INST 260 (Data Acquisition systems), section 1

Lab

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

Exam

Day 6 of section 3 – only a simple calculator may be used!

Specific objectives for the "mastery" exam:

- Electricity Review: Calculate 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
- INST230 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)

Recommended daily schedule

Day 1

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

Questions 1 through 20; answer questions 1-12 in preparation for discussion (remainder for practice)

Day 2

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

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

Day 3

Theory session topic: Data acquisition hardware

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

Day 4

Theory session topic: Serial communication principles

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

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

Introduction to Spring Quarter

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!

How To . . .

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

Maximize your learning: come to school prepared each and every day – this means completing all your homework *before* class starts. Use every minute of class and lab time productively. Follow all the tips outlined in "Question 0" (in every course worksheet) as well as your instructor's advice. Don't ask anyone to help you solve a problem until you have made every reasonable effort to solve it on your own.

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

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

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

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

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

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

Identify scholarship opportunities: check your BTC email in-box daily.

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, because your instructor broadcast-emails job postings to all students as employers submit them to BTC.

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

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

file `howto`

General Values and Expectations

Success in this career requires: professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. Poor judgment spells disaster in this career, which is why employer background checks (including social media and criminal records) and drug testing are common. The good news is that character and clear thinking are malleable traits: unlike intelligence, these qualities can be acquired and improved with effort. *This is what you are in school to do* – increase your "human capital" which is the sum of all knowledge, skills, and traits valuable in the marketplace.

Mastery: You must master the fundamentals of your chosen profession. "Mastery" assessments challenge you to demonstrate 100% competence (with multiple opportunities to re-try). Failure to complete any mastery objective(s) 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.

Punctuality and Attendance: You are expected to arrive on time and be "on-task" all day just as you would for a job. Each student has 12 hours of "sick time" per quarter applicable to absences not verifiably employment-related, school-related, weather-related, or required by law. Each student must confer with the instructor to apply these hours to any missed time – this is not done automatically. Students may donate unused "sick time" to whomever they specifically choose. You must contact your instructor and lab team members immediately if you know you will be late or absent or must leave early. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

Time Management: You are expected to budget and prioritize your time, just as you will be on the job. You will need to reserve enough time outside of school to complete homework, and strategically apply your time during school hours toward limited resources (e.g. lab equipment). Frivolous activities (e.g. games, social networking, internet surfing) are unacceptable when work is unfinished. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

Independent Study: This career is marked by continuous technological development and ongoing change, which is why *self-directed learning* is ultimately more important to your future success than specific knowledge. To acquire and hone this skill, all second-year Instrumentation courses follow an "inverted" model where lecture is replaced by independent study, and class time is devoted to addressing your questions and demonstrating your learning. Most students require a *minimum* of 3 hours daily study time outside of school. Arriving unprepared (e.g. homework incomplete) is unprofessional and counter-productive. Question 0 of every worksheet lists practical study tips.

Independent Problem-Solving: The best instrument technicians are versatile problem-solvers. General problem-solving is arguably the most valuable skill you can possess for this career, and it can only be built through persistent effort. This is why you must take every reasonable measure to *solve problems on your own* before seeking help. It is okay to be perplexed by an assignment, but you are expected to apply problem-solving strategies given to you (see Question 0) and to precisely identify where you are confused so your instructor will be able to offer targeted help. Asking classmates to solve problems for you is folly – this includes having others break the problem down into simple steps. The point is to learn how to *think on your own.* When troubleshooting systems in lab you are expected to run diagnostic tests (e.g. using a multimeter instead of visually seeking circuit faults), as well as consult the equipment manual(s) before seeking help.

Initiative: No single habit predicts your success or failure in this career better than personal initiative, which is why your instructor will demand *you do for yourself rather than rely on others to do for you.* Examples include setting up and using your BTC email account to communicate with your instructor(s), consulting manuals for technical information before asking for help, regularly checking the course calendar and assignment deadlines, avoiding procrastination, fixing small problems before they become larger problems, etc. If you find your performance compromised by poor understanding of prior course subjects, re-read those textbook sections and use the practice materials made available to you on the Socratic Instrumentation website – don't wait for anyone else to diagnose your need and offer help.

Safety: You are expected to work safely in the lab just as you will be on the job. This includes wearing proper attire (safety glasses and closed-toed shoes in the lab at all times), implementing lock-out/tag-out procedures when working on circuits with exposed conductors over 30 volts, using ladders to access elevated locations, and correctly using all tools. If you need to use an unfamiliar tool, see the instructor for directions.

Orderliness: You are expected to keep your work area clean and orderly just as you will be on the job. This includes discarding trash and returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. If you identify failed equipment in the lab, label that equipment with a detailed description of its symptoms.

Teamwork: You will work in instructor-assigned teams to complete lab assignments, just as you will work in teams to complete complex assignments on the job. As part of a team, you must keep your teammates informed of your whereabouts in the event you must step away from the lab or will be absent for *any* reason. Any student regularly compromising team performance through lack of participation, absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually for the remainder of the quarter. The same is true for students found relying on teammates to do their work for them.

Cooperation: The structure of these courses naturally lends itself to cooperation between students. Working together, students significantly impact each others' learning. You are expected to take this role seriously, offering real help when needed and not absolving classmates of their responsibility to think for themselves or to do their own work. Solving problems for classmates and/or explaining to them what they can easily read on their own is unacceptable because these actions circumvent learning. The best form of help you can give to your struggling classmates is to share with them your tips on independent learning and problem-solving, for example *asking questions* leading to solutions rather than simply providing solutions for them.

Grades: Employers prize trustworthy, hard working, knowledgeable, resourceful problem-solvers. The grade you receive in any course is but a *partial* measure of these traits. What matters most are the traits themselves, which is why your instructor maintains detailed student records (including individual exam scores, attendance, tardiness, and behavioral comments) and will share these records with employers if you have signed the FERPA release form. You are welcome to see your records at any time, and to compare calculated grades with your own records (i.e. the grade spreadsheet available to all students). You should expect employers to scrutinize your records on attendance and character, and also challenge you with technical questions when considering you for employment.

Representation: You are an ambassador for this program. Your actions, whether on tours, during a jobshadow or internship, or while employed, can open or shut doors of opportunity for other students. Most of the job opportunities open to you as a BTC graduate were earned by the good work of previous graduates, and as such you owe them a debt of gratitude. Future graduates depend on you to do the same.

Responsibility For Actions: If you lose or damage college property (e.g. lab equipment), you must find, repair, or help replace it. If you represent BTC poorly to employers (e.g. during a tour or an internship), you must make amends. The general rule here is this: *"If you break it, you fix it!"*

Non-negotiable terms: disciplinary action, up to and including immediate failure of a course, will result from academic dishonesty (e.g. cheating, plagiarism), willful safety violations, theft, harassment, intoxication, destruction of property, or willful disruption of the learning (work) environment. Such offenses are grounds for immediate termination in this career, and as such will not be tolerated here.

file `expectations`

Course Syllabus

INSTRUCTOR CONTACT INFORMATION:
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DEPT/COURSE #: INST 260

CREDITS: 4 **Lecture Hours:** 20 **Lab Hours:** 52 **Work-based Hours:** 0

COURSE TITLE: Data Acquisition Systems

COURSE DESCRIPTION: This course reviews digital theory learned in the first year (Core Electronics) courses, building upon that foundation to explore industrial data busses (including Ethernet) and indicating, datalogging, and SCADA systems. **Pre/Corequisite course:** INST 200 (Introduction to Instrumentation) **Prerequisite course:** MATH&141 (Precalculus 1) with a minimum grade of "C"

COURSE OUTCOMES: Commission, analyze, and efficiently diagnose instrumented systems using data acquisition units and industry-standard protocols to transport process data over wired and wireless networks.

COURSE OUTCOME ASSESSMENT: Data acquisition system commissioning, analysis, and diagnosis outcomes are ensured by measuring student performance against mastery standards, as documented in the Student Performance Objectives. Failure to meet all mastery standards by the next scheduled exam day will result in a failing grade for the course.

STUDENT PERFORMANCE OBJECTIVES:

- Without references or notes, within a limited time (3 hours total for each exam session), independently perform the following tasks. Multiple re-tries are allowed on mastery (100% accuracy) objectives, each with a different set of problems:
  → Calculate voltages and currents in a DC series-parallel resistor circuit given source and resistor values, with 100% accuracy (mastery)
  → Sketch proper wire connections for a data acquisition unit to measure an analog sensor signal, with 100% accuracy (mastery)
  → Convert between different numeration systems (decimal, binary, hexadecimal, octal), with 100% accuracy (mastery)
  → Calculate ADC (analog-digital converter) input and output values given calibrated ranges, with 100% accuracy (mastery)
  → Solve for specified variables in algebraic formulae, with 100% accuracy (mastery)
  → Determine the possibility of suggested faults in simple circuits given measured values (voltage, current), schematic diagrams, and reported symptoms, with 100% accuracy (mastery)
  → Predict the response of networked instrumentation systems to component faults and changes in process conditions, given pictorial and/or schematic illustrations
  → Sketch proper power and signal connections between individual instruments to fulfill specified control system functions, given pictorial and/or schematic illustrations of those instruments
- In a team environment and with full access to references, notes, and instructor assistance, perform the following tasks:
  → Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems
  → Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork
  → 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
  → Generate accurate schematic diagrams documenting your team's DAQ system
- Independently perform the following tasks with 100% accuracy (mastery). Multiple re-tries are allowed with different specifications/conditions each time):
  → Design and build a circuit responding to changes in either light intensity or ambient temperature
  → Diagnose a random fault placed in another team's data acquisition 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

COURSE OUTLINE: A course calendar in electronic format (Excel spreadsheet) resides on the Y: network drive, and also in printed paper format in classroom DMC130, for convenient student access. This calendar is updated to reflect schedule changes resulting from employer recruiting visits, interviews, and other impromptu events. Course worksheets provide comprehensive lists of all course assignments and activities, with the first page outlining the schedule and sequencing of topics and assignment due dates. These worksheets are available in PDF format at `http://www.ibiblio.org/kuphaldt/socratic/sinst`

- INST260 Section 1 (Digital data acquisition and serial communication): 4 days theory and labwork
- INST260 Section 2 (Serial network standards): 4 days theory and labwork
- INST260 Section 3 (Industrial networking): 5 days theory and labwork + 1 day for proportional Exam

METHODS OF INSTRUCTION: Course structure and methods are intentionally designed to develop critical-thinking and life-long learning abilities, continually placing the student in an active rather than a passive role.

- **Independent study:** daily worksheet questions specify *reading assignments*, *problems* to solve, and *experiments* to perform in preparation (before) classroom theory sessions. Open-note quizzes and work inspections ensure accountability for this essential preparatory work. The purpose of this is to convey information and basic concepts, so valuable class time isn't wasted transmitting bare facts, and also to foster the independent research ability necessary for self-directed learning in your career.
- **Classroom sessions:** a combination of *Socratic discussion*, short *lectures*, *small-group* problem-solving, and hands-on *demonstrations/experiments* review and illuminate concepts covered in the preparatory questions. The purpose of this is to develop problem-solving skills, strengthen conceptual understanding, and practice both quantitative and qualitative analysis techniques.
- **Lab activities:** an emphasis on constructing and documenting *working projects* (real instrumentation and control systems) to illuminate theoretical knowledge with practical contexts. Special projects off-campus or in different areas of campus (e.g. BTC's Fish Hatchery) are encouraged. Hands-on *troubleshooting exercises* build diagnostic skills.
- **Feedback questions:** sets of *practice problems* at the end of each course section challenge your knowledge and problem-solving ability in current as as well as first year (Electronics) subjects. These are optional assignments, counting neither for nor against your grade. Their purpose is to provide you and your instructor with direct feedback on what you have learned.
- **Tours and guest speakers:** quarterly *tours* of local industry and *guest speakers* on technical topics add breadth and additional context to the learning experience.

STUDENT ASSIGNMENTS/REQUIREMENTS: All assignments for this course are thoroughly documented in the following course worksheets located at:
`http://www.ibiblio.org/kuphaldt/socratic/sinst/index.html`

- `INST260_sec1.pdf`
- `INST260_sec2.pdf`
- `INST260_sec3.pdf`

EVALUATION AND GRADING STANDARDS: (out of 100% for the course grade)

- Completion of all mastery objectives = 50%
- Mastery exam score (first attempt) = 10%
- Proportional exam score = 30%
- Lab questions = 10%
- Quiz penalty = -1% per failed quiz
- Tardiness penalty = -1% per incident (1 "free" tardy per course)
- Attendance penalty = -1% per hour (12 hours "sick time" per quarter)
- Extra credit = +5% per project (assigned by instructor based on individual learning needs)

All grades are criterion-referenced (i.e. no grading on a "curve")

100% ≥ **A** ≥ 95%	95% > **A-** ≥ 90%		
90% > **B+** ≥ 86%	86% > **B** ≥ 83%	83% > **B-** ≥ 80%	
80% > **C+** ≥ 76%	76% > **C** ≥ 73%	73% > **C-** ≥ 70% (minimum passing course grade)	
70% > **D+** ≥ 66%	66% > **D** ≥ 63%	63% > **D-** ≥ 60%	60% > **F**

A graded "preparatory" quiz at the start of each classroom session gauges your independent learning prior to the session. A graded "summary" quiz at the conclusion of each classroom session gauges your comprehension of important concepts covered during that session. If absent during part or all of a classroom session, you may receive credit by passing comparable quizzes afterward or by having your preparatory work (reading outlines, work done answering questions) thoroughly reviewed prior to the absence.

Absence on a scheduled exam day will result in a 0% score for the proportional exam unless you provide documented evidence of an unavoidable emergency.

If you fail a mastery exam, you must re-take a different version of that mastery exam on a different day. Multiple re-tries are allowed, on a different version of the exam each re-try. There is no penalty levied on your course grade for re-taking mastery exams, but failure to successfully pass a mastery exam by the due date (i.e. by the date of the *next* exam in the course sequence) will result in a failing grade (F) for the course.

If any other "mastery" objectives are not completed by their specified deadlines, your overall grade for the course will be capped at 70% (C- grade), and you will have one more school day to complete the unfinished objectives. Failure to complete those mastery objectives by the end of that extra day (except in the case of documented, unavoidable emergencies) will result in a failing grade (F) for the course.

"Lab questions" are assessed by individual questioning, at any date after the respective lab objective (mastery) has been completed by your team. These questions serve to guide your completion of each lab exercise and confirm participation of each individual student. Grading is as follows: full credit for thorough, correct answers; half credit for partially correct answers; and zero credit for major conceptual errors. All lab questions must be answered by the due date of the lab exercise.

Extra credit opportunities exist for each course, and may be assigned to students upon request. The student and the instructor will first review the student's performance on feedback questions, homework, exams, and any other relevant indicators in order to identify areas of conceptual or practical weakness. Then, both will work together to select an appropriate extra credit activity focusing on those identified weaknesses, for the purpose of strengthening the student's competence. A due date will be assigned (typically two weeks following the request), which must be honored in order for any credit to be earned from the activity. Extra credit may be denied at the instructor's discretion if the student has not invested the necessary preparatory effort to perform well (e.g. lack of preparation for daily class sessions, poor attendance, no feedback questions submitted, etc.).

REQUIRED STUDENT SUPPLIES AND MATERIALS:

- Course worksheets available for download in PDF format
- *Lessons in Industrial Instrumentation* textbook, available for download in PDF format
  → Access worksheets and book at: `http://www.ibiblio.org/kuphaldt/socratic/sinst`
- Spiral-bound notebook for reading annotation, homework documentation, and note-taking.
- Laptop computer with Ethernet port (and ideally with a USB-to-serial RS-232 converter) for performing network experiments.
- Instrumentation reference CD-ROM (free, from instructor). This disk contains many tutorials and datasheets in PDF format to supplement your textbook(s).
- Tool kit (see detailed list)
- Simple scientific calculator (non-programmable, non-graphing, no unit conversions, no numeration system conversions), TI-30Xa or TI-30XIIS recommended

ADDITIONAL INSTRUCTIONAL RESOURCES:

