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Lab

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

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Exam

*Day 5* – 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:** Pressure instrument accessories

Questions 1 through 20; answer questions 1-11 in preparation for discussion (remainder for practice)

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Day 2

**Theory session topic:** Pneumatic pressure instruments

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

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Day 3

**Theory session topic:** Pneumatic pressure instruments (continued) and pressure switches

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

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Day 4

**Theory session topic:** Review for exam

Questions 61 through 80; answer questions 61-66 in preparation for discussion (remainder for practice)

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

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Day 5

**Exam**

## How To . . .

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

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

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

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

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

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

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

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

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

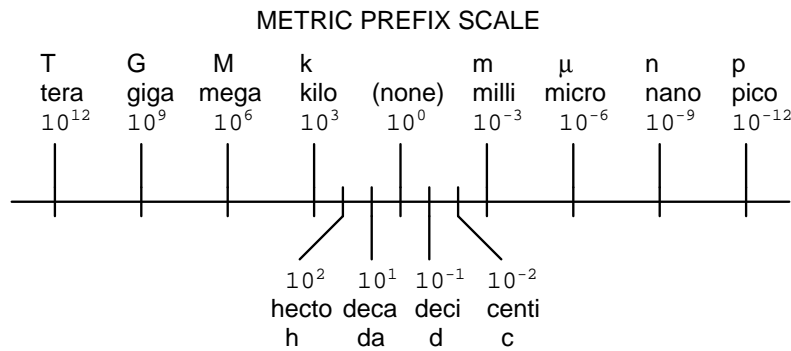
Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either 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  $20^\circ\text{C} = 1.0019 \text{ centipoise (cp)} = 0.0010019 \text{ Pascal-seconds (Pa}\cdot\text{s)}$

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

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

### Properties of Dry Air at sea level

Density of dry air at  $20^\circ\text{C}$  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 =  $0.018 \text{ centipoise (cp)} = 1.8 \times 10^{-5} \text{ Pascal-seconds (Pa}\cdot\text{s)}$

file conversion\_constants

### How to get the most out of academic reading:

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

### How to effectively problem-solve and troubleshoot:

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

### How to manage your time:

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

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

file question0

### 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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## Questions

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### Question 1

Read and outline the “Valve Manifolds” subsection of the “Pressure Sensor Accessories” 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 i03916](#)

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### Question 2

Read and outline the “Bleed (Vent) Fittings” subsection of the “Pressure Sensor Accessories” 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:

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

[file i03917](#)

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### Question 3

Read and outline the “Pressure Pulsation Damping” subsection of the “Pressure Sensor Accessories” 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:

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- Descriptions of problem-solving strategies applied by the author

[file i03918](#)

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### Question 4

Read and outline the “Remote and Chemical Seals” subsection of the “Pressure Sensor Accessories” section of the “Continuous Pressure Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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- Descriptions of problem-solving strategies applied by the author

[file i03919](#)

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#### Question 5

Read and outline the “Filled Impulse Lines” and “Purged Impulse Lines” subsections of the “Pressure Sensor Accessories” 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:

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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 i03920](#)

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#### Question 6

Read and outline the “Heat-Traced Impulse Lines” subsection of the “Pressure Sensor Accessories” 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:

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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 i03921](#)



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### Question 7

Read and outline the “Water Traps and Pigtail Siphons” subsection of the “Pressure Sensor Accessories” 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:

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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 i03922](#)

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### Question 8

Read the “Rosemount DP Level Fill Fluid Specifications” document (00840-2100-4016, revision DB), and answer the following questions:

In what ways does Silicone 704 fill fluid differ from the general-purpose Silicone 200?

Which fill fluid is most appropriate for high-reactivity applications such as pure oxygen pressure measurement?

Which fill fluid is most common in Rosemount remote seals?

Which fill fluids are appropriate for *sanitary* (food processing and pharmaceutical) applications?

Which fill fluid has the most potential to cause calibration errors as a result of large elevation differences between the transmitter and the remote seal(s)? Explain why.

Which fill fluid has the most potential to exhibit slow response times when measuring fast-changing process pressures? Explain why.

<b>Suggestions for Socratic discussion</b>
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- Why would we ever care about the reactivity of a fill fluid with the process fluid, since these two fluids are separated from contact with each other by isolating diaphragms?
- For any of the fill fluids with undesirable characteristics (e.g. extremely high viscosity), identify what *desirable* characteristics they possess. What special applications might demand the use of these fluid types?

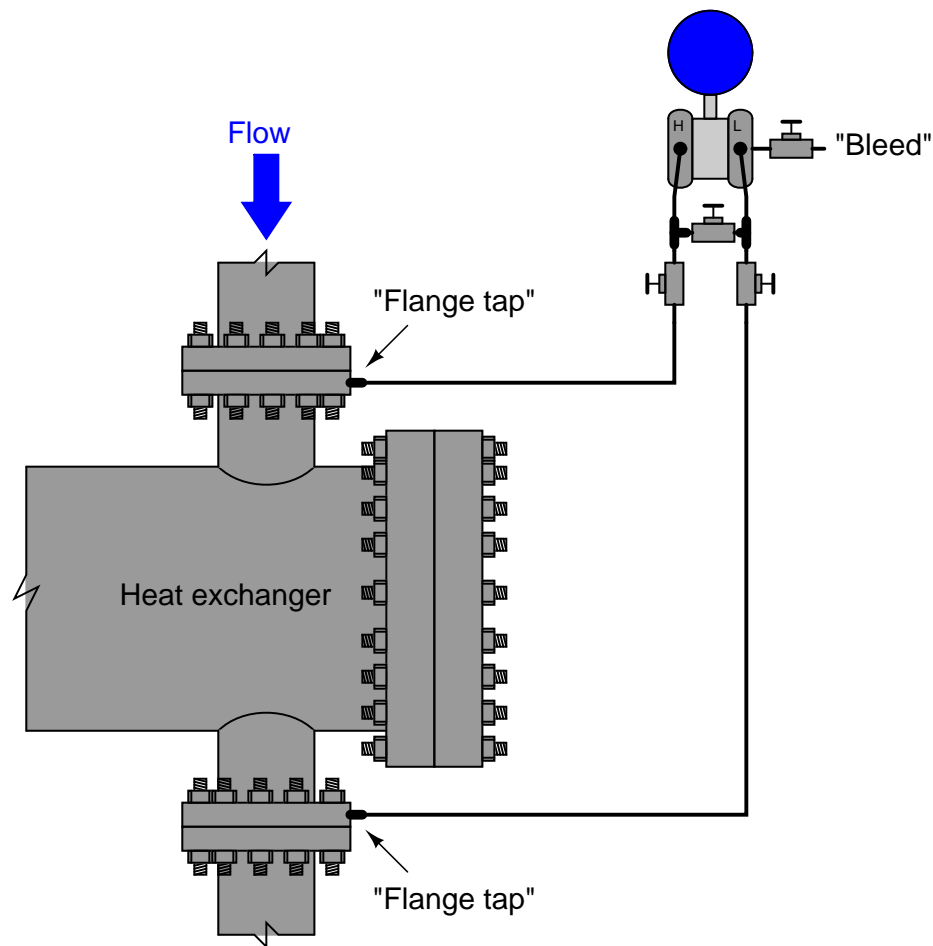
[file i03923](#)

### Question 9

Differential pressure transmitters are very common in the process industries. Besides being used to measure pressure (both differential and gauge), they may also be used to infer fluid level, fluid flow, and fluid density. A standard manifold called a *three-valve manifold* is often used to connect a differential pressure transmitter to the process. These manifolds consist of two block valves (to isolate the “high” and “low” transmitter ports from the process) and one “equalizing” valve (to connect both ports together to ensure zero differential pressure).

Three-valve manifolds are usually found as single units: a billet of metal with valves and ports machined into it, ready to bolt directly to a transmitter. However, you can build your own three-valve manifold using three individual valves, two tee fittings, and whatever other fittings are necessary to connect to the transmitter.

Suppose we encounter a differential pressure transmitter used to measure pressure drop across a heat exchanger. The typical pressure on the upstream side of this heat exchanger is 1000 PSI, while the typical pressure on the downstream side of this exchanger is 970 PSI. The transmitter connects to this heat exchanger via a three-valve manifold. A single “bleed” valve installed on the transmitter’s low-pressure side is used to vent pressure to atmosphere prior to removal of the transmitter from the manifold:



The common procedure for operating a 3-valve manifold to take a transmitter out of service is to first close the high-side block valve, then open the equalizing valve, then close the low-side block valve. Once these manifold valves have been thus arranged to isolate the transmitter from the process and equalize differential pressure inside the transmitter, the bleed valve may be carefully opened to release stored pressure

to atmosphere.

Determine how much fluid pressure will be on each side of the transmitter through every step of this procedure:

Step	High-side pressure	Low-side pressure	Differential pressure
Transmitter in service	1000 PSI	970 PSI	30 PSID
Close high-side block valve			
Open equalizing valve			
Close low-side block valve			
Open bleed valve			

Now, suppose someone else (at a later date) were to remove this transmitter from service using the three-valve manifold, but following a different order of steps: closing the low-side block valve first, then equalizing, then blocking the high side.

Determine how much fluid pressure will be on each side of the transmitter through every step of this (alternative) procedure:

Step	High-side pressure	Low-side pressure	Differential pressure
Transmitter in service	1000 PSI	970 PSI	30 PSID
Close low-side block valve			
Open equalizing valve			
Close high-side block valve			
Open bleed valve			

Based on the pressures seen by the transmitter in both procedures, would you recommend one procedure over the other? If so, why?

#### Suggestions for Socratic discussion

- A powerful problem-solving technique is performing a *thought experiment* where you mentally simulate the response of a system to some imagined set of conditions. Explain how this particular thought experiment is helpful in determining which is the safest procedure for operating a three-valve transmitter manifold.

file i00211

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### Question 10

Convert between the following units of pressure:

- 71.5 PSIA = ??? PSIG
- 5.03 bar (gauge) = ??? "Hg
- 101 kPa = ??? PSIA
- 800 torr = ??? PSIG
- 41 "Hg = ??? "W.C.
- 2.2 feet Hg = ??? kPa
- 11 PSI vacuum = ??? torr
- 350 "W.C.G = ??? "W.C.A
- 66 cm W.C. = ??? "Hg
- 910 PSIG = ??? atm
- 35 "W.C. = ??? "HgA
- 125 PSIA = ??? kPa

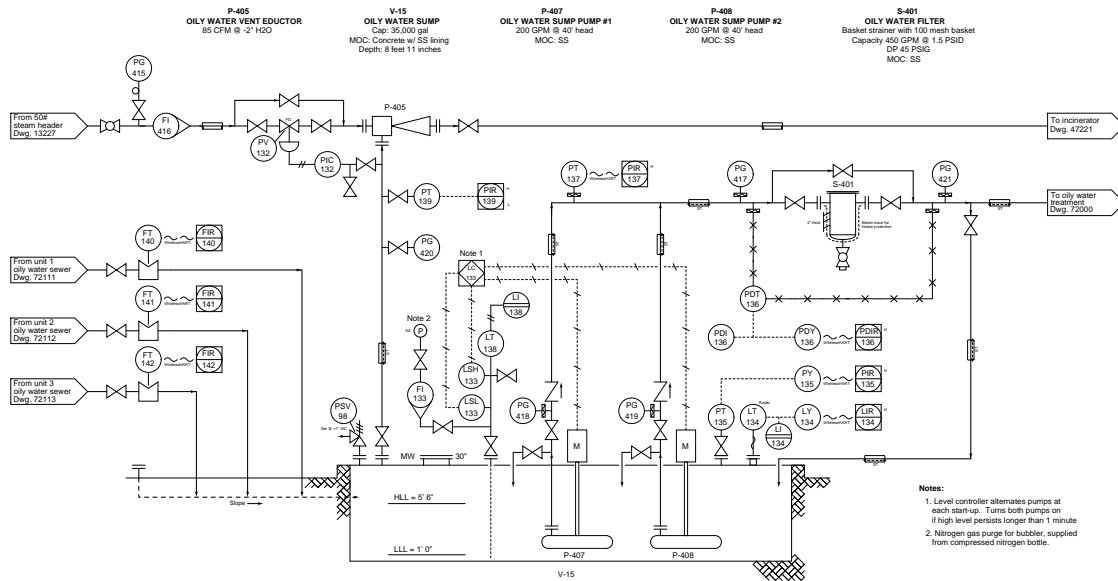
<b>Suggestions for Socratic discussion</b>
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- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.

file i04177

## Question 11

Suppose operators submitted a “trouble-call” to your instrument shop, claiming sump V-15 had an excessive liquid level inside of it (as indicated by LIR-134), and that the pump was not pumping that level down as it should:



Identify at least three possible faults, each one independently capable of accounting for the high sump level indication. Also, identify any diagnostic tests you could perform on this system to pinpoint the nature and location of the fault.

### Suggestions for Socratic discussion

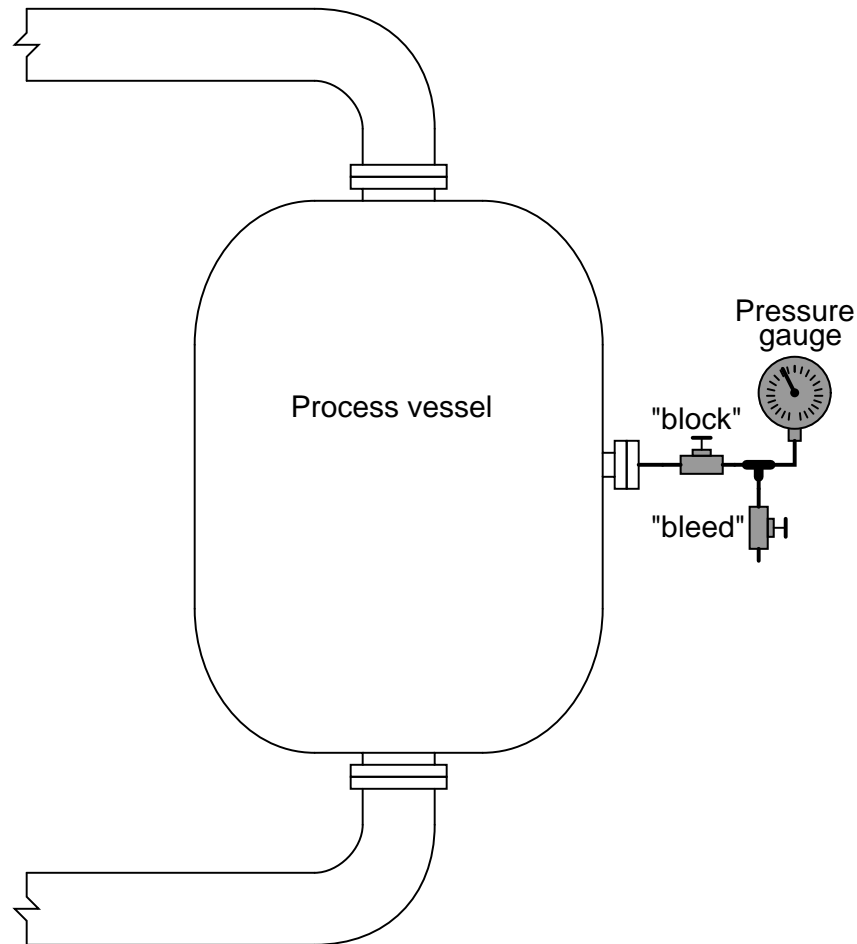
- Suppose this trouble-call came to you during a very cold winter day, when the outside temperature was well below freezing. How might this alter the list of potential faults?
- Explain the purpose for having *check valves* on the discharge lines of the two submersible sump pumps.
- Identify some of the different signal line types used in this P&ID, and what each of those line types means.
- Identify some of the different pressure-measurement accessory devices visible in this P&ID.

[file i03513](#)

## Question 12

In connecting a pressure transmitter or other pressure-measuring instrument to a process pipe or vessel, there must be some means of “disconnecting” the instrument from the pressurized process so that it may be calibrated or removed safely without depressurizing the entire process. Usually, this feature is provided in the form of an instrument “manifold,” consisting of one or more valves between the instrument and the process pipe or vessel.

Take this pressure gauge installation, for example:



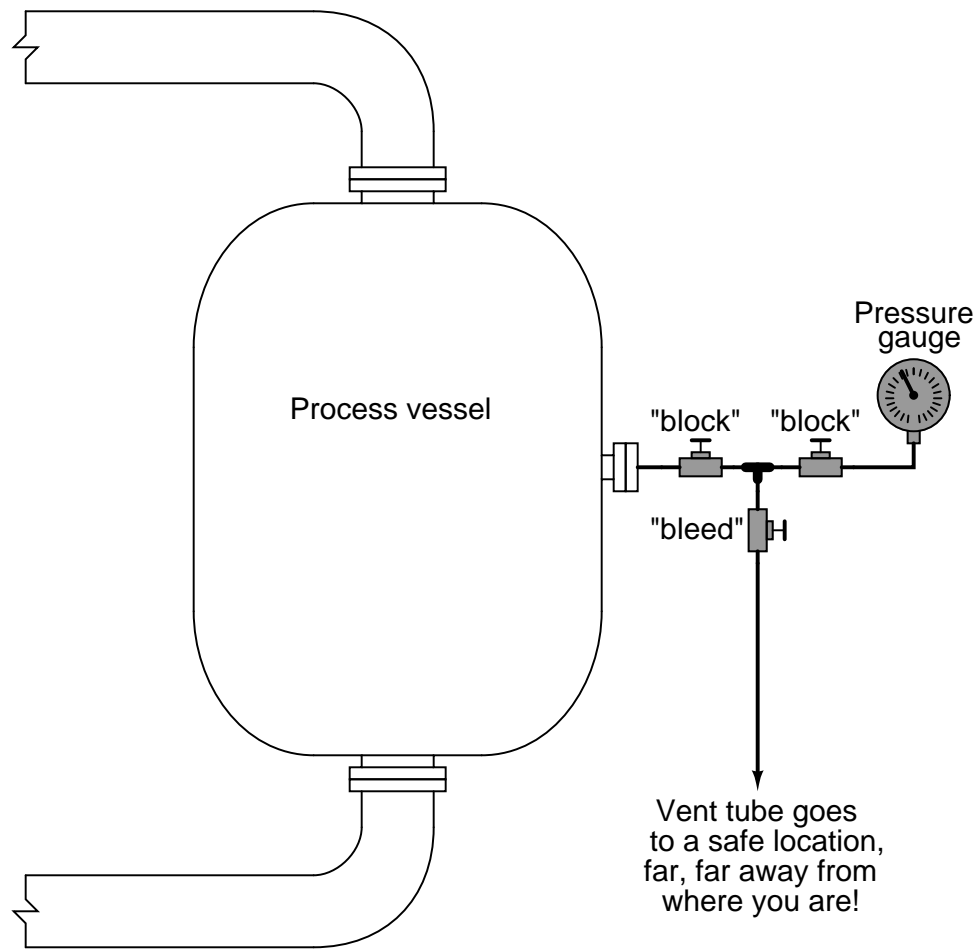
Two small valves connect the process vessel to the pressure gauge through a tee fitting, one called the “block” and the other called the “bleed.” In normal operation, the “block” valve remains in the open position and the “bleed” valve remains in the closed position.

Suppose you wished to remove this pressure gauge from the process vessel and take it to the instrument shop for re-calibration. In what sequence would you operate the “block” and “bleed” valves before loosening the gauge from the tubing? After the gauge had been calibrated and installed, and you are ready to place it back in service, how would you sequence the opening and closing of the “block” and “bleed” valves? *Be very careful about the sequence of your steps!*

file i00209

### Question 13

On processes where the fluid in question is especially dangerous, “double block-and-bleed” manifolds are often used to isolate instruments from the process piping. Consider this example:

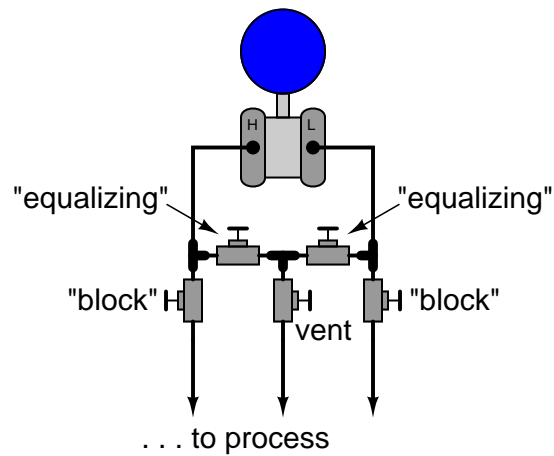


Describe the proper procedure for block and bleed valve opening/closing when removing and replacing an instrument connected to a process through such a manifold.

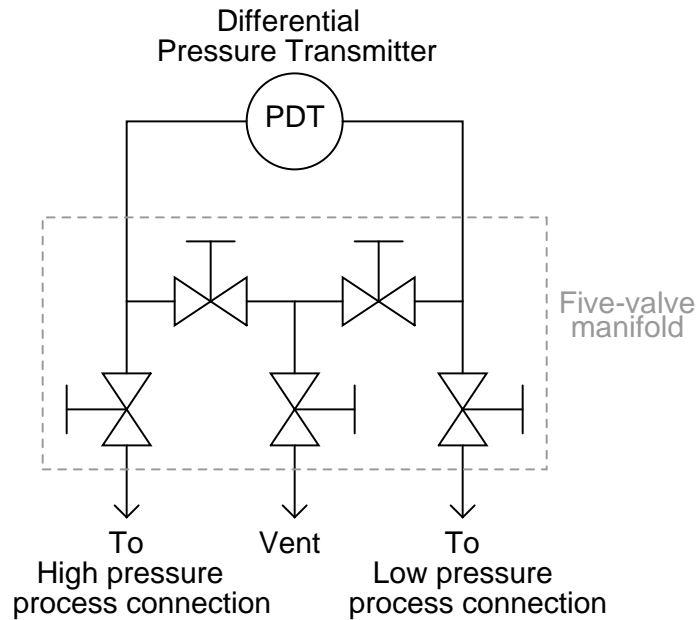
file i00210

# Question 14

Some differential pressure transmitters are equipped with *five-valve manifolds*. These valve networks allow for blocking, equalizing, and bleeding of the transmitter's two pressure ports, the valves being arranged in this pattern:



Shown using standard P&ID (Process and Instrument Diagram) symbols – instrumentation equivalent of an electrical schematic diagram – the transmitter and manifold arrangement looks like this:



Identify the normal, operating valve positions (open/closed) for a five-valve manifold. Describe the proper sequence of manifold valve operation to successfully prepare the transmitter for removal from the process.

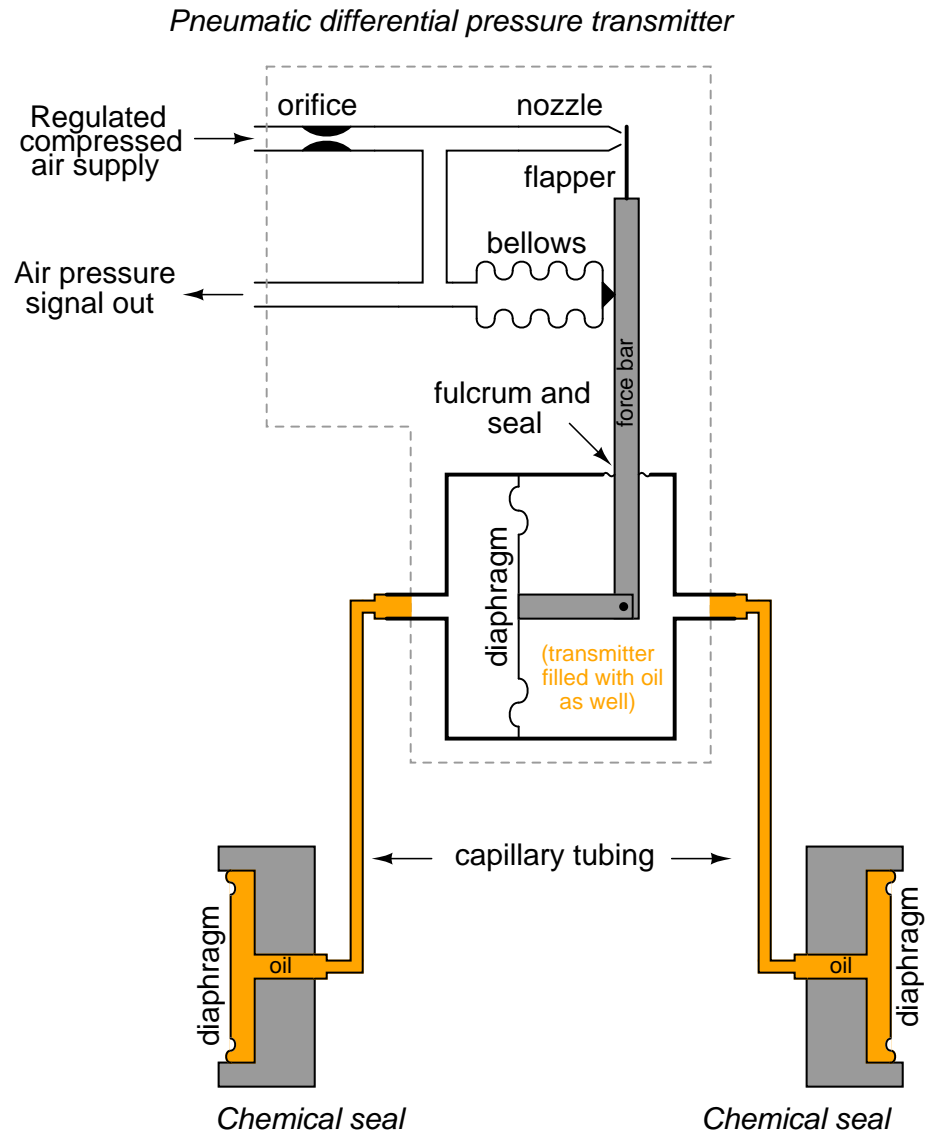
Why do you think we have such things as 5-valve manifolds? What can be done with this manifold that cannot be done with a three-valve manifold?

[file i00212](#)

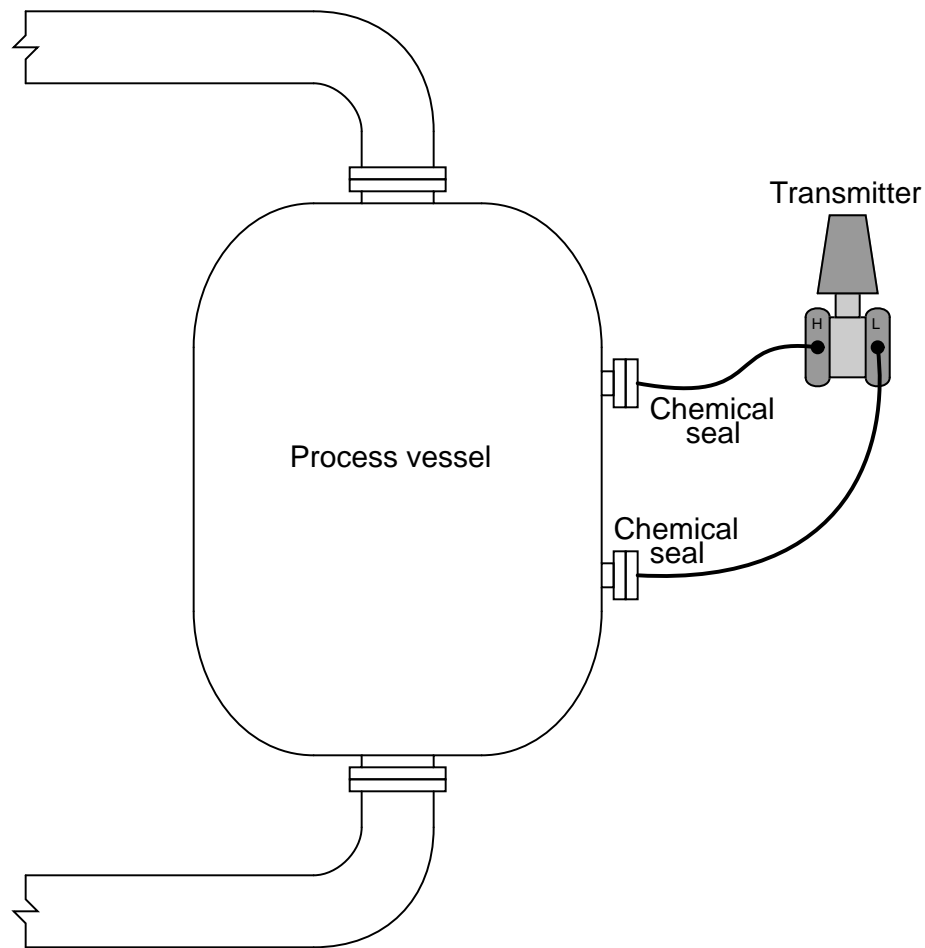


Question 15

Some pressure instruments come equipped with *chemical seals* consisting of diaphragm units connected to the instrument with small-bore “capillary” tubing filled with a liquid such as silicone oil:



These seals may then be connected to a process vessel to measure pressure, at some distance from the transmitter:



For what purpose(s) do these seals function? What advantage(s) do they lend to the instrument in measuring pressure?

[file i00216](#)

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#### Question 16

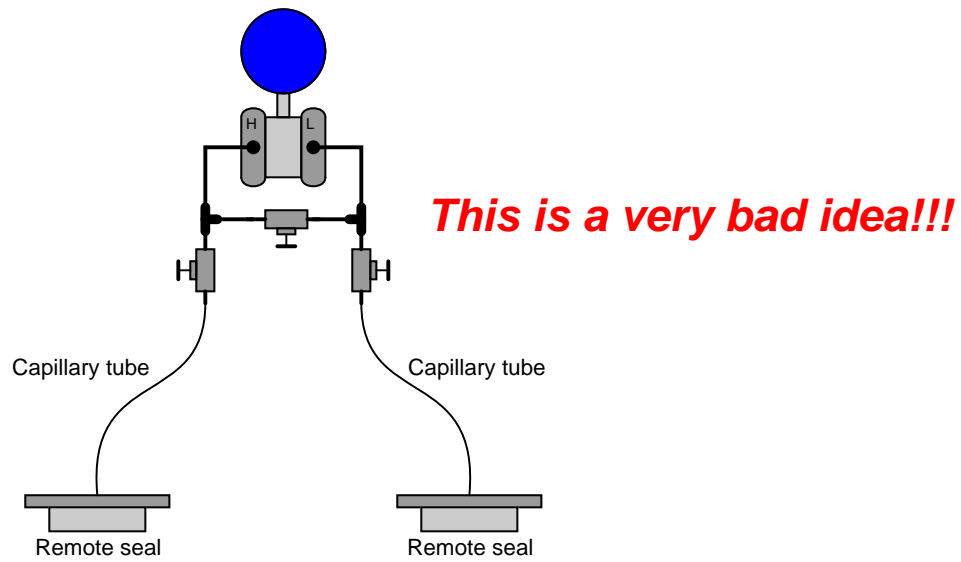
Why is *temperature* an important factor in pressure transmitters equipped with remote seals (sometimes called “chemical” seals)? Specifically, what temperature condition(s) could cause a differential pressure instrument with remote seals to experience measurement errors?

Also, describe what would happen to a pressure instrument equipped with remote seals if ever a leak developed in one of the capillary tubes.

