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Lab

Control system with automatic shutdown: *Questions 91 and 92, completed objectives due by the end of day 4, section 4*

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Exam

*Day 5 of next section*

*Capstone Assessment takes the place of a mastery exam (see question 93)*

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

- Electricity Review: Design a simple circuit to achieve a stated objective
  - Determine the effect of a component fault or condition change in a cascade-, ratio-, or feedforward-controlled process
  - Identify problem in control loop based on faceplate display and field data
  - Determine proper AI block parameters to range a Fieldbus transmitter for a given application
  - Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
  - Determine the possibility of suggested faults in a 4-20 mA loop circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
  - Motor/relay/3phase/PLC Review: Determine status of PLC output given input conditions and RLL program
  - INST241 Review: Determine suitability of different flow-measuring technologies for a given process fluid type
  - INST252 Review: Identify cause of poor loop performance from a trend graph
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**Recommended daily schedule**

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Day 1

**Theory session topic:** Introduction to Safety Instrumented Systems (SIS)

Questions 1 through 20; answer questions 1-10 in preparation for discussion (remainder for practice)

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

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Day 2

**Theory session topic:** Explosion hazards and intrinsic safety

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

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Day 3

**Theory session topic:** Solenoid valves and fail-safe design

Questions 41 through 60; answer questions 41-48 in preparation for discussion (remainder for practice)

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Day 4

**Theory session topic:** Electrical power system protection

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

**Tell continuing students about their need to purchase PLC equipment**

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](mailto:tony.kuphaldt@btc.edu) or by telephone at 360-752-8477.

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

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

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

file howto

## General Values, Expectations, and Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

**Independent Problem-Solving:** make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given unless and until you run your own diagnostic tests.

**Teamwork:** inform your teammates if you need to leave the work area for any reason. Any student regularly compromising team performance through absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually. The same is true for students found inappropriately relying on teammates.

**Communication:** check your email daily for important messages. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly.

**Academic Progress:** your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers if you sign the FERPA release form. You may see these records at any time, and you should track your own academic progress using the grade spreadsheet template. Extra-credit projects will be tailored to your learning needs.

**Office Hours:** your instructor’s office hours are by appointment, except in cases of emergency. Email is the preferred method for setting up an appointment with your instructor to discuss something in private.

**Grounds for Failure:** a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, or for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.

## 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.

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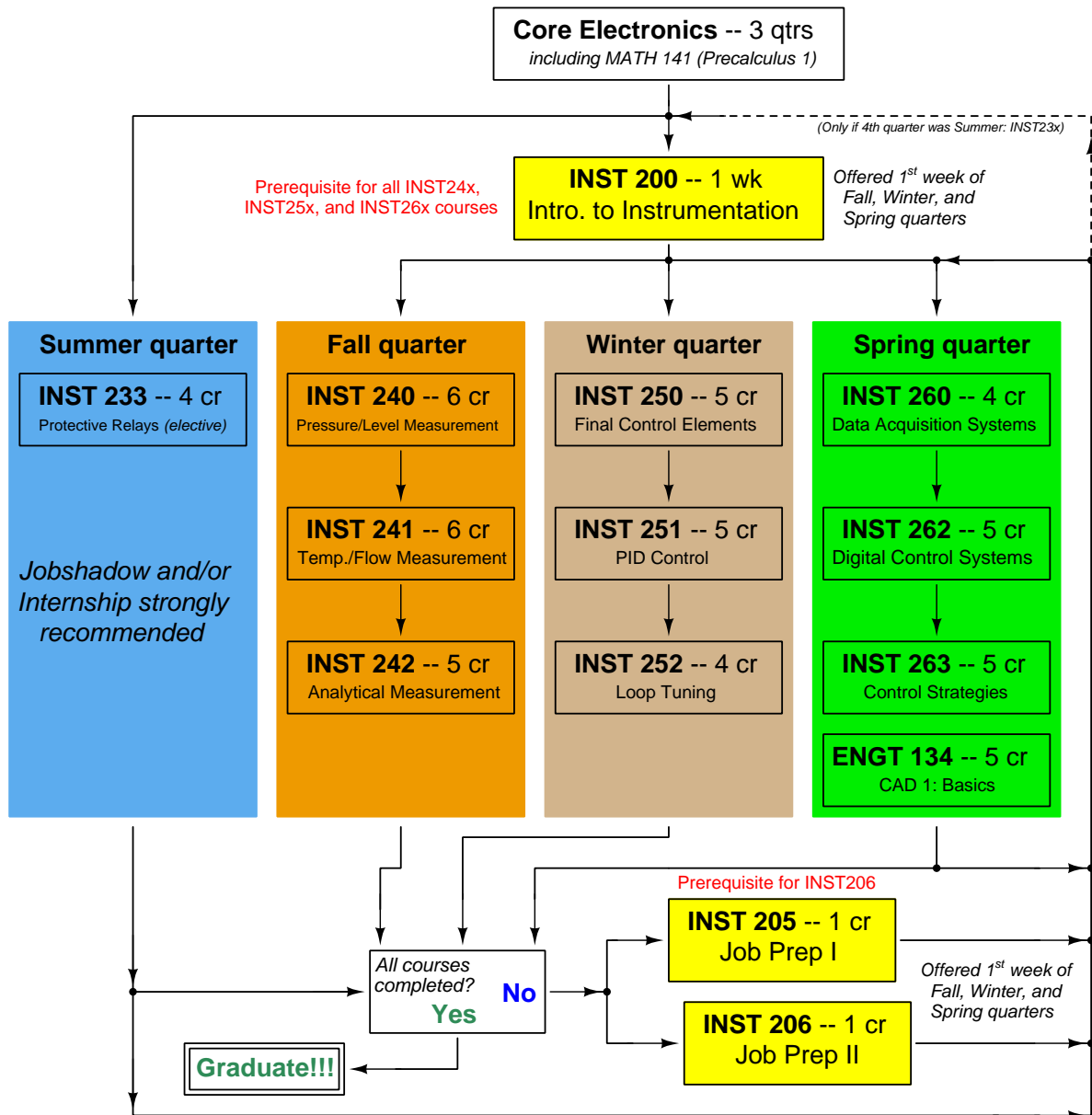
## INST 263 Course Outcomes

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

- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]
- Predict the response of an automatic control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]
- Predict the response of a cascade, ratio, or feedforward control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]
- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]
- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]
- Determine the possibility of suggested faults in simple 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 cascade-, ratio-, or feedforward-controlled process. [Ref: Program Learning Outcome #5]
- Augment an automatic control loop with safety shutdown logic. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team's control systems. [Ref: Program Learning Outcome #8]
- Build a circuit using an electromechanical relay to energize an AC load, and measure current in this circuit, given a switch and relay both randomly selected by the instructor. [Ref: Program Learning Outcome #5]
- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]
- Test the proper function of safety shutdown logic in a PID control system within a limited time, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #6]
- Construct a working control loop consisting of a pre-made process unit with transmitter and final control element, properly connected to a controller, within a limited time. Both the process and the controller are randomly selected by the instructor, with data acquisition of a variable specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

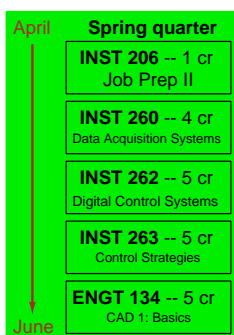
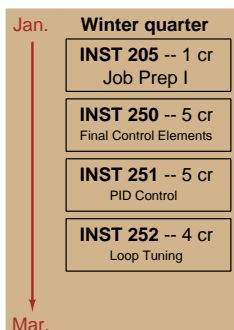
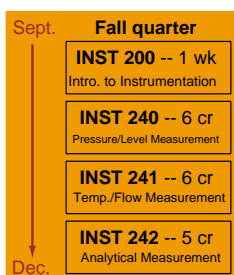
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## Sequence of second-year Instrumentation courses



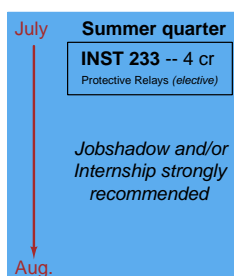
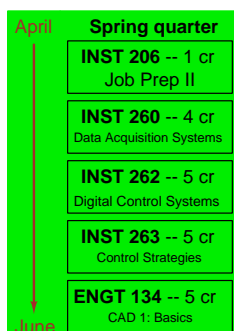
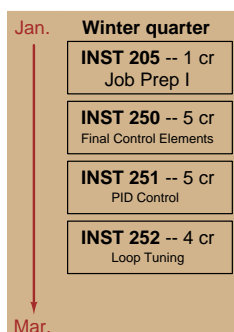
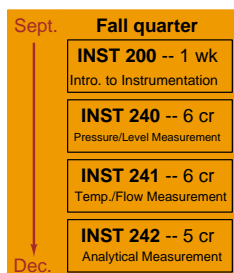
Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students,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

### *Beginning in Summer*



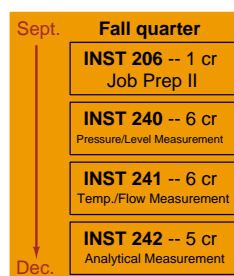
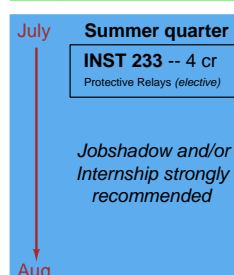
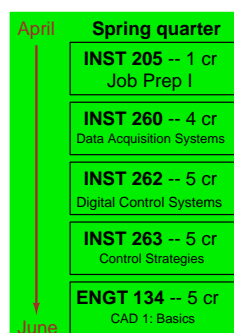
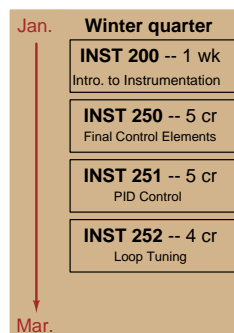
**Graduation!**

*Beginning in Fall*



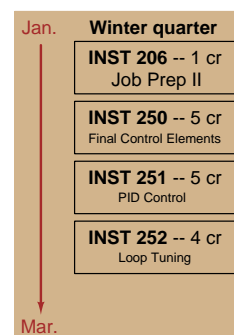
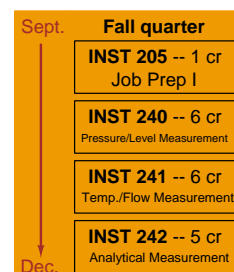
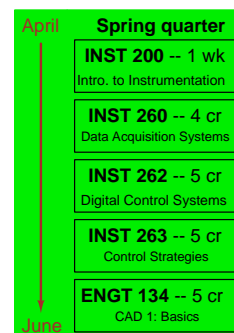
**Graduation!**

### Beginning in Winter



## Graduation!

**Beginning in Spring**



**Graduation!**

8



## General tool and supply list

### Wrenches

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

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

### Pliers

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

### Screwdrivers

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

### Electrical

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

### Safety

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

### Miscellaneous

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

file tools

## Methods of instruction

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

### Inverted theory sessions

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

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

#### Small sessions

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

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

#### Large sessions

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

#### Correspondence

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

## Methods of instruction (continued)

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

### Sample rubric for pre-assessments

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

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

### Sample rubric for post-assessments

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

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

## Methods of instruction (continued)

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

## Methods of instruction (continued)

### Lab sessions

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

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

### Troubleshooting assessments must meet the following guidelines:

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

## Distance delivery methods

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

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

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

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

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

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

## Metric prefixes and conversion constants

- **Metric prefixes**

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



- **Conversion formulae for temperature**

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

### Conversion equivalencies for distance

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

**Conversion equivalencies for volume**

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

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

**Conversion equivalencies for velocity**

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

**Conversion equivalencies for mass**

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

**Conversion equivalencies for force**

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

**Conversion equivalencies for area**

1 acre = 43560 square feet (ft<sup>2</sup>) = 4840 square yards (yd<sup>2</sup>) = 4046.86 square meters (m<sup>2</sup>)

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

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

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

**Conversion equivalencies for absolute pressure units (only)**

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

**Conversion equivalencies for energy or work**

1 british thermal unit (Btu – “International Table”) = 251.996 calories (cal – “International Table”)  
= 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10<sup>10</sup>  
ergs (erg) = 778.169 foot-pound-force (ft-lbf)

**Conversion equivalencies for power**

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

**Acceleration of gravity (free fall), Earth standard**

9.806650 meters per second per second (m/s<sup>2</sup>) = 32.1740 feet per second per second (ft/s<sup>2</sup>)

### Physical constants

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

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

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

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

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

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

### Properties of Water

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

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

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

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

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

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

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

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

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

### Properties of Dry Air at sea level

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

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

file conversion\_constants



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

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

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

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

**How to manage your time:**

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

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

## Checklist when reading an instructional text

*“Reading maketh a full man; conference a ready man; and writing an exact man” – Francis Bacon*

Francis Bacon’s advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner’s thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

- ☒ Briefly **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.
- ☒ Demonstrate **ACTIVE READING STRATEGIES**, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.
- ☒ Identify **IMPORTANT THEMES**, especially **GENERAL LAWS** and **PRINCIPLES**, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.
- ☒ Form **YOUR OWN QUESTIONS** based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.
- ☒ Devise **EXPERIMENTS** to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.
- ☒ Specifically identify any points you found **CONFUSING**. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

### General challenges following a tutorial reading assignment

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

### General follow-up challenges for assigned problems

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

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## Questions

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### Question 1

Read and outline the introduction to the “Concepts of Probability” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i00828](#)

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### Question 2

Read and outline the introduction to the “Safety Instrumented Functions and Systems” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04646](#)

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### Question 3

Read and outline the “SIS Sensors” subsection of the “Safety Instrumented Functions and Systems” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04642](#)

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### Question 4

Read and outline the “SIS Controllers (Logic Solvers)” subsection of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04725](#)

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### Question 5

Read and outline the “SIS Final Control Elements” subsection of the “Safety Instrumented Functions and Systems” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i03324](#)

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### Question 6

Read and outline the “Safety Integrity Levels” subsection of the “Safety Instrumented Functions and Systems” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04650](#)

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### Question 7

Read and outline the “SIS Example: Burner Management Systems” subsection of the “Safety Instrumented Functions and Systems” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

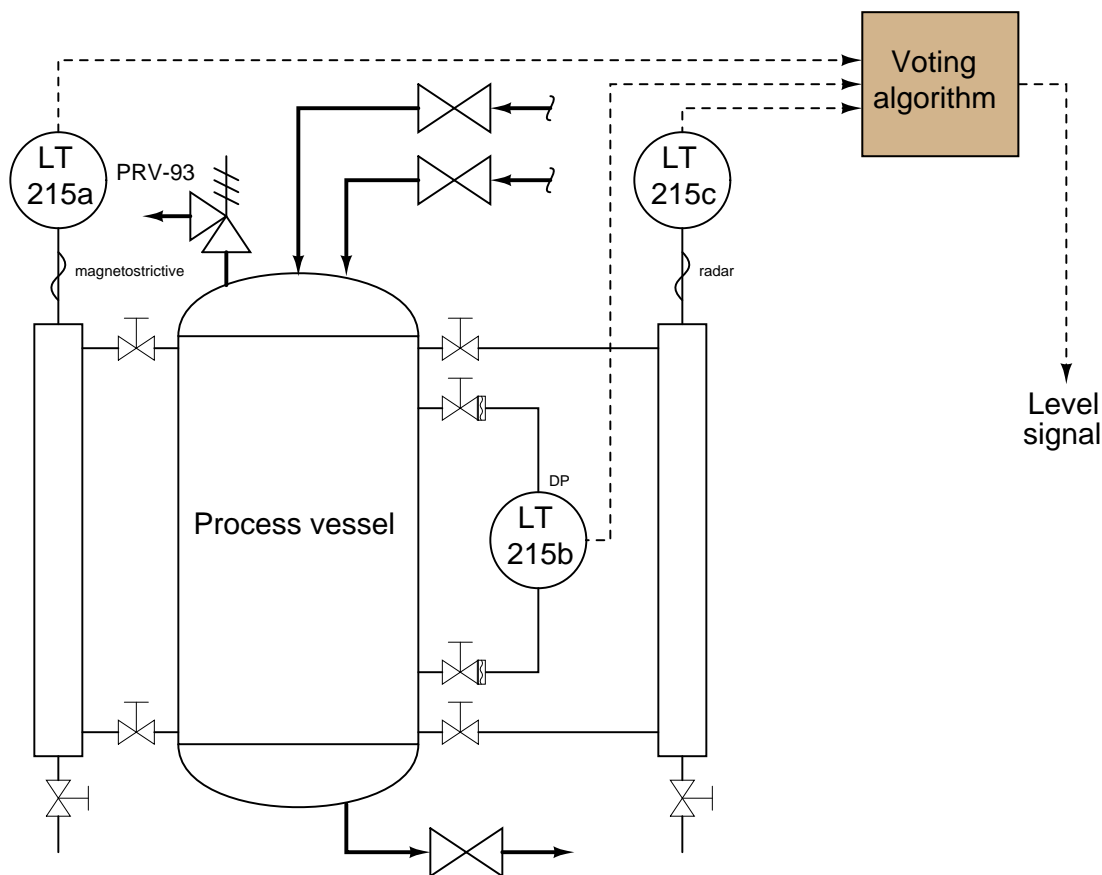
- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

file i04561



## Question 8

This critical process vessel is equipped with *three* different level transmitters, all measuring the same liquid level, sending their respective signals to a *logic solver* control device that “votes” on the three signals to determine whether or not the process is operating safely. The three level transmitters, however, each employ a different technology:



Transmitter LT-215a uses a hollow float on a metal rod to sense liquid level, and detects the float’s position along the rod by means of timing sound waves sent through the metal rod. Transmitter 215b senses differential pressure between the two nozzles (connection points to the vessel) as an indication of liquid level inside. Transmitter 215c senses liquid level by a radio wave echoed off the liquid surface along a metal rod called a waveguide.

Explain why it is important for the reliability of this redundant measurement system to use different technologies. Why not just use three identical transmitters instead?

### Suggestions for Socratic discussion

- What specific information would we need to determine a SIL level value (1 to 4) for the safety instrumented function protecting this process vessel from overfilling?
- Does the reliability of the pressure relief valve (PRV-93) in this process affect the SIL rating of the overfilling protective function? Explain why or why not.
- Explain how you would go about comprehensively *testing* this safety system to check for proper function. Could you specifically test *dependability* versus *security*? Why or why not?

- For those who have studied level measurement, explain how each of the three level transmitters work.

[file i04695](#)

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#### Question 9

In May 2007, a major instrument manufacturer placed an advertisement in an industry periodical touting the reliability of a new wireless instrument product line. According to the add, the data reliability for this wireless (radio) instrumentation product was “greater than 99%”. Bear in mind that *reliability* is nothing more than a probability value that a device or a system will faithfully perform its design function. A system that is 99% reliable is one that properly performs its design function 99 times out of 100.

Sounds pretty good, doesn’t it? It might, until you put this probability into perspective. Calculate what a 99.5% reliability rate would mean in the context of:

- Reliability of electric power delivered to your home (how much outage in one year’s time).
- How often the brakes would fail in your automobile (assuming 10 instances of using the brakes per short trip, and the number of short trips you take in your car during one year).
- The number of skipped heart beats in an average day.

[file i02480](#)

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#### Question 10

Two very important terms in safety engineering are *dependability* and *reliability*. These may be defined as follows:

- **Dependability** ( $D$ ): the probability that a component or system will perform its intended function when activated.
- **Security** ( $S$ ): the probability that a component or system will refrain from performing its function when no action is necessary.

The complement of these measures are *undependability* and *unreliability*, respectively:

- **Undependability** ( $\bar{D}$ ): the probability that a component or system will fail to perform its intended function when activated.
- **Unsecurity** ( $\bar{S}$ ): the probability that a component or system will unnecessarily function.

Provide practical examples of what each of these four terms mean for any of the following systems:

- Seatbelt
- Fire extinguisher
- Fire alarm system
- Email spam filter
- Vehicle brakes
- Electrical fuse
- Firearm

[file i01471](#)

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Question 11

Apply the concepts of *dependability*, *security*, *PFD*, and *RSA* to the context of a firearm. Label each quadrant of the following chart with these terms (note: some of them may be synonymous, and not all quadrants may have an appropriate term in this list!):

	Trigger pulled, safety "off"	Safety "on", trigger untouched
Gun discharges		
Gun does not discharge		

Which of these quadrants represents desirable conditions, and which represent undesirable conditions? Are there any laws of probability applicable to the quadrants, assuming we had probability values associated with each?

**Suggestions for Socratic discussion**

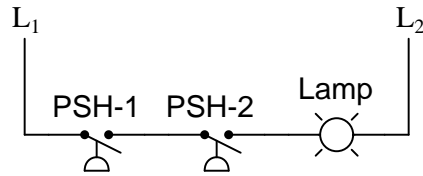
- Label each of the quadrants with the Boolean terms  $D$ ,  $S$ ,  $\overline{D}$ , and  $\overline{S}$  as appropriate.

[file i03021](#)

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### Question 12

This circuit uses two redundant pressure-actuated switches to sense the same fluid pressure. If both switches are functioning properly, they should actuate at the same times and in the same ways. Their combined effect controls power to a lamp to signify the process fluid pressure, an energized lamp for high pressure and a de-energized lamp for low pressure:



Construct a sentence using the conjunction “AND” to describe how the function of each pressure switch relates to the status of the lamp, choosing phrases from the bulleted list below:

*If* \_\_\_\_\_ *and* \_\_\_\_\_ *then* \_\_\_\_\_

- PSH-1 closes when it senses high pressure
- PSH-2 closes when it senses high pressure
- PSH-1 opens when it senses low pressure
- PSH-2 opens when it senses low pressure
- PSH-1 remains open when it senses high pressure
- PSH-2 remains open when it senses high pressure
- PSH-1 remains closed when it senses low pressure
- PSH-2 remains closed when it senses low pressure
- The lamp will energize as it should
- The lamp will remain energized when it should de-energize
- The lamp will remain de-energized when it should energize
- The lamp will de-energize as it should

Next, construct another sentence from the bullet-list of phrases, this time using the conjunction “OR” instead of “AND”:

*If* \_\_\_\_\_ *or* \_\_\_\_\_ *then* \_\_\_\_\_

Lastly, explain how this exercise in sentence construction might be helpful when deciding how to calculate probabilities in a system based on component dependability and unreliability (PFD).

[file i03361](#)

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Question 13

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Question 14

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Question 15

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Question 16

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Question 17

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Question 18

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Question 19

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Question 20

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Question 21

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Read selected portions of the US Chemical Safety and Hazard Investigation Board’s analysis of the 1998 catastrophic vessel overpressurization at the Sonat Exploration facility in Pitkin, Louisiana (Report number 1998-002-I-LA), and answer the following questions:

Pages 1 through 3 of the report outline the event and the Chemical Safety Board’s key findings. Describe what happened to the facility in your own words, based on what is reported in these pages.

William Shakespeare wrote in *Romeo and Juliet*, “What’s in a name? That which we call a rose by any other name would smell as sweet.” If the Bard were alive in 1998 in Pitkin, Louisiana, he might have written, “What’s in a name? A vapor recovery tower by any other name would blow up just as readily.” Explain how the decision to name this vessel a “vapor recovery tower” instead of a “separator” actually contributed to the danger at this facility.

