Flow measurement loop: *Questions 91 and 92,* **completed objectives due by the end of day 5, section 4**

Exam

Day 5 of next section – **Complete mastery of these objectives due by the next exam date**
Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages, currents, and phase shifts in an AC reactive circuit
- Calculate flow rate / pressure drop for a nonlinear flow element
- Determine suitability of different flow-measuring technologies for a given process fluid type
- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an "As-Found" table
- Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Calculate voltages and currents within balanced three-phase AC electrical circuits
- INST250 Review: Calculate split-ranged valve positions given signal value and valve calibration ranges
- INST262 Review: Determine proper AI block parameters to range a Fieldbus transmitter for a given application

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Recommended daily schedule

Day 1

Theory session topic: Flow measurement technologies
Questions 1 through 20; answer questions 1-10 in preparation for discussion (remainder for practice)

Day 2

Theory session topic: Fluid dynamics
Questions 21 through 40; answer questions 21-30 in preparation for discussion (remainder for practice)

Day 3

Theory session topic: Pressure-based flowmeters
Questions 41 through 60; answer questions 41-50 in preparation for discussion (remainder for practice)

Day 4

Theory session topic: High-accuracy pressure-based flow measurement
Questions 61 through 80; answer questions 61-70 in preparation for discussion (remainder for practice)

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

How To . . .

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

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

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

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

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

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

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

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

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

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

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

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

file `howto`

General Values, Expectations, and Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

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 241 Course Outcomes

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

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

- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]

- Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components. [Ref: Program Learning Outcome #5]

- Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Determine suitability of different flow-measuring technologies for a given process fluid type. [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]

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

- Determine the possibility of suggested faults in simple 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 labwork. [Ref: Program Learning Outcomes #1 and #2]

- Construct and commission a working temperature-measurement loop consisting of an electronic temperature transmitter, signal wiring, and SCADA RTU programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

- Construct and commission a working flow-measurement loop consisting of an electronic flow transmitter, signal wiring, and flow computer programmed in a text-based programming language. [Ref: Program Learning Outcome #5]

- Generate accurate loop diagrams compliant with ISA standards documenting your team's systems. [Ref: Program Learning Outcome #8]

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

- Calibrate an electronic RTD temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Calibrate an electronic thermocouple temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]

- Accurately simulate a thermocouple signal using a millivoltage source. [Ref: Program Learning Outcome #7]

- Accurately simulate an RTD signal using a potentiometer. [Ref: Program Learning Outcome #7]

- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]

- Edit text-based programming code for a flow computer. [Ref: Program Learning Outcome #5]

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

file `outcomes_INST241`

Sequence of second-year Instrumentation courses

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

(Only if 4th quarter was Summer: INST23x)

Prerequisite for all INST24x, INST25x, and INST26x courses

INST 200 -- 1 wk
Intro. to Instrumentation

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

Summer quarter

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

Jobshadow and/or Internship strongly recommended

Fall quarter

INST 240 -- 6 cr
Pressure/Level Measurement

INST 241 -- 6 cr
Temp./Flow Measurement

INST 242 -- 5 cr
Analytical Measurement

Winter quarter

INST 250 -- 5 cr
Final Control Elements

INST 251 -- 5 cr
PID Control

INST 252 -- 4 cr
Loop Tuning

Spring quarter

INST 260 -- 4 cr
Data Acquisition Systems

INST 262 -- 5 cr
Digital Control Systems

INST 263 -- 5 cr
Control Strategies

ENGT 134 -- 5 cr
CAD 1: Basics

Prerequisite for INST206

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

Graduate!!!

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

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

8

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

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

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

Beginning in Summer

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

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

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

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

Graduation!

Beginning in Fall

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

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

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

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

Graduation!

Beginning in Winter

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

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

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

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

Graduation!

Beginning in Spring

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

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

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

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

Graduation!

file sequence

General tool and supply list

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

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

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

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

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

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

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

file `tools`

Methods of instruction

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

Inverted theory sessions

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

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

Small sessions

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

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

Large sessions

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

Correspondence

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

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

Sample rubric for pre-assessments

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

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

Sample rubric for post-assessments

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

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

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

Methods of instruction (continued)

Lab sessions

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

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

Troubleshooting assessments must meet the following guidelines:

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

file `instructional`

Distance delivery methods

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

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

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

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

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

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

file distance

Metric prefixes and conversion constants

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

METRIC PREFIX SCALE

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

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

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

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^3) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

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

Conversion equivalencies for velocity

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

Conversion equivalencies for mass

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

Conversion equivalencies for force

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

Conversion equivalencies for area

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

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

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

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

Conversion equivalencies for absolute pressure units (only)

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

Conversion equivalencies for energy or work

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

Conversion equivalencies for power

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

Acceleration of gravity (free fall), Earth standard

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

Physical constants

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

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

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

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

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

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

Properties of Water

Freezing point at sea level = 32°F = 0°C

Boiling point at sea level = 212°F = 100°C

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

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

Specific heat of ice $\approx$ 0.5 calories/g·^{o}C

Specific heat of steam $\approx$ 0.48 calories/g·^{o}C

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

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

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

Properties of Dry Air at sea level

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

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

file `conversion_constants`

How to get the most out of academic reading:
- <u>Outline, don't highlight!</u> 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.

- <u>Articulate your thoughts</u> 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.

- <u>Work through all mathematical exercises</u> shown within the text, to ensure you understand all the steps.

- <u>Imagine explaining concepts you've just learned to someone else.</u> 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.

- <u>Create your own questions</u> based on what you read, as a teacher would to challenge students.

How to effectively problem-solve and troubleshoot:
- <u>Rely on principles, not procedures.</u> 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.

- <u>Sketch a diagram</u> to help visualize the problem. <u>Sketch a graph</u> showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.

- <u>Identify</u> what it is you need to solve, <u>identify</u> all relevant data, <u>identify</u> all units of measurement, <u>identify</u> any general principles or formulae linking the given information to the solution, and then <u>identify</u> any "missing pieces" to a solution. <u>Annotate</u> all diagrams with this data.

- <u>Perform "thought experiments"</u> to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.

- <u>Simplify the problem</u> 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.

- <u>Check for exceptions</u> – does your solution work for *all* conditions and criteria?

- <u>Work "backward"</u> from a hypothetical solution to a new set of given conditions.

How to manage your time:
- <u>Avoid procrastination.</u> Work now and play later, every single day.

- <u>Consider the place you're in</u> 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).

- <u>Eliminate distractions.</u> 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.

- <u>Use your "in between" time productively.</u> 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 <u>persistence</u>, 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!

<u>file `question0`</u>

General challenges following a tutorial reading assignment

- <u>Summarize</u> as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an <u>intelligent child</u>: as simple as you can without compromising too much accuracy.
- Where did the text <u>make the most sense</u> to you? What was it about the text's presentation that made it clear?
- Was the text <u>confusing</u> 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 <u>improved</u>? Articulate your ideas for improvement, and explain why those improvements are indeed better.
- Did you encounter any <u>new concepts</u> in the text? If so, explain each in your own words.
- Did the text apply any <u>familiar concepts</u> (including fundamental laws or principles) in new ways? What exactly was different about this application?
- Was the text <u>surprising</u> to you in any way? If so, how so?
- What <u>background knowledge</u> should a reader possess prior to reading this text?
- Devise a <u>proof of concept</u> experiment to empirically demonstrate an important principle, physical law, or technical innovation represented in the text.
- Devise your own <u>thought experiment</u> to virtually demonstrate the same.
- Did the text reveal any <u>misconceptions</u> you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Devise an experiment to clearly <u>disprove</u> one of these misconceptions, to show by counter-example how the misconception in question cannot be true.
- Did the text model any useful <u>problem-solving strategies</u> for the benefit of the reader? If so, describe one of those strategies in terms general enough to apply to some other problem.
- <u>Devise a question</u> of your own to challenge a reader's comprehension of the text.
- Identify where it might be easy for someone to <u>misunderstand the text</u>.
- Describe your own <u>reading process</u>. Did you skim the text first and then read it in detail from start to finish? Do you take notes are 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 <u>strategy</u> for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Identify where any <u>fundamental laws or principles</u> apply to the solution of this problem.
- What would you say was the <u>most challenging part</u> of this problem, and why was it so?
- Was any important information <u>missing</u> from the problem which you had to research or recall?
- Was there any <u>extraneous</u> information presented within this problem? If so, what was it and why did it not matter?
- <u>Show the work</u> you did in solving this problem, even if the solution is incomplete or incorrect.
- Examine <u>someone else's solution</u> to identify where they applied fundamental laws or principles.
- <u>Simplify</u> the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a <u>limiting case</u> (i.e. altering a variable to some extreme or ultimate value).
- Is there <u>more than one way</u> to solve this problem? Which method seems best to you?
- For quantitative problems, identify the <u>real-world meaning</u> of all intermediate calculations: their units of measurement, where they fit into the scenario at hand.
- For quantitative problems, try approaching it <u>qualitatively</u> instead, thinking in terms of "increase" and "decrease" rather than definite values.

- For qualitative problems, try approaching it <u>quantitatively</u> instead, proposing simple numerical values for the variables.

- Were there any <u>assumptions</u> you made while solving this problem? Would your solution change if one of those assumptions were altered?

- Identify where it would be easy for someone to <u>go astray</u> in attempting to solve this problem.

- <u>Formulate your own problem</u> based on what you learned solving this one.

file `license`

Question 1

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Pressure-based flowmeters work by forcing the fluid to *accelerate* or *decelerate* as it flows through a pipe, which causes a static pressure difference to develop. Identify some of the different *flow elements* used to create the acceleration/deceleration inside a pipe (hint: a "venturi tube" is one example of a flow element creating a pressure differential).

For each of the flow elements you identify, determine whether it works by fluid acceleration or by fluid deceleration, and explain your reasoning.

In which region of a flow element is the pressure greatest, the region of *greatest velocity* or the region of *least velocity*? Hint: the orientation of the DP transmitter's "H" and "L" ports is a clue!

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04020

Question 2

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Two common styles of "variable area" flowmeter are *rotameters* and *weirs*. Explain how each one of these flowmeter types functions, and where (exactly) is the flow-path area varying as flow rate increases and decreases.

Describe the difference between a *weir* and a *flume*, and identify a practical application in industry where either one of these flow elements might be used.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04021

Question 3

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain how a *turbine* flowmeter measures the velocity of a fluid as it flows through a pipe.

Explain what the *von Kármán* effect is, and how it may be exploited to measure the velocity of a gas or liquid.

Explain how a *magnetic* flowmeter measures fluid velocity.

Explain how an *ultrasonic* flowmeter measures fluid velocity.

Explain how an *optical* flowmeter measures fluid velocity.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04022

Question 4

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Positive displacement flowmeters have moving parts inside to measure the passage of fluids through them, yet they are different from other flowmeter types using moving parts (such as turbine meters). Explain what is different about a "positive displacement" flowmeter.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04025

Question 5

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

One of the stranger flow-measurement technologies is the *Coriolis* flowmeter. Do your best to explain how this type of flowmeter functions.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04023

Question 6

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

A cold day "feels colder" if a strong wind is blowing. Describe how this principle may be exploited to measure the velocity of a fluid flowing through a pipe.

Based on what you know of modes of heat transfer, is the operating principle of a thermal flowmeter based on *conduction*, *convection*, or *radiation*?

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04024

Question 7

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Describe what a *weighfeeder* is, and what sort of process material flowrate it is designed to measure.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04026

Question 8

Skim the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

You have already explored how *load cells* may be used to infer the amount of material stored in process vessels. Explain how these same devices may be used to infer flowrate in and out of the same vessels using the *change-of-quantity* technique.

Suppose an instrument technician decides to build a flowmeter for her propane-fueled barbecue, by placing the propane fuel tank on top of an electronic weigh scale (like a standard bathroom scale). Explain how the technician could take the measurements given by this scale and somehow convert them to register as a *flowrate* of propane gas.

| Suggestions for Socratic discussion |

- Identify different strategies for "skimming" a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?

  file i04027

Question 9

Read and outline the "Work, Energy, and Power" subsection of the "Classical Mechanics" section of the "Physics" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04028

Question 10

Calculate the amount of potential energy stored in the mass of an elevator plus its cargo of potatoes (570 pounds) as it lifts up to a height of 10 feet. Express this potential energy in both British and metric units. Also, identify which equation is more convenient to use for this calculation: $E_p = Fx$ or $E_p = mgh$?

Calculate the kinetic energy of a bullet with a mass of 150 grains (9.7198 grams) traveling at a velocity of 2820 feet per second, expressing your answer in both British and metric units.

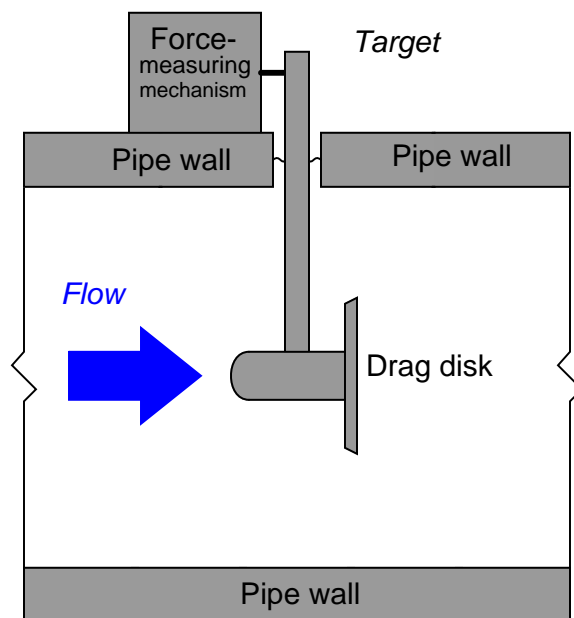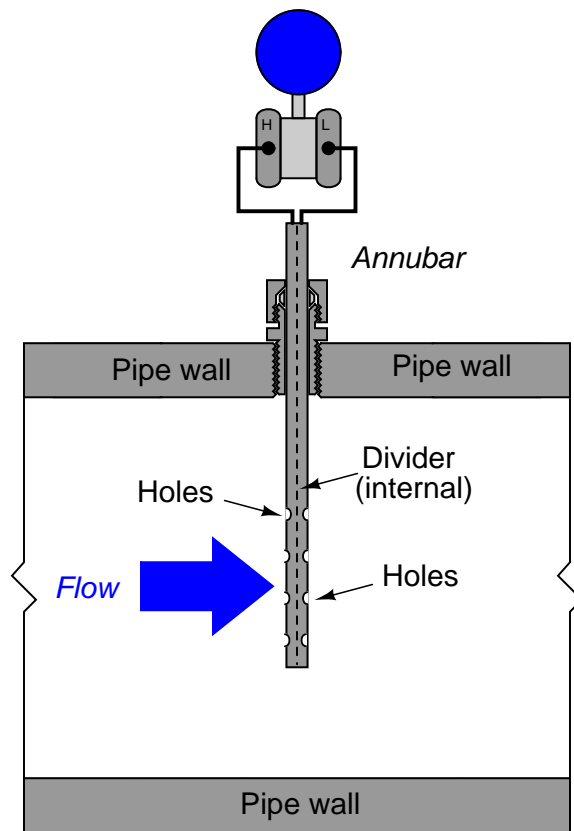| Suggestions for Socratic discussion |

- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Describe the various energy-transfer operations taking place when a crane lifts a heavy weight and then sets it down in a different location.
- If a crane lifts a weight 10 feet above the ground, then sets that weight down on top of an object 6 feet above the ground, is energy still conserved? Explain in detail.
- Identify how to secure a crane in a zero-energy state prior to performing maintenance work on it.
- Which has a greater effect on a moving object's kinetic energy: an increase in mass or an increase in velocity?
- If an automobile doubles its speed, how much longer (distance) will it take to skid to a complete stop if the driver suddenly applies the brakes?
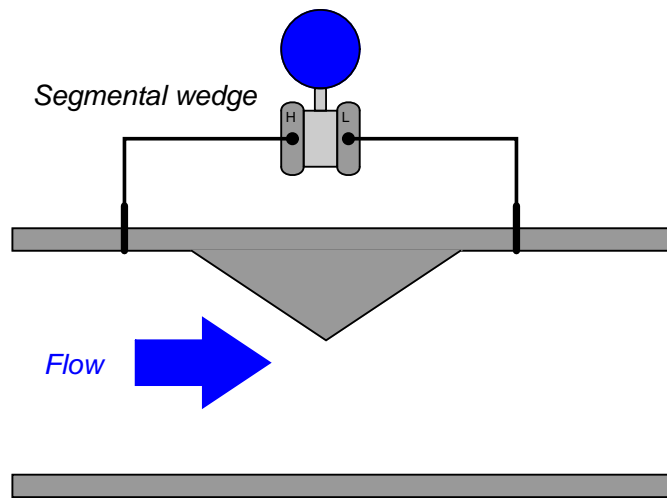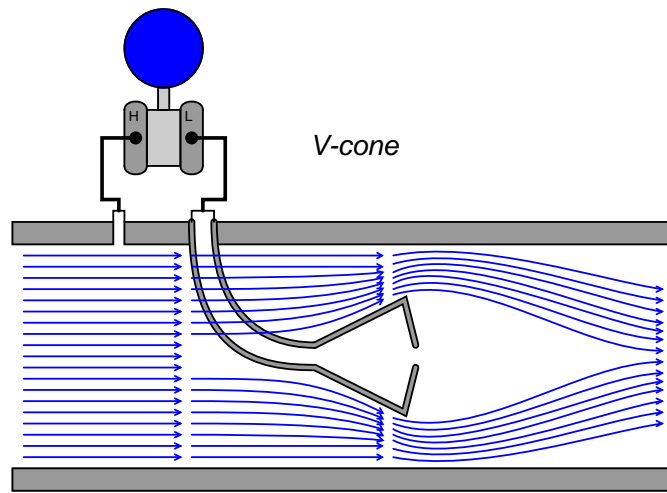
file i04029

The venerable *orifice plate* is but one of many different pressure-generating primary sensing elements (PSE's) for flow measurement. Briefly describe how each of these flow PSEs work, and how they compare against orifice plates in terms of application and performance:

Pipe elbow

Venturi tube

Flow

Flow

Flow nozzle

1D

¹/₂ D

Pipe wall

Flange   Flange

Pipe wall

Flange   Flange

Stud

Nut   Nut

Pitot tube

Pipe wall   Pipe wall

Holes

Flow

Pipe wall

Annubar

Pipe wall   Pipe wall

Divider
(internal)

Holes

Flow

Holes

Pipe wall

Force-
measuring
mechanism

Target

Pipe wall   Pipe wall

Flow

Drag disk

Pipe wall

28

V-cone

Segmental wedge
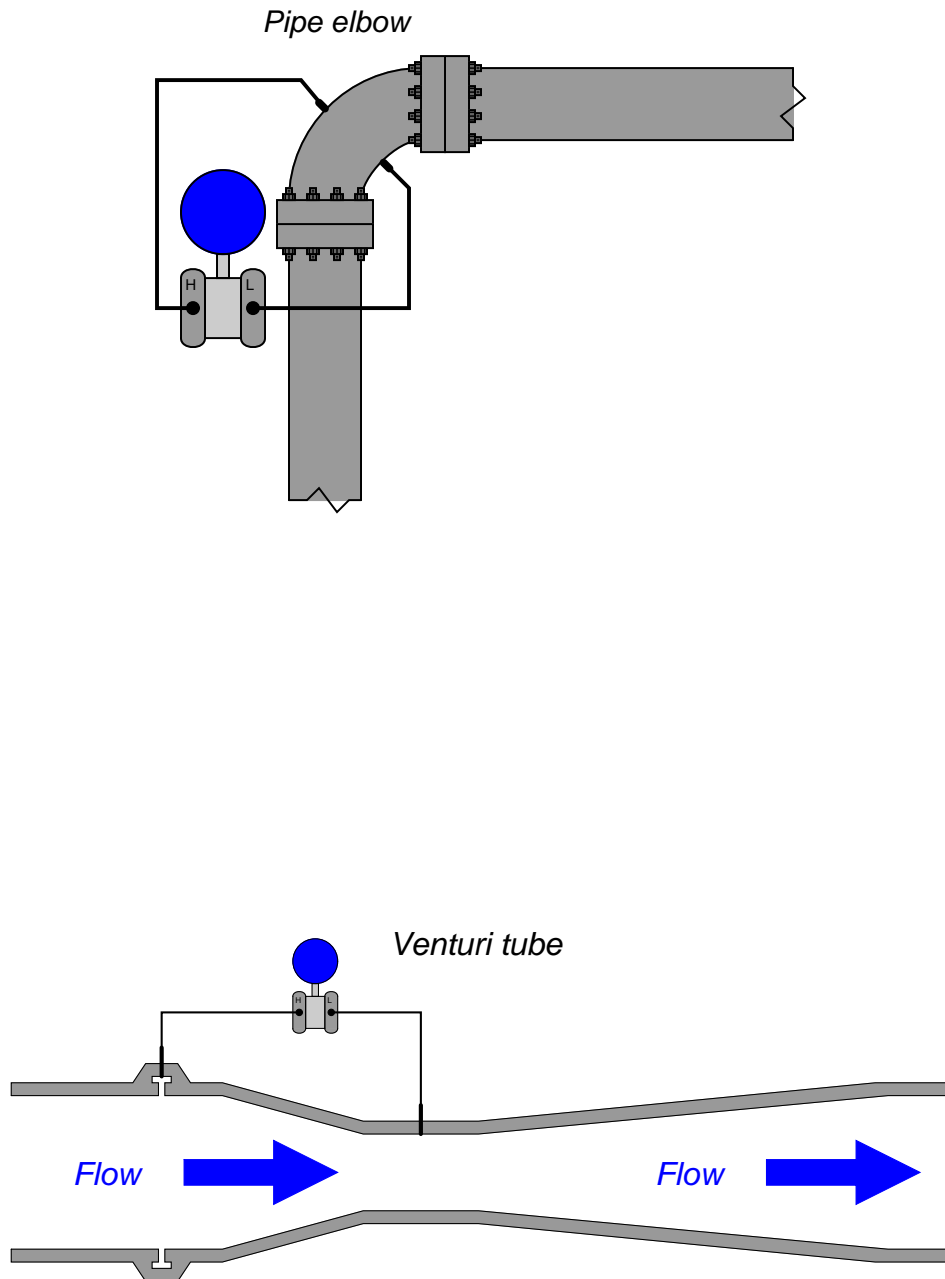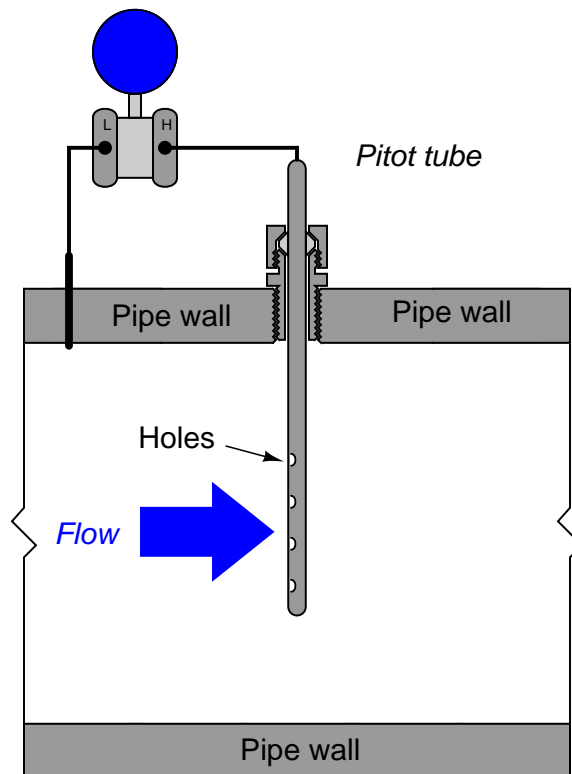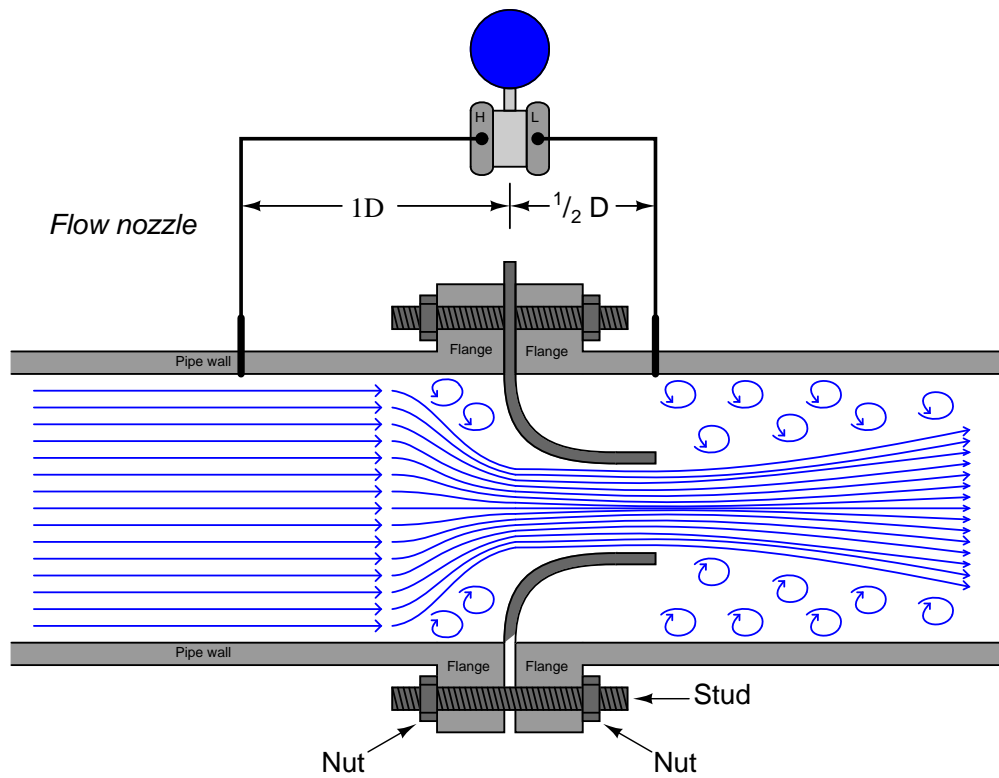
Flow

Question 12

Explain what a *weir* is, and how it works as a primary sensing element for flow.

Question 13

Explain what a *flume* is, and how it works as a primary sensing element for flow.

Question 14

Michael Faraday, the famous English physicist, once attempted to *electrically* measure the flow rate of the Thames river. His technique, unsuccessful as it was, was based on the idea of a fluid conductor moving perpendicular to a magnetic field. Explain what Michael Faraday did and how we may apply this technique (successfully!) to the measurement of fluids in pipes.

Question 15

Some animals use the principle of *echo-location* to find their way in the dark, where there is too little light to effectively use their eyes. Submarines use *sonar* to do the same thing. Explain how the same principle works to acoustically determine distance of a solid object, then determine how the same principle could be extended to determine the *speed* of a solid object.

file i00528

Question 16

What is meant by the phrase "mass flow measurement," especially as it compares to "volumetric flow measurement?" In other words, what is the practical difference between measuring flow rate in units of mass per time versus units of volume per time?

file i00499

Question 17

On cold days, the perception of ambient temperature becomes skewed with the presence of any substantial wind speed. Although a thermometer will not register a colder temperature if the wind blows, it certainly *feels* colder when the wind blows! This effect is commonly known as *wind chill*.

This same effect may be exploited to measure mass flow. Flowmeters based on this principle are called *thermal* mass flowmeters. Explain how a thermal mass flowmeter is constructed, and identify any physical properties of the fluid stream that will affect its calibration.

file i00534

Question 18

Coriolis-effect mass flowmeters have several advantages over other mass-flow technologies, which make them worth their high price in some applications. Identify what some of these advantages are. Also, identify some of their outstanding disadvantages (besides relatively high cost).

file i00539

Question 19

There is a problem somewhere in this liquid flow control system. The controller is in automatic mode, with a setpoint of 65%, yet the flow indicator and the flow controller both register 0.3%: (nearly) zero flow. A P&ID of the loop appears here:
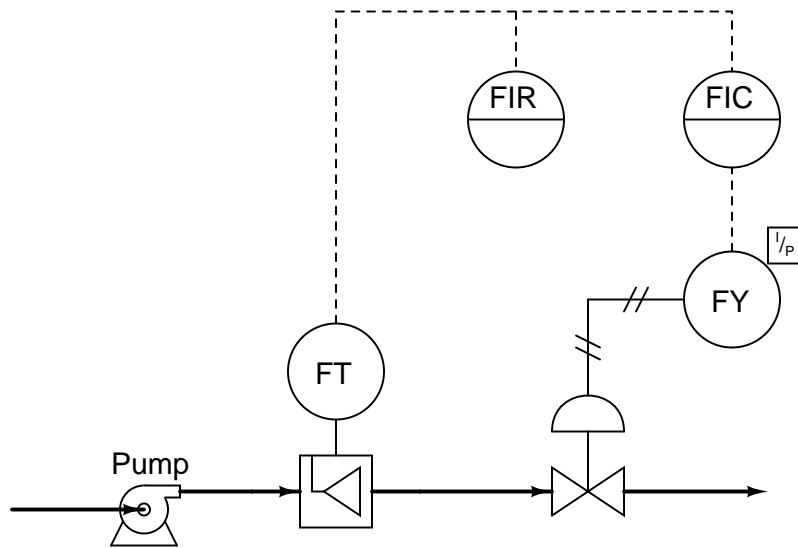
Explain how you would begin troubleshooting this system, and what possible faults could account for the controller not being able to maintain liquid flow at setpoint.

