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Lab

Pressure measurement loop: *Questions 91 and 92, completed objectives due by the end of day 5, section 2*

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Exam

*Day 5 of next section* – only a simple calculator may be used! **Complete mastery of these objectives due by the next exam date**

*Specific objectives for the “mastery” exam:*

- Electricity Review: Calculate and annotate voltages and currents in a DC series-parallel resistor circuit given source and resistor values
- Convert between different pressure units (PSI, "W.C., bar, etc.) showing proper mathematical cancellation of units (i.e. the “unity fraction” technique)
- Calculate pressure applied to a DP instrument in a realistic scenario
- Calculate instrument input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a series-parallel 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
- INST251 Review: Determine the effect of a component fault or condition change in a single-loop controlled process
- INST260 Review: Convert between different numeration systems (decimal, binary, hexadecimal, octal)

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**Recommended daily schedule**

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Day 1

**Theory session topic:** Concepts of pressure and pressure unit conversions

Questions 1 through 20; answer questions 1-9 in preparation for discussion (remainder for practice)

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Day 2

**Theory session topic:** Pressure measurement technologies

Questions 21 through 40; answer questions 21-28 in preparation for discussion (remainder for practice)

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Day 3

**Theory session topic:** Instrument calibration

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

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Day 4

**Theory session topic:** Electronic pressure measurement

Questions 61 through 80; answer questions 61-69 in preparation for discussion (remainder for practice)

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

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## Introduction to Fall Quarter

This quarter focuses on the subject of *measurement*. Ideas to keep in mind for special projects (alternatives to standard lab as well as extra-credit) include measuring and recording physical variables in and around the college campus. For those who have studied programmable logic controllers (PLCs), there will be application to use your PLCs again if equipped with analog inputs to receive the 4-20 mA signals produced by industrial transmitters.

## How To . . .

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

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

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

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

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

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

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

**Identify courses to register for:** read the “Sequence” page found in each worksheet.

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

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

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

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

file howto

## General Values, Expectations, and Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

## General Values, Expectations, and Standards (continued)

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

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

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

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

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

**Independent Problem-Solving:** make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given to you 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 account daily for important messages from your instructor. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly and compellingly.

**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 provided you have signed the FERPA release form. You are welcome to see these records at any time, and are encouraged to track your own academic progress using the grade spreadsheet template.

**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 240 Course Outcomes

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

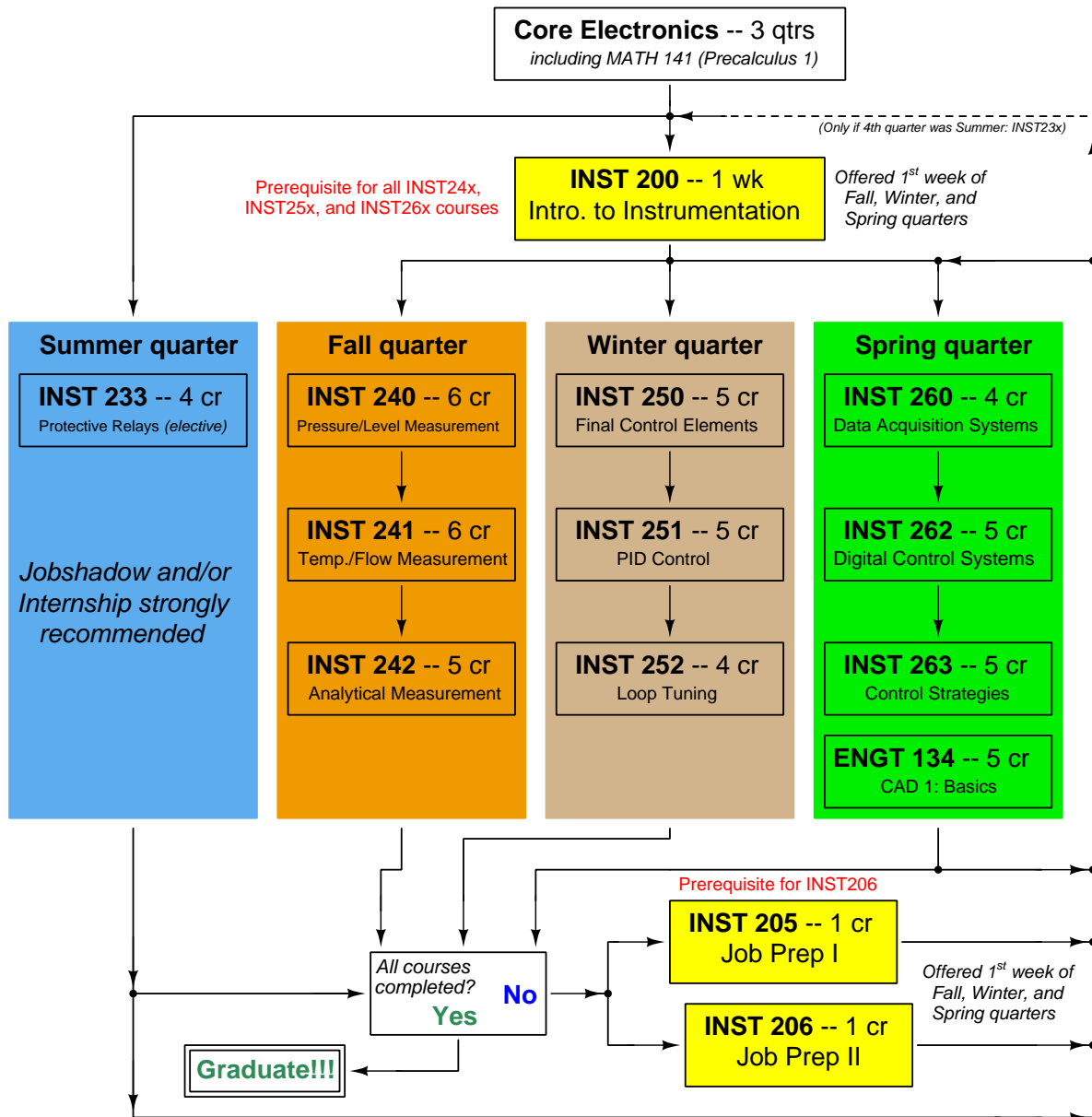
- Calculate and annotate voltages and currents in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]
- Calculate voltages, currents, powers, and/or resistances in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]
- Convert between different pressure units (PSI, "W.C., bar. etc.) showing proper mathematical cancellation of units (i.e. the "unity fraction" technique). [Ref: Program Learning Outcome #7]
- Determine suitability of different level-measuring technologies for a given process fluid type. [Ref: Program Learning Outcome #5]
- Calculate pressure applied to a DP instrument given a pictorial diagram. [Ref: Program Learning Outcome #4]
- Calculate ranges for hydrostatic (DP) level-measuring instruments given physical dimensions and fluid densities. [Ref: Program Learning Outcome #4]
- Calculate buoyant force values for a displacer-type level-measuring instrument at different liquid levels. [Ref: Program Learning Outcome #4]
- 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 series-parallel circuits and Wheatstone bridge circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]
- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all lab work. [Ref: Program Learning Outcomes #1 and #2]
- Construct and commission a working pressure-measurement loop consisting of an electronic pressure transmitter, signal wiring, and indicator. [Ref: Program Learning Outcome #5]
- Construct and commission a working level-measurement loop consisting of an electronic level transmitter, signal wiring, and indicator. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team's systems. [Ref: Program Learning Outcome #8]
- Build a circuit using an electromechanical relay to energize an AC load, and measure current in this circuit, given a switch and relay both randomly selected by the instructor. [Ref: Program Learning Outcome #5]
- 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]

- Calibrate an electronic pressure transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Demonstrate the proper usage of a deadweight tester for generating precise pressures. [Ref: Program Learning Outcome #7]
- Calibrate an electronic level transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Demonstrate the proper usage of a manometer for measuring gas pressure. [Ref: Program Learning Outcome #7]
- Diagnose a random fault placed in another team's pressure measurement 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]
- Diagnose a random fault placed in another team's level measurement 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]



## Sequence of second-year Instrumentation courses



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

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

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



file sequence

## General tool and supply list

### Wrenches

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

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

### Pliers

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

### Screwdrivers

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

### Electrical

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

### Safety

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

### Miscellaneous

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

file tools

## Methods of instruction

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

### Inverted theory sessions

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

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

#### Small sessions

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

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

#### Large sessions

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

#### Correspondence

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

## Methods of instruction (continued)

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

### Sample rubric for pre-assessments

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

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

### Sample rubric for post-assessments

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

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

## Methods of instruction (continued)

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

## Methods of instruction (continued)

### Lab sessions

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

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

### Troubleshooting assessments must meet the following guidelines:

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

## Distance delivery methods

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

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

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

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

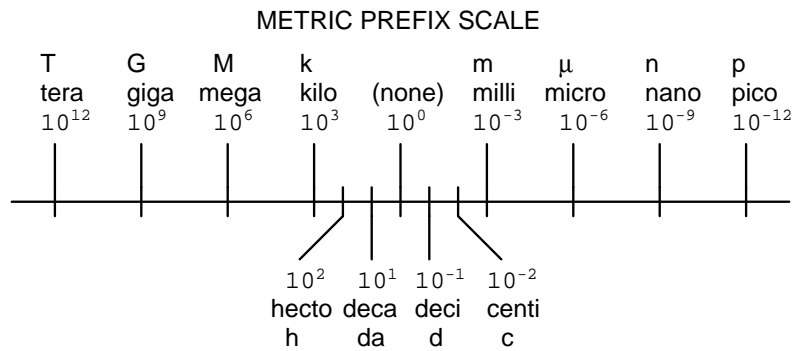
Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either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

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

## Metric prefixes and conversion constants

- **Metric prefixes**

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



- **Conversion formulae for temperature**

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

### Conversion equivalencies for distance

- 1 inch (in) = 2.540000 centimeter (cm)
- 1 foot (ft) = 12 inches (in)
- 1 yard (yd) = 3 feet (ft)
- 1 mile (mi) = 5280 feet (ft)



**Conversion equivalencies for volume**

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

1 milliliter (ml) = 1 cubic centimeter (cm<sup>3</sup>)

**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<sup>2</sup>) = 4840 square yards (yd<sup>2</sup>) = 4046.86 square meters (m<sup>2</sup>)

**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<sup>10</sup>  
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<sup>2</sup>) = 32.1740 feet per second per second (ft/s<sup>2</sup>)

### 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 ( $\text{mol}^{-1}$ )

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<sup>4</sup> ( $\text{W}/\text{m}^2 \cdot \text{K}^4$ )

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

### Properties of Water

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

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

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

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

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

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

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

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

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

### Properties of Dry Air at sea level

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

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

### General challenges following a tutorial reading assignment

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Was the text confusing at any point(s)? If so, what was it about the text's presentation that made it difficult to understand?
- Do you see any way(s) in which the text could be improved? Articulate your ideas for improvement, and explain why those improvements are indeed better.
- Did you encounter any new concepts in the text? If so, explain each in your own words.
- Did the text apply any familiar concepts (including fundamental laws or principles) in new ways? What exactly was different about this application?
- Was the text surprising to you in any way? If so, how so?
- What background knowledge should a reader possess prior to reading this text?
- Devise a proof of concept experiment to empirically demonstrate an important principle, physical law, or technical innovation represented in the text.
- Devise your own thought experiment to virtually demonstrate the same.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Devise an experiment to clearly disprove one of these misconceptions, to show by counter-example how the misconception in question cannot be true.
- Did the text model any useful problem-solving strategies for the benefit of the reader? If so, describe one of those strategies in terms general enough to apply to some other problem.
- Devise a question of your own to challenge a reader's comprehension of the text.
- Identify where it might be easy for someone to misunderstand the text.
- Describe your own reading process. Did you skim the text first and then read it in detail from start to finish? Do you take notes as you go along, or read large sections of the text before making any notes on it? Did you identify any key words, phrases, or ideas that helped make sense of the text overall? Were there sections of the text you needed to read multiple times? How do you divide your time between examining illustrations and the reading the text accompanying those illustrations?

### General follow-up challenges for assigned problems

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

- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

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### Question 1

Read and outline the “Pressure” subsection of the “Fluid Mechanics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

A note-taking technique you will find far more productive in your academic reading than mere highlighting or underlining is to write your own *outline* of the text you read. A section of your *Lessons In Industrial Instrumentation* textbook called “Marking Versus Outlining a Text” describes the technique and the learning benefits that come from practicing it. This approach is especially useful when the text in question is dense with facts and/or challenging to grasp. Ask your instructor for help if you would like assistance in applying this proven technique to your own reading.

#### Suggestions for Socratic discussion

- Explain how the Conservation of Energy – one of the most fundamental laws in physics – applies to levers, hydraulic systems, and electrical transformers.
- Can air be substituted for oil in a hydraulic jack, such as the type used to lift a car’s wheel off the ground? Why or why not?
- Describe some units of measurement for pressure other than the Pascal or the “pound per square inch”.

[file i03894](#)

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## Question 2

Read and outline the “Pascal’s Principle and hydrostatic pressure” subsection of the “Fluid Mechanics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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### **Suggestions for Socratic discussion**

- Does Pascal’s Law apply only to liquids, or to gases as well?
- Explain what is going on with the *dimensional analysis* example.
- How would the property(ies) of a fluid have to change in order for Pascal’s Law *not* to apply anymore?
- Explain how you could calculate the amount of water pressure at the bottom of a dam based on physical measurements of the lake or river held up by the dam as well as the dam itself.

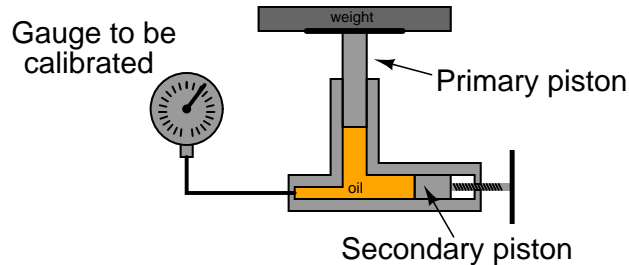
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### Question 3

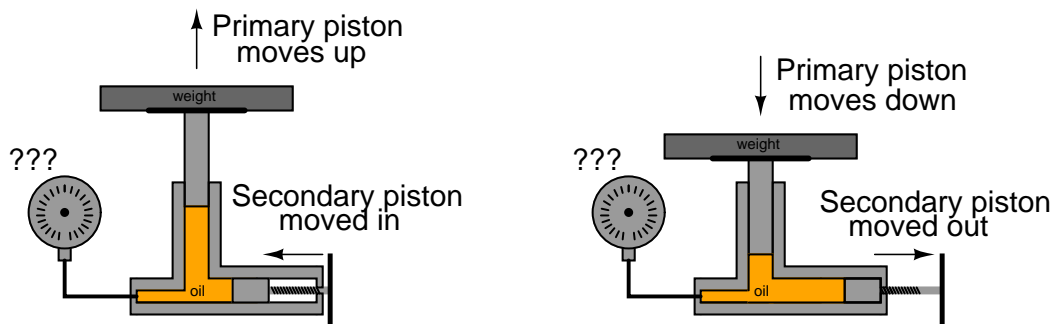
A pressure calibration device called a *deadweight tester* generates very precise pressures by means of calibrated weights placed on top of a hydraulic piston. The purpose of a deadweight tester is to serve as a guaranteed source of fluid pressure that may be trusted as a calibration standard, against which we may test the accuracy of a pressure-measuring instrument (e.g. a pressure gauge or pressure transmitter):

#### *Deadweight tester*



The secondary piston is moved in and out by turning a handle on a threaded rod. Its sole purpose is to displace enough oil to force the primary piston to rise from its resting position, so that it is entirely suspended by oil pressure. In that condition, the gauge will be subject to whatever pressure is proportional to the weights placed on top of the primary piston, and the area of the primary piston, according to the formula  $P = \frac{F}{A}$ .

What will happen to the gauge's indication if the secondary piston is pushed in further? What will happen to the gauge's indication if the secondary piston is pulled out, but not so far that the primary piston comes down to its resting position? In other words, what effect does the secondary piston *position* have on pressure applied to the gauge?



*In each condition, what happens to the gauge's indication?  
Does the applied pressure increase, decrease, or stay the same?*

#### Suggestions for Socratic discussion

- Why are deadweight testers considered accurate *standards* for fluid pressure? What is it about their design and operation that makes them so accurate? Conversely, what aspects of their construction would have to change in order to corrupt their inherent accuracy?
- If a technician changes the type of fluid used in a deadweight tester (for example, from one type of oil to another), will its accuracy change?

- Identify some potential problems one might encounter when using a deadweight tester. What things, specifically, do you see that could go wrong with this device?

[file i00153](#)

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#### Question 4

Read and outline the “Manometers” subsection of the “Fluid Mechanics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

#### Suggestions for Socratic discussion

- Which is simpler to use, a *U-tube* manometer or a *well* manometer? Explain why.
- Identify different manometer designs intended to increase sensitivity, and explain how each of these designs works.
- How large should the *well* be in a well-type manometer for us to safely ignore level changes within it?
- Where should one read the liquid column height when using an *inclined* manometer?
- One of the problems with manometers as practical measurement tools is their tendency to “blow out” their liquid if over-pressured. Design a manometer that is resistant to “blow-out” events, or at least won’t spew its contents everywhere when a blow-out happens.

[file i03896](#)

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### Question 5

Read and outline the “Systems of Pressure Measurement” subsection of the “Fluid Mechanics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook, paying close attention to the use of “unity fractions” for cancellation of units, and how to manage conversions between units of pressure measurement that do not share the same zero point.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

After outlining, use that same mathematical technique to convert between the following units of pressure using the following gauge pressure equivalencies:

*1.000 pound per square inch (PSI) = 2.036 inches of mercury (in. Hg) = 27.68 inches of water (in. W.C.) = 6.895 kilo-pascals (kPa) = 0.06895 bar*

$$\left(\frac{25 \text{ PSI}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? kPa}$$

$$\left(\frac{40 \text{ "WC}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? PSI}$$

$$\left(\frac{5.6 \text{ bar}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? PSI}$$

$$\left(\frac{1200 \text{ "Hg}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? "WC}$$

$$\left(\frac{12 \text{ "WC}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? bar}$$

$$\left(\frac{110 \text{ kPa}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? "WC}$$

$$\left(\frac{982 \text{ "Hg}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? kPa}$$

$$\left(\frac{50 \text{ PSI}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? bar}$$

$$\left(\frac{250 \text{ kPa}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? "Hg}$$

$$\left(\frac{31 \text{ bar}}{1}\right) \left(\frac{\text{---}}{\text{---}}\right) = \text{??? "Hg}$$

For more information on the “unity fraction” method of unit conversion, refer to the “Unity Fractions” subsection of the “Unit Conversions and Physical Constants” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

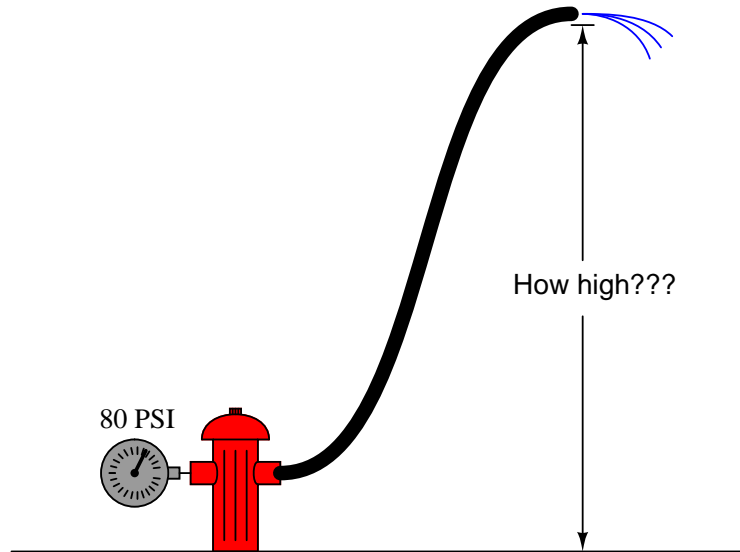
<b>Suggestions for Socratic discussion</b>
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- Identify some pressure units that are always absolute and never gauge.
- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.
- Explain why your ears “pop” when ascending or descending through large changes in altitude.
- Explain why a SCUBA diver is not crushed by the pressure of water as he or she descends.

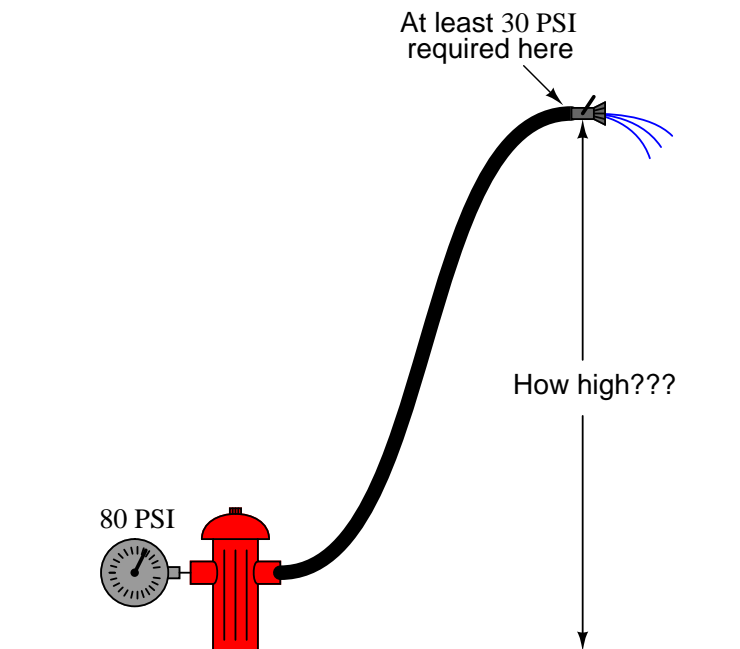
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### Question 6

Water pressure available at a fire hydrant is 80 PSI. If a fire hose is connected to the hydrant and the hydrant valve opened, how high can the end of the hose be raised and still have water flow out the end?



Now, suppose that a spray nozzle attached to the end of the hose requires at least 30 PSI of pressure at the coupling in order to create a proper spray of water. How high can the hose be raised then, and still have enough water pressure at the nozzle to allow for the fighting of a fire?



### Suggestions for Socratic discussion

- How may firefighters ensure they are able to spray water high enough to put out tall building fires, if the hydrant pressure is insufficient?

- Describe a scenario with this fire hose that would illustrate *Pascal's Principle*.

[file i00148](#)

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#### Question 7

Read selected portions of the National Transportation Safety Board's Pipeline Accident Report, *Pipeline Rupture and Subsequent Fire in Bellingham, Washington, June 10, 1999* (Document NTSB/PAR-02/02 ; PB2002-916502), and answer the following questions:

Page 6 of the report shows a graphical trend of pipeline pressure before, during, and after the rupture. How high did the pressure spike, in units of PSI? Do you suppose this was PSIG or PSIA? Convert this measurement into units of kilopascals (kPa) and into units of bar. Based on what you see on the trend graph, was this pipeline carrying a gas or a liquid? How can you tell, from the shape of the trend alone?

Examine the photographs of the ruptured pipeline on page 41 of the report. Based on what you know about fluid pressure, determine where along the pipeline's interior the force of the pressure was exerted.

Page 57 of the report discusses how the pipeline had been "hydrostatically tested" after its original installation. This means it was pressure-tested with non-moving (static) water. Why was this detail important to the investigation?

#### Suggestions for Socratic discussion

- Is it possible to monitor over-pressure conditions in a pipeline anywhere along the pipe, or must we use a multitude of pressure sensors along the pipeline's length to ensure we monitor pressure at all locations?
- How do you think an over-pressure condition in a pipeline may be prevented? What sort of devices might act as safety reliefs to ensure a pipeline does not become over-pressured?

[file i03898](#)

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#### Question 8

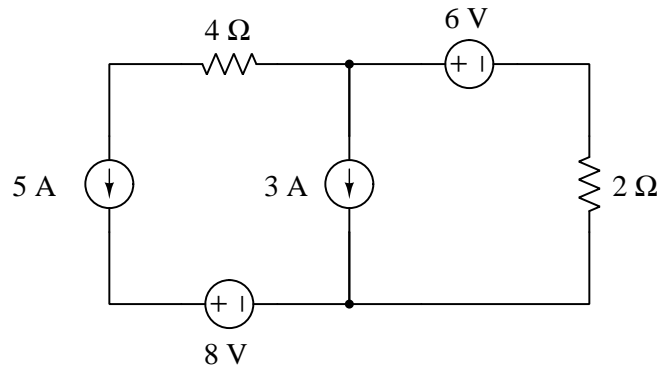
Electrical circuits are ubiquitous in industrial instrumentation, and so it is imperative that you master their analysis. Here we will practice the application of some fundamental laws of electric circuits, in order to strengthen these analytical abilities.

For each example circuit, solve for all voltage values, all current values, all voltage polarities and current directions (where applicable). Also, identify the function of each component as either a *source* or a *load*. Assume all components are ideal. In each step of your analysis, identify which of the following principles applies:

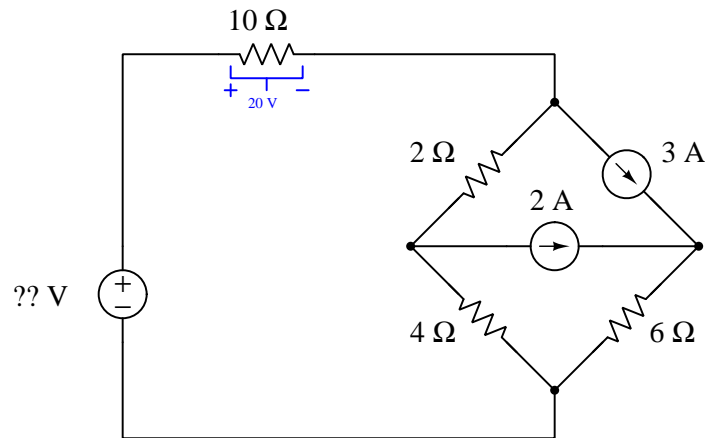
- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law
- Capacitance and Inductance

Survey all the examples shown below, and present your analysis for at least one of them.

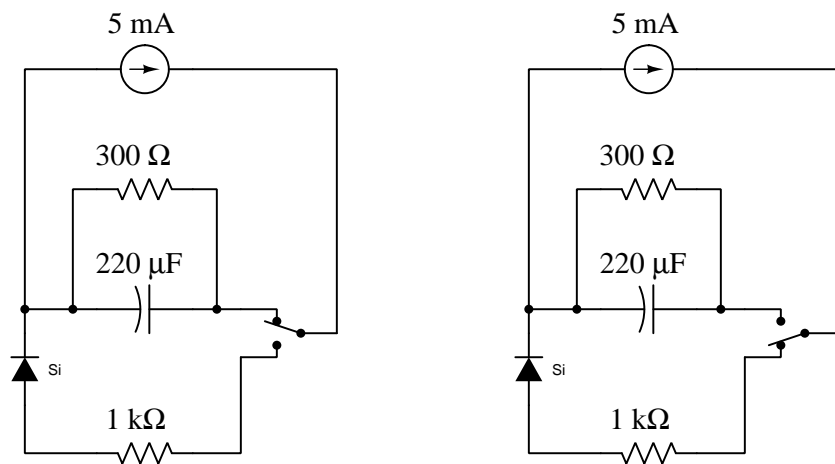
Circuit example #1:



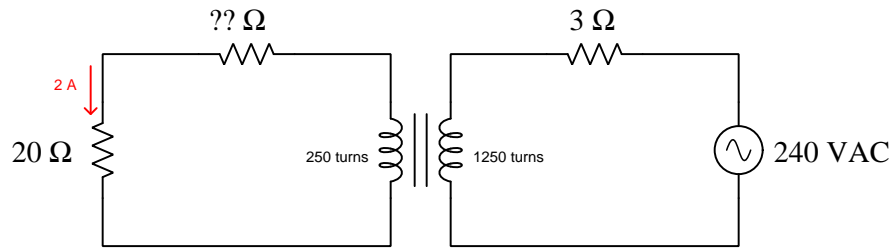
Circuit example #2:



Circuit example #3:



Circuit example #4:



**Suggestions for Socratic discussion**

- Alter one or more of the given values in a circuit, then re-analyze that circuit. Do any of the components switch from source to load or vice-versa?
- Consider a case where one of the components shown in the schematic diagram happen to fail, either *open* or *shorted*, then identify how this failure will affect your re-analysis of the circuit.

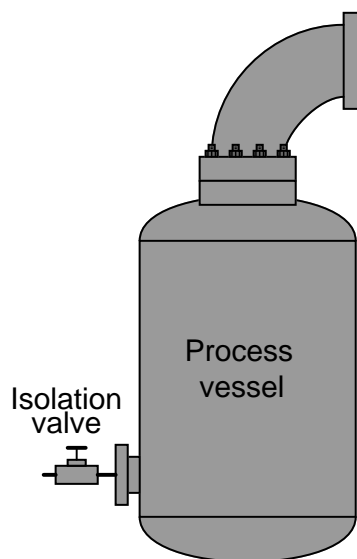
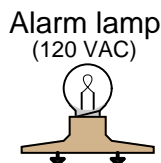
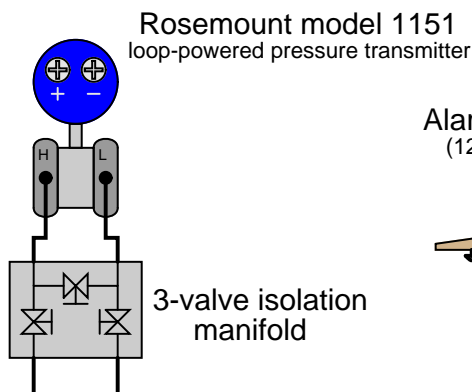
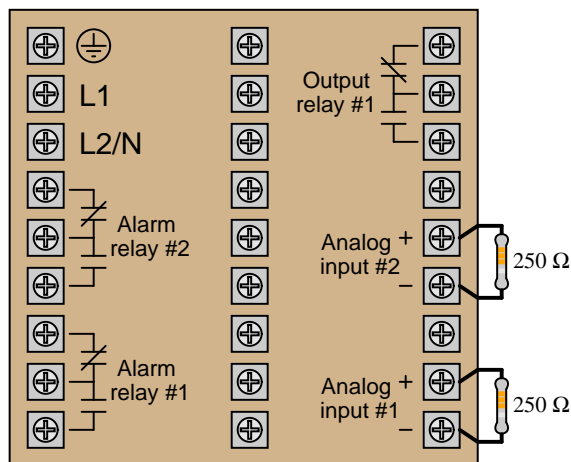
[file i02832](#)



### Question 9

This Honeywell model UDC2500 controller needs to connect to a loop-powered pressure transmitter in such a way that it displays the amount of pressure in the process vessel, and outputs a signal to the 120 VAC alarm lamp if the process pressure becomes too great. Alarm relay #1 in the controller has been configured for a high-pressure trip point of 140 PSI:

Honeywell model UDC2500 controller



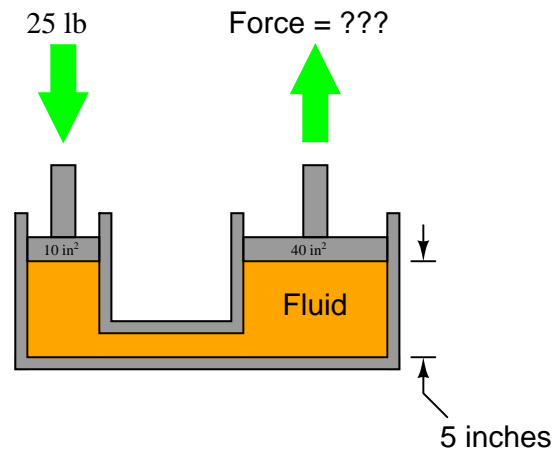
Sketch all necessary connecting wires and tubes to make this a working system. Note: you will need to add electrical power sources to the diagram! Also, identify the proper open/closed state for each hand valve contained in the pressure transmitter's three-valve isolation manifold.

### Suggestions for Socratic discussion

- 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.
- Supposing the transmitter outputs a current value of 14 mA, calculate all voltage drops in this circuit.

## Question 10

In this hydraulic system, a force of 25 pounds is applied to the small piston (area =  $10 \text{ in}^2$ ). How much force will be generated at the large piston (area =  $40 \text{ in}^2$ )? Also, calculate the fluid's pressure.