Figure 9 on page 22 of the report presents a pair of P&ID schematics showing the planned versus as-found “lineups” of valves for the third-stage separator vessel. Examine these diagrams and then explain why the vessel experienced an over-pressure incident because of the valve lineup.

Examine the “Causal Tree Analysis” diagram shown on the last page of this report, and explain how the logic symbols are helpful in explaining the probability of the accident occurring.

<b>Suggestions for Socratic discussion</b>
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- In the context of this report, what does the word “train” refer to?
- What is the purpose of a *pressure-relief valve*? Can you think of any examples of pressure-relief valves in everyday life, such as applications in homes or automobiles?
- According to the footnote on page 3, describe the distinction between pressure expressed in PSIG versus in PSIA.
- What symbolic convention do the diagrams use to distinguish closed valves from open valves?
- Given the type of logic “gate” symbols used in the Causal Tree diagram, how easy would it have been to prevent the final outcome (fatalities)?
- For those who have studied mathematical probability, identify which portions of the Causal Tree diagram have values of 1 (certainty), versus fractional (less than 1) probability values.
- How enforceable (in a legal sense) are the American Petroleum Institute’s rules for such things as relief valves?

[file i04656](#)

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### Question 22

Read and outline the “Classified Area Taxonomy” subsection of the “Classified Areas and Electrical Safety Measures” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04641](#)

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### Question 23

Identify the likeliest Class/Division ratings of the following classified areas:

- Inside a grain silo, fed from the top by a conveyor belt
- At the vent pipe of a gasoline storage tank
- In a vehicle parking area on the edge of an oil refinery unit
- Storage room of a textile mill, where cotton fibers are held
- Interior of a cyclone separator at a sawmill

<b>Suggestions for Socratic discussion</b>
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- For any classified area application, which is generally easier to change by re-designing the process: the class rating or the division rating?
- Identify the appropriate *zone* number for each of these scenarios.
- Suppose a portion of a manufacturing process is rated as Class I, Division 1. What mitigating steps, if any, are able to down-grade it to a different Class or Division? In other words, what could you add to, take away from, or otherwise alter in the process to change its Class/Division ratings to safer levels?
- Suppose an industrial area contains both dust and fibers. Which Class number do you think it should be rated, and why?
- Identify any classified areas you can think of on campus, and rate them according to the Class/Division system.
- Identify any classified areas you can think of on campus, and rate them according to the Zone system.

[file i02470](#)

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#### Question 24

Read and outline the “Explosive Limits” subsection of the “Classified Areas and Electrical Safety Measures” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

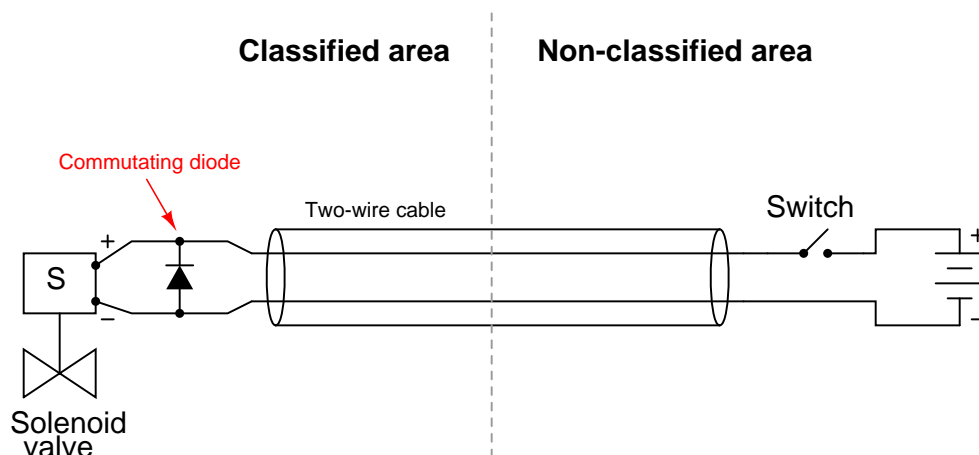
- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

file i04110

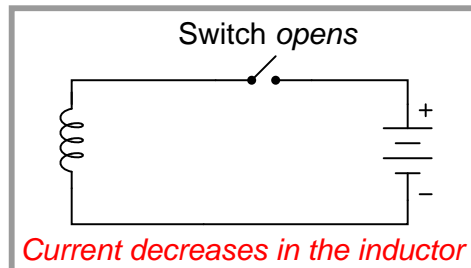
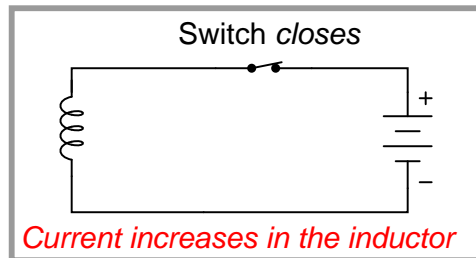
### Question 25

The wire coil of an electric solenoid valve has the ability to store energy in its magnetic field, just like any inductance ( $U = \frac{1}{2}LI^2$ ). The potential for energy release from a solenoid coil igniting a hazardous atmosphere is particularly high when the coil is energized by DC: when the circuit is suddenly broken by the opening of a switch contact or by a loose wire connection, the rapid collapse of the solenoid's magnetic field induces a large voltage according to the formula  $v = L \frac{di}{dt}$ .

One way to prevent this from occurring is to connect a *commutating diode* in parallel with the solenoid coil, as such:



In order to explain why this diode eliminates the problem of “kickback voltage” generated by the solenoid coil, you must be able to explain the behavior of an inductor as a *load* and as a *source*. Determine both the direction of current through the inductor and the polarity of voltage across the inductor in the following two example circuits, and identify whether the inductor is acting as an energy source or as an energy load in both circuits. Finally, explain how this relates to the solenoid circuit shown above:



#### Suggestions for Socratic discussion

- How would the circuit function if the commutating diode's polarity were reversed?
- Explain why the addition of a commutating diode *slows down* the decay of the solenoid's magnetic field when the switch is opened. In other words, explain why adding the diode to the circuit makes it so the solenoid valve takes longer to return to its “normal” (de-energized) state.
- Suppose you needed to connect a multimeter in this circuit to measure current. Identify the safest place to connect the meter in the circuit, and explain why.

[file i02472](#)



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#### Question 26

Read and outline the “Protective Measures” subsection of the “Classified Areas and Electrical Safety Measures” section of the “Process Safety and Instrumentation” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04640](#)

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#### Question 27

Examine the schematic diagrams in Section 9 (pages 49 to 65) of the Pepperl+Fuchs “Process Automation Engineer’s Guide” on intrinsic safety, and then identify some of the field instrument types (other than 4-20 mA loop-powered transmitters) may be protected by the appropriate type of intrinsic safety barrier.

Examine the minimum ignition curves shown on pages 80 to 84. Based on the data shown here, how much current is permissible in a resistive circuit for a Group IIC (hydrogen gas) environment when the maximum possible voltage is 28 volts DC?

Referencing a diagram showing a 4-20 mA current signal device connected through an intrinsic safety barrier, identify where the best place would be in the circuit to connect a milliammeter to measure loop current.

<b>Suggestions for Socratic discussion</b>
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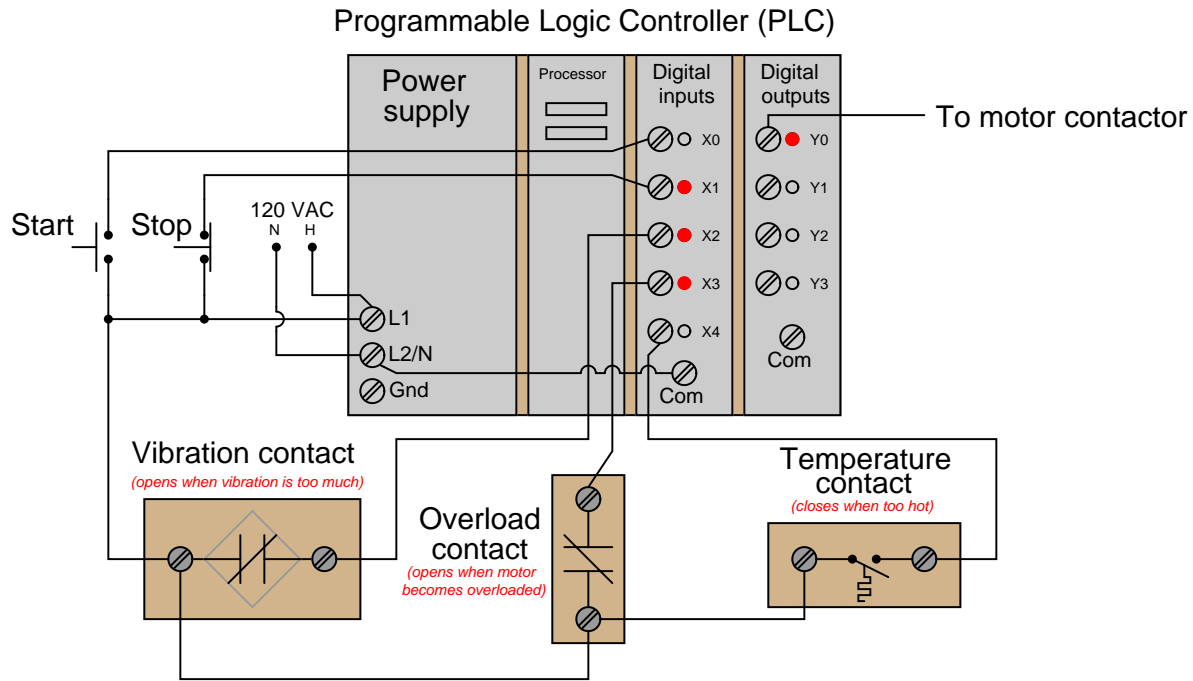
- Trace the directions of all currents in some of these IS barrier circuits, identify sources, loads, and polarities of all voltage drops.
- Figure 9.18 on page 51 shows the “most common method” of connecting a zener diode barrier to a 4-20 mA loop-powered transmitter. Identify how this circuit differs from the simpler version shown in figure 9.20 on page 52 (the “most efficient method” of connecting 2-wire transmitters).
- Figure 9.21 on page 52 shows a method for connecting a zener diode barrier to a 4-20 mA loop-powered transmitter when the I/O module requires a voltage signal input (as opposed to a current signal input). Identify where the 250 ohm load resistor is located in this circuit, necessary to generate a precision 1-5 VDC signal from the transmitter’s 4-20 mA output.
- Figure 9.49 on page 57 shows a zener diode barrier for use with 4-wire RTD sensors. Explain how this circuit functions, and how that barrier thoroughly protects the RTD from generating a hazardous-energy spark in the hazardous area.

[file i01241](#)

## Question 28

A Programmable Logic Controller (PLC) serves as the logic solver (safety shutdown controller) for a large motor-driven pump. It is programmed to shut off the pump if *any* of the following conditions occur:

- “Stop” pushbutton is pressed
- Pump vibrates too much
- Motor becomes overloaded
- Pump temperature gets too hot



Red LED indicator lights on the input and output cards of the PLC indicate if those respective I/O channels are energized. The light statuses shown in the above diagram are when the pump is running as it should (i.e. no abnormal conditions).

Suppose this pump is running just as it should. Identify how you could electrically simulate each of the following “trip” conditions, causing the pump to shut down even though nothing is physically wrong with the pump:

- Electrically simulate a high-vibration condition to the PLC
- Electrically simulate an overloaded motor condition to the PLC
- Electrically simulate a high-temperature condition to the PLC
- Electrically simulate a tripped PLC (to the motor contactor)

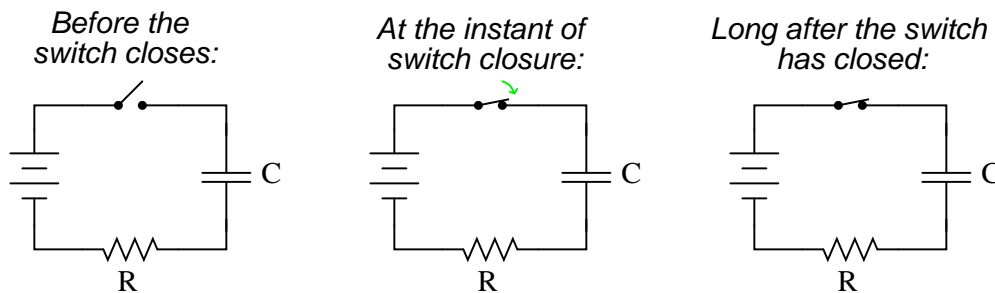
### Suggestions for Socratic discussion

- Identify any safety precautions to follow when working on a “live” 120 VAC circuit (e.g. the *one-hand* rule).

[file i02115](#)

### Question 29

Qualitatively determine the voltages across all components as well as the current through all components in this simple RC circuit at three different times: (1) just before the switch closes, (2) at the instant the switch contacts touch, and (3) after the switch has been closed for a long time. Assume that the capacitor begins in a completely discharged state:



Express your answers qualitatively: “maximum,” “minimum,” or perhaps “zero” if you know that to be the case.

**Before the switch closes:**

$$\begin{aligned} V_C &= \\ V_R &= \\ V_{\text{switch}} &= \\ I &= \end{aligned}$$

**At the instant of switch closure:**

$$\begin{aligned} V_C &= \\ V_R &= \\ V_{\text{switch}} &= \\ I &= \end{aligned}$$

**Long after the switch has closed:**

$$\begin{aligned} V_C &= \\ V_R &= \\ V_{\text{switch}} &= \\ I &= \end{aligned}$$

Hint: a graph may be a helpful tool for determining the answers!

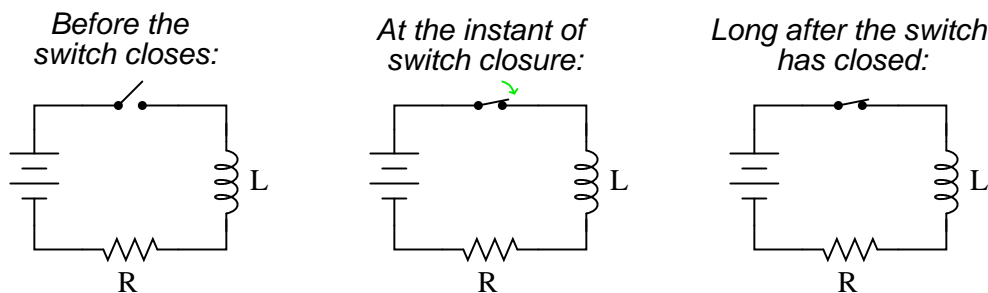
#### Suggestions for Socratic discussion

- A detail many students of electronics struggle to remember is whether or not capacitors oppose changes in *voltage* or changes in *current*. One way to better remember this important fact is to link it to fundamental principles of physics you already know well such as the *Conservation of Energy*. Explain whether *voltage* or *current* is the conserved quantity for a capacitor following a sudden circuit change based on what you know about how capacitors store energy.
- In this “experiment,” is the capacitor *absorbing* energy or *releasing* energy?
- Explain what will happen in the circuit when the switch is re-opened after the switch has been closed for a long period of time.

[file i00598](#)

### Question 30

Qualitatively determine the voltages across all components as well as the current through all components in this simple LR circuit at three different times: (1) just before the switch closes, (2) at the instant the switch contacts touch, and (3) after the switch has been closed for a long time.



Express your answers qualitatively: “maximum,” “minimum,” or perhaps “zero” if you know that to be the case.

**Before the switch closes:**

$$\begin{aligned}V_L &= \\V_R &= \\V_{\text{switch}} &= \\I &= \end{aligned}$$

**At the instant of switch closure:**

$$\begin{aligned}V_L &= \\V_R &= \\V_{\text{switch}} &= \\I &= \end{aligned}$$

**Long after the switch has closed:**

$$\begin{aligned}V_L &= \\V_R &= \\V_{\text{switch}} &= \\I &= \end{aligned}$$

Hint: a graph may be a helpful tool for determining the answers!

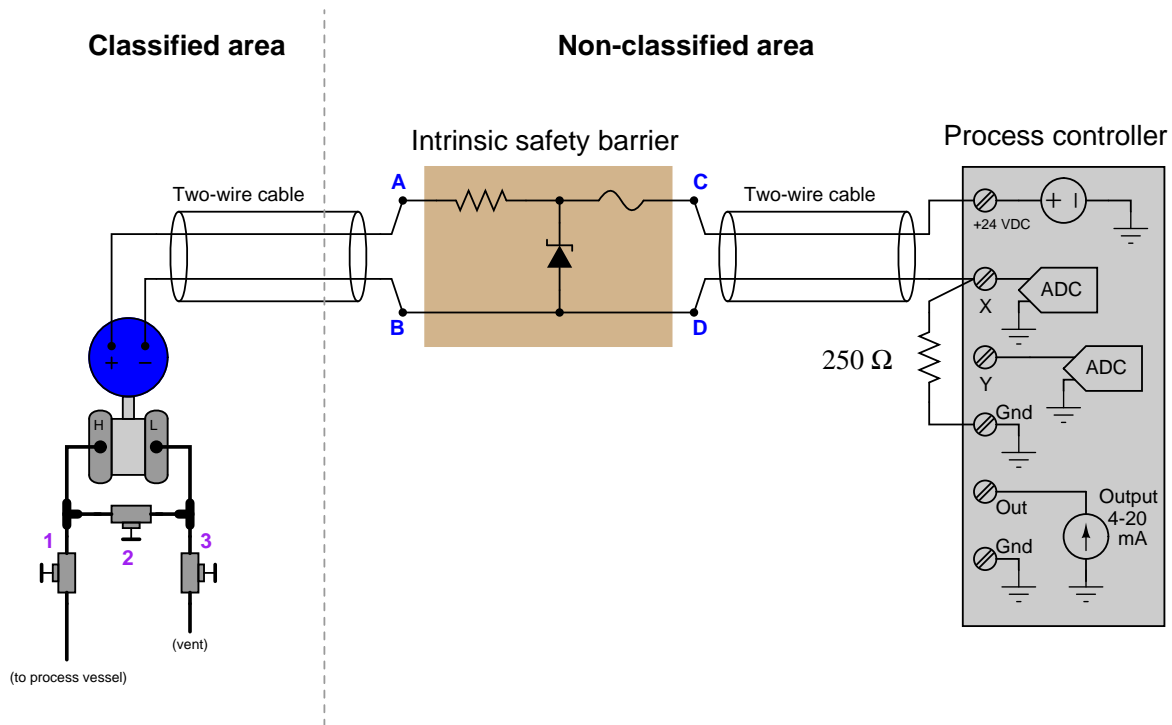
#### Suggestions for Socratic discussion

- A detail many students of electronics struggle to remember is whether or not inductors oppose changes in *voltage* or changes in *current*. One way to better remember this important fact is to link it to fundamental principles of physics you already know well such as the *Conservation of Energy*. Explain whether *voltage* or *current* is the conserved quantity for an inductor following a sudden circuit change based on what you know about how inductors store energy.
- In this “experiment,” is the inductor *absorbing* energy or *releasing* energy?
- Explain what will happen in the circuit when the switch is re-opened after the switch has been closed for a long period of time.

[file i00599](#)

# Question 31

Suppose this intrinsically safe pressure-measurement loop has a problem. The indicating controller registers a pressure of 186 PSI (on a 100 to 250 PSI scale) while a pressure gauge connected to the process impulse line registers only 135 PSI:



Your first step is to take a DC voltage measurement across the 250 ohm resistor, and there you measure 3.293 volts.

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

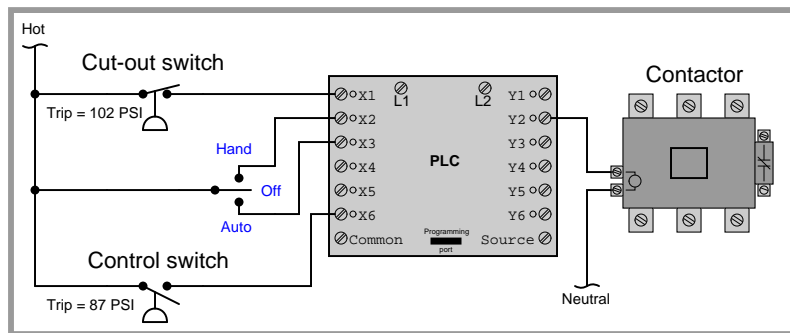
Fault	Possible	Impossible
Cable from points A/B to transmitter failed open		
Cable from IS barrier to controller failed open		
Blown fuse in IS barrier		
Controller ADC out of calibration		
Pressure transmitter out of calibration		
Cable from points A/B to transmitter failed shorted		
Cable from IS barrier to controller failed shorted		
Valve 1 shut		
Valve 2 open		
Valve 3 shut		

file i04691

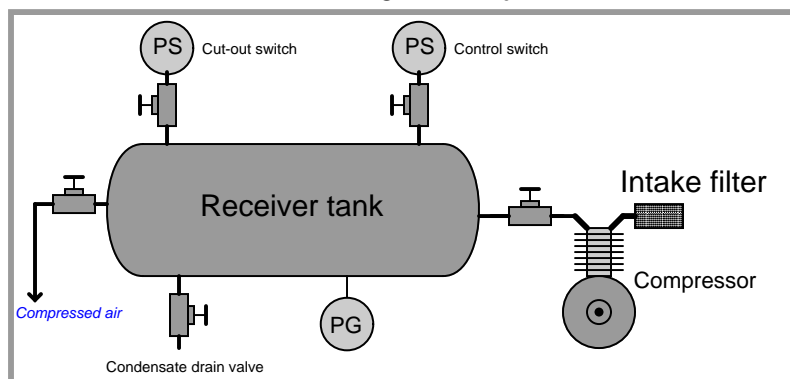
### Question 32

A PLC is used to control the starting and stopping of an air compressor:

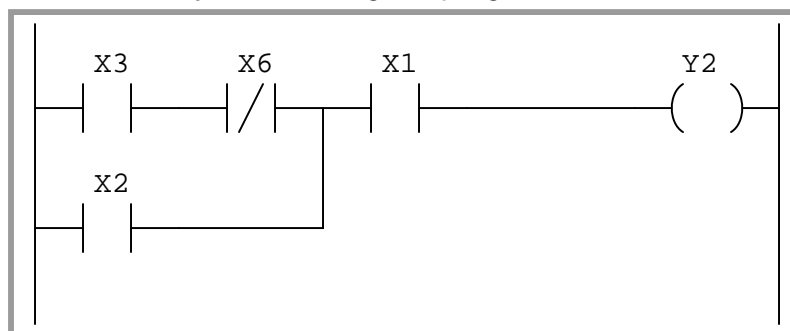
*Control circuit schematic*



*Pictorial diagram of system*



*Relay Ladder Diagram program in PLC*



Identify how you could safely remove the “cut-out” pressure switch from this running system for testing without shutting off the compressor.