Suggestions for Socratic discussion

- Explain how you could divide this control system into distinct areas or zones which you may then begin to refer to when "dividing and conquering" the problem.

  file i02518

Question 20

Question 21

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

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

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

file i04030

Question 22

Read and outline the "Reynolds Number" subsection of the "Fluid Mechanics" section of the "Physics" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

file i04031

Question 23

Read and outline the "Law of Continuity" subsection of the "Fluid Mechanics" section of the "Physics" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04032

Question 24

Suppose we have a pipe with oil flowing through it at a rate (Q) of 70 cubic feet per minute and at a temperature of 113 degrees Fahrenheit. The first section of pipe is 8-inch (internal diameter = 7.981 inches) while the next section narrows to 2.5 inch (internal diameter = 2.469 inches):
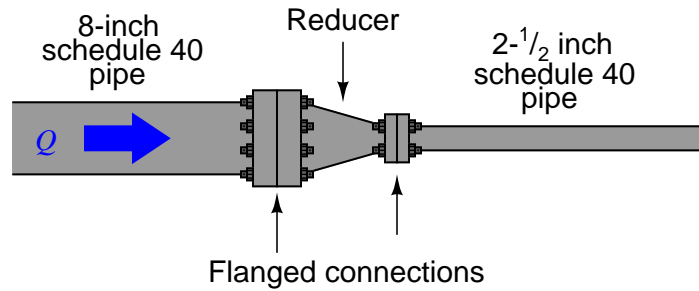
Calculate the average velocity of oil molecules as they travel through the 8-inch pipe section, and also the velocity as they travel through the narrower 2.5 inch pipe section. Also, calculate the volumetric flow rate in units of *gallons per minute* (GPM).

In which section of pipe does the oil flowstream have the greater Reynolds number?

Suggestions for Socratic discussion

- This question is a good application of the *Law of Continuity*, but this law is really nothing more than an expression of a more fundamental law in physics. What is this more fundamental law, and what does it tell us about flow through a pipe?
- Once we know the fluid velocity in one section of the pipe, show how we may calculate the velocity in the other section of the pipe using nothing but a ratio of pipe diameters ($\frac{7.981}{2.469}$), rather than re-calculate the continuity formula again ($v = \frac{Q}{A}$).
- Where along this pipe will individual fluid molecules possess the greatest kinetic energy?
- Explain why the *density* of the oil is irrelevant for calculating velocity.

file i04033

Question 25

A flowmeter installed in a 6-inch schedule 40 pipe (internal diameter = 6.065 inches) to measure the flow of olive oil requires a Reynolds number of at least 12,500 to function properly. Calculate the minimum flow rate of oil through this pipe that the flowmeter can measure, assuming the oil's density is 57.3 pounds per cubic foot and its absolute viscosity is 111 centipoise.

Additionally, calculate the minimum average flowing velocity of the olive oil for the flowmeter to properly function.

| Suggestions for Socratic discussion |

- How may a piping system be modified to increase the Reynolds number of the flow, for the sake of measuring that flow rate with a flowmeter requiring a high Reynolds number? Keep in mind that the actual flow rate is fixed here – we must vary something else to boost Reynolds number for any given flow rate.
- Does the temperature of the liquid have any effect on its Reynolds number? Why or why not?
- If this pipe were flowing water rather than olive oil, what would the minimum flow rate be to satisfy the Reynolds number requirement of this flowmeter?

file i04034

Question 26

Read and outline the "Bernoulli's Equation" subsection of the "Fluid Mechanics" section of the "Physics" chapter in your *Lessons In Industrial Instrumentation* textbook.

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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 i04035

Question 27

Read and outline the "Flow Through a Venturi Tube" subsection of the "Fluid Mechanics" section of the "Physics" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04036

Question 28

Examine this P&ID and explain how a vacuum is produced in the sour water storage tank (V-10):
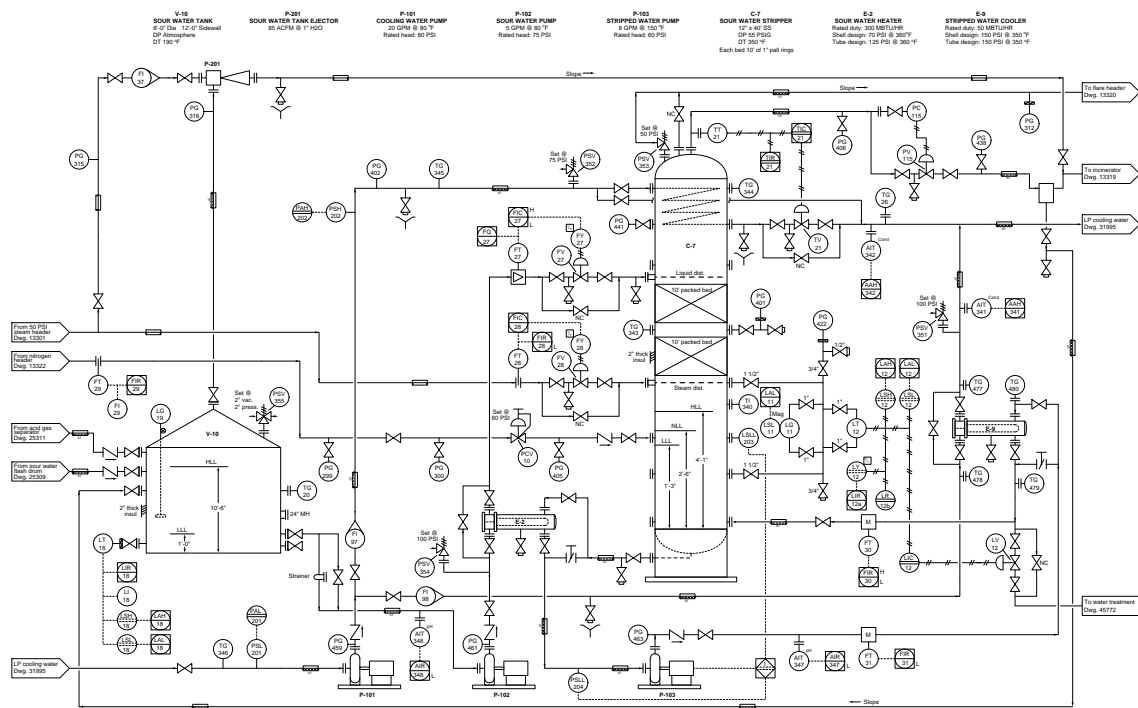
Furthermore, identify what operators would have to do in order to halt the production of vacuum, to make it safe to open an access hatch on V-10 for inspection. Also, identify how the level of sour water inside the tank is measured.
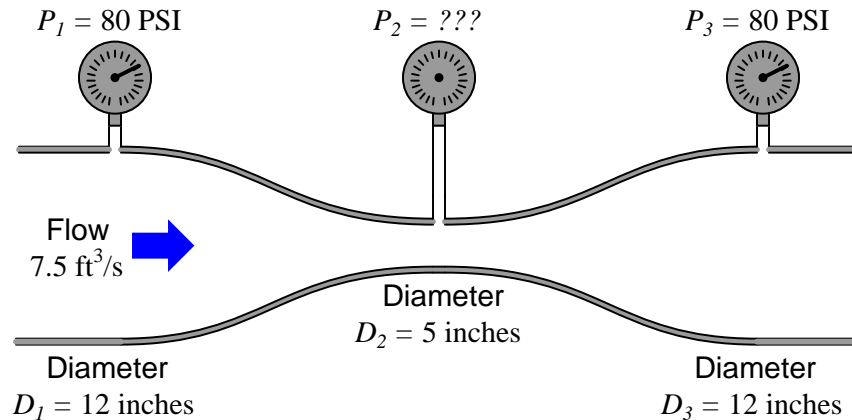

Suggestions for Socratic discussion

- Identify how this sour water storage tank is protected against excessive pressure or vacuum, which could rupture it or collapse it, respectively.

file i03490

Question 29

Use Bernoulli's equation to calculate the pressure at the throat of this "venturi" tube, assuming water flowing at a rate of 7.5 cubic feet per second (7.5 ft³/s), with a weight density (γ) of 62.4 lb/ft³ and a mass density (ρ) of 1.951 slugs/ft³:

Two versions of Bernoulli's equation are shown here, complete with descriptions of the variables and all the proper units of measurement. Either one should yield the same result:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

$$z_1 + \frac{v_1^2}{2g} + \frac{P_1}{\gamma} = z_2 + \frac{v_2^2}{2g} + \frac{P_2}{\gamma}$$

Where,
  z = Height of fluid, in feet (ft)
  ρ = Mass density of fluid, in slugs per cubic foot (slug/ft³)
  γ = Weight density of fluid ($\gamma = \rho g$), in pounds per cubic foot (lb/ft³)
  g = Acceleration of gravity (32.2 ft/s²)
  v = Velocity of fluid, in feet per second (ft/s)
  P = Pressure of fluid, in pounds per square foot (lb/ft²)

Lastly, calculate the *differential pressure* (DP) generated by this venturi tube.

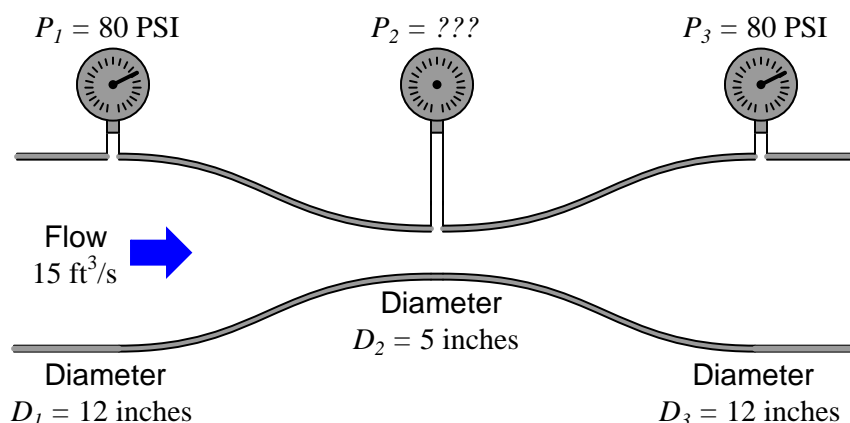### Suggestions for Socratic discussion

- The textbook outlines a general strategy for generating a problem-solving plan when tackling problems with complex mathematical formulae. Specifically, this strategy involved writing out the formulae and linking variables between formulae with arrow symbols. Explain how this strategy works, and show how it may be applied to the solution of this problem.
- A very helpful strategy for tackling Bernoulli's equation problems is to create a table in which to place each of the "head" terms of that equation. Explain why this is helpful to manage this specific type of problem.
- Once we know the velocity of the fluid (v) at any point in the tube, is there a way to easily solve for the velocity in any other point in the tube based on a ratio of tube diameters? For instance, here we know

there is a 5:12 ratio of diameters from the throat to the mouth of the tube. How can we employ this 5:12 ratio to easily determine the velocity at one point (either mouth or throat) knowing the velocity at another?

<u>file i00452</u>

Question 30

Use Bernoulli's equation to calculate the pressure at the throat of this "venturi" tube, assuming water flowing at a rate of 15 cubic feet per second (15 ft^3/s), with a weight density (γ) of 62.4 lb/ft^3 and a mass density (ρ) of 1.951 slugs/ft^3:

Two versions of Bernoulli's equation are shown here, complete with descriptions of the variables and all the proper units of measurement. Either one should yield the same result:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

$$z_1 + \frac{v_1^2}{2g} + \frac{P_1}{\gamma} = z_2 + \frac{v_2^2}{2g} + \frac{P_2}{\gamma}$$

Where,

z = Height of fluid, in feet (ft)
ρ = Mass density of fluid, in slugs per cubic foot (slug/ft^3)
γ = Weight density of fluid ($\gamma = \rho g$), in pounds per cubic foot (lb/ft^3)
g = Acceleration of gravity (32.2 ft/s^2)
v = Velocity of fluid, in feet per second (ft/s)
P = Pressure of fluid, in pounds per square foot (lb/ft^2)

Lastly, calculate the *differential pressure* (DP) generated by this venturi tube.

Suggestions for Socratic discussion

- The textbook outlines a general strategy for generating a problem-solving plan when tackling problems with complex mathematical formulae. Specifically, this strategy involved writing out the formulae and linking variables between formulae with arrow symbols. Explain how this strategy works, and show how it may be applied to the solution of this problem.
- A very helpful strategy for tackling Bernoulli's equation problems is to create a table in which to place each of the "head" terms of that equation. Explain why this is helpful to manage this specific type of problem.
- Venturi tubes are often used to create *vacuums*, by passing some fluid through the venturi at high speed and then providing a vacuum tap at the throat. Automobile engine carburetors and atomizing spray

guns are two prominent examples of this. In industry, another example is the so-called *steam eductor*, using a jet of high-velocity steam through a venturi to create continuous suction (vacuum). Are there any advantages to using eductors to create vacuums as opposed to using mechanical vacuum pumps? Are there any disadvantages to the use of eductors for creating vacuums?

file i00451

Question 31

As best as possible, define *Reynolds number* for a fluid flow using your own words.

Then, calculate the Reynolds number for 500 gallons per minute of water (at 20° C) flowing through a pipe with an inside diameter of 8.5 inches.

file i00440

Question 32

I can fill a 1-gallon jug with water from my kitchen faucet in 30 seconds. The copper tubing supplying water to the faucet has an inside diameter of 1/2 inch. Calculate the Reynolds number of the water flow stream inside the copper tubing. Is this Reynolds number value indicative of *laminar* or *turbulent* flow?

file i00442

Question 33

One of the most fundamental relationships in the study of electricity is *Ohm's Law*. This mathematical expression relates the flow of electric charge (I, which we call *current*) to electromotive potential (V, which we call *voltage*) and opposition to charge flow (R, which we call *resistance*):
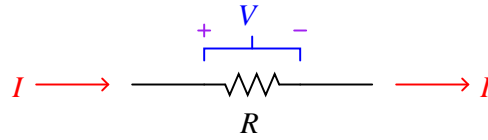
Arrows point in direction of conventional flow

$$I = \frac{V}{R} \quad \text{(For all conditions)}$$

The relationship between **liquid** flow rate, pressure drop, and "resistance" for a piping restriction (orifice, throttling valve, pipe bend, etc.) is not as simple. No single mathematical expression is sufficient to predict flow rates for all conditions:
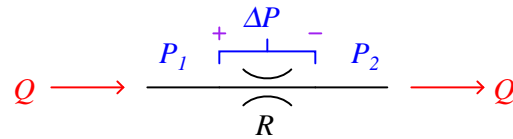

$$Q = \frac{P_1 - P_2}{R_1} = \frac{\Delta P}{R_1} \quad \text{(For laminar flow conditions only)}$$

$$Q = \sqrt{\frac{P_1 - P_2}{R_2}} = \sqrt{\frac{\Delta P}{R_2}} \quad \text{(For turbulent flow conditions only)}$$

Shunt resistors may be used as electric current-measuring elements, producing a voltage drop in precise proportion to the current through it. All we need to know is the shunt resistance, and we may infer current by measuring voltage. In a similar manner, orifices may be used as liquid flow-measuring elements, producing a pressure drop that varies with the amount of flow passing through it:

*Measuring electric current*   *Measuring fluid flow*
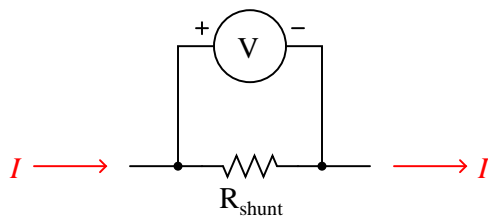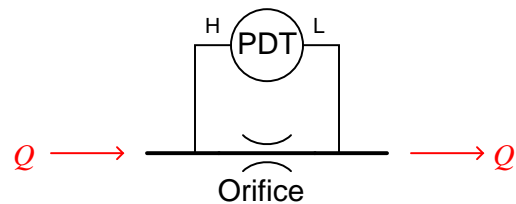
Given the "Ohm's Law" equations shown for liquid flow, identify what we would have to know before using an orifice as an accurate liquid flow-measuring device, and how we would be able to obtain that information. Also identify the type of sensing instrument we would need to measure the pressure, so we could infer flow rate from its reading.

file i00086

Question 34

One of the most fundamental relationships in the study of electricity is *Ohm's Law*. This mathematical expression relates the flow of electric charge (I, which we call *current*) to electromotive potential (V, which we call *voltage*) and opposition to charge flow (R, which we call *resistance*):
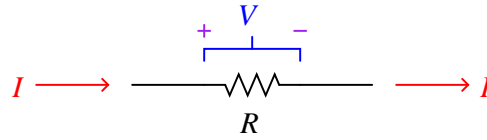
Arrows point in direction of conventional flow

$$I = \frac{V}{R} \quad \text{(For all conditions)}$$

The relationship between **gas** flow rate, pressure drop, and "resistance" for a piping restriction (orifice, throttling valve, pipe bend, etc.) is not as simple. No single mathematical expression is sufficient to predict flow rates for all conditions:
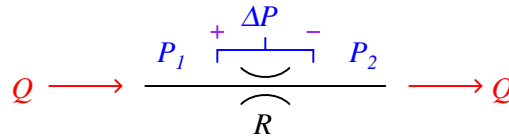

$$Q = \frac{P_1 - P_2}{R_1} = \frac{\Delta P}{R_1} \quad \text{Subsonic velocity with small } \Delta P$$

$$Q = \sqrt{\frac{P_1 - P_2}{R_2}} = \sqrt{\frac{\Delta P}{R_2}} \quad \text{Subsonic velocity with moderate } \Delta P$$

$$Q = \sqrt{\frac{P_2(P_1 - P_2)}{R_3}} = \quad \text{Subsonic velocity with large } \Delta P$$

Shunt resistors may be used as electric current-measuring elements, producing a voltage drop in precise proportion to the current through it. All we need to know is the shunt resistance, and we may infer current by measuring voltage. In a similar manner, orifices may be used as gas flow-measuring elements, producing a pressure drop that varies with the amount of flow passing through it:

*Measuring electric current*   *Measuring fluid flow*
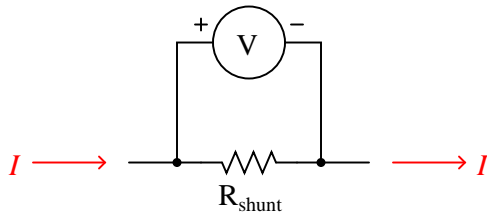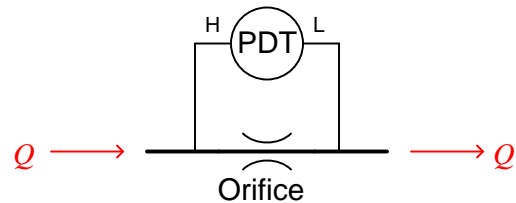
Given the "Ohm's Law" equations shown for gas flow, identify what we would have to know before using an orifice as an accurate gas flow-measuring device, and how we would be able to obtain that information.

Also identify the type of sensing instrument(s) we would need to measure the pressure, so we could infer flow rate from its reading.

file i00087

Question 35

If we poke a hole at the bottom of a vessel containing an otherwise static column of liquid, we have an application for Bernoulli's equation at three different points in the system:
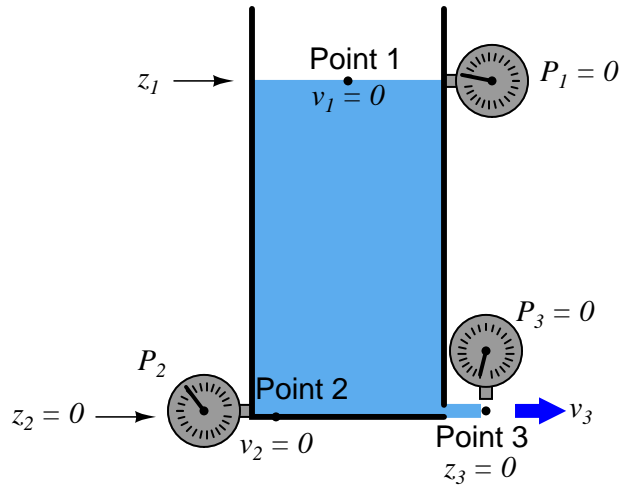
Note that point 1 has no velocity or pressure, but it does have elevation (height); point 2 has no velocity or elevation, but it does have pressure; and point 3 has no elevation or pressure, but it does have velocity.

Use Bernoulli's equation to write a new equation relating the elevation of point 1 with the pressure of point 2 and the velocity of point 3, and then solve for the velocity at point 3 in terms of the other two points' non-zero variables.
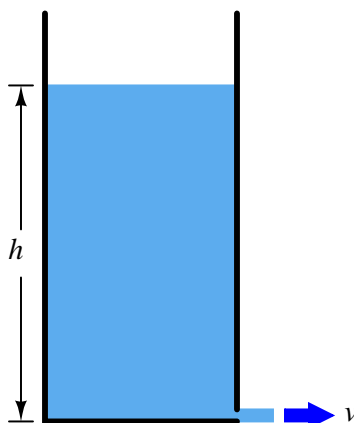
Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

file i00446

44

Question 36

Almost one century prior to Daniel Bernoulli's famous equation (1738), an Italian named Evangelista Torricelli (1643) discovered that the velocity of a liquid stream exiting a vessel was proportional to the square root of the height of the liquid column inside the vessel:

$$v = \sqrt{2gh}$$

Where,

v = Liquid stream velocity, in meters per second (m/s)

g = Acceleration of gravity, in meters per second squared (m/s^2)

h = Height of liquid column, in meters (m)

An interesting aspect of Torricelli's discovery was that this velocity did not depend at all on the density of the liquid. In other words, the velocity of a mercury stream would be the same as the velocity of a water stream so long as the two liquids' column heights were equal.

It should come as no surprise that Torricelli was a student of Galileo, the man who discovered that the velocity of a falling object did not depend upon the mass of the object (neglecting the effect of air friction).

Use algebra to prove falling objects follow the same basic rule, namely that free-fall velocity is a function of height alone and not mass (neglecting air friction):
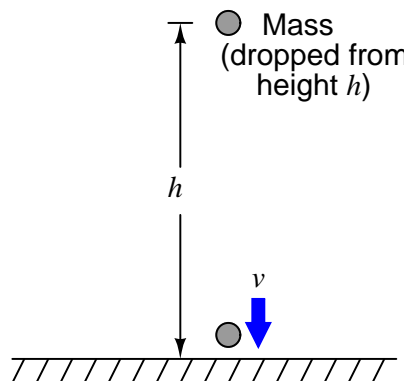
Potential energy of mass at height h (before falling) = mgh

Kinetic energy of mass just before it hits the ground = $\frac{1}{2}mv^2$

Do you notice a similarity between the Torricelli's formula and the one you derived from the potential and kinetic energy equations?

file i00447

Question 37

Calculate the pressure at the discharge end of this pipe (P_2), assuming water as the fluid (with a mass density $\rho = 1.951$ slugs/ft^3), 32.2 ft/s^2 as the acceleration of gravity (g), and frictionless flow (no pressure loss due to friction):
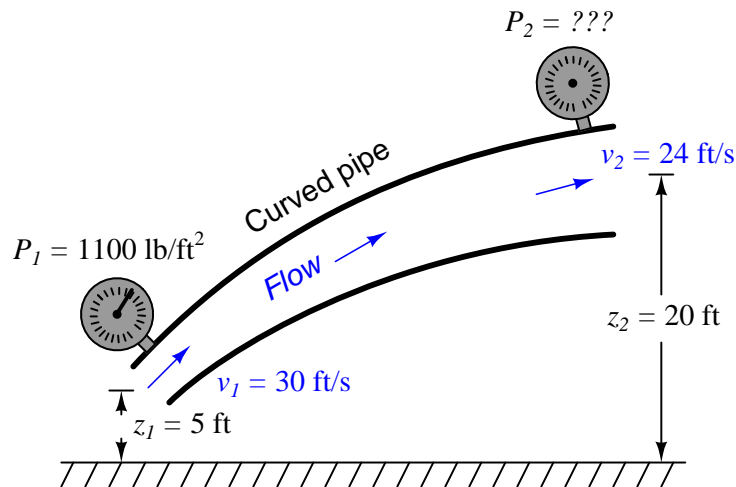
Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Suggestions for Socratic discussion

- One way students commonly fail to arrive at the correct answers with Bernoulli's Law calculations is by using incompatible units of measurement. Show how all the units of measurement provided to you in this question are compatible in their given forms, with no need for conversion.

file i00450

Question 38

Calculate the flow rate necessary (in units of gallons per minute) to create exactly 0 PSI gauge pressure at the throat of this venturi, and also calculate the (ideal) pressure at the third gauge. Assume water with a mass density (ρ) of 1.951 slugs per cubic foot:

$P_1 = 100$ PSI $P_2 = 0$ PSI $P_3 = ???$

$Q = ???$

Diameter
$D_2 = 5$ inches

Diameter
$D_1 = 12$ inches

Diameter
$D_3 = 12$ inches
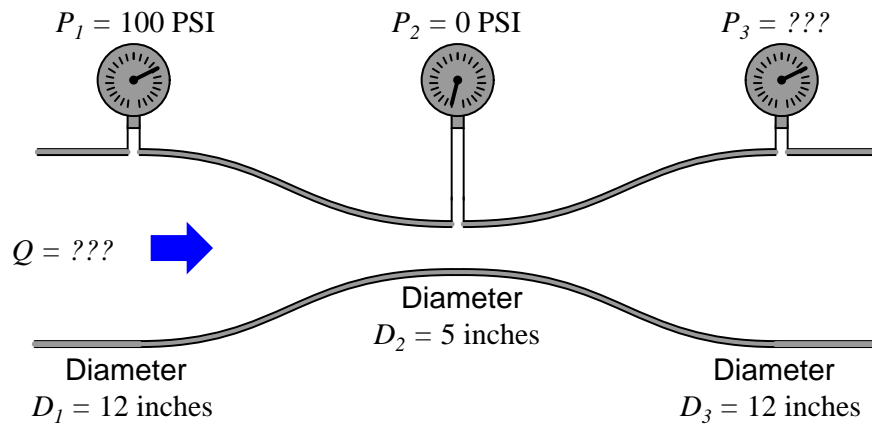
Furthermore, determine what will happen to the pressure at the throat if the flow rate increases beyond this rate, assuming all other factors remain unchanged?

file i00444

Question 39

Calculate the pressures P_1 and P_2, assuming a fluid mass density of 1.72 slugs per cubic foot:

$P_2 = ???$

8-inch pipe
(schedule 80)
ID = 7.625 inches

9.1 feet

6-inch pipe
(schedule 80)
ID = 5.761 inches

$P_1 = ???$

6.75 feet

$P = 302$ PSI

$P = 145$ PSI

8-inch pipe
(schedule 40)
ID = 7.981 inches

Pump

8-inch pipe
(schedule 40)
ID = 7.981 inches

$Q = 2000$ GPM
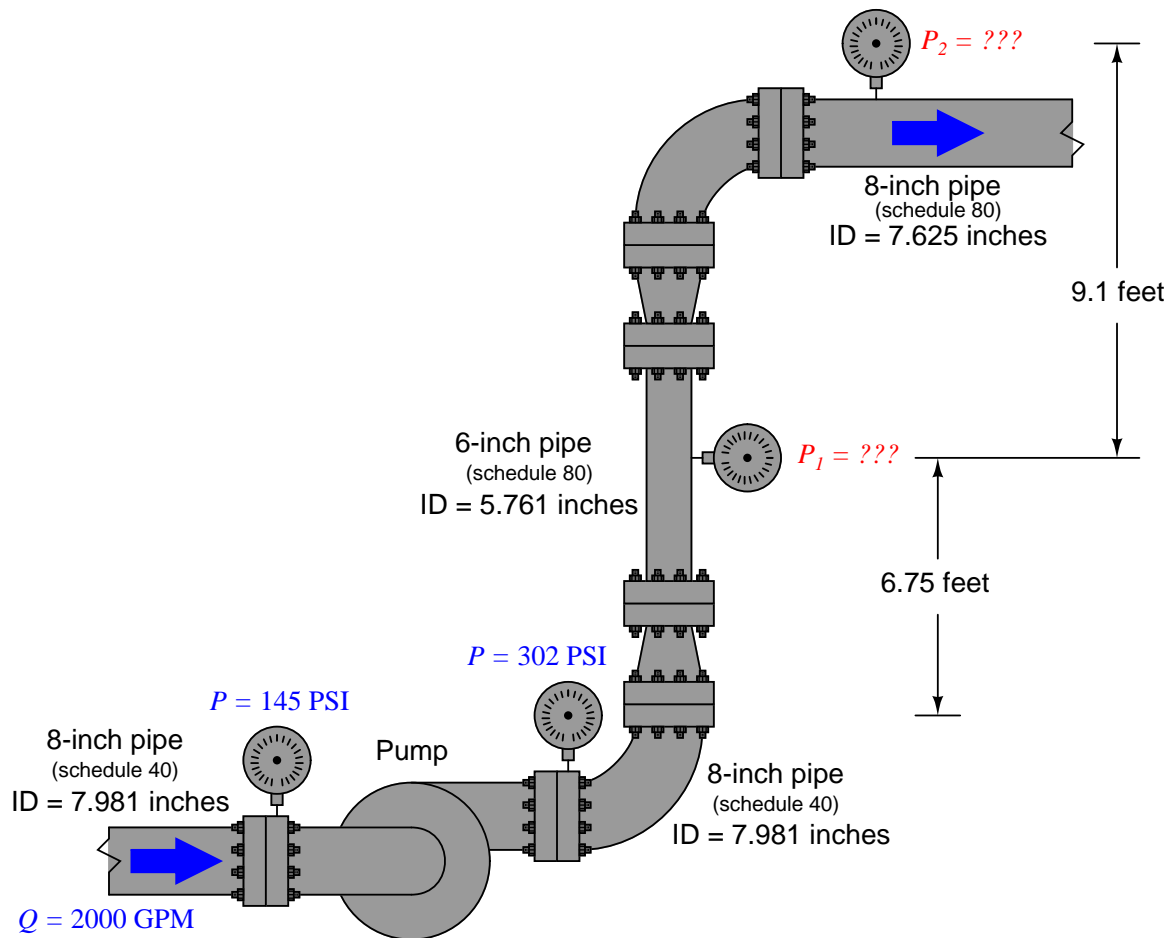
Also, comment on whether or not Bernoulli's equation could be used to compare the suction and discharge pressures of the pump, being that those two pressures (145 and 302 PSI) are measured on the same size pipe, with the same flow rate, and very similar elevations (heights).

