<u>Lab</u>

Data acquisition and transport over Ethernet: *Question 91*, **completed objectives due by the end of day 6, section 3**

<u>Exam</u>

*Day 6 of section 3* – only a simple calculator may be used! **Complete mastery of these objectives due by the next exam date**

*Specific objectives for the "mastery" exam:*
- Electricity Review: Calculate and annotate voltages and currents in a DC series-parallel resistor circuit given source and resistor values
- Sketch proper wire connections for a data acquisition unit to measure an analog sensor signal
- Convert between different numeration systems (decimal, binary, hexadecimal, octal)
- Calculate ADC (analog-digital converter) input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Determine status of a relay logic circuit given a schematic diagram and switch stimulus conditions
- INST241 Review: Identify (American) wire colors for different thermocouple types
- INST250 Review: Convert between different pressure units (PSI, "W.C., bar, etc.) showing proper mathematical cancellation of units (i.e. the "unity fraction" technique)

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**Recommended daily schedule**

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<u>Day 1</u>

**Theory session topic:** Signal coupling, shielding, and wiring practices

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

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<u>Day 2</u>

**Theory session topic:** Digital data representation and analog/digital converters

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

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<u>Day 3</u>

**Theory session topic:** Data acquisition hardware

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

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<u>Day 4</u>

**Theory session topic:** Serial communication principles

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

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

This quarter focuses on the use of *digital computer systems* for measurement and control. Ideas to keep in mind for special projects (alternatives to standard lab as well as extra-credit) include long-range measurement systems using wireless (radio) communication, as well as advanced process-control systems (beyond single-loop PID). For those who have studied programmable logic controllers (PLCs), there will be application to use your PLCs again when we build safety instrumented systems (SIS) later this quarter!

For those who have not yet taken the Summer-quarter PLC courses (INST23X), now is a good time to place orders for your PLC hardware or purchase used from classmates who have already finished those courses. See the INST231 or INST232 worksheets and syllabi for a list of required hardware and software!

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

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

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

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

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

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

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

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

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

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

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

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

<u>file howto</u>

## General Values, Expectations, and Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

file expectations

**Program Outcomes for Instrumentation and Control Technology (BTC)**

| #1 | **Communication** |

Communicate and express concepts and ideas across a variety of media (verbal, written, graphical) using industry-standard terms.

| #2 | **Time management** |

Arrives on time and prepared to work; Budgets time and meets deadlines when performing tasks and projects.

| #3 | **Safety** |

Complies with national, state, local, and college safety regulations when designing and performing work on systems.

| #4 | **Analysis and Diagnosis** |

Analyze, evaluate, and diagnose systems related to instrumentation and control including electrical and electronic circuits, fluid power and signaling systems, computer networks, and mechanisms; Select and apply correct mathematical techniques to these analytical and diagnostic problems; Select and correctly use appropriate test equipment to collect data.

| #5 | **Design and Commissioning** |

Select, design, construct, configure, and install components necessary for the proper function of systems related to instrumentation and control, applying industry standards and verifying correct system operation when complete.

| #6 | **System optimization** |

Improve technical system functions by collecting data and evaluating performance; Implement strategies to optimize the function of these systems.

| #7 | **Calibration** |

Assess instrument accuracy and correct inaccuracies using appropriate calibration procedures and test equipment; Select and apply correct mathematical techniques to these calibration tasks.

| #8 | **Documentation** |

Interpret and create technical documents (e.g. electronic schematics, loop diagrams, functional diagrams, P&IDs, graphs, narratives) according to industry standards.

| #9 | **Independent learning** |

Select and research information sources to learn new principles, technologies, and techniques.

| #10 | **Job searching** |

Develop a professional resume and research job openings in the field of industrial instrumentation.

file `outcomes_program`

# INST 260 Course Outcomes

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

- Calculate and annotate voltages and currents in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]

- Sketch proper wire connections for a data acquisition unit to measure an analog sensor signal. [Ref: Program Learning Outcome #5]

- Convert between different numeration systems (decimal, binary, hexadecimal, octal). [Ref: Program Learning Outcome #4]

- Calculate ADC (analog-digital converter) 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 working data acquisition system consisting of a DAQ unit, signal wiring, Ethernet wiring and components, and a personal computer running DAQ software. [Ref: Program Learning Outcome #5]

- Generate accurate schematic diagrams documenting your team's DAQ system. [Ref: Program Learning Outcome #8]

- Design and build a circuit responding to changes in either light intensity or temperature. [Ref: Program Learning Outcome #5]

- Diagnose a random fault placed in another team's DAQ system by the instructor within a limited time using no test equipment except a multimeter and network diagnostic utilities on the personal computer, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #4]

<u>file</u> `outcomes_INST260`

# Sequence of second-year Instrumentation courses

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

*(Only if 4th quarter was Summer: INST23x)*

Prerequisite for all INST24x, INST25x, and INST26x courses

**INST 200** -- 1 wk
Intro. to Instrumentation

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

## Summer quarter

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

*Jobshadow and/or Internship strongly recommended*

## Fall quarter

**INST 240** -- 6 cr
Pressure/Level Measurement

**INST 241** -- 6 cr
Temp./Flow Measurement

**INST 242** -- 5 cr
Analytical Measurement

## Winter quarter

**INST 250** -- 5 cr
Final Control Elements

**INST 251** -- 5 cr
PID Control

**INST 252** -- 4 cr
Loop Tuning

## Spring quarter

**INST 260** -- 4 cr
Data Acquisition Systems

**INST 262** -- 5 cr
Digital Control Systems

**INST 263** -- 5 cr
Control Strategies

**ENGT 134** -- 5 cr
CAD 1: Basics

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

**Graduate!!!**

Prerequisite for INST206

**INST 205** -- 1 cr
Job Prep I

**INST 206** -- 1 cr
Job Prep II

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

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

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

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

**Beginning in Summer**

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

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

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

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

*Graduation!*

**Beginning in Fall**

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

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

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

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

*Graduation!*

**Beginning in Winter**

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

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

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

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

*Graduation!*

**Beginning in Spring**

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

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

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

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

*Graduation!*

file sequence

9

## 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`

<h1 style="text-align:center">Methods of instruction</h1>

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

**Inverted theory sessions**

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

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

**Small sessions**

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

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

**Large sessions**

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

**Correspondence**

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

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

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### 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).*

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### 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.

<u>file</u> `instructional`

# Distance delivery methods

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

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

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

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

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

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

file `distance`

# Metric prefixes and conversion constants

- **Metric prefixes**
- Yotta = $10^{24}$ Symbol: Y
- Zeta = $10^{21}$ Symbol: Z
- Exa = $10^{18}$ Symbol: E
- Peta = $10^{15}$ Symbol: P
- Tera = $10^{12}$ Symbol: T
- Giga = $10^{9}$ Symbol: G
- Mega = $10^{6}$ Symbol: M
- Kilo = $10^{3}$ Symbol: k
- Hecto = $10^{2}$ Symbol: h
- Deca = $10^{1}$ Symbol: da
- Deci = $10^{-1}$ Symbol: d
- Centi = $10^{-2}$ Symbol: c
- Milli = $10^{-3}$ Symbol: m
- Micro = $10^{-6}$ Symbol: $\mu$
- 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

## METRIC PREFIX SCALE

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

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

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

## Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

**Conversion equivalencies for volume**

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

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


**Conversion equivalencies for velocity**

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


**Conversion equivalencies for mass**

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


**Conversion equivalencies for force**

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


**Conversion equivalencies for area**

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


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

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

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


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

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


**Conversion equivalencies for energy or work**

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


**Conversion equivalencies for power**

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


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

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

**Physical constants**

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

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

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

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

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

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


**Properties of Water**

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

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

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

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

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

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

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

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

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


**Properties of Dry Air at sea level**

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

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

file conversion_constants

**How to get the most out of academic reading:**
- <u>Outline, don't highlight!</u> Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.

- <u>Articulate your thoughts</u> as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.

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

- <u>Imagine explaining concepts you've just learned to someone else.</u> Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.

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

**How to effectively problem-solve and troubleshoot:**
- <u>Rely on principles, not procedures.</u> Don't be satisfied with memorizing steps – learn *why* those steps work. Each step should make logical sense and have real-world meaning to you.

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

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

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

- <u>Simplify the problem</u> and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.

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

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

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

- <u>Consider the place you're in</u> when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).

- <u>Eliminate distractions.</u> Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.

- <u>Use your "in between" time productively.</u> Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

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

<u>file</u> `question0`

| Checklist when reading an instructional text |
| --- |

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

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

☑ Briefly OUTLINE THE TEXT, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve <u>any</u> problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

## General challenges following a tutorial reading assignment

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

## General follow-up challenges for assigned problems

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

file `license`

Question 1

Read and outline the "Signal Coupling and Cable Separation" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" 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.

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

file i04412

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Question 2

Suppose you must run two signal cables from field-mounted instruments to a central room where the control system is located. Two different electrical conduits stretch from the field location to the control system room: one with 480 VAC power wiring in it, and another with low-level control signal wiring in it. The two cables you must run through these conduits are as follows:

- One twisted-pair cable carrying a 4-20 mA analog DC signal

- One twisted-pair cable carrying a Modbus digital signal (RS-485 physical layer)

At first, you plan to run both these cables through the signal wire conduit. However, you soon discover this signal conduit only has room to accommodate one cable but not both. The power wire conduit, however, has plenty of available room.

Which cable would you run through which conduit, and why?

| **Suggestions for Socratic discussion** |

- Explain why it is best to run all *signal* cables in conduit completely separate from *power* cables.

file i02281

Question 3

Read and outline the "Electric Field (Capacitive) De-coupling" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" 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 i04413

Question 4

Read and outline the "Magnetic Field (Inductive) De-coupling" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" 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 i04414

Question 5

Read and outline the "High-Frequency Signal Cables" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" 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 i04415

Question 6

The National Electrical Code, or *NEC* – otherwise known as *NFPA 70* – is a standard published by the National Fire Protection Agency. Among (many!) other things, it specifies the following maximum "fill" percentages for electrical conduit, given the number of conductors contained within:

1 conductor: 53%

2 conductors: 31%

3 or more conductor: 40%

Explain the rationale behind these figures. Why be worried about how "full" a conduit is at all? Additionally, why should the most conservative rating be for a condition where there are only *two* conductors in a conduit?

file i02413

Question 7

In the United States, electrical enclosures are usually rated for different environmental services by a *NEMA Type Designation*. Research what this type designation means, in general, as well as in particular for the following NEMA types:

- NEMA 1:
- NEMA 4:
- NEMA 4X:
- NEMA 6:
- NEMA 7:
- NEMA 8:

Suggestions for Socratic discussion

- Identify your source of information on NEMA panel designations.

file i02286

Question 8

Read selected portions of the Fluke "Series 80 Series V Multimeters users manual" (May 2004 revision 2, 11/08) and answer the following questions:

Pages 32-33 describe the *MIN/MAX* measuring mode. Explain what this does, in your own words, identifying a practical application for using this mode.

Suppose you trying to measure a 60 Hz AC voltage signal that you suspected was being corrupted by high-frequency noise voltage. Explain how the Low Pass Filter mode available in the model 87 multimeter (described on page 15) could be useful to you in this situation.

Page 31 describes the *HiRes* measuring mode available on the model 87. Explain what this does, in your own words, identifying a practical application for using this mode.

Page 34 describes the *Relative* measuring mode available on the model 87. Explain what this does, in your own words, identifying a practical application for using this mode.

Suggestions for Socratic discussion

- Suppose you attempted to measure the voltage of an AC+DC "mixed" signal (i.e. a signal with an AC component as well as a DC bias, like what you might encounter at the base terminal of the transistor in a class-A audio amplifier). It would be good to know how well your mulitmeter discriminates between AC and DC in both measurement modes. Devise a test by which you could determine how well your multimeter is able to selectively measure just the AC or just the DC portion of a "mixed" signal voltage.
- Is the MIN/MAX mode of your multimeter fast enough to capture the peak voltage value of a 60 Hz sine-wave? Demonstrate this if you can.
- Demonstrate some of the other special features of your multimeter, describing practical applications of these features.
- For those who have studied variable frequency motor drives (VFDs), explain why the Low Pass Filter mode is useful for taking AC voltage and current measurements on VFD power conductors.

file i02407

## Question 9

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

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

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

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

**Circuit example #1:**



26

**Circuit example #2:**



10 Ω

20 V

2 Ω

3 A

2 A

4 Ω

6 Ω

?? V

**Circuit example #3:**



5 mA

300 Ω

220 μF

Si

1 kΩ

5 mA

300 Ω

220 μF

Si

1 kΩ

27
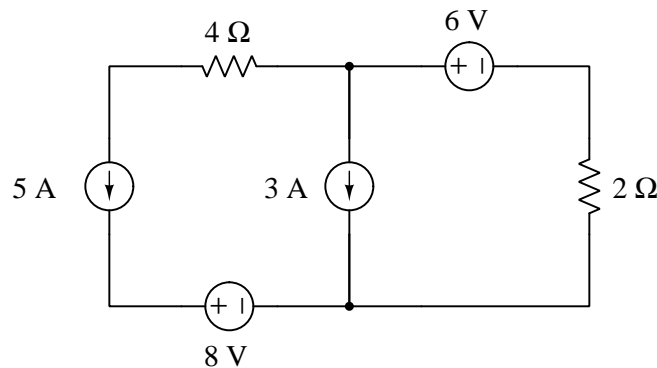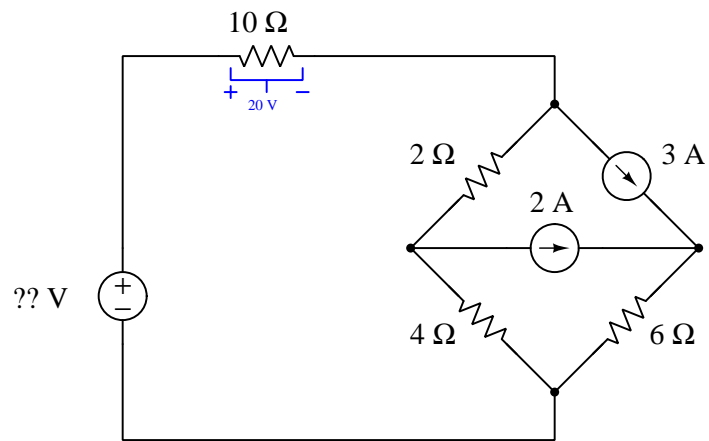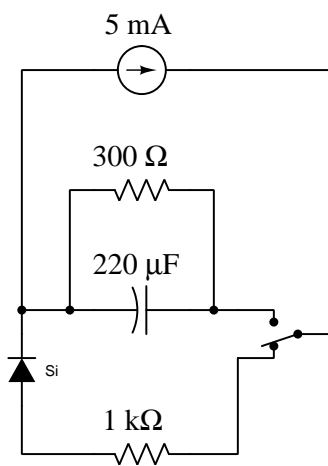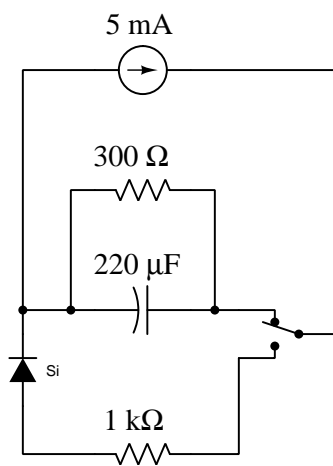
**Circuit example #4:**
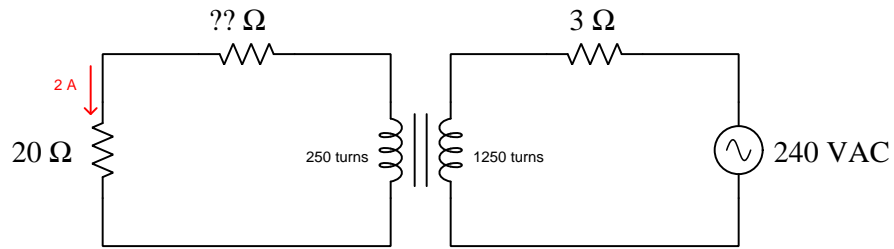
**Suggestions for Socratic discussion**

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

file i02832

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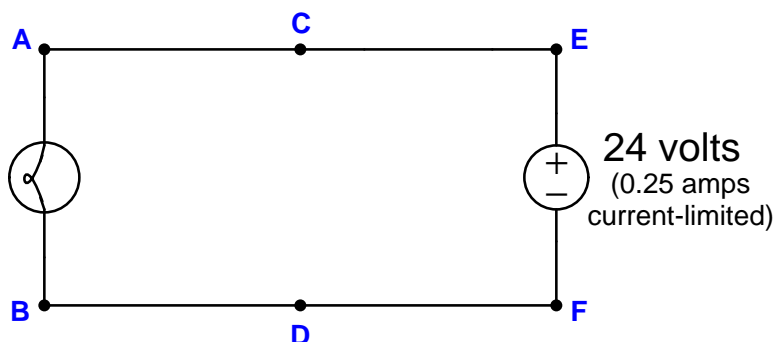


First, list all the possible (single) faults that could account for all measurements and symptoms in this circuit, including failed wires as well as failed components:

Now, determine the diagnostic value of each of the following tests, based on the faults you listed above. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

| Diagnostic test | Yes | No |
|---|---|---|
| Measure $V_{CF}$ | | |
| Measure $V_{ED}$ | | |
| Measure $V_{AB}$ | | |
| Measure $V_{AD}$ | | |
| Measure $V_{CB}$ | | |
| Measure $V_{EF}$ | | |
| Measure current through wire connecting **A** and **C** | | |
| Jumper **A** and **C** together | | |
| Jumper **B** and **D** together | | |
| Jumper **A** and **B** together | | |

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

---

**Suggestions for Socratic discussion**

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

file i01746

Question 11

A common way to route wires and cables inside of electrical control panels is inside of special plastic tracking called *wire duct*. A common brand-name of wire duct is *Panduit*. The duct is bolted to the back wall of the enclosure, wires and cables threaded through the side slots and down the length of the duct, and everything covered up with a snap-on plastic cover. Wire duct is often placed to either side of terminal block sections, for easy routing (and re-routing) of wires to the terminals:

Enclosure

wire duct

wires

wire duct

terminal blocks

wire duct
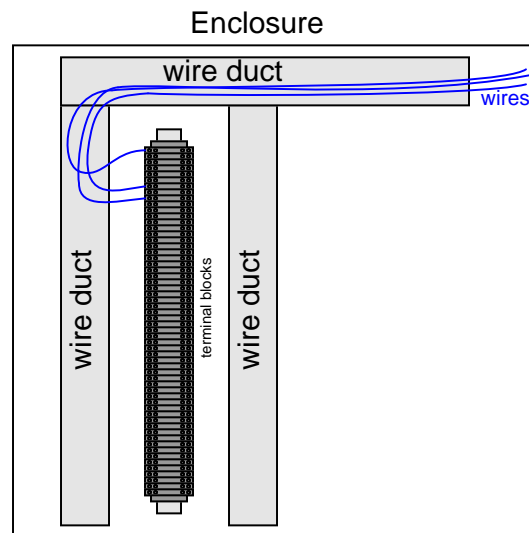
Suppose you are running a new wire to a terminal on this terminal strip. You could cut the wire so that its length is just right to reach the intended terminal, but there is a better way to do it:

Enclosure

new wire

*How long to cut this new wire?*
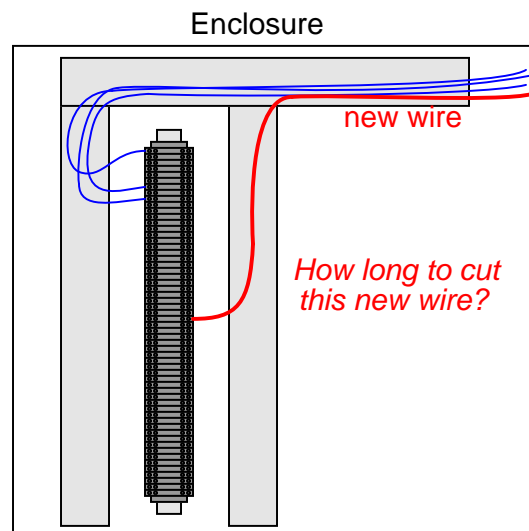
Identify the more practical wire length for this new wire, and explain why it is generally good to do this when adding wires to an existing system within an enclosure with wire duct.

file i02279

Question 12

Shielded cables are necessary for protecting small electrical signals from external interference in the form of electric fields, but one must be careful how to connect the shield wire. Examine the following illustration, and determine which of the three installations is wired incorrectly, and why:
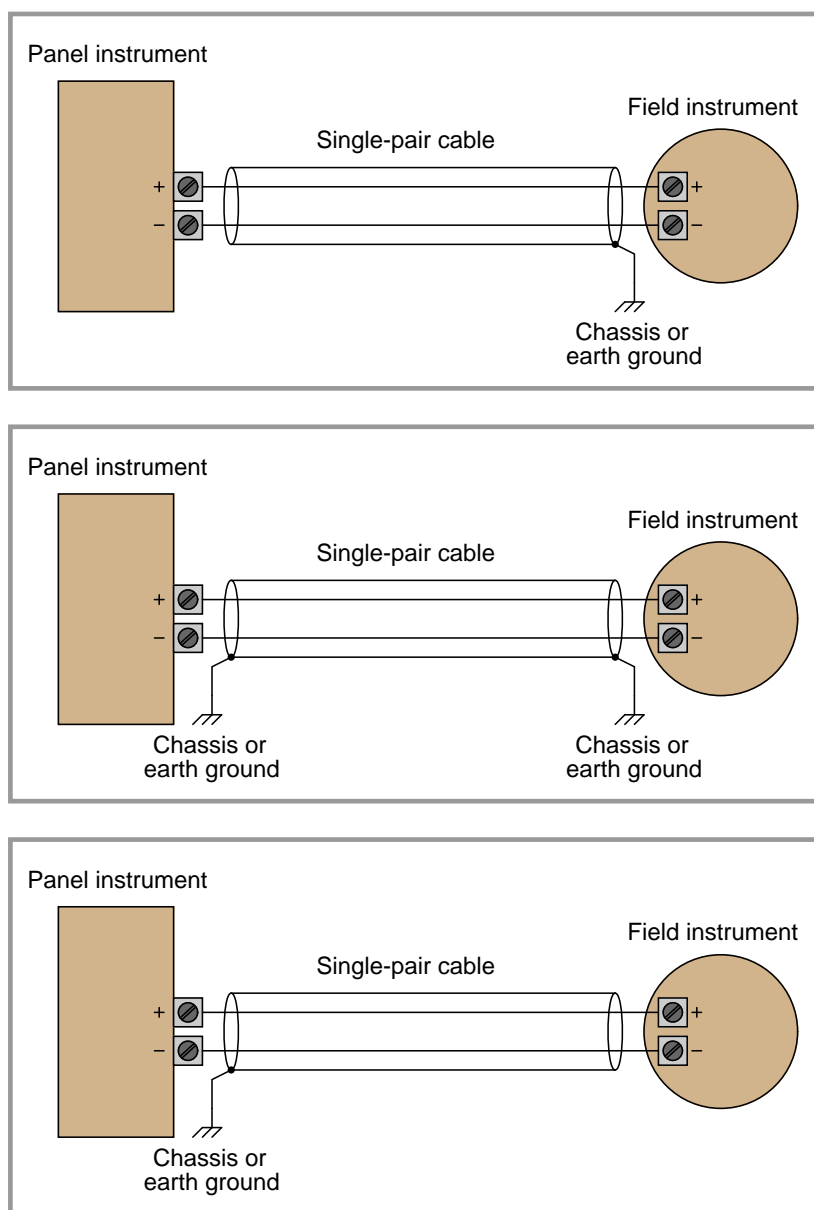


Of the two remaining installations, which of them do you think would be preferred over the other, and why?