[file i03362](#)

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**Question 33**

The amount of energy stored in an electrical capacitor is given by the following formula:

$$U = \frac{1}{2}CV^2$$

Where,

$U$  = Potential energy, in Joules (J)

$C$  = Capacitance, in Farads (F)

$V$  = Voltage across capacitor terminals, in volts (V)

Similarly, the amount of energy stored in an electrical inductor is given by the following formula:

$$U = \frac{1}{2}LI^2$$

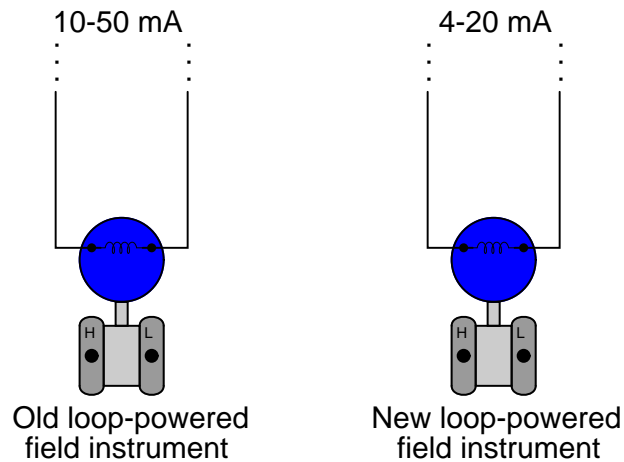
Where,

$U$  = Potential energy, in Joules (J)

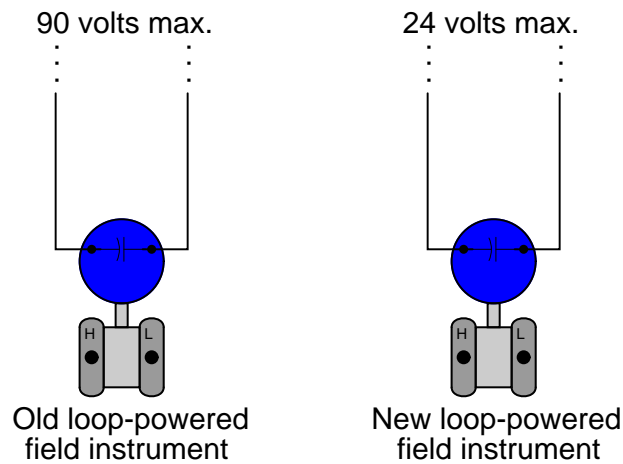
$L$  = Inductance, in Henrys (H)

$I$  = Current through inductor coil, in amperes (A)

A very early standard for analog instrumentation signals was 10 to 50 milliamps DC, in contrast to the more modern analog standard of 4 to 20 milliamps DC. Calculate how much more energy would be stored by a given inductance inside a 10-50 mA field instrument versus a 4-20 mA field instrument, at the same percentage of signal range. In other words, calculate the *ratio* of energy stored from the old instrument to the new instrument under equivalent operating conditions.



Older 10-50 mA instrument loops commonly used 90 volt DC power supplies, instead of the 24 volt DC power supplies typically used to power modern 4-20 mA loop-powered instruments. Calculate how much more energy would be stored by a given capacitance inside a 10-50 mA field instrument versus a 4-20 mA field instrument, at maximum terminal voltage. In other words, calculate the *ratio* of energy stored from the old instrument to the new instrument under equivalent operating conditions.



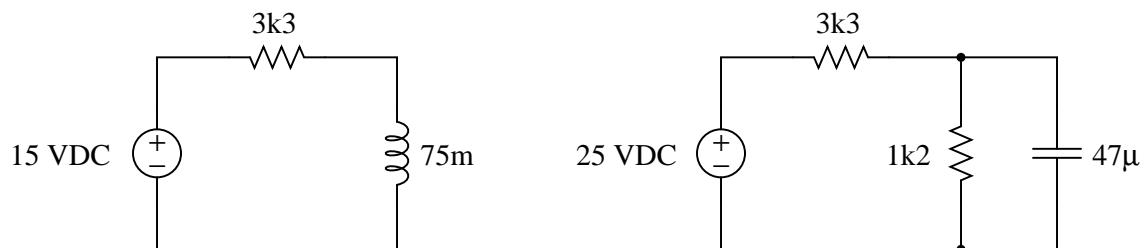
**Suggestions for Socratic discussion**

- Explain why the 10-50 mA signal standard was once widely used in industrial control systems. Why didn't a lower-value current standard such as 4-20 mA gain acceptance initially, especially when you consider that the power supplies used with most 10-50 mA transmitters were of a high enough voltage to pose a shock hazard?

[file i02466](#)

Question 34

Calculate the amount of energy stored in each of the reactive elements (inductor, capacitor), assuming enough time has passed for voltage and current to reach their “final” values in these devices:



[file i02512](#)

Question 35

Question 36

Question 37



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Question 38

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Question 39

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Question 40

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Question 41

Read and outline the introduction and the “2-Way Solenoid Valves” subsections of the “Solenoid valves” section of the “Discrete Control Elements” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04193](#)

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Question 42

Read and outline the “3-Way Solenoid Valves” subsection of the “Solenoid valves” section of the “Discrete Control Elements” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
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- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04194](#)

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#### Question 43

Read and outline the “4-Way Solenoid Valves” subsection of the “Solenoid valves” section of the “Discrete Control Elements” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04195](#)

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#### Question 44

Read and outline the “Normal Energization States” subsection of the “Solenoid valves” section of the “Discrete Control Elements” chapter in your *Lessons In Industrial Instrumentation* textbook.

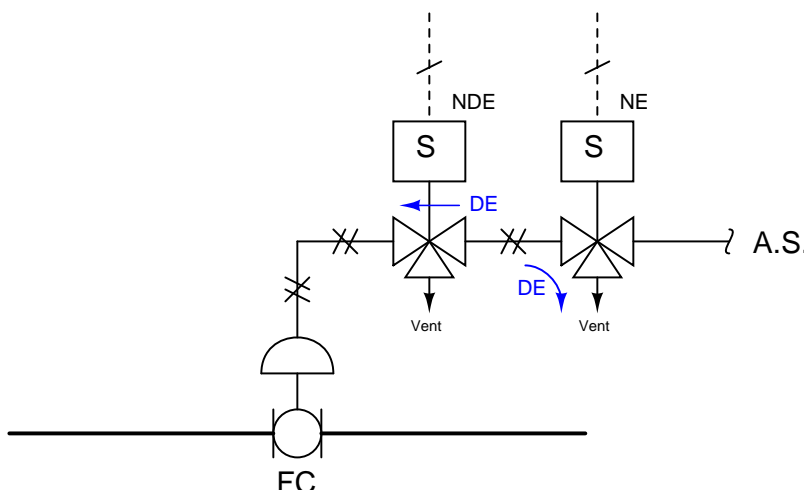
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
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- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i04141](#)

# Question 45

Examine this P&ID and answer the following questions:



Identify the “normal” mode of operation for this system as specified by the process engineer who built it: the status of the process valve and of both solenoid valves during typical process operations.

Identify the “normal” mode of operation for each solenoid valve as specified by the solenoid manufacturer: the status of each solenoid valve when it is in a condition of rest (no stimulation).

Explain what type of electrical signal status (power applied or power removed) is required at each solenoid valve to “trip” the process valve from its regular operating position. Must both solenoids change state to trip the process valve (2oo2 to trip), or is one sufficient (1oo2 to trip)?

## Suggestions for Socratic discussion

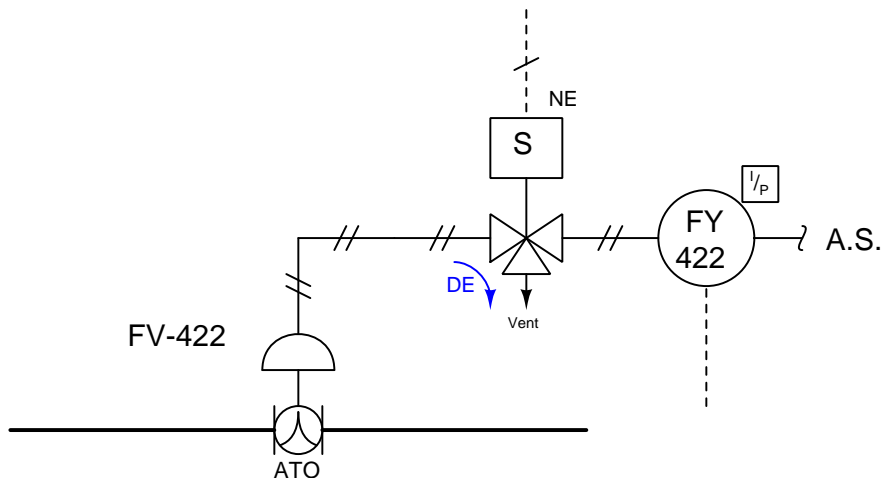
- The usage of the word “normal” is very different when describing a solenoid coil’s energization state versus when the same word is used to describe a spring-return valve being “normally-open” or “normally-closed.” Explain how these two meanings differ, and why this distinction – though confusing it may be – is important to understand.
- Explain the significance of the linetypes used in this diagram.
- Identify the type of process valve used in this system, from the symbol.
- Explain what *dependability* means in the context of this safety system.
- Explain what *security* means in the context of this safety system.
- If you have studied mathematical probability as it applies to system reliability, calculate the probability of the process valve shutting off when it shouldn’t (i.e. this trip system’s *unsecurity*) given the following probabilities of component failure:
  - $P$  of first solenoid valve accidentally venting air pressure = 0.02
  - $P$  of second solenoid valve accidentally venting air pressure = 0.01
  - $P$  of instrument air supply failing = 0.05
- If you have studied mathematical probability as it applies to system reliability, calculate the probability of the process valve shutting off during an emergency (trip) condition (i.e. this trip system’s *dependability*) given the following component dependability figures:
  - $P$  of first solenoid valve dependably venting air pressure = 0.99
  - $P$  of second solenoid valve dependably venting air pressure = 0.97

file i04197

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Question 46

Examine this P&ID and answer the following questions:



Identify the “normal” mode of operation for this system: the status of the process valve and of the solenoid valve.

Identify the “normal” mode of operation for the solenoid valve as specified by the solenoid manufacturer: the status of the solenoid valve when it is in a condition of rest (no stimulation).

Explain what type of electrical signal status (power applied or power removed) is required at the solenoid valve to force a “fail” state at the process valve.

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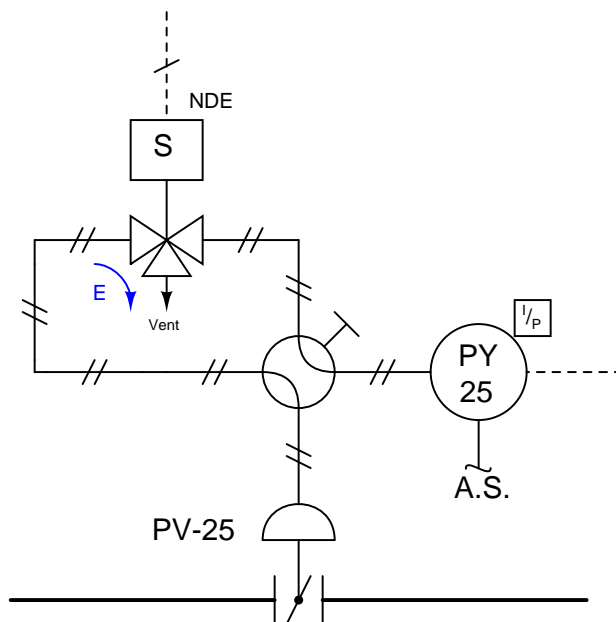
**Suggestions for Socratic discussion**

- The usage of the word “normal” is very different when describing a solenoid coil’s energization state versus when the same word is used to describe a spring-return valve being “normally-open” or “normally-closed.” Explain how these two meanings differ, and why this distinction – though confusing it may be – is important to understand.
- Identify the type of process valve used in this system, from the symbol.
- Explain what *dependability* means in the context of this safety system.
- Explain what *security* means in the context of this safety system.
- If you have studied mathematical probability as it applies to system reliability, calculate the probability of the process valve shutting off when it shouldn’t (i.e. this trip system’s *unsecurity*) given the following probabilities of component failure:
  - $P$  of solenoid valve passing air when commanded = 0.95
  - $P$  of instrument air supply maintaining good pressure = 0.99
  - $P$  of solenoid control signal remaining energized when it should = 0.985

file i04198

Question 47

Examine this P&ID and answer the following questions:



Identify the “normal” mode of operation for this system: the status of the process valve and of the solenoid valve, with the four-way hand valve in the position shown.

Explain what type of electrical signal status (power applied or power removed) is required at the solenoid valve to force a “fail” state at the process valve.

Identify the purpose of having the four-way hand valve in this system. Under what condition(s) would it ever be set to its other position (opposite from what is shown here)?

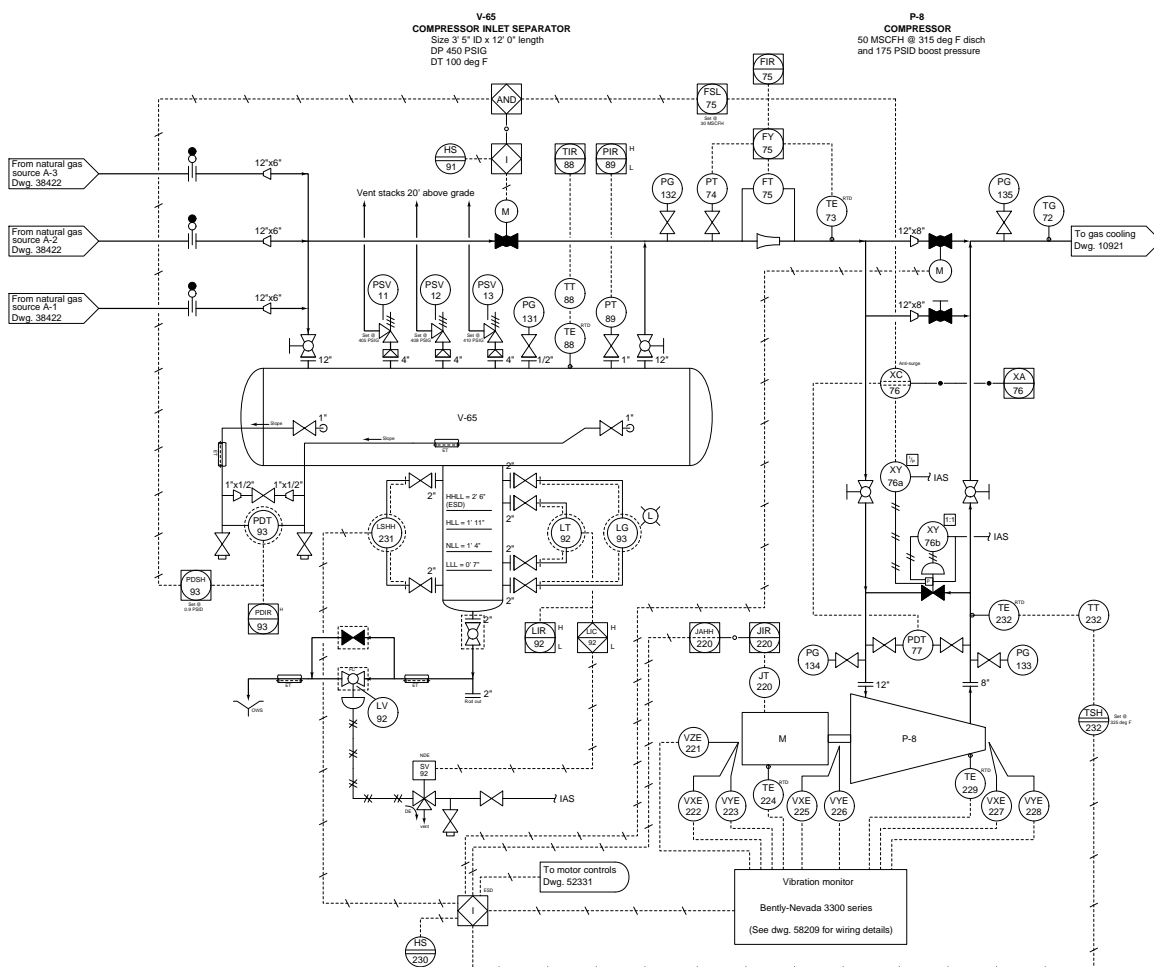
**Suggestions for Socratic discussion**

- The usage of the word “normal” is very different when describing a solenoid coil’s energization state versus when the same word is used to describe a spring-return valve being “normally-open” or “normally-closed.” Explain how these two meanings differ, and why this distinction – though confusing it may be – is important to understand.
- Identify the type of process valve used in this system, from the symbol.
- Explain what *dependability* means in the context of this safety system.
- Explain what *security* means in the context of this safety system.
- Devise a procedure by which the solenoid valve could be routinely tested for proper operation without interrupting the process (i.e. without causing PV-25 to go to its failed position).

[file i04199](#)

## Question 48

Suppose you are asked to do a “trip test” of the high-temperature shutdown controls for this natural gas compressor system. You need to test both the motor’s high-temperature shutdown function as well as the compressor’s high-temperature shutdown function. Your test(s) need to be a thorough and realistic as possible, but without actually interrupting the compression of natural gas!



Explain how you would simulate a high-temperature condition, and also how you would verify the proper operation of the emergency shutdown system (ESD) while ensuring the compressor does not actually shut down.

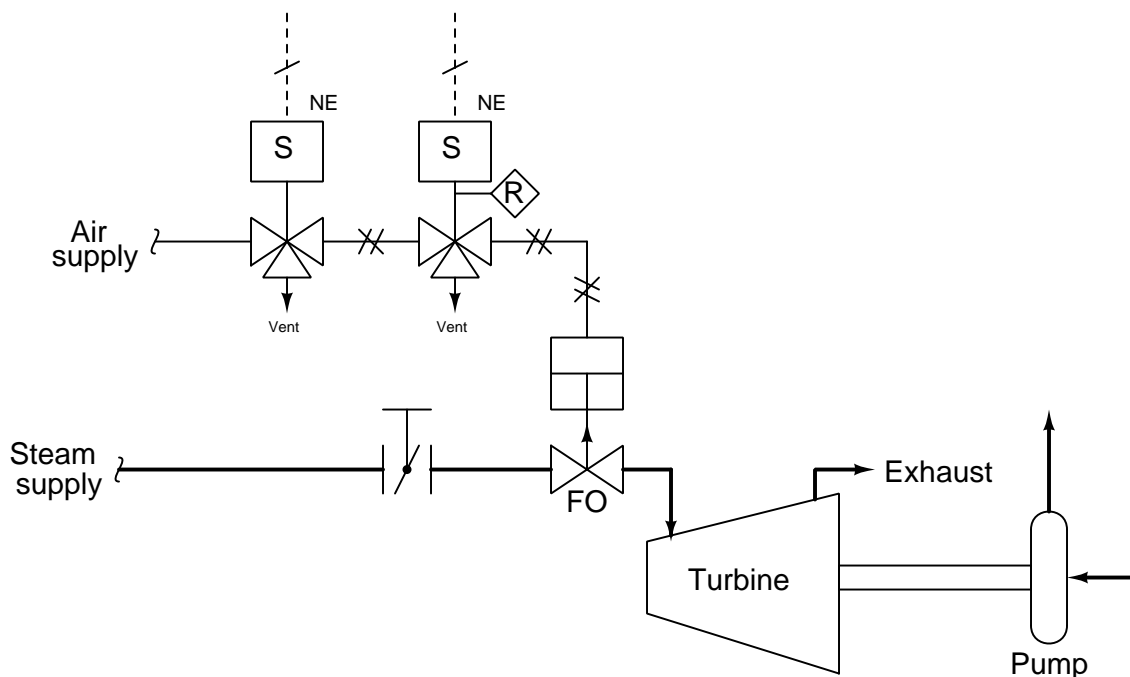
### Suggestions for Socratic discussion

- Based on what you see in this diagram, explain the purpose of the emergency shutdown system. What conditions, specifically, is it looking for to trip, and what are the consequences of a trip?

[file i01242](#)

# Question 49

Analyze the following P&ID segment showing a solenoid-controlled steam turbine start-up system (designed to “back up” an electric motor drive in the event the motor shuts down from power loss), explaining what will happen if either of the two solenoid valves loses electric power:



Sketch arrows for both these solenoids showing the directions of air flow in their energized and de-energized states. Must both solenoids change state to start the turbine (2oo2 to start), or is one sufficient (1oo2 to start)?

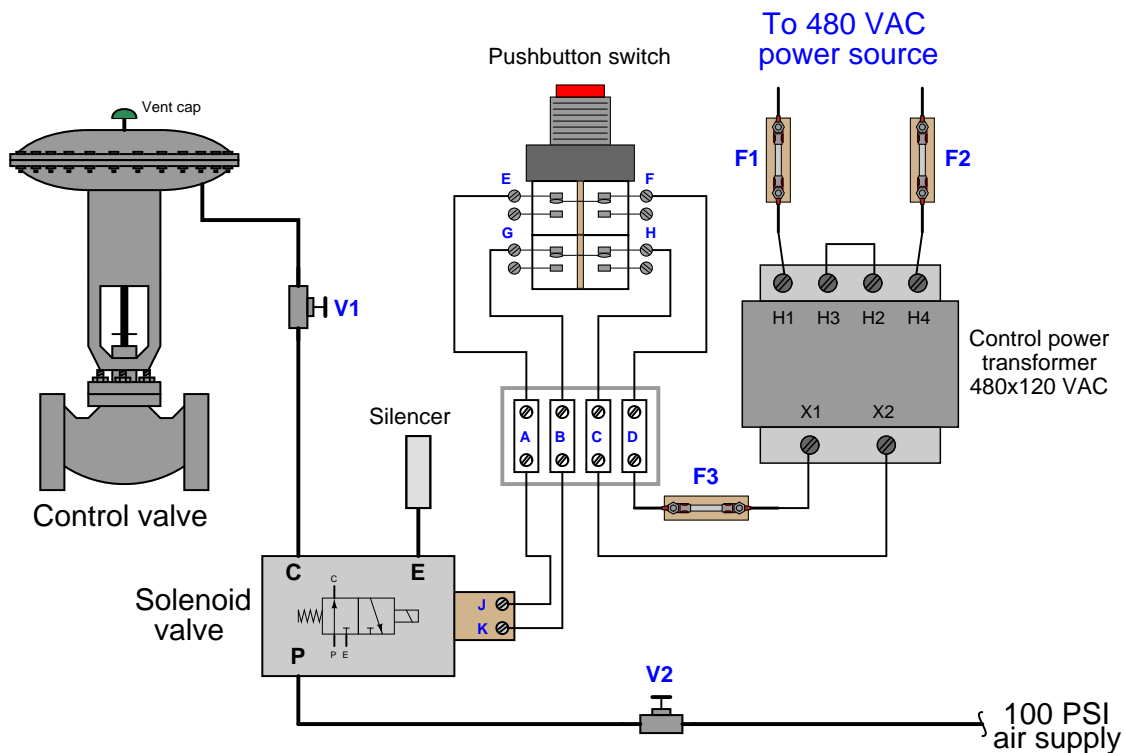
## Suggestions for Socratic discussion

- What, exactly, is a *steam turbine* and what purpose does it serve in this system?
- What practical purpose might a steam-driven turbine such as this serve in a process system, especially one ready to start up with one or more solenoids “tripping”?
- Explain the meaning of the letter “R” in the flag on the right-hand solenoid valve.
- Explain what *dependability* means in the context of this turbine start-up system.
- Explain what *security* means in the context of this turbine start-up system.

file i04196

# Question 50

Suppose this solenoid-controlled valve refuses to move when the operator pushes the switch. Whether the switch is pressed or unpressed, the control valve remains in the fully-closed (down) position:



Another technician has already measured 475 volts between terminals **H1** and **H4** on the transformer, and 0 volts between terminals **D** and **X1**, in both pushbutton switch positions. At that point he gave up and left the system for you to troubleshoot.