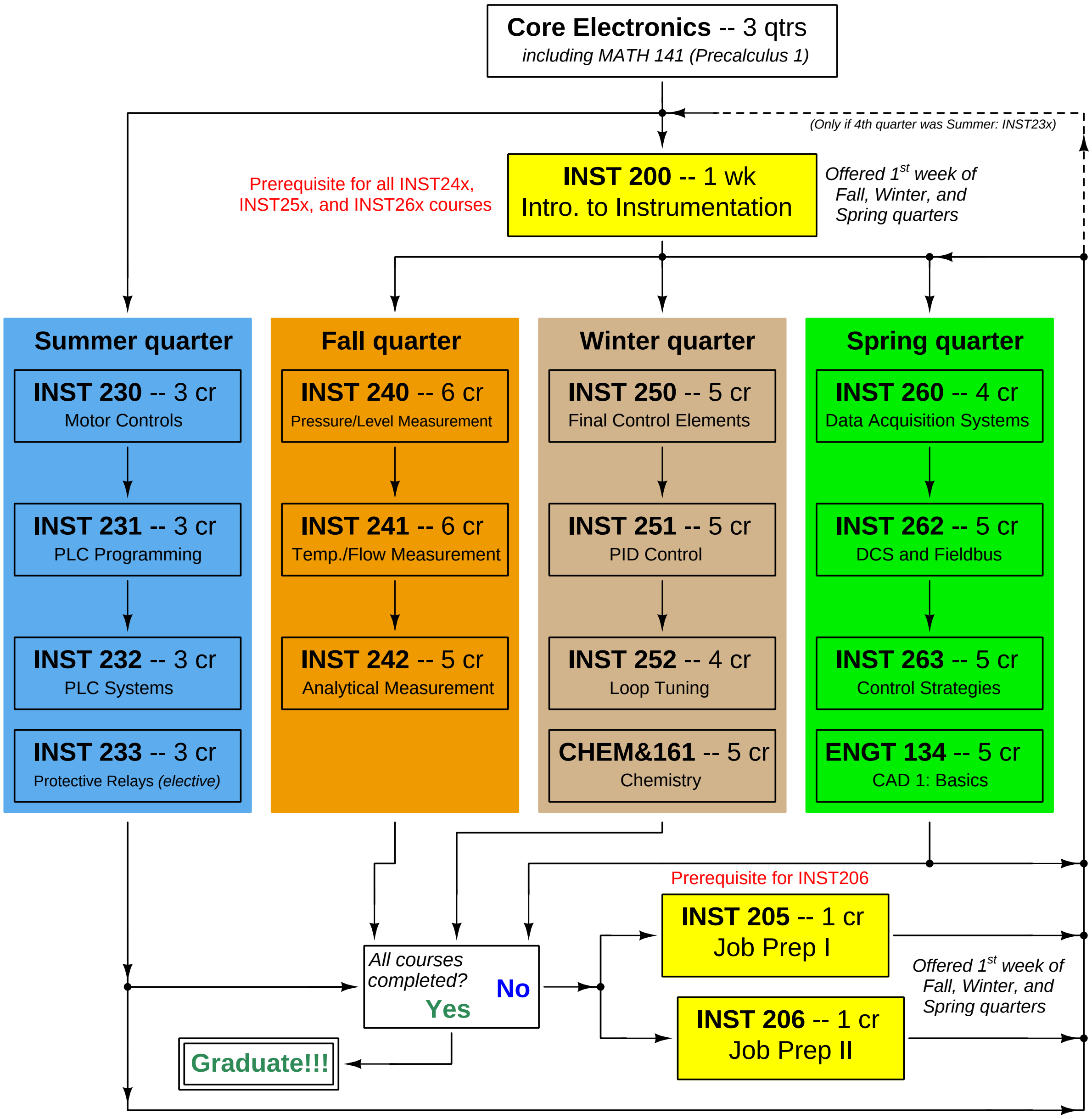
- The BTC Library hosts a substantial collection of textbooks and references on the subject of Instrumentation, as well as links in its online catalog to free Instrumentation e-book resources available on the Internet.
- "BTCInstrumentation" channel on YouTube (`http://www.youtube.com/BTCInstrumentation`), hosts a variety of short video tutorials and demonstrations on instrumentation.
- *Webster's New World Telecom Dictionary*, written by Ray Horak, published by Wiley Publishing; ISBN-13: 978-0471774570.
- *Ethernet: the definitive guide*, written by Charles E. Spurgeon, published by O'Reilly ; ISBN-10: 1565926609 ; ISBN-13: 978-1565926608.
- ISA Student Section at BTC meets regularly to set up industry tours, raise funds for scholarships, and serve as a general resource for Instrumentation students. Membership in the ISA is $10 per year, payable to the national ISA organization. Membership includes a complementary subscription to *InTech* magazine.
- ISA website (`http://www.isa.org`) provides all of its standards in electronic format, many of which are freely available to ISA members.
- *Purdy's Instrument Handbook*, by Ralph Dewey. ISBN-10: 1-880215-26-8. A pocket-sized field reference on basic measurement and control.
- *Cad Standard* (CadStd) or similar AutoCAD-like drafting software (useful for sketching loop and wiring diagrams). Cad Standard is a simplified clone of AutoCAD, and is freely available at: `http://www.cadstd.com`

CAMPUS EMERGENCIES: If an emergency arises, your instructor may inform you of actions to follow. You are responsible for knowing emergency evacuation routes from your classroom. If police or university officials order you to evacuate, do so calmly and assist those needing help. You may receive emergency information alerts via the building enunciation system, text message, email, or BTC's webpage (`http://www.btc.ctc.edu`), Facebook or Twitter. Refer to the emergency flipchart in the lab room (located on the main control panel) for more information on specific types of emergencies.

ACCOMMODATIONS: If you think you could benefit from classroom accommodations for a disability (physical, mental, emotional, or learning), please contact our Accessibility Resources office. Call (360)-752-8345, email `ar@btc.ctc.edu`, or stop by the AR Office in the Admissions and Student Resource Center (ASRC), Room 106, College Services Building

file `INST260syllabus`

Sequence of second-year Instrumentation courses



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

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

file sequence

General tool and supply list

Wrenches

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

Note: *when turning any threaded fastener, one should choose a tool engaging the maximum amount of surface area on the fastener's head in order 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
- Tongue-and-groove pliers (sometimes called "Channel-lock" 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
- Alligator-clip 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!
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

An inexpensive source of tools is your local pawn shop. Look for tools with unlimited lifetime guarantees (e.g. *Sears* "Craftsman" brand). Check for BTC student discounts as well!

file `tools`

Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*.

Theory

In the theory portion of each course, students independently research subjects *prior* to entering the classroom for discussion. This means working through all the day's assigned questions as completely as possible. This usually requires a fair amount of technical reading, and may also require setting up and running simple experiments. At the start of the classroom session, the instructor will check each student's preparation with a quiz. Students then spend the rest of the classroom time working in groups and directly with the instructor to *thoroughly* answer all questions assigned for that day, articulate problem-solving strategies, and to approach the questions from multiple perspectives. To put it simply: fact-gathering happens outside of class and is the individual responsibility of each student, so that class time may be devoted to the more complex tasks of critical thinking and problem solving where the instructor's attention is best applied.

Classroom theory sessions usually begin with either a brief Q&A discussion or with a "Virtual Troubleshooting" session where the instructor shows one of the day's diagnostic question diagrams while students propose diagnostic tests and the instructor tells those students what the test results would be given some imagined ("virtual") fault scenario, writing the test results on the board where all can see. The students then attempt to identify the nature and location of the fault, based on the test results.

Each student is free to leave the classroom when they have completely worked through all problems and have answered a "summary" quiz designed to gauge their learning during the theory session. If a student finishes ahead of time, they are free to leave, or may help tutor classmates who need extra help.

The express goal of this "inverted classroom" teaching methodology is to help each student cultivate critical-thinking and problem-solving skills, and to sharpen their abilities as independent learners. While this approach may be very new to you, it is more realistic and beneficial to the type of work done in instrumentation, where critical thinking, problem-solving, and independent learning are "must-have" skills.

Lab

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 eight-day period typically allotted 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)
(One day) Connect instrument(s) into a complete loop
(One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
(One or two days) Each team member calibrates/configures the instrument(s)
(Remaining days, up to last) Each team member troubleshoots the instrument loop
(3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

Troubleshooting assessments must meet the following guidelines:

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

file `instructional`

Distance delivery methods

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

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

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

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

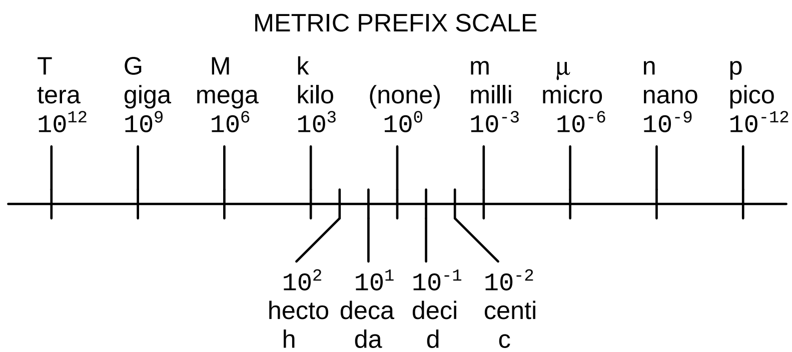
Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either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

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

file `distance`

Metric prefixes and conversion constants

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



- **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 (σ) = 5.67×10^{-8} Watts per square meter-Kelvin^4 ($\text{W/m}^2 \cdot \text{K}^4$)

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

Properties of Water

Freezing point at sea level = 32^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$\cdot^o$C = 1 BTU/lb$\cdot^o$F = 4.1869 Joules/g$\cdot^o$C

Specific heat of ice $\approx$ 0.5 calories/g$\cdot^o$C

Specific heat of steam $\approx$ 0.48 calories/g$\cdot^o$C

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

file `conversion_constants`

How to get the most out of academic reading:

- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Write your thoughts as you read, noting points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications. These notes should also document important math formulae, explaining in your own words what each formula means and the proper units of measurement used.
- Outline, don't highlight! Writing your own summary or outline is a far more effective way to comprehend a text than simply underlining and highlighting key words. A suggested ratio is one sentence of your own thoughts per paragraph of text read. Note points of disagreement or confusion to explore later.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Write your own questions based on what you read, as though you are a teacher preparing to test students' comprehension of the subject matter.

How to effectively problem-solve and troubleshoot:

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work. In mathematical problem-solving this means being able to identify the practical meaning (and units of measurement) of every intermediate calculation. In other words, *every step of your solution should make logical sense.*
- Sketch a diagram to help visualize the problem. When building a real system, always prototype it on paper and analyze its function *before* constructing it.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults.
- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Often you can add or remove components in a malfunctioning system to simplify it as well and better identify the nature and location of the problem.
- Work "backward" from a hypothetical solution to a new set of given conditions.

How to create more time for study:

- Kill your television and video games. Seriously – these are incredible wastes of time. Eliminate distractions (e.g. cell phone, internet, socializing) in your place and time of study.
- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin studying the next day's material.

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

file `question0`

file `license`

Question 1

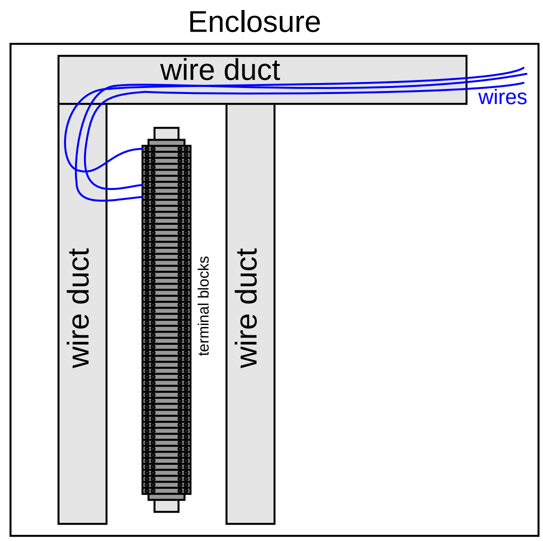
Read and outline the "Signal Coupling and Cable Separation" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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.

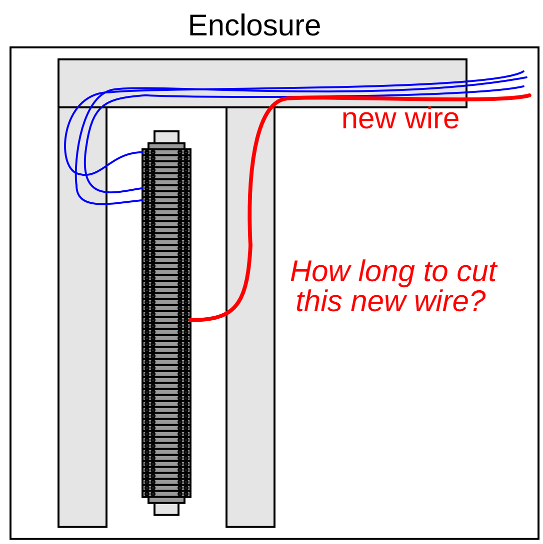
file i04412

Question 2

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:



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:



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 3

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

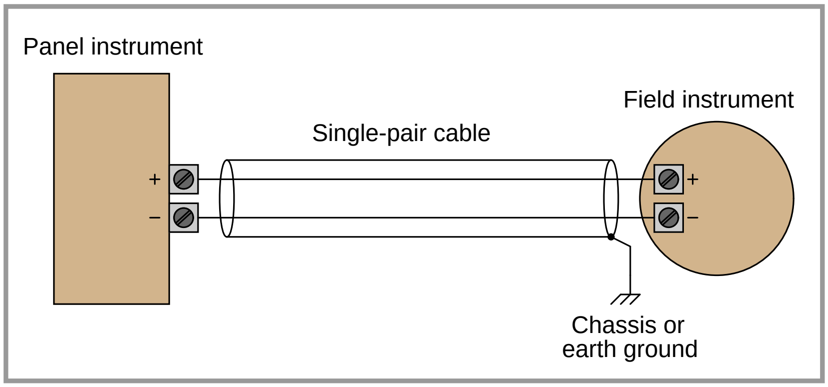
Question 4

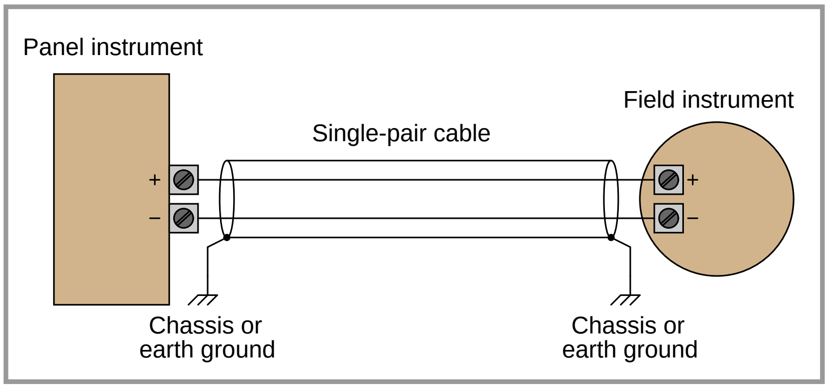
Read and outline the "Electric Field (Capacitive) De-coupling" subsection of the "Electrical Signal and Control Wiring" section of the "Instrument Connections" chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

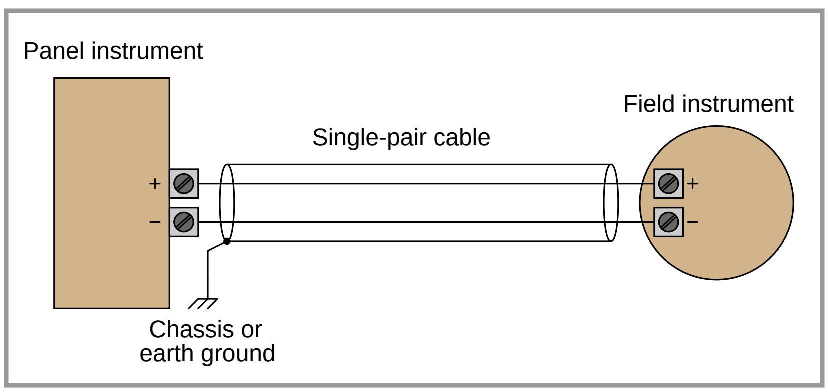
file i04413

Question 5

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

Question 6

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

file i04414

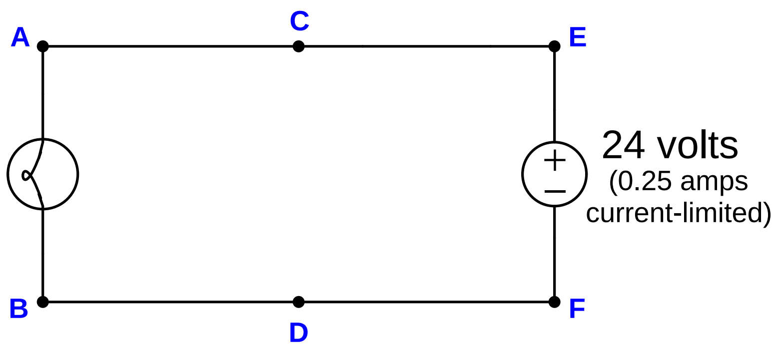
Question 7

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

file i04415

Question 8

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 9

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 10

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 11

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.

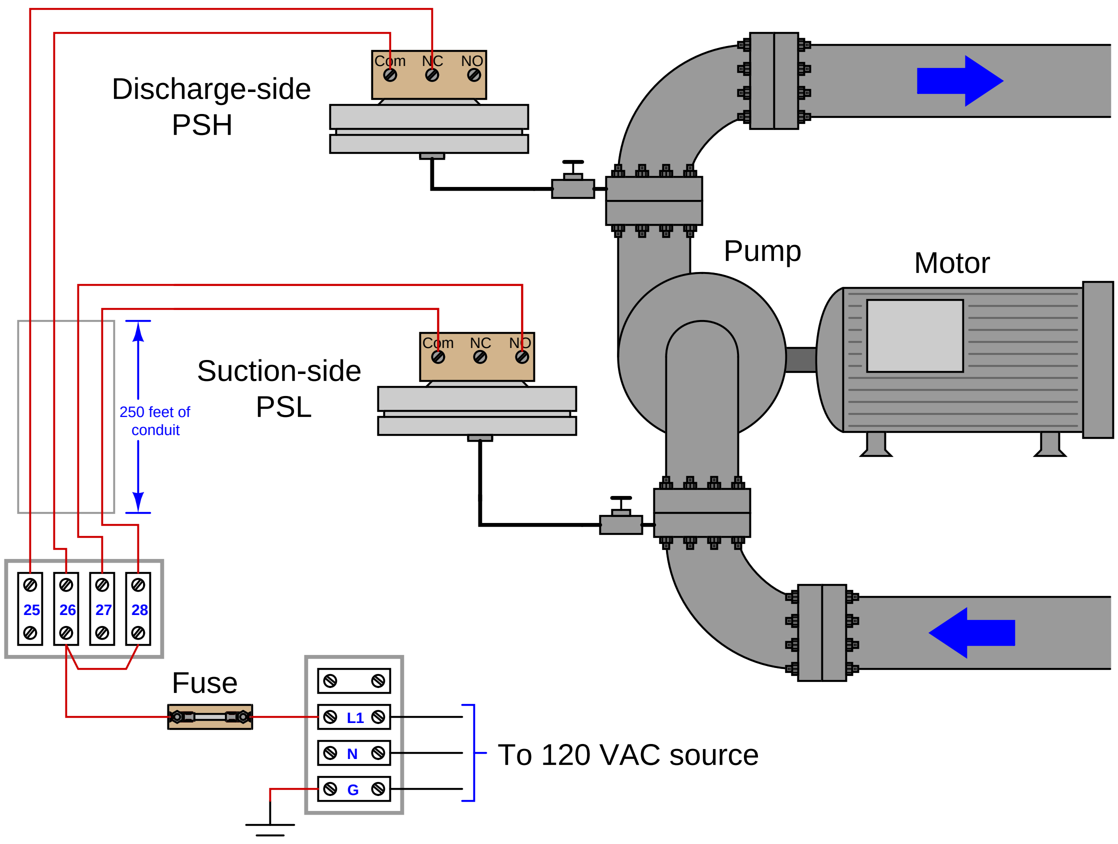
Suggestions for Socratic discussion

- 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 12

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?