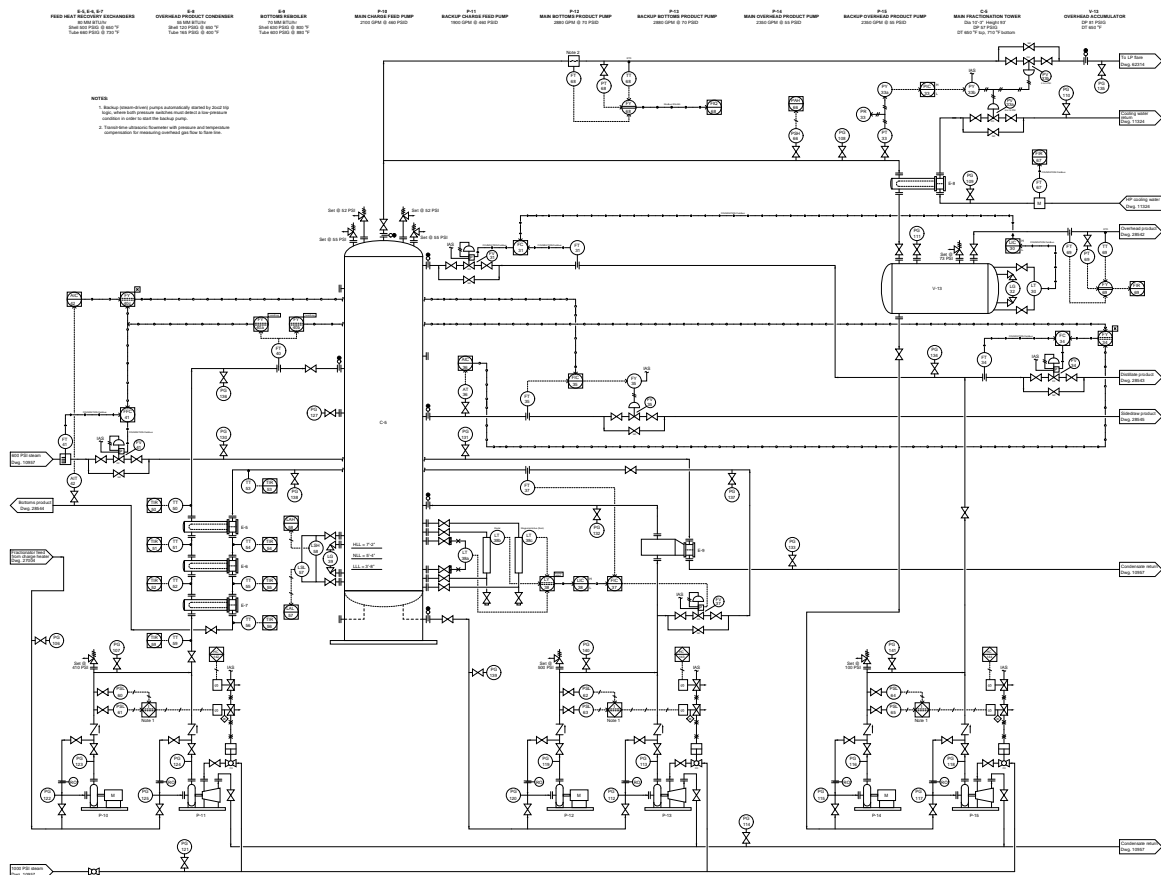
Finally, explain how *Pascal's Principle* relates to this scenario.

**Suggestions for Socratic discussion**

- Identify which fundamental principles of science, technology, and/or math apply to each step of your solution to this problem. In other words, be prepared to explain the reason(s) “why” for every step of your solution, rather than merely describing those steps.
- Identify a practical application for a hydraulic system such as this.
- Does the pressure/force/area equation hold true for all piston positions, or only with the pistons in mid-stroke as shown in the illustration?
- Would it matter whether the fluid in this system was a liquid or a gas? Explain in detail how the system's behavior would differ (or not differ) depending on the type of fluid used.
- This mechanism seems to multiply the applied force. How can it do so without violating the Law of Energy Conservation (energy out cannot exceed energy in)?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

## Question 11

Examine the overhead product pressure control loop (#33) in this distillation system (in the upper-right corner of the P&ID). Suppose PR-33 shows a pressure of 48.1 PSI, while PIC-33 shows a pressure of 50.0 PSI (equal to setpoint):



Identify which faults could account for the pressure indication discrepancy:

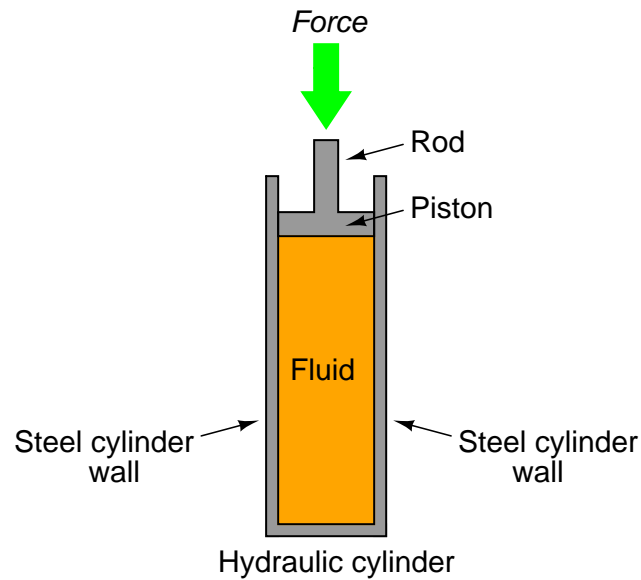
Fault	Possible	Impossible
PR-33 calibration error		
PT-33 calibration error		
PIC-33 (input) calibration error		
PY-33a calibration error		
PY-33b calibration error		
PV-33a calibration error		
PV-33b calibration error		

file i03514

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Question 12

If force is exerted on the piston of this hydraulic cylinder, in what direction(s) will this force be transmitted to the cylinder walls? In other words, how does a fluid under pressure push against its surrounding container?

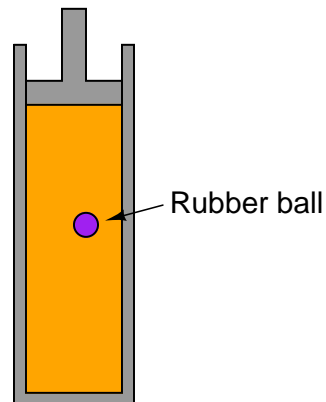


file i00142

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Question 13

Suppose a small rubber ball is floating inside the fluid of a hydraulic cylinder as shown below. What will happen to the ball when a pushing force is exerted on the cylinder's rod? What will happen to the ball when a pulling force is exerted on the rod?



file i00143

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#### Question 14

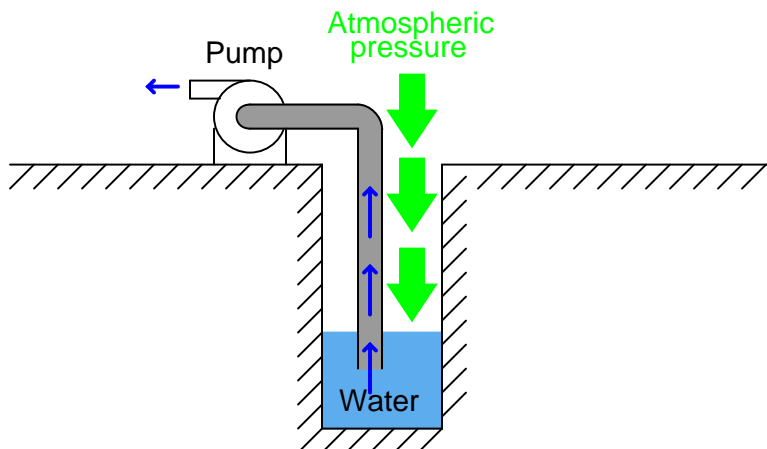
A scuba diver's air tank contains 2,000 PSI of air, as measured by a pressure gauge before descending into the water. The diver descends 50 feet into the water, where the surrounding water pressure caused by the water's weight (called *hydrostatic pressure*) is approximately 22 PSI. Assuming that the diver consumes an inconsequential amount of air from the tank during the 50 foot descent, express the air pressure inside the tank in terms of absolute pressure, gauge pressure, and differential pressure (the differential pressure between the tank and the surrounding hydrostatic pressure of the water).

[file i00145](#)

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#### Question 15

A surface-mounted water pump pulls water out of a well by creating a vacuum, though it might be more technically accurate to say that the pump works by reducing pressure in the inlet pipe to a level less than atmospheric pressure, allowing atmospheric pressure to then push water from the well up the pump's inlet pipe:



Based on this description of pump operation, what is the theoretical maximum height that any pump can lift water out of a well, assuming the well is located at sea level?

Water wells located at altitudes other than sea level will have different theoretical maximum lifting heights (i.e. the farthest distance a surface-mounted pump may suck water out of the well). Research the average barometric pressure in Denver, Colorado (the “mile-high” city) and determine how far up a surface pump may draw water from a well in Denver.

Domestic water wells may be hundreds of feet deep. How can water be pumped out of wells this deep, given the height limitation of vacuum pumping?

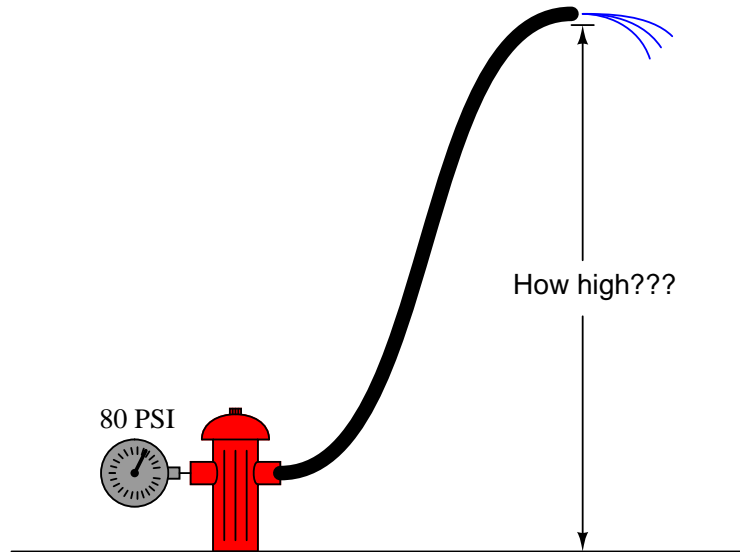
#### **Suggestions for Socratic discussion**

- If the liquid in question was something other than water, would the maximum “lift” depth be different? Why or why not?

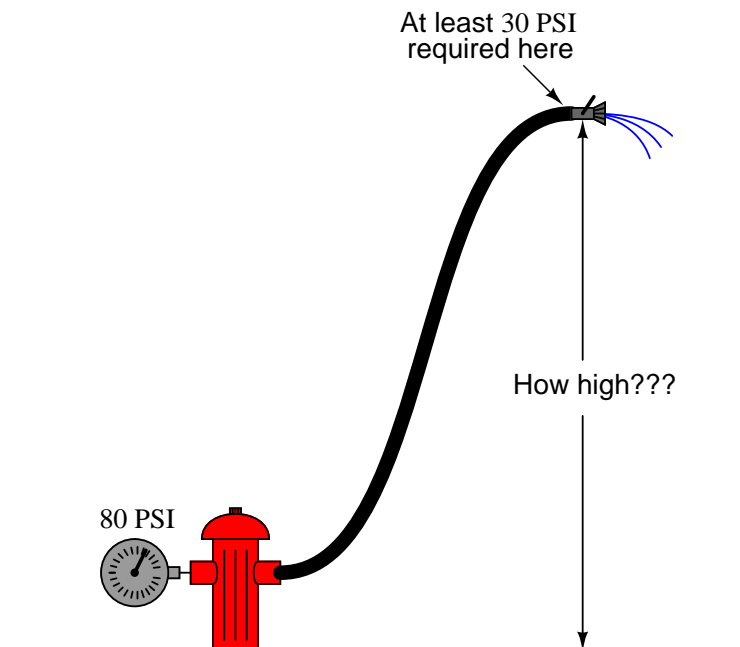
[file i00147](#)

### Question 16

Water pressure available at a fire hydrant is 80 PSI. If a fire hose is connected to the hydrant and the hydrant valve opened, how high can the end of the hose be raised and still have water flow out the end?



Now, suppose that a spray nozzle attached to the end of the hose requires at least 30 PSI of pressure at the coupling in order to create a proper spray of water. How high can the hose be raised then, and still have enough water pressure at the nozzle to allow for the fighting of a fire?



### Suggestions for Socratic discussion

- How may firefighters ensure they are able to spray water high enough to put out tall building fires, if the hydrant pressure is insufficient?

- Describe a scenario with this fire hose that would illustrate *Pascal's Principle*.

file i00148

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Question 17

Complete the following table of equivalent pressures:

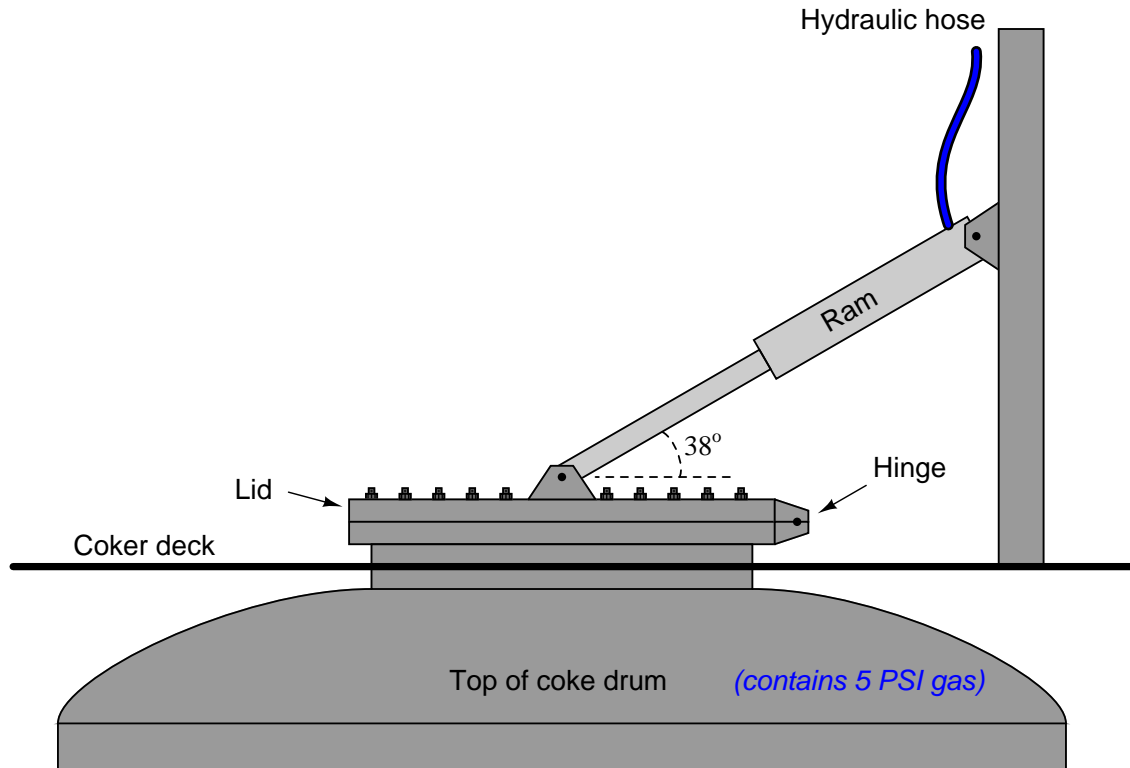
PSIG	PSIA	inches Hg (G)	inches W.C. (G)
18			
	400		
		33	
			60
		452	
			12
	1		
-5			

There is a technique for converting between different units of measurement called “unity fractions” which is imperative for students of Instrumentation to master. For more information on the “unity fraction” method of unit conversion, refer to the “Unity Fractions” subsection of the “Unit Conversions and Physical Constants” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

file i02938

### Question 18

A process called *delayed coking* is used in the oil refining industry to convert heavy oils and tars into higher-valued petroleum products. A process vessel called a *coke drum* has a removable lid held down by a series of bolts, and alternatively by a hydraulic ram. When it comes time to open up the coke drum, the hydraulic ram is pressurized to maintain adequate force on the coke drum lid, the bolts are removed, and then the ram's fluid pressure is reduced until the lid springs open from the force of the gas pressure inside the coke drum:



Calculate the hydraulic pressure necessary to hold down the lid on the coke drum when the gas pressure inside the drum is 5 PSI and all hold-down bolts have been removed from the lid. Assume a lid diameter of 30 inches, and a ram piston diameter of 4 inches. Hint: sketch a right triangle, representing forces as side lengths on the triangle – the ram's diagonal force will translate into both a horizontal force on the lid (which you may ignore) and a vertical force on the lid (which is what we're interested in here).

Hydraulic  $P =$  \_\_\_\_\_ PSI

#### Suggestions for Socratic discussion

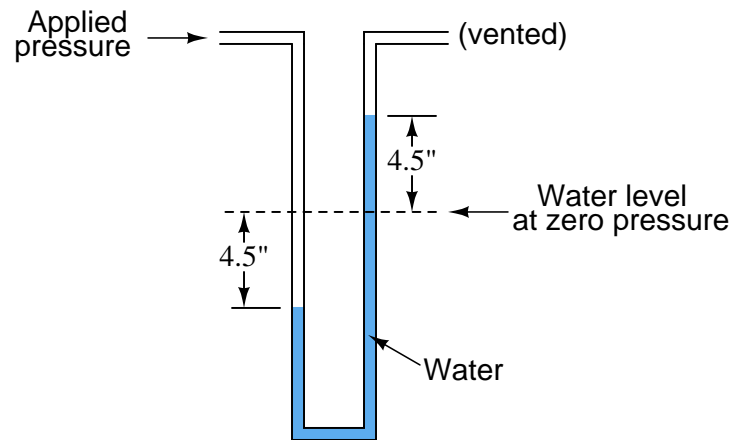
- Which direction will the horizontal force component be exerted on the lid?
- Identify the potential hazards of a hydraulic oil leak in this system. Compare the effects of a slow leak (e.g. a leaky fitting connecting the hose to the ram) versus a catastrophic leak (e.g. the hose bursting from excess pressure).

[file i04683](#)



Question 19

How much pressure is being applied to this U-tube water manometer, in units of “inches of water column” and “pounds per square inch”?

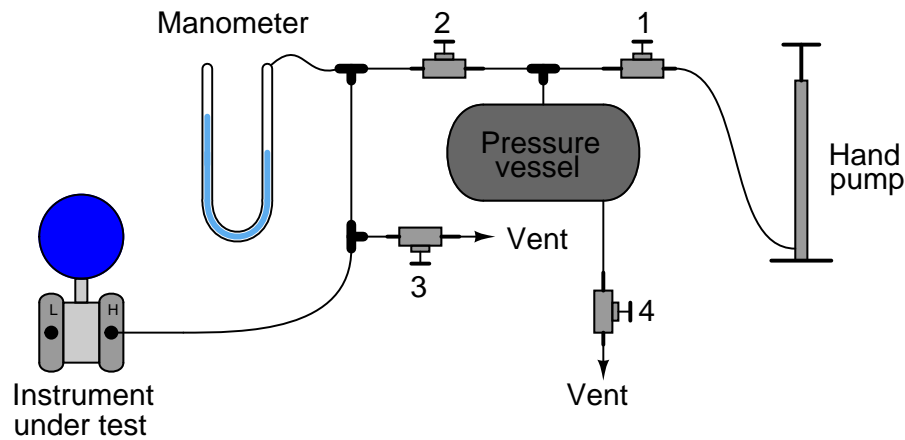


What would happen to the liquid levels if the water were replaced by an oil with a lesser *density*? Given the same applied pressure, would the distance between the two liquid columns be greater, less, or the same as shown in the above illustration?

file i00161

### Question 20

Determine what will happen at the following steps in the sequence (when prompted for a response) in this pressure transmitter calibration setup:



- **Step 1:** Open valves 1 and 2
- **Step 2:** Close valves 3 and 4
- **Step 3:** Operate hand pump until manometer registers maximum pressure
- **Step 4: (4 points)** Quickly open and close valve 4 – *does the manometer indication drop greatly, slightly, or not at all?*
- **Step 5:** Close valve 2
- **Step 6: (4 points)** Quickly open and close valve 4 – *does the manometer indication drop greatly, slightly, or not at all?*
- **Step 7:** Close valve 1
- **Step 8: (4 points)** Quickly open and close valve 3 – *does the manometer indication drop greatly, slightly, or not at all?*

file i00463

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### Question 21

Skim the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook to identify several different mechanical technologies for measuring pressure, then briefly describe the operating principle of each one:

- Manometers (identify some of the different types!)
- Bellows
- Diaphragm
- Bourdon tube (identify some of the different types!)

#### **Suggestions for Socratic discussion**

- Discuss ideas for “skimming” a text to identify key points so you do not have to read the whole thing.
- Explain why a *raised well* manometer is virtually blow-out proof.
- Explain how each “differential” pressure sensing mechanism works.
- Can a bourdon tube be used to measure vacuum as well as pressure? Explain why or why not.

[file i03899](#)

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### Question 22

Skim the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook to identify different electronic technologies for measuring pressure, then briefly describe the operating principle of each one:

- Strain gauge (electronic sensing)
- Capacitance sensors (electronic sensing)
- Resonant sensors (electronic sensing)

#### **Suggestions for Socratic discussion**

- Discuss ideas for “skimming” a text to identify key points so you do not have to read the whole thing.
- Explain how each “differential” pressure sensor works.

[file i03902](#)

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### Question 23

Read and outline the “DP Transmitter Construction and Behavior” subsection of the “Differential Pressure Transmitters” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03900

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### Question 24

Read and outline the “DP Transmitter Applications” subsection of the “Differential Pressure Transmitters” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

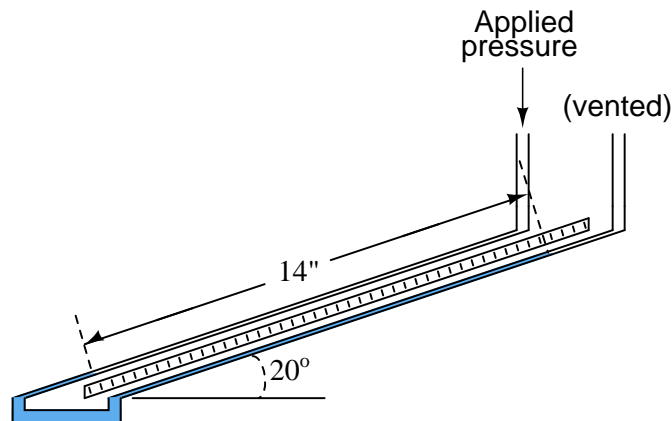
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03901

### Question 25

How much pressure, in inches of water column, is being applied to this inclined water manometer to create a total displacement of 14 inches along the length of the tubes, inclined at angles of  $20^\circ$  from horizontal? Assume the base of this manometer is located 24 inches above ground level.



Next, convert this pressure into units of kPa.

#### Suggestions for Socratic discussion

- Identify which fundamental principles of science, technology, and/or math apply to each step of your solution to this problem. In other words, be prepared to explain the reason(s) “why” for every step of your solution, rather than merely describing those steps.
- Does inclining a manometer make it more or less sensitive to applied pressure? Develop a “thought experiment” where you could test a manometer to answer this question.
- Is it possible to make a *well* version of an inclined manometer so that we need only to read one liquid column?
- What will happen to a manometer if it is exposed to a gas pressure greater than its measurement range?
- Would a *micromanometer* be more or less sensitive to applied pressure than this inclined manometer?

[file i00168](#)

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### Question 26

Convert between the following units of pressure. Remember that any pressure unit not explicitly specified as either absolute (A) or differential (D) is to be considered *gauge*. Also, remember those units which *always* represent absolute pressure, and have no need for a letter “A” suffix!

- 5 PSI vacuum = ??? PSIA
- 25 "Hg vacuum = ??? PSIA
- 2,800  $\mu$  torr = ??? PaA
- -59 "W.C. = ??? torr
- 4,630 PaA = ??? PSI
- 0.05 atm = ??? "W.C.
- -3 kPa = ??? atm
- 10 feet W.C. vacuum = ??? "HgA
- 300 cm Hg = ??? atm
- -2 mm W.C. = ??? bar (absolute)
- 4 atm = ??? "W.C.A

There is a technique for converting between different units of measurement called “unity fractions” which is imperative for students of Instrumentation to master. For more information on the “unity fraction” method of unit conversion, refer to the “Unity Fractions” subsection of the “Unit Conversions and Physical Constants” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

#### **Suggestions for Socratic discussion**

- Which of these conversions require an additive or subtractive offset, and which of these may be performed using multiplication and division alone?
- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.

[file i00158](#)

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### Question 27

Convert between the following units of pressure. Remember that any pressure unit not explicitly specified as either absolute (A) or differential (D) is to be considered *gauge*. Also, remember those units which *always* represent absolute pressure, and have no need for a letter “A” suffix!

- 25 PSIA = ??? atm
- 340 "W.C. = ??? PSIA
- 0.73 bar (gauge) = ??? "Hg
- 5.5 atm = ??? torr
- 2,300 cm Hg = ??? "W.C.A
- 500 m torr = ??? PSIA
- 91.2 cm W.C. = ??? kPa
- 110 kPa = ??? "W.C.
- 620 mm HgA = ??? torr
- 77 Pa = ??? PSIA
- 1 atm = ??? "W.C.A
- 270 PSIA = ??? atm

There is a technique for converting between different units of measurement called “unity fractions” which is imperative for students of Instrumentation to master. For more information on the “unity fraction” method of unit conversion, refer to the “Unity Fractions” subsection of the “Unit Conversions and Physical Constants” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

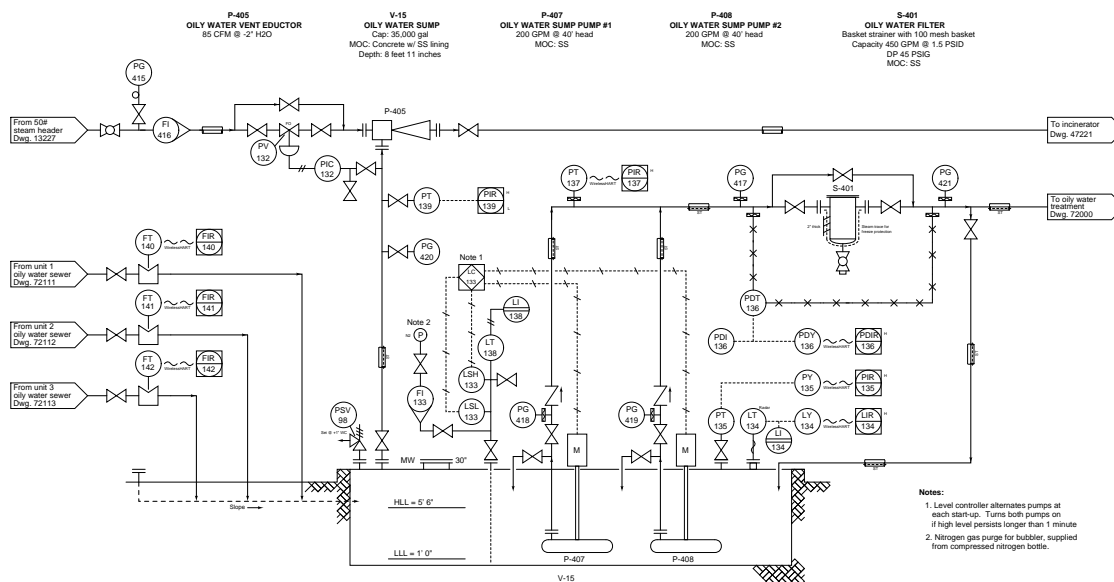
#### **Suggestions for Socratic discussion**

- Which of these conversions require an additive or subtractive offset, and which of these may be performed using multiplication and division alone?
- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.
- Suppose a novice tries to convert 3.5 atmospheres into PSIG, and arrives at a result of 51.45 PSIG. Identify the mistake made here, and also the proper conversion to go from units of atmospheres to PSIG.

file i00157

## Question 28

An operator reports a problem with the oily water filter instrumentation in this process: PDIR-136 indicates a differential pressure of 1.8 PSID, while PG-417 reads 12.5 PSI and PG-421 reads 11.3 PSI. Your first test is to check the indication of PIR-137, and you see that it reads 12.6 PSI:



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
Upstream filter block valve partially shut		
Downstream filter block valve partially shut		
PDT-136 calibration error		
PT-137 calibration error		
PG-417 calibration error		
PG-421 calibration error		
Filter drain valve to sump left open		

Explain why the idea to check PIR-137 was a good first diagnostic test.

### Suggestions for Socratic discussion

- Identify which fundamental principles of science, technology, and/or math apply to each step of your solution to this problem. In other words, be prepared to explain the reason(s) “why” for every step of your solution, rather than merely describing those steps.
- Identify the next diagnostic step you would take to isolate the problem in this system.
- Identify which port on each differential pressure indicator is the “high” and which is the “low”, explaining your rationale.
- Estimate the amount of force applied to the 30-inch diameter manway cover on the sump by the  $-2$  ”WC vacuum produced by the eductor.

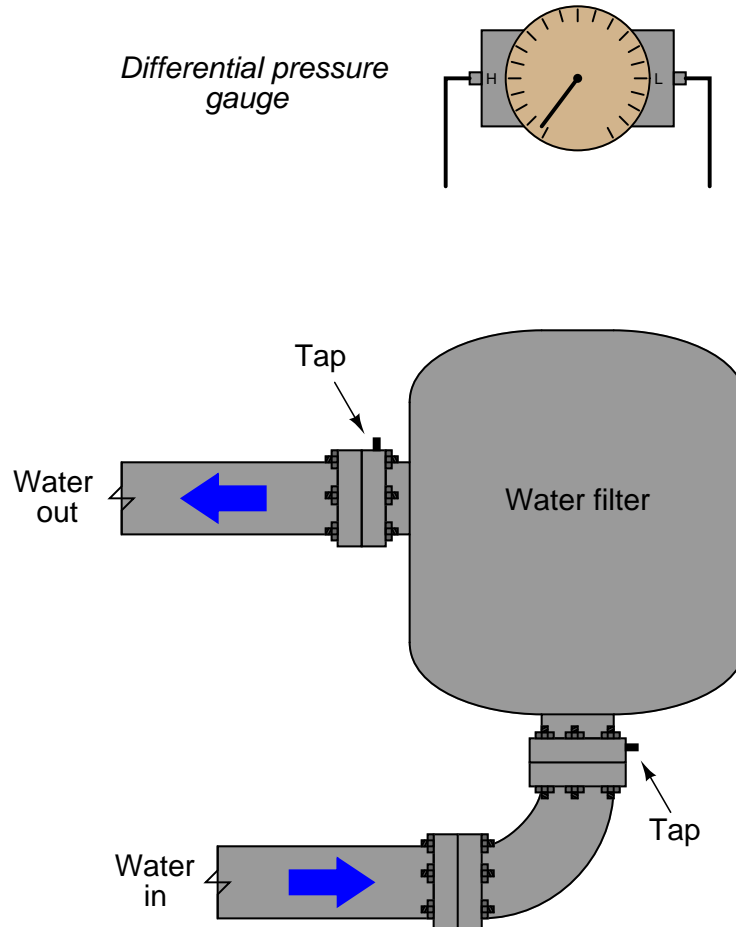
[file i03511](#)



### Question 29

A large water filter occasionally plugs with debris, and operations wants to have a gauge indication of this plugging. Since plugging of the filter will result in greater differential pressure drop across it for any given amount of water flow through it, measuring pressure drop with a differential pressure gauge will provide a simple indication of filter plugging.