[file i00217](#)

Question 17

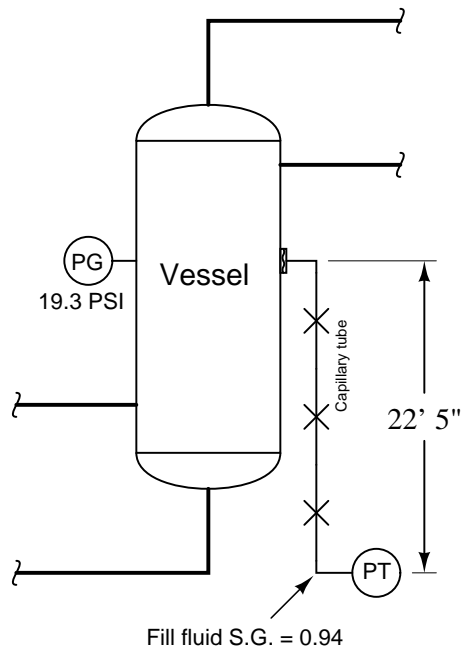
Explain why no one in their right mind would ever, *ever*, install a three-valve manifold on a DP transmitter with remote seals:



file i03460

Question 18

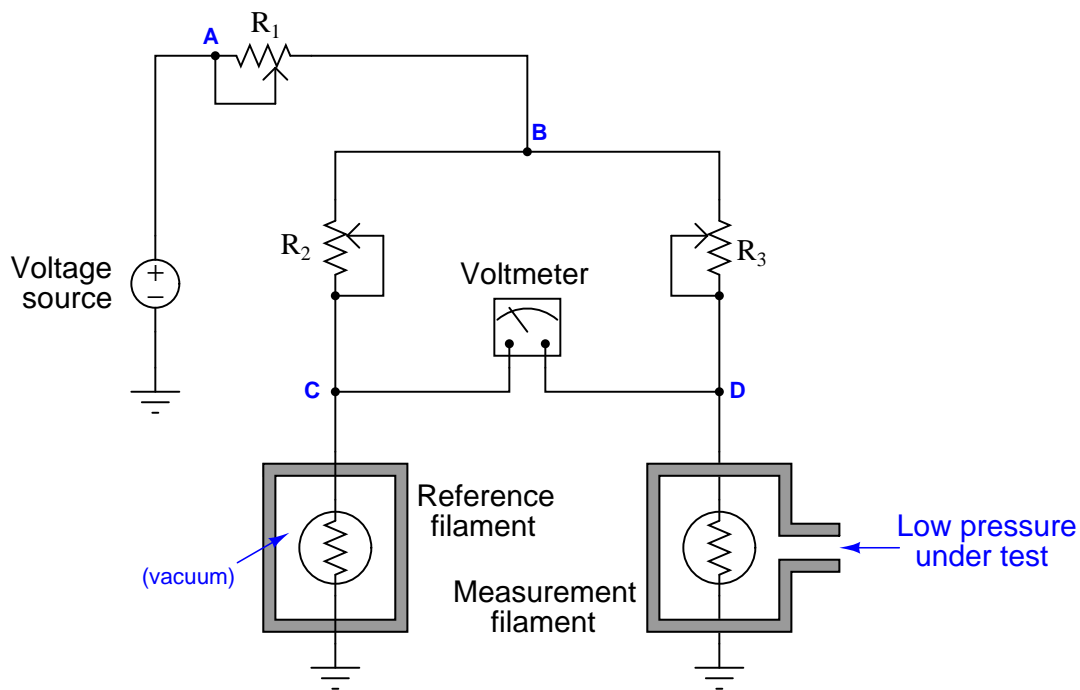
A pressure transmitter with a remote seal measures the pressure of a gas inside a process vessel. A pressure gauge directly attached to the vessel registers 19.3 PSI. The transmitter is located 22 feet 5 inches below this point, with a capillary tube filled with fluid having a specific gravity of 0.94:



How much pressure will the transmitter register?  
file i00240

# Question 19

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

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#### Question 20

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#### Question 21

Read and outline the introduction and the “Pneumatic Sensing Elements” sections of the “Pneumatic Instrumentation” 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 i03924](#)

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#### Question 22

Read and outline the “Self Balancing Pneumatic Instrument Principles” section of the “Pneumatic Instrumentation” 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 i03926](#)

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### Question 23

Read and outline the “Pilot Valves and Pneumatic Amplifying Relays” section of the “Pneumatic Instrumentation” 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:

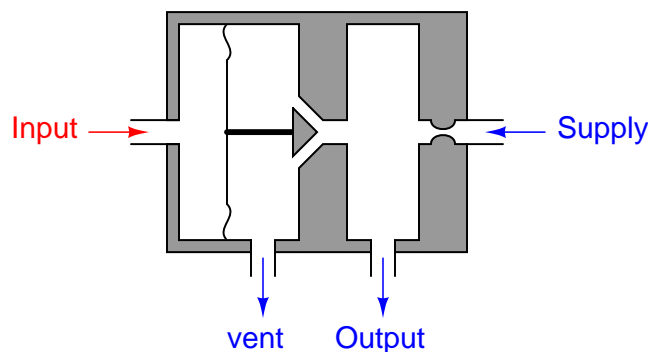
- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- Images copied from the text (or sketched by you) to illustrate concepts
- References to previously learned concepts
- Descriptions of problem-solving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

[file i03925](#)

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### Question 24

Does the output pressure of this relay *increase* with increasing input pressure, or *decrease* with increasing input pressure? In other words, is it a *direct-acting* or *reverse acting* type of relay?



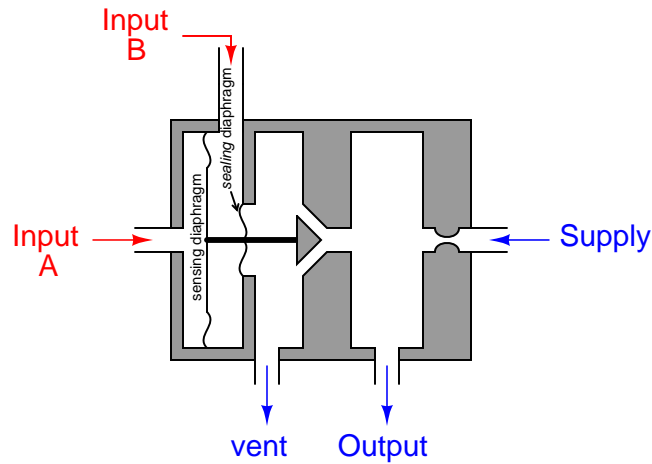
#### Suggestions for Socratic discussion

- Explain this comparison: “A relay is to a pilot what a transistor is to a hand switch”
- How do you think a leak or tear in the diaphragm would affect the behavior of this relay?
- How do you think a plugged orifice would affect the behavior of this relay?
- How do you think variations in the supply pressure would affect the behavior of this relay?
- Identify how to modify this relay mechanism so as to introduce a *zero* calibration shift.
- Identify how to modify this relay mechanism so as to introduce a *span* calibration shift.

[file i00197](#)

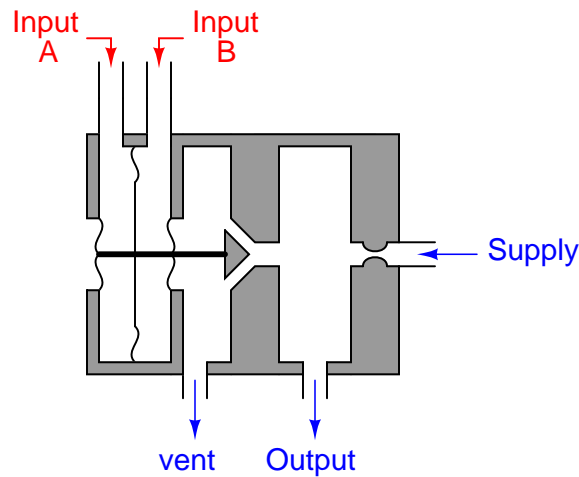
### Question 25

What is the response of this pneumatic relay to increasing pressure on each of its inputs? Does the output pressure increase as input A's pressure increases? What happens when input B's pressure increases? Note that both the sensing and sealing diaphragms are welded to the pilot rod, forming leak-proof and frictionless seals between chambers:



Can you think of an electronic circuit or device that acts in an analogous manner?

Also, explain why the following relay design is better, using two sealing diaphragms instead of just one. A hint is to consider the *common-mode rejection* capacity of each relay design. Once again, each of the metal diaphragms is welded to the rod to form leak-proof and frictionless seals:



#### Suggestions for Socratic discussion

- Explain how one might apply a “thought experiment” to these mechanisms to analyze their behavior.
- Why use *sealing diaphragms* in mechanisms such as this? Do you think there might be an alternative construction that achieves the same design goal?
- Explain how the behavior of this relay is similar to that of an *operational amplifier*. Which of the two inputs is the non-inverting (+) and which of the two is inverting (−)?
- Identify how to modify this relay mechanism so as to introduce a *zero* calibration shift.



- Identify how to modify this relay mechanism so as to introduce a *span* calibration shift.

[file i00198](#)

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#### Question 26

A pneumatic differential pressure transmitter has a calibrated range of  $-100$  to  $+100$  inches of water column (" W.C.), and its output signal range is 3 to 15 PSI. Complete the following table of values for this transmitter, assuming perfect calibration (no error). Be sure to show your work!

Input pressure applied ("W.C.)	Percent of span (%)	Output signal (PSI)
0	50	9
-30	35	7.2
-16.7	41.7	8
66.7	83.3	13
30	65	10.8
-80	10	4.2

#### Suggestions for Socratic discussion

- Develop a linear equation in the form of  $y = mx + b$  that directly relates input pressure ( $x$ ) to output pressure ( $y$ ).
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

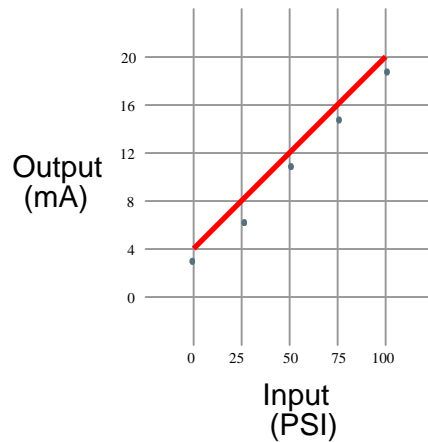
[file i00096](#)

### Question 27

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

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

Sketch this instrument’s ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *hysteresis*, and/or *linearity*):



Finally, identify how this calibration error might be corrected. What steps or procedures would you follow to rectify this problem?

#### Suggestions for Socratic discussion

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

file i00081

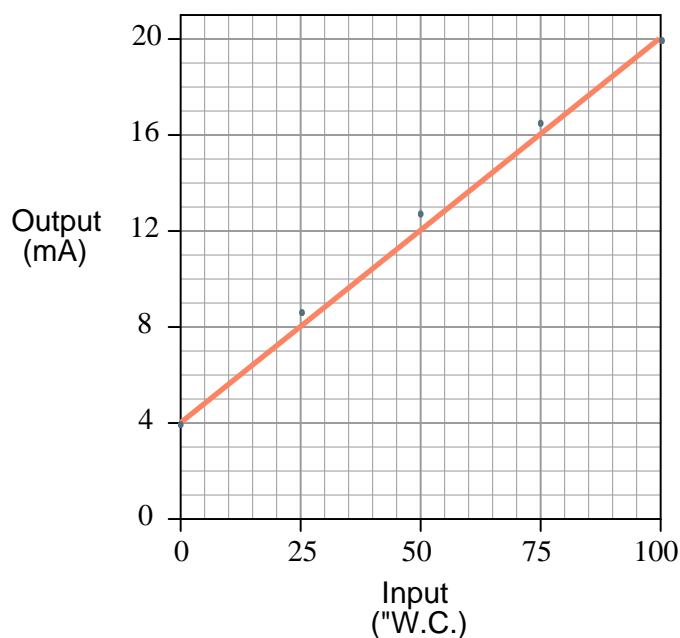
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**Question 28**

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

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

Graph this instrument’s ideal transfer function on the graph below, along with its *actual* transfer function graph based on the measured values recorded above. Then, determine what kind of calibration error it has (*zero shift*, *span shift*, *hysteresis*, and/or *linearity*).



Hint: a computer spreadsheet program might be a useful tool in graphing this instrument’s response. Feel free to attach a printed copy of a spreadsheet graph instead of hand-sketching one on this page.

<b>Suggestions for Socratic discussion</b>
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- How might the other three calibration errors appear when graphed?
- What purpose is served by doing an up-and-down test? Why not just check the instrument’s response in one direction only?

[file i03859](#)

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**Question 29**

Complete the following table of equivalent pressures:

bar	PSI	inches W.C.	inches mercury
0.59			
	4.1		
		200	
			35
		308	
			105
	88		
5.91			

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.

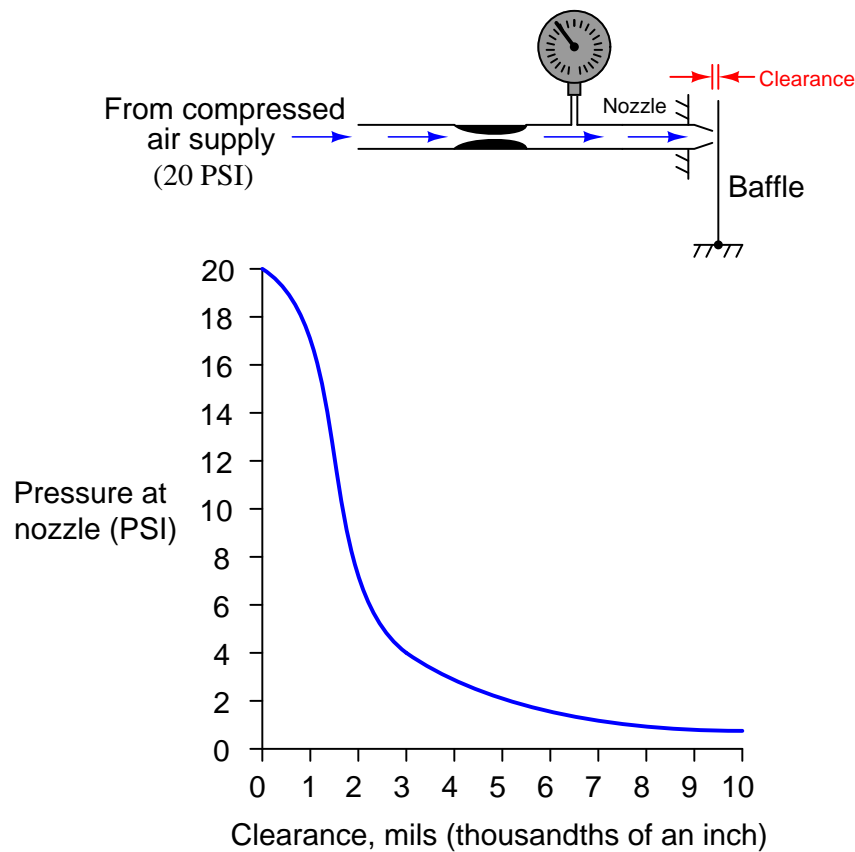
<b>Suggestions for Socratic discussion</b>
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- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.

[file i03927](#)

### Question 30

The *transfer function* (graph of output versus input) for a pneumatic baffle/nozzle assembly looks something like this:



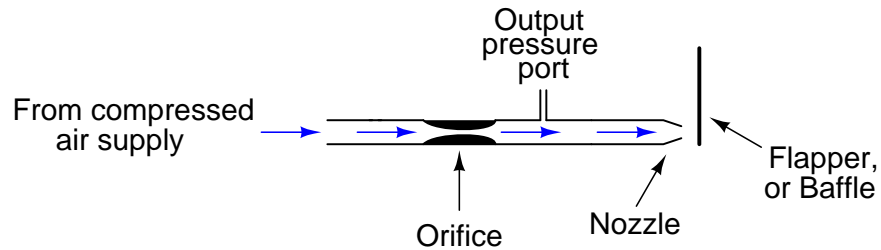
As you can see, this is a very sensitive mechanism. A nearly full swing of pressure (0 PSI to supply) is obtained with just several thousandths of an inch of baffle movement. It is this extreme sensitivity that allows us to assume there is negligible motion in a pneumatic force-balance mechanism operating within its calibrated range.

However, the baffle/nozzle mechanism is certainly not equally sensitive throughout all portions of its operating range. Identify the most sensitive portion of its range on the transfer function graph, and explain your selection criterion.

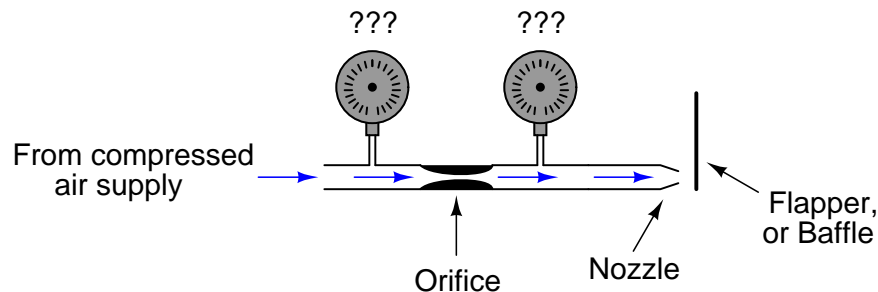
[file i02907](#)

Question 31

One of the most basic components of a pneumatic instrument is the so-called *flapper/nozzle*, or *baffle/nozzle* assembly. It consists of two restrictions to air flow, one within a tube (the *orifice*) and the other at the end of a tube (the *nozzle*). The *flapper*, or *baffle*, is nothing more than a flat piece of metal in close proximity to the nozzle tip. These mechanisms serve as extremely sensitive position detectors, generating a pneumatic pressure output signal that varies with flapper (baffle) position:

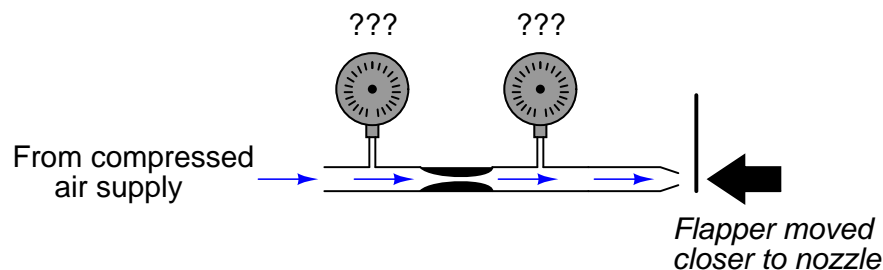


Suppose that two pressure gauges were installed along the length of the tube, one upstream of the orifice and the other downstream of the orifice, like this:

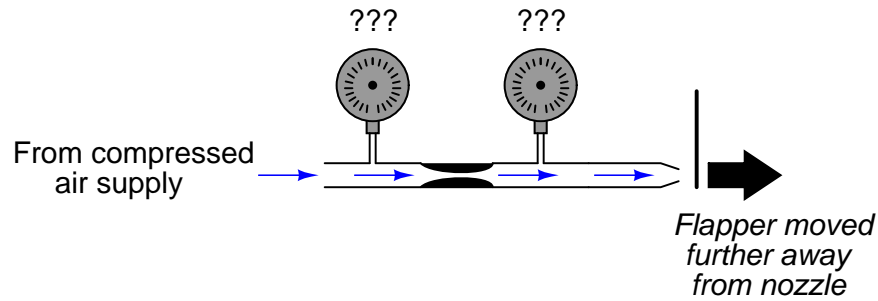


Qualitatively speaking, what would these two pressure gauges indicate? Assume that the air supply is regulated by a pressure regulator, and so remains at a constant pressure. Would the two pressure gauges indicate the same amount of pressure? Would one of them indicate a higher pressure than the other? Explain your answer.

If the flapper (baffle) is brought closer to the nozzle, the nozzle will become more restrictive to air flow through it. What effect will this have on the two pressure gauge indications in this flapper/nozzle system?



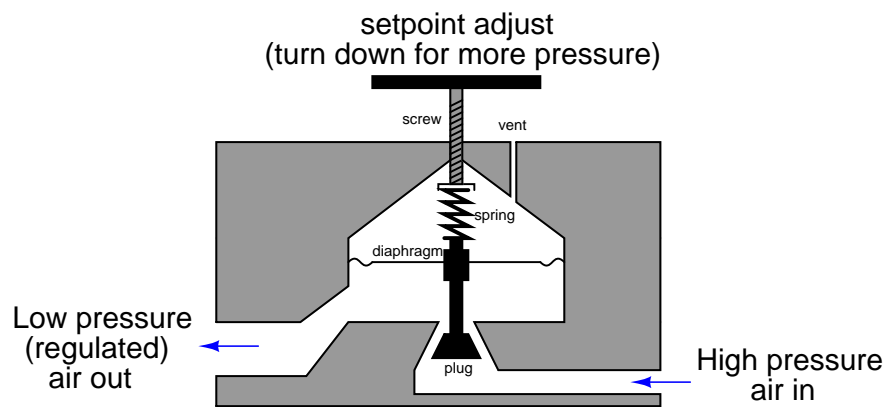
If the flapper travels further away from the nozzle, what effect will it have on the two pressure gauges' indications?



[file i00191](#)

### Question 32

Since precision pneumatic instruments operate best when their supply air pressure is at a constant pressure, it is necessary to *regulate* the fluctuating air pressure from the receiver vessel down to a lower, more constant level for the instrument. The device designed to do this is called an *air pressure regulator*. A cut-away diagram of an air pressure regulator is shown here:



The wedge-shaped *plug* can move down to open the passageway and allow more of the high-pressure air to enter the chamber below the diaphragm, and can move up to close off the passageway and reduce the flow of incoming air into the diaphragm chamber. The regulation setpoint is adjustable by the position of the threaded rod pressing down on the diaphragm through a spring.

Describe how this air pressure regulator functions. Suppose that the outlet air pressure is below setpoint. How does this mechanism respond to bring the outlet pressure back up to where it is supposed to be?

If the outlet air pressure rises to too high a level, how does the mechanism compensate to reduce it back down to the setpoint level?

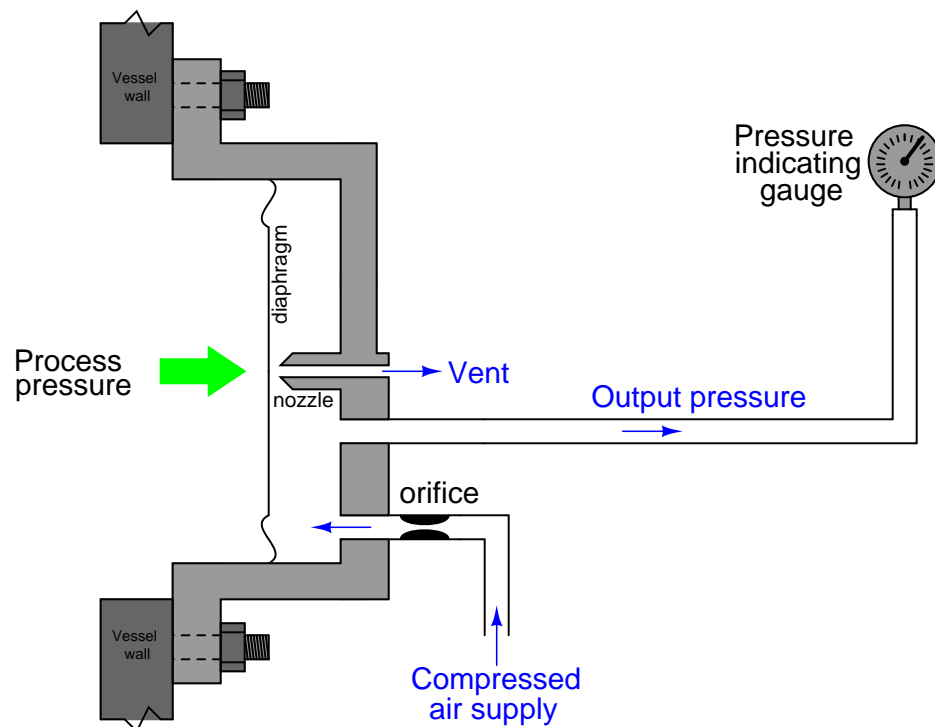
### Suggestions for Socratic discussion

- Suppose the spring inside this regulator were to break. What effect would this have on the regulator's output pressure, and why?
- Suppose the vent hole were to plug. What effect would this have on the regulator's output pressure, and why?

[file i00190](#)

### Question 33

Shown here is a “cut-away” diagram of a simple pressure repeater, a device used to duplicate the pressure inside an enclosed process vessel with clean pneumatic (air) pressure, so it may be read with a remote gauge:



Describe the response of this device, step by step, to an increase in process pressure. Hint: the diaphragm in this device is “slack,” meaning it has negligible spring effect. This means even very small pressure differences are sufficient to move the diaphragm significantly.

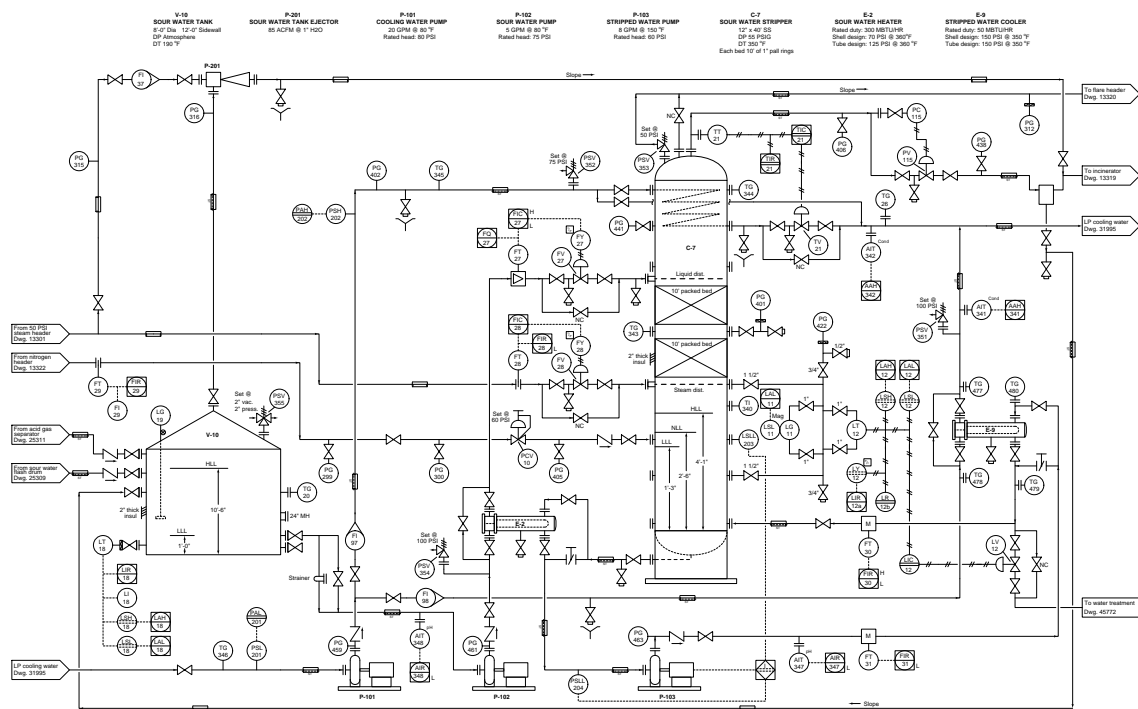
Also, explain where we might want to use such a device, in lieu of simply connecting the pressure indicating gauge directly to the process vessel.

file i00199



### Question 34

An operator reports a high level alarm (LAH-12) displayed at the control room for the last 13 hours of operation, in this sour water stripping tower unit (where sulfide-laden water is “stripped” of sulfur compounds by the addition of hot steam). Over that time period, the sightglass (level gauge LG-11) has shown the liquid level inside vessel C-406 drifting between 2 feet 5 inches and 2 feet 8 inches:



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.

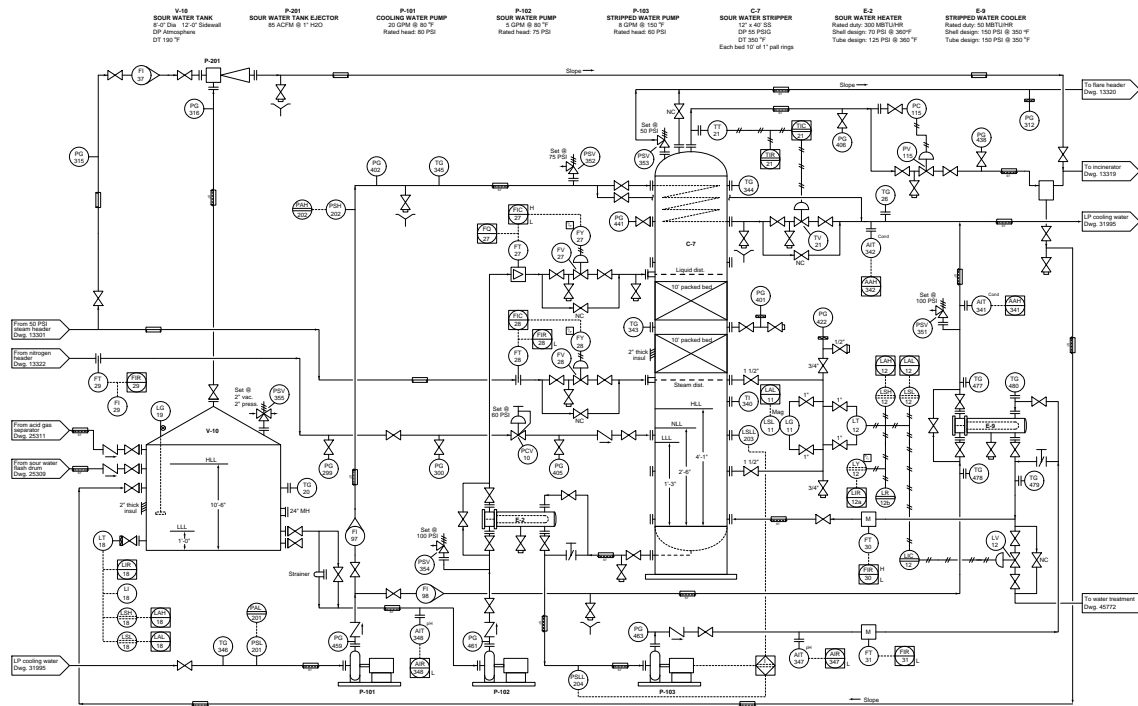
Fault	Possible	Impossible
LT-12 miscalibrated		
LG-11 block valve(s) shut		
LSH-12 switch failed		
LSL-12 switch failed		
Leak in tubing between LT-12 and LIC-12		
LIC-12 controller setpoint set too high		
LV-12 control valve failed open		
LV-12 control valve failed shut		

file i03540

### Question 35

In this process, steam is introduced into “stripping” vessel C-7 to help remove volatile sulfur compounds from “sour” water. The temperature of the stripped gases exiting the tower’s top is controlled by a pneumatic temperature control loop. Unfortunately, this loop seems to have a problem.

Temperature indicating recorder TIR-21 registers 304 degrees Fahrenheit, while temperature indicating controller TIC-21 registers 285 degrees Fahrenheit. The calibrated range of TT-21 is 100 to 350 degrees Fahrenheit. A technician connects a test gauge to the pneumatic signal line and reads a pressure of 12.8 PSI:



Which instrument is faulty: the transmitter, the recorder, or the controller, or is it impossible to tell from what little information is given here?

[file i03541](#)

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**Question 36**

Suppose you wish to calibrate a pneumatic pressure transmitter to an input range of 0 to 200 inches of water, with an output range of 3 to 15 PSI. Complete the following calibration table showing the test pressures to use and the allowable low/high output signals for a calibrated tolerance of  $\pm 0.5\%$  (of span):

Input pressure applied (" W.C.)	Percent of span (%)	Output signal <i>ideal</i> (PSI)	Output signal <i>low</i> (PSI)	Output signal <i>high</i> (PSI)
	0			
	25			
	50			
	75			
	100			

Suppose this transmitter is installed as part of a complete pressure measurement system (transmitter plus remote indicator and associated components), and the entire measurement system has been calibrated within the specified tolerance ( $\pm 0.5\%$ ) from beginning to end. If the operator happens to read a process pressure of 153 inches W.C. at the indicator, how far off might the actual process pressure be from this indicated value?

<b>Suggestions for Socratic discussion</b>
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- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i00227](#)

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**Question 37**

Examine the diagram for a Foxboro model 139PP pneumatic pressure repeater, then identify multiple faults which could cause this instrument to:

- Output *less* pressure than it should (i.e. less pneumatic signal pressure than process fluid pressure)
- Output *more* pressure than it should (i.e. more pneumatic signal pressure than process fluid pressure)

For each of your identified faults, explain *why* the pneumatic output signal pressure will be incorrect, and also identify how to correct the problem.

<b>Suggestions for Socratic discussion</b>
--

- Describe a practical application for this instrument.
- Explain how it is possible to determine from the cross-sectional diagram which portions of the mechanism move and which portions are stationary.
- Is this a “bleeding” or a “non-bleeding” pneumatic mechanism?
- Identify and explain how the sensing diaphragm of this instrument is protected from damage against modest process over-pressure events.

[file i00192](#)

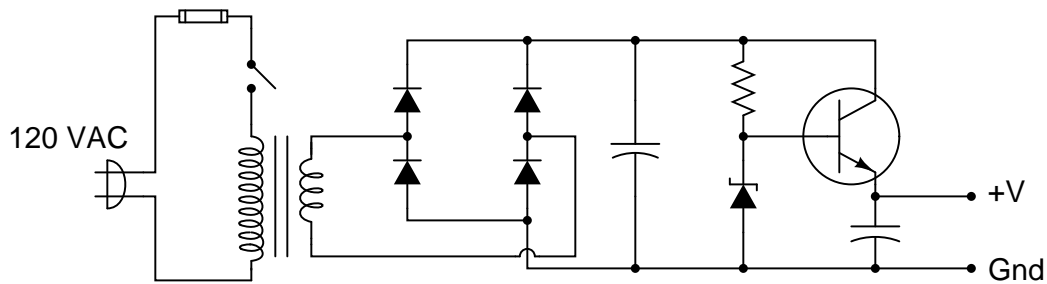
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**Question 38**

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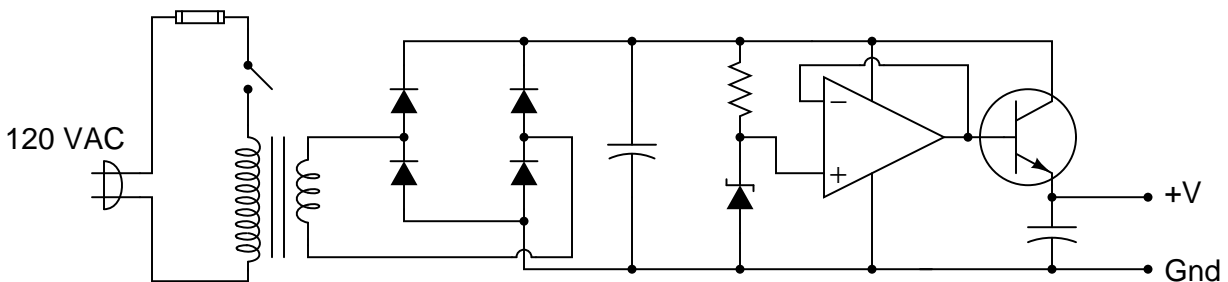
**Question 39**

A student builds the following regulated AC-DC power supply circuit, but is dissatisfied with its performance:



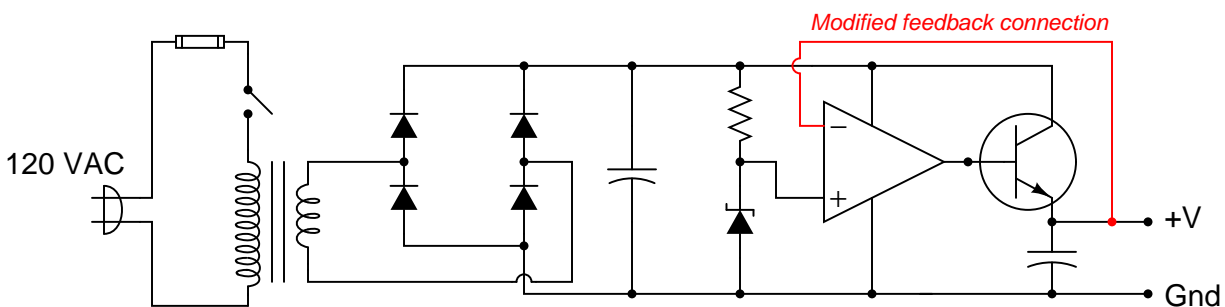
The voltage regulation is not as good as the student hoped. When loaded, the output voltage “sags” more than the student wants. When the zener diode’s voltage is measured under the same conditions (unloaded output, versus loaded output), its voltage is noted to sag a bit as well. The student realizes that part of the problem here is loading of the zener diode through the transistor.