file i02542

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

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

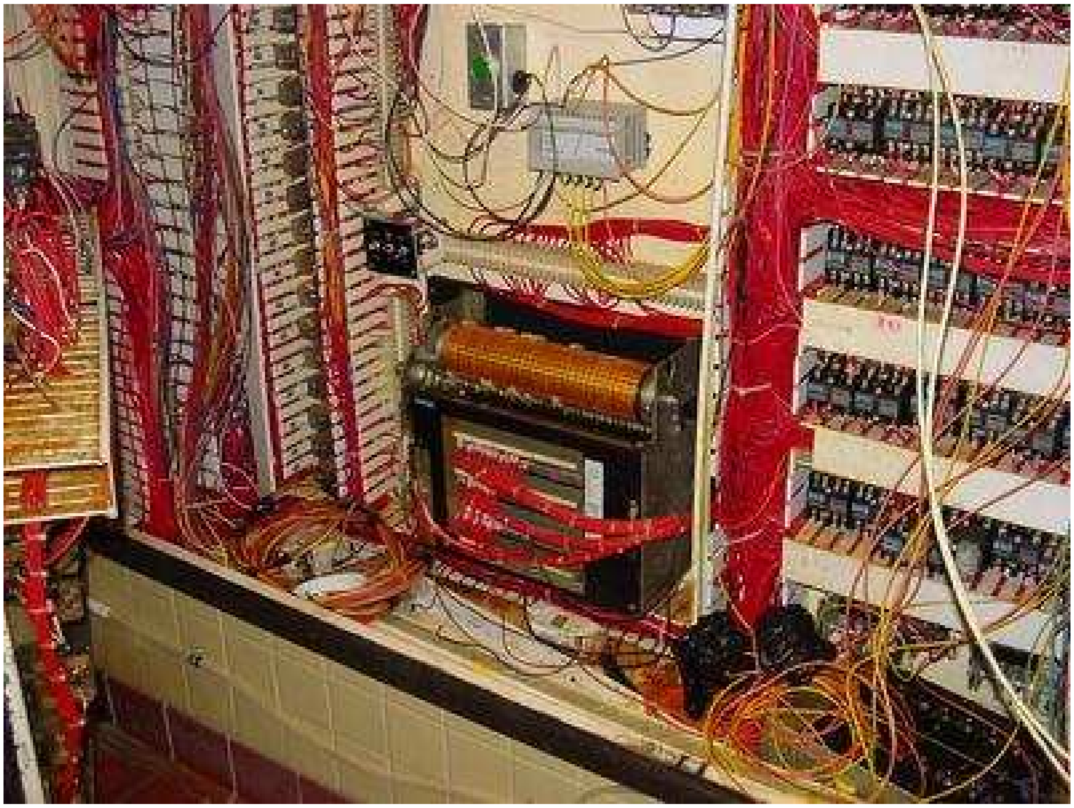
Suggestions for Socratic discussion

- 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

Question 15

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:

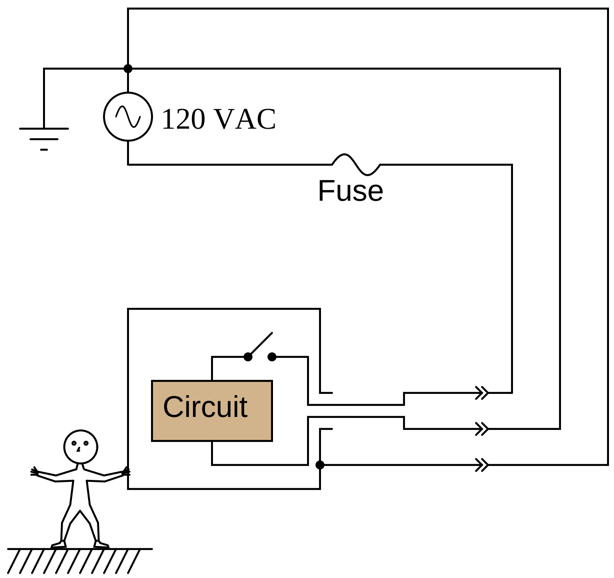


Identify some of the poor wiring practices in this photograph, trying not to laugh too loudly as you do.

file i02283

Question 16

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

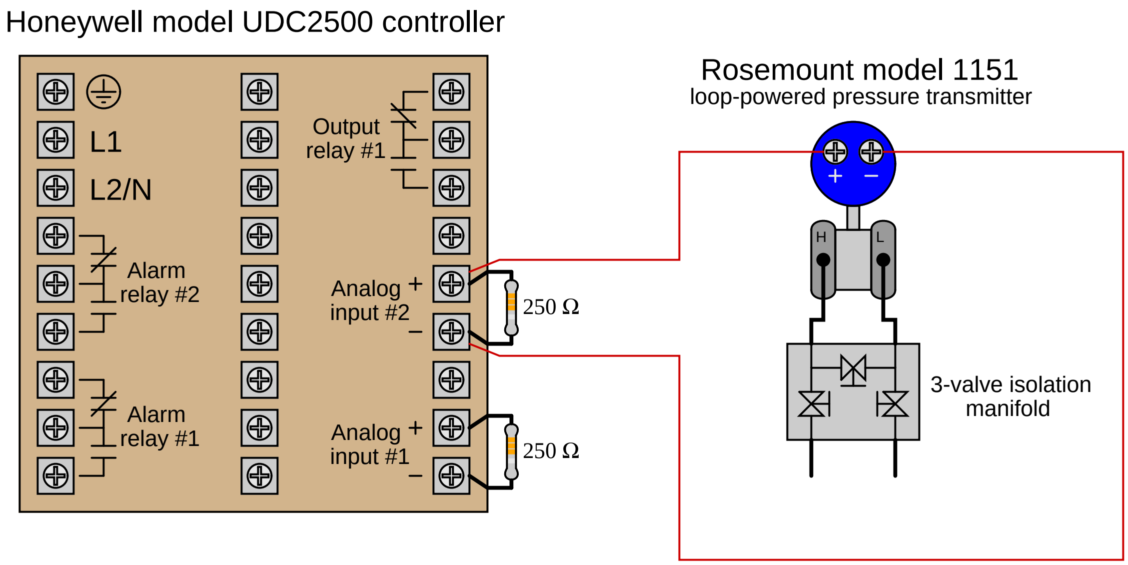


Explain how this grounding connection makes the appliance safer for anyone touching its metal case. Also, explain why both the fuse and the power switch are intentionally placed in series with the *ungrounded* ("hot") power conductor.

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.

file i02282

Question 18

Question 19

Question 20

Question 21

Read and outline the introduction to the "Digital Data Acquisition and Networks" chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

file i04394

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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

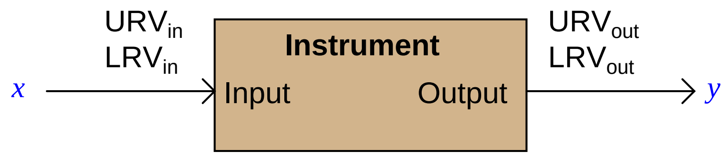
Question 24

Read and outline the "Analog-Digital Conversion" section of the "Digital Data Acquisition and Network" chapter in your *Lessons In Industrial Instrumentation* textbook. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

file i04396

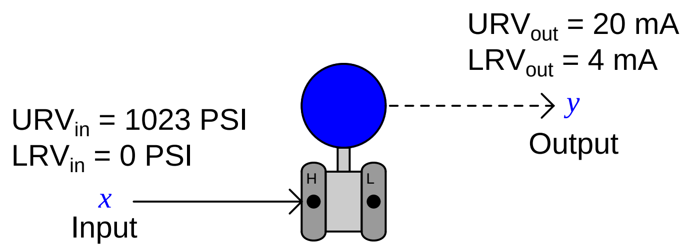
Question 25

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:

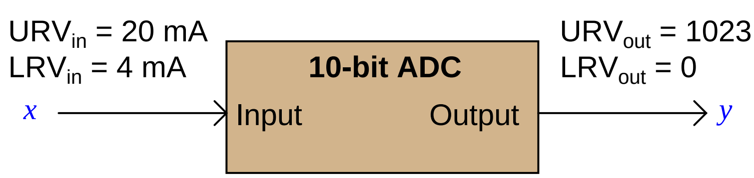


$$\frac{x - 0 \text{ PSI}}{1023 \text{ PSI}} = \frac{y - 4 \text{ mA}}{16 \text{ mA}}$$

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:

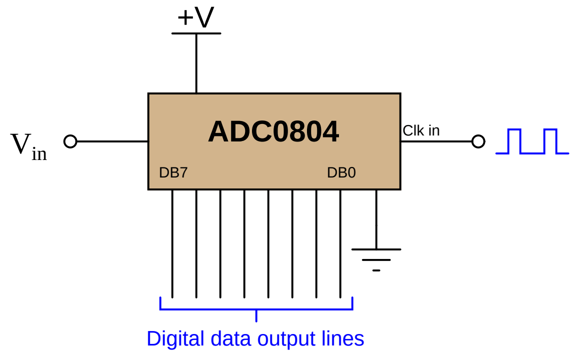


Calculate the corresponding "count" output of this ADC circuit given a 6.82 mA input signal.

file i04545

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:



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.

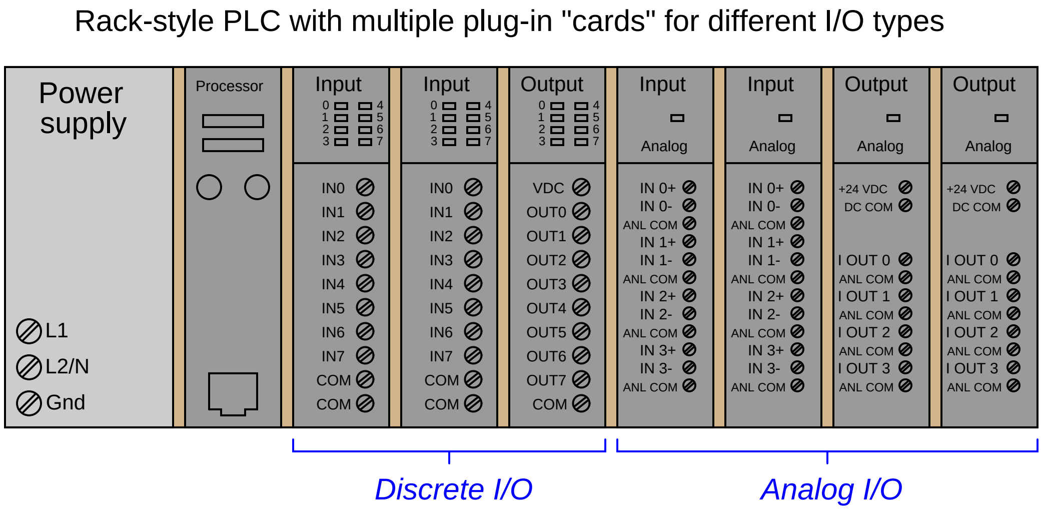
Complete this table of numbers, relating various DC input voltages with count values (expressed in binary, hex, and decimal) for an ADC0804 having an input range of 0.0 to 5.0 volts DC:

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		

file i03270

Question 27

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:



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.

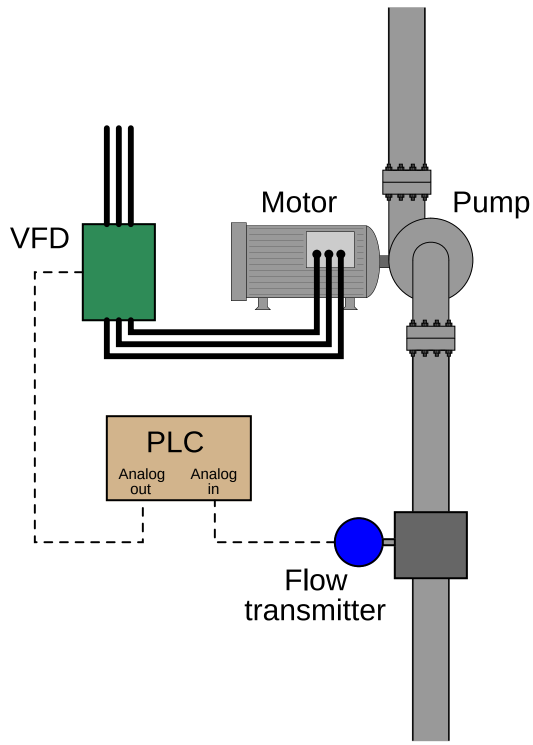
Suggestions for Socratic discussion

- 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.

file i02271

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."

file i04406

Question 29

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

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

file i02161

Question 30

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.
file i02164

Question 31

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 32

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 33

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.

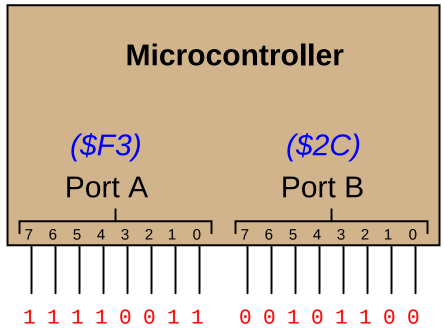
Also, perform the following conversions:

- 35_{16} into decimal:
- 34_{10} into hexadecimal:
- 11100010_2 into hexadecimal:
- 93_{16} into binary:

file i02167

Question 34

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:



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

Question 35

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

2	5	9	6	•	3	8	0	4
10^3	10^2	10^1	10^0		10^{-1}	10^{-2}	10^{-3}	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

file i02169

Question 36

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			

file i02170

Question 37

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

file i02171

Question 38

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

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

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

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

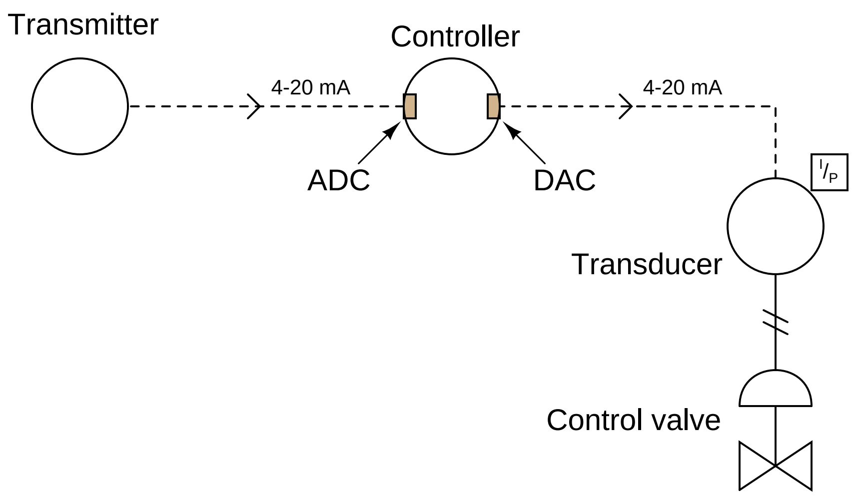
Sign	**Exponent** (E)	**Mantissa** (m)
1	00101100	00001110000001100000000
0	11001100	11010110000000000000000
0	00000000	11111100000110001000000

Finally, how do you represent the number 1 (1.0×2^0) in this floating-point format?
file i01851

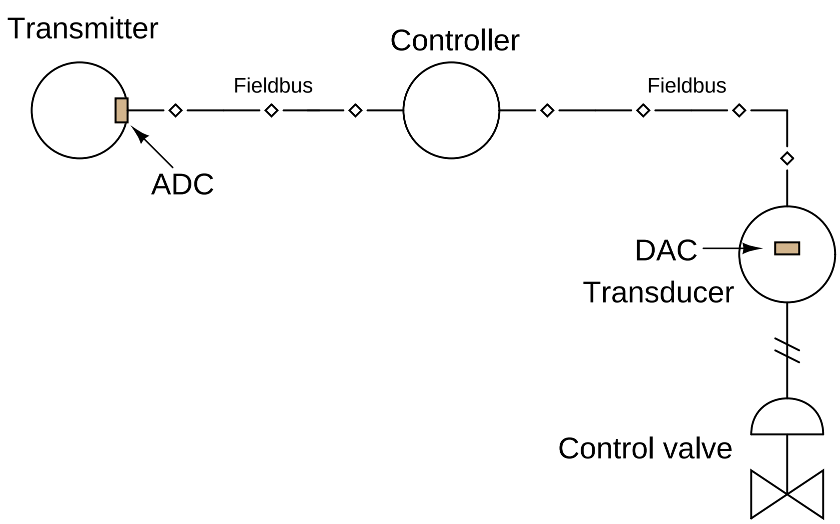
Question 39

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 40

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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 $R_G = 50$ kΩ 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

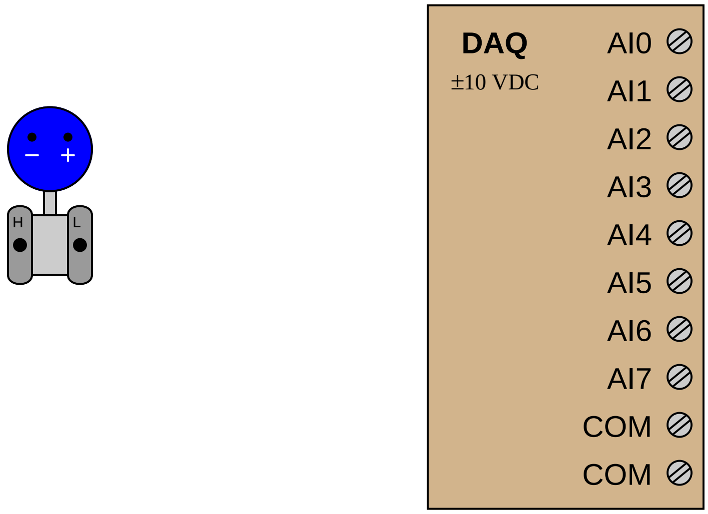
Question 44

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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.