file i00457

Question 40

Question 41

Read and outline the "Venturi Tubes and Basic Principles" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow 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 i04037

Question 42

Read and outline the "Volumetric Flow Calculations" and "Mass Flow Calculations" subsections of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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- 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 i04038

Question 43

Read and outline the "Square-Root Characterization" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow 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 i04039

Question 44

Read and outline the "Orifice Plates" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow 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 i04040

Question 45

Read and outline the "Other Differential Producers" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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- Descriptions of problem-solving strategies applied by the author

file i04041

Question 46

Read and outline the "Proper Installation" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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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 i04042

Question 47

The rate of volumetric flow through *any* head-generating flow element is proportional to the square root of the differential pressure measured across it, so long as the flow regime is "fully-developed" turbulent:

$$Q \propto \sqrt{P}$$

Re-write this proportionality in the form of an equation, then solve for the new constant of proportionality (k) given these full-flow ratings for an orifice plate:

- Full flow $Q = 1200$ GPM
- ΔP at full flow $= 100$ " H_2O

Now that you have a value for k, solve for the differential pressure across the orifice plate at these flow rates:

- $Q = 500$ GPM ; ΔP = _____ inches water column

- $Q = 245$ GPM ; ΔP = _____ inches water column

- $Q = 630$ GPM ; ΔP = _____ inches water column

- $Q = 950$ GPM ; ΔP = _____ inches water column

- Explain why we need not pay attention to maintaining compatible units of measurement for flow and pressure when solving this type of problem the way we did when using Bernoulli's equation directly.
- Why is it okay to use this general formula for *any* primary flow element based on differential pressure? There are many different types of flow elements (venturis, orifices, nozzles, Pitot tubes, segmented wedge tubes, etc.), each with its own unique design. What is common to all these elements that the same basic equation form may be used to describe the operation of them all?

file i00474

Question 48

Suppose a 6 inch V-cone flow element is sized to generate a ΔP of 125 inches water column at a flow rate of 700 gallons per minute of water. Determine the new differential pressure instrument calibration ranges if this same flow element will now be used to measure the following water flow ranges:

- Q range = 0 to 500 GPM ; ΔP range = _____

- Q range = 0 to 600 GPM ; ΔP range = _____

- Q range = 0 to 800 GPM ; ΔP range = _____

- Q range = 0 to 1000 GPM ; ΔP range = _____

Suggestions for Socratic discussion

- If the density of the fluid being measured by this flowmeter were to suddenly change, would it affect the *zero*, the *span*, or the *linearity* of the flowmeter's calibration?

file i00475

52

Question 49

A horizontal venturi tube at a seawater desalinization plant is sized to produce 11 inches of mercury column (11 "Hg) while flowing 6,000 gallons per minute of sea water (at a density of 1.025 grams per cubic centimeter).

Calculate the differential pressure produced by this same venturi tube at a flow rate of 4,250 GPM, and at a lighter density of 1.01 g/cm^3.

Assuming a water density of 1.03 g/cm^3 and a measured differential pressure of 3.1 PSID, calculate the volumetric flow rate through the venturi tube.

Assuming a water density of 1.02 g/cm^3 and a measured differential pressure of 12 kPaD, calculate the volumetric flow rate through the venturi tube.

Suggestions for Socratic discussion

- What is the purpose of a "desalinization" plant, and where might you expect to find one?

    file i04043

Question 50

A Foxboro pneumatic square root extractor has a calibrated range of 3 to 15 PSI for both input and output. Complete the following table of values for this relay, assuming perfect calibration (no error). Be sure to show your work!

Input signal (PSI)	Percent of input span (%)	Percent of output span (%)	Output signal (PSI)
5			
13			
	50		
	30		
		80	
		15	
			7
			12

Suggestions for Socratic discussion

- Why are pneumatic square-root extractors all but obsolete in modern industry? What has replaced their functionality?
- Share problem-solving techniques for obtaining answers to this problem.

    file i00100

Question 51

Calculate the volumetric flow rate (in units of cubic feet per minute) for water flowing out of the 10-inch diameter discharge pipe of a centrifugal pump at a velocity of 25 feet per second. Then, convert that flow rate into units of gallons per minute.

    file i00732

Question 52

Calculate the pressure at the discharge end of this pipe (P_2), assuming water as the fluid (with a mass density $\rho = 1.951$ slugs/ft^3), 32.2 ft/s^2 as the acceleration of gravity (g), and frictionless flow (no pressure loss due to friction):

$P_2 = 17{,}000$ lb/ft^2

$v_2 = 4$ ft/s

Curved pipe

$P_1 = $???

Flow

$z_2 = 21$ ft

$v_1 = 10$ ft/s

$z_1 = 7$ ft
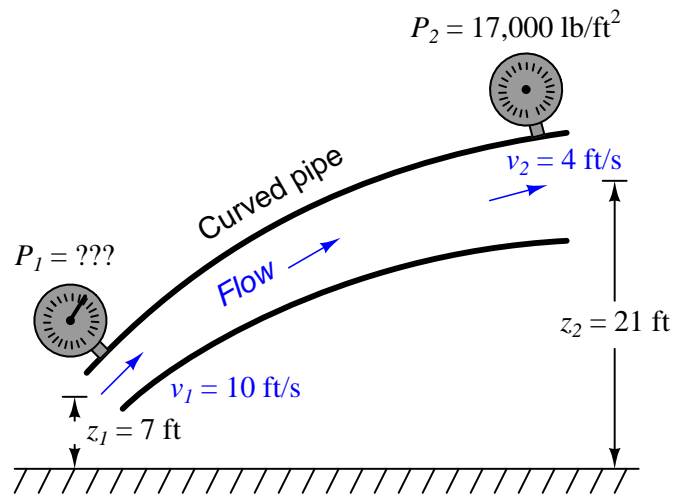
Express your answer in units of PSI as well as PSF (pounds per square foot).

Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

file i02978

54

Question 53

The following illustration shows a portion of water piping from an overhead view, looking down toward the ground (a "birds-eye" view). The pipe itself is completely level (parallel) with the ground, so that all points along the pipe centerline are at the same height:
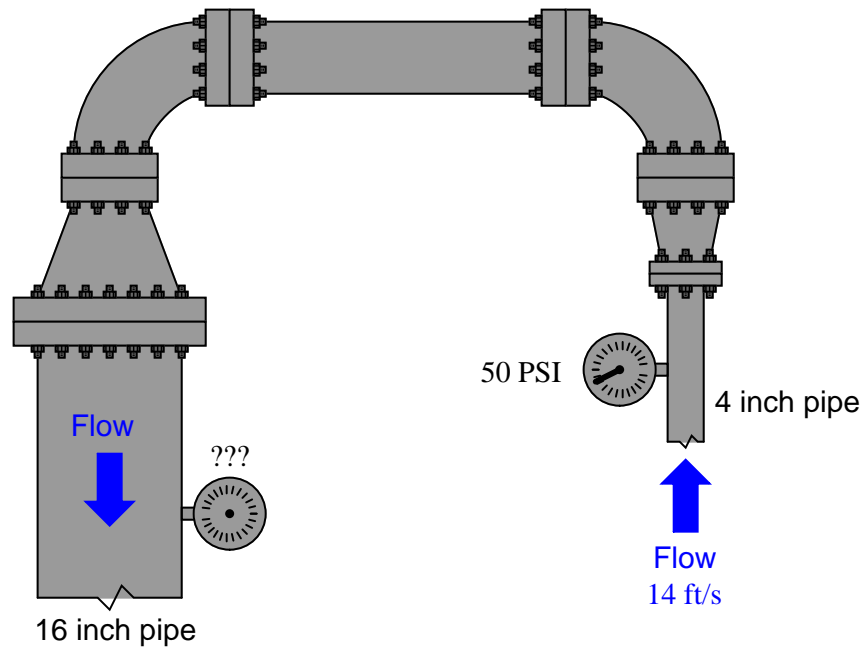
The inlet pressure gauge shows 50 PSI, and the velocity of the water entering through the 4 inch pipe is known to be 14 feet per second. Both pressure gauges are fixed at the centerline of the pipe, and are thus at the exact same height. Calculate the pressure registered at the outlet gauge (on the 16 inch pipe section) in units of PSI, assuming inviscid (frictionless) flow throughout, and a mass density for water of $\rho = 1.951$ slugs/ft^3.

Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

file i02979

55

Question 54

Elevation (z) and pressure (P) readings are taken at two different points in a piping system carrying liquid benzene ($\gamma = 56.1$ lb/ft^3):

$z_1 = 50$ inches $\qquad\qquad z_2 = 34$ inches

$P_1 = 70$ PSI $\qquad\qquad P_2 = 69$ PSI

Calculate the fluid velocity at point 2 (v_2) if the velocity at point 1 is known to be equal to 5 feet per second ($v_1 = 5$ ft/s).

Bernoulli's equation:

$$z_1\rho g + \frac{v_1^2\rho}{2} + P_1 = z_2\rho g + \frac{v_2^2\rho}{2} + P_2$$

file i02988

56

Question 55

Single-tube manometers (called *piezometers*, which literally means "pressure meters") installed on a level venturi tube clearly show the difference in pressure at different points within the tube. These pressure differences, of course, are due to the exchange of energy between potential and kinetic forms:
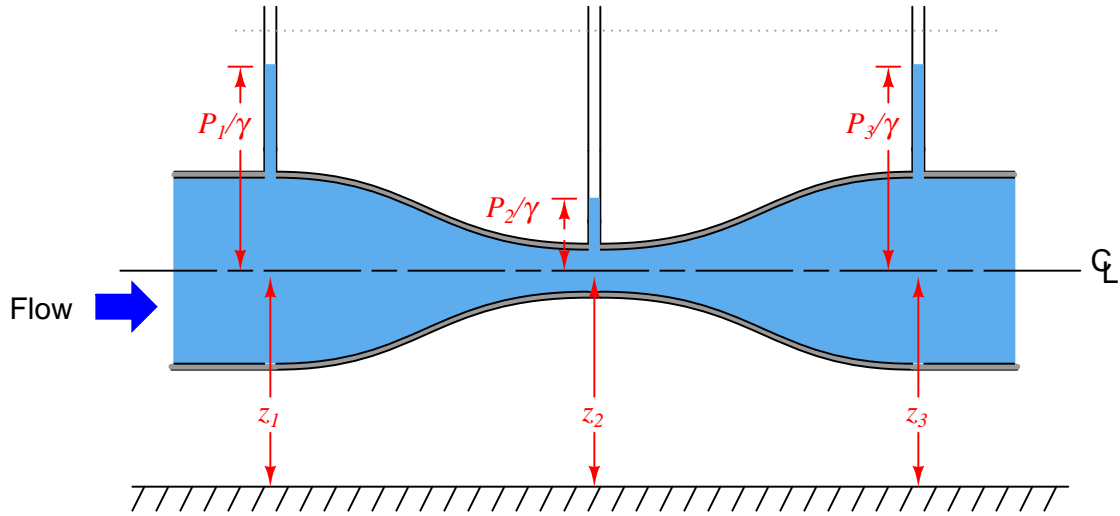
Note that the following form of Bernoulli's equation is used to describe pressure and height in the diagram, for the purpose of expressing all terms as vertical distances (in units of feet). This is why pressure is shown as P/γ instead of just P:

$$z_1 + \frac{v_1^2}{2g} + \frac{P_1}{\gamma} = z_2 + \frac{v_2^2}{2g} + \frac{P_2}{\gamma}$$

If we install three more piezometer tubes – this time with their tube ends facing the direction of oncoming liquid flow (called *Pitot tubes*) – we see something quite interesting: the heights of liquid in all the new tubes are equal.
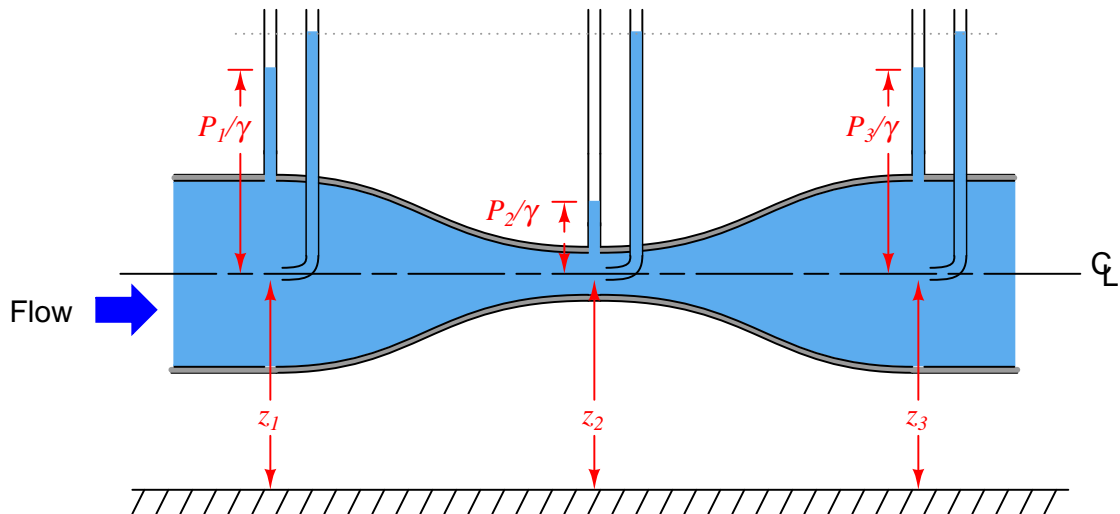
What accounts for the difference in height between liquid columns in the three sets of piezometers? How come the Pitot tube piezometers all register the same height? What is the significance of the line where all the Pitot tube piezometer liquid levels are equal?

Question 56

As fluid flows past a stationary object such as a *Pitot tube*, the fluid immediately in front of the tube comes to a full stop. This is called a *stagnation point*, and the pressure resulting from the complete loss of velocity at the stagnation point is called the *stagnation pressure*.
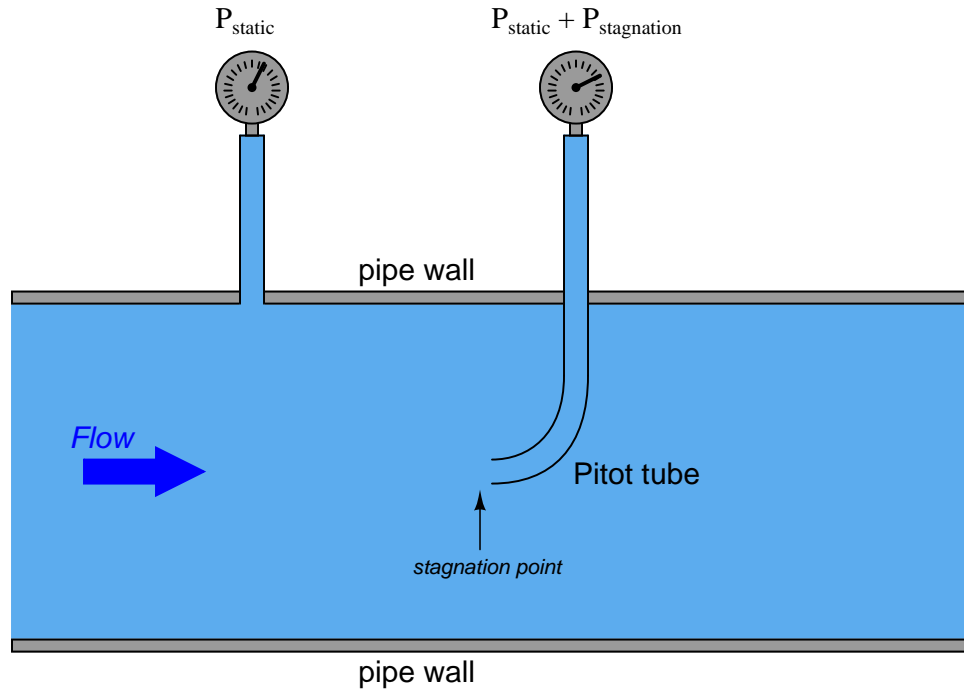
Manipulate Bernoulli's equation to show how this stagnation pressure is determined by fluid velocity (v).

Question 57

Calculate the pressure developed by a Pitot tube measuring air speed at 50 MPH, at sea level ($\rho_{air} = 0.00235$ slugs/ft^3).

Also, how much pressure will the Pitot tube develop at twice the air speed (100 MPH)?

Question 58

Calculate the differential pressure developed by an open venturi tube measuring air speed at 50 MPH, at sea level ($\rho_{air} = 0.00235$ slugs/ft^3), where the throat diameter is one-half that of the entrance diameter:
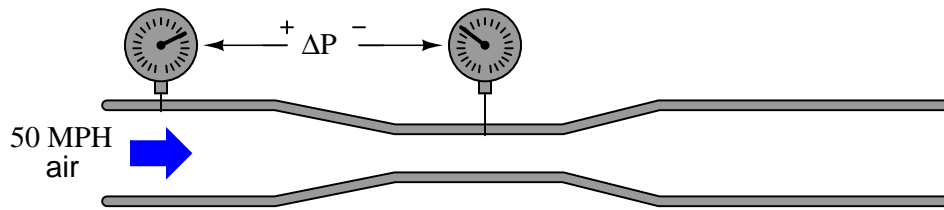
Also, how much pressure will the venturi tube develop at twice the air speed (100 MPH)?

file i02984

Question 59

From Bernoulli's equation, develop a formula for calculating volumetric flow rate (Q) given differential pressure drop ΔP between two flow streams with differing cross-sectional areas (A_1 and A_2). Assume an incompressible fluid ($\rho =$ constant) flowing along a level path ($z_1 = z_2$), and recall that volumetric flow rate is equal to the product of cross-sectional area and fluid velocity ($Q = Av$).
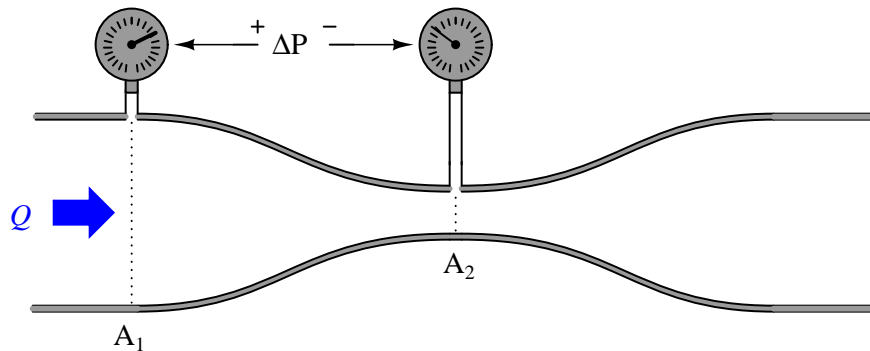
Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

file i02983

Question 60

Two flow-indicating instruments employ a common orifice plate to measure the flow of water through a pipe. The full differential pressure generated by this orifice plate at its rated flow of 800 GPM is 120 inches water column (120 ”WC):

- Receiver gauge (3-15 PSI input) connected to the output of a pneumatic DP transmitter connected across the orifice, registering 385 GPM on a 0-800 GPM square-root scale

- Panel-mounted indicator (3-15 PSI) connected to the output of the same pneumatic DP transmitter, registering 403 GPM on a 0-800 GPM square-root scale

Based on this information, where do you think the calibration error is located? If there isn't enough information yet to pinpoint the location of the error, devise a test to reveal where the error is.

file i00733

Question 61

Read and outline the "High-Accuracy Flow Measurement" subsection of the "Pressure-Based Flowmeters" section of the "Continuous Fluid Flow Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

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file i04044

Question 62

Read selected portions of the "Rosemount 3095MV MultiVariable Mass Flow Transmitter" reference manual (publication 00809-0100-4716 Revision JA), and answer the following questions:

Page 2-6 (Figure 2-3) shows proper transmitter locations relative to the flow element (e.g. orifice plate). Identify the proper mounting locations for the transmitter assuming steam service, gas service, and liquid service.

Page 2-7 lists a set of guidelines to follow when installing a DP transmitter in a flow-measuring application for optimum performance. Explain the rationale behind a few of these guidelines: *why* they should be followed.

Identify the type of temperature sensor used to measure the "flowing temperature" of the process fluid. Explain why Rosemount's choice of temperature sensors is ideal for an application such as this.

Write the formula this transmitter uses to calculate mass flow rate, and comment on the variables found within it. Also, identify the mass flow turndown ratio possible with the "Ultra for Flow" high-accuracy option (Code "U3" in the part number).

| Suggestions for Socratic discussion |

- Where might you find a transmitter such as the Rosemount model 3095 in use? What types of process applications demand the functionality provided by this instrument?
- According to this document, the rangeability for differential pressure measurement is substantially greater than the rangeability for flow measurement. Explain the mathematical principle relating these ratios together.
- Should the RTD sensing element be installed upstream or downstream of the orifice plate? Explain why.
- If the RTD malfunctioned such that it reported a greater temperature than was actually in the pipe, would this lead to a positive flow measurement error or a negative flow measurement error?

file i04045

Question 63

Read selected portions of the Rosemount Orifice Plate Elements manual ("1495 Orifice Plate, 1496 Flange Union, 1497 Meter Section, Installation & Operation Manual" publication 00809-0100-4792 Revision AA), and answer the following questions:

Page 3-1 of this manual (Figure 3-1) shows a typical "flange union" whereby an orifice plate is sandwiched between two pipe flanges. Page 4-1 (Figure 4-1) of the manual shows something called a "meter section," which serves a similar purpose. Identify the difference between a "meter section" and a normal "flange union." Explain in your own words why anyone might choose to install a "meter section" instead of a regular flange for their orifice plate flowmeter application.

Appendix C shows standard lengths for meter section tubes. Calculate the typical upstream straight-pipe length (as a ratio of pipe diameters), and also calculate the typical downstream straight-pipe length (as a ratio of pipe diameters), based on the standard lenghts and inside diameters (I.D.) shown in this table.

Appendix A of this manual provides information regarding the proper upstream and downstream straight-pipe requirements for different orifice plate installations. Based on what you read in this appendix, identify the most "challenging" installations for orifice plate elements (i.e. which applications require the longest straight-pipe runs to achieve good accuracy?).

Suppose we have an orifice plate flowmeter installation where there are two pipe elbows (not in the same plane) upstream of the orifice, an orifice plate with a beta ratio of 0.6, and no "straightening vanes" installed. Determine the minimum number of straight-pipe diameters needed upstream and downstream of the orifice plate for good performance in this installation.

| Suggestions for Socratic discussion |

- Why is the required straight-pipe length *upstream* of an orifice plate greater than the required straight-pipe length *downstream* of an orifice plate?
- Does the presence of straightening vanes in an orifice meter run affect only the upstream straight-pipe lengths requirement, or also the downstream straight-pipe length requirement?
- Why do you suppose a pair of pipe elbows in different planes produces a different amount of large-scale turbulence than a pair of pipe elbows in the same plane?
- If the amount of straight pipe between two elbows is increased, will the straight-pipe requirements between those elbows and the orifice plate be affected or not? Explain why.

file i04046

Question 64

A 5 inch diameter flow nozzle measuring volumetric flowrate of petroleum naphtha ($\gamma = 41.5$ lb/ft^3) develops a differential pressure of 75 inches water column at a flow rate of 280 GPM. Calculate the following:

- Differential pressure at 130 GPM = _____
- Differential pressure at 210 GPM and $\gamma = 42.0$ lb/ft^3 = _____
- Flow rate at 40 "W.C. = _____
- Flow rate at 24.1 "W.C. and $\gamma = 41.0$ lb/ft^3 = _____

Suggestions for Socratic discussion

- What realistic factors could cause the weight density of a liquid such as naphtha to change from 41.5 lb/ft^3 to 41.0 or 42.0 lb/ft^3?

  file i04048

Question 65

A vertical venturi tube measuring mass flowrate of high-pressure steam ($\rho = 1.3$ lbm/ft^3) develops a differential pressure of 110 inches water column at a flow rate of 500 pounds per minute. Calculate the following:

- Differential pressure at 230 lbm/min mass flow = _____
- Differential pressure at 409 lbm/min mass flow and $\rho = 1.25$ lbm/ft^3 = _____
- Mass flow rate at 95 "W.C. = _____
- Mass flow rate at 51 "W.C. and $\rho = 1.35$ lbm/ft^3 = _____

Suggestions for Socratic discussion

- What significance is there in using the unit of "pounds mass" (lbm) instead of "pounds force" (lbf) in these quantities? Is there an appropriate application for using lbf instead?
- What realistic factors could cause the weight density of a vapor such as steam to change from 1.3 lbm/ft^3 to 1.25 or 1.35 lbm/ft^3?

  file i04049

Question 66

Suppose you are calibrating a DP transmitter to go into service as a flow transmitter, measuring differential pressure generated by a segmental wedge flow element. This is a "smart" electronic transmitter with square-root characterization capability, which you decide to activate for this application.

Calculate the ideal current signal values at the following calibration pressures, assuming a calibrated range of 0 to 150 inches water column:

Input pressure (" W.C.)	Output current (mA)
0	
45	
75	
90	
110	
150	

Furthermore, suppose you performed an "As-Found" test on this DP transmitter and found it to respond as such:

Input pressure (" W.C.)	Output current (mA)
0	4.3
45	13.06
75	15.61
90	16.69
110	18.0
150	20.3

What type of calibration error is this (e.g. *zero* shift, *span* shift, or *nonlinearity*), and do you suspect it lies with the sensor or with the digital-to-analog converter? In other words, do you need to perform a *sensor trim* or an *output trim* on this instrument?

Suggestions for Socratic discussion

- Explain the difference between a *sensor trim* and an *output trim* in a "smart" transmitter.
- What tool(s) would you need to perform a sensor trim on a smart transmitter?
- What tool(s) would you need to perform an output trim on a smart transmitter?

file i04051

Suppose you are calibrating a panel-mounted indicator to be used for displaying flow rates, based on the signal coming from a (linear) DP transmitter sensing pressure across a venturi tube. The DP transmitter is an analog electronic transmitter with a linear characteristic, which means the panel-mounted indicator must be configured for square-root characterization.

Calculate the ideal display value at the following input currents, assuming a calibrated range of 0 to 700 GPM for the indicator:

Input current (mA)	Displayed flow (GPM)
4	
6	
9.3	
13	
14.8	
20	

Suggestions for Socratic discussion

- Suppose this analog transmitter were connected to an analog meter to indicate flow. How could the necessary square-root characterization be performed when all the components are analog and not digital?

file i04052

Question 68

An engineer contacts you to help her troubleshoot a chemical problem in an ammonium nitrate process, where this compound is created by mixing ammonia vapors with nitric acid.

