INST 262 (Digital Control Systems), section 2

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

Exam

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

Specific objectives for the "mastery" exam:

- Electricity Review: Calculate voltages, currents, powers and/or resistances in a DC series-parallel circuit
- Identify proper controller action (direct or reverse) for a given process
- Determine the effect of a component fault or condition change in an automatically-controlled process
- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table
- Solve for a specified variable in an algebraic formula
- 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: Sketch proper wire connections for sourcing or sinking PLC I/O points
- INST240 Review: Determine suitability of different level-measuring technologies for a given process fluid type
- INST251 Review: Identify the graphed response of a controller as being either P, I, or D

Recommended daily schedule

Day 1

Theory session topic: Instrument calibration

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

Day 2

Theory session topic: Instrument calibration (continued)

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

Day 3

Theory session topic: DCS and SCADA system security

Questions 41 through 60; <u>answer questions 41-46</u> in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Review for exam (site visit)

Questions 21 through 40; <u>answer questions 61-63</u> in preparation for discussion at an industrial site specified by your instructor. (All remaining questions for practice)

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

Day 5

Exam

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. <u>Download</u> and <u>save</u> 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: <u>Mastery exams</u> 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. <u>Proportional exams</u> 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 <u>all</u> 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.

<u>file howto</u>

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.

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 262 Course Outcomes

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

- Calculate voltages, currents, powers, and/or resistances in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]

- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]

- Identify proper controller action for a given process. [Ref: Program Learning Outcome #5]

- Predict the response of a single-loop control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]

- Determine proper AI block parameters to range a Fieldbus transmitter for a given application. [Ref: Program Learning Outcome #5]

- Use decibels to calculate power gains and losses. [Ref: Program Learning Outcome #4]

- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table. [Ref: Program Learning Outcome #7]

- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]

- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]

- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms. [Ref: Program Learning Outcome #4]

- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]

- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]

- Connect a loop controller to the electronic transmitter and final control element of a pre-constructed process, then commission all components to form a working feedback control loop. [Ref: Program Learning Outcome #5]

- Generate an accurate loop diagram compliant with ISA standards documenting your team's control system. [Ref: Program Learning Outcome #8]

- Commission and decommission a WirelessHART instrument. [Ref: Program Learning Outcome #5]

- Configure a digital indicator to poll instrument data via the Modbus/TCP protocol. [Ref: Program Learning Outcome #5]

- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Build a circuit to sense either pressure or vacuum using a differential pressure transmitter with HART

communication capability, reporting the sensed variable on an analog meter chosen by the instructor, setting the range values according to instructor specifications, capturing peak signal value using a digital multimeter, and capturing binary 0 and 1 bits using a digital oscilloscope. [Ref: Program Learning Outcome #5]

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

- Diagnose a random fault placed in another team's 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 #4]

file outcomes_INST262

Sequence of second-year Instrumentation courses

Core Electronics -- 3 qtrs
including MATH 141 (Precalculus 1)

(Only if 4th quarter was Summer: INST23x)

Prerequisite for all INST24x, INST25x, and INST26x courses

INST 200 -- 1 wk
Intro. to Instrumentation

Offered 1st week of Fall, Winter, and Spring quarters

Summer quarter

INST 233 -- 4 cr
Protective Relays *(elective)*

Jobshadow and/or Internship strongly recommended

Fall quarter

INST 240 -- 6 cr
Pressure/Level Measurement

INST 241 -- 6 cr
Temp./Flow Measurement

INST 242 -- 5 cr
Analytical Measurement

Winter quarter

INST 250 -- 5 cr
Final Control Elements

INST 251 -- 5 cr
PID Control

INST 252 -- 4 cr
Loop Tuning

Spring quarter

INST 260 -- 4 cr
Data Acquisition Systems

INST 262 -- 5 cr
Digital Control Systems

INST 263 -- 5 cr
Control Strategies

ENGT 134 -- 5 cr
CAD 1: Basics

Prerequisite for INST206

All courses completed? **No** **Yes**

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

Offered 1st week of Fall, Winter, and Spring quarters

Graduate!!!

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

Beginning in Summer

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 205 -- 1 cr — Job Prep I
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 206 -- 1 cr — Job Prep II
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

Graduation!

Beginning in Fall

Fall quarter (Sept. – Dec.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 205 -- 1 cr — Job Prep I
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 206 -- 1 cr — Job Prep II
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Graduation!

Beginning in Winter

Winter quarter (Jan. – Mar.)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Spring quarter (April – June)
- INST 205 -- 1 cr — Job Prep I
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 206 -- 1 cr — Job Prep II
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Graduation!

Beginning in Spring

Spring quarter (April – June)
- INST 200 -- 1 wk — Intro. to Instrumentation
- INST 260 -- 4 cr — Data Acquisition Systems
- INST 262 -- 5 cr — Digital Control Systems
- INST 263 -- 5 cr — Control Strategies
- ENGT 134 -- 5 cr — CAD 1: Basics

Summer quarter (July – Aug.)
- INST 233 -- 4 cr — Protective Relays (elective)
- Jobshadow and/or Internship strongly recommended

Fall quarter (Sept. – Dec.)
- INST 205 -- 1 cr — Job Prep I
- INST 240 -- 6 cr — Pressure/Level Measurement
- INST 241 -- 6 cr — Temp./Flow Measurement
- INST 242 -- 5 cr — Analytical Measurement

Winter quarter (Jan. – Mar.)
- INST 206 -- 1 cr — Job Prep II
- INST 250 -- 5 cr — Final Control Elements
- INST 251 -- 5 cr — PID Control
- INST 252 -- 4 cr — Loop Tuning

Graduation!

file sequence

General tool and supply list

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

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

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

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

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

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

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

file `tools`

Methods of instruction

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

Inverted theory sessions

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

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

Small sessions

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

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

Large sessions

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

Correspondence

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

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

Sample rubric for pre-assessments

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

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

Sample rubric for post-assessments

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

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

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.

<u>file `instructional`</u>

Distance delivery methods

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

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

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

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

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

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

file distance

Metric prefixes and conversion constants

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

METRIC PREFIX SCALE

T	G	M	k		m	μ	n	p
tera	giga	mega	kilo	(none)	milli	micro	nano	pico
10^{12}	10^9	10^6	10^3	10^0	10^{-3}	10^{-6}	10^{-9}	10^{-12}

10^2	10^1	10^{-1}	10^{-2}
hecto	deca	deci	centi
h	da	d	c

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

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

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

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

Conversion equivalencies for velocity

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

Conversion equivalencies for mass

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

Conversion equivalencies for force

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

Conversion equivalencies for area

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

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

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

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

Conversion equivalencies for absolute pressure units (only)

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

Conversion equivalencies for energy or work

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

Conversion equivalencies for power

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

Acceleration of gravity (free fall), Earth standard

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

Physical constants

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

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

Electronic charge $(e) = 1.602 \times 10^{-19}$ Coulomb (C)

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

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

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

Properties of Water

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

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

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

Specific heat of water at $14^oC = 1.00002$ calories/g$\cdot^oC = 1$ BTU/lb$\cdot^oF = 4.1869$ Joules/g$\cdot^oC$

Specific heat of ice ≈ 0.5 calories/g$\cdot^oC$

Specific heat of steam ≈ 0.48 calories/g$\cdot^oC$

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

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

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

Properties of Dry Air at sea level

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

Absolute viscosity of dry air at 20^oC and 760 torr $= 0.018$ centipoise (cp) $= 1.8 \times 10^{-5}$ Pascal-seconds (Pa$\cdot$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: <u>reading</u> provides the learner with knowledge, <u>writing</u> focuses the learner's thoughts, and <u>critical dialogue</u> 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 <u>all</u> 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 <u>any</u> 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

- <u>Summarize</u> 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 <u>intelligent child</u>: as simple as you can without compromising too much accuracy.
- <u>Simplify</u> 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 <u>make the most sense</u> to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to <u>misunderstand the text</u>, and explain why you think it could be confusing.
- Identify any <u>new concept(s)</u> presented in the text, and explain in your own words.
- Identify any <u>familiar concept(s)</u> such as physical laws or principles applied or referenced in the text.
- Devise a <u>proof of concept</u> experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to <u>disprove</u> a plausible misconception.
- Did the text reveal any <u>misconceptions</u> 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 <u>problem-solving strategies</u> applied in the text.
- <u>Devise a question</u> of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any <u>fundamental laws or principles</u> apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a <u>thought experiment</u> to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own <u>strategy</u> 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 <u>more than one way</u> to solve this problem? Which method seems best to you?
- <u>Show the work</u> you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the <u>most challenging part</u> of this problem, and why was it so?
- Was any important information <u>missing</u> from the problem which you had to research or recall?
- Was there any <u>extraneous</u> information presented within this problem? If so, what was it and why did it not matter?
- Examine <u>someone else's solution</u> to identify where they applied fundamental laws or principles.
- <u>Simplify</u> 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 <u>limiting case</u> (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the <u>real-world meaning</u> of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it <u>qualitatively</u> instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it <u>quantitatively</u> instead, proposing simple numerical values for the variables.
- Were there any <u>assumptions</u> 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 <u>go astray</u> in attempting to solve this problem.
- <u>Formulate your own problem</u> based on what you learned solving this one.

file `license`

Question 1

Read and outline the "Zero and Span Adjustments (Analog Instruments)" section of the "Instrument Calibration" 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 i03903

Question 2

Read and outline the "Calibration Errors and Testing" section of the "Instrument Calibration" 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 i03908

Question 3

Read and outline the "Damping Adjustments" section of the "Instrument Calibration" 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 i03904

Question 4

Read and outline the "LRV and URV Settings, Digital Trim (Digital Transmitters)" section of the "Instrument Calibration" 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 i03905

Question 5

Read the "An Analogy for Calibration versus Ranging" section of the "Instrument Calibration" 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 i03907

Question 6

Read and outline the "Calibration Procedures" section of the "Instrument Calibration" 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 i03906

Question 7

A "smart" (digital) DP pressure transmitter is removed from service and taken to a calibration bench for testing. A technician connects a precision pressure gauge and air source to the transmitter's high port while monitoring the 4-20 mA output signal using a DMM:
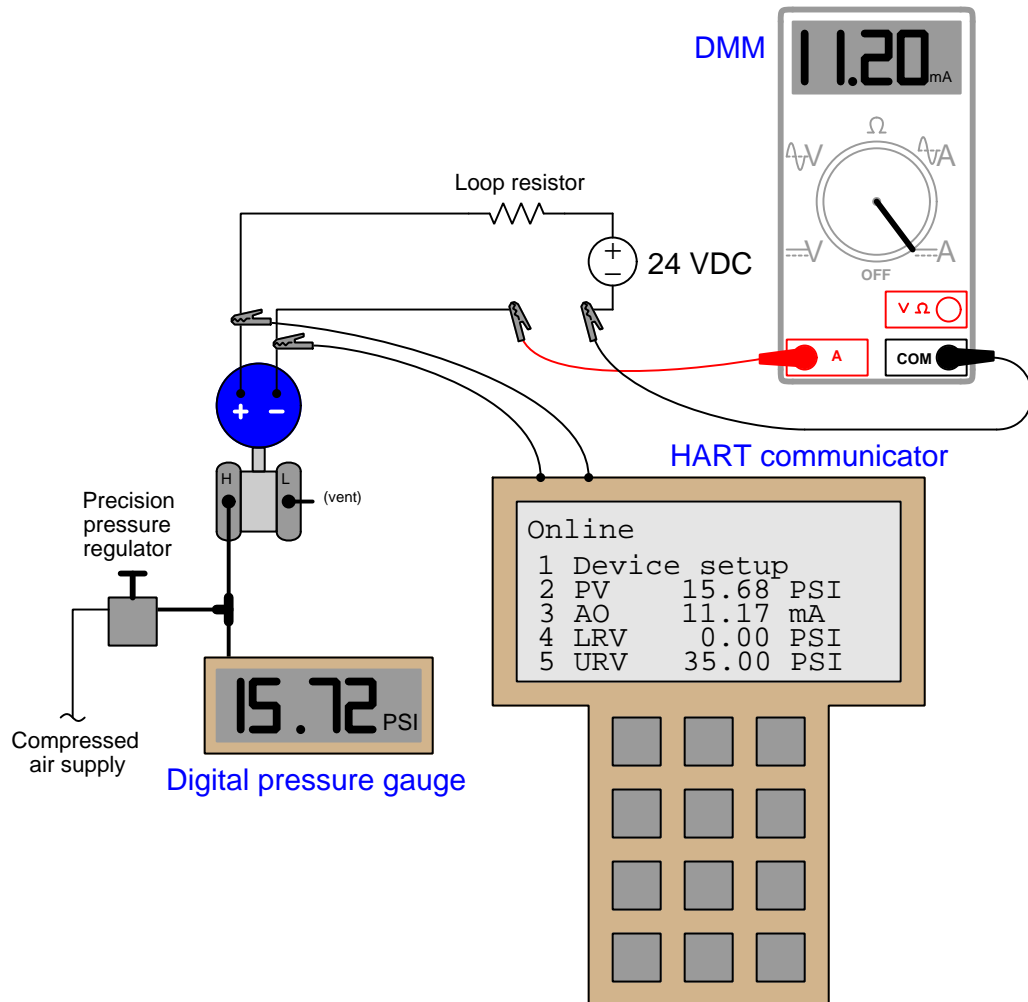

Does this transmitter exhibit a *sensor trim* error, an *output trim* error, or both? If both errors exist, which of the two is more significant?

| Suggestions for Socratic discussion |

- What other possible sources of error besides the transmitter could account for these discrepancies?
- Suppose another instrument technician suggests to you that a problem within the precision air pressure regulator might account for some (or all!) of the calibration error seen in the data, and that we should replace the regulator with another. How would you respond to this suggestion?
- Suppose another instrument technician suggests to you that a problem within the loop resistor might account for some (or all!) of the calibration error seen in the data, and that we should replace the resistor with another. How would you respond to this suggestion?
- Does the HART communicator need to be NIST traceable? Why or why not?

Question 8

In this exercise, you will calibrate an *analog RTD transmitter*: a field instrument designed to sense the electrical resistance of an *RTD* (Resistive Temperature Detector) and output a corresponding 4-20 mA DC signal. To do this exercise, you will need a small flat-bladed screwdriver, a precision digital multimeter, and some alligator-clip style jumper wires. Your instructor will provide the RTD transmitter, terminal blocks, batteries, and a *decade resistance box* to use as a precision resistance standard. It is advised that each and every student bring their multimeter, as multiple meters are useful in this exercise:

Decade resistance box
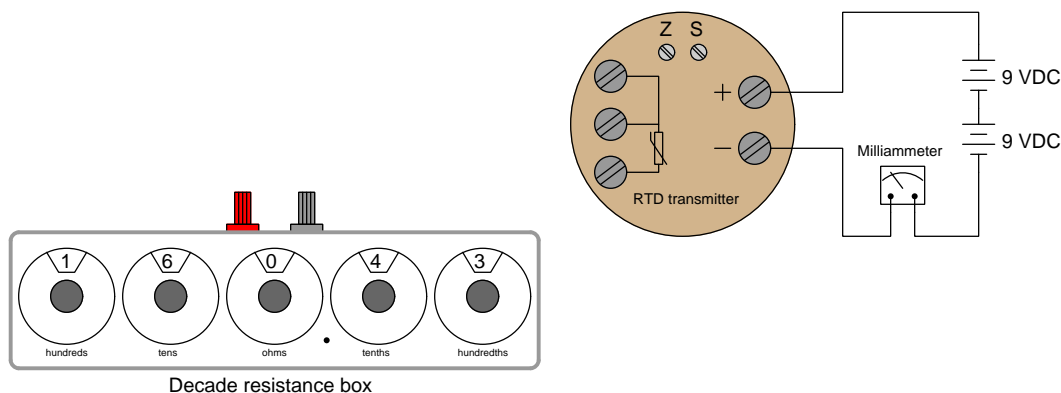
Your transmitter has a *zero adjustment potentiometer* as well as a *span adjustment potentiometer* allowing you to make calibration adjustments. Normally, you would use an RTD sensor to provide the input resistance to this transmitter, but for the purpose of a classroom exercise we will *simulate* the resistance of an RTD using a decade resistance box. Your task will be to check the calibration of this transmitter over an instructor-specified range to ensure it outputs 4 mA at the lower range value (LRV) and 20 mA at the upper range value (URV).

Your first step should be determining how to connect the decade box to the transmitter to simulate an RTD (a variable resistance). *Note that simply connecting the two terminals of the decade box to any two input terminals on the transmitter is incorrect!* Pay close attention to the symbols drawn on the transmitter near the input terminals – they show you how you must connect an RTD (and therefore your variable test resistance) to the transmitter. You must have your instructor verify your intended wire connections before powering the transmitter, in order to ensure the circuit will work properly and that the transmitter will not be damaged during the procedure.

Instructor checks wiring plan before power-up: _____

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Your instructor will provide you with the resistance range your transmitter is currently calibrated for:

- LRV (0% of range) = _____ Ω

- URV (100% of range) = _____ Ω

Simulate five points along this resistance measurement range, recording the transmitter's output in an *As-Found* calibration table. Calculate the error as a percentage of span (e.g. if the transmitter outputs 3.95 mA when it should output 4.00 mA, the error is −0.3125%):

Input (%)	Resistance (Ω)	Output (Ideal)	Output (As-Found)	Error (%)
0		4 mA		
25		8 mA		
50		12 mA		
75		16 mA		
100		20 mA		

$$\text{Error as \% of span} = \left(\frac{\text{Actual} - \text{Ideal}}{\text{Span}} \right) (100\%)$$

After recording the As-Found values, your instructor will provide you with new LRV and URV values for your calibration:

- LRV (0% of range) = _____ Ω

- URV (100% of range) = _____ Ω

Adjust the "zero" and "span" potentiometers of the transmitter as necessary to make it output 4 mA at the new LRV and 20 mA at the new URV.

After calibration, you will simulate five points along the new resistance measurement range specified by the instructor, recording the transmitter's output in an *As-Left* calibration table along with the calculated errors:

Input (%)	Resistance (Ω)	Output (Ideal)	Output (As-Left)	Error (%)
0		4 mA		
25		8 mA		
50		12 mA		
75		16 mA		
100		20 mA		

Feel free to use a computer spreadsheet to tabulate and graph the As-Found and As-Left results.

Suggestions for Socratic discussion

- Did your transmitter initially exhibit a *zero* error, a *span* error, and/or a *linearity* error?
- In general terms, how is a *zero* error revealed in a table of As-Found values?
- In general terms, how is a *span* error revealed in a table of As-Found values?
- In general terms, how is a *linearity* error revealed in a table of As-Found values?
- In general terms, how is a *hysteresis* error revealed in a table of As-Found values?
- Why is it important for an instrument technician to record both *As-Found* and *As-Left* results for an instrument being calibrated?