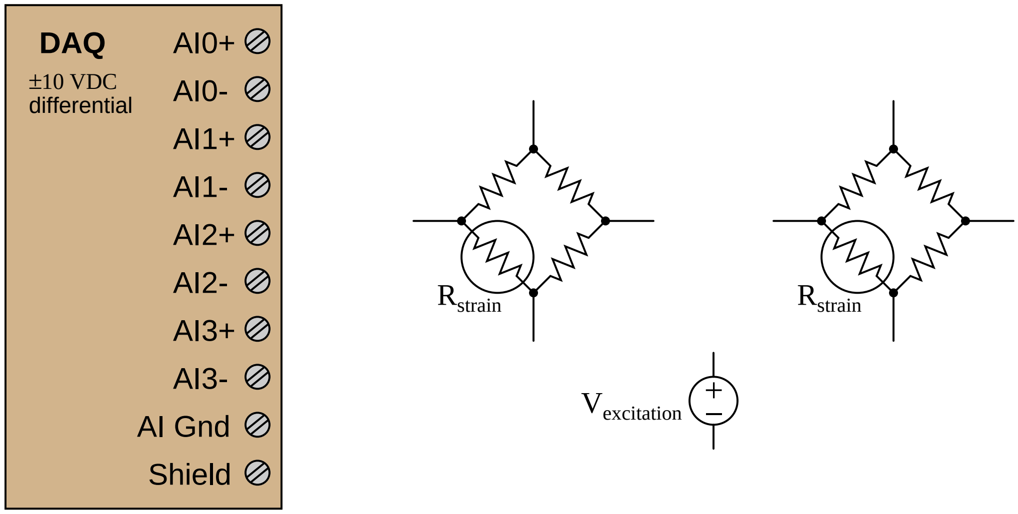
Suggestions for Socratic discussion

- 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

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:



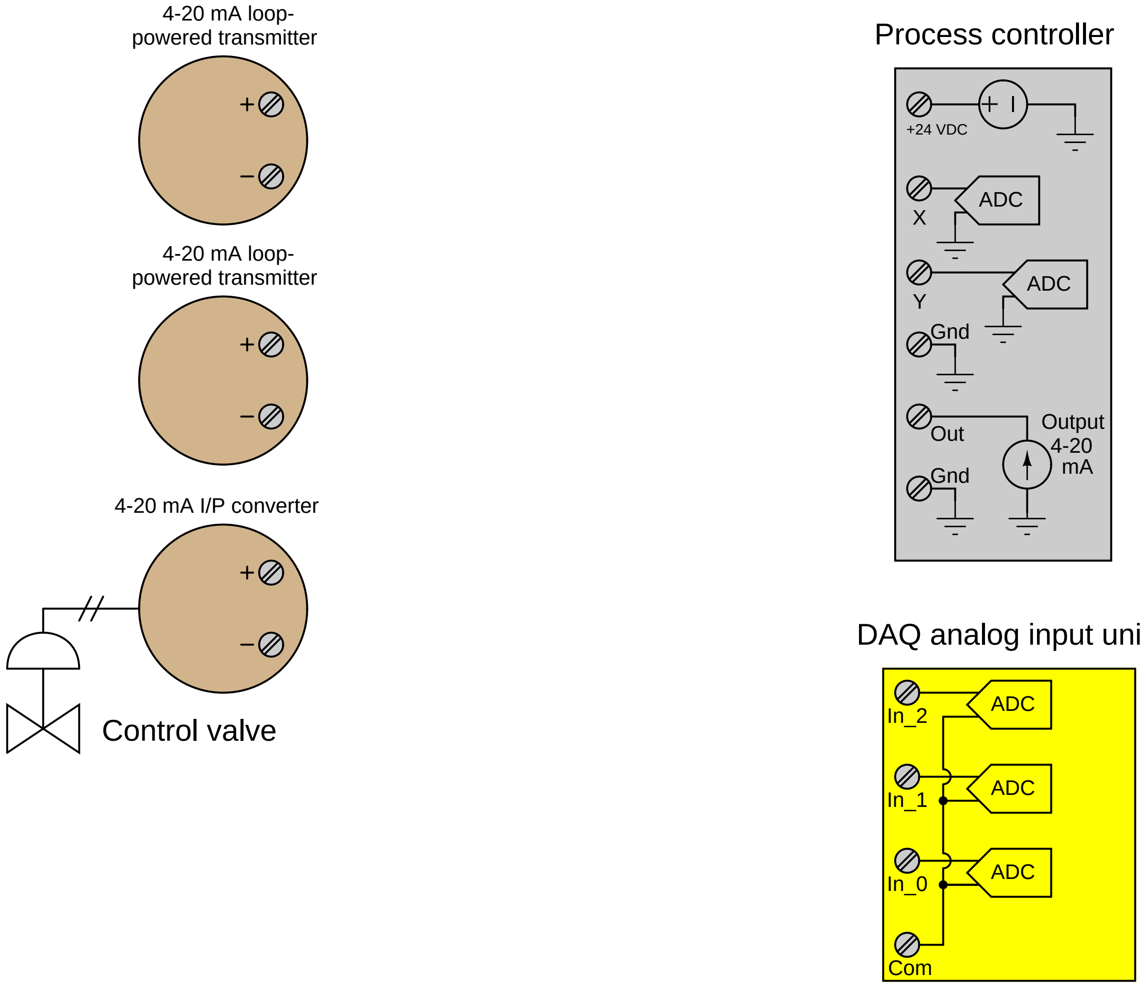
Suggestions for Socratic discussion

- 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 47

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

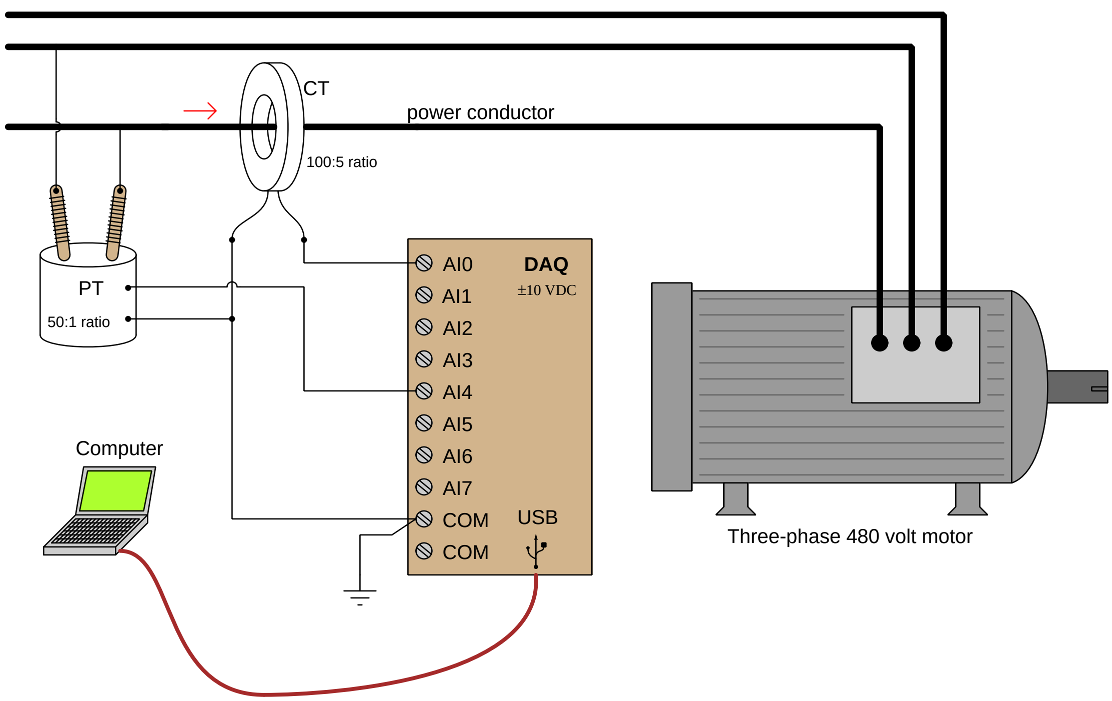
- A problem-solving technique useful for making proper connections in pictorial circuit diagrams is to first identify the directions of all DC currents entering and exiting component terminals, as well as the respective voltage polarity marks (+,−) for those terminals, based on your knowledge of each 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.

file i02274

Question 48

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 instrument transformers shown here, but somehow make them work with another 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?

file i02035

Question 49

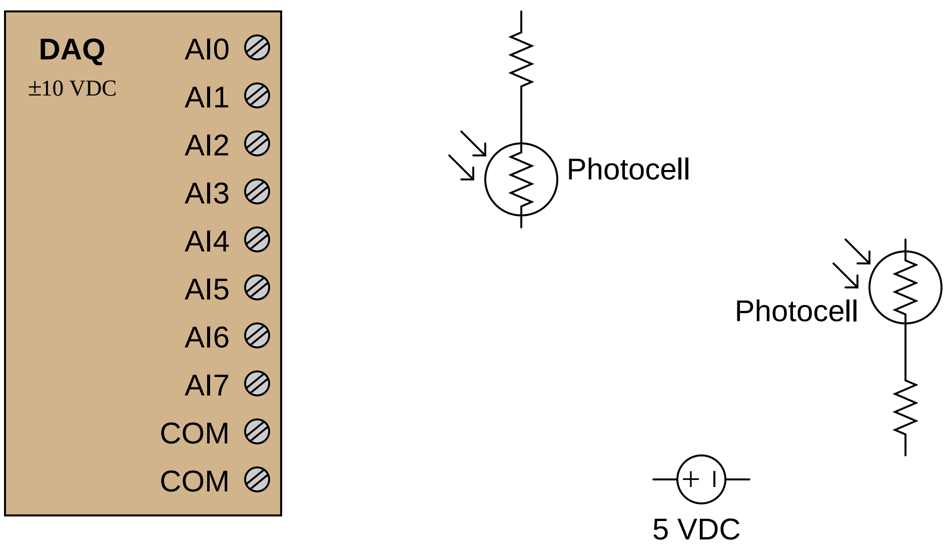
An analog-to-digital converter has a 12-bit binary output and an analog input voltage range of 0.0 to + 5.0 volts. Calculate:

- 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 50

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

Question 51

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

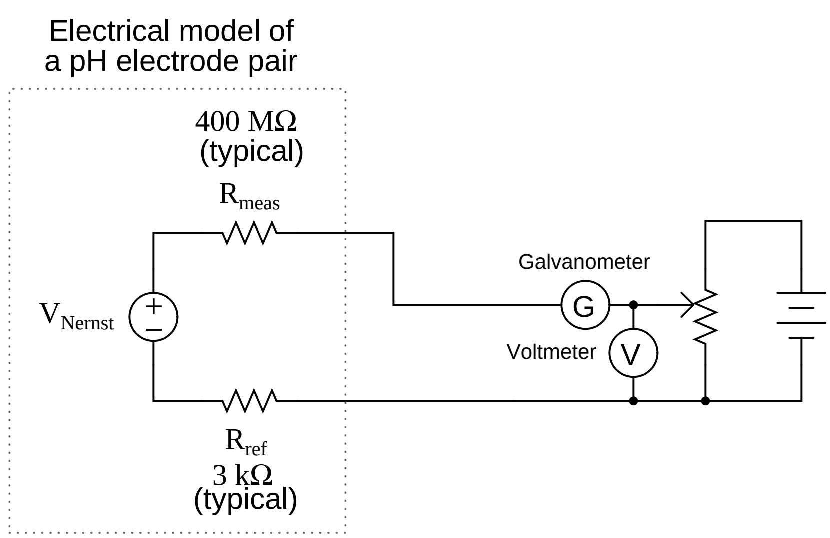
Question 52

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.

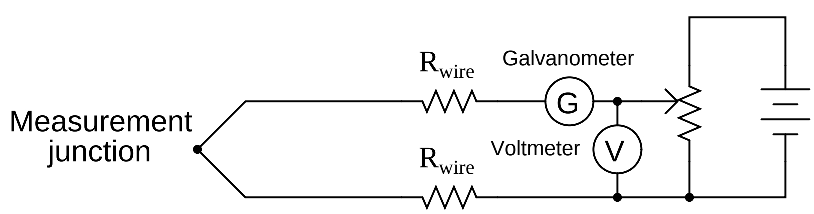
In the days before the advent of solid-state digital multimeters with their operational amplifier (high impedance) inputs, a technique called *null-balance* was used to accurately measure small voltages such as those produced by thermocouple junctions and pH probes. This "potentiometric" technique allowed 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



Null-balance measurement of thermocouple voltage



file i00621

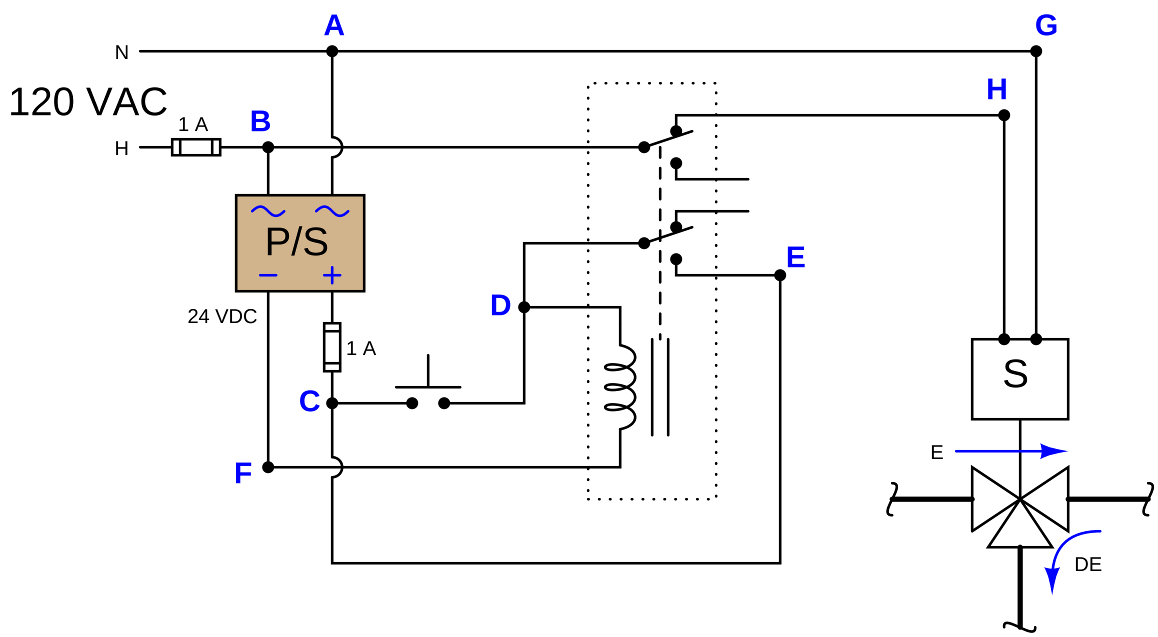
Question 53

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

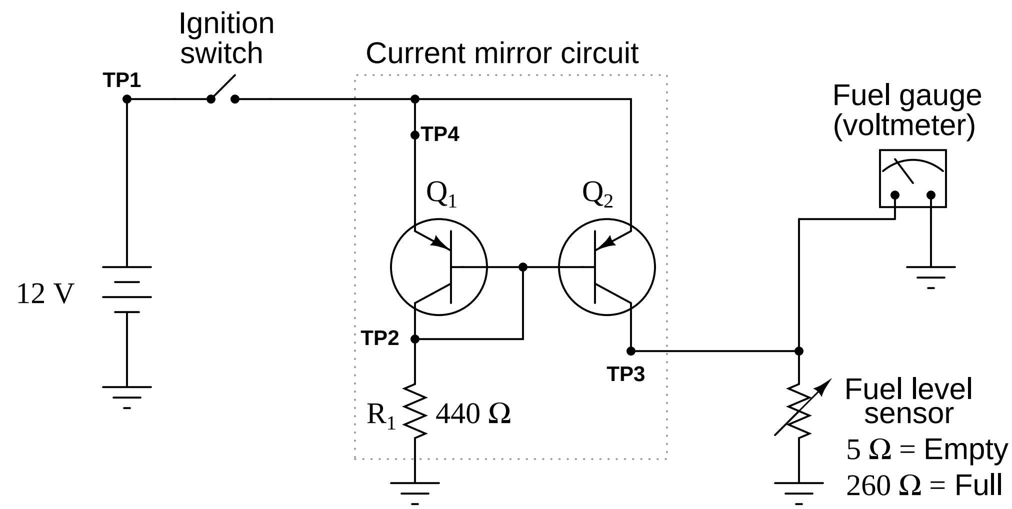
Industrial system diagrams also have *schema* associated with them. One does not interpret a P&ID in the same manner that one interprets an electronic schematic or a block diagram, despite their many similarities. This exercise will ask you to identify the meanings of similar symbols used in several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

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

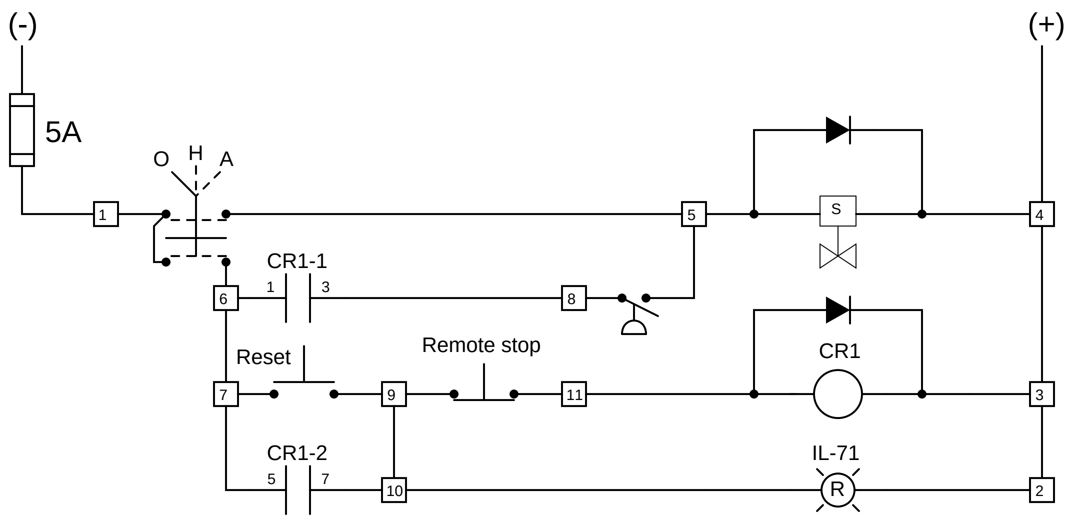
Schematic diagram of a relay circuit



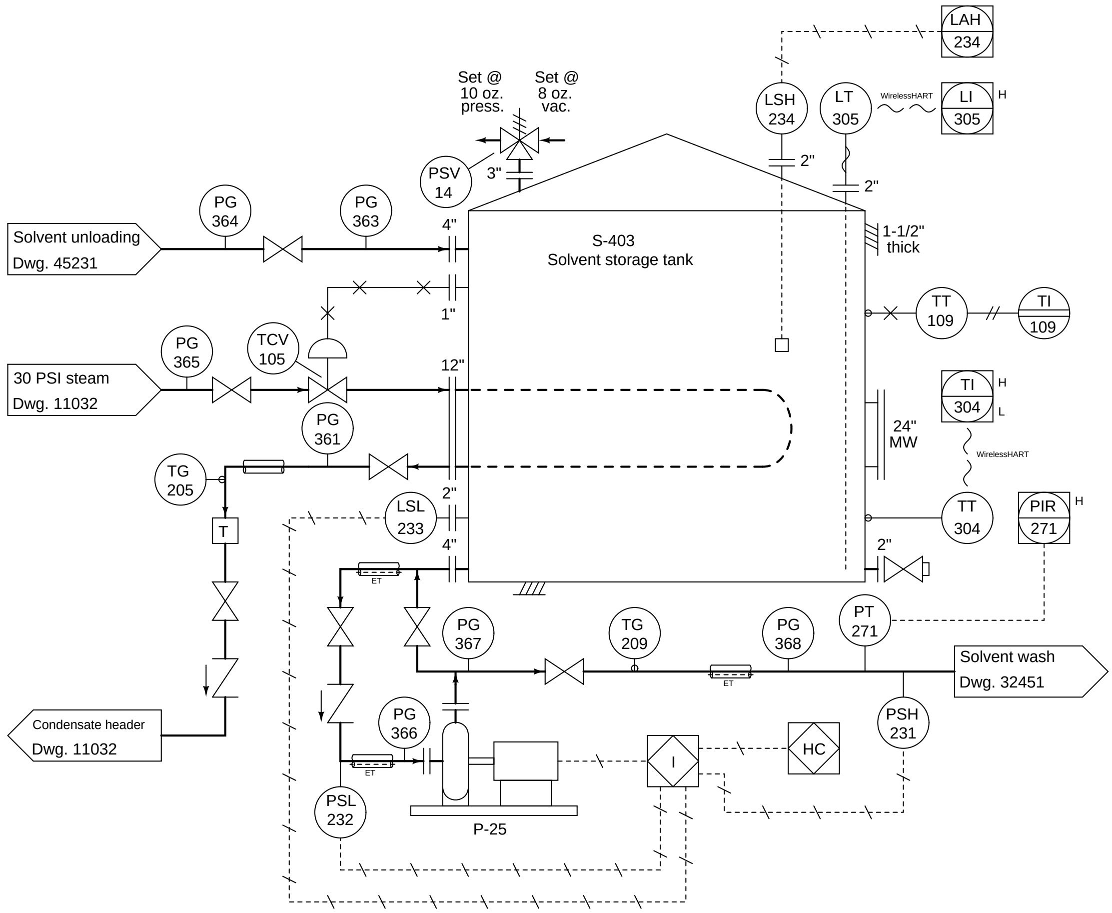
Schematic diagram of a fuel tank level sensor circuit