Suggestions for Socratic discussion

- A principle to bear in mind here is that the earth is not a perfect conductor of electricity, and as such it is possible to develop significant voltage drops between different locations on the earth. Propose at least one mechanism by which such a voltage drop might develop between different locations on the

earth. The fact that the earth is not a perfect conductor is not sufficient in itself to guarantee a voltage will exist between different locations – rather, it merely *permits* such a phenomenon – so there must be something else at work to actually generate the potential differences. What might this "something else" be?

file i02226

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Question 13

An important component used in conjunction with electrical conduit connectors is a *bushing*. It looks like a sort of locknut, designed to fit over the threaded end of a conduit connector inside of an enclosure. Although bushings do not necessarily add mechanical integrity to the conduit fitting, they do serve an important protective role. What is this role, and what might happen if the bushing were not in place?

file i02410

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Question 14

Electrical *conduit* is important for safe and durable electrical wiring in outside environments. Conduit is manufactured in both plastic (PVC) and metal (steel, aluminum) forms. Determine which type of conduit is preferable for each of the following priorities:

- Ease of assembly
- Resistance to corrosive gases/liquids
- Minimal material cost (assuming other factors do not take precedence)
- Best shielding from electromagnetic interference
- Maximum physical strength
- Tightest sealing against vapor/liquid intrusion

### Suggestions for Socratic discussion

- Considering the type of conduit providing the better electrical shielding, is it better with regard to electric field shielding, to magnetic field shielding, or to both? Explain why.

file i02409

The following photograph (showing the back side of a control panel) contains so many examples of *bad* wiring practice that it is difficult to know where to begin criticism:
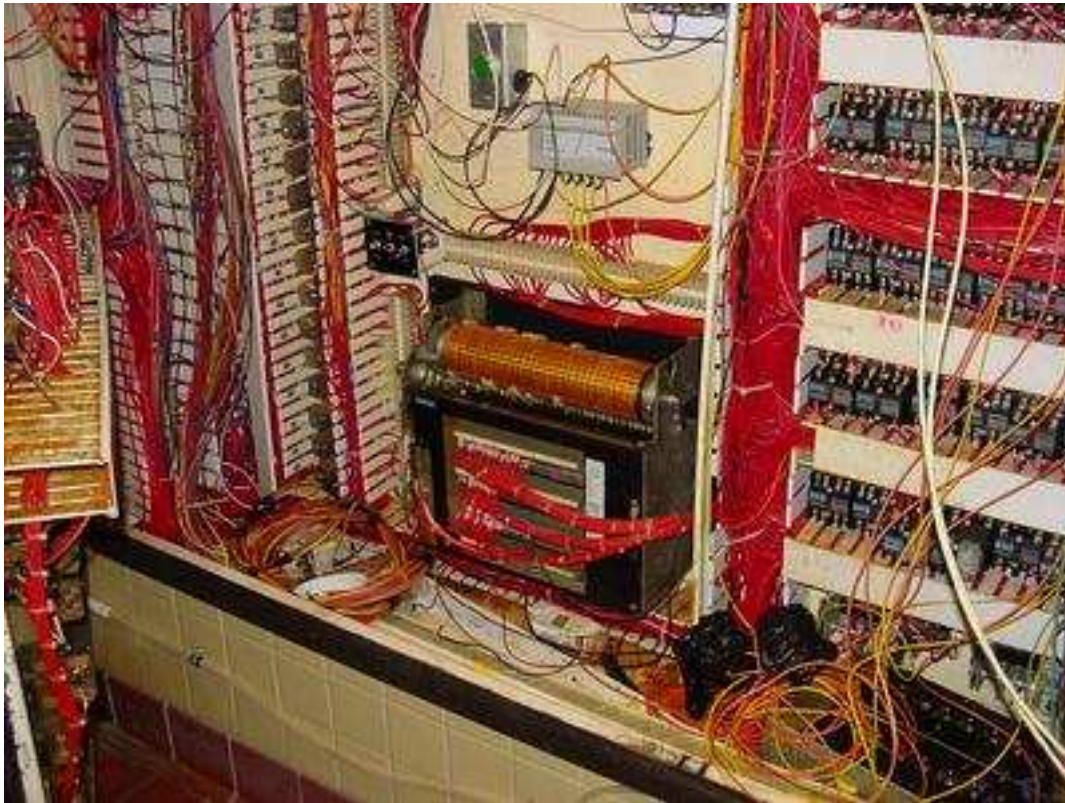


Identify some of the poor wiring practices in this photograph, trying not to laugh too loudly as you do.
file i02283

Question 16

The metal case of this appliance is *grounded* by means of a third conductor:
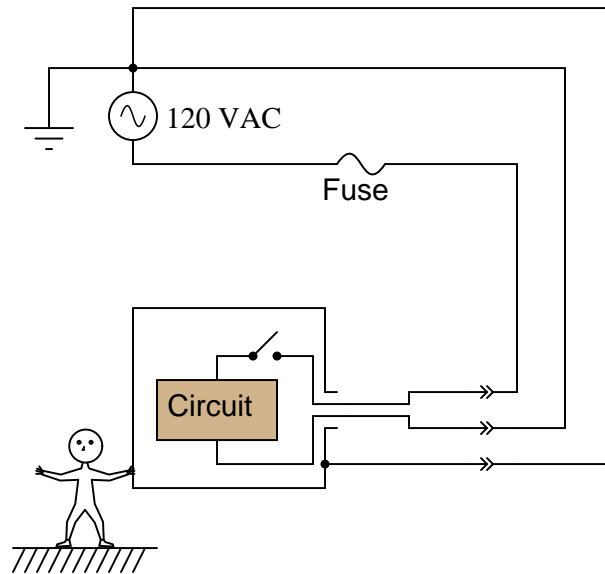


Explain how this grounding connection makes the appliance safer for anyone touching its metal case. Also, explain why both the fuse and the power switch are intentionally placed in series with the *ungrounded* ("hot") power conductor.

file i02411

## Question 17

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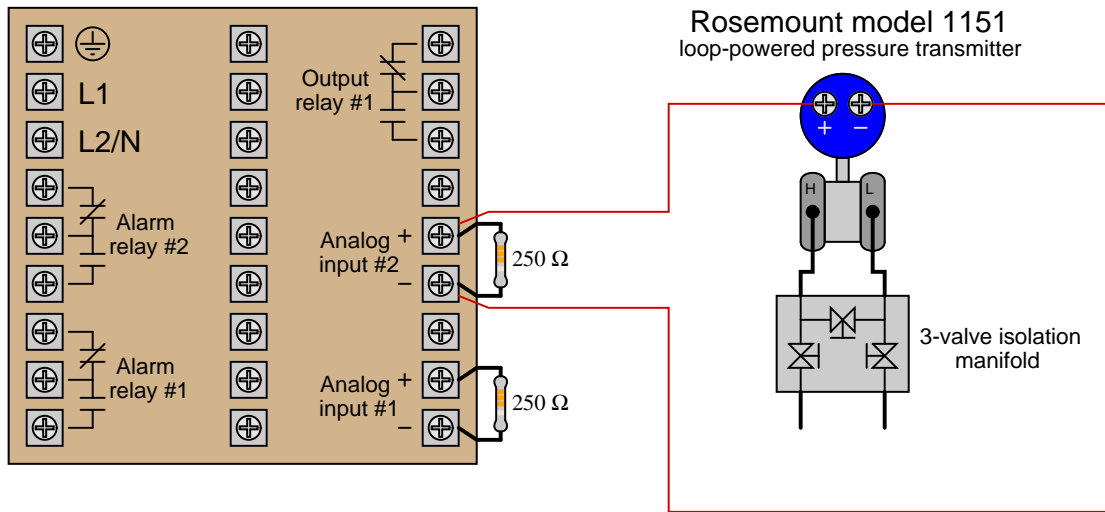


Explain what is wrong with this circuit, and what is needed to fix the problem.
<u>file i02282</u>

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## Question 18

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## Question 19

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## Question 20

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## Question 21

Read and outline the introduction to the "Digital Data Acquisition and Networks" 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.

<u>file i04394</u>

## Question 22

Read and outline the "Digital Representation of Numerical Data" section of the "Digital Data Acquisition and Network" 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 i04395

## Question 23

Convert the following 16-bit unsigned integer values into decimal (note the use of hexadecimal notation rather than direct binary):

- 5A24 (hexadecimal) = _____ (decimal)

- FFFF (hexadecimal) = _____ (decimal)

- E109 (hexadecimal) = _____ (decimal)

Convert the following 16-bit signed integer values into decimal (note the use of hexadecimal notation rather than direct binary):

- 3B11 (hexadecimal) = _____ (decimal)

- C9D0 (hexadecimal) = _____ (decimal)

- FFFF (hexadecimal) = _____ (decimal)

### Suggestions for Socratic discussion

- Outline the procedure(s) you used to perform these conversions.
- Is there any way to tell if any of the signed values is positive or negative just by examining the hexadecimal characters (i.e. without translating into binary first)?
- A powerful problem-solving technique is to simplify the problem so that it is easier to solve, then use that solution as a starting point for the final solution of the given (complex) problem. Try laying out the place-weights for a *4-bit signed integer binary number* and then figuring out the bit combinations that would give you the greatest possible positive value, the greatest possible negative value, 0, $-1$, and any other arbitrary values between. Seeing how a short (4-bit) signed integer works helps you see how larger (e.g. 16-bit) signed integers are constructed from 1 and 0 bits.

file i04405

Question 24

Read and outline the "Analog-Digital Conversion" section of the "Digital Data Acquisition and Network" 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 i04396

Question 25

Every instrument has at least one input and at least one output. For instruments responding linearly, the correspondence between input and output is proportional:
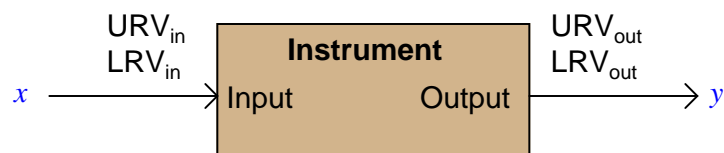
$$\frac{x - LRV_{in}}{URV_{in} - LRV_{in}} = \frac{y - LRV_{out}}{URV_{out} - LRV_{out}}$$

A practical example of this is a pressure transmitter, in this case one with an input range of 0 to 1023 PSI and an output of 4-20 mA:
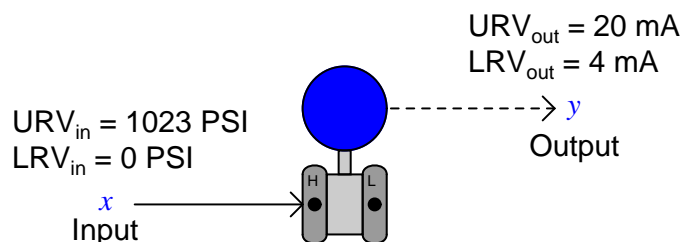
$$\frac{x - 0 \text{ PSI}}{1023 \text{ PSI}} = \frac{y - 4 \text{ mA}}{16 \text{ mA}}$$

If you happened to measure an output current of 14.7 mA from this pressure transmitter, it would be a simple matter for you to calculate the corresponding input pressure to be 684.13 PSI.

However, students are often taken by surprise when they encounter an analog-to-digital converter (ADC) or digital-to-analog converter (DAC) and are asked to correlate input and output for such devices. What might seem a daunting task at first, though, soon reveals itself to be the same input-to-output correspondence calculations they've seen all along in the guise of analog sensors and other instruments.

Take for example this analog-to-digital converter, with a 10-bit output (a "count" range of 0 to 1023) and a 4-20 mA input:
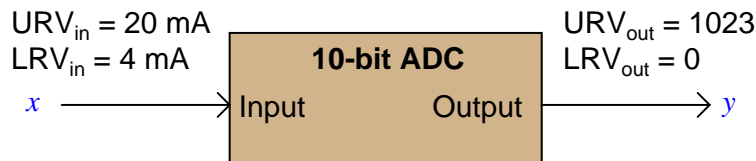
Calculate the corresponding "count" output of this ADC circuit given a 6.82 mA input signal.
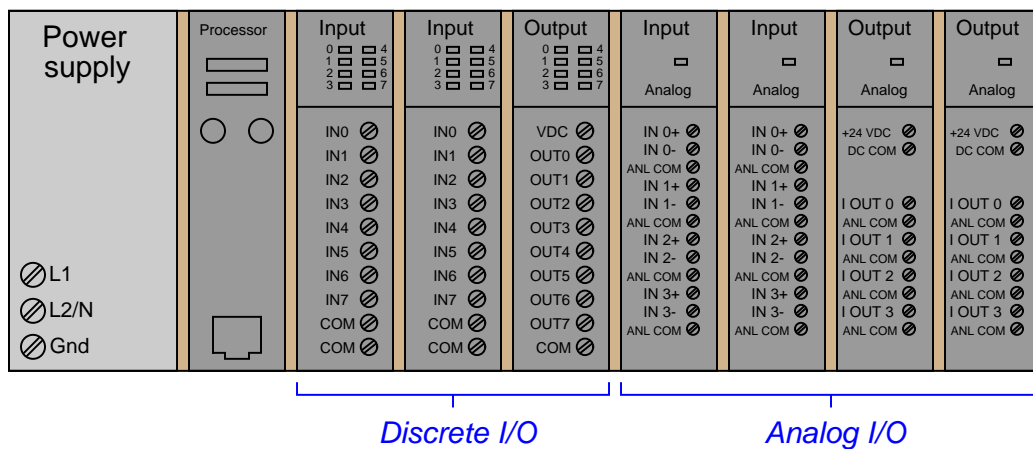
Suggestions for Socratic discussion

- Explain why the "count" value generated by an analog-to-digital converter must be an integer number. For example, explain why a count value of 3275 might be valid, but a count value of 3274.83 is not.

file i04545

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Question 26

The ADC0804 is an example of an integrated circuit analog-to-digital converter (ADC), converting an analog input voltage signal into an 8-bit binary output:



Digital data output lines
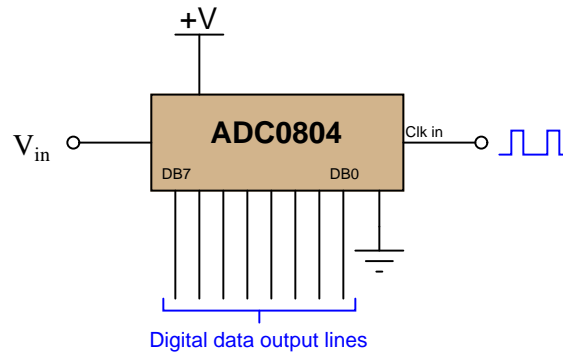
When operated from a 5.0 volt DC power supply in its simplest mode, the ADC0804 converts any DC input voltage between 0.0 volts and 5.0 volts into an 8-bit number at the command of a clock pulse. A 0.0 volt input yields a binary output (or "count") of 00000000, of course, while a 5.0 volt input yields a count of 11111111.

Complete this table of numbers, relating various DC input voltages with count values (expressed in binary, hex, and decimal) for an ADC0804 having an input range of 0.0 to 5.0 volts DC:

| DC input voltage | Binary count | Hex count | Decimal count |
|---|---|---|---|
| 0.0 volts | 00000000 | | |
| | 00110011 | | 51 |
| 2.2 volts | | 70 | |
| | | B3 | 179 |
| | 11001100 | CC | |
| 5.0 volts | 11111111 | | |

- Explain why the "count" value generated by an analog-to-digital converter must be an integer number. For example, explain why a count value of 3275 might be valid, but a count value of 3274.83 is not.

file i03270

39

A *Programmable Logic Controller* or *PLC* is an industrial control computer designed to input and output many types of signals. To handle different signal types (on/off, analog, digital networking), large-scale PLCs use different "cards" that plug into a common frame to provide I/O capacity to the processor:

## Rack-style PLC with multiple plug-in "cards" for different I/O types

| Power supply | Processor | Input | Input | Output | Input | Input | Output | Output |
|---|---|---|---|---|---|---|---|---|
| | | Analog | Analog | Analog | Analog | Analog | Analog | Analog |
| | | IN0 | IN0 | VDC | IN 0+ | IN 0+ | +24 VDC | +24 VDC |
| | | IN1 | IN1 | OUT0 | IN 0- | IN 0- | DC COM | DC COM |
| | | IN2 | IN2 | OUT1 | ANL COM | ANL COM | | |
| | | IN3 | IN3 | OUT2 | IN 1+ | IN 1+ | | |
| | | IN4 | IN4 | OUT3 | IN 1- | IN 1- | I OUT 0 | I OUT 0 |
| | | IN5 | IN5 | OUT4 | ANL COM | ANL COM | ANL COM | ANL COM |
| | | IN6 | IN6 | OUT5 | IN 2+ | IN 2+ | I OUT 1 | I OUT 1 |
| L1 | | IN7 | IN7 | OUT6 | IN 2- | IN 2- | ANL COM | ANL COM |
| L2/N | | COM | COM | OUT7 | ANL COM | ANL COM | I OUT 2 | I OUT 2 |
| Gnd | | COM | COM | COM | IN 3+ | IN 3+ | ANL COM | ANL COM |
| | | | | | IN 3- | IN 3- | I OUT 3 | I OUT 3 |
| | | | | | ANL COM | ANL COM | ANL COM | ANL COM |

Discrete I/O          Analog I/O

Read selected portions of the Allen-Bradley PLC "1756 ControlLogix I/O Modules" publication (document 1756-TD002A-EN-E, May 2009), and answer the following questions:

Locate the sample 4-20 mA device wiring diagrams for the 1756-IF6CIS "sourcing current loop analog input module", identifying the different types of 4-20 mA field devices supported.

Identify the rated input current range for this analog card, and also the "count" values associated with the low and high signal values.

Calculate the number of counts per milliamp of signal with this analog input card, and also the resolution (mA per count).

Calculate the "User counts" value for a 8.51 mA signal value input to this analog card.

Calculate the mA current signal value at a "User counts" value of +4592.

---

**Suggestions for Socratic discussion**

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks help make sense of the sample wiring diagrams shown in this manual.
- Examine the sample diagrams shown in the Rockwell manual, showing connections between 4-20 mA transmitters and the analog input channels. Then, identify the consequences of the shielded cable in each diagram either failing *open* or failing *shorted*.
- Sketch what you think are the internal components between terminals VOUT, IN, and RTN for one of the channels on the 1756-IF6CIS sourcing analog input modules, based on the recommended connections to different kinds of 4-20 mA transmitters shown in the manual.

- Explain why the "count" value generated by an analog-to-digital converter must be an integer number. For example, explain why a count value of 3275 might be valid, but a count value of 3274.83 is not.

Question 28

Once upon a time, your instructor was asked to troubleshoot a flow control system where a PLC (Programmable Logic Controller) received a flow measurement signal from a 4-20 mA flow transmitter and sent a 4-20 mA command signal to a variable-frequency motor drive (VFD) turning a pump. The PLC's job was to turn the pump at the speed necessary to deliver a flow rate at a specified setpoint value:
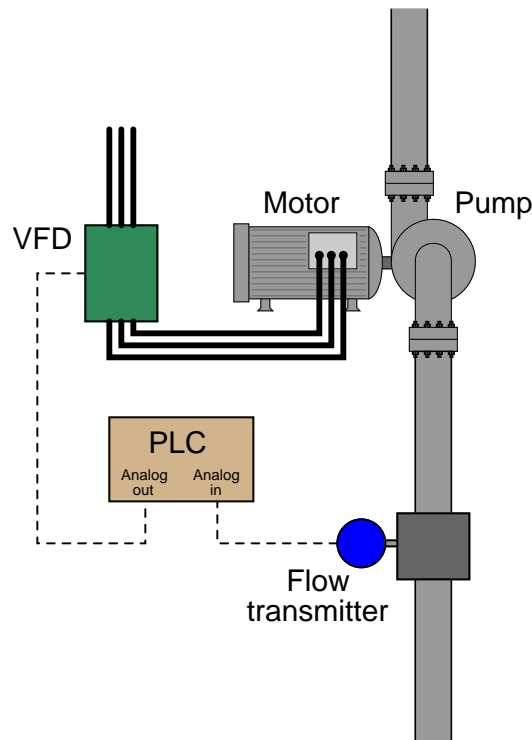


The operator pressed the "Start" button, but the pump refused to turn. Upon examining the PLC's live program, it was found that the analog input value (a 16 bit binary number) was $FFFF. The measured current signal from the flow transmitter was 3.99 mA: just a little bit below 0% of range, which was reasonable for a no-flow condition.

Your instructor was able to fix this problem by adjusting the "zero" screw on the flow transmitter until it output a current signal of exactly 4.00 mA at zero flow. As soon as this was done, the analog input in the PLC's program registered a value of $0000, and the pump started up as it was supposed to when the operator pressed the "Start" button.

Explain why this simple transmitter calibration adjustment was able to allow the system to run again, and why the real problem was a design flaw in the PLC.

Hint: The key to understanding what the problem was in this system is the difference between signed and unsigned integers, and how an under-ranged ADC circuit can "underflow."

41

Question 29

A technician is installing two pressure alarm switches on a new liquid pipeline pumping station. The station is still being constructed, with the pipeline empty of all liquid and vented to atmosphere. One switch detects improper high-pressure conditions on the discharge side of the pump, while the other switch detects improper low-pressure conditions on the suction side of the pump:
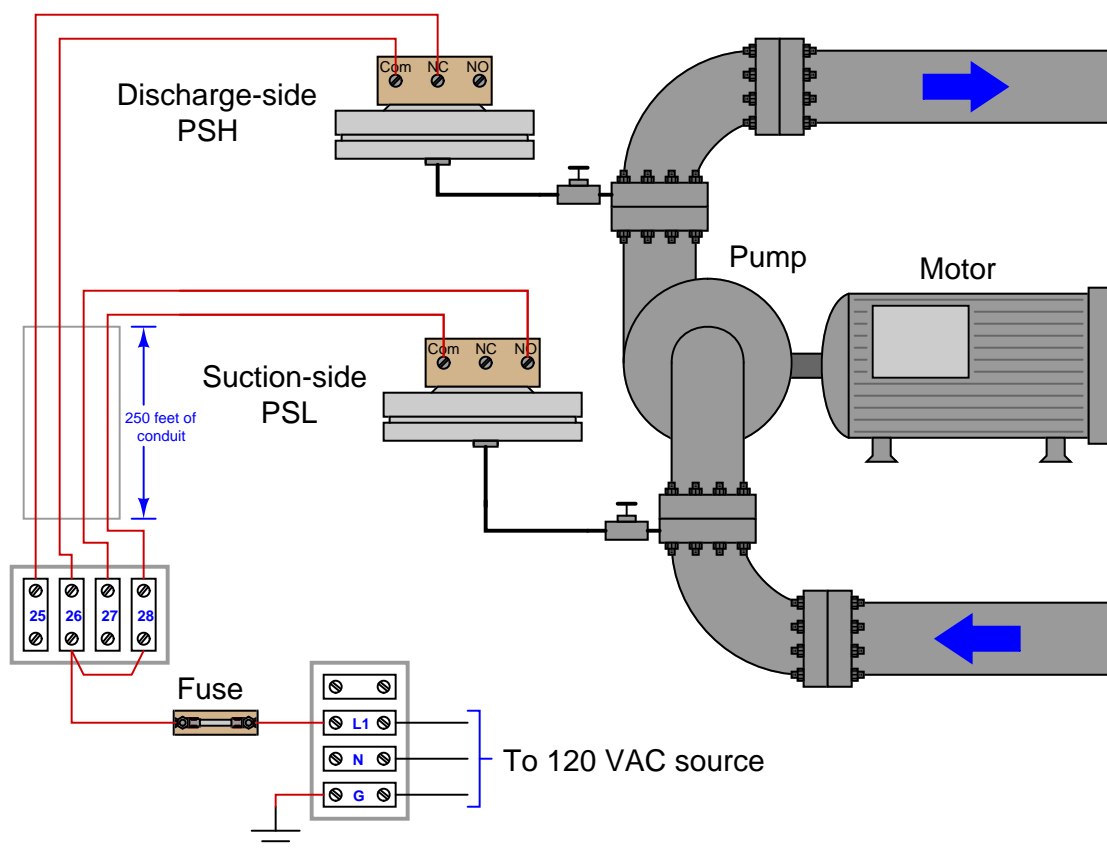


Using a digital multimeter (DMM), the technician first measures 118 VAC between terminals "L1" and "N" (to check the meter for proper operation). Next, he measures 118 VAC as expected between terminal 25 and terminal "N". For the last test, the technician measures 41 volts between terminal 27 and "N". This last result was very unexpected! Thinking perhaps the PSL switch is faulty, he walks to the field location and measures resistance between the "Com" and "NO" terminals on that switch, measuring infinite ("OL") resistance with his multimeter.

A fellow technician says to the first technician, "Oh, that 41 volt measurement is just a *phantom voltage*. Ignore it!" Explain what this technician means by the phrase "phantom voltage" and comment on whether or not you think it should be ignored.

---

| Suggestions for Socratic discussion |

- Explain why these two pressure switches are wired as they are (PSH wired NC and PSL wired NO). In each case, what will an improper pressure do to the status of each switch?
- How could the DMM be altered so as to not be fooled by "phantom" voltages again?
- Try inserting one test probe of your DMM into the "hot" side of an electrical receptacle, while not touching anything else with the other test probe. How much AC voltage will your DMM read in this

condition? Explain the results based on what you have learned about signal coupling and phantom voltages.

<u>file i02542</u>

---

Question 30

Complete this table, performing all necessary conversions between numeration systems:

| Binary | Octal | Decimal | Hexadecimal |
|---|---|---|---|
| 10010 | | | |
| | | 92 | |
| | | | 1A |
| | 67 | | |
| 1100101 | | | |
| | | | 122 |
| | | 1000 | |
| | 336 | | |
| 1011010110 | | | |

<u>file i02161</u>

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Question 31

Convert the following numbers from binary (base-two) to decimal (base-ten):

- $10_2 =$
- $1010_2 =$
- $10011_2 =$
- $11100_2 =$
- $10111_2 =$
- $101011_2 =$
- $11100110_2 =$
- $10001101011_2 =$

Describe a general, step-by-step procedure for converting binary numbers into decimal numbers.
<u>file i02164</u>

## Question 32

Convert the following numbers from decimal (base-ten) to binary (base-two):

- $7_{10} =$

- $10_{10} =$

- $19_{10} =$

- $250_{10} =$

- $511_{10} =$

- $824_{10} =$

- $1044_{10} =$

- $9241_{10} =$

Describe a general, step-by-step procedure for converting decimal numbers into binary numbers.
file i02165

## Question 33

A numeration system often used as a "shorthand" way of writing large binary numbers is the *octal*, or base-eight, system. Based on what you know of place-weighted numeration systems, describe how many valid ciphers exist in the octal system, and the respective "weights" of each place in an octal number.

Also, perform the following conversions:

- $35_8$ into decimal:

- $16_{10}$ into octal:

- $110010_2$ into octal:

- $51_8$ into binary:

### Suggestions for Socratic discussion

- If binary is the "natural language" of digital electronic circuits, why do we even bother with other numeration systems such as hex and octal?
- Why is octal considered a "shorthand" notation for binary numbers?

file i02166

## Question 34

A numeration system often used as a "shorthand" way of writing large binary numbers is the *hexadecimal*, or base-sixteen, system.

Based on what you know of place-weighted numeration systems, describe how many valid ciphers exist in the hexadecimal system, and the respective "weights" of each place in a hexadecimal number.

