why or why not.

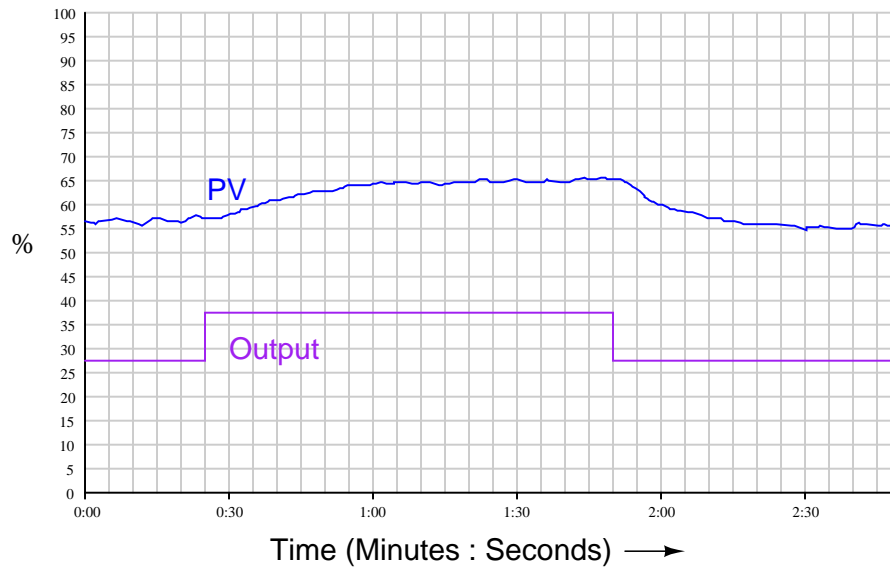
Suggestions for Socratic discussion

- One area of confusion for new students is whether any given trend graph reveals an *open-loop* test or a *closed-loop* test. Explain how it is possible to discern the kind of test done on this process just by looking at the trend lines.
- Explain why it is important to determine whether the trend graph reveals an *open-loop* test or a *closed-loop* test. What difference does this determination make?
- What type of physical process (e.g. gas pressure, liquid temperature, gas flow, etc.) do you think this might be, based solely on the trend you see here?
- Based on what you see here, does the controller need to be configured for *direct* action or for *reverse* action?

[file i01721](#)

Question 47

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, do you think the process might benefit from a controller with aggressive P, I, or D action? Explain why or why not for each action.

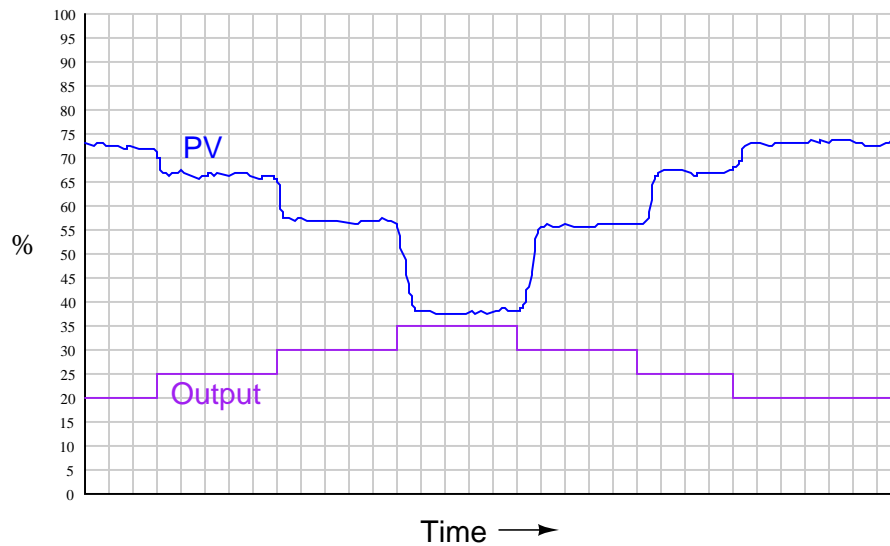
Suggestions for Socratic discussion

- One area of confusion for new students is whether any given trend graph reveals an *open-loop* test or a *closed-loop* test. Explain how it is possible to discern the kind of test done on this process just by looking at the trend lines.
- Explain why it is important to determine whether the trend graph reveals an *open-loop* test or a *closed-loop* test. What difference does this determination make?
- Suppose an inexperienced instrument technician looks at this trend and declares, “Look, you can see that the controller here is direct-acting, because the PV and Output go in the same direction!” Explain what is wrong with this conclusion, and how we know it is wrong from a careful inspection of the graph.

[file i01724](#)

Question 48

Examine this process trend, showing the response of the process variable to a series of step changes in the controller output (placed in manual mode):



What kind of problem do you see evident in this trend? Based on what you see here, do you think the process might benefit from a controller with aggressive P, I, or D action? Explain why or why not for each action.

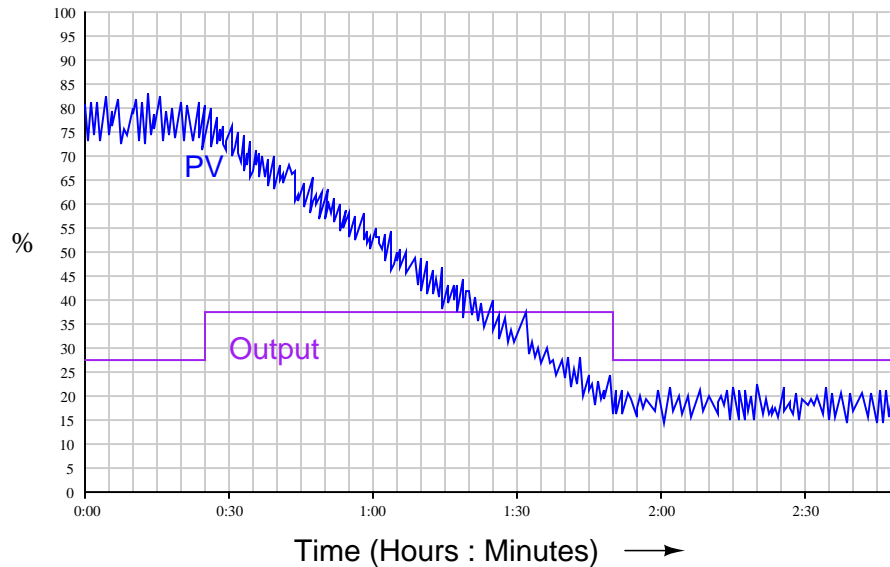
Suggestions for Socratic discussion

- One way to manage this problem is to use an *adaptive-gain* controller. Explain what this means and why it may work.
- A more direct way to rectify the problem is to alter the opening characteristic of the control valve. Assuming the control valve has an inherently *linear* characteristic now, would you recommend changing the characteristic to *quick-opening* or to *equal-percentage*?
- Based on what you see here, does the controller need to be configured for *direct* action or for *reverse* action?

[file i01726](#)

Question 49

Suppose you are asked to tune the controller of a liquid level process. After obtaining permission from the operator, you analyze the response of the process variable (liquid level) to a 10% up-and-down step change in the controller output (placed in manual mode):



The first thing you notice is that the PV trend is extremely noisy. Investigating a little further, you find that the level transmitter is *ultrasonic*: it measures the height of liquid in the vessel by firing sound waves down at the liquid surface from above, and measuring the time delay of the echo. Normally, ultrasonic level transmitters work well to measure liquid surface level, but in this process there are problems because the liquid's surface is constantly agitated by a powerful mixer inside the vessel which must be run constantly to prevent solids from settling and compacting at the bottom of the vessel.

How does the presence of this noise affect your decisions on how to tune it? Would you tune this liquid level controller the same as you would any other liquid level controller, or would you tune it differently? Explain your reasoning.

Furthermore, can you think of a way to obtain an accurate level measurement in this vessel without all the noise?

Suggestions for Socratic discussion

- Is it possible to tell from this trend whether the control valve *adds* liquid to the vessel or whether it *drains* liquid from the vessel? Why or why not?
- Based on what you see here, does the controller need to be configured for *direct* action or for *reverse* action?
- Suppose a fellow instrument technician recommended you activate the level transmitter's *damping* function in order to help stabilize the PV trend. Would you agree with this line of action? Explain why or why not.

[file i01727](#)

Question 50

Use loop simulation software on a personal computer (e.g. the `looptune` application that is part of the caSCADA software suite) to simulate the effects of an “ultimate gain” test. This means placing the loop controller in automatic mode with proportional-only control action and incrementally increasing the controller gain until the loop sustains sinusoidal oscillations. The controller gain value at which the loop self-oscillates is called the *ultimate gain* (K_u). The period of those oscillations is called the *ultimate period* (P_u).

Select a loop from those offered in the software’s library (if you are using caSCADA `looptune`, choose the “Surprise me!” option for process type, and the “Perfect valve” option for the control valve type), and record the results of this test:

Ultimate gain of loop (K_u) = _____

Ultimate period of loop (P_u) = _____

Now, explain how we may use these measured values to determine good P, I, and D settings for a loop controller.

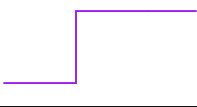
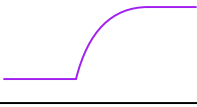
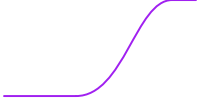
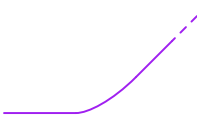

Suggestions for Socratic discussion

- Explain the procedure you would follow to perform a closed-loop test like this.
- Explain why it is important to avoid a *limit cycle* when performing a closed-loop test.
- How practical do you think this tuning procedure is? Explain your answer in detail.
- In the hilarious book *How to Become an Instrument Engineer – The Making of a Prima Donna*, authors Greg McMillan and Stanley Weiner have an entire chapter called “How To Tune Controllers” in which they strongly recommend the Ziegler-Nichols closed-loop method. Benefits of this method cited by the authors include (1) the inclusion of all nonlinearities and controller characteristics in the test, (2) no need for complex interpretation of the trend graph, (3) no need to switch controller modes (auto to manual and vice-versa), (4) applicability to integrating and runaway processes, and (5) more tolerance of intermittent disturbances during the test. Comment on these advantages, especially as they compare against the Ziegler-Nichols open-loop method.

[file i04327](#)

Question 51

The following table shows recommended PID tuning settings for different process characteristic types. The graph segments shown in the left-most column of the table characterize each process according to response to an open-loop (manual mode) step-change in controller output:

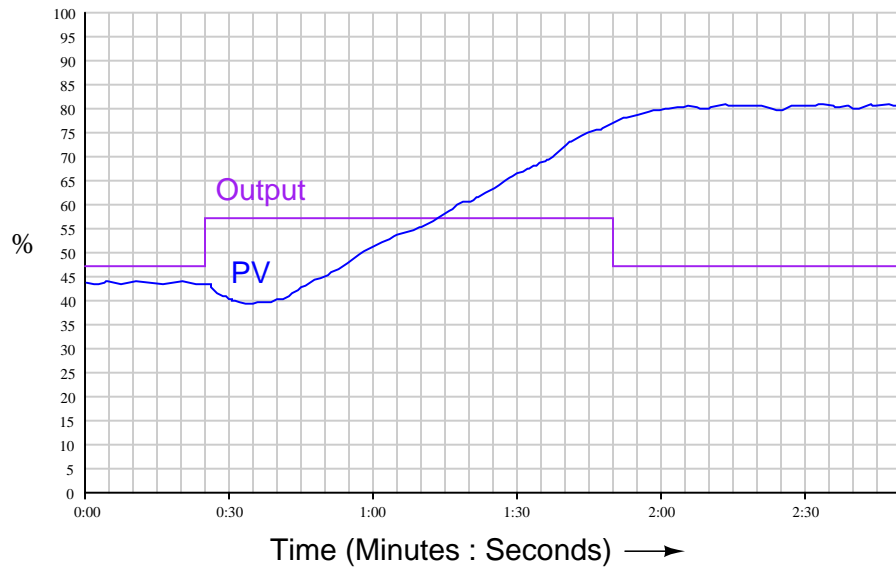
	Pure self-regulating	<i>May be controlled with aggressive integral action, and perhaps with a bit of proportional action. Use absolutely no derivative action!</i>
	Self-reg w/ pure 1 st order lag	<i>Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.</i>
	Self-reg w/ multiple lags	<i>Proportional action needed for quick response to setpoint changes, integral action needed for recovery from load changes, and derivative needed to prevent overshoot. Proportional and integral actions are limited by tendency to oscillate.</i>
	Integrating w/ lag(s)	<i>Proportional action should be aggressive as possible without generating oscillations. Integral action needed only for recovery from load changes.</i>
	Pure integrating	<i>Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.</i>

These recommendations must be altered, however, in the presence of substantial process noise. Identify which control modes are affected by process noise (P, I, and/or D) and explain why.

[file i03375](#)

Question 52

Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, hypothesize how you think the controller should be tuned to respond. In other words, how aggressive should the controller's P, I, and D terms be relative to each other?

[file i01725](#)

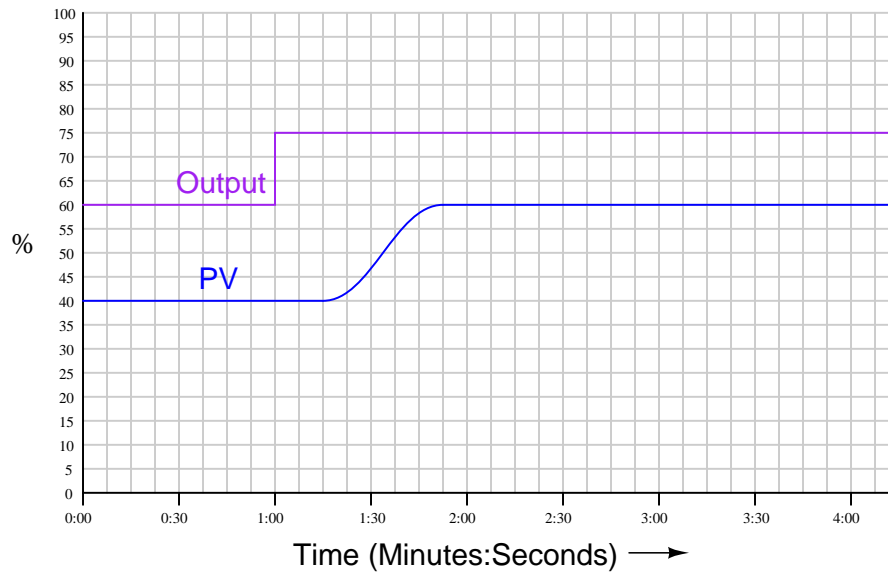
Question 53

Identify some factors *other* than poor controller tuning that can cause control loop instability, and how to rectify them.