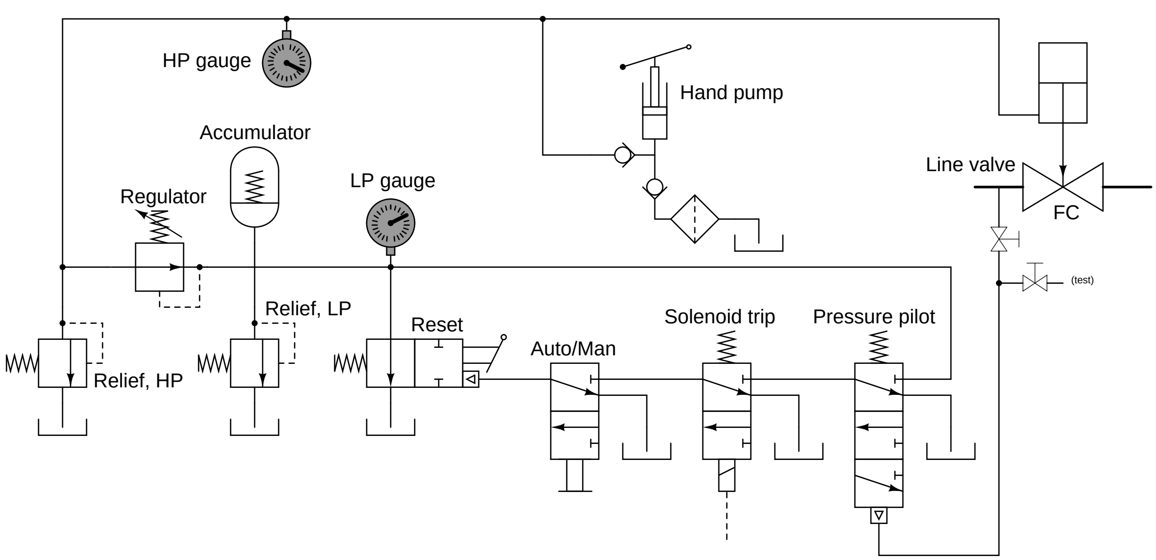
Ladder diagram of a solenoid valve control circuit



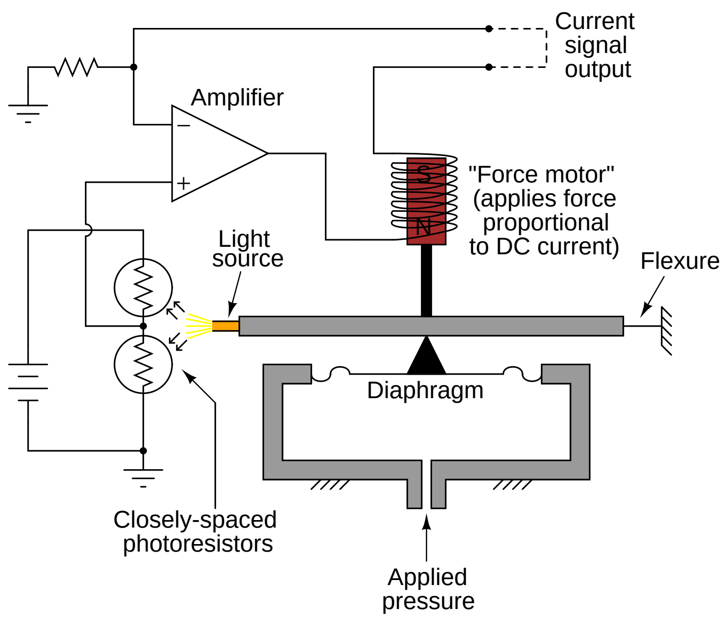
P&ID of a solvent storage tank



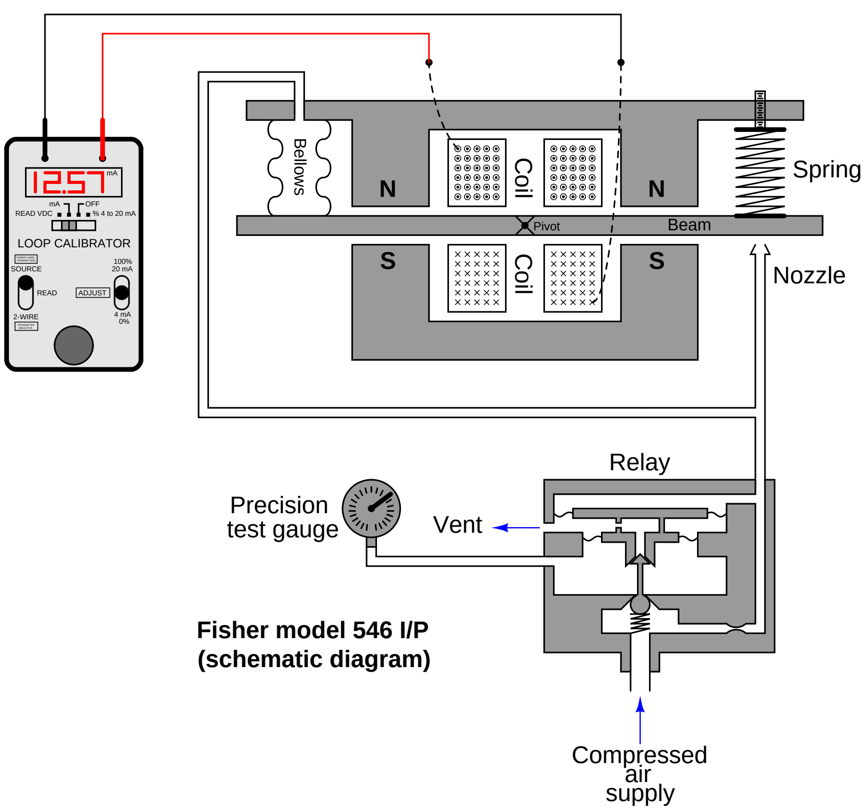
Schematic diagram of a hydraulic valve control system



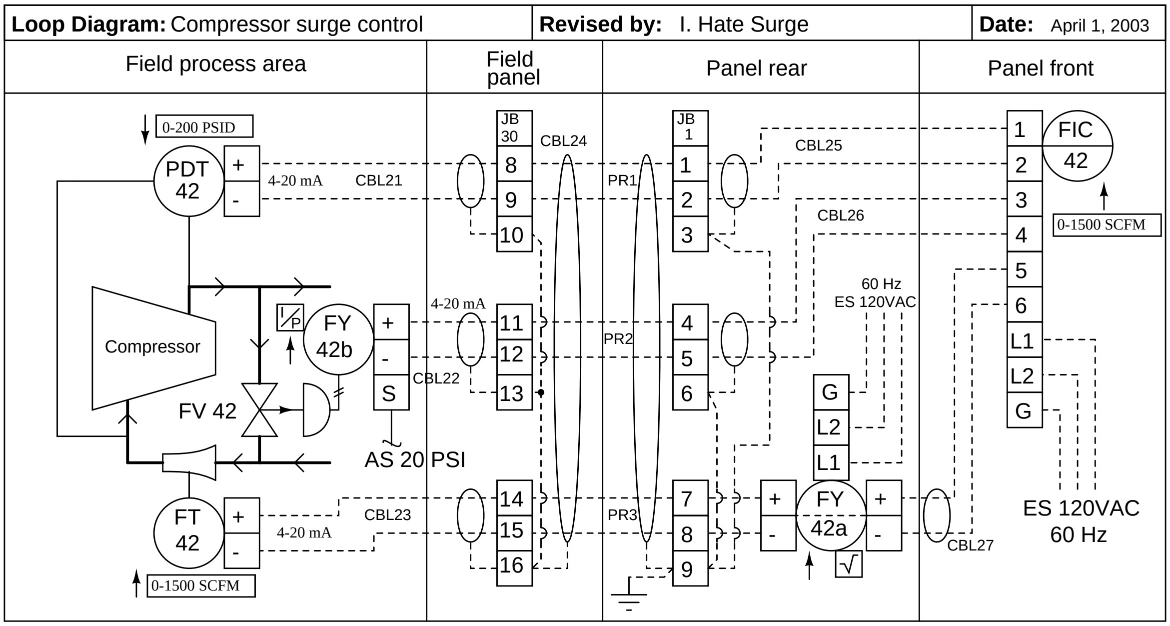
Schematic/pictorial diagram of a pressure transmitter



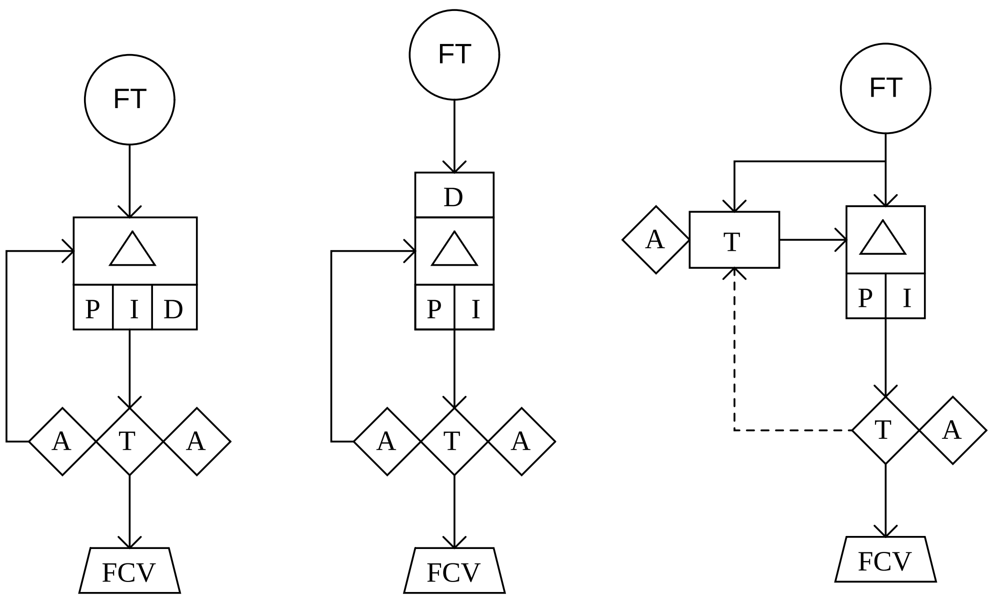
Pictorial diagram of an I/P transducer



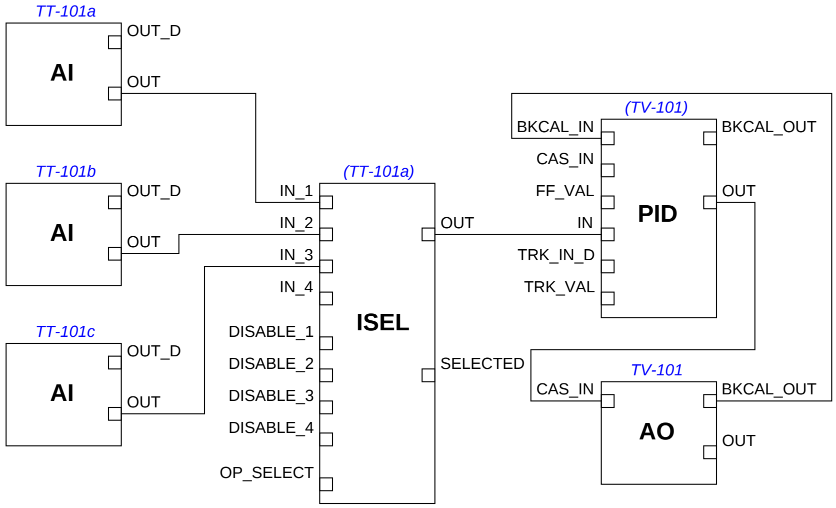
Loop diagram of a compressor surge control system



Functional diagram of control loops



FOUNDATION Fieldbus function block diagram



Questions:

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

file i02683

Question 54

Question 55

Question 56

Question 57

Question 58

Question 59

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

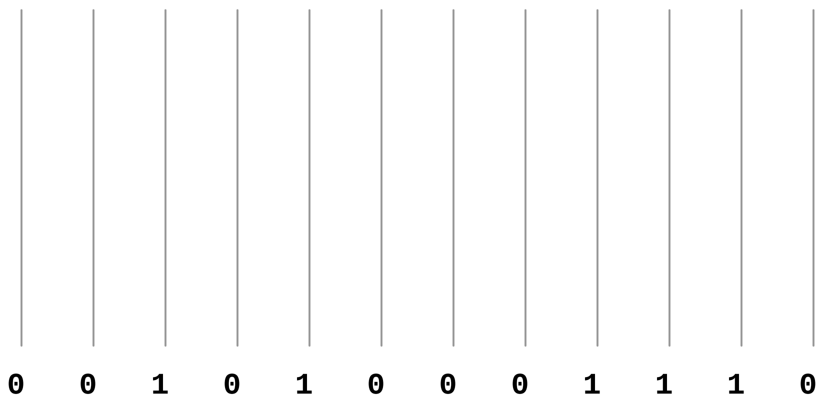
file i04400

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:



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.

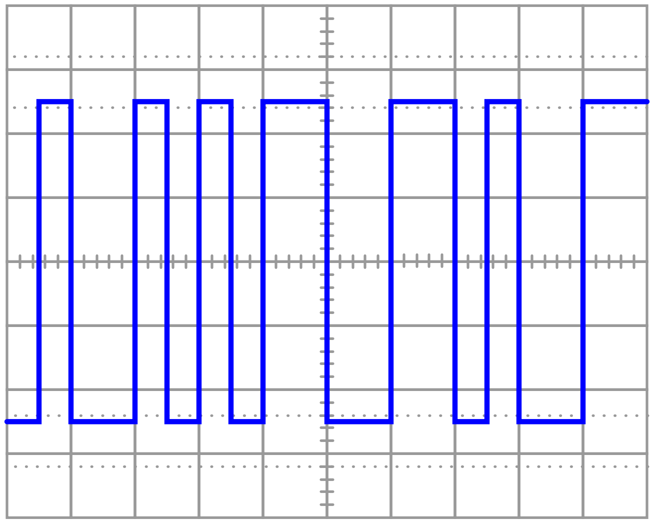
It should quickly become apparent to you where "reversals" are necessary in order to "set up" properly for the next data pulse.

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.

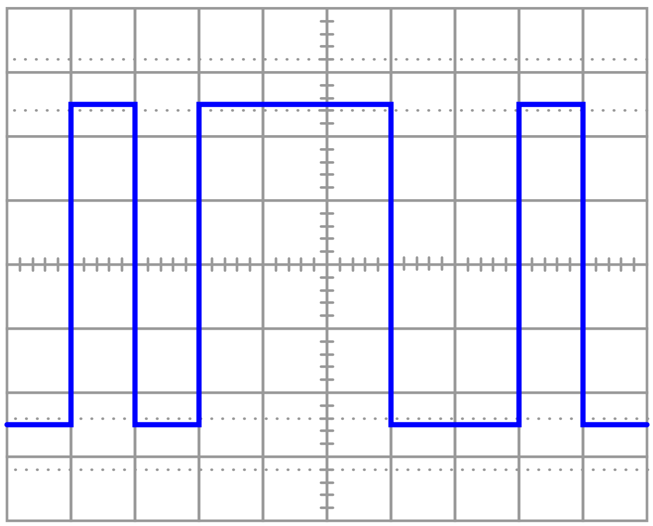
file i02128

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

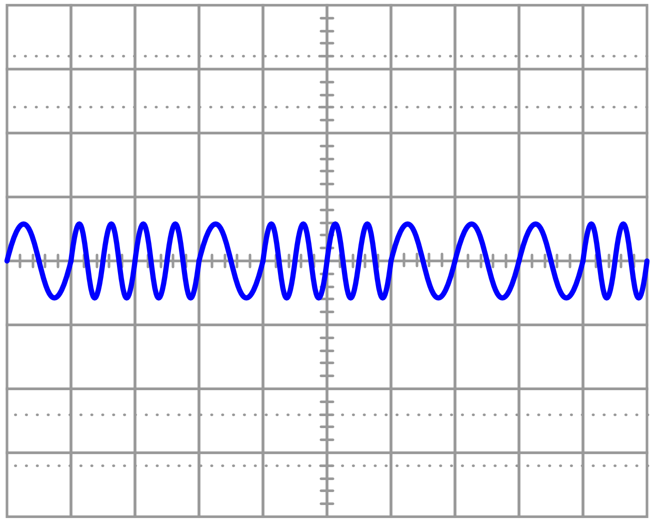
(Manchester encoding)



(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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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. Note the page numbers where important illustrations, photographs, equations, tables, and other relevant details are found. Prepare to thoughtfully discuss with your instructor and classmates the concepts and examples explored in this reading.