Draw the connecting tubes between the differential pressure gauge and the filter (the two “taps” shown on the pipes are ready to connect to instrument tubing) so that the gauge registers positive pressure as the filter becomes plugged:



file i00215

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**Question 30**

2.036 inches of mercury ("Hg) is an equivalent pressure to 27.68 inches of water ("W.C. or "H<sub>2</sub>O). This fact allows us to create a "unity fraction" from these two quantities for use in converting pressure units from inches mercury to inches water or vice-versa. Two examples are shown here:

$$\left( \frac{310 \text{ "Hg}}{1} \right) \left( \frac{27.68 \text{ "W.C.}}{2.036 \text{ "Hg}} \right) = 4215 \text{ "W.C.}$$

$$\left( \frac{45 \text{ "W.C.}}{1} \right) \left( \frac{2.036 \text{ "Hg}}{27.68 \text{ "W.C.}} \right) = 3.31 \text{ "Hg}$$

But what if we are performing a unit conversion where the initial pressure is given in inches of mercury or inches of water *absolute*? Can we properly make a unity fraction with the quantities 2.036 "HgA and 27.68 "W.C.A as in the following examples?

$$\left( \frac{310 \text{ "HgA}}{1} \right) \left( \frac{27.68 \text{ "W.C.A}}{2.036 \text{ "HgA}} \right) = 4215 \text{ "W.C.A}$$

$$\left( \frac{45 \text{ "W.C.A}}{1} \right) \left( \frac{2.036 \text{ "HgA}}{27.68 \text{ "W.C.A}} \right) = 3.31 \text{ "HgA}$$

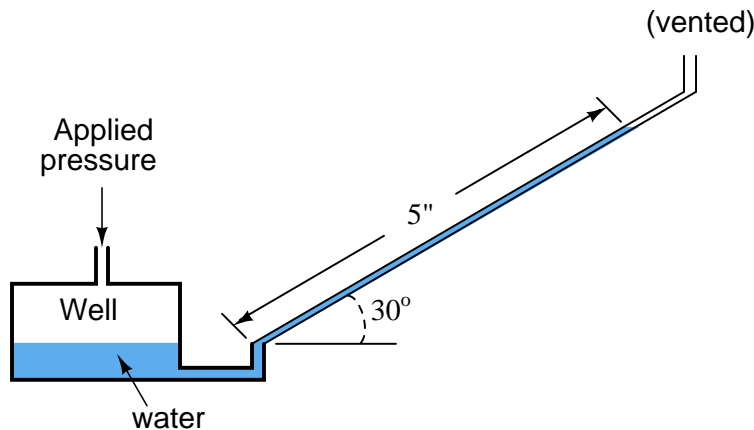
Explain why or why not.

file i02942

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**Question 31**

How much pressure, in inches of water column, is being applied to this *inclined* water manometer to displace water 5 inches along the length of the tube, inclined at an angle of 30° from horizontal? Assume a negligible change in liquid level inside the "well" throughout the measurement range of the instrument:



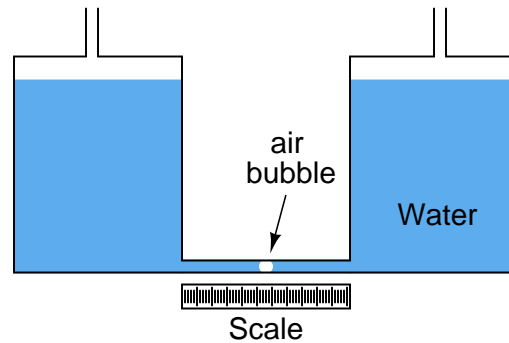
file i00167

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Question 32

A simple way to make a *micromanometer* (an extremely sensitive manometer) is to connect two large-diameter vertical tubes by a small-diameter, transparent tube with an air bubble in it. The air bubble becomes the marker for reading pressure along a scale:

*A simple micromanometer*

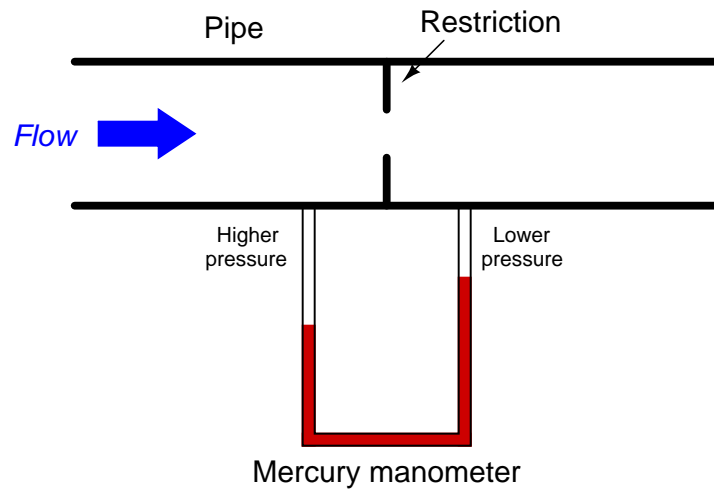


If both of the large vertical tubes are 2.5 inches in diameter, and the transparent, horizontal tube is 0.25 inches in diameter, how much differential pressure will be indicated by 1 inch of horizontal bubble displacement? Assume the use of water for the manometer liquid.

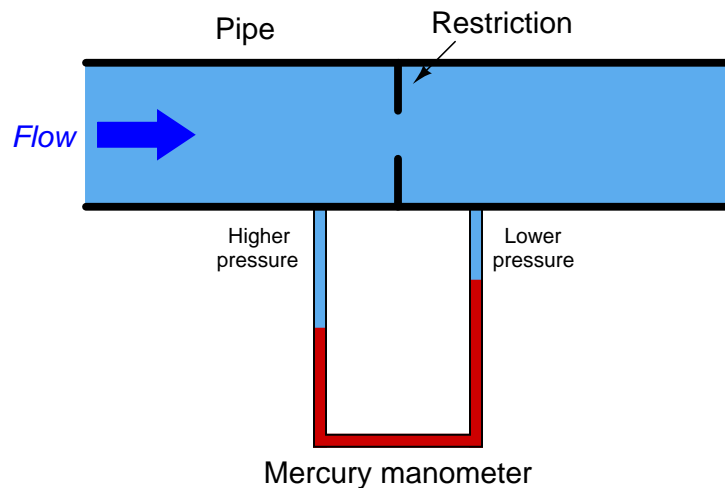
file i00169

### Question 33

A manometer may be used to measure differential pressure across a restriction placed within a pipe. Pressure will be dropped as a result of flow through the pipe, making the manometer capable of (indirectly) measuring flow:



In the example shown above, the fluid moving through the pipe is air, and the manometer uses mercury as the indicating liquid. If we try to measure the flow rate of a *liquid* such as water using the same technique, though, we will find that the manometer does not register quite the way we might expect:



That is to say, given the exact same amount of differential pressure generated by the restriction, the manometer will register differently than if it was measuring air pressure. Determine whether the manometer will register falsely high or falsely low, and also *why* it will do so.

file i00796

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### Question 34

A very useful principle in physics is the *Ideal Gas Law*, so called because it relates pressure, volume, molecular quantity, and temperature of an ideal gas together in one neat mathematical expression:

$$PV = nRT$$

Where,

$P$  = Absolute pressure (atmospheres)

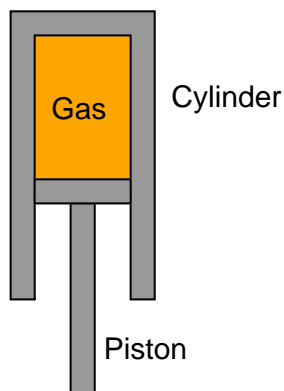
$V$  = Volume (liters)

$n$  = Gas quantity (moles)

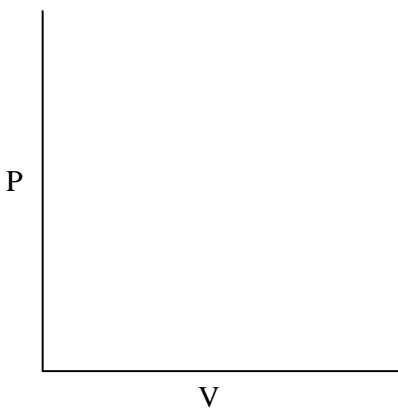
$R$  = Universal gas constant (0.0821 L · atm / mol · K)

$T$  = Absolute temperature (K)

Apply this law to the scenario of a gas-filled cylinder and movable piston:



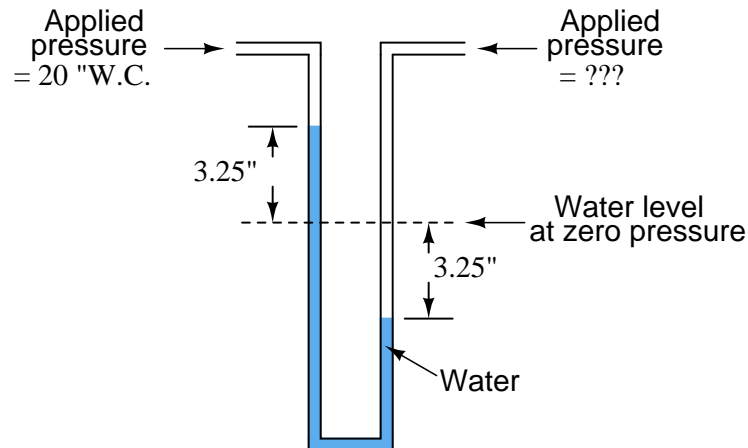
In particular, sketch how the gas pressure inside the cylinder relates to changes in cylinder volume caused by piston movement, assuming no change in gas temperature or leakage of gas molecules from the cylinder:



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Question 35

How much pressure, in units of “inches of water column,” is being applied to the right-hand tube of this U-tube water manometer?



Also, convert this pressure into units of Pascals.

**Suggestions for Socratic discussion**

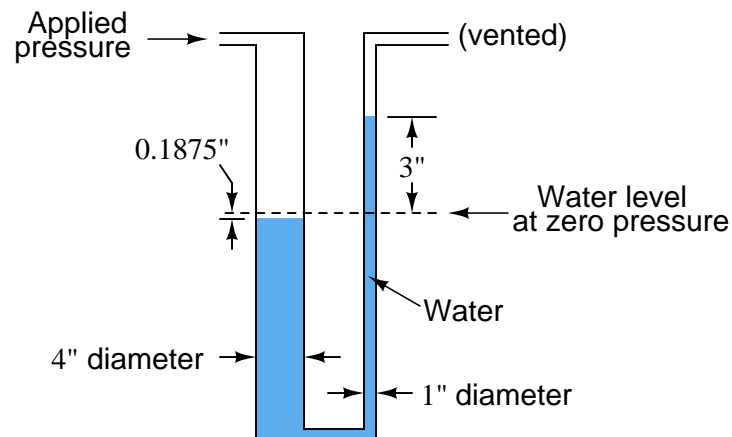
- How much *differential pressure* is registered by this manometer?

[file i00163](#)

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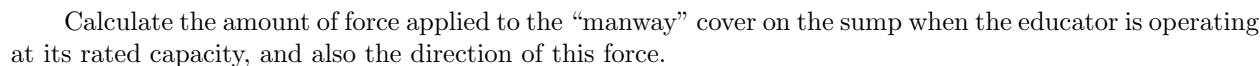
Question 36

How much pressure is being applied to this U-tube water manometer, in units of “inches of water column” and “pounds per square inch”?



[file i00162](#)

A *steam eductor* is a device used to create a vacuum, by passing steam through a “venturi” tube. In this process, a steam eductor is used to apply a constant venting suction to an oily water sump (underground storage vessel for collecting liquid):



Will the applied vacuum from the eductor help or hinder the two pumps' ability to move liquid out of the sump and to water treatment? Will the effect be minimal or substantial?

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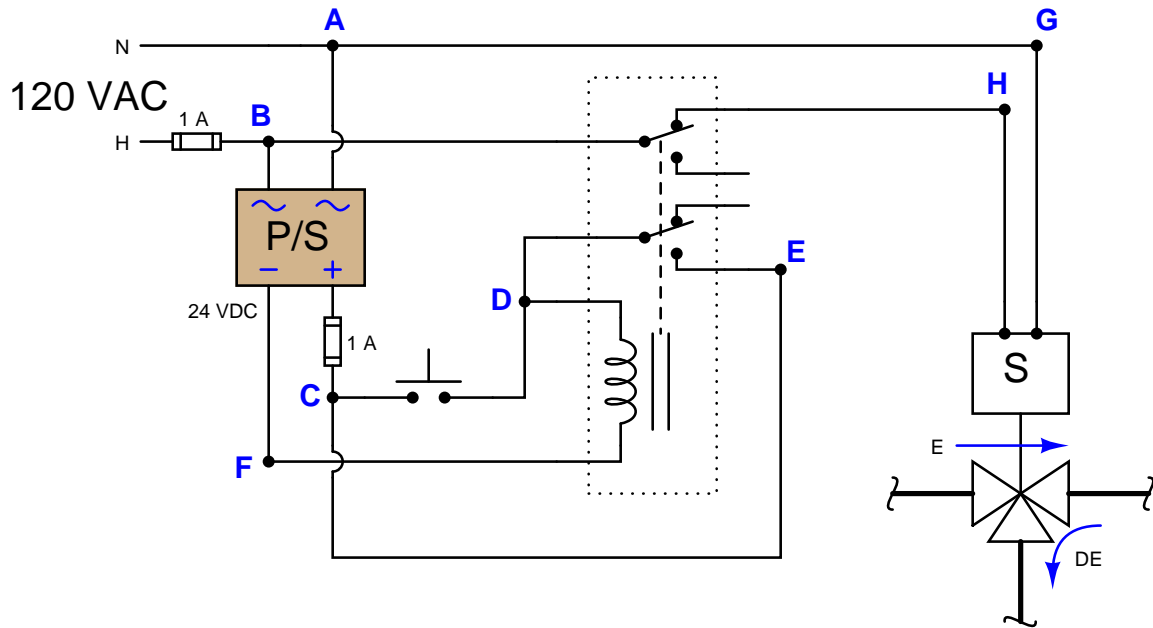
Question 38

An important concept in education is something called *schema*: the body of knowledge, expectations, and assumptions that someone uses to interpret any form of communication they are receiving, whether that communication be in the form of speech, text, or even something as abstract as art. One does not approach an action-adventure novel in the same way or with the same expectations that one would approach instructions for filing tax returns with the IRS. One does not interpret and appreciate a live jazz band in the same way they would interpret and appreciate choral music. We have different schema for understanding and appreciating these different forms of communication, even if they occur in the same medium (e.g. printed text, or audible tones).

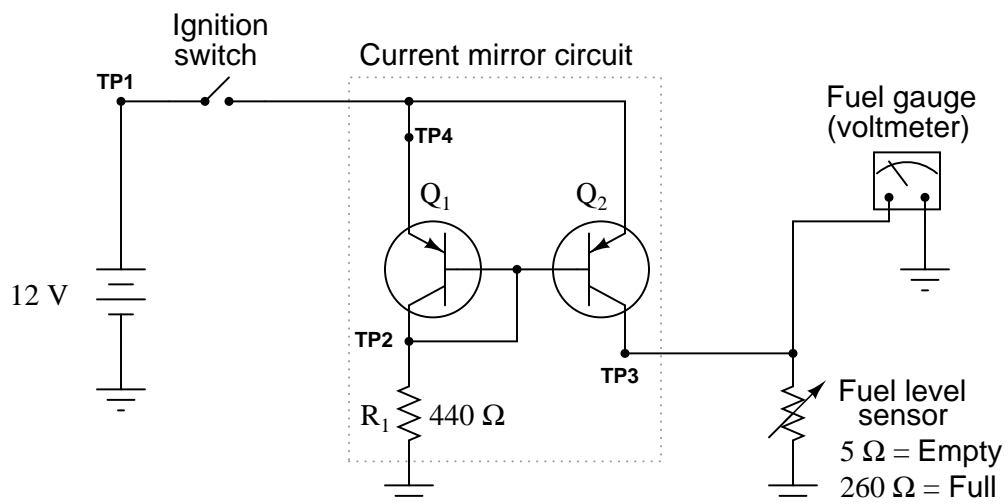
Industrial system diagrams also have *schema* associated with them. One does not interpret a P&ID in the same manner that one interprets an electronic schematic or a block diagram, despite their many similarities. This exercise will ask you to identify the meanings of similar symbols used in several types of diagrams, in order to expose some of the schema you have (or that you are in the process of building).

Reference the following diagrams, and then answer the comparison/contrast questions that follow:

Schematic diagram of a relay circuit

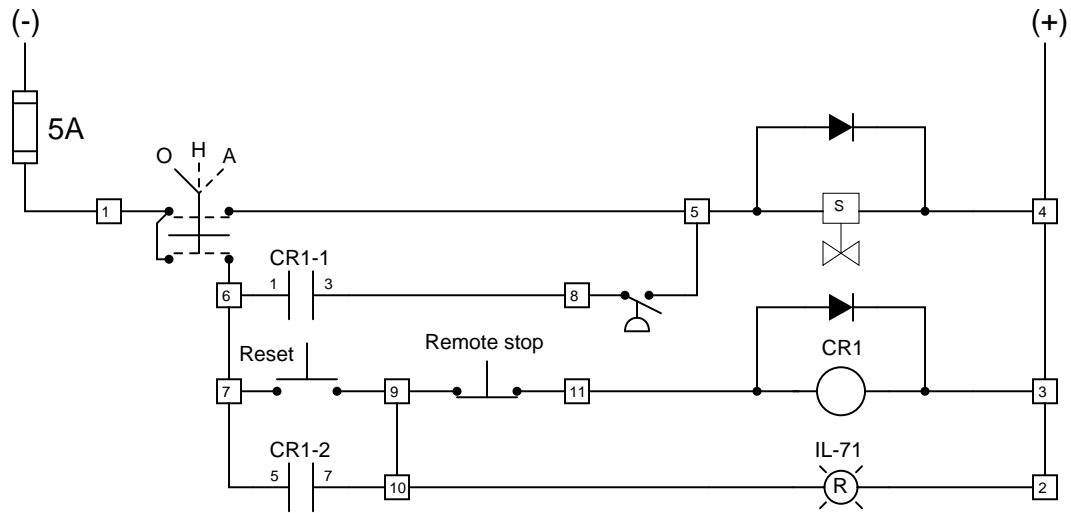


Schematic diagram of a fuel tank level sensor circuit

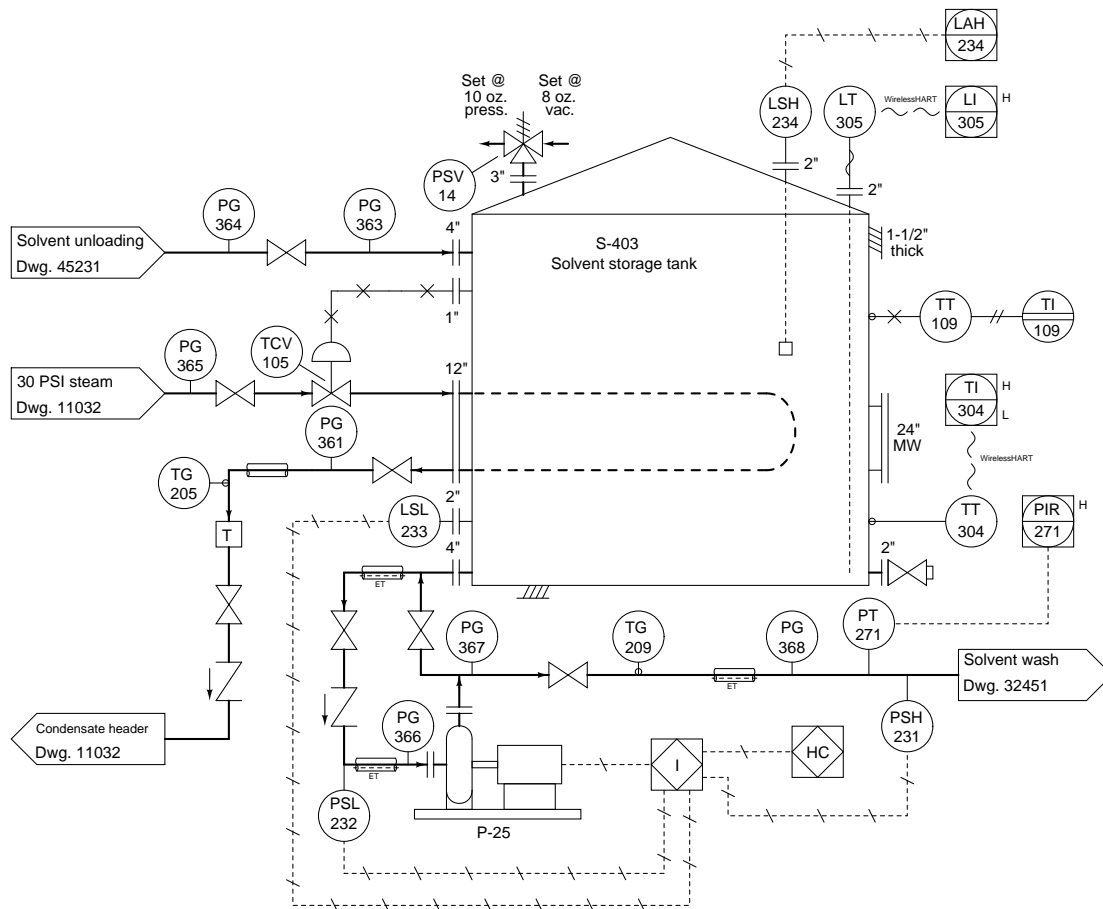




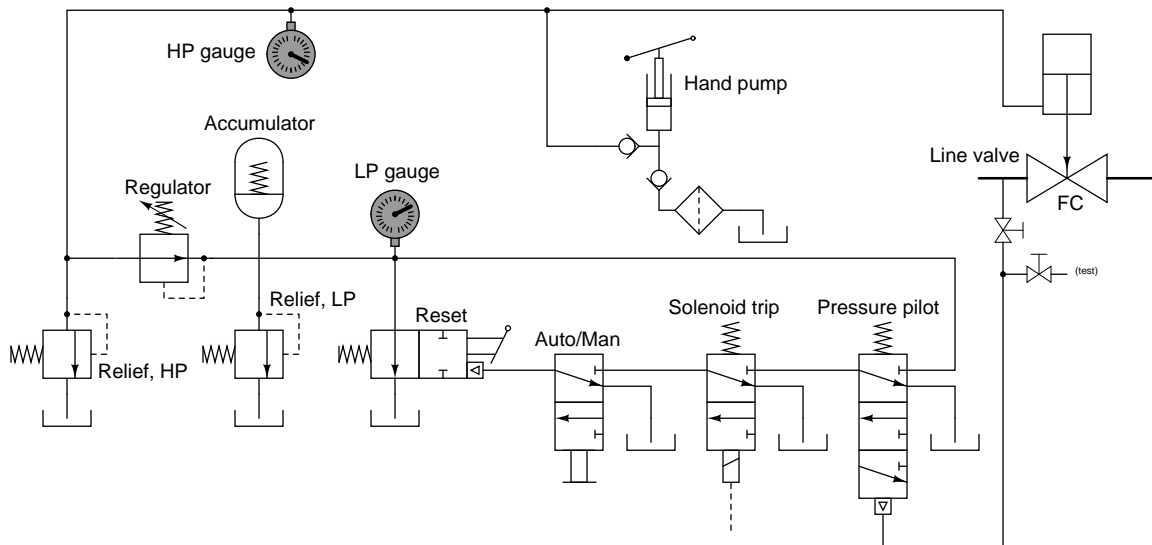
## Ladder diagram of a solenoid valve control circuit



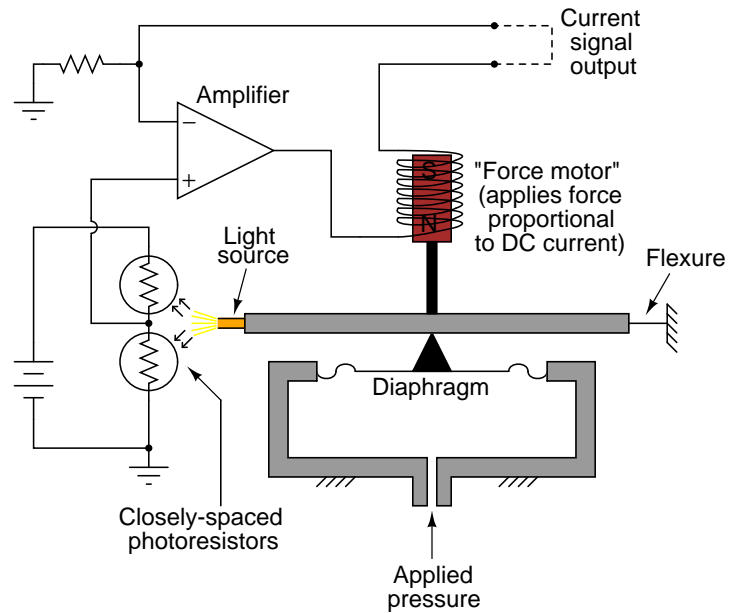
## P&ID of a solvent storage tank



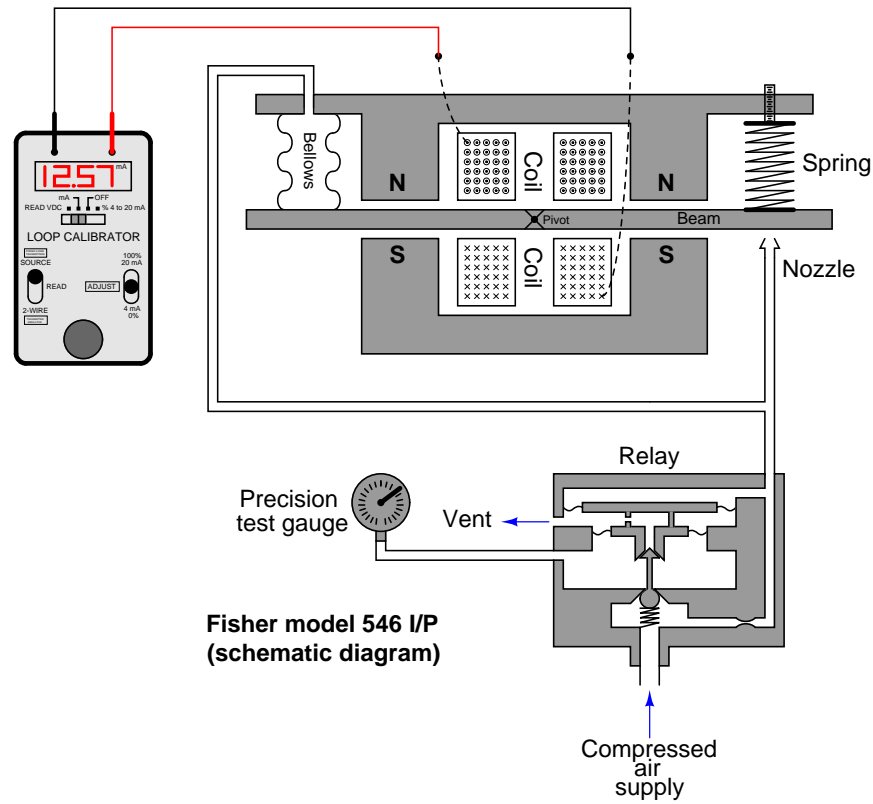
## Schematic diagram of a hydraulic valve control system



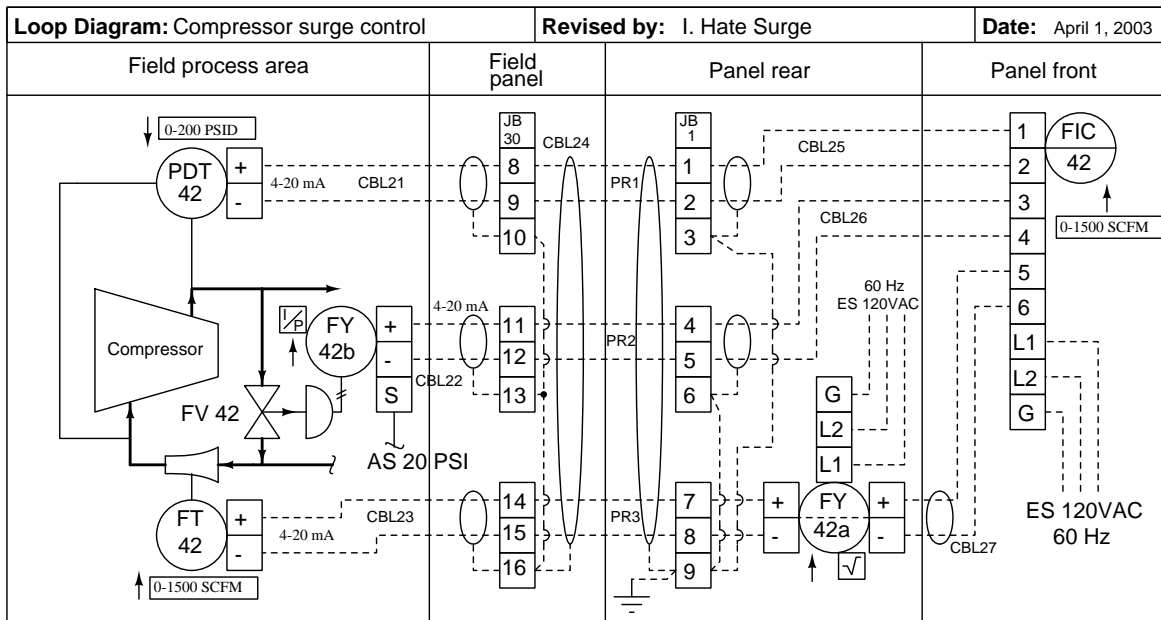
## Schematic/pictorial diagram of a pressure transmitter



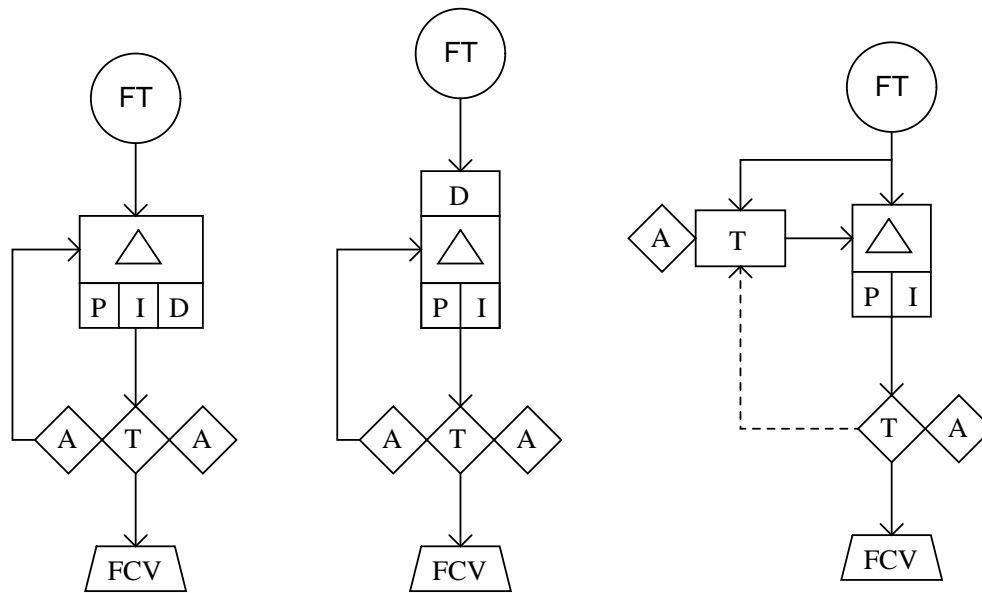
## Pictorial diagram of an I/P transducer



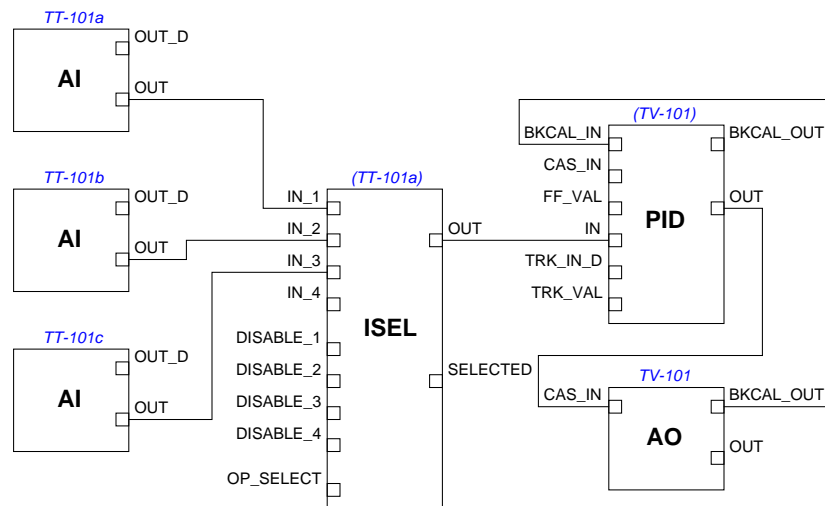
## Loop diagram of a compressor surge control system



## Functional diagram of control loops



## FOUNDATION Fieldbus function block diagram



## Questions:

- Identify the meaning(s) of all *dashed lines* in these diagrams
- Identify the meaning(s) of all *arrows* in these diagrams
- Identify the meaning(s) of all *triangles* in these diagrams
- Identify the meaning(s) of all *boxes* in these diagrams
- Identify the meaning(s) of all *circles* in these diagrams
- Identify how directions of motion are indicated in each diagram (if at all)
- Identify how sources of energy are indicated in each diagram (if at all)

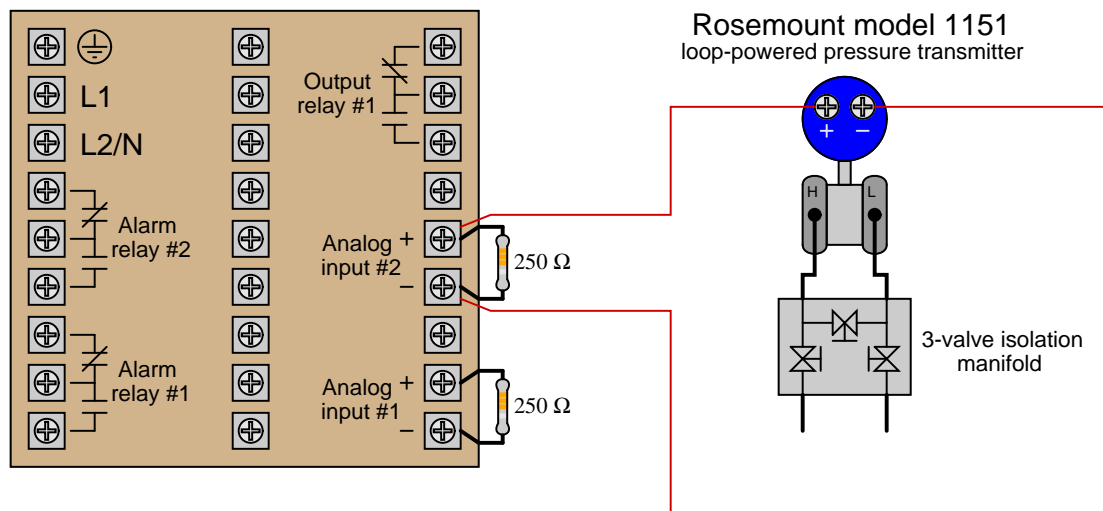
file i02683

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### Question 39

Suppose an instrument technician needs to connect a loop-powered 4-20 mA pressure transmitter to the input of a loop controller, and does so like this:

Honeywell model UDC2500 controller



Explain what is wrong with this circuit, and what is needed to fix the problem.  
[file i02282](#)

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### Question 40

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### Question 41

Read and outline the “Zero and Span Adjustments (Analog Instruments)” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03903](#)

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#### Question 42

Read and outline the “Calibration Errors and Testing” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03908](#)

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#### Question 43

Read and outline the “Damping Adjustments” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03904](#)

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#### Question 44

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.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03905](#)

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#### Question 45

Read the “An Analogy for Calibration versus Ranging” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03907](#)

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#### Question 46

Read and outline the “Calibration Procedures” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03906](#)

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#### Question 47

Read and outline the “Instrument Turndown” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03909](#)



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#### Question 48

Read and outline the “NIST Traceability” section of the “Instrument Calibration” chapter in your *Lessons In Industrial Instrumentation* textbook.