[file i01748](#)

Question 54

Shown here is the response of a process to a single step-change on the controller output (made with the controller in “manual” mode). Based on your observations, determine the steady-state gain (K), dead time (L_R), and reaction rate (R_R):



$K =$ _____ $L_R =$ _____ $R_R =$ _____

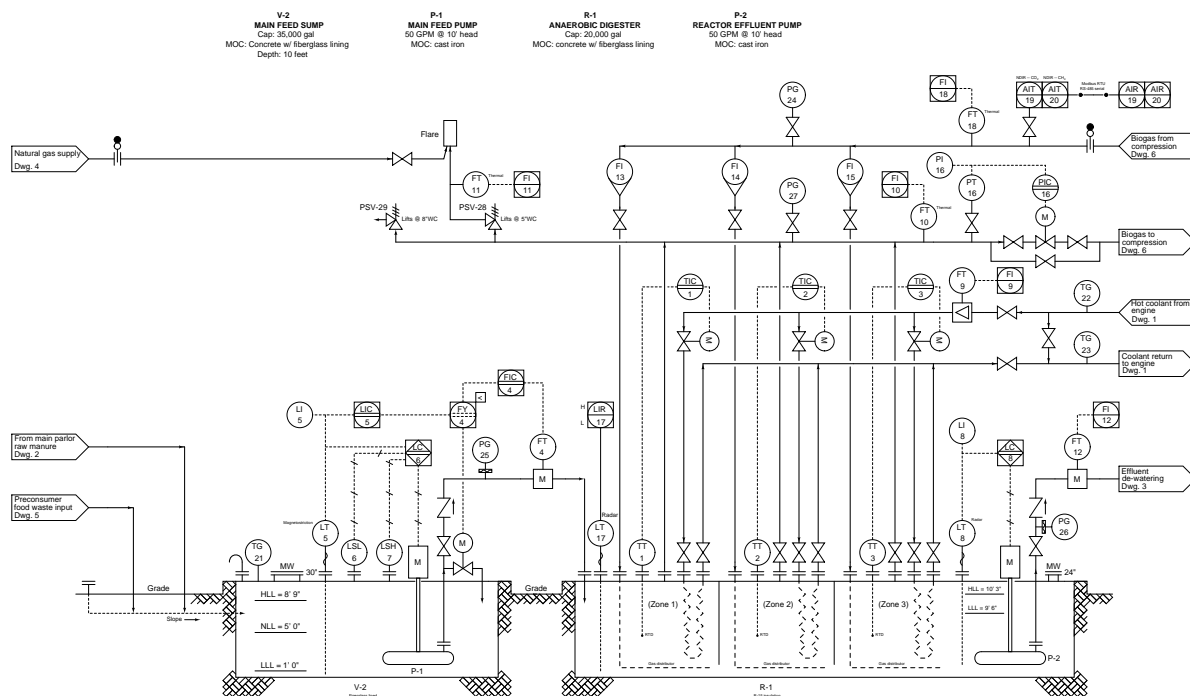
Suppose that this process were to be subjected to a larger step-change in output, say 25% instead of 15%. What effect would this have had on the L_R and R_R calculations?

Finally, calculate the time constant (τ) of this process.

file i01656

Question 55

This P&ID is for an *anaerobic digester*, which takes in cow manure and preconsumer food waste (e.g. waste products from slaughterhouses, fish processing plants, etc.) and generates flammable methane gas which is used as fuel for an engine generator, producing electricity and usable heat from agricultural waste.



Heat from the engine’s circulating coolant is used to maintain the digester at around 100 °F for optimum methane gas generation, because the mildly exothermic reaction of anaerobic methane production does not create enough heat to maintain its own temperature at optimum levels:



Suppose you were asked to tune the zone temperature controllers (TIC-1, TIC-2, and TIC-3) in this process. Answer the following questions regarding tuning:

- Which controller would you tune first, or does it matter?
- Do you suspect these zones will be *self-regulating*, *integrating*, or *runaway* processes?
- Should these controllers be tuned P-dominant or I-dominant? Explain your reasoning.
- What precautions, if any, would you need to take when tuning these controllers? Are there any safety considerations we would need to be aware of before beginning the tuning procedure?
- Identify any *loads* in the process, and explain how you would adjust them in order to test the robustness of your controller tuning.
- Do you suppose the tuning parameters of TIC-1 will be much different from those used in TIC-3? Explain why or why not.
- What process change(s) would be required in order for the anaerobic reaction to be self-sustaining in terms of heat, so that an external heat source would not be required to sustain its operation at around 100 °F?
- Suppose maintenance personnel had to enter the digester vessel to physically clean the heat-exchange “coils” of fouling. What personal safety precautions would they need to take before entering the vessel?

[file i04777](#)

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

Read and outline the introduction to the “Before You Tune . . .” section of the “Process Dynamics and PID Controller Tuning” 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 i04332](#)

Question 62

Read and outline the “Identifying Operational Needs” subsection of the “Before You Tune . . .” section of the “Process Dynamics and PID Controller Tuning” 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 i04331](#)

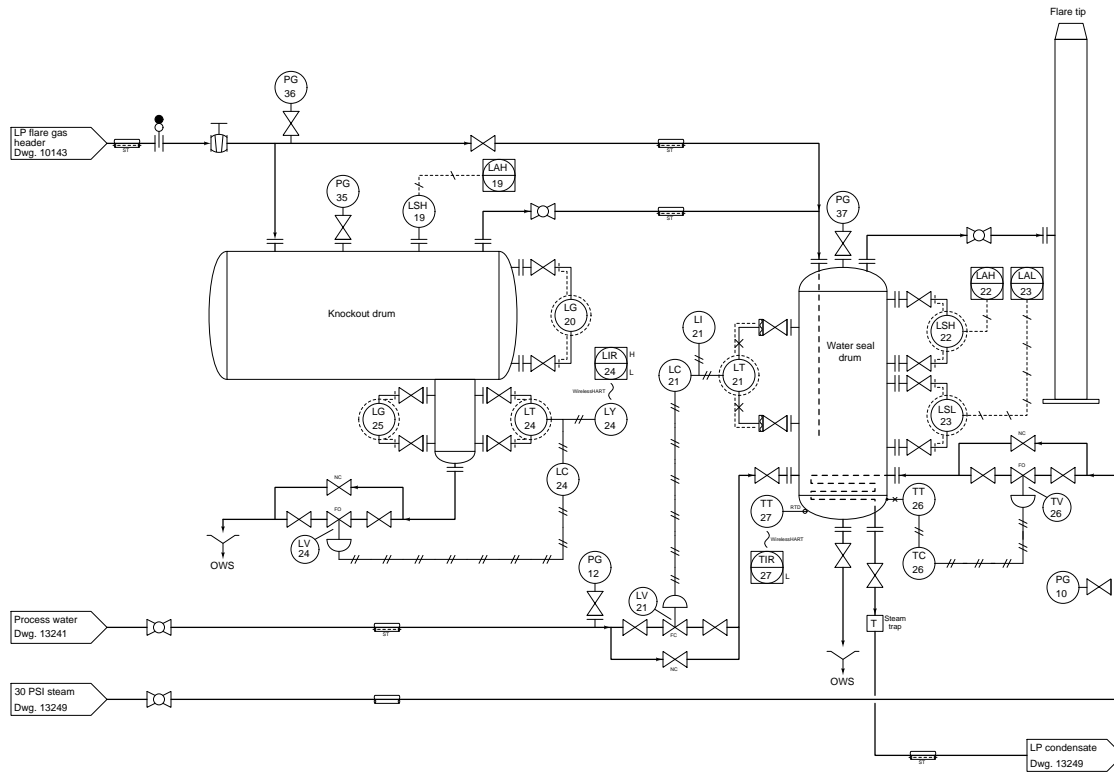
Question 63

Read and outline the “Identifying Process and System Hazards” subsection of the “Before You Tune . . .” section of the “Process Dynamics and PID Controller Tuning” 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.

Applying what you have learned, examine this P&ID to assess some of the potential hazards associated with tuning one of the loop controllers:



[file i04333](#)

Question 64

Read and outline the “Identifying the Problem(s)” subsection of the “Before You Tune . . .” section of the “Process Dynamics and PID Controller Tuning” 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 i04334](#)

Question 65

Read and outline Loop Problem Signatures #3 (“Process Dynamics – Process Gain”) from Michael Brown’s collection of control loop optimization tutorials.

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.

Be sure to answer the following questions:

- According to Mr. Brown, why do simple algorithmic tuning procedures such as those outlined by Ziegler and Nichols often fail to produce good results?
- In this tutorial, Mr. Brown states, “[a] disadvantage of oversized valves is that the process gain actually amplifies the valve imperfections, and results in a degradation of control performance.” Explain how an oversized control valve “amplifies” its mechanical imperfections.
- Examine the trends shown in Figure 2 (taken on a flow control loop at a South African oil refinery). How is it evident that the control valve is oversized from this trend display?
- How did the controller on that flow loop have to be tuned in order to achieve good control with the hugely oversized valve?
- How does Mr. Brown define “process gain” for an integrating process that does not self-regulate following a step-change in valve position?

Suggestions for Socratic discussion

- Michael Brown uses the abbreviation “PD” to show the output of loop controllers in many of the trend graphs found within his articles. Identify what “PD” means.
- In this article, Michael Brown makes a mathematical error converting proportional band into gain. Identify and correct this error!
- Michael Brown’s definition of process gain for an integrating process looks a lot like Ziegler and Nichols’ *reaction rate*. Identify and explain the similarities between the two.

[file i03593](#)

Question 66

Configure a PID simulator for any process control application, and then try tuning this process using both the closed-loop and the open-loop Ziegler-Nichols methods. Document all the process parameters (e.g. dead time, lag time, reaction rate, ultimate gain, etc.) and then show the P, I, and D tuning parameter values calculated by these techniques.

Closed-loop test parameters (I and D actions disabled, P increased until oscillation):

$$K_u = \underline{\hspace{2cm}} \qquad P_u = \underline{\hspace{2cm}}$$

Calculated results of Ziegler-Nichols closed-loop (“Ultimate”) tuning method:

$$P = \underline{\hspace{2cm}} \qquad I = \underline{\hspace{2cm}} \qquad D = \underline{\hspace{2cm}}$$

Open-loop test parameters (controller in manual mode):

$$L = \underline{\hspace{2cm}} \qquad R = \underline{\hspace{2cm}} \qquad \Delta m = \underline{\hspace{2cm}}$$

Calculated results of Ziegler-Nichols open-loop tuning method:

$$P = \underline{\hspace{2cm}} \qquad I = \underline{\hspace{2cm}} \qquad D = \underline{\hspace{2cm}}$$

If you think you can improve on these results by experimenting with P, I, and/or D parameter values, feel free to do so, and then document the settings you found to work best:

$$P = \underline{\hspace{2cm}} \qquad I = \underline{\hspace{2cm}} \qquad D = \underline{\hspace{2cm}}$$

Suggestions for Socratic discussion

- A common mistake when students try to apply either Ziegler-Nichols tuning method is ignoring the units of time measurement used by the controller for τ_i and τ_d . For example, a student may measure the period of ultimate cycle (P_u) in seconds, but then their controller needs to have a τ_d value in units of *minutes*, or worse yet a τ_i value in units of *repeats per minute*. Explain why the units of measurement matter when you apply either Ziegler-Nichols PID tuning method.

[file i01014](#)

Question 67

Read and outline Case History #70 (“Flow Loops Behaving Badly”) from Michael Brown’s collection of control loop optimization tutorials.

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.

Be sure to answer the following questions:

- The first flow-control example shown in this report is graphed in Figure 1. Mr. Brown tells us how we may conclude this oscillation (“cycling”) is *not* the result of an overly-aggressive controller, but rather indicative of a control valve problem. Explain this in your own words.
- Describe what the open-loop test (Figure 2) reveals about this flow loop’s valve condition. Explain in your own words why an open-loop test of the system is so important to perform when diagnosing a control problem.
- Figure 6 shows a test of a different flow-control system. Explain how we can tell just by examining the trends that this is an *open-loop* test (i.e. controller in manual mode) rather than a *closed-loop* test (i.e. controller in automatic mode).
- Toward the end of this case history, Mr. Brown relates the challenges he encountered at a mine. Describe some of the problems he found there, in your own words.
- An interesting comment Mr. Brown makes toward the end of this report is, “Luckily the plant uses a lot of variable speed devices for control flows and speeds of feeders. These loops can be optimized.” Here, he is referring to the use of variable-speed motors as final control elements (e.g. VFDs powering pumps, etc.) instead of control valves. Explain why these control loops are so much easier to optimize than those with control valves. Are there any disadvantages to using VFDs as control elements compared to valves, or do you think VFDs are universally superior?

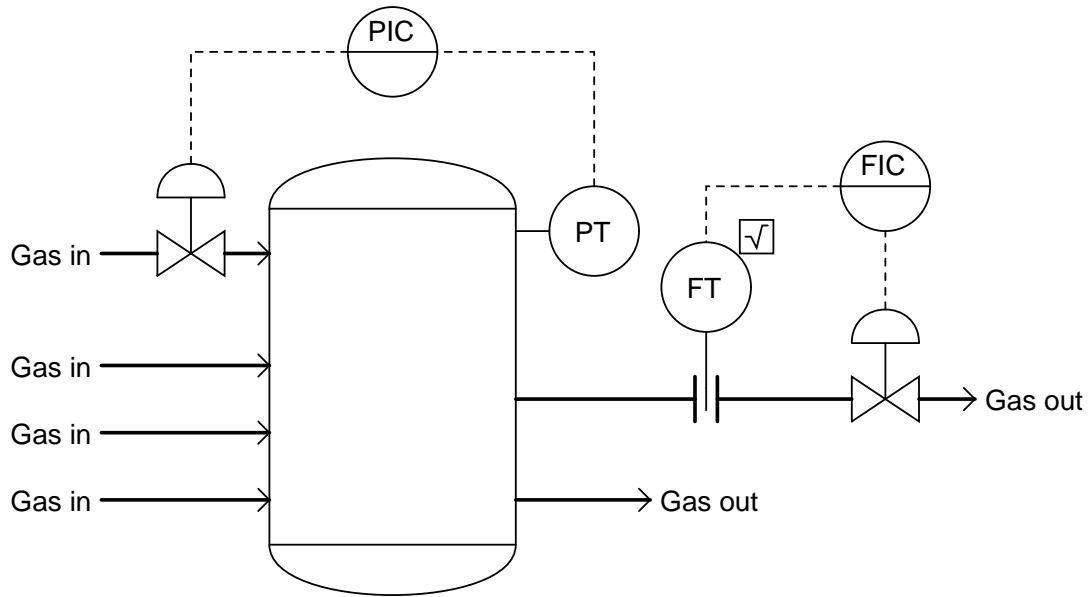
Suggestions for Socratic discussion

- A theme common to Michael Brown’s “Case History” reports on control loop optimization is that basic PID controls are often performing very poorly at industrial facilities world-wide. Explain why you think this is the normal state of affairs. Why don’t the people working at these facilities recognize and correct these problems themselves?
- One of the problem-solving techniques Michael Brown applied to the cycling flow control loop shown in Figure 1 is to compare the cycle’s period against what he knew to be the typical period for a flow control loop. Explain how this relates to the concept of *ultimate period* as defined in the Ziegler-Nichols closed-loop tuning technique.

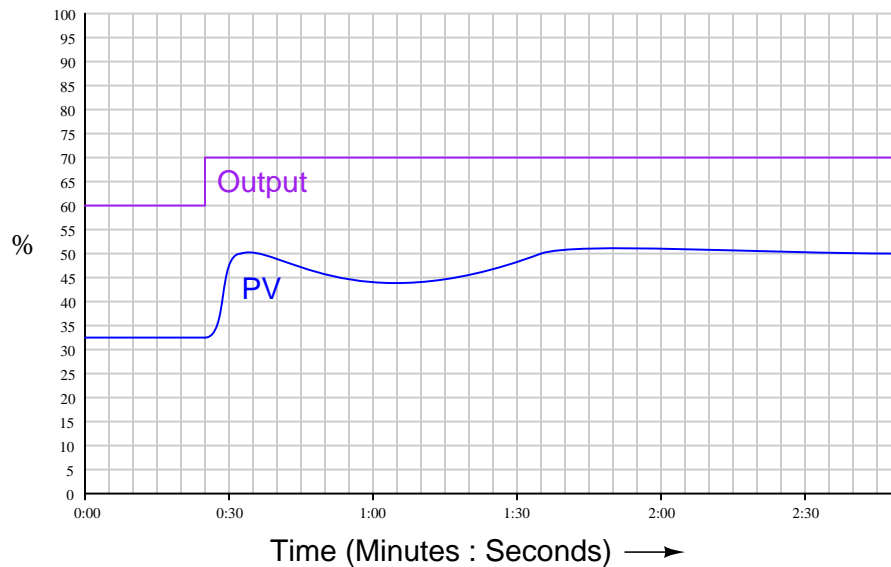
[file i01819](#)

Question 68

Gas flow control processes differ somewhat from liquid flow control processes, the former tending to be more difficult to control than the latter. Consider the following process, controlling the flow of gas out of a pressure-controlled vessel:



When the flow indicating controller (FIC) is placed in manual mode and the output “bumped” 10%, the result is certainly not what you would expect to see in a liquid flow control system:



Explain the odd shape of the process variable (PV) trend following the output step-change: why the flow increases, then “sags,” then stabilizes. Identify a diagnostic test you could perform on this process to positively identify the source of this strange behavior, explaining how the result(s) of this next test would help you identify the cause.