Question 9

Question 10

Question 11

Question 12

Question 13

Question 14

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Read and outline the "Instrument Turndown" section of the "Instrument Calibration" 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 i03909

Question 22

Read and outline the "NIST Traceability" section of the "Instrument Calibration" 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 i03910

Question 23

Identify the types of instrument calibration errors shown in these graphs:
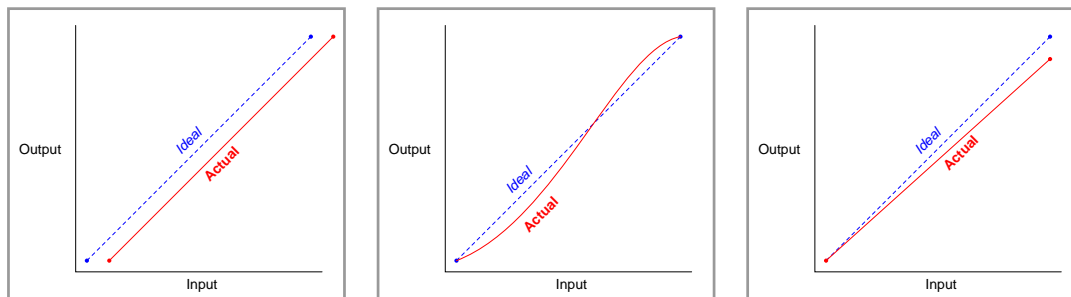
Suggestions for Socratic discussion

- Identify and sketch a calibration error other than the three represented here.
- For each of the calibration errors shown, identify whether the error would be *positive* or *negative* in sign.
- Explain how you may interpret any of these errors by inspection of tabulated numbers (i.e. without the benefit of a visual graph). What numerical patterns, specifically, would you look for when identifying a zero error, or a span error, or any other type of calibration error?

file i01036

29

Question 24

A "smart" (digital) DP pressure transmitter is removed from service and taken to a calibration bench for testing. A technician connects a precision pressure gauge and air source to the transmitter's high port while monitoring the 4-20 mA output signal using a DMM:
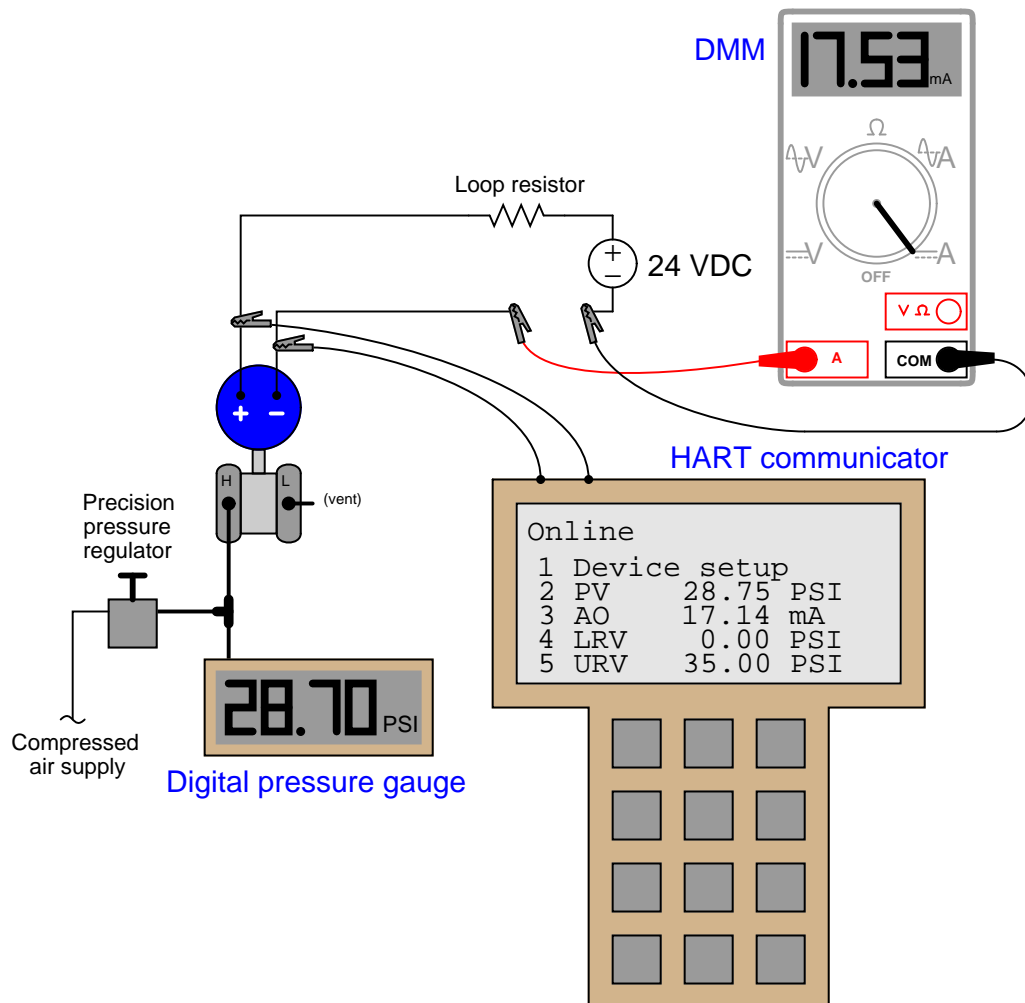
Calculate the amount of *sensor trim* error as well as the amount of *output trim* error, both expressed in percent of span. Also, explain why the HART communicator is necessary to be able to separately calculate these error values.

Suggestions for Socratic discussion

- What other possible sources of error besides the transmitter could account for these discrepancies?
- Suppose another instrument technician suggests to you that a problem within the precision air pressure regulator might account for some (or all!) of the calibration error seen in the data, and that we should replace the regulator with another. How would you respond to this suggestion?
- Suppose another instrument technician suggests to you that a problem within the loop resistor might account for some (or all!) of the calibration error seen in the data, and that we should replace the resistor with another. How would you respond to this suggestion?
- Does the HART communicator need to be NIST traceable? Why or why not?

Question 25

Read Fluke's *Transmitter Calibration with the Fluke 750 Series Documenting Process Calibrator* application note (document 3792201B A-EN-N, August 2011) and answer the following questions:

Identify the four different instrument calibration examples in this application note. Are any of these similar to an instrument calibration you have done?

Explain the advantage of using the "Auto Test" feature of the Fluke DPC to perform an instrument calibration, compared to performing a manual calibration test.

Explain why the fourth calibration example in this application note cannot be done using the "Auto Test" capability of the Fluke DPC.

When manually providing the input values for the instrument under test as is the case in the last calibration example, is it necessary for you to exactly settle at each test point? Explain why or why not.

| Suggestions for Socratic discussion |

- One of the Auto Test features not mentioned in this application note is the ability to perform an "Up/Down" test. Explain why this feature might be useful for certain calibration procedures, specifically identifying the sort of calibration error it would be intended to detect.
- Explain what would have to be different about the Fluke 750 series DPC in order for it to perform all the calibration tests described in automatic mode. In other words, devise a solution to the "manual-only" test option given in the fourth calibration example.

Question 26

Read Fluke's *Calibrating Pressure Switches with a DPC* application note (document 2069058B A-EN-N, July 2011) and answer the following questions:

Define "deadband" as used in this document with reference to a pressure switch, and explain why this is an important parameter for a process switch.

Explain why it is important to tell the DPC whether the setpoint type is "low" or "high".

Explain why a pressure switch calibration check cannot be done using the "Auto Test" capability of the Fluke DPC, but rather must be done using the "Manual Test" feature.

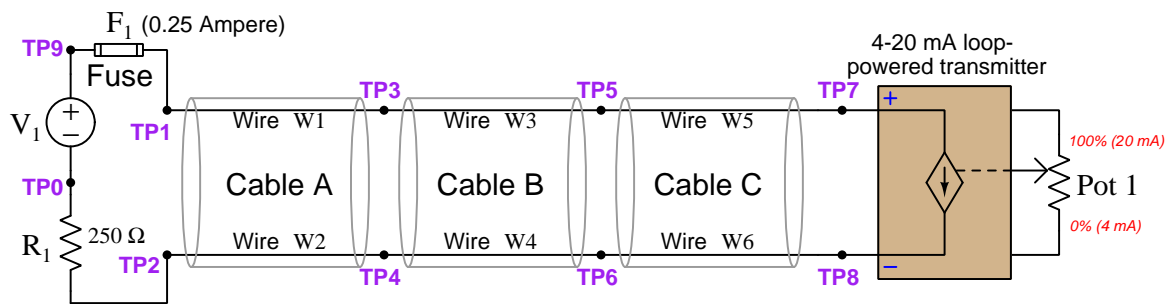| Suggestions for Socratic discussion |

- Explain why this document advises you to repeatedly cycle the test pressure past the set and reset switch states, instead of traversing those values just once.
- At the conclusion of the described test, the Fluke DPC displays both *setpoint error* and *deadband error* figures. Explain the meaning of each.
- Explain what would have to be different about the Fluke 750 series DPC in order for it to perform all the calibration tests described in automatic mode. In other words, devise a solution to the "manual-only" test option given in the fourth calibration example.

Question 27

Simulated troubleshooting exercise

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

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

Circuit #006

F_1 (0.25 Ampere)

TP9
Fuse
V_1
TP1
TP0
R_1 250 Ω
TP2

Wire W1   Wire W3   Wire W5
TP3   TP5   TP7
Cable A   Cable B   Cable C
Wire W2   Wire W4   Wire W6
TP4   TP6   TP8

4-20 mA loop-powered transmitter

Pot 1
100% (20 mA)
0% (4 mA)

Nominal component values:

$V_1 =$ _____ Volts +/- _____ %

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

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

file i02850

32

Question 28

The Fluke corporation sells a software product called *DPCTrack2* that may be downloaded and run for a free trial basis. Locate this software on the Fluke website (`http://www.fluke.com`) and download it to your PC so that you may experiment with it in class.

DPCTrack2 is used to upload calibration specifications to a process calibrator (e.g. the Fluke model 754) prior to instrument technicians performing a field or a bench calibration. After the calibration(s) have been completed, the calibrator is re-connected to the personal computer so the As-Found and As-Left calibration results may be downloaded to DPCTrack2 for archival. Thus, DPCTrack2 is useful for calibration *workload* management: ensuring all technicians have the information necessary to properly complete mission-critical field instrument calibrations, and ensuring all the calibration data gets properly archived.

In this exercise, you will enter data for a few instruments as they appear on the following P&ID. Choose any instruments you wish from the P&ID (choosing a few instruments bearing the same ISA "tag" or "loop" number would be best, because that would allow you to define a "Loop" in the DPCTrack software as well as the instruments themselves), giving yourself license to invent realistic calibration ranges for each of them:
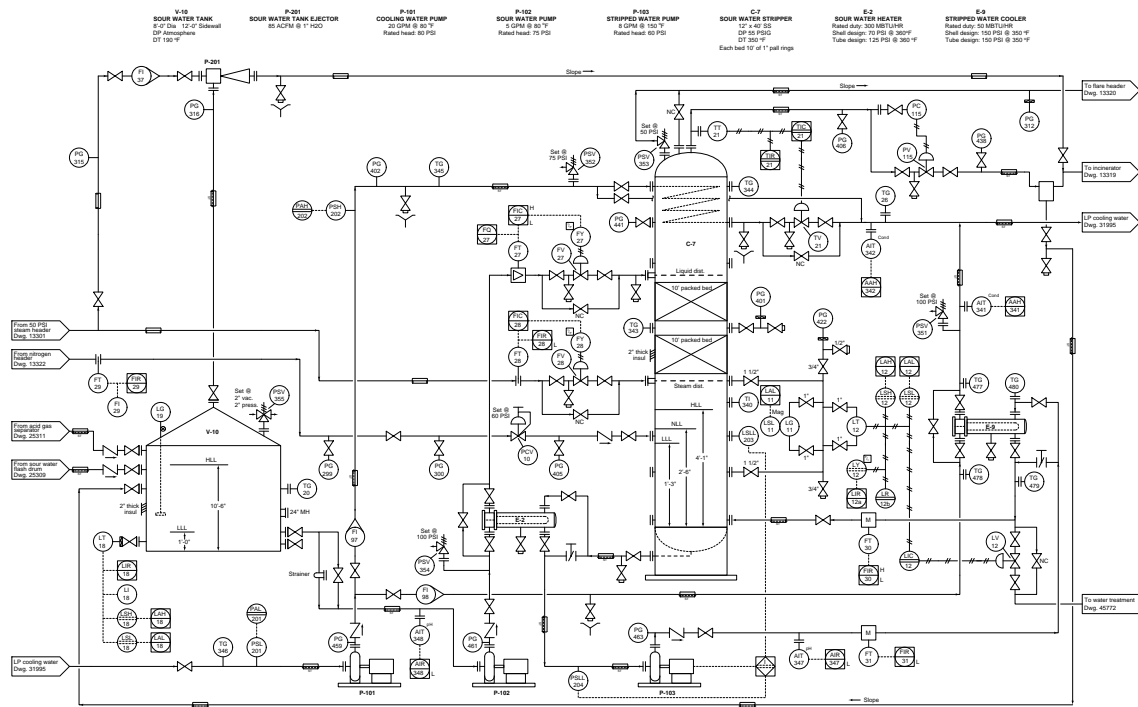
Your assignment – at minimum – is to enter multiple instruments into the DPCTrack2 database, complete with one or more "Test Point Groups" specifying calibration parameters for those instruments. An example of this is shown here:
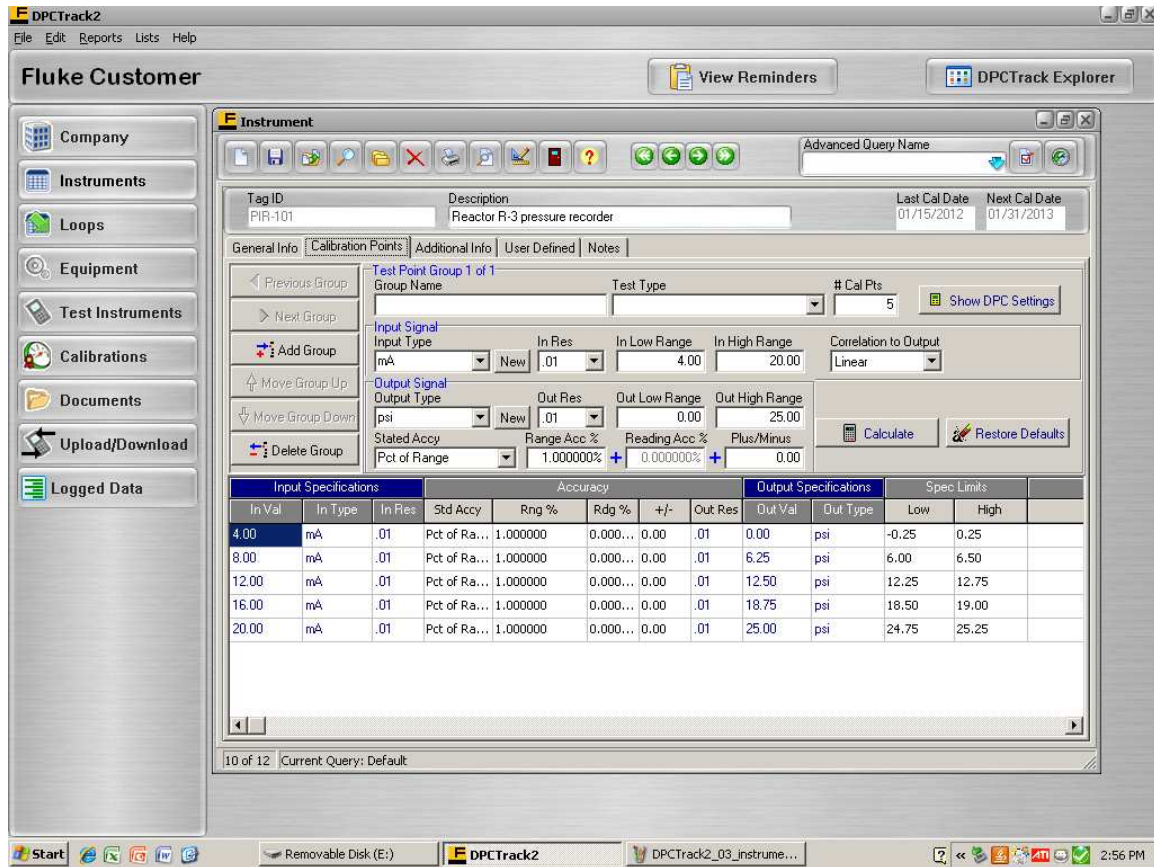
Beyond that, feel free to experiment with entering more data into the DPCTrack2 database:

- Equipment data (assigning individual instruments to a piece of equipment)
- Loop data (assigning individual instruments to a loop)
- Location data (assigning equipment to certain buildings or other physical locations)
- Technician information
- User's manuals or other instructional documents linked to loops or instruments

file i02034

Question 29

An important part of performing instrument calibration is determining the extent of an instrument's error. Error is usually measured in *percent of span*. Calculate the percent of span error for each of the following examples, and be sure to note the sign of the error (positive or negative):

- **Pressure gauge**
- LRV = 0 PSI
- URV = 100 PSI
- Test pressure = 65 PSI
- Instrument indication = 67 PSI
- Error = _____ % of span

- **Weigh scale**
- LRV = 0 pounds
- URV = 40,000 pounds
- Test weight = 10,000 pounds
- Instrument indication = 9,995 pounds
- Error = _____ % of span

- **Thermometer**
- LRV = -40°F
- URV = 250°F
- Test temperature = 70°F
- Instrument indication = 68°F
- Error = _____ % of span

- **pH analyzer**
- LRV = 4 pH
- URV = 10 pH
- Test buffer solution = 7.04 pH
- Instrument indication = 7.13 pH
- Error = _____ % of span

Also, show the math you used to calculate each of the error percentages.

Challenge: build a computer spreadsheet that calculates error in percent of span, given the LRV, URV, test value, and actual indicated value for each instrument.

file i00089

Question 30

A common form of measurement error in instruments is called *hysteresis*. A very similar type of measurement error is called *deadband*. Describe what these errors are, and differentiate between the two.

file i00091

Question 31

An instrument technician working for a pharmaceutical processing company is given the task of calibrating a temperature recording device used to display and log the temperature of a critical batch vessel used to grow cultures of bacteria. After removing the instrument from the vessel and bringing it to a workbench in the calibration lab, the technician connects it to a calibration standard which has the ability to simulate a wide range of temperatures. This way, she will be able to test how the device responds to different temperatures and make adjustments if necessary.

Before making any adjustments, though, the technician first inputs the full range of temperatures to this instrument to see how it responds in its present condition. Then, the instrument indications are recorded as *As-Found* data. Only after this step is taken does the technician make corrections to the instrument's calibration. Then, the instrument is put through one more full-range test and the indications recorded as *As-Left* data.

Explain why it is important that the technician make note of both "As-Found" and "As-Left" data? Why not just immediately make adjustments as soon as an error is detected? Why record any of this data at all? Try to think of a practical scenario where this might matter.
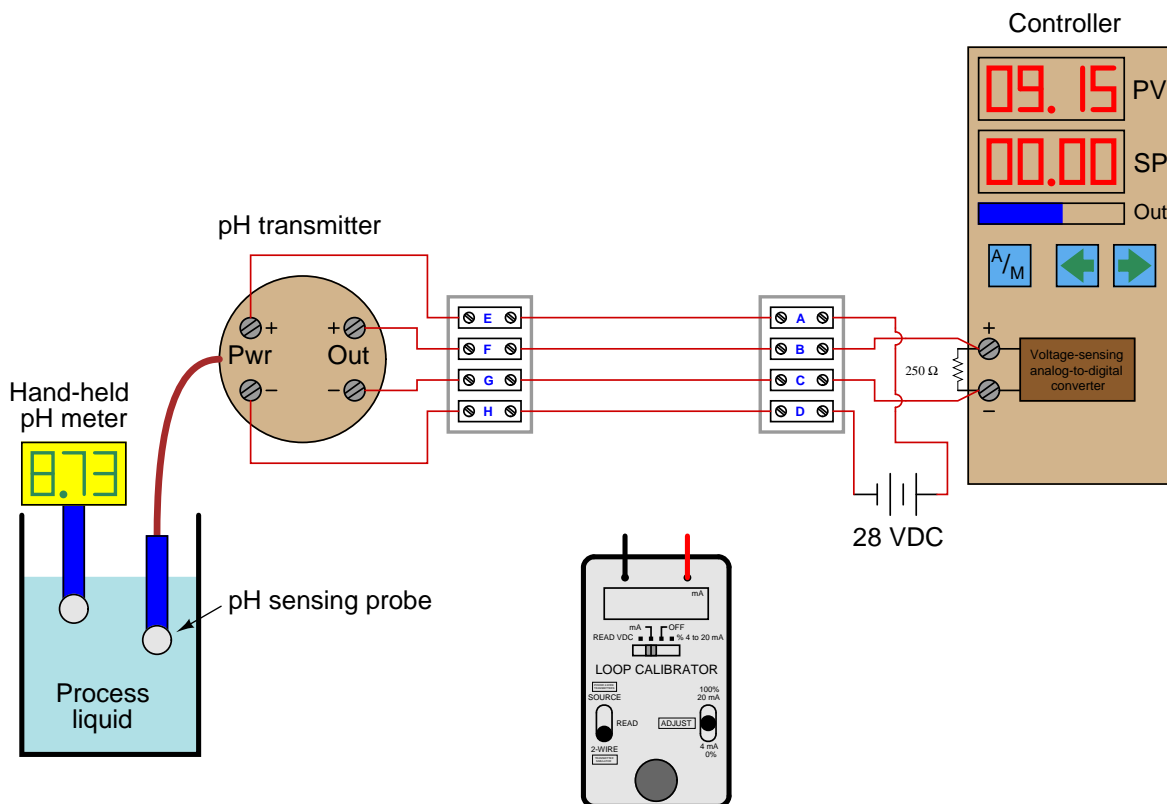
file i00082

Question 32

An error tolerance of ± 0.4% of span is _____ milliamps for a 4-20 mA instrument signal.

file i03105

A newly-installed pH measurement system does not seem to be measuring the pH of the process liquid accurately. The indicating controller's display does not match the display of the hand-held pH meter used by an operator:

The calibrated range of the 4-wire pH transmitter is supposed to be 2 to 12 pH, with a 4 to 20 mA signal output range. An instrument technician begins to diagnose the problem by taking a loop calibrator and measuring the current signal being sent to the indicating controller. The loop calibrator registers 15.43 milliamps.

Based on this information, determine where the problem is in this system. Also, show how the loop calibrator could be connected to the wiring to measure the loop current (specifying the proper calibrator mode as well).

| **Suggestions for Socratic discussion** |

- Review the problem-solving tips listed in Question 0 and apply them to this problem.
- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- If the technician had no test equipment except for a voltmeter, could a good diagnostic test still be made in this system?

- Identify where you could install a rectifying diode in this circuit to allow convenient measurement of loop current.

file i00976

Question 34

Analog electronic process transmitters typically have only two calibration adjustments: one for *zero* and another for *span*. Occasionally you may find an analog electronic transmitter with a third adjustment: one for *linearity*.