In an effort to improve the voltage regulation of this circuit, the student inserts an opamp “voltage follower” circuit between the zener diode and the transistor:



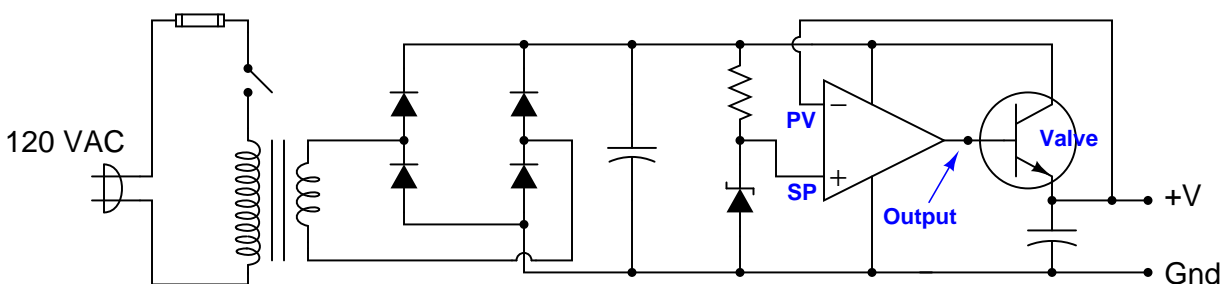
Now the zener diode is effectively isolated from the loading effects of the transistor, and by extension from the output load as well. The opamp simply takes the zener’s voltage and reproduces it at the transistor base, delivering as much current to the transistor as necessary without imposing any additional load on the zener diode. While this modification does indeed improve the circuit’s ability to hold a steady output voltage under changing load conditions, there is still room for improvement.

Another student looks at the modified circuit, and suggests one small change to dramatically improve the voltage regulation:



Now the output voltage holds steady at the zener diode's voltage with almost no "sag" under load! The second student is pleased with the success, but the first student does not understand why this version of the circuit functions any better than previous version. How would you explain this circuit's improved performance to the first student? How is an understanding of negative feedback essential to being able to comprehend the operation of this circuit?

One hint for explaining the opamp's new role is to relate it to the function of a *loop controller*, representing the input signals as *PV* and *SP*, and the output signal as the *Output*, with the transistor functioning like a *control valve*:



#### Suggestions for Socratic discussion

- Assuming a zener diode breakdown voltage of 5.0 volts, calculate the output voltage for each version of the power supply circuit.
- Is the opamp "loop controller" functioning with *direct action* or *reverse action*?
- Is the gain of the opamp "loop controller" significant to the regulation of power supply voltage? In other words, will the voltage regulation be any better or worse if the internal (open-loop) voltage gain of the opamp were to change?
- What would happen to this voltage regulator circuit if the resistor in series with the zener diode were to fail open?
- What would happen to this voltage regulator circuit if the feedback wire connecting the opamp's inverting input terminal to the output terminal of the power supply were to fail open?
- What would happen to this voltage regulator circuit if the transistor were to fail open from collector to emitter?

[file i01473](#)

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#### Question 42

Read and outline the “Analogy to Opamp Circuits” section of the “Pneumatic Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

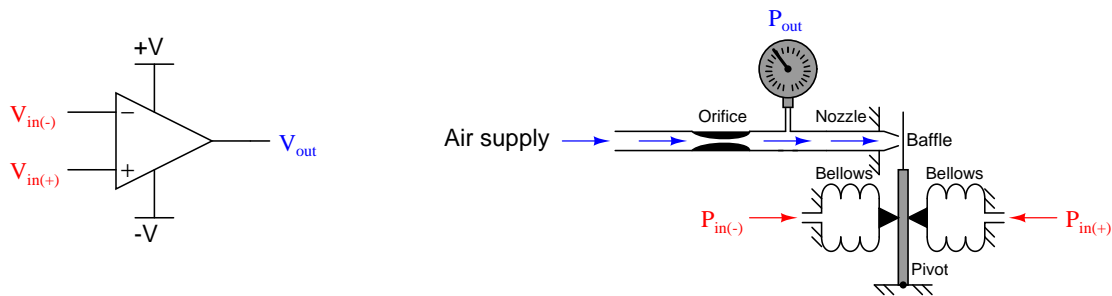
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text 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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- Descriptions of problem-solving strategies applied by the author

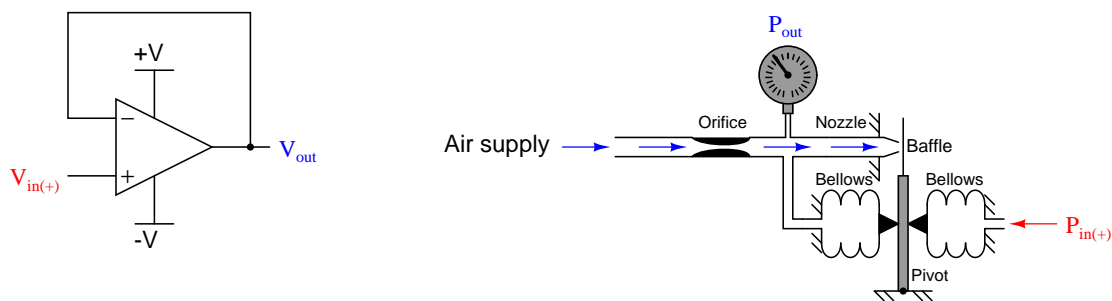
file i03930

### Question 43

Explain how the following systems (analog electronic versus pneumatic) are similar in their behavior:



Explain how the following systems (analog electronic versus pneumatic) are similar in their behavior:



#### Further exploration . . . (optional)

Research the work of Harold Black in his patent (“Wave Translation System,” U.S. Patent number 2,102,671 filed in 1932 and granted in 1937), when he applied the principle of *negative feedback* to the design of telephone amplifier circuits. How well was this novel concept accepted by the professional community?

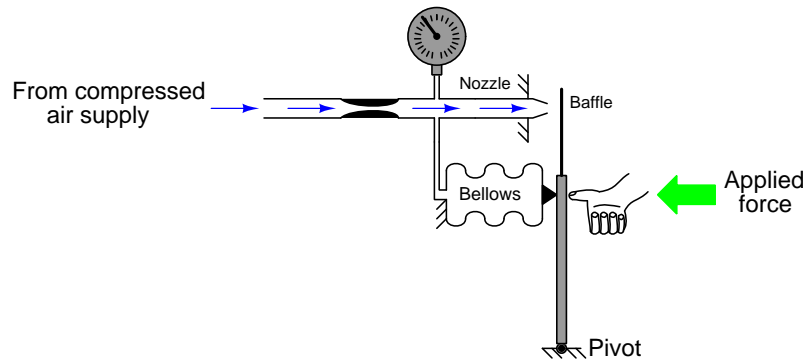
#### Suggestions for Socratic discussion

- Feedback systems are highly non-intuitive, and therefore cause much grief for students learning to master them. Discuss how to use “thought experiments” to help better understand the operation of a feedback system, whether it be an operational amplifier circuit or a pneumatic mechanism.
- In general terms, what does the addition of negative feedback do to the over-all *gain* of a system?
- What practical uses might we find for each of these circuits (and pneumatic systems)?
- Modify the lower circuit and lower mechanism so that both of them have *adjustable gains*.
- What would happen to the self-balancing pneumatic mechanism if the tube between the gauge and the nozzle were to develop a small leak (smaller than the nozzle bore itself)?
- What would happen to the self-balancing pneumatic mechanism if the tube between the gauge and the nozzle were to develop a large leak (equal to or greater than the nozzle bore itself)?

[file i03928](#)

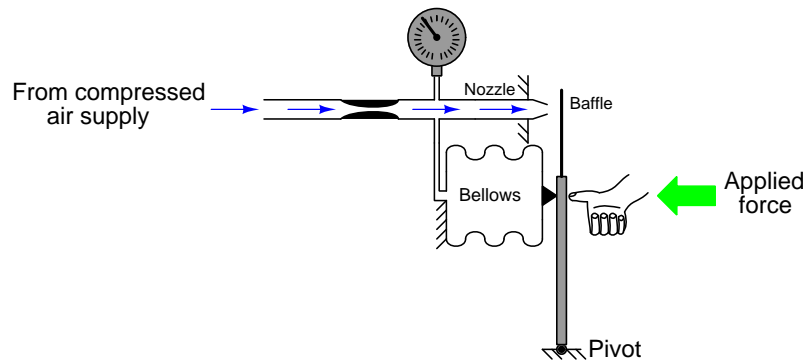
#### Question 44

In the following baffle/nozzle system, the nozzle pressure is allowed to react against any external force by generating a force with a bellows unit, to push the baffle away from the nozzle. The particular bellows in this mechanism is designed to be “slack,” having little spring effect to self-restrain its motion. Whatever force generated by the pressure acting against the bellows’ surface area gets directly transferred to the lever:



What will happen in this system if someone pushes the lever toward the nozzle with their thumb? Explain every step in your reasoning – don’t just describe a final result!

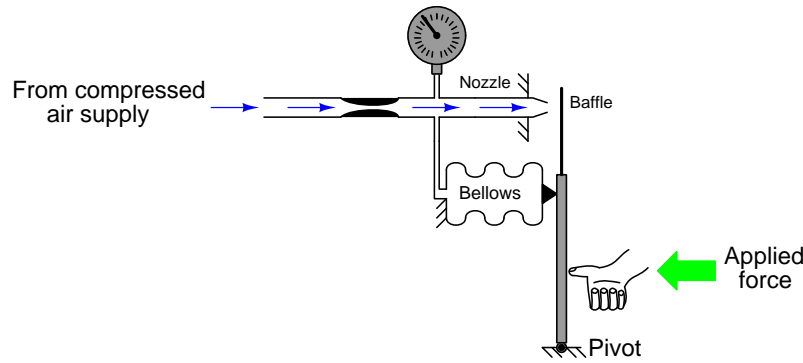
Now, suppose we modify this system to have a bellows with a larger diameter:



What will happen in this system if someone pushes the lever toward the nozzle with the same amount of force as before (with the smaller bellows)? How will this system respond to the same stimulus? Again, explain every step in your reasoning – don’t just describe a final result!



What will happen in this system if we were to take the original (smaller) bellows mechanism and push on it with the same force but at a position closer to the pivot point than the bellows? As usual, explain every step in your reasoning:



#### Suggestions for Socratic discussion

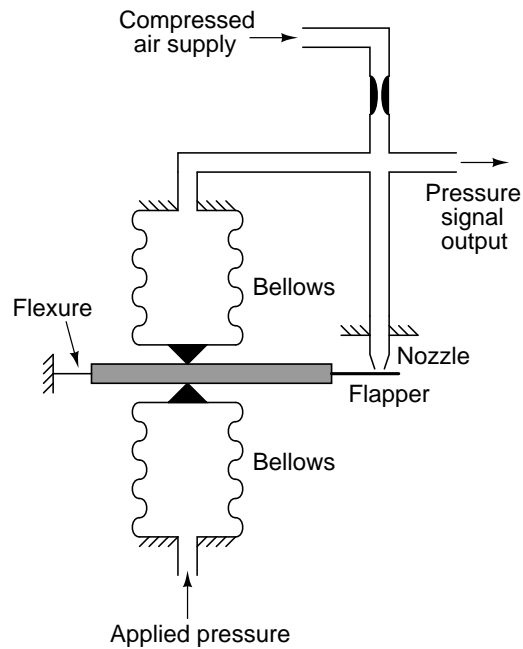
- Explain, in simple terms, what effect bellows size has on the *gain* of the system, and why.
- Suppose the compressed air supply pressure was 10 PSI in both cases. If this supply pressure were to drop to a lower value such as 8 PSI, what effect (if any) would this have on the gauge pressure in each scenario as the system responds to the same amount of applied force? Why or why not?
- Determine whether or not the output pressure would rise to the same level with force applied to the lever if the air supply was cut off (and the supply tube plugged so that air could not leak out).
- A common misconception among students first analyzing these mechanisms is that the output pressure is being generated by the bellows: that is to say, that the action of *collapsing* the bellows by the force of the hand is what makes the air inside become compressed. Explain why this is a misconception, and further explain how and why the resulting pressure arises.

file i00200

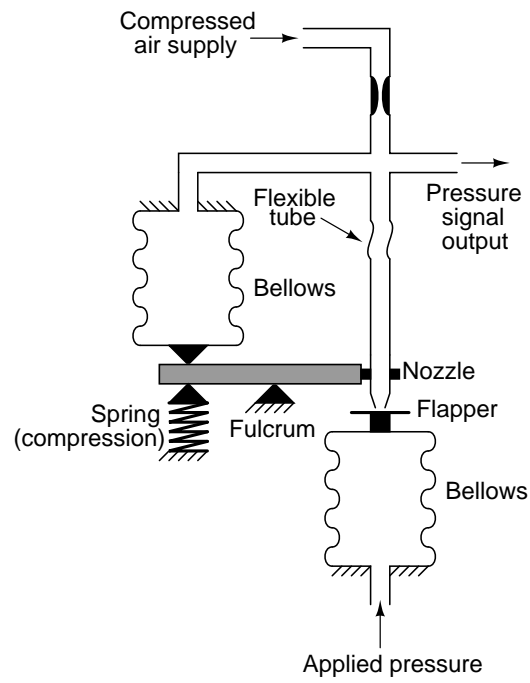
#### Question 45

Explain how each of the following pressure instruments works, identifying whether each one uses the principle of *motion-balance* or the principle of *force-balance*. Please note that a series of angled lines projecting from a vertical or horizontal line represents a point of anchoring, where that horizontal or vertical surface is stationary:

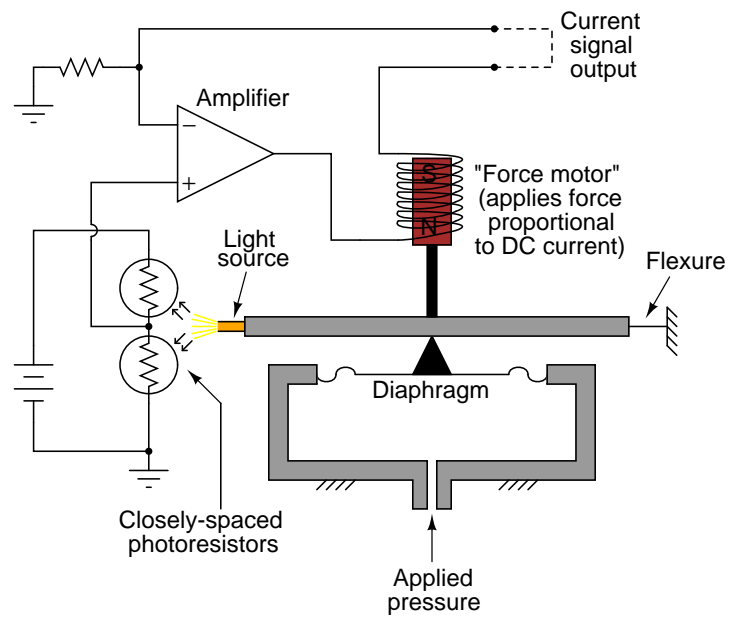
##### Example 1:



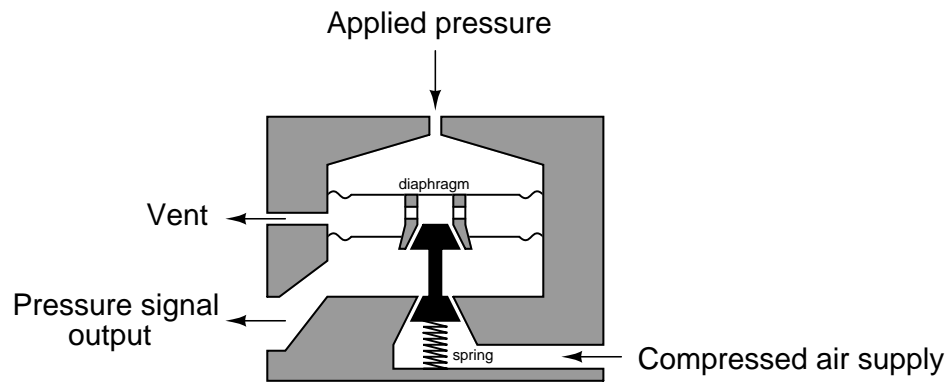
**Example 2:**



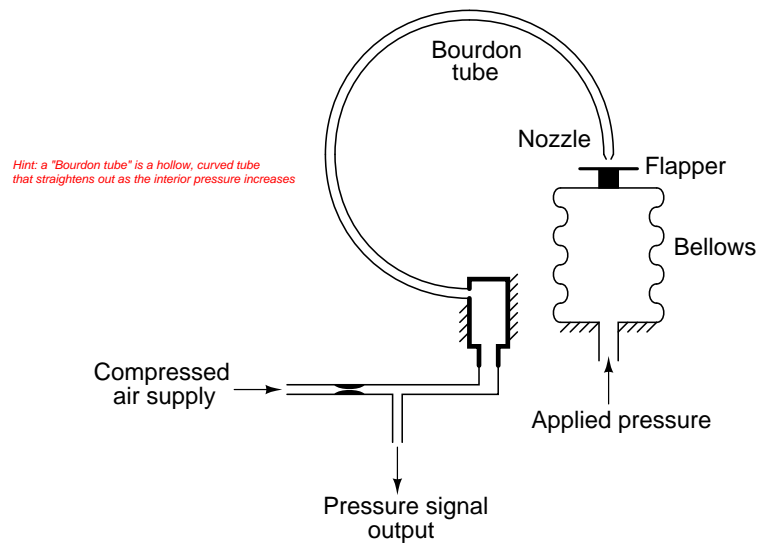
**Example 3:**



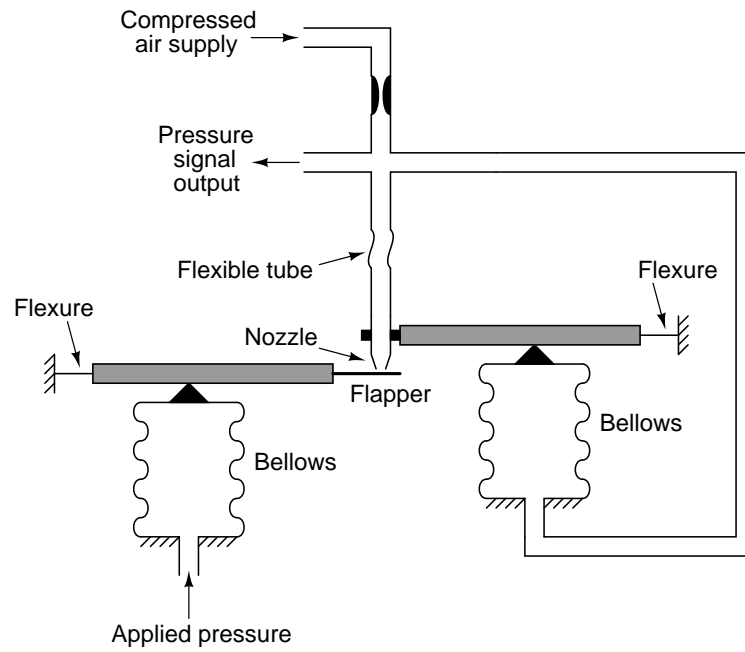
Example 4:



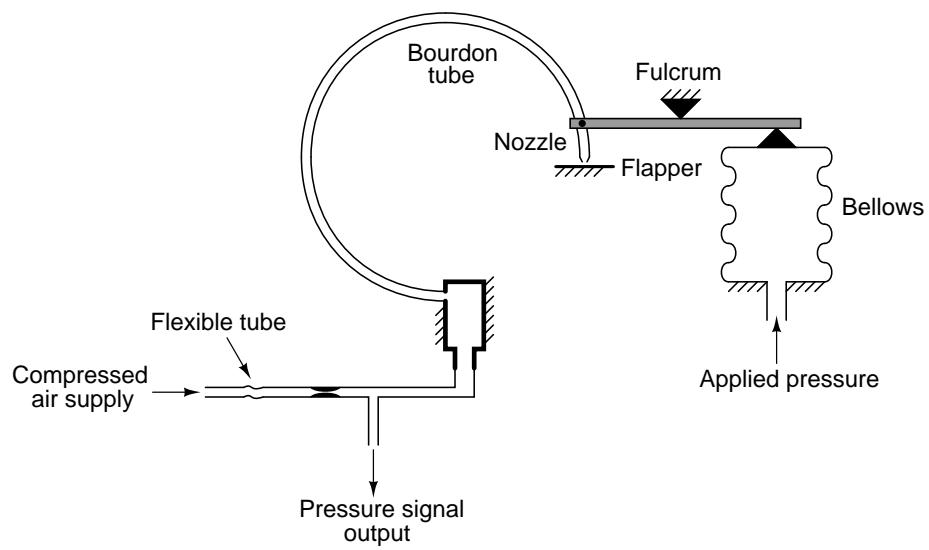
Example 5:



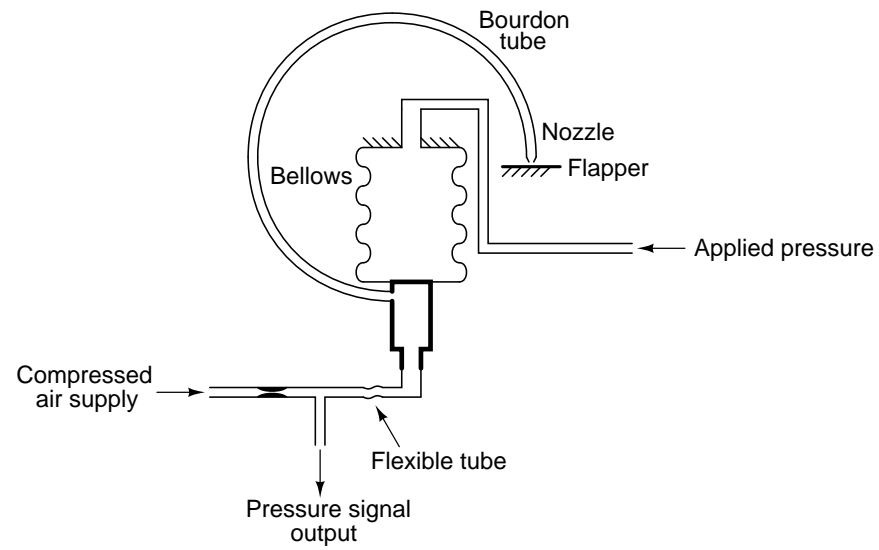
**Example 6:**



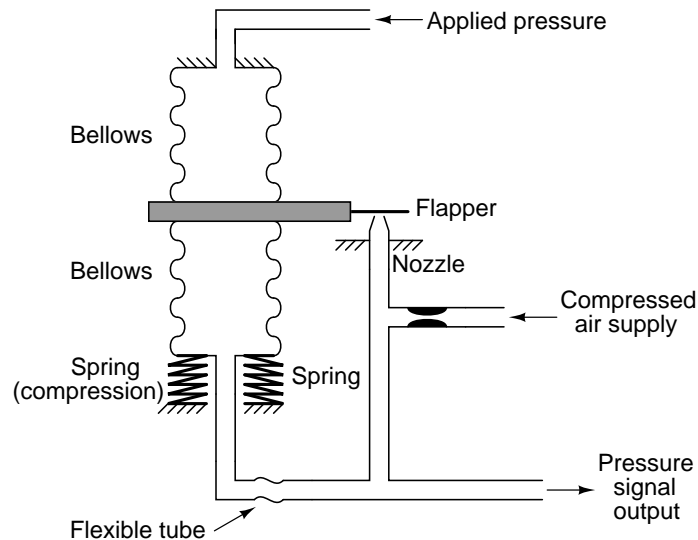
**Example 7:**



Example 8:



### Example 9:



#### Suggestions for Socratic discussion

- The distinction between force-balance and motion-balance is one that tends to confuse students. A common tactical error students make is to attempt to memorize distinguishing characteristics in order to identify what type of balancing a particular mechanism employs. A better approach is to *think through* the operation of such pneumatic mechanisms using “thought experiments” to identify which balance principle they employ. Why do you think it is bad to go with the memorization approach instead of the “thought experiment” approach?
- What difference does it make to us (as technicians) to know whether a mechanism is force- or motion-balance? In other words, who cares???
- Identify changes that could be made to each mechanism in order to alter its *zero*.
- Identify changes that could be made to each mechanism in order to alter its *span*.
- An interesting “thought experiment” to run is to modify some aspect of the mechanism (e.g. stiffer spring, greater supply air pressure, relocating the orifice) and re-analyze that mechanism to see what effect(s) that change will have on its operation.

[file i00208](#)

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#### Question 46

Read and outline the “Foxboro Model 13A Differential Pressure Transmitter” subsection of the “Analysis of Practical Pneumatic Instruments” section of the “Pneumatic Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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- Descriptions of problem-solving strategies applied by the author

[file i03931](#)

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#### Question 47

Read and outline the “Foxboro Model E69 ‘I/P’ Electro-Pneumatic Transducer” subsection of the “Analysis of Practical Pneumatic Instruments” section of the “Pneumatic Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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A video resource you may find helpful for understanding force-balance versus motion-balance I/P converter mechanisms may be found on BTC’s YouTube channel ([www.youtube.com/BTCinstrumentation](http://www.youtube.com/BTCinstrumentation)).

[file i03932](#)



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#### Question 48

Read and outline the “Fisher Model 546 ‘I/P’ Electro-Pneumatic Transducer” subsection of the “Analysis of Practical Pneumatic Instruments” section of the “Pneumatic Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i03933](#)

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#### Question 49

Read and outline the “Pressure Switches” section of the “Discrete Process Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

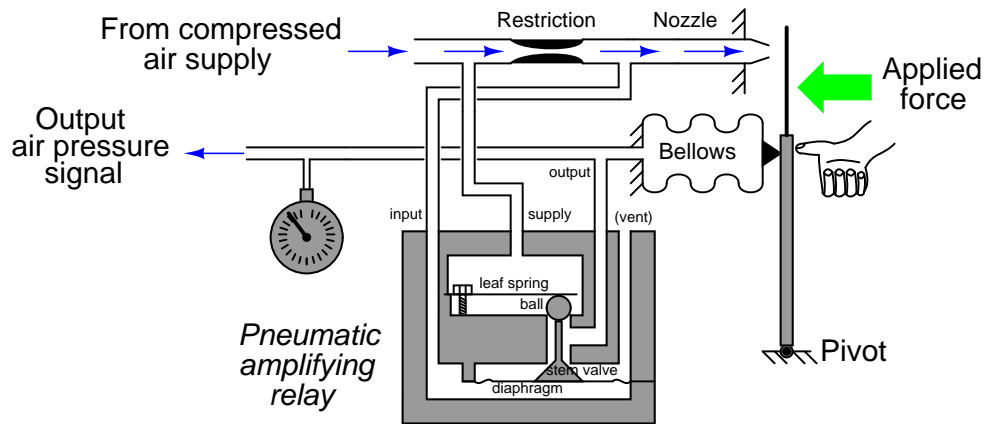
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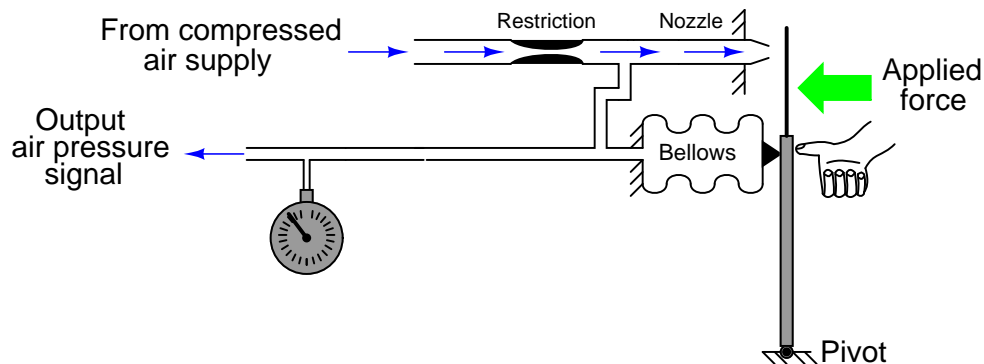
[file i03934](#)

# Question 50

The sensitivity and linearity of a pneumatic force-balance instrument may be improved with the addition of a *pneumatic amplifying relay* to amplify the response of the flapper/nozzle assembly. In other words, the inclusion of an amplifier into the system increases the system's *gain*. Explain what happens, step by step, in the system shown, if force is applied to the lever by someone's thumb:



Also, determine whether the mechanism will still produce the same amount of output pressure for any given amount of applied force without the amplifying relay in place. In other words, if we removed the relay from the system, would the output pressure be greater than before, less than before, or the same as before given the same force applied to the lever?



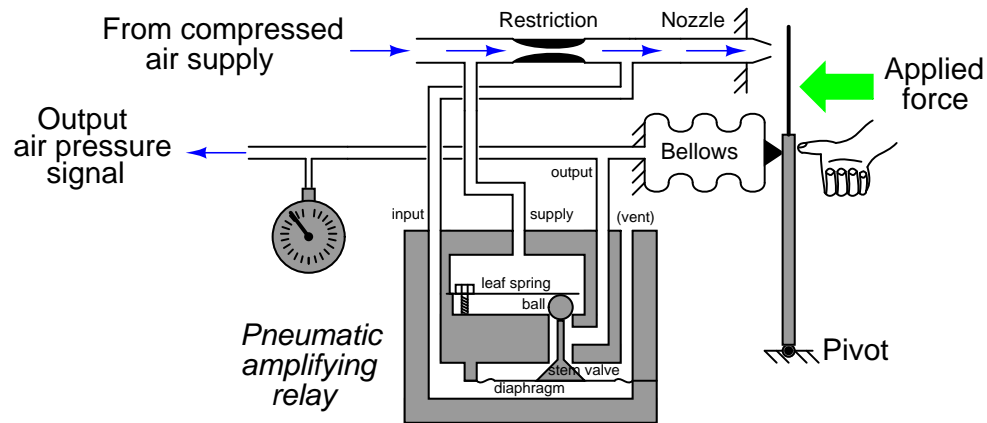
Challenge question: if we reduced the restriction (orifice) bore size in this system such that less air flowed through the nozzle, would the output pressure be greater than before, less than before, or the same as before given the same force applied to the lever?

file i00201

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Question 51

Determine the final effect of each fault for this pneumatic force-balance system:



- Clogged nozzle
- Clogged restriction
- Clogged tube at supply port of amplifying relay
- Broken leaf spring inside amplifying relay
- Major hole or tear in diaphragm inside amplifying relay

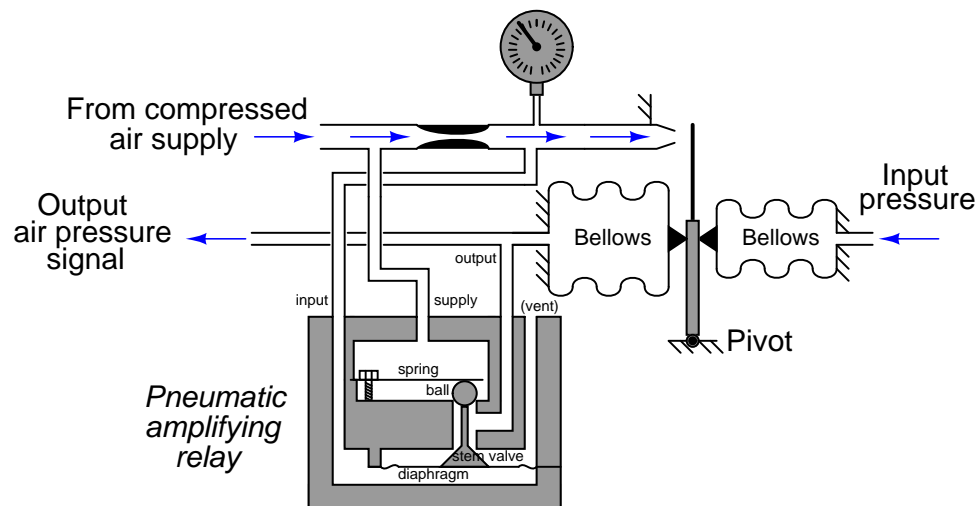
Be sure to explain the final effects for each of these faults!

file i00202

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Question 52

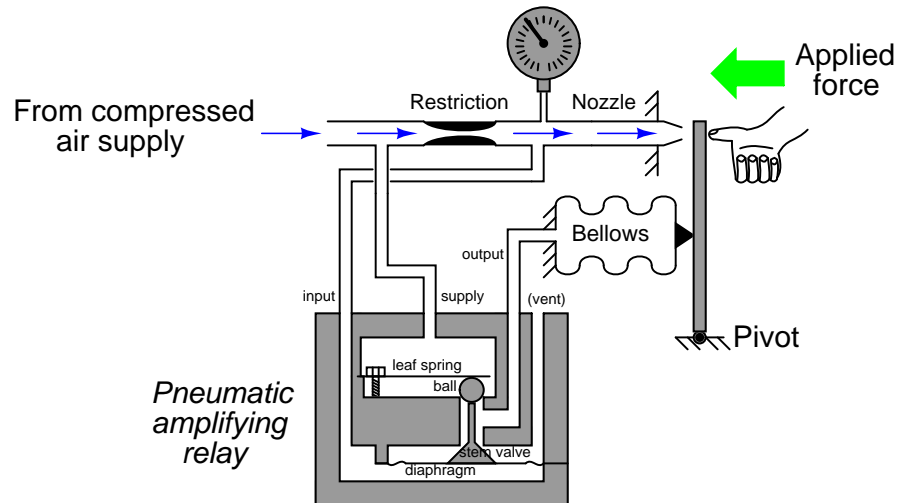
The following pneumatic transducer converts between a 3-15 PSI signal range and a 6-30 PSI signal range. Based on the illustration shown here, which pressure range corresponds to the input and which pressure range corresponds to the output? Does it input 3-15 PSI and output 6-30 PSI, or vice-versa? How can you tell??