[file i03400](#)

Question 69

Identify types of processes that respond well to aggressive *proportional* action, and why they do.

Identify types of processes that respond poorly to aggressive *proportional* action, and why they do.

Question 70

Identify types of processes that respond well to aggressive *integral* action, and why they do.

Identify types of processes that respond poorly to aggressive *integral* action, and why they do.

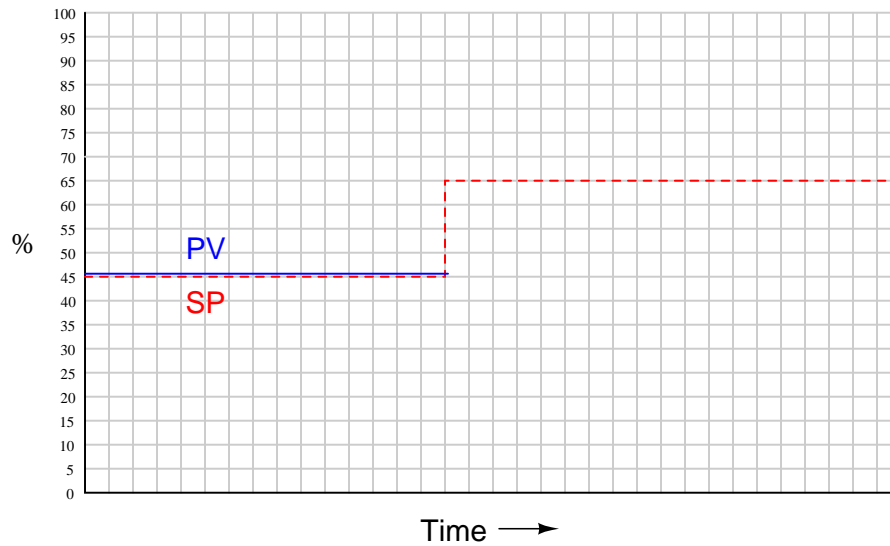
Question 71

Identify types of processes that respond well to aggressive *derivative* action, and why they do.

Identify types of processes that respond poorly to aggressive *derivative* action, and why they do.

Question 72

Often, the phrase *quarter-amplitude damping* (sometimes called *quarter-wave damping*) is used to describe good process response to a disturbance or setpoint change (perturbation). What does this phrase mean? Sketch the response of a process to a setpoint change (continue the PV plot), where the controller has been tuned for quarter-wave damping:



[file i01668](#)

Question 73

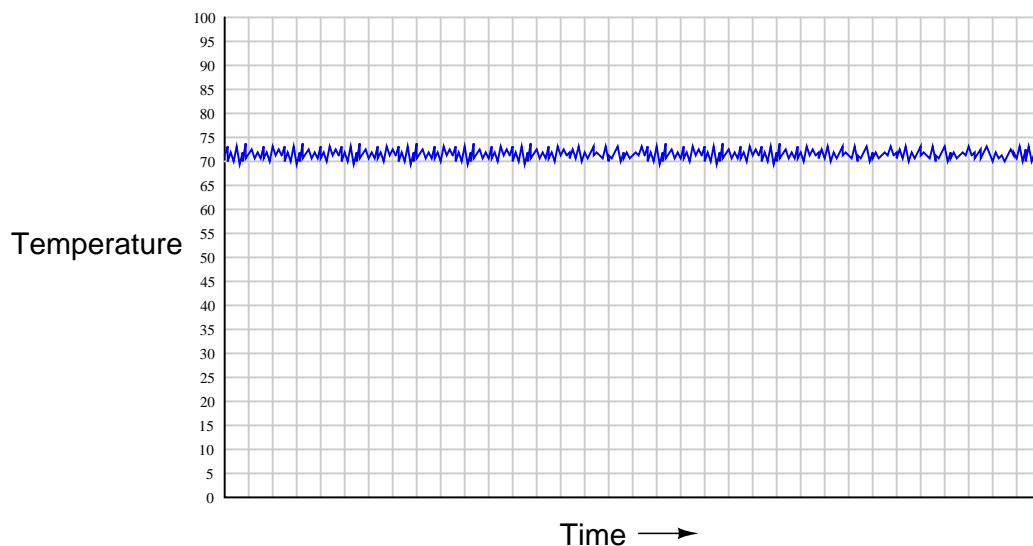
If a process exhibits a large dead time (L_R), how does this affect your choice of P, I, and D tuning constants? In other words, as the dead time of a process increases, you would generally do what (make more aggressive or less aggressive) to each tuning constant?

- Proportional: (*more or less aggressive?*)
- Integral: (*more or less aggressive?*)
- Derivative: (*more or less aggressive?*)

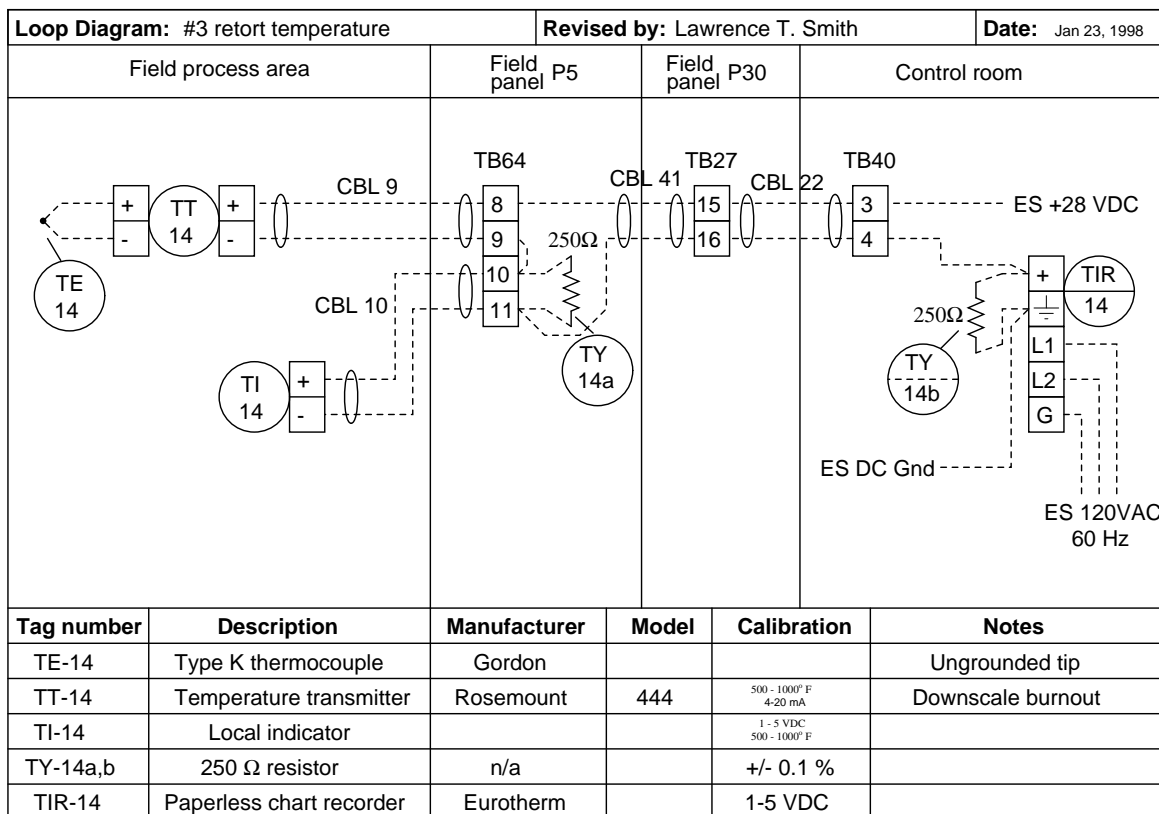
[file i01667](#)

Question 74

One day the trend on a retort temperature monitoring system is seen to exhibit a “noisy” signal, which operations personnel have never noticed before. According to them, this trend recorder’s trace is always smooth, never noisy:



The loop sheet for this monitoring system is shown here:



Explain how you would proceed to troubleshoot this problem, specifying what equipment you might use to do so.

file i03574

Question 75

Question 76

Question 77

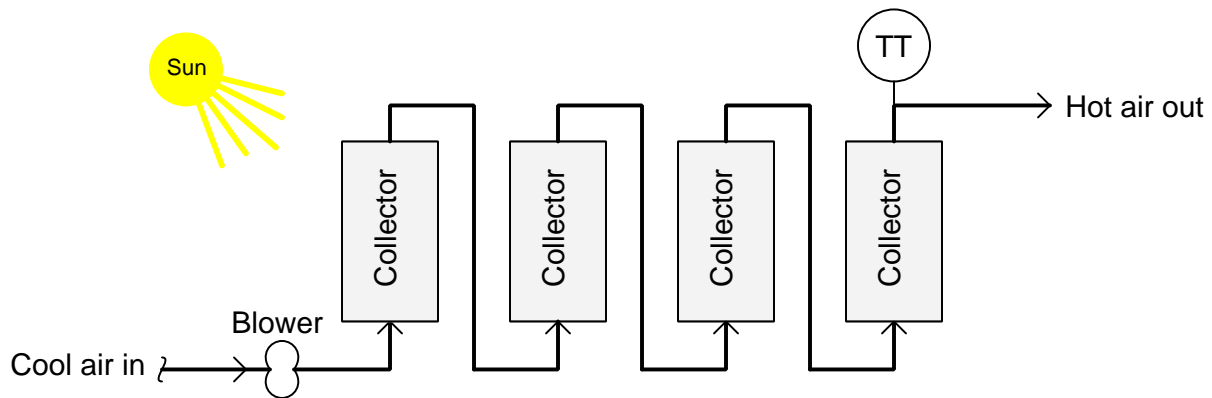
Question 78

Question 79

Question 80

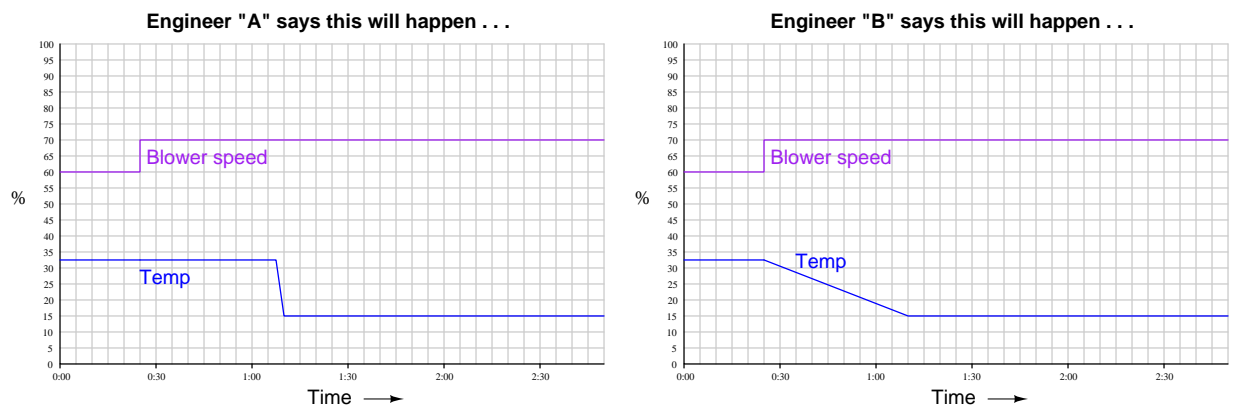
Question 81

Two engineers are arguing over the open-loop response of a multi-collector solar air heating process:



They both agree that the amount of temperature rise the air experiences from the inlet to the outlet of each collector panel is a function of the air's residence time in that collector: the slower the air moves through, the more heat it will absorb from the sun and the hotter its temperature will rise. They also agree that this process has a lot of *transport delay* (dead time) from the inlet of the first panel to the outlet of the last, given the long path length the air must travel to get through all the collectors.

What they cannot agree on is how the final temperature will respond to a step-change in air flow rate (i.e. suddenly changing the blower speed). The two engineers propose these differing open-loop responses for this system:



The two engineers have been arguing over this for hours because they don't have permission to actually test the system by varying the blower speed. Their co-workers are getting really tired of hearing this argument go back and forth, and so they call you to settle it.

Which engineer do you think is correct, and why? Or, are neither of them correct?

[file i00075](#)

Question 82

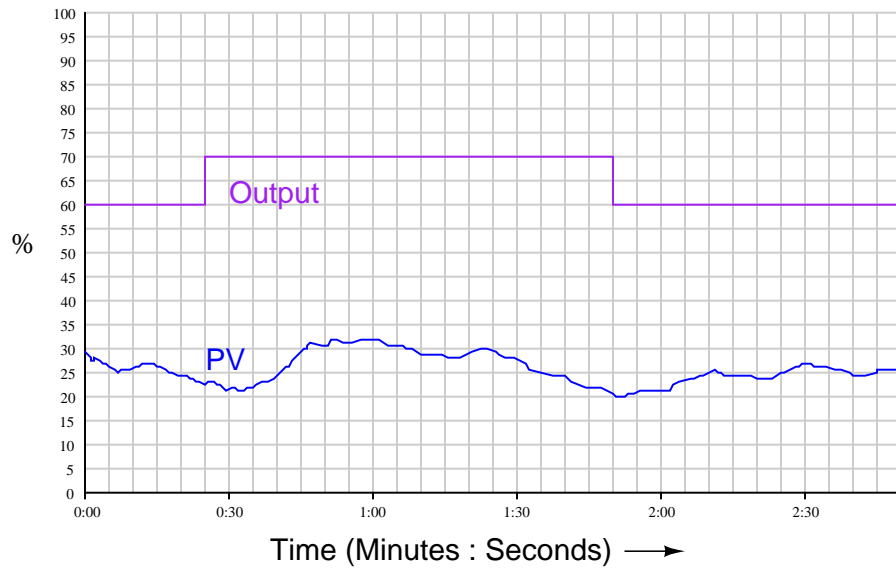
Suppose you are asked to calibrate a pH transmitter, sensing the pH of water flowing through a pipe. The water treatment process it is a part of must be kept running and not shut down while you do this task.

The company's standard maintenance procedure for this loop tells you to place the pH transmitter in its "Hold" mode during the calibration so that the readings it gets from being "standardized" with 4 pH and 10 pH calibration standard solutions do not get sent to the control system and mess things up for the operating process. The transmitter's "Hold" mode essentially freezes its 4-20 mA signal to the loop controller at the last value it was outputting while it was running normally.

You happen to know the pH controller is a full PID unit (P, I, and D terms all active), and that this could cause a control problem if you engage the pH transmitter's "Hold" function during a long calibration procedure with the loop controller still in Automatic mode. Describe what the potential problem is, why it is better to place the controller in Manual mode than to rely on the transmitter's "Hold" function to prevent process upset, and also what you would do if faced with a company-standard procedure that you knew could be improved.