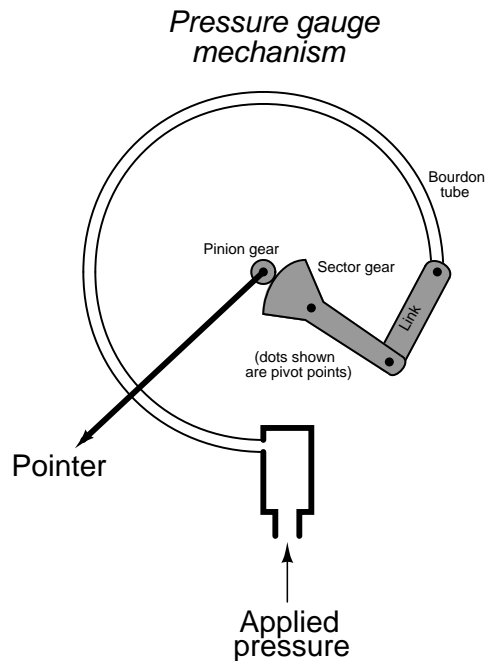
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

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- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

file i03910

#### Question 49

Shown here is a diagram of a standard pressure gauge, based on the pressure-sensing action of a hollow, C-shaped metal tube called a *bourdon tube*:



Using arrows, trace the motions of all moving components in this mechanism as an increasing pressure is applied to the fitting at the bottom of the bourdon tube.

Also, describe how the measurement span of this pressure gauge could be changed. In other words, what would have to be moved, adjusted, or altered in this mechanism in order to change the proportionality of applied pressure to pointer movement?

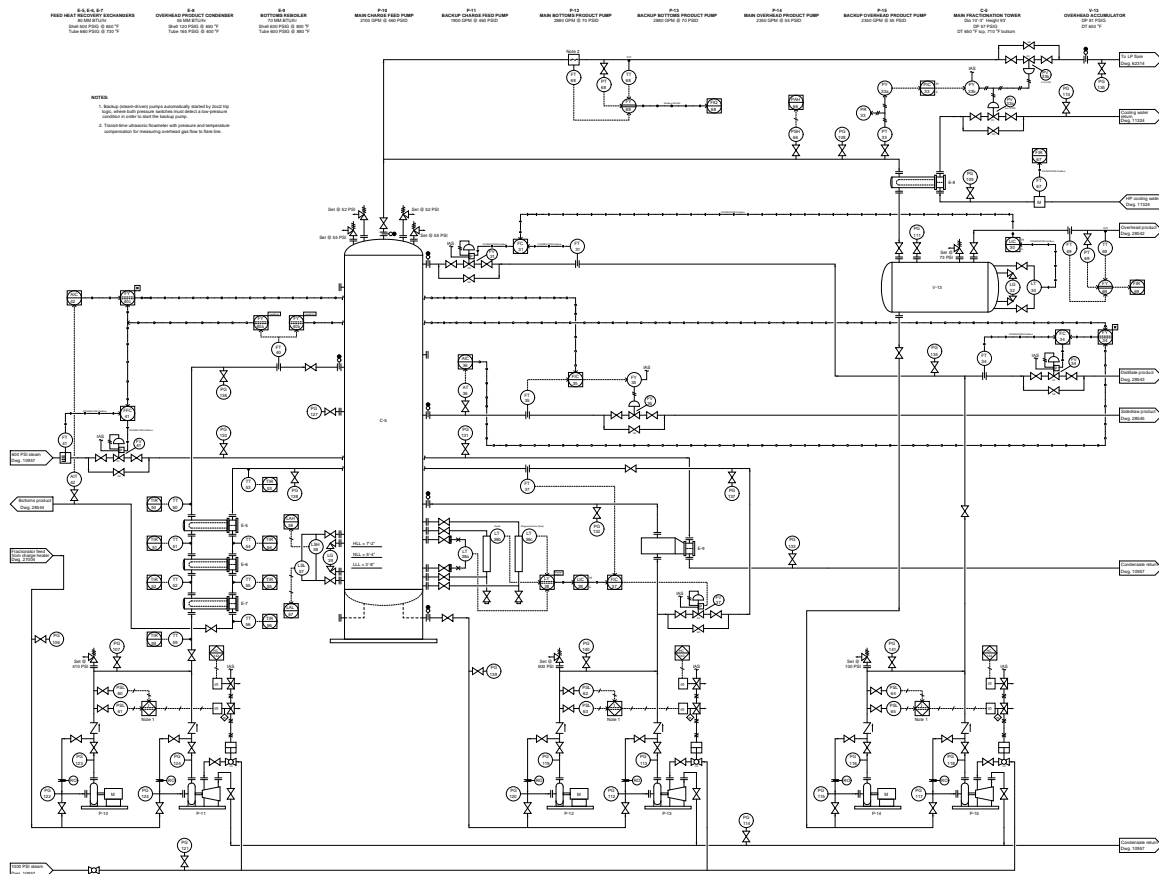
#### Suggestions for Socratic discussion

- Questions such as this tend to be challenging for people with limited experience working on mechanical devices. Identify some problem-solving strategies for a mechanically innocent student to apply to problems such as this.
- What sort of device(s) would you suggest using to apply a precisely known pressure to a gauge for calibration purposes?
- Suppose a pressure gauge is intended for service in a process measuring liquid pressure. Is it okay to calibrate this gauge on a test bench using compressed *air* instead of the liquid it will be exposed to in the field? Why or why not?

file i00173

## Question 50

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.

### Suggestions for Socratic discussion

- 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

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#### Question 51

Answer the following four questions about deadweight testers:

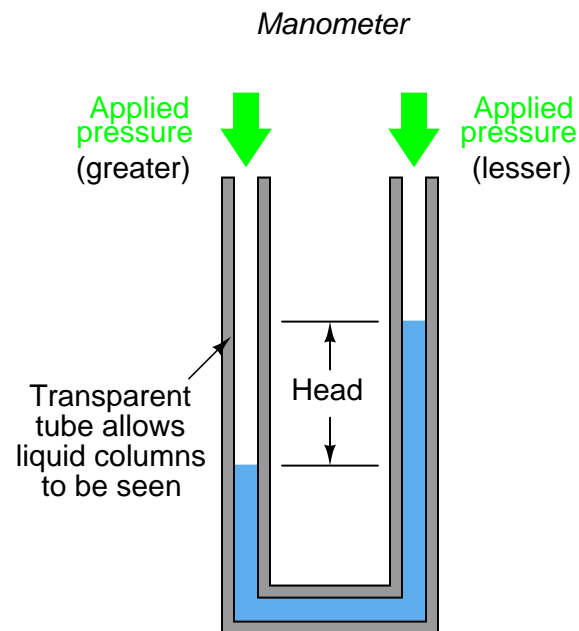
- (1) What is it about the nature of a deadweight tester that makes it so accurate and repeatable? To phrase this question in the negative, what would have to change in order to affect the accuracy of a deadweight tester's output pressure?
- (2) Why is it important for a deadweight tester to be *level* while it is being used to calibrate a pressure instrument?
- (3) What effect will trapped air have inside a deadweight tester?
- (4) Why is it advisable to *gently* spin the primary piston and weights while the piston is suspended by oil pressure?

file i00154

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Question 52

A device called a *manometer* is a very simple and yet very precise pressure measuring instrument. It works on the principle of a differential pressure displacing a vertical liquid column. The distance between the tops of the two liquid columns is proportional to the difference in pressure applied to tops of the two vertical tubes. This is where we get pressure units of “inches/centimeters of water column” and “inches/centimeters/millimeters of mercury” – from the operation of a manometer:



Explain how this instrument may serve as a standard for pressure measurement, just as a deadweight tester may serve as a standard for pressure generation. To phrase this question in the negative, what would have to change in order to affect the pressure measurement accuracy of a manometer?

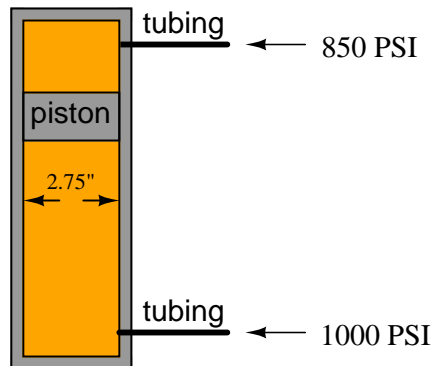
file i00160

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Question 53

A free-floating piston inside a hydraulic cylinder has a 1000 PSI of fluid pressure applied to one side of the piston, and 850 PSI of pressure applied to the other side of the piston. The piston itself is 2.75 inches in diameter. How much force will act on the piston, with these pressures applied to it?

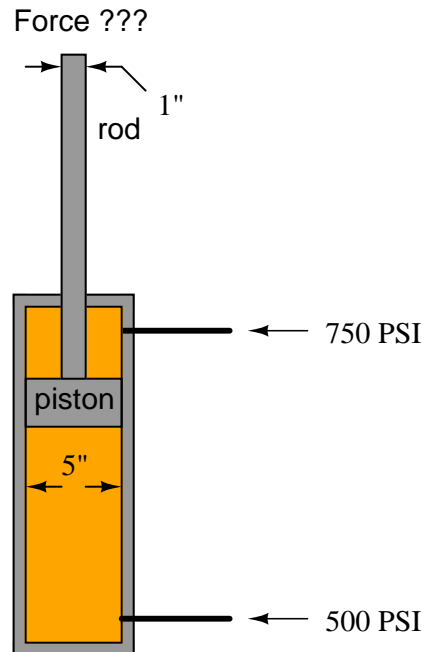
Force on piston ???



file i00155

#### Question 54

A double-acting hydraulic cylinder has 500 PSI of pressure applied to the side without the rod and 750 PSI of pressure applied to the rod-side. Calculate the resultant force generated at the piston and transmitted through to the rod, and also determine this force's direction. The piston is 5 inches in diameter, and the rod is 1 inch in diameter.



#### Suggestions for Socratic discussion

- Identify which fundamental principles of science, technology, and/or math apply to each step of your solution to this problem. In other words, be prepared to explain the reason(s) “why” for every step of your solution, rather than merely describing those steps.
- What would happen if fluid pressure were applied to the bottom port and a fluid *vacuum* were applied to the top port? Would this generate more force, less force, or the same amount of force as if the same fluid pressure were applied to bottom port and the top port left vented?
- Would the piston experience a resultant force if both ports were connected together with a length of tubing (made “common” to each other) and then pressurized with the exact same amount of fluid pressure? Why or why not?
- Suppose both ports of this cylinder were connected together with a length of tubing (made “common” to each other) and to a pressure gauge. What would that gauge register if the piston were then pushed in the downward direction? Would the gauge’s reading increase, decrease, or remain the same? Explain your answer in detail.

[file i00156](#)

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Question 55

A very useful principle in physics is the *Ideal Gas Law*, so called because it relates pressure, volume, molecular quantity, and temperature of an ideal gas together in one neat mathematical expression:

$$PV = nRT$$

Where,

$P$  = Absolute pressure (atmospheres)

$V$  = Volume (liters)

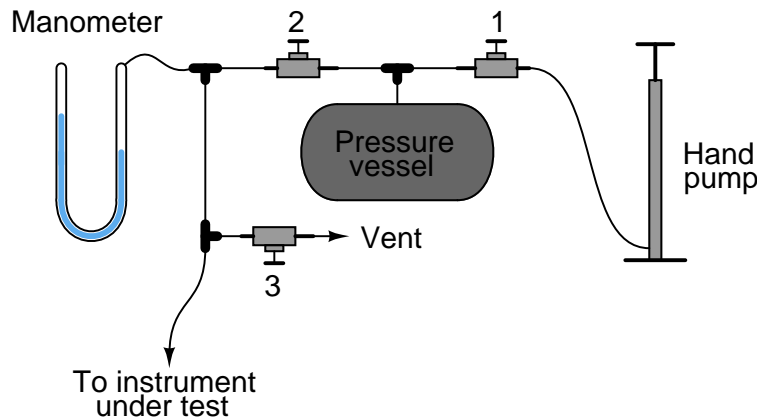
$n$  = Gas quantity (moles)

$R$  = Universal gas constant (0.0821 L · atm / mol · K)

$T$  = Absolute temperature (K)

Although this “law” is not perfectly accurate for real gases, especially at high pressures and/or near the point of liquefaction, it is quite accurate for air near ambient temperature and pressure.

One very practical application of this law is found in a method for generating low air pressures such as those easily measured by water- or oil-based manometers. Most mechanical air compressors generate pressures far exceeding the range of all but the largest manometers. Though it is possible to purchase precision pressure regulators for reducing such large pressures down to a level measurable by a manometer, these devices are expensive. An alternative is to generate the air pressure with a hand pump (such as a bicycle tire pump) connected to a relatively large pressure vessel:



Without the volume of the pressure vessel connected to the tubing system, the air pressure would increase dramatically for each stroke of the air pump. With the pressure vessel connected, each pump stroke contributes a much smaller amount of additional pressure to the system. Use the Ideal Gas Law equation to explain why this is.

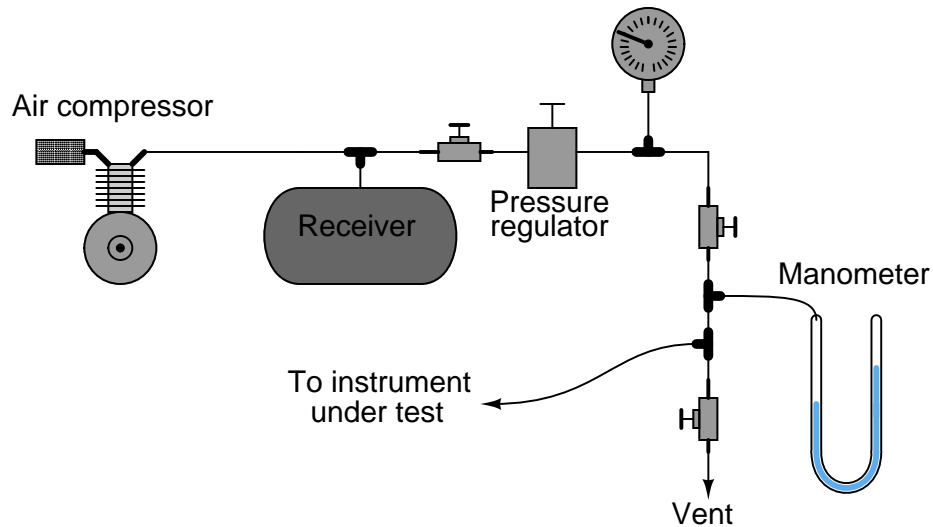
file i00286



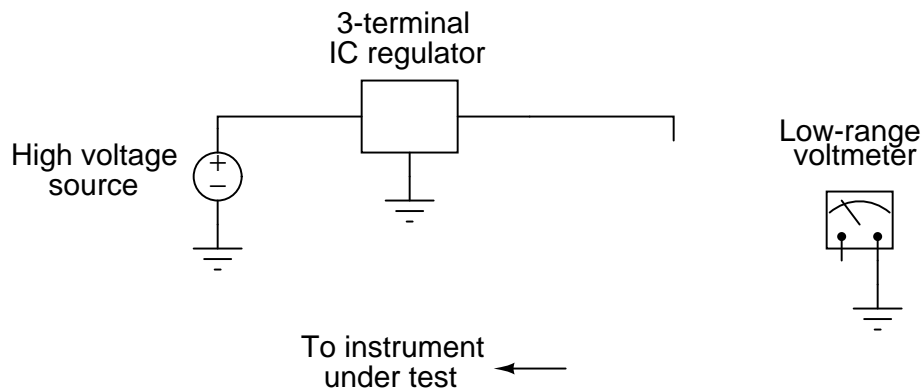
# Question 56

One challenge technicians face when calibrating low-pressure instruments is how to generate very low air pressures to simulate different low-pressure conditions for the pressure instrument under test. Measuring low pressures is no problem at all: very simple manometers will do the job quite nicely. Most mechanical air compressors, however, generate pressures far exceeding the range of most manometers. Though it is possible to purchase precision pressure regulators for reducing such large pressures down to a level measurable by a manometer, these devices are expensive.

A simple way to “divide” the pressure output of a standard pressure regulator from a few PSI to a few inches of water is to use a pair of small valves (preferably needle valves allowing for precise adjustment) to throttle the flow of compressed air and vent the regulator’s output to atmosphere, then tap between those valves to obtain a reduced pressure:



Complete the following schematic diagram showing an electrical model for this pneumatic system, and then explain how it works:

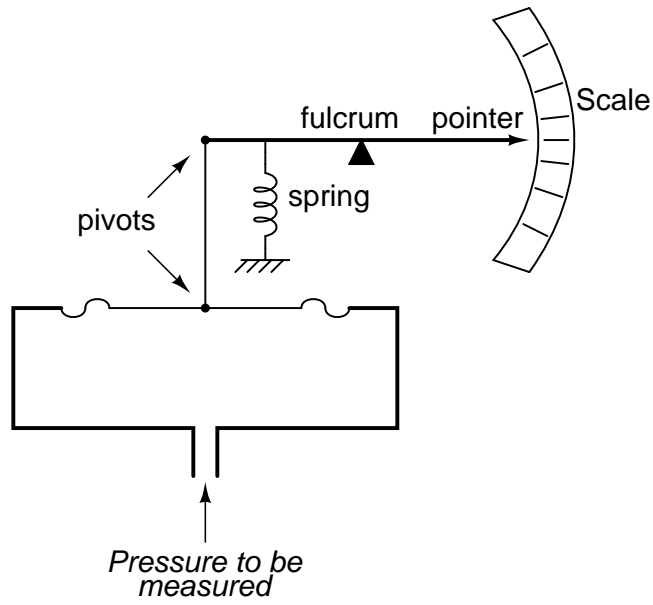


[file i00287](#)

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Question 57

Suppose a pressure gauge uses a diaphragm as its pressure-sensing element, like this:



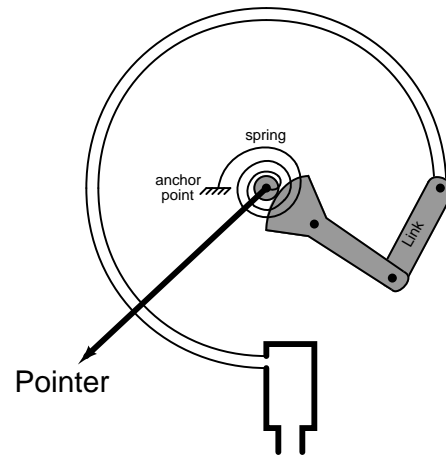
This mechanism will work, but what if we desired to make it more sensitive? That is, we wished to decrease its measurement span so that less pressure would drive the pointer to full-scale. What could we alter in this mechanism to decrease the measurement span?

file i00172

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Question 58

Some bourdon tube gauges are equipped with a very small spiral spring attached to the pointer shaft:



Now, this spring is much too weak to have any detectable effect on the span of the gauge. In other words, it does not measurably resist the bending action of the bourdon tube, as a “range spring” would in another design of instrument.

Given its weakness, what possible purpose does this spring serve in the gauge mechanism?

[file i00175](#)

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Question 59

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

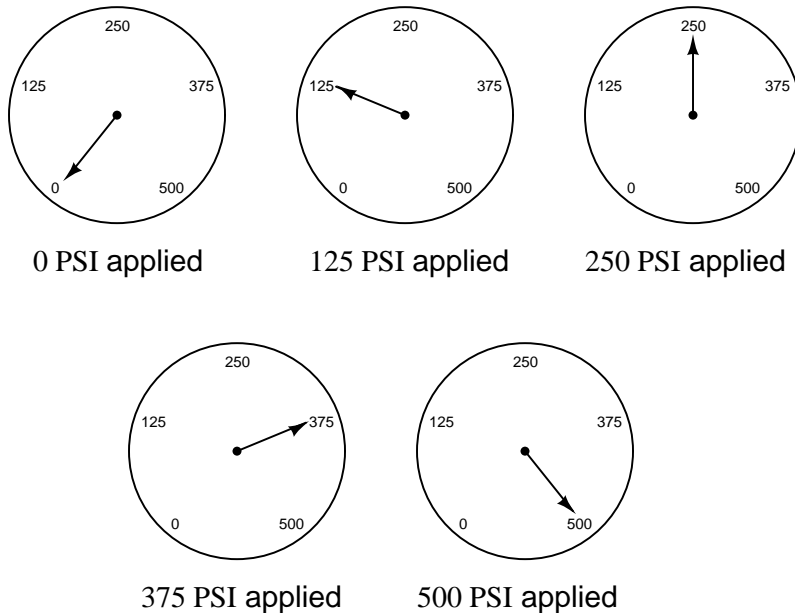
Also, show the math you used to calculate each of the error percentages.

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 60

A pressure gauge is supposed to accurately indicate applied pressure over its full calibrated range. In this example, a gauge with a range of 0 to 500 PSI is subjected to five different pressures along that range, and its response is accurate at all those points:



Describe, by drawing a set of five meter readings such as the set shown above, how a pressure gauge accurate at 0% and 100% of applied pressure – but with a *nonlinearity* problem between the LRV and URV points – might respond to the same five applied pressures.

Furthermore, describe how a bourdon tube pressure gauge instrument might be adjusted for linearity. In other words, how may a nonlinear pressure gauge be calibrated to become more linear?

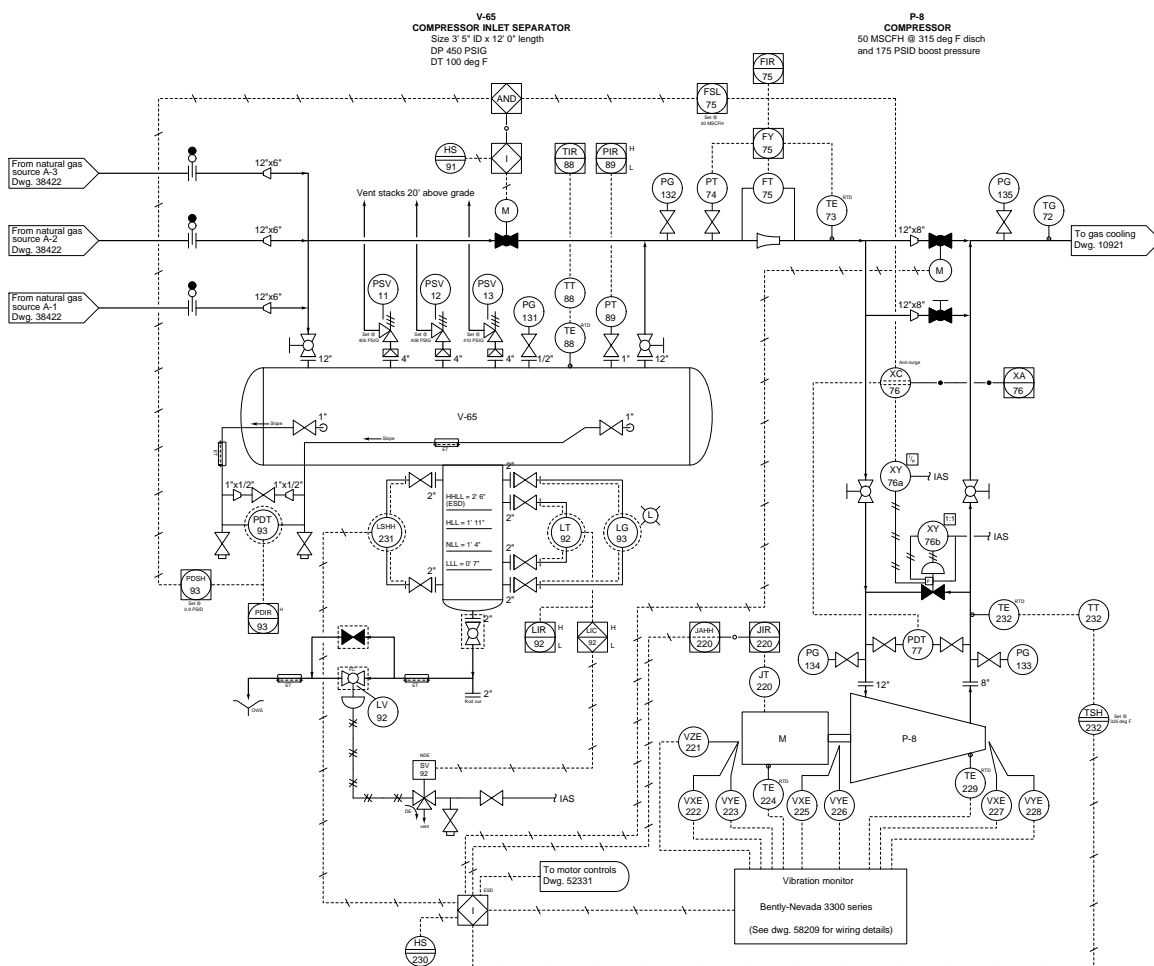
#### Suggestions for Socratic discussion

- Explain how keeping both “As-Found” and “As-Left” calibration records on instruments such as this pressure gauge make it possible to track long-term calibration drift.
- Can a non-linearity error be corrected by adjusting the zero and/or span screws on an instrument? Why or why not?

[file i00174](#)

## Question 61

Pressure transmitter PT-89 on this natural gas separator vessel presently has a calibrated range of 0 to 400 PSIG. Operations personnel would like you to re-range this transmitter for 300 to 375 PSIG instead:



Answer the following questions about the task of re-ranging, explaining each of your answers:

- Does the new, requested range constitute a *zero* shift, a *span* shift, or both?
- If this is a “smart” (digital) transmitter, does it need to be *re-trimmed* as well as *re-ranged*?
- Will the control room indicator PIR-89 need to be *re-calibrated*, *re-ranged*, or both?
- Will the local pressure gauge PG-131 need to be *re-calibrated* as well?
- Will the pressure safety valves PSV-11, PSV-12, and/or PSV-13 need to be set for lower “lift” pressures?
- If the maximum (factory) range of this pressure transmitter is 0 to 750 PSI and the maximum turndown ratio for the required accuracy is 20:1, will it be able to meet the new range? If not, what might you have to do in order to fulfill operations’ request?
- Why do you suppose operations would like you to re-range this transmitter? In other words, what operational advantage(s) might be gained from doing so? Are there any potential disadvantages of having the new range versus the old?

### Question 62

Read the product manual for the WIKA (brand) “DELTA-trans” (model 891-34-2189) differential pressure transmitter, which uses a Hall Effect sensor to generate an electronic output signal from a sensed differential pressure. Then, answer the following questions:

Explain how an applied pressure is sensed by this DP transmitter, and how the mechanical motion is converted into an electronic signal. You may need to do some research on “Hall Effect” sensors in order to fully answer this question.

Identify how the zero and span adjustments are implemented – are they mechanical, or electrical?

Identify how the “high” and “low” ports of this DP instrument are labeled. Which way does the sensing element move when a fluid pressure is applied to the “low” port?

How is this electronic device powered? Is there a battery that needs to be replaced periodically?

### **Suggestions for Socratic discussion**

- Cut-away diagrams such as the one shown in the manual for this Wika pressure gauge/transmitter can be confusing for those unaccustomed to interpreting mechanical drawings. To try explain what the different shadings and “hatchings” in this diagram represent, and also how to visualize the mechanism in motion from applied pressure.
- Identify a mechanical change that could be made to this mechanism affecting the *zero*.
- Identify a mechanical change that could be made to this mechanism affecting the *span*.
- Modify the design of this pressure transmitter to operate differently in some way, perhaps substituting some other sort of sensor in place of the Hall Effect chip.
- Examine the “Technical Data” table in this document and explain what the phrase *exposed to medium* refers to.

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### Question 63

Read and outline the “Piezoresistive (Strain Gauge) Sensors” subsection of the “Electrical Pressure Elements” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03912](#)

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### Question 64

Read and outline the “Differential Capacitance Sensors” subsection of the “Electrical Pressure Elements” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03913](#)



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### Question 65

Read and outline the “Resonant Element Sensors” subsection of the “Electrical Pressure Elements” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text represented in your outline, entirely in your own words (i.e. no copying of text), written in a legible and comprehensible manner, of sufficient quality that others would find it informative.* Incomplete, illegible, cryptic, and/or plagiarized outlines will not receive full credit. A suggestion is one sentence of your own per paragraph of source text. A well-written outline contains the following:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03914](#)

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## Question 66

Research specifications for the Rosemount model 3051S Series “coplanar” differential pressure transmitter (model 3051S\_CD), located in the Product Data Sheet document (00813-0100-4801 Revision GA, April 2006). Then, answer the following questions:

Identify the different “performance classes” for this instrument model. Specifically, identify the percentage accuracy and the “rangedown” (otherwise known as “turndown”) limits for each.

Identify some of the different codes for pressure measurement ranges. What is the lowest pressure measurement range you can order this instrument in? What is the highest pressure measurement range?

Identify some of the maximum working pressures (“overpressure limits”) for different range codes. What consequence(s) might follow exceeding these limits, according to the manual?

Explain why the higher gage pressure ranges are asymmetrical (i.e. why their negative pressure limits are so much less than their positive pressure limits). All the differential models have symmetrical ranges, so why don’t the gage models?

Identify some of the different isolating diaphragm materials available for this instrument. Explain why the sensing diaphragms don’t come in different material types as well.

Identify the sensor fill fluid options available for this “coplanar” model. Note: this is the fill fluid used to fill the transmitter’s internal sensor, *not* to fill remote-seal capillary tubes and diaphragms (that would be the model 3051S\_L).

### Suggestions for Socratic discussion

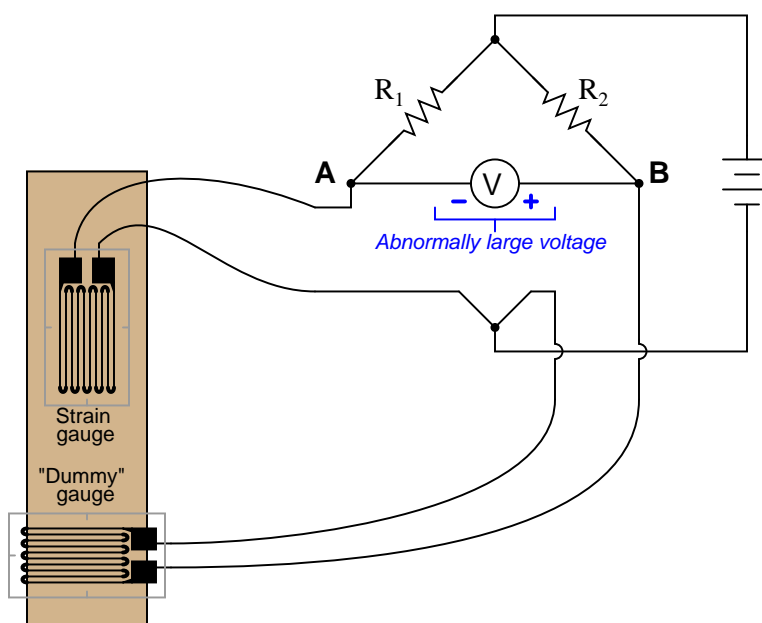
- Suppose you had a model 3051S\_CD transmitter with range code 1. Determine the *lower range limit* (LRL), *upper range limit* (URL), *overpressure limit*, *static pressure limit*, and *burst pressure limit* for this particular transmitter, explaining how each of these parameters differ from the others in meaning.
- The “Ultra for Flow” performance class model has some interesting limitations, necessary for achieving the exceptionally high accuracy advertised. Identify what some of these limitations are.
- Identify the meaning of the typical model number given on page 30.

[file i03915](#)

# Question 67

A *strain gauge* is an array constructed from thin metal film designed to increase resistance as it is stretched and decrease resistance as it is compressed. Strain gauges are typically bonded to metal specimens undergoing mechanical testing, as a means of sensing how much strain is being applied to that metal specimen. In order to translate the resistance of the strain gauge into a measurable voltage signal, the strain gauge is typically incorporated into one arm of a “bridge” circuit.