Modern "smart" process transmitters have more components in need of adjustment. A block diagram of a typical smart pressure transmitter shows this very clearly:
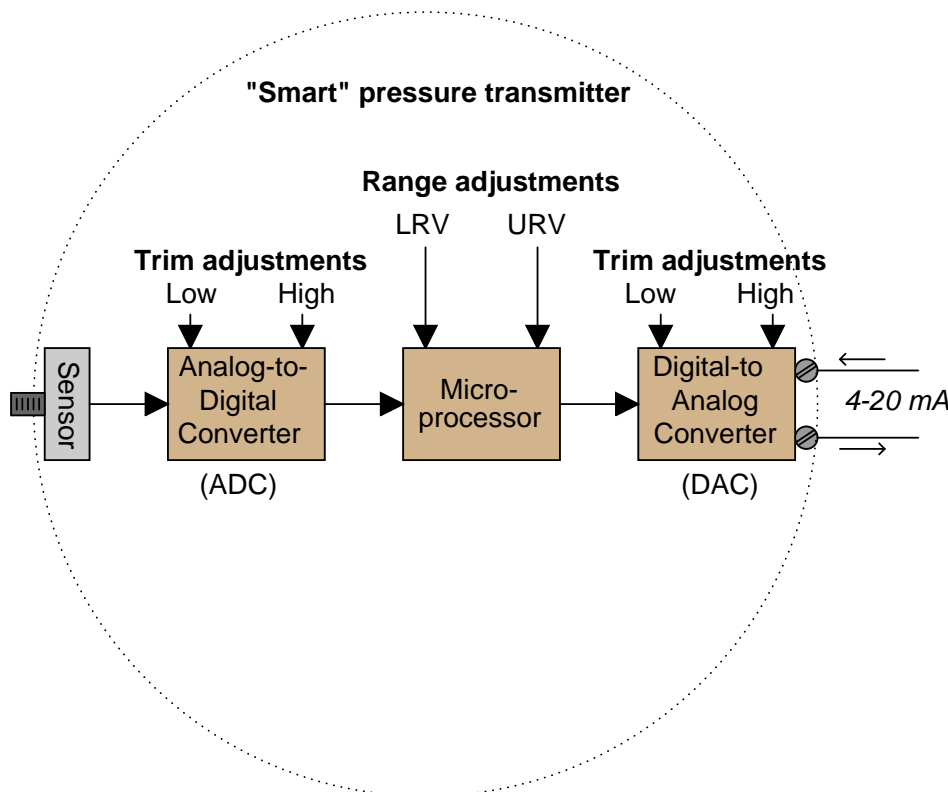
The purpose of the analog-to-digital converter (ADC) is to translate the pressure sensor's electrical output signal into a digital number the microprocessor can understand. Likewise, the purpose of the digital-to-analog converter (DAC) is to translate the digital output of the microprocessor into a 4 to 20 mA DC current signal representing measured pressure. The procedure of calibrating the ADC is called a *sensor trim*, while the process of calibrating the DAC is called an *output trim*.

Explain the importance of performing both a sensor trim and an output trim whenever calibrating a "smart" transmitter. In other words, explain why it is not enough to simply program LRV and URV values into the microprocessor (e.g. LRV = 0 PSI ; URV = 30 PSI) and declare the job finished.

Furthermore, explain what external calibration equipment must be connected to the transmitter to complete a sensor trim procedure, and also what external calibration equipment must be connected in order to complete an output trim procedure.
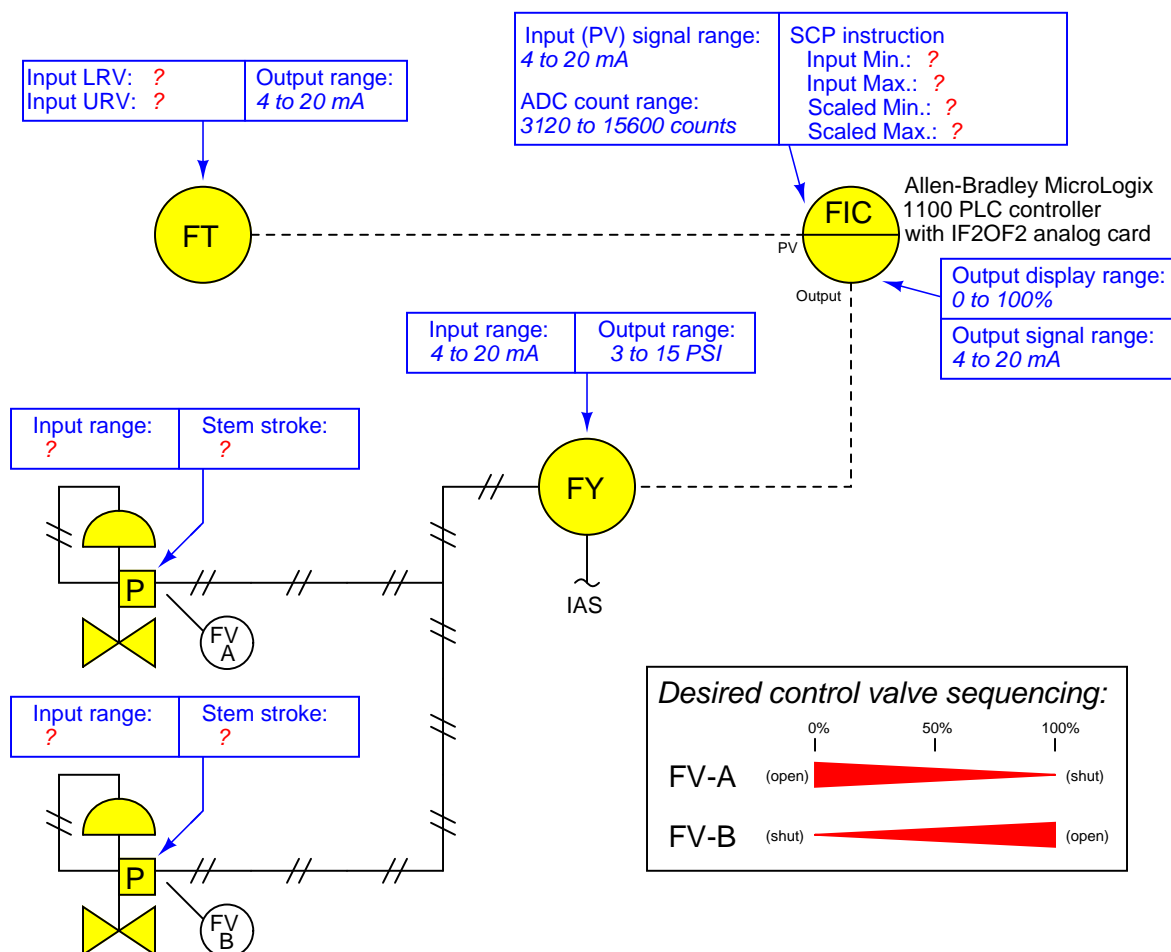
file i00090

Question 35

A level indicator is registering a liquid level that is falsely low. The operator has hand-gauged the storage vessel with a tape measure and determined the actual level to be 9 feet, but the level indicator (LI) registers 7.5 feet. The calibrated range of the 4-20 mA transmitter is 0 feet to 12 feet. You measure the current signal with your multimeter and find that it is 14 mA. Which instrument is at fault in this system? How do you know?
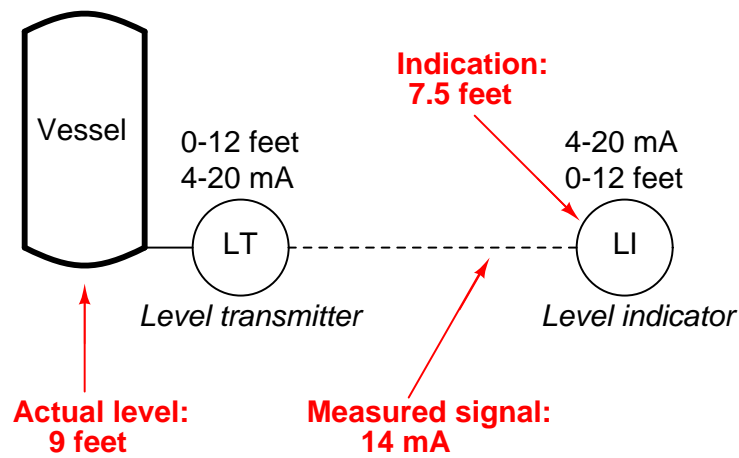
file i00321

Suppose you are asked to configure the instruments in this flow control loop to sense and display process flow over a range of 0 to 180 gallons per minute (GPM), with the loop controller actuating two split-ranged control valves in a complementary sequence. A "Scale-with-Parameters" (SCP) instruction programmed into the Allen-Bradley controller is supposed to take the analog-to-digital converter's raw count value as an input and scale it into units of GPM for the operator to read on a display:

Input LRV: ?
Input URV: ?

Output range:
4 to 20 mA

Input (PV) signal range:
4 to 20 mA

ADC count range:
3120 to 15600 counts

SCP instruction
Input Min.: ?
Input Max.: ?
Scaled Min.: ?
Scaled Max.: ?

FT

FIC

PV

Allen-Bradley MicroLogix
1100 PLC controller
with IF2OF2 analog card

Output

Output display range:
0 to 100%

Output signal range:
4 to 20 mA

Input range:
4 to 20 mA

Output range:
3 to 15 PSI

Input range:
?

Stem stroke:
?

P

FV
A

FY

IAS

Input range:
?

Stem stroke:
?

P

FV
B

Desired control valve sequencing:

0%   50%   100%

FV-A   (open)   (shut)

FV-B   (shut)   (open)

Write the proper range values inside the boxes near each instrument, showing the proper configuration for each instrument needed to achieve the desired result.

Suggestions for Socratic discussion

- Suppose the controller displayed a flow of 129 GPM when the actual process flow was 135 GPM. First, identify *two* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with a single diagnostic test.
- Suppose valve FV-A was 41% open and FV-B was 59% open when the controller output displayed 50%. First, identify *two* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with a single diagnostic test.

Question 37

Question 38

Question 39

Question 40

Question 41

Read selected portions of the "Attack and Defend Tools for Remotely Accessible Control and Protection Equipment in Electric Power Systems" paper written by Paul W. Oman, Allen D. Risley, Jeff Roberts, and Edmund O. Schweitzer III of Schweitzer Engineering Laboratories (March 2002) and answer the following questions:

Although this paper was written for technical professionals within the electric power industry and even uses some specialized terminology (e.g. IED = Intelligent Electronic Device, or what is more commonly known as a "smart" instrument), its warnings and advice applies to all kinds of digital industrial control systems.

Read the *Anatomy of a Cyber-Attack* section of this paper, and explain in your own words the four different levels of attack described therein.

Read the *Defensive Strategies* section of this paper, and summarize in your own words how each of the listed strategies works to foil attacks.

Question 42

Online databases of known data cyberattack vulnerabilities are archived and available for your perusal. One of these is the CVE (Common Vulnerabilities and Exposures) databased maintained at Mitre.org. The URL for this database is shown here:

```
cve.mitre.org
```

Search this database for industrial control equipment brands and models you are familiar with, and note some of the vulnerabilities discovered to date!

Question 43

In this course section you are required to build and operate a PID-controlled process. Imagine that this process were industrial-scale, and represented some critically important piece of a larger system upon which the facility's productivity and/or safety depended. Identify the type of control system used to regulate the process variable in your team's process, and assess vulnerabilities from a digital security perspective.

When listing vulnerabilities, think both of *network* vulnerabilities (i.e. ways for a person to gain access to the digital control system) and *process* vulnerabilities (i.e. ways to mess up the operating process once the network has been breached).
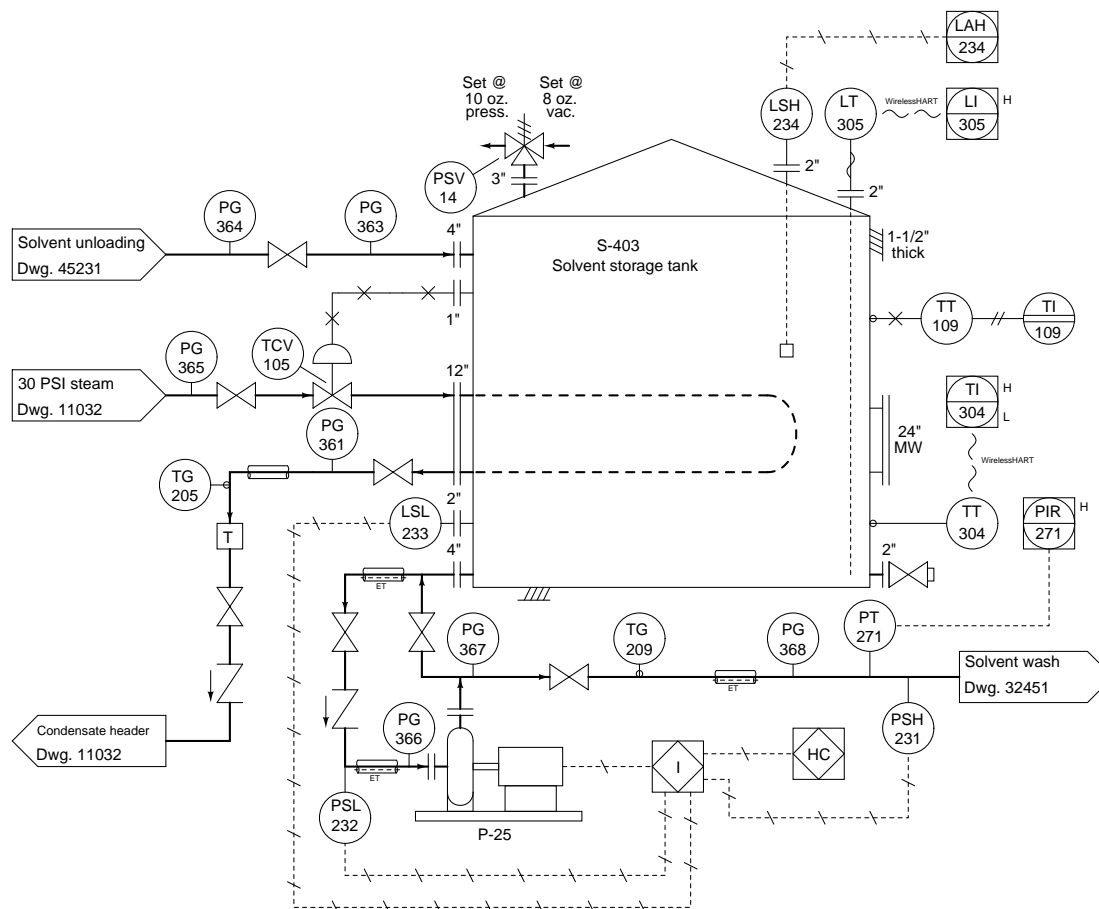
Vulnerabilities:

-

-

-

Next, propose ways to mitigate each of these vulnerabilities based on principles you have learned about digital security.

file i01184

Question 44

A chemical manufacturer uses a particular type of solvent in one of its processes, and stores this solvent inside of an insulated storage tank. The tank is equipped with a number of automated measurement and control systems, as shown in this P&ID:

Examine this diagram closely to look for any process vulnerabilities that could be exploited through a cyber-attack (i.e. what adjustments or "spoofing" of variables or changing of modes might be made to the control system after the network has been breached), and what the effects of those attacks might be on the process. Also, identify any instrumentation in this solvent storage tank that appears immune to cyber-attack.
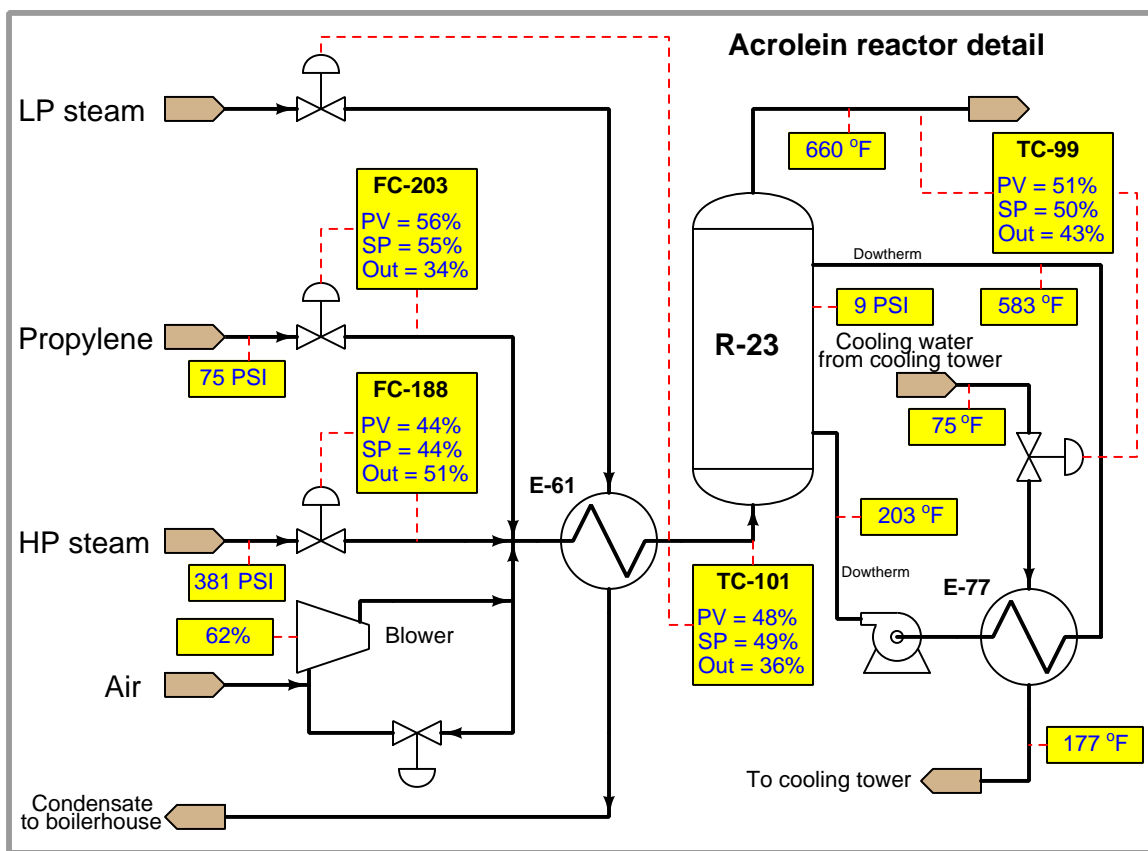

Suggestions for Socratic discussion

- How might a cyber-attacker wreak havoc in a process by introducing a *calibration error* in a digital instrument or control system?
- How might a cyber-attacker wreak havoc in a process by altering the *tuning parameters* of a PID control loop?

file i01049

Question 45

An antimicrobial agent called *acrolein* used to protect diesel fuel from fungal growth may be manufactured by reacting propylene with steam and air in a reactor vessel. The ensuing chemical reaction is exothermic, and so a coolant loop using a special heat-transfer oil called "Dowtherm" is used to remove heat from the reactor vessel. This DCS display shows an overview of the reactor and associated instrumentation:

Examine this display closely to look for any process vulnerabilities that could be exploited through a cyber-attack (i.e. what adjustments or "spoofing" of variables or changing of modes might be made to the control system after the network has been breached), and what the effects of those attacks might be on the process.

Suggestions for Socratic discussion

- How might a cyber-attacker wreak havoc in a process by introducing a *calibration error* in a digital instrument or control system?
- How might a cyber-attacker wreak havoc in a process by altering the *tuning parameters* of a PID control loop?
- Do you suppose the *redundant* design of a typical DCS would be any defense against a cyber-attack? Why or why not?

file i01974

44

Question 46

Refer to selected portions of the "The SIMATIC PCS 7 Process Control System" brochure dated March 2009 and answer the following questions:

Examine the "SIMATIC PCS 7 System Architecture" diagram shown on page 4, assuming for the sake of this exercise that it is a realistic diagram for a particular facility's control system rather than merely being an illustrative example. How many different types of networks do you see in this system? Which of these networks do you think would be "nearest" to the internet? Barring any network connection to the outside world, how many different points of access do you see for malware to infiltrate the system?

A special point of vulnerability for industrial control systems is the software used to program and configure devices connected to the control system network. This software, once hijacked by malware or accessed by a malicious party, may be used to reconfigure practically every critical parameter in the control system to cripple the system. The Siemens PCS 7 equivalent is called *Process Device Manager*, abbreviated *PDM*. Identify where this software typically resides in a SIMATIC PCS control network, and what its capabilities are. Also, identify strategies you would recommend for controlling access to this software.

Find the section entitled "Operation and monitoring via World Wide Web" and identify best practices for securing this kind of remote operations capability.

Find the section entitled "IT Security" and describe some of the design features of the SIMATIC PCS 7 system providing security.

User authentication is handled in the SIMATIC PCS 7 system through the "SIMATIC Logon" application which is integrated throughout the system software. Identify some of the important features of SIMATIC Logon, and explain why those features enhance security.

Suggestions for Socratic discussion

- One of the mantras often heard in industrial control system security is "*In control systems, vulnerabilities are features, not bugs.*" Explain what this phrase means, referencing the familiar control systems such as DCSs and PLCs to illustrate this concept.
- No system, no matter how robustly-featured, will be secure if it is not implemented wisely. Identify ways in which a system such as the Siemens SIMATIC PCS 7 could be poorly implemented, such that some of its built-in security features would be compromised or bypassed altogether.
- Identify how this system's security could be improved by the inclusion of a *DMZ* (DeMilitarized Zone), specifying exactly where the necessary components would be installed and how they would be configured.

file i01077

Question 47

Read selected portions of the "Securing Communications for SCADA and Critical Industrial Systems" paper written by Tom Bartman and Kevin Carson of Schweitzer Engineering Laboratories (document TP6678-01, November 2015) and answer the following questions:

Section II ("SCADA and ICSs") of this paper declares that most SCADA systems do not employ authentication or encryption, and often use *cleartext* communication. Explain what this means, and why it is significant to the topic of control system security.