Question 83

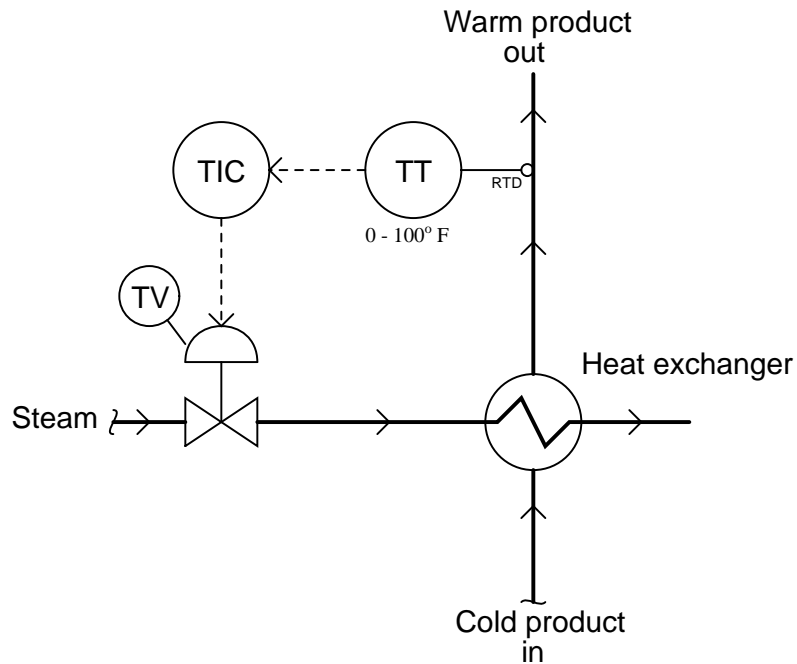
Examine this process trend, showing the response of the process variable to a 10% up-and-down step change in the controller output (placed in manual mode):



What characteristics of the process (and its related instrumentation) can you discern from this trend? Based on this information, hypothesize how you think the controller should be tuned to respond. In other words, how aggressive should the controller's P, I, and D terms be relative to each other?

Question 84

Suppose this process is optimally tuned, with a measurement range of 0° F to 100° F:



Then, one day the decision is made to re-range the temperature transmitter (TT) for greater resolution: 50° F to 70° F instead of 0° F to 100° F. As a result of this range-change, the process begins to oscillate around setpoint rather than hold steady at setpoint as it used to.

Explain why this range-change caused the process control to become unstable, and propose a solution that will restore the previous quality of control.

Question 85

Francis G. Shinskey, in his book *Process Control Systems – Application, Design, and Tuning* (3rd edition), gives a table of generalizations and PID tuning recommendations for different types of processes. What follows is a modified version:

Property	Flow and liquid pressure	Gas pressure	Liquid level	Composition	Temperature and vapor pressure
Linearity	square/linear	Linear	Linear	Linear / Log	Nonlinear
Noise	Always	None	Always	Often	None
Period	1-10 sec	0-2 min	1-10 sec	Minutes to hours	Minutes to hours
Int/Self-reg	Self-reg	Int	Int	Self-reg	Self-reg

Controller action	Flow and liquid pressure	Gas pressure	Liquid level	Composition	Temperature and vapor pressure
Proportional	Moderate-weak	Strong	Strong	Weak	Strong
Integral	Strong	None	Seldom	Essential	Yes
Derivative	Never	None	None	If possible	Essential

Choose one of these process types and explain *why* the tuning recommendations are as stated in the second table. Note: “Essential” does not imply “Strong,” but rather that at least *some* of this action must be present for good control. “Strong,” however, *does* imply necessity!

Question 86

The fraction of radio wave energy reflected off a liquid surface after traveling through the air may be calculated by the following equation:

$$R = \frac{(\sqrt{\epsilon} - 1)^2}{(\sqrt{\epsilon} + 1)^2}$$

Where,

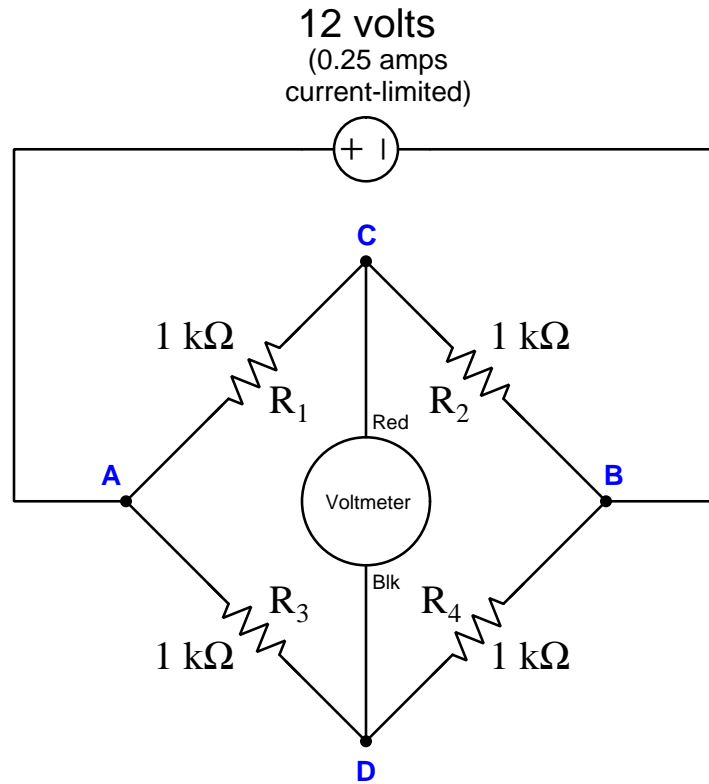
R = Reflection ratio (a number between 0 and 1)

ϵ = Dielectric permittivity of the liquid relative to a vacuum ($\epsilon_{air} \approx 1$)

Manipulate this equation to solve for ϵ if the value of R is known.

Question 87

Suppose the voltmeter in this bridge circuit registers a strong *positive* voltage. A test using a digital multimeter (DMM) shows the voltage between test points **D** and **B** to be 0 volts:



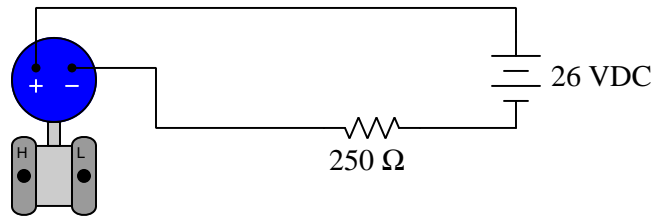
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_4 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 failed shorted		
R_4 failed shorted		
Voltage source dead		

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.

Question 88

Calculate the current and all voltage drops in this loop-powered transmitter circuit, assuming the pressure transmitter is calibrated for a range of 0 to 70 PSI, 4 to 20 mADC. Be sure to show all your work!

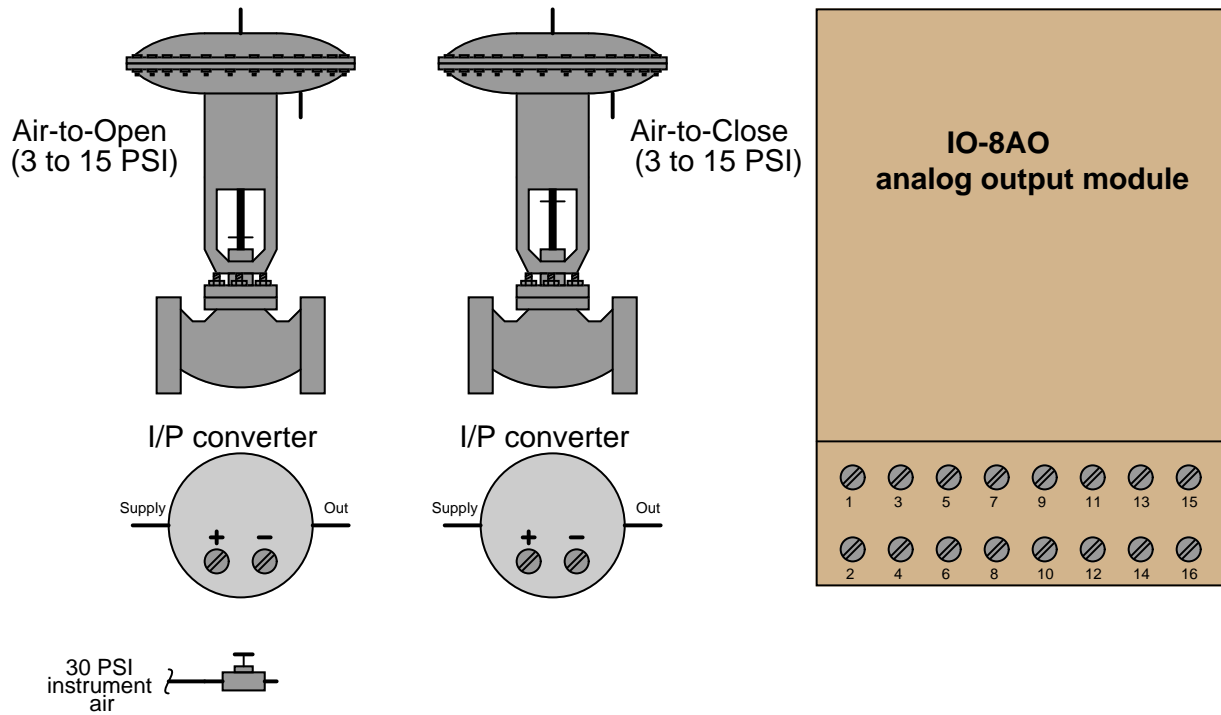


Loop-powered
4-20 mA transmitter

Applied pressure (PSI)	Current (mA)	Transmitter voltage (V)	Resistor voltage (V)
0 PSI			
10 PSI			
20 PSI			
35 PSI			
60 PSI			
70 PSI			

Question 89

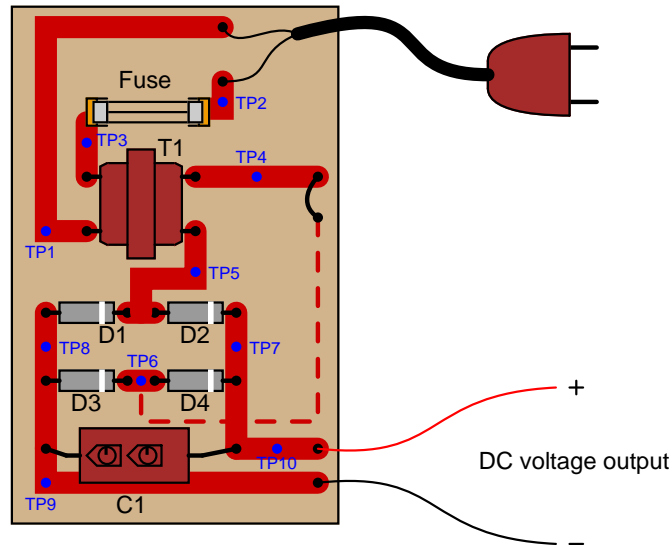
Suppose you are asked to connect a pair of split-ranged control valves to a single 4-20 mA analog output of a Siemens 353R rack-mounted controller. The analog output card plugged into the terminal block assembly (shown) is a model IO-8AO, and the channel you are to use is channel 3:



Sketch the necessary tube and wire connections to make both split-range valves function properly, controlled by channel 3 of the Siemens 353R controller.

Question 90

A technician is troubleshooting a power supply circuit that outputs substantially less DC voltage than it should. The output voltage is supposed to be 15 volts DC under load, but instead it is actually outputting less than 8 volts DC under load:



The technician measures approximately 12 volts AC (RMS) across the secondary winding of the transformer. Based on this voltage measurement and the knowledge that there is reduced DC output voltage, 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.

Lab Exercise

Your primary task is to independently (i.e. no assistance from team members or other classmates) tune multiple control loops, documenting the process open-loop response as well as the process closed-loop responses to both setpoint and load changes. This documentation must be in the form of computer screen captures, showing the graphic trends of the process as it responds to open-loop and closed-loop tests. You must do your own loop testing and tuning, the consequence of plagiarism being a failing grade for the course.

Two of the processes you will tune must be *real*, working processes of differing type (e.g. pressure versus temperature). The last process may be simulated, or it may be another real process with different characteristics than the first two. All tuning objectives are “mastery” – they must be demonstrated to instructor satisfaction for completion.

Performance objective	Real #1	Real #2	Real #3 or Simulated
Description of process			
PV range of process loop			
PV alarm points (<i>set by instructor</i>)			
Self-reg. <i>vs.</i> Integ. <i>vs.</i> Runaway?			
Measurement of dead time (sec)			
Measurement of time constant (sec)			
Measurement of valve stiction (%)			
P value after tuning (K_p)			
I value after tuning (K_i or τ_i)			
D value after tuning (K_d or τ_d)			
Robust response to SP change?			
Robust response to load change?			
<i>Instructor initials</i>			

In addition to process tuning, you must also complete a circuit design challenge and troubleshoot a control system the same as in regular team-based lab exercises. A crucial difference is that none of the objectives in this entire lab exercise are team-based; rather, all are individual.

Performance objective	Grading	Individual
Circuit design challenge	mastery	
Troubleshooting	mastery	
<i>Safety and professionalism</i>	deduction	
<i>Lab percentage score</i>	proportional	
Decommission and lab clean-up	(ungraded)	

The “proportional” score for this activity is based on the number of attempts required to master each student performance objective (note that the process description and PV alarm points do not count as objectives). 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. The *Safety and professionalism* deduction is a flat –10% per instance, levied on occasions of unprofessional or unsafe conduct.

When all students are finished with their circuit design challenges, as well as tuning and troubleshooting their control loops, the last step is to decommission all the working systems as per usual procedure. On the last day of the quarter (dedicated to lab clean-up) each team will show their team tool locker for inspection.

Note: this lab worksheet is your only record of the instructor's validation (signed initials). Do not lose it, and do not lose your screen-captures of the process responses either!

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.

Loop tuning

Gather data and tune three different processes (one of which may be a computer simulation of a process). Capture screenshots of trend graphs as evidence of your work, both for characterizing the process (e.g. measuring dead time) and for demonstrating robust control response. The instructor will assign high and low process alarm values prior to your working on that system, and all trend graphs must show the PV between these prescribed limits in order to receive credit.

Circuit design challenge

Design, build, and demonstrate the operation of a simple circuit based on random selections by the instructor, using a digital oscilloscope as the test instrument.

Troubleshooting

Logically diagnose the nature and location of a fault placed in a working system that your team did not build. This will be limited in time, with each student passing or failing individually.

Lab Exercise – objectives and expectations (continued)

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 entirely individual, with each student challenged to complete a number of performance objectives, budgeting time and resources to complete them all 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.

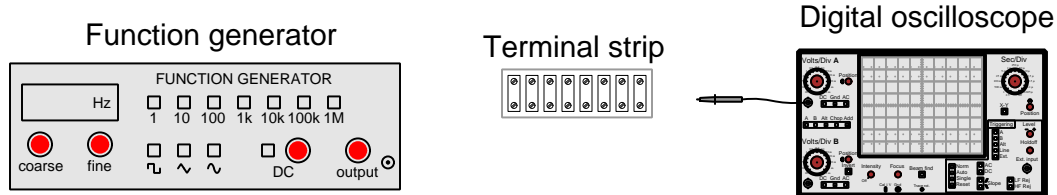
Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's 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 – circuit design challenge

Design, build, and test a circuit to fulfill one of the functions listed below (randomly selected by your instructor). All electrical connections must be made using a terminal strip (no solderless breadboards, twisted wires, crimp splices, wire nuts, spring clips, or “alligator” clips permitted). The only electrical source allowed in this circuit will be the function generator.

This exercise tests your ability to apply basic electrical principles to the design, construction, and proving (testing) of a simple passive circuit intended to fulfill a specific function, as well as your ability to use a digital oscilloscope and function generator.



The following components and materials will be available to you: **terminal strips** ; lengths of **hook-up wire** ; digital **oscilloscope** ; and **function generator**. You must provide all electronic components, tools, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

SEQUENCE: (1) Instructor chooses criteria; (2) You build and test circuit without any power sources at all; (3) Instructor observes you energizing the circuit for the first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function.