Analytical controller AIC-28 has been placed in manual mode for the purpose of maintaining a constant ratio of ammonia to nitric acid entering the neutralizer vessel. AIC-28's output has been set at an ammonia:acid value that the plant's chemical engineer predicts should yield optimum results. However, the chemical composition of the product exiting the neutralizer proves to be off spec, as though the ammonia to acid ratio is too lean (i.e. too little ammonia per unit measure of acid entering the vessel). Flow ratio controller FFC-23's task is to maintain the proper flow ratio of ammonia to acid:
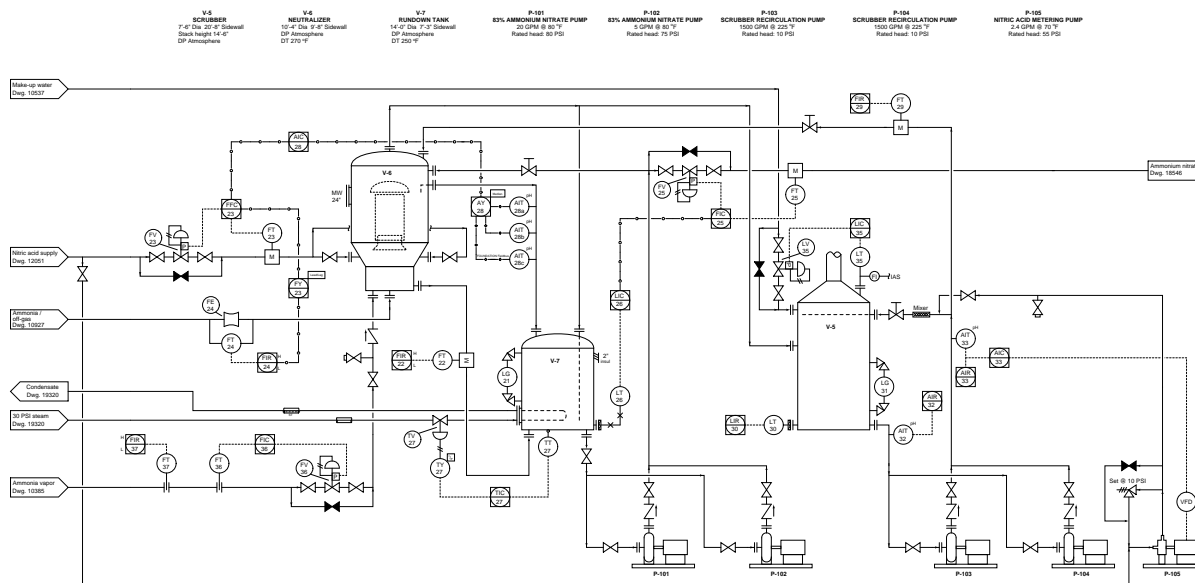
Identify the likelihood of each specified fault in this process. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this process.

Fault	Possible	Impossible
Bypass valve around FV-23 left open		
Plugged impulse line on FT-24		
FT-23 calibration error (high)		
FT-23 calibration error (low)		
FT-24 calibration error (high)		
FT-24 calibration error (low)		
Nitric acid supply line plugged		
Ammonia off-gas line plugged		
Ammonia vapor line plugged		

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

Suggestions for Socratic discussion

- Identify each type of flowmeter shown in this diagram, based on the P&ID symbols used.

- Assuming FV-23 is air-to-open (fail-closed) identify the proper control action for FFC-23 (either direct or reverse).
- Explain why this system uses three pH transmitters (AIT-28a, b, and c) rather than just one.
- Explain what would happen in this system if FT-36 failed with a high signal.
- Explain what would happen in this system if TT-27 failed with a high signal.
- Explain what would happen in this system if LT-26 failed with a low signal.

file i03501

Question 69

A flow measurement loop has a problem, and you are called to diagnose it. According to the loop sheet, the transmitter is supposed to be configured with square-root characterization, while the indicator is supposed to be linear:
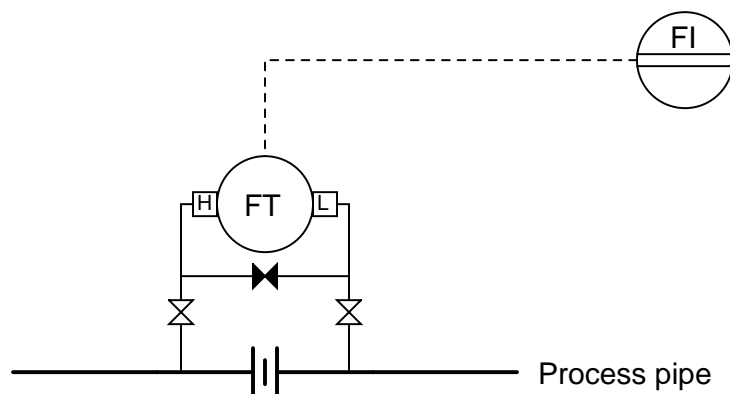
The DP transmitter's range is 0 to 100 inches water column, and the indicator's range is 0 to 250 GPM. Disconnecting the transmitter from the orifice plate impulse tubes, you connect a hand pump and precision test gauge to the "high" input port and proceed to apply the following pressures to the transmitter, while calling a fellow technician over a hand-held radio to read what the indicator says, and watching the display of a digital multimeter as it measures the transmitter's output current. The result is this table of values:

Applied pressure	Current signal	Indicator display
0 "W.C.	5.6 mA	25.0 GPM
40 "W.C.	14.2 mA	159.4 GPM
80 "W.C.	18.4 mA	225.0 GPM
100 "W.C.	20.08 mA	251.3 GPM

Determine the location of the problem in this loop, based on these measurements. Also, explain why it is very helpful in your diagnosis to have the meter measurements of signal current, rather than just know what the indicator reads for each of the applied pressures.

Suggestions for Socratic discussion

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which values agree with each other: applied pressure, current signal, and indicator. Explain how a check of correspondence tells us which instrument is at fault in this system.
- Describe the proper procedure for isolating this transmitter from the process line prior to applying test pressures to check its calibration.
- Supposing this was a flow *control* loop with a PID controller sensing the flow rate and adjusting a control valve's position in response, what would we have to do to the controller before proceeding with the hand pump test in a live process? If we did not properly configure the controller prior to this test, how would our hand pump test affect the working loop as it tried to stabilize flow at setpoint?

file i04053

Question 70

A flow measurement loop has a problem, and you are called to diagnose it. According to the loop sheet, the transmitter is supposed to be configured with square-root characterization, while the indicator is supposed to be linear:
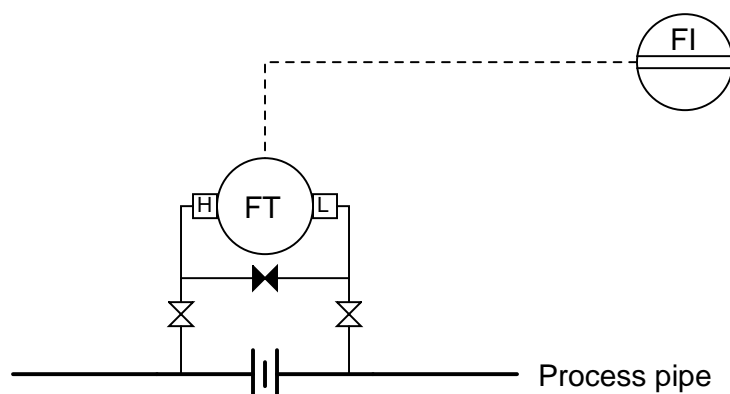
The DP transmitter's range is 0 to 150 inches water column, and the indicator's range is 0 to 1000 GPM. Disconnecting the transmitter from the orifice plate impulse tubes, you connect a hand pump and precision test gauge to the "high" input port and proceed to apply the following pressures to the transmitter, while calling a fellow technician over a hand-held radio to read what the indicator says, and watching the display of a digital multimeter as it measures the transmitter's output current. The result is this table of values:

Applied pressure	Current signal	Indicator display
0 "W.C.	4.0 mA	0 GPM
88 "W.C.	13.4 mA	586.7 GPM
105 "W.C.	15.2 mA	700 GPM
150 "W.C.	20.0 mA	1000 GPM

Determine the location of the problem in this loop, based on these measurements. Also, explain why it is very helpful in your diagnosis to have the meter measurements of signal current, rather than just know what the indicator reads for each of the applied pressures.

Suggestions for Socratic discussion

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which values agree with each other: applied pressure, current signal, and indicator. Explain how a check of correspondence tells us which instrument is at fault in this system.
- Which way does fluid flow through this orifice plate, and how can we tell?

file i04054

69

Question 71

Use Bernoulli's equation to calculate the hydrostatic pressure at the bottom of this water storage tank:
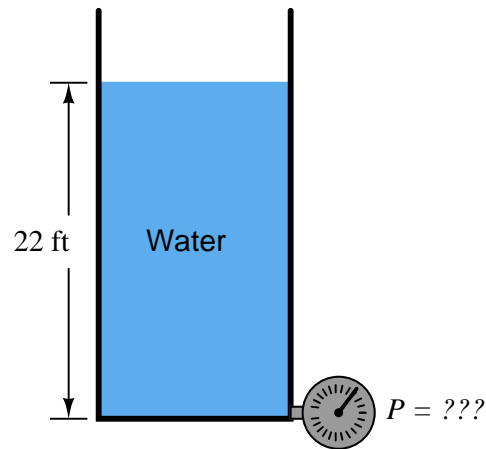
Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Where,
  $\rho = 1.951$ slugs/ft^3 (for water)
  $g = 32.2$ ft/s^2

file i02987

Question 72

Suppose an old orifice plate is replaced by a new orifice plate with a lesser *Beta ratio*. What effect will this change have on the differential pressure generated by the plate at any given flow rate? What effect will this change have on the amount of flow it can measure with the same ΔP range? What effect will this change have on permanent pressure loss and energy dissipation resulting from the orifice plate?
  file i00807

Question 73

Suppose an orifice plate is designed with a hole appropriately sized so that a water flow rate of 0 to 800 gallons per minute produces a differential pressure drop of 0 to 250 inches of water column. Write the transfer function for this orifice plate, in terms of flow rate (Q), as determined by pressure drop (ΔP). In other words, write an equation with "Q" all by itself on one side of the = sign and ΔP on the other side, along with whatever operations and factors are necessary to make it work.

```
                 ┆
                 ┆
               ╱───╲
              │ FT  │
               ╲───╱
                 │
                 │      0 - 250 "W.C.
        ─────────┤├─────────
              0 - 800 GPM
```
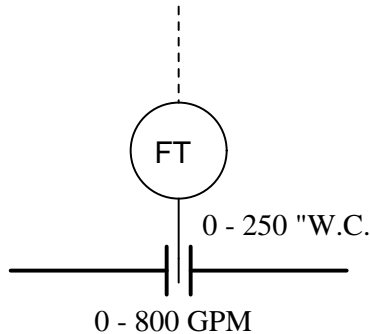
file i00482

Question 74

A differential pressure flowmeter (e.g. orifice plate, venturi, etc.) has a calibrated flow range of 0 to 1000 GPM and a differential pressure range of 0 to 200 inches of water.

Calculate a new differential pressure range for the transmitter to give this flowmeter a new flow range of 0 to 750 GPM.

Calculate a new differential pressure range for the transmitter to give this flowmeter a new flow range of 0 to 1200 GPM.

Calculate a new differential pressure range for the transmitter to give this flowmeter a new flow range of 0 to 510 GPM, and express this new pressure range in units of PSI rather than inches of water.
file i00692

71

Question 75

Complete the calibration table for this flow-measuring loop, consisting of an orifice plate, ΔP transmitter, square root extractor, and indicator. Assume the following instrument ranges:
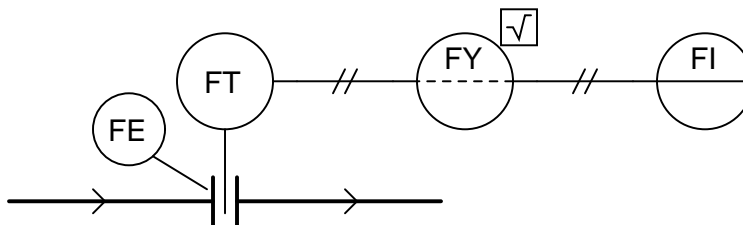
- FE: 0-400 GPM, 0-125 "W.C. ΔP
- FT: 0-125 "W.C. in, 3-15 PSI out (linear)
- FY: 3-15 PSI in and out (square-root)
- FI: 3-15 PSI in, 0-400 GPM indication

Flow rate (GPM)	Percent of max. flow (%)	Orifice ΔP ("W.C.)	FT output signal (PSI)	FY output signal (PSI)	FI indication (GPM)
	0				
	10				
	25				
	50				
	75				
	90				
	100				

file i00693

Question 76

Prove that these two orifice plate flow equations are equivalent:

$$Q = k\sqrt{\frac{2\Delta P}{\rho}} \qquad\qquad Q = k\sqrt{\frac{2g\Delta P}{\gamma}}$$

file i02985

The following illustration shows a simple pneumatic "square-root extractor" relay mechanism.
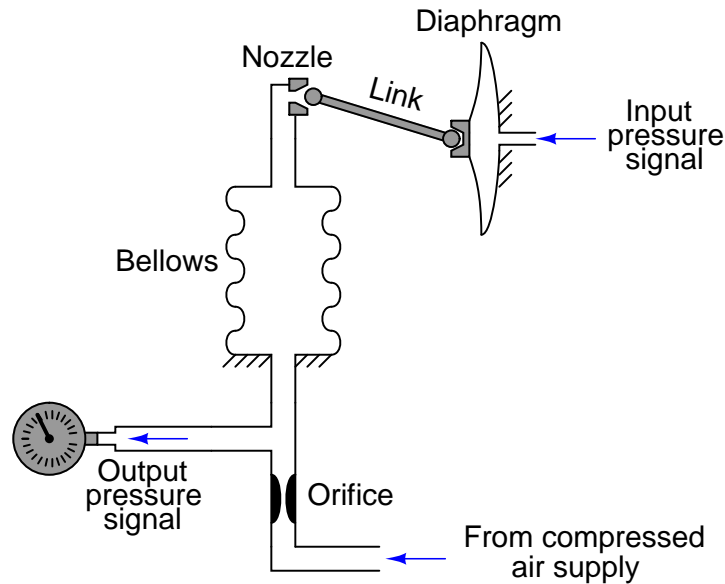
As the input pressure increases, the diaphragm expands, pushing the link to the left. This plugs off the nozzle, increasing the backpressure within the bellows, causing it to expand upward. As the bellows expands, the nozzle moves up, re-establishing the gap between it and the link's ball-shaped end, until a condition of equilibrium is reached. The link, of course, will be nearer to level (horizontal) at low input pressure, and more angled (approaching vertical) at high input pressure.

Explain how this angled-link produces the kind of nonlinearity that approximates the square root function. Also, determine whether this mechanism employs the *force-balance* or *motion-balance* principle.

file i00486

Question 78

An orifice plate measuring mass flowrate of 300 PSIG saturated steam ($\rho = 0.68$ lbm/ft^3) develops a differential pressure of 100 inches water column at a flow rate of 120 pounds per minute. Calculate the following:

- Differential pressure at 60 lbm/min mass flow = _____
- Differential pressure at 77 lbm/min mass flow and $\rho = 0.69$ lbm/ft^3 = _____
- Mass flow rate at 90 "W.C. = _____
- Mass flow rate at 43 "W.C. and $\rho = 0.70$ lbm/ft^3 = _____

  file i04050

Question 79

A pitot tube measuring airspeed on an airplane develops 4.4 inches water column differential pressure at an airspeed of 100 MPH. Calculate the following:

- Differential pressure at 200 MPH = _____

- Differential pressure at 475 MPH = _____

- Airspeed at 7.3 "W.C. = _____

- Airspeed at 24.1 "W.C. = _____

| Suggestions for Socratic discussion |

- Why are Pitot tubes ideally suited for airspeed measurement on airplanes?

  file i04047

Question 80

Calculate the amount of differential pressure produced by a liquid flowing through various orifice plates given the following parameters:

Scenario #1
- Liquid specific gravity = 1.00 (unitless)
- Pipe ID = 3.25 inches
- Orifice ID = 1.72 inches
- Flow rate = 120.0 gallons per minute

Scenario #2
- Liquid specific gravity = 0.84 (unitless)
- Pipe ID = 5.025 inches
- Orifice ID = 3.55 inches
- Flow rate = 900.0 gallons per minute

Scenario #3
- Liquid specific gravity = 0.64 (unitless)
- Pipe ID = 6.000 inches
- Orifice ID = 2.500 inches
- Flow rate = 410.0 gallons per minute

Scenario #4
- Liquid density = 70.0 lb/ft^3
- Pipe ID = 8.000 inches
- Orifice ID = 3.500 inches
- Flow rate = 600.0 gallons per minute

Scenario #5
- Liquid density = 50.0 lb/ft^3
- Pipe ID = 5.250 inches
- Orifice ID = 4.180 inches
- Flow rate = 1200.0 gallons per minute

Calculate the rate of liquid flowing through an orifice plate given the following parameters:

Scenario #6
- Liquid specific gravity = 0.95 (unitless)
- Pipe ID = 9.790 inches
- Orifice ID = 4.210 inches
- Differential pressure = 100.0 inches WC

Scenario #7
- Liquid specific gravity = 0.834 (unitless)
- Pipe ID = 10.03 inches
- Orifice ID = 6.750 inches
- Differential pressure = 68.7255 inches WC

Scenario #8
- Liquid density = 42.451 lb/ft^3
- Pipe ID = 3.480 inches
- Orifice ID = 2.100 inches
- Differential pressure = 58.9771 inches WC

file i02990

Question 81

Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):

V_{in}
5.4 VAC
1.2 kHz

0.033 µF

V_{out}

2.2 kΩ
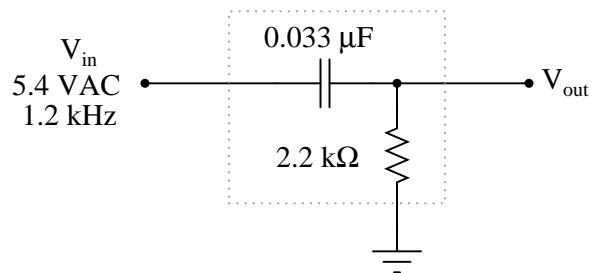
file i01062

Question 82

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 series of known pressures (5-point up/down test), it responds as such:

Applied pressure (" WC)	Output signal (mA)
0	3.7
25	7.9
50	12.1
75	16.3
100	20.5
75	16.3
50	12.1
25	7.9
0	3.7

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*, *linearity*, and/or *hysteresis*).
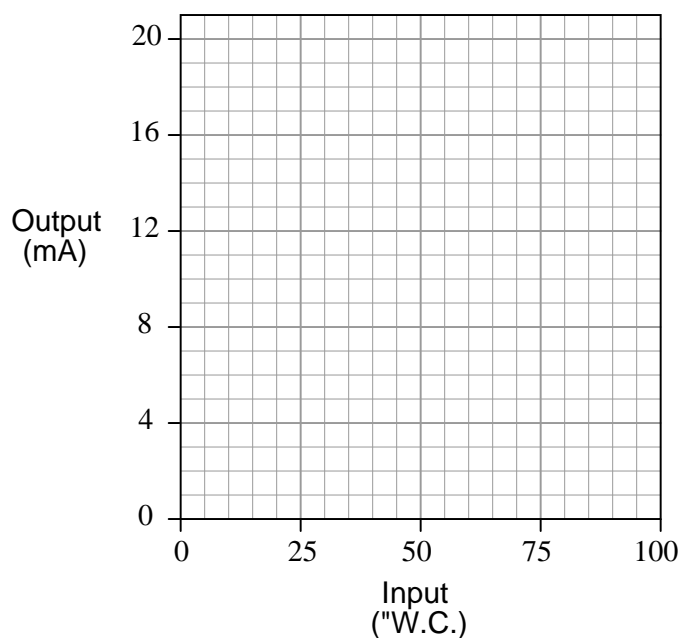
Hint: a computer spreadsheet program might be a useful tool in graphing this instrument's response. Feel free to attach a printed copy of a spreadsheet graph instead of hand-sketching one on this page.

file i03730

A pump pushes liquid kerosene ($\rho = 1.59$ slugs/ft^3) through a piping system. Calculate the pressure measured at the gauge, assuming a pump discharge pressure of 45.1 PSI and a discharge flow of 250 GPM:
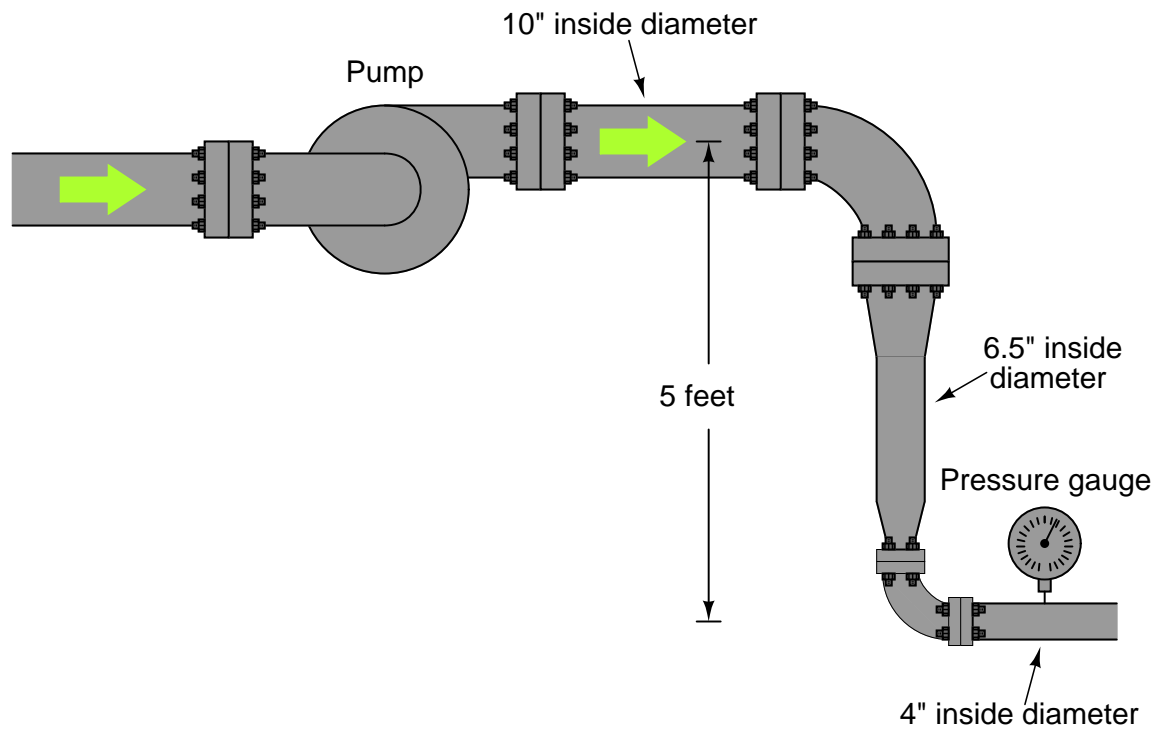
Question 84

Complete the calibration table for this flow-measuring loop, consisting of an orifice plate, ΔP transmitter, square root extractor, and indicator. Assume the following instrument ranges:
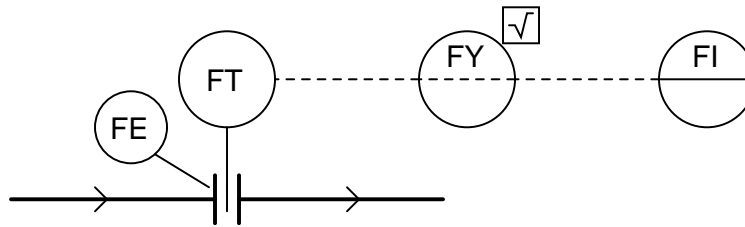
- FE: 0-750 GPM, 0-100 "W.C. ΔP
- FT: 0-100 "W.C. in, 4-20 mA out (linear)
- FY: 4-20 mA in and out (square-root)
- FI: 4-20 mA in, 0-750 GPM indication

Flow rate (GPM)	Percent of max. flow (%)	Orifice ΔP ("W.C.)	FT output signal (mA)	FY output signal (mA)	FI indication (GPM)
0	0				0
	10				
	25				
375	50				375
	75				
	90				
750	100				750

file i00048

Question 85

A water-cooled generator at a power plant has two sources of cooling water flow, each source equipped with a flow switch that returns to its normally-open status if the water flow through the pipe stops. If either water source ceases supplying cooling water to the generator (for whatever reason), that flow switch will de-actuate and turn the warning light on. This is all that is required, as the generator will still receive adequate cooling from only one source. If both water sources cease supplying water, however, a "trip" solenoid will de-energize to shut down the generator before it overheats:
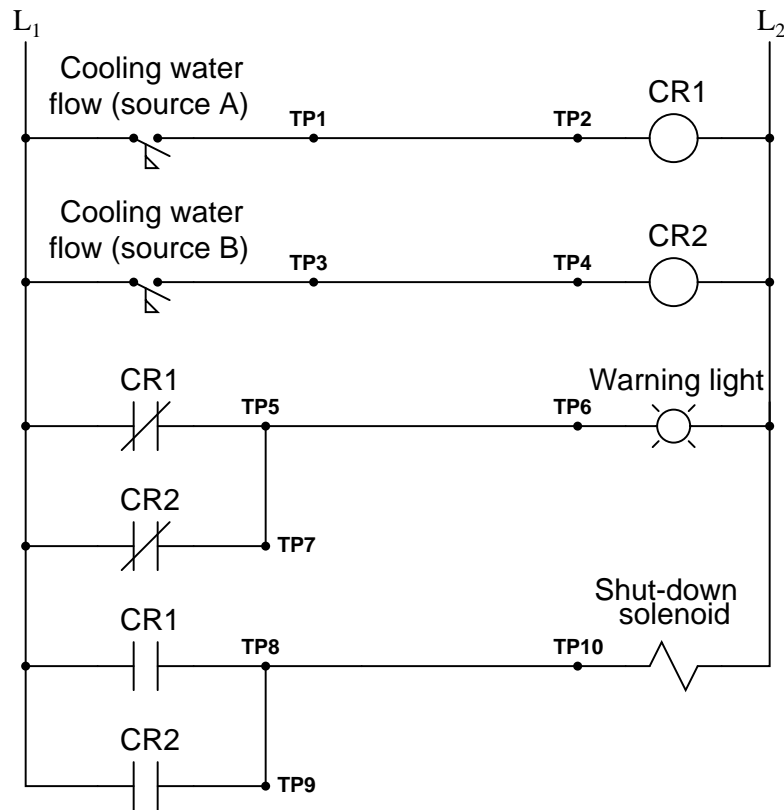
One day the generator shuts down automatically, even though the warning light never came on. An operator verifies that there is adequate cooling water flow going through both pipes. Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* symptoms in this circuit.

Fault	Possible	Impossible
Solenoid coil failed open		
Flow switch A failed open		
Flow switch B failed open		
Open wire TP5-TP6		
Open wire TP8-TP9		
Open wire TP8-TP10		
Relay coil CR1 failed open		
Relay coil CR2 failed open		

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.

file i00046

Question 86

This DP transmitter measures the pressure drop developed by an orifice plate as a hydrocarbon liquid ($\gamma = 47$ lb/ft^3) flows through the pipe. The orifice plate flow range is 0 to 550 GPM and its corresponding differential pressure range is 0 to 125 inches H$_2$O:
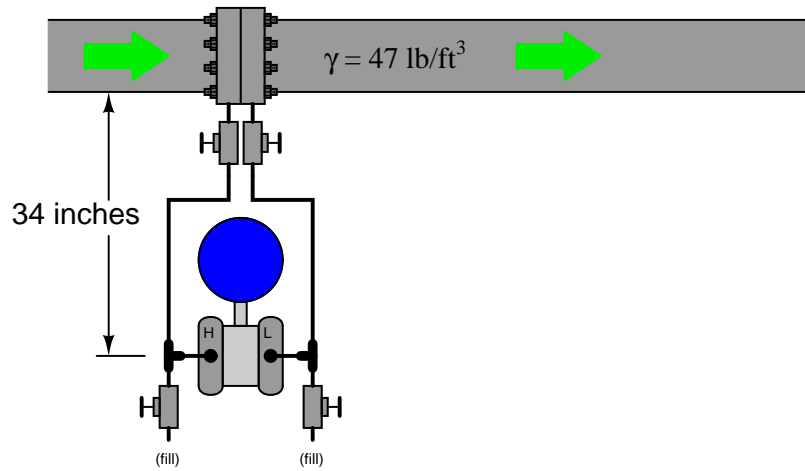
Normally, high-density glycol (S.G. = 1.8) is pumped into both impulse lines to completely fill them and displace any light hydrocarbon liquid that might otherwise collect there. Unfortunately, some of this fill fluid has leaked out of the low-side impulse line, so that only 30 out of its 34 vertical inches of height are filled with glycol, the upper 4 inches filled with process liquid. The high-side impulse line still has all of its fill fluid intact.

Calculate the amount of differential pressure this filling error will impart to the DP transmitter, and then calculate how much flow the transmitter will "think" is going through the pipe as a result of this false pressure difference when in fact the flow is completely stopped.