Explain how each of the "threat vectors" described in this paper work.

Explain how "hash functions" such as those used by the HMAC (Hash-based Message Authentication Code) method within the IPsec protocol may be used to verify the integrity of data communicated between devices in an industrial data network.

Explain how each of the recommendations described in this paper for protecting SCADA and control system communications are supposed to function.

| Suggestions for Socratic discussion |

- Explain why a malicious party positioned as a "Man-in-the-Middle" could not simply intercept an IPsec packet, modify the data contained therein, generate a new HMAC hash signature, and transmit that modified packet such that the receiver could not tell the data had been tampered with.

  file i01048

Question 48

Question 49

Question 50

Question 51

Question 52

Question 53

Question 54

Question 55

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

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

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

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

A helpful guide to traits and skills valued by employers are the "General Values, Expectations, and Standards" pages near the beginning of this worksheet. Another is the "So You Want To Be An Instrument Technician?" career guide.
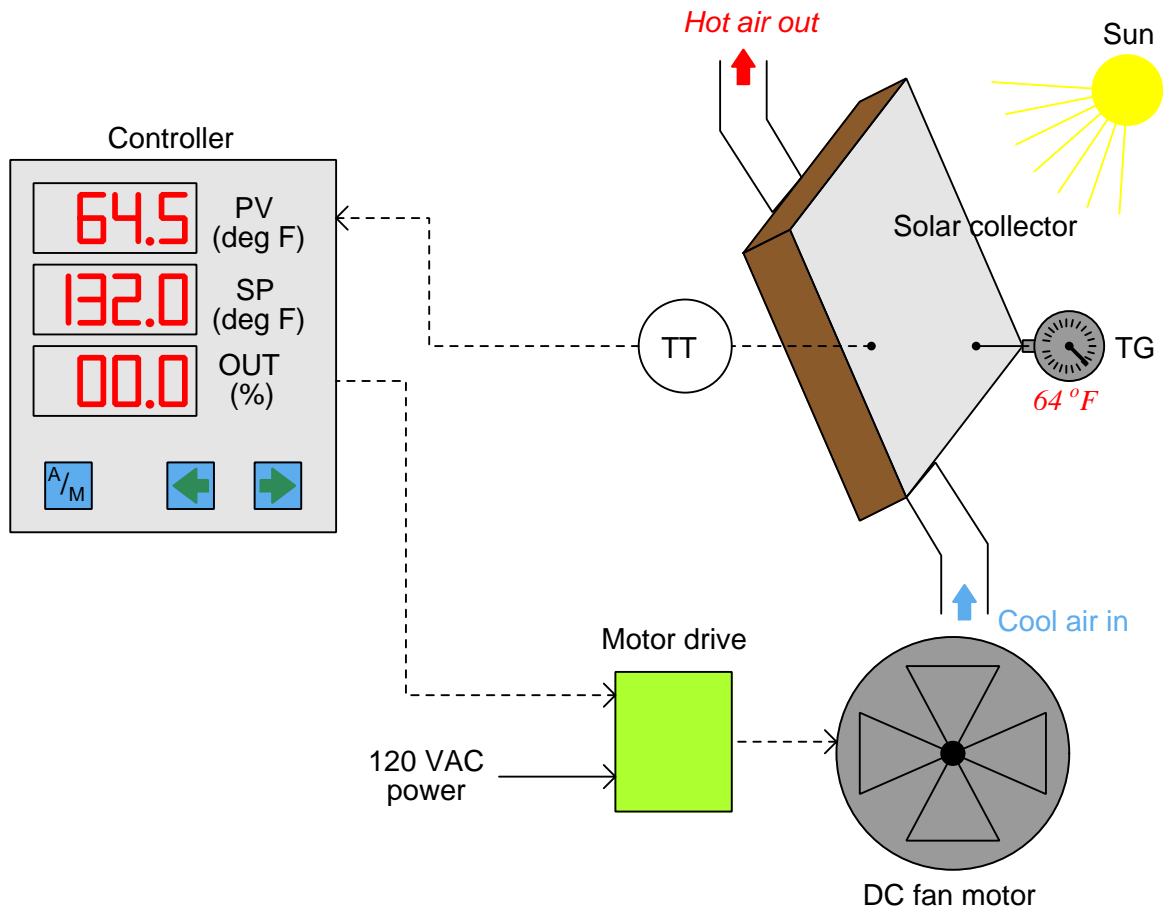
file i00999

Question 62

The following processes all have some problem, which may be diagnosed by careful observation of the controller's faceplate display (PV, SP, and Output values) and/or indications given by gauges in the field. Examine each control system and determine possible faults in each system from the information given.
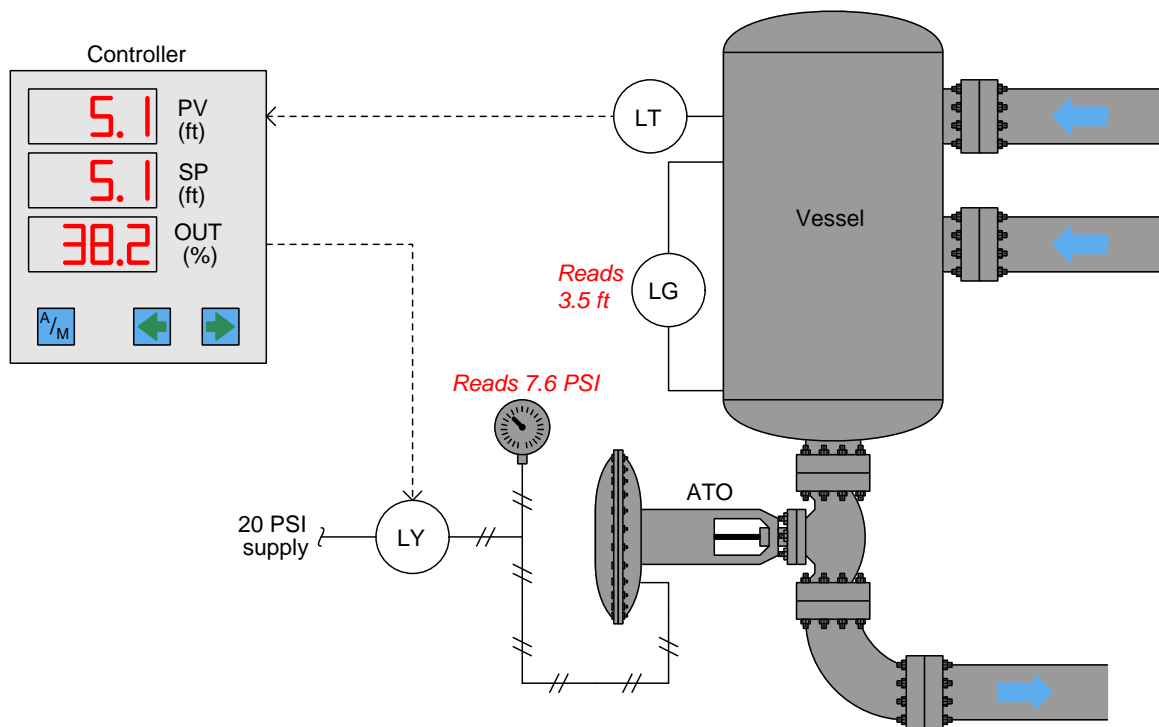
Assume that the conditions shown have existed for quite some time, long enough for the control system to have brought the process variable back to setpoint if everything were operating correctly:

Example 1:

Example 2:

Controller

5.1	PV (ft)
5.1	SP (ft)
38.2	OUT (%)

A/M ← →

LT

Vessel

Reads
3.5 ft

LG

Reads 7.6 PSI

ATO

20 PSI
supply

LY

Example 3:

Cold fluid
in

Air supply

ATO

TY

Controller

192.4	PV (deg C)
150.0	SP (deg C)
12.7	OUT (%)

A/M ← →

Steam in

Heat exchanger

Steam out

Warm fluid
out

Thermocouple

TT

49
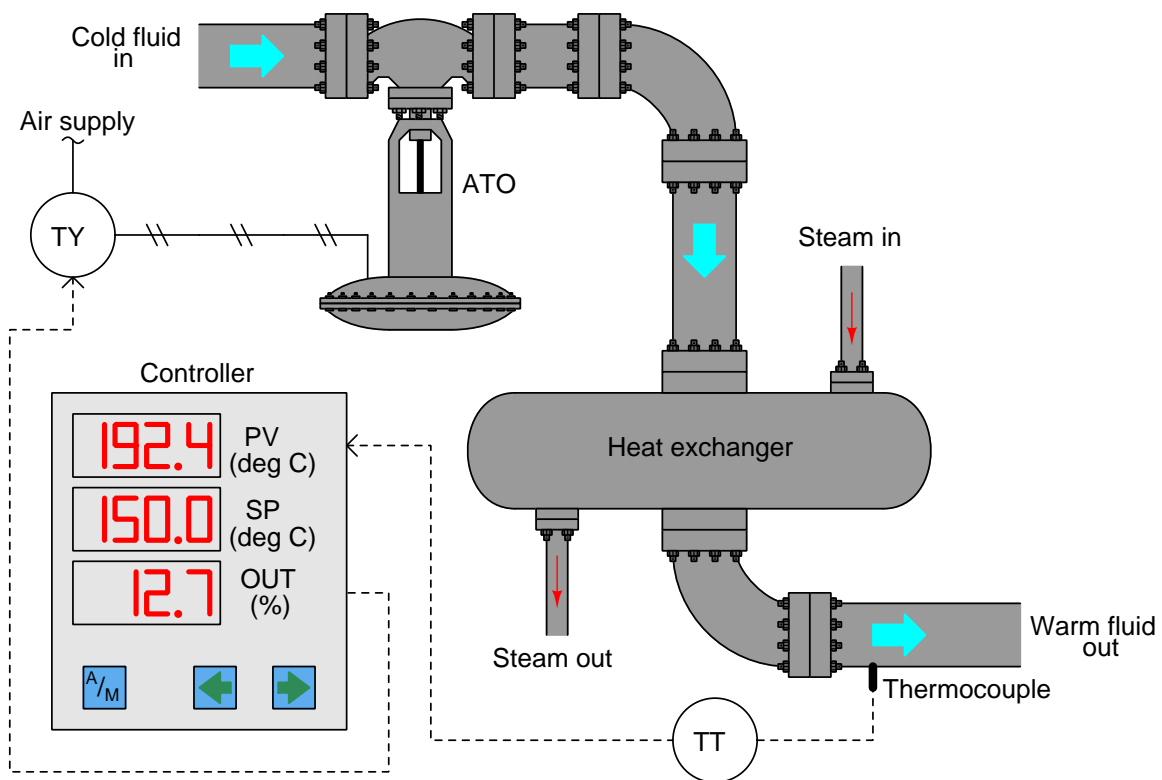
- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which values agree with each other. Explain how a check of correspondence tells us which instrument is at fault in any of these control loops.
- For each of these scenarios, determine what your next diagnostic test might be to further pinpoint the location and nature of the problem.

file i00642

Question 63

Site visit!

As part of today's inverted theory session, you will meet your instructor at a site containing real processes and control systems, where you will evaluate the calibration needs of those control systems and also any potential cybersecurity vulnerabilities. Prepare yourself to do the following while on site:

- Identify proper controller action based on inspection of process equipment
- Identify loads in the process based on an inspection of the piping and vessels
- Identify how to easily check for out-of-calibration instruments
- Identify appropriate calibration standards and procedures for those instruments
- Identify possibly cybersecurity vulnerabilities, and how to mitigate them
- Wear safety glasses and sturdy (closed-toed) shoes

file i02106

50

Question 64

Suppose an electronic pressure transmitter has an input range of 0 to 100 PSI and an output range of 4 to 20 mA. When subjected to a 5-step up-and-down "As-Found" calibration test, it responds as such:

Applied pressure (PSI)	Output signal (mA)
0	3.5
25	7.5
50	11.5
75	15.5
100	19.5
75	15.5
50	11.5
25	7.5
0	3.5

Sketch this instrument's ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *hysteresis*, and/or *linearity*):
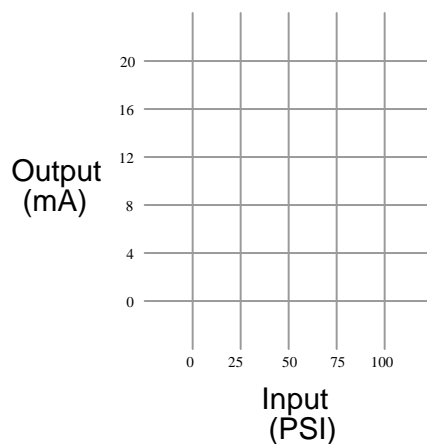
Finally, identify how this calibration error might be corrected. What steps or procedures would you follow to rectify this problem?

Suggestions for Socratic discussion

- How might the other three calibration errors appear when graphed?
- What purpose is served by doing an up-and-*down* test? Why not just check the instrument's response in one direction only?
- Which constant in the $y = mx + b$ linear equation represents *zero*, and which represents *span*?
- Describe how a computer spreadsheet program (e.g. Microsoft Excel) might be a useful tool in graphing this instrument's response.

file i00081

Question 65

An electronic DP transmitter has an input range of 0 to 100 inches water column and an output range of 4 to 20 mA. When subjected to a 5-step up-and-down "As-Found" calibration test, it responds as such:

Applied pressure (" WC)	Output signal (mA)
0	4.0
25	8.7
50	12.8
75	16.6
100	20.0
75	16.6
50	12.8
25	8.7
0	4.0

Graph this instrument's ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *hysteresis*, and/or *linearity*).
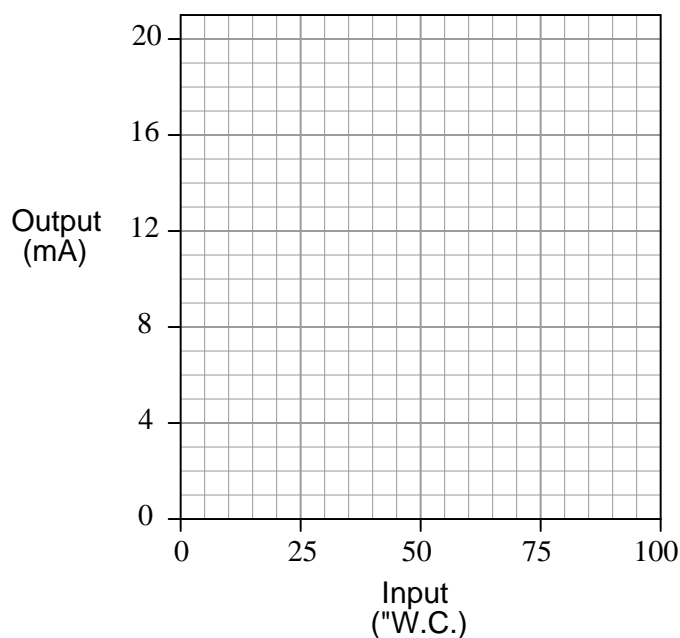
Hint: a computer spreadsheet program might be a useful tool in graphing this instrument's response. Feel free to attach a printed copy of a spreadsheet graph instead of hand-sketching one on this page.


Suggestions for Socratic discussion

- How might the other three calibration errors appear when graphed?
- What purpose is served by doing an up-and-*down* test? Why not just check the instrument's response in one direction only?

file i03859

Question 66

In this process, two chemical streams are mixed together in a reactor vessel. The ensuing chemical reaction is endothermic (heat-absorbing) and must be heated by steam to ensure the solution is at the necessary temperature to thoroughly react. A temperature transmitter (TT) senses the reaction product temperature and sends a 4-20 mA signal to a temperature indicating controller (TIC). The controller then sends a 4-20 mA control signal to the temperature valve (TV) to throttle steam flow:
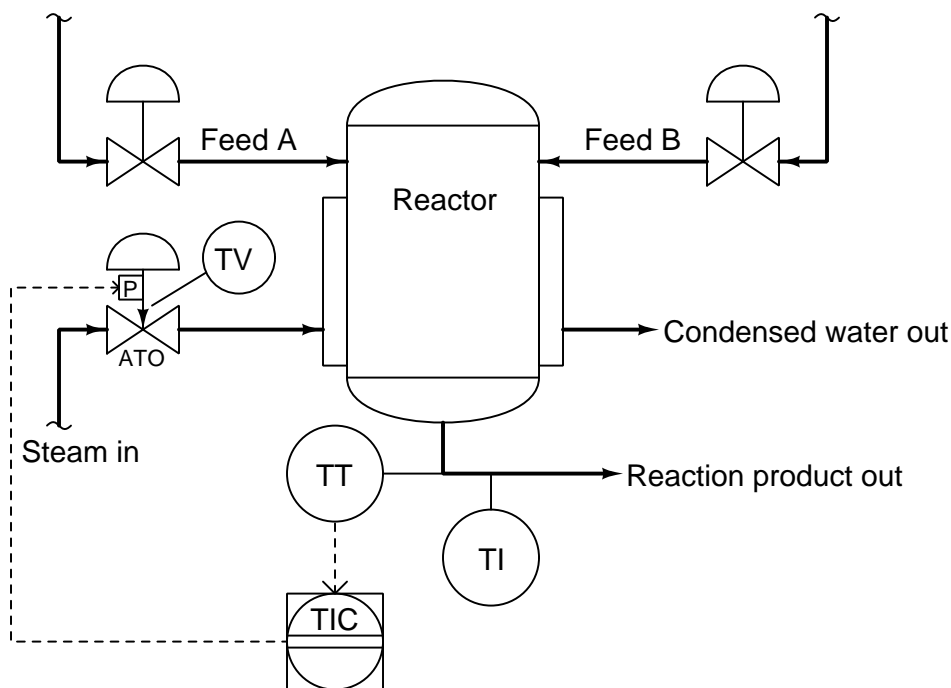
Suppose the last instrument technician to calibrate the temperature transmitter made a mistake, and the transmitter consistently reads 15° too hot. For example, if the reaction product temperature is actually 275° F, the transmitter outputs a current signal corresponding to 290° F.

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

Suggestions for Socratic discussion

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

file i04386

This single-loop control system has a problem: the pressure indicated on the controller's faceplate shows it to be precisely at setpoint (95 inches W.C.), yet the pressure gauge does not agree.
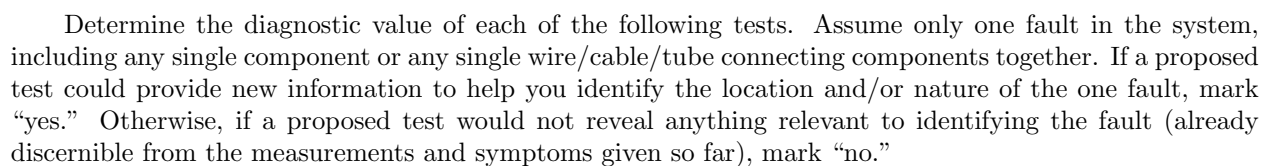
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Measure AC line voltage		
Measure DC power supply output voltage		
Inspect PID tuning parameters in controller		
Check pressure transmitter calibration		
Measure transmitter current signal		
Put controller into manual mode and move valve		
Measure DC voltage between TB1-3 and TB1-4		
Measure DC voltage between TB1-7 and TB1-8		

file i00583

Question 68

This boiler steam drum level control system has a problem. The water level in the steam drum is below setpoint (as indicated by the controller display showing 42% water level with a 58% setpoint), and has been for the past several hours despite the operator's attempt to raise water level by raising the setpoint on the controller. Meanwhile, the boiler is operating at full power, making steam at a normal rate of flow:
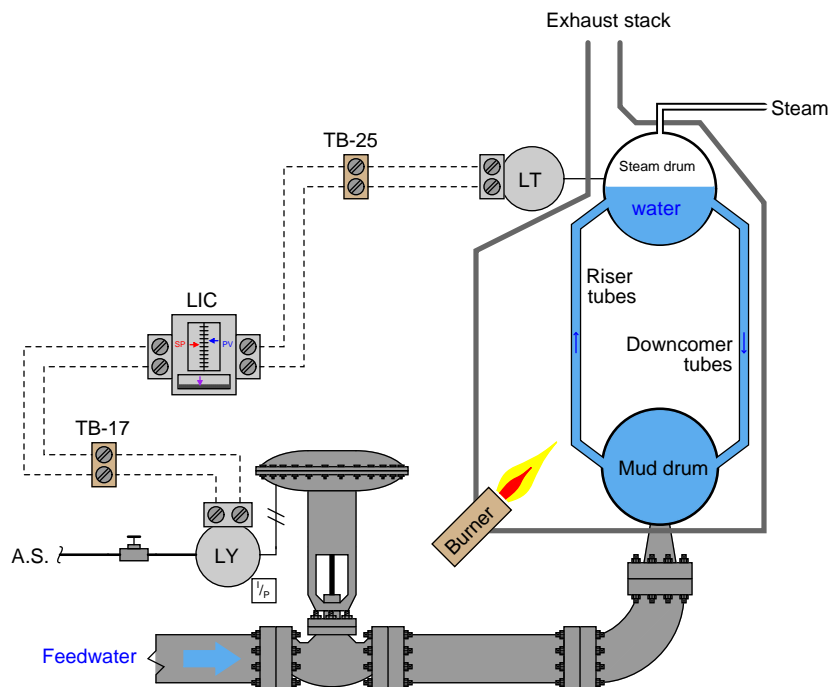
Identify the likelihood of each specified fault for this system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this system.