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

Fault	Possible	Impossible
Fuse F3 blown (failed open)		
Solenoid stuck in “energized” position		
Solenoid stuck in “de-energized” position		
Solenoid coil failed open		
Solenoid coil failed shorted		
Silencer plugged		
Vent cap plugged		
Wire open between terminals A and E		
Wire open between terminals C and H		
Wire open between terminals K and B		
Valve V1 shut		
Valve V2 shut		

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.



<b>Suggestions for Socratic discussion</b>
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- Describe some of the problem-solving techniques you could (or did) apply to this question, explaining how your techniques translated the problem into something more manageable.

file i04202

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Question 51

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Question 52

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Question 53

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Question 54

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Question 55

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Question 56

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Question 57

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Question 58

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Question 59

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Question 60

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## Question 61

Read and outline the first four pages of Chapter 1 (“What Are Protective Relays”) in the book *Protective Relays* by Victor H. Todd. Note that this book is available through Google Books as well as the Socratic Instrumentation web page as a downloadable PDF file free of copyright due to its age (copyright 1922).

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

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

### **Suggestions for Socratic discussion**

- Describe in your own words the evolution of electric power system protection, from the days of no protection to the “state of the art” circa 1922 shown in this book. What, exactly, are these power systems being protected against, and how are protective relays superior in their functionality?
- What similarities do you find between protective relays in power systems and safety instrumented systems (SIS)?
- Two important concepts are used in the electric power industry to express the reliability of the system: *dependability* and *security*. Dependability is the likelihood that a protective device or system will shut off power as designed in the event of an fault. Security is the likelihood that a protective device will allow power to remain on when there is no fault (i.e. the likelihood it will not needlessly trip). Apply these terms in describing the evolution of power system protection as described by this reading.
- Formulate your own question based on the reading, as though you were an instructor querying students on their understanding of the text.

[file i02859](#)

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Question 62

Read and outline the “Introduction to Power System Automation” section of the “Electric Power Measurement and Control” chapter in your *Lessons In Industrial Instrumentation* textbook.

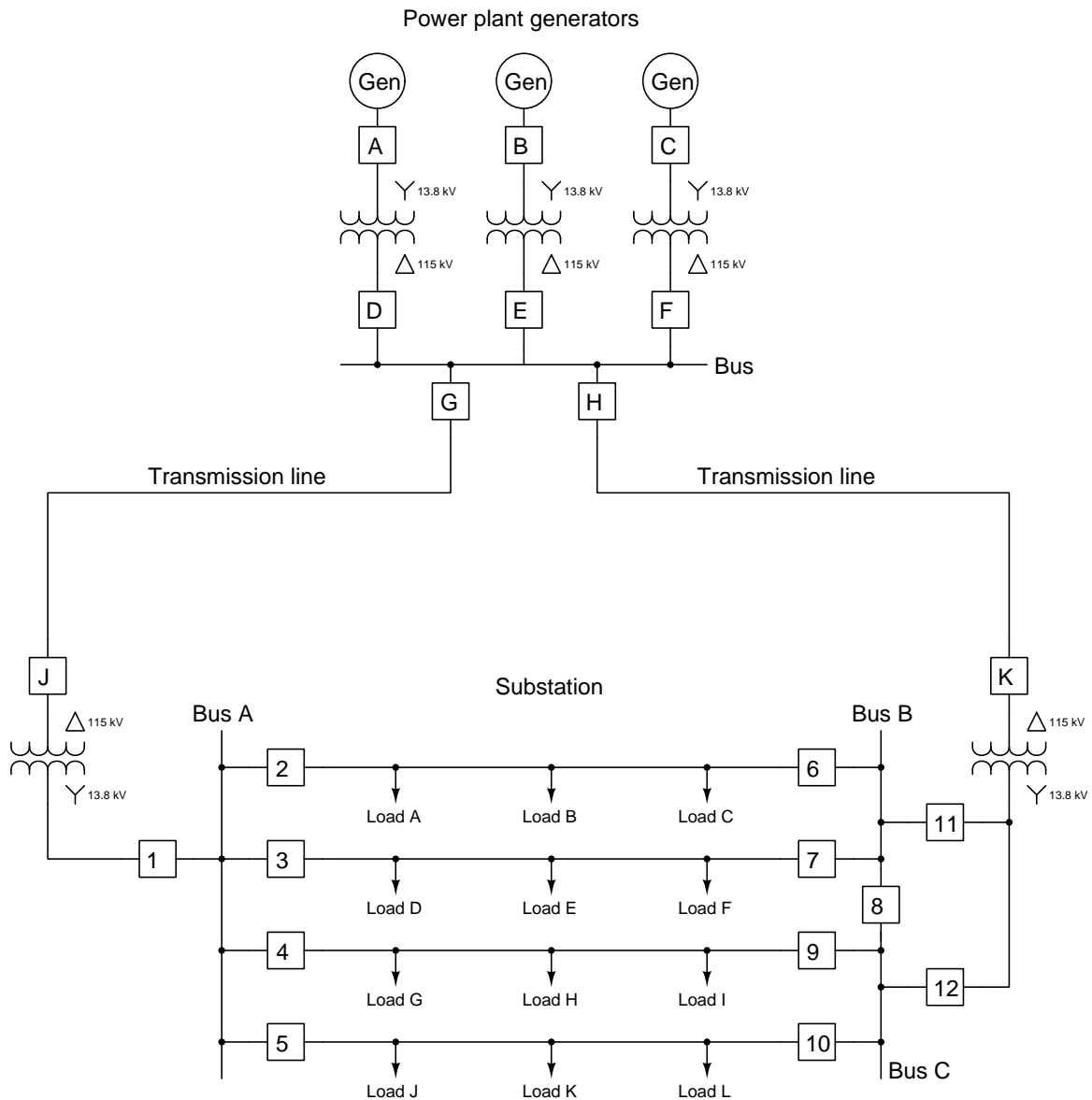
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

file i02856

Question 63

Examine this single-line diagram of a power system and answer the following questions:



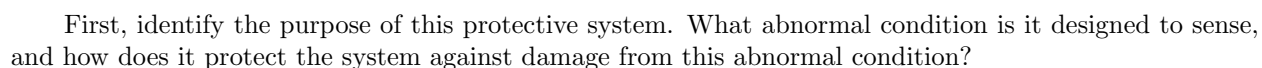
Suppose Load F fails in such a way that it draws far more current than it should. Identify which circuit breaker(s) must trip in order to interrupt the fault current while maintaining power to as many other loads as possible.

Suppose circuit breaker #5 fails to trip when commanded. Identify which other circuit breaker(s) must trip in order to de-energize breaker #5 while maintaining power to as many loads as possible.

Suppose one of the high-voltage insulators on Bus C fails, causing a high amount of current to flow into that bus. Identify which circuit breakers must trip in order to de-energize that bus while maintaining power to as many loads as possible.

[file i02864](#)

Examine this schematic diagram sampled from Victor H. Todd’s 1922 book *Protective Relays* showing a very simple protection circuit comprised of a two-pole power circuit breaker with an externally energized “trip coil”, a current transformer, a DC storage battery, and a “plunger-style” protective relay:



Suppose this relay has been calibrated to “pick up” at a current transformer output of 3.2 amps AC. If the current transformer’s ratio is 800:5, how many amps of line current does this represent?

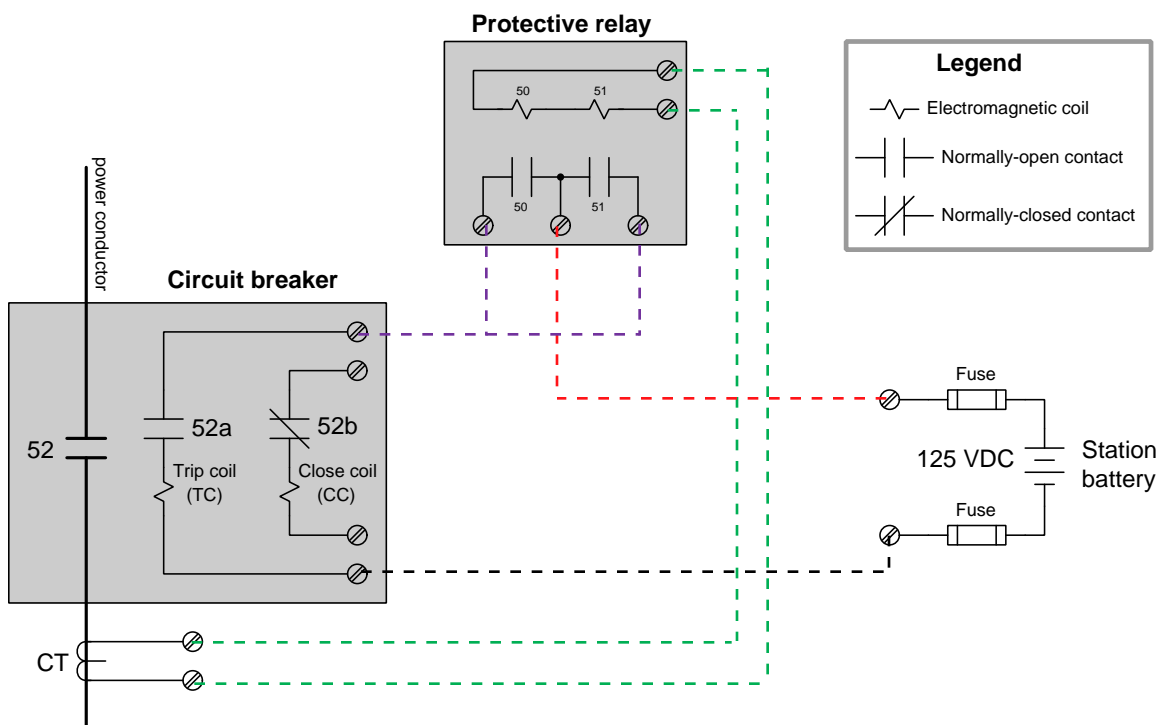
Finally, identify how the “pickup” value (i.e. the trip threshold) for this protective relay might be adjusted by a technician.

- Which ANSI number code best corresponds to this particular protective relay function? How can you tell?
- Suppose the storage battery became discharged so that it measured only about 90 volts rather than 120 volts. How would this affect the operation of this protective system, if at all?
- Suppose the current transformer failed with an internally shorted winding, so that its effective turns ratio became closer to being 1:1 than it is now. How would this affect the operation of this protective system, if at all?
- Two important concepts are used in the electric power industry to express the reliability of the system: *dependability* and *security*. Dependability is the likelihood that a protective device or system will shut off power as designed in the event of an fault. Security is the likelihood that a protective device will allow power to remain on when there is no fault (i.e. the likelihood it will not needlessly trip). Identify a specific fault in this protective system that could compromise its dependability, and another specific fault that could compromise its security.

53

# Question 65

Examine this partial schematic diagram for an overcurrent protection trip circuit, using a protective relay to perform the functions of instantaneous overcurrent (ANSI function code 50) and/or time-overcurrent (ANSI function code 51). The electrical symbols inside each box reveal the components inside the circuit breaker and protective relay, respectively. Screw heads are also shown as termination points for wires you will sketch between these devices to form a functional system. Note that each of the relay's contacts will *close* when it commands the circuit breaker to trip, and that the auxiliary contacts inside the circuit breaker (52a and 52b) operate in unison with the high-current power contact (ANSI device code 52):



First, sketch wires between the protective relay and the current transformer (CT) so that the CT's output current will drive the electromagnetic coils inside the protective relay, to actuate the trip contact(s) in the event of an overcurrent condition.

Next, sketch wires between the protective relay and the circuit breaker so that the protective relay fulfills both the 50 (*instantaneous overcurrent*) function as well as the 51 (*time-overcurrent*) function.

Finally, determine the effects of the following faults, and be prepared to explain why for each case:

- Fuse *blown* on 125 VDC station battery
- Cable connecting CT to protective relay failed *shorted*
- 52a breaker auxiliary switch contact failed *open*
- 50 relay switch contact failed *open*
- 51 relay switch contact failed *open*

[file i02861](#)

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## Question 66

Work with your instructor to use the protective relay demonstration unit in the lab room to test the operation of some overcurrent relays. Schematic wiring diagrams for this system are found in the Answer section to this question.

(1) Configure the system to trip using the General Electric electromechanical overcurrent (ANSI code 51) relay, simulating an overcurrent condition by gently rotating the induction disk until the trip contact closes. Examine the schematic diagram for this system and discuss what would normally cause that relay's disk to operate.

(2) Configure the system to trip using (only) the General Electric electromechanical overcurrent (ANSI code 51) relay, and plug in a high-current load such as a large shop vacuum cleaner to generate a mild overcurrent condition. Watch the 51 relay's induction disk slowly spin and then trip the circuit breaker open.

(3) Configure the system to trip using (only) the SEL-501 digital overcurrent (ANSI code 50/51) relay, and plug in a high-current load such as a large shop vacuum cleaner to generate a mild overcurrent condition. Note the time-delayed tripping action of this relay, just like the General Electric electromechanical unit.

(4) Your instructor will decrease the pickup current value on the SEL-501 digital relay for the instantaneous overcurrent (ANSI code 50) function. Try starting the vacuum cleaner again, and note what happens.

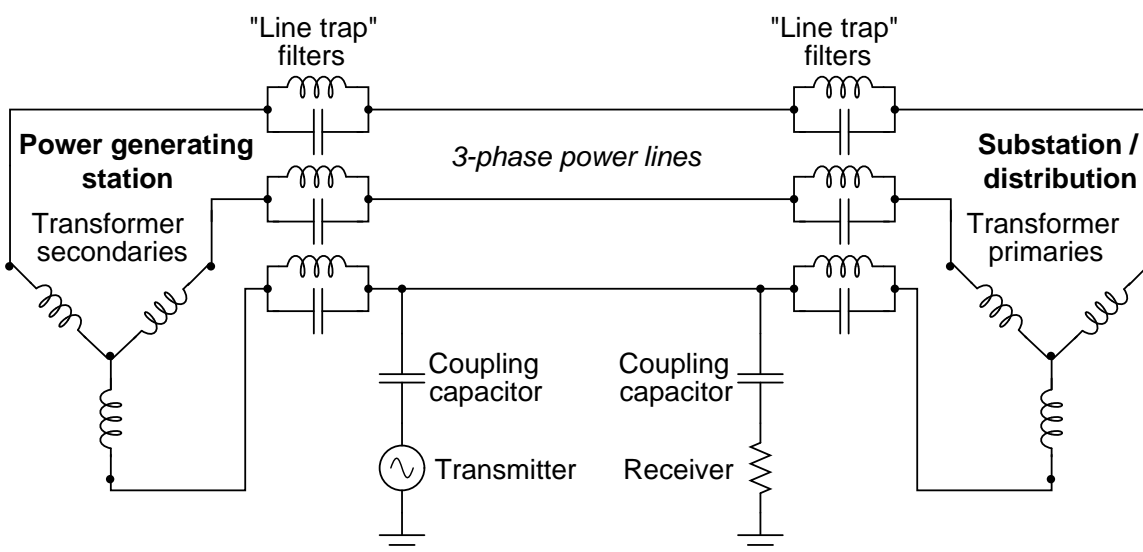
(5) Your instructor will use the `EVENT` command in the command-line interface for the SEL-501 digital relay to display the fault report for the last two trip events. Analyze these reports, noting how they differ from one another.

[file i02857](#)

# Question 67

An interesting technology dating back at least as far as the 1940's, but which is still of interest today is *power line carrier*: the ability to communicate information as well as electrical power over power line conductors. Hard-wired electronic data communication consists of high-frequency, low voltage AC signals, while electrical power is low-frequency, high-voltage AC. For rather obvious reasons, it is important to be able to separate these two types of AC voltage quantities from entering the wrong equipment (especially the high-voltage AC power from reaching sensitive electronic communications circuitry).

Here is a simplified diagram of a power-line carrier system:



The communications transmitter is shown in simplified form as an AC voltage source, while the receiver is shown as a resistor. Though each of these components is much more complex than what is suggested by these symbols, the purpose here is to show the transmitter as a *source* of high-frequency AC, and the receiver as a *load* of high-frequency AC.

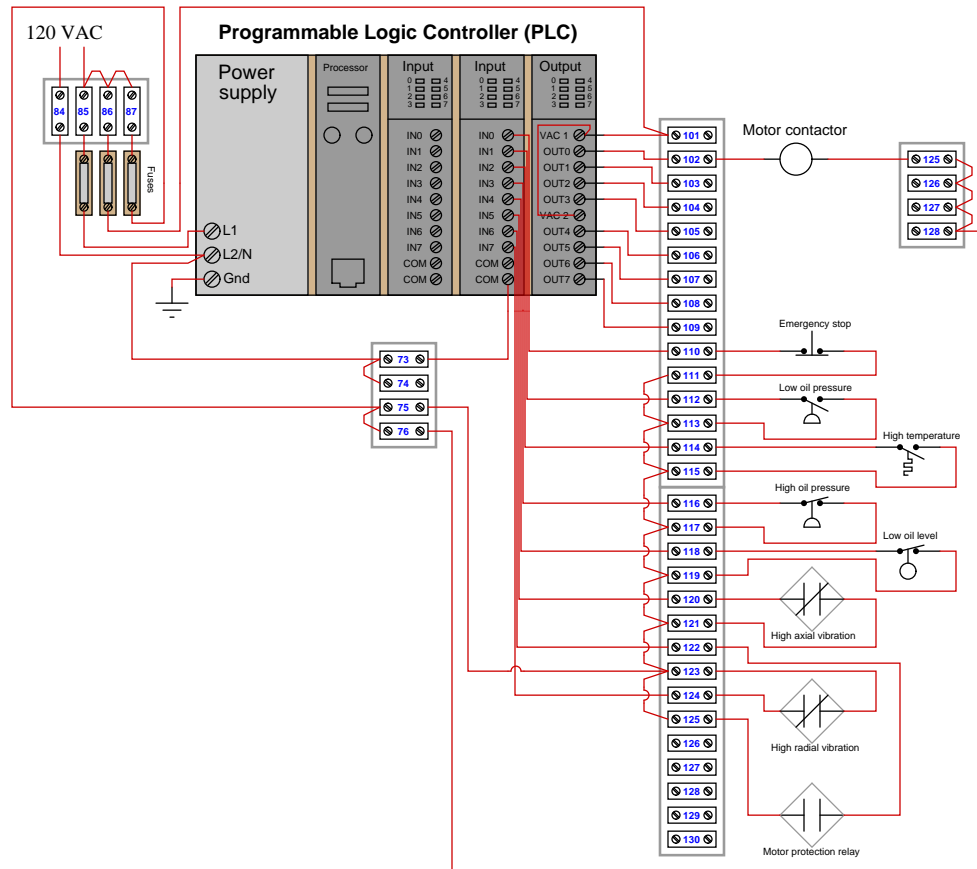
Trace the complete circuit for the high-frequency AC signal generated by the "Transmitter" in the diagram. How many power line conductors are being used in this communications circuit? Explain how the combination of "line trap" *LC* networks and "coupling" capacitors ensure the communications equipment never becomes exposed to high-voltage electrical power carried by the power lines, and vice-versa.

[file i01214](#)



# Question 68

In this safety shutdown system, a programmable logic controller (PLC) monitors inputs coming from various switches located on a large motor-driven gas compressor system, and trips the compressor off (shuts off power to the motor's contactor coil) if any of these conditions becomes dangerous.



Identify the “trip state” for each of the PLC inputs (sensing switches): whether each input must *energize* or *de-energize* to trip the compressor. Note that the PLC input channels are not drawn here showing operating conditions (i.e. there are no LED lights shown in an illuminated state to help you determine switch status).

- Emergency stop = *Energize to trip* or *De-energize to trip*
- Low oil pressure = *Energize to trip* or *De-energize to trip*
- High temperature = *Energize to trip* or *De-energize to trip*
- High oil pressure = *Energize to trip* or *De-energize to trip*
- Low oil level = *Energize to trip* or *De-energize to trip*
- High axial vibration = *Energize to trip* or *De-energize to trip*
- High radial vibration = *Energize to trip* or *De-energize to trip*
- Motor protection relay = *Energize to trip* or *De-energize to trip*

Hint: remember that the “normal” status of a switch (i.e. the way a switch is always drawn in a schematic diagram) is its *resting* or *minimum-stimulus* state.

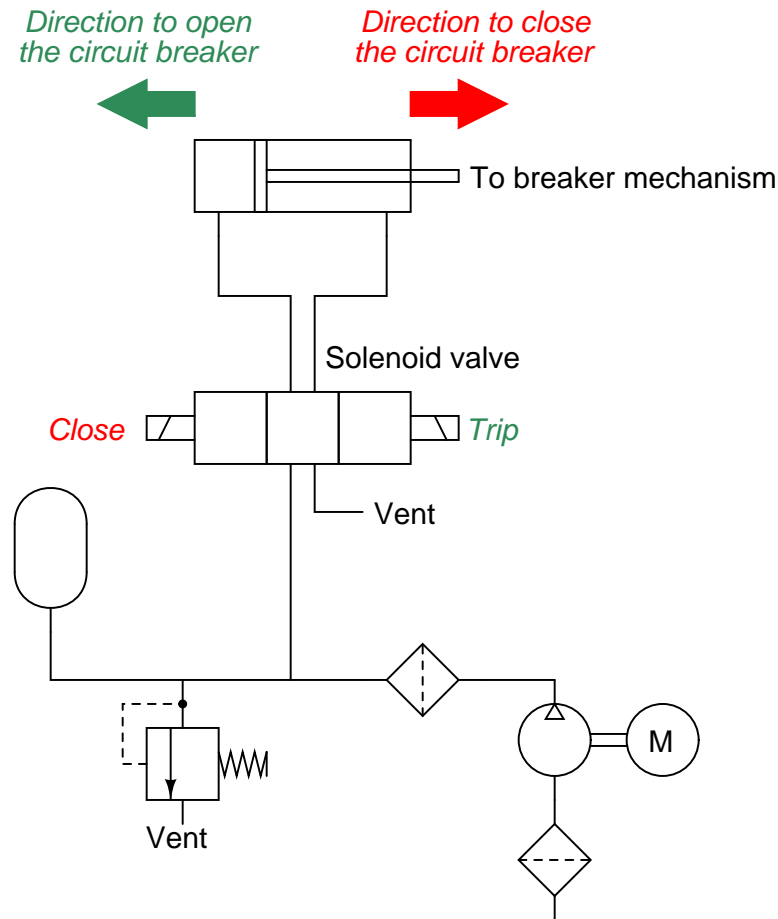
<b>Suggestions for Socratic discussion</b>
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- A common mistake is to assume the normal status of the switch is the only piece of information you need to determine whether it will be “energize to trip” versus “de-energize to trip”. Explain why it is a bit more complicated than that.

file i02100

# Question 69

The mechanism of a high-voltage oil-tank circuit breaker is typically actuated by the power of compressed air in a double-acting cylinder:



Sketch the correct arrow symbols inside the spool valve's square symbols in order to make the breaker trip and close as those respective solenoid coils are energized. The actuating cylinder needs to remain "locked" in position when neither solenoid coil is energized.

Finally, identify the other pneumatic components in the system.