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

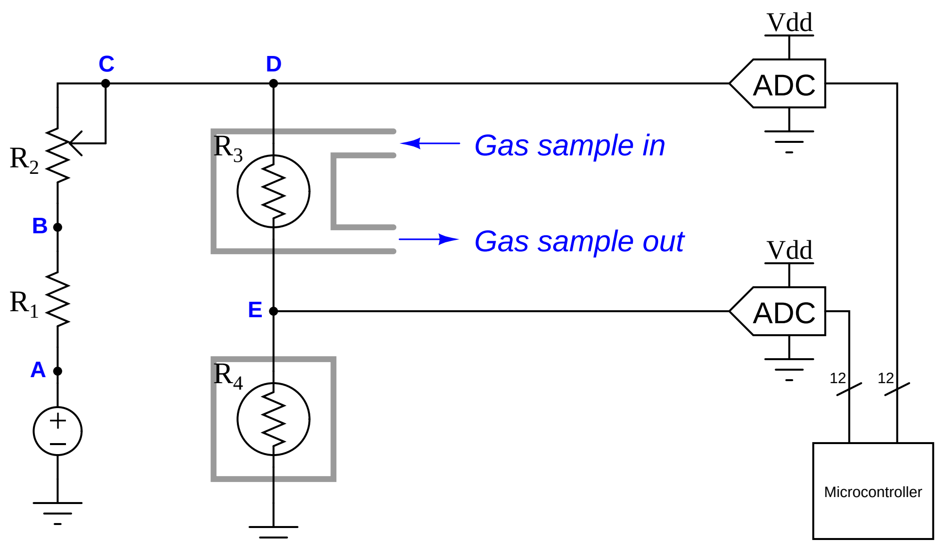
- How could you modify the spreadsheet to have its analog input range be user-adjustable? In other words, allowing anyone to simulate the performance of a 0 to 10 volt range or 0 to 20 volt range without having to modify any of the formulae in the spreadsheet?
- How could you *test* your spreadsheet 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?

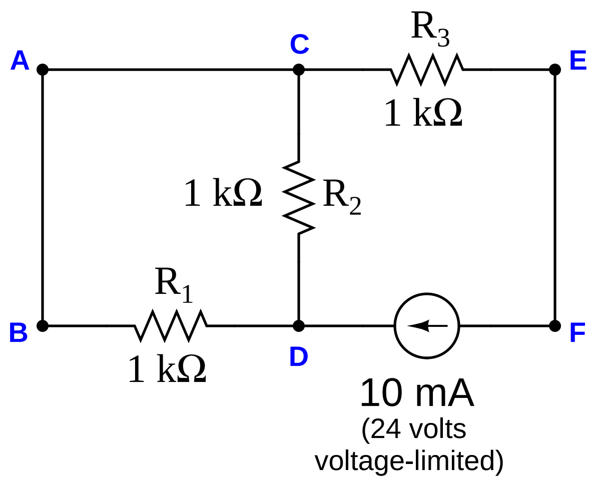
Suggestions for Socratic discussion

- Why do you suppose the two catalytic wire sensors are connected in *series*?
- 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.

file i01592

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

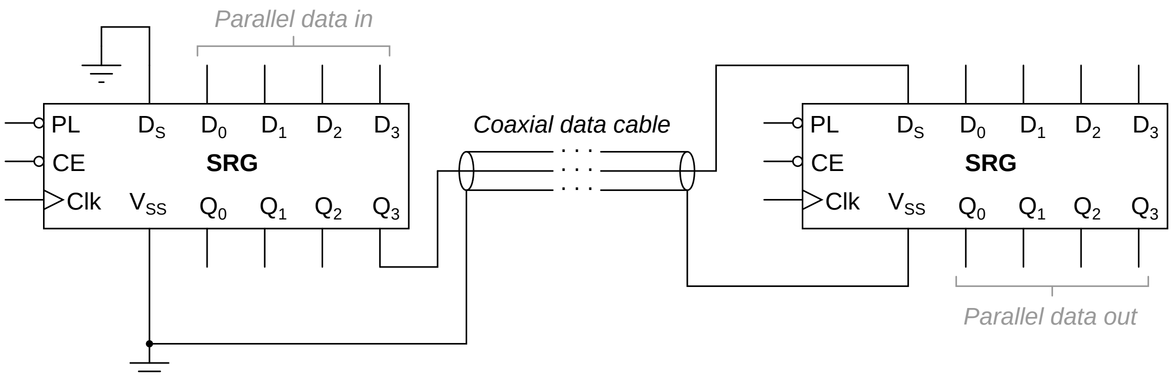
Suggestions for Socratic discussion

- 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

Question 76

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

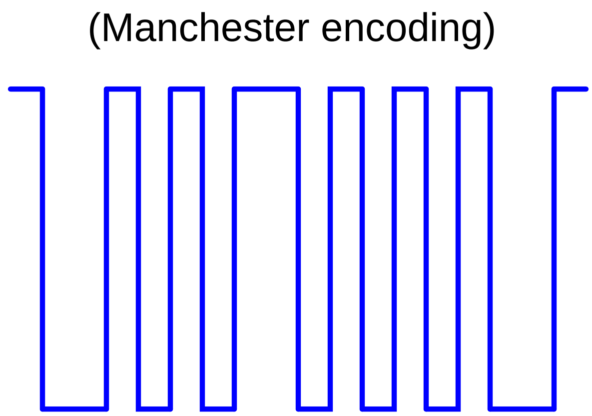
Question 77

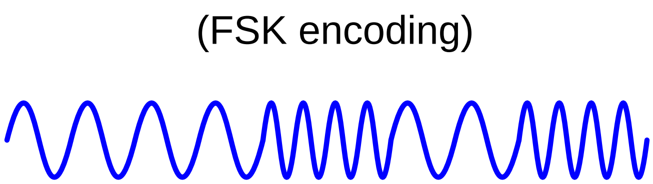
An important integrated circuit (IC) used in digital data communication is a *UART*. Describe what this acronym stands for, and explain the purpose of this circuit.

file i02172

Question 78

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

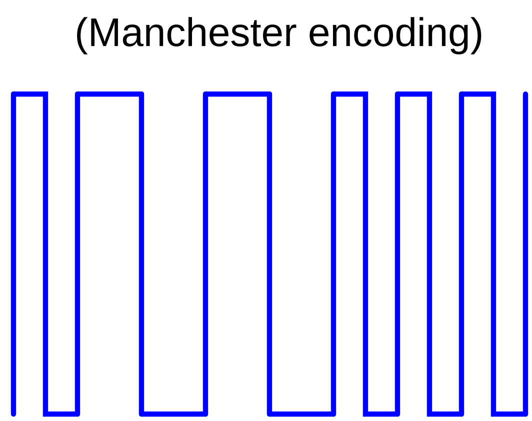


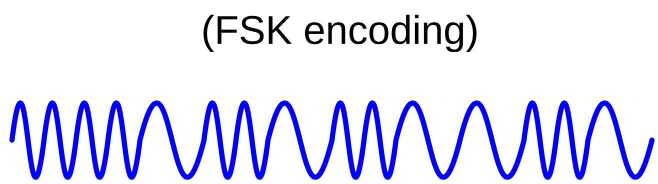


file i02917

Question 79

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





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:

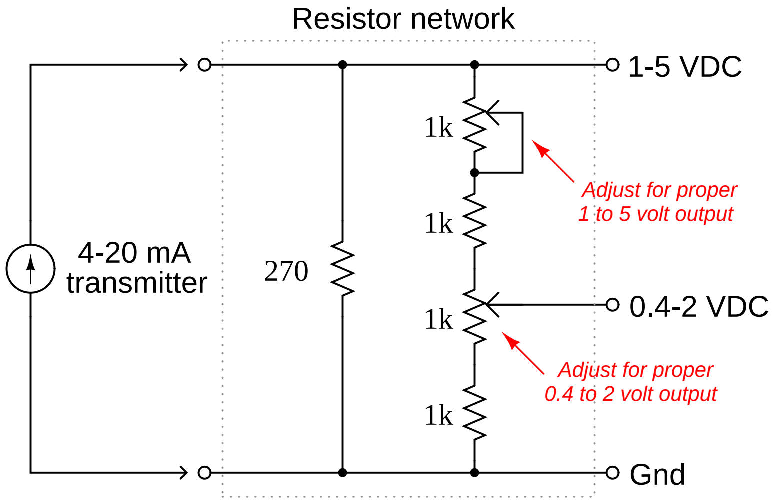
Separating power wiring from signal wiring in an enclosure:

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

file i02288

Question 82

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:

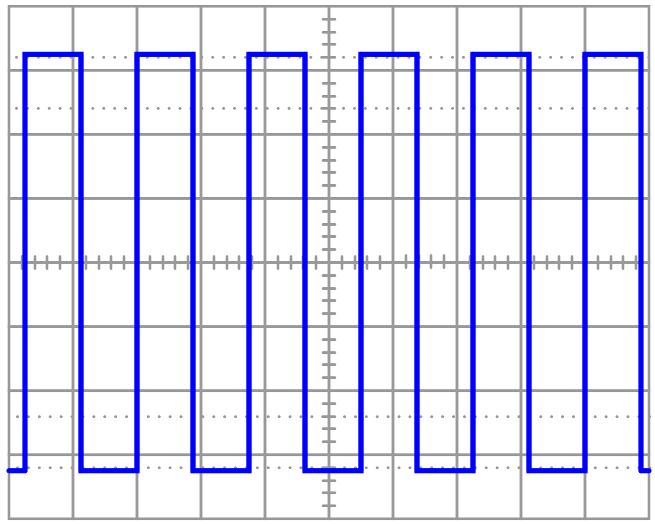


Assume the resistor values shown in the schematic are exact, calculate the required settings for both potentiometers to yield the desired output voltages given a 4 to 20 mA DC input signal range. Also, determine which of these calibrations should be made first, because one of these potentiometer adjustments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

file i02277

Question 83

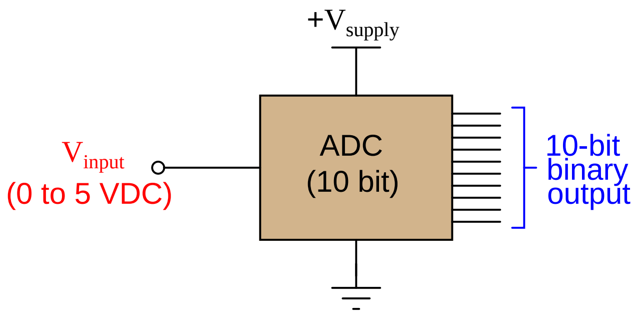
Try to interpret this Manchester-encoded digital signal as viewed on an oscilloscope display, and explain why the task is difficult (or impossible) without further information:



file i02415

Question 84

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) =

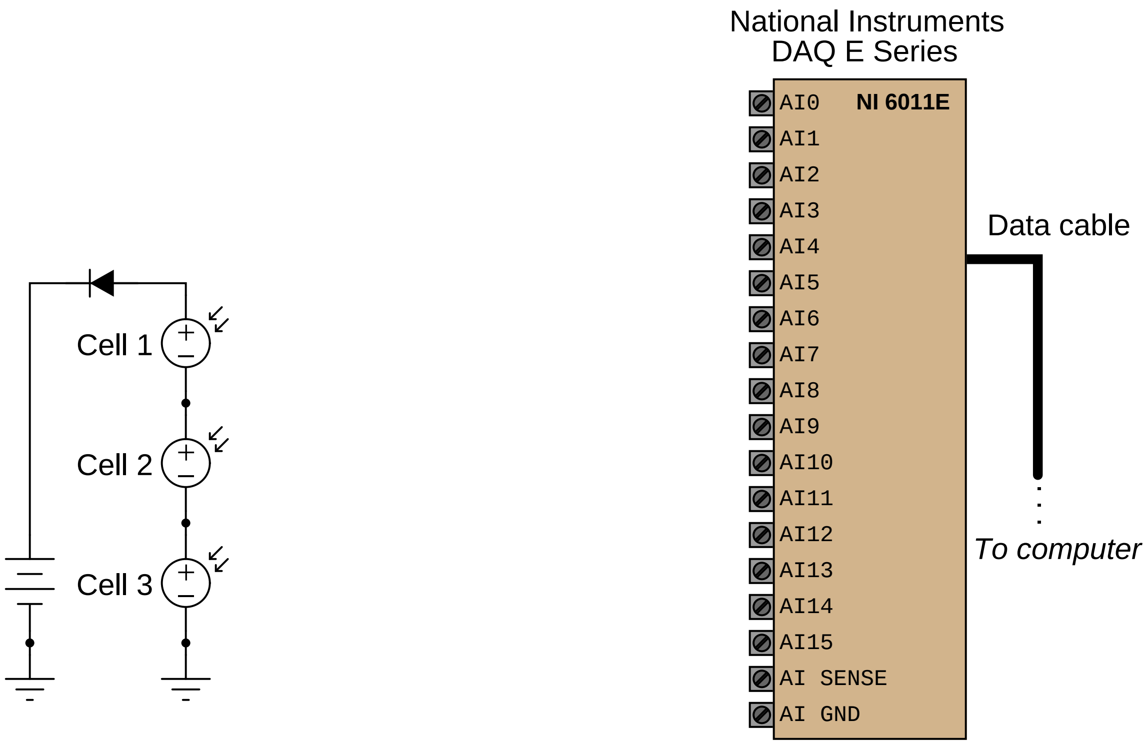
Counts (decimal) =

Counts (hexadecimal) =

file i03299

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:



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:

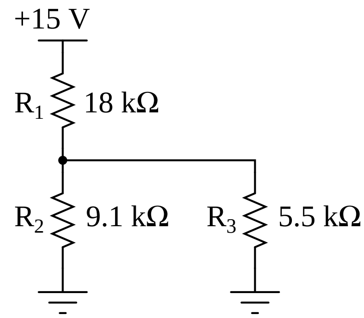
V_S = Analog span (volts)
V_R = Resolution (volts)
n = Number of digital bits

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

file i03618

Question 87

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



	R_1	R_2	R_3	Total
V				
I				
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!*

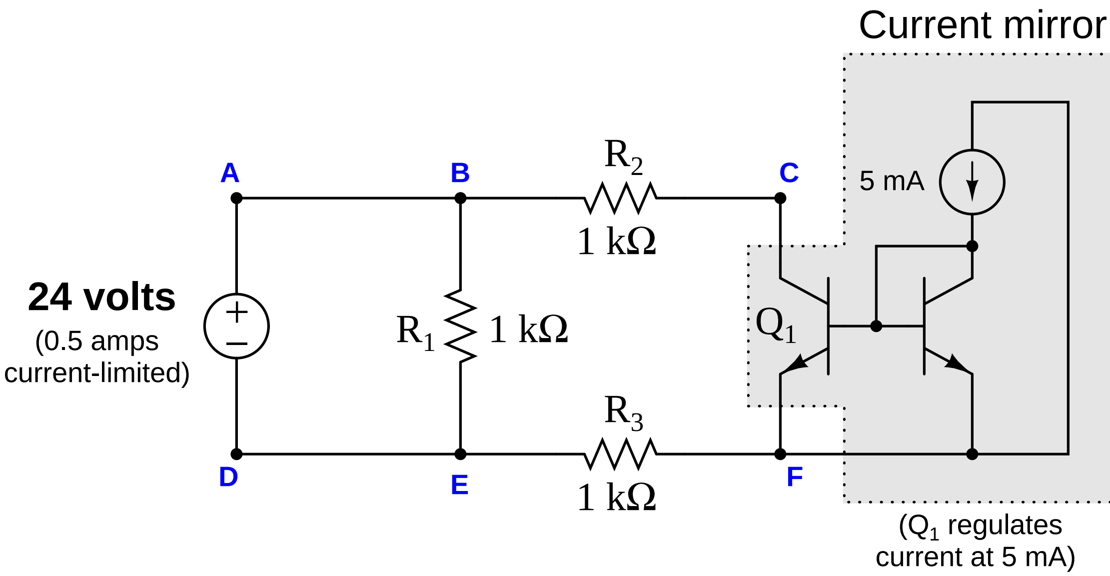
If your final answers are rounded as a result of not doing this, you will only receive half-credit for your work. This is a general policy for all your mathematical work in this program, not just this particular problem!