Fault	Possible	Impossible
LT calibration error		
LY calibration error		
Controller failed		
Low air supply pressure		
Excessive resistance in LT circuit		
Excessive resistance in LY circuit		
Feedwater pump worn		
Controller in manual mode		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Bear in mind that this is an *operating system* and cannot be shut down to accommodate any arbitrary test. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.

| Suggestions for Socratic discussion |

- Identify the steps you would need to follow in order to safely check the level transmitter's calibration while the boiler is running.

  file i01368

55

Question 69

Large electric power distribution transformers are filled with a special high-dielectric oil that helps transfer heat from the transformer core to cooling tubes, as well as displace moisture from the internal volume of the device. One of the important operational parameters of such transformers is the temperature of this oil.

A special-purpose protection device called a *thermal overload protective relay* (ANSI/IEEE code number 49) uses an RTD sensor to detect the transformer's temperature, then energizes the circuit breaker's "trip" coil (causing the breaker to open its contacts) if ever this temperature exceeds a certain pre-set value. A basic schematic diagram shows how this relay device triggers the circuit breaker to trip if necessary to protect the transformer against over-temperature:
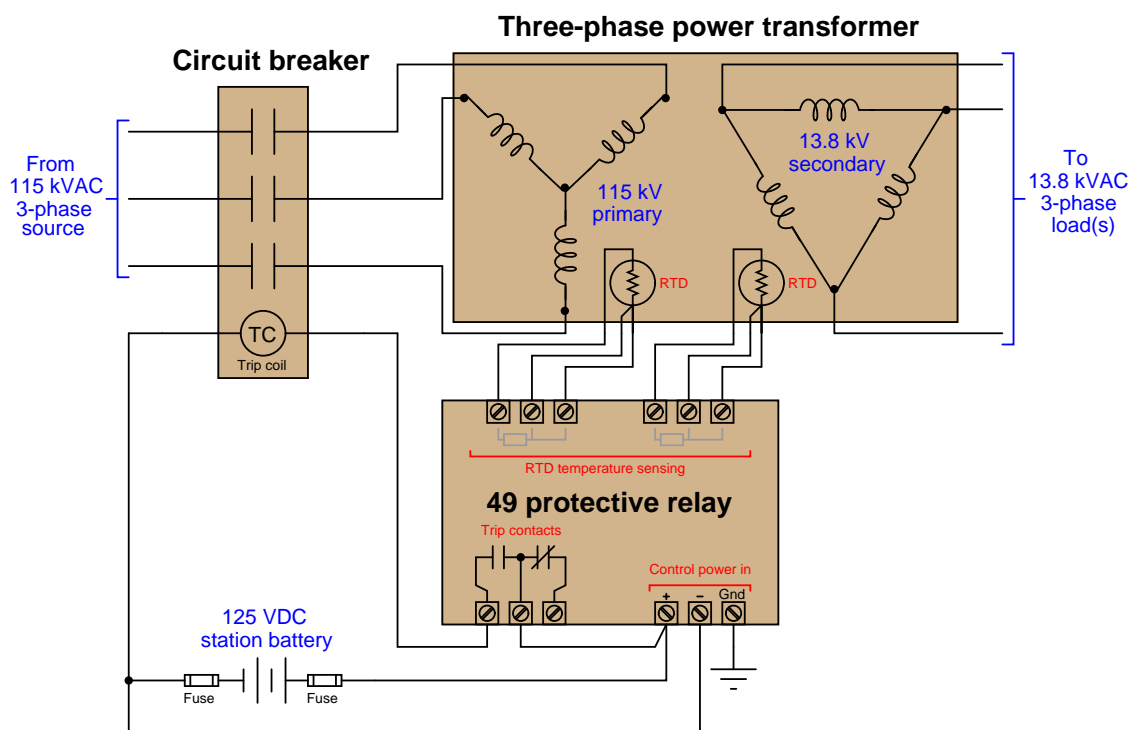
Identify how you would perform an "As-Found" test on this protective relay to ensure it would act to trip the circuit breaker in the event the transformer got too hot, without actually tripping the breaker. In other words, devise a "live" test of the protective relay that does not actually interrupt power to the transformer during the test. Assume the transformer's trip temperature setting is 60 degrees Celsius, and that the formula relating RTD resistance with temperature is as follows:

$$R = 100[1 + 0.00385T]$$

Be sure to specify any temporary changes you would make to the wiring in order to safely conduct your "As-Found" test, and describe the step-by-step procedure as though you were giving instuctions to another technician to perform the test instead of you.

- The specific *sequence* in which you perform the steps of your As-Found calibration test is every bit as important as the steps themselves! Identify where an improper sequence of otherwise proper steps would cause things to go wrong during the test.

- For those who have studied RTD sensors before, identify the proper amount of resistance equivalent to 60 degrees Celsius from an *RTD table* rather than using the given formula.

  <u>file i02032</u>

Question 70

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:

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 help further identify the location and/or nature of the fault.

| **Suggestions for Socratic discussion** |

- Based on the evidence presented, how do you know this problem is definitely *not* caused by poor PID controller tuning?
- What other methods exist for controlling differential pressure across a large gas compressor, other than using a recirculation valve?

file i00586

58

Question 71

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:
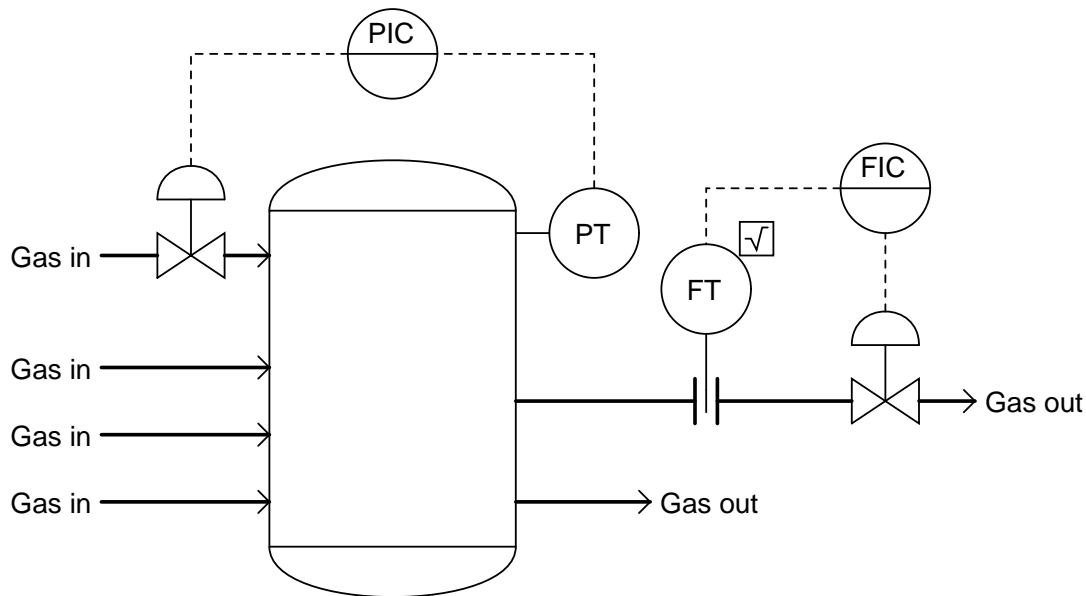
When the flow indicating controller (FIC) is placed in manual mode and the output "bumped" 10%, the result is certainly not what you would expect to see in a liquid flow control system:
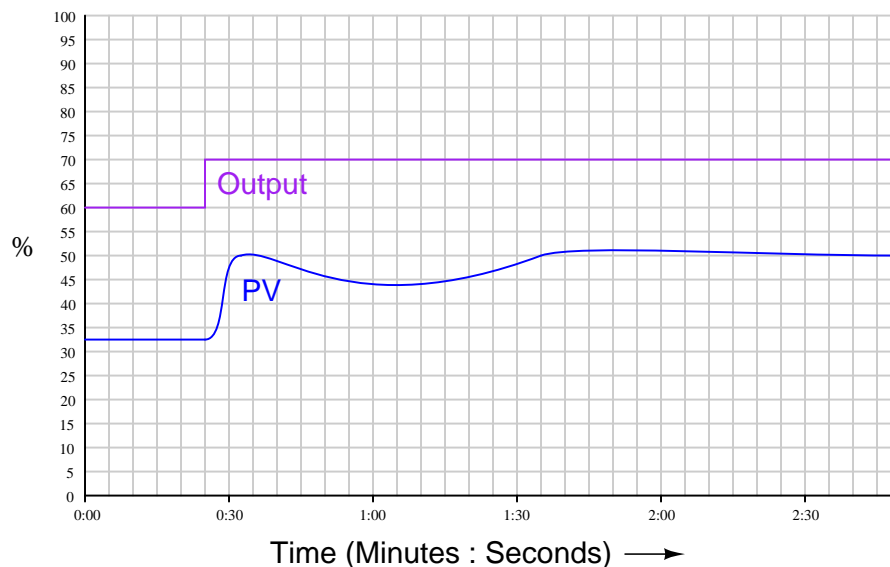
Explain the odd shape of the process variable (PV) trend following the output step-change: why the flow increases, then "sags," then stabilizes. Identify a diagnostic test you could perform on this process to positively identify the source of this strange behavior, explaining how the result(s) of this next test would help you identify the cause.

file i03400

59

Question 72

An operator claims pressure gauge PG-108 is defective and needs to be replaced. This pressure gauge registers 50 PSI, while pressure controller PIC-33 and pressure recorder PR-33 both register the pressure as being equal to setpoint: 43 PSI. Before replacing this pressure gauge, however, you decide to do some diagnostic thinking to see if there might be other causes for the abnormally high reading at PG-108. The first thing you check is the position of control valve PV-33a, and you find its stem position to be at 35% open.
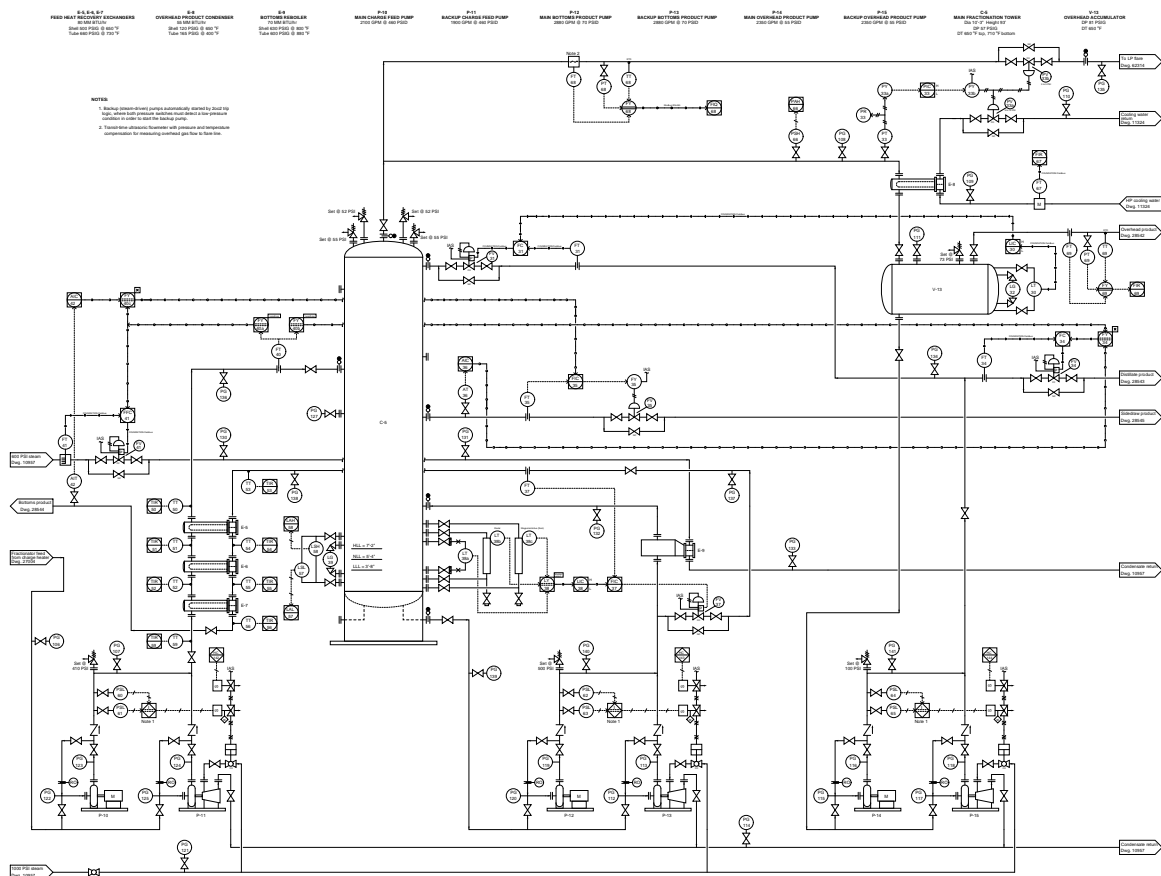
Identify the likelihood of each specified fault in this process. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this process.

Fault	Possible	Impossible
PG-108 calibration error		
PT-33 calibration error		
PIC-33 left in manual mode		
PY-33a calibration error		
PY-33b calibration error		

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.

- Based on the information you have at this point, can you tell whether any suspected calibration error is due to a mis-adjustment of *zero* or of *span*? Explain why or why not.
- Is controller PIC-33 direct-acting or reverse-acting? How can you tell?
- Does control valve PV-33a throttle gas or liquid? How can you tell?
- Identify a typographical error in this P&ID.
- A useful diagnostic technique for identifying which instrument is miscalibrated is to compare the readings of multiple instruments (all sensing the same process variable) to see which one of them disagrees most with the others. May we apply this technique to the problem at hand? If so, which instrument readings should we compare? If not, explain why not.

file i03512

Question 73

This room pressure control system maintains a slightly positive pressure in a precision electronic assembly room to prevent dust from entering from the outside, while always ensuring a rapid flow rate of air through the room. It regulates pressure by modulating two variable-speed fans: one introducing air to the room (the "forced draft" fan) and one venting air from the room (the "induced draft" fan). A pressure transmitter outputs 4 mA at 0 "W.C room pressure and 20 mA at 2 "W.C. room pressure:
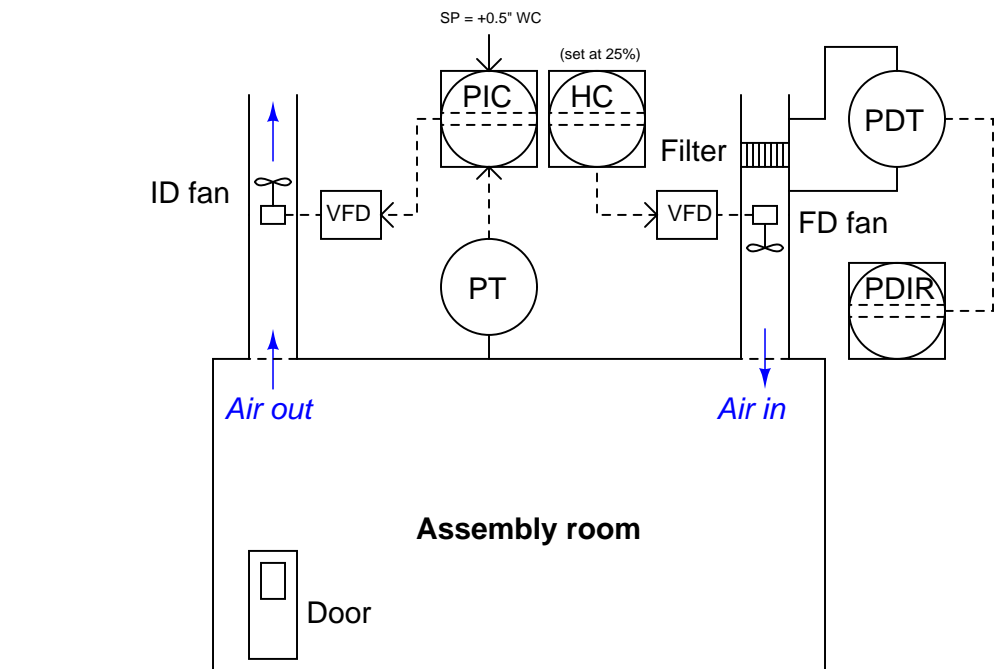
Suppose you are called to troubleshoot a problem in this system: the room air pressure is holding steady at +1.03 inches WC (according to the display on the DDC control system). Based on this data, identify the most likely cause of the problem, and also how you would confirm your diagnosis *before* making any repairs.

| Suggestions for Socratic discussion |

- What does "VFD" stand for, and what exactly do the "VFD" boxes do to exert control over the speed of the two fan motors?
- Explain why VFD control of air flow into and out of a forced-ventilation building makes more sense than using valve, dampers, or louvers to do the same.

file i00403

Question 74

Suppose you are asked to configure the instruments in this pressure control loop to sense and display process pressure over a range of 0 to 150 kPa, with the loop controller actuating two split-ranged control valves in a progressive sequence:

Write the proper range values inside the boxes near each instrument, showing the proper configuration for each instrument needed to achieve the desired result.

Suggestions for Socratic discussion
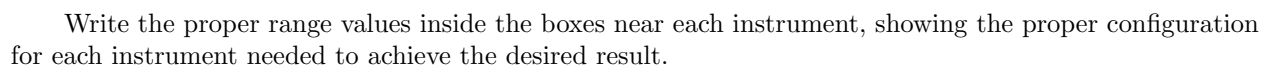
- Suppose the controller displayed a pressure of 80 kPa when the actual process pressure was 87 kPa PSIG. First, identify *two* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with a single diagnostic test.
- Suppose valve PV-A was 100% open and PV-B was 60% open when the controller output displayed 75%. First, identify *three* possible locations in this loop for a calibration error that would account for this discrepancy. Then, assuming only one fault, explain how you could positively determine the location of this calibration error with no more than two diagnostic tests.

file i02081

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Question 75

Question 76

Question 77

Question 78

Question 79

Question 80

Question 81

Determine all component voltages and currents in this circuit, being sure to mark directions of all currents (conventional flow notation) and polarities of all voltages:
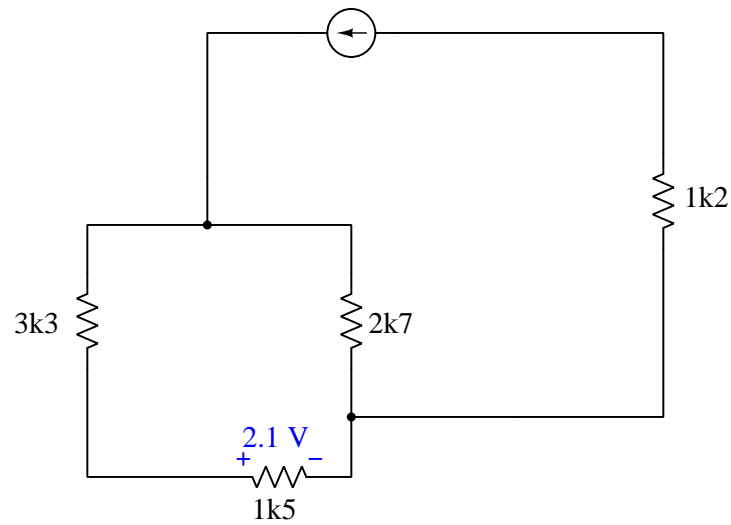
Question 82

Oil refineries and other heavy industries dealing with large quantities of flammable gases often use *flares* as emergency devices to safely burn off gas vented from one or more process units. This P&ID of a typical flare gas system shows how liquids are "knocked out" of the flammable gas headed to the flare, and how flames are prevented from following back from the flare tip to the flare line by means of a water seal:
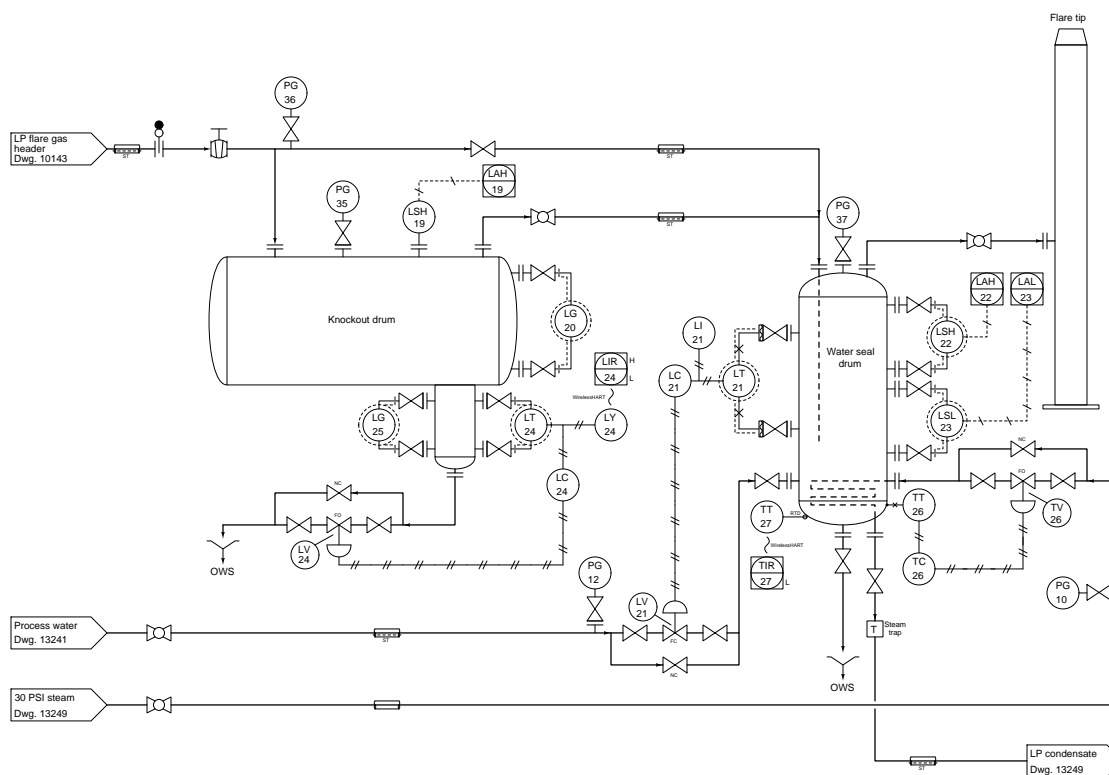
Describe the practical purpose of each controller in this P&ID (i.e. explain the reason why we have a controller installed and working in each case), and then determine its proper action. Assuming all transmitters are direct-acting (greater measured variable = greater signal output), determine the proper action (*direct* or *reverse*) for each controller in this system.