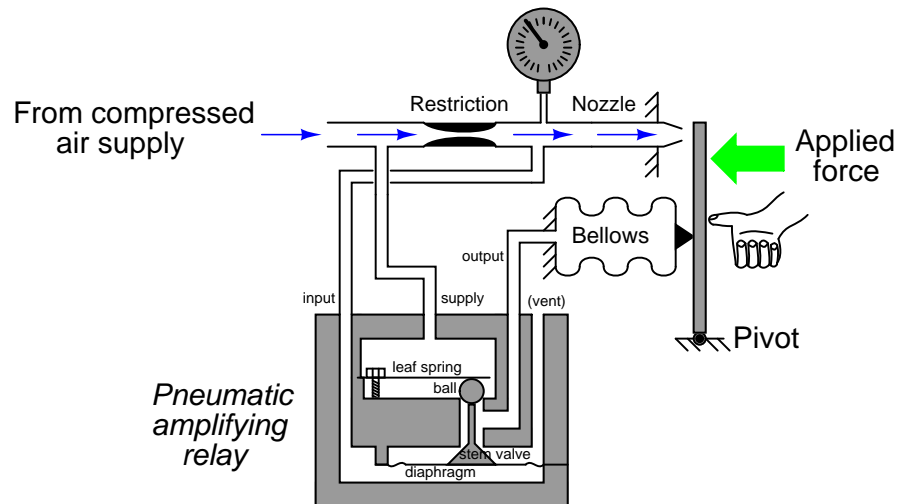
file i00680

Question 53

The following force-balance mechanism responds to an applied force by increasing its output pressure:



How will this mechanism respond to the exact same amount of manual force applied at a *lower* level, closer to the pivot point?



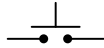
Be sure to explain *why* this is!  
[file i00798](#)

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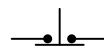
## Question 54

Switches, whether they be hand-actuated or actuated by a physical process, come in two varieties: *normally-open* (NO) and *normally-closed* (NC). You are probably accustomed to seeing both types of switch represented in pushbutton form on schematic diagrams:

*Normally-open*  
pushbutton switch



*Normally-closed*  
pushbutton switch



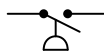
*Normally-open* pushbutton switches close (pass current) when actuated (pressed). When un-actuated, they return to their “normal” (open) state.

*Normally-closed* pushbutton switches are just the opposite: they open (stop current) when actuated (pressed) and return to their “normal” (closed, passing current) state when un-actuated.

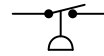
This is simple enough to comprehend: the “normal” status of a momentary-contact pushbutton switch is the state it is in when no one is touching it. When pressed, the pushbutton switch goes to the other (opposite) state.

Things get more confusing, though, when we examine *process switches*, such as pressure switches, level switches, temperature switches, and flow switches:

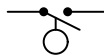
*Normally-open*  
pressure switch



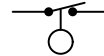
*Normally-closed*  
pressure switch



*Normally-open*  
level switch



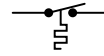
*Normally-closed*  
level switch



*Normally-open*  
temperature switch



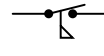
*Normally-closed*  
temperature switch



*Normally-open*  
flow switch



*Normally-closed*  
flow switch



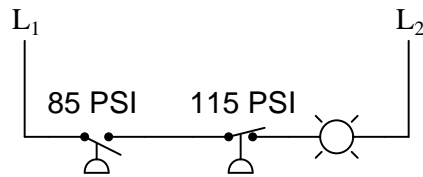
Define “normal” for each of these process switches. In other words, explain what condition(s) each process switch must be in to ensure it is in the “normal” state; and conversely, what condition(s) need to be applied to each switch to force it into its other state.

[file i02966](#)

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**Question 55**

Two pressure switches are plumbed together so as to receive the exact same pressure at all times, and they both sense the pressure of compressed air in a pneumatic system. Based on the wiring diagram for these switches, identify the function of the lamp:

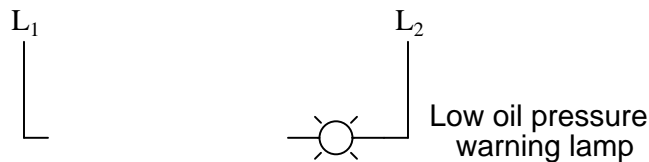


[file i02964](#)

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**Question 56**

Draw the appropriate pressure switch symbol in this ladder-logic diagram for a *low-pressure alarm* which turns on a lamp if the oil pressure of an industrial machine ever drops below 10 PSI:

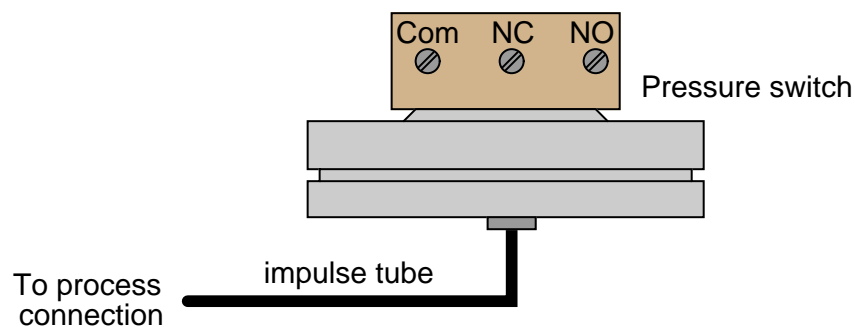


Be sure to specify whether the pressure switch needs to be *normally-open* (NO) or *normally-closed* (NC).  
[file i02965](#)

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**Question 57**

This illustration shows a diaphragm-operated pressure switch. The “impulse tube” is the tube connecting process fluid pressure to the switch:

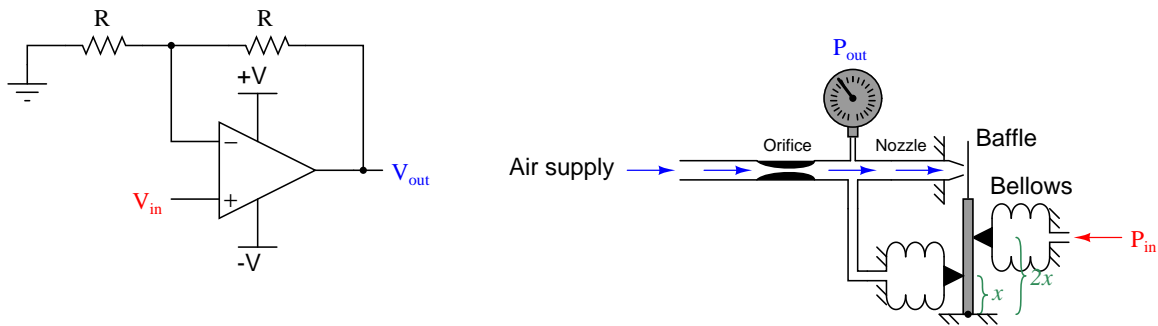


Show how a voltage source and lamp would be connected to this switch to form a *high-pressure alarm*, turning the lamp on if the process pressure ever exceeds a certain set value.

[file i02968](#)

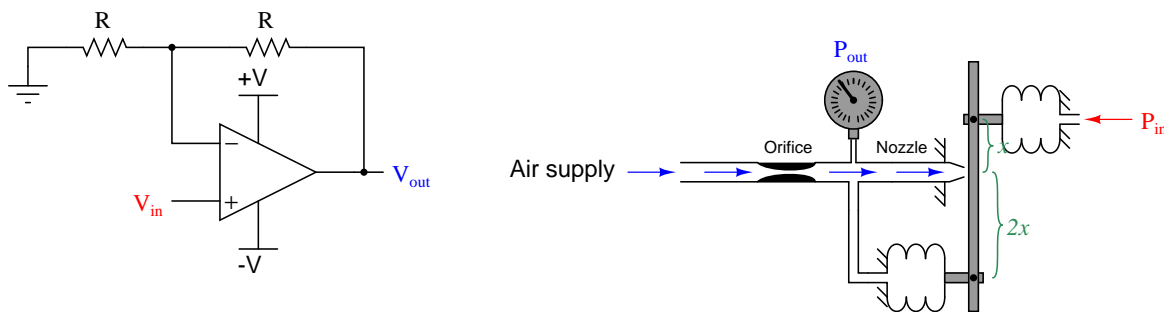
### Question 58

Explain how the following systems (analog electronic versus pneumatic) are similar in their behavior:



Calculate  $V_{out}$  if  $V_{in} = 3.4$  volts. Calculate  $P_{out}$  if  $P_{in} = 3.4$  PSI. Is the pneumatic system a *motion-balance* or a *force-balance* mechanism?

Explain how the following systems (analog electronic versus pneumatic) are similar in their behavior:



Calculate  $V_{out}$  if  $V_{in} = 5.1$  volts. Calculate  $P_{out}$  if  $P_{in} = 5.1$  PSI. Is the pneumatic system a *motion-balance* or a *force-balance* mechanism?

### Suggestions for Socratic discussion

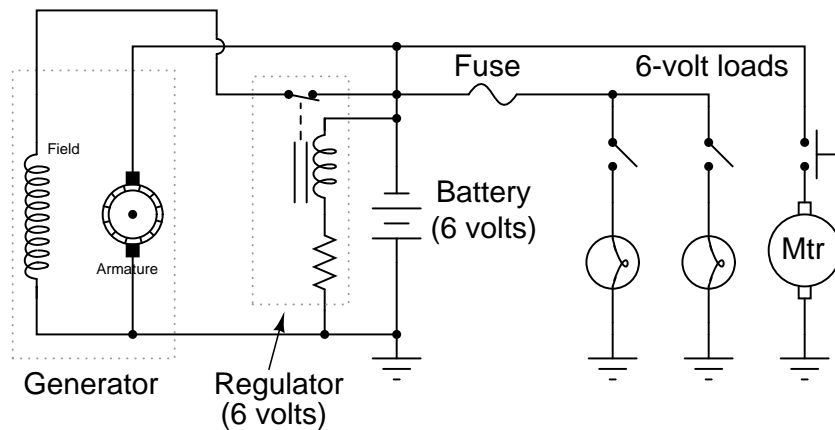
- The distinction between force-balance and motion-balance is one that tends to confuse students. A common tactical error students make is to attempt to memorize distinguishing characteristics in order to identify what type of balancing a particular mechanism employs. A better approach is to *think through* the operation of such pneumatic mechanisms using “thought experiments” to identify which balance principle they employ. Why do you think it is bad to go with the memorization approach instead of the “thought experiment” approach?
- To many students, the 2:1 lever lengths in each example seem very confusing, because the lever lengths are opposite yet the gain in each case is identical. For instance, in the top example the feedback has only *half* the lever length as the input, yet in the bottom example the feedback has *twice* the lever length as the input, yet these two different mechanisms exhibit the same overall gain. How is this possible?
- What difference does it make to us (as technicians) to know whether a mechanism is force- or motion-balance? In other words, who cares???

file i03929

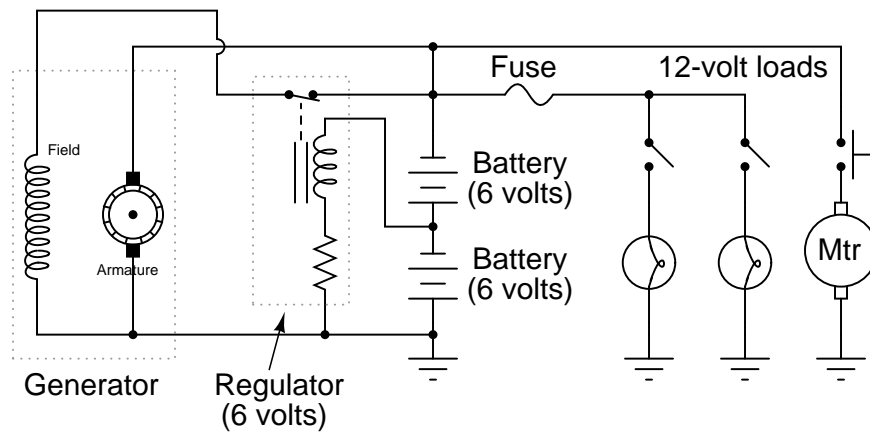
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Question 59

A mechanic has an idea for upgrading the electrical system in an automobile originally designed for 6 volt operation. He wants to upgrade the 6 volt headlights, starter motor, battery, etc, to 12 volts, but wishes to retain the original 6-volt generator and regulator. Shown here is the original 6-volt electrical system:



The mechanic's plan is to replace all the 6-volt loads with 12-volt loads, and use two 6-volt batteries connected in series, with the original (6-volt) regulator sensing voltage across only one of those batteries:



Explain how this system is supposed to work. Do you think the mechanic's plan is practical, or are there any problems with it?

[file i02651](#)

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Question 60



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Question 61

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

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

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

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

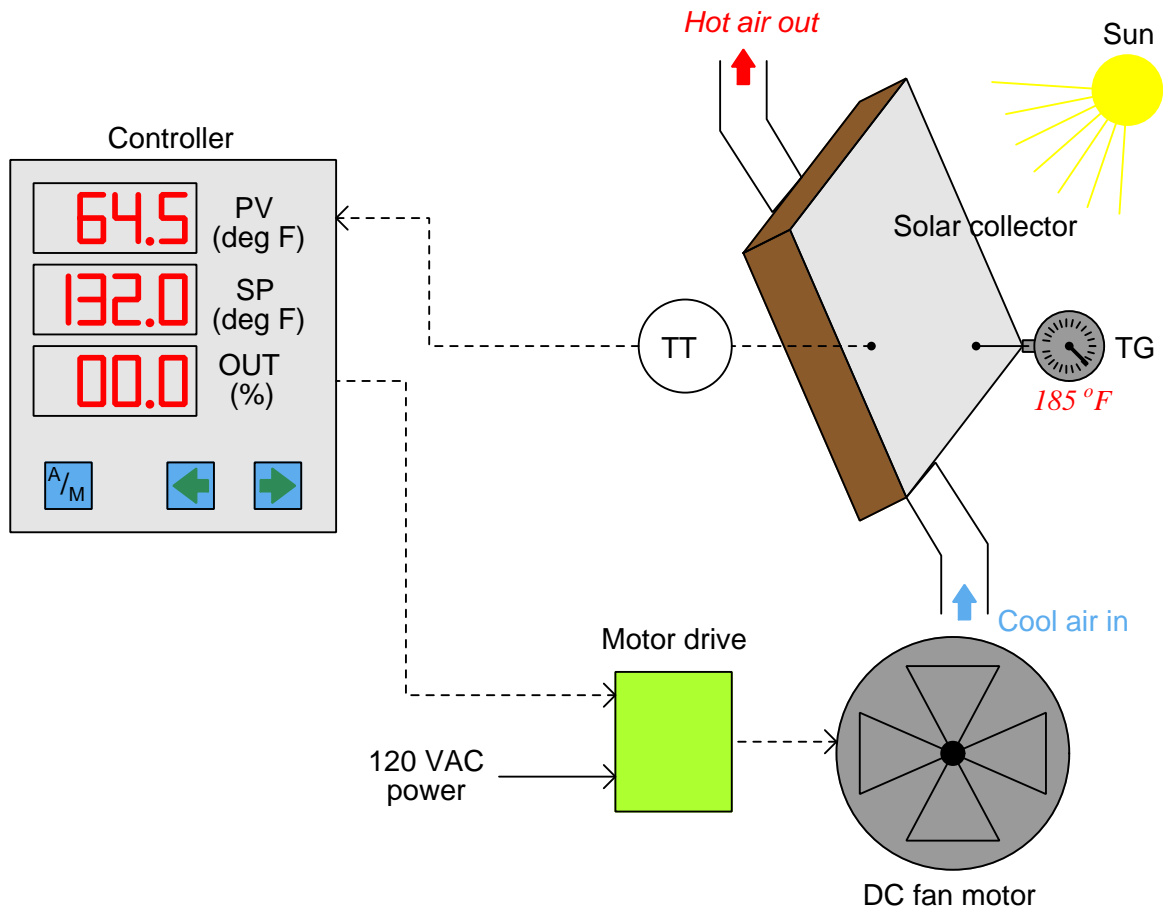
file i00999

### Question 62

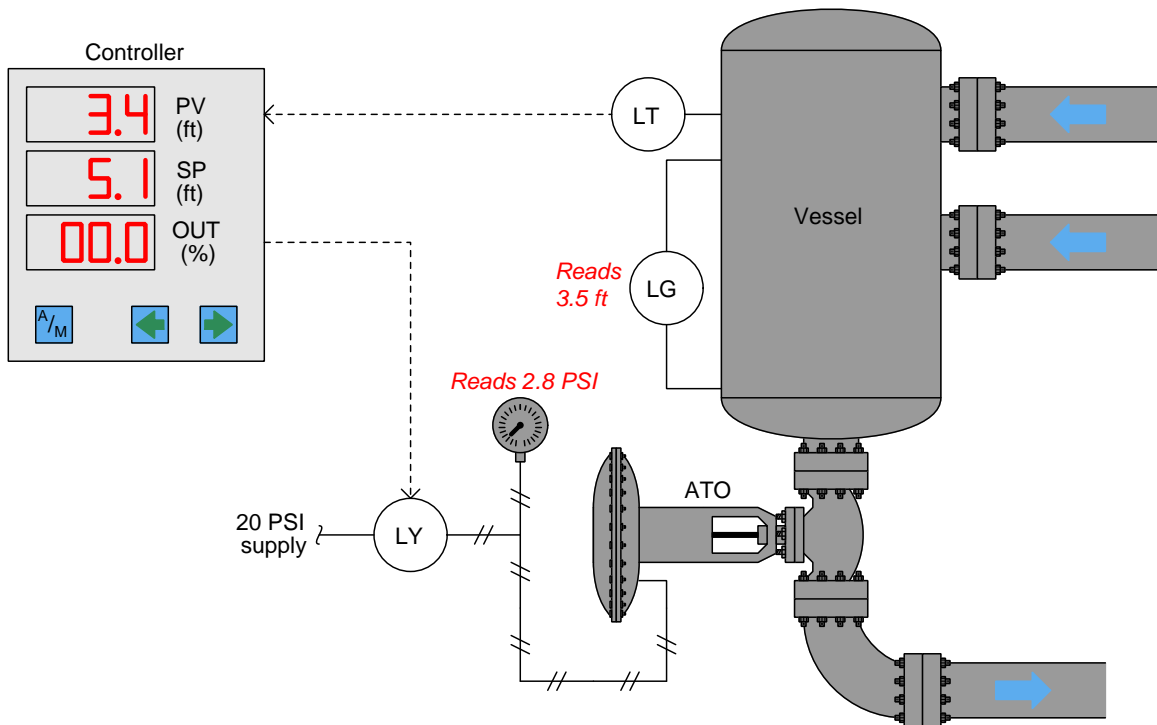
The following processes all have some problem, which may be diagnosed by careful observation of the controller's faceplate display (PV, SP, and Output values) and/or indications given by gauges in the field. Examine each control system and determine the fault in each one from the information given.

Assume that the conditions shown have existed for quite some time (long enough for the control system to have brought the process variable back to setpoint if everything were operating correctly):

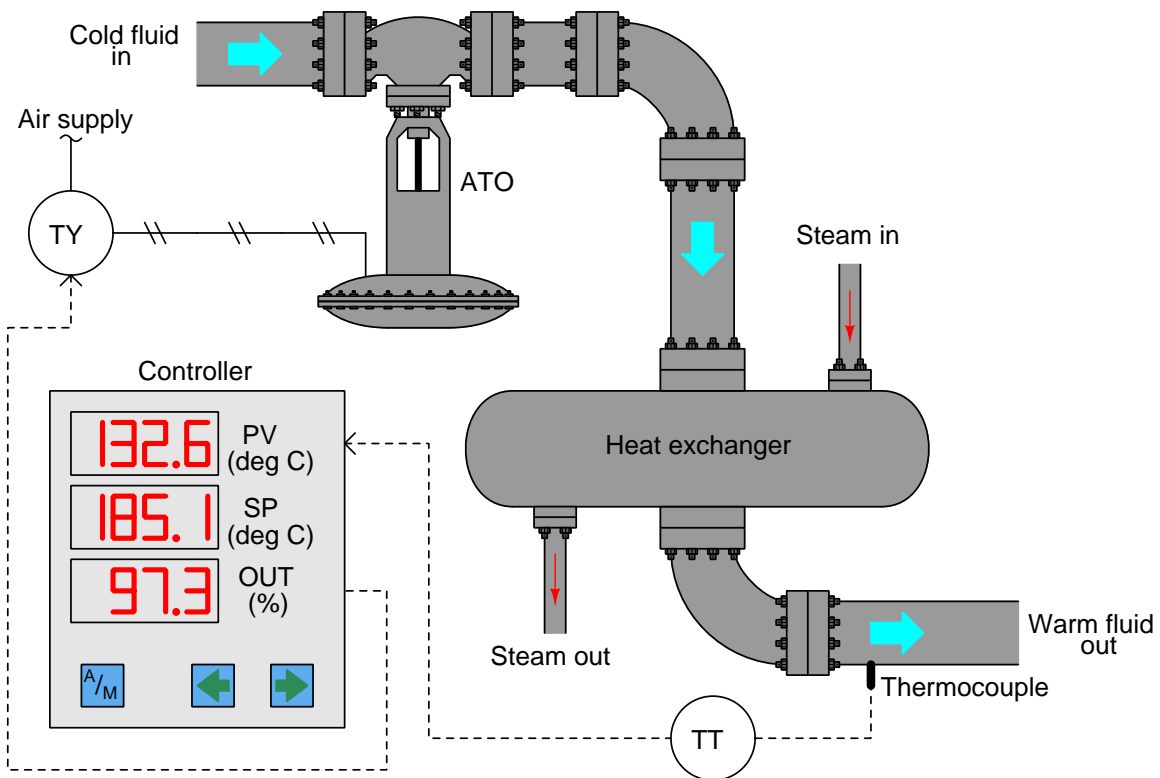
#### Example 1:



### Example 2:



### Example 3:



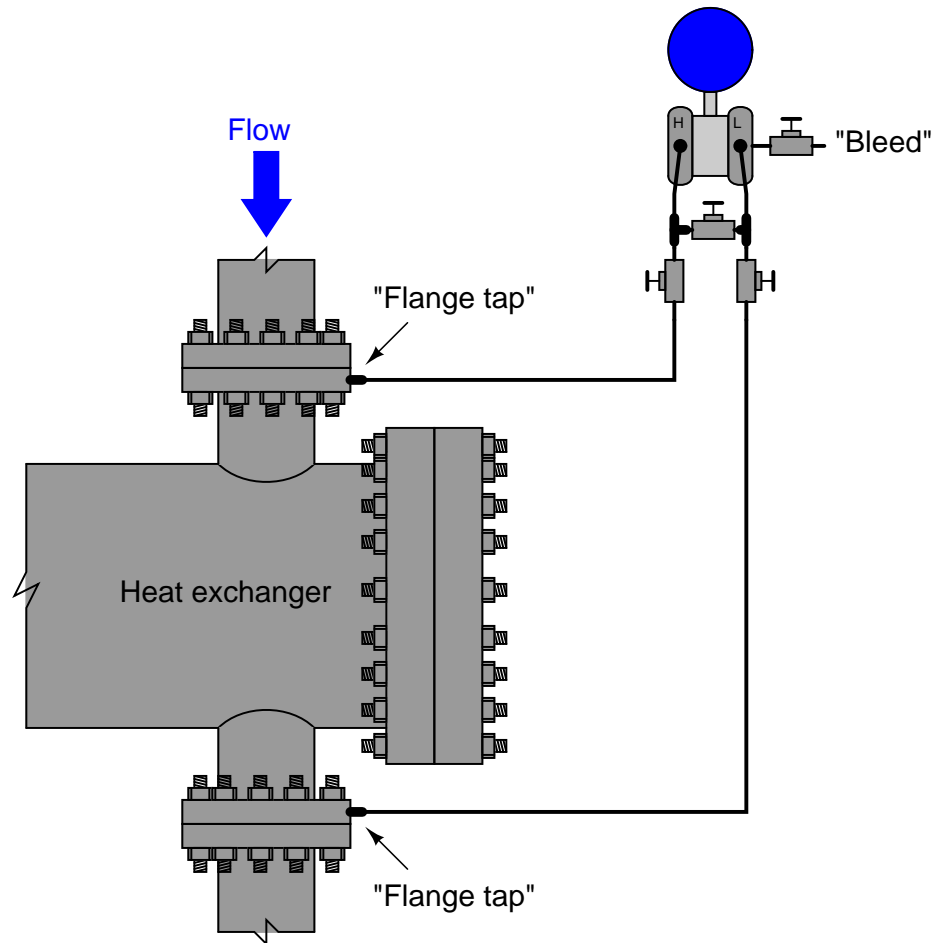
<b>Suggestions for Socratic discussion</b>
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- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which values agree with each other. Explain how a check of correspondence tells us which instrument is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

file i00640

# Question 63

Suppose we encounter a differential pressure transmitter used to measure pressure drop across a heat exchanger. The typical pressure on the upstream side of this heat exchanger is 850 PSI, while the typical pressure on the downstream side of this exchanger is 837 PSI. The transmitter connects to this heat exchanger via a three-valve manifold. A single “bleed” valve installed on the transmitter’s low-pressure side is used to vent pressure to atmosphere prior to removal of the transmitter from the manifold:



The common procedure for operating a 3-valve manifold to place a transmitter back into service after having isolated it from the process and bleeding any stored pressure to atmosphere is to first close the bleed valve, then open the low-side block valve, then close off the equalizing valve, and finally open the high-side block valve.

Determine how much fluid pressure will be on each side of the transmitter through every step of this procedure:

Step	High-side pressure	Low-side pressure	Differential pressure
Transmitter out of service	0 PSI	0 PSI	0 PSID
Close bleed valve	0 PSI	0 PSI	0 PSID
Open low-side block valve	837 PSI	837 PSI	0 PSID
Close equalizing valve	837 PSI	837 PSI	0 PSID
Open high-side block valve	850 PSI	837 PSI	13 PSID

Now, suppose someone else (at a later date) were to remove this transmitter from service using the three-valve manifold, and then return it to service following a *different* order of steps: closing the equalizing valve first, then opening the low-side block valve, and finally opening the high side block valve.

Determine how much fluid pressure will be on each side of the transmitter through every step of this (alternative) procedure:

Step	High-side pressure	Low-side pressure	Differential pressure
Transmitter out of service	0 PSI	0 PSI	0 PSID
Close bleed valve	0 PSI	0 PSI	0 PSID
Close equalizing valve	0 PSI	0 PSI	0 PSID
Open low-side block valve	0 PSI	837 PSI	-837 PSID
Open high-side block valve	850 PSI	837 PSI	13 PSID

Based on the pressures seen by the transmitter in both procedures, would you recommend one procedure over the other? If so, why?

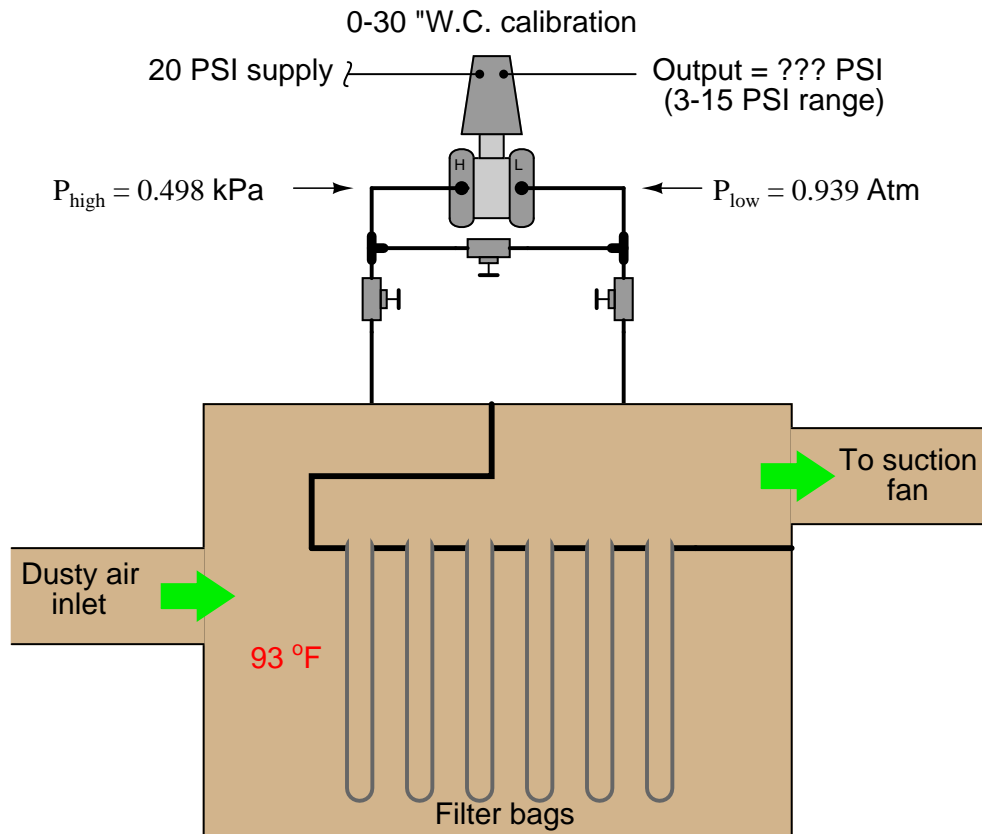
#### **Suggestions for Socratic discussion**

- A powerful problem-solving technique is performing a *thought experiment* where you mentally simulate the response of a system to some imagined set of conditions. Explain how this particular thought experiment is helpful in determining which is the safest procedure for operating a three-valve transmitter manifold.

file i00213

#### Question 64

Calculate the amount of differential pressure “seen” by this pneumatic DP transmitter across this baghouse (used to filter dust from air) in units of PSID and units of bar (differential), then calculate its output signal (in units of PSIG) assuming a calibrated range of 0 to 30 inches water column differential:



#### Suggestions for Socratic discussion

- Why do you suppose it is important to continuously measure the pressure differential across an industrial baghouse?
- Why measure *differential* pressure across the baghouse, rather than simply measure either the upstream or downstream (*gauge*) pressure?
- How would a rip in one of the fabric bags affect the differential pressure drop across the baghouse?
- Suppose a technician accidentally left one of the block valves shut on one of the transmitter's impulse lines. How might this change affect the transmitter's ability to sense differential pressure?
- Suppose a technician accidentally left the equalizing valve open between the transmitter's impulse lines. How might this change affect the transmitter's ability to sense differential pressure?