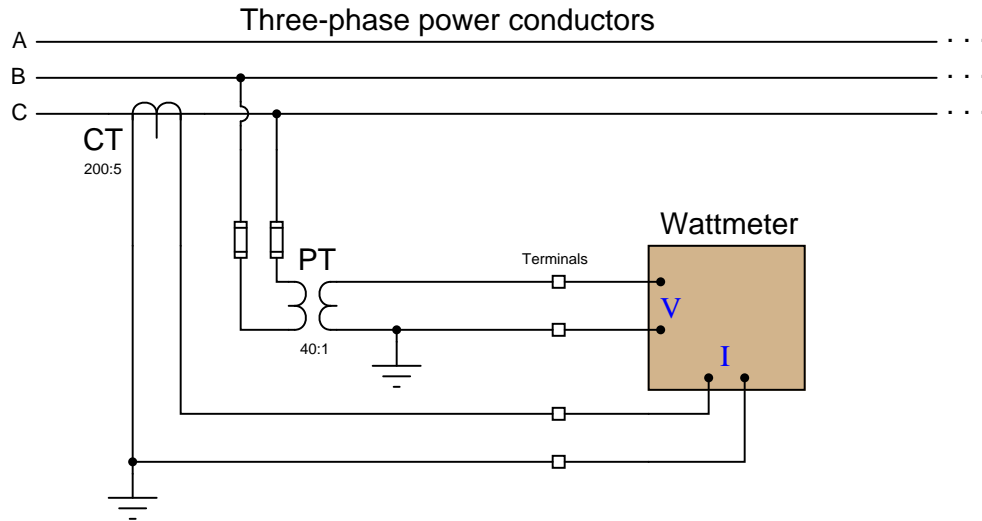
## **Suggestions for Socratic discussion**

- Explain why the circuit breaker must be actuated by compressed air, rather than being directly actuated by solenoid coils.
- Suppose the compressed air reliability (i.e. the probability there will be sufficient pressure and volume of compressed air for the breaker to actuate) has a rating of 0.992, the "Close" valve function has a dependability rating of 0.942, and the cylinder has a dependability rating of 0.9991. From these ratings calculate the dependability of the breaker's "close" function.

file i01213

### Question 70

This wattmeter measures power on one phase of a three-phase power system by sensing both line voltage and line current through instrument transformers. The nominal line voltage of this power system is 4160 volts AC, while the current may extend upwards of 180 amps AC under full-load conditions:



What would you have to do in order to check the calibration of this wattmeter? Specifically, devise a step-by-step procedure that you could give to another technician telling them what they would have to do in order to simulate precise amounts of electrical power to the wattmeter's input, keeping safety in mind as the first priority. Note: you are not allowed to shut power off in the three-phase system to do your test – it must be done “live.”

The power of a balanced three-phase system is given by the following formula:

$$P = \sqrt{3}V_{line}I_{line}$$

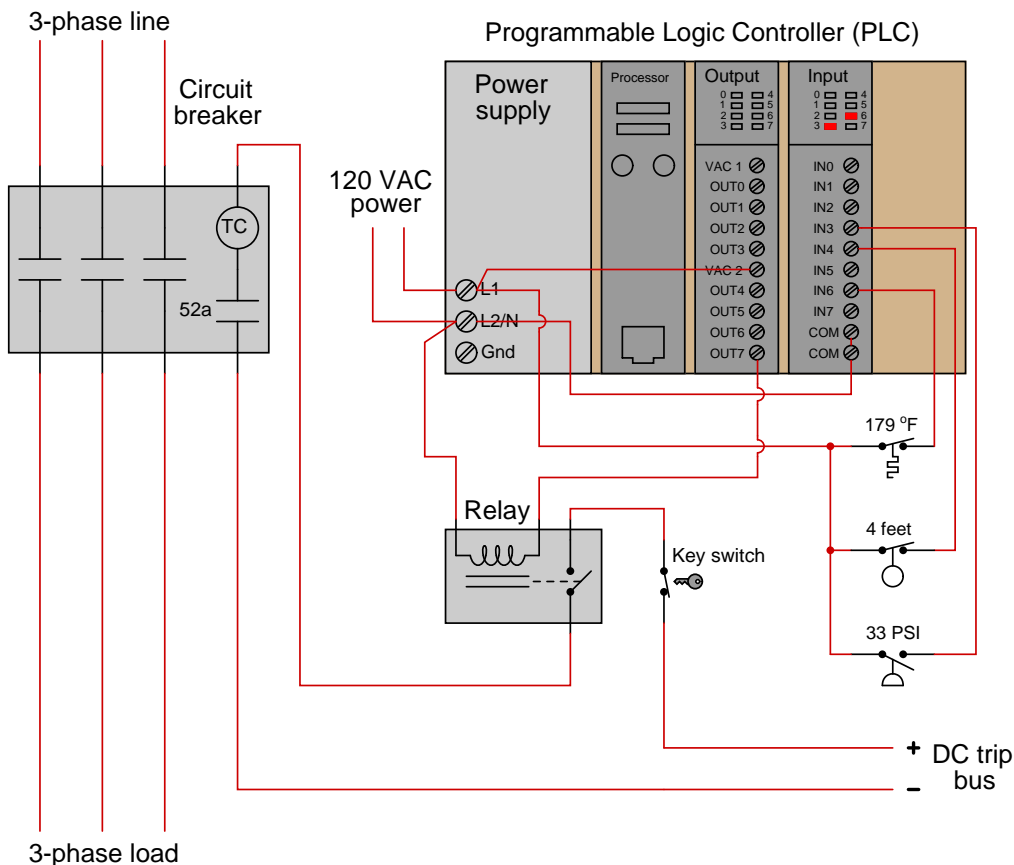
#### Suggestions for Socratic discussion

- An important safety rule to apply when working with live circuit is the “one-hand rule.” Explain what this rule is, and how it is applied to a scenario such as this.
- When loosening the screws on a terminal block to remove wires for the PT signal, should you remove the wires from the left-hand side of the terminals (as shown in the diagram) or from the right-hand side, or does this matter at all?
- The task of disconnecting a wattmeter from live instrument transformers presents significant hazard. Devise a way to make this procedure safer, using special “test switches” installed on the signal wires at the time of construction, so that a technician may simply throw the switches’ levers to isolate the wattmeter instead of putting a screwdriver on “live” terminals and removing wires from terminal blocks.
- Suppose the PT’s output signal were 113.6 volts RMS, and the CT’s output signal were 2.9 amps RMS. How much power does this represent flowing through the three-phase lines?
- Why are both instrument transformers’ secondary circuits grounded?
- Suppose the potential transformer has a reliability rating of 0.9995 and the current transformer has a reliability rating of 0.9998. Calculate the probability that the wattmeter will receive good information from which to calculate power.

[file i01212](#)

## Question 71

A *programmable logic controller* (PLC) may be used to command a high-voltage circuit breaker to trip in the event of dangerous process conditions, such as the system shown here:



Assume this process system is operating as it should (i.e. no abnormal conditions). Based on the status LED indicators you see on the input card of the PLC, determine whether each of the process switches is designed to trip on a *low* condition or a *high* condition. Then, determine what you would have to do to the circuit to simulate a shutdown condition for each of the process switches (i.e. make the PLC “think” it sees an abnormal condition, so that it will act to trip the breaker):

- Temperature switch: trips on *low* temperature or *high* temperature? How to simulate trip condition?
- Level switch: trips on *low* liquid level or *high* liquid level? How to simulate trip condition?
- Pressure switch: trips on *low* fluid pressure or *high* fluid pressure? How to simulate trip condition?

### Suggestions for Socratic discussion

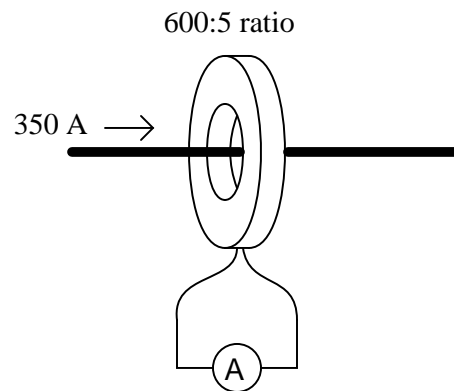
- Explain why the LED status indicators are so helpful for system troubleshooting in a PLC-controlled system.
- Identify the purpose of the key switch in this circuit.
- Suppose you were asked to install a manual pushbutton “Emergency Trip” switch to trip the circuit breaker. Where would you connect such a switch in this circuit?

[file i02113](#)

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Question 72

How much current will be output by a current transformer if the load current is 350 amps and the CT ratio is 600:5?

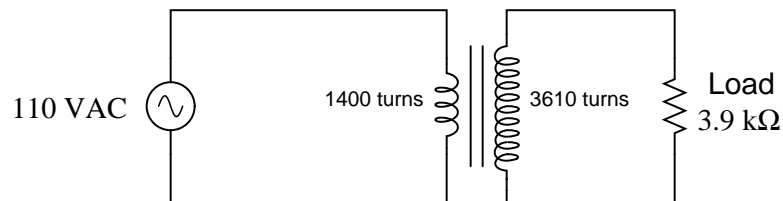


[file i01260](#)

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Question 73

Calculate the source current and load current in this transformer circuit:



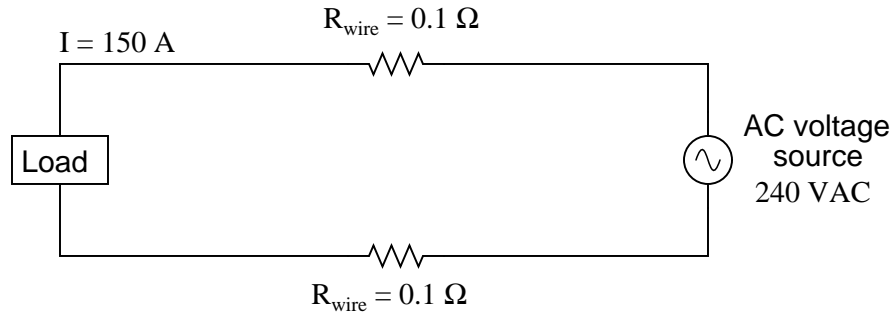
$I_{source} =$

$I_{load} =$

[file i01255](#)

Question 74

Suppose a power system were delivering AC power to a resistive load drawing 150 amps:



Calculate the load voltage, load power dissipation, the power dissipated by the wire resistance ( $R_{wire}$ ), and the overall power efficiency ( $\eta = \frac{P_{load}}{P_{source}}$ ).

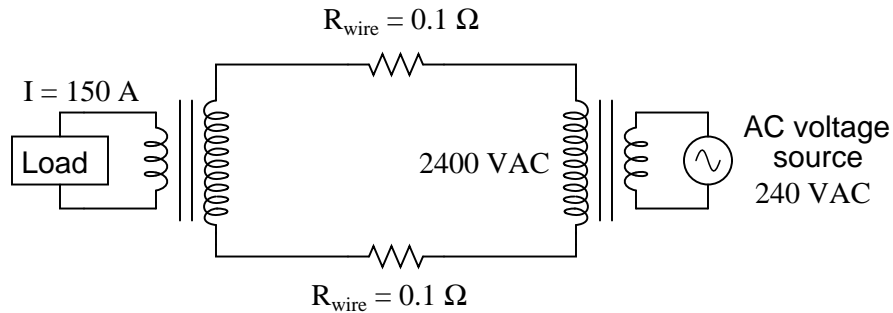
$$E_{load} =$$

$$P_{load} =$$

$$P_{lines} =$$

$$\eta =$$

Now, suppose we were to use a pair of perfectly efficient 10:1 transformers to step the voltage up for transmission, and back down again for use at the load. Re-calculate the load voltage, load power, wasted power, and overall efficiency of this system:



$$E_{load} =$$

$$P_{load} =$$

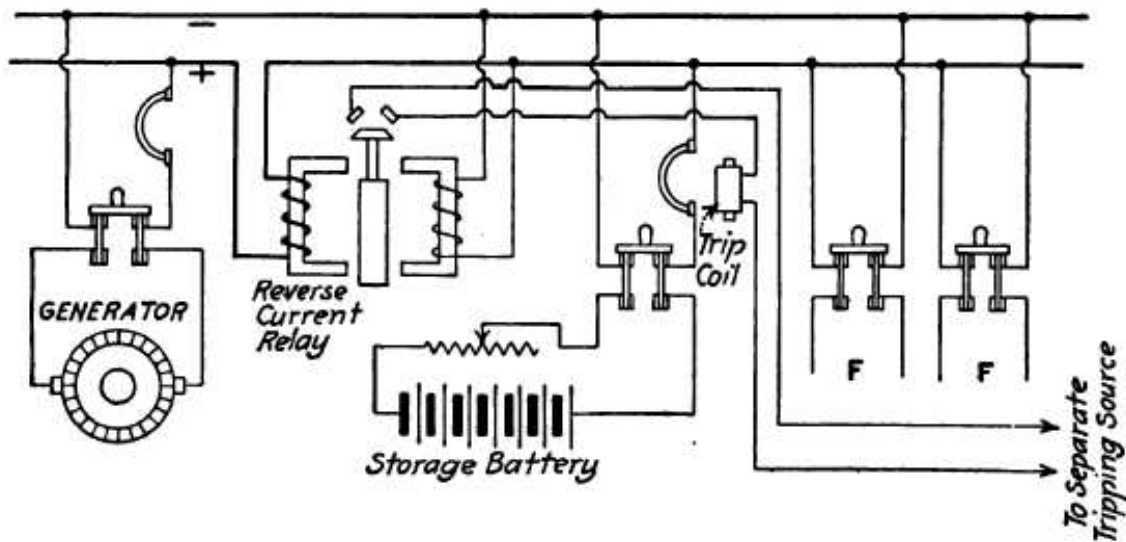
$$P_{lines} =$$

$$\eta =$$

[file i01258](#)

Question 75

Examine this schematic diagram sampled from Victor H. Todd's 1922 book *Protective Relays* showing a *reverse power* protection circuit for a DC power system whereby a generator typically supplies a load with power and maintains a storage battery in a continual state of full charge:



If the generator's mechanical prime mover ever fails (e.g. water gets shut off to the hydro turbine, engine runs out of fuel, etc.), the purpose of the directional relay is to trip the storage battery's breaker so that the storage battery does not discharge itself powering the generator as an electric motor.

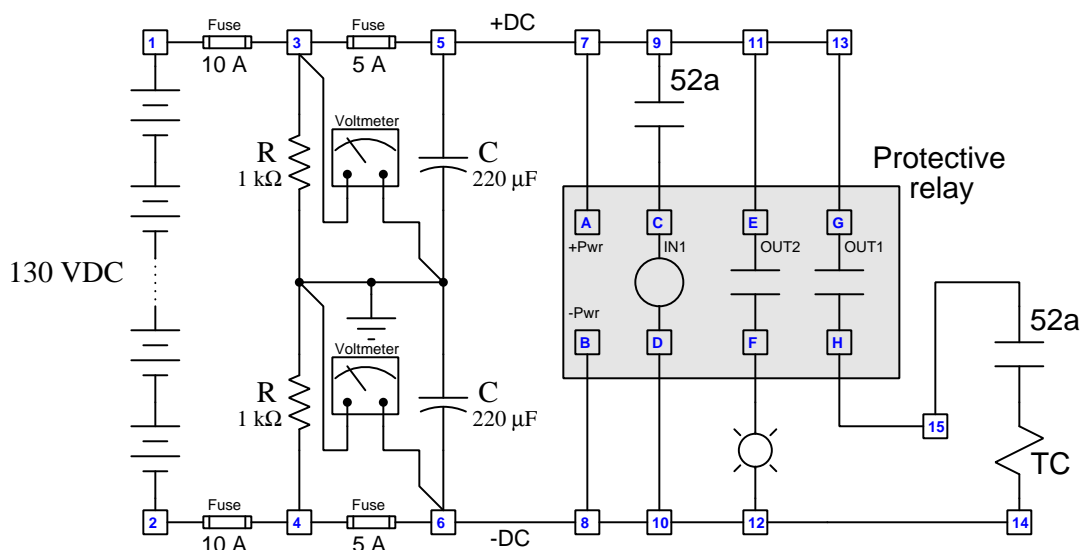
Examine this relay closely and determine how it fulfills its directional function.

[file i02863](#)



# Question 76

Identify the effects of the following faults in this protective relay DC trip circuit. Note the omission of all instrument transformer (e.g. PT, CT) wiring and an exclusive focus on DC trip wiring in this diagram. Also note the resistive voltage divider and dual voltmeters used to detect any ground faults in the DC station power wiring:



- Upper resistor failing open
- Upper capacitor failing shorted
- Loose connection on left side of terminal 12
- Broken wire between terminals D and 10
- Broken wire between terminals E and 11
- Ground fault at terminal 7
- Simultaneous ground faults at terminals 9 and 6

## Suggestions for Socratic discussion

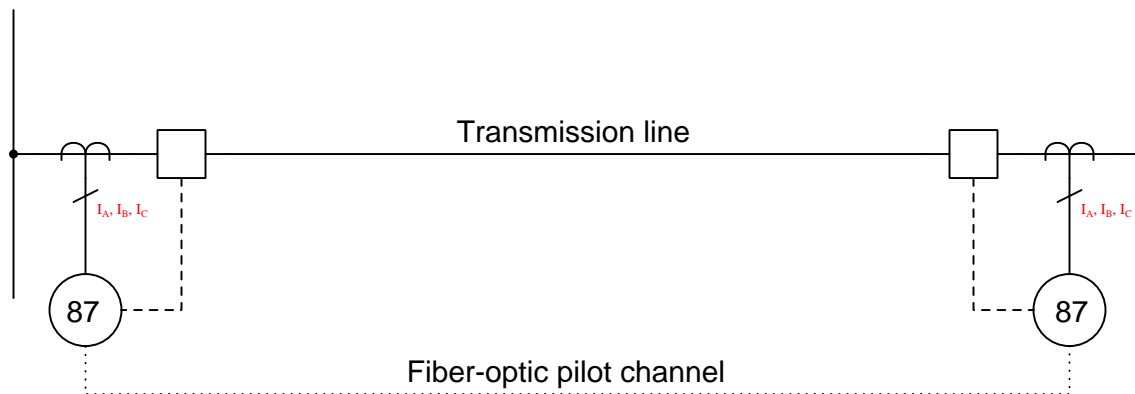
- What is the point of having both 5 amp and 10 amp fuses in this circuit?
- What should a voltmeter register between terminal 3 and ground? Between terminal 4 and ground? If we permanently installed two voltmeters to register these voltages, could their indications help us pinpoint certain faults before they become serious?
- Can we tell what ANSI/IEEE function this protective relay implements? Why or why not?

[file i03098](#)

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### Question 77

In this system, a pair of line current differential relays (87) provide protection for a power line, each relay sensing current through the three line conductors at each end. The optional slash mark and “ $I_A$ ,  $I_B$ ,  $I_C$ ” notations emphasize the fact that the relays are monitoring all three phases:



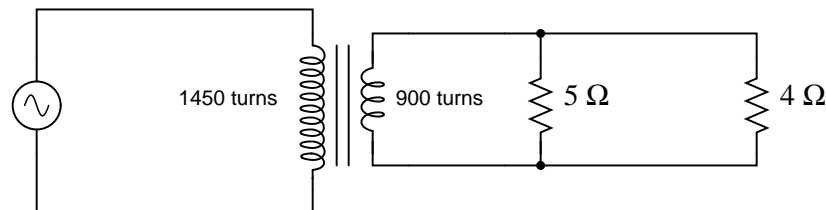
Suppose a line-to-line fault develops between phases A and B of this power line, with no connection whatsoever to earth ground. Determine whether or not the 87 relays will trip, and explain why.

[file i00852](#)

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### Question 78

Calculate all voltages and all currents in this transformer circuit, assuming the 5 ohm resistor carries a current of 10 amps:



- $V_{primary} =$
- $V_{secondary} =$
- $I_{primary} =$
- $I_{secondary} =$

[file i01269](#)

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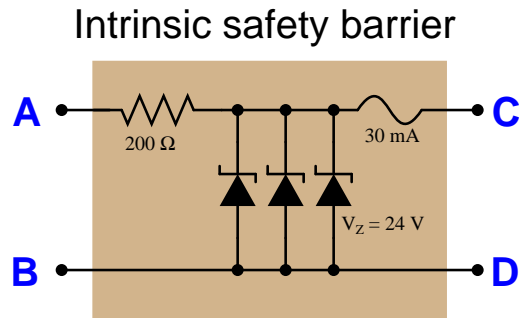
### Question 79

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### Question 80

### Question 81

Explain how you would use a multimeter (and any other appropriate electronic test equipment) to test the following components of a passive (zener) IS barrier module. For each test, identify both the multimeter setting and the connection points for the multimeter's test leads (A, B, C, D; red, black), as well as the reading expected if the component in question is good.



- How to test for proper zener breakdown voltage:

- How to check for a shorted zener diode:

- How to check for a good fuse:

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### Question 82

The “strength” of any password against a brute-force cyberattack is a simple exponential function: the number of possible unique passwords given a given number of characters in the password and a given number of symbols for each character:

$$n = S^C$$

Where,

$n$  = Number of possible unique passwords

$S$  = Number of possible symbols for each character

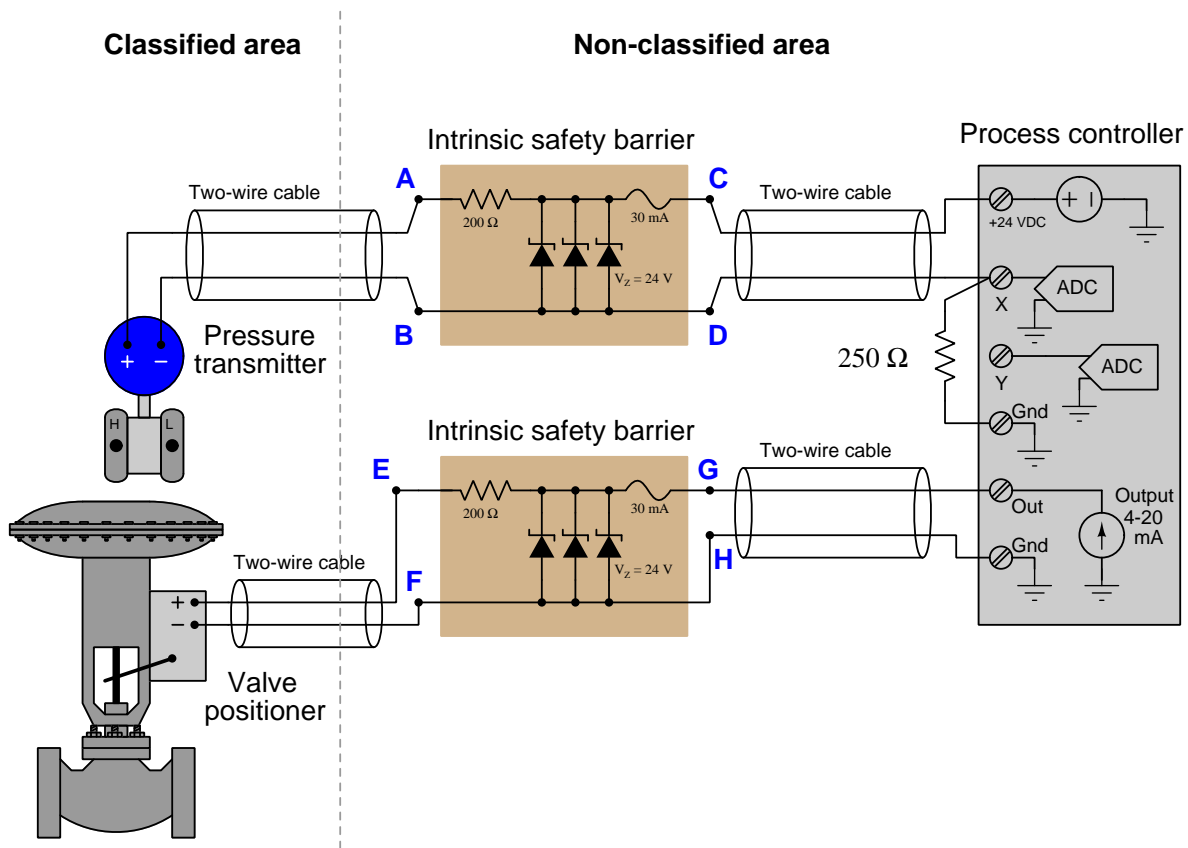
$C$  = Number of characters in the password

For example, a password consisting of 5 letters, case-insensitive (i.e. lower- and upper-case letters are equivalent) has  $26^5 = 11,881,376$  possible combinations.