DP error = _____ inches H$_2$O

Flow error (at zero flow) = _____ GPM

Question 87

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


```
Online
1 Device setup
2 PV
3 AO
4 LRV    0.000  inH2O
5 URV  100.00  inH2O
```
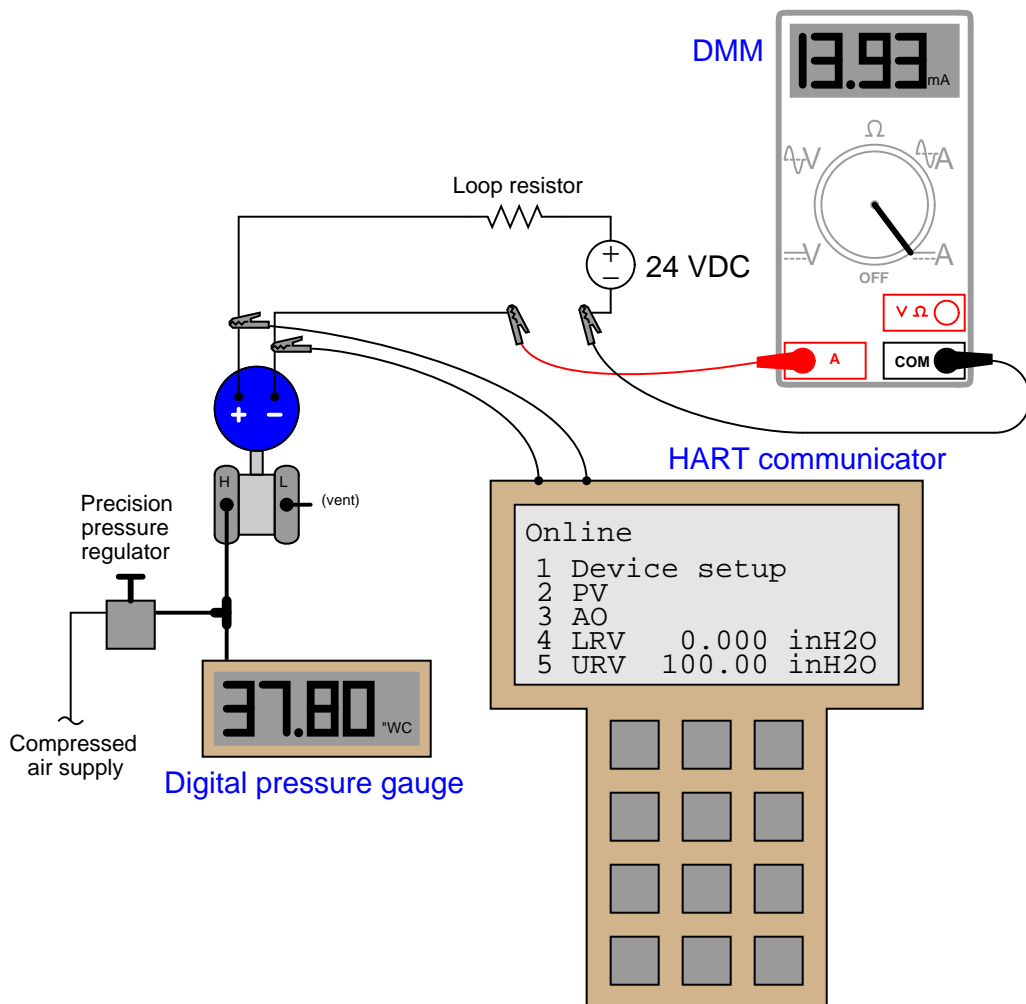
Determine what **PV** and **AO** values will be displayed on the HART communicator display if the calibration error lies entirely in the sensor (i.e. the transmitter requires a sensor trim) versus if it lies entirely in the digital-analog converter (i.e. the transmitter requires an output trim).

Parameter	If sensor trim error	If output trim error
PV		
AO		

file i03473

Question 88

Suppose an agricultural feed supply company needs to measure the rate at which grain is lifted to the top of a storage silo by a motor-driven conveyor belt. One solution to this measurement problem is to install a *weighfeeder* on the belt, sensing the weight of grain per unit length and multiplying this figure by belt speed to calculate mass flow rate (e.g. pounds per minute). However, if good accuracy is not essential, a crude determination of mass flow rate may be obtained by measuring the true power (P) of the AC motor driving the conveyor.

Attaching a power monitor to the motor leads, you collect the following data:

- $V = 238$ volts AC
- $I = 17.4$ amps AC
- Phase angle (θ) $= 35^o$

Assuming this motor is 93% efficient, calculate the true mechanical power output by this electric motor.

Next, explain what will be necessary to do to convert the motor's power output value in units of *horsepower* into a mass flow rate in units of *pounds of grain per second*.

Question 89

The Rockwell/Allen-Bradley MicroLogix 1000 programmable logic controller (PLC) can handle up to four analog input signals: two with a 0-10 V maximum range and two with a 0-20 mA maximum signal range. This PLC's analog input terminal block looks like this (the internal resistors are shown inside the PLC box):
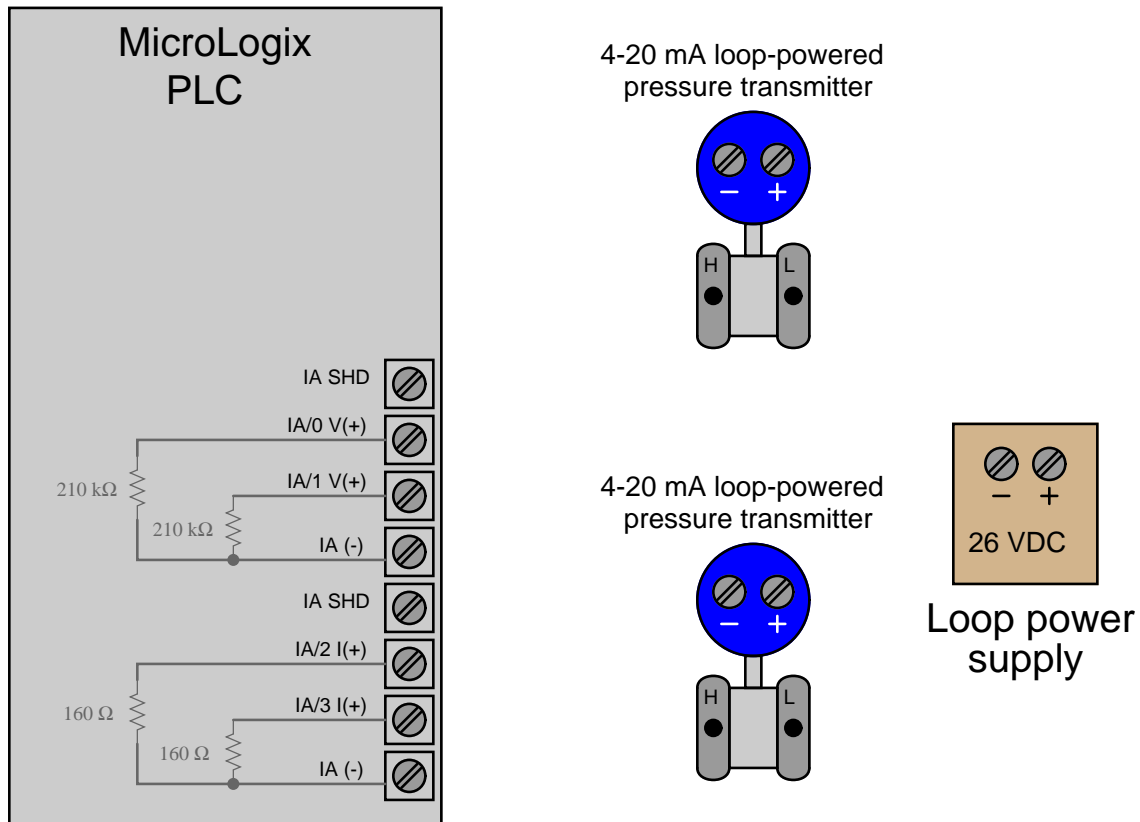
Sketch the appropriate wiring to connect a pair of 4-20 mA loop-powered transmitters to the two current inputs (IA/2 and IA/3) on the PLC.

Note: the two "IA SHD" terminals are provided for cable shield conductor attachment. You may ignore cable shield wires and these terminals for simplicity's sake.

file i03252

84

This single-loop flow control system has a problem: the flow rate indicated on the controller's faceplate shows it to be precisely at setpoint (250 SCFM), yet the Annubar flow gauge does not agree. The two indications used to agree with one another just fine, until some time recently.
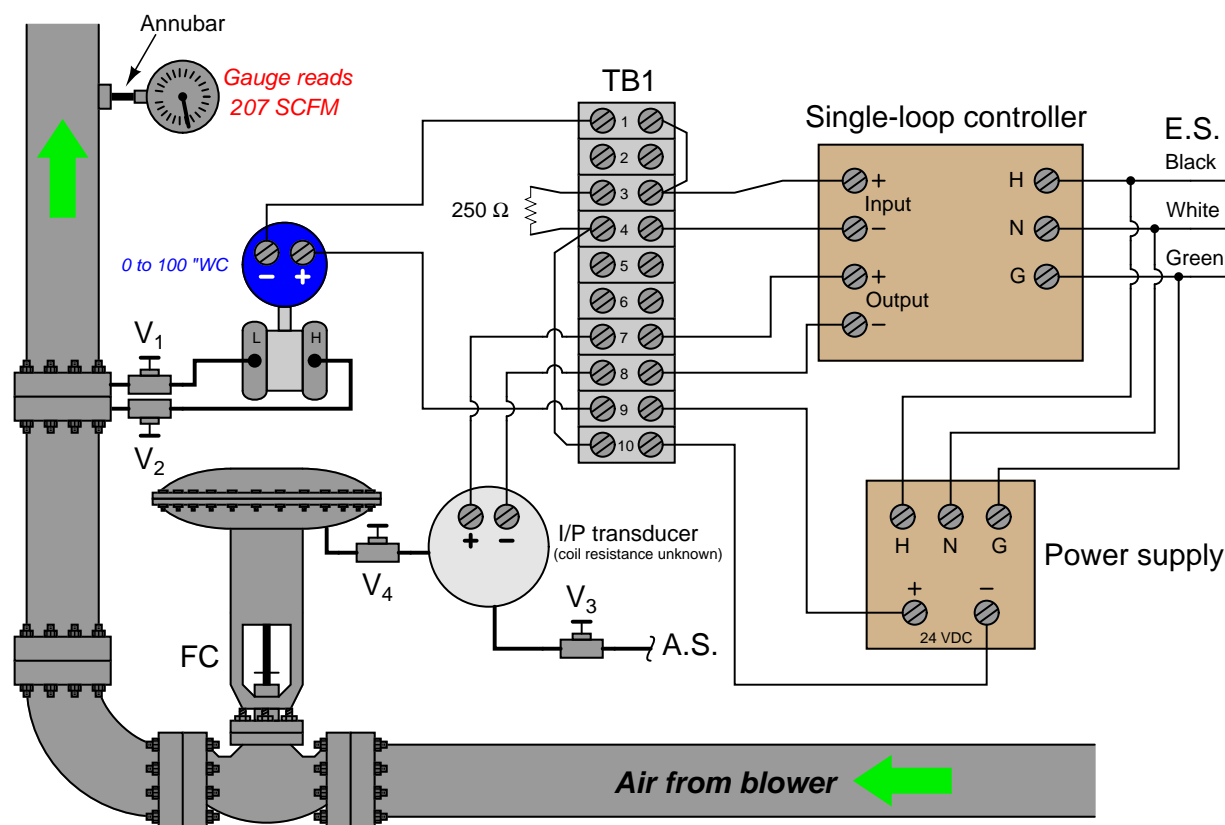
Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

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

file i03480

Lab Exercise – introduction

Your task is to build, calibrate, document, and program a flow measurement system consisting of an electronic differential flow transmitter connected to one of the analog inputs of a data acquisition module (DAQ) for a SCADA RTU (Remote Terminal Unit) node which will serve as a *flow computer*. The particular SCADA system we will be using has been designed specifically for BTC Instrumentation students. It is called *caSCADA* and it is based on a single-board computer running the Linux operating system. In this lab exercise you will be configuring the RTU node to receive the flow transmitter's analog signal and compute the flow rate of that fluid. This will involve editing some of the programming code written in the "C" language. Your instructor will assign the flow to be measured, as well as the specific channel(s) to use on the caSCADA system for your loop.

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 *first!*)	mastery	–	–	–	–	███████
Circuit design challenge	mastery	███				– – – –
Transmitter calibration (with As-Found/As-Left)	mastery	–	–	–	–	███████
Spreadsheet characterizing flow element	mastery	–	–	–	–	
Flow/DP prediction ($\pm$ 5% of span)	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Simulated troubleshooting of 4-20 mA circuit	mastery					– – – –
Editing code for transmitter channel	mastery					– – – –
Editing code for flow computation channel	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	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

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

Transmitter calibration

Trim both the pressure sensor and the output (4-20 mA) of the differential pressure transmitter, using trusted test instruments for verifying applied pressure and signal current values. Complete both As-Found and As-Left calibration tables, and tag when complete.

Spreadsheet characterizing flow element

Test your team's flow element based on known flow rate and measured differential pressure values, documenting and plotting these values using an electronic spreadsheet. Use the spreadsheet's *trendline* feature to fit a mathematical function to the data, with that mathematical function eventually being programmed into the caSCADA system.

Flow / DP prediction

Calculate flow rate given differential pressure, or vice-versa, on an actual flow element where the instructor randomizes the actual flow rate. Known values of flow rate and differential pressure for this element will be provided to you as a reference.

Final loop diagram and system inspection

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

Troubleshooting simulation

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

Editing code for transmitter channel

Individually edit your team's caSCADA code to express the transmitter's output in inches of water column for a range specified by your instructor. Add a conditional statement to the channel's source code causing the status value to change based on pressure.

Editing code for flow computation channel

Edit your team's caSCADA code (as a team) to express flow rate based on one or more transmitter channel output values as specified by the instructor.

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!

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

An important first step in completing this lab project 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 project 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.

In this particular lab, you will most likely use a low-range "draft" pressure transmitter to sense the differential pressure created by a primary flow element such as a pitot tube. DP transmitters designed to sense low pressures in HVAC systems work well for this task if the process fluid is air. For liquid flow processes, an industrial DP transmitter such as the Rosemount model 3051 should be used instead. In either case, the transmitter should have a range that can turn down to less than 10 inches water column.

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. Since the range of this transmitter is so small, the source of air pressure you use must be very low, and could even be your own breath applied to a tube connected to the transmitter's "H" port. 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 – building the system

The major purpose of this lab exercise is to configure the caSCADA system as a *flow computer*. To this end, you may connect any suitable set of transmitters to the caSCADA system for monitoring flow variables, and measure any available fluid flow. An easy option for flow measurement is the volumetric rate of air flow through a tube, driven by a motor-controlled fan. Another option for flow measurement is *wind speed*, treating air as the process fluid and the speed of the wind as the flow to be measured, and using a Pitot tube as the sensing element.

It is relatively easy to construct a crude venturi tube using PVC plastic piping, and to control air flow through that tube using a type of blower called a *regenerative* or *ring* blower. Volumetric air flow rate is very nearly linear with shaft speed on this type of blower, which means one may drive such a blower using a VFD-powered AC motor and read the VFD's frequency output value as a proportion of flow rate.

One venturi tube may provide differential pressure to multiple DP transmitters, allowing for either redundant measurement (each DP transmitter having the same range) or multi-range measurement (each DP transmitter having a progressively larger range) of fluid flow. The computational power of the caSCADA system may be put to good use by taking the differential pressure measurement and computing flow rate using a nonlinear formula. In other words, the DP transmitter may be configured for linear operation, with the caSCADA RTU computer doing all the necessary calculations to translate this sensed differential pressure into a wind speed. If multiple DP transmitters are plumbed to the same flow sensing element, the caSCADA system may be programmed to average those transmitters readings, or perform a selection function on the redundant signals (e.g. low-select, high-select, median-select) to yield a more reliable wind speed measurement. It is even possible to connect temperature, differential pressure, and absolute pressure transmitters to the caSCADA system's analog inputs and have the RTU computer calculate *mass flow rate* based on the AGA 3 formula (or something similar to it).

Whatever the configuration, the purpose of this system is to showcase the calculation of fluid flow using the computational powers of the caSCADA system, above and beyond a single transmitter registering a single variable.

The caSCADA RTU nodes are built to operate in outdoor locations, each with its own battery backup power system to continue operation when AC line power fails. This lends itself to the measurement of real-world flows such as wind speed, water flow in pipes and streams, tidal motion, etc.

Sample diagrams of the caSCADA system wiring, including loop diagram examples, are given in the next question of this worksheet. The loop diagrams are fairly self-explanatory, and follow a prescribed convention of terminal numbering (versus analog inputs).

Lab Exercise – circuit design challenge

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

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

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

4-20 mA transmitter options

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

Controller options

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

4-20 mA Final Control Element options

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

Correct circuit sketch (instructor verifies): ____

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

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

Correct source/load identifications (instructor verifies): ____

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

Lab Exercise – transmitter calibration

If your team's flow transmitter is based on pressure, you must calibrate the differential pressure transmitter ("trim" both the sensor and the output) to ensure it interprets pressure accurately and outputs an accurate current.

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 *manometer*, 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
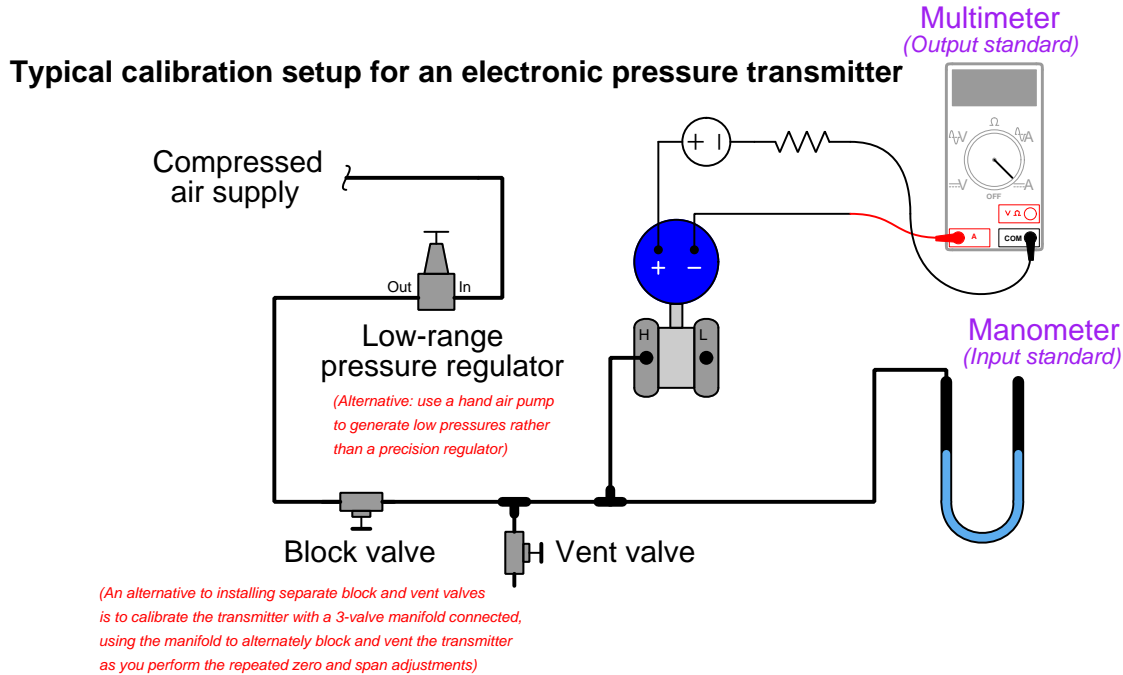
If the low-range pressure regulator does not reliably generate low enough pressures, you may throttle both the block and vent valves, using them as a sort of "pressure divider" (analogous to two resistors throttling current to make a voltage divider) to apply a lower pressure to the manometer and DP transmitter than the regulator outputs:

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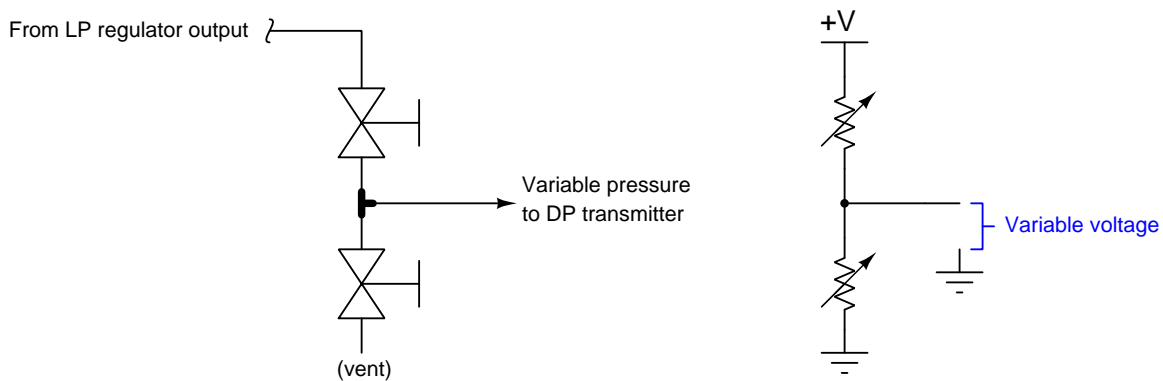
An alternative method for generating very low air pressures is to use a small-volume air pump (e.g. a bicycle tire pump works well for this purpose) connected to a chamber of large volume, such that each stroke of the pump results in a tiny increment of pressure increase applied to the manometer and DP transmitter:

Alternative calibration setup for a pneumatic pressure transmitter
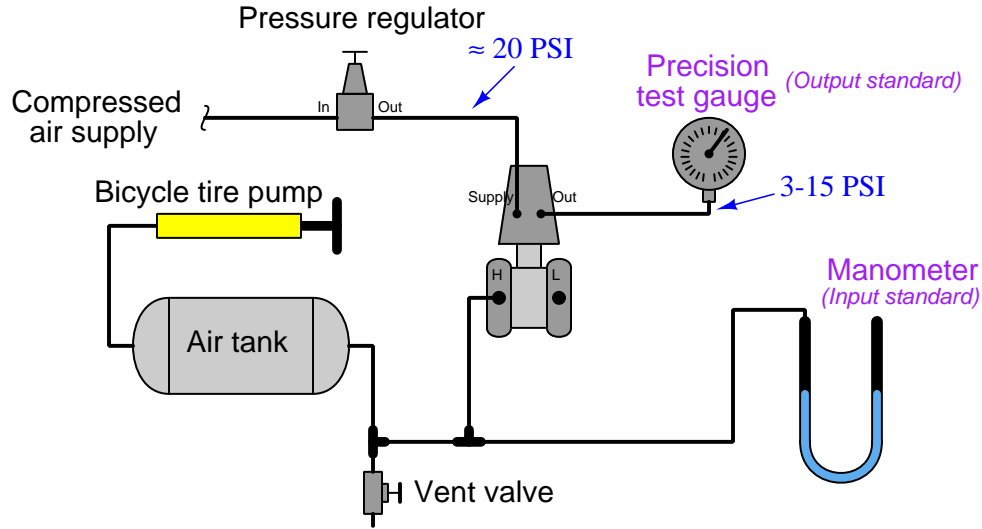
It is entirely permissible for teams to share one transmitter. No matter how well-calibrated one team might have left a transmitter, there is always room for another team to re-calibrate that same transmitter and at least attempt to calibrate it better. A comparison of your team's As-Found versus As-Left values will demonstrate the improvement(s) you were able to make.

It should be noted that when calibrating pressure transmitters with very low ranges, as is often the case when measuring flow in a lab environment, the physical mounting position of the transmitter may make a significant difference in its calibration. If the transmitter is re-oriented, gravity will tug at the pressure-sensing element in a different direction and thereby cause its calibration to shift. This shift is typically just a "zero" error, and is therefore fairly easy to correct, but it will necessitate another calibration check in the field. A good field test, therefore, is to mount the transmitter in its final position and then check its analog output signal with zero differential pressure applied (i.e. with the equalizing valve of a three-valve manifold opened, or by connecting the "H" and "L" ports of the transmitter together with a tube to absolutely ensure no differential pressure exists.

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:

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 shown here which you may cut out and tape to the transmitter after completing your calibration:

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

CALIBRATED	CALIBRATED	CALIBRATED	CALIBRATED
By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____	By: _____ Date: _____
Range:_____	Range:_____	Range:_____	Range:_____
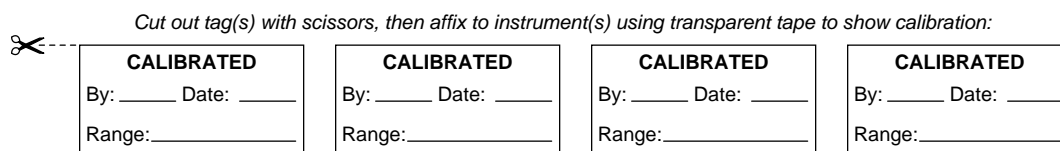
If your team's flow transmitter is not pressure-based (e.g. vortex, magnetic, turbine, Coriolis, etc.) then the input standard you must provide for calibration will not be pressure. In some cases the input standard may be electrically simulated (e.g. simulating the voltage induced by the flowtube in a magnetic flowmeter), but in other cases you may have to do a "bucket test" which involves timing how long it takes to fill a bucket of known volume with the liquid passing through the flowmeter.

Common mistakes:

- 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.
- Changing the physical orientation of the differential pressure transmitter between calibration and field mounting, without re-trimming the sensor's zero point.
- Ignoring the mathematical signs (+ or −) of error calculations.
- Neglecting to place a calibration tag on the transmitter after calibrating it.

Characterizing your team's flow element and calibrating your team's transmitter to match should take no more than one full lab session (3 hours) if the team is working efficiently!

Lab Exercise – flow element characterization

Flowmeters based on the generation of a differential pressure (DP) by acceleration or deceleration of the fluid are inherently non-linear in nature: doubling the flow rate results in approximately quadrupling the DP generated. In order to be able to program the caSCADA system to accurately compute flow rate from differential pressure measurements, you must *characterize* the flow element. This means testing the flow element against known flow rates to see how much pressure it generates at those rates, and then deriving a formula relating pressure to flow rate. You may think of this as analogous to developing a *strapping table* for tank liquid level measurement: exposing the sensor to a set of known values to see how it responds across a wide range of values, and then recording those values for later use in interpreting the process variable.

An important tool for this task is an *electronic spreadsheet program* such as Microsoft Excel. You will take the flow/DP data measured for your flow element, enter those data points in a spreadsheet, and have the spreadsheet plot a graph of the data with DP as the independent variable (horizontal axis) and flow rate as the dependent variable (vertical axis). Most spreadsheets permit both linear and logarithmic plotting. Examples of each type of plot are shown here, with flow rate as the independent (horizontal axis) variable and pressure as the dependent (vertical axis) variable:
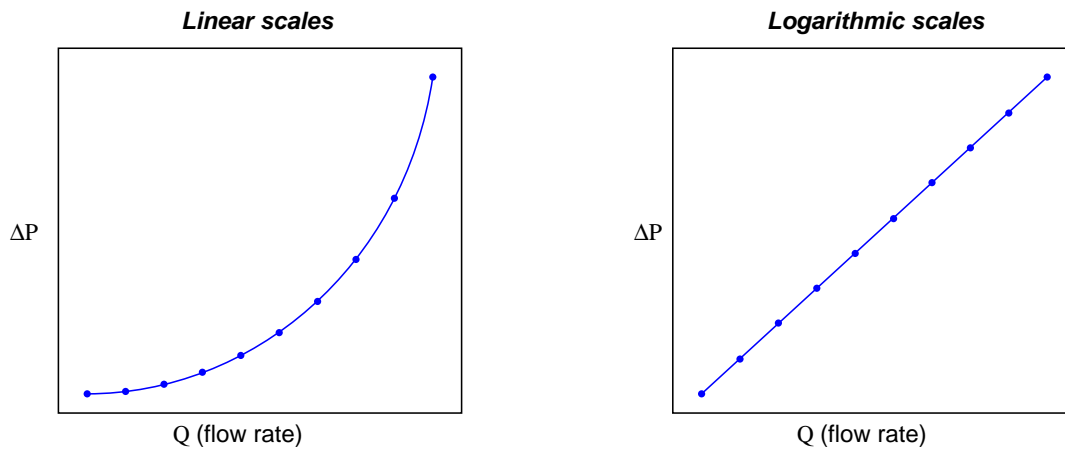
Flow elements such as orifice plates, venturi tubes, Pitot tubes, and flow nozzles should exhibit a simple quadratic characteristic, represented by the formula $Q = k\sqrt{\Delta P}$. Logarithmic scales are very helpful when graphing inherently nonlinear functions such as this. Note what happens to this quadratic function when the logarithm is taken of both sides:

$$Q = \sqrt{\Delta P} = \Delta P^{1/2}$$

$$\log Q = \log \Delta P^{1/2}$$

$$\log Q = \frac{1}{2} \log \Delta P$$

$$\frac{\log Q}{\log \Delta P} = \frac{1}{2}$$

Thus, a graph of the *logarithm* of Q plotted with respect to the *logarithm* of ΔP yields a line with constant slope of one-half ($\frac{1}{2}$). Deviations from the ideal quadratic function are more readily seen in such a log/log plot because they appear as deviations from a straight line. It is more difficult for a person to detect the same deviations on a graph when the ideal plot is a curve instead of a line.