[file i03935](#)

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**Question 65**

Suppose you wish to calibrate an electronic pressure transmitter to an input range of  $-50$  to  $300$  inches of water, with an output range of  $4$  to  $20$  mA. Complete the following calibration table showing the test pressures to use and the allowable low/high output signals for a calibrated tolerance of  $\pm 0.1\%$  (of span). Assume you can only use positive test pressures (no vacuum), and be sure to designate which side the test pressure should be applied to (H = high ; L = low):

Input pressure applied (" W.C.)	Percent of span (%)	Output signal <i>ideal</i> (mA)	Output signal <i>low</i> (mA)	Output signal <i>high</i> (mA)
50 "WC (L)	0	4 mA	3.98 mA	4.02 mA
37.5 "WC (H)	25	8 mA	7.98 mA	8.02 mA
125 "WC (H)	50	12 mA	11.98 mA	12.02 mA
212.5 "WC (H)	75	16 mA	15.98 mA	16.02 mA
300 "WC (H)	100	20 mA	19.98 mA	20.02 mA

Suppose this transmitter is installed as part of a complete pressure measurement system (transmitter plus remote indicator and associated components), and the entire measurement system has been calibrated within the specified tolerance ( $\pm 0.1\%$ ) from beginning to end. If the operator happens to read a process pressure of  $210$  inches W.C. at the indicator, how far off might the actual process pressure be from this indicated value?

<b>Suggestions for Socratic discussion</b>
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- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

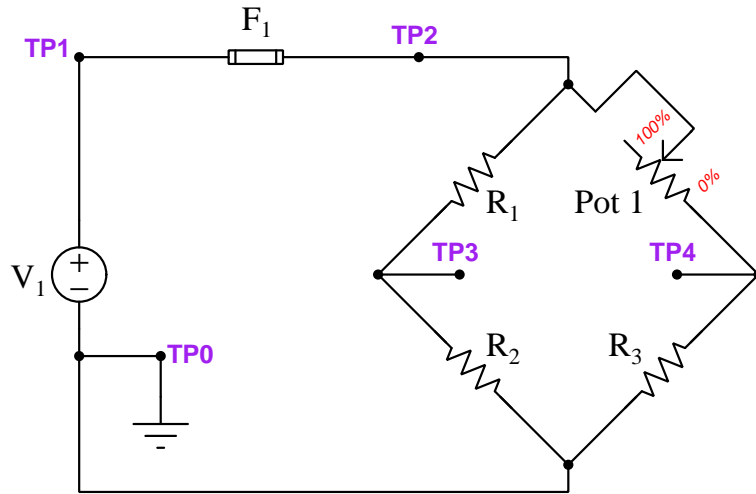
file i00228



**Simulated troubleshooting exercise**

During today's session your instructor will have a computer set up to run an electric circuit troubleshooting simulation program called **TROUBLESHOOT**, so that you can practice your troubleshooting skills on a simulated Wheatstone bridge circuit.

The circuit we will be simulating today is a Wheatstone bridge with a DC voltage source as the power supply. This is circuit number 005 selectable within the **TROUBLESHOOT** simulating program:

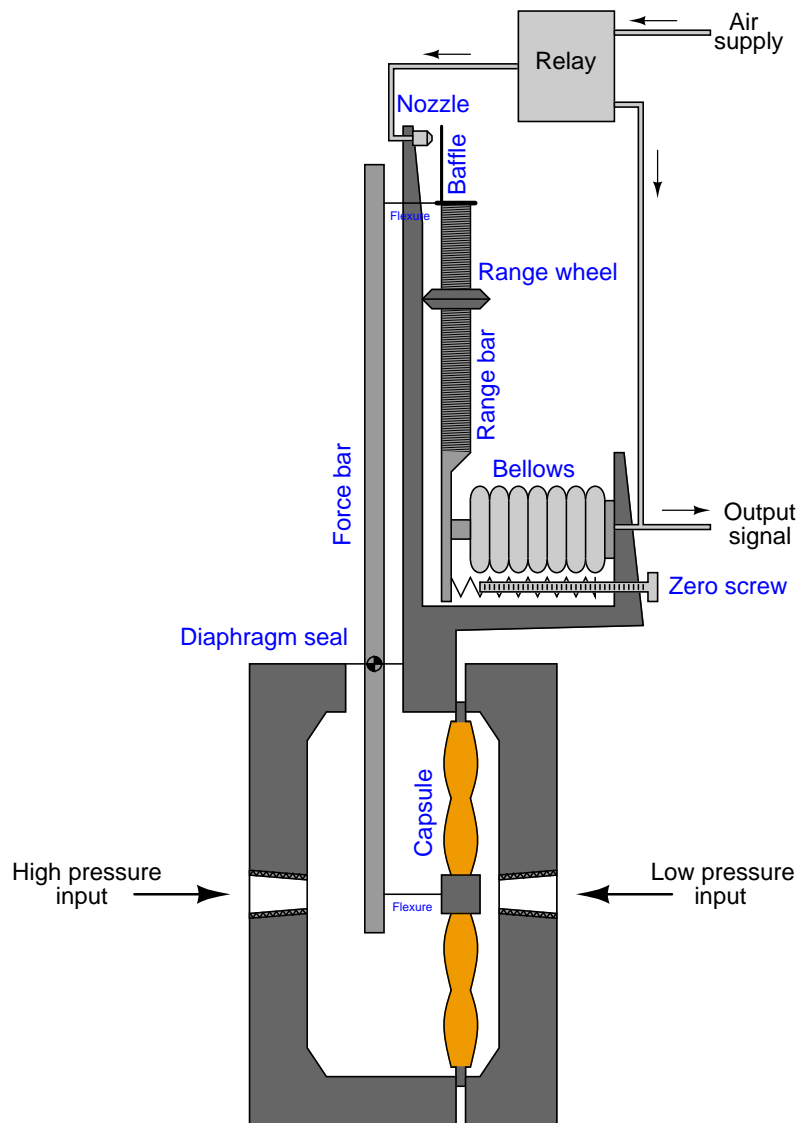
**Circuit #005**

You may find it convenient to bring a printed copy of this schematic diagram with you to the session for this purpose.

[file i02846](#)

### Question 67

Suppose this Foxboro model 13 DP transmitter has a calibrated range of 0 to 125 inches water column and an instrument air supply pressure of 20 PSI:



Identify which way the range wheel would have to be moved in order to re-calibrate the transmitter to a new range of 0 to 180 inches water column (from 0 to 125 "W.C.), explaining your reasoning.

Identify which way the zero screw would have to be turned in order to re-calibrate the transmitter to a new range of 15 to 140 inches water column (from 0 to 125 "W.C.), explaining your reasoning.

#### Suggestions for Socratic discussion

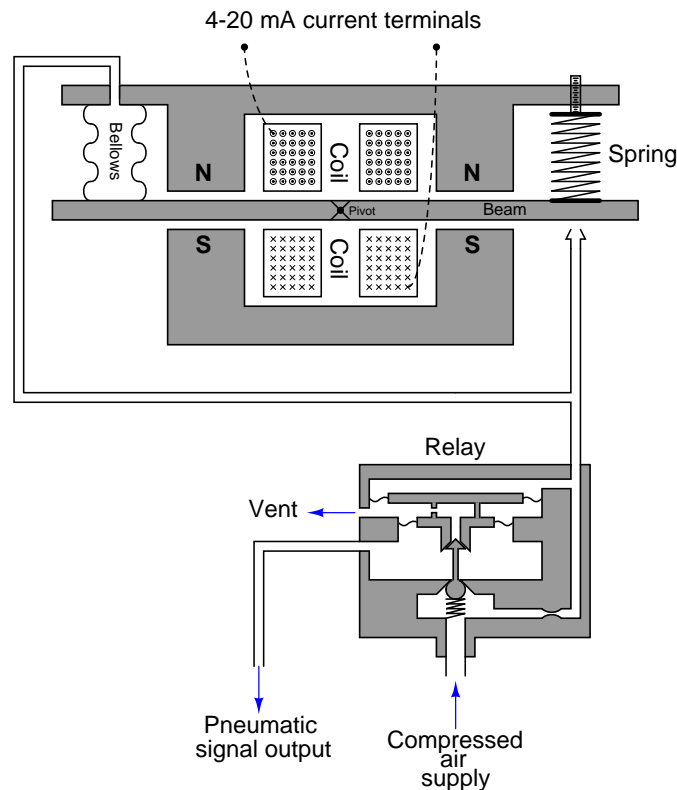
- Explain why it is important we know whether this mechanism is motion- or force-balance to be able to correctly determine the effects these changes will have on calibration.
- What would happen if the capsule were to develop a leak?

- What would happen if the flexure connecting the tops of the force and range bars were to break in half, leaving those two bars disconnected from each other?
- What would happen if the air supply pressure were to increase from 20 PSI to 22 PSI?
- What would happen if the air supply pressure were to decrease from 20 PSI to 18 PSI?

file i03936

### Question 68

Suppose this Fisher model 546 I/P transducer has an input range of 4-20 mA and an output range of 3-15 PSI:



Identify which way the magnetic shunt would have to be moved in order to re-calibrate the I/P transducer to a new output range of 4-20 PSI (from 3-15 PSI), explaining your reasoning.

Identify which way the zero screw would have to be turned in order to re-calibrate the I/P transducer to a new output range of 2-14 PSI (from 3-15 PSI), explaining your reasoning.

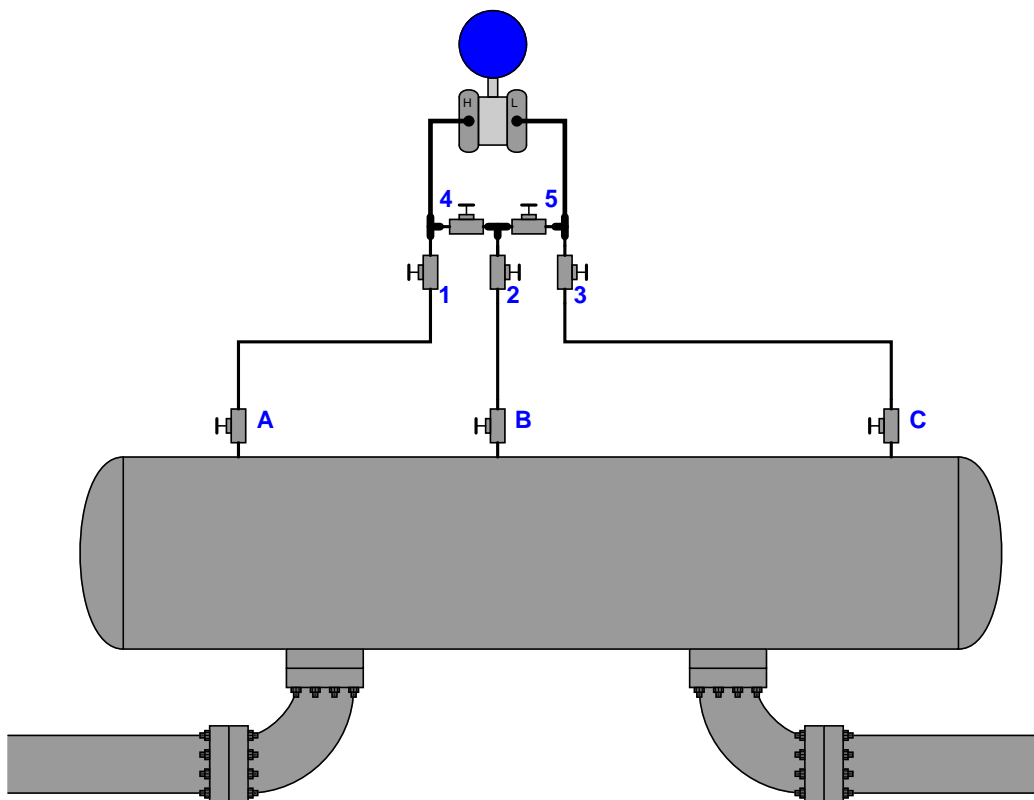
#### Suggestions for Socratic discussion

- What would happen if some of the turns in the electromagnet coil were shorted past? Would this cause a *zero* shift, a *span* shift, or a *linearity* shift?
- What would happen if the zero spring broke into two separate pieces? Would this cause a *zero* shift, a *span* shift, or a *linearity* shift?
- Suppose this I/P outputs a pressure of 9.0 PSI at an input current of 12.3 mA. Calculate the error, *in percent of span*.
- Suppose this I/P outputs a pressure of 12.5 PSI at an input current of 16.0 mA. Calculate the error, *in percent of span*.
- Suppose this I/P outputs a pressure of 5.7 PSI at an input current of 8.0 mA. Calculate the error, *in percent of span*.

file i03937

# Question 69

An interesting application for a *5-valve manifold* is when a single DP transmitter needs to be able to measure differences in pressure between any two of three sample ports on a process vessel, such as in this example here:



Determine the necessary statuses for each of the valves in this system (e.g. *open* versus *shut*) in order to measure differential pressure between the specified ports on the process vessel:

Pressure	$V_A$	$V_B$	$V_C$	$V_1$	$V_2$	$V_3$	$V_4$	$V_5$
$P_{AB}$								
$P_{BC}$								
$P_{AC}$								

## Suggestions for Socratic discussion

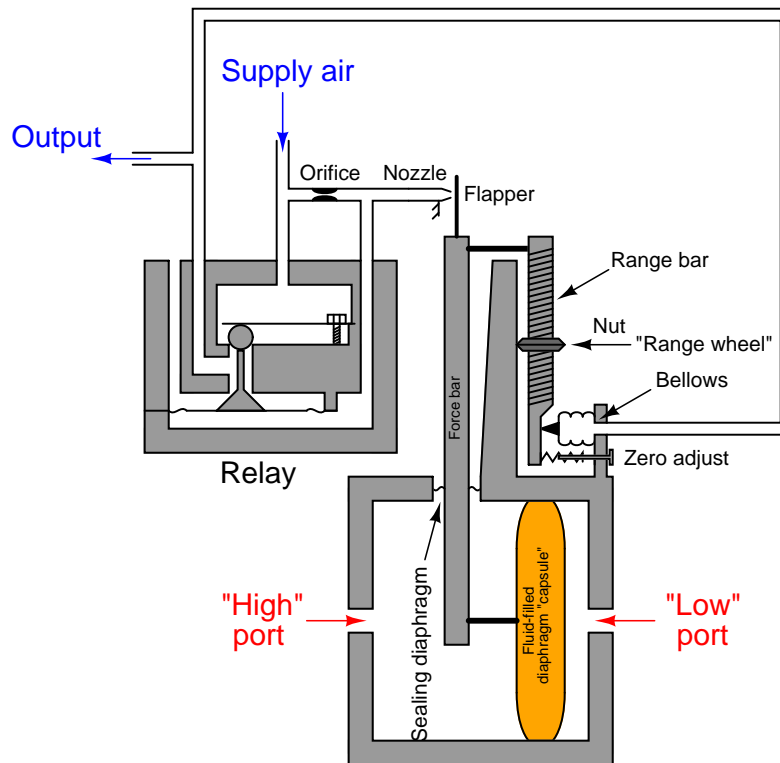
- For any of the giving valve “lineups,” identify a good procedure for taking the transmitter out of service (i.e. which manifold valves to manipulate, in which order).
- Where in this impulse tubing system would you recommend installing a *bleed* fitting?

[file i02576](#)



### Question 71

The following diagram is that of a pneumatic *moment-balance* differential pressure transmitter, similar to the Foxboro model 13A. The term “moment” refers to the physics principle of a force acting on a lever to produce a torque. “Moment-balance” is more appropriate than “force-balance” in this case because the device pits moment against moment, rather than force against force directly:



Describe this instrument's response to an increasing differential pressure (increasing pressure on the “High” side, and a steady pressure on the “Low” side; or a decreasing pressure on the “Low” side with a steady pressure on the “High” side), step by step.

#### Suggestions for Socratic discussion

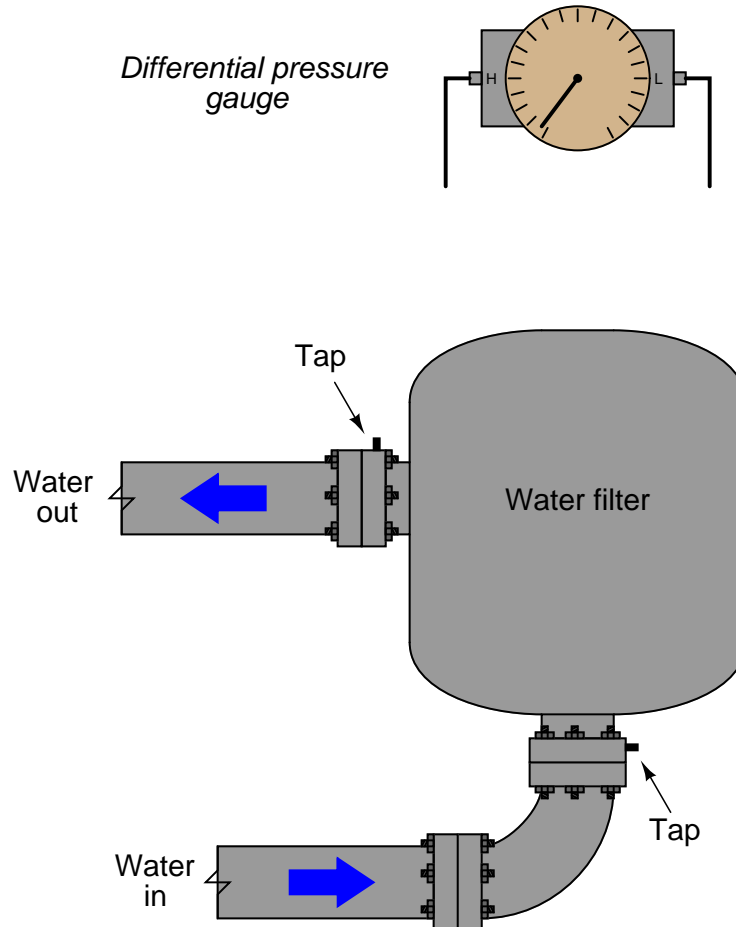
- Describe the purpose of the *sealing diaphragm* shown roughly mid-way along the length of the force bar.
- Identify how this instrument will respond to obstructions (blockages) in the following locations:
  - Orifice
  - Nozzle
  - Vent (located on relay body)

file i00205

Question 72

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:

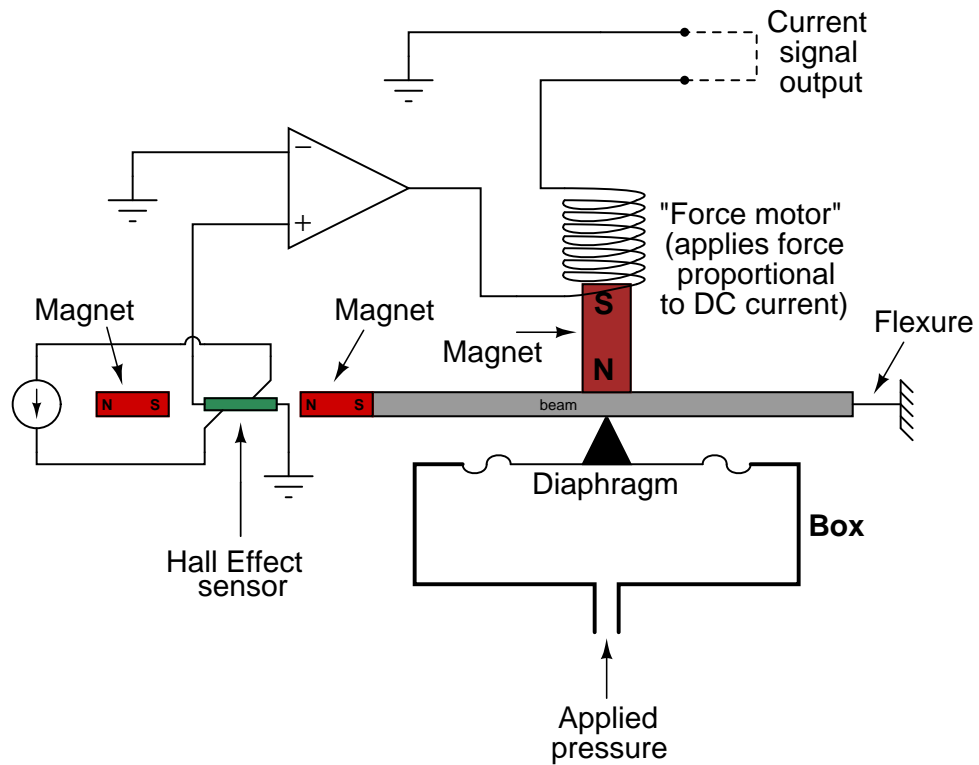


file i00215



Question 73

Shown here is a diagram for an *electronic* force-balance pressure transmitter:



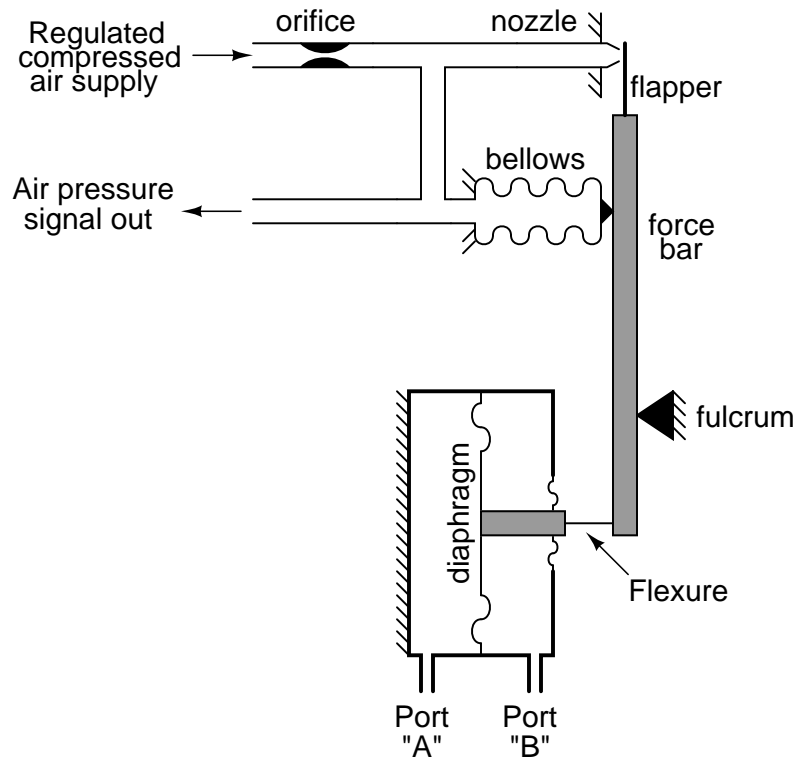
Explain the following things in reference to this transmitter:

- What is a *flexure*?
- How is the opposing force generated?
- What does a *Hall Effect* sensor do?
- How is an imbalance of force detected?
- How would you incorporate a zero adjustment into this transmitter?
- How would you incorporate a span adjustment into this transmitter?

file i00207

Question 74

Identify the “high” and “low” ports on this pneumatic differential pressure transmitter, and explain your reasoning:

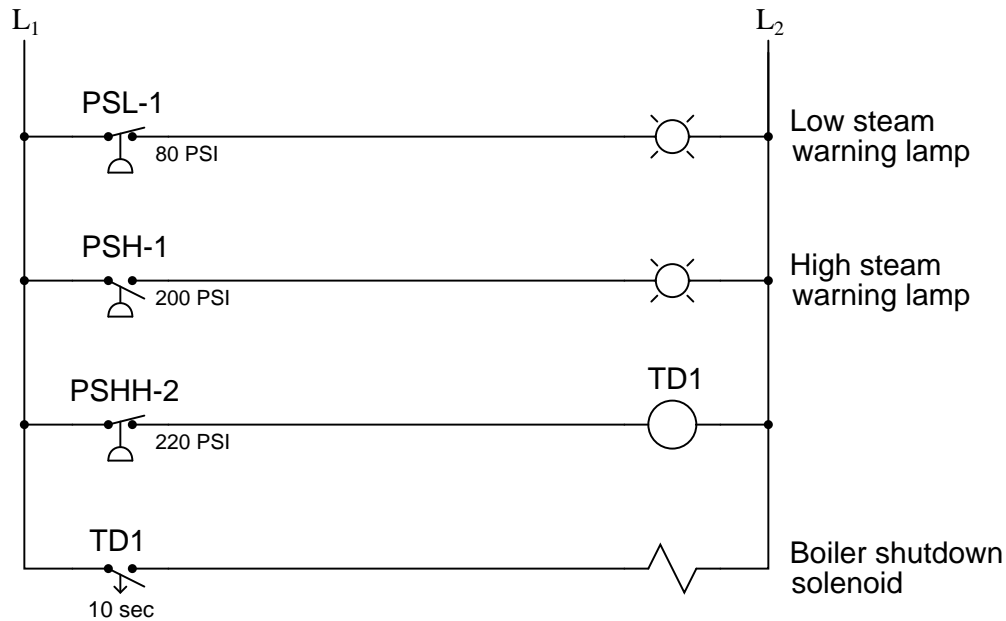


Also, explain how this transmitter will respond to an increasing pressure at each of its two ports, including the operation of the bellows feedback mechanism.

file i00223

### Question 75

Determine the functions of all pressure switches and relays in this steam boiler monitoring circuit, and what each of their designations mean:



Also, explain the significance of the switch symbols: normally open versus normally closed. The time-delay relay (TD1) is especially important here!

Finally, add a “Lamp Test” pushbutton switch to this circuit which will force all lamps to energize when pressed, in order to test the proper operation of the lamps without waiting for an abnormal process condition to occur.

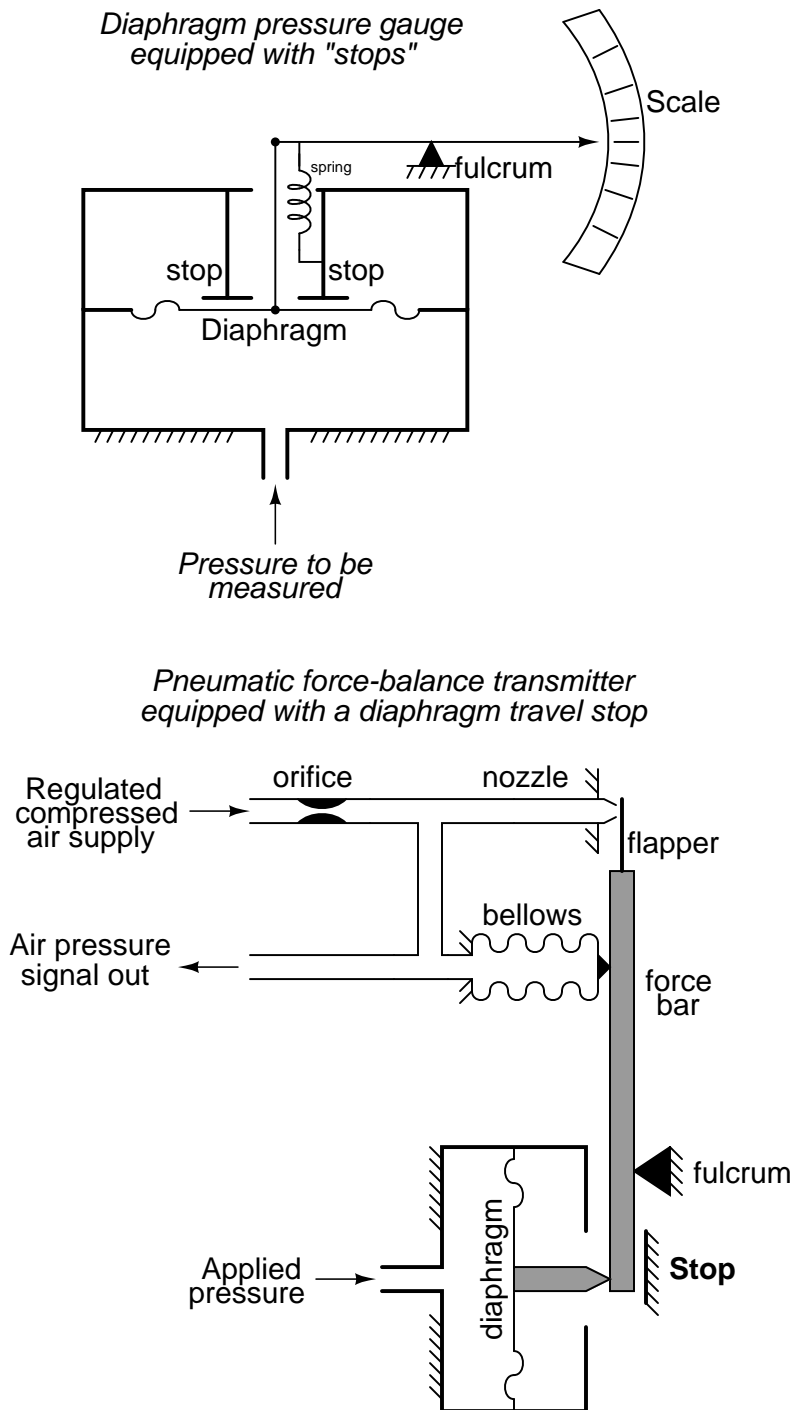
#### Suggestions for Socratic discussion

- Why do you suppose a time-delay relay is used in this particular control application?
- Is the boiler shutdown solenoid *energize-to-trip* or *de-energize-to-trip*? Explain how we can tell from an examination of the schematic.
- Identify where in this circuit you could install a PSHHH (pressure switch high-high-high) that would trip the boiler immediately.
- Identify a circuit fault that would cause the boiler to needlessly shut down (a “safe” fault).
- Identify a circuit fault that would cause the boiler to not be able to shut down when it needs to (a “dangerous” fault).

file i00221

Question 76

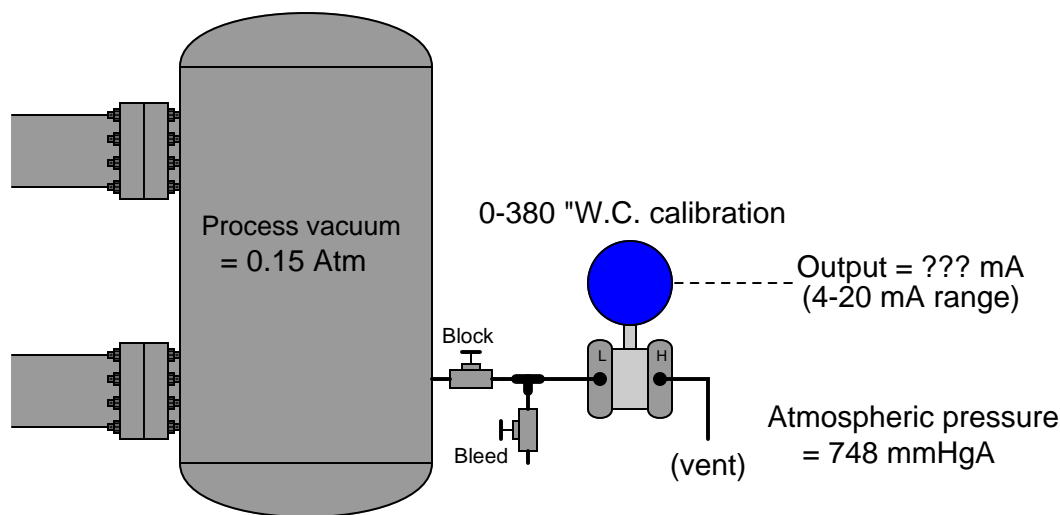
Many industrial pressure sensing elements, especially diaphragms and bellows, are equipped with *stops* to limit the physical travel of the sensing element:



What important purpose is served by a *stop* in a pressure measuring instrument?  
[file i00224](#)

### Question 77

Suppose a DP transmitter is connected to a process vessel so it may measure a vacuum inside that vessel. Calculate the amount of differential pressure “seen” by this electronic DP transmitter in units of PSID, then calculate its output signal assuming a calibrated range of 0 to 380 inches water column differential and an output range of 4-20 mA:



There is definitely more than one way to calculate the transmitter’s output signal value! Outline more than one of these solutions.

Furthermore, suppose an instrument technician decides to remove this transmitter from service in order to disconnect it from the process and then calibrate it back at the instrument shop. Describe how the technician should operate the block and bleed valves to safely remove it from service, and then describe what the technician should do *before* operating either the block or the bleed valve to ensure no process upsets occur as a result.