The following bridge circuit uses two strain gauges (one to measure strain, the other to compensate for temperature changes), the amount of strain indicated by the voltmeter in the center of the bridge. Unfortunately, though, it has a problem. Instead of registering a very small voltage as it normally does, the voltmeter is “pegged” (driven beyond its normal full-range measurement) by a large voltage difference, with point **B** positive and point **A** negative as shown here:



Something is wrong in the bridge circuit, because this voltage is present even when there is no physical stress on the specimen. Identify which of the following faults could cause the excessive voltage to appear across the voltmeter, and which could not. Consider only one of these faults at a time (no multiple, simultaneous faults):

Fault	Possible	Impossible
$R_1$ failed open		
$R_2$ failed open		
Strain gauge failed open		
Dummy gauge failed open		
$R_1$ failed shorted		
$R_2$ failed shorted		
Strain gauge failed shorted		
Dummy gauge failed shorted		
Voltage source dead		

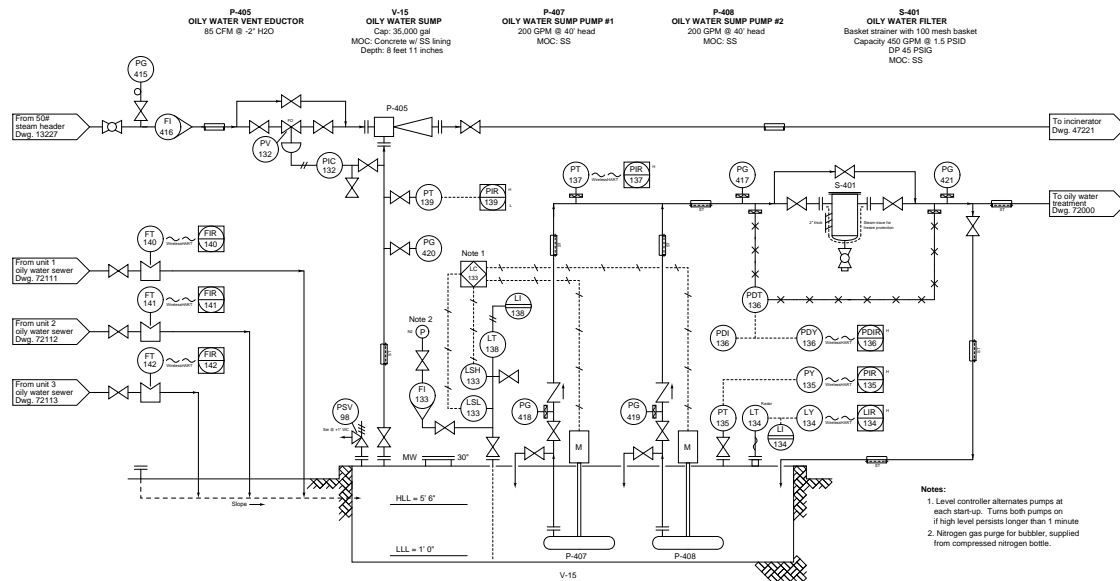
Suggestions for Socratic discussion

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) “why” for every step of your analysis, rather than merely describing those steps.
- Explain why the two strain gauge elements are orthogonally bonded (i.e. attached 90° to each other) to the specimen.

[file i00188](#)

### Question 68

An operator reports a series of false pressure alarms reported by pressure indicating recorder PIR-139 every few minutes. An instrument technician investigated this problem the previous day and declared it was most likely due to an electrical wiring fault between PT-139 and PIR-139 after measuring some intermittent high-current signals at the input terminals of PIR-139:



You are called to re-examine this system, because the other instrument technician didn't actually do anything to fix the problem. Your first test is to close the block (isolation) valve between PT-139 and the process pipe. After doing this, the mysterious pressure alarms cease. Later, you re-open that block valve and the pressure alarms resume.

Explain what the results of this simple test tell you about the nature and location of the fault. Does it confirm the first technician's diagnosis, or does it point to something else being wrong? Explain your answer in detail.

### Suggestions for Socratic discussion

- One detail not described in the scenario is just how the first technician measured those intermittent high-current signals at PIR-139. Presumably it could have been done by continuously monitoring the display of a digital multimeter (DMM) long enough to see an alarm event occur. However, if the alarm events were infrequent enough, this could be a laborious task for someone to continuously watch a meter waiting to see the current change. Describe how you could use the *Min/Max* mode of a DMM instead to “automate” this task and free up the technician's time.

[file i02553](#)

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**Question 69**

Complete the following table of equivalent pressures:

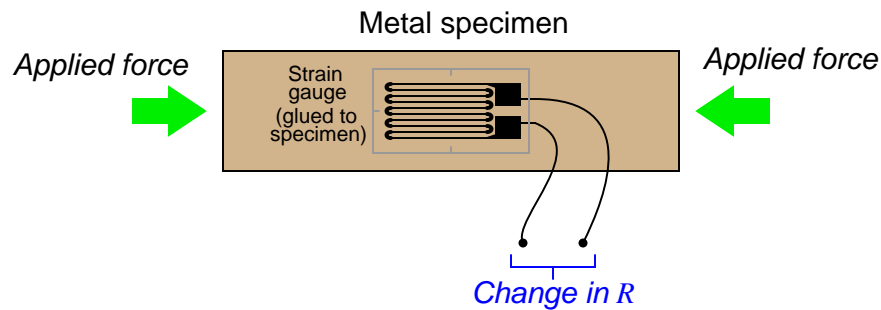
Atm	PSIG	inches W.C. (G)	PSIA
3.5			
	81		
		8834	
			0
		7.12	
			368
	2		
100			

There is a technique for converting between different units of measurement called “unity fractions” which is imperative for students of Instrumentation to master. For more information on the “unity fraction” method of unit conversion, refer to the “Unity Fractions” subsection of the “Unit Conversions and Physical Constants” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

file i02939

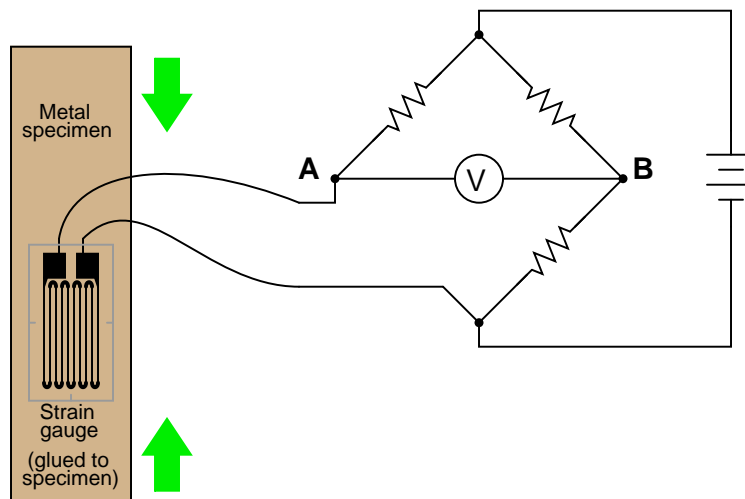
### Question 70

A *strain gauge* is a device used to measure the strain (compression or expansion) of a solid object by producing a resistance change proportional to the amount of strain. As the gauge is strained, its electrical resistance alters slightly:



Explain *why* the electrical resistance of a strain gauge changes as it stretches and shrinks, and also correlate the direction of resistance change (more or less) with the direction of applied force.

The following strain gauge is shown connected in a “quarter-bridge” circuit (meaning only one-quarter of the bridge actively senses strain, while the other three-quarters of the bridge are fixed in resistance):



Explain what would happen to the voltage measured across this bridge circuit ( $V_{AB}$ ) if the strain gauge were to be *compressed*, assuming that the bridge begins in a balanced condition with no strain on the gauge.

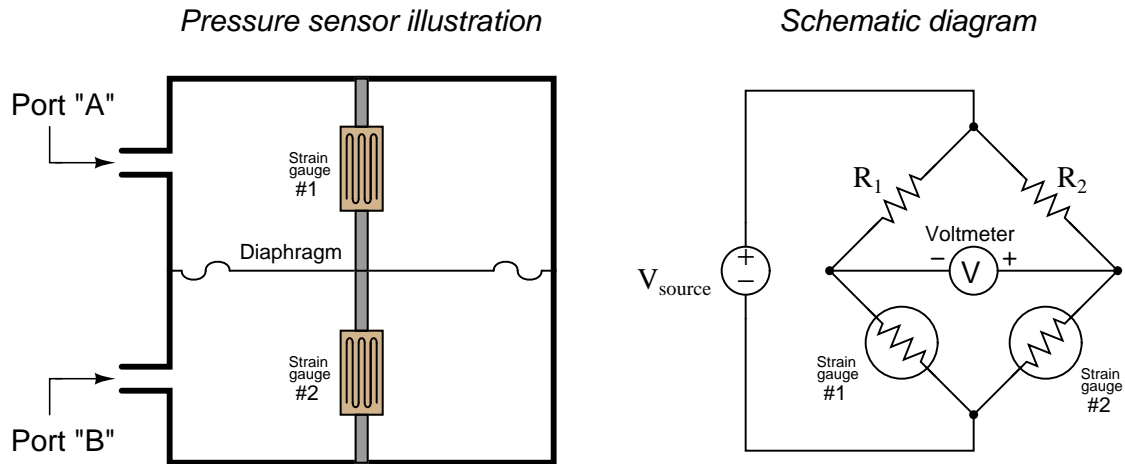
#### Suggestions for Socratic discussion

- A good problem-solving technique to apply when analyzing directions of change in a Wheatstone bridge circuit is to consider *limiting cases*. Instead of asking ourselves what would happen in the circuit if the strain gauge resistance changed slightly, we ask ourselves what would happen if the resistance changed *dramatically* (i.e. full open or full short). Explain how we could apply this problem-solving technique to this circuit.
- Strain gauges are widely used in the automotive and aerospace industries to study the strain of mechanical assemblies. Explain how a strain gauge might be used to measure the strain of something like a truck axle.

[file i00181](#)

### Question 71

The following differential pressure sensor uses a matched pair of strain gauges. As the differential pressure increases, one strain gauge becomes compressed while the other becomes stretched. A voltmeter registers the bridge circuit's imbalance and displays it as a pressure measurement:



Determine the following:

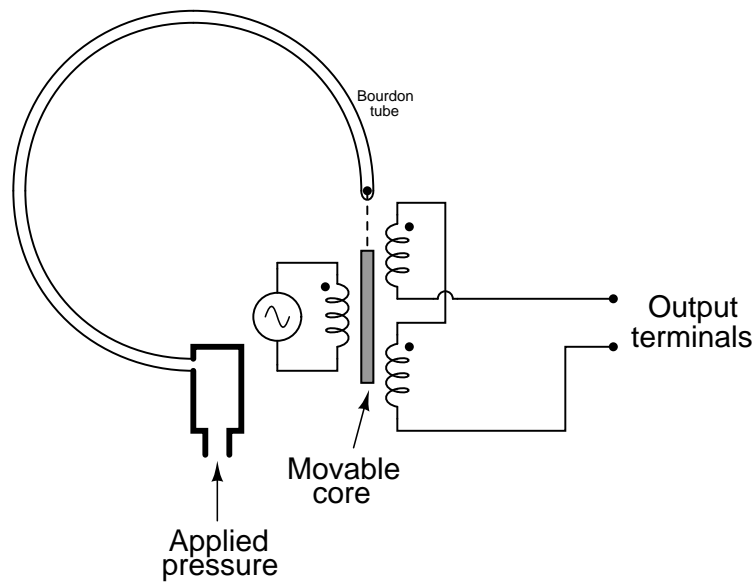
- Identify which port is the “high” pressure port
- Identify what the voltmeter will register if fixed resistor  $R_1$  fails open
- Identify a component fault that would drive the voltmeter full upscale (“peg” positive)
- Identify another component fault that would drive the voltmeter full upscale (“peg” positive)

[file i02944](#)

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Question 72

A simple form of electronic pressure transmitter could be made with a bourdon tube and a *Linear Variable Differential Transformer*, or *LVDT*:



Explain how this instrument works, what type of electrical output signal it generates (e.g. current, voltage, resistance, etc.), and what polarity (if any) that output signal has.

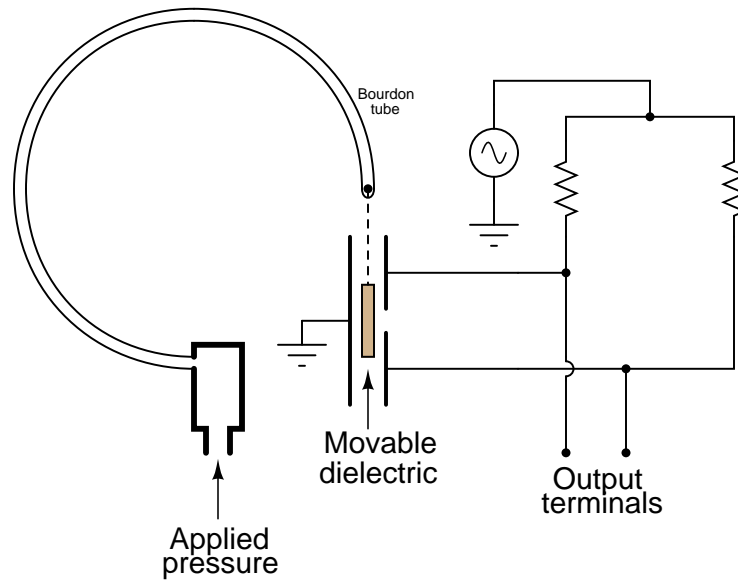
[file i00183](#)



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### Question 73

A simple form of electronic pressure transmitter could be made with a bourdon tube and a *differential capacitor*:



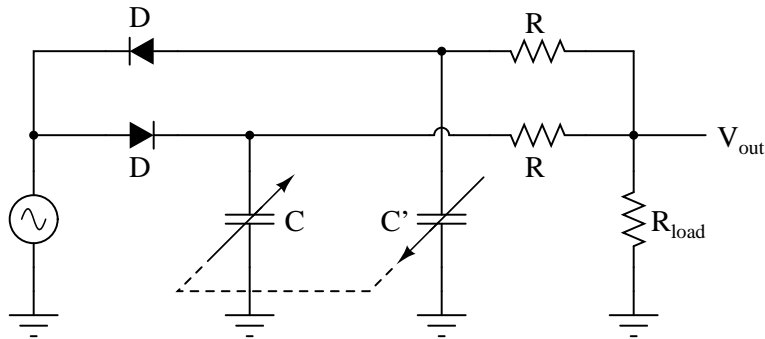
Explain how this instrument works, what type of electrical output signal it generates (e.g. current, voltage, resistance, etc.), and what polarity (if any) that output signal has.

[file i00184](#)

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### Question 74

An ingenious circuit used to convert the output of a differential capacitance sensor into a DC voltage signal is the *diode twin-T circuit* shown here:



The AC “excitation” voltage source is typically of high frequency, at least 1 MHz. The diodes are fast-switching units, ideally Schottky diodes. Resistors  $R$  must be equal in value, but  $R_{load}$  is usually much greater than  $R$ . Together, the two matched resistors ( $R$ ) form an *averaging network* for the two capacitances  $C$  and  $C'$  as they alternately discharge through  $R_{load}$ .

Identify which capacitance ( $C$  or  $C'$ ) must increase in value to generate a positive DC output voltage, and why this is so.

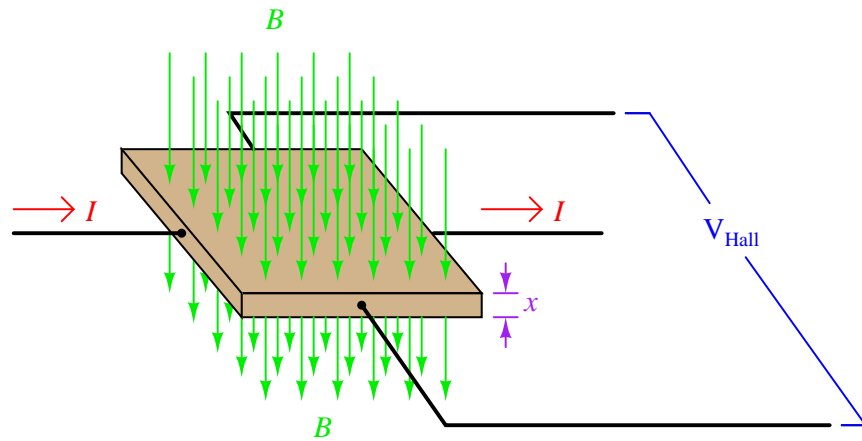
[file i00186](#)

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Question 75

The *Hall Effect* describes the voltage generated across the width of a conductive strip ( $V_{Hall}$ ) with a certain thickness ( $x$ ), given a perpendicular magnetic field ( $B$ ) and electric current ( $I$ ):

$$V_{Hall} = K \frac{IB}{x}$$

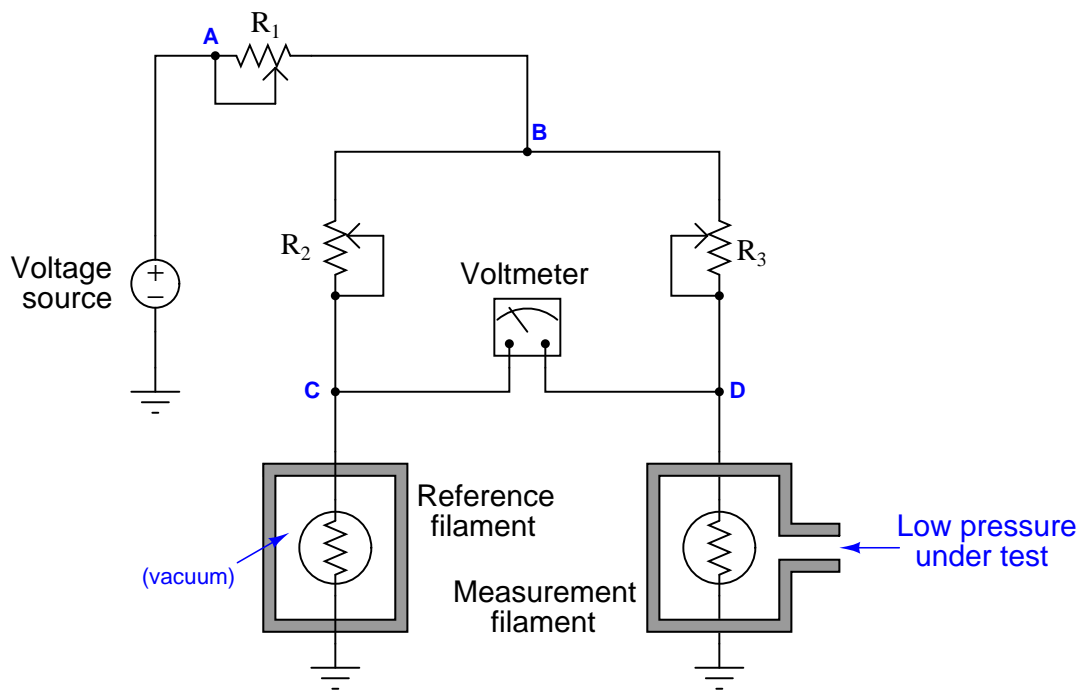


Manipulate the Hall Effect equation to solve for magnetic flux density  $B$  in terms of the other variables. Be sure to show all your work!

$B =$   
file i03295

# Question 76

A *Pirani gauge* is a special pressure instrument designed to measure very low pressures (i.e. hard vacuums). It uses two electrically heated filaments, one of which is sealed in a vacuum “reference” chamber, while the other is exposed to the process gas pressure under test. Gas molecules contacting the measurement filament causes it to cool and decrease resistance:



*Measurement filament cools and decreases resistance when it contacts air molecules (i.e. when test pressure increases)*

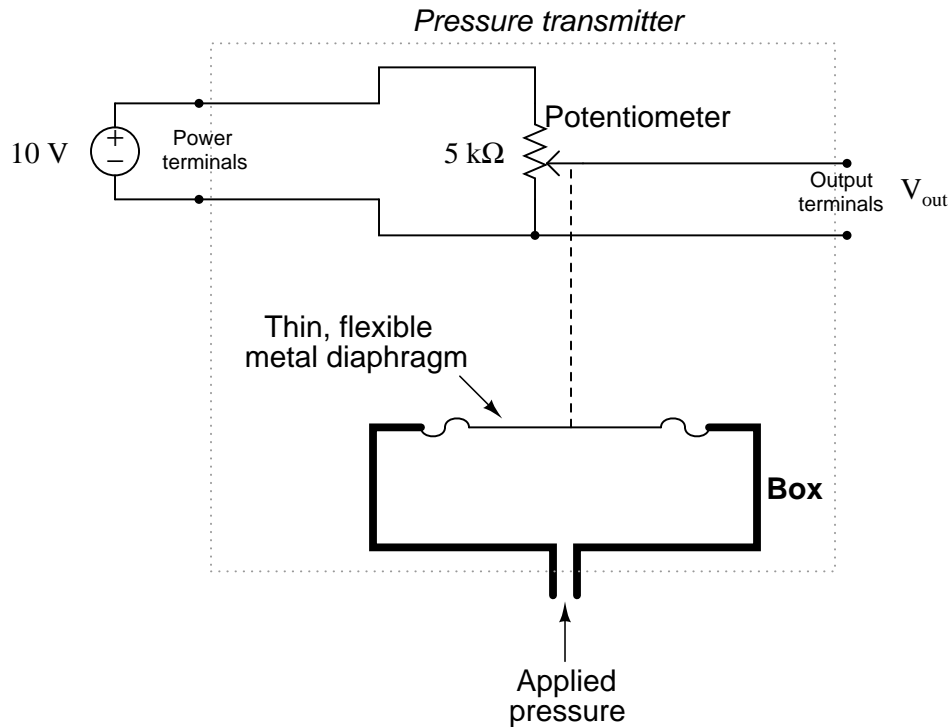
This Pirani gauge, however, has a problem. It registers a high pressure all the time, regardless of the strength of the vacuum connected to the measurement cell. A digital multimeter connected between test points **D** and ground registers 0 volts.

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

Fault	Possible	Impossible
$R_1$ failed open		
$R_1$ failed shorted		
$R_2$ failed open		
$R_2$ failed shorted		
$R_3$ failed open		
$R_3$ failed shorted		
Reference filament burned out		
Measurement filament burned out		

file i00300

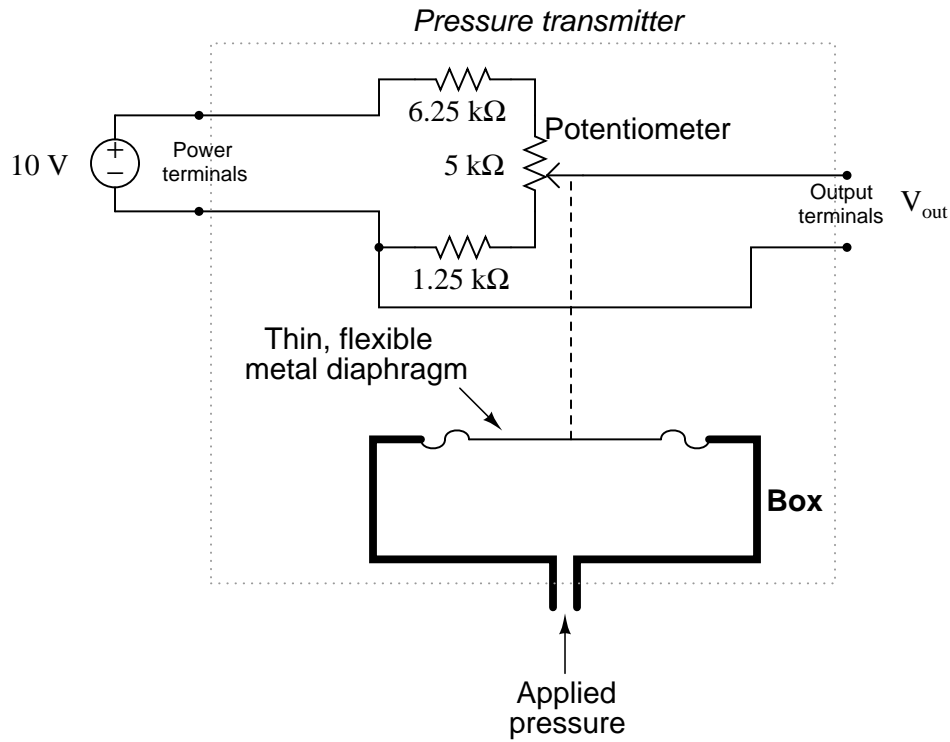
Shown here is a very simple *pressure transmitter*, a device that measures a fluid pressure and converts that measurement into an electrical signal:



Suppose the potentiometer wiper will be at its full-down position with no pressure applied to the diaphragm, and will be at its full-up position with 15 PSI (15 pounds per square inch) of pressure applied to the diaphragm. Based on this information, and what you see in the schematic diagram, answer the following questions:

- Lower Range Value (LRV) of input, in units of PSI:
- Upper Range Value (URV) of input, in units of PSI:
- Input span, in units of PSI:
- Lower Range Value (LRV) of output, in units of volts:
- Upper Range Value (URV) of output, in units of volts:
- Output span, in units of volts:

Now, suppose we make a modification to the electrical circuit portion of the pressure transmitter. Assume the diaphragm still responds to pressure and moves the potentiometer wiper the same way it did before. Answer the same questions again:



- Lower Range Value (LRV) of input, in units of PSI:
- Upper Range Value (URV) of input, in units of PSI:
- Input span, in units of PSI:
- Lower Range Value (LRV) of output, in units of volts:
- Upper Range Value (URV) of output, in units of volts:
- Output span, in units of volts:

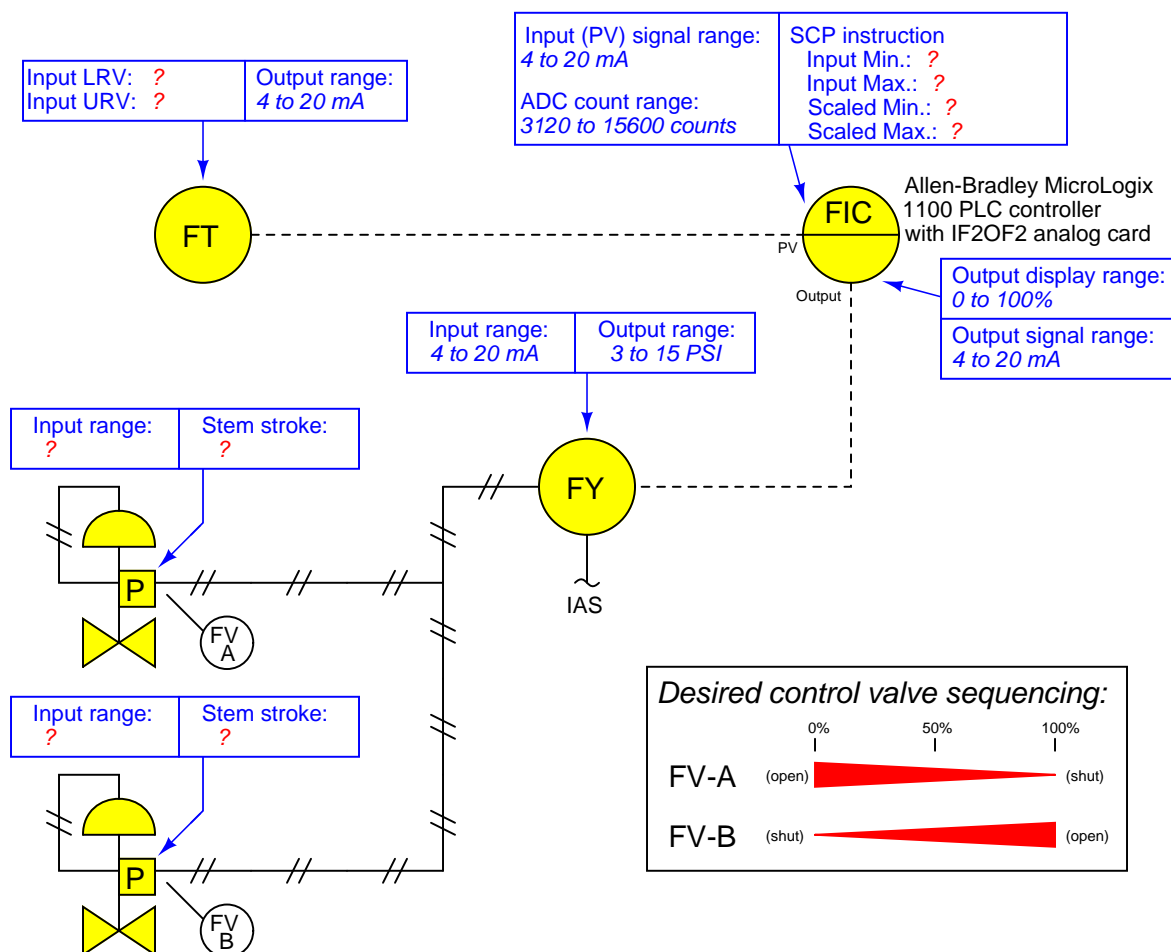
The latter design outputs what is commonly called a *live-zero* signal, whereas the first transmitter outputs a *dead-zero* signal. Live-zero signals are much preferred in industrial instrumentation, because they more readily betray wiring failures than dead-zero signals.

Explain how you answered all the questions, and also show currents and voltage drops in both circuits (complete with arrows showing directions of current). Then, elaborate on why you think live-zero signals are preferable to dead-zero signals.

file i00083

## Question 78

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:



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

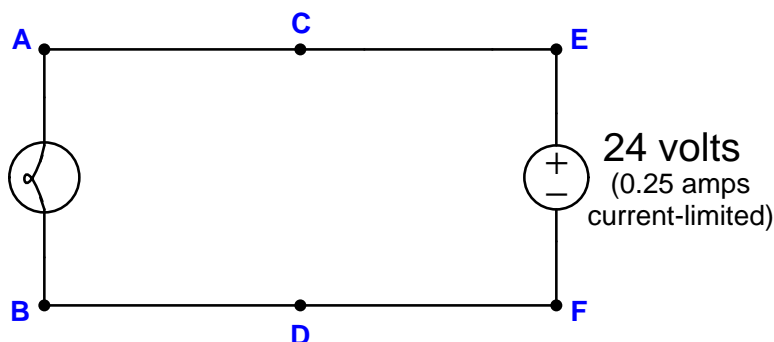
### Suggestions for Socratic discussion

- 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 79

Suppose the lamp refuses to light up. A voltmeter registers 24 volts between test points **C** and **D**:



First, list all the possible (single) faults that could account for all measurements and symptoms in this circuit, including failed wires as well as failed components:

Now, determine the diagnostic value of each of the following tests, based on the faults you listed above. 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 $V_{CF}$		
Measure $V_{ED}$		
Measure $V_{AB}$		
Measure $V_{AD}$		
Measure $V_{CB}$		
Measure $V_{EF}$		
Measure current through wire connecting <b>A</b> and <b>C</b>		
Jumper <b>A</b> and <b>C</b> together		
Jumper <b>B</b> and <b>D</b> together		
Jumper <b>A</b> and <b>B</b> together		

Finally, develop a rule you may use when assessing the value of each proposed test, based on a comprehensive list of possible faults.

**Suggestions for Socratic discussion**

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) “why” for every step of your analysis, rather than merely describing those steps.
- Suppose the fault were intermittent: sometimes the lamp lights up, and other times it goes out. Explain how you could use a digital multimeter (DMM) set to *record* voltage as a troubleshooting tool to determine where the fault is located in the circuit over a span of time too long for you to personally observe the circuit.