Also, perform the following conversions:

- $35_{16}$ into decimal:

- $34_{10}$ into hexadecimal:

- $11100010_2$ into hexadecimal:

- $93_{16}$ into binary:

file i02167

Question 35

Digital computers communicate with external devices through *ports*: sets of terminals usually arranged in groups of 4, 8, 16, or more (4 bits = 1 *nybble*, 8 bits = 1 *byte*, 16 bits = 2 bytes). These terminals may be set to high or low logic states by writing a program for the computer that sends a numerical value to the port. For example, here is an illustration of a microcontroller being instructed to send the hexadecimal number F3 to port A and 2C to port B:

**Microcontroller**

*($F3)*          *($2C)*

Port A          Port B

7 6 5 4 3 2 1 0    7 6 5 4 3 2 1 0
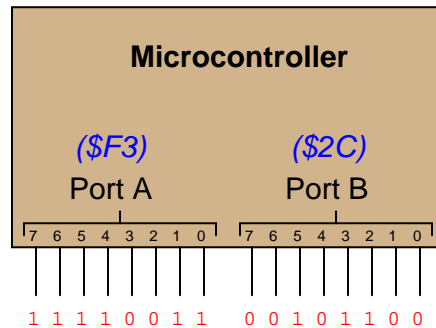
1 1 1 1 0 0 1 1    0 0 1 0 1 1 0 0

Suppose we wished to use the upper four bits of port A (pins 7, 6, 5, and 4) to drive the coils of a stepper motor in this eight-step sequence:

Step 1: 0001
Step 2: 0011
Step 3: 0010
Step 4: 0110
Step 5: 0100
Step 6: 1100
Step 7: 1000
Step 8: 1001

As each pin goes high, it drives a power MOSFET on, which sends current through that respective coil of the stepper motor. By following a "shift" sequence as shown, the motor will rotate a small amount for each cycle.

Write the necessary sequence of numbers to be sent to port A to generate this specific order of bit shifts, in hexadecimal. Leave the lower four bit of port A all in the low logic state.

file i02168

When representing non-whole numbers, we extend the "places" of our decimal numeration system past the right of the decimal point, like this:

---

### Decimal place-weights

| $\dfrac{2}{10^3}$ | $\dfrac{5}{10^2}$ | $\dfrac{9}{10^1}$ | $\dfrac{6}{10^0}$ | • | $\dfrac{3}{10^{-1}}$ | $\dfrac{8}{10^{-2}}$ | $\dfrac{0}{10^{-3}}$ | $\dfrac{4}{10^{-4}}$ |

$$2 \times 10^3 = 2000 \qquad 3 \times 10^{-1} = {}^3/_{10}$$
$$5 \times 10^2 = 500 \qquad 8 \times 10^{-2} = {}^8/_{100}$$
$$9 \times 10^1 = 90 \qquad 0 \times 10^{-3} = {}^0/_{1000}$$
$$6 \times 10^0 = 6 \qquad 4 \times 10^{-4} = {}^4/_{10000}$$

How do you suppose we represent non-whole numbers in a numeration system with a base (or "radix") other than ten? In the following examples, write the place-weight values underneath each place, and then determine the decimal equivalent of each example number:

---

### Binary place-weights

| 1 | 0 | 0 | 1 | • | 1 | 0 | 1 | 1 |

---

### Octal place-weights

| 4 | 0 | 2 | 7 | • | 3 | 6 | 1 | 2 |

---

### Hexadecimal place-weights

| C | 1 | A | 6 | • | 3 | 2 | B | 9 |

---

## Question 37

Complete this table, performing all necessary conversions between numeration systems on these fixed-point number values. Truncate all answers to three characters past the point:

| Binary | Octal | Decimal | Hexadecimal |
|--------|-------|---------|-------------|
| 101.011 | | | |
| | | 25.2 | |
| | | | 4.B |
| | 72.52 | | |
| 1011.101 | | | |
| | | | AC.11 |
| | | 934.79 | |
| | 641.7 | | |
| 101100.1 | | | |

## Question 38

In digital computer systems, binary numbers are often represented by a fixed number of bits, such as 8, or 16, or 32. Such bit groupings are often given special names, because they are so common in digital systems:

- byte
- nybble
- word

How many binary bits is represented by each of the above terms?

And, for those looking for more challenge, try defining these terms:

- nickle
- deckle
- chawmp
- playte
- dynner

Question 39

The IEEE 754-1985 standard for representing floating-point numbers uses 32 bits for single-precision numbers. The first bit is the *sign*, the next eight bits are the *exponent*, and the last 23 bits are the *mantissa*:

| Sign | Exponent ($E$) | Mantissa ($m$) |
|---|---|---|
| 0 | 00000000 | 00000000000000000000000 |

$\pm 0.m \times 2^{E-127}$          Single-precision, when exponent bits are all zero

$\pm 1.m \times 2^{E-127}$          Single-precision, when exponent bits are not all zero

Based on this standard, determine the values of the following single-precision IEEE 754 floating-point numbers:

| Sign | Exponent ($E$) | Mantissa ($m$) |
|---|---|---|
| 1 | 00101100 | 00001110000001100000000 |
| 0 | 11001100 | 11010110000000000000000 |
| 0 | 00000000 | 11111100000110001000000 |

Finally, how do you represent the number 1 ($1.0 \times 2^0$) in this floating-point format?
<u>file i01851</u>

Question 40

An essential component of any digital control system is an *analog-to-digital converter*, or *ADC*. This is necessary to convert the analog process variable measurement into a digital number for the control algorithm to process. Another essential component is a *digital-to-analog converter*, or *DAC*, which does the exact opposite.

In a system using 4-20 mA analog currents to relay instrument signals, there is an ADC located at the process variable input of the controller, and a DAC located at the output of the controller:
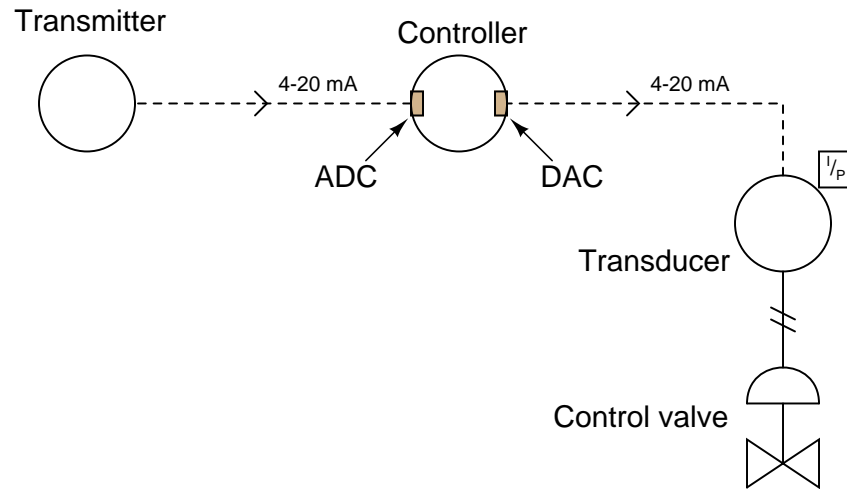


In digital "Fieldbus" systems, the communication is all digital, which places the ADC at the transmitter and the DAC at the transducer:
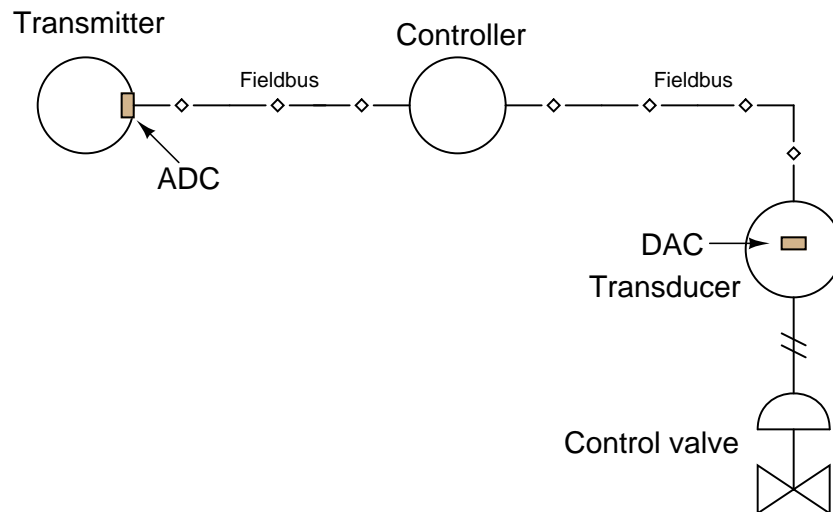
In either case, we need to "scale" the binary count of the ADC and DAC to their respective analog variable values. Consider a flow control system, with a flow transmitter ranged from 0 to 200 GPM and a pneumatic control valve operating on a pressure range of 3 to 15 PSI (instrument air). Assuming the ADC has a resolution of 16 bits (a digital conversion range of $0000 to $FFFF) and the DAC has a resolution of 14 bits (a digital conversion range of $0000 to $3FFF), determine the digital values corresponding to a 50% PV signal (100 GPM flow rate) and a 50% valve position (9 PSI pneumatic signal). Write these hexadecimal number values in the following tables:

**Calibration table for process variable signal (ADC)**

| Measurement | Digital output |
| --- | --- |
| 0 GPM | $0000 |
| 100 GPM | |
| 200 GPM | $FFFF |

**Calibration table for output signal (DAC)**

| Measurement | Digital output |
| --- | --- |
| $0000 | 0 PSI |
| | 9 PSI |
| $3FFF | 15 PSI |

Note that the DAC output does *not* correspond to a live zero scale. In other words, a digital input value of $0000 will output no pressure to the valve (0 PSI), rather than a standard pneumatic "zero" signal of 3 PSI.

file i01498

---

Question 41

Read and outline the "Instrumentation Amplifiers" subsection and introduction to the "Analog Signal Conditioning and Referencing" section of the "Digital Data Acquisition and Networks" 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 i00882

Question 42

Read portions of the Burr-Brown (Texas Instruments) datasheet for the INA111 high-speed instrumentation amplifier and answer the following questions:

Calculate the necessary gain resistor value ($R_G$) to give the amplifier a gain of 30. Also, express this gain value in decibels.

Manipulate the given gain formula to solve for $R_G$ provided any arbitrary gain value desired.

Identify the typical input resistance of this instrumentation amplifier, as well as the typical bias current value. Describe what will happen if there are no "return paths" provided for the amplifier's input bias currents.

This datasheet recommends the use of *clamping diodes* to protect the amplifier's inputs from gross over-voltages. Examine the schematic diagram shown in figure 5 and explain how these clamping diodes work to protect the amplifier. Note that there is actually a mistake in this schematic – can you find it?

---

| Suggestions for Socratic discussion |

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) "why" for every step of your analysis, rather than merely describing those steps.
- The datasheet recommends that only one bias current return resistor need be used if the differential source resistance is low. Explain why the resistance of the voltage signal source matters at all to the bias currents.
- Referring to the internal schematic diagram of the INA111 shown on the first page of the datasheet, calculate $V_O$ given $V_{in(+)} = +3.5$ volts, $V_{in(-)} = +1.5$ volts, and $R_G = 50$ k$\Omega$ by applying Ohm's Law and Kirchhoff's Voltage and Current Laws to the three-opamp circuit.

file i00887

Question 43

Read the section entitled "Input Polarity and Range" (pages 2-2 through 2-5) of the National Instruments "DAQ E Series User Manual" (document 370503K-01) and answer the following questions:

Based on the resolution ("precision") you see listed in Table 2-1 for the NI 6020E data acquisition module, how many bits does its ADC use?

Based on the resolution ("precision") you see listed in Table 2-1 for the NI 6052E data acquisition module, how many bits does its ADC use?

Describe the difference between *unipolar* and *bipolar* analog ranges.

Page 2-21 contains a table (2-6) of diagrams showing how to connect various analog signal sources to a DAQ. Explain why the one connection scheme (middle row, right column) is not recommended.

| Suggestions for Socratic discussion |

- Why do you suppose the E-series DAQ modules use a PGIA (Programmable Gain Instrumentation Amplifier) as a front-end to the ADC (Analog-to-Digital Converter)? Why not use a fixed-gain instrumentation amplifier instead?
- Note the two different ground symbols used in the "Not Recommended" diagram in table 2-6. What specifically are the authors trying to convey to you by using two different ground symbols?
- Explain the necessity of $R_{ext}$ in some of the diagrams shown in table 2-6.
- Identify the purpose for each function in the block diagram of figure 2-1.

file i02162

Question 44

Read and outline the "Analog Input References and Connections" subsection of the "Analog Signal Conditioning and Referencing" section of the "Digital Data Acquisition and Networks" 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 i00884

Question 45

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense pressure measured by the loop-powered 4-20 mA pressure transmitter, on input channel #5:
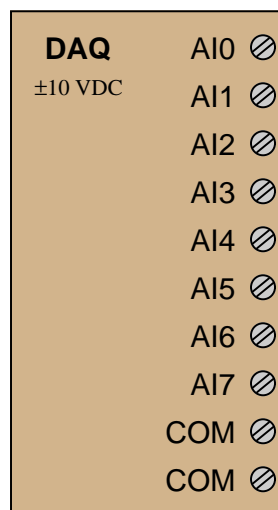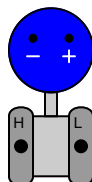


Your circuit should be wired in such a way that greater pressure applied to the transmitter produces a more *positive* signal measured by the DAQ. Note that you must add other components to make this a complete circuit!

Additionally, determine whether this DAQ has *single-ended* or *differential* voltage inputs.

**Suggestions for Socratic discussion**

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- Why do you suppose there are *two* "Common" terminals on the DAQ module?
- How could you test the "Common" terminals to see if they are connected to each other internally to the DAQ?
- Challenge yourself to design more than one viable circuit for this application.
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.

file i04582

Question 46

| Simulated troubleshooting exercise |

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

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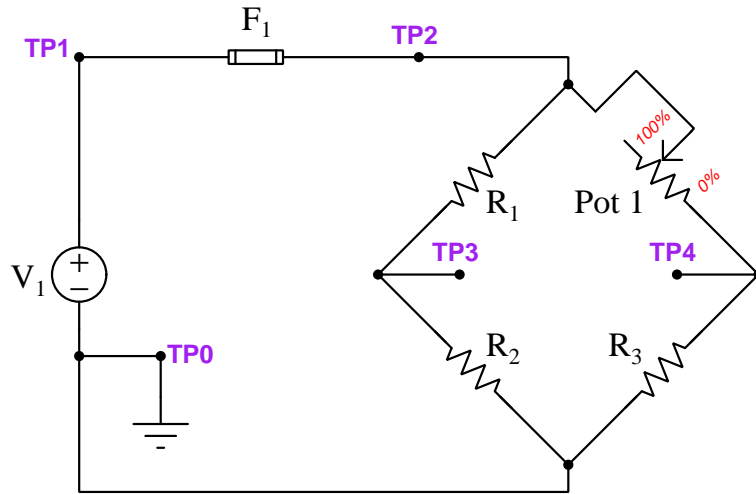


You may find it convenient to bring a printed copy of this schematic diagram with you to the session for this purpose.

file i02846

Question 47

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense strain using quarter-bridge strain gauge circuits on input channels #1 and #3, such that increasing tension on the strain gauge (increasing gauge resistance) generates a more *positive* signal voltage on each channel:
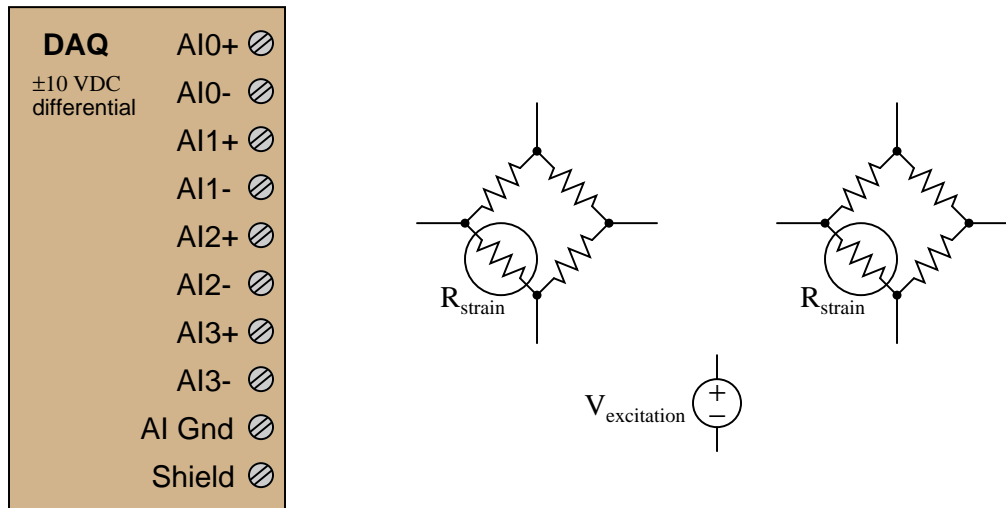
- Explain why in order for differential DAQ inputs to work, the power supply must share a common connection with the DAQ power supply.
- Explain what the "AI Gnd" and "Shield" input terminals are generally used for.
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.
- Identify whether or not *bias resistors* are necessary to connect to the DAQ's input terminals. If so, where should those resistors connect, and what should their approximate sizes be?

file i04584

## Question 48

Shown here is a pair of loop-powered 4-20 mA process transmitters, a process controller with dual measurement inputs, a 4-20 mA I/P (current-to-pressure) converter used to drive a pneumatically-actuated control valve, and a DAQ (data acquisition) unit for interfacing to a computer. Both the process controller and DAQ unit inputs are ranged from 1 to 5 volts DC, not 4-20 mA:
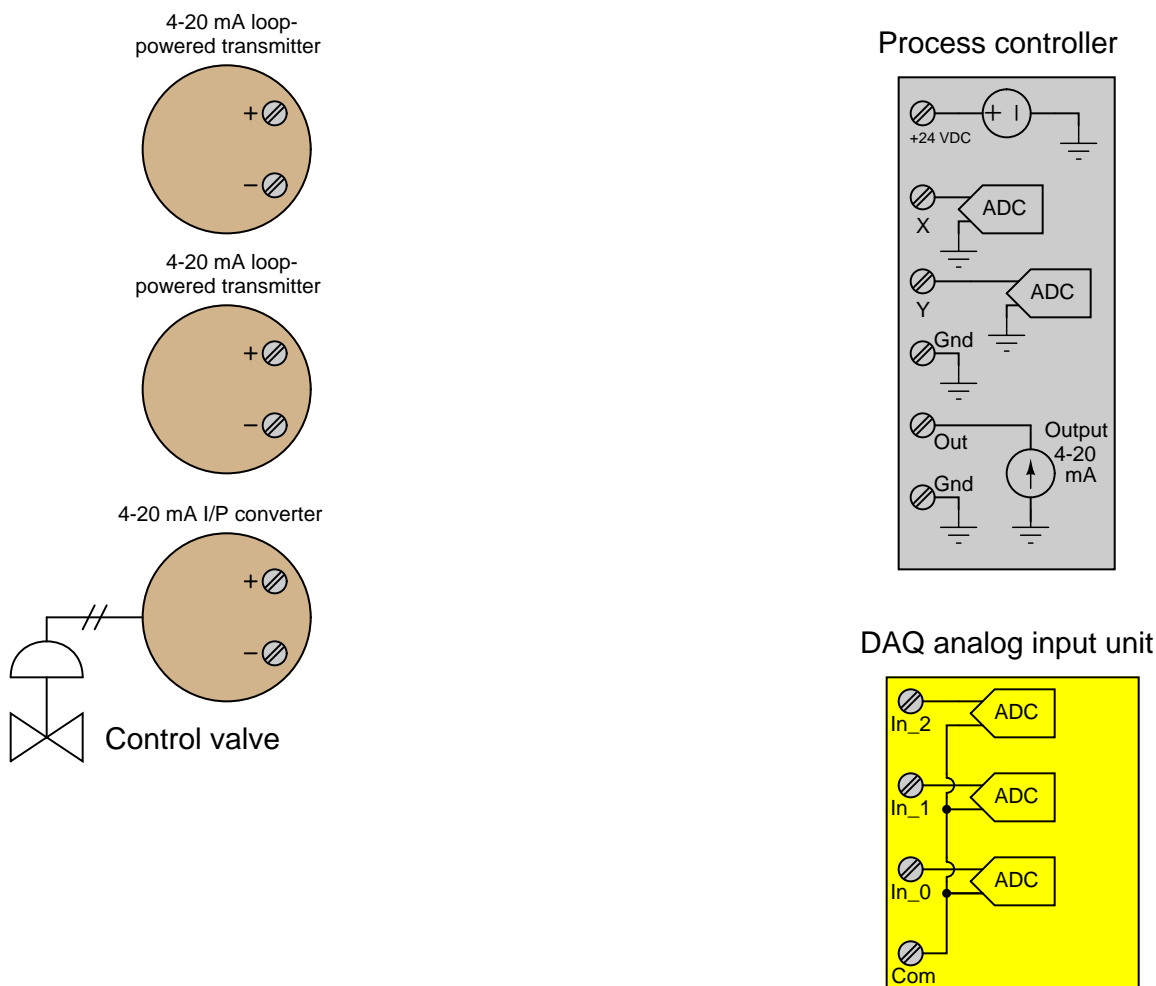


Show how all three field devices would properly connect to the controller and to the DAQ unit at the same time, including the placement of resistors to convert the current signals into voltage signals that both the controller and the DAQ may interpret.

---

### Suggestions for Socratic discussion

- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each component acting either as an electrical *source* or an electrical *load*. Discuss and compare how these arrows and polarity marks simplify the task of properly connecting wires between components.
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.

Question 49

A technician connects a DAQ (Data Acquisition) module to one phase of a 480 VAC three-phase electric motor in order to measure and record that motor's voltage and current simultaneously on a laptop computer. The DAQ functions as a high-speed data recorder, allowing the computer to display and record a time-based graph of motor voltage and motor current over time.

Knowing that the phase-to-phase voltage of approximately 480 volts and the line current of approximately 25 amps will be far too great for the DAQ to directly measure, the technician uses *instrument transformers* (a "PT" potential transformer and a "CT" current transformer) to step these voltages and currents to more reasonable values:
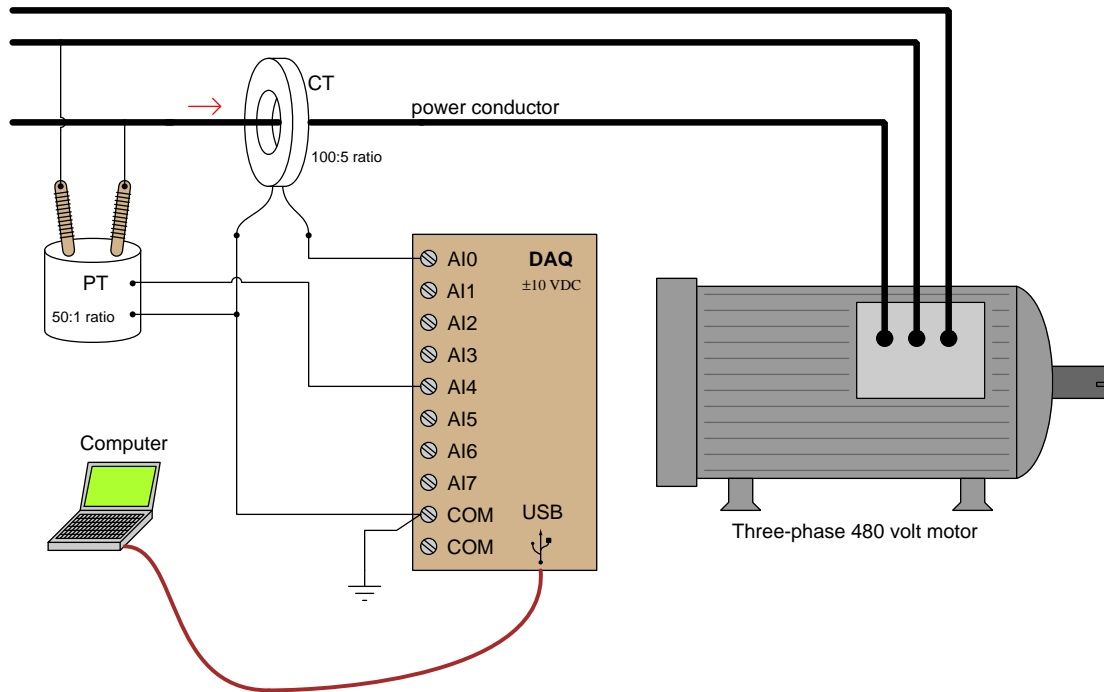


Unfortunately, as soon as the motor is energized, the DAQ disappears in a bright flash of light and cloud of smoke. The destruction also propagated to the PC the DAQ was connected to (through the USB cable)! What went wrong, and how should the technician correct his mistake? Assume we must use the same model of DAQ unit having the same ± 10 volt input limits.