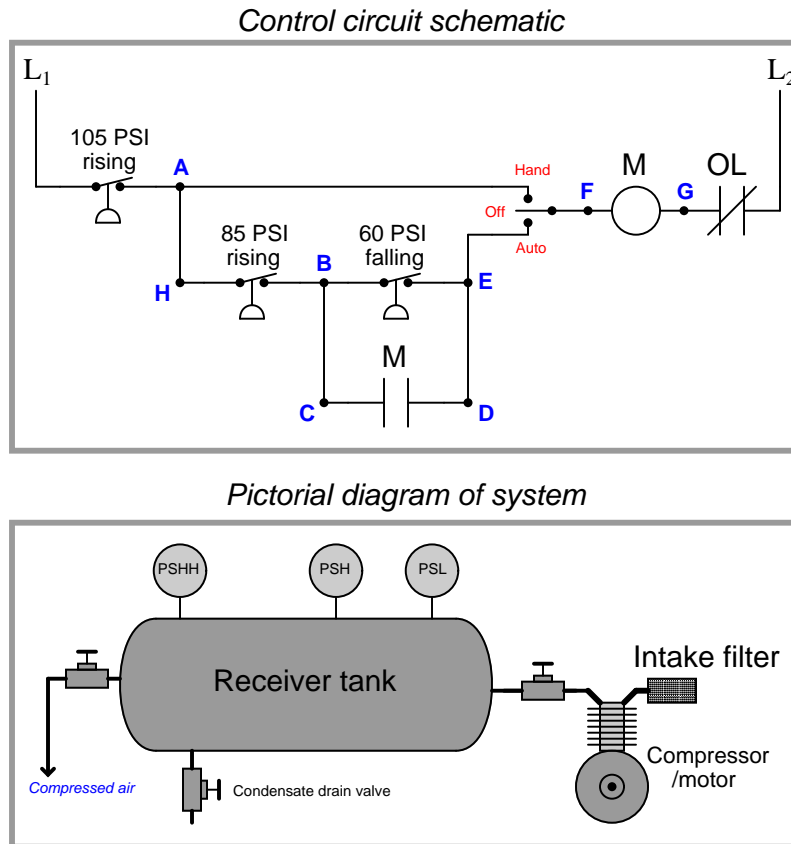
#### Suggestions for Socratic discussion

- What safety hazards might there be for a technician disconnecting and connecting a pressure transmitter to a process vessel such as this?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- What might happen if the vent tube on the “L” side of the transmitter were to become completely plugged?

file i03939

# Question 78

Suppose this electric-driven air compressor refuses to start when the switch is in the “Auto” position, but starts up immediately when the switch is placed in the “Hand” position. The first test performed by a technician is to measure AC voltage between test points **A** and **F** with the switch in the “Auto” position. There, the meter registers 117 volts AC. You are then called in to help:



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.

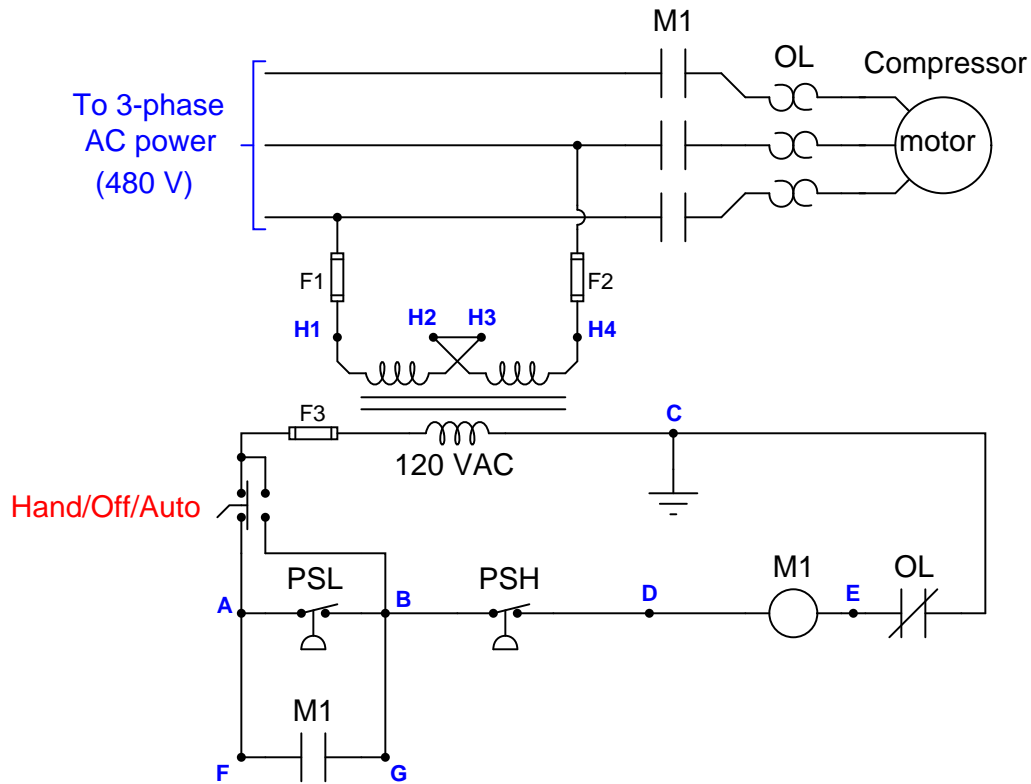
Fault	Possible	Impossible
PSHH failed open		
PSH failed open		
PSL failed open		
“Hand” switch position failed open		
“Auto” switch position failed open		
OL contact failed open		
Auxiliary “M” contact failed		
Contactors “M” coil failed open		

Also, comment on whether or not the initial test between points **A** and **F** was a useful one (i.e. did it provide any new information to help diagnose the problem?).

[file i03458](#)

Question 79

This air compressor control circuit has a problem. The air compressor refuses to start even when the air pressure is zero PSI. A technician begins diagnosing the circuit, following the steps shown (in order):

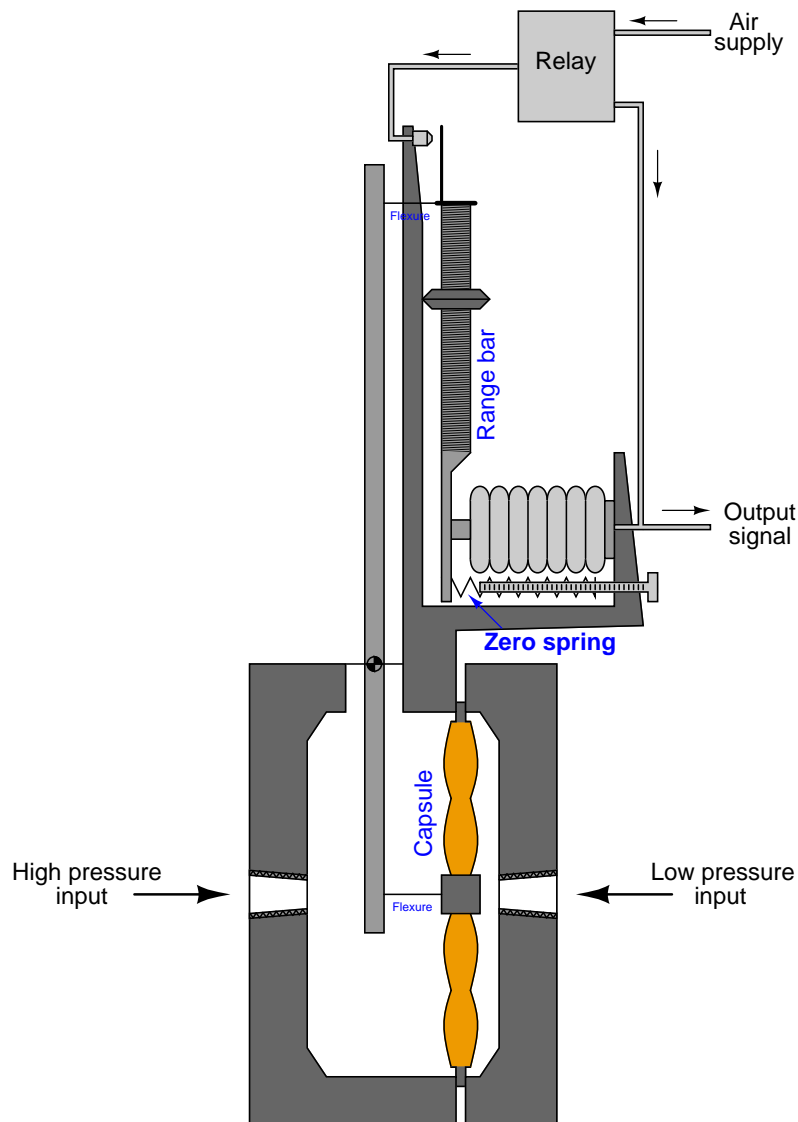


- **Test 1:** Measured 120 VAC between points **A** and **C**, with “Hand/Off/Auto” switch in the “Auto” position.
- **Test 2:** Measured 120 VAC between points **A** and **D**, with “Hand/Off/Auto” switch in “Auto” position.
- **Test 3:** Measured 0 VAC between points **E** and **C**, with “Hand/Off/Auto” switch in “Auto” position.
- **Test 4:** Jumpered points **A** and **B**, with “Hand/Off/Auto” switch in “Auto” position. The motor did not start.

Identify any useful information about the nature or location of the fault derived from the results of each test, in order of the tests performed. If the test is not useful (i.e. provides no new information), mark it as such. Assuming there is only one fault in the circuit, identify the location and nature of the fault as precisely as you can from the test results shown above.

### Question 80

This Foxboro model 13 DP transmitter is designed to output a pneumatic pressure signal of 3 PSI when there is no process pressure applied to the diaphragm (capsule):



From this information, determine whether the “zero” spring is a *tension* spring (pulling to the right on the range bar) or a *compression* spring (pushing to the left on the range bar).

#### Suggestions for Socratic discussion

- Suppose this transmitter output a signal of 3.1 PSI when it should output a signal of 3.0 PSI. Calculate the error, *in percent of span*.
- Suppose this transmitter output a signal of 14.9 PSI when it should output a signal of 15.0 PSI. Calculate the error, *in percent of span*.
- Suppose this transmitter output a signal of 12.4 PSI when it should output a signal of 12.0 PSI. Calculate the error, *in percent of span*.



- Suppose this transmitter output a signal of 8.8 PSI when it should output a signal of 9.0 PSI. Calculate the error, *in percent of span*.

file i03938

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Question 81

Complete the following table of equivalent pressures. Assume units of “gauge” pressure except where “absolute” is implied by the unit:

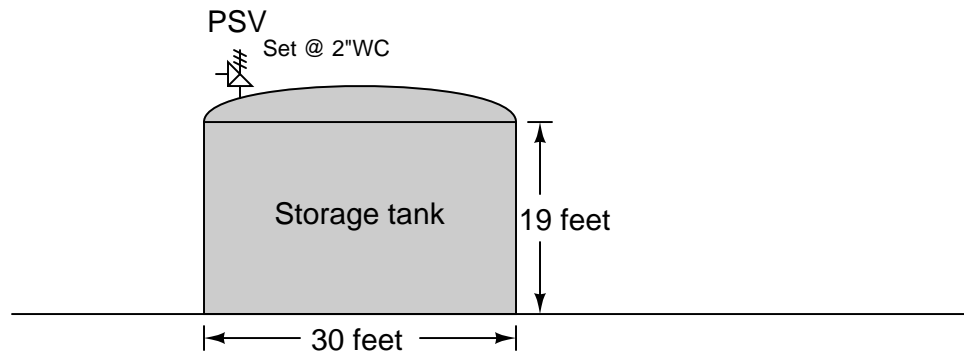
inches Hg	inches H <sub>2</sub> O	Atmospheres	PSI
82			
	250		
		1.5	
			10
		9	
0			
	−25		
			40

file i00024

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Question 82

A safety device commonly installed on process vessels containing pressurized gases is a *Pressure Safety Valve*, or PSV. In this example, a PSV protects a storage tank against rupture from excessive internal gas pressure, with the PSV set to open (“lift”) and vent the tank if the internal pressure exceeds 2 inches water column:

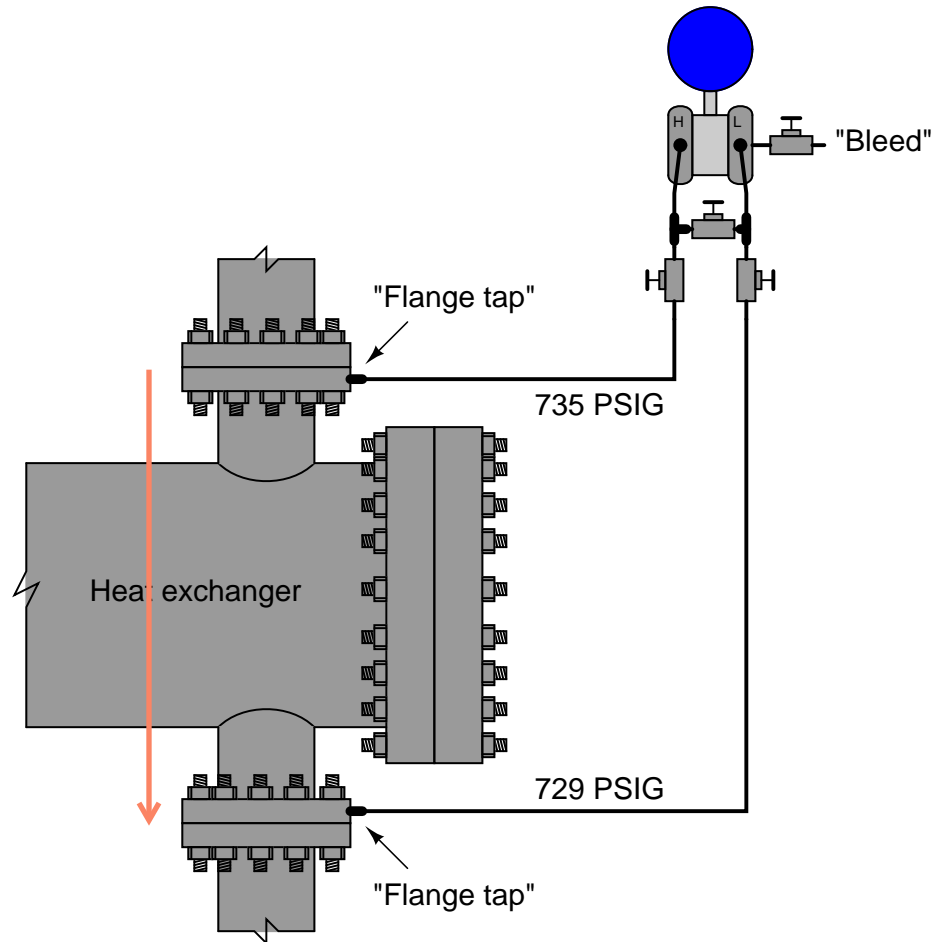


Calculate the total upward force exerted on the circular roof of this cylindrical storage tank at the PSV lift pressure, expressed in the unit of *tons*.

$F =$  \_\_\_\_\_ tons

Question 83

Determine the pressure at each port of the DP transmitter during an instrument technician's step-by-step valve isolation procedure. Assume the process fluid sensed by the transmitter is a gas and not a liquid:



Step	High-side pressure	Low-side pressure
1: Transmitter in service		
2: Close high-side block valve		
3: Close low-side block valve		
4: Open equalizing valve		
5: Open bleed valve		

Based on the process pressures shown, identify the direction of process gas through this heat exchanger.

Also, identify what the technician needs to tell the process operator(s) prior to isolating the transmitter from this process.

file i00026

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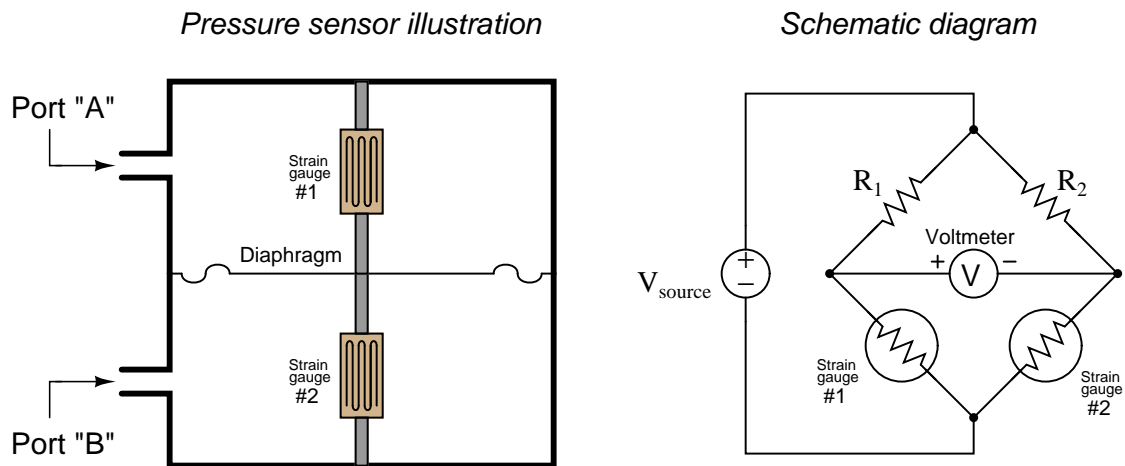
**Question 84**

A pneumatic pressure transmitter has a calibrated range of 50 to 250 PSI, and its output signal range is 3 to 15 PSI. Complete the following table of values for this transmitter, assuming perfect calibration (no error). Be sure to show your work!

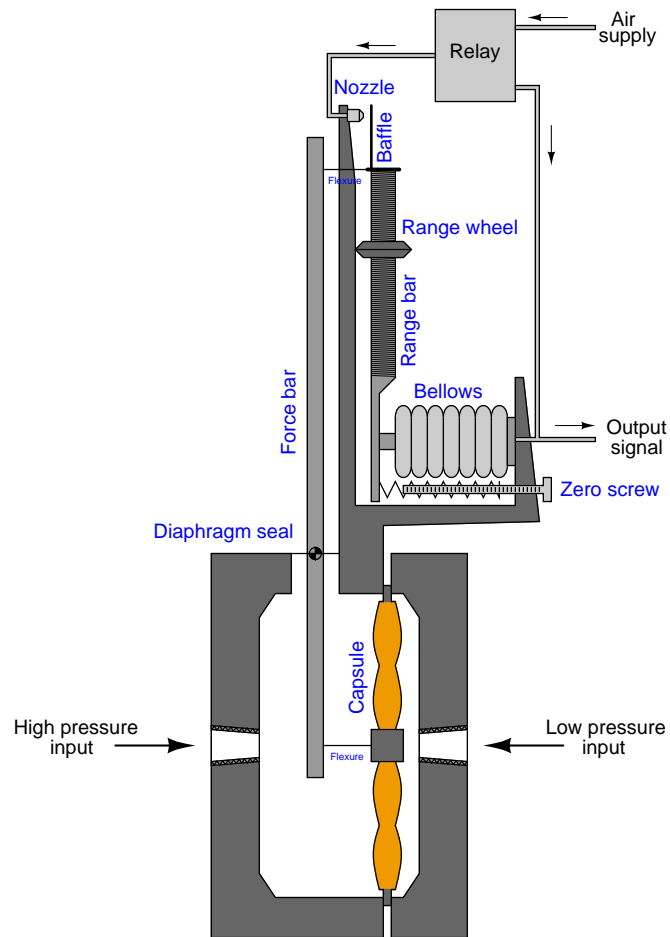
Input pressure applied (PSI)	Percent of span (%)	Output signal (PSI)
	30	
58		
		7.5
		13.7

### Question 85

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. The polarity symbols shown on the diagram next to the voltmeter show the polarity necessary to drive the meter upscale:



- 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)

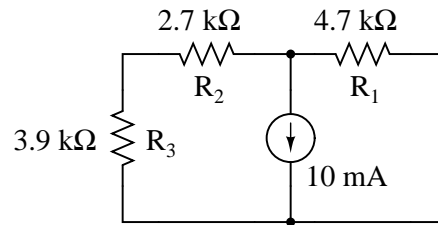


Sketch an arrow showing the direction the *range wheel* must be moved in order to increase the transmitter's measurement span (i.e. so that 3-15 PSI output represents a *greater* span of process pressures than before).

Sketch an arrow showing the direction of force applied by the *zero screw* on the *range bar* to increase the output pressure when there is no process pressure applied to the transmitter (e.g. 3.1 PSI instead of 3.0 PSI at 0 PSID input).

Question 87

Complete the table of values for this circuit. Be sure to show all your work!



	$R_1$	$R_2$	$R_3$	Total
V				
I				10 mA
R	4.7 k $\Omega$	2.7 k $\Omega$	3.9 k $\Omega$	
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!*

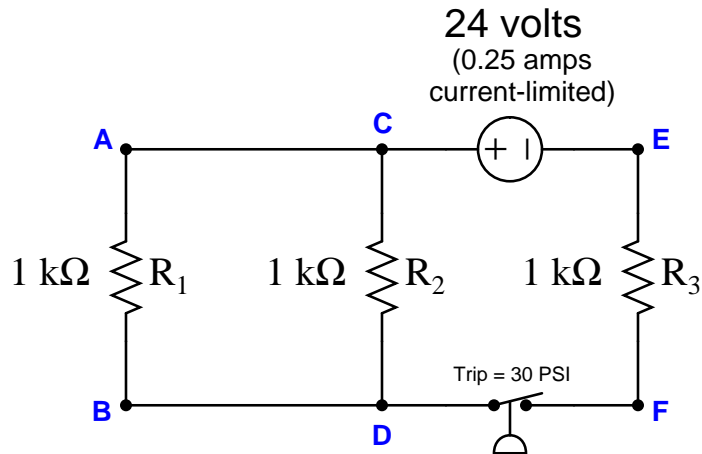
If your final answers are rounded as a result of not doing this, you will only receive half-credit for your work. This is a general policy for all your mathematical work in this program, not just this particular problem!

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 i03149](#)

Question 88

Suppose a voltmeter registers 0 volts between test points **D** and **E** in this series-parallel circuit, with 22 PSI applied to the pressure switch:



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

Fault	Possible	Impossible
$R_1$ failed open		
$R_2$ failed open		
$R_3$ failed open		
Pressure switch failed open		
$R_1$ failed shorted		
$R_2$ failed shorted		
$R_3$ failed shorted		
Pressure switch 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.

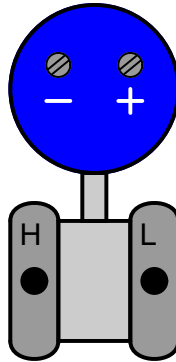


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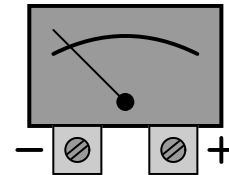
Question 89

Sketch a circuit whereby this loop-powered pressure transmitter sends a signal to an analog current meter (acting as a remote pressure gauge). Include any necessary power sources in your completed circuit:

4-20 mA loop-powered  
pressure transmitter



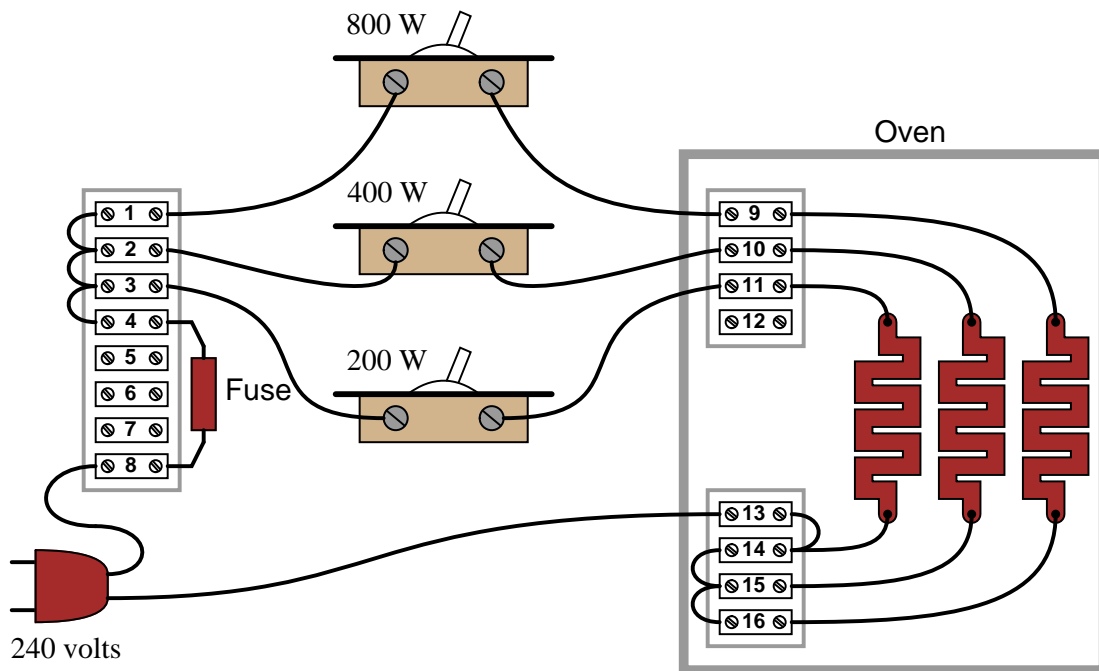
4-20 mA ammeter



Also, identify each component in the circuit as being either a *Source* or a *Load* and annotate the direction of each component's current using an arrow pointing in the direction of conventional flow.

### Question 90

The following electric heater seems to have a problem: it heats up slower than usual with all three switches turned “on.”



With three differently-sized heating elements (200 watt, 400 watt, and 800 watt), the oven operator can set the power in seven discrete steps by turning on specific combinations of switches: 200 watts, 400 watts, 600 watts, 800 watts, 1000 watts, 1200 watts, and 1400 watts.

You are summoned to diagnose this oven's problem *without turning it off*. You are allowed to turn off any single switch for a few seconds at most, but otherwise you need to leave all three heaters on because the oven needs to heat up as fast as it can! The idea is to figure out where the problem might be, then gather together any parts necessary for repairs while the oven is still being used, and fix the oven as fast as possible when you finally get the chance to turn it off completely.

First, assess whether or not the following diagnostic test would provide any useful information about the fault: *suppose a technician connects an AC voltmeter between terminals 4 and 8*. Will this test provide information to help us diagnose the nature and/or location of the fault? Why or why not?

Next, propose a diagnostic test that would definitely provide useful information about either the location or the nature of the fault in this system. Your proposal must identify the meaning of at least one possible result of the test (e.g. “*If I jumper terminals X and Y together and I measure a decrease in source voltage, it means the fault must be a short somewhere in branch A-B-C of the circuit*”). Remember that the best diagnostic test is one that yields definitive answers no matter what its result might be. Directly checking a suspected component is *not* a good diagnostic test, unless there are simply no other options!

**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).

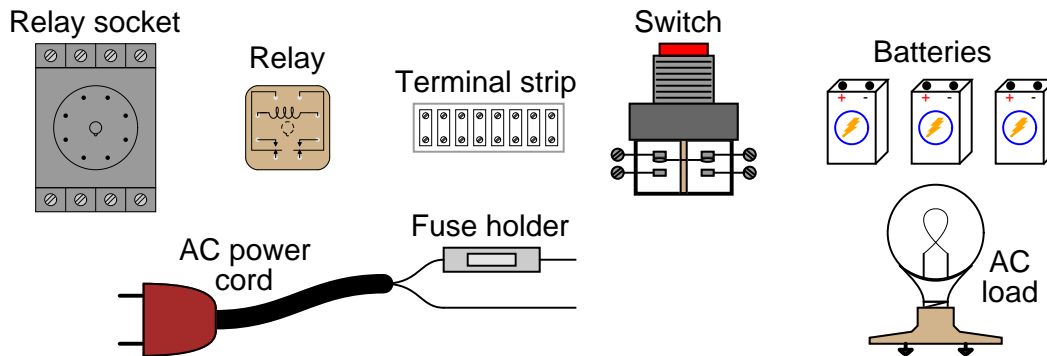
After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a pressure transmitter, this entails applying an air pressure to the “high” pressure port and measuring the transmitter’s milliamp output signal to see if 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).

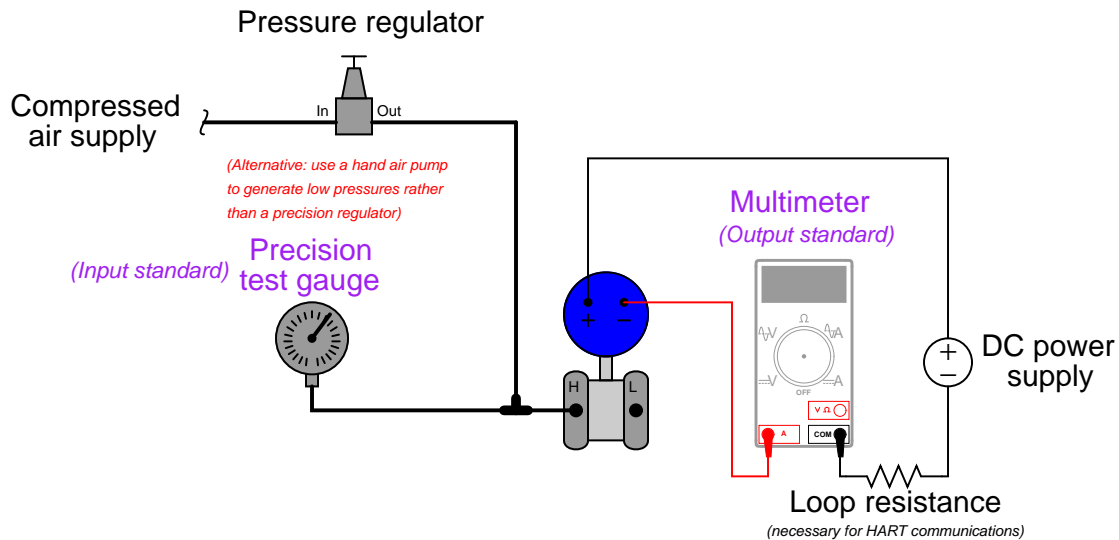
**Creating and inspecting accurate loop diagrams should take no more than one full lab session (3 hours) if the team is working efficiently!**

## 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).

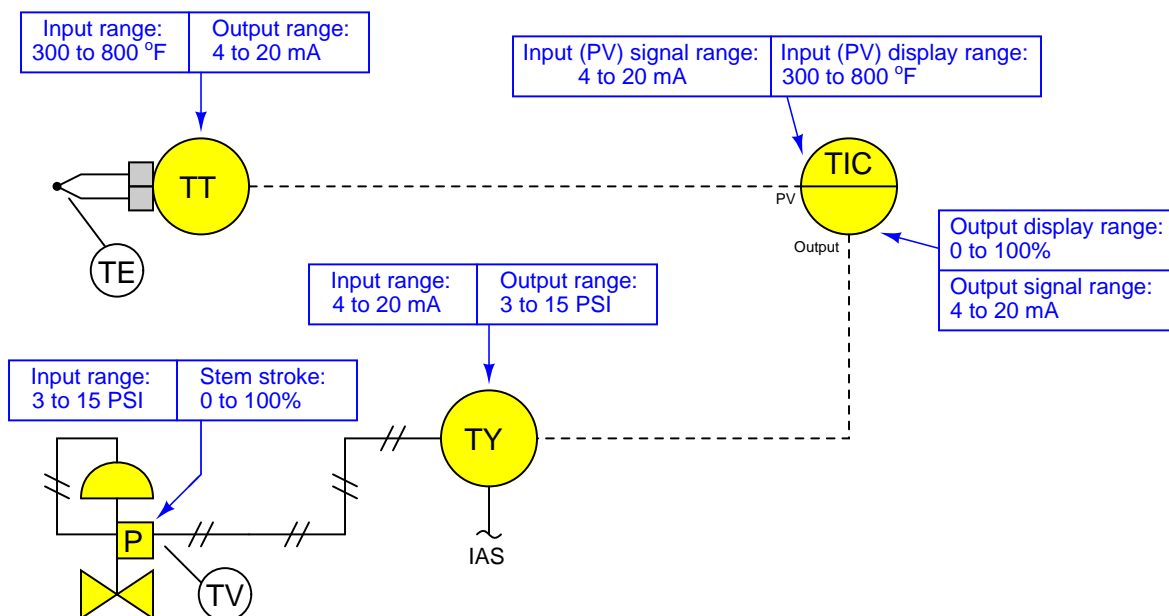
- Choosing a calibration (“trim”) range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Choosing a poor-accuracy calibration 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:**