This raises an interesting question: which is more effective in “strengthening” a password against a brute-force attack, more symbols or more characters? Mathematically prove your conclusion.

Question 83

Suppose a voltmeter registers 0 volts between test points **A** and **B** in this pressure control loop circuit:

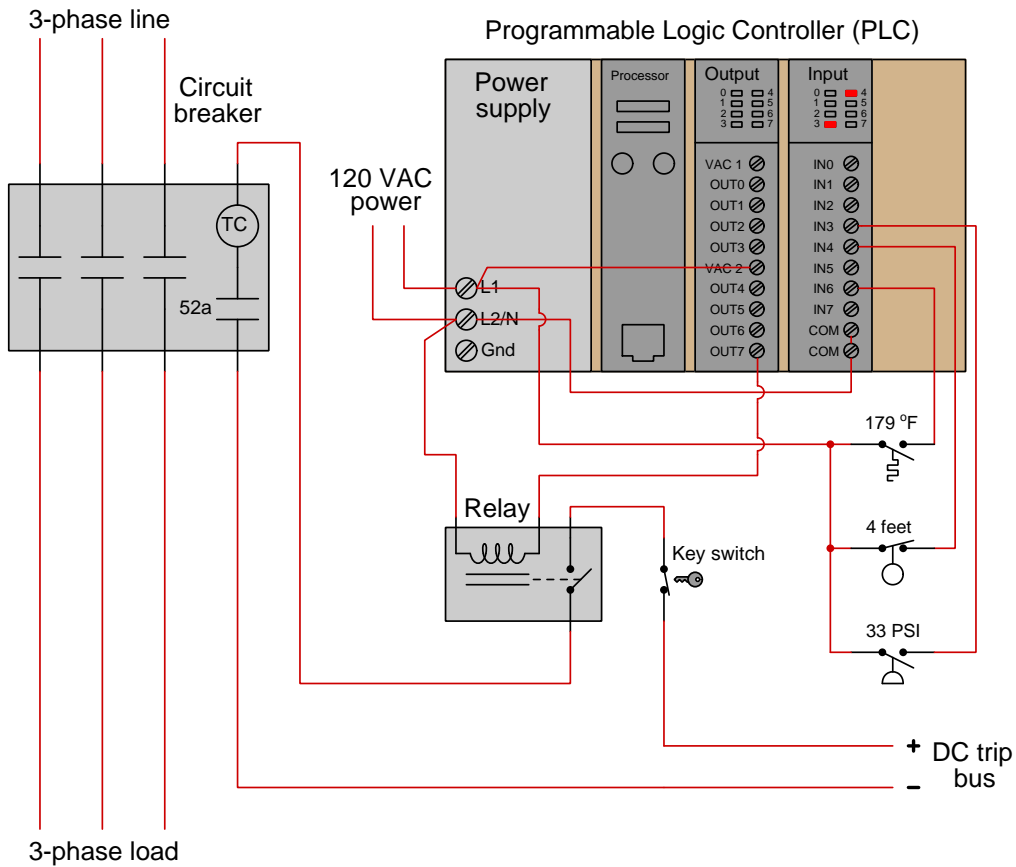


Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Pressure transmitter failed open		
Zener diode failed open		
Valve positioner failed open		
Cable from C-D to controller failed open		
Cable from G-H to controller failed open		
Pressure transmitter failed shorted		
Valve positioner failed shorted		
Zener diode failed shorted		
Cable from C-D to controller failed shorted		
Cable from G-H to controller failed shorted		

# Question 84

The following diagram shows a PLC controlling the tripping of a power circuit breaker, complete with status indications on the input and output cards showing I/O states during typical (non-trip) conditions:

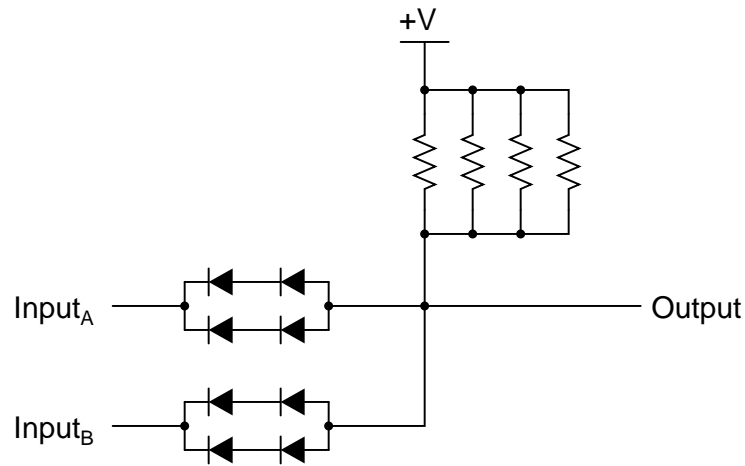


Devise a complete test procedure for verifying the dependability of the relay in this system, without actually tripping the circuit breaker which would interrupt power to the operating load.

Question 85

The *Orbiting Astronomical Observatory* was a NASA project during the late 1960's and 1970's to place precision observational instruments in earth orbit for scientific purposes. Satellites designed for this program had to have “hardened” circuitry to withstand the radiation, extreme temperatures, and other harsh conditions of space.

An example of some of this “fail-safe” circuitry is shown here: a passive, quad-redundant, two-input AND gate:



Determine how many component failures this circuit is able to tolerate and still be guaranteed to work. Specify whether the tolerable faults are *opens* or *shorts*.

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Question 86

The *Nernst equation* is the primary formula used to predict voltage generated across an ion-selective membrane due to ion exchange from one side of the membrane to the other. This equation is commonly used to predict the amount of voltage generated by a pH electrode pair, when measuring the pH of an aqueous (water-based) solution:

$$V = \frac{2.303RT}{nF} \log \left( \frac{C_1}{C_2} \right)$$

Where,

$V$  = Voltage produced across membrane due to ion exchange, in volts (V)

$R$  = Universal gas constant (8.315 J/mol·K)

$T$  = Absolute temperature, in Kelvin (K)

$n$  = Number of electrons transferred per ion exchanged (unitless)

$F$  = Faraday constant, in coulombs per mole (96,485 C/mol e<sup>-</sup>)

$C_1$  = Concentration of ion in measured solution, in moles per liter of solution (M)

$C_2$  = Concentration of ion in reference solution (on other side of membrane), in moles per liter of solution (M)

How much voltage will develop across a membrane when the ion concentrations ( $C_1$  and  $C_2$ ) are precisely equal on both sides of the membrane?

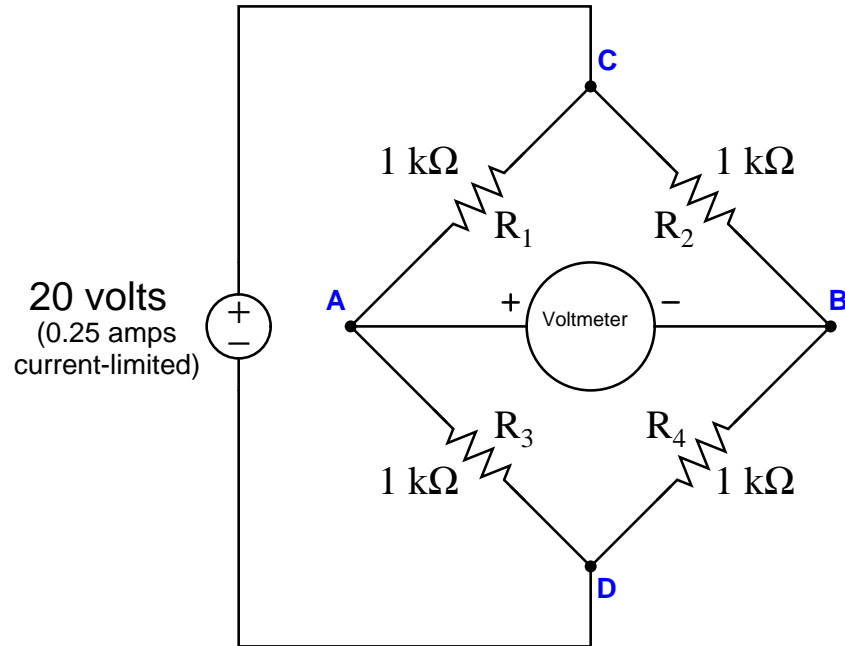
What condition is necessary to generate a *positive* voltage across the membrane, according to the equation?

What condition is necessary to generate a *negative* voltage across the membrane, according to the equation?



Question 87

Suppose the voltmeter in this bridge circuit registers a strong *positive* voltage:



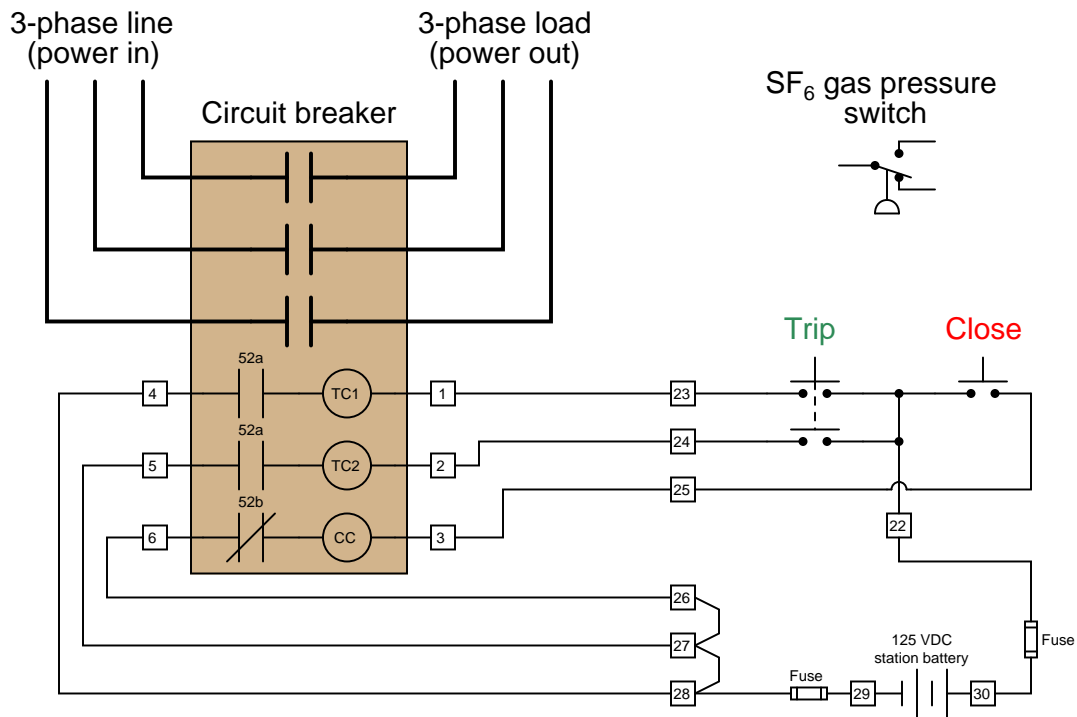
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

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

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

# Question 88

A high-voltage circuit breaker is manually operated from a remote location using a pair of pushbutton switches, connected to “trip” and “close” solenoid coils within the breaker:



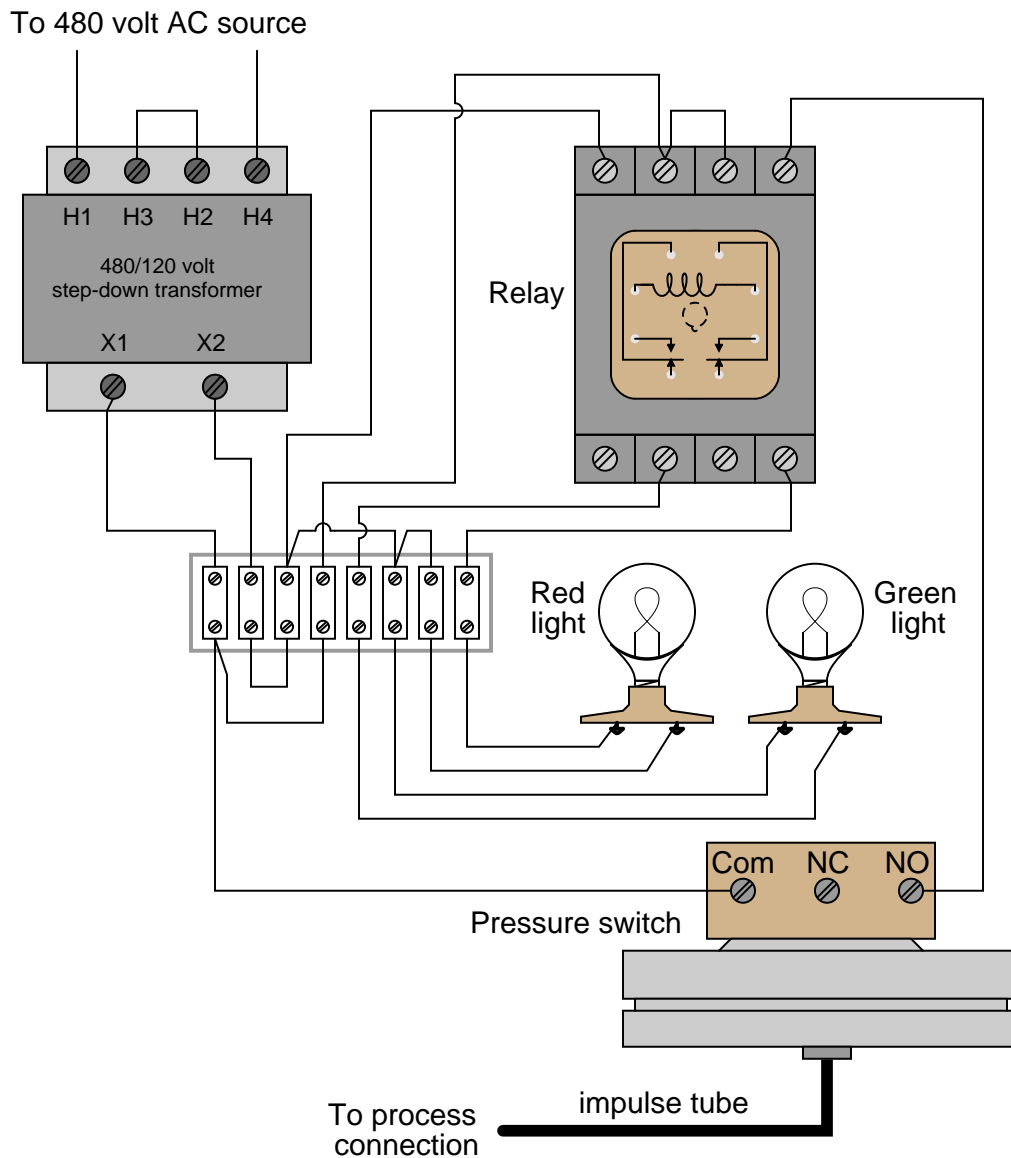
This particular circuit breaker is gas-quenched by sulfur hexafluoride gas ( $\text{SF}_6$ ), which is normally pressurized inside the circuit breaker to approximately 45 PSI for optimum electrical performance.

A low-pressure lockout switch is being installed on the circuit breaker to detect if the  $\text{SF}_6$  gas pressure ever drops below 35 PSI. The purpose of this switch is to disable the breaker from either closing or tripping if the gas pressure is abnormally low.

Your task is to modify the circuit shown above to include this pressure switch. The single-pole, double-throw pressure switch is shown in the upper-right corner of the diagram, not yet connected to the 125 VDC trip/close circuit.

Question 89

Identify the states of both light bulbs when the normally-open pressure switch contact *opens*:



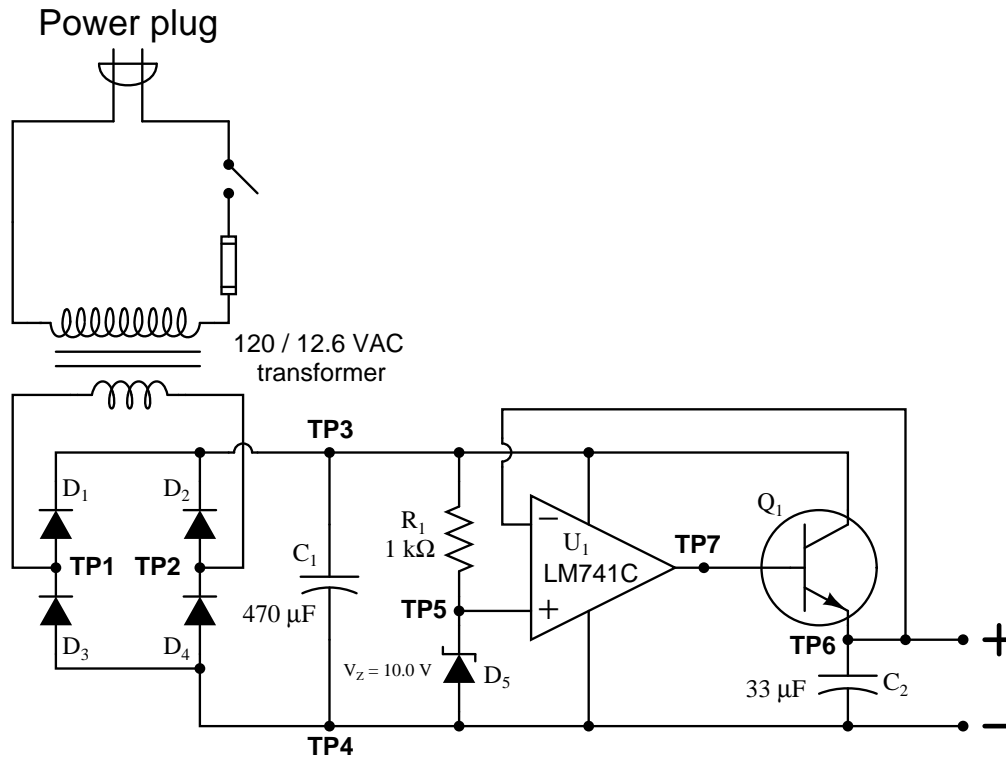
Assuming that the green light bulb signifies a “good” process condition and the red light bulb signifies a “bad” (alarm) process condition, determine whether this is a *low-pressure* alarm or a *high pressure* alarm circuit.

Hint: remember that the “normal” status of a switch is defined as the status of *minimum stimulus*: when the switch is exposed to the lowest possible degree of process stimulation (in this particular case, to the lowest possible pressure).

file i03205

# Question 90

Something is wrong with this regulated DC power supply circuit. The output is supposed to be +10.0 volts, but instead it measures only about 1 volt:



Using your digital multimeter, you measure 15.3 volts between test points TP7 (red test lead) and TP4 (black test lead). Note that  $V_Z$  shown in the schematic is a *specification* for the zener diode, and not an actual voltmeter measurement. From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted) other than the 120 volt AC power source, on/off switch, and fuse. The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted
  - 1.
  - 2.
- Circuit elements that must be functioning properly
  - 1.
  - 2.

[file i03189](#)

**Lab Exercise – introduction**

Your team’s task is to construct and test a safety “shutdown” system designed to bring some process to an idle condition if one or more variables drift beyond acceptable parameters. This may take the form of an additional layer of sensors and controls incorporated into your existing process control loop (e.g. a high-pressure shutdown system on an air pressure control loop), or it may be entirely separate (e.g. a protective relay system designed to trip a circuit breaker on excessive load current).

If implemented as an additional layer of controls to a functioning process loop, the shutdown function must bring the process to a “safe” condition (power off, vessels drained/vented, etc.) independent of any action on the part of the loop PID controller. In other words, the safety function must work *no matter what the loop controller is trying to do*. This shutdown condition must “latch” and be re-settable only from a manual pushbutton, also independent of the loop PID controller. You may use either a hard-wired relay, a PLC, or a dedicated safety controller to implement the latching safety shutdown function. The safety control element must be a solenoid valve if the process final control element is pneumatically actuated!

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

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Safety “trip” testing	mastery					– – – –
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	
Team tool locker inspection	(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 testing these working instrument systems!**

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

## Lab Exercise – objectives and expectations

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

### Team meeting and prototype sketch

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

### Circuit design challenge

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

### Final loop diagram and system inspection

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

### Demonstration of working system

Show that the safety shutdown system overrides the control system when the measured variable crosses the trip threshold value. The instructor will randomly select a trip threshold at the time of demonstration, and all team members must be able to demonstrate how to accurately set that value for the safety shutdown system.

### Safety “trip” testing

Test the function of a safety shutdown system in a working system that your team did not build. This will be limited in time, with each student passing or failing individually.

## Lab Exercise – objectives and expectations (continued)

### Lab percentage score

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

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

### Safety and professionalism (deduction)

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

## General format and philosophy

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

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

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

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

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

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

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

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

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

Your first design step needs to be deciding what process variable condition might be deemed dangerous in a full-scale process, and what the automated shutdown action(s) should be to limit that process variable’s value. The variable to monitor may or may not be the process variable (PV) being regulated by the loop controller. Whatever action the shutdown system automatically takes, however, should completely override the action of the loop controller in a shutdown condition.

Once you have defined the shutdown variable and action(s), the next step is to design an independent control system to add to your working process. This SIS (Safety Instrumented System) needs to be based on a *latch*: the SIS will “trip” whenever a shutdown condition is detected, and will not “reset” (even after the condition clears) until an operator manually presses a reset pushbutton. A typical SIS for the scope of a lab project such as this usually consists of these components:

- Sensor for detecting shutdown condition (separate from PV sensor used in the PID control system)
- Threshold detection relay (outputs a discrete signal to trip the latch)
- Latching system (e.g. electromechanical relay, PLC, or dedicated SIS controller)
- FCE override (e.g. solenoid valve forcing the control valve to its “fail-safe” position)

Your instructor will verify that your team’s SIS design is practical. Note that the SIS need not be complex: in fact, simpler is better here. A system consisting of a process switch, and an ice-cube relay to latch on as well as energize or de-energize a “dump” solenoid when tripped, is sufficient for many student-built processes. If your SIS sensor is a 4-20 mA analog transmitter, you will need some “alarm” module or relay to trigger the latch. A PLC with an analog input works well for this purpose, as does a stand-alone alarm module such as the Moore Industries DDA or SPA units.