---

**Suggestions for Socratic discussion**

- What exactly does an *instrument transformer* do?
- Could this system be made to work with a differential-input DAQ? Why or why not?
- Suppose we were free to select a different DAQ for this application. What specifications would we be looking for in the new DAQ to make it function properly in the circuit as shown?

file i02035

Question 50

An analog-to-digital converter has a 12-bit binary output and an analog input voltage range of 0.0 to + 5.0 volts. Calculate:

- The digital output (in hexadecimal) at 0.0 volts analog input = _____

- The digital output (in hexadecimal) at 5.0 volts analog input = _____

- The digital output (in hexadecimal) at 2.1 volts analog input = _____

- The analog input corresponding to a digital output of `2D0` = _____ volts

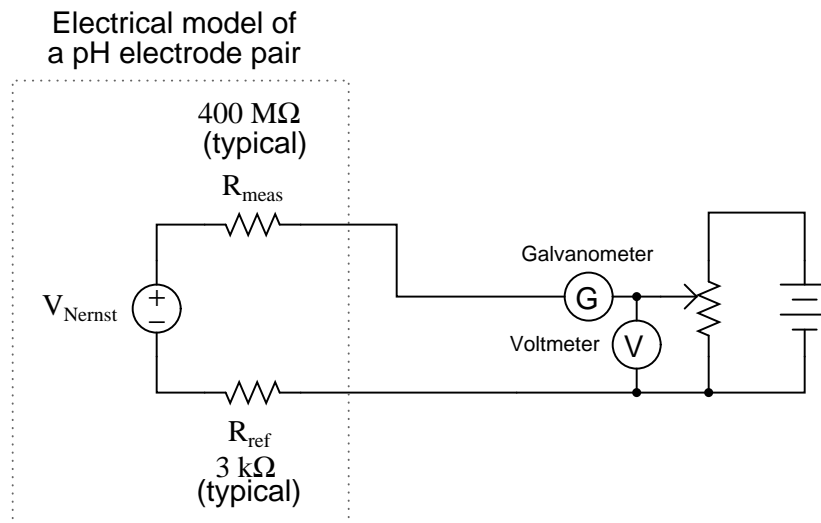- The analog input corresponding to a digital output of `F14` = _____ volts

file i03587

Question 51

Sketch connecting wires to allow this data acquisition unit (DAQ) to sense light on input channels #3 and #7, such that increasing light at each photocell generates an *increasing positive* signal voltage on each channel. Note that all the analog input channels on this DAQ are single-ended, bipolar:
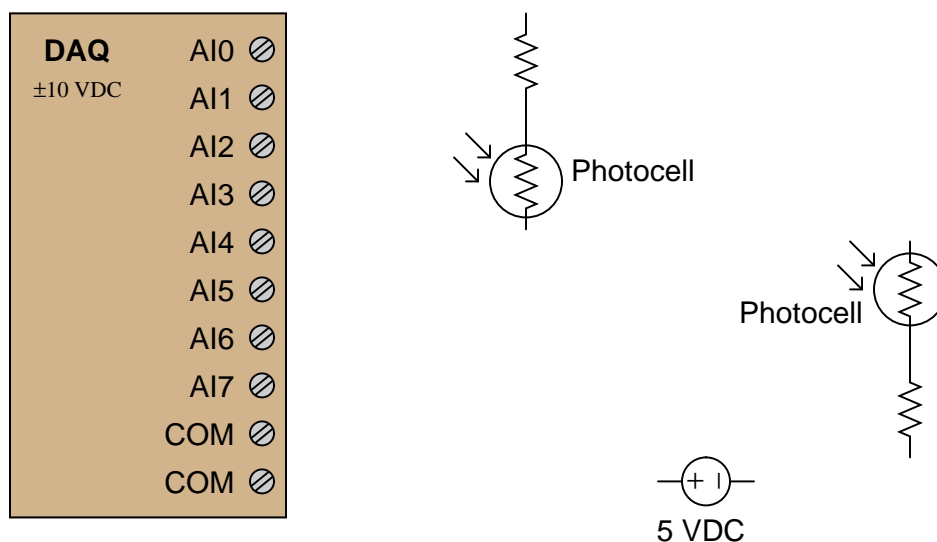


Recall that the electrical resistance of a photocell *decreases* with increasing light.

---

**Suggestions for Socratic discussion**

- A good problem-solving technique to apply in cases where we need to determine the direction of a change for a component's resistance in order to design a functioning circuit is to consider *limiting cases* for that component's resistance. For example, instead of asking ourselves what would happen if the intensity of light *slightly*, we ask ourselves what would happen if light intensity changed *dramatically*. Explain how this problem-solving technique applies to this particular system.
- After you have sketched your circuit, evaluate the effects of various components failing either open or shorted, one at a time.

file i04587

An analog-to-digital converter has a 16-bit binary output and an analog input voltage range of 0.0 to + 10.0 volts. Calculate:

- The digital output (in hexadecimal) at 0.0 volts analog input = _____

- The digital output (in hexadecimal) at 10.0 volts analog input = _____

- The digital output (in hexadecimal) at 3.4 volts analog input = _____

- The analog input corresponding to a digital output of 3D6A = _____ volts

- The analog input corresponding to a digital output of C005 = _____ volts

  file i02661

Question 53

Modern pH and temperature (thermocouple) transmitters are constructed with extremely high input impedances (typically in the hundreds of megaohms). Explain why a high input impedance voltmeter is important when measuring the voltage output by a source, when the voltage in question is very small.

In the days before the advent of solid-state digital multimeters with their operational amplifier (high impedance) inputs, a technique called *null-balance* was used to accurately measure small voltages such as those produced by thermocouple junctions and pH probes. This "potentiometric" technique allowed people to use rather primitive voltmeter technology without incurring the errors that would be experienced if the voltmeter were directly connected to the signal source.

Examine the circuits shown below, and explain how the two meters (one "galvanometer" and one voltmeter) plus a power source and a potentiometer would be used to measure voltage from the signal source (pH probe or thermocouple junction):

**Null-balance measurement of pH probe voltage**

Electrical model of
a pH electrode pair

400 MΩ
(typical)

$R_{meas}$

$V_{Nernst}$

Galvanometer
G

Voltmeter
V

$R_{ref}$
3 kΩ
(typical)

**Null-balance measurement of thermocouple voltage**

$R_{wire}$   Galvanometer
G

Measurement
junction

Voltmeter
V

$R_{wire}$

file i00621

60
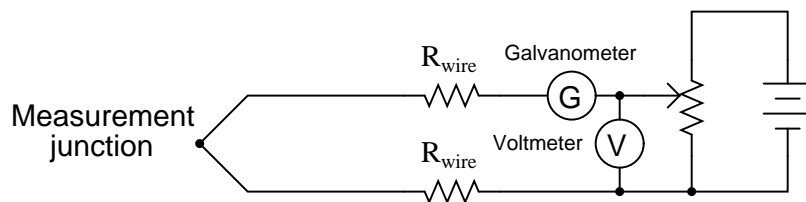
Question 54

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

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

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

**Schematic diagram of a relay circuit**
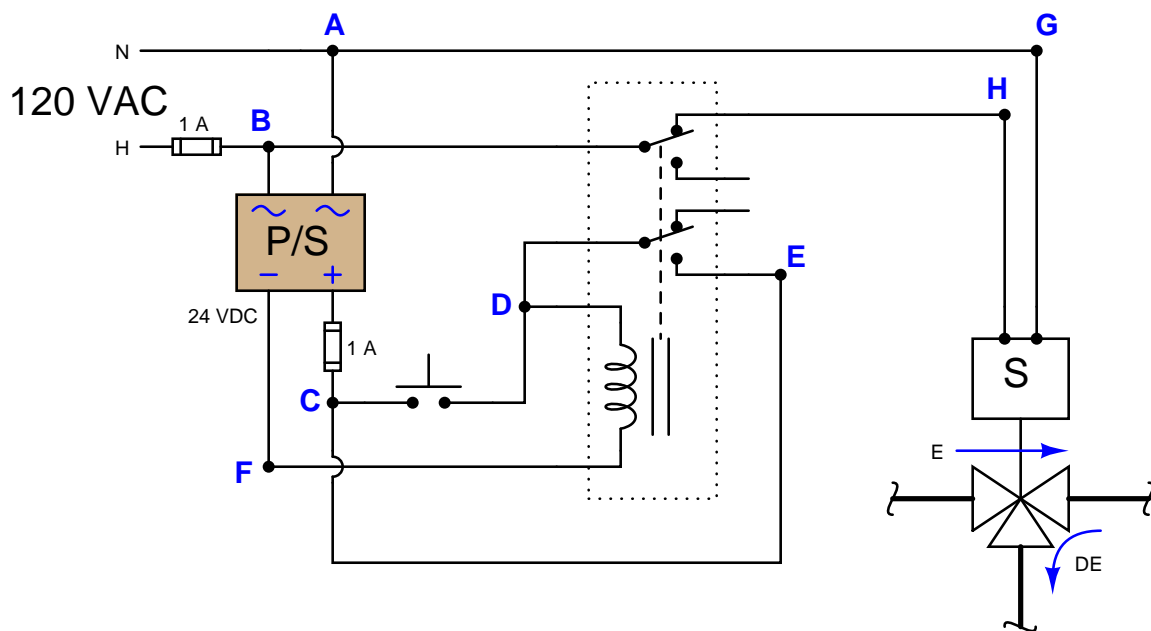
**Schematic diagram of a fuel tank level sensor circuit**

Ignition switch

Current mirror circuit

TP1

TP4

$Q_1$

$Q_2$

12 V

TP2

TP3

$R_1$ 440 Ω

Fuel gauge (voltmeter)

Fuel level sensor
5 Ω = Empty
260 Ω = Full
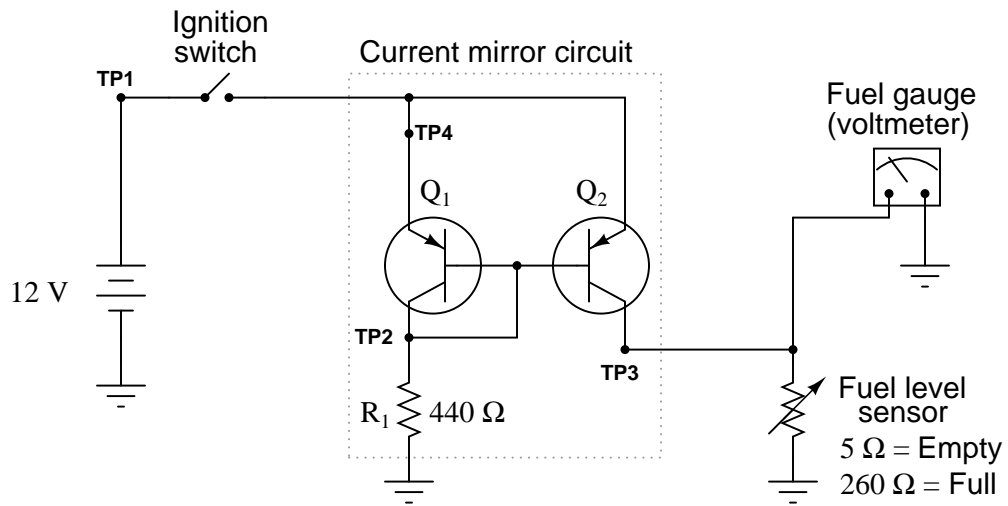
**Ladder diagram of a solenoid valve control circuit**

(-)

(+)

5A

O  H  A

1

5

S

6

CR1-1

1    3

8

4

Reset

Remote stop

CR1

7

9

11

3

CR1-2

5    7

10

IL-71

R

2

62
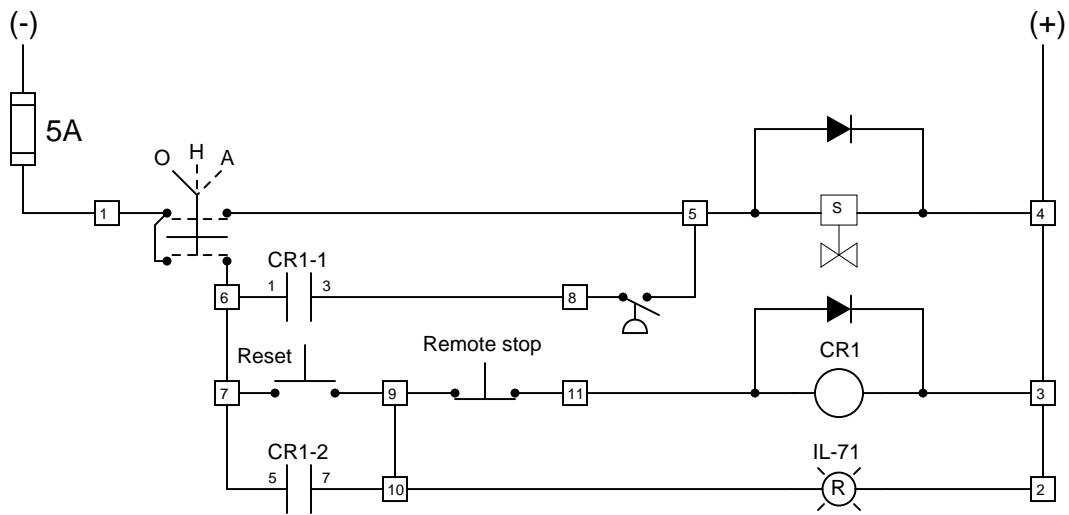
**P&ID of a solvent storage tank**
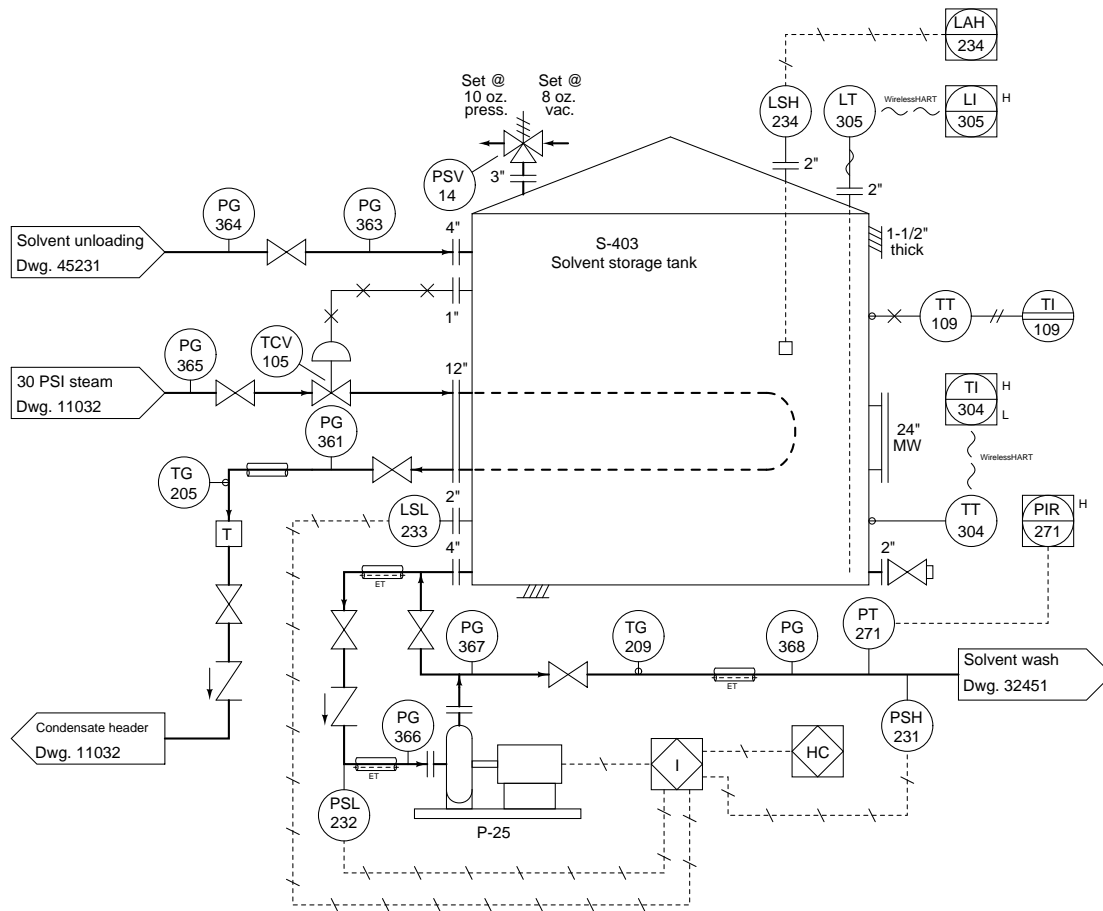


**Schematic diagram of a hydraulic valve control system**
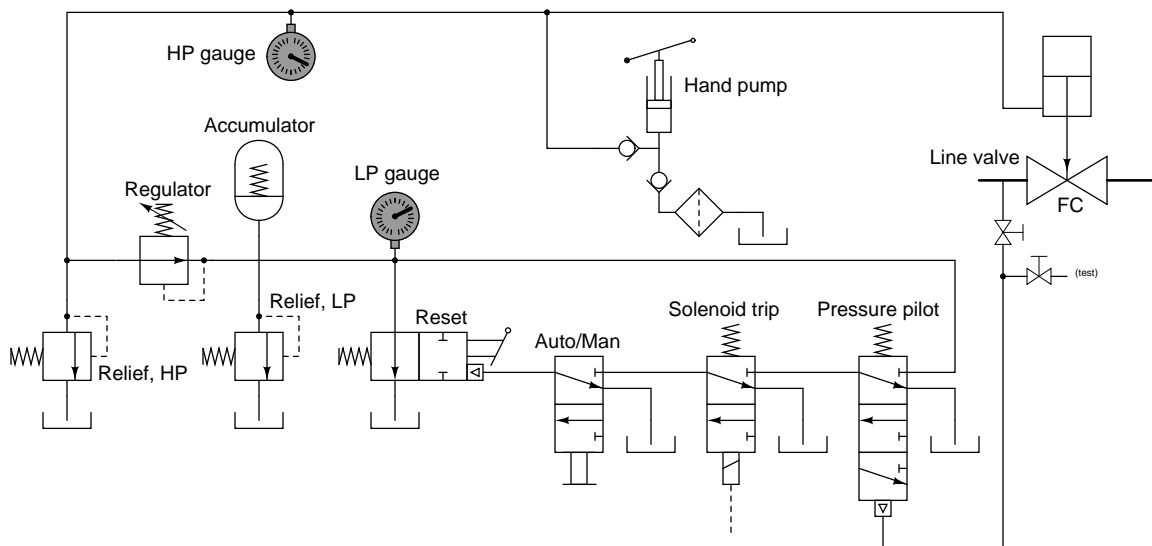
**Schematic/pictorial diagram of a pressure transmitter**
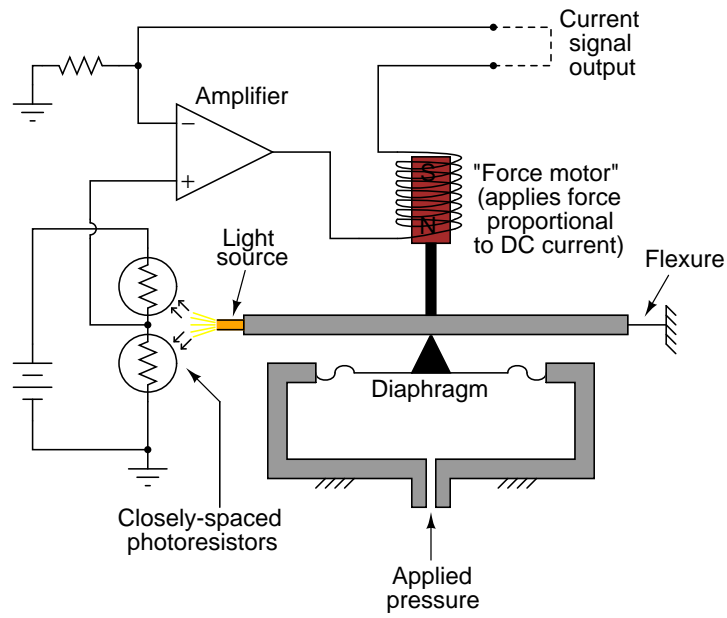


**Pictorial diagram of an I/P transducer**
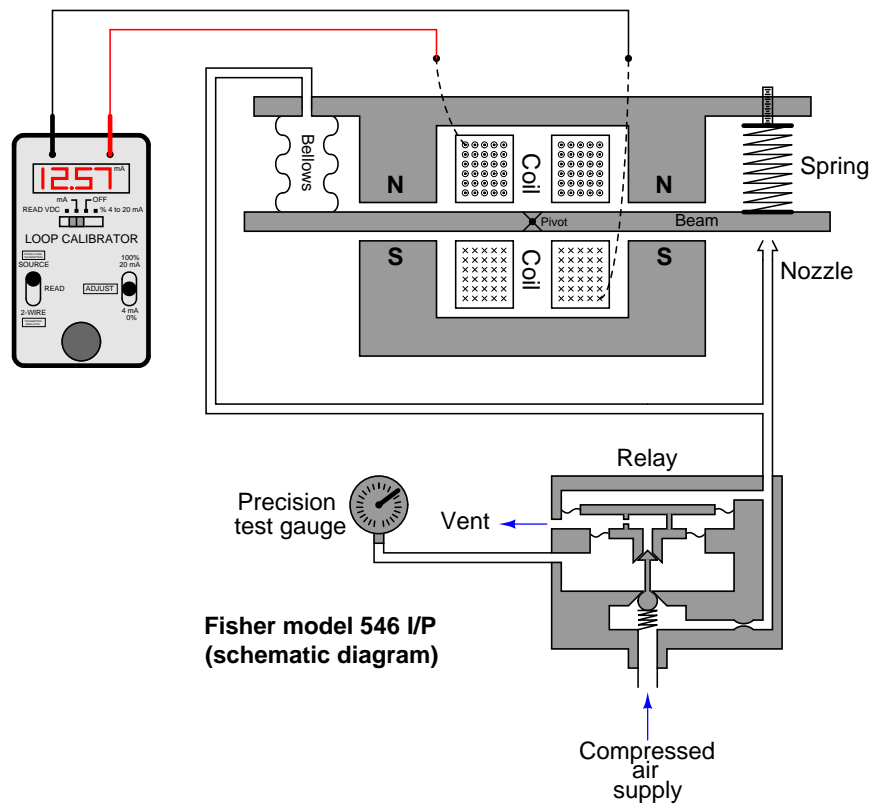
**Loop diagram of a compressor surge control system**

| **Loop Diagram:** Compressor surge control | | **Revised by:** I. Hate Surge | **Date:** April 1, 2003 |
|---|---|---|---|
| Field process area | Field panel | Panel rear | Panel front |



0-200 PSID

PDT 42  +  4-20 mA  CBL21  −

Compressor

I/P  FY 42b  +  4-20 mA  −  S

FV 42

AS 20 PSI

FT 42  +  4-20 mA  CBL23  −

0-1500 SCFM

JB 30  8  9  10  CBL24

JB 1  1  2  3  CBL25  PR1

CBL26

60 Hz  ES 120VAC

4  5  6  PR2

7  8  9  PR3

G  L2  L1

+  FY 42a  +  −  √  −  CBL27

1  FIC 42  2  3  4  0-1500 SCFM  5  6  L1  L2  G

ES 120VAC  60 Hz
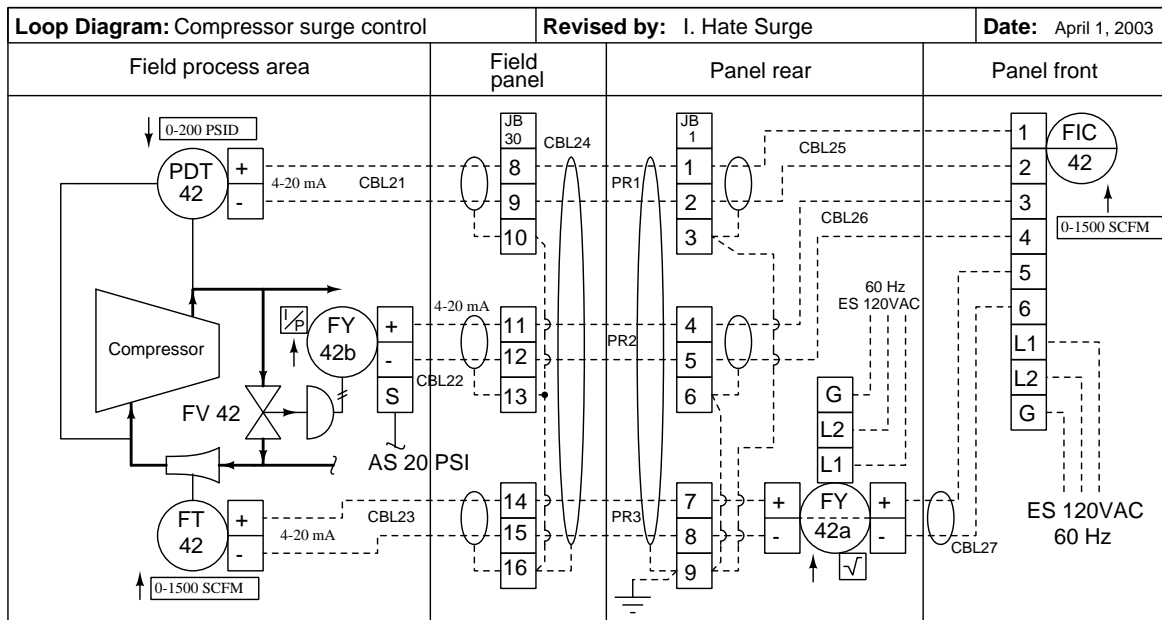
**Functional diagram of control loops**



FT → [△ P I D] ← A T A → FCV

FT → [D △ P I] ← A T A → FCV

FT → A T [△ P I] T A → FCV
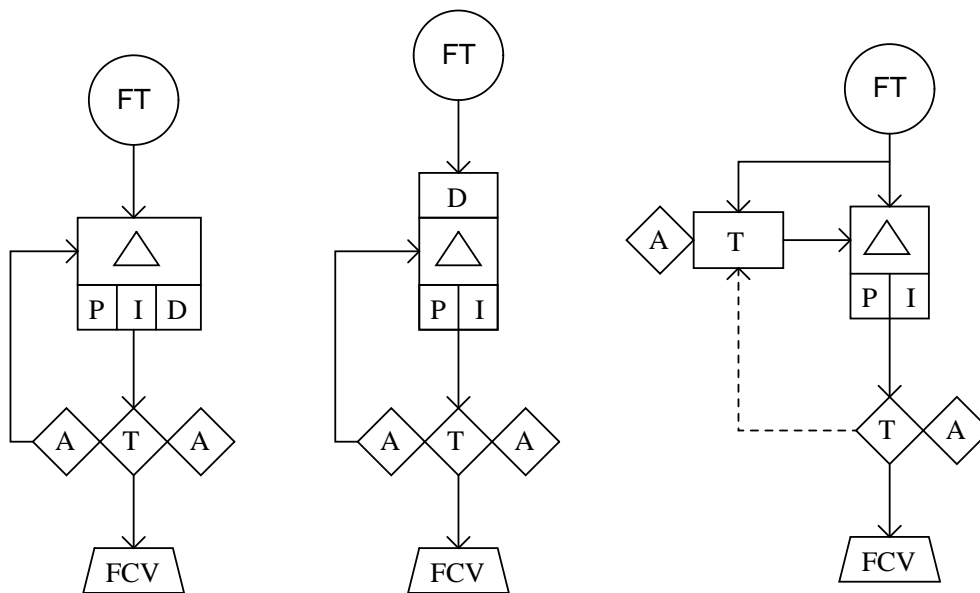
**FOUNDATION Fieldbus function block diagram**
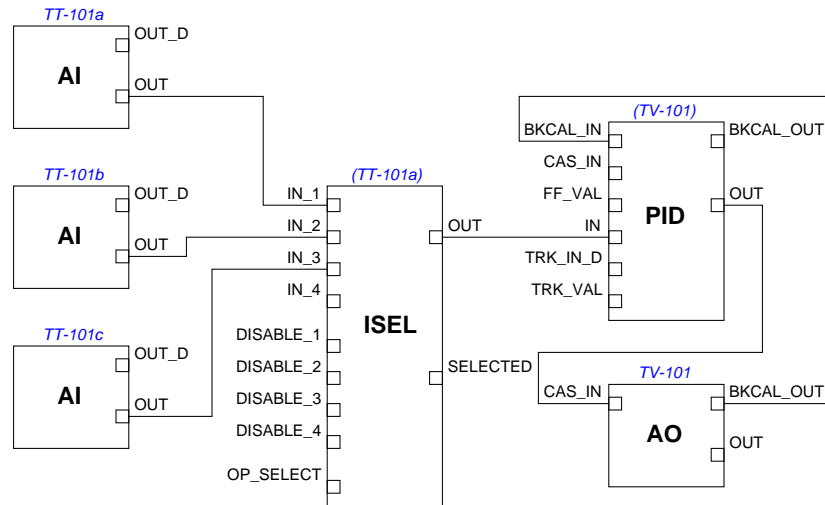


**Questions:**

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

file i02683

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Question 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

## Question 61

Read and outline the introduction of the "Digital Data Communication Theory" section of the "Digital Data Acquisition and Networks" 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 i04398

## Question 62

Read and outline the "Serial Communication Principles" subsection of the "Digital Data Communication Theory" section of the "Digital Data Acquisition and Networks" 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 i04399

Question 63

Read and outline the "Physical Encoding of Bits" subsection of the "Digital Data Communication Theory" section of the "Digital Data Acquisition and Networks" 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 i04400

## Question 64

Decoding a Manchester-encoded waveform is challenging to many students, because it's not clear at first how to differentiate "real" signal transitions (i.e. those pulse edges representing actual binary data bits) from transitions that are merely "reversals" (i.e. those pulse edges that are simply set-up for the next "real" data pulse). Here, I will show you a practical problem-solving method to gain a deeper understanding.