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:



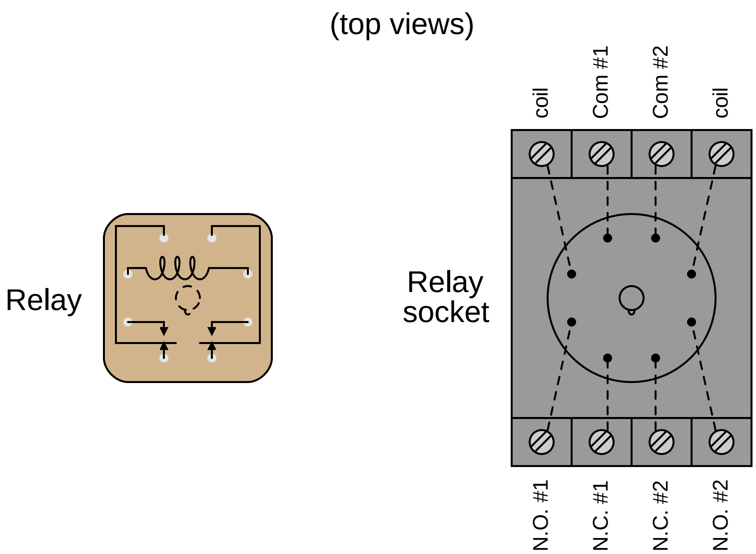
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

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		

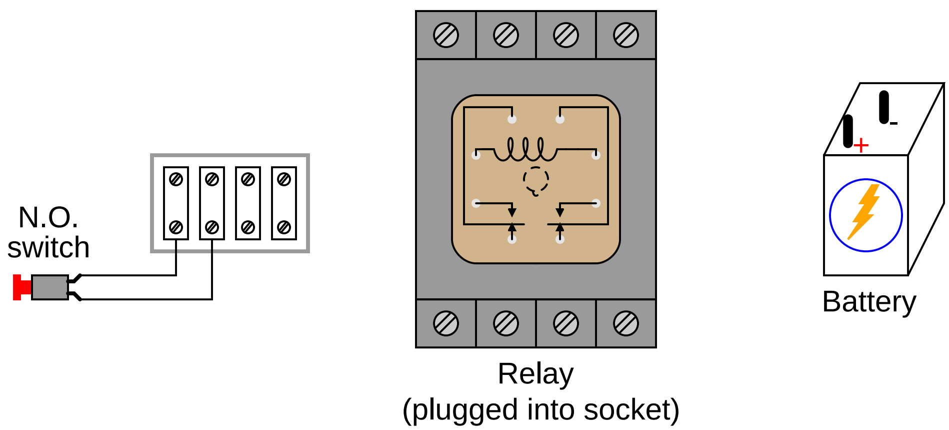
file i03193

Question 89

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



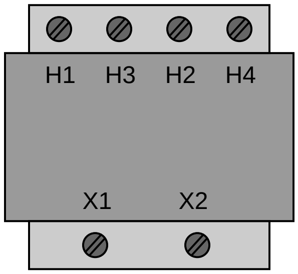
Draw the necessary connecting wires between terminals in this circuit, so that actuating the normally-open pushbutton switch sends power from the battery to the coil to energize the relay:

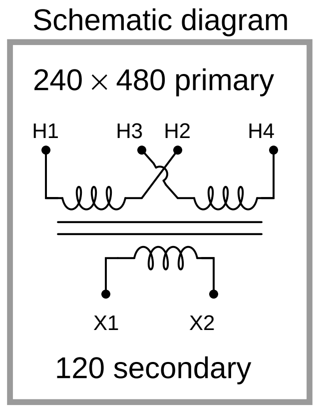


file i03208

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:





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.

<u>First (left) primary winding failed open</u>

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

<u>Second (right) primary winding failed open</u>

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

<u>First (left) primary winding shorted to iron core</u>

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

<u>Secondary winding shorted to iron core</u>

- 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 a personal computer. 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. In fact, setting up an electronic protective relay to sense AC current and initiate a breaker "trip" signal is an excellent alternative to using a generic DAQ. 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					– – – –
Lab question: Instrument connections	proportional					– – – –
Lab question: Commissioning	proportional					– – – –
Lab question: Mental math	proportional					– – – –
Lab question: Diagnostics	proportional					– – – –
Decommission and lab clean-up	mastery	–	–	–	–	

The only "proportional" scoring in this activity are the lab questions, which are answered by each student individually. A listing of potential lab questions are shown at the end of this worksheet question. The lab questions are intended to guide your labwork as much as they are intended to measure your comprehension, and as such the instructor may ask these questions of your team day by day, rather than all at once (on a single day).

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 – 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.

For example, if you intend to connect field devices to a PLC (Programmable Logic Controller), your prototype sketch must show how those devices will connect to typical input/output terminals on the PLC, where electrical power will be supplied, etc. Prototype sketches need not show all intermediary connections between components, such as terminal blocks in junction boxes between the field device and the controller.

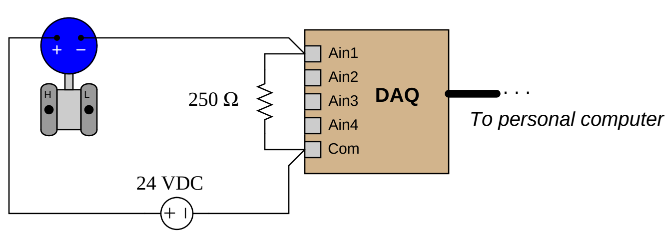
You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of electric current, voltage polarities, and identifying electrical sources/loads. Use this task as an opportunity 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.

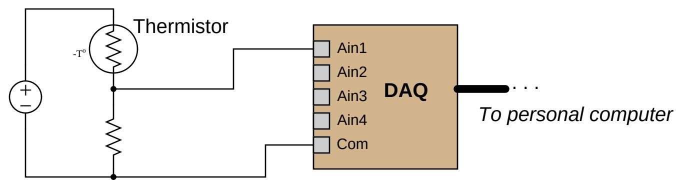
Each lab team locker has its own data acquisition unit (DAQ), and other DAQ units are available from the instructor. You will need to install software on a personal computer in order for that computer to gather analog data from the DAQ unit.

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.

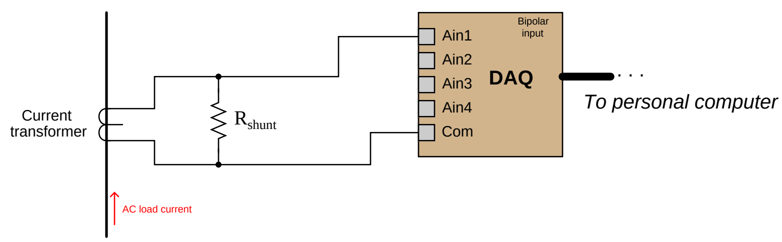
You will need to choose a suitable sensor to connect to one of the DAQ analog inputs. For greatest accuracy, I recommend using a standard 4-20 mA loop-powered pressure or temperature transmitter, with a 250 ohm resistor connected to the DAQ so it can read a 1-5 volt signal:



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.



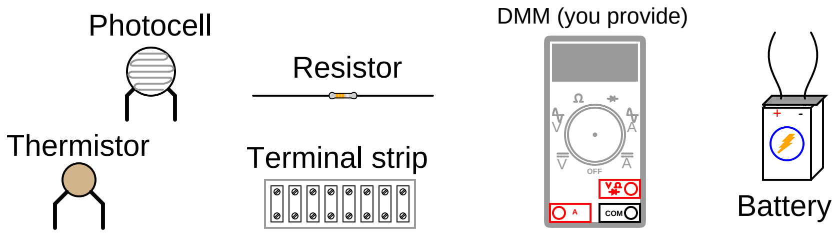
If you choose to build a system to measure AC current using a current transformer (CT, shown above), you will need to select a suitable shunt resistor to drop voltage generated by current output by the CT. This is done by researching the "burden" rating of the CT, which will tell you how large that load 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!!!*

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. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, or "alligator" clips permitted). 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.

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.



The following components and materials will be available to you: assorted CdS **photocells** and **thermistors** ; an assortment of **resistors** ; **terminal strips** ; lengths of **hook-up wire** ; **battery clips** (holders).

You will be expected to supply your own screwdrivers and digital multimeter (DMM) for assembling and testing the circuit at your desk. The instructor will supply the battery(ies) to power your circuit when you are ready to see if it works. Until that time, your circuit will remain unpowered.

Meter response (instructor chooses): ____ Direct ____ Reverse

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

Sensor type (instructor chooses): ____ Photocell ____ Thermistor

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 personal computer attached to the DAQ may be your own laptop, or one of the lab's computers. Regardless of which computer you use, it needs to be connected to the lab's Ethernet network so that another computer in the lab may acquire the data from it.

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 – advanced multimeter usage

Part of this lab exercise is learning how to use an incredibly powerful feature of your digital multimeter: its ability to capture and record minimum and maximum measurements. On Fluke-brand multimeters, this mode is engaged by pressing a button labeled "Min/Max". Once engaged, the meter will store in its memory the lowest, highest, and average values of that measurement from the time the mode is engaged until the time you read those captured values.

Some digital multimeters (DMMs) have even more advanced functionality, whereby they record multiple data points over time, more like a data recorder. Additionally, other advanced features such as *high-speed Min/Max*, *high-resolution measurement*, and *low-pass filtering* are provided by Fluke-brand multimeters. Take the time to try all of these measurement features while using your multimeter in this lab exercise.

These functions are important when diagnosing intermittent faults in a system. The multimeter's ability to capture and remember measurement values over long spans of time gives the technician the flexibility to set the multimeter as a recording device, leave to do other tasks, then return to see what the meter recorded during that span of time.

It should be noted that your multimeter may not retain its automatic ranging capability when set to record data. If your meter is like this and you engage this mode while the measurement value is low, the meter may respond with an "overload" indication should the measurement value exceed the range locked in at the time the record mode was engaged. In this case, the you are advised to manually set the meter's measurement range before engaging the recording mode.

It should also be noted that some DMMs provide multiple sampling times for their record function. In other words, your meter might provide a "slow" recording mode plus a "fast" recording mode. The trade-off for faster sampling time is – as always for DAQ hardware – less measurement resolution. In other words, you might not be able to record data as precisely as you would like in the fast speed. Conversely, if you desire maximum resolution, you may have to settle for a slower sampling rate.

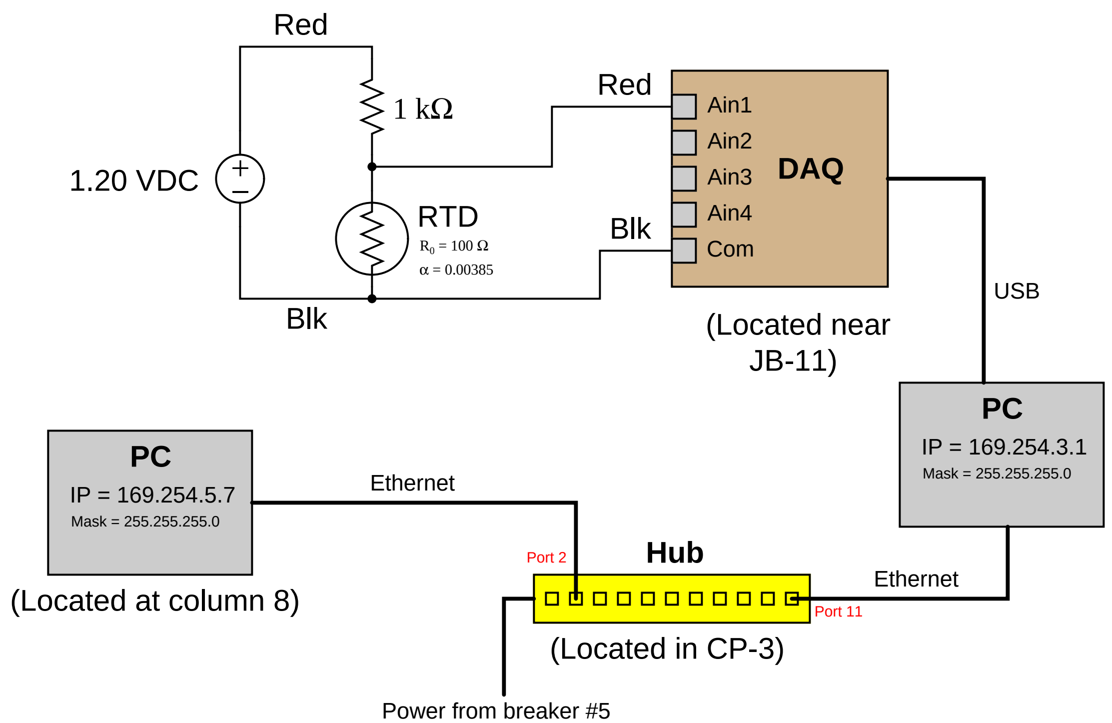
Common mistakes:

- Failing to consult the multimeter's instruction manual.
- Failing to consult the multimeter's instruction manual.
- Failing to consult the multimeter's instruction manual.
- Note: *this repetition is not a typographical error. I* **really** *want you to consult the instruction manual that came with your multimeter!*

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:



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:

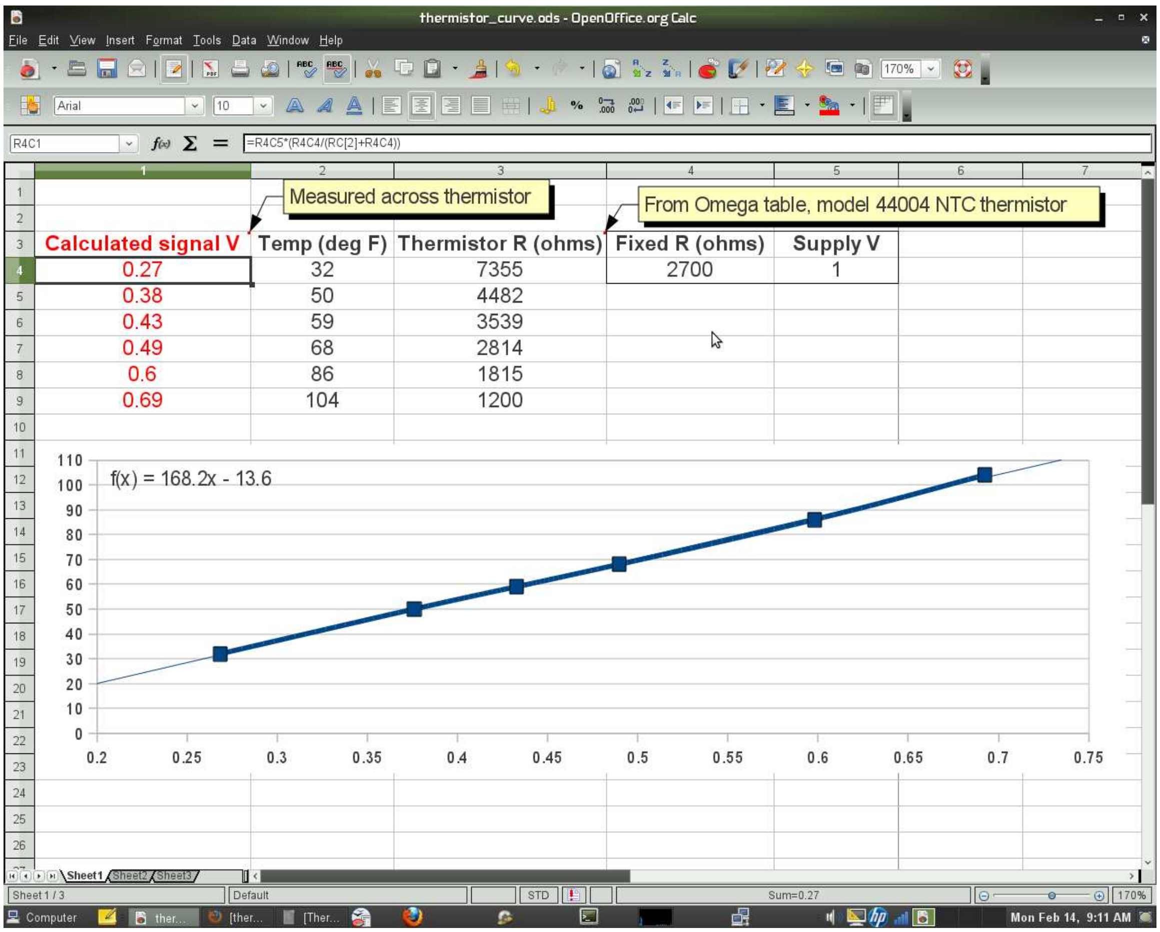
- Forgetting to label all signal wires.
- Forgetting to note all wire colors.
- Forgetting to put your name on the diagram!
- Basing your diagram off of a team-mate's diagram, rather than closely inspecting the system for yourself.
- Not placing instruments in the correct orientation (field instruments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

Lab Exercise – DAQ signal scaling/linearization

Each team must configure the DAQ system to ensure it accurately measures and reports the measured variable. 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).

If your system uses a loop-powered 4-20mA 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 Ω) 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. Unless the DAQ software is quite sophisticated, this feature is not likely to be directly supported. A suitable alternative is to have one computer acquiring data from the DAQ module, and use another computer to remotely view the display of the first computer. This remote viewing may be done using "Remote Desktop" in Microsoft Windows operating systems, or by installing free remote-administration software such as `RealVNC`.

Not only will remote access allow you to view the live DAQ data from another computer over the Ethernet network, but it also allows you do *operate* the DAQ computer remotely. Knowing how to use remote-viewing software, therefore, is a very useful skill.

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. 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. 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 challenging aspect of this lab exercise is *troubleshooting*, where you demonstrate your ability to logically isolate a problem in the system. All troubleshooting is done on an individual basis (no team credit!), and must be done *on a system you did not help build*, so that you must rely on loop diagrams 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 general location and nature of the fault, logically justifying all diagnostic steps taken. All troubleshooting activities will take place under direct instructor supervision to ensure students are working independently and efficiently.

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

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

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

Common mistakes:

- Neglecting to take measurements with your multimeter.
- Neglecting to check other measurements in the system (e.g. pressure gauge readings).
- Incorrectly interpreting the 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!

Remember that the purpose of the 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 not a successful demonstration of skill. The only thing that counts as competence is 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. Be sure your team budgets for this amount of time as you plan your work, and also be sure to take advantage of your freedom to observe others as they troubleshoot, to better learn this art.

Lab questions

- **Instrument connections**
- Determine correct wire connections between a DAQ module and an electrical sensor, based on diagrams of instruments with terminals labeled
- Correctly determine all electrical sources and loads, as well as all voltage polarities and current directions in a DAQ/sensor circuit, based on diagrams of instruments with terminals labeled

- **Commissioning and Documentation**
- Explain the operating principle of the sensor used in your system
- Explain the difference between a *single-ended* input channel and a *differential* input channel on an analog DAQ module
- Describe the use of some of the advanced functions of your multimeter *besides* record ("Min/Max") mode
- Explain why power and signal wiring should not be run together in conduit or in a panel
- Explain why it is necessary to use a *bushing* to protect electrical wires that enter and exit an electrical enclosure through a hole in the side of that enclosure

- **Mental math** (no calculator allowed!)
- Determine allowable calibration error of instrument (e.g. +/- 0.5% for an instrument ranged 200 to 500 degrees)
- Convert 1-5 V signal into a percentage of span (e.g. 3.5 V = ____%)
- Convert percentage of span into a 1-5 V signal value (e.g. 70% = ____ V)
- Calculate resolution of ADC given number of bits and input signal range

- **Diagnostics**
- Explain how to distinguish an "open" cable fault from a "shorted" cable fault using only a voltmeter (no current or resistance measurement, but assuming you are able to break the circuit to perform the test)
- Determine whether or not a given diagnostic test will provide useful information, given a set of symptoms exhibited by a failed system
- Identify at least two plausible faults given the results of a diagnostic test and a set of symptoms exhibited by a failed system
- Propose a diagnostic test for troubleshooting a failed system and then explain the meanings of two different test results

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

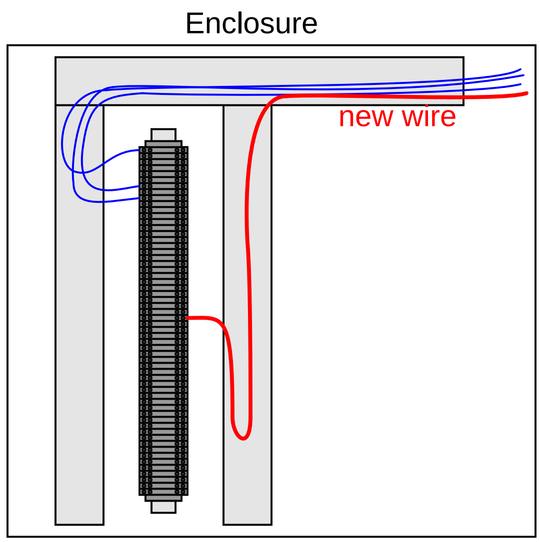
Finally, you shall return any control system components to their original (factory default) configurations. This includes controller PID settings, function block programs, input signal ranges, etc.

file i00350

Answer 1

Answer 2

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 3

Answer 4

Answer 5

The best installation is the one without a *ground loop*.