Circuit function (randomly selected by the instructor):

- Voltage divider with total resistance between _____ and _____ ohms, with a division ratio of _____ : _____
- Low-pass filter with total impedance between _____ and _____ ohms, with a cutoff frequency of _____ Hz
- High-pass filter with total impedance between _____ and _____ ohms, with a cutoff frequency of _____ Hz
- Time-delay *charging* where the voltage rises to a value of _____ percent of the final (maximum) in _____ seconds
- Time-delay *discharging* where the voltage falls to a value of _____ percent of the initial (maximum) in _____ seconds
- Phase-shifter with total impedance between _____ and _____ ohms, where the output voltage lags the input voltage by _____ degrees
- Phase-shifter with total impedance between _____ and _____ ohms, where the output voltage leads the input voltage by _____ degrees

Study references: all your textbooks and lessons from the first year of the program. Also, specific modules contained in the *Modular Electronics Learning Project* which is found online at <http://www.ibiblio.org/kuphaldt/socratic/model/index.html>.

Lab Exercise – PV alarm points

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 according to values set by the instructor. The purpose in doing this is to set limits beyond which you should never take the process variable for two different reasons: (1) to mimic real-life constraints whereby process quality may be affected if the PV wanders too far away from normal values, and (2) to force you to tune the controller differently to match the process characteristics in a different range.

This second reason for PV alarm limits bears further explanation. It is quite common for processes to exhibit different operating characteristics at different PV ranges. Parameters such as dead time, lag time, and/or self-regulation may vary depending on the exact value of the process variable. This is why PID controller tuning parameters which may work very well to control a process within a certain PV range fail to achieve the same level of robust control within a different PV range. When the instructor sets PV alarm points at different values for each student, the process essentially poses a new tuning challenge for each student so that the PID tuning work of another student cannot simply be copied.

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.

When showing your screen-shots of open-loop testing and closed-loop PID response to the instructor, these high and low PV limits should be denoted on the trend graph for easy reference, as proof that the system’s PV never strayed beyond these prescribed limits.

Note that if you are using the `looptune` application on a caSCADA system to simulate a process, all PV alarm values (low-low, low, high, and high-high) are randomly assigned by the computer upon invocation. Your documented work needs to show the PV remaining between the low and high alarm limits at all times, but know that the simulation will automatically abort if the process variable goes beyond either the low-low or high-high limits, resulting in a complete loss of data (your PID tuning parameter values, the simulation process parameters, the randomized PV alarm points, etc.)!

Lab Exercise – how to capture “screen-shots” on a PC

An essential part of this lab exercise is capturing graphical trend data from the screen of a personal computer, either running control software (e.g. Emerson DeltaV Operate) or data acquisition software used to monitor process data (e.g. WinDAQ, LabVIEW). Fortunately, this is really easy to do on any personal computer.

When you have the screen of the computer displaying what you wish to capture, simply press the “Print Screen” key on your keyboard. This key is usually located to the right of the “Function” key row at the top (on a standard desktop keyboard layout – laptop keyboards are famous for locating seldom-used keys like this in random places). Pressing the “Print Screen” key tells the computer’s operating system to copy the entire screen image into a buffer for pasting into any graphics-manipulation or word-processing program you desire.

A utility standard on every Windows operating system is *Paint*: a bitmap image creation and manipulation program. Paint is simple to the point of being crude, but it works just fine for this purpose. After starting Paint, simply “Paste” the captured screen-shot image and save it under any filename you wish. I strongly recommend using a filename that is unique to you (e.g. `John.Doe.process1.trend2.bmp`). Remember that you will be capturing multiple screen-shots in this lab exercise, and will need to save every one for presentation to the instructor.

You may also use Paint (or even a more sophisticated image-manipulation program such as *Photoshop* or *Gimp*) to add text annotations to your screen-shot images. For example, some students like to add arrows and lines showing where they measured process gain, or arrows pointing to problems in the trend such as where the control valve sticks.

The `looptune` PID loop simulation software has a special feature for capturing trend data: simply press the “T” button (or the F12 function key) at any time, and the software will save all displayed trend data into a comma-separated value text file (`.csv` filename extension) into the same directory as the `looptune` software. Double-clicking on the filename will start your computer’s spreadsheet software. When that opens, you will see multiple columns of data representing points on the simulation’s trend graph (time index (“Sample”), PV, SP, Output, and “Wild” representing the process load). Highlight (i.e. select with a mouse) the first four of those columns (i.e. “Sample” through “Output”) and then insert a “scatter” plot, and you will have a very nicely formatted trend graph that is actually more precise than the one running during the live simulation. Being a spreadsheet, you may then use mathematical functions to calculate rates of change from the tabular data, fit linear trendlines, insert text notes, alter colors, etc. to create a nice record of the process characteristics. Going back to `looptune` and pressing “T” again over-writes the last `.csv` file.

Common mistakes:

- Forgetting to move screenshot files to personal drive, leaving them on the hard drive of the school computer where they may be deleted by other students
- Not collecting enough screenshots to adequately document work done on the process
- Failing to save all screenshot files for later reference after you relinquish the process to others for their tuning objectives
- Failing to label and organize the screenshot files so as to be able to remember what exactly was being done during each one of the trends

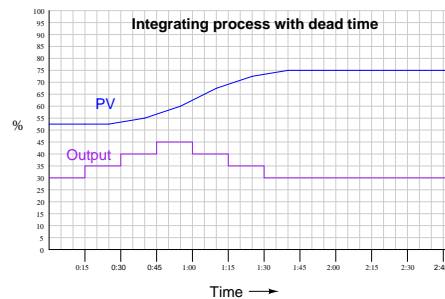
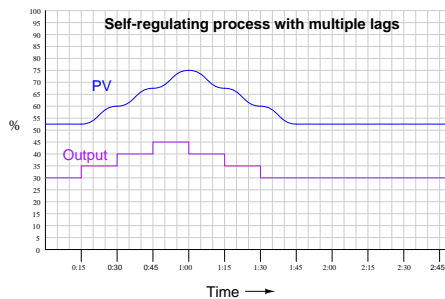
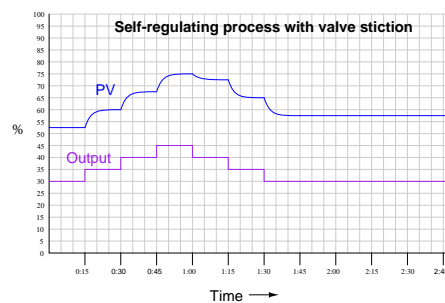
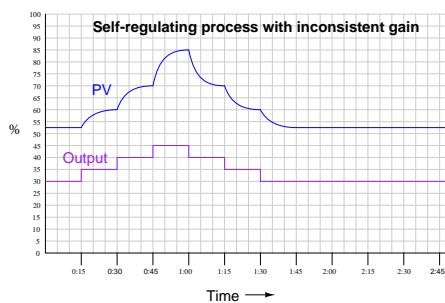
Lab Exercise – open-loop testing

Before you can begin to successfully tune a PID-controlled process, you must first understand the characteristics of that process. A very good way to do this is by performing an *open-loop* test: placing the PID controller in manual mode and changing the output value (5% or so is usually a good amount for the first test) to see what effect this has on the process variable over time. The PV's response to this "step-change" in output can not only reveal the basic characteristics of the process (i.e. self-regulating, integrating, runaway, lag time magnitude, lag order(s), dead time magnitude) but also certain instrument problems (valve stiction, transmitter filtering, etc.).

During all your testing, be sure to maintain the process variable within the alarm limits prescribed by the instructor! All of your documentation for the process characteristics (and the final tuning results) must show the PV remaining within these limits.

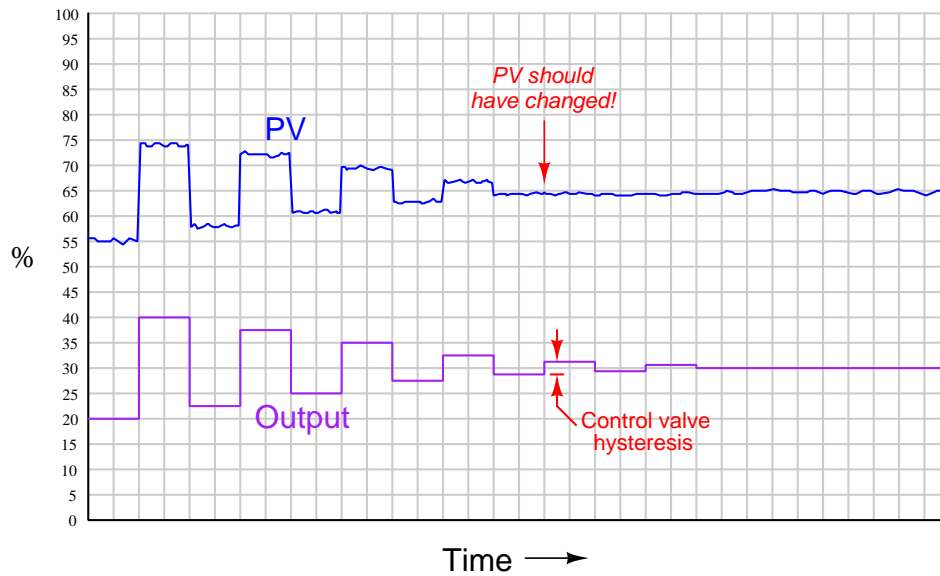
You should perform several open-loop step-changes to probe the process characteristics: a few in the same direction, then the rest in the other direction. An analysis of the PV responses following multiple output step-changes will reveal two important characteristics of the process:

- How consistent the process gain is
- Whether the valve has significant hysteresis or stiction (compare opening versus closing)



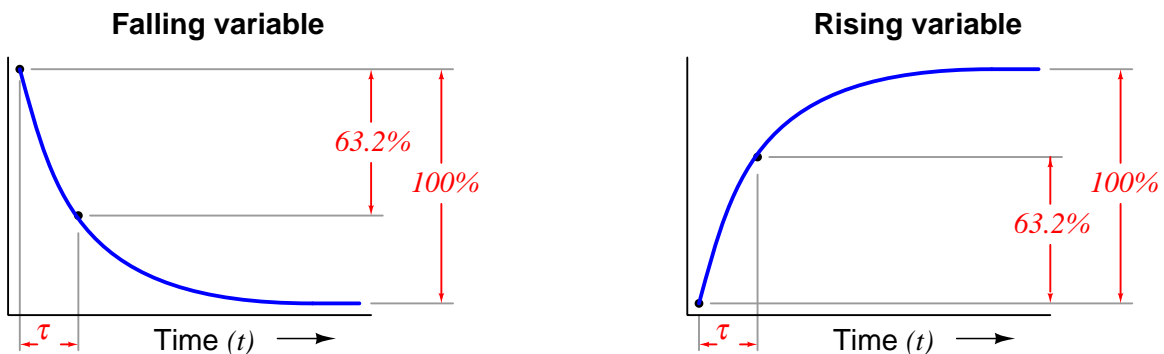
A common mistake among students is to try to determine process characteristics with the controller in *automatic* mode (i.e. closed-loop testing). This generally gives poor results because the process response seen on the trend graph while in automatic mode is not just the natural response of the process, but also the automatic (regulating) response of the controller. A controller that isn't tuned aggressively enough, for example, may make a fast process appear to have long lag times. By placing the controller in manual mode and performing open-loop tests, you get to see the natural response of the process itself without any controller interference.

Valve stiction is best determined by making alternating (up and down) step-changes in manual mode in progressively smaller intervals, noting the largest of those step-changes resulting in no measurable PV change. This is a superior test to multiple step-changes in the same direction because step-changes in the same direction tend to be additive while reversing steps are not. The following illustration shows this test applied to a fast, self-regulating process:



Another important test of process characteristics is the process *lag time*, also known as the process *time constant* symbolized by the Greek letter τ . This is precisely the same concept you have explored in previous courses with charging and discharging circuits (i.e. resistor-capacitor and inductor-capacitor circuits), and is empirically measured in precisely the same way.

With the controller in manual mode, you are to introduce a step-change in the output signal and then record the process variable's response. For self-regulating processes, the process variable will initially begin to ramp at a high rate of change, and then level off until it settles at its new self-regulated value. The amount of time it takes for the process variable to go 63.2% of the way from its initial to final values is the lag time (τ).



One "time constant" (τ) is the amount of time required for the variable to change 63.2% of the way from its starting point to its ultimate (terminal) value

One of the common misconceptions regarding time constant is that you can first measure the amount of time it takes for the variable in question to reach its final value, and then divide that time by 5, because

it is commonly taught that it takes 5 time constants' worth of time (5τ) for the changing variable to settle to its final value. *The truth is that five is the closest whole-number multiple of τ that gets you within just 1 percent of the variable's final (settled) value.* One percent is an entirely arbitrary figure, and so “five time constants' worth of time” is a poor standard to use in this manner.

Instead, what you must do to measure the lag time of a process is to follow the model presented to you in the previous graphs, where you base the time strictly by the horizontal distance on the trend that it takes for the process variable to traverse a 63.2% vertical interval. If the trend graph of your loop's controller does not provide fine-line divisions to help mark the variable's value (vertical) as well as the time (horizontal), you may have to resort to printing the trend on paper and sketching your own division lines to mark where these important points are.

One final note on the subject of lag time is that integrating processes do not strictly possess a lag time. Since in an integrating process the process variable never “levels out” on its own, there is no basis upon which to determine when it has traversed 63.2% of the way to its final value (because it *has no* final value).

Common mistakes:

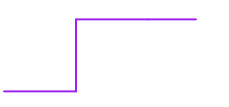

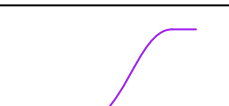


- Trying to probe the process characteristics with the controller in *automatic* mode rather than *manual* mode
- Making output step-changes that are too large (resulting in PV excursions beyond the alarm limit values)
- Not making enough step-changes to fully test process gain consistency or valve stiction
- Incorrectly measuring process lag time (time constant τ)

Notes on process characteristics and PID tuning strategies

After you have determined the characteristics of the process and corrected any instrument problems such as transmitter filtering or valve stiction, your next step is to determine how you will tune the PID controller. Several algorithmic procedures exist, including two methods proposed by Ziegler and Nichols in their 1942 paper, and several more modern methods. You are free to use whatever tuning method you would like to try, so long as you document the data supporting your tuning decisions (i.e. process characteristics) and also document the trend data showing improvement in process stability as you use your understanding of PID control to fine-tune each process.

Truth be told, many working professionals use algorithmic methods such as Ziegler-Nichols because they really don't understand how PID works, or is supposed to be applied to a real process. The goal of this lab exercise is to give you plenty of opportunity to try your hand at PID tuning, and to improve upon simple step-by-step methods such as Ziegler-Nichols. With practice, you will find it possible to make dramatic improvements over "canned" PID tuning methods simply by understanding the characteristics of the process and choosing control actions appropriate for those characteristics.

The following table shows several PV responses following a single controller output step-change in manual mode, with suggesting heuristic tuning strategies for each:

	Pure self-regulating	<i>May be controlled with aggressive integral action, and perhaps with a bit of proportional action. Use absolutely no derivative action!</i>
	Self-reg w/ pure 1 st order lag	<i>Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.</i>
	Self-reg w/ multiple lags	<i>Proportional action needed for quick response to setpoint changes, integral action needed for recovery from load changes, and derivative needed to prevent overshoot. Proportional and integral actions are limited by tendency to oscillate.</i>
	Integrating w/ lag(s)	<i>Proportional action should be aggressive as possible without generating oscillations. Integral action needed only for recovery from load changes.</i>
	Pure integrating	<i>Responds well to aggressive proportional action, with integral action needed only for recovery from load changes.</i>

Remember that the presence of certain other characteristics in significant amounts (e.g. PV noise, dead time, etc.) also impacts how one should tune a controller.

Common mistakes:

- Making tuning parameter changes that are too large without considering the ill effects those changes might have (e.g. increasing gain by a factor of 10)
- Attempting to "de-tune" process or instrument problems that should be repaired (transmitter filtering, valve stiction, etc.)