[file i01746](#)



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Question 80

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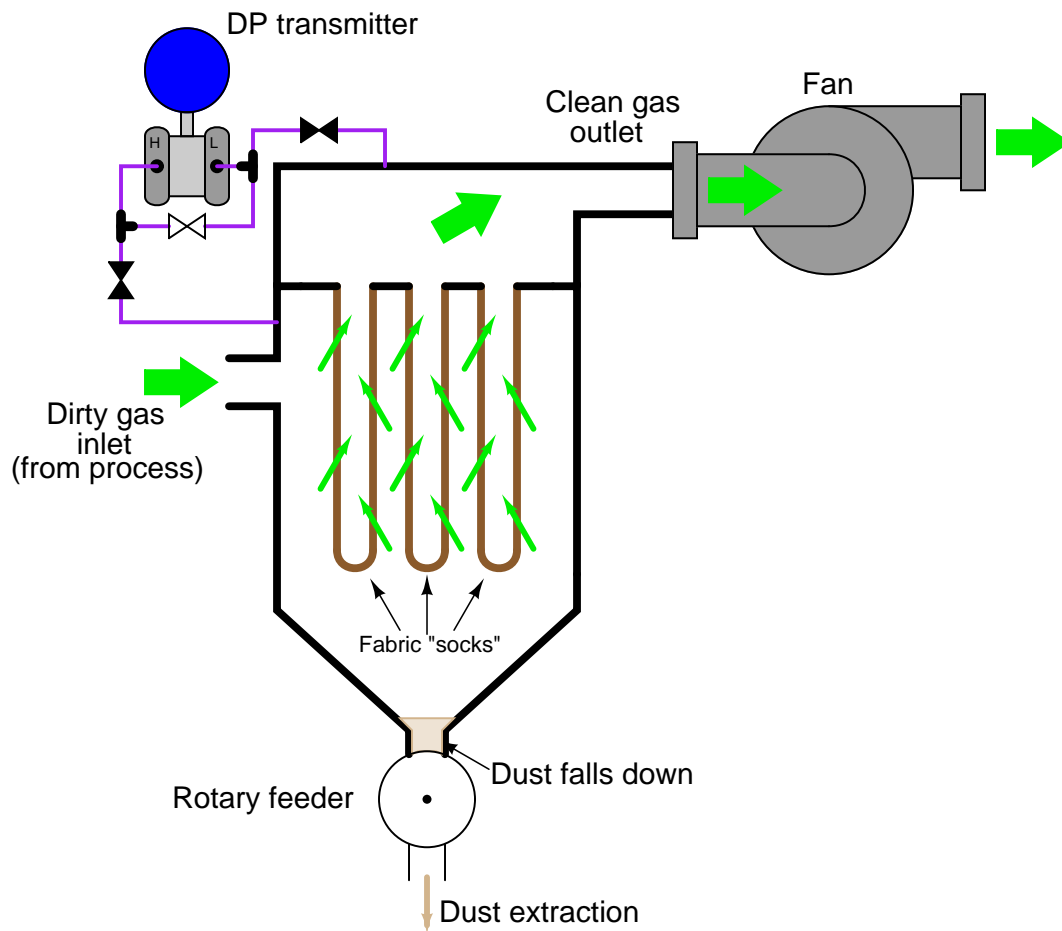
Question 81

Complete the following table of equivalent pressures. Show enough of your work that it is clear how you performed each type of conversion (e.g. from PSIG to PSIA, from Torr to PSIA, etc.):

PSIG	PSIA	Torr	inches W.C. (G)
15			
	2.1		
		900	
			100
		5	
			−30
	10		
85			

### Question 82

Suppose a differential pressure transmitter is used to measure the pressure dropped across a *baghouse*, an assembly using multiple fabric “socks” to filter particulate material from a gas stream, like a large-scale vacuum cleaner. Gas passes through the socks, filtering out the particulate matter. The DP transmitter’s pressure measurement serves to indicate how clogged the socks are:



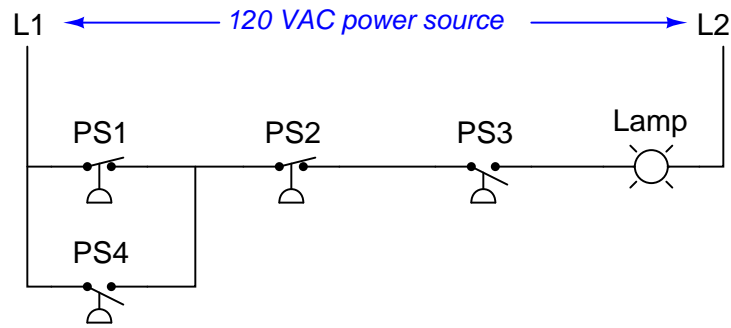
When the transmitter signal reaches a certain value (indicating clogged filter socks), a control system triggers either a mechanical shaker or a blast of gas from jets located near each sock shakes the dust from the outside area of each sock, the dust falling down into the narrow area below where it is extracted over time from the baghouse.

Suppose an instrument technician leaves the three valves in the positions shown (hollow = open ; solid = closed). What effect will this have on the socks over time as they perform their filtering job, assuming the control system continues to operate as designed?

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Question 83

Determine what pressure conditions must be met at each of the four pressure switches in order for the lamp to energize:

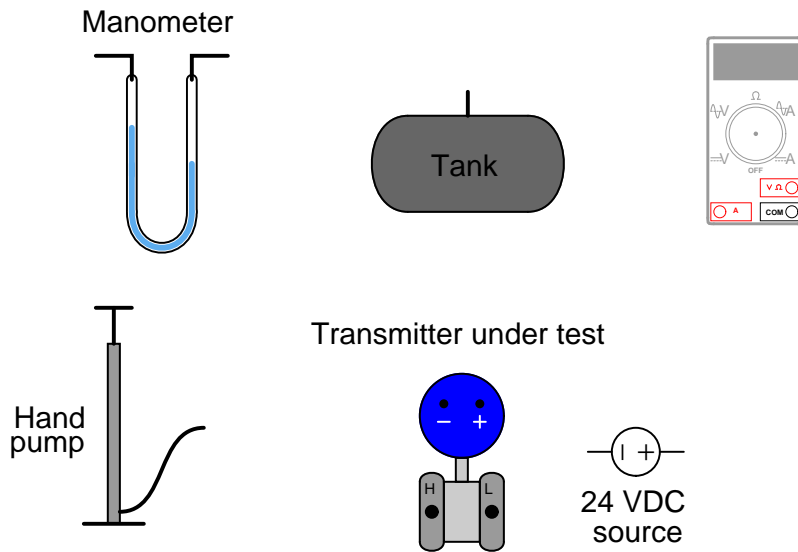


Trip settings for each pressure switch:

- PS1 = 50 PSI
- PS2 = 31 PSI
- PS3 = 77 PSI
- PS4 = 8 PSI

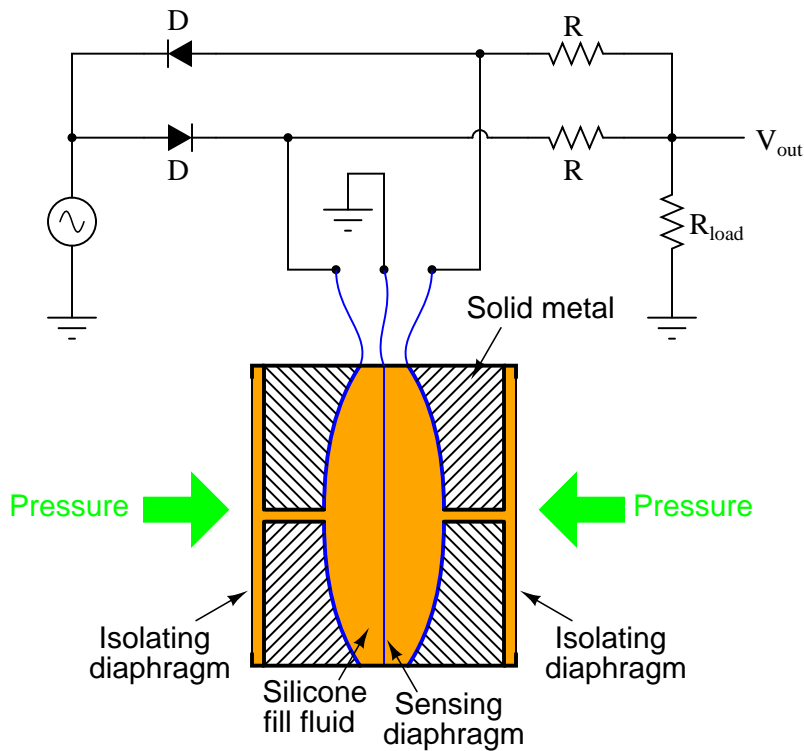
# Question 84

Sketch the necessary connecting tubes and wires to calibrate a DP transmitter to a low pressure range (somewhere in the range of a few inches of water), using a hand (bicycle-style) air pump as the pressure source and a U-tube manometer as a pressure standard. As pressure increases, the transmitter's output signal should increase as well:



Question 85

An ingenious circuit used to generate an electrical voltage signal from a differential capacitance sensor is the *Twin-T diode circuit*, shown here connected to a Rosemount-style differential capacitance pressure sensor:



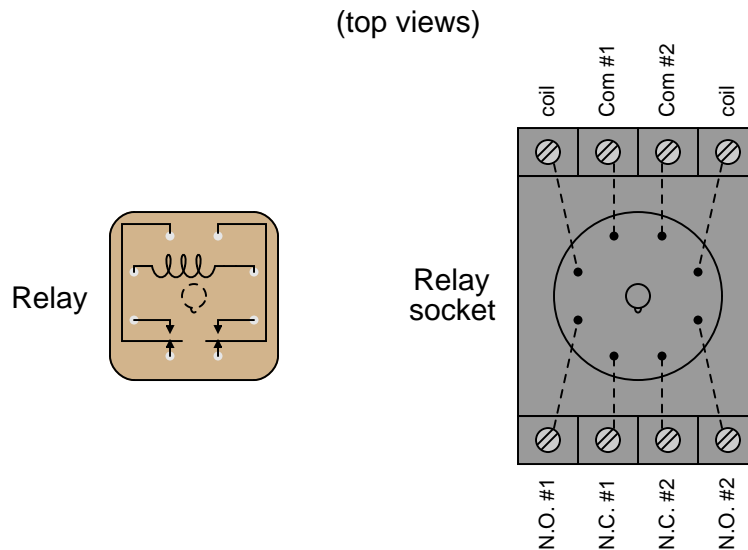
One capacitor is charged positive with respect to ground, while the other is charged negative with respect to ground, as the AC voltage source alternates positive and negative. While one capacitor of the pressure sensor is charging, the other is discharging through  $R_{load}$ , producing an output voltage ( $V_{out}$ ).

If both capacitances are equal, the output voltage will alternate equally between positive and negative values, having a DC average value of zero. If one capacitance is larger than the other, it will store additional charge on its plates, causing it to sway the output voltage of the Twin-T circuit in the direction of its polarity. Thus,  $V_{out}$  becomes more positive as pressure increases on one side of the sensor, and more negative as pressure increases on the other side of the sensor.

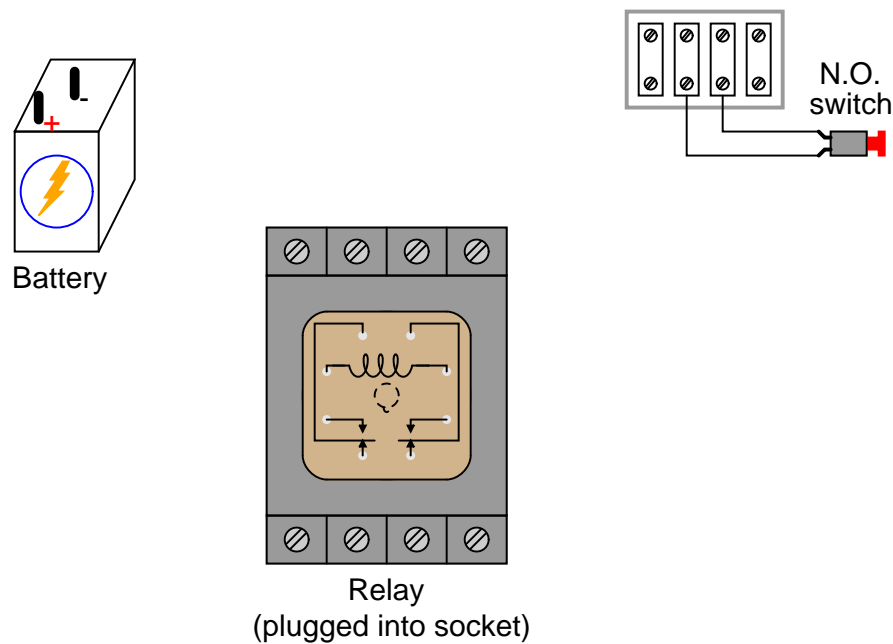
Based on this explanation of the Twin-T circuit's operation, determine which side of the pictured differential capacitance sensor is the "High" pressure side, and which is the "Low" pressure side. Be sure to explain your reasoning!

# Question 86

Small relays often come packaged in clear, rectangular, plastic cases. These so-called “ice cube” relays have either eight or eleven pins protruding from the bottom, allowing them to be plugged into a special socket for connection with wires in a circuit. Note the labels near terminals on the relay socket, showing the locations of the coil terminals and contact terminals:



Draw the necessary connecting wires between terminals in this circuit, so that actuating the normally-open pushbutton switch sends power from the battery to the coil to energize the relay:



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Question 87

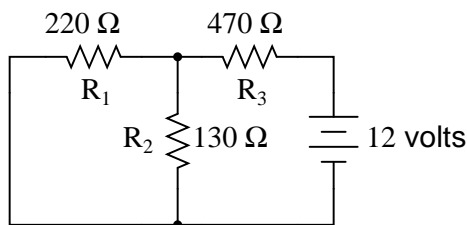
Solve for values of  $x$  and  $y$  that will satisfy both of the following equations at the same time:

$$3x - y = 17$$

$$x + 2y = 1$$

Question 88

Complete the table of values for this circuit, and also annotate the diagram with + and – symbols to show voltage polarities and arrows to show directions of current (conventional flow notation) for each component. Be sure to show all your mathematical work!



	$R_1$	$R_2$	$R_3$	Total
V				
I				
R	$220\ \Omega$	$130\ \Omega$	$470\ \Omega$	
P				

As you solve this problem, be sure to store all intermediate calculations (i.e. answers given to you by your calculator which you will use later in the problem) in your calculator’s memory locations, so as to avoid re-entering those values by hand. Re-entering calculated values unnecessarily introduces rounding errors into your work, as well as invites keystroke errors. *Avoiding the unnecessary introduction of error is a very important concept in Instrumentation!*

If your final answers are rounded as a result of not doing this, you will only receive half-credit for your work. This is a general policy for all your mathematical work in this program, not just this particular problem!

Note: the task of analyzing any series-parallel resistor network is greatly simplified by an approach outlined in the online textbook *Lessons In Electric Circuits*, in the “Series-Parallel Combination Circuits” chapter. There, a technique is demonstrated by which one may reduce a complex series-parallel network step-by-step into a single equivalent resistance. After this reduction, Ohm’s Law and Kirchhoff’s Laws of voltage and current are applied while “expanding” the circuit back into its original form. Even though the current notation in this textbook is electron flow rather than conventional flow, the series-parallel analysis technique works all the same.

[file i03145](#)



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Question 89

Suppose you are going to install a Rosemount model 1151 “Alphaline” (analog) differential pressure transmitter in a process, calibrated to a range of 0 to 100 inches W.C. The transmitter’s model number shows the following specifications:

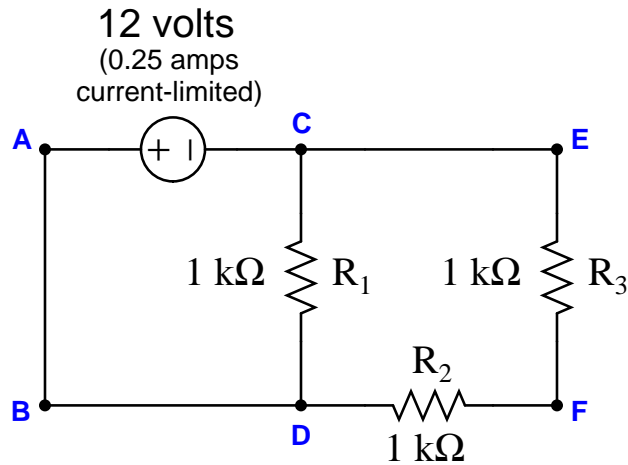
- Model = *1151DP*
- Pressure range code = *4*
- Output code = *E*
- Material code = *22*

Answer the following questions regarding this transmitter as it applies to the application you intend to install it in:

- Does this transmitter have sufficient turndown (“rangeability”) for the application? Show your calculation to prove whether it does or not.
- Calculate the expected accuracy for this transmitter once installed, expressed in  $\pm$  inches of water column.
- Calculate the six-month calibration stability of this transmitter after installation, expressed in  $\pm$  inches of water column.
- Calculate the amount of total measurement error this transmitter may exhibit given an ambient temperature shift of 65 degrees Fahrenheit, expressed in  $\pm$  inches of water column.

Question 90

Suppose a voltmeter registers 0 volts between test points **F** 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 <sub>1</sub> failed open		
R <sub>2</sub> failed open		
R <sub>3</sub> failed open		
R <sub>1</sub> failed shorted		
R <sub>2</sub> failed shorted		
R <sub>3</sub> 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.

**Lab Exercise – introduction**

Your task is to build, document, and troubleshoot a pressure measurement system consisting of a “smart” electronic  $\Delta P$  or gauge pressure transmitter connected to an electronic indicator, recorder, or indicating controller. Instrument air pressure, either regulated or unregulated, is the suggested process variable to measure. Other process variables are open for consideration, though. Alternatives to the standard pressure-measurement lab are authorized by instructor permission only.

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 (do <i>first!</i> )	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Digital trim (sensor and output)	mastery	–	–	–	–	
Loop ranging ( $\pm 1\%$ of span accuracy)	mastery					– – – –
Deadweight tester research and usage	mastery					– – – –
Transmitter valve manifold usage	mastery					– – – –
Troubleshooting	mastery					– – – –
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

The “proportional” score for this activity is based on the number of attempts 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 goals, plans, 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, plans, 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

Wire an electromechanical relay to switch power to a 120 VAC load, controlled by a low-voltage pushbutton circuit (either *on* when pressed or *off* when pressed, as chosen by the instructor).

### 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 exceeds all standards described in the lab exercise documentation.

### Digital trim

Calibrate both the sensor and the 4-20 mA output (DAC) of the “smart” transmitter against trusted standards. Complete both As-Found and As-Left calibration tables, and tag when complete.

### Loop ranging

Set the lower- and upper-range values of the “smart” transmitter according to values randomly chosen by the instructor, and also set the range values in the indicating device so that any operator will see the actual process variable value shown in real-world units of measurement (e.g. PSI). The indicator’s reading must match the true process variable by  $\pm 1\%$ .

### Deadweight tester research and usage

Read the operating manual for an Ashcroft deadweight tester and then demonstrate its proper usage applying an instructor-specified pressure to a gauge.

### Transmitter valve manifold usage

Demonstrate the correct manipulation of hand valves on a transmitter manifold to safely remove that transmitter from service and return it to service, correctly identifying the amount of fluid pressure experienced at the transmitter ports at each step.

### Troubleshooting

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

## Lab Exercise – objectives and expectations (continued)

### Lab percentage score

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

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

### Safety and professionalism (deduction)

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

## General format and philosophy

This lab exercise is *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 – 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 *pressure transmitter* with electronic (4-20 mA) signal output as well as a valve “manifold” to isolate that transmitter from the process pressure. Refer to the “Valve manifolds” subsection of *Lessons In Industrial Instrumentation* for more detail on what these manifolds look like and how they are used. You should choose a transmitter with a pressure range somewhere between 10 PSI and 200 PSI. Avoid low-range (“draft”) transmitters with ranges of just a few inches of water column, and also high-pressure transmitters ranged for hundreds or thousands of PSI.

Consult documentation from the manufacturer’s website to identify how to properly wire, power, and calibrate the transmitter. Your instructor will check to see you have located and are familiar with the equipment manual(s).

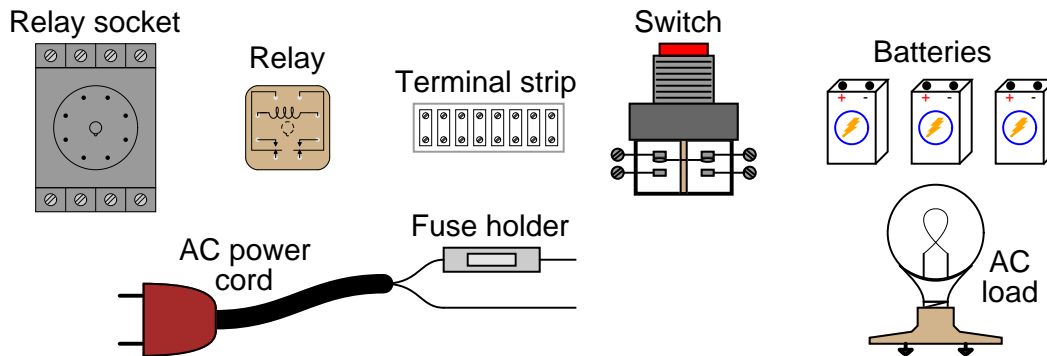
After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a pressure transmitter, this entails applying an air pressure to the “high” pressure port and measuring the transmitter’s milliamp output signal to see if it responds to the application of pressure. If the transmitter fails to respond properly, tag it with a label explaining what it does (or what it fails to do).

**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

Connect an “ice-cube” relay to a low-voltage DC source as well as 120 volts AC so that a hand-operated switch will control the energization of a 120 VAC load. Use a digital multimeter to either measure relay coil current or measure AC load current, as selected by the instructor. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) “Alligator” clips permitted for making connections to battery terminals only. The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to properly interpret the “pinout” of an electromechanical relay, properly wire a switch to control a relay’s coil, properly wire a load to the contacts of a relay, properly select NO/NC contacts on both the switch and the relay, properly use a multimeter to measure current, and use a terminal strip to organize all electrical connections.



The following components and materials will be available to you: assorted “ice cube” **relays** with DC-rated coils and matching **sockets** ; assorted pushbutton **switches** ; **terminal strips** ; lengths of **hook-up wire** ; **batteries** ; 120 VAC **power cord** with **fuse assembly** ; 120 VAC **lamp** or **other suitable load**. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test circuit without any power sources at all; (3) Instructor provides batteries and observes you energizing the circuit for the very first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function. (5) You connect your DMM into the circuit and demonstrate the correct current being measured.

**Load/switch status** (instructor chooses):    \_\_\_ On when pressed    *or*    \_\_\_ Off when pressed

**Current measurement** (instructor chooses):    \_\_\_ Relay coil    *or*    \_\_\_ AC load

Study reference: the “Control Relays” section of *Lessons In Industrial Instrumentation*.

## 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. 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. Transmitters attach to 2-inch pipes using special brackets and U-bolts. These brackets and U-bolts are located along with the transmitters in the instrument storage area.

Select a specific controller to act as a display indicator for the measured pressure. 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 pressure-measurement 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 system should take no more than one full lab session (3 hours) if all components are readily available and the team is working efficiently!**



## Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simultaneous 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 separation 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).

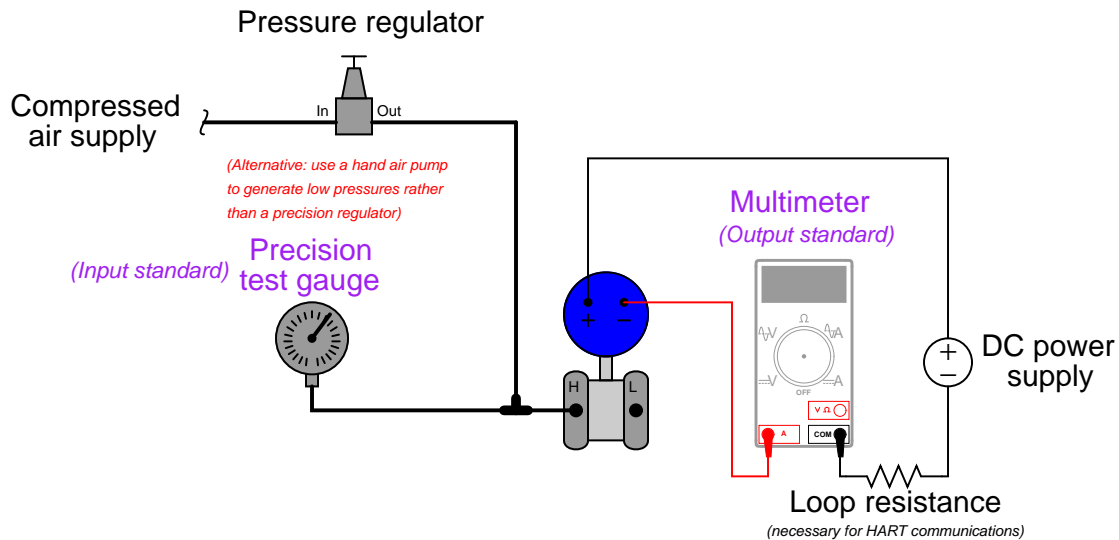
**Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!**

## Lab Exercise – instrument calibration

Each team must calibrate the transmitter (“trim” both the sensor and the output) to ensure it interprets pressure accurately and outputs an accurate current. Then, each team member must configure the transmitter for a unique range (set the LRV and URV parameters) and scale the indicator (or indicating controller) to register in the proper engineering units (e.g. a pressure transmitter ranged for 30 to 70 PSI should actually register 30 to 70 PSI back at the control room display). The accuracy of this ranging will be checked by the instructor by applying random air pressures to the transmitter while each student verifies the indicator display.

As in all cases where an instrument must be calibrated, you will need to check the instrument’s response against one or more *standards*. In this case, the ideal standard to use for setting the input pressure to the transmitter is a *precision test gauge* (either mechanical or electronic), and the ideal standard to use for measuring the transmitter’s electronic output signal is a *multimeter* configured to measure DC milliamps:

### Typical calibration setup for an electronic pressure transmitter



The difference between “calibrating” a transmitter and “ranging” a transmitter is confusing to many students. With legacy-style *analog* transmitters, calibrating and ranging are one and the same. With modern *digital* instruments, calibration and ranging are separate tasks. To calibrate a digital instrument means to subject it to a known (standard) stimulus and adjust the “trim” settings to ensure the instrument’s microprocessor accurately recognizes that stimulus condition. To “range” a digital instrument means to define the values of measurement for its 0% and 100% scale points. For more information on this distinction, refer to the “Instrument Calibration” chapter of *Lessons In Industrial Instrumentation*.

Document the accuracy of your transmitter's sensor trim before and after adjustment in this table, at five different points throughout its sensing range using these two tables. Error in percent of span is calculated by dividing the difference between actual and ideal signal values by the span of the signal range:

**As-Found calibration table**

Applied pressure	Output signal (actual)	Output signal (ideal)	Error (% of span)

**As-Left calibration table**

Applied pressure	Output signal (actual)	Output signal (ideal)	Error (% of span)

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

When finished calibrating your team's transmitter, be sure to place a calibration tag on it showing the range and the date it was calibrated. A set of calibration tags are given here, which you may tape to the transmitter:

*Cut out tag(s) with scissors, then affix to instrument(s) using transparent tape to show calibration:*

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

Each student, however, must individually re-range the transmitter and the receiving instrument (indicator, controller, and/or recorder). Re-ranging a digital instrument is a brief procedure using either a HART communicator or a computer-based tool such as Emerson AMS (if the instrument is connected to a host system with that software). Each student's ranging is confirmed by the instructor by applying random pressures to the transmitter and verifying that the indicating controller reads the same (to within  $\pm 1\%$  of span). This is also a good opportunity for students to demonstrate the use of the transmitter's valve manifold, showing how to "block in" the transmitter so it does not "see" process pressure.

**Common mistakes:**

- Failing to closely inspect pressure regulators before connecting them to an air source (e.g. connecting the air supply to the "out" port)
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).

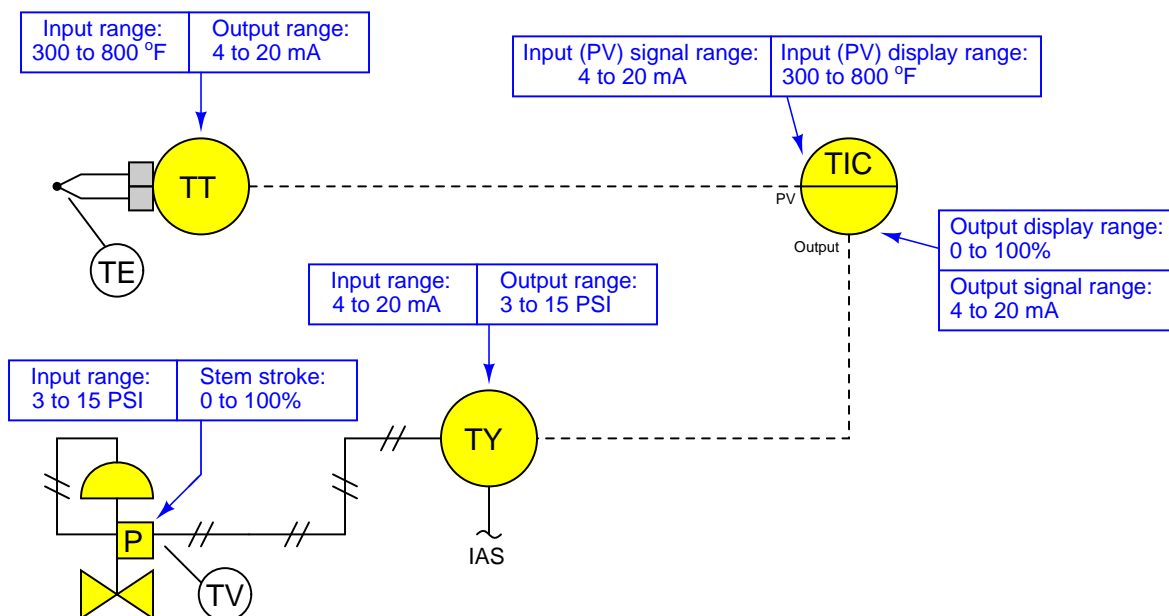
- Choosing a calibration (“trim”) range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Choosing a poor-accuracy calibration standard (e.g. trying to calibrate your \$1500 precision Rosemount pressure transmitter to  $\pm 0.1$  PSI using a \$30 pressure gauge that only reads to the nearest 5 PSI!).
- Ignoring the mathematical signs (+ or –) of error calculations.
- Neglecting to place a calibration tag on the transmitter after “trimming” it.

**Trimming and individually ranging your transmitter should take no more than one full lab session (3 hours) if 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 °F and output 20 mA when sensing 800 °F, but the controller must display an indication of 300 °F when it receives a 4 mA signal from the transmitter, and display an indication of 800 °F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 °F input (and 4-20 mA output) as well as range the controller to display 300-800 °F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:



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

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

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

## Notes on instrument ranging (continued)

- Siemens/Moore 352 controller: process variable range parameters are located in the “Operator’s Display” function block (FB15):
  - LRV = *Process Lo*
  - URV = *Process Hi*
- Siemens/Moore 352P and 353 controller: process variable range parameters are located in the “Analog Input” function block (AIN):
  - LRV = *Minscale*
  - URV = *Maxscale*
- Emerson DeltaV DCS: process variable range parameters are located in the “Analog Input” function block (AI) and “PID” function block (PID):
  - (AI block) = the *OUT\_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. The *L\_Type* parameter needs to be set to “indirect” to allow scaling to occur (“direct” mode prohibits scaling), and the *XD\_Scale* parameter needs to be ranged 0 to 100%. Note that the “direct” and “indirect” options for *L\_Type* have absolutely nothing to do with “direct” and “reverse” PID controller action, which is configured elsewhere.
  - (PID block) = the *PV\_SCALE* parameter contains both high and low range limits, engineering units (e.g. deg F), and decimal point position. Note: the PID block’s *PV\_SCALE* range must exactly match the *OUT\_SCALE* range of the AI block!
- Honeywell UDC 2500 controller: process variable input #1 range parameters are located in the “Input 1” set-up group of parameters:
  - LRV = *IN1 LO*
  - URV = *IN1 HI*
- Automation Direct “SOLO” controller: process variable range parameters are located in the following registers:
  - LRV = *P3-4 Input Range Low*
  - URV = *P3-3 Input Range High*
- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: process variable scaling parameters are typically located either in a “Scale” instruction (SCL) or a “Scale with Parameters” instruction (SCP). In either case, the instruction takes the raw count value from the input channel’s analog-to-digital converter and scales it into the desired process variable display range. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab using the SCP instruction. *Note: SCP instruction parameters may be edited online. For this reason, downloading edits is not necessary for the MicroLogix PLCs in our lab. In fact, it is very important that you not save or download the PLC program, because doing so may alter the PLC’s network address and lead to communication problems. Just make the changes while the PLC is in “Run” mode and then exit the program:*
  - (SCL instruction) = *Rate* and *Offset* values scale the signal according to the slope-intercept formula  $y = mx + b$ , where *Rate* is  $10000m$  and *Offset* is  $b$
  - (SCP instruction LRV) = *Scaled Min.*
  - (SCP instruction URV) = *Scaled Max.*
- Allen-Bradley Logix5000 controller: process variable scaling parameters are located in the “PID” instruction (PID):
  - LRV = *.MINS*
  - URV = *.MAXS*

- 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.
  - $LRV = pid[0].LRV$
  - $URV = pid[0].URV$



## Lab Exercise – deadweight tester usage

Deadweight testers are devices used to generate known amounts of fluid pressure, to be used as standards for calibrating pressure-measuring instruments. When properly configured and operated, the fluid pressure generated by a deadweight tester will be exactly what it should be, and this precisely-known pressure may then be used to test the accuracy of any pressure-sensing instrument. Part of this lab exercise is for each student to properly demonstrate the use of a deadweight tester to check the calibration of a pressure gauge. Several deadweight testers are located in the lab, using petroleum-based oil as the working fluid.

Information on how to use a deadweight tester may be found in the *Lessons In Industrial Instrumentation* textbook, on the BTCInstrumentation YouTube channel, and also in manufacturer's literature for the deadweight testers themselves. *You are expected to read the written documentation before using a deadweight tester, and you will be orally quizzed on the function and purpose of the deadweight tester as described therein.*

When you are ready to demonstrate, the instructor will observe you safely applying pressure to the gauge under test, showing and explaining how the deadweight tester functions. You will be expected to answer some basic questions about how and why the deadweight tester works. This will be done privately, with no other students spectating.