If your team plans to build a protective relay system, you will need to first select a suitable relay to use. Modern digital relays such as the SEL model 501 are highly recommended. Due to the fact your electrical load won’t be drawing much current, you will need to use a CT (current transformer) with multiple turns of wire run through its core in order to achieve a workable load:relay current ratio. I rule of thumb here is



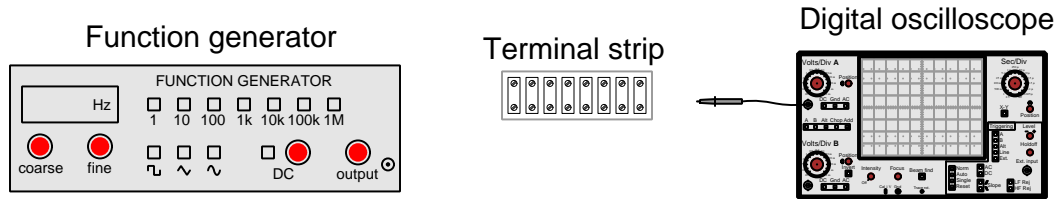
to not wrap more than 4 turns of wire through the core of the small CT you will be given, in order to avoid saturation and inaccurate performance.

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

## Lab Exercise – circuit design challenge

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

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



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

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

**Circuit function** (randomly selected by the instructor):

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

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

## Lab Exercise – building/modifying the system

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

You may install your SIS control hardware inside the nearest field junction box. The installation should be neat and professional, like the rest of the control system. Instruments should attach to 2-inch pipes using special brackets and U-bolts, located in the instrument storage area. Liquid-tight flexible conduits should be used to route signal cable between the instrument(s) and the junction box.

Finally, your SIS needs to have a loop number, so all instruments may be properly labeled. This loop number needs to be unique, not only from other SIS installations in the lab but also different from the instruments used for regulatory control in the process (i.e. the PID controller, transmitter, FCE).

If your choice of shutdown systems is a protective relay and circuit breaker, there will be no 2-inch-pipe-mount devices such as pressure transmitters. Neither will there be ISA-standard loop numbers, as protective relays are labeled according their specific function rather than according to the general process. You may choose to set up such a system entirely inside an electrical enclosure, or perhaps between two different enclosures (e.g. one for the circuit breaker and load, the other for the relay). An “open” design such as on an enclosure subpanel is also acceptable, so long as all electrical terminals are “touch-safe” (recessed) so as to present little shock hazard and the system is locked and tagged out when not in use.

### Common mistakes:

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

## Lab Exercise – loop diagram and system inspection

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

### Construction Standards

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

### Documentation Standards

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

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

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

#### **Common mistakes:**

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

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

## Lab Exercise – safety “trip” testing

Instead of troubleshooting a fault in the system as is customary for lab exercises, your task in this lab is to test a SIS (Safety Instrumented System) to ensure its proper operation with the process running. The goal is to validate the correct operation of one SIF (Safety Instrumented Function) to ensure its readiness to act when needed. All “trip” testing is done on an individual basis (no team credit!), and must be done *on a system you did not help build*, so that you must rely on schematic diagrams to find your way around the system and to determine how to do the test instead of from your own memory of building it.

The instructor will choose the SIF for you to test, as well as the instrument(s) within that SIF to be tested. This may be a process constructed by another student team, or it may be one of the permanently constructed processes in the lab (e.g. the turbocompressor system, the protective relay demonstration system, one of the protective relays in the lab’s miniature AC power grid system). Your procedure will need to adequately test the system as specified by the instructor in the following check-box format:

**Safety Instrumented Function (SIF) to test:** \_\_\_\_\_  
(e.g. high vessel pressure, high turbine speed)

**Instrument(s) to test:**  
(may select more than one)

☐

Sensor

☐

Logic (controller)

☐

Final control element

**Process status:**  
(select only one option)

☐

Maintain regular operation

☐

Test to shutdown

For example, if the instructor writes “low oil pressure” in the SIF line and checks the “Logic” and “Maintain regular operation” boxes, it means you will need to electrically simulate a low-oil pressure condition to the input of the SIS logic solver and verify that the logic produces the proper output response, while ensuring the process does not actually shut down (i.e. you will need to somehow simulate a “good” output condition from the logic to ensure the final control element will not shut down the process). As another example, if the instructor checks the “Final control element” and “Test to shutdown” boxes for the same SIF (“low oil pressure”), it means you will simulate the same shut-down signal as would be generated by a low oil pressure condition to the input of the final control element and let it actually shut down the process. If multiple boxes are checked in the Instrument(s) section, it means your one procedure will need to verify all of the selected SIS elements at once. Note that it *is* possible to test the final control element of an SIS without shutting down the process, if the test is done quickly enough!

A common point of confusion for many students is to test the wrong instrument(s). A helpful hint is to identify both the *input* and *output* of the instrument your instructor has assigned you to test, and to be sure your test is based on those specific signals or process states. For example, if your instructor has assigned you to test SIS *sensor*, this means you must stimulate the sensor at its input (pressure, temperature, etc.) and measure the sensor’s output signal. An example of an incorrect test for this application would be to use a loop calibrator to simulate a signal from the sensor: this would not actually test the sensor itself!

Each student is given 5 minutes to plan their test after having been given the conditions by the instructor. The student must then describe their test in step-by-step detail to the instructor. If the test as described is safe to perform and meets all the specified criteria, the student will then be allowed to execute the test. All testing activities will take place under direct instructor supervision to ensure students are working independently and efficiently.

Failure to formulate a safe and effective test strategy at the end of the 5-minute time period, or failure to execute the planned test, will disqualify the effort in which case the student must re-try with a different set of conditions (perhaps on a different system as well).

A standard multimeter and signal source (e.g. loop calibrator or protective relay test set) are the only pieces of test equipment allowed during the time limit. If the SIS makes use of a PLC as the logic solver,

a computer with PLC programming software *may* be provided to aid in planning and executing the test (e.g. using this software to force bits in the PLC as part of the test). If an electrical “jumper” connection is necessary to perform the test, it is expected that you will use your multimeter (test leads plugged into the “Amp” jacks) as the jumper, so that your jumper will be fused to protect against personal hazard if it is incorrectly applied.

**Common mistakes:**

- Testing the wrong portion of the SIS (i.e. not carefully identifying the necessary stimulus and measurement points to encompass just specified portion(s) of the SIS)
- Making or breaking electrical connections in such a way that causes the system to trip before the test is supposed to begin
- Neglecting to confirm the system’s status with a multimeter before proceeding
- Incorrectly interpreting the loop diagram (e.g. thinking you’re at the wrong place in the system when taking measurements).
- Incorrect multimeter usage (e.g. AC rather than DC, wrong range, wrong test lead placement). This is especially true when a student comes to lab unprepared and must borrow someone else’s meter that is different from theirs!

**Even though this exercise is not called “troubleshooting,” it is every bit as analytical as diagnostic work, and may require some amount of creativity to execute. This takes a lot of lab time, usually at least two 3-hour lab sessions for everyone in a full class to successfully pass. Be sure your team budgets for this amount of time as you plan your work, and also be sure to take advantage of your freedom to observe others as they trip-test, to better learn this art.**

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

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

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

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

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

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

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



**Lab Exercise – team tool locker inspection**

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

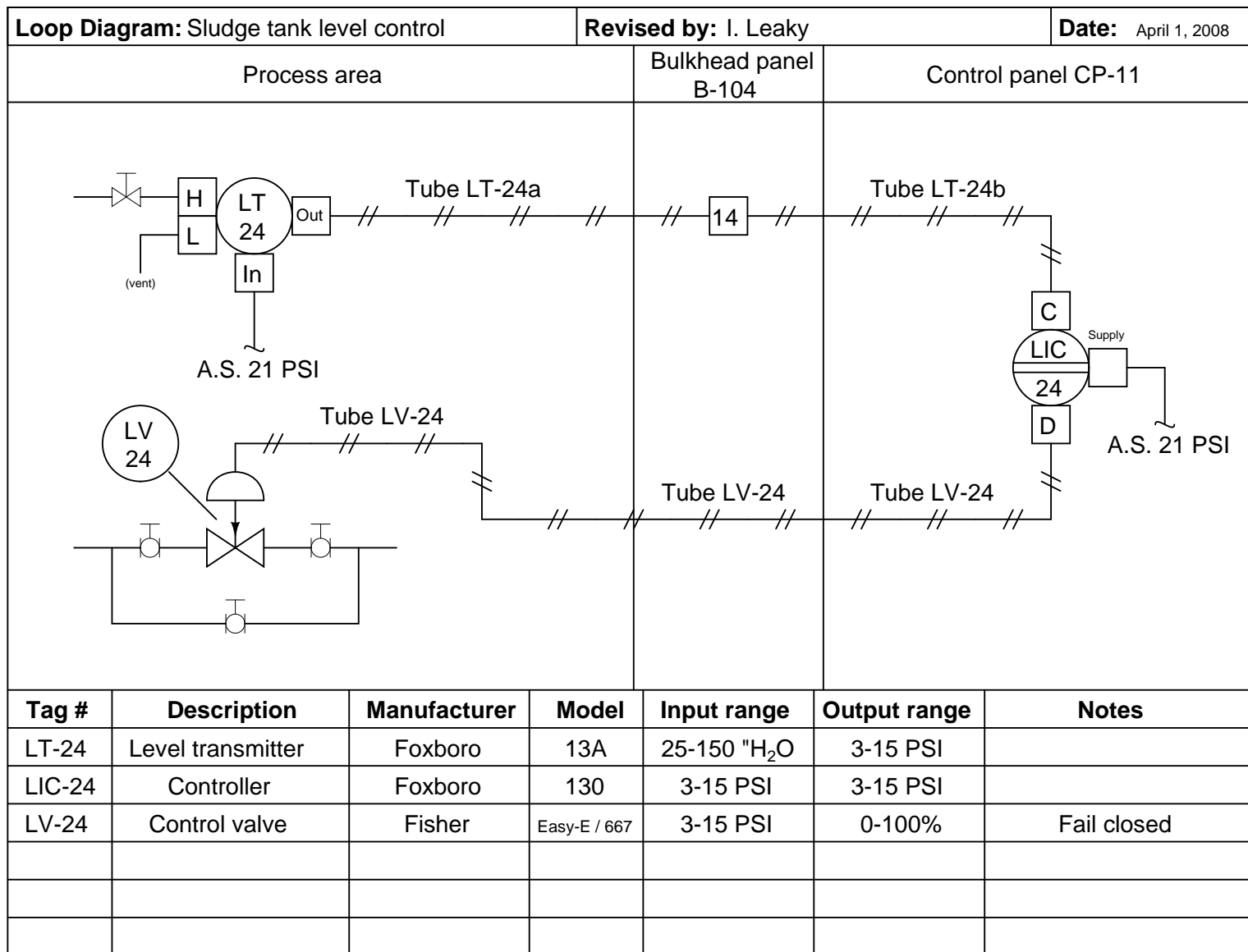
First, the locker will be entirely emptied. Next, the instructor will inspect each tool before placing it in the locker, following the order of the inventory list taped to the inside of the locker door. The team is responsible for finding or replacing any missing items. Any items not on the inventory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

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

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## Lab Exercise – loop diagram and system inspection

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

### Construction Standards

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

### Documentation Standards

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

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

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

#### **Common mistakes:**

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

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

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**Capstone Assessment** (end of quarter)

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

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

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

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

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

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

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



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

**No teamwork is allowed while wearing the vest!**

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

**The time clock starts now!**

**Start time:** \_\_\_\_\_

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

**Now you may begin wiring and configuring the components**

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

**The time clock stops now!**

**Stop time:** \_\_\_\_\_

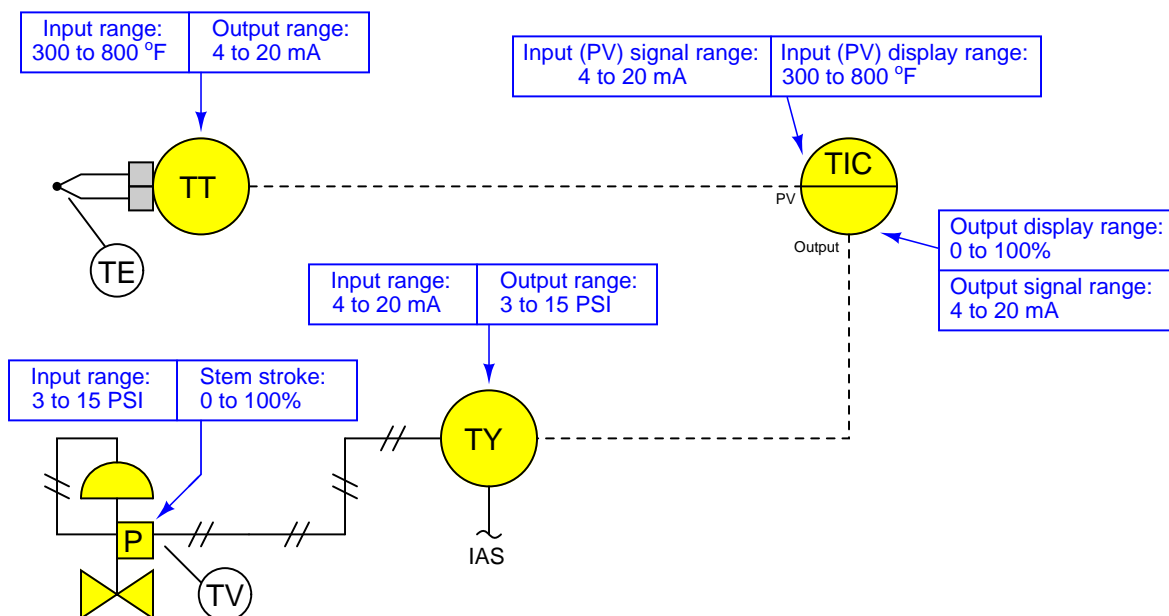
Criterion	(Instructor verifies)
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

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

## Notes on instrument ranging

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

The reason this is an issue at all is because loop controllers operating on 4-20 mA analog signals don’t “know” what those signals are supposed to represent unless someone configures the controller with the proper range reflecting real-world conditions. For example, if a student is assigned a temperature transmitter with a range of 300 to 800 degrees Fahrenheit, not only does the transmitter have to output 4 mA when sensing 300 °F and output 20 mA when sensing 800 °F, but the controller must display an indication of 300 °F when it receives a 4 mA signal from the transmitter, and display an indication of 800 °F when it receives a 20 mA signal from the transmitter. None of this happens on its own – the student must range the transmitter for 300-800 °F input (and 4-20 mA output) as well as range the controller to display 300-800 °F over its 4-20 mA input scale. A typical loop is shown here with all instrument ranges displayed:



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

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

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

## Notes on instrument ranging (continued)

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

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

## Notes on controller action

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

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

- Siemens/Moore 352 controller: control action parameters are located in the “PID” function block (FB13). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the “Tune” button rather than by entering the PID function block edit menu:
  - Direction (Direct/Reverse) = *SA1*
  - Proportional (P) = *SPG1* as a unitless gain value
  - Integral (I) = *STI1* in units of minutes per repeat
  - Derivative (D) = *STD1* in units of minutes
- Siemens/Moore 352P and 353 controller: control action parameters are located in the “PID” function block (PID). Note that the P, I, and D tuning parameters may be quickly accessed by pressing the “Tune” button rather than by entering the PID function block edit menu:
  - Direction (Direct/Reverse) = *DIR ACT*
  - Proportional (P) = *PG* as a unitless gain value
  - Integral (I) = *TI* in units of minutes per repeat
  - Derivative (D) = *TD* in units of minutes
- Emerson DeltaV DCS: control action parameters are located in the “PID” function block (PID) conforming to the FOUNDATION Fieldbus standard:
  - Direction (Direct/Reverse) = Found in the *CONTROL\_OPTS* set of parameters as a “check-box” where a checked box sets direct action and an unchecked box sets reverse action.
  - Proportional (P) = *GAIN* as a unitless gain value
  - Integral (I) = *RESET* in units of seconds per repeat
  - Derivative (D) = *RATE* in units of seconds
- Honeywell UDC 2500 controller: control direction is located in the “CONTRL” set-up group of parameters, while the PID tuning coefficients are located in the “TUNING” set-up group of parameters:
  - Direction (Direct/Reverse) = *Action*
  - Proportional (P) = *PB* or *Gain* as a proportional band percentage or as a unitless gain value, respectively
  - Integral (I) = *I Min* or *I RPM* in units of minutes or repeats per minute, respectively
  - Derivative (D) = *Rate T* in units of minutes

## Notes on controller action (continued)

- Automation Direct “SOLO” controller: process variable range parameters are located in the following registers:
  - Direction (Direct/Reverse)= *P3-7 Heating/Cooling*
  - Proportional (P) = *P1-4 Proportional band* as a proportional band percentage
  - Integral (I) = *P1-5 Integral time* in units of seconds
  - Derivative (D) = *P1-6 Derivative time* in units of seconds
- Allen-Bradley PLC5, SLC500, and MicroLogix controllers: control action parameters are located in the “PID” instruction. A YouTube video on our BTCInstrumentation channel shows how to do this for the networked MicroLogix PLCs in the lab (reading the PV on the first analog input and sending the output to the first analog output of the I/O card):
  - Direction (Direct/Reverse)= Found in the *Control Mode* field where  $E = PV - SP$  represents direct action and  $E = SP - PV$  represents reverse action.
  - Proportional (P) = *Controller Gain  $K_c$*  as a unitless gain value
  - Integral (I) = *Reset  $T_i$*  in units of minutes per repeat
  - Derivative (D) = *Rate  $T_d$*  in units of minutes
- Allen-Bradley Logix5000 controller: control action parameters are located in the “PID” instruction (PID):
  - Direction (Direct/Reverse)= *E* where  $PV - SP$  represents direct action and  $SP - PV$  represents reverse action.
  - Proportional (P) =  $K_p$  or  $K_c$  as a unitless gain value
  - Integral (I) =  $K_i$  in units of seconds per repeat
  - Derivative (D) =  $K_d$  in units of minutes
- caSCADA “pid” control program: control action parameters are located on the operator interface screen, above the trend graph. This control program may be initiated from the Linux command line by typing `./pid` and pressing the Enter key. Once the `pid` control program is running (reading the PV on analog input AIN0 and sending the output to analog output DAC0 of the LabJack DAQ), each parameter may be selected by pressing the **S** key as often as needed, and the parameter values changed by pressing the arrow and page up/down keys. Note that the control direction may only be switched while the controller is in manual mode. Tuning parameters may be altered in either manual or automatic modes.
  - Direction (Direct/Reverse)= will either show “**Direct-acting**” or “**Reverse-acting**”
  - Proportional (P) =  $K_P$  as a unitless gain value
  - Integral (I) =  $K_I$  in units of repeats per minute
  - Derivative (D) =  $K_D$  in units of seconds

## Notes on controller tuning

For those who have never tuned a controller before but need to set the PID parameters for basic loop stability in automatic mode, here are some tips for setting the P, I, and D parameter values. Every PID controller provides means to alter the tuning coefficients named *proportional* (also called *gain*), *integral* (also called *reset*), and *derivative* (also called *rate or pre-act*). Settings which are virtually assured to yield stable control are as follows:

- **P** – a “gain” value of less than one (i.e. a “proportional band” value of at least 100%).
- **I** – a “reset” value of zero repeats per minute, or the largest value possible for minutes per repeat.
- **D** – a “rate” value of zero.

Mind you, these parameters will not yield *good* control, but merely *stable* control. In other words, these tuning parameter values will make the controller fairly unresponsive, but at least it won’t oscillate out of control. Also bear in mind that having an integral (reset) value set for minimum action (i.e. zero repeats per minute, or very high minutes per repeat) will result in a controller that never quite makes the process variable value reach setpoint – instead, there will be a persistent “offset” between PV and SP with integral action essentially turned off.





## Answers

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Answer 7

Answer 8

Answer 9

**Partial answer:**

At a reliability rate of 99.5%, your home would be out of power almost 2 whole days per year (43.8 hours per year), *every year*.

Answer 10

Answer 11

	Trigger pulled, safety "off"	Safety "on", trigger untouched
Gun discharges	<b>Dependability (RSA)</b>  $D$	$\overline{S}$
Gun does not discharge	<b>PFD</b>  $\overline{D}$	<b>Security</b>  $S$

Probability values in the same column but in different rows (e.g. RSA versus PFD) are *mathematical complements* of each other, because their sum must be equal to 100% (1). For example, an RSA of 99.98% is equivalent to a PFD of 0.02% because there are only two (exclusive) possibilities of what will happen when the trigger is pulled and the safety is off: either the gun will fire or it will not fire.

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Answer 12

Many correct statements are possible, using both AND and OR conjunctions. Here are some samples:

*If PSH-1 closes when it senses high pressure and PSH-2 closes when it senses high pressure then the lamp will energize as it should*

*If PSH-1 remains open when it senses high pressure and PSH-2 closes when it senses high pressure then the lamp will remain de-energized when it should energize*

*If PSH-1 opens when it senses low pressure or PSH-2 opens when it senses low pressure then the lamp will de-energize as it should*

Constructing accurate sentences describing the operation of the system reveals the proper Boolean operations to apply to known component probabilities, in order to calculate the probability of the end-result. For example, if the probability that each switch will close when it senses a high pressure is 0.992, then the probability that the lamp will energize when it should is  $0.992 \times 0.992 = 0.984064$ .

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Answer 13

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Answer 14

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Answer 15

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Answer 16

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Answer 17

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Answer 18

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Answer 19

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Answer 20

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Answer 21

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Answer 22

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Answer 23

**Partial answer:**

- Inside a grain silo, fed from the top by a conveyor belt: *Class II, Division 1*
- Storage room of a textile mill, where cotton fibers are held: *Class III, Division 2*
- Interior of a cyclone separator at a sawmill: *Class III, Division 1* or *Class II, Division 1* if there is enough dust present in addition to chips and fibers

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Answer 24

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Answer 25

The inductor acts as a *load* when the switch initially closes, and as a *source* when it opens. The polarity reversal as the inductor transitions from load to source (with current maintaining the same direction) is what turns the diode on to provide a discharge current path for the inductor.

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Answer 26

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Answer 27

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Answer 28

**Partial answer:**

- Electrically simulate a high-temperature condition to the PLC: *connect a temporary jumper wire between terminal L1 and PLC input terminal X4*
- Electrically simulate a tripped PLC (to the motor contactor): *open the wire connecting to PLC output terminal Y0*

---

Answer 29

**Before the switch closes:**

$V_C = \text{zero}$   
 $V_R = \text{zero}$   
 $V_{\text{switch}} = \text{maximum}$   
 $I = \text{zero}$

**At the instant of switch closure:**

$V_C = \text{zero}$   
 $V_R = \text{maximum}$   
 $V_{\text{switch}} = \text{zero}$   
 $I = \text{maximum}$

**Long after the switch has closed:**

$V_C = \text{maximum}$   
 $V_R = \text{zero}$   
 $V_{\text{switch}} = \text{zero}$   
 $I = \text{zero}$

Follow-up question: which of these variables remained the same immediately before and immediately after switch closure? Explain why.

---

Answer 30

**Before the switch closes:**

$V_L = \text{zero}$   
 $V_R = \text{zero}$   
 $V_{\text{switch}} = \text{maximum}$   
 $I = \text{zero}$

**At the instant of switch closure:**

$V_L = \text{maximum}$   
 $V_R = \text{zero}$   
 $V_{\text{switch}} = \text{zero}$   
 $I = \text{zero}$

**Long after the switch has closed:**

$V_L = \text{zero}$   
 $V_R = \text{maximum}$   
 $V_{\text{switch}} = \text{zero}$   
 $I = \text{maximum}$

Follow-up question: which of these variables remained the same immediately before and immediately after switch closure? Explain why.