Another powerful feature of electronic spreadsheets is their ability to *fit a mathematical function* to your data. Once you have plots of your flow/DP data, you will instruct the spreadsheet to trace a function over that same data to mathematically approximate it. In Microsoft Excel, this feature is called a *trendline*, which may be enabled and configured by right-clicking on any of the points on the plotted function. This function in the form of $y = f(x)$ will be something you may then program into the caSCADA system to convert x (differential pressure) into y (flow rate or flow velocity). The formula fit by the spreadsheet will likely be more accurate to your flow element than $Q = k\sqrt{\Delta P}$ because the latter is based on theory while the former is based on empirical data.

It is highly recommended that you plot differential pressure as the independent variable (x) and flow rate (Q) as the dependent variable (y), so that the mathematical function fit to the data will be ready to accept values of DP in inches water column and output values for flow rate when programmed into the caSCADA system. A good rule of thumb here is that your mathematical function should fit all data points to within $\pm 1\%$ of range.

This is the end-goal of your spreadsheet use in this lab exercise: to generate a formula relating differential pressure (in inches water column) to flow rate (e.g. volumetric units, or mass units, or flowing velocity, or blower speed). Your team must show your spreadsheet to the instructor, explain how you plotted the data and displayed the trendline formula, and explain what the data and formula mean.

You may find it challenging to find one mathematical function that fits *all* data points precisely, especially when you include the data point (0,0) (i.e. zero differential pressure at zero flow). It may be more practical to fit one mathematical function to part of the data, and a different mathematical function to the rest of the data. One option you have when programming your caSCADA RTU to calculate flow from measured pressure is to use this multi-function approach (called a *piecewise function*): program the flow computation channel function using "if" conditional statements telling the computer to use one mathematical function for part of the flow range and a different mathematical function for the rest of the flow range. You may set up your spreadsheet to generate multiple functions, each one fitting a portion of the data range:
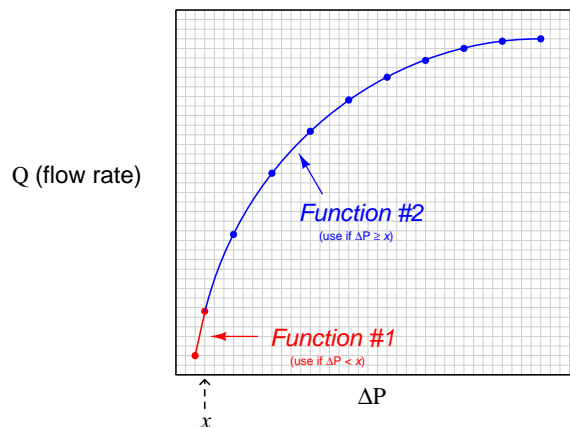
Common mistakes:

- Not recording enough data points. There really is no maximum number of data points to collect during your characterization test. The more data points, the better, because it means the spreadsheet will have more data to analyze in deriving its mathematical function, and that function will likely be a better fit to the true measurement!
- Not including zero (no flow) as part of the collected data set.
- Not recognizing poor data. The data you collect during the characterization process should closely resemble the function predicted by theory. If you see one or more data points that deviate substantially from the smooth curve connecting the other data points together (i.e. "outliers"), something likely went wrong during the testing process and it should be repeated.

- Reversing the axes on the plots. Remember, in order for the spreadsheet-generated formula to be useful to you in programming the caSCADA system, differential pressure must be the independent variable (x) and flow must be the dependent variable (y).

Lab Exercise – flow/DP prediction

Regardless of the type of flowmeter used by your team to measure process flow rate, everyone must also demonstrate competence calculating differential pressure generated by a DP-based flow element given a known flow rate, or vice-versa. A system called the *turbocompressor* already exists in the main lab room with a variable-frequency-driven air fan blowing air through a venturi tube, and an indicating differential pressure transmitter sensing the DP generated by that venturi tube. Air flow rate is a direct (linear) function of the fan's speed, which is a direct (linear) function of the motor's drive frequency.

The mathematical relationship between flow rate and DP for any given flow element and fluid type, of course, is given by the following formula:

$$Q = k\sqrt{\Delta P}$$

Where,
Q = Flow rate
k = Proportionality constant
ΔP = Differential pressure

The "k factor" of this venturi tube assembly may be derived by manipulating that formula to solve for k and plugging in known values of Q (i.e. fan drive frequency) and ΔP. Known values for one particular fan speed will be provided by the instructor prior to each student's challenge. After providing these Q and ΔP values, the instructor will then randomly change the fan's speed and either hide that new fan speed or hide the new ΔP value, and have each student calculate the hidden value based on the *other* value which will be evident for all to see.

Each student passes this challenge when they are able to correctly calculate the hidden variable from the revealed variable.

Lab Exercise – Linux command-line usage

The caSCADA telemetry system is built on the foundation of a single-board computer running the Linux operating system. Linux is a free and open-source version of the venerable Unix operating system which was developed for large mainframe computers in the early 1970's. In this lab exercise you will find the following Linux commands useful in addition to the commands you have already learned in the last lab exercise.

`man`

A standard feature of all Unix systems is the *manual* library with documentation on virtually all commands and installed software. This documentation is available at the command line simply by typing `man` followed by the name of the command or program you wish to learn about. For example, if you wished to learn how to properly use the `ifconfig` command to view network parameters, you would type `man ifconfig`. The screen then switches to a display of the "manual" page for that command, where you may scroll up and down using arrow keys and page up/down keys, and search for terms by pressing the `/` key. You may exit the manual page at any time by pressing the `q` key.

`cp`

The `cp` command makes a *copy* of a file. Both the original file name and the new (copied) file name are specified, in that order, as arguments to the `cp` command. For example, entering the command `cp data.txt mydata` copies the contents of the text file `data.txt` into a new file within that same directory named `mydata`.

Without any options specified, the `cp` command acts silently, not prompting for confirmation of a file's duplication or even giving any indication that the job is done. For this reason, I prefer to get into the habit of including the `v` ("verbose") and `i` ("interactive") options when invoking the `cp` command. If you were to type `cp -vi data.txt mydata` and press Enter, it would prompt you with a question to confirm whether you really wanted to copy this file if indeed a file named `mydata` already existed (press `y` to confirm and `n` to escape) which is the "interactive" option at work. It would also tell you the file had been copied when complete – that's the "verbose" option at work.

Here are some example uses of the `cp` command:

`cp -i mydata yourdata`   *copies the contents of the file "mydata" into a new file named "yourdata". If the file "yourdata" already exists, the command will prompt you to confirm whether or not to over-write the existing file (this is the "interactive" option at work).*

`cp data.txt newdir/`   *copies the file "data.txt" into a directory named "newdir" where a new file named "data.txt" will be created. If the file "data.txt" already exists within the "newdir" directory, its contents will be over-written without asking.*

`cp -v source/input.dat .`   *copies the file "input.dat" located in a directory named "source" to the present directory (.) where a new file named "input.dat" will be created. If the file "input.dat" already exists within the present directory, its contents will be over-written. The -v option instructs the copy command to print a short message confirming completion of the copying task.*

`cp -vi data.txt ../`   *copies the file "data.txt" into the next higher-level directory (../) where a new file named "data.txt" will be created. The interactive option prompts you confirm over-writing is the file "data.txt" already exists in that directory, and the verbose option instructs the copy command to print a short message of confirmation when complete.*

`mv`

The `mv` command does the same thing as the `cp` command, but deletes the original file after the copying process is complete. In other words, the `mv` command *moves* the file rather than duplicating it. Like the `cp` command, the `mv` command also obeys the `-vi` options. This is highly recommended as a habit to build, as it will save you someday from accidently relocating a file.

`rm`

Okay, here is where we could potentially do some damage to the system! The `rm` command removes, or deletes, any file specified. If you were to type `rm data.txt` it would delete any file named `data.txt`. Like the copy (`cp`) command, `rm` supports both the "verbose" and "interactive" options which are highly recommended to avoid accidental deletions.

To get some practice using this command, you will need to have some files available that are safe to delete. Two such files are the `data.txt` and `data.html` files which are refreshed and re-written periodically any time the `poll` or `simulate` caSCADA processes are running. Another way to practice using the `rm` command is to first use the `touch` command to create a new file of zero byte size which you may then delete (e.g. typing `touch junk` creates a new file named "junk" which of course is safe for anyone to remove because it contains no data whatsoever).

`*`

The asterisk symbol isn't really a command, but rather a "wildcard" character useful for representing portions of file names or directory names. Specifically, the asterisk character represents *any* one or multiple characters that might be part of a file name or directory name. For example, if you were to issue the command `ls -l *.txt` it would display a listing of all files ending with the `.txt` extension (i.e. all text files).

The asterisk wildcard may be used at the beginning, middle, or even end of a specified file or directory name. Note the following examples:

`cd engineer*`   *Relocates you to the directory beginning with the letters "engineer". If more than one directory is so named, this will return an error message.*

`rm -vi junk*txt`   *Removes all files having names beginning with the letters "junk" and ending with the letters "txt".*

`cp -vi *poll* ../../`   *Copies all files containing the letters "poll" in their names two directory levels above where we are right now. If multiple files exist fitting this name pattern, all of them will be copied to that location under their original names.*

`cp -vi ../* .`   *Copies all files residing one directory level above where we are right now, to where we are right now (the present directory).*

Another wildcard character that is sometimes useful is the `?` which is a wildcard *only for a single character* in a file name or directory name, versus `*` which is a wildcard for any number of consecutive characters in a name.

`mkdir`

This command creates ("makes") a new subdirectory under the directory you happen to presently reside. The name of the new subdirectory must be specified as an argument to the `mkdir` command. For example, if you were to type `mkdir Elvis` it would create a new subdirectory named `Elvis`.

rmdir

This command deletes ("removes") a specified subdirectory. For example, `rmdir Elvis` will delete the `Elvis` subdirectory, but only if that directory is empty. The `rmdir` command does nothing if there are files located within the specified subdirectory, acting out of precaution.

grep

This highly useful command scans a text file and prints to the screen only those lines within the file containing a specified string of text you specify as an argument to the command. The `grep` command requires you to provide at least two arguments: the first specifying the text string to search for, and the second specifying the file to search within. Multiple files may be specified. For example, if you were to type the command `grep PT-45 data.txt` it would scan the file `data.txt` and only print out those lines of the file containing the text `PT-45`.

The text string `grep` searches for is case-sensitive, and must be spelled perfectly. If space characters are part of the desired search string, you will need to enclose the text string in quotation marks (e.g. `grep "Is anyone there" letter.txt`) in order to not interpret the space characters between `Is` and `anyone` and `there` as delimiters between additional arguments to the `grep` command. If we were to have omitted the quotation marks, `grep` would only have searched for the text string `Is`, but it would have looked for that string within three different files: `anyone`, `there`, and `letter.txt`!

Note the following example uses of `grep`:

`grep AIN3 f_channel_03.c`   *returns any line(s) within the file f_channel_03.c containing the text string "AIN3".*

`grep data README.txt LICENSE.txt`   *returns any line(s) within the files README.txt or INSTALL.txt containing the text string "data".*

`grep "float x" *.c`   *searches any file whose filename ends in ".c" for the text string "float x".*

As you can probably guess, the `grep` command is very useful when using the caSCADA system, as it allows you to scan any of the live data files updated by the `poll` or `simulate` processes for just the channel you are interested in.

grep -v

The `-v` option for the `grep` command instructs it to obey an *inverse match* rule. That is to say, the `-v` option tells `grep` to search for lines in a file that *do not* contain the text string you specify.

Note that the `-v` option in `grep` does something entirely different from the `-v` option in either the `cp` or `mv` commands. As it happens, each person who developed these Unix commands was free to assign any meaning they wished to the various options, and there appears to be little standardization between different commands. As always, the `man` utility is helpful here, showing you which options exist for each command and what each of them mean.

| | |

Like the asterisk character (*), the "pipe" character (|, which is located on most keyboards as the shift-character on the backslash key) isn't really a command at all, but rather a different kind of function in the Unix command-line environment. The "pipe" character links two or more commands together, so that the text output of the first command gets sent as input into the next command, as though those two commands were linked together with a section of virtual pipe.

One of the most common uses of such "plumbing" in Unix systems is the pipe a command to the `grep` command to filter for a particular string of text. Consider, for example, the `ps -e` command, which displays to the terminal a list of all "processes" currently running on the computer. If you wished to scan that list of running processes to look for a particular process name, or process ID number, or terminal ID, it could be very tedious and error-prone to do it manually by visually scanning the list with your eyes. Instead, we could issue the `ps -e` command followed by the pipe symbol and then use `grep` to display only certain lines. For example, the command `ps -e | grep poll` will display all instances of processes running which contain the string "poll" anywhere in the line output by `ps`.

Note how when using the "pipe" symbol between `ps -e` and `grep`, the `grep` command does not need a filename specified to search in. This is because the text output by the `ps -e` command is what is being searched through by `grep`. Whenever Unix commands are "plumbed" together by the pipe symbol, the following command gets its data from the output of the previous command.

Consider the following example, used by someone to screen all files and directories owned by "root" and edited in the year 2017:

```
ls -l | grep 2017 | grep root
```

This example uses the `ls` command to list all files and subdirectories within the current directory, and so do in "long" format (`-l`) so as to show all dates, sizes, owners, and permissions. The *two* casdaded `grep` commands first select only those lines containing the number 2017 (a calendar year), and then select from that list only those lines containing the word "root". Of course, this will screen for *any* lines of text in the listing containing the number 2017 and the word root, so if there is a file that happens to be named `groot.txt` and is 2017 bytes in size, that file will be listed as well. The `grep` command merely searches for matching text, not appropriate context. However, even with this limitation it should be clear how piping multiple `grep` commands can make fast work of an otherwise tedious searching operation.

Common mistakes:

- Not practicing the use of these commands!
- Not practicing the use of these commands!!
- *Not practicing the use of these commands!!!*

Lab Exercise – troubleshooting

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

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

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

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

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

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

Common mistakes:

- Not practicing the use of the TROUBLESHOOT software.

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

Lab Exercise – editing and running caSCADA code

For each transmitter connected to the DAQ unit in the RTU, there will be one designated caSCADA channel. For a flow measurement system with three redundant pressure transmitters sensing DP generated by a common flow element, this means three channels: one for each of the redundant transmitters.

Each of these transmitter channels will be scaled linearly, representing the variable directly sensed by the transmitter. If the transmitters in question sense differential pressure, then the scaled value will be in units appropriate to differential pressure rather than units appropriate to flow. A new requirement for this lab exercise is that the transmitter channel must employ conditional ("if") statements to set the channel's status value to something other than 1 if the reading falls outside of the proper or usable range.

Additional channel(s) will be designated on the caSCADA system for the computation of flow rate. These channels will take value and status data from the transmitter channels and perform appropriate mathematical calculations on that data to convert it into a flow rate. It is each *team's* responsibility to edit the C code for a flow-computation channel.

For example, suppose the system you're assigned will have three redundant DP transmitters wired to analog inputs 1, 2, and 3 on the LabJack DAQ. Each of the channel functions will be written to scale the 4-20 mA signal into appropriate pressure readings, as shown in this example code for the file **f_channel_02.c** which takes in the 1-5 VDC analog signal and scales it into 0-5 inches WC differential pressure. Here, the status is set to 0 if the transmitter becomes under-ranged (less than 0.0) or over-ranged (more than 5.0):

```
/********************************************************
Consult the "README.txt" file for help editing this function!
********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_02 (void)
{

  f_channel[2].value = ain[2] * 1.25 - 1.25;
  f_channel[2].tag = "PDT-102";
  f_channel[2].unit = "Inches WC";

  if (f_channel[2].value < 0.0 || f_channel[2].value > 5.0)
    f_channel[2].status = 0;

  else
    f_channel[2].status = 1;

  f_channel[2].comment = "Redundant DP transmitter number 2";

  return 1;
}
```

Since each student will be responsible for editing the transmitter channel code, the instructor will assign different "if" conditions to every student to ensure a genuine learning experience. For example, the instructor may assign a different threshold for a "bad" (0) status value on a DP transmitter: perhaps any signal less than 10% of the scaled range rather than only for values less than zero. Alternatively, the instructor may request that the comment change dynamically with the status as well.

Using conditional ("if") expressions in C language programming is a new objective and requires new knowledge. First, a list of the relational (comparative) and logical (AND/OR) operators used by the `if` conditional:

Relational operator	Meaning
==	Equal to
!=	Not equal to
<	Less than
<=	Less than or equal to
>	Greater than
>=	Greater than or equal to

Logical operator	Meaning
&&	AND
||	OR

Next, some examples of `if` conditionals shown in code snippets (with explanatory comments). This first example sets the status to different values depending on if the measurement is under-ranged, over-ranged, or within range:

```
    if (f_channel[2].value < 0.0)
       f_channel[2].status = 0;          // Sets status = 0 if negative

    else if (f_channel[2].value > 5.0)
       f_channel[2].status = 2;          // Sets status = 2 if over 5.0 inches WC

    else
       f_channel[2].status = 1;          // Sets status = 1 if neither
```

Pay close attention to which lines are terminated with semicolon characters (;) and which are not. Every "action" statement ends with one, but the `if` conditional lines do not.

This next example takes multiple actions with each condition of the measurement. Note the use of curly-brace characters to encompass all the statements executed for a given condition, which were not needed when there was only one statement executed per "if" condition:

```
    if (f_channel[2].value < 0.0 || f_channel[2].value > 5.0)
    {
       f_channel[2].status = 0;                  // Sets status = 0 if out of range
       f_channel[2].comment = "Out of range";    // Sets comment too
    }

    else
    {
       f_channel[2].status = 1;                  // Sets status = 1 if range is good
       f_channel[2].comment = "Range okay";      // Sets comment too
    }
```

Again, it will be the instructor who decides what conditions shall trigger a different status value, and each student's task will be to implement that functionality in code.

As mentioned previously, additional channels will be assigned in the caSCADA system for the computation of flow rates from the scaled transmitter signals. The coding for these channels will be done by *team* effort rather than by *individual* students. Your instructor will assign each team a programming challenge for this flow computation channel, such as averaging multiple transmitter pressures, selecting one pressure from multiple pressures, or capturing high or low values of flow.

These other channels will have no direct association with the analog inputs on the LabJack, but instead will get their data from the transmitter channels. Take for example this code for channel 5, which reads the scaled differential pressures from channels 1, 2, and 3 and averages them together before calculating flow using the formula $Q = k\sqrt{\Delta P}$:

```c
/***********************************************************
Consult the "README.txt" file for help editing this function!
***********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float average;
  float k = 34.6;

  average = (f_channel[1].value + f_channel[2].value + f_channel[3].value) / 3.0;
  f_channel[5].value = k * sqrt(average);
  f_channel[5].tag = "FY-101";
  f_channel[5].unit = "SCFM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Air flow rate";

  return 1;
}
```

Note the introduction of two new floating-point variables: `average` which gets computed as the mathematical mean of the three transmitter channel values, and `k` which is set as the k factor in the $Q = k\sqrt{\Delta P}$ flow formula. These are not strictly necessary, for it is possible to consolidate all the arithmetic in a single statement where we compute `f_channel[5].value`. The result would function just the same:

```c
f_channel[5].value = 34.6 * sqrt((f_channel[1].value + f_channel[2].value +
f_channel[3].value) / 3.0);
```

However, inserting these "local" variables into the channel function makes it easier for any human being reading the code to understand, in the same way that writing intermediate calculations on paper makes any long-winded computation easier to comprehend and therefore less liable to misinterpret.

It should be mentioned that variables declared inside a function (such as `average` and `k` shown in this example) are called *automatic* variables in the C programming language, which means they are usable to that function only: their values are discarded and forgotten after the function finishes executing. The next time that function is "called" by the main portion of the program, the variables `average` and `k` will no longer contain their previous values. This stands in contrast to *external* (also called *global*) variables which are defined outside of the function and retain their values whether the function is called or not. All `f_channel[]` variables in caSCADA, for example, are external which means they are accessible globally to functions within the caSCADA program.

If we have need for a variable within a function to retain its last value each time the function is called again, we may do so by making that function's variable *static*. Consider this example, where channel 5's function displays the *maximum* float rate seen:

```
/**********************************************************
Consult the "README.txt" file for help editing this function!
**********************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float average, flow;
  float k = 34.6;
  static float maxflow;

  average = (f_channel[1].value + f_channel[2].value + f_channel[3].value) / 3.0;

  flow = k * sqrt(average);

  if (flow > maxflow)          // Checks for a new (high) value for flow
    maxflow = flow;            // and updates maxflow if necessary

  f_channel[5].value = maxflow;
  f_channel[5].tag = "FY-101";
  f_channel[5].unit = "SCFM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Maximum air flow rate";

  return 1;
}
```

Here we declare two new variables: another floating-point called `flow` and a *static* floating-point called `maxflow`. Both are accessible only to this function, but while `average` and `flow` are regular "automatic" variables, `maxflow` retains its previous value every time the function is called. Therefore it remembers its value from the last time that function executes. The "if" conditional updates `maxflow` any time the newly computed `flow` is seen to be greater in value.

The capabilities of caSCADA are limited only by the features available within the C programming language, which is to say *essentially limitless* given the requisite programming knowledge. Some of the mathematical functions available for your use in coding this flow-computation channel are listed here, some of which may become extremely useful when implementing the formula given to you by the electronic spreadsheet for your flow element:

Mathematical function	Explanation
`pow(x,y)`	calculates x^y
`sqrt(x)`	calculates $\sqrt{x}$
`exp(x)`	calculates e^y
`log(x)`	calculates $\ln x$
`log10(x)`	calculates $\log x$

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Consider an example where we need the value of caSCADA channel #5 to be set by the following formula, where x is the measured differential pressure from the median (i.e. *middle* value) of three redundant transmitter measurements and y is the computed flow rate:

$$y = 2.4x^2 - 0.83x^3$$

Comments (text preceded by double-slash symbols //) are included in this example to help explain what the code is doing:

```c
/************************************************************
Consult the "README.txt" file for help editing this function!
************************************************************/

#include <stdio.h>
#include <math.h> // Necessary for any advanced math functions
#include "cascada.h" // Contains all the declarations specific to caSCADA

int
f_channel_05 (void)
{

  float p1, p2, p3, median;     // Declares four floating-point variables

  p1 = f_channel[1].value;      // Assigns channel 1's value to variable p1
  p2 = f_channel[2].value;      // etc.
  p3 = f_channel[3].value;      // etc.

  if ((p1 >= p2 && p1 <= p3) || (p1 >= p3 && p1 <= p2) )   // Selects p1 as middle
     median = p1;

  if ((p2 >= p1 && p2 <= p3) || (p2 >= p3 && p2 <= p1) )   // Selects p2 as middle
     median = p2;

  if ((p3 >= p1 && p3 <= p2) || (p3 >= p2 && p3 <= p1) )   // Selects p3 as middle
     median = p3;

  f_channel[5].value = (2.4 * pow(median,2)) - (0.83 * pow(median,3));
  f_channel[5].tag = "FY-114";
  f_channel[5].unit = "GPM";
  f_channel[5].status = 1;
  f_channel[5].comment = "Water flow rate";

  return 1;
}
```

Note once again the use of "local" variables p1, p2, p3, and median to simplify the reading of this code. The "p" variables serve as aliases for the three pressure-measurement channel values, so that the "if" conditional expressions don't become cumbersome and hard to read (and therefore hard to identify problems within).

Note also that the else conditional is not strictly necessary in C programming. Three if conditionals in sequence work just fine for this purpose.

Common mistakes:

- Syntax errors resulting from incorrect characters added to the code, or necessary characters deleted from it. *Pay close attention to the color highlighting presented by the text editor (*`nano`*), as this often reveals such errors.*
- Failing to follow all steps of the programming development cycle (e.g. neglecting to recompile edited source code using the `make` command, failing to kill the old (running) version and re-start the new version).
- Running multiple instances of `poll` and/or `simulate` on the same RTU. This will cause conflicting data to be written and re-written to the `data.txt` file. The most common cause of this problem is when multiple students log in to the same caSCADA RTU and attempt to test their code simultaneously.
- Leaving a HART communicator connected to the transmitter's 4-20 mA circuit, which will result in the caSCADA system picking up on bursts of FSK data. This will make the signal appear to "jump" around.
- Not using ISA-standard tag names for each channel.

file i00490

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RTU component layout

An "RTU" is a *Remote Terminal Unit* in a SCADA system serving as the interface between field instruments and a central control/display unit called the "MTU" (*Master Terminal Unit*). In our caSCADA system, the MTU is just a laptop computer viewing data generated by the single-board Linux computer in each RTU. Each RTU uses a LabJack data acquisition unit to sense analog signals sent by field transmitters and a single-board computer to condition and present that data in the form of digital data files readable by the MTU. Communication takes place via a wireless access point (WAP) router:
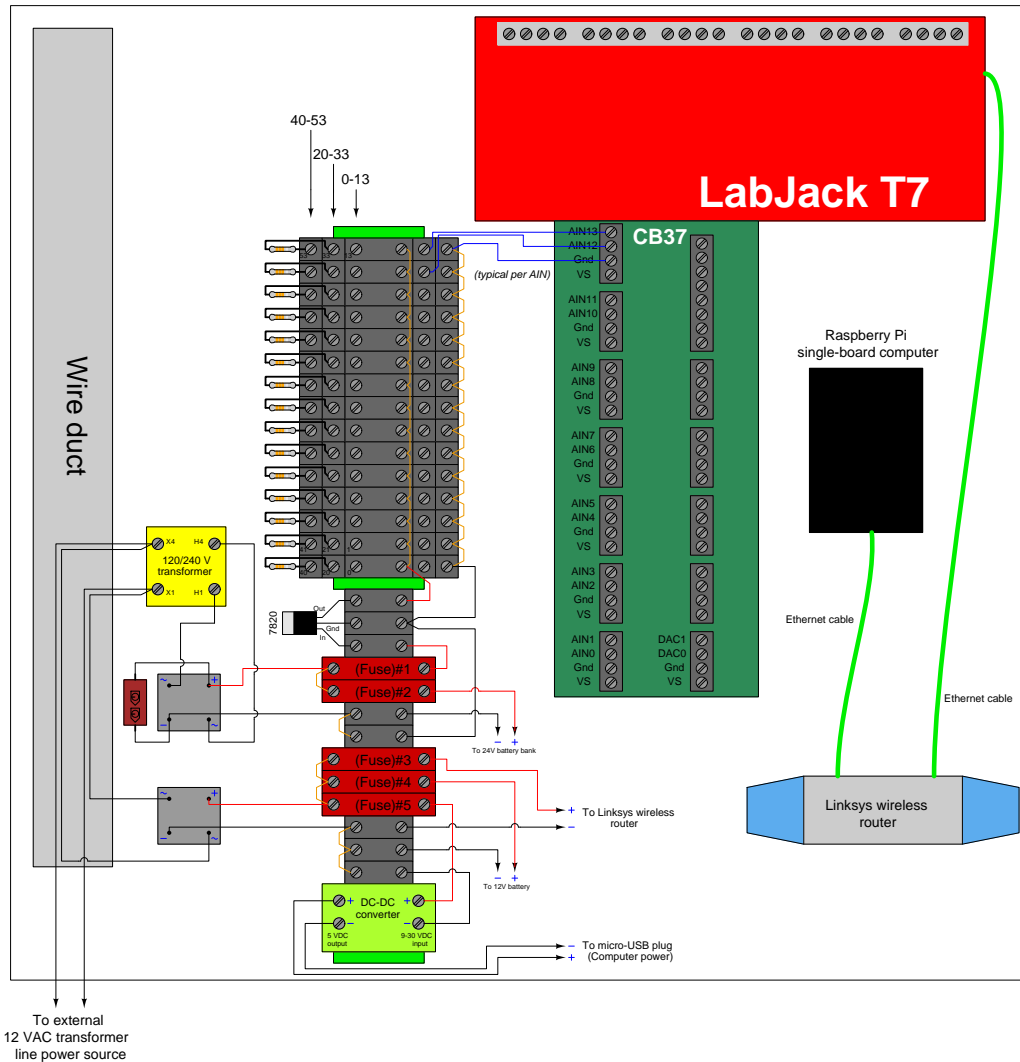
Each RTU enclosure is weatherproof, and equipped with a set of batteries to maintain DC power to all the system components in the event of an external AC power failure.

The upper level of terminals on the triple-level blocks should all be jumpered together because this is the 20 VDC "bus" used to power all field instruments. The lower level of terminals should also be jumpered together because they comprise the negative side ("Common" or "GND") of that same 20 VDC loop power supply.