We will apply the problem-solving technique of *working backwards* to understand the concept better. If the part we're struggling with is how to convert a waveform into a series of bits, then we'll turn the problem backwards by starting with a known series of bits and working to convert that series of bits into a waveform:

Here we see a series of bits aligned with a set of grey lines which we know will be pulse edges:

```
    0    0    1    0    1    0    0    0    1    1    1    0
```
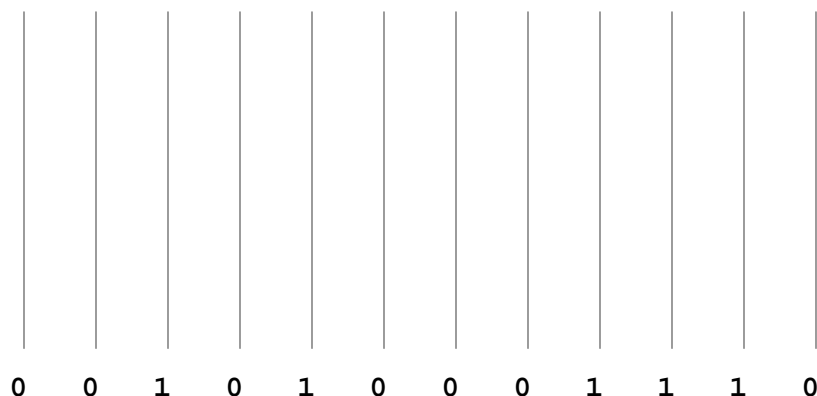
Begin by tracing the rising- and falling-edge pulses for each bit, following the standard of a rising edge representing a "1" bit and a falling edge representing a "0" bit. Feel free to draw small arrows distinguishing the rising versus falling transitions. Then, figure out how to connect these rising and falling edges together to form an actual pulse waveform.

It should quickly become apparent to you where "reversals" are necessary in order to "set up" properly for the next data pulse.

After you have done this, cover up the "1" and "0" bits so you can only see the waveform you've skeched. Erase any arrow-heads you might have sketched, so there is nothing visible to you except a clean pulse waveform. Now, explain to yourself how you would interpret this waveform to know which pulse edges represented real data as opposed to reversals.
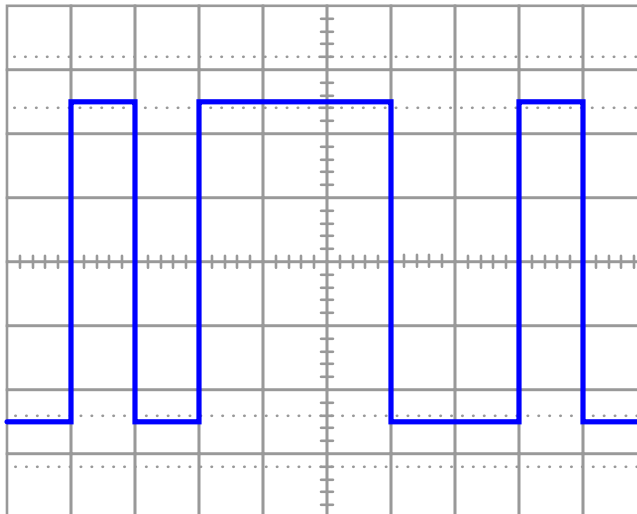
file i02128

## Question 65

Decode the following serial data streams, each one encoded using a different method:
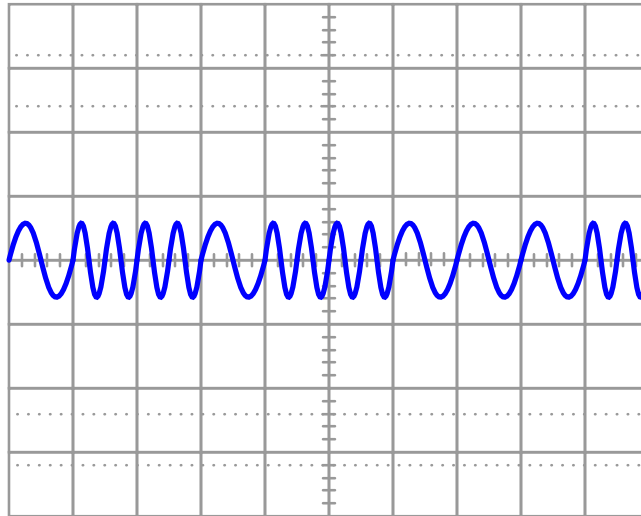
### (Manchester encoding)
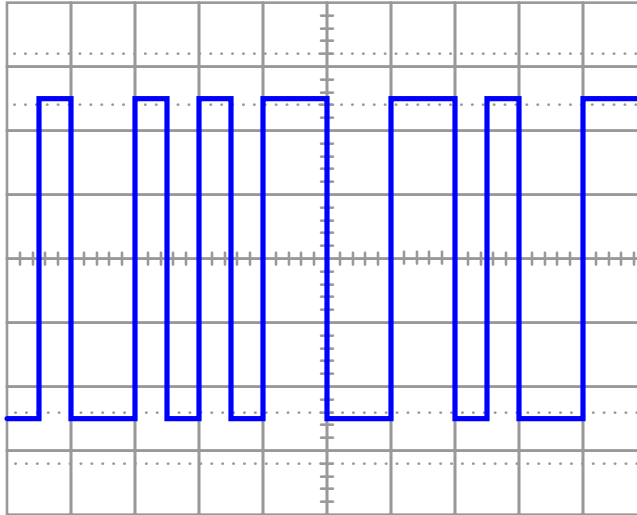


### (NRZ encoding)

# (FSK encoding)

**Suggestions for Socratic discussion**

- Students often experience confusion interpreting data streams when viewed like this, especially Manchester-encoded data. One problem-solving strategy that works well to help interpret waveform patterns is to *work the problem backwards*. Start with a known data stream (binary 1's and 0's) and then sketch a waveform representing that data stream. Do this for several different data streams, experimenting with different pattern combinations of 1's and 0's (repeating bits versus alternating bits, etc.), and then examine the waveforms you sketched to see what general principles you might apply to reliably interpret any data stream encoded in that manner.
- Explain how these three different encoding methods provide an excellent contrast between *bit rate* and *baud*.

file i04411

Question 66

Read and outline the "Communication Speed" subsection of the "Digital Data Communication Theory" section of the "Digital Data Acquisition and Networks" 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 i04401

Question 67

Read and outline the "Digital Representation of Text" section of the "Digital Data Acquisition and Network" 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 i04397

Question 68

A computer spreadsheet program may be used as a simulator for an analog-digital converter, taking an analog voltage signal value and converting it into a digital "count" value.

Begin creating your own spreadsheet by following the format shown below, allowing anyone to enter an analog input value in volts, while the spreadsheet calculates the "count" value and displays it in decimal, binary, and hexadecimal formats. Note that the yellow and blue shading in this example spreadsheet is strictly for aesthetic value (distinguishing input values from calculated values) and is not necessary for the spreadsheet to function:

|   | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| 1 | Input (V) |  | Counts (decimal) = | 179 |  |
| 2 | 3.5 |  | Counts (binary) = | 10110011 |  |
| 3 |  |  | Counts (hex) = | B3 |  |
| 4 |  |  |  |  |  |
| 5 |  |  |  |  |  |

Assume a 0 to 5 volt analog input range, and a 8-bit (00 to FF hex) digital output range.

---

**Suggestions for Socratic discussion**

- How could you modify the spreadsheet to have its analog input range be user-adjustable? In other words, allowing anyone to simulate the performance of a 0 to 10 volt range or 0 to 20 volt range without having to modify any of the formulae in the spreadsheet?
- How could you *test* your spreadsheet cable-length calculator for accuracy (to verify you haven't made any mistakes) once you've entered all your equations?

file i04408

## Question 69

A common analytical sensor used to detect potentially explosive gases (often called a *LEL analyzer* in reference to "Lower Explosive Limit") is the *catalytic combustible gas sensor*. In this type of sensor, a fine platinum wire is heated by an electric current, and covered by a catalytic substance. If a mixture of flammable gas(es) and air comes into contact with the sensor, the ensuing combustion will cause the platinum wire to heat up, thus increasing the wire's resistance and signaling the presence of a potentially explosive gas.

In this particular LEL analyzer, two identical platinum wire sensors are connected in series, one of them exposed to a steady stream of sample gas and the other sealed where no gas can reach it. The voltages dropped by these two resistance elements are digitized by a pair of analog-to-digital converters (ADCs) and interpreted by a microcontroller:
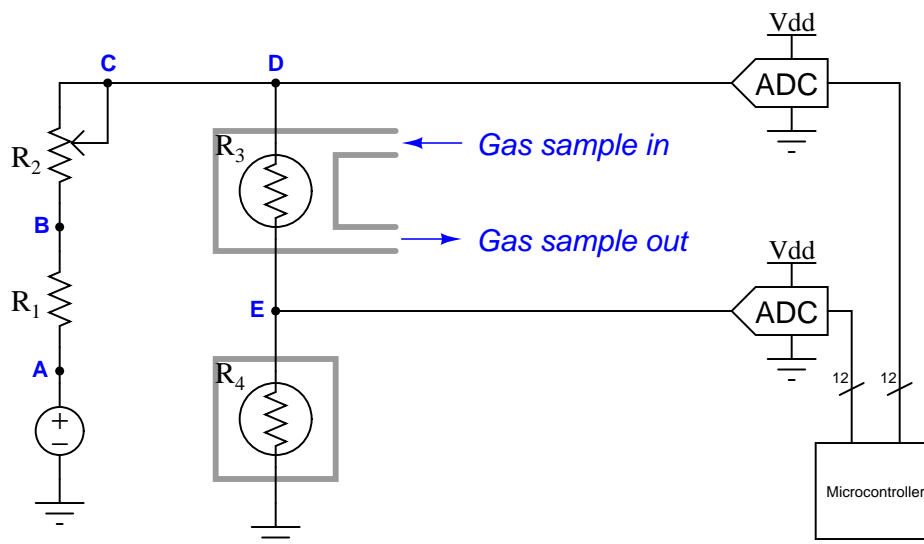


Supposing this circuit is faulty (signaling the presence of explosive gas even when there is no gas present), where would you begin taking diagnostic measurements to isolate the nature of the fault? Under what sample gas conditions would you prefer to perform these measurements, and why?

---

**Suggestions for Socratic discussion**

- Why do you suppose the two catalytic wire sensors are connected in *series* rather than in parallel?
- What are the values of some electrical measurements you would expect to see in a "healthy" circuit, and what might you expect to see in a circuit where the active gas sensor has failed?
- What are some component failures that could cause the microcontroller to see a "hotter" signal for $R_3$ than for $R_4$? What effect would this have on gas detection?
- What are some component failures that could cause the microcontroller to see a "colder" signal for $R_3$ than for $R_4$? What effect would this have on gas detection?
- What would happen if resistor $R_1$ were to fail open?
- What would happen if resistor $R_1$ were to fail shorted?
- What would happen if rheostat $R_2$ were to decrease in resistance?
- What would happen if rheostat $R_2$ were to increase in resistance?
- Why do you suppose the sensor's platinum wire is coated with a *catalyst*?
- This type of LEL sensor is dependent upon the amount of oxygen present in the gas sample. Determine the effect that oxygen concentration will have on this type of analyzer (i.e. will an increased oxygen concentration make the instrument "think" there is *more* or *less* flammable gas present?), and then devise a method by which this interference may be compensated.

74

Question 70

Suppose an ammeter inserted between test point **C** and the nearest lead of resistor $R_2$ registers 10 mA in this series-parallel circuit:



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

| Fault | Possible | Impossible |
|---|---|---|
| $R_1$ failed open | | |
| $R_2$ failed open | | |
| $R_3$ failed open | | |
| $R_1$ failed shorted | | |
| $R_2$ failed shorted | | |
| $R_3$ failed shorted | | |
| Current source dead | | |

---

**Suggestions for Socratic discussion**

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) "why" for every step of your analysis, rather than merely describing those steps.
- This type of problem-solving question is common throughout the Instrumentation course worksheets. What specific skills will you build answering questions such as this? How might these skills be practical in your chosen career?
- An assumption implicit in this activity is that it is more likely a single fault occurred than multiple, coincidental faults. Identify realistic circumstances where you think this would be a valid assumption. Hint: research the philosophical proverb called *Occam's Razor* for more information! Are there any realistic circumstances where the assumption of only one fault would not be wise?

This question is typical of those in the "Fault Analysis of Simple Circuits" worksheet found in the *Socratic Instrumentation* practice worksheet collection (online), except that all answers are provided for those questions. Feel free to use this practice worksheet to supplement your studies on this very important topic.

file i04489

## Question 71

An analog-to-digital converter (ADC) has a calibrated input range of 0 to 10 volts, and a 12-bit output (0 to 4095 "count" range). Complete the following table of values for this converter, assuming perfect calibration (no error):

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| | 0 | | |
| | 25 | | |
| | 50 | | |
| | 75 | | |
| | 100 | | |

file i03823

## Question 72

An analog-to-digital converter (ADC) has a calibrated input range of 0 to 10 volts, and a 16-bit output (0 to 65535 "count" range). Complete the following table of values for this converter, assuming perfect calibration (no error):

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| | 0 | | |
| | 25 | | |
| | 50 | | |
| | 75 | | |
| | 100 | | |

file i03824

## Question 73

A digital pressure transmitter has a calibrated input range of 0 to 75 PSI, and a 14-bit output (0 to 16383 "count" range). Complete the following table of values for this transmitter, assuming perfect calibration (no error):

| Input pressure (PSI) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| | 0 | | |
| | 36 | | |
| | 62 | | |
| | 89 | | |
| | 95 | | |

file i03825

Question 74

A digital level transmitter has a calibrated input range of 20 to 170 inches of liquid level, and a 10-bit output (0 to 1023 "count" range). Complete the following table of values for this transmitter, assuming perfect calibration (no error):

| Input level (inches) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| | 11 | | |
| | 28 | | |
| | 55 | | |
| | 73 | | |
| | 92 | | |

file i03827

Question 75

An analog-to-digital converter (ADC) has a calibrated input range of 0 to 5 volts, and a 12-bit output. Complete the following table of values for this converter, assuming perfect calibration (no error):

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 1.6 | | | |
| | | 3022 | |
| | 40 | | |
| | | | A2F |

**Suggestions for Socratic discussion**

• Calculate the resolution of this ADC in *percent* of full-scale range. In other words, what is the smallest percentage of input signal change it is able to resolve?

file i03822

The following schematic diagram shows two four-bit universal shift registers used to communicate data serially over a coaxial cable of unspecified length:
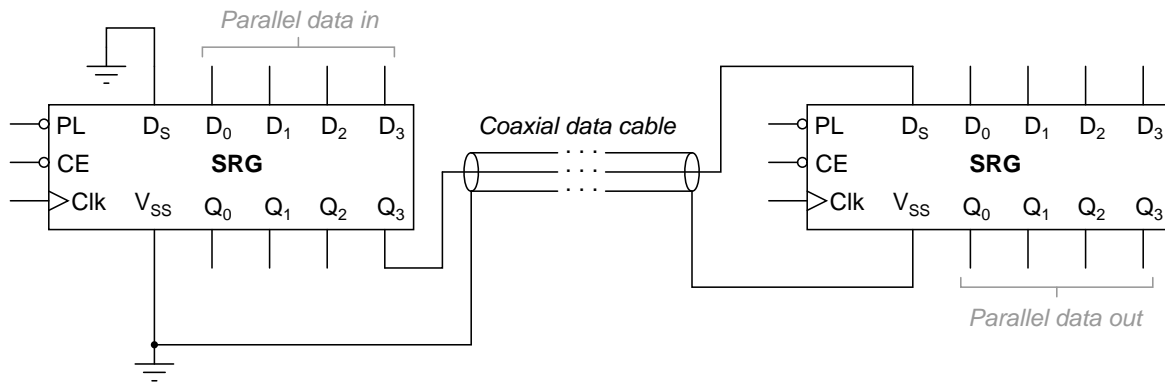


Explain how both registers would be used to transmit four bits of parallel data in serial form over the coaxial data cable.
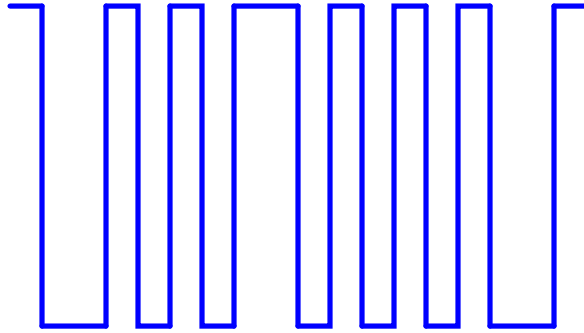
file i02163

Question 77

An important integrated circuit (IC) used in digital data communication is a *UART*. Describe what this acronym stands for, and explain the purpose of this circuit.
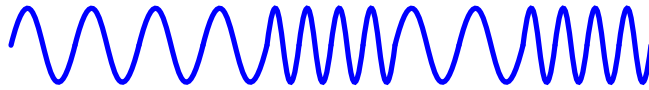
file i02172

Decode the following serial data streams, each one encoded using a different method:

## (Manchester encoding)



## (FSK encoding)

Decode the following serial data streams, each one encoded using a different method:

## (Manchester encoding)
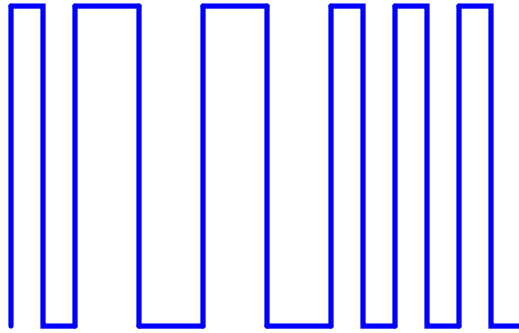


## (FSK encoding)



Suggestions for Socratic discussion

- Assuming a common time scale for both data streams shown, which of the two has the highest *bit rate*?
- Assuming a common time scale for both data streams shown, which of the two has the highest *baud rate*?

file i02919

Question 80

Decode this set of ASCII characters, to reveal a secret message (all codes given in hexadecimal format):

49 20 4C 6F 76 65 20 49 6E 73 74 72 75 6D 65 6E 74 61 74 69 6F 6E 21

file i02176

Question 81

Explain why the following wiring practices are standard:

**Separating power wiring from signal wiring in an enclosure:**

**Using wire duct and/or wire "looms" to organize wires in electrical enclosures:**

This resistor circuit is supposed to function as a precision resistance and voltage divider, for use in a 4-20 mA analog current circuit where one device has a 1-5 volt DC signal input range, and another device has a 0.4-2 volt signal range:
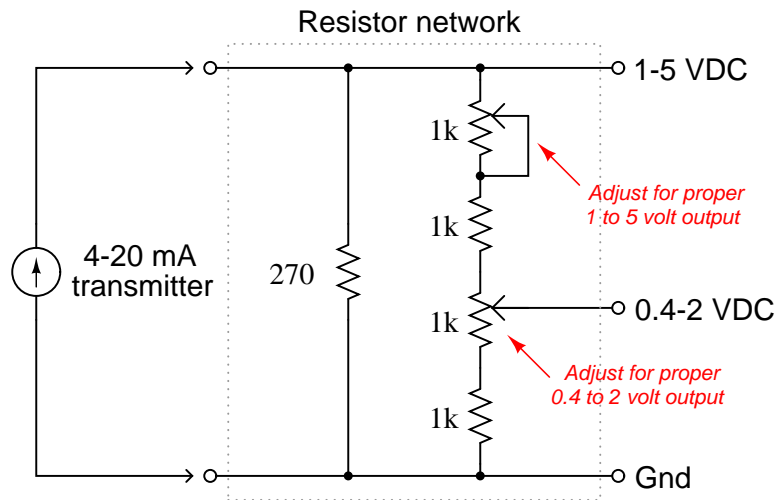


Assume the resistor values shown in the schematic are exact, calculate the required settings for both potentiometers to yield the desired output voltages given a 4 to 20 mA DC input signal range. Also, determine which of these calibrations should be made first, because one of these potentiometer adjustments affects the other (but not vice-versa)!

file i02277

## Question 83

Try to interpret this Manchester-encoded digital signal as viewed on an oscilloscope display, and explain why the task is difficult (or impossible) without further information:
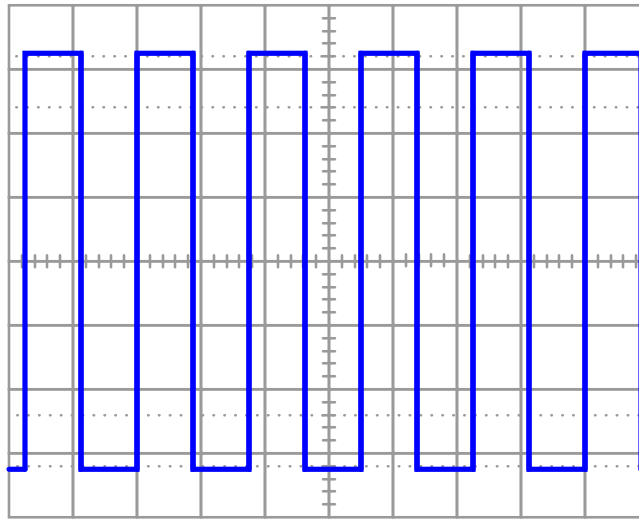
An analog-to-digital converter (ADC) circuit takes an analog input voltage and converts it to an equivalent digital number output. In the following diagram, the ADC inputs an analog voltage between 0 and 5 volts DC and outputs a 10-bit binary value between 0000000000 (at exactly 0 volts input) and 1111111111 (at exactly 5 volts input). Expressing these digital output values in decimal form, the output is 0 "counts" at 0 volts DC input, and 1023 "counts" at 5 volts DC input:
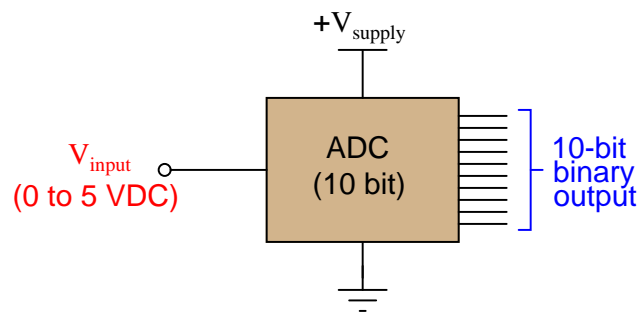