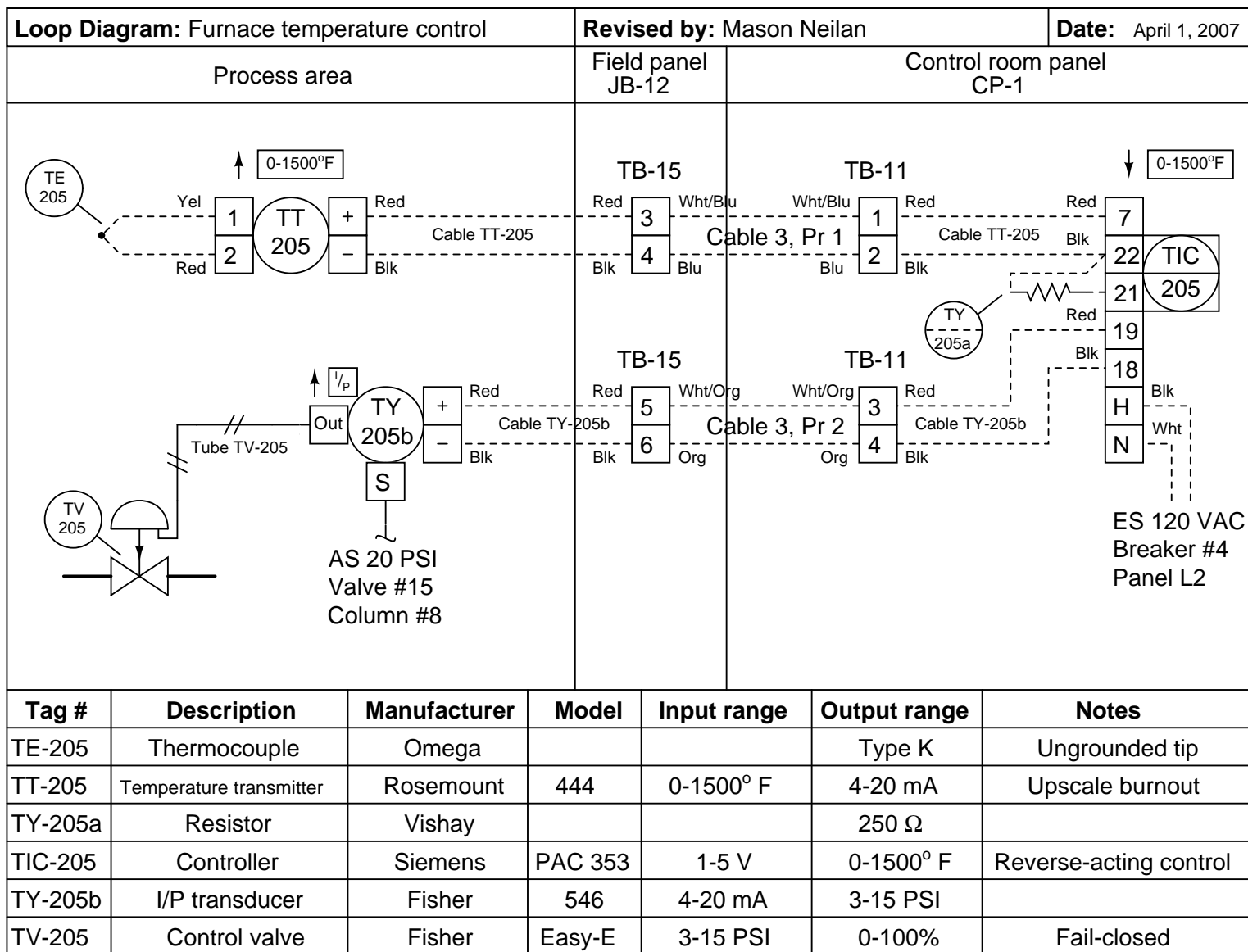
- Large control valves and positioners
- I/P transducers
- Large electric motors
- Large variable-frequency drive (VFD) units
- Cables inside conduit interconnecting junction boxes together
- Pipe and tube fittings (do not unscrew pipe threads)
- Supply air pressure regulators

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

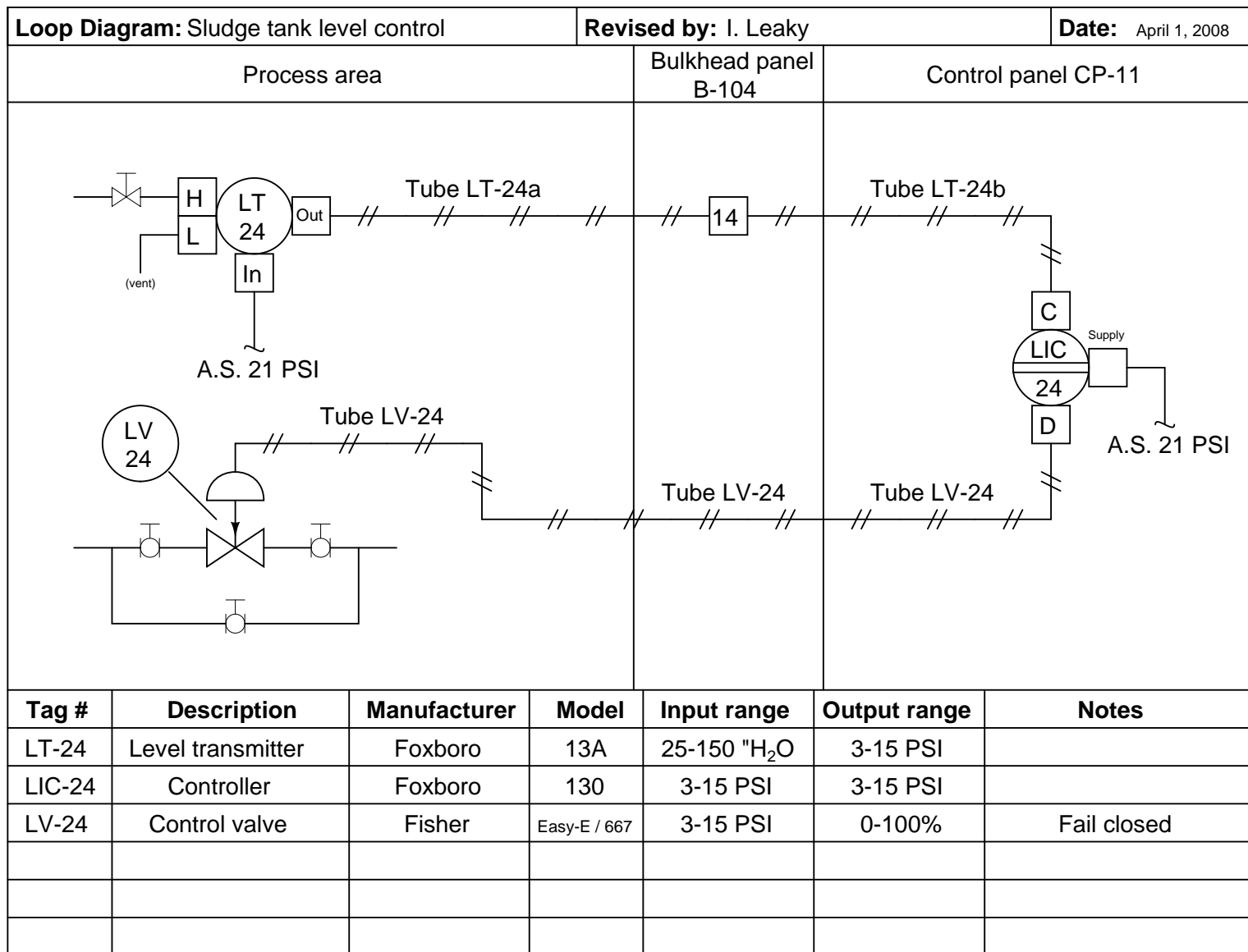
- Sensing elements (e.g. thermocouples, pH probes, etc.)
- Process transmitters
- “Jumper” cables used to connect terminal blocks within a single junction box
- Plastic tubing and tube fittings (disconnect compression-style tube fittings)
- Power cables and extension cords
- Adjustment (loading station)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

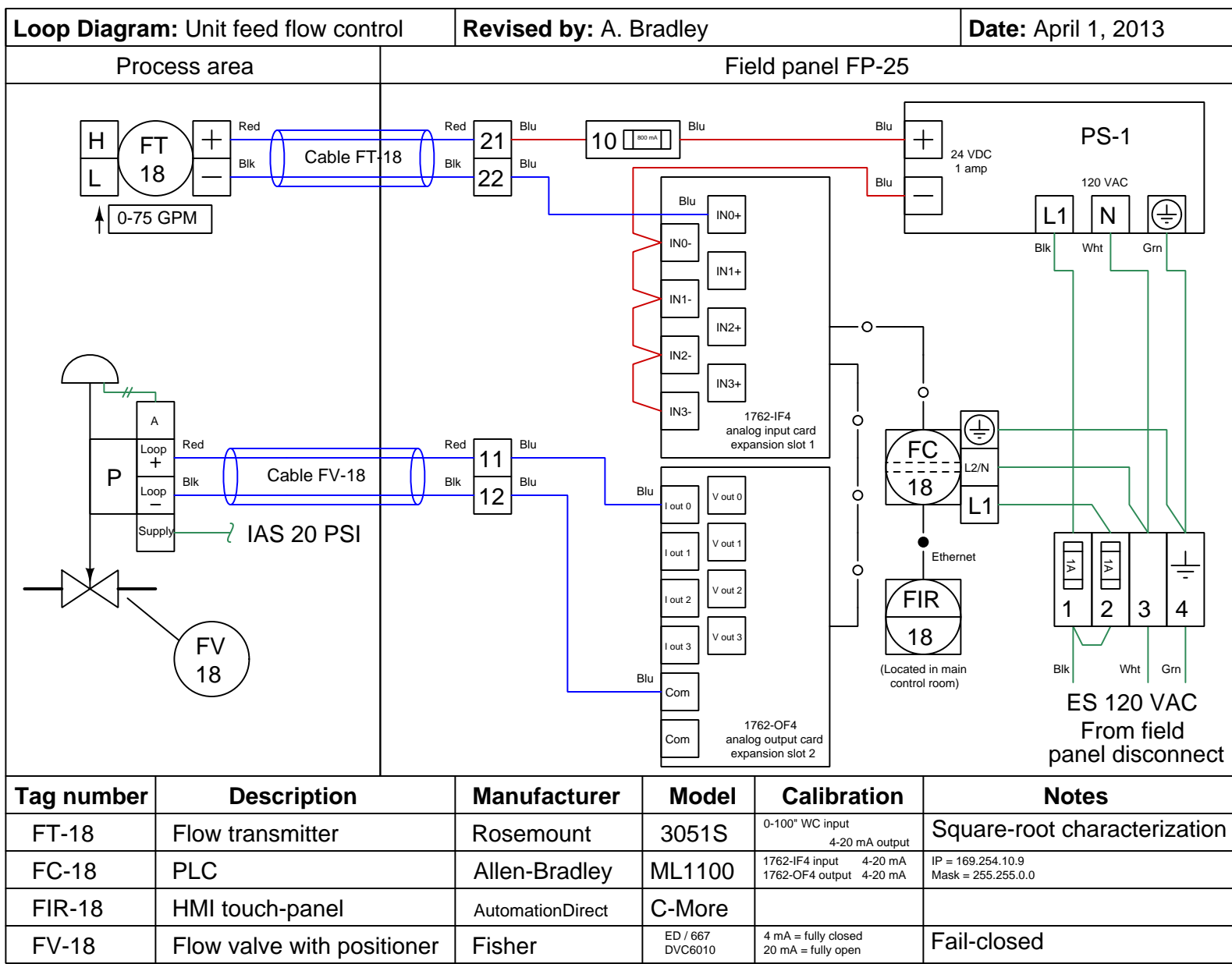
Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.

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

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Answer 4

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Answer 5

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Answer 6

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Answer 7

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Answer 8

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Answer 9

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Answer 10

- $71.5 \text{ PSIA} = 56.8 \text{ PSIG}$
- $5.03 \text{ bar (gauge)} = 148.5 \text{ "Hg}$
- $101 \text{ kPa} = 29.35 \text{ PSIA}$
- $800 \text{ torr} = 0.774 \text{ PSIG}$
- $41 \text{ "Hg} = 557.4 \text{ "W.C.}$
- $2.2 \text{ feet Hg} = 89.4 \text{ kPa}$
- $11 \text{ PSI vacuum} = 191.3 \text{ torr}$
- $350 \text{ "W.C.G} = 756.9 \text{ "W.C.A}$
- $66 \text{ cm W.C.} = 1.911 \text{ "Hg}$
- $910 \text{ PSIG} = 62.9 \text{ atm}$
- $35 \text{ "W.C.} = 32.5 \text{ "HgA}$
- $125 \text{ PSIA} = 760.5 \text{ kPa}$

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Answer 11

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## Answer 12

Removing the gauge from service:

- Close the “block” valve.
- Open the “bleed” valve. If the process fluid is dangerous (toxic, flammable, etc.), be *very careful* when “bleeding” it to the atmosphere!
- Place lock-out tags on both valve handles to notify operators and technicians of the instrument’s removal and pending return.
- Remove the gauge from the piping or tubing.

It is very important to place tags on the valve handles as notifiers of your service to the gauge. Even if these tags do not serve a safety purpose (i.e. it is visually obvious that the “block” valve should not be opened when there is no instrument connected to it), they still notify anyone looking for the missing gauge that you are servicing it and will have it returned by a certain time/date.

Placing the gauge back into service:

- Re-attach the gauge to the piping or tubing.
- Remove the lock-out tags on both valve handles.
- Close the “bleed” valve.
- Open the “block” valve.

An added touch of professionalism when opening the “block” valve is to not leave it open all the way so that the handle cannot turn any further counterclockwise. Instead, open it all the way (counterclockwise) until you feel the handle “stop,” then turn it back clockwise (in the closing direction) about 1/4 turn. This helps to prevent the valve from seizing in the fully open position, by backing the valve stem off the reverse seat. Valves left to sit in the fully open position have a tendency to become “frozen” in that position. The worse thing about a “frozen” valve is that you cannot determine what position it is in by feel!

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## Answer 13

Removing the gauge from service:

- Close the “block” valve closest to the process.
- Open the “bleed” valve. Monitor the instrument’s pressure indication, to make sure it is changing to register atmospheric pressure. This tells you that the “bleeding” is successful.
- Close the “block” valve closest to the instrument.
- Close the “bleed” valve.
- Place lock-out tags on all three valve handles to notify operators and technicians of the instrument’s removal and pending return.
- Remove the gauge from the piping or tubing.

Assuming the process fluid is especially dangerous, there may be some sort of recommended decontamination process for the instrument prior to you connecting it to calibration equipment in the shop. As always, be aware of any special safety considerations on any process you are working around.

Placing the gauge back into service:

- Remove the lock-out tags on all valve handles.
- Open the “bleed” valve (to relieve any pressure that may have built up between the two closed block valves from a leak in the first block valve).
- Re-attach the gauge to the piping or tubing.
- Open the “block” valve closest to the instrument.
- Close the “bleed” valve.
- Open the “block” valve closest to the process.

Normal valve positions:

- Both block valves open.
- Both equalizing valves closed.
- Vent valve closed.

Removing differential pressure transmitter from service:

- Close one block valve.
- Open both equalizing valves (which one first does not matter).
- Close the other block valve.
- Open the vent valve.
- Tag all valves, notifying of transmitter's planned return time/date.
- Disconnect the transmitter from the manifold.

Restoring the transmitter back to service is as simple as reversing all the steps taken to remove it from service (i.e. go through the list backwards, doing the reverse of each instruction).

One feature that 5-valve manifolds provide over 3-valve manifolds is the ability to route a vent tube to a remote (safer) location, for use with particularly hazardous process fluids.

5-valve manifolds allow for in-place transmitter calibration, provided one of the  $\Delta P$  transmitter's sides has an atmospheric vent. By connecting the calibrating pressure source to the vent line, one can route the calibrating pressure to either side of the transmitter (only), while keeping the other side vented.

Remote, chemical seals provide a means for pressure transmitters to measure the pressure of extremely corrosive process fluids. The only portions of the instrument in contact with the process fluid are the seal elements themselves: their housings and diaphragms. The capillary tubing connecting the seals to the transmitter contain only clean oil, as does the transmitter itself.

Now you're probably wondering, "What's the point of using a remote diaphragm to contact the process fluid? If the fluid were too corrosive for the transmitter, wouldn't it be too corrosive for the remote seal diaphragm as well? And if a remote seal can be made to withstand the corrosive effects of the fluid, then why not a regular transmitter?"

For one, pressure transmitters (especially the motion-balance kind) are limited in the kinds materials their pressure elements may be constructed of. The pressure element (bellows, diaphragm, bourdon tube) must be made of a material with good elastic properties, and that usually means a fairly narrow range of metals. The seal diaphragms, on the other hand, are designed to be "slack." That is, they are not supposed to provide any spring resistance to motion, but be limp and transfer all the process pressure to the transmitter's sensing element. Because they need not function as spring elements, their elastic properties are not as critical as for the transmitter's sensing element, and this allows a wider range of materials with different corrosion resistances. In some cases, the remote diaphragm may be non-metallic, and thus have corrosion resistance properties very different from that of a metal.

Even if the seal diaphragms are metallic, like the transmitter's sensing element, there is still good reason to use chemical seals in some applications. With a normal pressure transmitter mounted remotely from the process vessel, some kind of tubing will be necessary to transfer fluid pressure to it from the vessel. The range of available materials for instrument tubing is far more limited than the range of materials for seal diaphragms or even transmitter sensing elements. It may be that even the best instrument tubing cannot tolerate the corrosive effects of the process fluid, but a seal diaphragm made of some exotic metal alloy can. Using remote seals and capillary tubes filled with nice, clean oil neatly solves the problem, containing the process fluid within the seals and not allowing it to enter the tubing.

Another, entirely different, reason for using remote seals is in food processing, where no "pockets" are allowed in the fluid system due to the need for regular disinfection and decontamination. Standard  $\Delta P$  transmitter capsule assemblies and impulse tubing would create cavities for bacteria to collect and grow in nutrient-rich fluid. Remote seals present a flat surface to the process fluid, transmitting the pressure to the fill fluid where bacteria cannot enter.

A similar reason for using remote seals is to avoid plugging. With standard "impulse" tubes connecting a process vessel or pipe to a transmitter, there exists the possibility of sediment or debris plugging the tubes. However, flush-mounted remote seals provide no place for sediment or debris to collect.

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**Answer 16**

Increased temperature causes the fill liquid in the capillary tube to expand, thus creating a pressure at the transmitter's sensing element independent of the process fluid pressure being measured.

If the seal-equipped transmitter is differential in nature, and the temperatures of both seal units and capillary tubes are equal, then any temperature-induced pressures will cancel out at the transmitter, and there will be no problem. However, if the temperature of one seal or capillary is greater than the other, there will be a *differential* pressure induced by temperature that the transmitter will detect and interpret as process fluid differential pressure.

Remote seal/capillary systems must be completely gas-free (nothing but liquid inside) in order to work. If even a small air or other gas bubble works its way in to the fill fluid between the remote seal diaphragm and the instrument sensing element, the fill fluid will be compressible, meaning that the seal diaphragm will displace a greater volume of fill fluid than the instrument's sensing element. Thus, the instrument may not "see" the entire amount of process pressure change applied to the seal diaphragm, and its measurement accuracy will be compromised.

In summary, leaks in a remote seal system have *very detrimental effects* on instrument accuracy. If ever such a system develops a leak, the whole instrument must be replaced. Even if you could patch the leak, you would have to "pack" the seal unit, capillary tubing, and transmitter pressure housing with new fill liquid under a strong vacuum to "pull" any dissolved gas bubbles out of the liquid. Needless to say, the facilities required for such an operation are typically not available in a plant instrument shop, thus rendering the instrument unrepairable by you.

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**Answer 17**

If the equalizing valve is ever opened, it could shuttle fill fluid from one remote seal to the other, imbalancing the system. This would make the transmitter read less differential pressure than there actually was applied between the remote seals. The problem would be difficult to correct without dismantling the system entirely and re-packing the seals and capillary tubes with fill fluid.

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**Answer 18**

The transmitter will measure 28.4 PSI, due to the added pressure of the fluid inside the capillary tube.

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**Answer 19**

<b>Fault</b>	<b>Possible</b>	<b>Impossible</b>
$R_1$ 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		✓

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**Answer 20**

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**Answer 21**

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**Answer 22**

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**Answer 23**

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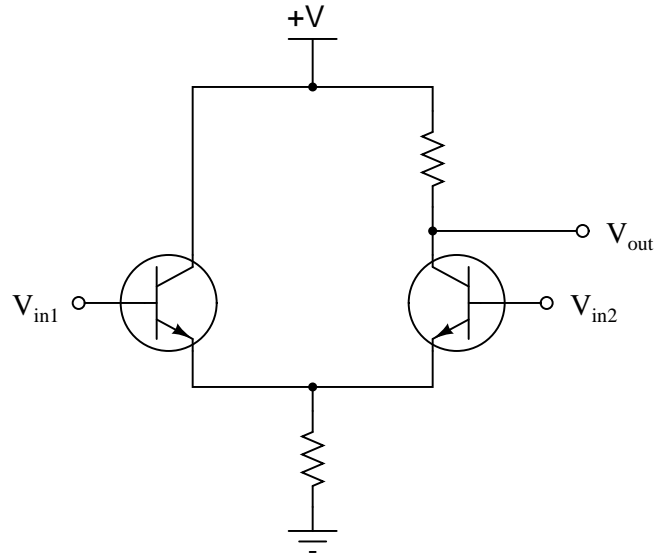
Answer 24

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Answer 25

A bit of explanation might be in order for the two diaphragms. The larger diaphragm is called the *sensing* diaphragm, while the smaller diaphragm is called the *sealing* diaphragm. The purpose of the sealing diaphragm is to prevent air pressure at input B from leaking out into the vented chamber just to the left of the wedge-shaped pilot plug. This sealing diaphragm is made small enough that its contribution to force on the stem is negligible. Only the sensing diaphragm is large enough to have any consequence upon the pilot valve's action.

This is an equivalent electronic circuit:



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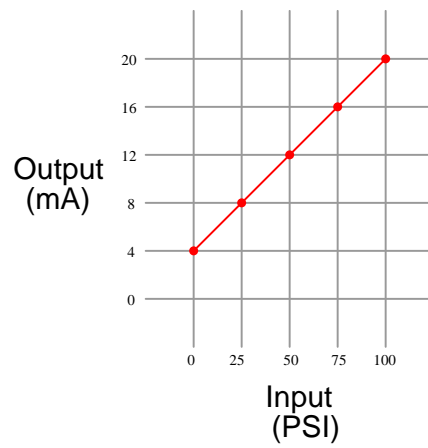
Answer 26

Input pressure applied ("W.C.)	Percent of span (%)	Output signal (PSI)
0	50	9
-30	35	7.2
-16.67	41.67	8
66.67	83.33	13
30	65	10.8
-80	10	4.2

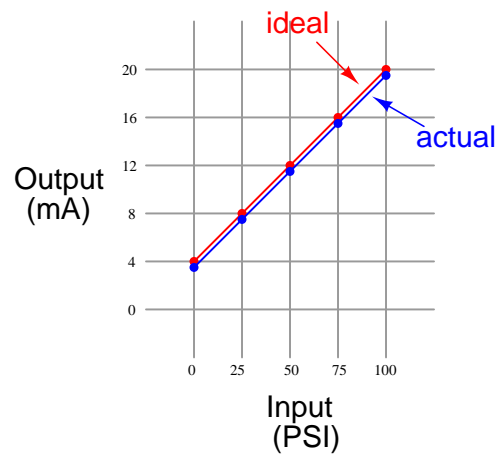


This instrument has a *zero shift* error, but not a *span shift* or *linearity* error.

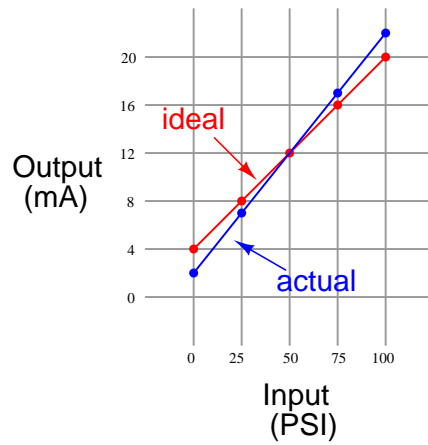
**Ideal transfer function:**



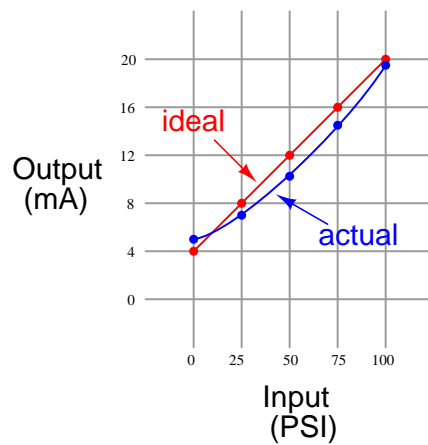
**Actual transfer function:** (zero error)



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



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

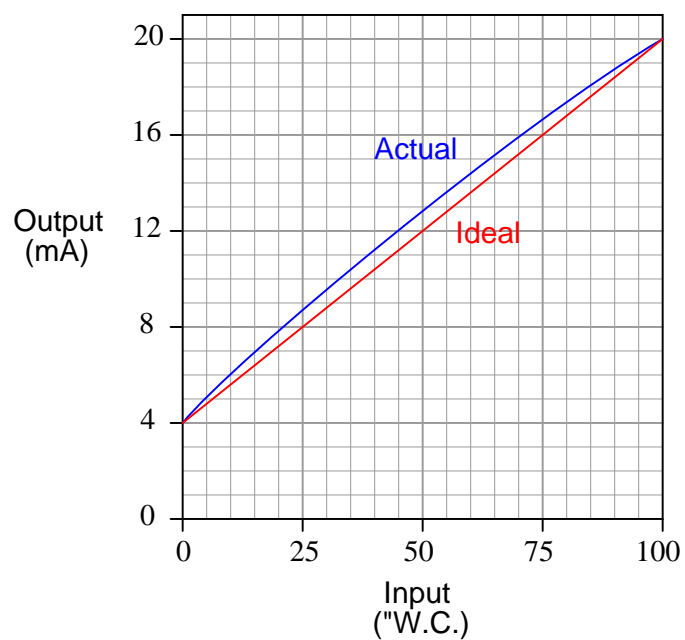


A zero error is usually correctable by simply adjusting the “zero” screw on an analog instrument, without making any other adjustments. Span errors, by contrast, usually require multiple adjustments of the “zero” and “span” screws while alternately applying 0% and 100% input range values to check for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

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Answer 28

This transmitter definitely has a *linearity* error:



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Answer 29

bar	PSI	inches W.C.	inches mercury
0.59	8.557	236.9	17.42
0.2827	4.1	113.5	8.348
0.4982	7.225	200	14.71
1.185	17.19	475.8	35
0.7672	11.13	308	22.65
3.556	51.57	1428	105
6.068	88	2436	179.2
5.91	85.71	2373	174.5

---

Answer 30

The most sensitive portion of this mechanism's range is where the derivative of the transfer function reaches its maximum (absolute) value.

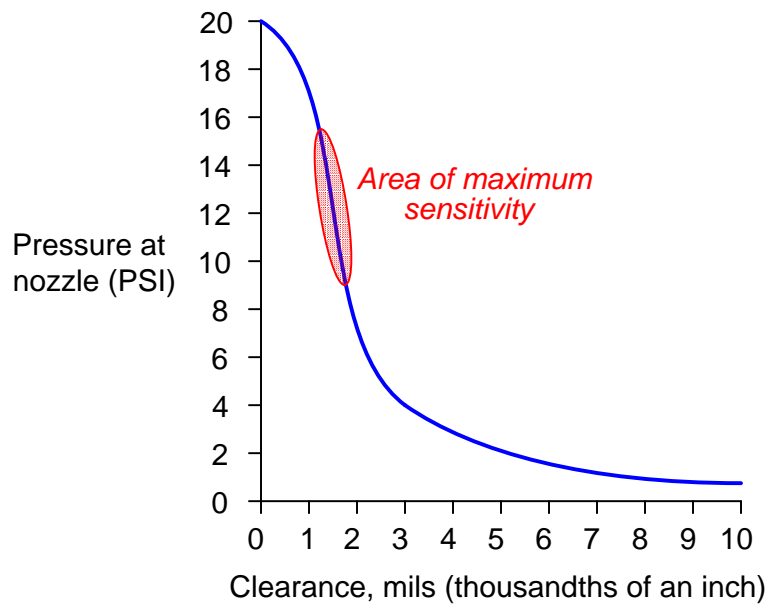
Most sensitive where  $\frac{dP}{dx}$  is at its greatest (absolute) value

Where,

$P$  = Pressure at nozzle

$x$  = Clearance between baffle and nozzle

The answer refers to the calculus principle of the *derivative*. In plain English, the most sensitive range of the baffle/nozzle mechanism is where the graph is *steepest*:



This is where the *gain* of the system is greatest.

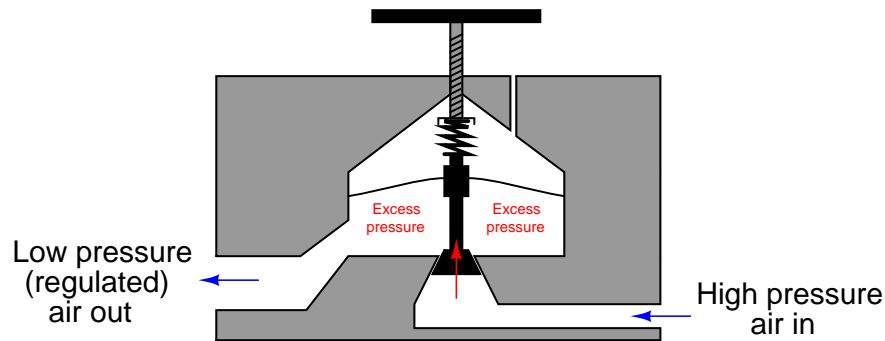
---

Answer 31

The pressure gauge downstream of the orifice will indicate a lower pressure than the gauge upstream of the orifice. Moving the flapper closer to the nozzle increases the downstream pressure, while moving the flapper away from the nozzle decreases the downstream pressure.

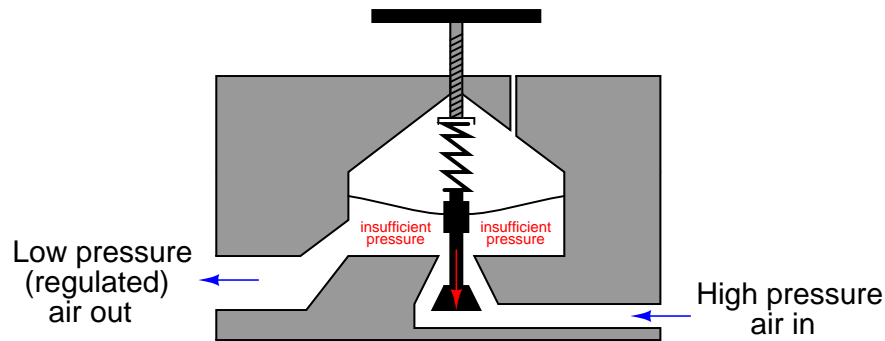
Follow-up question: sketch a schematic diagram for an electrical circuit analogous to this pneumatic "circuit" formed by the pressure source, orifice, nozzle, and flapper.

If the chamber air pressure is too high, the excess pressure will exert more force on the underside of the diaphragm to push it up, thus moving the plug up and closing off the passageway, reducing the air supply flow:



As the outlet air continues to flow out of the regulator, the chamber pressure will eventually drop back down to setpoint, and the passageway will open again.

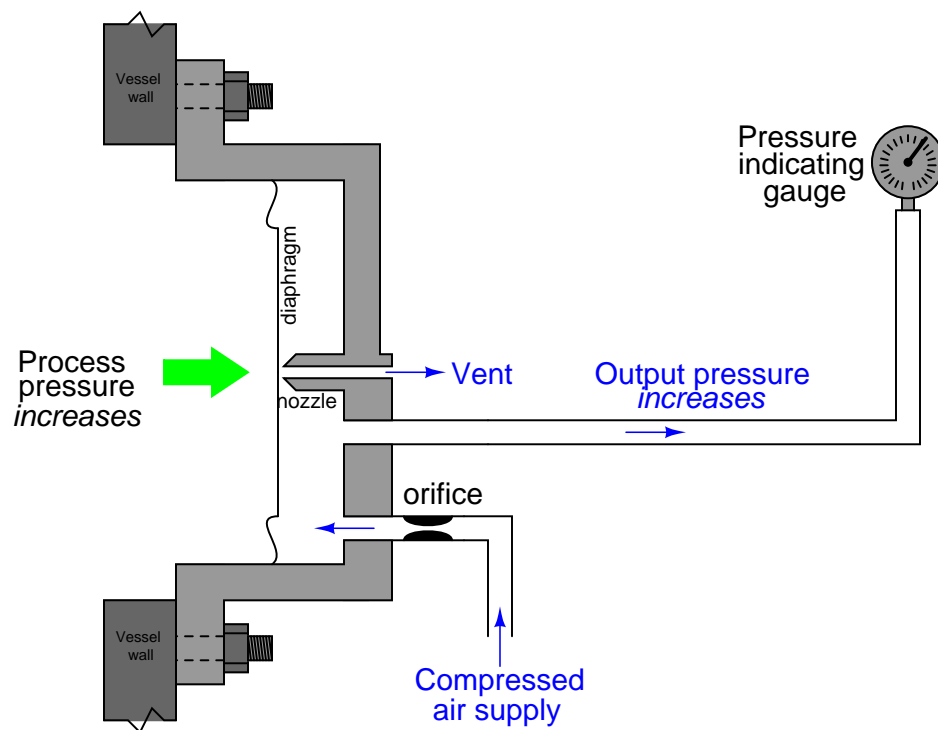
If the chamber air pressure is too low, the reduced force on the underside of the diaphragm cannot resist the spring force from above, and the plug moves down. This opens up the passageway, allowing more of the supply air to enter the chamber and increase the pressure:



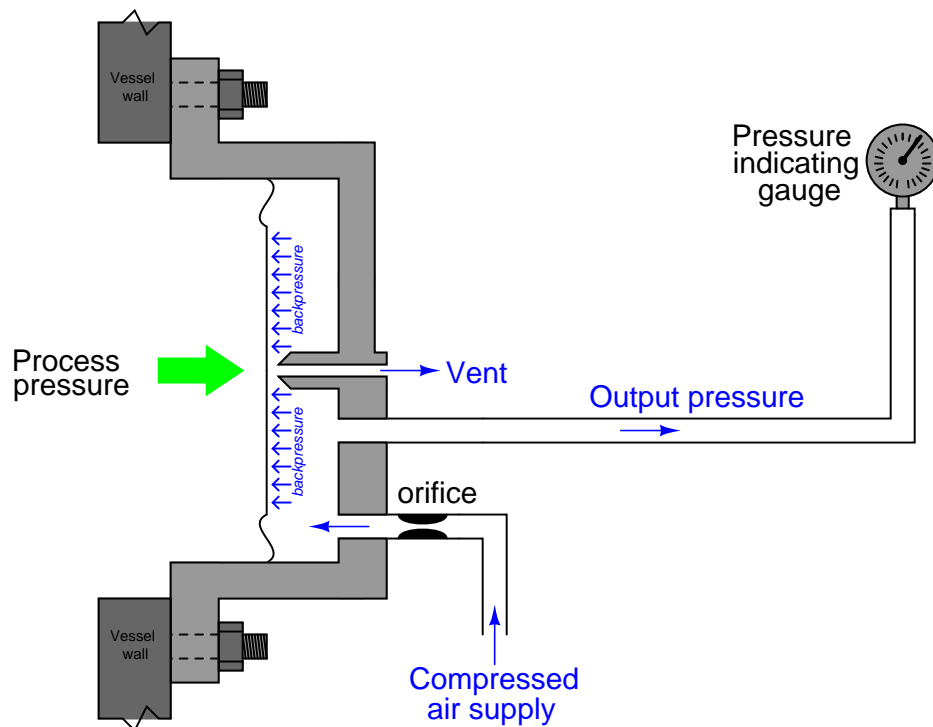
In short, the opposing forces of spring pressure (and atmospheric air pressure) above the diaphragm, versus the chamber pressure below the diaphragm, act to move the plug up or down as needed to maintain the chamber pressure approximately equal to the equivalent pressure of atmospheric air + spring force on the diaphragm.