Lab Exercise – robust PID response

In this exercise you will be asked to demonstrate “robust” loop response to both setpoint changes and load changes, which naturally demands a definition for “robust” response. In this context, robust PID response meets all of the following criteria:

- The process variable is brought to setpoint as fast as possible following both setpoint changes and load changes
- The process variable exhibits as little over/undershoot as possible following both setpoint changes and load changes
- The process variable *never* strays outside of the prescribed alarm limits
- The process variable *never* porpoises (i.e. oscillates prior to reaching setpoint)

A controller that is tuned too “fast” will take little time reaching setpoint, but it will do so at the expense of overshooting or undershooting the setpoint value before settling in to the setpoint value. A controller that is tuned too “slow” will not over- or under-shoot setpoint, but will exhibit extended periods of time where the PV is approaching setpoint yet the output value is nowhere near saturation (i.e. the controller is not “trying” as hard as it can).

When testing for robust response to load changes, you should introduce load changes in a manner similar to how you introduce setpoint changes: change the load *and leave the load in that new state long enough to watch the controller compensate for it*. A very common error students make when introducing load changes is to do so very briefly, so briefly in fact that the controller never gets a chance to correct for the new load condition. What you see in such a case is the PV changing due to the load change, and then returning back to setpoint *only because the load returned to its previous value, not because the controller actually did anything to make PV return to setpoint!* So remember, when you introduce load changes, do so the same way you introduce setpoint changes: change the load condition and leave it in that new state, then watch the controller’s response to see how quickly the PV returns to the setpoint value, whether there is under- or over-shooting of the setpoint, and/or whether any porpoising occurs.

You will notice that ideal tuning for response to setpoint changes is often different from ideal tuning for response to load changes. One reason for this is that setpoint changes typically occur more suddenly than load changes. Another reason is that load changes tend to alter the processes’ equilibrium point (i.e. the FCE value necessary to maintain the setpoint) more than setpoint changes. If you notice a great difference between these two responses, you may wish to set the PID algorithm to one where more of the PID equation responds only to changes in *PV* and not to changes in *error*. If you cannot achieve robust control for both setpoint *and* load changes, you may consult your instructor as you would operations personnel on the job to see which of these two scenarios is more realistic to the process, and then optimize your controller’s response accordingly.

If your controller “porpoises” at all, it is detrimental to process control. “Porpoising” occurs when either the controller’s proportional action or derivative action is too aggressive, causing the controller to over-correct during the PV’s approach to setpoint. Integral is incapable of causing porpoising, because integral action cannot reverse direction unless and until the error changes sign (i.e. until PV crosses setpoint), and porpoising is defined as oscillations occurring *prior* to setpoint. Perhaps the best tool for determining whether excessive gain or excessive derivative action is causing porpoising is to examine the *phase shift* between PV and Output during the porpoising period: little or no phase shift reveals excessive P action, while nearly 90° phase shift reveals excessive D action.

Common mistakes:

- Not properly diagnosing field instrument problems (e.g. sticky valves, over-damped transmitters) prior to tuning. *Pay close attention to your open-loop tests prior to any PID tuning parameter adjustments!!!*
- Relying too much on proportional action (gain) to control fast-acting, self-regulating processes.
- Introducing transient load changes that don’t persist long enough to test the controller’s ability to correct (i.e. to bring the PV back to SP with different load conditions).

Lab Exercise – troubleshooting

The most important aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a problem in the system. All troubleshooting must be done on a system you did not help build, so that you must rely on others' documentation to find your way around the system instead of from your own memory of building it. Each student is given a limited amount of time to identify both the location and nature of the fault. All troubleshooting activities must be proctored by the instructor to assess proper diagnostic reasoning and technique.

The standard procedure involves a group of no more than four students troubleshooting the same faulted system, with the builders of that system playing the role of operators. All troubleshooters are given a two-minute period to individually identify a plausible fault based on observable symptoms and submit it in writing to the instructor for assessment. Those students whose faults are indeed plausible advance to the next round, where each one takes turns making diagnostic tests on the system. One minute is given to each student for devising this test, but no time limit is placed on the execution of that test. Whenever someone decides enough data has been collected to pinpoint the location and nature of the fault, they declare to have reached a conclusion and submit to the instructor in writing for assessment.

Individual troubleshooting with a five-minute time limit is also an acceptable format, but this generally only works with small class sizes.

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault.

A standard multimeter is the only test equipment allowed during the time limit. No diagnostic circuit breaks are allowed except by instructor permission, and then only after correctly explaining what trouble this could cause in a real system.

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:

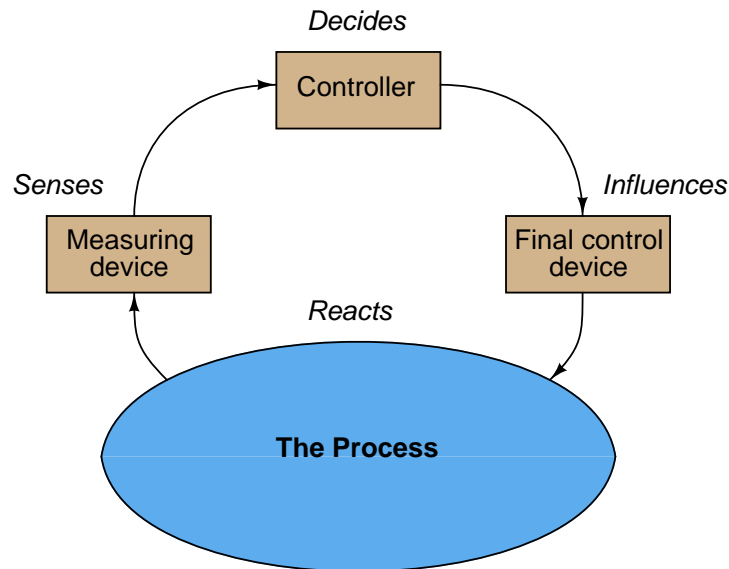
- Attempting to *visually* locate the fault.
- Neglecting to take measurements with your multimeter.
- Neglecting to check other measurements in the system (e.g. pressure gauge readings).
- Incorrectly interpreting the loop diagram (e.g. thinking you're at the wrong place in the system when taking measurements).
- Incorrect multimeter usage (e.g. AC rather than DC, wrong range, wrong test lead placement). This is especially true when a student comes to lab unprepared and must borrow someone else's meter that is different from theirs!

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!

Troubleshooting takes a lot of lab time, usually at least two 3-hour lab sessions for everyone in a full class to successfully pass. Budget for this amount of time as you plan your work, and also be sure to take advantage of your freedom to observe others as they troubleshoot.

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.

Lab Exercise – decommissioning and clean-up

The final step of this lab exercise is to decommission your team's entire system and re-stock certain components back to their proper storage locations, the purpose of which being to prepare the lab for the next lab exercise. Remove your system documentation (e.g. loop diagram) from the common holding area, either discarding it or keeping it for your own records. Also, remove instrument tag labels (e.g. FT-101) from instruments and from cables. Perform general clean-up of your lab space, disposing of all trash, placing all tools back in their proper storage locations, sweeping up bits of wire off the floor and out of junction boxes, etc.

Leave the following components in place, mounted on the racks:

- Large control valves and positioners
- I/P transducers
- Large electric motors
- Large variable-frequency drive (VFD) units
- Cables inside conduit interconnecting junction boxes together
- Pipe and tube fittings (do not unscrew pipe threads)
- Supply air pressure regulators

Return the following components to their proper storage locations:

- Sensing elements (e.g. thermocouples, pH probes, etc.)
- Process transmitters
- “Jumper” cables used to connect terminal blocks within a single junction box
- Plastic tubing and tube fittings (disconnect compression-style tube fittings)
- Power cables and extension cords
- Adjustment (loading station) air pressure regulators

Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.

Lab Exercise – team tool locker inspection

The instructor will work with each team to inspect their tool locker for all required items, and also to ensure nothing else is being stored there.

First, the locker will be entirely emptied. Next, the instructor will inspect each tool before placing it in the locker, following the order of the inventory list taped to the inside of the locker door. The team is responsible for finding or replacing any missing items. Any items not on the inventory list will be left out of the locker.

Any damaged or worn components will be replaced. Inexpensive items such as drill bits and taps will be replaced at student expense. More expensive items will be replaced at the school's expense, with students doing research to identify the replacement cost of the item(s) in question.

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Capstone Assessment (end of quarter)

This performance assessment tests your mastery of many important instrumentation concepts. You are to automate a pre-built process based on prototype diagrams you sketch of all instrument connections, and demonstrate the automatic control of this process. All this must be done individually with no assistance from anyone else, within one continuous time block not to exceed three hours. You may refer to manufacturer documentation and/or textbooks, but not to personal notes, while building your loop.

You are entirely responsible for figuring out how the process works and what you must do to control it, based on your inspection of it after it has been selected for you. This includes identifying the process variable, the final control element, any loads, instrument model numbers, and locating manufacturer's documentation for the instrumentation.

You may perform the assessment activity at any time in the quarter. Successful completion counts as the "mastery" portion of the course exam(s). There will be no grade penalty for repeated attempts, however successful completion of this activity is required to pass the course.

In addition to exhibiting a steady-state control in automatic mode (i.e. the process variable follows changes made to the setpoint and settles at or near the setpoint value without oscillation after some time), the process must also meet the following criteria based on courses you have completed:

- If you have passed or are currently taking the *INST241* course, your transmitter and controller must be properly configured to register the process variable (in engineering units, not percent) over a range specified by the instructor. Note: if the transmitter is analog rather than "smart," the instructor will have you determine its "As-Found" range and direct you to range the loop controller to match the transmitter rather than calibrate the analog transmitter to a specified range.
- If you have passed or are currently taking the *INST252* course, the controller must be tuned for robust response to perturbations (changes) in either setpoint or load as selected by the instructor at or near a setpoint value also specified by the instructor. "Robust" control is defined here as the controller compensating for perturbations as quickly as possible without creating any process variable oscillations (i.e. a *critically damped* response). It will be your decision to use P, I, D, or any combination thereof in the controller's tuning.
- If you have passed or are currently taking the *INST260* course, you must connect a data acquisition unit (DAQ) to record a variable in the process selected by the instructor and display a trend graph and/or a scaled representation of the measured variable on a personal computer networked to the DAQ. For example, if you are instructed to display the controller's output value using the DAQ, the display should register on a scale of 0% to 100% just like the controller's output is ranged from 0% to 100%. If the DAQ needs to show the process variable, it must register that variable in the same range as the transmitter. If your DAQ provides a trend graph, the vertical scale markings of that trend graph must be similarly ranged.

Given the time constraint of this assessment, you will not be required to cut and fit flexible conduit to the field instruments. All other wiring must be neatly installed so as to avoid creating safety hazards (tripping, etc.) and confusion for other students assembling their loops.

Limited availability of components and physical space in the lab means that only a few students will be able to work on this assessment at once, so plan on attempting this *well before* the final due date!

Bring a printed copy of this check-list with you when beginning the capstone assessment! Remember that you must work independently once the instructor assigns you a vest to wear. Any consultation with classmates, use of personal notes, or deviation from your approved diagram(s) will result in immediate disqualification, which means you must take everything apart and re-try the capstone assessment on a different process. Any damage done to the process or instrumentation will similarly result in disqualification, and you must repair the damage prior to re-trying the capstone assessment. You are allowed to use manufacturer documentation, as well as any documentation provided by the instructor (e.g. textbooks).

No teamwork is allowed while wearing the vest!

Selection	(Instructor writes/checks)
Instructor assigns a vest for you to wear	
Instructor selects a process for you to automate	
Instructor selects process variable range (<i>INST241 only</i>)	
Instructor selects setpoint/load & SP value (<i>INST252 only</i>)	@ SP =
Instructor selects DAQ variable to measure (<i>INST260 only</i>)	
Instructor selects controller – label with your name!	
Instructor verifies no wiring connected to the process	

The time clock starts now!

Start time: _____

Criterion	(Instructor verifies)
You sketch basic loop diagram – instructor verifies correctness	
You sketch DAQ connection diagram – instructor verifies correctness	

Now you may begin wiring and configuring the components

Criterion	(Instructor verifies)
Steady-state control in automatic mode	
Controller correctly registers the process variable (<i>INST241 only</i>)	
Controller responds robustly to perturbations (<i>INST252 only</i>)	
DAQ measurement correctly scaled and/or graphed (<i>INST260 only</i>)	

The time clock stops now!

Stop time: _____

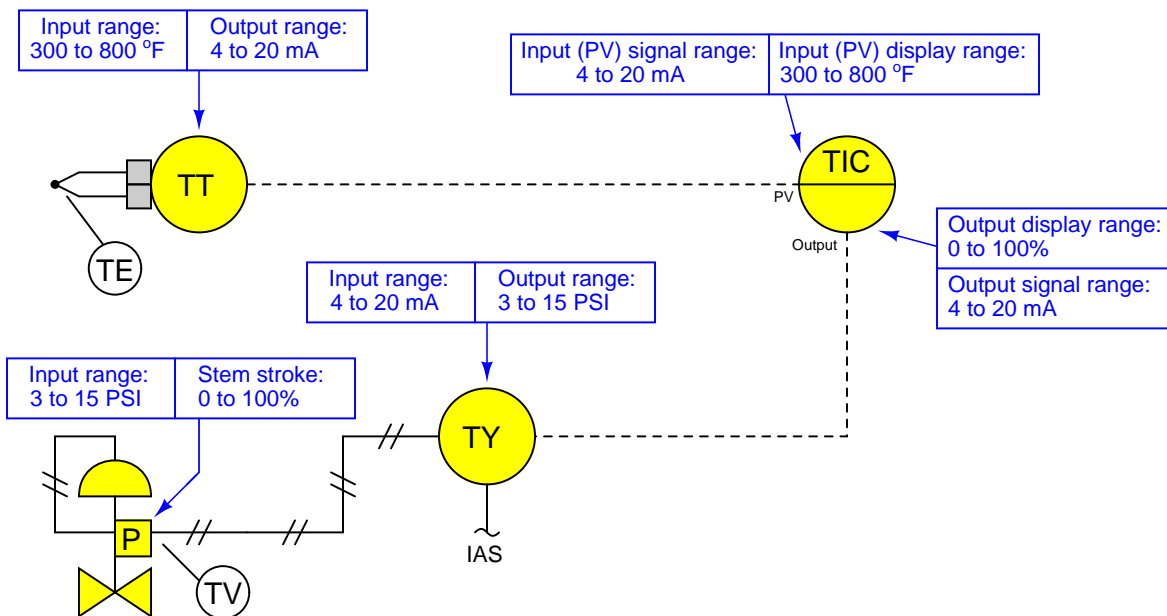
Criterion	(Instructor verifies)
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

Your mastery score will not be recorded until all steps are complete!

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 °F and output 20 mA when sensing 800 °F, but the controller must display an indication of 300 °F when it receives a 4 mA signal from the transmitter, and display an indication of 800 °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 °F input (and 4-20 mA output) as well as range the controller to display 300-800 °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.

Notes on instrument ranging (continued)

- 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 not 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*

Notes on instrument ranging (continued)

- 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

Notes on controller action (continued)

- 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.

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Here is are two important principles to bear in mind whenever you are examining trend graphs:

(1) When a controller is in *automatic* mode, its output signal is a function of its PV and SP signals. Therefore, a closed-loop (automatic) trend is useful for identifying characteristics of the *controller*. Simply put, you can tell how the controller behaves by watching how the Output responds to changes in PV and/or SP.

(2) When a controller is in *manual* mode, its output signal is solely determined by the human operator, as the controller completely ignores both PV and SP signals. Without a controller responding to changes in PV or SP, an open-loop PV trend is strictly a function of process dynamics (i.e. the physics of the process being monitored). Therefore, an open-loop (manual) trend is useful only for identifying characteristics of the *process*, not characteristics of the controller. Simply put, you can tell how the process behaves by watching how the PV responds to changes in Output.

This distinction between closed-loop and open-loop trends is vitally important for instrumentation professionals to grasp. It is analogous to identifying a pneumatic mechanism as being either force-balance or motion-balance before proceeding with any analysis of gain or calibration adjustments: if you err in the first determination, you will certainly err in your subsequent analysis.