Determine the output of this ADC when it sees an input voltage of 2.502 volts. Express your answer in binary, decimal, and hexadecimal forms. Be sure to show all your work!
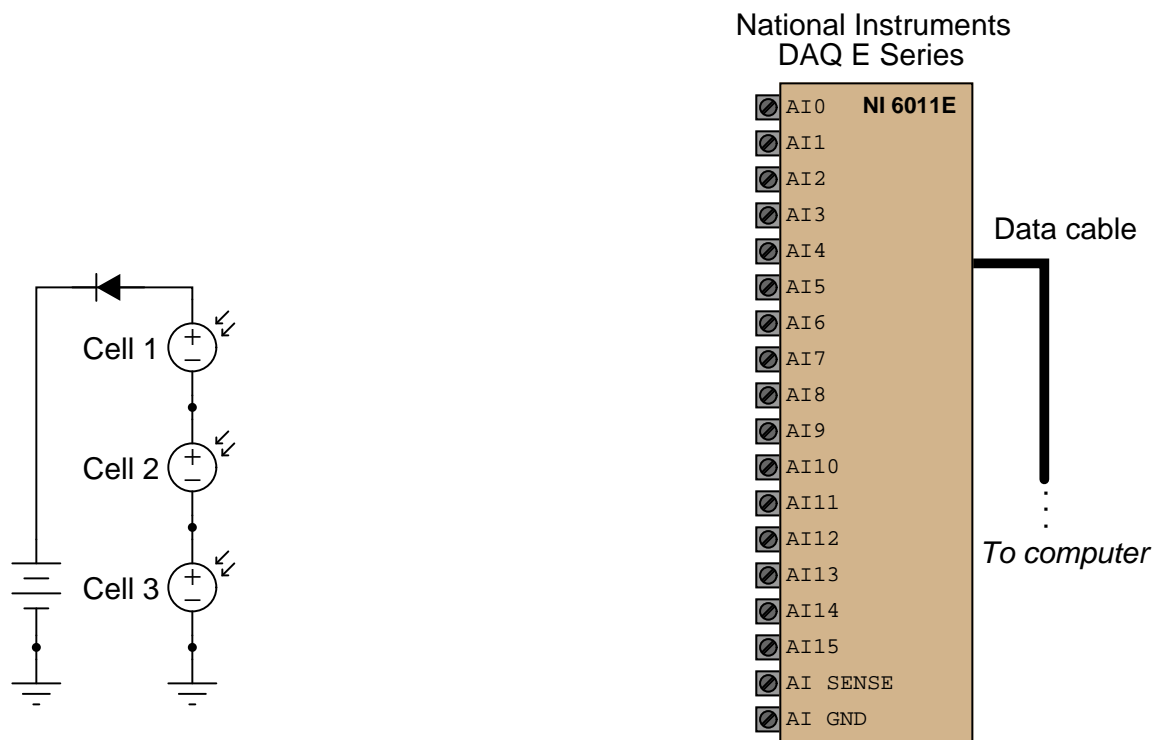
Counts (binary) =

Counts (decimal) =

Counts (hexadecimal) =

Question 85

Identify suitable input terminals, proper modes, and necessary connecting wires to allow this National Instruments E-series data acquisition unit (DAQ) to independently sense the voltages of the three series-connected solar cells shown:

National Instruments
DAQ E Series

NI 6011E

AI0
AI1
AI2
AI3
AI4
AI5
AI6
AI7
AI8
AI9
AI10
AI11
AI12
AI13
AI14
AI15
AI SENSE
AI GND

Data cable

To computer

Cell 1
Cell 2
Cell 3

The available modes for the input channels are RSE, NRSE, and DIFF:

| Channel | Mode | First terminal | Second terminal |
| --- | --- | --- | --- |
| 0 | | | |
| 1 | | | |
| 2 | | | |

file i01616

## Question 86

The resolution of an analog-to-digital or digital-to-analog converter circuit is a function of how many bits of binary data it inputs or outputs. For example, an 8-bit converter resolves the signal into 256 discrete states (counts). The formula for determining the number of counts ($M$) from the number of binary bits ($n$) is as follows:

$$M = 2^n$$

In order to calculate the resultion of a converter circuit in units of *volts* (i.e. how many volts of analog signal each digital "count" value represents), we divide the analog span by the number of digital counts less one:

$$\text{Resolution} = \frac{\text{Span}}{\text{Counts} - 1}$$

Based on this knowledge, write a single mathematical formula solving for the resolution of an analog/digital converter circuit given the analog span and number of bits. Use only the following variables in your formula:

$V_S$ = Analog span (volts)
$V_R$ = Resolution (volts)
$n$ = Number of digital bits

Next, manipulate this formula to solve for the number of bits needed given a specified resolution and span.

file i03618

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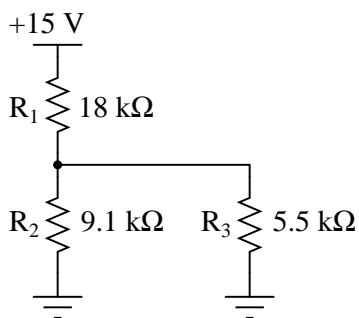


|   | $R_1$ | $R_2$ | $R_3$ | Total |
|---|---|---|---|---|
| V |  |  |  |  |
| I |  |  |  |  |
| R | 18 kΩ | 9.1 kΩ | 5.5 kΩ |  |
| P |  |  |  |  |

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

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

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

file i03147

Question 88

Suppose an ammeter inserted between test points **E** and **D** registers 24 mA in this circuit:
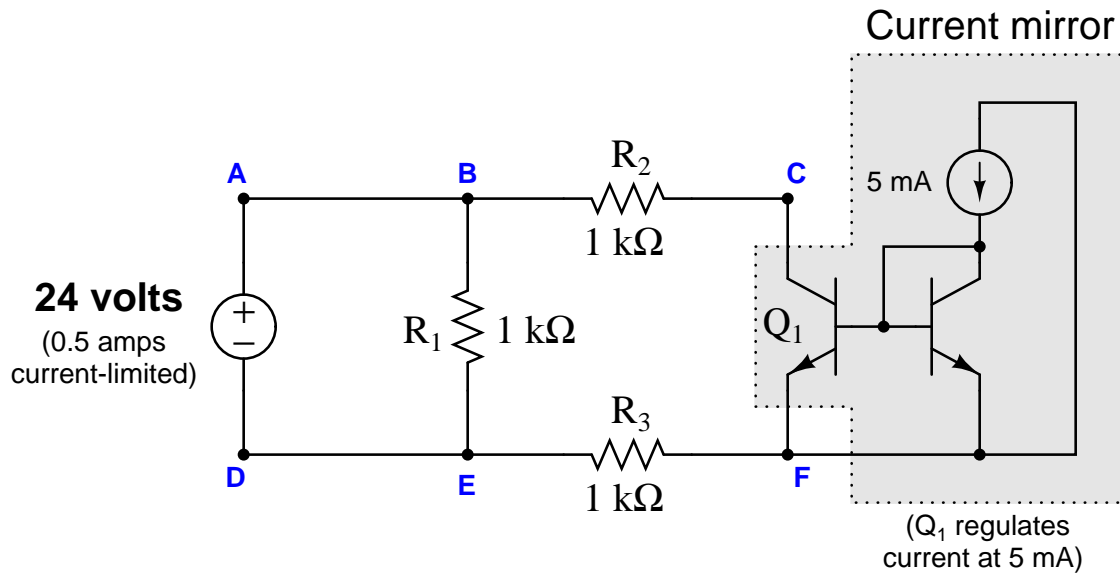


Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

| Fault | Possible | Impossible |
|-------|----------|------------|
| $R_1$ failed open | | |
| $R_2$ failed open | | |
| $R_3$ failed open | | |
| $Q_1$ failed open | | |
| $R_1$ failed shorted | | |
| $R_2$ failed shorted | | |
| $R_3$ failed shorted | | |
| $Q_1$ failed shorted | | |
| Voltage source dead | | |

file i03193

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

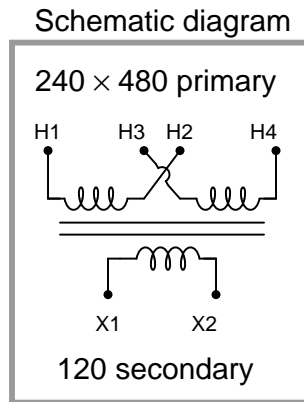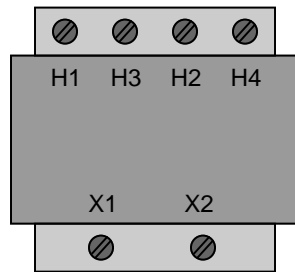(top views)



Relay

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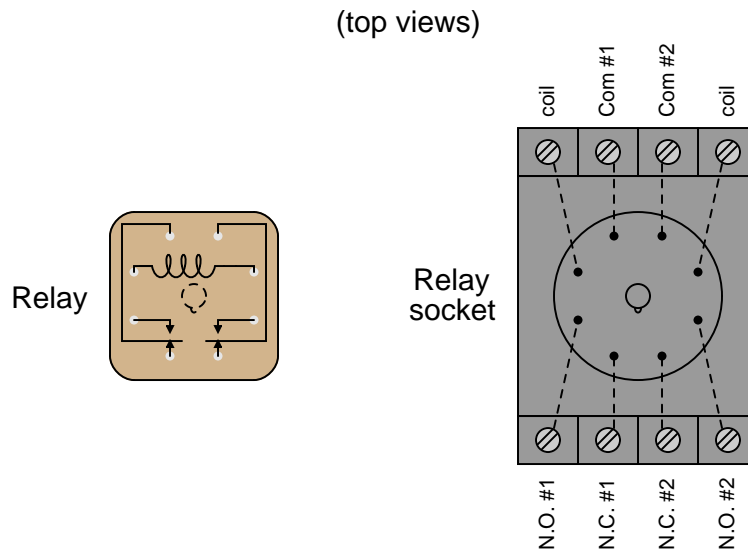
Draw the necessary connecting wires between terminals in this circuit, so that actuating the normally-open pushbutton switch sends power from the battery to the coil to energize the relay:



N.O. switch

Battery

Relay
(plugged into socket)

file i03208
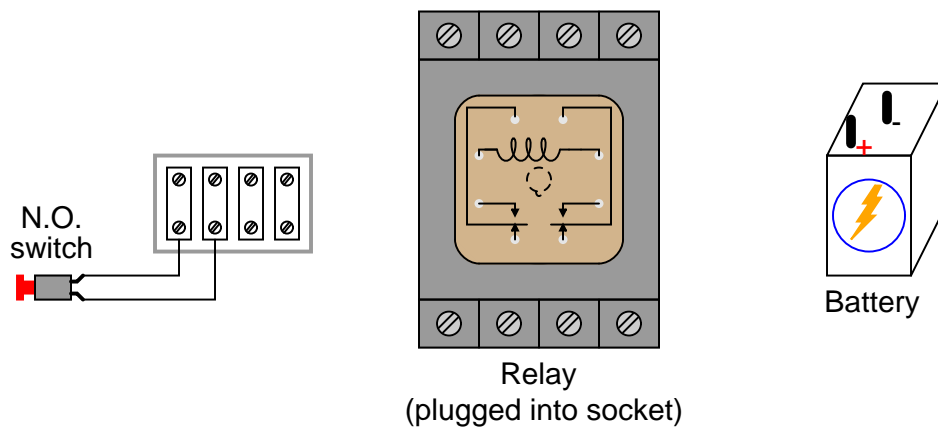
Question 90

A technician brings a control power transformer into your repair shop for diagnosis. It is a dual-voltage primary unit, and was used on the job site to step 480 volts down to 120 volts:

Schematic diagram

240 × 480 primary

H1    H3   H2      H4

120 secondary

X1        X2

H1    H3    H2    H4

X1        X2

According to the person who did the field troubleshooting, the transformer is simply "bad." As is typical, you were given no other information to help diagnose the precise fault. Describe how you would test this transformer in your shop for the following faults, noting the transformer terminals you would connect your multimeter to and the type of meter measurement you would expect to see for each specified fault.

First (left) primary winding failed open

- Meter connected between:
- Measurement expected for this type of fault:

Second (right) primary winding failed open

- Meter connected between:
- Measurement expected for this type of fault:

First (left) primary winding shorted to iron core

- Meter connected between:
- Measurement expected for this type of fault:

Secondary winding shorted to iron core

- Meter connected between:
- Measurement expected for this type of fault:

file i03173

Question 91

**Lab Exercise – introduction**

Your task is to build, document, and troubleshoot a telemetry system consisting of an analog sensor connected to a data acquisition (DAQ) module, which then sends the data over Ethernet to some form of digital display console (e.g. a personal computer running appropriate software, an HMI panel, etc.). Temperature and pressure are suggested process variables to measure. Electric current (measured using a shunt resistor or a current transformer) is another excellent process variable to measure, and this works well to introduce the specialized topic of electric power metering and protection. Other process variables are open for consideration, though.

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

Objective completion table:

| Performance objective | Grading | 1 | 2 | 3 | 4 | Team |
|---|---|---|---|---|---|---|
| Team meeting and prototype sketch (do *first!*) | mastery | – | – | – | – | |
| Circuit design challenge | mastery | | | | | – – – – |
| Final documentation and system inspection | mastery | | | | | – – – – |
| Demonstrate IP "ping" utility | mastery | – | – | – | – | |
| Demonstrate use of a "knockout punch" tool | mastery | – | – | – | – | |
| Accurate measurement of variable (± 1% of span) | mastery | – | – | – | – | |
| Data communicated via Ethernet | mastery | – | – | – | – | |
| Troubleshooting | mastery | | | | | – – – – |
| *Safety and professionalism* | deduction | | | | | |
| *Lab percentage score* | proportional | | | | | – – – – |
| Decommission and lab clean-up | (ungraded) | – | – | – | – | |

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

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

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

**Lab Exercise – objectives and expectations**

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

### Team meeting and prototype sketch

Read the lab exercise documentation and discuss with your teammates the objectives to be achieved and the time allotted to do so. Formulate a plan to achieve these objectives and draft a prototype design for the system you intend to build. Then, meet with your instructor to present your 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 and build either a light-sensing or temperature-sensing circuit from components meeting criteria randomly specified by the instructor, using a digital multimeter (DMM) to record either minimum or maximum signal levels.

### Final loop diagram and system inspection

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

### Demonstration of IP "ping" utility

Correctly use the `ping` command-line utility to test connectivity between two or more IP-networked devices.

### Demonstrate use of a "knockout punch" tool

Safely use a "knockout punch" tool to punch a hole in sheet metal suitable for connection to an electrical conduit fitting.

### Accurate measurement of variable

Demonstrate that your data acquisition system accurately registers the process variable to within $\pm 1\%$ of span over the entire measurement range. This will require you to enter a mathematical formula into the DAQ polling software to convert the "raw" voltage signal into a value representing the real process variable value.

### Data communicated via Ethernet

Demonstrate that your data acquisition system communicates data over an Ethernet network.

### Troubleshooting

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

**Lab Exercise – objectives and expectations** (continued)

### Lab percentage score

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

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

### Safety and professionalism (deduction)

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

## General format and philosophy

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

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

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

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

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

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

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

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

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

Each lab team locker has its own data acquisition unit (DAQ), and other DAQ units are available from the instructor. You will need to install software on a personal computer in order for that computer to gather analog data from the DAQ unit.

It is recommended that you test your DAQ before connecting it to any external circuitry. For a simple test of an analog input, set your multimeter to "Diode Test" so that it outputs a small voltage, then connect your meter leads to one of the analog input channels on the DAQ: the software should register a small voltage on that channel, letting you know the DAQ is functioning.

You will need to choose a suitable sensor to connect to one of the DAQ analog inputs. For greatest accuracy, I recommend using a standard 4-20 mA loop-powered pressure or temperature transmitter, with a 250 ohm resistor connected to the DAQ so it can read a 1-5 volt signal:
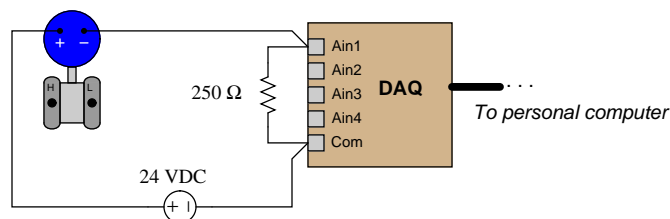
You are also welcome to be more creative and build yourself a simpler analog sensing circuit such as this:
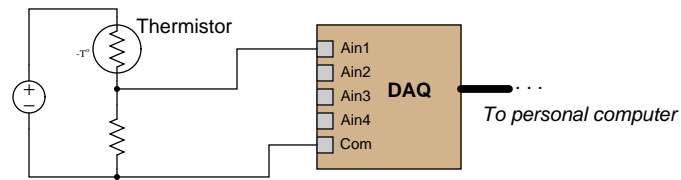
The challenge with a circuit such as this is that it will *not* output a signal that is linearly proportional to temperature like the loop-powered transmitter will. In order to make this work, you will have to program a formula into the DAQ software to "linearize" the voltage signal into a proportional temperature value. This will require extra work on your part to characterize the sensor, then develop a formula describing the signal voltage value as a function of the measured variable. You may find a computer spreadsheet program to be helpful, plotting a curve of voltage versus sensor stimulus (e.g. temperature), then using the curve-fitting utility in the spreadsheet to develop an equation relating voltage to the measurement.
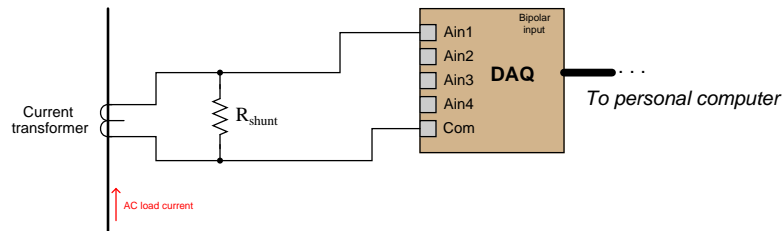
If you choose to build a system to measure AC current using a current transformer (CT, shown above), you will need to select a suitable shunt resistor to drop voltage generated by current output by the CT. This is done by researching the "burden" rating of the CT, which will tell you how large that load resistor may be. CTs act as current sources, and so "want" to drive a low-resistance load (e.g. an ammeter to measure the CT secondary current). However, the DAQ needs to see a strong enough voltage drop across the shunt resistor to use a reasonable percentage of its range, in order to make good use of its resolution. *If you build this circuit, you must be sure to do so in a way that the CT's secondary winding will never become open-circuited when load current goes through it! Open-circuited current transformers are capable of generating dangerously high voltages!!!*

For any application, it is extremely important to check the input ratings of your DAQ unit to ensure they are appropriate for the measurement task, and also check to see that the *absolute maximum* ratings are such that the DAQ will not become damaged in the event of any single-component failure. For example, if your DAQ happens to have an absolute maximum input voltage rating of 20 volts and your circuit could potentially apply 24 volts to the DAQ input in the event of a particular component fault, it means you must re-design your circuit to prevent this ever from happening.

**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**

Build a simple circuit using either a light sensor (photocell) or a temperature sensor (thermistor) connected to a fixed-value resistor and a battery such that a variable output voltage will be generated as the sensor is stimulated. Your circuit must either make the voltmeter indication increase with increasing sensor stimulus (more voltage for more light or heat – direct action), or do the exact opposite (reverse action), as specified by the instructor. You will also need to demonstrate how to record and display the lowest and highest voltages output by this circuit using your digital multimeter's "min/max" recording function function. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) "Alligator" clips are permitted for making connections to battery terminals only.

This exercise tests your ability to properly identify the operating characteristics of a light or temperature sensor, properly size a resistor to form a voltage divider circuit with the sensor, properly connect a voltmeter into the circuit to achieve the specified response direction, properly use a DMM to capture minimum and maximum voltage values, and use a terminal strip to organize all electrical connections.



Thermistor     Photocell     Terminal strip     Battery
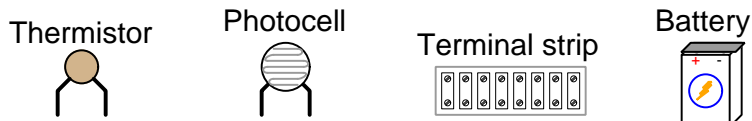
The following components and materials will be available to you: assorted CdS **photocells** and **thermistors** ; **terminal strips** ; lengths of **hook-up wire** ; **battery**. You must provide resistor(s), your own tools, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test circuit without any power sources at all; (3) Instructor provides battery and observes you energizing the circuit for the very first time; (4) You demonstrate to the instructor that the circuit fulfills its intended function. (5) You demonstrate how to capture the minimum or maximum value using your DMM.

**Sensor type** (instructor chooses):          ____ Photocell          ____ Thermistor

**Meter response** (instructor chooses):          ____ Direct          ____ Reverse

**Captured value** (instructor chooses):          ____ $V_{minimum}$          ____ $V_{maximum}$

**Lab Exercise – building the system**

The Instrumentation lab is set up to facilitate the construction of working instrument "loops," with over a dozen junction boxes, pre-pulled signal cables, and "racks" set up with 2-inch vertical pipes for mounting instruments. The only wires you should need to install to build a working system are those connecting the field instrument to the nearest junction box, and then small "jumper" cables connecting different pre-installed cables together within intermediate junction boxes.

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. All wire connections should be made using terminal blocks. No twisted or taped wire connections will be allowed.

You will need to configure the DAQ software to "scale" the 1-5 VDC signal into an actual measurement of your process variable (e.g. temperature, pressure). A requirement of this lab is that the DAQ software accurately register the process variable you are measuring, rather than merely displaying a voltage value from the sensor.

The DAQ provided in your team's tool locker is equipped with its own Ethernet port, which means you may use any Ethernet-equipped personal computer to run the DAQ software and poll data from the DAQ unit over the lab's Ethernet network. For those teams interested in learning Modbus programming and familiar with programming the lab's caSCADA system(s), I recommend writing C-language code to poll data from a Modbus-compliant DAQ and executing that code in any computer with a C compiler. Examples of Modbus programming using the `libmodbus` library are shown in the Modbus section of the *Lessons In Industrial Instrumentation* textbook.

Your chosen system may require its own electrical enclosure to house the DAQ and/or other components, not already a part of the lab's permanently-installed loop system. If you need to punch a hole in the side of a custom enclosure as part of your system, you must use a special tool called a *knockout punch* to make these holes (rather than use a hole saw on a drill). The Greenlee company manufactures a line of knockout punches called the *Slug Buster*, which you may wish to research in preparing to use this tool.

**Common mistakes:**

- Starting to build the circuit before planning its construction on paper with a proposed circuit sketch.
- Failing to heed signal voltage limits for the DAQ analog input channels. *Be careful not to over-power the DAQ with signal voltages exceeding its measurement limits!*
- Failing to tug on each and every wire where it terminates to ensure a mechanically sound connection.
- Students working on portions of the system in isolation, not sharing with their teammates what they did and how. It is important that the whole team learns all aspects of their system!

**Building a functioning system should take no more than one full lab session (3 hours) if all components are readily available and the team is working efficiently!**

**Lab Exercise – documenting the system**

Each student must sketch their own *system diagram* for their team's data acquisition system. This will not be an ISA-standard loop diagram, but rather a combination of schematic diagram (showing the sensor and DAQ connections) and block diagram (showing the computer Ethernet network complete with IP addresses). Your diagram must be *comprehensive* and *detailed*, showing every wire connection, every cable, every terminal block, range points, network addresses, etc.

An example system diagram is shown here:
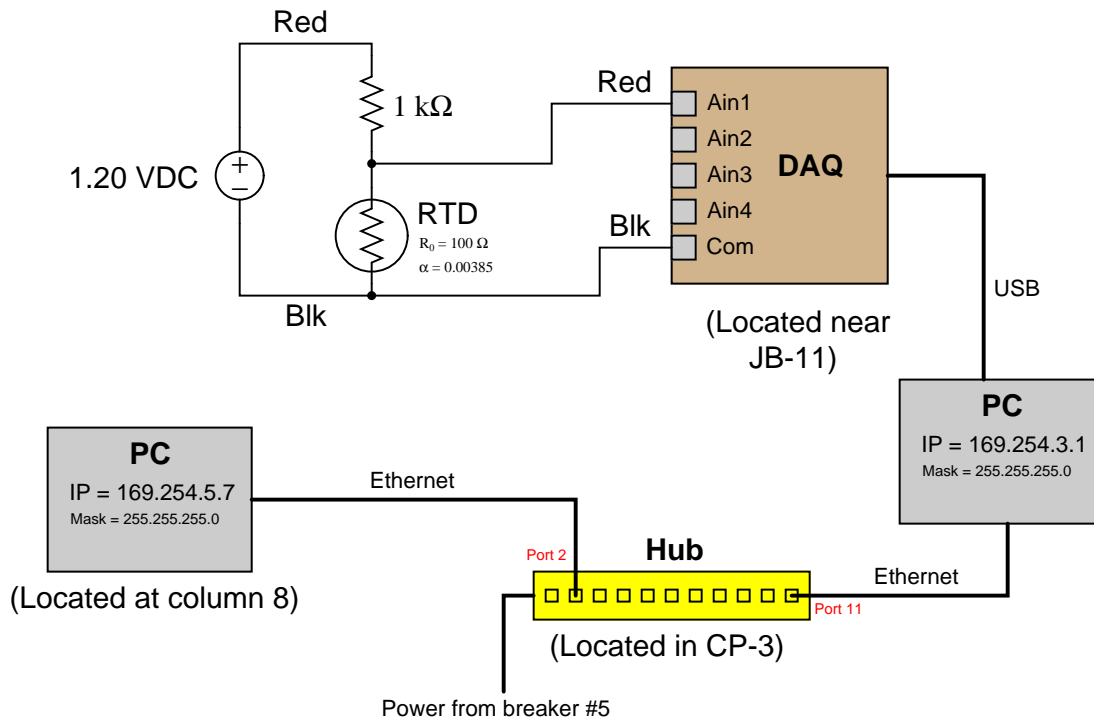


Note that if using an Ethernet-equipped DAQ unit, the DAQ will be able to plug directly into the Ethernet hub without need for an intermediary computer (e.g. 169.254.3.1 shown in this diagram.)