- Knockout drum LC-24 = *direct* or *reverse*? The purpose of this controller is to . . .

- Water seal drum LC-21 = *direct* or *reverse*? The purpose of this controller is to . . .

- Water seal drum TC-26 = *direct* or *reverse*? The purpose of this controller is to . . .

file i04694

65

This pressure-control system does not appear to be regulating water pressure correctly. The SP is set for 110 PSI (out of a 0-150 PSI range), but the PV display on the controller faceplate registers only 27 PSI, and has for quite a while. You happen to notice that the controller output reads 38% on the faceplate:
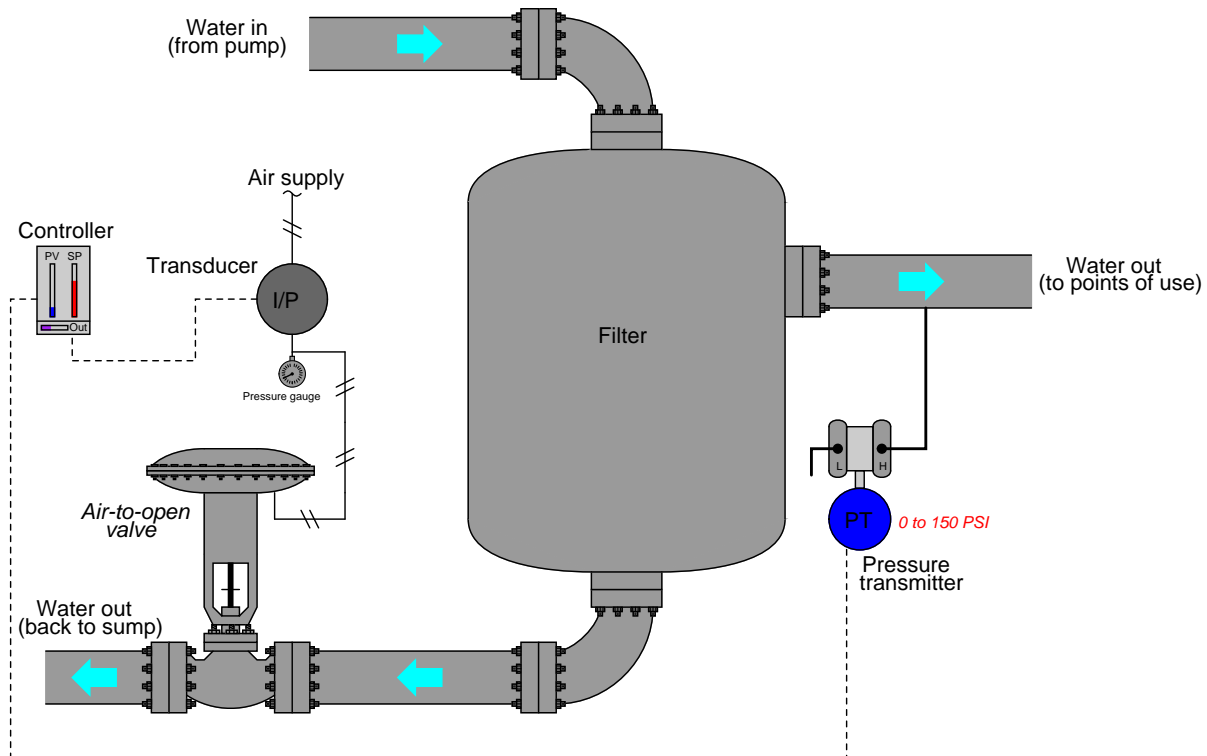
Your first test is to measure loop current in the circuit connecting the pressure transmitter to the pressure controller. There, your multimeter registers 6.88 milliamps. Your next step is to record the pressure gauge's indication (at the I/P output tube): 7.5 PSI.

Identify the likelihood of each specified fault for this control system. 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
PT out of calibration (outputting wrong current)		
PIC input out of calibration (not interpreting PV signal properly)		
PIC output out of calibration (not sending correct mA signal to I/P)		
Pressure gauge out of calibration (not displaying pressure properly)		
I/P out of calibration (not outputting correct pressure)		
Control valve is oversized		
Control valve is undersized		
PIC is poorly tuned (not making good control "decisions")		
Instrument air supply not at full pressure		

file i00338

66

Question 84

In preparation to disconnect and remove an electric motor for rebuild, an electrician shuts off the circuit breaker feeding the motor control circuit, then places a lock and an informational tag on that breaker so that no one turns it back on before she is done with the job.

The next step is to confirm the absence of dangerous voltage on the motor conductors before physically touching any of them. This confirmation, of course, is done with a voltmeter, and we all know that voltage is measured *between two points*. The question now is, how many different combinations of points must the electrician measure between using her voltmeter to ensure there is *no* hazardous voltage present?
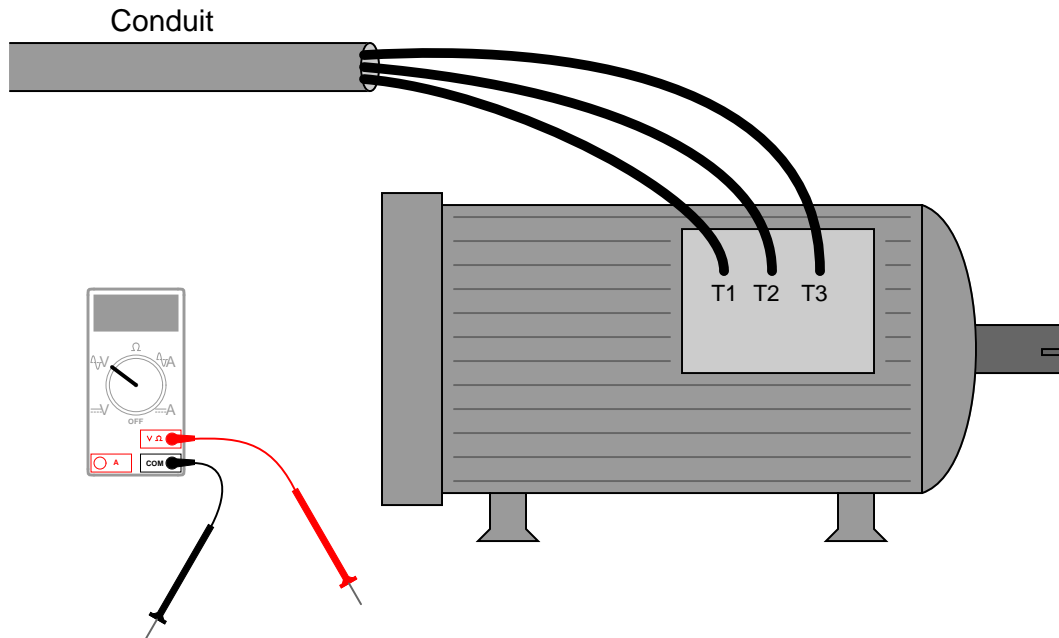
List all possible pairs of points the electrician must check for voltage between. Don't forget to include earth ground as one of those points, in addition to T1, T2, and T3!

Next, write a mathematical formula to calculate the number of point-pair combinations (i.e. the number of different voltage measurements that must be taken) given N number of connection points in the circuit.

file i04259

Question 85

Suppose a voltmeter registers 0 volts between test points **C** and **E** in this series-parallel circuit:
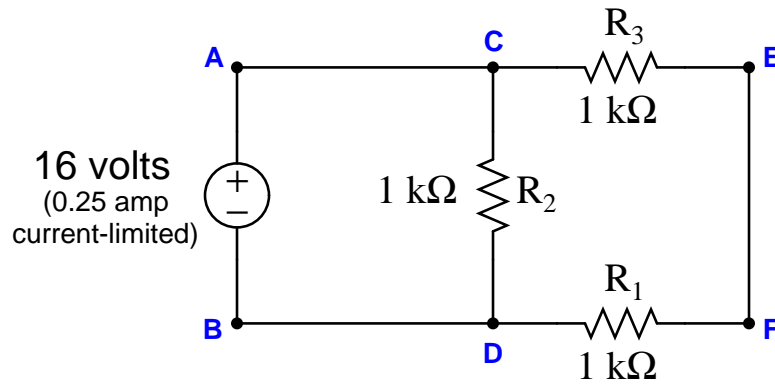
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
R_1 failed open		
R_2 failed open		
R_3 failed open		
R_1 failed shorted		
R_2 failed shorted		
R_3 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 86

A *V-notch weir* is a type of flow-sensing element for measuring liquid flow through open channels. Its construction is similar to a dam, and the height of liquid ("head") on its upstream side is related to flow rate over the weir by a nonlinear equation.

Suppose the height signal from a level transmitter upstream of a 60° V-notch weir gets sent to the analog input of a process recorder. Displaying the height measurement directly on the recorder would not be very useful, because height (H) is not linearly proportional to flow rate (Q). A human operator looking at a trend of head could not tell what this trend means in terms of *flow*, or worse yet might mistakenly interpret the head trend as a flow trend. However, this recorder does have the feature of *characterization*, where you may enter an equation to "linearize" an otherwise non-linear signal.

Write a "linearization" formula so that the trend recorder will be able to input the measured height (H, in inches) upstream of a 60° V-notch weir and display as a flow rate (Q) in units of cubic feet per second.

file i04347

Question 87

A digital pressure transmitter has a calibrated input range of 50 to 200 PSI, and a 10-bit output (0 to 1023 "count" range). Complete the following table of values for this transmitter, assuming perfect calibration (no error):

Input pressure (PSI)	Percent of span (%)	Counts (decimal)	Counts (hexadecimal)
	7		
	22		
	39		
	56		
	78		

Question 88

Suppose an electronic pressure transmitter has an input range of 0 to 400 PSI and an output range of 4 to 20 mA. When subjected to a series of known pressures to obtain an "As-Found" calibration table, it responds as such:

Applied pressure (PSI)	Output signal (mA)
0	4.0
100	8.0
200	12.0
300	16.0
400	20.0
300	16.1
200	12.1
100	8.1
0	4.1

Identify the type of calibration error this transmitter suffers from.

file i01205

Shown here is a pair of loop-powered 4-20 mA process transmitters, a process controller with dual measurement inputs, and a 4-20 mA I/P (current-to-pressure) converter used to drive a pneumatically-actuated control valve. The controller inputs are ranged from 1 to 5 volts DC, not 4-20 mA:
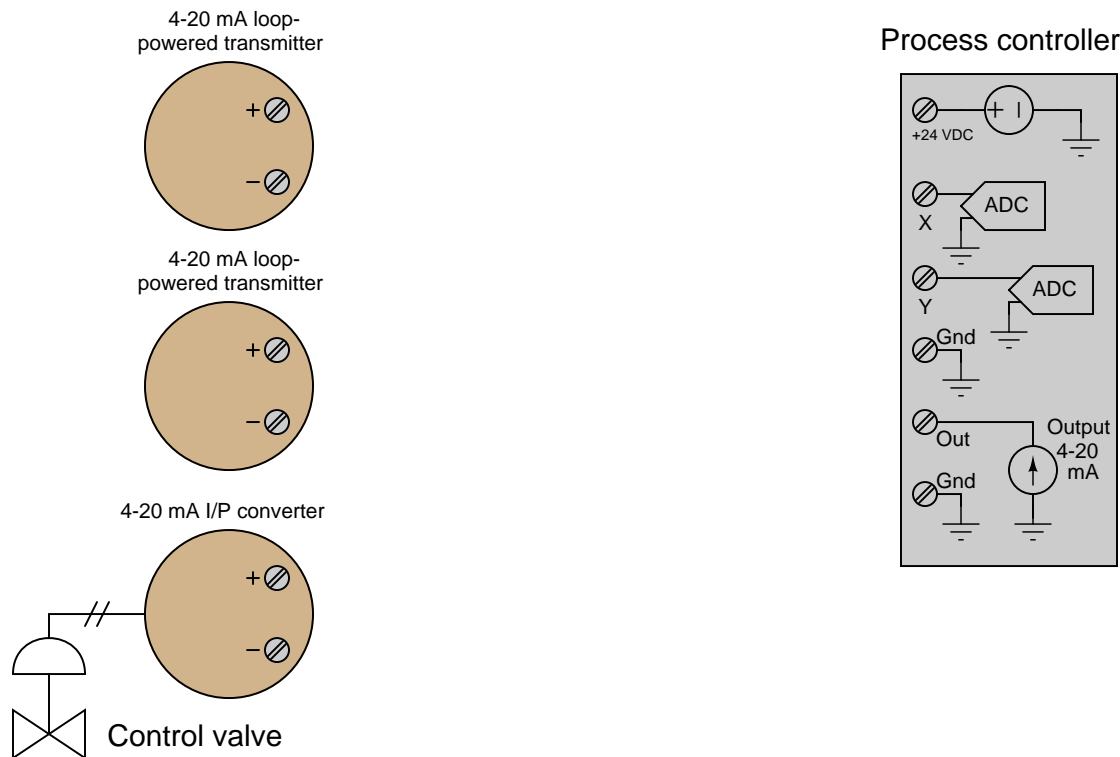
Show how all three field devices would properly connect to the controller, including the placement of resistors to convert the current signals into voltage signals that the controller's ADC's may interpret. Furthermore, use shielded cable, showing where all shield ground connections should be located.

file i02273

Question 90

The following strobe light has a problem: the flash tube never flashes.
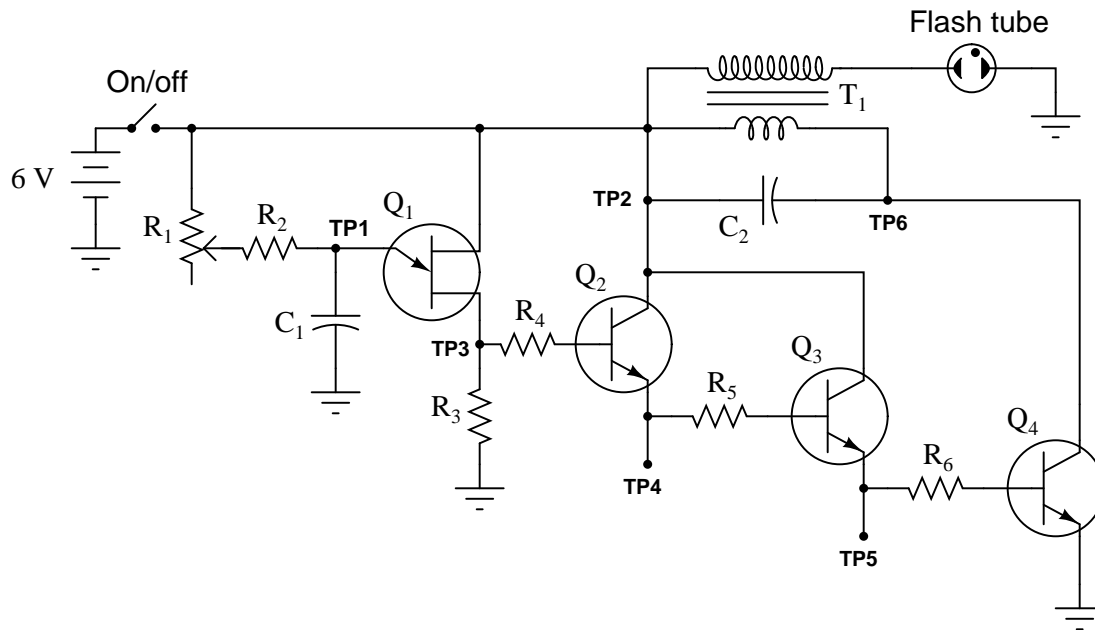
Turning the flash rate control (rheostat R_1) to the slowest position, you take two voltage measurements with a voltmeter: at test point 3 (between TP3 and ground) you measure a voltage rhythmically pulsating between about 1.5 and 4 volts DC. At test point 6 (between TP6 and ground) you measure about 0.3 volts DC all the time.

From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted) other than the 6 volt battery and the on/off switch. The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted
1.
2.

- Circuit elements that must be functioning properly
1.
2.

file i03187

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Question 91

Lab Exercise

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

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

Objective completion table:

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

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

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

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

Lab Exercise – objectives and expectations

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

Team meeting and prototype sketch

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

Circuit design challenge

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

Final loop diagram and system inspection

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

Troubleshooting simulation

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

Trend graph displays PV and Output

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

PV alarms defined and enabled

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

Process exhibits good control behavior

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

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

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

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

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

Lab Exercise – choosing a process to commission

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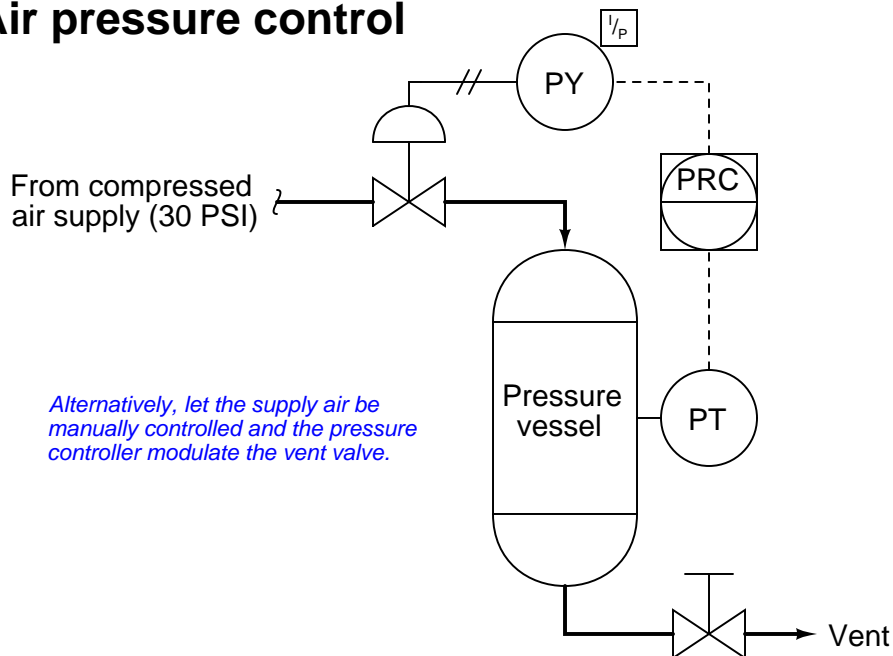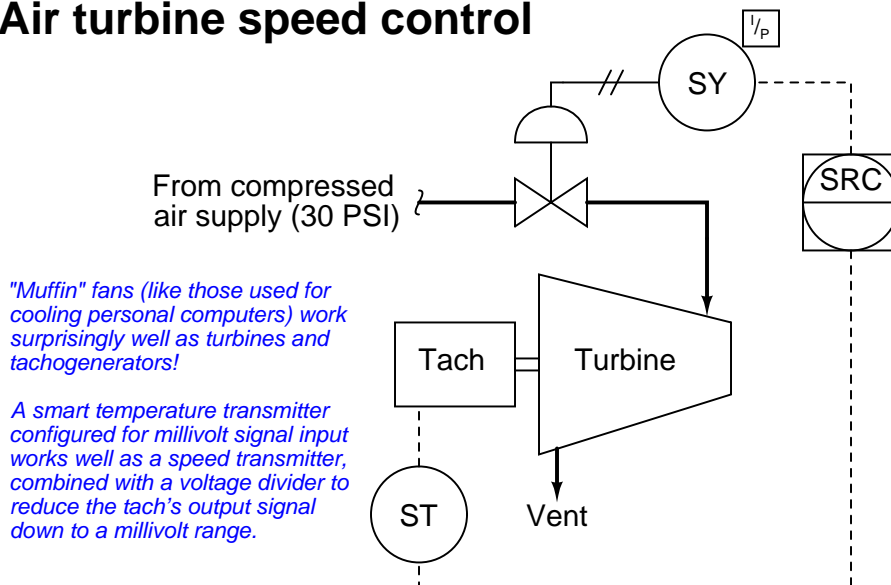
Water level control