Of the various mistakes students tend to make when demonstrating the use of a deadweight tester, the most common and most serious fall into two categories: (1) Failing to read the manufacturer's literature on the tester prior to using it, and (2) Misunderstanding the purpose of a deadweight tester when coupled to a pressure gauge. These two mistakes are so common that they deserve ample warning ahead of time.

The first mistake is caused by a tendency to take shortcuts, relying on classmates' advice and easy-to-watch videos rather than taking the time to actually read the manual. You will find that reading the manual is an essential step for *all* the work we do in Instrumentation, so get used to it now!

The second mistake is caused by an over-reliance on the pressure gauge to indicate the fluid's true pressure. Remember, the purpose of a deadweight tester is to produce a highly accurate fluid pressure against which we may *test* a gauge or other pressure instrument. If you correctly operate a deadweight tester and the gauge fails to register the correct pressure, it is the gauge's fault and not the deadweight tester's fault! I've lost count of the number of times I've requested a student to apply 400 PSI to a gauge using a deadweight tester, and then the student thinks they've done something wrong with the deadweight tester when the gauge registers 395 PSI instead. The student then adjusts the deadweight tester in vain to try to get the gauge to read 400 PSI, or worse yet they resort to improperly operating the deadweight tester until they force the gauge to read 400 PSI. In fact, the only way to make an out-of-calibration gauge register any specified pressure is to *incorrectly* use the deadweight tester!

### Common mistakes:

- Not understanding the operation of the device prior to trying to demonstrate it!
- Failing to bleed air out of the lines when setting up the tester.
- Not recognizing when the piston is "bottomed" or "topped" out, or why this matters.
- Not spinning the weights (gently!) to eliminate static friction on the piston.
- Removing weights from the piston while pressure still remains in the system.
- Not counting the weight of the piston's plate when adding weights to achieve a desired pressure.
- Trusting the reading of the pressure gauge more than the deadweight tester (i.e. not realizing the purpose of using a deadweight tester to check a pressure gauge).

## Lab Exercise – transmitter valve manifold usage

Part of this lab exercise requires the demonstration of a transmitter *valve manifold*, either 3-valve or 5-valve. This involves hands-on manipulation of the block, equalizing, and bleed (vent) valves in proper order, explaining the rationale for each action, as well as being able to accurately predict the amount of fluid pressure at each port of the pressure transmitter given a process scenario (i.e. the instructor stating the amount of pressure in each impulse line).

It is highly recommended to perform the demonstration of a valve manifold with air pressure applied to the transmitter, so that certain mistakes may be immediately apparent. Leaving a bleed fitting open when opening block valves, for example, will result in compressed air leaking out of the bleed hole. It is also highly recommended that you rehearse the procedure on your own, without help from classmates, prior to demonstrating it for the instructor.

Information on how to use instrument valve manifolds may be found in the *Lessons In Industrial Instrumentation* textbook. *As with the deadweight tester, you are expected to read this documentation before demonstrating the use of a valve manifold.* You will be expected to answer some basic questions about how and why instrument valve manifolds work. This will be done privately, with no other students spectating.

### Common mistakes:

- Following a memorized procedure of valve operations without understanding why that procedure should be followed.
- Not rehearsing the procedure on your own prior to demonstrating it for the instructor.
- Not paying attention to the direction each bleed port faces (for safety when opening the bleed fittings).
- Confusion regarding which way to turn the valve handle to open versus closed, especially when viewing the handle from the opposite side.

## Lab Exercise – troubleshooting

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

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

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

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault. Multiple re-tries are permitted with no reduction in grade.

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

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

### Common mistakes:

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

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

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

### **Lab Exercise – decommissioning and clean-up**

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

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

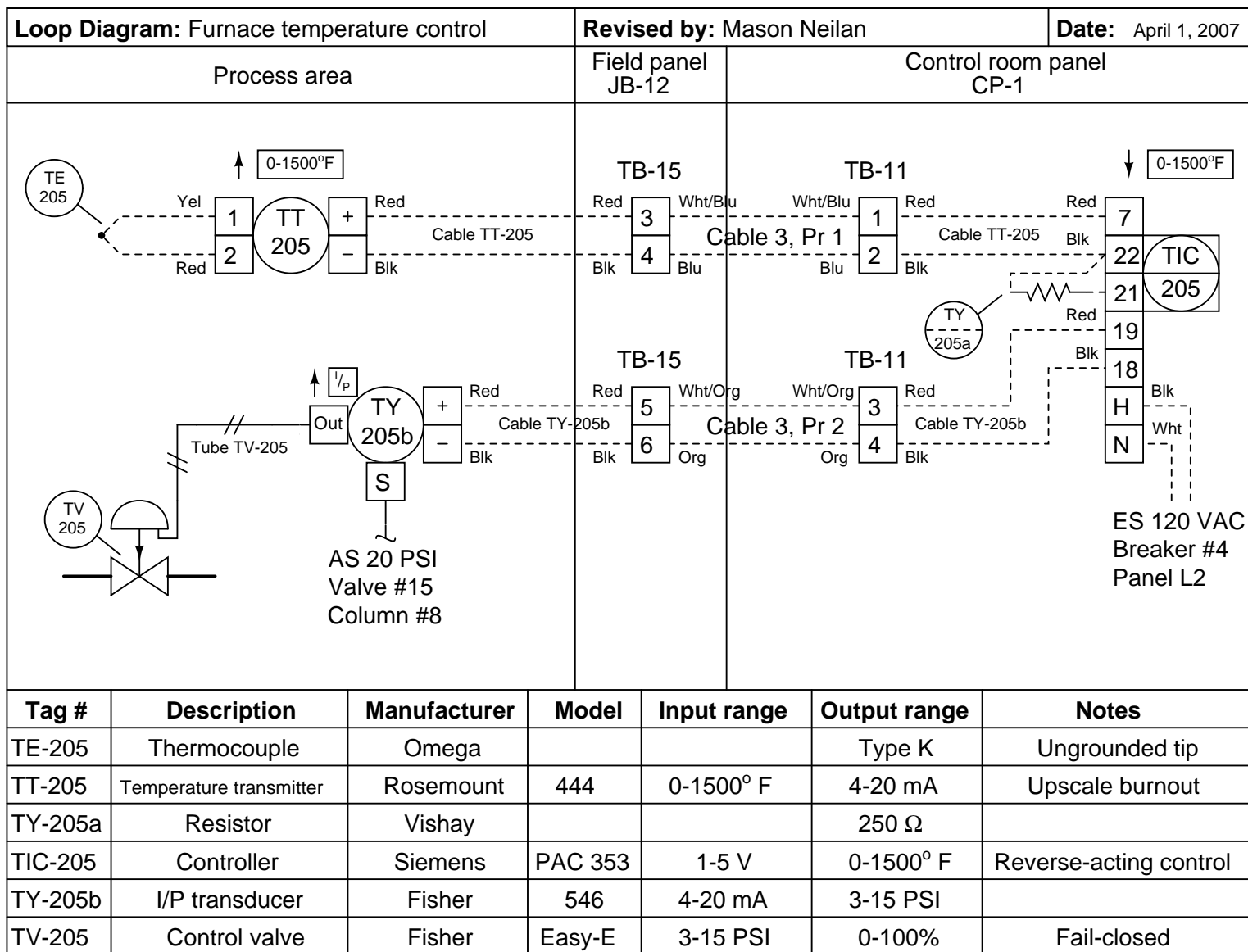
- Large control valves and positioners
- I/P transducers
- Large electric motors
- Large variable-frequency drive (VFD) units
- Cables inside conduit interconnecting junction boxes together
- Pipe and tube fittings (do not unscrew pipe threads)
- Supply air pressure regulators

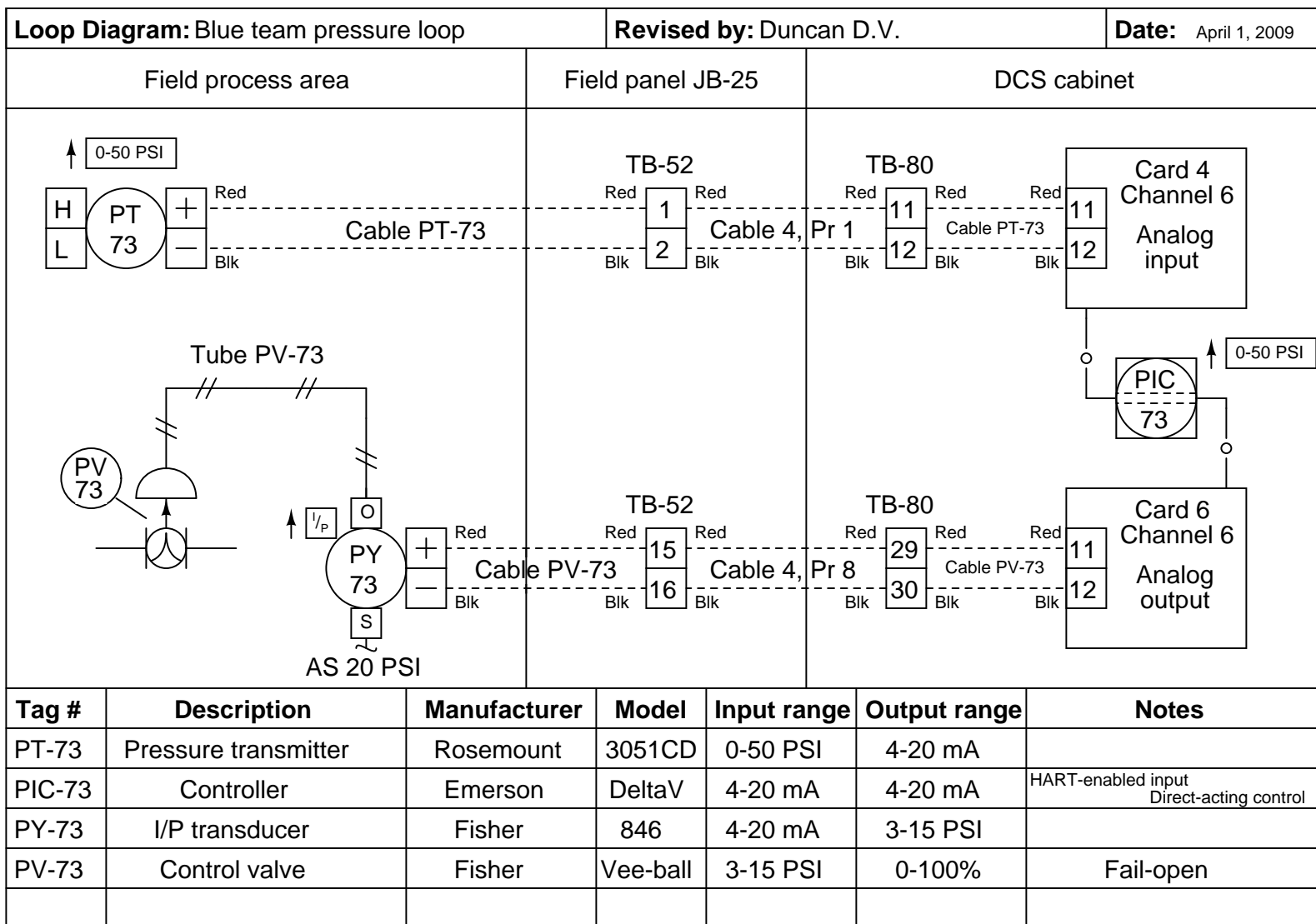
#### **Return the following components to their proper storage locations:**

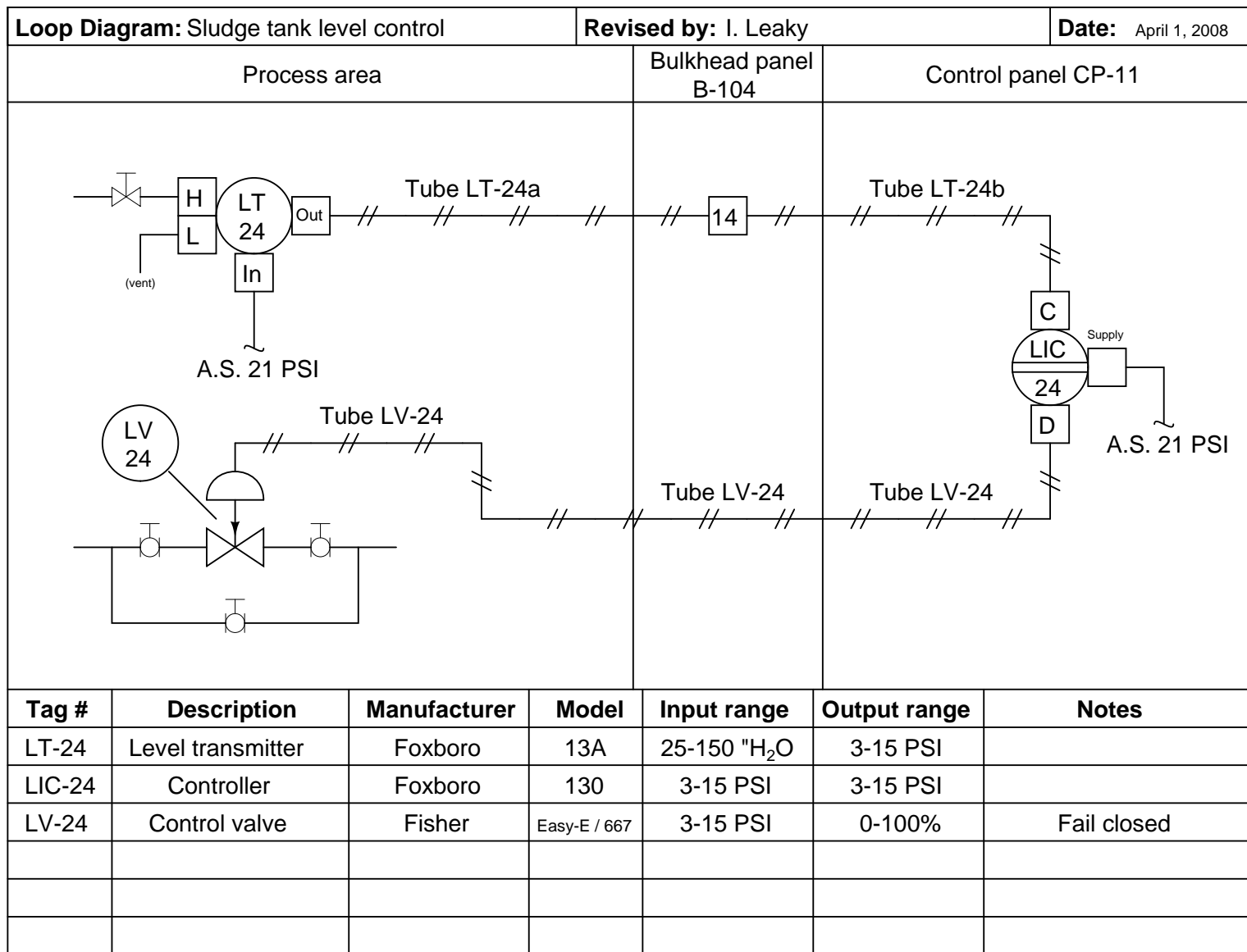
- Sensing elements (e.g. thermocouples, pH probes, etc.)
- Process transmitters
- “Jumper” cables used to connect terminal blocks within a single junction box
- Plastic tubing and tube fittings (disconnect compression-style tube fittings)
- Power cables and extension cords
- Adjustment (loading station)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

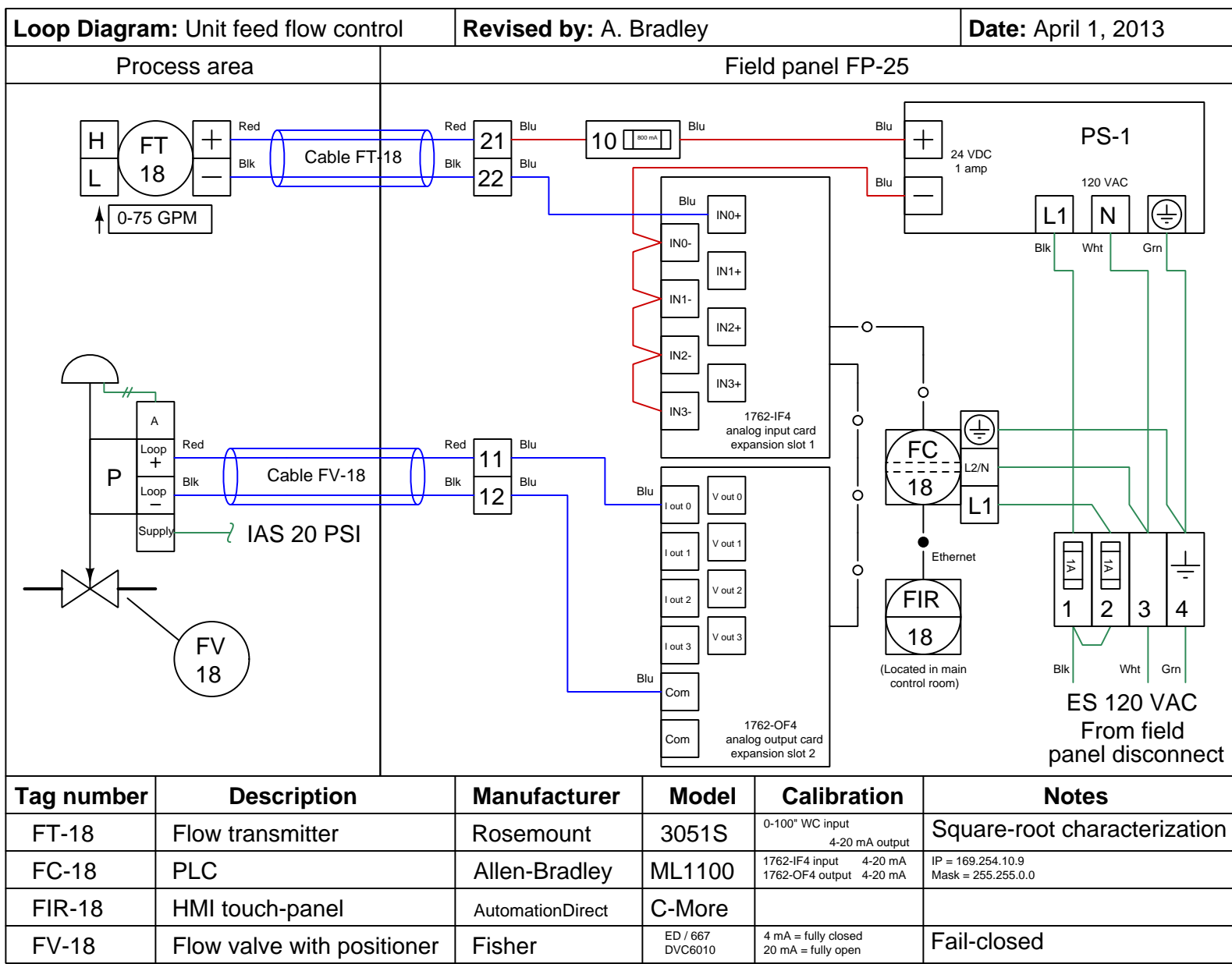
Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.

file i00112











## Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simultaneous 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 separation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. “Where is the controller for this loop?”) or determining important configuration parameters (e.g. range settings).

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

#### **Common mistakes:**

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

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

[file i00654](#)

## Answers

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Answer 1

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Answer 2

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Answer 3

Ideally, the secondary piston's position will have *no effect* on the oil pressure sent to the gauge. Consequently, the gauge indication should not change.

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Answer 4

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Answer 5

**Partial answer:**

Note how each and every “unity fraction” is comprised of *physically equal* pressures, in order to have a physical value of one (i.e. unity). We purposely arrange the units in the numerator and denominator of each unity fraction in such a way that the original unit gets canceled out and replaced by the desired unit:

*Here, the unity fraction is made from the equivalence  $6.895 \text{ kPa} = 1 \text{ PSI}$ :*

$$\left(\frac{25 \text{ PSI}}{1}\right) \left(\frac{6.895 \text{ kPa}}{1 \text{ PSI}}\right) = 172.4 \text{ kPa}$$

*Here, the unity fraction is made from the equivalence  $0.06895 \text{ bar} = 27.68 \text{ "WC}$ :*

$$\left(\frac{12 \text{ "WC}}{1}\right) \left(\frac{0.06895 \text{ bar}}{27.68 \text{ "WC}}\right) = 0.02989 \text{ bar}$$

*Here, the unity fraction is made from the equivalence  $6.895 \text{ kPa} = 2.036 \text{ "Hg}$ :*

$$\left(\frac{982 \text{ "Hg}}{1}\right) \left(\frac{6.895 \text{ kPa}}{2.036 \text{ "Hg}}\right) = 3326 \text{ kPa}$$

*Here, the unity fraction is made from the equivalence  $2.036 \text{ "Hg} = 0.06895 \text{ bar}$ :*

$$\left(\frac{31 \text{ bar}}{1}\right) \left(\frac{2.036 \text{ "Hg}}{0.06895 \text{ bar}}\right) = 915.4 \text{ "Hg}$$

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Answer 6

With no nozzle on the end of the hose, the end may be raised a maximum of 184.54 feet. With a nozzle in place, the hose end may be raised only 115.33 feet.

Essentially, this is just another pressure unit conversion problem: in this case, PSI-to-feet of water column. 80 PSI is equivalent to 184.54 feet, so that is how high 80 PSI can force a column of water.

With a nozzle attached to the end of the hose, though, we are only allowed to “drop” 50 feet of hydrostatic pressure, in order to leave 30 PSI remaining at the nozzle coupling for proper operation. 50 PSI is equivalent to 115.33 feet, so this is how high we may raise the hose end with a nozzle on it.

It must be understood that the first calculation is not a very practical one. 80 PSI of pressure at the hydrant will *just* push water 184.54 feet high. If the hose were 190 feet and poised vertically, there would be a column of water inside 184.54 feet tall, with no water at all coming out the end. If the hose end were brought exactly to a height of 184.54 feet, water would be right at the lip of the hose, not even trickling out. Obviously, some pressure is needed at the hose end in order to push water out onto a fire, so the *practical*, no-hose height for 80 PSI will be somewhat lower than 184.54 feet.

The hose-with-nozzle scenario is more realistic, because an actual figure for minimum hose-end pressure is given for us to incorporate into our calculations.

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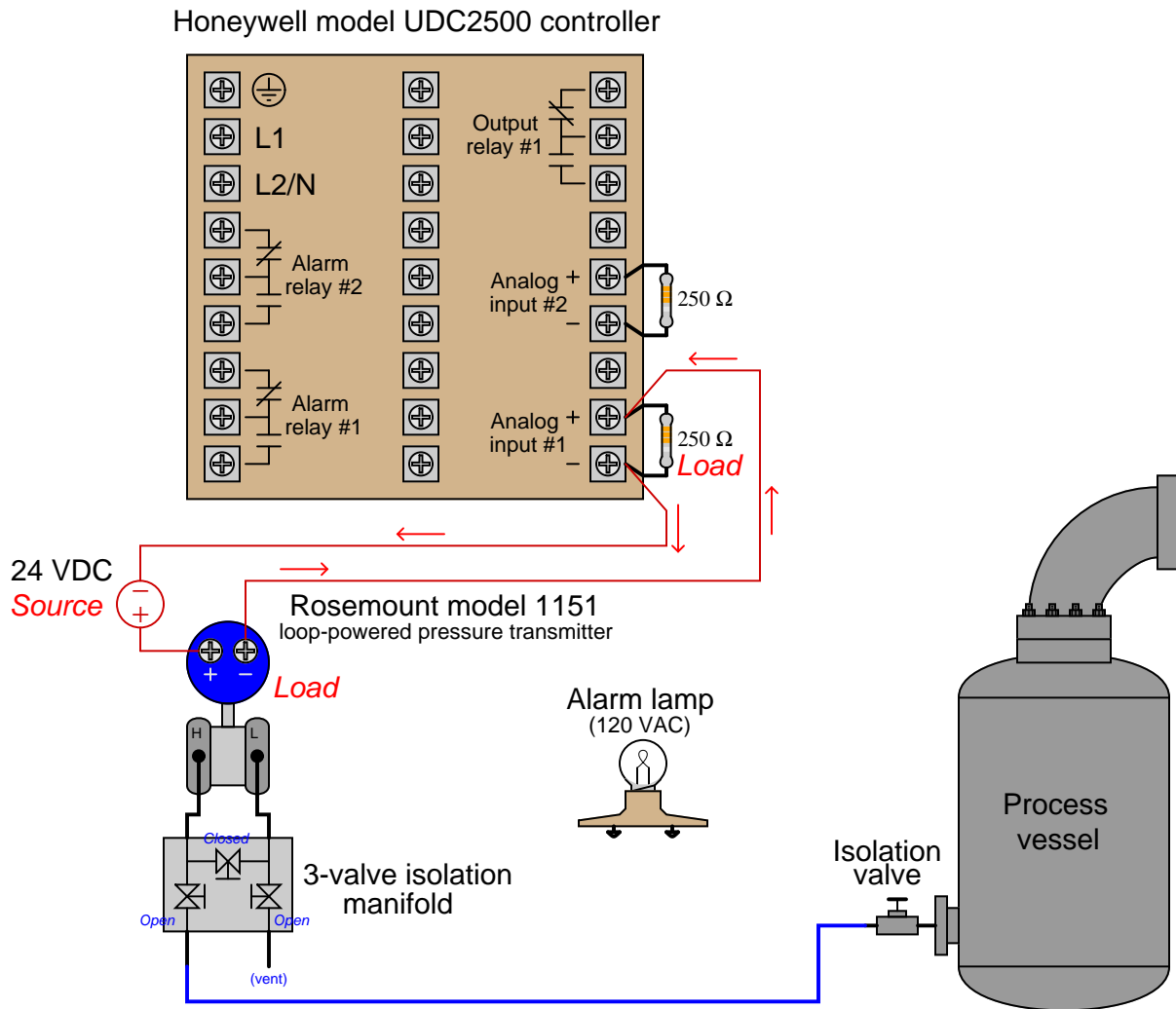
Answer 7

### Summary of principles:

- Conservation of Energy
  - Energy cannot be created or destroyed
- Conservation of Electric Charge
  - Electric charges cannot be created or destroyed
- Properties of a series network
  - Definition: *only one path for electric current*
  - Current the same through each component (Conservation of Electric Charge)
  - Voltages add to equal the total (Conservation of Energy)
  - Resistances add to equal to total
- Properties of a parallel network
  - Definition: *each component connected across the same two sets of electrically common points*
  - Voltage the same across each component (Conservation of Energy)
  - Currents add to equal the total (Conservation of Electric Charge)
  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$
- Capacitance and Inductance
  - The ability to store energy in and retrieve energy from electric fields and magnetic fields, respectively
  - Current through capacitance is equal to the product of its capacitance and the rate-of-change of voltage across it:  $I = C \frac{dV}{dt}$
  - Voltage across inductance is equal to the product of its inductance and the rate-of-change of current through it:  $V = L \frac{dI}{dt}$

Answer 9

Partial answer:



Answer 10

Force at large piston = 100 pounds. Fluid pressure = 2.5 PSI.

Pascal's principle states that any pressure applied to a contained fluid will be experienced at all points throughout that fluid. Thus, pressure generated by the 25 lb of force on the small piston creates a pressure (2.5 PSI) distributed throughout the fluid's volume which is experienced in full at the large piston to create the 100 lb force there.

The 5 inch dimension is extraneous information, included for the purpose of challenging students to identify whether or not information is relevant to solving a particular problem.

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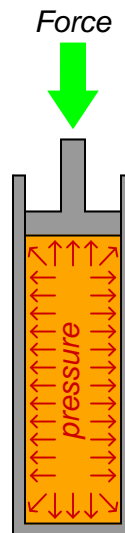
Answer 11

Fault	Possible	Impossible
PR-33 calibration error	✓	
PT-33 calibration error		✓
PIC-33 (input) calibration error	✓	
PY-33a calibration error	✓	
PY-33b calibration error		✓
PV-33a calibration error		✓
PV-33b calibration error		✓

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Answer 12

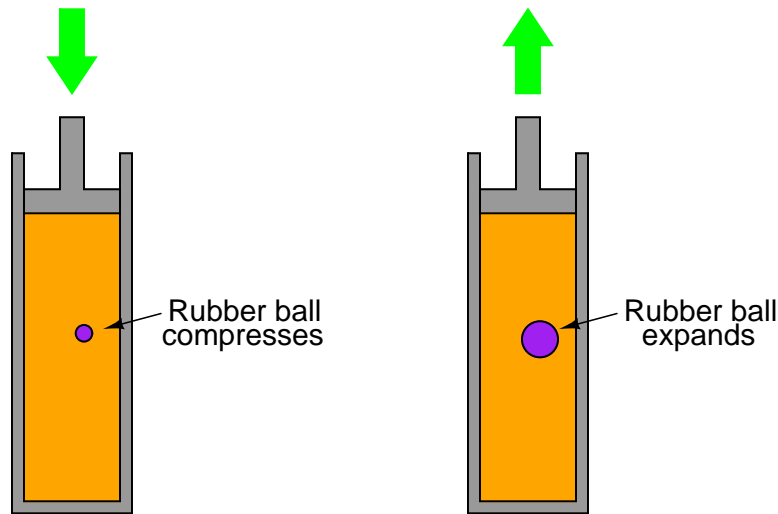
The fluid pressure will exert an outward force on the cylinder walls, like this:



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Answer 13

A pushing force on the rod will compress the rubber ball to a smaller diameter. A pulling force will expand it to a larger diameter.



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Answer 14

Absolute pressure = 2,014.7 PSIA. Gauge pressure = 2,000 PSIG. Differential pressure (between tank and water) = 1,978 PSID.

Gauge pressure is simple: it is the figure initially measured by the pressure gauge (2,000 PSIG). Again, we are assuming that the diver has not significantly decreased the tank's air pressure by consuming air from it as he or she descended to the specified depth. In reality, the pressure in the tank would have decreased a bit in supplying the diver with air to breathe during the descent time.

Absolute pressure is simply gauge pressure added to the pressure of Earth's atmosphere. Since the gauge pressure measured at the water's surface was (obviously) at sea level, and atmospheric pressure at sea level is approximately 14.7 PSIG, absolute air pressure inside the tank is  $2,000 \text{ PSI} + 14.7 \text{ PSI} = 2,014.7 \text{ PSIG}$ .

Differential pressure is simply the difference (subtraction) between the tank's gauge pressure of 2,000 PSI and the water's hydrostatic pressure (gauge) of 22 PSI. This is equal to 1,978 PSID. The same differential figure will be found even if atmospheric pressure is taken into consideration: the tank's absolute air pressure is 2,014.7 PSIA and the water's hydrostatic pressure is 36.7 PSIA (22 PSI + 14.7 PSI), resulting in a difference that is still 1,978 PSID. The key here in figuring differential pressure is to always keep pressure units the same: don't mix gauge and absolute pressures!



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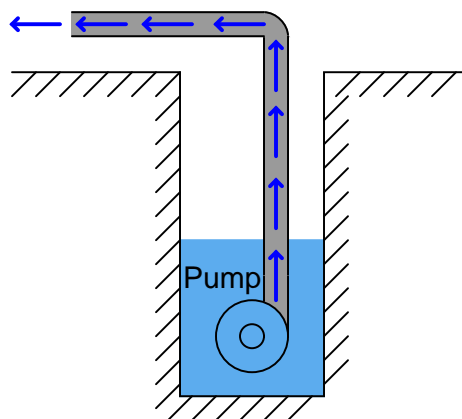
Answer 15

406.9 inches, which is a little bit less than 34 feet. For this amount of “lift height,” the pump would have to create a near-perfect vacuum in the inlet pipe. To calculate this figure, convert 14.7 PSIA into inches of water column absolute (14.7 PSIA)(2.768 "W.C. / PSI).

Since this kind of water pump works by creating a vacuum (reducing the inlet pressure to something less than 14.7 PSIA), it is inherently limited in lift height. Since atmospheric pressure is always 14.7 PSIA (on Earth, anyway), this kind of pump simply cannot suck water any higher than this amount of pressure expressed in inches or feet of water.

The average barometric pressure in Denver is 24.63 inches of mercury absolute (12.097 PSIA). This equates to a water-lifting height of 334.9 inches, or 27.9 feet.

Submersible pumps overcome this limit by creating a *positive pressure* rather than a *vacuum*. The pumping action is therefore not limited by the relatively low pressure of Earth’s atmosphere, but only by the capacity and design of the pump itself:



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Answer 16

With no nozzle on the end of the hose, the end may be raised a maximum of 184.54 feet. With a nozzle in place, the hose end may be raised only 115.33 feet.

Essentially, this is just another pressure unit conversion problem: in this case, PSI-to-feet of water column. 80 PSI is equivalent to 184.54 feet, so that is how high 80 PSI can force a column of water.

With a nozzle attached to the end of the hose, though, we are only allowed to “drop” 50 feet of hydrostatic pressure, in order to leave 30 PSI remaining at the nozzle coupling for proper operation. 50 PSI is equivalent to 115.33 feet, so this is how high we may raise the hose end with a nozzle on it.