When your entire team is finished drafting your individual diagrams, call the instructor to do an inspection of the system. Here, the instructor will have students take turns going through the entire system, with the other students checking their diagrams for errors and omissions along the way. During this time the instructor will also inspect the quality of the installation, identifying problems such as frayed wires, improperly crimped terminals, poor cable routing, missing labels, lack of wire duct covers, etc. The team must correct all identified errors in order to receive credit for their system.

After successfully passing the inspection, each team member needs to place their system diagram in the diagram holder located in the middle of the lab behind the main control panel. When it comes time to troubleshoot another team's system, this is where you will go to find a diagram for that system!

**Common mistakes:**

- Forgetting to label all signal wires.
- Forgetting to note all wire colors.
- Forgetting to put your name on the diagram!
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.
- Not placing instruments in the correct orientation (field instruments on the left, control room instruments on the right).

## Notes on DAQ signal scaling/linearization

Each team must configure their DAQ system to accurately report the measured variable in appropriate units of measurement. The measurement accuracy will be checked by the instructor by applying random stimuli to the sensor while the team verifies the remote indication (on a computer connected through the network to the DAQ module). DAQ polling software contains a provision for entering your own mathematical scaling formula to perform this function.

If your system uses a loop-powered 4-20 mA transmitter, the only DAQ configuration you will need to do is "scale" the DAQ so that it converts the linear 1-5 VDC signal into a linear representation of the measured variable. However, you will need to rely on those teammates who have taken the INST24X courses to calibrate the transmitter so that it accurately outputs the 4-20 mA signal.

If your system reads a raw voltage signal from a resistive sensor in a bridge or other voltage-divider network, you will need to program the DAQ software to "linearize" the signal so that it will register the actual process variable and not just a plain signal voltage. The following screenshot shows how a computer spreadsheet may be used to generate a linearizing equation from published sensor data:
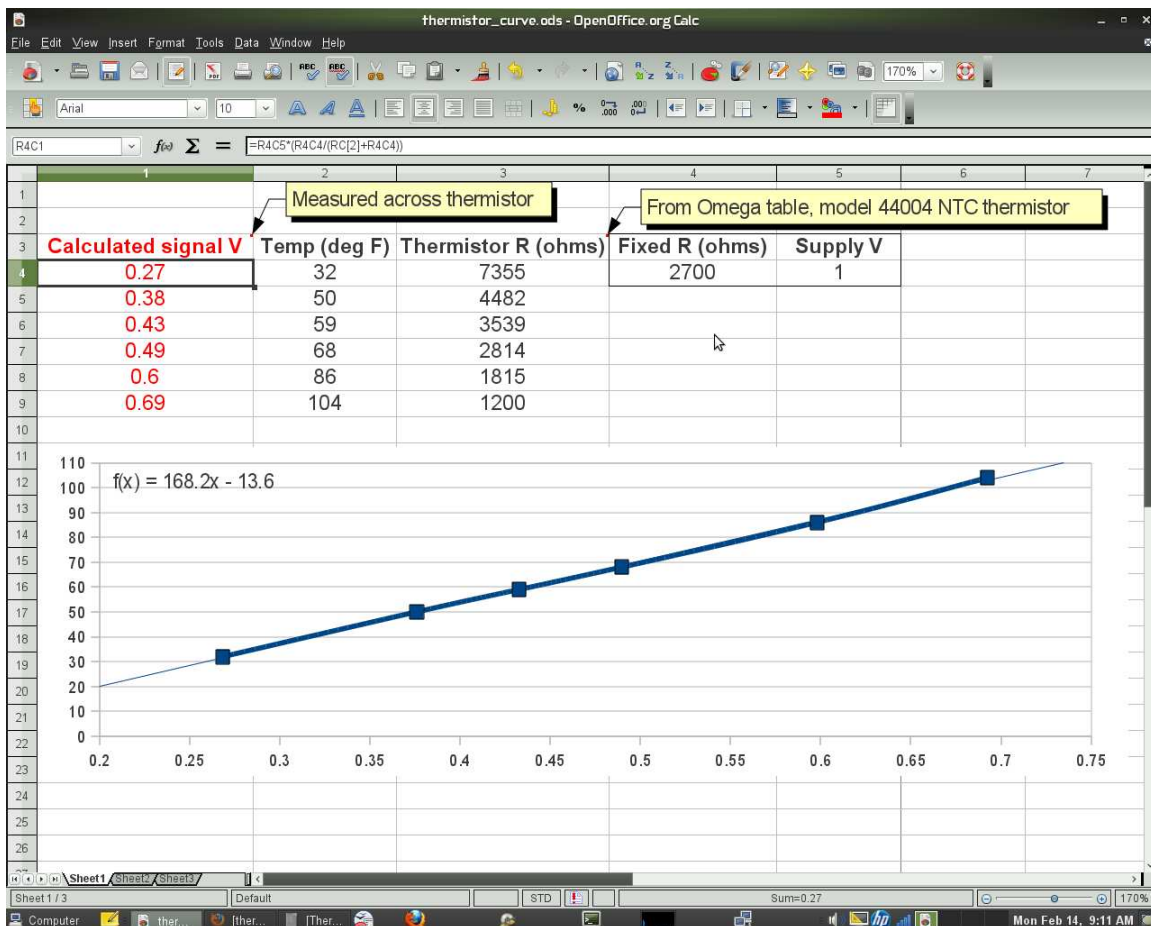


In this particular example, the sensor is a negative temperature coefficient (NTC) thermistor, model 44004, manufactured by Omega. The formula entered into cells R4C1 through R9C1 calculates the voltage dropped across a fixed resistor (2700 $\Omega$) connected in series with the thermistor and powered by a 1 volt DC source, using the voltage divider equation ($V_R = V_{source} \frac{R}{R_{total}}$). The thermistor resistance values seen in column 3 were taken from an Omega-published table for the model 44004 thermistor. A "scatter" plot graphs temperature as a function of voltage, and a "trendline" plotted by the spreadsheet program attempts to match the data points to a mathematical formula. In this particular case, the fitted formula happens to

be Temp = 168.2 * (Voltage) − 13.6. It is this formula you must enter into the DAQ software, so it knows how to translate the measured voltage signal into a temperature value.

If the sensor you choose does not have a data table describing its characteristics, you may generate your own by subjecting it to known stimuli and measuring its resistance at those known values. Then, you may use a spreadsheet to plot the voltage response and derive an equation to fit the data.

Another huge advantage of using a computer spreadsheet to model the signal voltage as a function of temperature is that it allows you to "experiment" with different values of fixed resistance, to see the effect it has on linearity. By entering a new fixed-resistor value into the spreadsheet, you may immediately see the effect that value change has on the curvature of the scatter plot, as well as the effect it has on the signal voltage strength.

**Common mistakes:**

- Choosing a poor-accuracy calibration standard (e.g. trying to calibrate your $1500 precision Rosemount pressure transmitter to ± 0.1 PSI using a $30 pressure gauge that only reads to the nearest 5 PSI!).
- Improperly configuring the spreadsheet scatter plot to generate a fitted equation (e.g. having variables on wrong axes)

**Characterizing your sensor and scaling the DAQ software should take no more than one full lab session (3 hours) if the team is working efficiently!**

**Lab Exercise – Ethernet data transfer**

An essential part of this lab exercise is to have the acquired data transported over an Ethernet network. Each team's tool locker DAQ is equipped with an Ethernet port, and software is freely available for polling data over Ethernet using any personal computer. You are encouraged to install this free software on your own laptop PC and experiment with it independent of your teammates. Part of the capstone challenge at the end of every quarter (for those students who have completed this course) will include use of a DAQ on your own personal computer.

If you are familiar with C-language programming, there is a free C library called `libmodbus` which may be used to write your own data polling software to acquire data from any Modbus-compliant DAQ unit. Examples of Modbus programming using the `libmodbus` library are shown in the Modbus section of the *Lessons In Industrial Instrumentation* textbook. Writing your own polling code is fairly advanced DAQ usage, but is certainly within the capabilities of any student who has programmed any of the lab's caSCADA systems. A convenient computing platform to use for this code-writing is a Raspberry Pi, a single-board computer running the Linux operating system that is available for very modest cost.

Another Ethernet-related objective in this lab exercise is using the `ping` utility to test for network connections. When two personal computers have been successfully connected to a common Ethernet network, you should be able to "ping" one computer from the other by invoking the `ping` utility with the IP address of the destination computer as an argument to the `ping` command. The ping query and response is part of the ICMP (Internet Control Message Protocol) specified in RFC 792. You may run the `ping` command from a command-line window on a Microsoft Windows operating system. More detailed instructions on the use of `ping` may be found in your *Lessons In Industrial Instrumentation* textbook.

A successful "ping" from one computer to another is a *necessary* condition for remote viewing of that computer's display, but it is not a *sufficient* condition. That is to say, although a computer that refuses to "ping" is definitely not ready to be logged into remotely, a computer that does "ping" without trouble may not necessarily be ready for remote login. Getting a successful "ping" from a computer is merely the first step in establishing full communication with it.

If a "ping" attempt proves unsuccessful, it means something is inhibiting communication between that device and the computer you're using to issue the ping. A good test to do in this circumstance is try "pinging" other devices on that same network. Any successful ping attempts will definitively prove OSI layers 1, 2, and 3 are all functional between those two points, since "ping" requires those three layers to function. Once you know which portion(s) of the network are functional, you may narrow the field of fault possibilities.

Network functions above OSI layer 3 (e.g. "firewall" software running on personal computers) are capable of inhibiting communication between devices on the lab's Ethernet network, including "ping" messages. For example, a firewall configured with a rule to drop or reject any ICMP communications will block all "ping" queries. If you decide to connect your own personal computer (laptop) to the lab's Ethernet network, you may find it easier to temporarily disable all security features on your personal computer to enable free and open communication between your computer and all other devices on the network. Just be sure to re-enable the security features when you are done, so your computer will not be unprotected the next time you connect to the Internet!

**Lab Exercise – troubleshooting**

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

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

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

Failure to correctly identify both the general location and nature of the fault within the allotted time, and/or failing to demonstrate rational diagnostic procedure to the supervising instructor will disqualify the effort, in which case the student must re-try with a different fault.

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

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

**Common mistakes:**

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

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

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

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

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

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

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

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

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

Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.
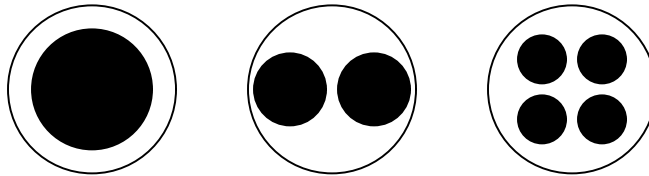
file i00350

Answer 1

Answer 2

Answer 3

Answer 4

Answer 5

Answer 6

Here is a hint:



Answer 7

**Partial answer:**

- NEMA 4: *Intended for indoor or outdoor use, including "washdown" with a water hose.*
- NEMA 6: *Same as NEMA 4, but also protects against temporary submersion at a limited depth.*

Answer 8

Answer 9

**Summary of principles:**

- Conservation of Energy
  - → Energy cannot be created or destroyed

- Conservation of Electric Charge
  - → Electric charges cannot be created or destroyed

- Properties of a series network
  - → Definition: *only one path for electric current*
  - → Current the same through each component (Conservation of Electric Charge)
  - → Voltages add to equal the total (Conservation of Energy)
  - → Resistances add to equal to total

- Properties of a parallel network
  - → Definition: *each component connected across the same two sets of electrically common points*
  - → Voltage the same across each component (Conservation of Energy)
  - → Currents add to equal the total (Conservation of Electric Charge)
  - → Resistances diminish to equal to total

- Kirchhoff's Voltage Law (KVL)
  - → A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)

- Kirchhoff's Current Law (KCL)
  - → Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)

- Ohm's Law
  - → The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it: $V = IR$

- Capacitance and Inductance
  - → The ability to store energy in and retrieve energy from electric fields and magnetic fields, respectively
  - → Current through capacitance is equal to the product of its capacitance and the rate-of-change of voltage across it: $I = C\frac{dV}{dt}$
  - → Voltage across inductance is equal to the product of its inductance and the rate-of-change of current through it: $V = L\frac{dI}{dt}$

Answer 10

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

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

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

| Diagnostic test | Yes | No |
|---|---|---|
| Measure $V_{CF}$ | | $\checkmark$ |
| Measure $V_{ED}$ | | $\checkmark$ |
| Measure $V_{AB}$ | $\checkmark$ | |
| Measure $V_{AD}$ | $\checkmark$ | |
| Measure $V_{CB}$ | $\checkmark$ | |
| Measure $V_{EF}$ | | $\checkmark$ |
| Measure current through wire connecting **A** and **C** | | $\checkmark$ |
| Jumper **A** and **C** together | $\checkmark$ | |
| Jumper **B** and **D** together | $\checkmark$ | |
| Jumper **A** and **B** together | | $\checkmark$ |

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

---

Answer 11

Cut the length of the new wire so it is long enough to relocate to *any* terminal in the strip if it later must be moved:

Answer 12
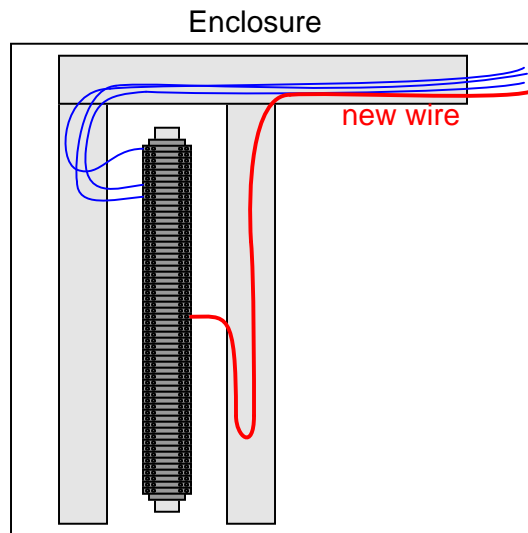
The middle installation, with the shield wire connected to ground at both ends is incorrect. This forms a ground loop as such:
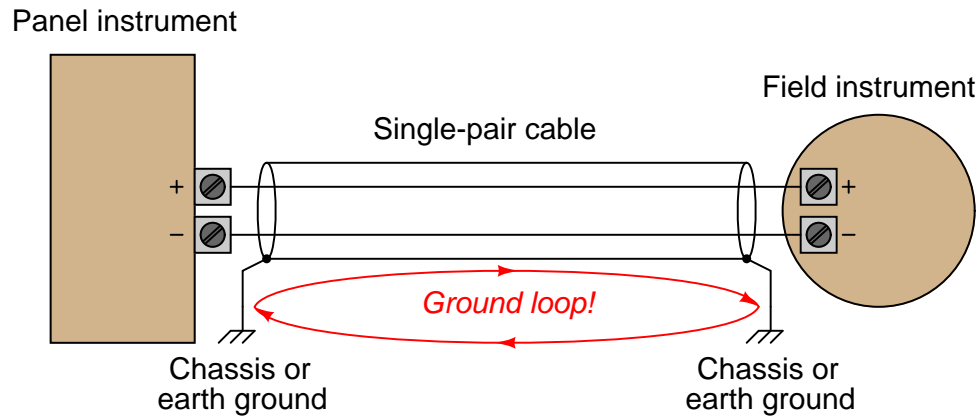


The existence of a ground loop permits the formation of an electric current through the shield wire. This, in turn, creates a magnetic field in close proximity to the signal wires which can induce a significant amount of common-mode noise. This may be problematic even in differential signaling systems if the induced common-mode voltage is excessive.

Of the two remaining (acceptable) installations, the one with the cable shield grounded at the panel is generally preferred, if for no other reason than it allows for quick and easy inspection of shield ground connections at one physical location. Grounding at a common point also eliminates the possibility of different cables having shield wires at different potentials inside the panel, which could pose a safety hazard to technicians working in the panel in certain industrial applications where ground current leakage from high-power devices may cause significant variations in earth ground potential at different sites around the facility.

Answer 13

The grey plastic piece is a conduit *bushing*:



Bushings protect wires from chafing against sharp corners on the conduit connector, as the wires exit the connector and go in different directions inside an enclosure. There are some cases where bushings may serve double-duty as wire protectors and locknuts, but their best application is purely to cover sharp edges and not to bear mechanical load.

Answer 14

- Ease of assembly: **Plastic**
- Resistance to corrosive gases/liquids: **Plastic**
- Minimal material cost (assuming other factors do not take precedence): **Plastic**
- Best shielding from electromagnetic interference: **Metal**
- Maximum physical strength: **Metal**
- Tightest sealing against vapor/liquid intrusion: **Plastic**

Answer 15

- Covers left off of many wire ducts.
- It looks like someone didn't even attempt to put some of the wires inside wire ducts, but instead left them draped directly over components.
- In areas where there are no wire ducts, the wires should have been "loomed" together instead of randomly strewn.
- Junk items left on the bottom of the cabinet.
- Colored stains on the wire duct (on the left-hand side of the photograph, on the cabinet door) suggest liquid intrusion into the cabinet, most likely from a lack of proper door-to-cabinet sealing.

Answer 16

The ground wire connection makes the metal case of the appliance electrically common with earth ground.

Answer 17

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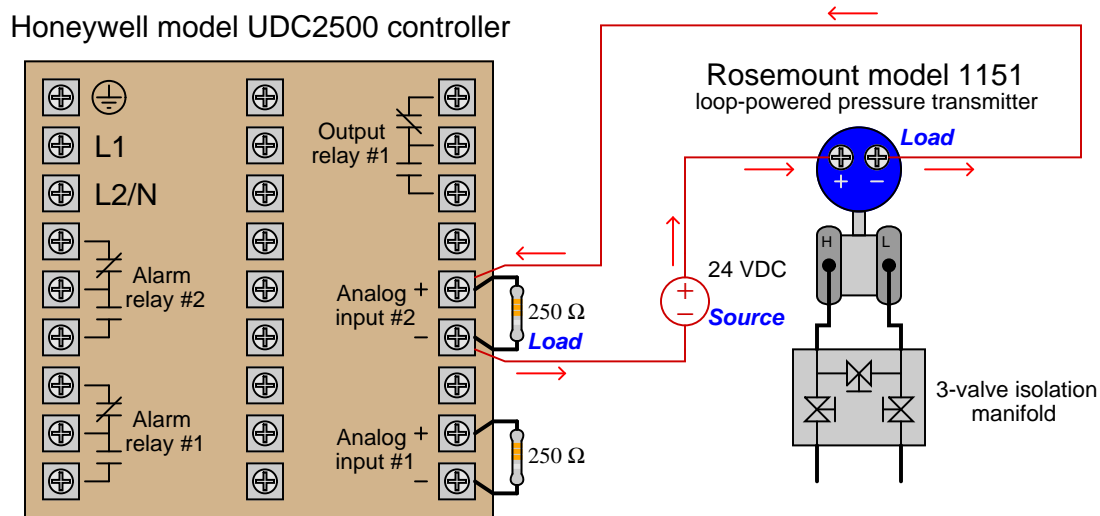


Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

Answer 23

**Partial answer:**

Unsigned:
• FFFF (hexadecimal) = **65535** (decimal)

Signed:
• FFFF (hexadecimal) = **−1** (decimal)

Answer 24

Answer 25

Count = 180 (rounding low) or 181 (rounding high)

Answer 26

**Partial answer:**

| DC input voltage | Binary count | Hex count | Decimal count |
|---|---|---|---|
| 0.0 volts | 00000000 | | |
| 1.0 volts | 00110011 | | 51 |
| 2.2 volts | 01110000 | 70 | 112 |
| 3.51 volts | 10110011 | B3 | 179 |
| 4.0 volts | 11001100 | CC | 204 |
| 5.0 volts | 11111111 | FF | |

Answer 27

**Partial answer:**

Pages 28 and 29: this card may connect to loop-powered (2-wire) 4-20 mA devices as well as self-powered (4-wire) devices. Three connection terminals are provided per channel: a positive voltage terminal (VOUT), an input terminal (IN), and a ground (RTN).

3106.8 counts per mA (equivalent to 0.3 microamps per count).

Answer 28

**Partial answer:**

The ADC circuit was designed to output a *signed* 16-bit integer value where 4.00 mA would be converted into a value of 0000h and 20.00 mA would be converted into a value of FFFFh. The control instructions running in the PLC program, meanwhile, interpreted this count value as an *unsigned* 16-bit binary quantity. The problem didn't reveal itself until the fateful day when the flow transmitter's calibration drifted enough to make the current signal 3.99 mA at zero flow rather than 4.00 mA at zero flow. Recognizing the way the ADC inside the analog input card interpreted this 3.99 mA signal is the key to understanding why the system failed.

Follow-up question: explain why it would be prudent to adjust the flow transmitter's zero slightly higher than 4.00 mA at zero flow to help avoid this problem in the future.

Answer 29

"Phantom" AC voltage measurements are caused by capacitive coupling between adjacent wires, which along with the DMM's extremely large input impedance (millions of ohms) forms a voltage divider so that the meter will register a substantial fraction of the AC line voltage.

Answer 30

| Binary | Octal | Decimal | Hexadecimal |
|---|---|---|---|
| 10010 | 22 | 18 | 12 |
| 1011100 | 134 | 92 | 5C |
| 11010 | 32 | 26 | 1A |
| 110111 | 67 | 55 | 37 |
| 1100101 | 145 | 101 | 65 |
| 100100010 | 442 | 290 | 122 |
| 1111101000 | 1750 | 1000 | 3E8 |
| 11011110 | 336 | 222 | DE |
| 1011010110 | 1326 | 726 | 2D6 |

Answer 31

- $10_2 = 2_{10}$
- $1010_2 = 10_{10}$
- $10011_2 = 19_{10}$
- $11100_2 = 28_{10}$
- $10111_2 = 23_{10}$
- $101011_2 = 43_{10}$
- $11100110_2 = 230_{10}$
- $10001101011_2 = 1131_{10}$

Answer 32

- $7_{10} = 111_2$
- $10_{10} = 1010_2$
- $19_{10} = 10011_2$
- $250_{10} = 11111010_2$
- $511_{10} = 111111111_2$
- $824_{10} = 1100111000_2$
- $1044_{10} = 10000010100_2$
- $9241_{10} = 10010000011001_2$

## Answer 33

There are only eight valid ciphers in the octal system (0, 1, 2, 3, 4, 5, 6, and 7), with each successive place carrying eight times the "weight" of the place before it.

- $35_8$ into decimal: $29_{10}$

- $16_{10}$ into octal: $20_8$

- $110010_2$ into octal: $62_8$

- $51_8$ into binary: $101001_2$

## Answer 34

There are sixteen valid ciphers in the hexadecimal system (0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, and F), with each successive place carrying sixteen times the "weight" of the place before it.

- $35_{16}$ into decimal: $53_{10}$

- $34_{10}$ into hexadecimal: $22_{16}$

- $11100010_2$ into hexadecimal: $E2_{16}$

- $93_{16}$ into binary: $10010011_2$

Follow-up question: why is hexadecimal considered a "shorthand" notation for binary numbers?

## Answer 35

Step 1: $10_{16}$
Step 2: $30_{16}$
Step 3: $20_{16}$
Step 4: $60_{16}$
Step 5: $40_{16}$
Step 6: $C0_{16}$
Step 7: $80_{16}$
Step 8: $90_{16}$

Follow-up question: write the same sequence in decimal rather than hexadecimal:

Step 1:
Step 2:
Step 3:
Step 4:
Step 5:
Step 6:
Step 7:
Step 8:

*Binary place-weights*

$1001.1011_2 = 9.6875_{10}$

| $\dfrac{1}{2^3}$ | $\dfrac{0}{2^2}$ | $\dfrac{0}{2^1}$ | $\dfrac{1}{2^0}$ | • | $\dfrac{1}{2^{-1}}$ | $\dfrac{0}{2^{-2}}$ | $\dfrac{1}{2^{-3}}$ | $\dfrac{1}{2^{-4}}$ |

*Octal place-weights*

$4027.3612_8 = 2071.471191406_{10}$

| $\dfrac{4}{8^3}$ | $\dfrac{0}{8^2}$ | $\dfrac{2}{8^1}$ | $\dfrac{7}{8^0}$ | • | $\dfrac{3}{8^{-1}}$ | $\dfrac{6}{8^{-2}}$ | $\dfrac{1}{8^{-3}}$ | $\dfrac{2}{8^{-4}}$ |

*Hexadecimal place-weights*

$C1A6.32B9_{16} = 49574.198135376_{10}$

| $\dfrac{C}{16^3}$ | $\dfrac{1}{16^2}$ | $\dfrac{A}{16^1}$ | $\dfrac{6}{16^0}$ | • | $\dfrac{3}{16^{-1}}$ | $\dfrac{2}{16^{-2}}$ | $\dfrac{B}{16^{-3}}$ | $\dfrac{9}{16^{-4}}$ |

Answer 37

| Binary | Octal | Decimal | Hexadecimal |
|---|---|---|---|
| 101.011 | 5.3 | 5.375 | 5.6 |
| 11001.001 | 31.146 | 25.2 | 19.333 |
| 100.101 | 4.54 | 4.687 | 4.B |
| 111010.101 | 72.52 | 58.656 | 3A.A8 |
| 1011.101 | 13.5 | 11.625 | B.A |
| 10101100.000 | 254.042 | 172.066 | AC.11 |
| 1110100110.110 | 1646.624 | 934.79 | 3A6.CA3 |
| 110100001.111 | 641.7 | 417.875 | 1A1.E |
| 101100.1 | 54.4 | 44.5 | 2C.8 |

Answer 38

- byte = 8 bits
- nybble = 4 bits
- word = *depends on the system*

The term "word," is often used to represent 16 bits, but it really depends on the particular system being spoken of. A binary "word" is more accurately defined as the default width of a binary bit grouping in a digital system.