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

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

LY

I/P

LRC

LT

Bypass
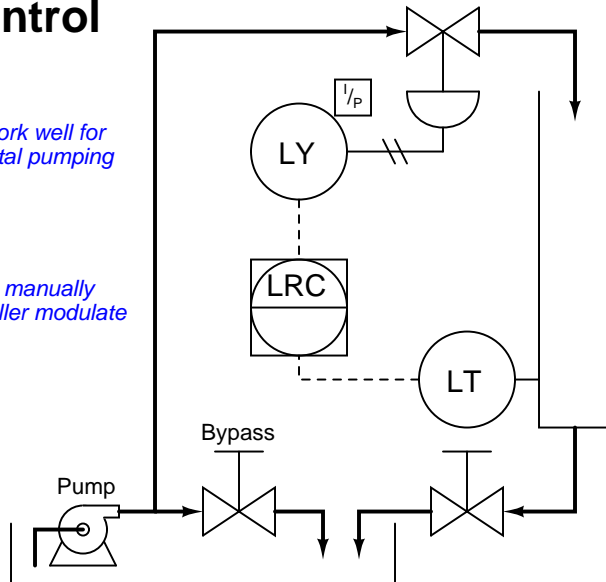
Pump

Water flow control

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

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

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

FT

√

FY

I/P

FRC

Bypass

Pump

78
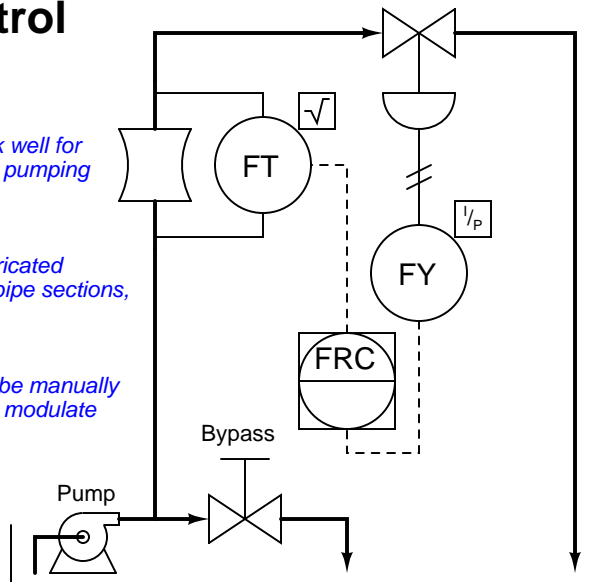
Oven temperature control

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

TT

TRC

TZ
(PWM)

Convection oven
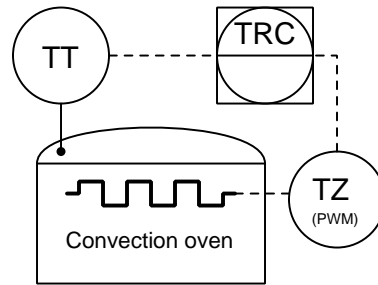
Solar air heater control

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

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

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

TT

TRC

TZ
(VFD or PWM)

Collector

Air fan
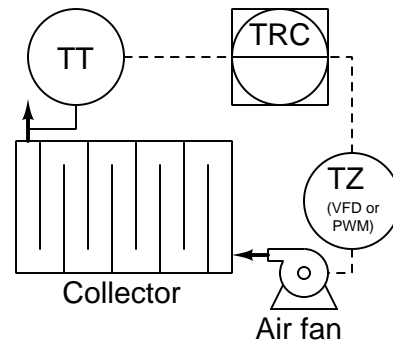
Other process ideas include:

- Soldering iron temperature control (blowing air over tip with variable-speed fan).

- Draft pressure control (controlling very low air pressure inside of a box).

- Pneumatic piston height control (using lengths of PVC pipe to build a simple piston/cylinder which may be used to lift small weights using modest air pressures). A good way to control air pressure to the piston is to route the I/P transducer's output to a *volume booster* relay and let the relay's output directly drive the piston. Piston height may be sensed using a flexible water tube attached to the piston rod, running to a stationary pressure transmitter.

- Sterno-fired air heat exchanger.

- Miniature steam boiler. *Note: this is an advanced project!*

- Air/Fuel ratio burner control. *Note: this is an advanced project!*

- Servomechanism position control. *Note: this is an advanced project!*

- Inverted pendulum balance. *Note: this is a <u>very</u> advanced project!*

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

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

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

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

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

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

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

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

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

Lab Exercise – circuit design challenge

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

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

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

4-20 mA transmitter options

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

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Controller options

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

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4-20 mA Final Control Element options

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

</div>

Correct circuit sketch (instructor verifies):   ____

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

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

Correct source/load identifications (instructor verifies):   ____

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

Lab Exercise – building the system

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

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

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

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

Common mistakes:

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

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

Notes on instrument ranging

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

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don't "know" what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 ^{o}F and output 20 mA when sensing 800 ^{o}F, but the controller must display an indication of 300 ^{o}F when it receives a 4 mA signal from the transmitter, and display an indication of 800 ^{o}F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 ^{o}F input (and 4-20 mA output) as well as range the controller to display 300-800 ^{o}F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:
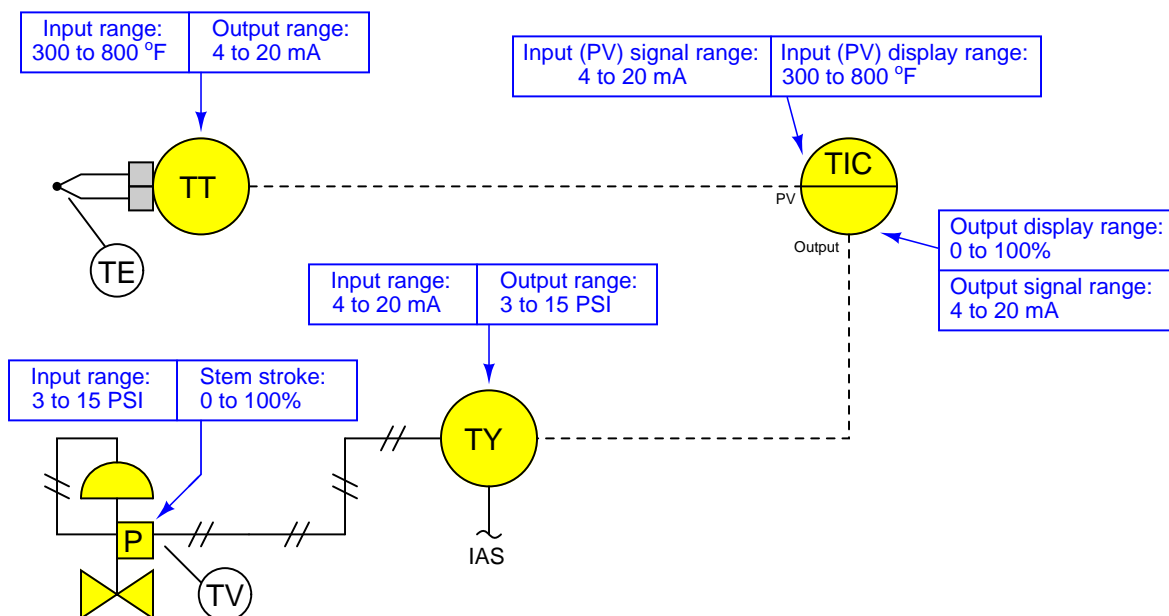
Analog (non-"smart") transmitters, I/P transducers, and valve positioners are ranged using "zero" and "span" adjustments, typically screws or nuts. The ranging of analog instruments is discussed in the "Instrument Calibration" chapter of the *Lessons In Industrial Instrumentation* textbook.

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

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

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

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

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

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

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

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

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

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

file `ranging`

Notes on controller action

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

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

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

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

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

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

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.

<u>file</u> `control`

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

Lab Exercise – troubleshooting

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

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

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

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

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

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

Common mistakes:

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

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

Lab Exercise – PV alarms

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

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

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

Lab Exercise – operating the system

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

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

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

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

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

Notes on troubleshooting feedback control loops

Recall that every feedback control loop consists of four basic elements: an element that *senses* the process variable (e.g. primary sensing element, transmitter), an element that *decides* what how to regulate this process variable (e.g. a PID controller), an element that *influences* the process variable (e.g. a control valve, motor drive, or some other final control device), and finally the process itself which *reacts* to the final control device's actions:
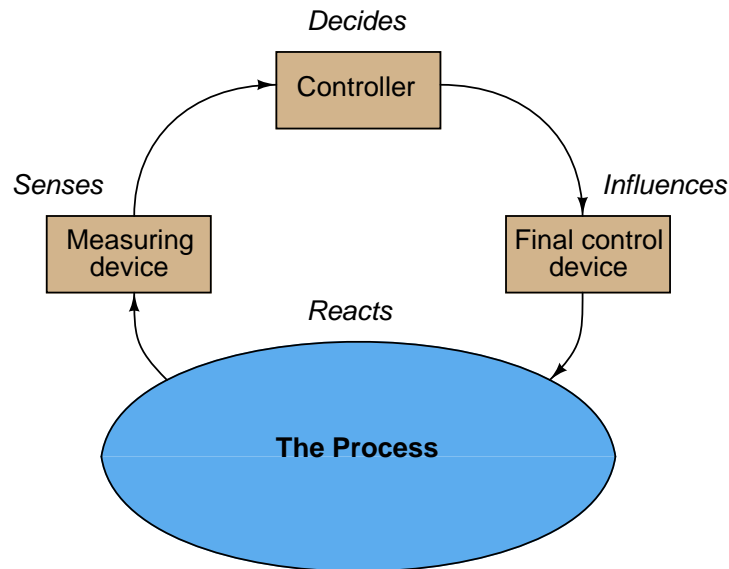
You can check each element of your feedback control loop by comparing its input with its output to see if each element is doing what it should:

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

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

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

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

A crude closed-loop PID tuning procedure

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

Step 1

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

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

Step 2

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

Step 3

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

Step 4

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

Step 5

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

Step 6

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

Step 7

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

Step 8

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

Step 9

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

Step 10

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

<div align="center">

Caveats

</div>

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

   file i01558

Loop Diagram: Furnace temperature control | **Revised by:** Mason Neilan | **Date:** April 1, 2007

| Process area | Field panel JB-12 | Control room panel CP-1 |

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

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

0-50 PSI

H
L
PT 73
+
−
Red
Blk
Cable PT-73

TB-52
Red | 1 | Red
Blk | 2 | Blk
Cable 4, Pr 1

TB-80
Red | 11 | Red
Blk | 12 | Blk
Cable PT-73
Red | 11
Blk | 12

Card 4
Channel 6
Analog
input

0-50 PSI
PIC 73

Tube PV-73

PV 73

I/P

O
PY 73
+
−
S
Red
Blk

AS 20 PSI

Cable PV-73

TB-52
Red | 15 | Red
Blk | 16 | Blk
Cable 4, Pr 8

TB-80
Red | 29 | Red
Blk | 30 | Blk
Cable PV-73
Red | 11
Blk | 12

Card 6
Channel 6
Analog
output

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

Sample Loop Diagram (using pneumatic controller)

Loop Diagram: Sludge tank level control	**Revised by:** I. Leaky	**Date:** April 1, 2008

Process area	Bulkhead panel B-104	Control panel CP-11

H
L
LT 24
Out
(vent)
In
A.S. 21 PSI

Tube LT-24a

14

Tube LT-24b

C
LIC 24
D
Supply
A.S. 21 PSI

LV 24

Tube LV-24

Tube LV-24

Tube LV-24

Tube LV-24

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

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

Process area | Field panel FP-25

Sample Loop Diagram (using PLC, with electronic positioner installed on valve)

101

Diagram labels:

- H, L, FT 18, +, −, Red, Blk, Cable FT-18, 0-75 GPM
- Red, 21, Blu, 22, Blu, 10, 800 mA, Blu, Blu, +, 24 VDC 1 amp, Blu, PS-1
- 120 VAC, L1, N, Blk, Wht, Grn
- Blu, IN0+, IN0-, IN1+, IN1-, IN2+, IN2-, IN3+, IN3-, 1762-IF4 analog input card expansion slot 1
- A, P, Loop +, Loop −, Supply, Red, Blk, Cable FV-18, IAS 20 PSI
- FV 18
- Red, 11, Blu, 12, Blu, I out 0, V out 0, I out 1, V out 1, I out 2, V out 2, I out 3, V out 3, Blu, Com, Com, 1762-OF4 analog output card expansion slot 2
- FC 18, L2/N, L1, Ethernet, FIR 18, (Located in main control room)
- 1A, 1A, 1, 2, 3, 4, Blk, Wht, Grn, ES 120 VAC From field panel disconnect

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

Lab Exercise – loop diagram and system inspection

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

Construction Standards

- All construction must be *safe* (i.e. must not pose any unnecessary hazard to students or visitors). This includes electrical, chemical, thermal, pressure, and general safety hazards (e.g. trip hazards, cut hazards). *Unsafe construction will be dismantled upon discovery.*
- All electrical sources greater than 30 volts must be overcurrent-protected and all related wire connections must be guarded against accidental contact (e.g. use recessed terminals with no exposed metal).
- Proper use of colors for electrical power source wiring (e.g. red and black for DC + and −, black and white for AC "hot" and "neutral", green for earth ground).
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- Each signal cable and each signal tube must have an identifying label documented and attached. Long cables must be labeled at each end, as close to the termination points as practical.
- Each team must have its own unique loop number.
- Each instrument's (final) calibrated range must be shown.
- Each control valve's fail mode (e.g. fail-open, fail-closed) or action must be shown.
- All writing must be legible (i.e. easy for anyone to read). *Hint: large-format paper helps!*
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- Any controller I/O cards must be labeled with slot number and channel number in addition to terminal numbers.

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

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

Common mistakes:

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

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

file i00654

Answers

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7

Partial answer:

Both errors are exhibited in this test.

Answer 8

Alternatively, one could use a *potentiometer* connected as a limited-range variable resistance rather than a decade box. If using a potentiometer, you would have to rely on a multimeter as the resistance calibration standard, measuring the resistance while precisely adjusting it to the desired resistance value.

You may find that a potentiometer by itself provides too coarse of an adjustment to settle at precisely the resistance values you wish during calibration. This will be especially true if the potentiometer's full-scale value is large compared to the desired resistance (e.g. a 1 kΩ potentiometer being used to simulate an RTD resistance of 123.7 Ω results in you having to use a very small range of the potentiometer). One way to narrow the resistance range of your potentiometer is to connect it in parallel with a fixed resistor like this:
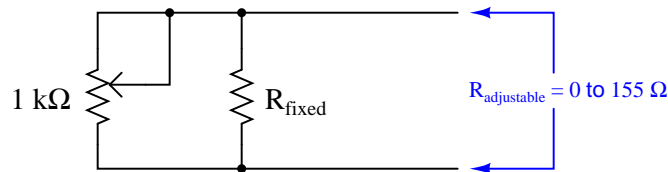
What must the size of R_{fixed} be in order
to provide the desired range of 0 to 155 Ω ?

For practice, calculate the fixed resistor value necessary to limit this 1 kΩ potentiometer's adjustment range to 0 to 155 Ω.

$R_{fixed} =$ _____ Ω

Of course, finding a potentiometer with a full-scale range close to the desired resistance adjustment range is the best way to go. The parallel fixed-resistor solution is merely a way to "make do" with a potentiometer that is less than ideal.

Answer 9

Answer 10

Answer 11

Answer 12

Answer 13

Answer 14

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

Answer 23

Answer 24

Answer 25

Answer 26

Answer 27

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

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

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

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

```
tar xvf tshoot*tar

make
```

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

```
./tshoot
```

Answer 28

Answer 29

- **Pressure gauge**
- LRV = 0 PSI
- URV = 100 PSI
- Test pressure = 65 PSI
- Instrument indication = 67 PSI
- Error = *+2* % of span

- **Weigh scale**
- LRV = 0 pounds
- URV = 40,000 pounds
- Test weight = 10,000 pounds
- Instrument indication = 9,995 pounds
- Error = *-0.0125* % of span

- **Thermometer**
- LRV = -40°F
- URV = 250°F
- Test temperature = 70°F
- Instrument indication = 68°F
- Error = *-0.69* % of span

- **pH analyzer**
- LRV = 4 pH
- URV = 10 pH
- Test buffer solution = 7.04 pH
- Instrument indication = 7.13 pH
- Error = *+1.5* % of span

Answer 30

Hysteresis and dead band are not exactly the same type of calibration error, but they are closely related. "Dead band" refers to a range of instrument measurement during reversal of input where the output does not change at all. A common example of this is a "loose" steering system in an automobile, where the steering wheel must be turned excessively to take up "backlash" (mechanical slack) in the linkage system.

Hysteresis refers to the situation where a reversal of input causes an immediate, but not proportionate, reversal of output. This is commonly seen in air-actuated valves, where air pressure acts against the action of a large spring to precisely position a valve mechanism. Ideally, the valve mechanism will move proportionally to the air pressure signal sent to it, and this positioning will be both repeatable and accurate. Unfortunately, friction in the valve mechanism produces hysteresis: a different air pressure signal may be required to position the valve mechanism at the same location opening versus closing, but unlike dead band, *any* amount of signal reversal (change of direction: increasing vs. decreasing) will cause the valve to move slightly.

Compare the following transfer function graphs to understand the difference between hysteresis and dead band:
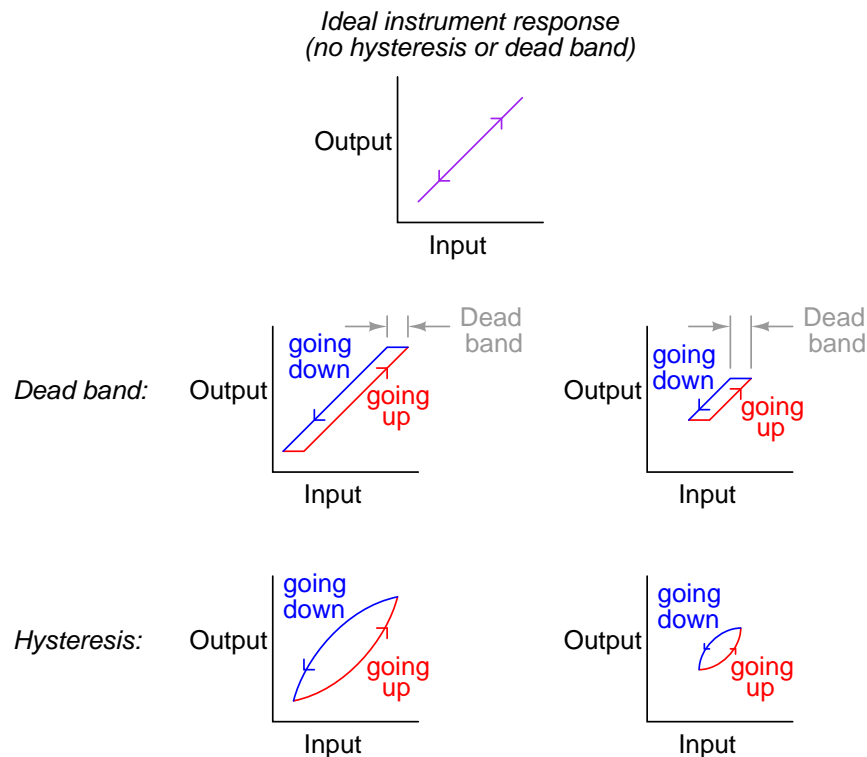
Both dead band and hysteresis are characteristically mechanical phenomena. Electronic circuits rarely exhibit such "artifacts" of measurement or control. Dead band and hysteresis are more often found together than separately in any instrument.

Interestingly, both effects are present in magnetic circuits. The magnetization curves for typical transformer core steels and irons are classic examples of hysteresis, whereas the magnetization curve for ferrite (in the saturation region) is quite close to being a true representation of deadband.

Answer 31

I'll answer the question with a scenario of my own: suppose it is discovered that some patients suffered complications after taking drugs manufactured by this company, and that the particular batch of suspect drugs were processed in this very same vessel about 6 months ago? Now imagine that this temperature recording instrument gets routinely calibrated once a month. See the problem?

Answer 32

± 0.064 mA

Answer 33

15.43 milliamps of current equates to a percentage value of 71.44%:

$$\frac{15.43 - 4}{16} \times 100\% = 71.44\%$$

This, in turn, represents a pH value of:

$$0.7144 \times (12 - 2) + 2 = 9.144 \text{ pH}$$

This largely agrees with the controller's display, which tells us there is a *slight* calibration error on either the part of the controller or the resistor. The huge discrepancy between this calculated pH value and what the hand-held pH meter registers, however, tells us there is either a problem with the pH transmitter, the pH probe, or the hand-held meter. We may further conclude there is no problem with the 250 Ω resistor or the indicating controller.