A striking demonstration of the importance of this distinction is in how we interpret the direction of action within these two trend graphs. Note how in the closed-loop trend, reverse controller action is clearly revealed: as the PV increases, the Output decreases. However, when we switch the same controller into manual mode and perform an open-loop trend, we see the PV changing *in the same direction* as the Output. The open-loop test is revealing to us that the *process* responds directly to changes in the final control element's state.

If you imagine a process such as liquid flow control, where a further-open control valve results in more flow (e.g. greater Output signal results in greater PV while in manual mode), it is clear to see that the controller *must* be configured for reverse action if there is any hope for it to regulate the flow.

Answer 6

Alternatively, you may run this free software on your own computer if you have the Linux operating system running on it. You will need to install the caSCADA source code package, as well as the `ncurses` programming library, then compile the `looptune` executable by running `make` at the command prompt from within the caSCADA directory.

Additional notes on using SSH to remotely log into a computer running the Linux operating system appear on the following page.

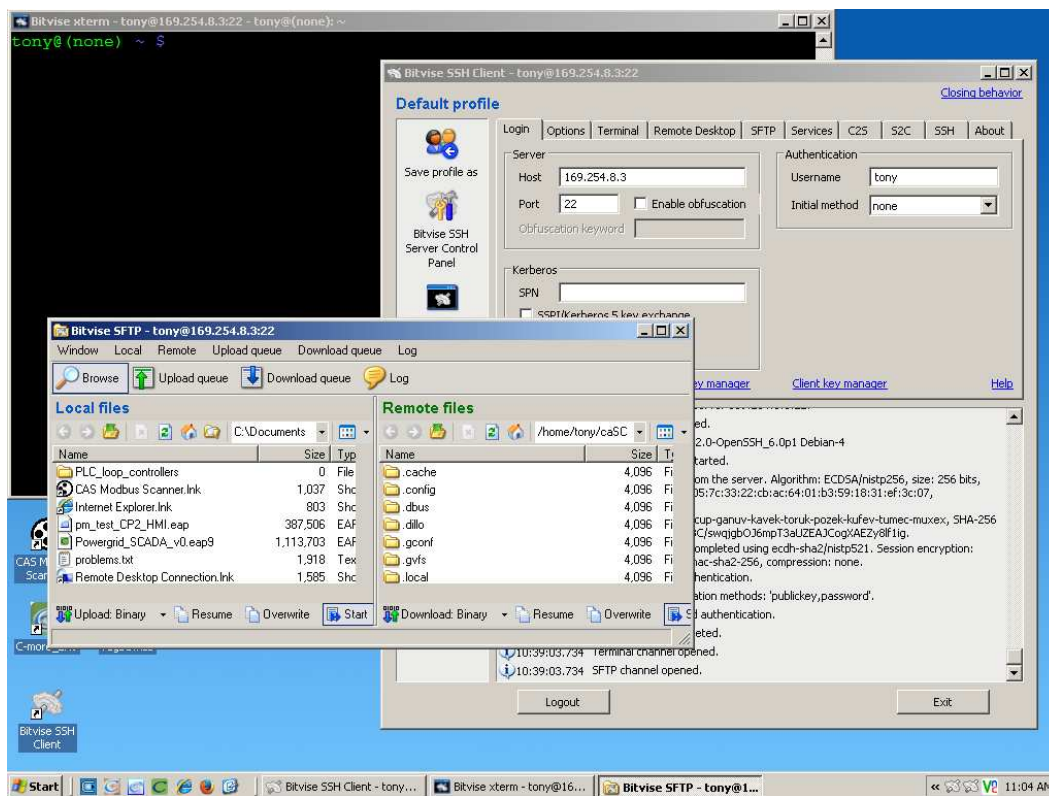
Notes on using SSH for remote administration

Each caSCADA RTU is based on single-board computer running Linux operating system software, located inside an electrical enclosure without convenient physical access. Attaching a keyboard and monitor is impractical, therefore you will need to log in to this computer through some other means.

Fortunately, a digital communication protocol has been developed to permit remote access of Unix-based operating systems called *SSH*, which stands for *Secure SHell*. Any computer running an SSH client program is able to log into any Linux computer running an SSH server program. Any personal computers running a Unix-based operating system (e.g. FreeBSD, Linux, Apple's OS X) have SSH clients built in.

Microsoft Windows operating systems do not have native SSH client software, but one available for free download is **Bitvise**. Another one is called PuTTY. For the really ambitious there is even a complete Linux terminal emulation package for Microsoft Windows called Cygwin. Any of these programs will suffice, but the easiest to download, install, and use is **Bitvise**. Be sure you download and install the *client* software for **Bitvise**, and not the *server* software (which should already be installed and running on the single-board Linux computer)!

The following screenshot shows **Bitvise** running on a Windows XP machine, communicating with a model of single-board computer called a "Raspberry Pi":



Three windows appear in this screenshot: the **Bitvise** client through which the login connection is established (you must enter the RTU computer's IP address and Linux user name, then later enter the Linux password for that user account), the **Bitvise** SFTP window for file transfer between the two computers, and the **xterm** terminal window (the one with the black background and colorful prompt) where you may enter typed commands to the RTU computer. Since Linux is a multi-user operating system, many people can log into the RTU using their own individual Windows PCs, even under the same user name! All you need is a network connection to the RTU and its IP network address.

Answer 7

Answer 8

Answer 9

Temperature rise (ΔT) is a *self-regulating* variable with respect to air flow as the independent variable. The reason for this comes from a direct analysis of the given formula:

$$\frac{dQ}{dt} = \frac{dm}{dt} c \Delta T$$

For any given amount of solar influx ($\frac{dQ}{dt}$) and any given mass flow rate ($\frac{dm}{dt}$), the ΔT is a predictable value, since c is constant. This means the process must be self-regulating, seeking a new ΔT value *on its own* for any new flow rate or for any new solar influx.

Answer 10

There is reason to believe the low pressure is real, because the two pressure readings agree with each other. This means the problem – whatever it is – is not in the transmitter (PT-45) or in the controller input, but is most likely in the final control element side of the loop.

PSV-14 is a pressure safety valve providing over-pressure protection for the accumulator vessel, but it is unlikely to be the source of trouble. If PSV-14 were “lifting” when it should not be (at this low of pressure!), the noise it would be making would be quite substantial and likely to attract the attention of the field operator who knows well what the process should sound like.

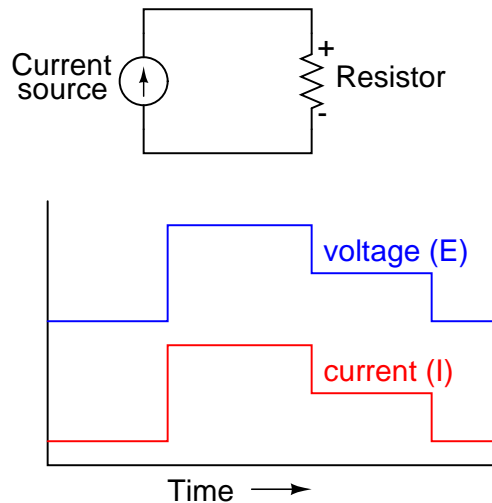
Answer 11

A *resistive* (“self-regulating”) process is one where changes in the manipulated variable result in proportional changes to the process variable. In other words, if the manipulated variable “steps” by a certain amount, the process variable will also “step” by a certain amount (although this “step” response may not necessarily be immediate).

An example of a resistive process is a liquid flow control system. Step-changes in valve position result in proportional step-changes to the flow rate.

Resistive processes are inherently stable. So long as the manipulated variable and “load(s)” on the process remain steady, the process variable will naturally stabilize at some point.

Consider the response of a resistor to a changing current through it:



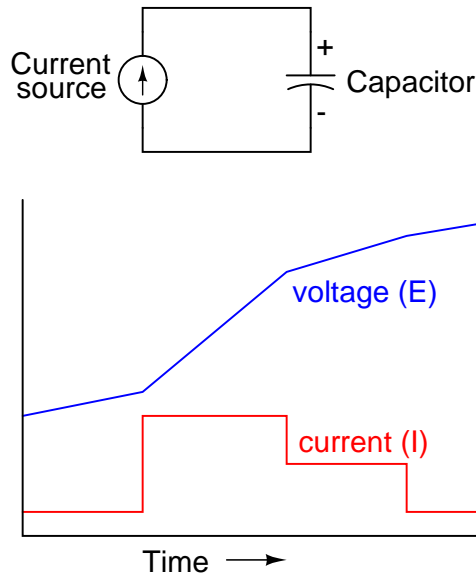
A *capacitive* (“integrating”) process is one where changes in the manipulated variable result in proportional changes to the process variable’s *rate-of-change* over time. In other words, if the manipulated variable “steps” by a certain amount, the process variable will alter its rate-of-change over time.

An example of a capacitive process is a liquid level control system. Step-changes in valve position result in changes to the *rate* of level change over time.

Capacitive processes are inherently *unstable*. The process variable will stabilize if and only if the manipulated variable precisely matches the process load(s), since the process variable is a function of the integral of the difference between process input and process output.

It should be noted that most real processes exhibit a combination of “resistive” and “capacitive” tendencies, but that often one of these characteristics predominates over the other.

Consider the response of a capacitor to a changing current through it:



Answer 12

The time constant of an RC circuit is the amount of time it takes for voltage or current in the circuit to change by 63.2% from its initial (starting) value to its ultimate (final) value. In an RC circuit, the time constant (τ) may be calculated by multiplying resistance in ohms by capacitance in Farads, for an answer in units of seconds.

Answer 13

The time constant of a process is the amount of time it takes for the process variable to change by 63.2% from its initial value to its ultimate value, following a “step-change” in the final control element or any “load” in the process affecting the measured variable.

Answer 14

The classic example of a “runaway” process is position control on an *inverted pendulum* mechanism. I will let you research what an “inverted pendulum” is and describe for yourself what characterizes a runaway process.

Answer 15

The automobile with “sensitive” steering has the greater process gain. As always, the “gain” of a system is a ratio of its output change to its input change ($\frac{\Delta \text{Out}}{\Delta \text{In}}$, or $\frac{d\text{Out}}{d\text{In}}$), and process gain is no exception.

Answer 16

Reducing the differential pressure drop across the valve will result in less flow when the valve is fully open. Of course, the flow rate will still be zero when the valve is fully closed. This means that the controllable flow *range* has been decreased as a result of decreased pressure drop across the valve.

With less of a controllable flow range, the flow will not change as much as it did before given the same change in valve position. That is to say, the process variable in this control system will be less sensitive to changes in valve position than before. In other words, we are faced with a *decreased* process gain.

Given a larger valve, the process gain will *increase*, because greater changes in flow rate will result from the same changes in valve position with a valve of greater size.

Technically speaking, the gain of the valve (ratio of valve coefficient, or C_v , versus position change) is a separate variable from the gain of the process itself (ratio of flow rate versus valve coefficient), and this is separate from the gain of the sensor (ratio of transmitter output percentage versus flow rate). However, here I use the term “process gain” to refer to the sensitivity of the whole control system, except the controller (the process vessels and piping, control valve, and flow transmitter).

Given a flow transmitter with a smaller range, the process gain will *increase*, because the same changes in valve position will now result in greater *percentage* changes in the transmitter output.

Answer 17

This is a *self-regulating* process. We know this because the process variable (PV) quickly reaches a point of equilibrium following a perturbation of the controller output.

Answer 18

The liquid level inside the vessel will drift either up or down (depending on which pump moves more liquid) at a rate determined by the differential liquid flow ($Q_{in} - Q_{out}$). This makes it an *integrating* process.

Integrating processes are characterized by the capacity to experience persistent mass and/or energy imbalances, where the out-flow of mass and/or energy does not naturally reach equilibrium the in-flow over time. Self-regulating processes, by contrast, naturally equalize their mass and energy balances as the process variable changes.

Answer 19

The water flow rate will very quickly decrease, settling at a new (lower) amount of flow. This makes it a *self-regulating* process.

Answer 20

The level inside the hopper will drift either up or down (depending on which conveyor moves more material) at a rate determined by the differential material flow ($Q_{in} - Q_{out}$). This makes it an *integrating* process.

Integrating processes are characterized by the capacity to experience persistent mass and/or energy imbalances, where the out-flow of mass and/or energy does not naturally reach equilibrium the in-flow over time. Self-regulating processes, by contrast, naturally equalize their mass and energy balances as the process variable changes.

Answer 21

Answer 22

Answer 23

Answer 24

Answer 25

Answer 26

Answer 27

The problem is clearly on the measurement side of this control loop: the controller (for whatever reason) is not “seeing” the change in DP across the compressor as quickly as it should. I will leave it to you to determine how to isolate the problem.

Hint: *use your multimeter!*

Answer 28

What you see here is the infamous *slip-stick* cycle, caused by hysteresis in the valve mechanism. The control valve in this process, most likely due to excessive friction in the packing, tends to “stick” in certain positions and only move when enough air pressure on the diaphragm accumulates due to the controller’s integral action. When the valve finally “slips,” the flow then moves to a new value opposite the setpoint, and the integral action winds in the opposite direction.

The technician’s “de-tuning” of the controller will not correct the problem, because the problem lies in the valve and not the controller. Reducing the integral action’s aggressiveness will merely increase the period of the oscillation.

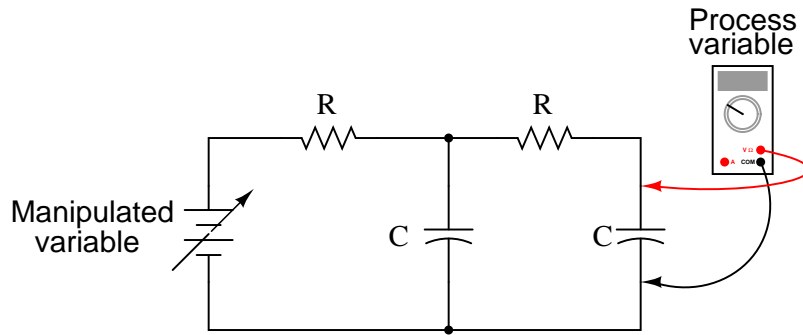
It is important to understand that no amount of creative tuning will fix a fundamental defect in the control system hardware. While “de-tuning” may make a problem appear less significant than it is, the problem still remains. Perhaps the most serious consequence of “de-tuning” is sluggishness in response to setpoint and load changes.

Answer 29

A first-order process is one having a single mode of storage (either of energy or of matter) and “resistive” element limiting the rate at which the storage element may be filled or unfilled. This leads to behavior like that of a simple RC circuit. In fact, first-order processes may be electrically simulated using nothing but a single capacitor and a single resistor.

Answer 30

A second-order process is essentially two first-order processes in sequence: it has two modes of energy/mass storage and two “resistances,” leading to a response that is more sluggish than a first-order process.



The mass has thermal “capacitance” in that it stores heat energy, and the insulating box enclosing the mass offers “resistance” to the flow of heat energy to or from the mass. This mass-in-box system comprises one order of dynamic lag. The oven itself, with its own mass (metal shell) and insulation (air space within), comprises the second order of dynamic lag, making this a second-order system.

Answer 32

This is an *integrating* process. We know this because the process variable (PV) does not reach equilibrium after the output perturbation. Rather, it “integrates” onward to full-scale saturation over time, with little sign of stabilizing.

Answer 33

Self-regulating processes are naturally stable when their controllers are left in manual. Integrating processes are naturally *unstable*, and require the supervisory action of a controller in order to achieve equilibrium.

This is not to say that self-regulating processes are without need of a controller. Controllers in any type of process are necessary to maintain *precise* control of the process variable (PV) close to setpoint (SP). A self-regulating process without a controller may achieve equilibrium on its own, but that point of equilibrium may or may not be anywhere near setpoint!

The reason integrating processes are naturally unstable is due to the requirement of balanced loads (input and output) to achieve equilibrium. A self-regulating process tends to naturally balance its loads when something changes, due to the physics of the process alone. Integrating processes have no inherent mode of self-balance, and thus will eventually “saturate” if all loads are not balanced by an external control system.