The threaded rod with an attached turn handle adjusts the compression of the spring above the diaphragm, and changes the pressure regulation setpoint. Screwing the threaded rod in the downward direction will increase the spring force on the top of the diaphragm and likewise increase the equilibrium point between the three forces, increasing the output air pressure regulation setpoint as a consequence. Screwing the threaded rod in the upward direction will decrease the spring force on the diaphragm's top, decreasing the equilibrium point between the three forces and decreasing the pressure setpoint.

As process pressure increases, the force pressing right on the diaphragm increases as well. This makes the diaphragm move closer to the nozzle, making it more restrictive to air flow:



As air flow through the nozzle reduces, the “backpressure” built up by supply air through coming through the orifice increases. This increased backpressure forces the diaphragm to the left, against the process pressure, until the diaphragm begins to back away from the nozzle and a new point of balance (equilibrium) is reached:



Because both pressures (process fluid, and air backpressure) act against the same amount of surface area on the diaphragm, the point of force balance between them will be when the two pressures are equal to each other. Thus, the output air pressure (sensed by some remote pressure-measuring instrument) mirrors, or “repeats,” the process pressure.

Applications for a pressure repeater are found in the biopharmaceutical and food processing industries. If a pressure gauge were connected directly to the process vessel, the impulse tube connecting the gauge to the vessel would inevitably retain some of the process fluid. In biopharmaceutical and food processes, bacteria will grow in stagnant process fluid, meaning that such lengths of tubing will act as reservoirs of harmful bacteria which may contaminate subsequent batches within the vessel.

The flush-mounted diaphragm of a pressure repeater is easily cleaned by “clean-in-place” (CIP) protocols used to clean the process vessel. There are no crevices or small chambers for fluid to lie stagnant on the process side of a pressure repeater, therefore pressure repeaters eliminate the problem of bacterial contamination.

---

Answer 34

Fault	Possible	Impossible
LT-12 miscalibrated		✓
LG-11 block valve(s) shut		✓
LSH-12 switch failed	✓	
LSL-12 switch failed		✓
Leak in tubing between LT-12 and LIC-12		✓
LIC-12 controller setpoint set too high		✓
LV-12 control valve failed open		✓
LV-12 control valve failed shut		✓

---

Answer 35

We know the indicating controller (TIC-21) must be miscalibrated, because the pneumatic signal pressure of 12.8 PSI agrees with the recorder's indication of 304 degrees F.

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Answer 36

Input pressure applied (PSI)	Percent of span (%)	Output signal <i>ideal</i> (PSI)	Output signal <i>low</i> (PSI)	Output signal <i>high</i> (PSI)
0	0	3	2.94	3.06
50	25	6	5.94	6.06
100	50	9	8.94	9.06
150	75	12	11.94	12.06
200	100	15	14.94	15.06

Given the tolerance of  $\pm 0.5\%$  of the 200" span ( $\pm 1"$ ), the actual process pressure could be as low as 152 "W.C. or as high as 154 "W.C.

---

Answer 37

Reasons for the output pressure to be too low:

- Air supply pressure too low
- Supply air port clogged
- Leak in output signal tube

Reasons for the output pressure to be too high:

- Air supply pressure much too high
- Vent air port clogged
- Control valve plug not fully seating (shutting off)
- Suppression spring too compressed

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Answer 38

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Answer 39

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Answer 40

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Answer 41

With the relocated feedback connection, the opamp now "senses" the load voltage at the output terminals, and is able to correct for *any* voltage losses in the power transistor. With the previous feedback connection (from the output terminal of the opamp), the opamp was only able to regulate voltage at the base of the transistor, not at the load itself.

---

Answer 42



Part of Harold Black's patent application reads,

The invention is applicable to any kind of wave transmission such as electrical, mechanical, or acoustical, and thus far in the description the terms used have been generic to all such systems. The invention will be disclosed herein, however, as specifically applied to electrical systems, it being understood that the principles involved are equally applicable to other types of wave transmission and that the generic claims are intended to include electrical and other than electrical wave systems and apparatus.

Black's patent application gives a very easy-to-understand description of *positive feedback* which leads a system into oscillation, and also describes how negative feedback had been used in radio engineering (in the "prior art") to counter-act positive feedback for the purpose of eliminating oscillations. Black's patent, however goes further than this by using greater amounts of negative feedback to stabilize the amplifier's performance rather than merely prevent oscillation. In his own words:

Applicant has discovered how to use larger amounts of negative feedback than were contemplated by prior art workers with a new and important kind of improvement in tube operation. One improvement is in lowered distortion arising in the amplifier. Another improvement is greater constancy of operation, in particular a more nearly constant gain despite variable factors such as ordinarily would influence the gain. Various other operating characteristics of the circuit are likewise rendered more nearly constant. Applicant has discovered that these improvements are attained in proportion to the sacrifice that is made in amplifier gain, and that by constructing a circuit with excess gain and reducing the gain by negative feedback, any desired degree of linearity between output and input and any desired degree of constancy or stability of operating characteristics can be realized, the limiting factor being in the amount of gain that can be attained rather than any limitation in the method of improvement provided by the invention.

The system with the 0.75 square inch bellows unit will respond to the 1.2 pound force by generating a nozzle pressure of 1.6 PSI. The baffle will hardly move at all: perhaps only  $\frac{1}{1000}$  of an inch!

With a larger bellows in place, the system becomes less sensitive. The nozzle pressure indicated by the gauge will be *less* for the same amount of hand force (only 0.8 PSI instead of 1.6 PSI). Another way to say this is that the *gain* of this pneumatic system is less with a larger bellows. Once again, the baffle will hardly move at all.

With the smaller bellows at work, and the force applied at the mid-point of the lever, the pressure will be 0.8 PSI because the bellows will only have to exert 0.6 pounds of force to balance the applied 1.2 pounds at the mid-point. Here, we see a different way to achieve a reduced gain that does not require a new bellows size.

---

Answer 45

- (1) Force-balance
- (2) Motion-balance
- (3) Force-balance
- (4) Force-balance
- (5) Motion-balance
- (6) Motion-balance
- (7) Force-balance
- (8) Motion-balance
- (9) Force-balance

The general principle to keep in mind here is that motion-balance instruments generate a *motion* to counteract an input motion in order to maintain a constant detector (flapper/nozzle) gap, while force-balance instruments generate a *force* to counteract an input force in order to maintain a constant detector (flapper/nozzle) gap.

Example number 9 is tricky, because one might argue it is *motion-balance* by virtue of the lower bellows' stretching motion as output pressure increases. However, the fact that the two bellows' forces oppose each other to ensure the flapper remains *stationary* in order to hold a constant flapper/nozzle gap is a defining characteristic of any force-balance mechanism. Also, the degree of spring stiffness has no effect whatsoever on the gain of this mechanism, which it would if it were motion-balance (i.e. if the amount of motion generated per unit increase in output pressure were related at all to the amount of input pressure increase). The two bellows' *forces* will cancel each other to achieve equilibrium regardless of how much or how little the spring must compress in the process of achieving that balance. If this were a true motion-balance mechanism, weakening the spring (making it less stiff) would result in a decrease of output pressure because less pressure would be required to move as far as before. Here, a weakened spring would indeed result in the lower bellows expanding a greater distance than before to balance the same amount of input pressure, but this would actually be the same output pressure as before, meaning the change in required motion has no effect on the gain.

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Answer 46

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Answer 47

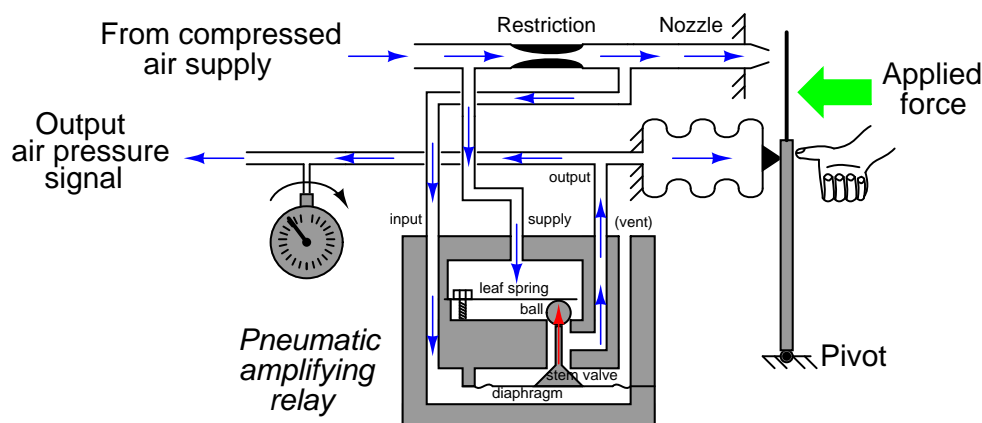
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Answer 48

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Answer 49

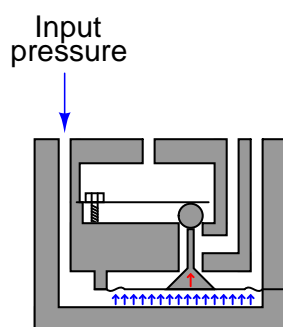
The particular pneumatic amplifying relay shown is the one typically used in Foxboro pneumatic instruments. It is not the only type of amplifying relay design, but a very common one.



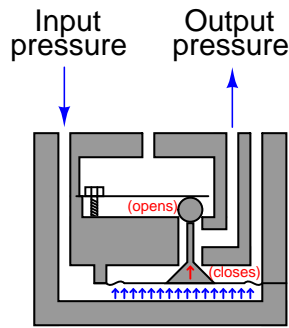
If the lever is pushed toward the nozzle by an external force, the following will happen:

- Pressure upstream of the nozzle will increase, as the nozzle becomes more restricted by the flapper.
- This pressure, going to the relay through the “input” port, will push *up* on the relay diaphragm.
- The relay diaphragm lifts up, pushing the stem valve closer to its seat, and lifting the ball off of its seat.
- As the ball lifts off its seat, more supply air is allowed to go into the area between the ball and stem.
- As the stem closes on its seat, the passage from this middle area to the vent port becomes more restrictive.
- As a result of the previous two factors, the output air pressure to the bellows will increase dramatically.
- The bellows will expand, pushing to the right on the lever.
- As the flapper will move to the right until a condition of equilibrium is reached with the force from the thumb.

The operation of the pneumatic relay might require a bit more explanation for full understanding. The “input” pressure sent to the relay from the nozzle tube pushes against the full area of the diaphragm, creating an upward force. Since the area above the diaphragm is vented (at atmospheric pressure), there can be no substantial pressure buildup on the top side of the diaphragm, and thus no downward force generated by the diaphragm to counter the input pressure’s upward force:



This force acts to lift the “ball” valve off its seat and also close the cone-shaped “stem valve,” adding more pressure to the output chamber by opening the passage for supply air to enter and closing the passage for air to vent, respectively:



The only force opposing the diaphragm's upward motion is a small leaf spring pressing down against the ball. This spring is not very strong, meaning that small changes in input pressure result in large changes in output pressure. In other words, the pneumatic amplifying relay has a very large *gain*.

Pneumatic relays such as this serve the same purpose as operational amplifiers in electronic circuits: amplifiers with extremely high gains, used within negative feedback loops to achieve some lesser amount of amplification that is very nearly linear. In this particular example, the final result (flapper, nozzle, lever, relay, and bellows) is a force-balance system that aggressively responds to any external force applied to the lever, such as the force exerted by someone's thumb. In a real pneumatic instrument, this external force would represent some signal or process variable, and the balancing pressure at the bellows would be the instrument's pneumatic output signal.

The presence or absence of the pneumatic amplifying relay does *not* alter the pressure/force relationship of this mechanism. The relay merely increases sensitivity to small changes in force, and increases the speed of response.

Answer to challenge question: although narrowing the restriction would decrease nozzle air flow, this would have no effect on the pressure/force relationship of this mechanism. It is *still* a force-balance system where bellows force must equal applied force to reach a state of equilibrium, and this bellows force is strictly a function of nozzle pressure ( $F = PA$ ) not nozzle flow rate.

It should be noted that the actual gain of the pneumatic amplifier ( $\frac{\Delta P_{out}}{\Delta P_{in}}$ ) is irrelevant, so long as it is arbitrarily large. This is analogous to the open-loop voltage gain of an operational amplifier being largely irrelevant to the overall voltage gain of a negative-feedback circuit. In other words, the presence of this amplifying relay does not alter the input force / output pressure relationship of this pneumatic mechanism.

In order to alter the pressure/force relationship of this mechanism, one would have to alter the feedback components: either change the effective area of the bellows, or the moment arm through which it acts to counteract the applied force.

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Answer 51

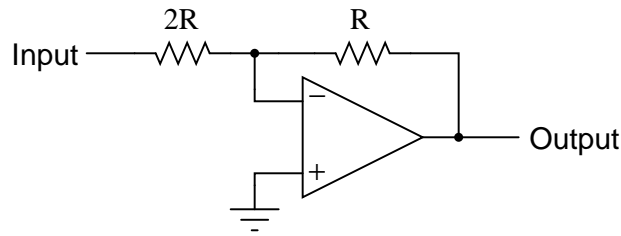
- Clogged nozzle: *output pressure saturates high*
- Clogged restriction: *output pressure saturates low*
- Clogged tube at supply port of amplifying relay: *output pressure saturates low*
- Broken leaf spring inside amplifying relay: *output pressure may saturate high or possibly oscillate*
- Major hole or tear in diaphragm inside amplifying relay: *System responds very little to applied force*

---

Answer 52

The input pressure range is the greater of the two (6-30 PSI), and the output is the lesser of the two (3-15 PSI).

Follow-up question: explain how the following op-amp circuit is similar to the pneumatic system shown in the question.



---

Answer 53

The output pressure will not rise as much, with the same force applied to a point closer to the pivot.

---

Answer 54

The “normal” condition for a process switch is the condition of *least stimulus*. For example:

- A pressure switch will be in its “normal” state when there is *minimum pressure applied*
- A level switch will be in its “normal” state when there is *no level detected by the switch*
- A temperature switch will be in its “normal” state when it is *cold*
- A flow switch will be in its “normal” state when there is *no flow detected by the switch*

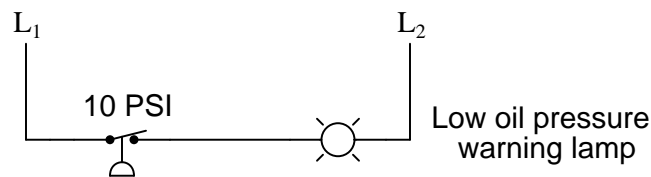
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Answer 55

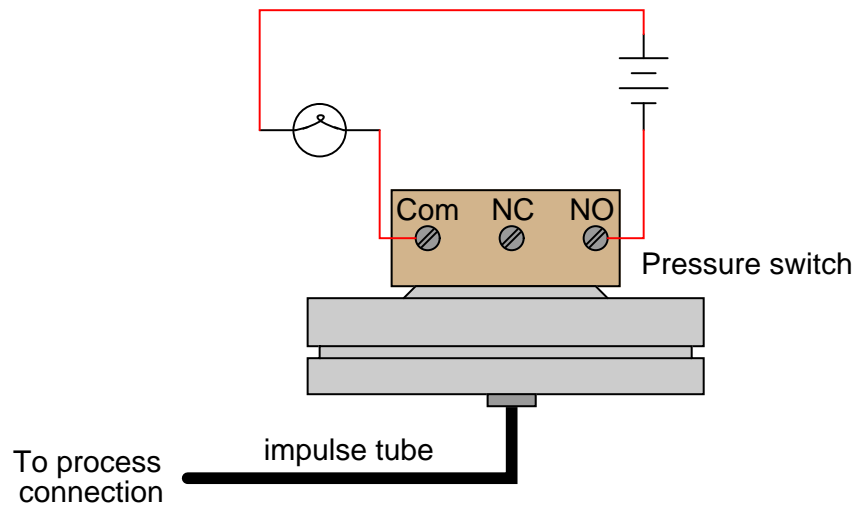
The lamp’s illumination signifies a condition where the compressed air pressure is somewhere between 85 and 115 PSI. The lamp will turn off if the pressure drops below 85 PSI *or* if the pressure rises above 115 PSI.

---

Answer 56



As the diagram shows, this needs to be a **normally-closed** switch.



First example:  $V_{out} = 6.8$  volts ;  $P_{out} = 6.8$  PSI ; force-balance.

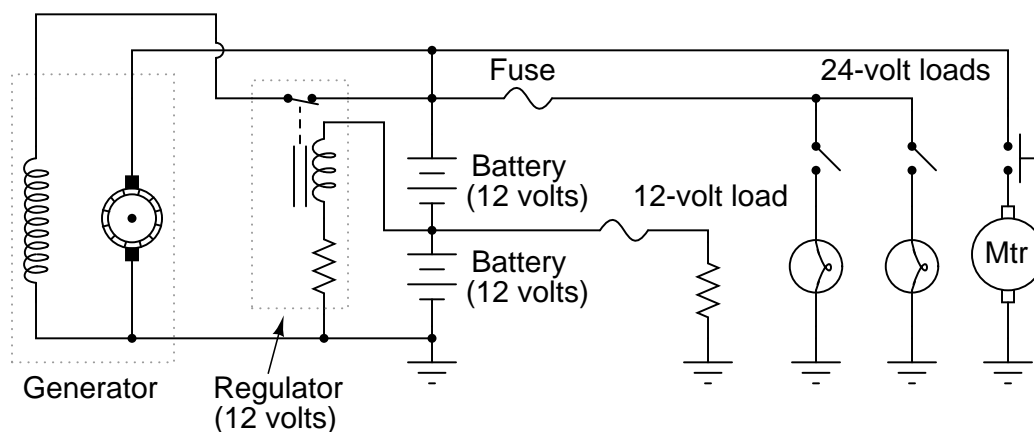
Second example:  $V_{out} = 10.2$  volts ;  $P_{out} = 10.2$  PSI ; motion-balance.

So long as the generator is capable of outputting 12 volts, this system will work!

In this question, we see a foreshadowing of op-amp theory, with the regulator's negative feedback applied to what is essentially a voltage divider (two equal-voltage batteries being charged by the generator). The regulator circuit senses only 6 volts, but the generator outputs 12 volts. Fundamentally, the focus of this question is *negative feedback* and one of its many practical applications in electrical engineering.

This idea actually came from my father, who did this very thing on an International T-4 bulldozer. An important difference is that he used a single 12-volt battery rather than two 6-volt batteries, creating a center-tap connection on the 12-volt battery to make it perform as two 6-volt batteries. To do this, he carefully drilled a hole in the top of the battery to intersect with the lead bus bar between the third and fourth cells, threading a screw into that bus bar as the center-tap terminal. In fact, the entire motivation for this project was that it was far cheaper for him to get a new 12-volt battery than to buy a new 6-volt battery, and he had plenty of 12-volt electrical accessories (headlights, ignition coils, etc.) to upgrade the bulldozer.

One of the readers of my online textbook wished to do something similar, except his plan was to make the vehicle's original 12-volt system output 24 volts so he could power surplus military accessories. An important distinction for this fellow's system is that he planned to have more than a few 12-volt loads remaining in the vehicle, such as a 12-volt radio:



As a challenge for your students, ask them how well they think *this* system would work. It is a bit more complex than the system shown in the question, due to the two different load banks.

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 Answer 60

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 Answer 61

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 Answer 62

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 Answer 63

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Answer 64

**Partial answer:**

Applied differential pressure = 0.969 PSID = 0.0668 bar (differential)

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Answer 65

Input pressure applied (" W.C.)	Percent of span (%)	Output signal <i>ideal</i> (mA)	Output signal <i>low</i> (mA)	Output signal <i>high</i> (mA)
50 L	0	4	3.984	4.016
37.5 H	25	8	7.984	8.016
125 H	50	12	11.984	12.016
212.5 H	75	16	15.984	16.016
350 H	100	20	19.984	20.016

Given the tolerance of  $\pm 0.1\%$  of the 350" span ( $\pm 0.35"$ ), the actual process pressure could be as low as 209.65 "W.C. or as high as 210.35 "W.C.



---

**Answer 66**

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

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

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

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

```
tar xvf tshoot*tar
```

```
make
```

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

```
./tshoot
```

---

**Answer 67**

Move the range wheel *up* in order to re-calibrate from 0-125 ”W.C. to 0-180 ”W.C.

Turn the zero screw for *less* tension against the range bar (less force pulling the bottom of the range bar to the right) in order to re-calibrate from 0-125 ”W.C. to 15-140 ”W.C.

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**Answer 68**

Move the magnetic shunt *further out* in order to re-calibrate from 3-15 PSI to 4-20 PSI.

Turn the zero screw so the spring doesn’t push down as hard on the right-hand side of the beam in order to re-calibrate from 3-15 PSI to 2-14 PSI.

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Answer 69

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Answer 70

- Receiver vessel drain valve left open – **No**
- Transmitter block valve shut and bleed valve open – **No**
- Transmitter block valve open and bleed valve shut – **No**
- PIC left in manual mode, 100% output (20 mA to I/P) – **Yes**
- Cable PV-6 severed (failed open) – **No**
- I/P air supply shut off – **No**
- Short between TB-52, terminals 1 and 2 – **Yes**
- Short between TB-52, terminals 15 and 16 – **No**
- PT-6 miscalibrated, registering 5 PSI too high – **No**
- PY-6 output failed high (15 PSI) – **Yes**

---

Answer 71

As the differential pressure increases (“high” side pressure increases relative to “low” side pressure):

- Diaphragm “capsule” is forced to the right.
- Force bar rotates counter-clockwise about the sealing diaphragm, which acts as a fulcrum for the force bar.
- Flapper approaches nozzle.
- Nozzle backpressure increases.
- Increased nozzle backpressure presses up on relay diaphragm.
- Inside relay, the ball-shaped supply valve opens and the cone-shaped vent valve closes.
- Relay output pressure increases (more than the nozzle backpressure increase, due to amplification).
- This output pressure is sent to the bellows, which presses to the left at the range bar’s lower end.
- Range bar rotates clockwise about the “range wheel” (movable fulcrum nut).
- Top of range bar moves to the right, pulling against the force bar to move the flapper away from the nozzle.
- System reaches equilibrium, where force exerted by the bellows against the range bar balances force exerted by diaphragm capsule against the force bar.

End result: output pressure equals some proportion (multiple or fraction) of differential pressure across diaphragm capsule.

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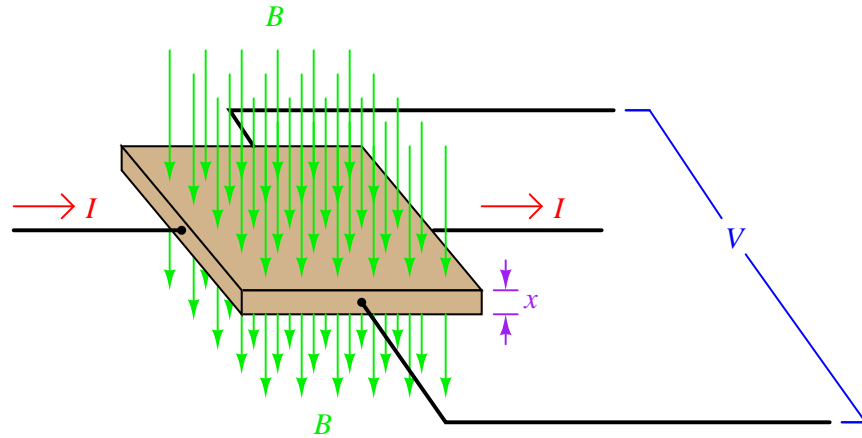
Answer 72

**Partial answer:**

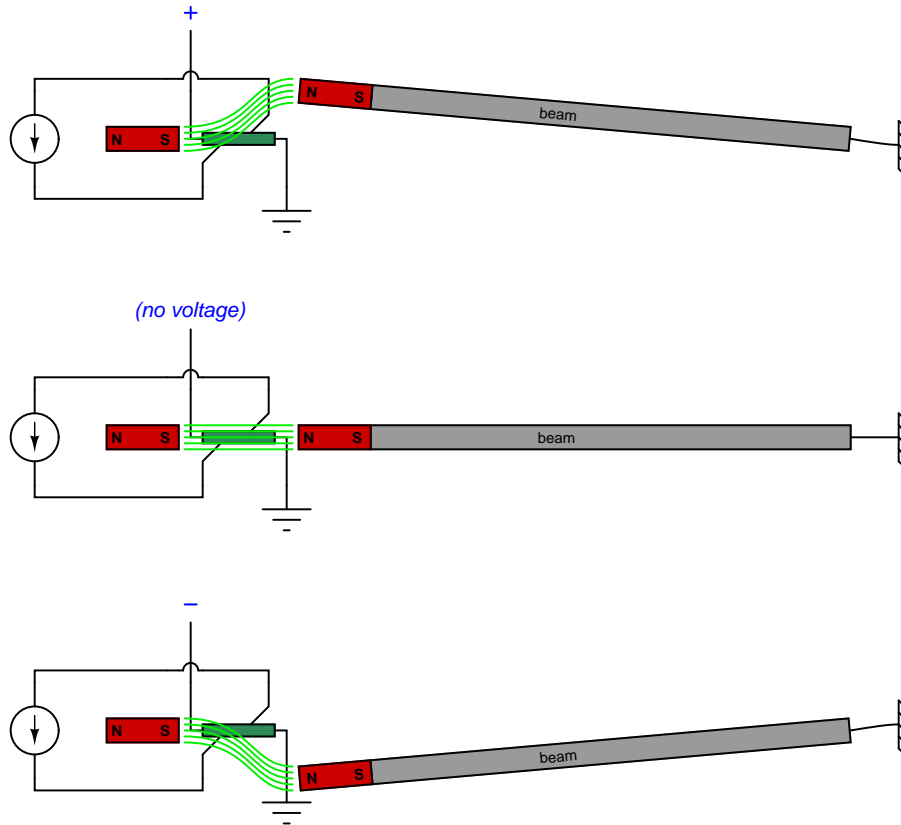
A *flexure* is a thin strip of springy material, usually spring steel, designed to act as a frictionless fulcrum and/or a pivoting link. Unlike bearings, flexures are usually not able to handle a lot of angular motion.

*Hall Effect* sensors are used to detect magnetic fields. They generate a DC voltage proportional to the magnitude and polarity of an applied magnetic field and the magnitude and direction of a perpendicular DC current:

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



The operation of the Hall Effect sensor may not be clear to all readers. It is oriented such that the magnetic field is parallel to the Hall Voltage axis and not perpendicular to it, when the beam is exactly level. When the beam tips up or down, however, the magnetic flux lines passing from the “North” tip of the beam’s magnet to the “South” tip of the stationary magnet to the left of the Hall Effect sensor will angle, passing through the Hall Effect sensor with a definite direction, either up or down, depending on which way the beam tips:



Thus, any output voltage from the Hall Effect sensor indicates an out-of-balance condition between the diaphragm and force motor.

---

#### Answer 74

Port “A” is the “high” pressure port on this transmitter, and port “B” is the “low” pressure port. Remember: an increasing pressure applied to the “high” port causes an increasing signal out of the transmitter. Conversely, an increasing pressure applied to the “low” port causes a decreasing signal out of the transmitter.

- PSL = Pressure Switch, Low
- PSH = Pressure Switch, High
- PSHH = Pressure Switch, High-High

Both warning lamps should be off when the steam pressure is between 80 and 200 PSI. The boiler will automatically shut down when the shutdown solenoid de-energizes, and this will happen if the steam pressure exceeds 220 PSI for at least 10 seconds.

The difference between a “normally open” process switch and a “normally closed” process switch is vitally important for technicians to understand. The “normal” condition referred to in each label does *not* mean the condition that is typical for the process. Rather, it refers to a condition where the switch is subjected to *minimum stimulus*. In other words, the “normal” condition for each switch is:

- Temperature switch = cold
- Pressure switch = low or no pressure
- Level switch = empty vessel
- Flow switch = low or no flow

---

Answer 76

A *stop* prevents the pressure element from being excessively strained by overpressure. Ultimately, it helps to prevent rupture of the element in the case of accidental overpressure.

When a pressure element flexes so far that it comes to rest against a stop, the stop begins to provide the opposition force to the force generated by the applied pressure, so the element does not have to strain further. Ideally, the stop(s) in an instrument will be set up to limit the element’s travel enough so that its elastic limit is never exceeded. However, the presence of a stop does not guarantee that the instrument will remain within calibration specifications after exposure to an overpressure!

Stops are important even in force-balance transmitters where the pressure element (hypothetically) never moves. Under certain overpressure conditions, the element will generate more force than the balance mechanism is able to counter, and so the pressure element will most definitely strain. A stop in a force-balance instrument helps ensure that even if the element strains, it will not strain too much.

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Answer 77

$$P_{high} = 748 \text{ mmHgA} = 0.9842 \text{ Atm} = 14.468 \text{ PSIA}$$

$$P_{low} = 0.15 \text{ Atm} = 2.205 \text{ PSIA}$$

$$\Delta P = 14.468 \text{ PSIA} - 2.205 \text{ PSIA} = 12.263 \text{ PSID}$$

Shut the block valve first, then open the bleed valve in order to remove the transmitter from service.

Prior to operating either the block or the bleed valve, the technician should first notify operations personnel that the transmitter will be taken out of service and therefore will *not* register any process vacuum in the near future. If the transmitter connects to a controller, that controller will need to be placed into manual mode. If the transmitter connects to any pressure alarms or (worse yet!) an emergency shutdown system, those alarms will have to be disabled and/or the shutdown function will have to be bypassed before taking the transmitter out of service.

Incidentally, the atmospheric pressure of 748 torr is equivalent to an altitude of 136 meters above sea level, which makes this a very realistic figure for an industrial application.

Fault	Possible	Impossible
PSHH failed open		✓
PSH failed open	✓	
PSL failed open	✓	
“Hand” switch position failed open		✓
“Auto” switch position failed open	✓	
OL contact failed open		✓
Auxiliary “M” contact failed		✓
Contactor “M” coil failed open		✓

The initial test between points **A** and **F** was useless. We already knew from the symptom of the compressor running in “Hand” but not in “Auto” that the fault must be an open, and it must lie between the Hand/Off/Auto switch and test point **A** somewhere. An open fault anywhere between points **A** and **F** would of course drop the full control voltage, so the measurement of 117 volts AC should come as no surprise.

- **Test 1:** Measured 120 VAC between points **A** and **C**, with “Hand/Off/Auto” switch in the “Auto” position. *Proves there is 120 VAC control power available, that the fuse is good, and that the Hand/Off/Auto switch is passing power through to point A.*
- **Test 2:** Measured 120 VAC between points **A** and **D**, with “Hand/Off/Auto” switch in “Auto” position. *Proves there is an “open” fault somewhere between those points, in one of the two switches, and that we do not have any other “open” faults in the contactor coil circuit.*
- **Test 3:** Measured 0 VAC between points **E** and **C**, with “Hand/Off/Auto” switch in “Auto” position. *This is an unnecessary test, as we already know there is continuity through the overload contact.*
- **Test 4:** Jumpered points **A** and **B**, with “Hand/Off/Auto” switch in “Auto” position. The motor did not start. *Combined with the results of previous tests, this test proves the “open” fault must lie between points B and D: namely the PSH.*

The fault is an “open” high pressure switch (PSH), or in the wires connecting the PSH to points **B** and **D**.

The Foxboro model 13 transmitter’s “zero” spring is a **tension** spring, pulling to the right on the bottom of the range bar. Tension is needed here to give the feedback bellows a force to push against with 3 PSI, since the diaphragm capsule generates no such force for the feedback bellows to react against.

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

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

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.