Sample loop diagrams

Generic loop diagram for LabJack T7 based caSCADA RTU	
Field	RTU enclosure

Note: single-loop PID control uses AIN0 for PV and DAC0 for Output
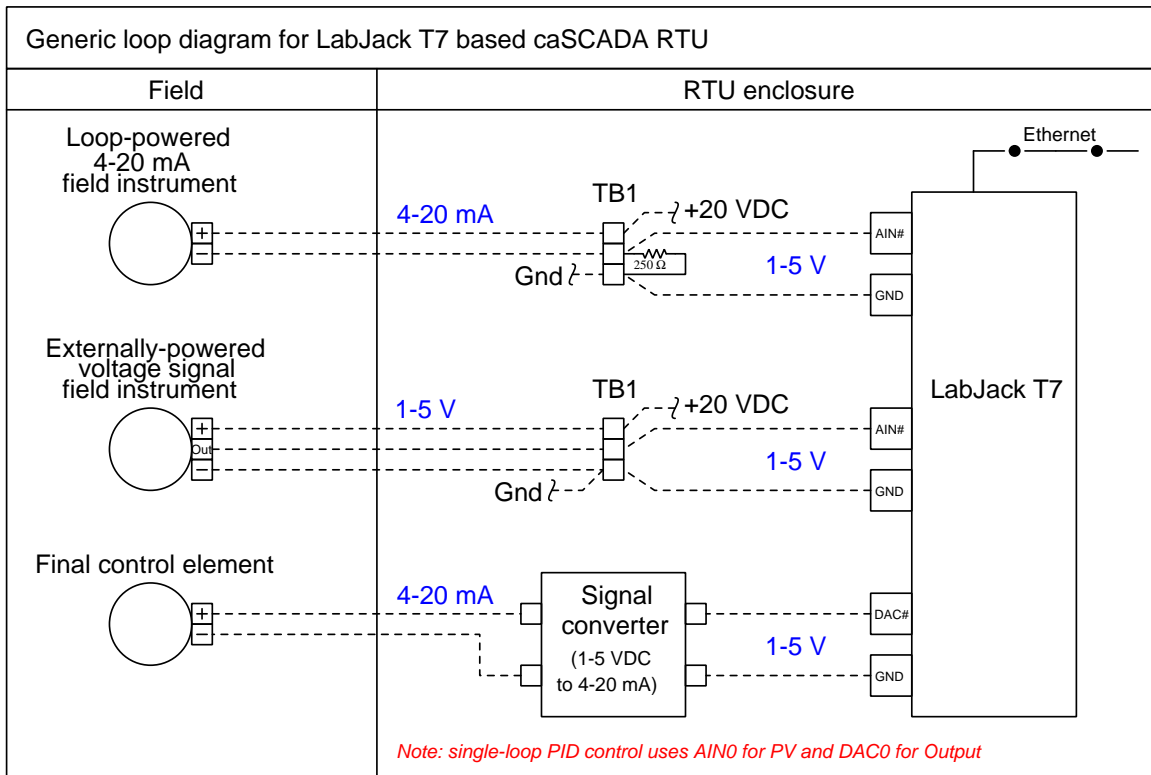
A set of triple-height terminal blocks marshall field instrument signals to the DAQ input terminals, with the three terminals of each block represented in the above diagram. The top-most terminal is the $+$ DC power supply bus, the middle terminal connects to the LabJack DAQ input channel, and the bottom terminal is the $-$ DC power (GND) supply bus. Both current-based and voltage-based instrument signals may be accepted by the DAQ. In the case of 4-20 mA loop instruments, a precision 250 Ω resistor is connected in such a way to provide a 1-5 VDC signal for the DAQ to sense. If the field instrument outputs a voltage signal instead (which is actually quite common for RTU loops in remote installations relying on solar power) then the resistor is omitted and the LabJack AIN directly reads that instrument's output voltage.

The LabJack DAQ also provides two analog *output* channels (DAC0 and DAC1) for analog control of a final control element. In a caSCADA system these output channels are connected to an external signal converter, and the resulting 4-20 mA output signal may be used to drive an I/P transducer, electronic valve positioner, or VFD.

When using a caSCADA system for PID loop control, the Process Variable (PV) input is input channel AIN0 and the Manipulated Variable output is output channel DAC0. The PID control application may be invoked by entering `./pid` at the command line.

Electrical power diagram
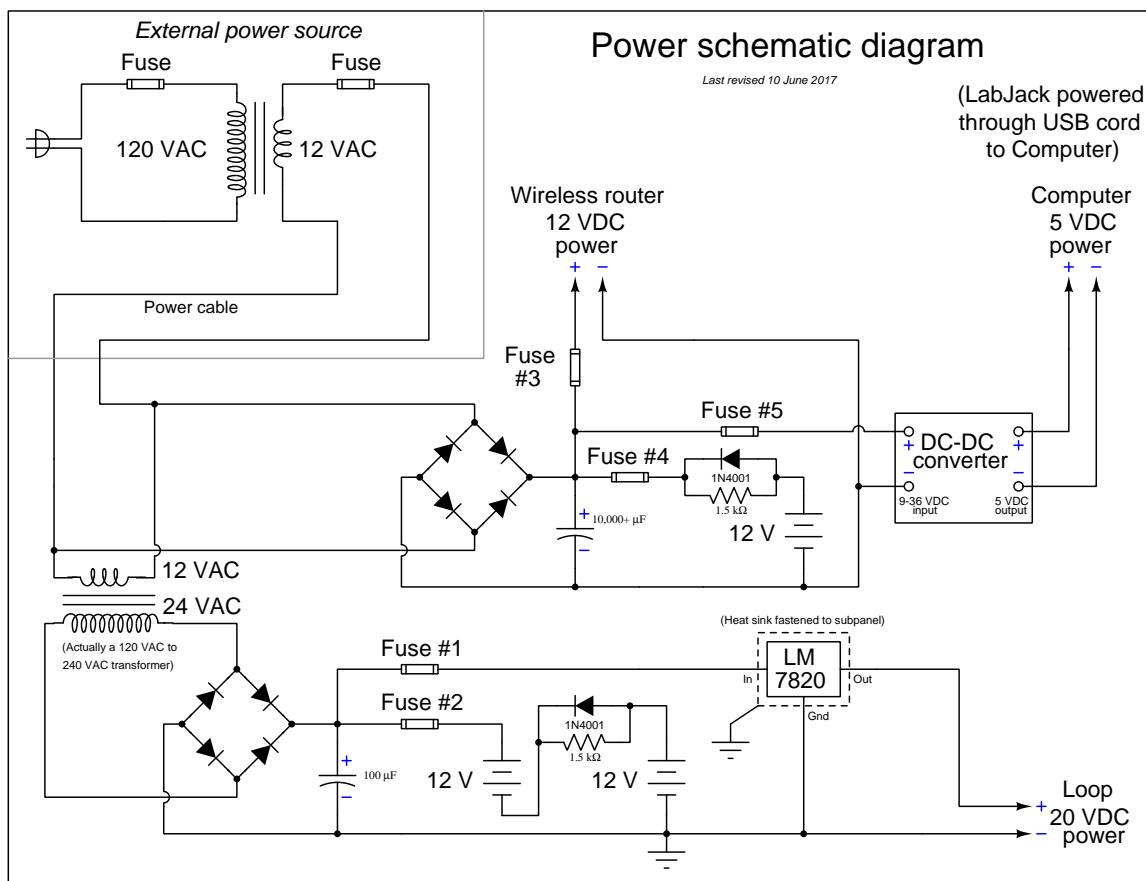
Power is sent to each RTU box at 12 volts AC, from a transformer located near a 120 VAC power source. This keeps the field power cable at a safe, low voltage (similar to outside sprinkler control systems and walkway lighting).

Internal to each RTU is a dual-voltage DC system: 12 volts (regulated down to 5 VDC) for running the Linux-based computer, LabJack DAQ, and Linksys WRT54GL wireless router; and 20 volts for powering the field instruments. Lead-acid batteries provide back-up power for the RTU to continue running in the event of a power outage. The resistor-diode network limits battery charging current to a bare minimum, while providing full current capacity in the discharge direction (in the event of an AC line power outage).

24 volts is a more customary DC supply voltage for loop-powered field instruments, but the LabJack model T7 DAQ has an absolute maximum input voltage of 20 VDC. Thus, the loop supply voltage is limited to this value to avoid the potential for damage to the LabJack in the event of a shorted instrument cable which would apply full power supply voltage to the DAQ input.

RTU power system testing procedure

You must follow this procedure when first commissioning a new RTU. When working with an existing RTU, you may follow the same procedure to test the continuing health of the DC power system.

(1) Test the external 12 VAC transformer by itself: when plugged into a 120 volt AC source, does it output at least 12 volts AC?

(2) Open up all fuses (#1 through #5) to ensure no device will become powered until you intend so.

(3) Connect this external 12 VAC transformer's output to the RTU as shown in the diagrams and apply power. Check the output of both bridge rectifiers for proper DC voltage magnitude and polarity. Due to the filter capacitors the DC voltage magnitudes will register greater than the AC voltage magnitudes feeding each of the bridge rectifiers.

(4) Ensure the batteries are wired to the proper terminal blocks and fuse holders, and measure DC voltage magnitudes and polarities at the battery-side of each open fuse. This ensures the batteries are properly connected.

(5) Close fuses #2 and #4. This connects the two battery banks to their respective charging sources. Re-measure the voltage magnitudes at the battery-side of each closed fuse. You should read slightly higher voltage now than in the previous step, because the batteries are charging.

(6) Ensure all power plugs are removed from the caSCADA electronic devices: the LabJack DAQ unit, the RTU computer, and the Linksys wireless router. Prepare to measure DC voltage at the ends of those power plugs.

(7) Close fuse #3 and measure DC voltage magnitude and polarity at the Linksys router's power plug. Check the router's documentation for the proper DC polarity of the plug's shell and tip to see that the polarity is correct. If all is well, plug the power cable into the router and check to see that it powers up. Re-measure voltage magnitude at fuse #3 to see that the router is receiving adequate voltage while powered (i.e. under load).

(8) Close fuse #5 and measure DC voltage magnitude and polarity at the RTU computer's micro-USB power plug. Check online for the "pinout" specification of a micro-USB power plug to see that the polarity is correct. If the pins on the micro-USB plug are too small to safely probe using your multimeter, you may check DC voltage at the stripped end of that cable where it lands at the terminal block, and verify correct voltage and polarity according to the colors of that cable's wires. If all is well, plug the power cable into the RTU computer and check to see that it powers up.

(9) Plug the B-style USB cable into the LabJack. It receives power through the RTU computer and should power up immediately. Re-measure voltage magnitude at fuse #5 to see that both the RTU computer and LabJack units are receiving adequate voltage while powered (i.e. under load).

(10) Close fuse #1 to apply 20 VDC power to the field instrument terminal blocks. Measure DC voltage magnitude and polarity between terminals 13 and 53 to ensure 20 VDC is supplied all the way to the end of the terminal block section.

(11) At this point in time you may initialize the caSCADA system MTU (a laptop PC) and test the system for proper data. A procedure for this is given on the following page.

(12) Unplug the external 12 VAC transformer from its line power source, and re-measure all DC supply voltages to ensure all devices are receiving adequate voltage under battery power alone.

(13) Repeat these DC voltage measurements at one-hour intervals to check the health of the batteries.

RTU data system testing

You must follow this procedure when first commissioning new devices for an RTU.

(1) Ensure that the proper IP addresses are all written on labels affixed to each of the networked devices in the RTU: the LabJack DAQ unit, the Linksys wireless router, and the single-board computer.

(2) Set the IP address and subnet mask of your personal computer to appropriate values for the Ethernet device you wish to connect to. For each octet of the subnet mask with the value "255" the octet of your PC's IP address must match the IP addresses of all devices in the RTU. For each octet of the subnet mask with the value of "0" the octet of your PC's IP address must be different from any device in the RTU. This will prepare your PC for direct Ethernet cable connection to the device you intend to configure.

(3) Plug your computer into the Linksys router using an Ethernet cable, and set the router's IP address and subnet mask and name using a web browser. Follow the instructions given in the manual for the router. The router's name should make sense to any user of the system. In an area with multiple RTUs, the name should be specific enough to clearly identify which RTU it is.

(4) Plug your computer into the LabJack DAQ using an Ethernet cable, and set the DAQ's IP address and subnet mask using the software provided by LabJack for this task. Follow the instructions given in the LabJack manual.

(5) Plug an HDMI monitor and USB keyboard into the single-board computer, and log in directly to set its IP address and subnet mask. To check its current settings, use the `ifconfig` command (similar to the `ipconfig` command in Microsoft Windows). If the settings are not correct, you may change them by editing the file `/etc/network/interfaces`. This requires "root" privileges. Lines of text in this `interfaces` file follow this pattern:
   - The line specifying the `eth0` interface must read `iface eth0 inet static`
   - Prior to the `eth0` line must be a line that reads `auto eth0`
   - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
   - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.0.0`)

(6) Unplug the Ethernet cable from your personal computer and wirelessly connect to the Linksys router. The router will automatically assign an appropriate IP address to your computer's wireless card, as routers are designed to do.

(7) Use the `ping` command in your computer to test network connectivity with each device in the RTU. This command is simply the word "ping" followed by the IP address of the device you wish to ping. For example, `ping 169.254.8.1` will test to see whether your computer has connectivity with the device bearing the IP address 169.254.8.1.

(8) Once all devices have been proven to ping successfully, you may use an SSH client program in your personal computer (e.g. `Bitvise`) to log into the RTU computer. The login account is simply `btc` with the password `btc`.

(9) Once you are logged in to the Linux operating system, you may try compiling the caSCADA code and then running it (either `poll` process or the `pid` process) to test its ability to communicate with the DAQ unit.

Preparing the "Raspberry Pi" single-board computer for use in the caSCADA system

To initially configuring a Raspberry Pi to be used in the caSCADA system, there are several things which must be done:

- Log in as the default user (name = `pi` and password = `raspberry`)

- Use the `sudo` and `passwd` commands to reset the root account's password to your liking (e.g. `sudo passwd root`). There are several tasks for which root privileges are necessary, so it's convenient to be able to log into the root account and do that work there, rather than have to preface all those commands typed under the `pi` login user with the "`sudo`" qualifier.

- Use the `raspi-config` utility to set the system's hostname, configure the keyboard for US mapping (as British "UK" mapping is the default!), and also enable the `ssh` server which will be essential for remote login and system administration.

- Add a new user account called `btc`.

- Feel free to edit the hidden file named `.profile` in the `/home/btc` directory with any special instructions to be executed at login. For example, you may add lines containing the `echo` shell command to print messages to the screen for the user once they log in (e.g. `echo "Welcome to the fish hatchery RTU"`).

- Set the current time and date using the `date` command. The format is MMDDhhmmCCYY. For example, 3:21 PM on November 5, 2016 would be set by issuing the command `date 110515212016`.

- Navigate to the `/etc/network` directory and edit the file named `interfaces` to set all the required IP address and netmask information to give the Raspberry Pi a static IP address for use in the caSCADA system. Lines of text in this `interfaces` file follow this pattern:
  - The line specifying the `eth0` interface must read `iface eth0 inet static`
  - Prior to the `eth0` line must be a line that reads `auto eth0`
  - The "address" line contains the IP address (e.g. `address 169.254.8.3`)
  - The "netmask" line contains the subnet mask (e.g. `netmask 255.255.255.0`)

- Install the `cascada.tar` archive file in the `/home/btc` directory, and then use the command `tar xvf cascada.tar` to unpack that archive file.

- Install the latest `libmodbus` library archive file in the `root` directory, then uncompress it (`gunzip libmodbus*.gz`) and unpack the archive (`tar xvf libmodbus*tar`) and then descend into the new `libmodbus` directory to build it. This library is absolutely necessary for caSCADA to run, as it contains all the code necessary to read and write Modbus device registers over a TCP/IP network. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`. Check the general header file repository (located in the directory `/usr/include/`) to see if the installation script successfully copied the file named `modbus.h` there. In the versions of `libmodbus` I've installed, I have had to copy the `modbus.h` file to the `/usr/include` directory manually.

- Install the latest `ncurses` library archive file in the `root` directory, then uncompress it (`gunzip ncurses*.gz`) and unpack the archive (`tar xvf ncurses*tar`) and then descend into the new `ncurses` directory to build it. This library is necessary to run the `lynx` web browser, as well as the graphic interface for the caSCADA `pid` controller process. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

- Install the latest `lynx` text-based web browser software archive file in the `root` directory, then uncompress it (`gunzip lynx*.gz`) and unpack the archive (`tar xvf lynx*tar`) and then descend into the new `lynx` directory to build it. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

- Navigate to the `/home/btc` directory and edit the file `cascada_poll.c` with the correct IP address to establish a Modbus/TCP connection with the LabJack DAQ unit in your RTU. The function establishing the address will be easy to find in this file, as it calls out the IP address in standard four-octet format. Just edit the IP address that's shown, and the caSCADA `poll` software will be able to communicate with that LabJack DAQ.

- Try running `make` in the `/home/btc` directory to verify all the caSCADA software components successfully compile.

file i02566

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

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

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

Sample Loop Diagram (using DCS controller)

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| Loop Diagram: Blue team pressure loop | | Revised by: Duncan D.V. | | Date: April 1, 2009 |

Field process area · **Field panel JB-25** · **DCS cabinet**

0-50 PSI

H / L — PT 73 — + / − — Red / Blk — Cable PT-73

TB-52 — Red 1 Red / Blk 2 Blk — Cable 4, Pr 1

TB-80 — Red 11 Red / Blk 12 Blk — Cable PT-73

Card 4 Channel 6 — Red 11 / Blk 12 — Analog input

0-50 PSI — PIC 73

Tube PV-73

PV 73

I/P — O — PY 73 — + / − — S — Red / Blk — Cable PV-73

AS 20 PSI

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

TB-80 — Red 29 Red / Blk 30 Blk — Cable PV-73

Card 6 Channel 6 — Red 11 / Blk 12 — Analog output

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

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

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

Tube LT-24a

Tube LT-24b

14

H
L
LT 24   Out

In

(vent)

A.S. 21 PSI

C
LIC 24
D

Supply

A.S. 21 PSI

LV 24

Tube LV-24

Tube LV-24   Tube LV-24

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

121

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

| Process area | Field panel FP-25 |

H L FT 18

0-75 GPM

Red
Blk
Cable FT-18

Red
Blk
21 Blu
22 Blu

10 | 800 mA | Blu

Blu

+ 24 VDC 1 amp −

PS-1

L1 N ⏚

120 VAC

Blk Wht Grn

Blu
IN0+
IN0−
IN1+
IN1−
IN2+
IN2−
IN3+
IN3−

1762-IF4
analog input card
expansion slot 1

A
Loop +
Loop −
Supply

P

IAS 20 PSI

Red
Blk
Cable FV-18

Red
Blk
11 Blu
12 Blu

Blu
I out 0   V out 0
I out 1   V out 1
I out 2   V out 2
I out 3   V out 3
Blu
Com

Com

1762-OF4
analog output card
expansion slot 2

FV 18

FC 18

⏚
L2/N
L1

Ethernet

FIR 18

(Located in main
control room)

1A 1A ⏚
1   2   3   4

Blk Wht Grn

ES 120 VAC
From field
panel disconnect

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

Lab Exercise – loop diagram and system inspection

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

Construction Standards

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

Documentation Standards

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

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

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

Common mistakes:

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

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

file i00654

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7

Answer 8

Answer 9

Answer 10

Partial answer:
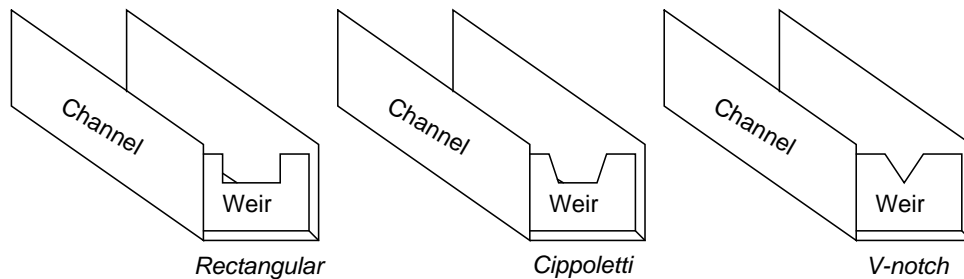
Elevator energy = 5700 ft-lb

Bullet energy = 2648.2 ft-lb

Answer 11

Hint: to explain how each of these head-generating primary flow elements functions, begin by identifying the location of the flow's *vena contracta*.

Answer 12

They say a picture is worth a thousand words . . .

A *weir* is nothing more than a dam that impedes the flow of liquid in an open channel. In order for liquid to flow past this dam, its upstream level must rise high enough so that it spills over the top of the dam. The more volumetric flow there is, the higher the upstream liquid level will rise. So, by measuring level, the flow rate may be inferred.

Most instrumentation weirs have notches cut into them to create exact flow characteristics. Among the more popular weir types are *rectangular*, *Cippoletti* (*trapezoidal*), and *V-notch*.

To measure the upstream liquid level, a displacer or ultrasonic type of level instrument is usually used, inside of a *stilling well*: a length of vertical pipe inserted into the water to provide a "still" column of liquid to measure. If there were no stilling well, the turbulent surface of the liquid might produce measurement errors.

Answer 13

Ooooh . . . aahhhhh . . . a *three-dimensional* picture is worth 1000^3 words!
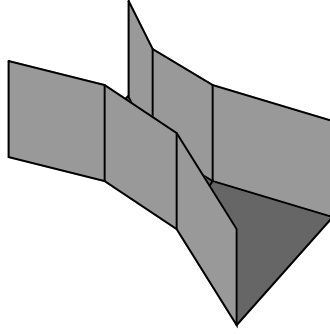
A *flume* is a constricted channel that produces different upstream liquid levels for different flow rates through it. Whereas a weir is a dam installed in the path of the liquid flow, a flume is a special channel section with no abrupt obstructions in it.

While flumes are more difficult to construct than weirs, their advantages over weirs are significant: flumes tend to be self-cleaning of silt and other debris that would otherwise plug up a weir, and flumes do not lose as much liquid head from entry to exit as weirs do (less permanent head loss).

Answer 14

I'll let you figure out the answer to this question!

Answer 15

The time elapsed between the generation of an acoustic pulse and the reception of its echo (reflected off the solid object) is directly proportional to the distance between the pulse source and the object. *Velocity* is simply the first derivative of distance with respect to time ($v = \frac{dx}{dt}$).

Answer 16

Mass flow measurement entails detecting units of mass (pounds, kilograms, etc.) passing by a specific point in a pipe or tube. Volumetric flow measurement entails detecting units of volume (cubic feet, gallons, liters, etc.) passing by a specific point in a pipe or tube.

Mass flow measurement will give true mass figures for the fluid flow rate. Volumetric flow measurement must be corrected for fluid density in order to obtain real figures for mass.

Answer 17

Thermal mass flowmeters use an electric heating element and at least two temperature sensors to detect difference in temperature related to convection.

The calibration of a thermal flowmeter depends on the fluid's thermal conductivity, as well as its specific heat (the amount of heat energy it absorbs per mass unit per temperature rise), similar to how an orifice plate's calibration depends on the fluid's density. If either or both of these factors are variable in the process flow stream, a thermal mass flowmeter will give erratic indications, just as an orifice plate will give erratic readings of flow if the process fluid's density changes randomly.

An example of a substance with a very high specific heat value is *hydrogen* gas. If a thermal mass flowmeter is calibrated to accurately read the mass flow rate of air, for example, and then it is subjected to a stream of hydrogen gas, it will falsely register an excessive flow rate for the hydrogen due to that gas's extremely large specific heat value.

Answer 18

Advantages:

- Very high accuracy
- Immunity to upstream/downstream piping disturbances
- Provides real measurement of mass flow, fluid density, and fluid temperature
- Excellent rangeability
- Immunity to changes in density – this makes Coriolis flowmeters particularly well-suited for measuring non-Newtonian fluids
- Bidirectional

Disadvantages:

- Relatively low operating temperature limit ($< 800^o$ F)
- Difficulty measuring multi-phase flows (e.g. gas + liquid)
- Prohibitively expensive for large pipe sizes
- Cannot measure low-pressure gases very well (Coriolis forces too small)
- May suffer errors from external vibrations

Mass flow measurement is obtained by measuring the phase shift of the tube's oscillation between the two ends.

Density measurement is obtained by measuring the resonant frequency of the tubes. The basic equation for a mass-and-spring mechanical system is as follows:

$$f_r = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

Where,

f_r = Resonant frequency
k = Spring constant
m = Mass

Given a known tube mass and a known tube volume, knowing the resonant frequency of the tubes makes it quite easy to calculate the mass of the fluid filling the tubes, and thus the fluid density.

Temperature measurement comes from an RTD sensing fluid temperature as it enters the tube assembly.

Answer 19

One possible fault has to do with the control valve: perhaps something has happened to make it fail closed (loss of air supply, signal, etc.). Other possible problems include the following:

- Pump not running (no source of fluid power to motivate flow)
- Very poor controller tuning
- Wrong controller action
- Valve failed closed (loss of air supply, signal, etc.)
- Transmitter failed, showing no flow when in fact there is

A good "first test" for troubleshooting the loop is to check the controller output: is it trying to open up the valve?

Answer 20

Answer 21

Answer 22

Answer 23

Answer 24

Partial answer:

$\bar{v}$ through the 8-inch pipe $= 201.49$ feet per minute.

Answer 25

Partial answer:

Q (minimum) $= 2900.1$ GPM

Answer 26

Answer 27

Answer 28

Answer 29

$P_2 = 60.12$ PSI (using top equation, with $\rho = 1.951$ slugs/ft^3)

$P_2 = 60.13$ PSI (using bottom equation, with $\gamma = 62.4$ lb/ft^3)

Hint: $v_1 = v_3 = 9.549$ ft/s ; $v_2 = 55.0$ ft/s ; $P_1 = 11{,}520$ lb/ft^2

Follow-up question: calculate the *differential* pressure between either P_1 or P_3 and P_2.

Answer 30

$P_2 = 0.490$ PSI (using top equation, with $\rho = 1.951$ slugs/ft^3)

$P_2 = 0.531$ PSI (using bottom equation, with $\gamma = 62.4$ lb/ft^3)

Hint: $v_1 = v_3 = 19.1$ ft/s ; $v_2 = 110.0$ ft/s ; $P_1 = 11{,}520$ lb/ft^2

Note: even slight amounts of rounding error may add up to skew the P_2 pressure calculation so that it ends up being as high as 1 PSI instead of half of a PSI. In order to avoid incurring rounding errors, you must store all intermediate calculated results in your calculator's memory locations rather than write them on paper and re-enter them. This is a good practice in general, not only because it avoids unnecessary rounding being introduced into your calculations, but also because it completely avoids simple keystroke errors!

Answer 31

The *Reynolds number* for a fluid flow is the ratio of a fluid's inertial (motion) forces as compared to its friction (viscous) forces.

To calculate Reynolds number given metric units:

$$\mathrm{Re} = \frac{D\overline{V}\rho}{\mu}$$

Where,
Re = Reynolds number (unitless)
D = Diameter of pipe, in meters (m)
$\overline{V}$ = Average velocity of fluid, in meters per second (m/s)
ρ = Mass density of fluid, in kilograms per cubic meter (kg/m^3)
μ = Absolute viscosity of fluid, in Pascal-seconds (Pa · s)

To calculate Reynolds number given English units (liquid flow):

$$\mathrm{Re} = \frac{(50.7)\rho Q}{D\mu}$$

Where,
Re = Reynolds number (unitless)
ρ = Mass density of liquid, in pounds (mass) per cubic foot (lbm/ft^3)
Q = Flow rate, gallons per minute (GPM)
D = Diameter of pipe, in inches (in)
μ = Absolute viscosity of fluid, in centipoise (cP)

To calculate Reynolds number given English units (gas flow):

$$\mathrm{Re} = \frac{(6.32)\rho Q}{D\mu}$$

Where,
Re = Reynolds number (unitless)
ρ = Mass density of gas, in pounds (mass) per cubic foot (lbm/ft^3)
Q = Flow rate, standard cubic feet per hour (SCFH)
D = Diameter of pipe, in inches (in)
μ = Absolute viscosity of fluid, in centipoise (cP)

To calculate Reynolds number given specific gravity instead of density (liquid flow):

$$\text{Re} = \frac{(3160)G_f Q}{D\mu}$$

Where,

Re = Reynolds number (unitless)

G_f = Specific gravity of liquid (unitless)

Q = Flow rate, gallons per minute (GPM)

D = Diameter of pipe, in inches (in)

μ = Absolute viscosity of fluid, in centipoise (cP)

Re = 186,000 for 500 gallons per minute of water flowing through an 8.5 inch pipe.

Answer 32

Re $\approx$ 12,600 = *turbulent*

Reynolds numbers less than 2,000 usually correspond to laminar flows, while Reynolds numbers above 10,000 usually correspond to turbulent flows. Reynolds numbers between 2,000 and 10,000 usually represent conditions of mild turbulence called "transitional flow." Bear in mind these cutoff points are *very approximate*, and depend on many factors including pipe geometry and wall smoothness.

Examples of Reynolds number thresholds for laminar vs. turbulent flows are given here, from different sources:

- Re < 2,000 = "Laminar"
- 2,000 < Re < 10,000 = "Transitional"
- Re > 10,000 = "Fully developed turbulent"
- Source: R. Siev, J.B. Arant, B.G. Lipták; Chapter 2.8: Laminar Flowmeters; *Instrument Engineer's Handbook, Process Measurement and Analysis, Third Edition*; pg. 105

- Re > 10,000 = "Definitely turbulent"
- Source: W.H. Howe, J.B. Arant, B.G. Lipták; Chapter 2.14: Orifices; *Instrument Engineer's Handbook, Process Measurement and Analysis, Third Edition*; pg. 153

- Re < 2,000 = "Laminar"
- 2,000 < Re < 4,000 = "Transitional"
- Re > 4,000 = "Turbulent"
- Source: Instrument Society of America; Chapter 2: Fluid Properties – Part II; *ISA Industrial Measurement Series – Flow*; pg. 11

- Re < 2,100 = "Laminar"
- Re > 3,000 = "Turbulent"
- Source: Tyler G. Hicks, P.E.; Laminar Flow in a Pipe; *Standard Handbook of Engineering Calculations*; pg. 1-202

- Re < 1,200 = "Laminar"
- Re > 2,500 = "Turbulent"
- Source: Tyler G. Hicks, P.E.; Piping and Fluid Flow; *Standard Handbook of Engineering Calculations*; pg. 3-384

You've got to laugh when you see such vastly different threshold values given in the exact same reference book!