A purely integrating process ideally requires no integral action from the controller at all. This is because a single controller output value is capable of maintaining the process variable stable at any given value (at least with a constant load). In other words, PV equilibrium may be achieved at any point along the PV range with just a single output value.

Proportional-only control provides this functionality: outputting the same (bias) value when SP and PV are equal, regardless of the absolute value of the PV. If SP does not equal PV, the proportional-only controller output will be something other than the bias value, and the process will “integrate” up or down until $PV = SP$ again. Once the PV has attained the new SP, the controller output will be equal to the bias value again, balancing input and output in the process and holding the PV steady. In a manner of speaking, the process itself provides all the necessary integral action lacking in the controller to counter offset. In such a process, integral action would only be needed to adjust for changes in load.

In a self-regulating process, integral action is necessary for the controller to minimize error following either a setpoint or a load change, because each point of PV equilibrium requires a different output value. A proportional-only algorithm will almost always suffer offset when used in a self-regulating process, because the single bias value (output value when $PV = SP$) will be sufficient to achieve PV equilibrium for only one SP value (for any given load). Any SP value other than that one “magic” value will result in proportional-only offset, unless integral action is provided to “reset” the controller’s action to a new equilibrium point.

To summarize, integrating processes are capable of being (ideally) controlled with proportional action only. Self-regulating processes require integral action in order to avoid proportional-only offset.

Answer 34

Answer 35

Answer 36

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

This is definitely a self-regulating process with an overall process gain (including instruments) of about 2. The fact that it is self-regulating suggests it may be primarily controlled by integral action. The fact that it is relatively fast-acting suggests it may tolerate rather aggressive integral action. This same fact suggests derivative action would *not* do much good.

The reason new students commit the error of interpreting a trend such as this as an indication of *controller* proportional action is because they do not recognize the significance of the controller being in manual mode rather than automatic mode. In manual mode as we see here (revealed as such by the long, flat periods of the output signal despite changes in PV), what the trend reveals to us are the characteristics of the *process* itself, not of the *controller*. What students are accustomed to seeing is a matched-shape response between PV and output being indicative of proportional action *in a controller that is in automatic mode, actively trying to control a process*. Here, where any automatic control action has been disabled, the response of the PV to any change in output is revealing to us how the process actually responds to the valve. Thus, a trend where PV steps up in a manner similar to the output step-change, we know that the *process* has a self-regulating characteristic, but we don't know anything yet about how the controller happens to be set up for automatic mode.

Answer 45

The amount of dead time is enormous, compared to the time constant and reaction rate. Possible sources include *transport delay* in the process and/or valve stiction combined with insufficient air flow to the (pneumatic) actuator.

Answer 46

This is an *integrating* process, and as such it should respond well to aggressive proportional action.

The ramping we see in the PV following the output step-change tells us absolutely nothing about the status of the controller, but rather how the process itself happens to react to changes in its stimulus (the FCE). The mistake of interpreting open-loop (manual mode) tests as indicators of controller action is based on the person not noticing or appreciating the fact that the controller is in manual mode. In manual mode, the response we see in the PV following the output signal change is due entirely to the physics of the process, not the programming of the controller.

Answer 47

This is a self-regulating process with about half a minute of lag time and just a bit of dead time.

Aggressive integral action should be avoided, however some integral action will be necessary to avoid proportional-only offset. This process is a good candidate for some derivative control action (so long as the noise is not too severe), as derivative tends to cancel out first-order lag.

Answer 48

This is a self-regulating process with a variable gain. The variation in gain means that no one set of PID settings will be adequate for robust, stable control across the measurement range. You may be able to tune the controller for good response at one setpoint, but not for a wide range of setpoints. This problem must be fixed before there will be any hope of tuning it well.

Answer 49

This is definitely an *integrating* process, and as such it would normally respond well to aggressive proportional action. However, with all the noise present, proportional action will cause the control valve to “jump” noisily as well, prematurely wearing out its packing and consuming a lot of instrument air in the process!

Probably the best way to minimize noise in the process measurement is to equip the ultrasonic level transmitter with a *stilling well*.

Answer 50

Answer 51

Process noise affects P and D control modes, but not I.

Answer 52

This is an integrating process with a strange characteristic near the beginning of the step. Unless the initial “up” response was merely a coincidental load change, it means this process exhibits a *negative lead* characteristic. This is a fancy way of saying that the process initially moves in the “wrong” direction before correcting itself and moving the “right” way.

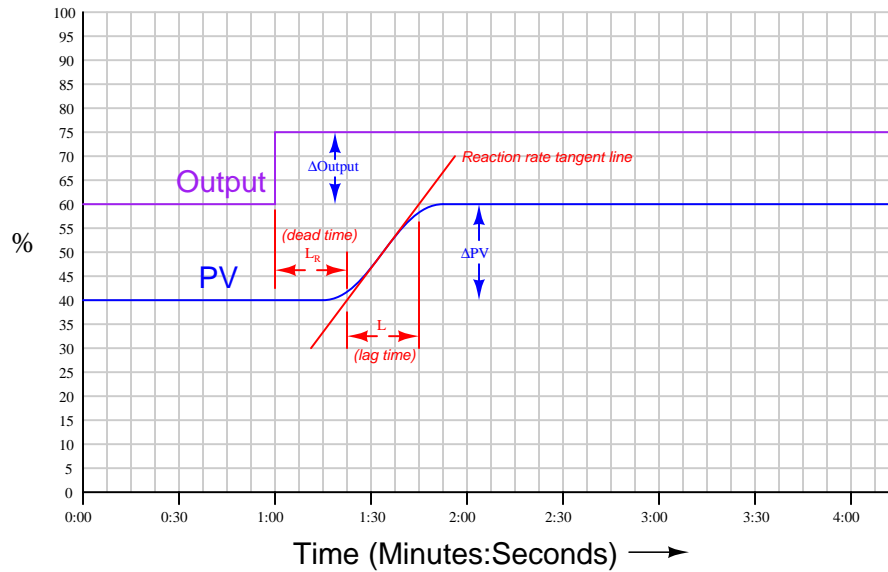
Processes such as this should be tuned for slow response, treating the negative lead period as though it were *dead time*.

Answer 53

Here are a few:

- Noise in the process variable signal
- Stiction in the control valve
- Slow control valve response
- Transport time in the process
- Wrong control valve characteristic (linear vs. quick-opening vs. equal percent)
- Nonlinear process gain
- Slow controller update time (compared to process reaction rate)

I’ll let you determine how to fix these problems to improve control quality!



- Steady-state gain (K) = 1.333
- Dead time (L_R) = 0.375 minutes
- Reaction rate (R_R) = 3.556% / unit-minute

Note: the unit of “unit-minute” for reaction rate refers to reaction rate corrected for percentage of output step. In other words, this is not the raw reaction rate figure, but rather the reaction rate per percent of output step.

Ideally, there will be minimal effect on the apparent dead time (L_R) of the process, since such “transport delays” are usually unrelated to the manipulated variable.

The reaction rate (R_R) will also (ideally) remain constant. Although the slope of the tangent line to the point of inflection on the PV curve will be steeper, this increase in steepness should be proportional to the increase in output step-change, resulting in an R_R figure that is the same as with a lesser output step-change.

Of course, if the process gain changes throughout the PV range, then the reaction rate (R_R) will be affected by an increase in output step-change.

$$\tau = 0.375 \text{ minutes (approximately)}$$

- Which controller would you tune first, or does it matter? *You should definitely tune TIC-1 before TIC-2, and TIC-2 before TIC-3. If you don't, then poor tuning in an upstream controller may present an unstable load to downstream controllers, thus complicating your tuning efforts.*
- Do you suspect these zones will be *self-regulating, integrating, or runaway* processes? *They should be self-regulating, with a long (slow) first-order time constant.*
- Should these controllers be tuned P-dominant or I-dominant? Explain your reasoning. *The tuning will most likely be P-dominant, as a purely first-order lag process should respond very well to aggressive controller action, and the large mass of liquid makes "noise" in the PV signal unlikely.*
- What precautions, if any, would you need to take when tuning these controllers? Are there any safety considerations we would need to be aware of before beginning the tuning procedure? *This is a fairly safe process to tune. No amount of temperature swing capable from engine coolant as the heat source will cause the slurry to become chemically or physically unstable. At worse, you might risk killing off the bacterial culture if the process remains much too hot for much too long, but this would require a severe temperature excursion.*
- Identify any *loads* in the process, and explain how you would adjust them in order to test the robustness of your controller tuning. *Influent flow rate is definitely one load, adjustable by the setpoint on FIC-4. Engine coolant temperature is another load, but this is harder to adjust since it is set by the engine's mechanical thermostat (these are normally non-adjustable).*
- Do you suppose the tuning parameters of TIC-1 will be much different from those used in TIC-3? Explain why or why not. *Probably not, unless the zones differ substantially in volume.*
- What process change(s) would be required in order for the anaerobic reaction to be self-sustaining in terms of heat, so that an external heat source would not be required to sustain its operation at around 100 °F? *Influent/effluent heat exchangers would be necessary to capture as much heat from the digested slurry as possible and put that heat into the incoming slurry, as well as lots of thermal insulation surrounding the digester vessel itself (to prevent heat loss). The major problem here is the sheer mass of water in the slurry, water having a high specific heat capacity. This requires a lot of heat energy in order to raise its temperature even by small amounts. If the incoming feed is at ambient temperature, the amount of heat necessary to raise the slurry's temperature to 100 °F will be likely much more than the amount of heat liberated by the digesting sugars, which means it will require "help" in the form of heat exchange with the hot effluent in order to achieve this temperature. Furthermore, even if all these measures were in place, the start-up time of such a process would be very long without some external heat source to get it going.*
- Suppose maintenance personnel had to enter the digester vessel to physically clean the heat-exchange "coils" of fouling. What personal safety precautions would they need to take before entering the vessel? *As the digester vessel is most definitely a "confined space," personnel would have to first flush it of all dangerous materials (including slurry), purge the space with fresh air, and check oxygen concentrations with a safety analyzer before entering. Once inside, a person standing outside with a safety rope would have to stand watch in case anyone were to become incapacitated for some reason inside the vessel.*

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

Answer 65

Answer 66

The “answers” can only be found by actually tuning a controller! It is recommended to review the results of your tuning with your instructor to grasp the significance of each process and its PID tuning requirements.

Answer 67

Answer 68

This is an example of a process with *interacting* control loops!

One could try placing the pressure controller in manual mode as well to see if this alters the flow loop’s response. If so, then we know the PIC played a role in the strange response. If not, then something in the flow loop is to blame.

Another test we could do is monitor the vessel pressure to see if it changes significantly during the flow open-loop test. If so, we have reason to believe the PIC loop is the source of the weird droop. If not, we should probably look toward the flow loop instrumentation as the source of the trouble (or see if there are any other interacting loops in the process we don’t see on this diagram!).

Answer 69

Processes having absolutely no dead time but significant lag time (i.e. pure *first-order lag*) processes tend to respond well to aggressive proportional control action. Also, integrating processes do as well, as strong proportional action in the controller allows the natural integrating action in the process to correct offset.

Processes having significant dead times can oscillate with proportional control action. Noisy processes don’t fare well with aggressive proportional action either because the gain transfers process noise directly to the manipulated variable where it wears out the control valve.

Answer 70

Fast, self-regulating processes tend to respond well to aggressive integral action. This is even true if the process in question has considerable noise (because integral ignores noise)!

Processes having significant lag time do not respond well to aggressive integral action at all.

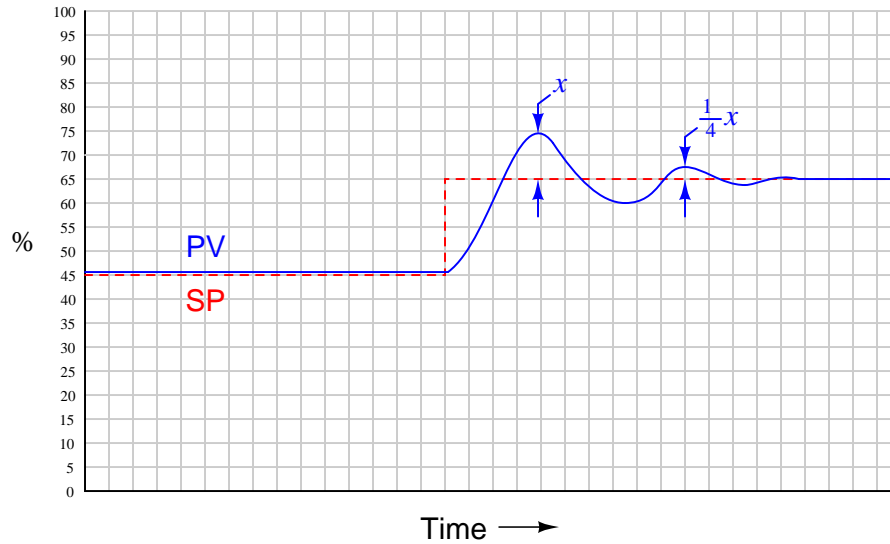
Answer 71

Slow processes having large first-order lags tend to respond well to aggressive derivative action.

Noisy and fast processes do not derivative action at all, neither do processes having large dead times.

Answer 72

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:



Quarter-amplitude damping means that the oscillations of process variable (PV) following a disturbance will decay, with each successive peak being $\frac{1}{4}$ the amplitude of the one before. This is considered by many to be a “baseline” standard for loop tuning, and not necessarily optimum. For many types of processes, oscillations of this nature would be unacceptable.

Answer 73

Starting with proportional, you would tend to make this term less aggressive because the controller needs to make smaller adjustments for larger dead times, since the controller is “running blind” during the dead time period, and large upsets in the process variable caused by excessive changes in the manipulated variable (output) will be more difficult to counteract.

That integral action should be less aggressive should be obvious. Since integral action integrates error accumulated over time, dead time will increase the amount of accumulation for any given amount of error, tending to make integral over-react. Think of it this way: integral action may be likened to *impatience* in the controller, and that last thing you want in a process with large dead time is an impatient controller!

There is a noteworthy exception to this rule, though, and that is for self-regulating processes dominated by dead time. Moderate integral action is surprisingly capable of controlling such a process, just as it is capable of controlling self-regulating processes with little dead time.

That derivative action should be less aggressive is not necessarily obvious. Derivative action looks at the rate of error change over time, taking action to limit how fast the PV may rise or fall. This type of “cautious” control action is normally very good in processes with large first-order lag times. However, when the *dead time* is large, excessive derivative action can cause oscillations due to the phase shift caused by the dead time.

In processes with little dead time, it is almost impossible to make the PV oscillate due to excessive derivative action. At most, excessive derivative action only causes the output (valve) to move around a lot. Given a large dead time, though, the action of derivative will be delayed in having effect on the PV, and thus will have the opportunity to react to its own changes where it otherwise would not.

As you can see by the necessary reduction for all three control modes, increased dead time means that feedback control (of any kind) becomes less and less useful.

Answer 74

Temperature processes are naturally slow to change, and so the presence of high-frequency noise is simply not possible in the actual process variable (temperature). Therefore, we know the noise must represent an equipment problem of some sort, causing a noisy PV *signal*.

Since a noisy electronic signal is really nothing more than *AC* superimposed on the DC signal, we may use any test equipment capable of measuring AC to track the location of the problem. Some modern digital multimeters are really good at discriminating between AC and DC in voltage and current measurements, meaning we can set one of these meters to measure AC and it will *only* register the noise within the signal, rejecting the DC component of the signal.

Therefore, a good test would be to use a DMM set to measure AC millivolts, and measure voltage signals at these points of the circuit:

- At the input terminals of TT-14 (to see if the thermocouple is picking up AC noise)
- Between either input terminal of TT-14 and earth ground (to see if the thermocouple is picking up common-mode AC noise)
- Between the (+) and (Gnd) terminals on the paperless chart recorder, to see if a noisy signal is present at the input of the recorder
- Across the terminals of the loop power supply, to see if it is noisy itself

Answer 75

Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

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

The only “answer” to this question is a properly documented and functioning instrument loop!