The proper setup of the loop calibrator is to place it into the "READ" (measure) mode so that it functions as a simple ammeter, then connect it in series with the output of the 4-wire transmitter. This may be done either with the indicating controller still in the circuit, or removed from the circuit.
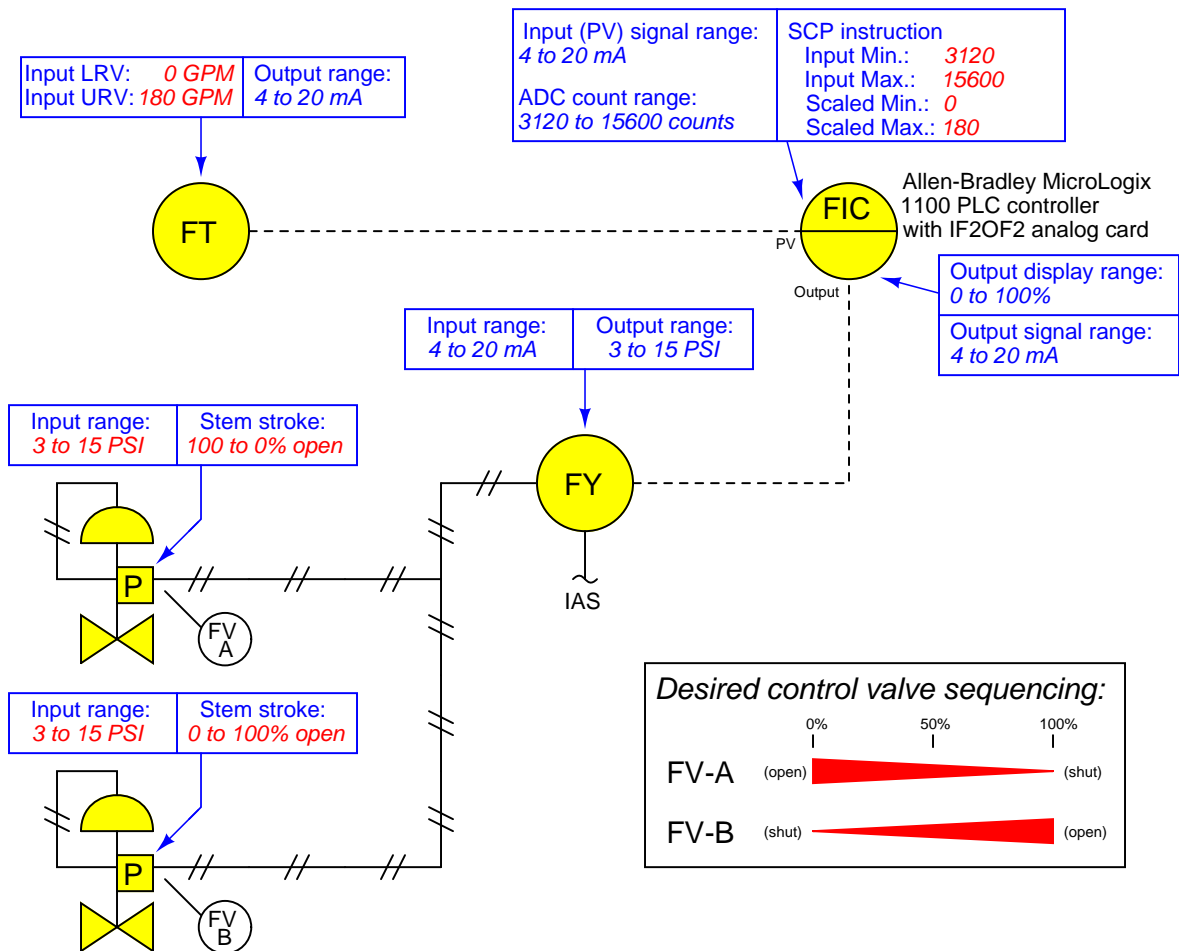
Answer 34

Simply setting the LRV and URV values is not actually *calibrating* the transmitter to accurately correspond to reality. If this concept is hard to grasp, imagine a transmitter whose LRV and URV values are set perfectly, and whose DAC is calibrated just right, but whose ADC suffers from a zero shift. The microprocessor will "think" the pressure is something different from what it really is, and it will output an incorrect (zero-shifted) milliamp signal as a result.

In order to perform a sensor trim, you must connect a known pressure source (a *standard*) to the transmitter's input port and correlate that standard pressure to the pressure value registered by the microprocessor. When trimming the output, you must connect a precise milli-ammeter in series with the transmitter's output current to correlate the intended current signal of the microprocessor to the actual current.

Answer 35

The transmitter is at fault, not the indicator.

Input (PV) signal range: *4 to 20 mA*

ADC count range: *3120 to 15600 counts*

SCP instruction
Input Min.: *3120*
Input Max.: *15600*
Scaled Min.: *0*
Scaled Max.: *180*

Input LRV: *0 GPM*
Input URV: *180 GPM*

Output range: *4 to 20 mA*

Allen-Bradley MicroLogix 1100 PLC controller with IF2OF2 analog card

FT

FIC

PV

Output

Output display range: *0 to 100%*

Output signal range: *4 to 20 mA*

Input range: *4 to 20 mA*

Output range: *3 to 15 PSI*

Input range: *3 to 15 PSI*

Stem stroke: *100 to 0% open*

FY

IAS

P

FV A

Input range: *3 to 15 PSI*

Stem stroke: *0 to 100% open*

P

FV B

Desired control valve sequencing:

0%   50%   100%

FV-A   (open)   (shut)

FV-B   (shut)   (open)

A PV measurement error could lie within the transmitter, or within the controller's analog input. A single current measurement of the transmitter's signal will tell you where the calibration error resides.

A valve positioning error affecting both control valves could lie within the I/P transducer or within the controller's analog output. A single current measurement of the controller's output signal will tell you where the calibration error resides.

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

Answer 45

It is worthy to note that in addition to its use as a fungicide for diesel fuel, acrolein has seen application as a *chemical weapon* due to its extreme toxicity.

Answer 46

Note: "OS" refers to "Operator Station" in this diagram, not "operating system" as one might think.

Answer 47

Lack of authentication (i.e. determining user identity) and encryption (obscuring data to outside observers) is a function of convenience. SCADA systems are generally made to be as simple and reliable as possible to maximize their uptime in industrial applications. Security measures complicate commissioning, and up to now have not been considered important. "Cleartext" refers to data being communicated in plain-ASCII format where anyone intercepting the data could easily tell what the data meant. Cleartext communications makes eavesdropping very simple.

Threat vectors:

- **Replay attack**: where a communicated message is copied by a malicious party and re-sent at a later time to cause trouble.

- **Man-in-the-Middle attack**: where the malicious party positions themselves in the middle of a communication path, so as to intercept and control all data flowing through.

- **Brute force attack**: cracking a password or an encrypted data packet by trying combinations of characters as the key.

- **Dictionary attack**: a more sophisticated approach to cracking passwords or encrypted data, relying on a lexicon of common phrases to try rather than random character combinations.

- **Eavesdropping**: self-explanatory

- **Denial-of-Service attack**: an attack which halts the system's intended functionality.

- **War Dialing**: Randomly calling phone numbers to check for the existence of modems which may later be attacked for access into their systems.

- **Data modification**: when intercepted data is modified during a Man-in-the-Middle attack.

A "hash" is a fixed-length data string generated from a data set of arbitrary length. If two data sets are "hashed" using the same algorithm, and the resulting hash signatures don't match, then the data sets are not identical. If the hash signatures do match, then the data sets are very likely identical. The HMAC method uses a secret key to generate a hash signature from a data set. That hash signature is transmitted along with the original data, and the receiver checks integrity of the data by running it through the same hashing algorithm using the same secret key. If the hash signatures match, then the receiver knows with a high degree of confidence that the data is untampered. Hash signatures are very similar to *checksums* used to test for data corruption due to communication errors, and in fact fulfill the same role in addition to checking for evidence of tampering.

- **Use dependable WAN infrastructure**: proven communication methods such as SONET equipped with strong encryption should be used for all wide-area networks (WANs).

- **Fortifying Ethernet**: a secure gateway should bridge Ethernet-based devices to the WAN, serving as an authentication proxy for all remote connections; limitations should be placed on MAC addresses for Ethernet switches; all Ethernet traffic should be logged; loss of link status may flagged via special gateways to signal cable breach or vandalism.

- **Fortifying wireless**: use encrypted radio transceivers; use encryption with all Bluetooth connections (Enhanced Data Rate [EDR] and Secure Simple Pairing [SSP]).

- **Fortifying serial**: use encryption devices at both ends of every serial communication link.

- **Exploit precision timestamps**: the precision time signatures present in some SCADA systems (e.g. the IRIG-B time based on GPS satellites, used for synchrophasor protection in electric power systems) may be put to use to identify the time of security-related events.

- **Close backdoor passwords and maintenance accounts**: ensure that equipment does not come from the manufacturer with these vulnerabilities.

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- **Fortify engineering access**: remote access necessary for maintenance and engineering tasks of the SCADA system must be equipped with encryption, authentication, and access control (authentication); such access must also be logged (audited).

- **Authentication**: *admittedly, this section is not very well-written.*

- **Use whitelisting instead of blacklisting**: traditional anti-malware techniques prioritized freedom over security by allowing any application to run except for those that appeared suspicious (blacklisted); whitelisting takes the opposite stance, that nothing is allowed to run except for what appears on the permitted list (whitelist).

- **Detect physical tampering**: equip field installations with sensors to detect intrusion.

- **Layer networks**: use switches and gateways to segregate SCADA networks into layers, the most critical layer being the furthest away from the internet.

- **Use highly-reliable computers**: computers lacking cooling fans and other moving parts have much higher MTBFs than consumer-grade PCs, and should be used for critical security controls.

- **Intrusion Detection System (IDS)**: apply systems designed to look for suspicious activity within the protected network such as port scanning, improper message format, rejected access attempts, buffer overflows, etc.

Answer 48

Answer 49

Answer 50

Answer 51

Answer 52

Answer 53

Answer 54

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

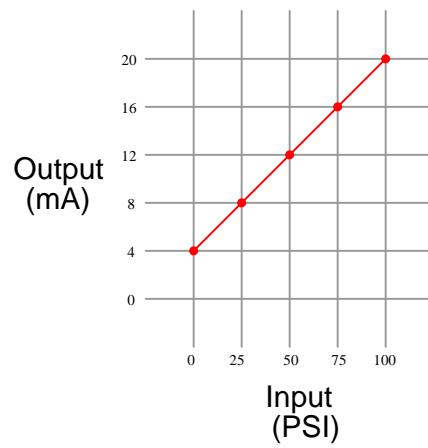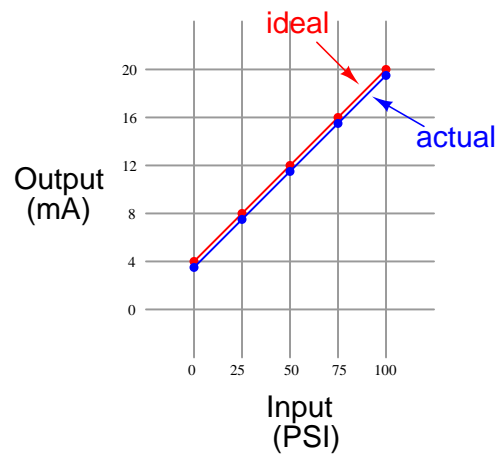---

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

This instrument has a *zero shift* error, but not a *span shift* or *linearity* error.
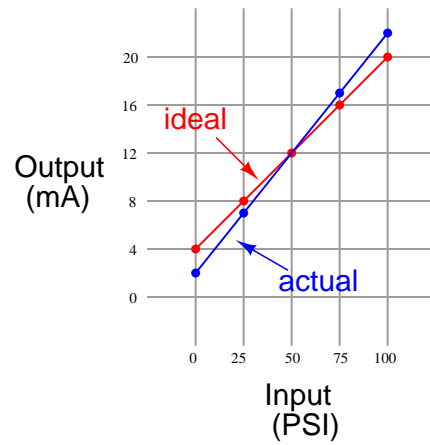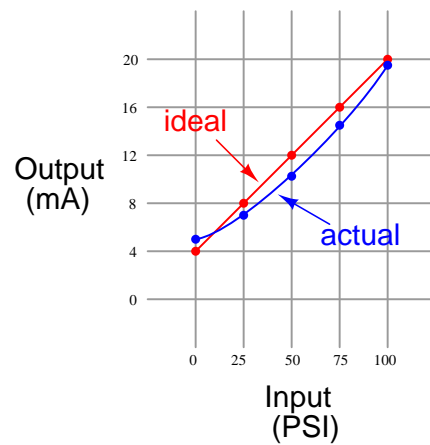
Ideal transfer function:

Actual transfer function: (zero error)

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A span error would look something like this (wrong slope):

A linearity error would look something like this (not a straight line):

A zero error is usually correctable by simply adjusting the "zero" screw on an analog instrument, without making any other adjustments. Span errors, by contrast, usually require multiple adjustments of the "zero" and "span" screws while alternately applying 0% and 100% input range values to check for correspondence at both ends of the linear function.

Answer 65

This transmitter definitely has a *linearity* error:
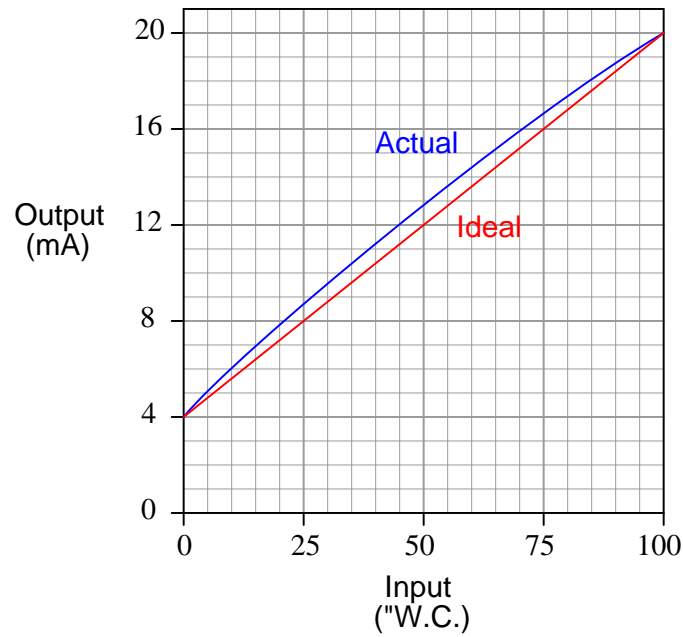
Answer 66

Answer 67

Diagnostic test	Yes	No
Measure AC line voltage		√
Measure DC power supply output voltage		√
Inspect PID tuning parameters in controller		√
Check pressure transmitter calibration	√	
Measure transmitter current signal	√	
Put controller into manual mode and move valve	√	
Measure DC voltage between TB1-3 and TB1-4	√	
Measure DC voltage between TB1-7 and TB1-8		√

The fact that the gauge and controller disagree on pressure tells us the problem is either with the gauge, or with the transmitter-controller signal path. Nothing else (tuning, power, valve) could cause this to happen. Therefore, valid tests include anything to help is discern whether there is a problem in the gauge, in the transmitter, in the resistor, or in the controller's PV input.

Answer 68

Fault	Possible	Impossible
LT calibration error		✓
LY calibration error	?	
Controller failed	✓	
Low air supply pressure	✓	
Excessive resistance in LT circuit		✓
Excessive resistance in LY circuit		✓
Feedwater pump worn	✓	
Controller in manual mode	?	

An LY calibration error is possible only if the error is quite significant. Otherwise, the controller will compensate for any modest valve errors through feedback.

The "excessive resistance" faults are not possible if we assume the extra resistance to be insufficient to cause the controller or transmitter to saturate. Ideally, both current sources (LT and LIC) will fight as hard as they must to maintain proper current in each circuit, even with extra resistance. However, if the extra resistance is very large, it would be possible for that resistance to force either current value to be less than it should be.

A controller in manual usually does not allow changes in setpoint due to the standard "setpoint tracking" feature. If this feature is turned off, however, changes in setpoint are possible in manual mode.

A good "next test" is to inspect the controller's output indication to see what it is trying to do to remedy the low process variable. The output should be saturated at 100% (wide-open valve) if the controller is doing its job. If not, the controller has a problem (e.g. left in manual mode, poor tuning). If the output is saturated as we would expect it to be, then the next logical place to check is the control valve to see whether or not the valve is actually making it to the full-open position.

Answer 69

Calculating the proper RTD resistance for 60 degrees Celsius:

$$R = 100[1 + 0.00385T]$$

$$R = 100[1 + (0.00385)(60)]$$

$$R = 100[1 + 0.231]$$

$$R = 100[1.231]$$

$$R = 123.1 \, \Omega$$

The very first step to perform is to disable the relay's ability to trip the circuit breaker. Disconnecting the wire between the relay and the breaker's trip coil would suffice, taking care to perform this disconnection in such a way as to avoid shock hazard. Re-enabling the relay's ability to trip the breaker should be the very last step.

Given that this will be a *high* temperature trip function, the calibration test should be done with the resistance *increasing* rather than decreasing. In other words, the relay should issue a trip command (as verified by an ohmmeter) at 123.1 Ω *rising*.

Answer 70

A good step to take next is to figure out whether the problem is on the output side of the control system or on the input side of the control system. Is the slow pressure trend real, and the control valve not responding as quickly as it should? Is the pressure actually changing quickly, but the measurement side of the system not accurately reporting it as it should?

Probably the best first-step here is to actually go to the control valve and observe how fast it responds to step-changes from the controller (manual mode).

Answer 71

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 72

Fault	Possible	Impossible
PG-108 calibration error	√	
PT-33 calibration error	√	
PIC-33 left in manual mode		√
PY-33a calibration error		√
PY-33b calibration error		√

The fact that the gauge disagrees with both the recorder and the controller tells us the problem is either with the gauge, or with the transmitter. Nothing else (controller mode, valve signal path, PY-33a) could cause this to happen. Therefore, valid tests include anything to help is discern whether there is a problem in the gauge, in the transmitter, in the resistor, or in the controller's PV input.
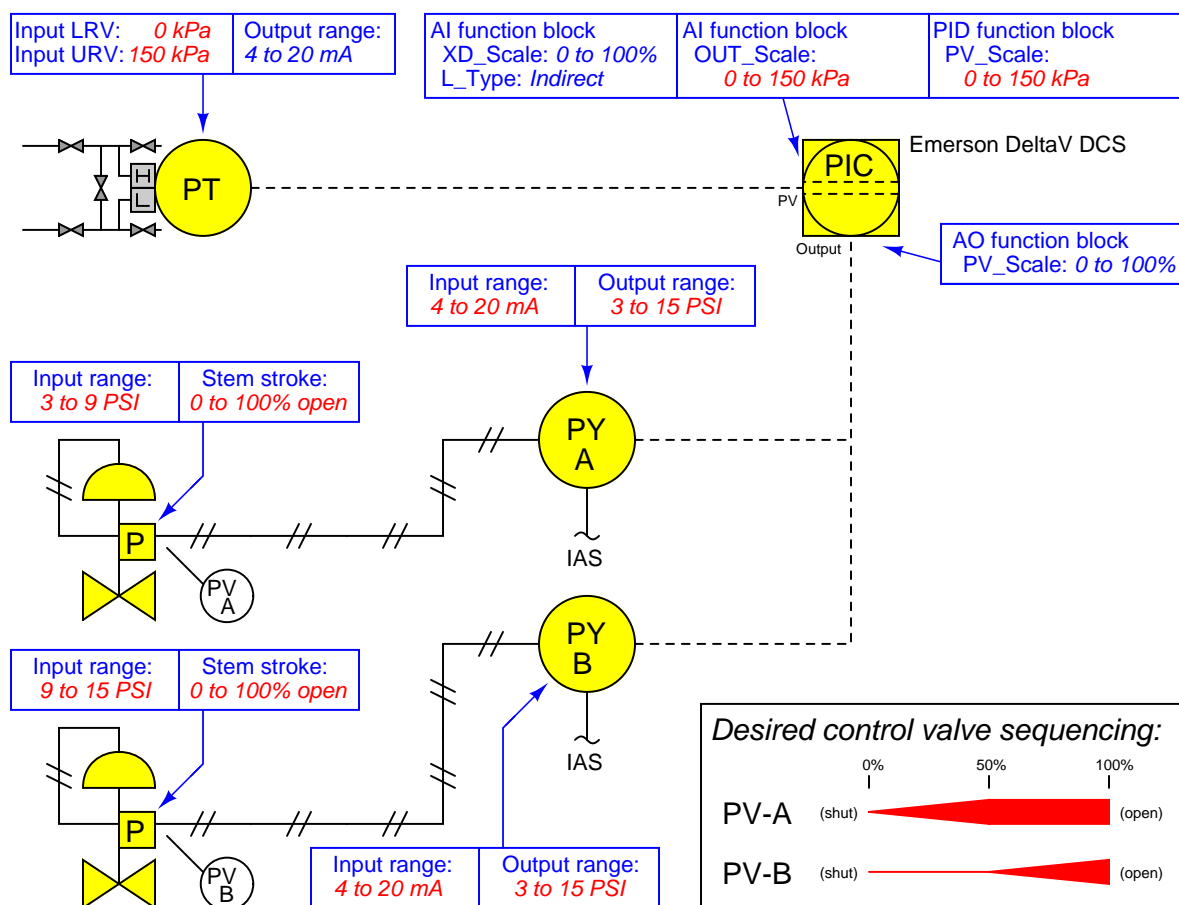
Answer 73

Chances are there is something wrong with the ID fan, causing it to move less air than it should. Alternatively, the FD fan could be at fault, spinning faster than it should.

Answer 74

This ranges shown here for split-ranging the two control valves do not constitute the only possible range values that will work!

Try to identify what *other* I/P and control valve positioner range values will also yield the desired split-range sequencing.

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

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