Follow-up question: what binary grouping corresponds to a single hexadecimal character?

Answer 39

$-1.0000111000000110000000 \times 2^{-83}$

$+1.1101011000000000000000000 \times 2^{77}$

$+0.1111110000011000100000 \times 2^{-126}$

The number 1 is represented as follows (literally, $1.0 \times 2^{127-127}$):

| Sign | Exponent ($E$) | Mantissa ($m$) |
|---|---|---|
| 0 | 01111111 | 00000000000000000000000 |

Answer 40

**Calibration table for process variable signal (ADC)**

| Measurement | Digital output |
|---|---|
| 0 GPM | $0000 |
| 100 GPM | **$8000** |
| 200 GPM | $FFFF |

**Calibration table for output signal (DAC)**

| Measurement | Digital output |
|---|---|
| $0000 | 0 PSI |
| **$2666** | 9 PSI |
| $3FFF | 15 PSI |

Answer 41

Answer 42

$R_G = 1.724$ k$\Omega$ for a gain of $30 = 29.54$ dB

$$R_G = \frac{50000}{A_v - 1}$$

Answer 43

The NI 6020E DAQ uses 12-bit (4096 count) conversion. The NI 6052E uses 16-bit (65,536 count) conversion.

Answer 44

Answer 45

**Partial answer:**

This DAQ uses *single-ended* inputs.

Answer 46

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

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

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

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

```
tar xvf tshoot*tar

make
```

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

```
./tshoot
```

Answer 47

Strain gauges increase resistance with increasing tension. If we want this to make an increasing positive signal for the DAQ to see, we must connect the (+) input to the positive side of the strain gauge, and connect the (−) input to the other side of the bridge.
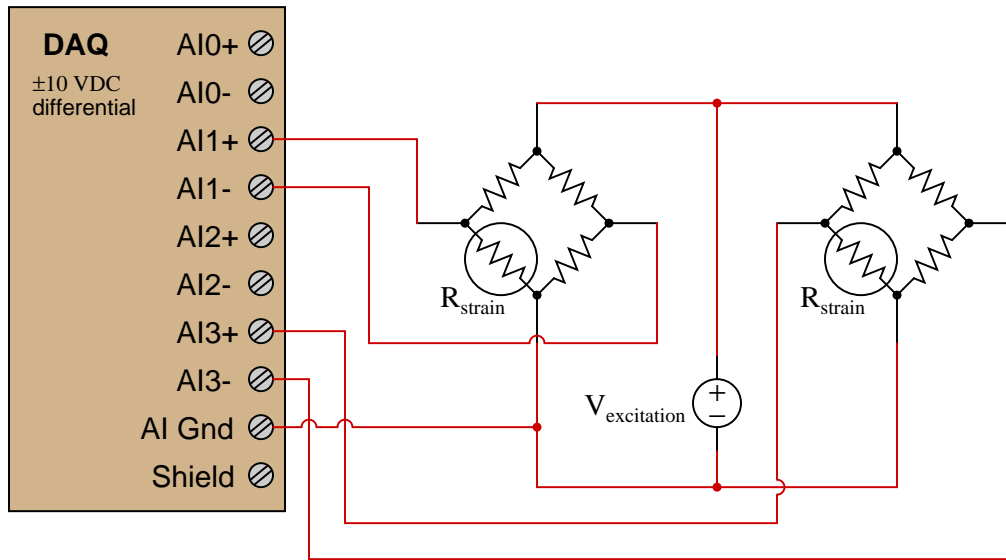


No bias resistors are necessary for the differential DAQ inputs in this application, because the bridge networks provide ample pathways for amplifier bias currents to travel.
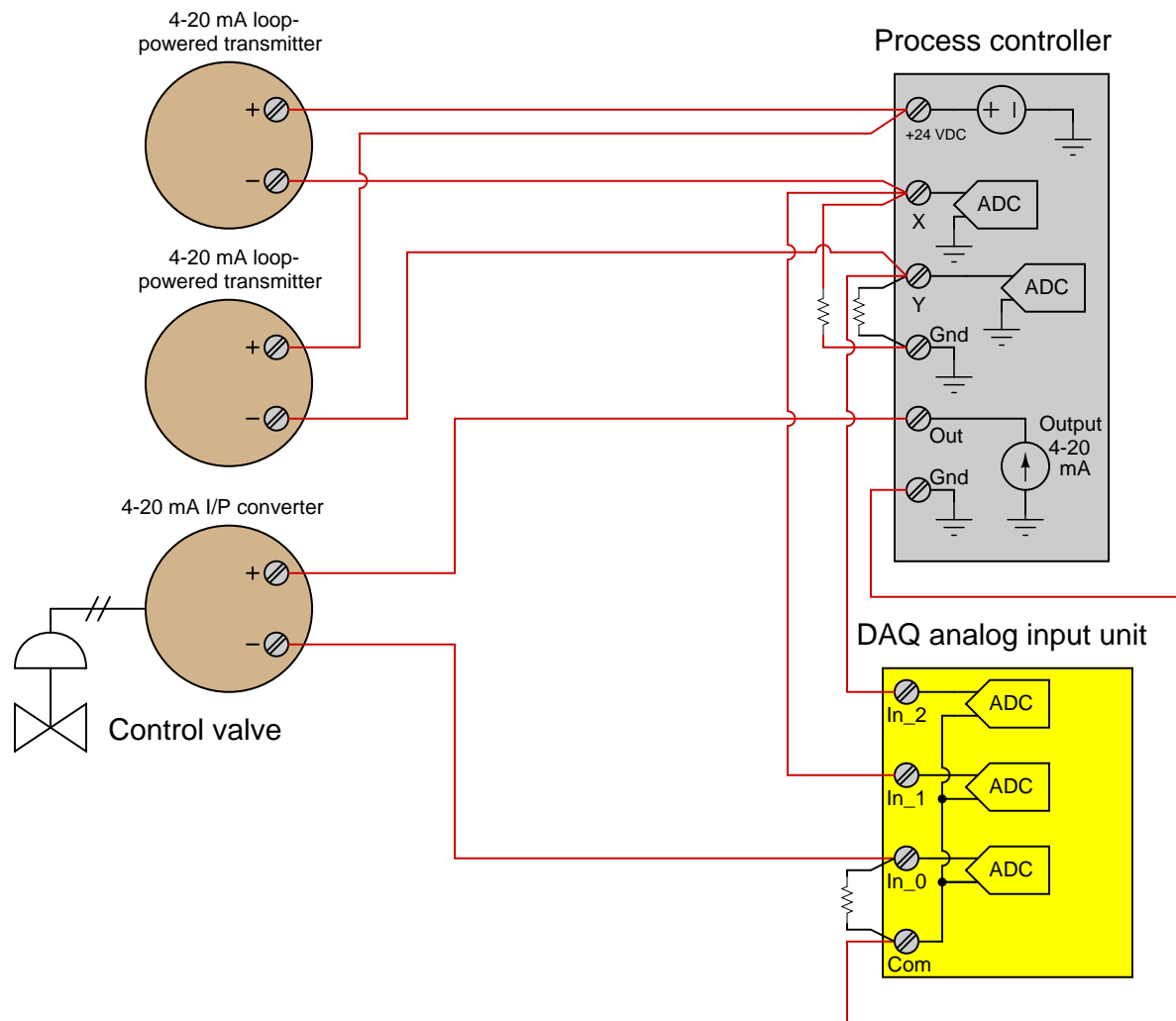
One important detail is that the DAQ "Common" terminal must be made common to the "Ground" terminal of the controller, in order to measure all three signals successfully.

Note that shielded cables and shield grounds are omitted from this diagram for the same of simplicity.

Answer 49

The PT ratio does not step the 480 VAC down enough. A 50:1 ratio will step 480 volts RMS down to 9.6 volts RMS, but remember that the DAQ must measure the *peak* voltage and not just the RMS value! Here, the peak output of the PT with a ratio of 50:1 and 480 volts RMS at the primary winding will be approximately 13.58 volts peak, which exceeds the DAQ's input range of ± 10 volts.

The more serious problem is in the CT circuit, where a current of approximately 1.25 amps is being forced through the DAQ's high input impedance of millions of ohms. What we need is a low-value *shunt resistor* to drop a voltage within the DAQ's measurement range. It would be advisable not to use the full ± 10 volt range, due to over-burdening the CT, so I would recommend a shunt resistor dropping mere millivolts (e.g. A precision 10 mΩ shunt resistor would work quite nicely).

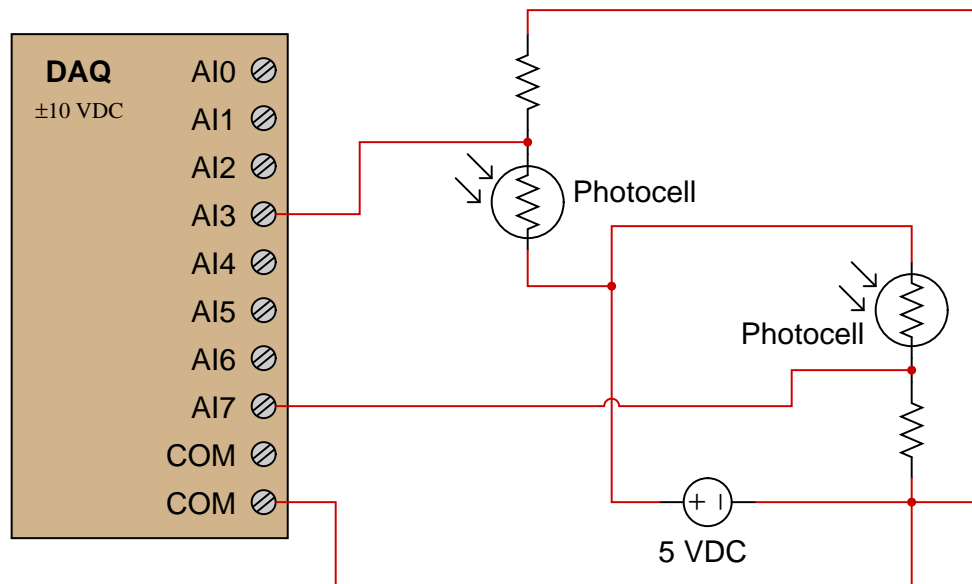Here is a proposed solution to both problems:
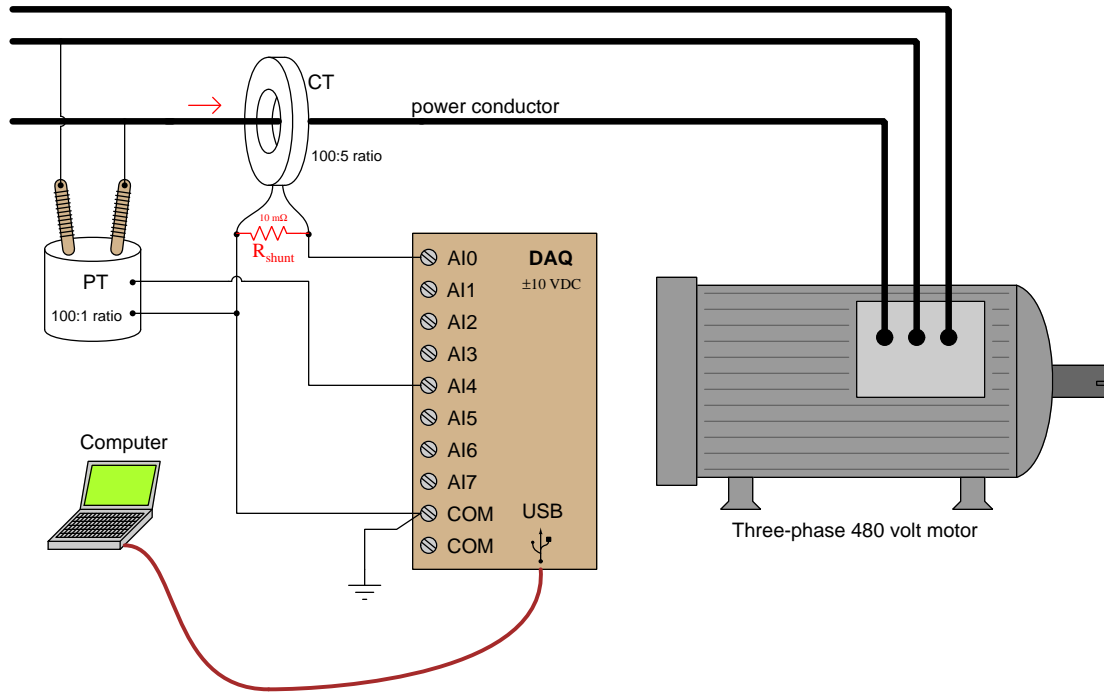


Answer 50

- The digital output (in hexadecimal) at 0.0 volts analog input = **000**

- The digital output (in hexadecimal) at 5.0 volts analog input = **FFF**

- The digital output (in hexadecimal) at 2.1 volts analog input = **6B7** or **6B8**

- The analog input corresponding to a digital output of 2D0 = **0.8791** volts

- The analog input corresponding to a digital output of F14 = **4.713** volts

Answer 51

If we need the signal voltage to increase with increasing light intensity, and we know a photocell's resistance decreases with increasing light intensity, we need the DAQ to sense voltage across the fixed resistor and not across the photocell.



Answer 52

- The digital output (in hexadecimal) at 0.0 volts analog input = **0000**

- The digital output (in hexadecimal) at 10.0 volts analog input = **FFFF**

- The digital output (in hexadecimal) at 3.4 volts analog input = **5709** or **570A**

- The analog input corresponding to a digital output of 3D6A = **2.399** volts

- The analog input corresponding to a digital output of C005 = **7.501** volts

Answer 53

The problem may be summarized using just one word: *loading.* All voltmeters draw some current from the signal under test, but analog-style voltmeters drew signficantly more current than their modern DMM equivalents. This is a problem because the current drawn by a voltmeter tends to "load down" the voltage output by the signal source, resulting in a negative error (reading less voltage than the source is actually trying to output).

The "null-balance" technique works like this:

- Adjust the potentiometer until the sensitive galvanometer registers *zero current*
- Read the voltmeter's indication – this will be precisely equal to the signal source

Galvanometers are nothing more than hyper-sensitive ammeters. When the galvanometer reads zero, you know the potentiometer's output voltage is precisely equal to the signal source voltage. This is why the voltmeter's reading in this condition is precisely equal to the signal source voltage. However, the current required by the voltmeter to allow it to function is being supplied by the battery, not by the signal source. This "unloads" the signal source so that it does not have to power the voltmeter.

Answer 54

Answer 55
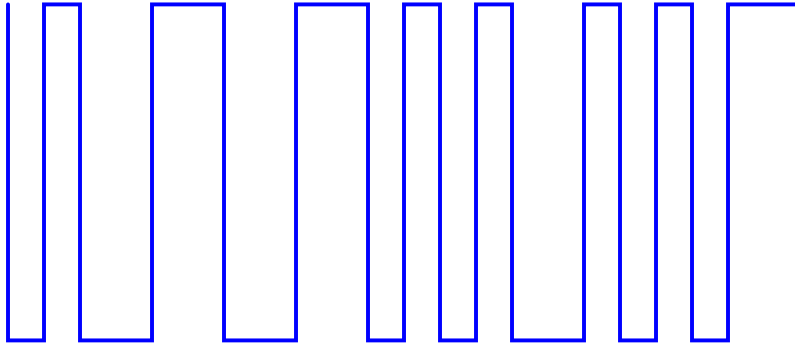
Answer 56

Answer 57

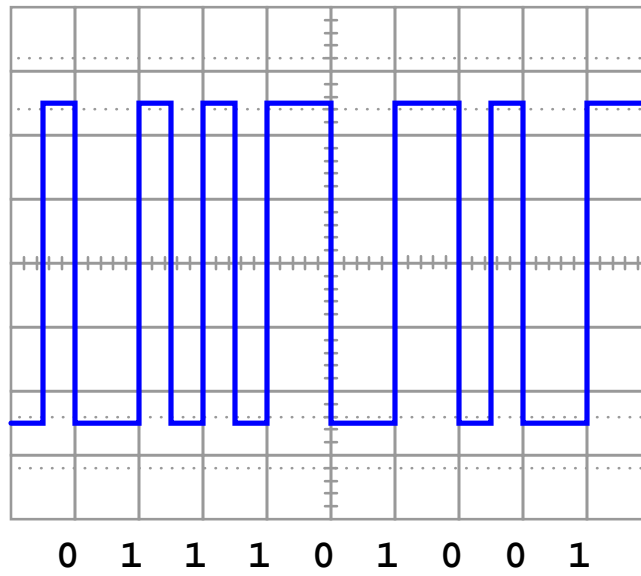Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64

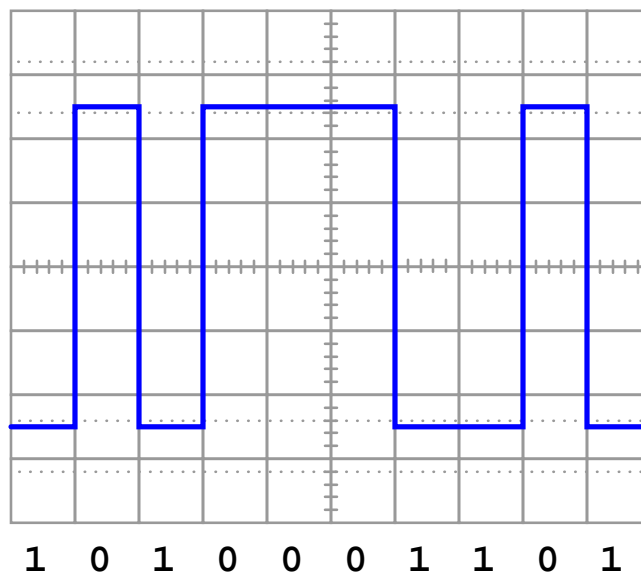The "clean" waveform, with no bit markings:



Hint: *all* the pulse edges representing "real" data bits are evenly spaced! *All* "reversal" pulse edges are out-of-step with the regular pattern of data bit pulse edges.
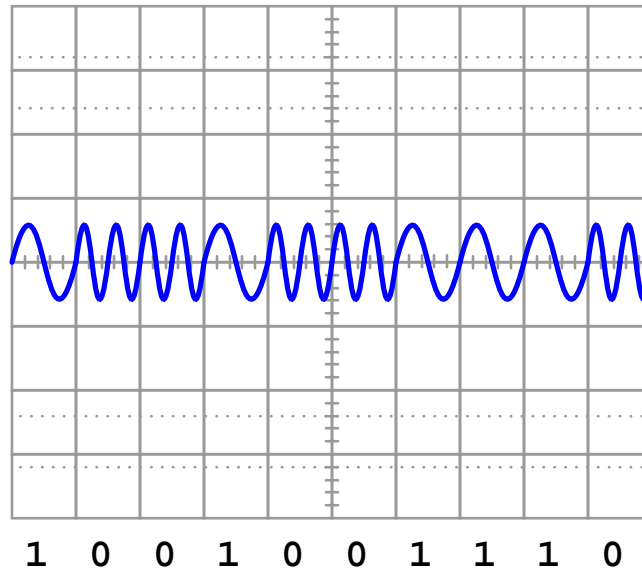
## (Manchester encoding)



0   1   1   1   0   1   0   0   1

## (NRZ encoding)



1   0   1   0   0   0   1   1   0   1

# (FSK encoding)



**1   0   0   1   0   0   1   1   1   0**

---

Answer 66

---

Answer 67

---

Answer 68

- Formula for cell `R1C4`: `ROUND((R2C1 / 5) * 255)`
- Formula for cell `R2C4`: `DEC2BIN(R1C4)`
- Formula for cell `R3C4`: `DEC2HEX(R1C4)`

---

Answer 69

In a properly operating circuit with no explosive gas present, $V_{R3} = V_{R4}$ or $V_D = 2V_E$. I will leave it to you to identify good diagnostic tests!

---

Answer 70

The ammeter shows $R_2$ carrying all the current, therefore either $R_2$ must be shorted or $R_1$ must be open.

| Fault | Possible | Impossible |
|---|---|---|
| $R_1$ failed open | √ | |
| $R_2$ failed open | | √ |
| $R_3$ failed open | | √ |
| $R_1$ failed shorted | | √ |
| $R_2$ failed shorted | √ | |
| $R_3$ failed shorted | | √ |
| Current source dead | | √ |

Answer 71

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 0 | 0 | 0 | 000 |
| 2.5 | 25 | 1023 or 1024 | 3FF or 400 |
| 5.0 | 50 | 2047 or 2048 | 7FF or 800 |
| 7.5 | 75 | 3071 or 3072 | BFF or C00 |
| 10 | 100 | 4095 | FFF |

Answer 72

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 0 | 0 | 0 | 0000 |
| 2.5 | 25 | 16383 or 16384 | 3FFF or 4000 |
| 5.0 | 50 | 32767 or 32768 | 7FFF or 8000 |
| 7.5 | 75 | 49151 or 49152 | BFFF or C000 |
| 10 | 100 | 65535 | FFFF |

Answer 73

| Input pressure (PSI) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 0 | 0 | 0 | 000 |
| 27 | 36 | 5897 or 5898 | 1709 or 170A |
| 46.5 | 62 | 10157 or 10158 | 27AD or 27AE |
| 66.75 | 89 | 14580 or 14581 | 38F4 or 38F5 |
| 71.25 | 95 | 15563 or 15564 | 3CCB or 3CCC |

Answer 74

| Input level (inches) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 36.5 | 11 | 112 or 113 | 070 or 071 |
| 62.0 | 28 | 286 or 287 | 11E or 11F |
| 102.5 | 55 | 562 or 563 | 232 or 233 |
| 129.5 | 73 | 746 or 747 | 2EA or 2EB |
| 158.0 | 92 | 941 or 942 | 3AD or 3AE |

Answer 75

**Partial answer:**

| Input voltage (volts) | Percent of span (%) | Counts (decimal) | Counts (hexadecimal) |
|---|---|---|---|
| 1.6 | 32 | 1310 or 1311 | |
| | 73.8 | 3022 | |
| | 40 | | 666 |
| 3.18 | | | A2F |

Answer 76

I won't give you all the details here, but I will get you started with a few steps:

- De-activate the clock enable (CE) inputs of both shift registers.
- Apply the four desired bits (logic levels) to the $D_0$ through $D_3$ inputs of the left-hand shift register.
- Briefly activate the parallel load (PL) input of the left-hand shift register.
- Activate the clock enable (CE) inputs of both shift registers simultaneously for four clock pulses.
- etc.
- etc. . . .

Answer 77

"UART" stands for *Universal Asynchronous Receiver Transmitter*, and its job is to act as an interface between two parallel-data devices, managing communications in serial format along a communication line of some sort.

Follow-up question: research an example of a UART IC available for purchase today.
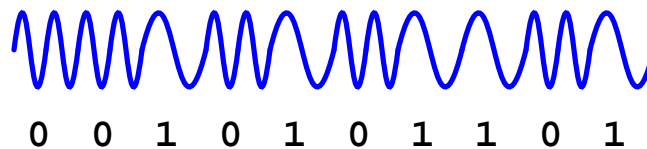
Answer 78

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

## (Manchester encoding)



**1  1  0  1  0  1  1  1  1**

## (FSK encoding)



**0  0  1  0  1  0  1  1  0  1**
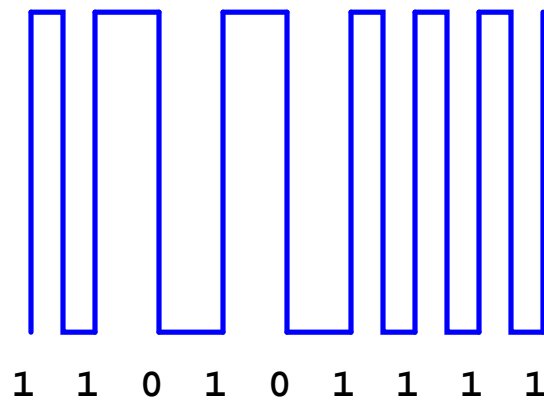
Answer 80

I'll let you decode this message on your own!

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

## Answer 87

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

## Answer 88

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

## Answer 89

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

## Answer 90

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

## Answer 91

There exist some inexpensive data acquisition modules on the market for personal computers, including some with USB interfaces (and most with RS-232 serial interfaces). If all you have is a serial-interface module and a USB-only computer (as most laptop computers are!), you may use a USB-to-serial adapter to connect the serial DAQ device to the personal computer. Within Microsoft Windows, you may force the operating system to recognize the USB adapter as an old-style COM 1 or COM 2 RS-232 serial device, at which time the DAQ software should "talk" through the adapter to the DAQ module seamlessly.

In order to meet the project standard of data communication via Ethernet with a non-Ethernet DAQ module, you will have to use an intermediary personal computer to poll the DAQ over its serial cable connection, and then use "Remote Desktop" software on another personal computer to view the display of that intermediary personal computer (the remote access taking place over an Ethernet network). `RealVNC` is an example of a very powerful third-party remote access application which may be used for this purpose.