It must be understood that the first calculation is not a very practical one. 80 PSI of pressure at the hydrant will *just* push water 184.54 feet high. If the hose were 190 feet and poised vertically, there would be a column of water inside 184.54 feet tall, with no water at all coming out the end. If the hose end were brought exactly to a height of 184.54 feet, water would be right at the lip of the hose, not even trickling out. Obviously, some pressure is needed at the hose end in order to push water out onto a fire, so the *practical*, no-hose height for 80 PSI will be somewhat lower than 184.54 feet.

The hose-with-nozzle scenario is more realistic, because an actual figure for minimum hose-end pressure is given for us to incorporate into our calculations.

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Answer 17

PSIG	PSIA	inches Hg (G)	inches W.C. (G)
18	32.7	36.65	498.25
385.3	400	784.5	10665
16.21	30.91	33	448.6
2.168	16.87	4.413	60
222.0	236.7	452	6145.1
0.4335	15.13	0.8826	12
-13.7	1	-27.89	-379.2
-5	9.7	-10.18	-138.4

---

Answer 18

With a piston diameter of 4 inches, a hydraulic pressure of 456.83 PSI is necessary to generate 5740.6 pounds. This is a *minimum* pressure, for safety reasons. More than 456.83 PSI won't do any harm, but less than this amount will fail to hold down the lid!

---

Answer 19

Applied pressure = 9 "W.C., which is equal to 0.32514 PSI.

For the same applied pressure, the distance between the two liquid columns will be *greater* than with water. In other words, for a pressure of 9" W.C., there will be *more* than 9 inches of vertical distance separating the two liquid columns.

Essentially, manometers work on the principle of balanced pressures: the applied gas pressure forces the liquid columns to shift height. When they do so, they generate a hydrostatic pressure proportional to their differential height. When this hydrostatic pressure equals the applied pressure, the liquid columns stop moving and a condition of equilibrium is reached.

If a lighter fluid such as oil is used instead of water, a greater height will have to be developed to generate the same amount of hydrostatic pressure to oppose the applied gas pressure and reach equilibrium. Conversely, if a heavier (denser) liquid such as mercury were to be used, a much smaller vertical height would develop between the two columns for the same pressure.

---

Answer 20

- **Step 4:** Quickly open and close valve 4 – manometer indication drops **slightly**
- **Step 6:** Quickly open and close valve 4 – manometer indication **does not drop** at all
- **Step 8:** Quickly open and close valve 3 – manometer indication drops **greatly**

---

Answer 21

---

Answer 22

---

Answer 23

---

Answer 24

---

Answer 25

Applied pressure = 1.193 kPa

---

Answer 26

- 5 PSI vacuum = 9.7 PSIA
- 25 "Hg vacuum = 2.421 PSIA
- 2,800  $\mu$  torr = 0.3733 PaA
- -59 "W.C. = 649.98 torr
- 4,630 PaA = -14.028 PSI
- 0.05 atm = -386.56 "W.C.
- -3 kPa = 0.9704 atm
- 10 feet W.C. vacuum = 21.103 "HgA
- 300 cm Hg = 4.946 atm
- -2 mm W.C. = 1.0133 bar (absolute)
- 4 atm = 1,627.63 "W.C.A

---

Answer 27

- 25 PSIA = 1.701 atm
- 340 "W.C. = 26.983 PSIA
- 0.73 bar (gauge) = 21.557 "Hg
- 5.5 atm = 4,180 torr
- 2,300 cm Hg = 12,717.72 "W.C.A
- 500 m torr = 0.0096683 PSIA
- 91.2 cm W.C. = 8.9434 kPa
- 110 kPa = 441.62 "W.C.
- 620 mm HgA = 620 torr (*A "trick" question . . .*)
- 77 Pa = 14.711168 PSIA
- 1 atm = 406.91 "W.C.A
- 270 PSIA = 18.367 atm

---

Answer 28

**Partial answer:**

Fault	Possible	Impossible
Upstream filter block valve partially shut		
Downstream filter block valve partially shut		✓
PDT-136 calibration error		
PT-137 calibration error		
PG-417 calibration error		✓
PG-421 calibration error		
Filter drain valve to sump left open		✓

---

Answer 29

---

**Answer 30**

This is perfectly legitimate, because in either case all the pressure units involved in each conversion are of the same type: either all gauge or all absolute. Where we encounter difficulties is if we try to mix different units in the same “unity fraction” conversion that do not share a common zero point.

A classic example of this mistake is trying to do a temperature conversion from degrees F to degrees C using unity fractions (e.g.  $100^{\circ}\text{C} = 212^{\circ}\text{F}$ ):

$$\left(\frac{60^{\circ}\text{F}}{1}\right)\left(\frac{100^{\circ}\text{C}}{212^{\circ}\text{F}}\right) \neq 28.3^{\circ}\text{C}$$

This cannot work because the technique of unity fractions is based on proportion, and there is no simple proportional relationship between degrees F and degrees C; rather, there is an *offset* of 32 degrees between the two temperature scales. The only way to properly manage this offset in the calculation is to include an appropriate addition or subtraction (as needed).

However, if there is no offset between the units involved in a conversion problem, there is no need to add or subtract anything, and we may perform the entire conversion using nothing but multiplication and division (unity fractions). Such is the case if we convert pressure units that are all gauge, or if we convert pressure units that are all absolute.

To summarize, it is perfectly acceptable to construct a unity fraction of  $\frac{27.68^{\circ}\text{W.C.}}{2.036^{\circ}\text{Hg}}$  because  $0^{\circ}\text{W.C.}$  is the same as  $0^{\circ}\text{Hg}$  (i.e. they share the same zero point; there is no offset between units  $^{\circ}\text{W.C.}$  and  $^{\circ}\text{Hg}$ ). Likewise, it is perfectly acceptable to construct a unity fraction of  $\frac{27.68^{\circ}\text{W.C.A}}{2.036^{\circ}\text{HgA}}$  because  $0^{\circ}\text{W.C.A}$  is the same as  $0^{\circ}\text{HgA}$  (i.e. they share the same zero point; there is no offset between units  $^{\circ}\text{W.C.A}$  and  $^{\circ}\text{HgA}$ ).

---

**Answer 31**

Applied pressure = 2.5  $^{\circ}\text{W.C.}$

What matters in manometer calculations is the *vertical* height difference between the two liquid columns. Inclining one or more of the tubes only causes the liquid to displace further along the tube(s); it does not change the vertical height necessary to balance the applied pressure.

Thus, with a  $30^{\circ}$  inclined tube, a liquid displacement of 5 inches along the length of the tube equates to one-half that ( $\sin 30^{\circ} = 0.5$ ). Therefore, the applied pressure is 2.5 inches of water column.

Note that the inclined manometer makes very sensitive pressure measurements possible using standard-density liquids such as water! Great care, though, must be taken in ensuring the instrument is level (that the inclined tube is at precisely the angle it should be).

---

**Answer 32**

1 inch of bubble motion represents 0.02 inches of water column pressure (differential), or 2/100 "W.C., applied across this micromanometer.

To solve for this pressure, first determine the amount of liquid volume that would have to be displaced to move the bubble 1 inch. Since the bubble resides in a tube 0.25 inches in diameter, the volume for 1 inch of bubble motion is:

$$(1 \text{ inch})[\pi(0.25 \text{ inch} / 2)^2] = 0.04909 \text{ in}^3$$

This is a very small amount of liquid volume! The water levels in the larger (2.5 inch diameter) tubes will not have to change much to accommodate this tiny amount of displacement. Dividing the displaced fluid volume by the area of the vertical tubes will tell us how far the water levels must change in each of the vertical tubes:

$$(0.04909 \text{ in}^3) / [\pi(2.5 \text{ inch} / 2)^2] = 0.01 \text{ inch}$$

So, a vertical liquid column height change of only 0.01 inch will cause a horizontal bubble displacement of 1 inch. Since there will be 0.01 inch of movement in *each* vertical tube, the combined total vertical displacement is twice this figure, or 0.02 inches of water column.

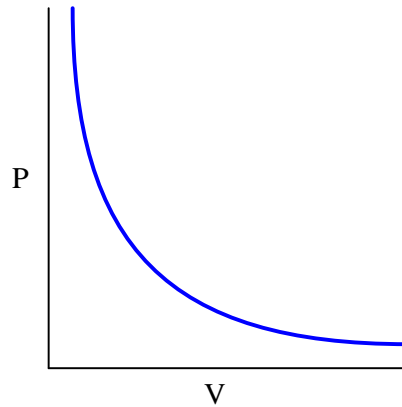
A much simpler way to solve this problem is to recognize that the vertical tube areas are 100 times as great as the horizontal tube (2.5 inches is ten times as large as 0.25 inches, and area is proportional to diameter *squared*), so 1 inch of horizontal fluid displacement is proportional to 1/100 inch of vertical fluid displacement. Once again, since *each* vertical tube experiences 0.01 inch of vertical water level displacement, the total water column shift is 0.02 inches.

---

**Answer 33**

The manometer will register falsely high, showing greater differential pressure than what is actually there. If you are having difficulty figuring this out, imagine if the liquid moving through the pipe was just as dense as the mercury within the manometer: what would *that* do to the mercury in the manometer given any applied  $\Delta P$ ? In other words, set up a *thought experiment* with absurdly (simple) conditions and then look for patterns or trends which you may generalize for any condition.

Challenge question: derive a mathematical correction factor for interpreting the manometer's indication to yield true inches of mercury  $\Delta P$ .



Note that the function is a curve and not a straight line! In essence, the function plotted is this:

$$P = \frac{k}{V}$$

Where  $k$  is a constant equal to  $nRT$ .

---

Answer 35

Pressure applied to right-hand tube = 26.5 "W.C = 6600.8 Pa.

Follow-up question: demonstrate how we could have arrived at an approximate answer by using rounded figures for our unit-conversion constants, and "mental math" instead of a calculator.

---

Answer 36

Applied pressure = 3.1875 "W.C., which is equal to 0.1152 PSI.

Follow-up question: demonstrate how we could have arrived at an approximate answer by using rounded figures for our unit-conversion constants, and "mental math" instead of a calculator.

---

Answer 37

$F = 51.07$  pounds of force, downward (holding the cover onto the flange).

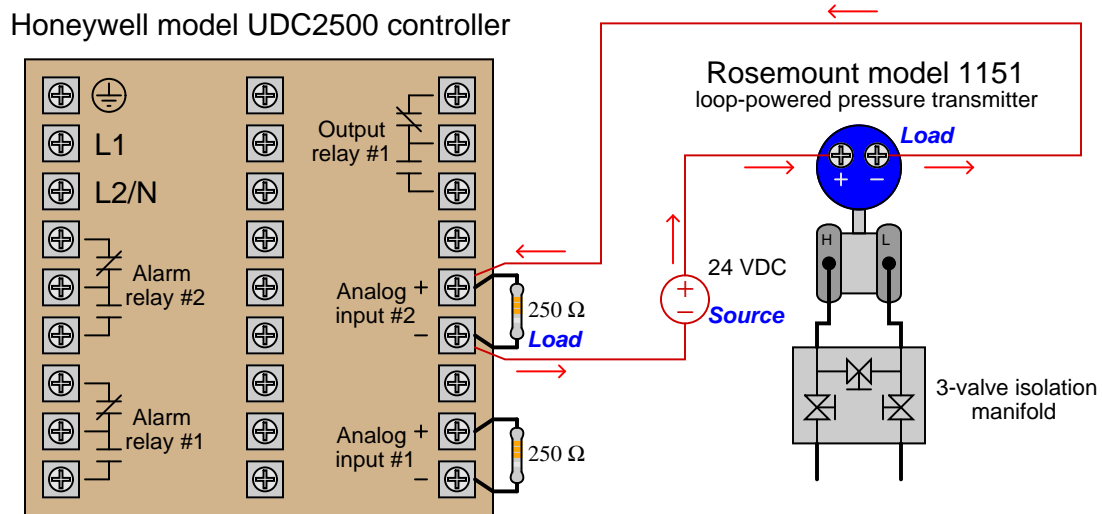
Although the eductor's suction will in fact hinder the pumps' ability to move liquid out of the sump to treatment, the effect will be minimal since 2 inches WC is tiny compared to the rated head (pressure) of the pumps at 40 feet WC.

---

Answer 38

Answer 39

Right now the circuit consists of two electrical *loads* and no *source(s)*. Since both the controller (with a 250 ohm resistor) and the transmitter require an external power supply, we must connect a DC voltage source in series with both to provide the power necessary to generate a 4-20 mA current signal:



Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

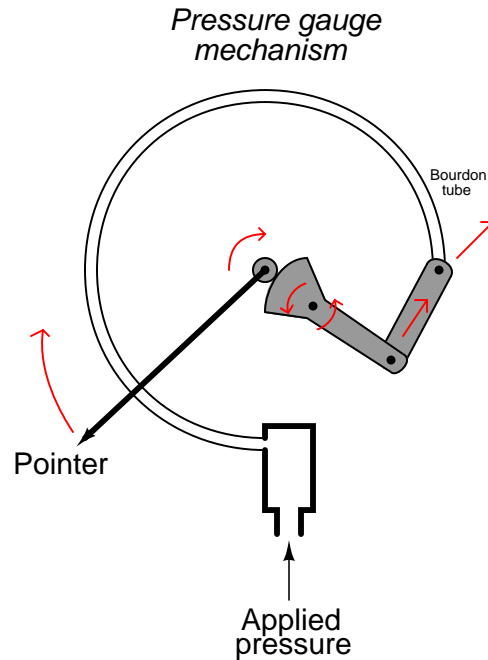
Answer 45

Answer 46

Answer 47

Answer 48

The parts in this gauge mechanism would move as such:



Possible things to change to make this pressure-measuring mechanism more sensitive:

- Decrease the spring rate (“stiffness”) of the bourdon tube
- Shorted the arm of the sector gear (the portion to the right of the pivot, joining with the link)
- Increase the sector gear radius
- Decrease the pinion gear radius

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 51

(1) The accuracy of a deadweight tester is fixed by three fundamental variables, all of which are quite constant, two of which can be manufactured to highly accurate specifications, and the third being a constant of nature:

- The mass of the calibration weights
- The area of the primary piston
- The gravity of the Earth

(2) If a deadweight is not level, the force generated by the precision weights will not be parallel to the primary piston's axis of travel, meaning that the piston will not support their full weight.

(3) Entrapped air will make the piston's motion "springy" rather than solid and secure.

(4) Spinning the primary piston eliminates static friction, leaving only dynamic friction (which is much less) to interfere with gravity's force on the primary piston.

---

Answer 52

The accuracy of a manometer is fixed by two fundamental variables, both of which are quite constant:

- The density (mass per unit volume) of the manometer liquid
- The gravity of Earth

So long as these two variables do not change, neither will the accuracy of the manometer.

---

Answer 53

Net piston force = 890.936 pounds.

In this scenario, there are two pressures fighting against each other: the 850 PSI pressure is pressing downward on the piston while the 1000 PSI pressure is pressing upward. The resultant (differential) pressure is 150 PSI (1000 PSI - 850 PSI). This is the pressure figure to be used in the final force calculation.

---

Answer 54

Net force = **4,319.69 pounds**, in the downward direction.

If your calculated force turned out to be 4,908.7 pounds, you made a very common error. Once you have figured out what this error is, go back and try to see how the scenario would have to be altered in order to actually generate 4,908.7 pounds of force with the two pressures being 750 PSI and 500 PSI, respectively.

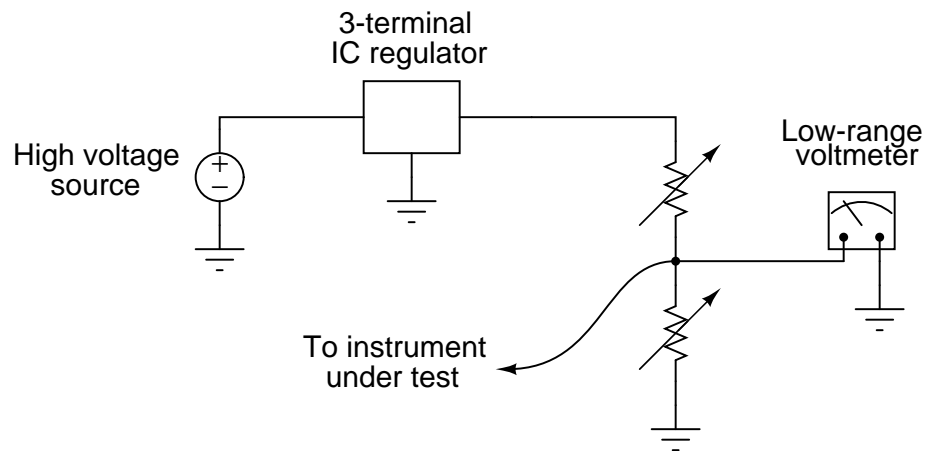
Actuating the hand pump introduces more air molecules to the system ( $n$ ). Assuming temperature ( $T$ ) remains constant, the air pressure ( $P$ ) will increase in inverse proportion to the volume ( $V$ ) of the pressure vessel for each additional stroke of the pump.

Follow-up question: If we wished the pressure to increase *less* for every stroke of the pump, would we want a smaller pressure vessel or a larger pressure vessel? Explain your answer.

Challenge question: suppose a technician follows these steps in using this system.

- Close valve 2, open valves 1 and 3
- Pump several strokes' worth of air into the pressure vessel
- Close valves 1 and 3
- *Slowly* open valve 2 until manometer registers desired pressure, then close

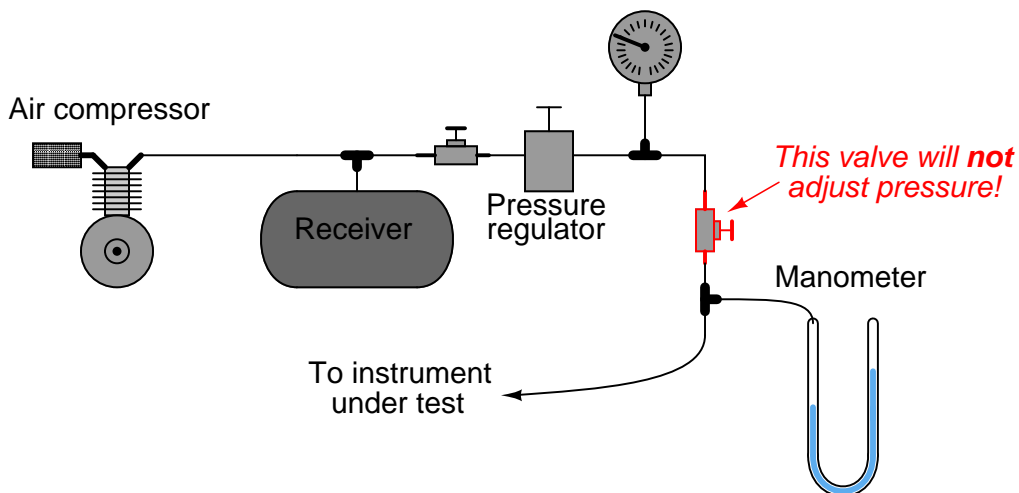
Is the air pressure going to the instrument under test greater than, less than, or equal to the air pressure in the vessel?



I'll leave the explanation to you!

Follow-up question #1: explain what you could do with one or both of the two needle valves to *increase* the amount of pressure sent to the instrument under test.

Follow-up question #2: explain why placing a valve in "series" with the regulator's output will *not* adjust pressure to the instrument under test or the manometer.



Possible things to change to make this pressure-measuring mechanism more sensitive:

- Increase the area of the diaphragm
- Decrease the spring rate of the diaphragm
- Move the fulcrum towards the linkage, to the left, away from the scale

---

Answer 58

It is an “anti-backlash” spring, supplying enough torque to rid the sector/pinion gear set of any “slack” or “play,” so that the pointer always responds to the slightest change in bourdon tube position.

---

Answer 59

- **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

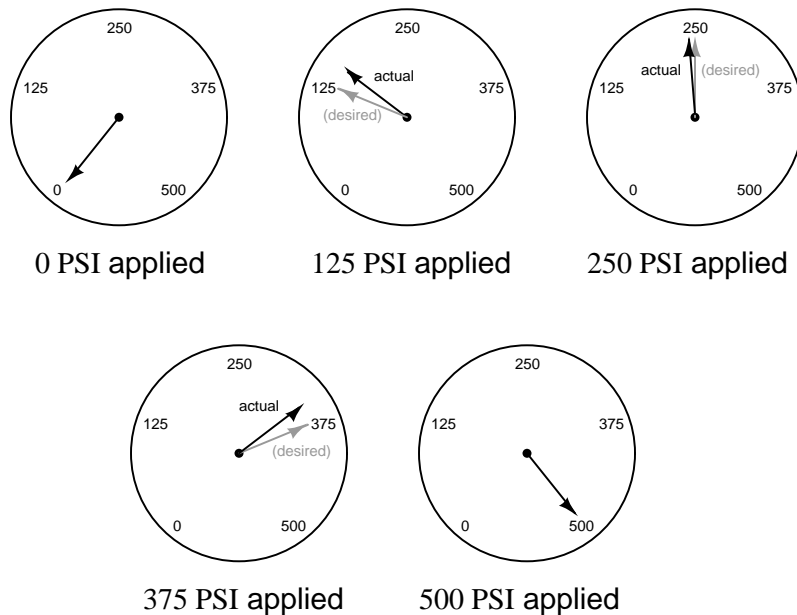
- **Thermometer**

- LRV =  $-40^{\circ}\text{F}$
- URV =  $250^{\circ}\text{F}$
- Test temperature =  $70^{\circ}\text{F}$
- Instrument indication =  $68^{\circ}\text{F}$
- Error =  $-0.69\%$  of span

- **pH analyzer**

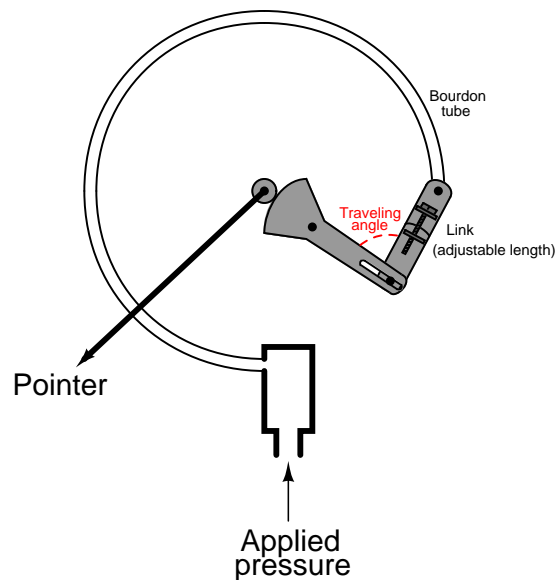
- LRV = 4 pH
- URV = 10 pH
- Test buffer solution = 7.04 pH
- Instrument indication = 7.13 pH
- Error =  $+1.5\%$  of span

Here is one example of how a pressure gauge might respond in a non-linear fashion to the same five applied pressures, while still being accurate at the LRV and URV points:



Here, the gauge reads high at the 25% point (125 PSI), slightly low at the 50% point (250 PSI), and low at the 75% point (375 PSI), while still accurate at 0% (0 PSI) and 100% (500 PSI).

Any adjustment that affects the *traveling angle* of the mechanism will have an effect on linearity. Some (high-quality) pressure gauge mechanisms are equipped with an adjustable-length link to facilitate changes to this angle:



It is sage advice to *leave all angle adjustment(s) untouched* until all possible zero and span adjustments have been made to the instrument. Usually, it is possible to get a nonlinear instrument to read within specified tolerance in a 5-point calibration just by adjusting the zero and span adjustments.

In many mechanical instruments, a simple linearity alignment is to apply a 50% input signal and check for link/lever perpendicularity (that all links and levers intersect at  $90^\circ$  angles to each other).

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Answer 61

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Answer 62

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Answer 63

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Answer 64

---

Answer 65

---

Answer 66

---

Answer 67

**Partial answer:**

Fault	Possible	Impossible
$R_1$ failed open	✓	
$R_2$ failed open		
Strain gauge failed open		✓
Dummy gauge failed open		
$R_1$ failed shorted		
$R_2$ failed shorted		
Strain gauge failed shorted		
Dummy gauge failed shorted		
Voltage source dead		✓

---

Answer 68

---

Answer 69

Atm	PSIG	inches W.C. (G)	PSIA
3.5	36.75	1017.3	51.45
6.51	81	2242	95.7
22.71	319.1	8834	333.8
0	-14.7	-406.9	0
1.017	0.2572	7.12	14.96
25.03	353.3	9779.6	368
1.136	2	55.36	16.7
100	1455.3	40284	1470

---

Answer 70

As a strain gauge is stretched, its conductors become longer and thinner, thus increasing resistance. As a strain gauge is compressed, its conductors become shorter and fatter, thus decreasing resistance. The bridge circuit becomes more unbalanced as the strain gauge's resistance changes from the neutral (resting) value.

In this circuit, voltage drop across the strain gauge decreases as it is compressed. This causes the potential at point A to become more negative, resulting in  $V_{AB}$  developing with A negative and B positive.

---

Answer 71

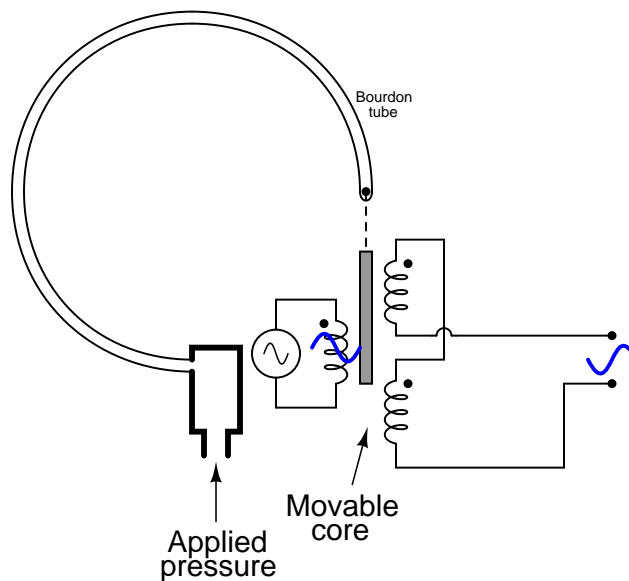
- Which port is the “high” pressure port: **Port “B”**
- What will happen if fixed resistor  $R_1$  fails open: **Voltmeter will drive fully upscale (“peg” positive)**
- Identify a component fault that would drive the voltmeter full upscale (“peg” positive):
  - Strain gauge #1 fails shorted
  - Strain gauge #2 fails open
  - $R_1$  fails open
  - $R_2$  fails shorted

---

Answer 72

Note very carefully how the two secondary coils are connected in series-opposing (as denoted by the phase dots)! This detail is essential in figuring out how the LVDT works.

The output is an AC voltage, the magnitude of which is proportional to core position, which in turn is proportional to applied pressure. For what it’s worth, the phase of the output voltage will be inverted with respect to the excitation voltage as the bourdon tube draws the core up:



LVDTs have several advantages over potentiometers:

- No friction
- No wear
- No potential to generate a spark in normal operating conditions

Their major disadvantage is requiring an AC excitation voltage. The frequency of this excitation voltage is important as well: it must be much larger than the highest frequency of pressure changes you wish to measure (as per the Nyquist sampling theorem).

---

Answer 73

Hint: although it may not look like it at first, the two resistors form a *bridge circuit* with the differential capacitor.

---

Answer 74

The output voltage will be positive with respect to ground if  $C > C'$  and negative if  $C' > C$ .

---

Answer 75

$$B = \frac{xV_{Hall}}{KI}$$

---

Answer 76

Fault	Possible	Impossible
$R_1$ failed open		✓
$R_1$ failed shorted		✓
$R_2$ failed open		✓
$R_2$ failed shorted		✓
$R_3$ failed open	✓	
$R_3$ failed shorted		✓
Reference filament burned out		✓
Measurement filament burned out		✓

---

Answer 77

**First transmitter design:**

Input range: 0 to 15 PSI

Output range: 0 to 10 volts DC

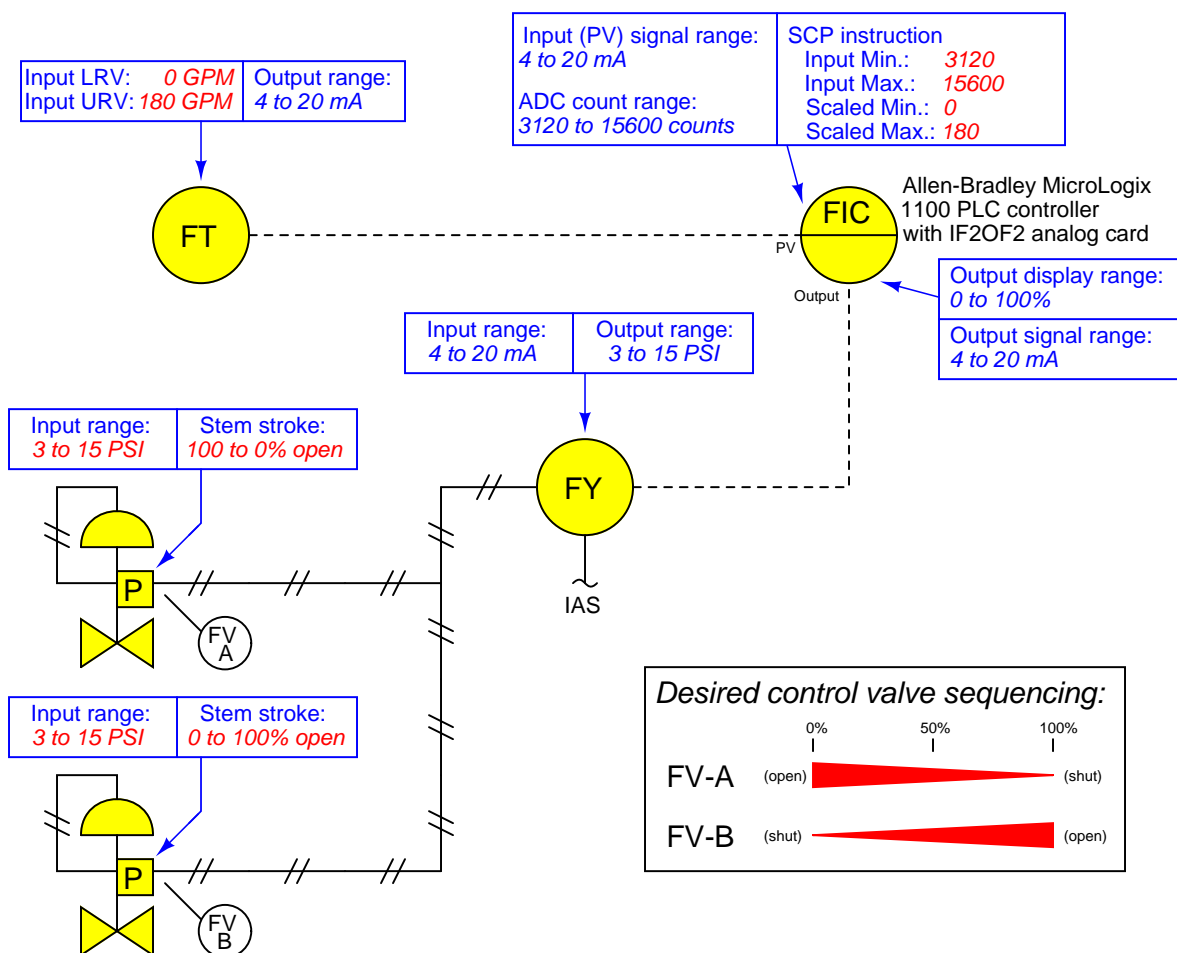
**Last transmitter design:**

Input range: 0 to 15 PSI

Output range: 1 to 5 volts DC

Follow-up question: show the current in both circuits using both conventional flow notation and electron flow notation.





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 79

Here is a comprehensive list of faults, each one individually capable of accounting for the symptom (no light) and the measurement of 24 volts between **C** and **D**:

- Lamp burned out (failed open)
- Wire failed open between **A** and **C**
- Wire failed open between **B** and **D**

Based on this short list of possible faults – assuming only *one* of them is actually true – the value of each proposed test is as follows:

Diagnostic test	Yes	No
Measure $V_{CF}$		✓
Measure $V_{ED}$		✓
Measure $V_{AB}$	✓	
Measure $V_{AD}$	✓	
Measure $V_{CB}$	✓	
Measure $V_{EF}$		✓
Measure current through wire connecting <b>A</b> and <b>C</b>		✓
Jumper <b>A</b> and <b>C</b> together	✓	
Jumper <b>B</b> and <b>D</b> together	✓	
Jumper <b>A</b> and <b>B</b> together		✓

A good rule to apply when evaluating proposed tests is to ask the question: “Will this test give me the exact same result no matter which one of the possible faults is true?” If so, the test is useless. If not (i.e. the results would differ depending on which of the possible faults was true), then the test has value because it will help narrow the field of possibilities.

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Answer 80

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Answer 81

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

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Answer 82

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

---

Answer 83

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

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Answer 84

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

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Answer 85

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

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Answer 86

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

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Answer 87

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

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Answer 88

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

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Answer 89

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

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Answer 90

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

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Answer 91

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Answer 92

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