- Re < (about) 2,000 = "Laminar"
- Re > 2,000 = "Turbulent"
- Source: Douglas C. Giancoli; Chapter 10: Fluids; *Physics (Third Edition)*; pg. 11

- Re < (about) 2,000 = "Laminar"
- 2,000 < Re < 4,000 = "Transitional"
- Re > 4,000 = "Turbulent"
- Source: Schoolcraft Publishing; Chapter 20: Properties of Fluid Flow; *Process Instrumentation – Volume I*; pg. 258

Another source, laughable in its attempt to precisely demarcate the threshold of turbulence, gives these figures:

- Re < 2,320 = "Laminar"
- Re > 2,320 = "Turbulent"
- Source: Website (`http://flow.netfirms.com/reynolds/theory.htm`)

It should be noted that laminar flow can be sustained at Reynolds numbers significantly in excess of 10,000 under very special circumstances. For example, in certain coiled capillary tubes, laminar flow may be sustained all the way up to Re = 15,000, due to something known as the *Dean effect*!

Answer 33

Here, what we do not know about the flow-measurement scenario is the flow regime (laminar or turbulent), and also what the "resistance" of the fluid restriction is. Of course, the Reynolds number for our flowstream will indicate its regime status, and the R factor for the orifice may be either determined experimentally or derived from orifice equations (available in any exhaustive reference book).

The proper pressure-sensing instrument to use for fluid flow is a *differential pressure* instrument, such as a DP cell or DP gauge, or perhaps even a mercury manometer.

Answer 34

Here, what we do not know about the flow-measurement scenario is the flow regime (laminar or turbulent), and also what the "resistance" of the fluid restriction is. Of course, the Reynolds number for our flowstream will indicate its regime status, and the R factor for the orifice may be either determined experimentally or derived from orifice equations (available in any exhaustive reference book).

The proper pressure-sensing instrument to use for fluid flow is a *differential pressure* instrument, such as a DP cell or DP gauge, or perhaps even a mercury manometer. In the case of large pressure drops, it may also be important to measure downstream pressure (P_2) with reference to atmosphere.

$$z_1\rho g + \frac{v_1^2\rho}{2} + P_1 = z_2\rho g + \frac{v_2^2\rho}{2} + P_2 = z_3\rho g + \frac{v_3^2\rho}{2} + P_3$$

$$z_1\rho g + 0 + 0 = 0 + 0 + P_2 = 0 + \frac{v_3^2\rho}{2} + 0$$

$$z_1\rho g = P_2 = \frac{v_3^2\rho}{2}$$

$$v_3 = \sqrt{2gz_1}$$

$$v_3 = \sqrt{\frac{2P_2}{\rho}}$$

The Pitot tube converts the outlet stream's velocity head $(\frac{v^2\rho}{2})$ into a stagnation pressure head (P), then into an elevation head $(z\rho g)$.

Challenge question: explain why a *Pitot tube* placed in the path of the outlet stream generates a liquid column equal in height to z_1:

Answer 36
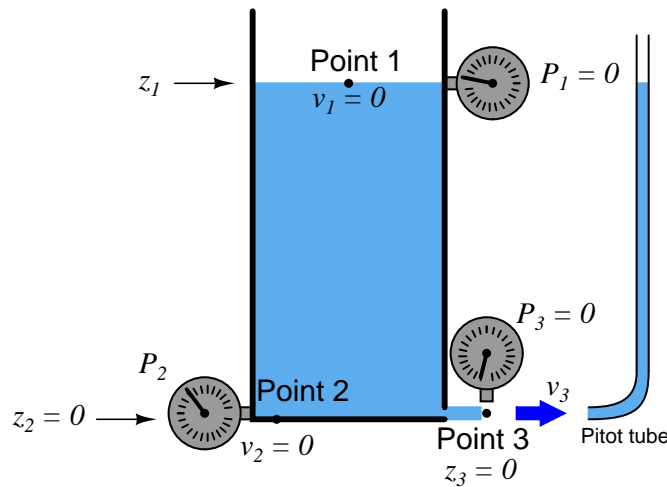
There is more than just a similarity here – the two equations are absolutely identical! This means the velocity of the liquid stream is equal to the final velocity of a falling object, if the liquid column height is the same as the object's drop height.

Follow-up question: are the units of measurement specified for Torricelli's Theorem specific to this form of the equation, or can we use different units of measurement with the exact same equation?

Answer 37

$P_2 = 473.7$ lb/ft^2

It is tempting to alter Bernoulli's Equation to handle measurements in inches rather than feet (especially the annoying unit of pressure measurement: pounds per square *foot*, rather than PSI). However, caution must be exercised when attempting this, because there is more to it than simply converting feet into inches every place you see "ft" in the equation.

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

There is the unit of "feet" lurking inside the unit of "slugs" which must also be accounted for. Here is the standard weight-mass-gravity equation relating slugs to pounds:

$$W = mg$$

$$[\text{lb}] = [\text{slug}] \left[\frac{\text{ft}}{\text{s}^2}\right]$$

If we re-write the unit analysis equation to show slugs as a compound unit, we see that "feet" lurks within:

$$[\text{lb}] = \left[\frac{\text{lb} \cdot \text{s}^2}{\text{ft}}\right] \left[\frac{\text{ft}}{\text{s}^2}\right]$$

Thus, expressing g in inches per second squared would require us to invent a new unit of mass (lb · s^2 per in) instead of slugs (lb · s^2 per ft).

Answer 38

$Q = 7550.29$ GPM

If the flow rate increases beyond 7550.29 GPM, the pressure at P_2 will decrease further, creating a vacuum.

Answer 39

$P_1 = 296.77$ PSI $P_2 = 293.27$ PSI

Bernoulli's equation assumes no gain or loss of energy between the two locations compared, and so it *cannot* be used to contrast the pump's suction and discharge pressures. The pump is a machine that adds energy to the fluid going through it, and so the assumption of equal (total) energy between the incoming and outgoing flow streams is not correct.

Answer 40

Answer 41

Answer 42

Answer 43

Answer 44

Answer 45

Answer 46

Answer 47

Partial answer:

- Q = 500 GPM ; ΔP = **17.36** inches water column
- Q = 630 GPM ; ΔP = **27.56** inches water column

Answer 48

Partial answer:

- Q range = 0 to 600 GPM ; ΔP range = **0 to 91.84 "W.C.**
- Q range = 0 to 800 GPM ; ΔP range = **0 to 163.3 "W.C.**

Answer 49

Partial answer:

Q = 4,533.9 GPM flow rate at 3.1 PSID and 1.03 g/cm^3

Q = 3,413.7 GPM flow rate at 12 kPaD and 1.02 g/cm^3

Answer 50

Partial answer:

Input signal (PSI)	Percent of input span (%)	Percent of output span (%)	Output signal (PSI)
5			
13	83.33	91.29	13.95
	50		
	30		
		80	
3.27	2.25	15	4.8
			7
			12

Answer 51

Q = 818.12 ft^3/min = 6120 GPM

Answer 52

P_2 = 17,792 lb/ft^2 = 123.6 PSI

Answer 53

P_{out} = 51.32 PSI

Note: with a pipe diameter ratio of 4:1 (out:in), the exit velocity will be *16 times* slower than the inlet velocity $(1:4)^2 = (1:16)$.

Answer 54

$v_2 = 16.57$ ft/s

Note that the two pressures are given in units of PSI (not pounds per square *foot*), and that the two heights are given in inches instead of feet. Also, $\rho_{benzene} = 1.753$ slugs/ft^3.

Answer 55

The difference in height is due to the "velocity head" at each point:
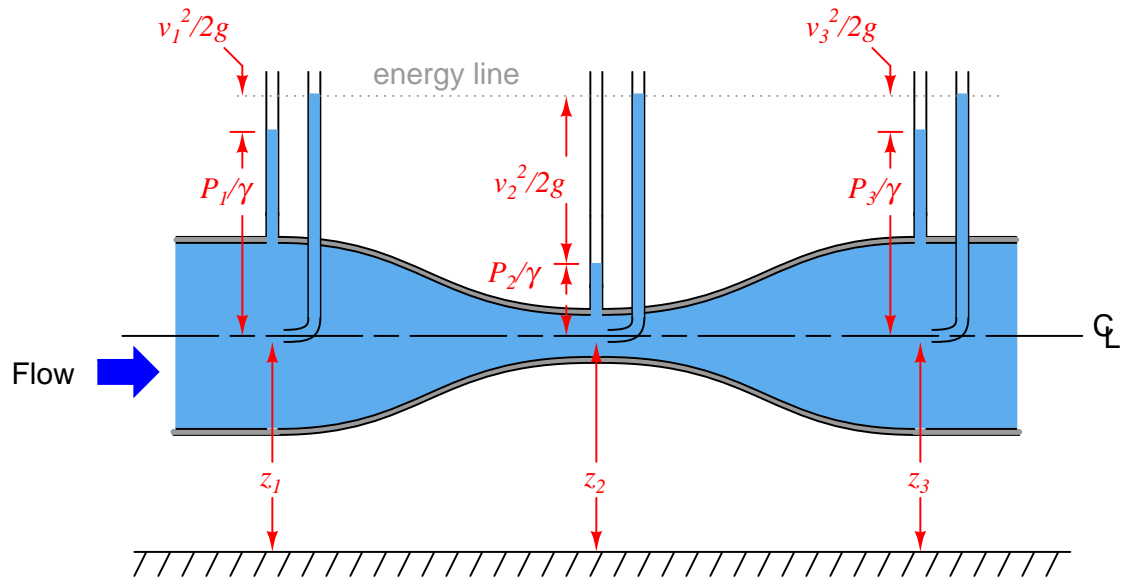
The line where all the Pitot tube piezometers match is sometimes called the *energy line* of the system.

Follow-up question: in a realistic piping system, this energy line has a downward slope. Explain why:
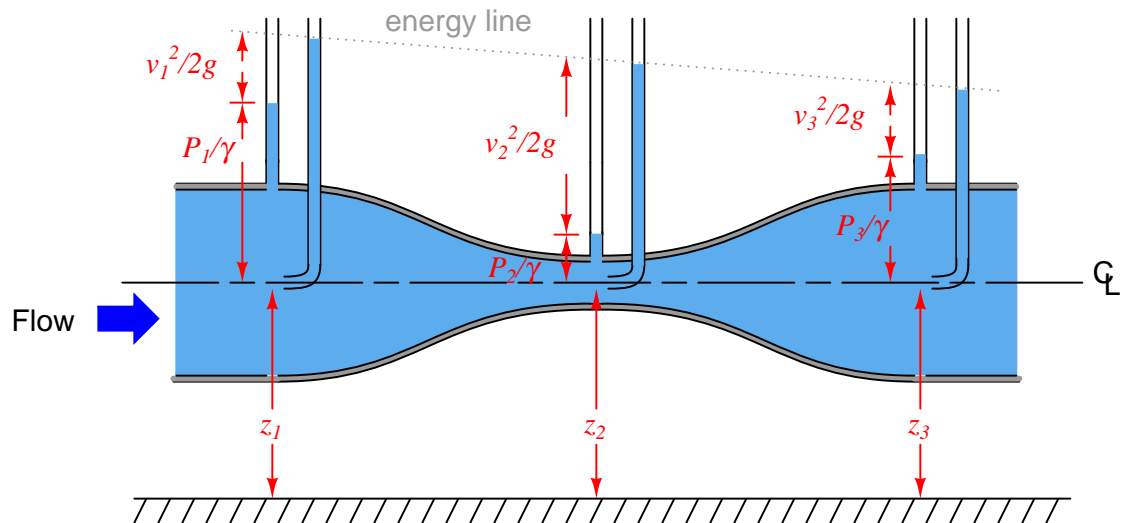
Answer 56

Bernoulli's equation:

$$z_1 \rho g + \frac{v_1^2 \rho}{2} + P_1 = z_2 \rho g + \frac{v_2^2 \rho}{2} + P_2$$

Assuming no change in height (z) is involved:

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

Knowing that P_1 is the static pressure and that P_2 is equal to $P_{static} + P_{stagnation}$:

$$\frac{v_1^2 \rho}{2} + P_{static} = \frac{v_2^2 \rho}{2} + P_{static} + P_{stagnation}$$

$$\frac{v_1^2 \rho}{2} = \frac{v_2^2 \rho}{2} + P_{stagnation}$$

Knowing that v_2 is zero at the stagnation point:

$$\frac{v_1^2 \rho}{2} = P_{stagnation}$$

Therefore, $P_{stagnation} = \frac{1}{2} v^2 \rho$

Answer 57

P at 50 MPH $= 1.215$ inches H_2O

P at 100 MPH $= 4.859$ inches H_2O

Answer 58

ΔP at 50 MPH $= 18.22$ "W.C.

ΔP at 100 MPH $= 72.88$ "W.C.

Answer 59

Assuming no difference in height (z):

$$\frac{v_1^2 \rho}{2} + P_1 = \frac{v_2^2 \rho}{2} + P_2$$

$$P_1 - P_2 = \frac{v_2^2 \rho}{2} - \frac{v_1^2 \rho}{2}$$

$$\Delta P = \frac{\rho}{2} \left(v_2^2 - v_1^2 \right)$$

$$\frac{2\Delta P}{\rho} = v_2^2 - v_1^2$$

If $Q = Av$ then $v = \frac{Q}{A}$

$$\frac{2\Delta P}{\rho} = \left(\frac{Q}{A_2} \right)^2 - \left(\frac{Q}{A_1} \right)^2$$

$$\frac{2\Delta P}{\rho} = \frac{Q^2}{A_2^2} - \frac{Q^2}{A_1^2}$$

$$\frac{2\Delta P}{\rho} = \frac{Q^2 A_1^2}{A_1^2 A_2^2} - \frac{Q^2 A_2^2}{A_1^2 A_2^2}$$

$$\frac{2\Delta P}{\rho} = Q^2 \frac{A_1^2 - A_2^2}{A_1^2 A_2^2}$$

$$Q^2 = \left(\frac{A_1^2 A_2^2}{A_1^2 - A_2^2} \right) \left(\frac{2\Delta P}{\rho} \right)$$

$$Q = \sqrt{\frac{A_1^2 A_2^2}{A_1^2 - A_2^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

$$Q = \frac{A_1 A_2}{\sqrt{A_1^2 - A_2^2}} \sqrt{\frac{2\Delta P}{\rho}}$$

Where,

Q = Volumetric flow rate (ft^3/s)
A_1 = Large flow area (ft^2)
A_2 = Small (throat) flow area (ft^2)
ΔP = Differential pressure drop (lb/ft^2)
ρ = Mass density of fluid (slugs/ft^3)

Answer 60

We cannot tell exactly where the problem is, but we know it must be either in the receiver gauge or in the panel-mounted indicator (assuming only one fault in the system).

One test would be to block and equalize the DP transmitter's manifold, to see which indicator goes closest to zero. Chances are, the error is (at least) a zero shift, and as such should reveal itself in this test. Whichever indicator goes exactly to zero during this test is good; whichever one reads some non-zero value during this test is in error.

Another test would be to use a pressure gauge to measure the 3-15 PSI pneumatic signal coming from the transmitter. If the pressure is 5.78 PSI, the receiver gauge is good and the panel-mounted indicator must be in error. If the pressure is 6.05 PSI, the receiver gauge is in error and the panel-mounted indicator is good.

Answer 61

Answer 62

Answer 63

Answer 64

Partial answer:

- Differential pressure at 210 GPM and $\gamma = 42.0$ lb/ft^3 = **42.70 "W.C.**
- Flow rate at 40 "W.C. = **204.5 GPM**

Answer 65

Partial answer:

- Differential pressure at 230 lbm/min mass flow = **23.28 "W.C.**
- Mass flow rate at 51 "W.C. and $\rho = 1.35$ lbm/ft^3 = **346.9 lbm/min**

Answer 66

Partial answer:

Input pressure (" W.C.)	Output current (mA)
0	
45	12.76
75	
90	
110	17.70
150	20

Answer 67

Partial answer:

Input current (mA)	Displayed flow (GPM)
4	0
6	
9.3	402.9
13	525
14.8	
20	

Answer 68

Answer 69

Answer 70

Answer 71

$P = 1373.5 \text{ lb/ft}^2 = 9.538 \text{ PSI}$

Answer 72

A smaller-Beta orifice plate will generate *more* ΔP for any given flow rate, and will measure *lesser* flow rates with the same ΔP range. A smaller-Beta orifice plate will also induce greater permanent pressure loss and energy dissipation.

Answer 73

$$Q = 50.596\sqrt{\Delta P}$$

Answer 74

New ΔP range = 0 to 112.5 inches of water for Q = 0 to 750 GPM

New ΔP range = 0 to 288 inches of water for Q = 0 to 1200 GPM

New ΔP range = 0 to 1.879 PSI for Q = 0 to 510 GPM

Answer 75

Flow rate (GPM)	Percent of max. flow (%)	Orifice ΔP ("W.C.)	FT output signal (PSI)	FY output signal (PSI)	FI indication (GPM)
0	0	0	3	3	0
40	10	1.25	3.12	4.2	40
100	25	7.81	3.75	6	100
200	50	31.25	6	9	200
300	75	70.31	9.75	12	300
360	90	101.25	12.72	13.8	360
400	100	125	15	15	400

$$\text{If } \gamma = \rho g \text{ then } \rho = \frac{\gamma}{g} \text{ and } \frac{1}{\rho} = \frac{g}{\gamma}$$
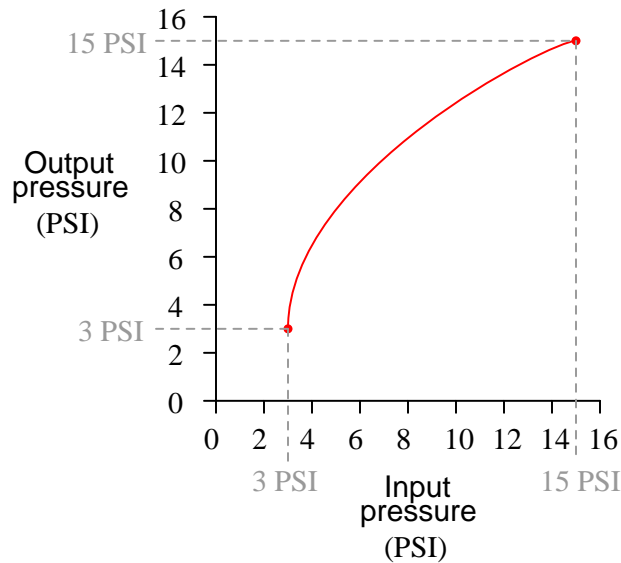
$$Q = k\sqrt{\frac{2\Delta P}{\rho}}$$

$$Q = k\sqrt{\frac{2\Delta P}{1}\frac{1}{\rho}}$$

Substituting $\frac{g}{\gamma}$ for $\frac{1}{\rho}$:

$$Q = k\sqrt{\frac{2\Delta P}{1}\frac{g}{\gamma}}$$

$$Q = k\sqrt{\frac{2g\Delta P}{\gamma}}$$

At low input pressures, the link will be nearly horizontal. At such a shallow angle, the bellows will have to move quite a bit in order to change the link ball/nozzle gap significantly. This makes the "gain" of the system (output/input) rather high at low input pressures, resulting in a graph that is steep at the left end:

Conversely, when the input pressure is higher, the link will be angled more sharply from horizontal. The steeper this angle, the more vertical motion from the bellows has an effect on link ball/nozzle gap. Think of it this way: if the link were perfectly vertical (the steepest angle possible), bellows motion would be 100% effective in changing the gap. With a perfectly horizontal link, bellows motion has almost no effect on changing the gap. Thus, as the input pressure increases (and link angle becomes steeper), the "gain" of the system decreases. This results in a transfer function graph that isn't so steep at the right end.

This pneumatic transducer is a real device. In fact, the Moore Products model 65 transducer uses this very same operating principle to create a "pseudo" square root transfer function, used to linearize the output of a differential pressure pneumatic transmitter as it infers flow from the pressure drop across a restriction in a pipe.

This is an example of a *motion-balance* mechanism, because the bellows acts as a spring element, converting pressure into a proportional *motion*.

Answer 78

- Differential pressure at 60 lbm/min mass flow = **25 "W.C.**
- Differential pressure at 77 lbm/min mass flow and $\rho = 0.69$ lbm/ft^3 = **40.58 "W.C.**
- Mass flow rate at 90 "W.C. = **113.84 lbm/min**
- Mass flow rate at 43 "W.C. and $\rho = 0.70$ lbm/ft^3 = **79.84 lbm/min**

Answer 79

- Differential pressure at 200 MPH = **17.6 "W.C.**
- Differential pressure at 475 MPH = **99.3 "W.C.**
- Airspeed at 7.3 "W.C. = **128.8 MPH**
- Airspeed at 24.1 "W.C. = **234 MPH**

Answer 80

All answers shown were generated by a spreadsheet program implementing Bernoulli's equation using imperial units.

Scenario #1

Given conditions		Enter all your variables here in the yellow area
Liquid specific gravity =	1.0000000 (unitless)	
Liquid density =	1.9400000 slugs/ft^3	
Pipe ID =	3.2500000 in	
Orifice ID =	1.7200000 in	
Flow rate	120.0000000 GPM	

Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	3.5703421 (unitless)	
Pipe area =	8.2957681 in^2	
Pipe area =	0.0576095 ft^2	
Flow rate =	462.0000000 in^3/sec	
Flow rate =	0.2673611 ft^3/sec	
Velocity in pipe =	4.6409205 ft/sec	

Final Result		Do NOT enter any values in the green area!
Differential pressure =	245.4254632 lb/ft^2	
Differential pressure =	1.7043435 lb/in^2 (PSI)	
Differential pressure =	47.1762279 inches W.C.	

This calculation assumes a perfect orifice with no permanent pressure losses, a liquid with zero viscosity, and measuring differential pressure between the full pipe diameter and the vena contracta.

Scenario #2

Given conditions		Enter all your variables here in the yellow area
Liquid specific gravity =	0.8400000 (unitless)	
Liquid density =	1.6296000 slugs/ft^3	
Pipe ID =	5.0250000 in	
Orifice ID =	3.5500000 in	
Flow rate	900.0000000 GPM	

Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	2.0036203 (unitless)	
Pipe area =	19.8317945 in^2	
Pipe area =	0.1377208 ft^2	
Flow rate =	3465.0000000 in^3/sec	
Flow rate =	2.0052083 ft^3/sec	
Velocity in pipe =	14.5599532 ft/sec	

Final Result		Do NOT enter any values in the green area!
Differential pressure =	520.6974547 lb/ft^2	
Differential pressure =	3.6159545 lb/in^2 (PSI)	
Differential pressure =	100.0896218 inches W.C.	

This calculation assumes a perfect orifice with no permanent pressure losses, a liquid with zero viscosity, and measuring differential pressure between the full pipe diameter and the vena contracta.

Scenario #3

Given conditions		Enter all your variables here in the yellow area
Liquid specific gravity =	0.6400000 (unitless)	
Liquid density =	1.2416000 slugs/ft^3	39.95392 lb/ft^3
Pipe ID =	6.0000000 in	
Orifice ID =	2.5000000 in	
Flow rate	410.0000000 GPM	

Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	5.7600000 (unitless)	
Pipe area =	28.2743339 in^2	
Pipe area =	0.1963495 ft^2	
Flow rate =	1578.5000000 in^3/sec	
Flow rate =	0.9134838 ft^3/sec	
Velocity in pipe =	4.6523348 ft/sec	

Final Result		Do NOT enter any values in the green area!
Differential pressure =	432.3617570 lb/ft^2	
Differential pressure =	3.0025122 lb/in^2 (PSI)	
Differential pressure =	*83.1095377 inches W.C.*	

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Scenario #4

Given conditions		Enter all your variables here in the yellow area
Liquid specific gravity =	1.1212900 (unitless)	
Liquid density =	2.1753026 slugs/ft^3	69.99989 lb/ft^3
Pipe ID =	8.0000000 in	
Orifice ID =	3.5000000 in	
Flow rate	600.0000000 GPM	

Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	5.2244898 (unitless)	
Pipe area =	50.2654825 in^2	
Pipe area =	0.3490659 ft^2	
Flow rate =	2310.0000000 in^3/sec	
Flow rate =	1.3368056 ft^3/sec	
Velocity in pipe =	3.8296658 ft/sec	

Final Result		Do NOT enter any values in the green area!
Differential pressure =	419.4589496 lb/ft^2	
Differential pressure =	2.9129094 lb/in^2 (PSI)	
Differential pressure =	*80.6293314 inches W.C.*	

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Scenario #5

Given conditions			Enter all given values in the yellow area!
Liquid specific gravity =	0.8010000	(unitless)	
Liquid density =	1.5539400	slugs/ft^3	50.00483 lb/ft^3
Pipe ID =	5.2500000	in	
Orifice ID =	4.1800000	in	
Flow rate	1200.0000000	GPM	

Intermediate calculations			Do NOT enter any values in the blue area!
Velocity ratio =	1.5774879	(unitless)	
Pipe area =	21.6475369	in^2	
Pipe area =	0.1503301	ft^2	
Flow rate =	4620.0000000	in^3/sec	
Flow rate =	2.6736111	ft^3/sec	
Velocity in pipe =	17.7849333	ft/sec	

Final Result			Do NOT enter any values in the green area!
Differential pressure =	365.8038559	lb/ft^2	
Differential pressure =	2.5403046	lb/in^2 (PSI)	
Differential pressure =	*70.3156301*	*inches W.C.*	

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Scenario #6

Given conditions			Enter all given values in the yellow area!
Liquid specific gravity =	0.9500000	(unitless)	
Liquid density =	1.8430000	slugs/ft^3	59.3066 lb/ft^3
Pipe ID =	9.7900000	in	
Orifice ID =	4.2100000	in	
Flow rate	1049.0000000	GPM	

Intermediate calculations			Do NOT enter any values in the blue area!
Velocity ratio =	5.4075581	(unitless)	
Pipe area =	75.2757801	in^2	
Pipe area =	0.5227485	ft^2	
Flow rate =	4038.6500000	in^3/sec	
Flow rate =	2.3371817	ft^3/sec	
Velocity in pipe =	4.4709489	ft/sec	

Final Result			Do NOT enter any values in the green area!
Differential pressure =	520.2179660	lb/ft^2	
Differential pressure =	3.6126248	lb/in^2 (PSI)	
Differential pressure =	*99.9974535*	*inches W.C.*	

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Scenario #7

	Given conditions		Enter all given values in the yellow area!
Liquid specific gravity =	0.8340000 (unitless)		
Liquid density =	1.6179600 slugs/ft^3		52.06495 lb/ft^3
Pipe ID =	10.0300000 in		
Orifice ID =	6.7500000 in		
Flow rate	2630.0000000 GPM		

	Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	2.2079759 (unitless)		
Pipe area =	79.0117621 in^2		
Pipe area =	0.5486928 ft^2		
Flow rate =	10125.5000000 in^3/sec		
Flow rate =	5.8596644 ft^3/sec		
Velocity in pipe =	10.6793172 ft/sec		

	Final Result		Do NOT enter any values in the green area!
Differential pressure =	357.5313261 lb/ft^2		
Differential pressure =	2.4828564 lb/in^2 (PSI)		
Differential pressure =	*68.7254660 inches W.C.*		

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Scenario #8

	Given conditions		Enter all given values in the yellow area!
Liquid specific gravity =	0.6800000 (unitless)		
Liquid density =	1.3192000 slugs/ft^3		42.45104 lb/ft^3
Pipe ID =	3.4800000 in		
Orifice ID =	2.1000000 in		
Flow rate	250.0000000 GPM		

	Intermediate calculations		Do NOT enter any values in the blue area!
Velocity ratio =	2.7461224 (unitless)		
Pipe area =	9.5114859 in^2		
Pipe area =	0.0660520 ft^2		
Flow rate =	962.5000000 in^3/sec		
Flow rate =	0.5570023 ft^3/sec		
Velocity in pipe =	8.4327868 ft/sec		

	Final Result		Do NOT enter any values in the green area!
Differential pressure =	306.8170978 lb/ft^2		
Differential pressure =	2.1306743 lb/in^2 (PSI)		
Differential pressure =	*58.9770644 inches W.C.*		

This calculation assumes a perfect orifice
with no permanent pressure losses, a
liquid with zero viscosity, and measuring
differential pressure between the
full pipe diameter and the vena contracta.

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

Answer 87

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

Answer 88

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

Answer 89

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

Answer 90

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

Answer 91

Answer 92

Answer 93

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