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Answer 31

Fault	Possible	Impossible
Cable from points A/B to transmitter failed open		✓
Cable from IS barrier to controller failed open		✓
Blown fuse in IS barrier		✓
Controller ADC out of calibration		✓
Pressure transmitter out of calibration	✓	
Cable from points A/B to transmitter failed shorted	✓	✓
Cable from IS barrier to controller failed shorted		✓
Valve 1 shut	✓	
Valve 2 open		✓
Valve 3 shut		✓

A shorted transmitter cable is possible if one considers it to be a *partial* (resistive) short, bypassing extra current around the loop-powered transmitter. A dead short, however, would not be possible since it would result in a much higher reading (and resistor voltage).

---

Answer 32

The PLC's "X1" input must somehow be *forced* to an active state in order for the cut-out switch to be disconnected without shutting off the compressor motor. PLC programming software provides the ability for the user to "force" bits in the PLC's memory for purposes just like this.

Another issue to consider is how to safely un-wire the cut-out pressure switch when it is powered by potentially dangerous voltage (120 VAC). The wiring for this switch would have to be provided with disconnecting terminal blocks or some other form of electrical disconnect in order for you to un-do the wire connections without contacting live conductors.

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Answer 33

Energy ratio from perspective of voltage =  $\left(\frac{90}{24}\right)^2 = 14.0625:1$ .

Energy ratio from perspective of current =  $\left(\frac{50}{20}\right)^2 = 6.25:1$ .

I find it fascinating how the physics of electricity so closely parallels the physics of Newtonian mechanics. Note how both formulae for energy closely resemble the formula for kinetic energy of a moving object:

$$E_k = \frac{1}{2}mv^2$$

Inductors store energy in the form of a magnetic field, and magnetic fields are directly proportional in strength to the amount of current going through a conductor. Current ( $I$ ) in this case is analogous to the velocity ( $v$ ) of a mass, and inductance ( $L$ ) is analogous to the mass itself ( $m$ ), making stored energy proportional to  $LI^2$ .

Capacitors store energy in the form of an electric field, and electric fields are directly proportional in strength to the amount of voltage existing between two conductors. Voltage ( $V$ ) in this case is analogous to the velocity ( $v$ ) of a mass, and capacitance ( $C$ ) is analogous to the mass itself ( $m$ ), making stored energy proportional to  $CV^2$ .

---

Answer 34

Energy storage in an inductor is a function of the current through that inductor. Therefore, we must first solve for inductor current. Assuming the inductor contains zero resistance, and the only limit to maximum current in this circuit will be the resistor, we may calculate the current using Ohm's Law. A 15 VDC source and a 3.3 k $\Omega$  resistor yields a current of 4.545 mA:

$$E_L = \frac{1}{2}LI^2$$

$$E_L = \frac{1}{2}(0.075)(0.004545)^2$$

$$E_L = 774.79 \text{ nJ}$$

Energy storage in a capacitor is a function of the voltage across that capacitor. Therefore, we must first solve for capacitor voltage. We may do this by applying the voltage divider formula to the two resistors in this circuit, calculating the voltage across the 1.2 k $\Omega$  resistor. With a 25 VDC supply, we get 6.667 volts:

$$E_C = \frac{1}{2}CV^2$$

$$E_C = \frac{1}{2}(47 \times 10^{-6})(6.667)^2$$

$$E_C = 1.0444 \text{ mJ}$$

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Answer 35

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Answer 36

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Answer 37

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Answer 38

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Answer 39

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Answer 40

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Answer 41

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Answer 42

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Answer 43

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Answer 44

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Answer 45

The design engineer made it so that air will pass to the process valve actuator during typical (good) operating conditions, holding the process valve open.

This is a 1oo2 to trip system, because the process valve will go to its “fail” position if either of the two solenoid valves trip (go to their abnormal operating states).

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Answer 46

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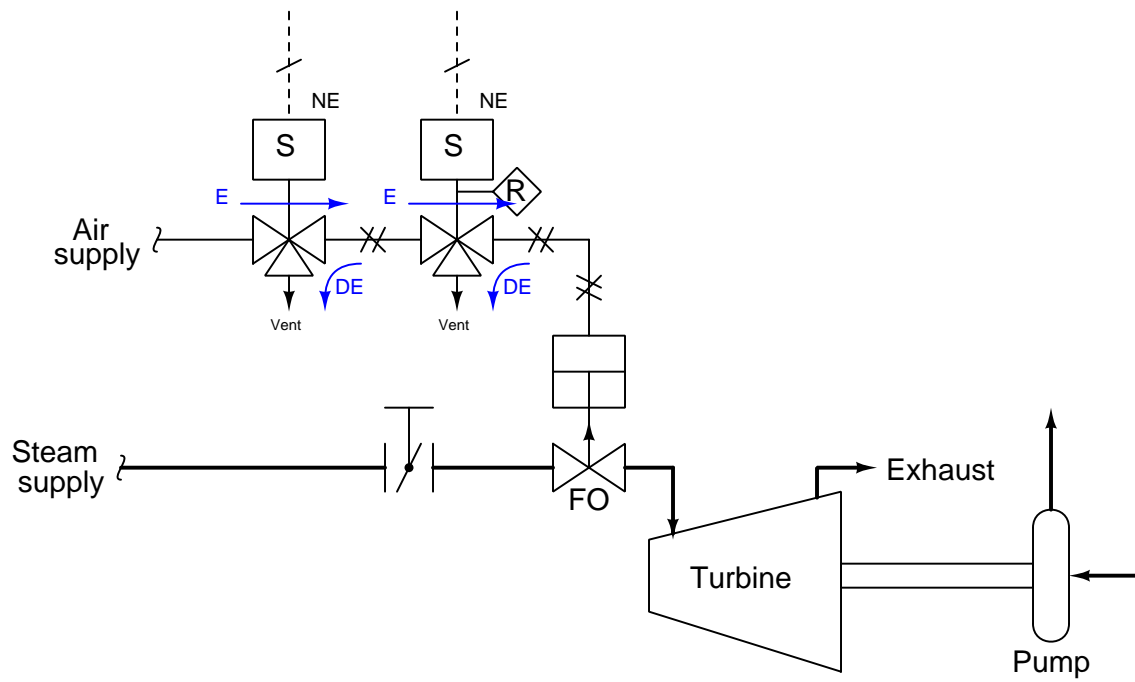
Answer 47

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Answer 48

Simulation hint: the temperature sensors are *RTDs*.

If either solenoid loses electric power, it vents air pressure from the piston actuator of the fail-open steam valve, sending steam to the turbine to start it up:



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Answer 50

<b>Fault</b>	<b>Possible</b>	<b>Impossible</b>
Fuse F3 blown (failed open)		✓
Solenoid stuck in “energized” position	✓	
Solenoid stuck in “de-energized” position		✓
Solenoid coil failed open		✓
Solenoid coil failed shorted		✓
Silencer plugged		✓
Vent cap plugged		✓
Wire open between terminals A and E		✓
Wire open between terminals C and H		✓
Wire open between terminals K and B		✓
Valve V1 shut	✓	
Valve V2 shut	✓	

A plugged vent on the valve actuator, while in theory capable of limiting the control valve’s upward motion, would not prevent any motion at all from occurring when full pressure is applied to the bottom of the diaphragm. This is why “Vent cap plugged” is checked as impossible rather than possible for this scenario.

A good “next test” would be to crack the fitting at port “C” of the solenoid valve. If there is pressure, it means the problem must lie past the solenoid (e.g. valve V1 shut, or a problem in the process control valve). If there is no pressure at that point, either the solenoid valve is stuck in the “energized” position or there is a lack of supply pressure to the solenoid.

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Answer 51

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Answer 52

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Answer 53

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Answer 54

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Answer 55

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Answer 56

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Answer 57

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Answer 58

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Answer 59

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Answer 60



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Answer 61

No answers given here! A recommendation for writing your outline, though, is to write approximately one sentence of your own thoughts per paragraph of text read. It's okay to have questions and uncertainties about the reading, too – *bring those to class ready to discuss as well!* Feel free to write a digital version of your outline, copying and pasting images from the electronic text files into your own document, if you prefer to write in electronic format rather than by hand.

One of the purposes of an “inverted” classroom structure where students encounter new topics on their own through reading is to develop technical reading skills in addition to learning about the topic at hand. If you struggle with the subject matter or just with technical reading in general, that's okay. *This is a skill you will gain by doing!* Do your best, come to class fully prepared to ask questions and explain what does make sense to you, and you will be well on your way to becoming an autonomous technical learner.

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Answer 62

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Answer 63

**Partial answer:**

Fault on circuit breaker #5: we will need to trip breakers *1, 2, 3, 4, and 10*. This will unfortunately interrupt power to loads *J, K, and L*.

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Answer 64

**Partial answer:**

This is an *instantaneous overcurrent* relay, corresponding to ANSI function code *50*.

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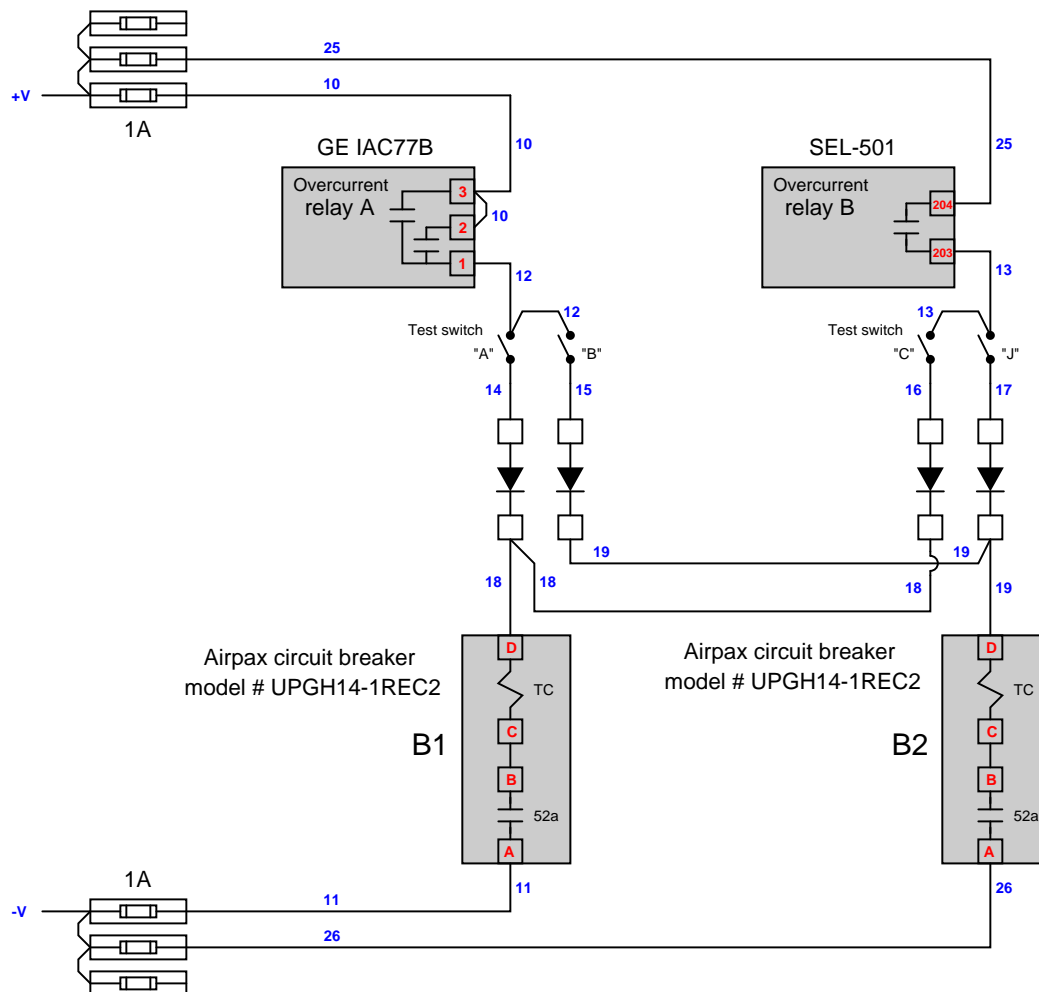
Answer 65

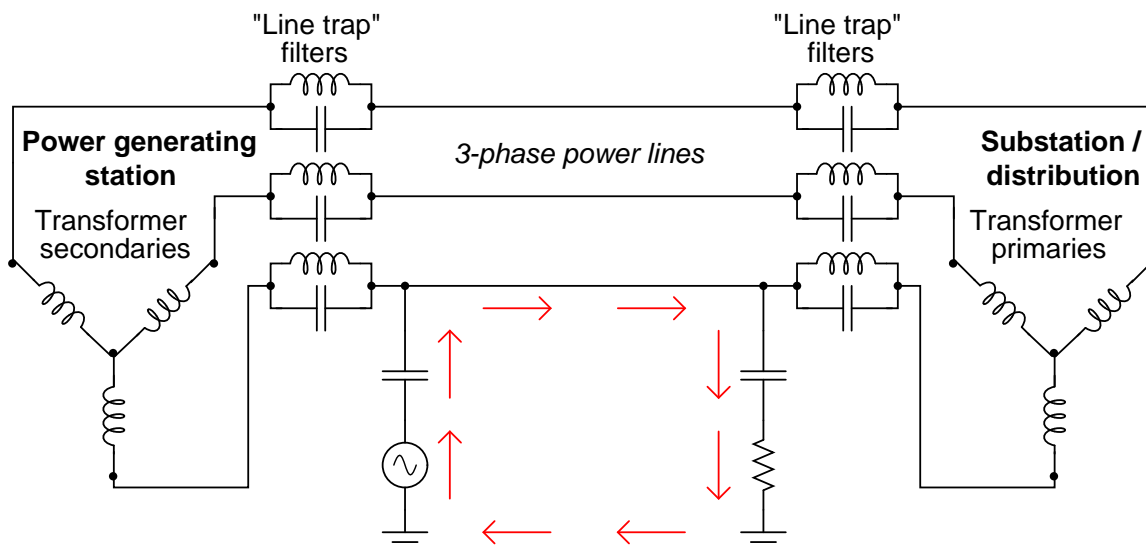
No answers given here, but just a few hints. The 52a and 52b auxiliary contacts within the circuit breaker serve to selectively disable the actuating coils, depending on the state of the breaker. When the breaker is closed (i.e. power contact 52 conducting line current), contact 52a will be closed (permitting the trip coil to energize at the relay's command) and contact 52b will be open (prohibiting the close coil from energizing). This should make sense: if the circuit breaker is already in the closed state, it would be pointless to allow the close coil to become energized and so the open 52b contact will prohibit that.



### Trip circuit wiring diagram:

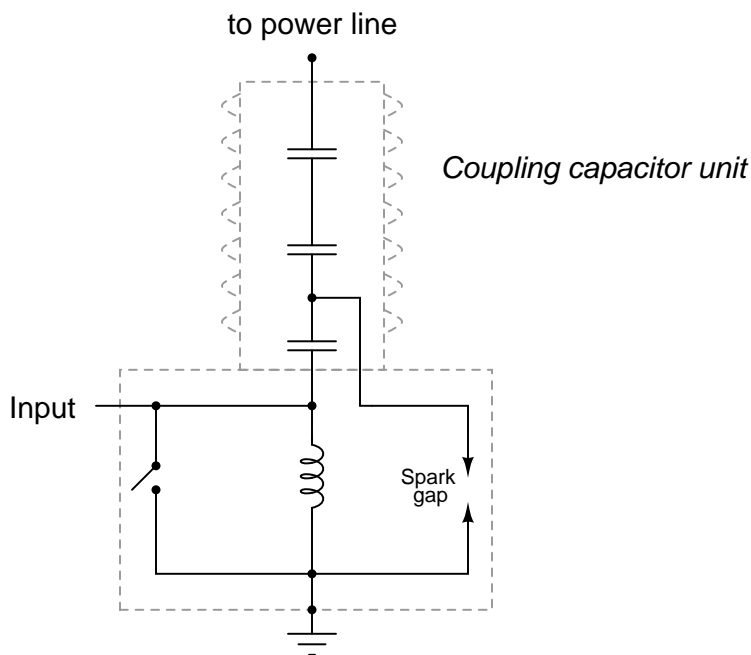
Note that “B1” and “B2” are manually actuated circuit breaker units, which control the action of contactors “C1” and “C2” respectively. Each circuit breaker has a shunt trip coil energized by one or both of the protective relays through a set of switches and “voting diodes” allowing either relay to control either (or both) of the two circuit breakers.





Follow-up question #1: trace the path of line-frequency (50 Hz or 60 Hz) load current in this system, identifying which component of the line trap filters ( $L$  or  $C$ ) is more important to the passage of power to the load. Remember that the line trap filters are tuned to resonate at the frequency of the communication signal (50-150 kHz is typical).

Follow-up question #2: coupling capacitor units used in power line carrier systems are special-purpose, high-voltage devices. One of the features of a standard coupling capacitor unit is a *spark gap* intended to "clamp" overvoltages arising from lightning strikes and other transient events on the power line:

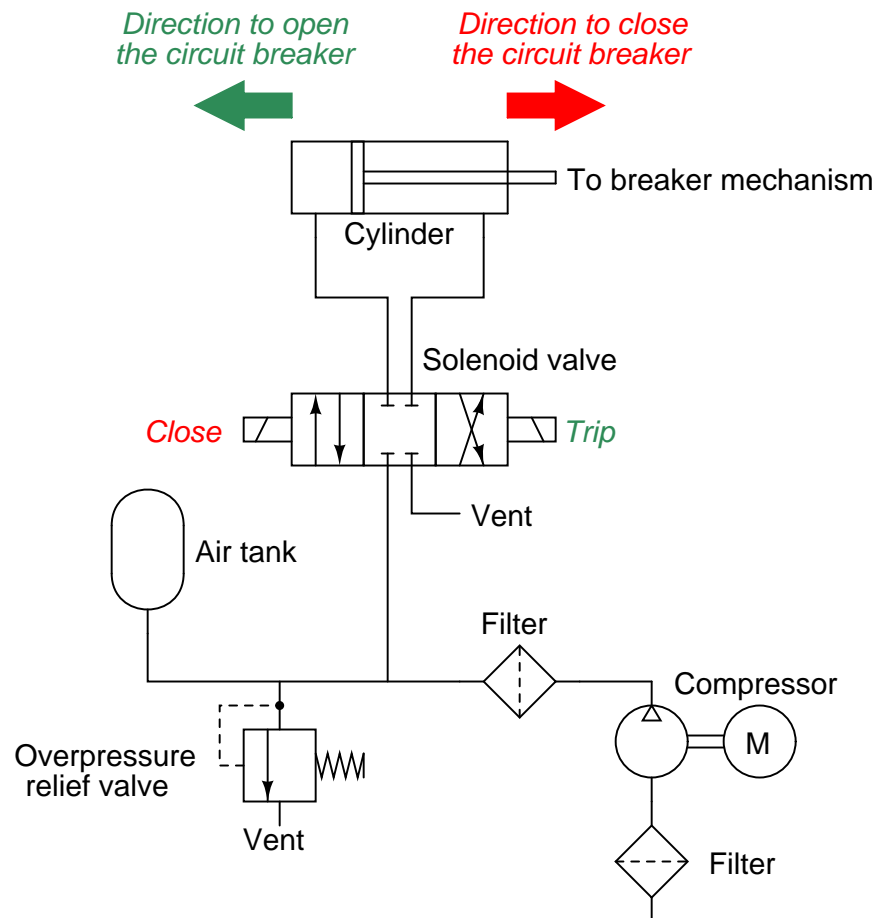


Explain how such a spark gap is supposed to work, and why it functions as an over-voltage protection device.

Answer 68

- Emergency stop = **De-energize to trip**
- Low oil pressure = **De-energize to trip**
- High temperature = **Energize to trip**
- High oil pressure = **De-energize to trip**
- Low oil level = **Energize to trip**
- High axial vibration = **De-energize to trip**
- High radial vibration = **De-energize to trip**
- Motor protection relay = **Energize to trip**

Answer 69



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**Answer 70**

The output of a PT is typically somewhere at or below 120 volts AC. The output of a CT is typically at or below 5 amps AC. One of the things your procedure must address is how to accurately simulate these voltage and current levels to the wattmeter!

At the given line voltage of 4160 volts the 40:1 ratio PT should output  $\frac{1}{40}$  of that (104 volts AC) to the wattmeter's voltage input terminals. At the maximum line current of 180 amps the 200:5 ratio CT should output  $\frac{5}{200}$  of that (4.5 amps AC) to the wattmeter's current input terminals.

---

**Answer 71**

The indicators for channels 3 and 6 are lit on the input card of this PLC. This tells us channels 3 and 6 are receiving power through their respective process switches, but channel 4 is not. Since we are told the system is operating as it should (no abnormal conditions), we may assume the opposite state for each input channel will initiate a trip. Thus:

- Temperature switch (channel 6) is currently closed, and opens with a *high* temperature.
- Level switch (channel 4) is currently open, and closes with a *low* level.
- Pressure switch (channel 3) is currently closed, and opens with a *low* pressure.

Since the temperature switch channel is *de-energize to trip*, you must open that circuit in order to force the system to trip.

Since the level switch channel is *energize to trip*, you must jumper power to PLC input channel 4 in order to force the system to trip.

Since the pressure switch channel is *de-energize to trip*, you must open that circuit in order to force the system to trip.

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**Answer 72**

Secondary current = 2.917 amps

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**Answer 73**

$$I_{source} = 187.5 \text{ mA}$$

$$I_{load} = 72.73 \text{ mA}$$

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**Answer 74**

Simple system (no transformers):

$$E_{load} = 210 \text{ volts}$$

$$P_{load} = 31.5 \text{ kW}$$

$$P_{lines} = 4.5 \text{ kW}$$

$$\eta = 87.5\%$$

Complex system (with transformers):

$$E_{load} = 239.7 \text{ volts}$$

$$P_{load} = 35.96 \text{ kW}$$

$$P_{lines} = 45 \text{ W}$$

$$\eta = 99.88\%$$

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Answer 75

The protective relay contains two electromagnetic coils: one powered by the DC line voltage, and the other powered by DC line current. If the relative polarities of these two coils are such that they aid each other, the iron armature will be lifted up by the magnetic force to close the relay contacts and trip the circuit breaker. DC line current flowing in the proper direction, however, will set up the wrong polarity of magnetic field to attract the armature, and so the relay will not trip under these conditions. Only if the generator begins to “motor” and draw current the wrong way through this relay will it pick up and trip the breaker.

---

Answer 76

**Partial answer:**

- Upper capacitor failing shorted: *Negative DC bus line goes to ground potential ; Positive DC bus line rises to +130 VDC above ground potential.*
- Loose connection on left side of terminal 12: *Indicator lamp refuses to energize when relay contact OUT2 asserts ; AC power circuit breaker refuses to trip when relay contact OUT1 asserts.*
- Broken wire between terminals E and 11: *Indicator lamp refuses to energize when relay contact OUT2 asserts.*

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Answer 77

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Answer 78

- $V_{primary} = 80.56$  volts
- $V_{secondary} = 50$  volts
- $I_{primary} = 13.97$  amps
- $I_{secondary} = 22.5$  amps

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Answer 79

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Answer 80

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Answer 81

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

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Answer 82

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

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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!

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Answer 91

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Answer 92

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

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Answer 93

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