When choosing between the other two shield-grounding strategies, it is best to imagine an installation where many shielded cables terminate at a single enclosure on one end, and terminate at far-flung field locations at the other ends. What we must try to avoid here is the possibility of electric shock hazard to any technicians working on these cables, resulting from large differences in earth ground potential at different locations.

Answer 6

Answer 7

Answer 8

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**

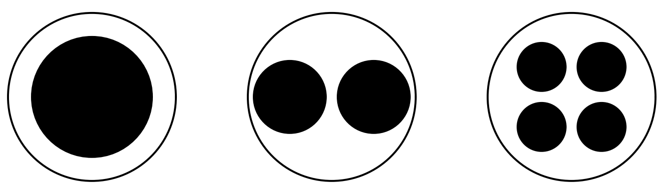
Based on this short list of possible faults – assuming only *one* of them is actually true – the value of each proposed test is as follows:

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

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 9

Here is a hint:



Answer 10

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 11

Answer 12

"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 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

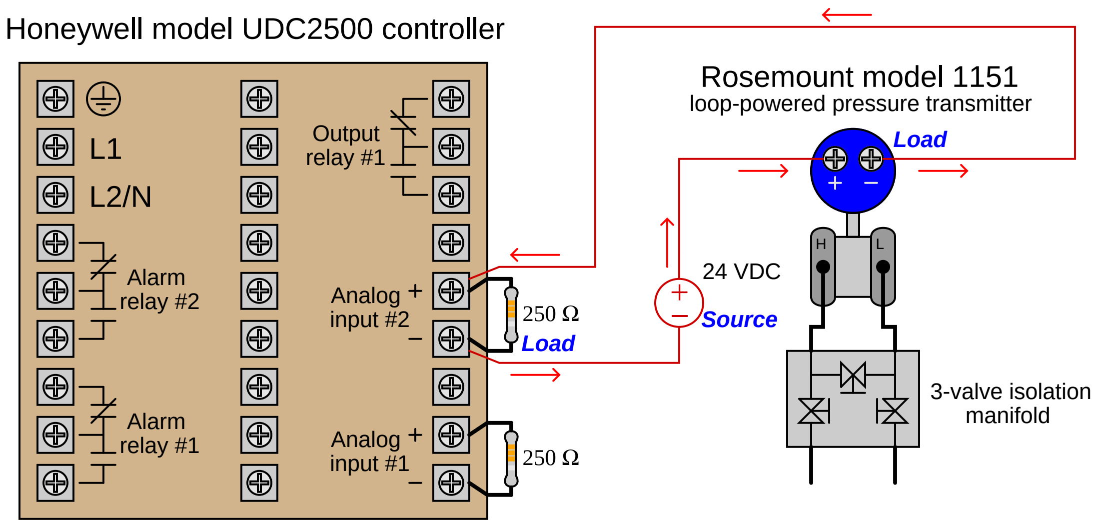
- Covers left off of many wire ducts.
- It looks like someone didn't even attempt to put some of the wires inside wire ducts, but instead left them draped directly over components.
- In areas where there are no wire ducts, the wires should have been "loomed" together instead of randomly strewn.
- Junk 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) = **<u>65535</u>** (decimal)

Signed:
- FFFF (hexadecimal) = **<u>−1</u>** (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

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 30

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

Answer 31

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

Answer 32

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 33

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 34

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

$1001.1011_2 = 9.6875_{10}$

1	0	0	1	•	1	0	1	1
2^3	2^2	2^1	2^0		2^{-1}	2^{-2}	2^{-3}	2^{-4}

Octal place-weights

$4027.3612_8 = 2071.471191406_{10}$

4	0	2	7	•	3	6	1	2
8^3	8^2	8^1	8^0		8^{-1}	8^{-2}	8^{-3}	8^{-4}

Hexadecimal place-weights

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

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

Answer 36

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 37

- 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 38

$-1.00001110000001100000000 \times 2^{-83}$

$+1.11010110000000000000000 \times 2^{77}$

$+0.11111100000110001000000 \times 2^{-126}$

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

Sign	**Exponent** (E)	**Mantissa** (m)
0	01111111	00000000000000000000000

Answer 39

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 40

Answer 41

Answer 42

R_G = 1.724 kΩ 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

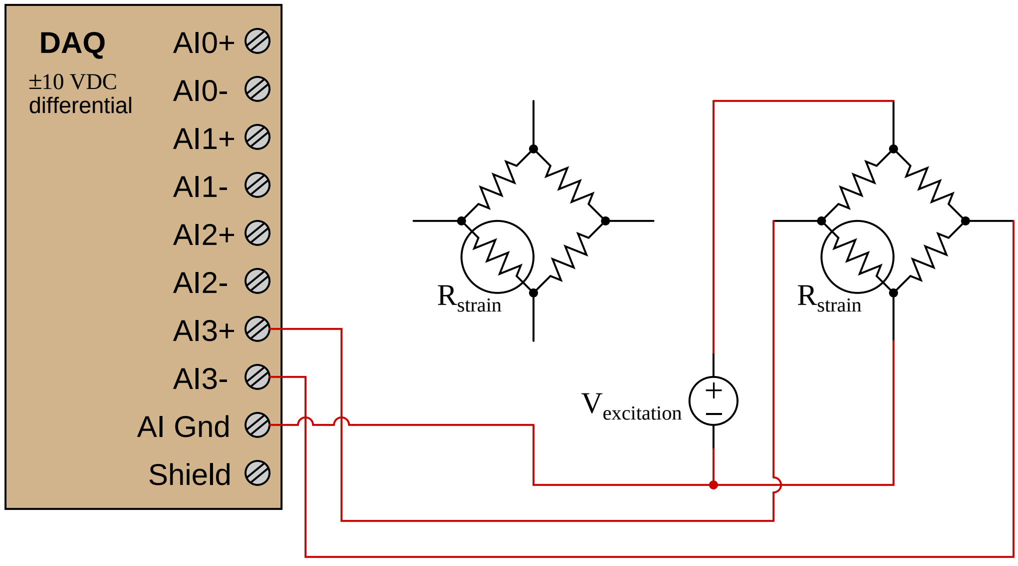
Answer 45

Partial answer:

This DAQ uses *single-ended* inputs.

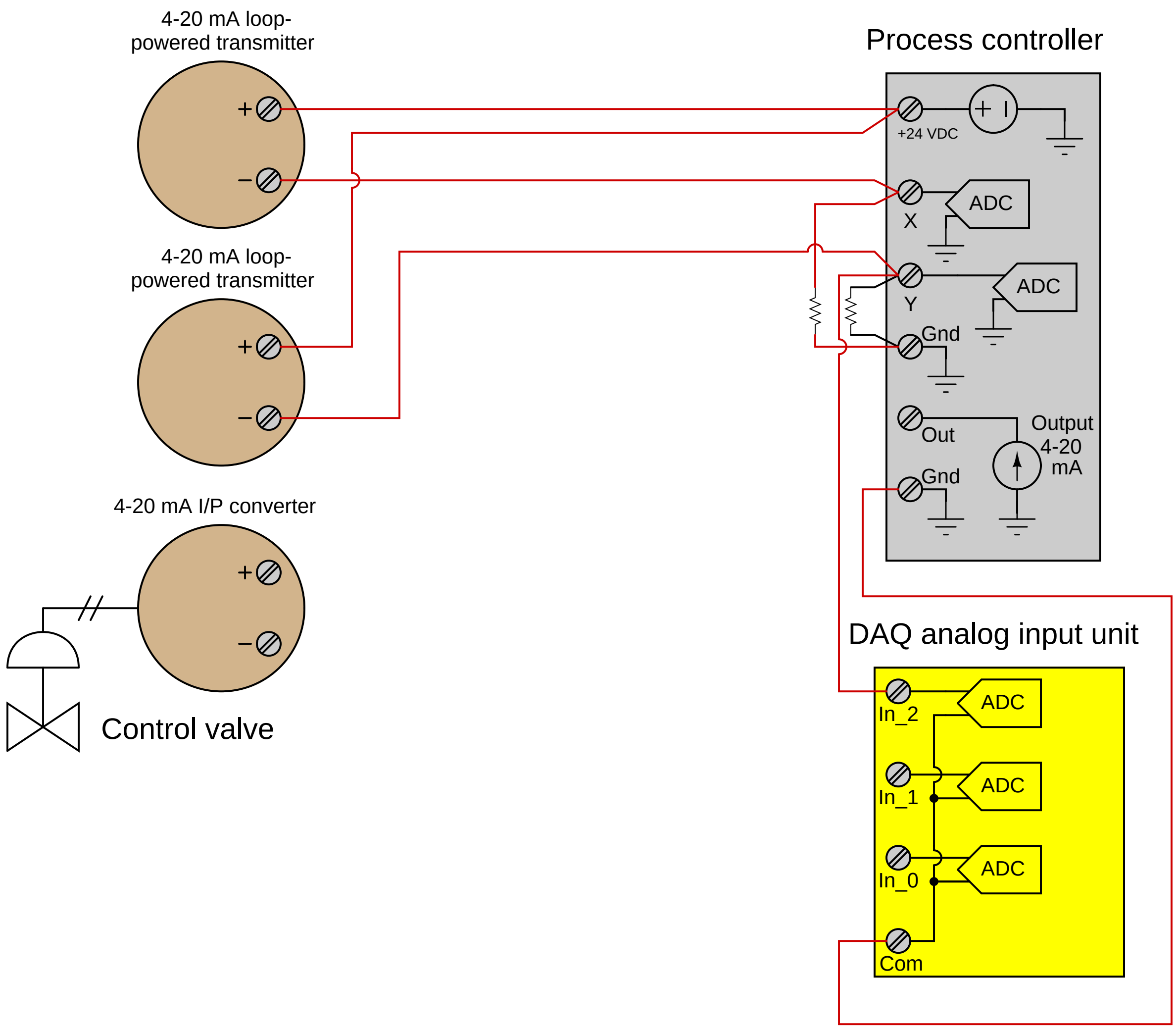
Answer 46

Partial answer:



Answer 47

Partial answer:



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

Answer 48

There are problems with *both* the PT circuit and the CT circuit, although the more severe of the two by far is the CT circuit.

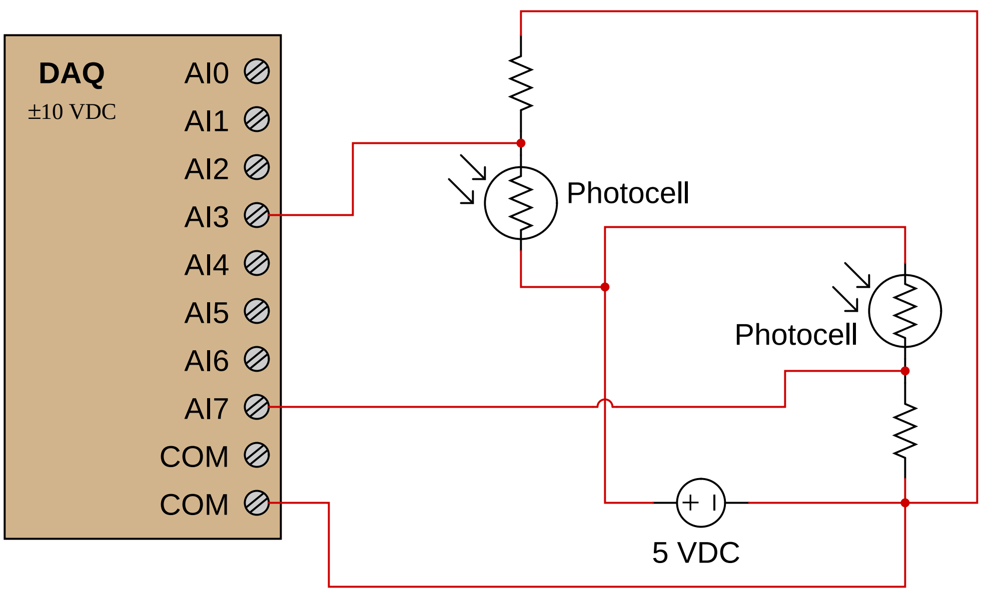
Hint: from the DAQ's perspective, the PT acts as an AC *voltage source* while the CT acts as an AC *current source*. The DAQ itself acts like a voltmeter, having an extremely high input impedance (in the millions of ohms).

Answer 49

- 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 50

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 51

- 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 52

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 53

Answer 54

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

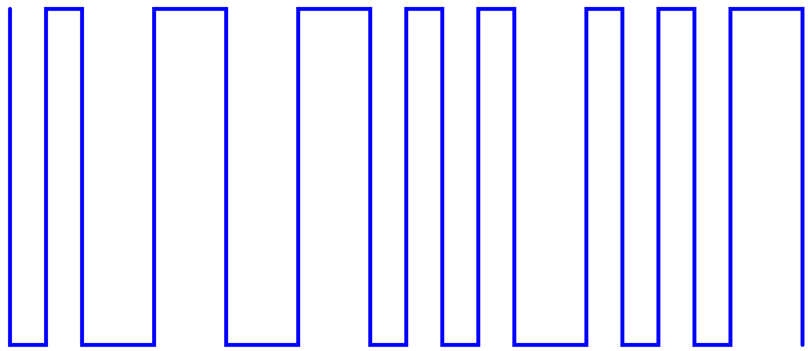
Answer 61

Answer 62

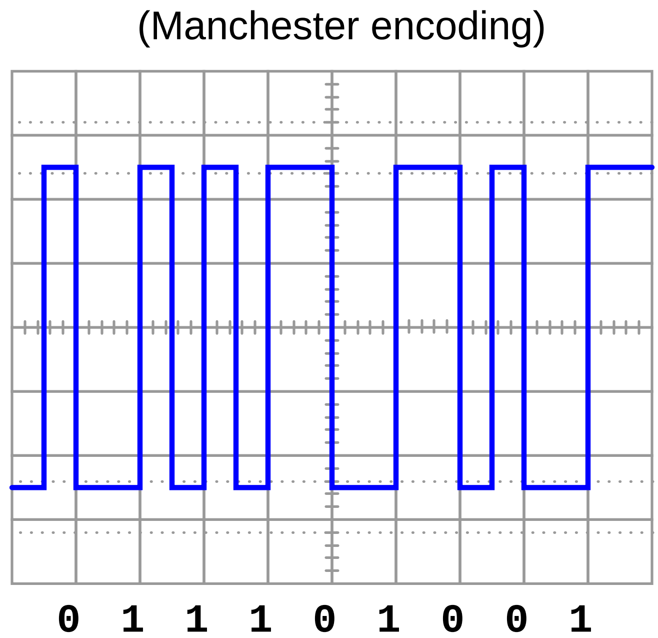
Answer 63

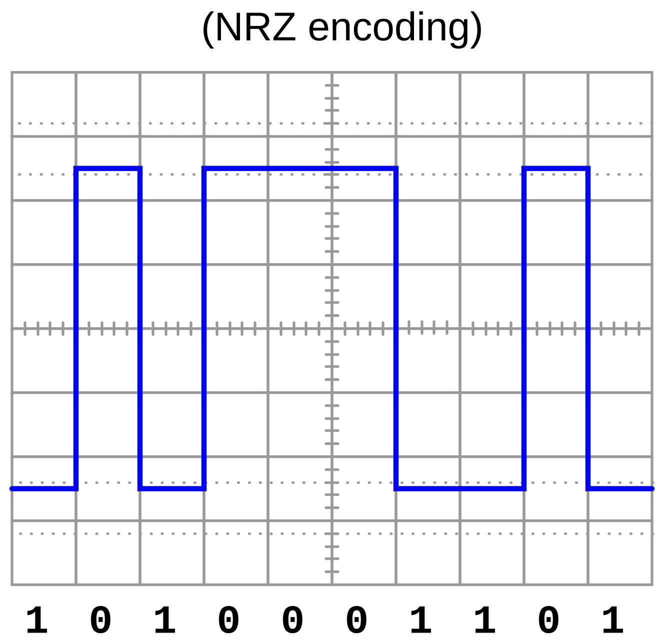
Answer 64

The "clean" waveform, with no bit markings:

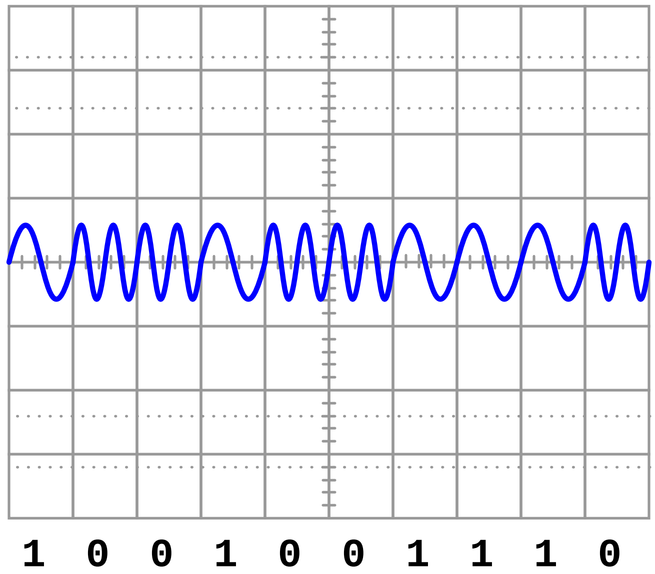


Hint: *all* the pulse edges representing "real" data bits are evenly spaced! *All* "reversal" pulse edges are out-of-step with the regular pattern of data bit pulse edges.


(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)



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.

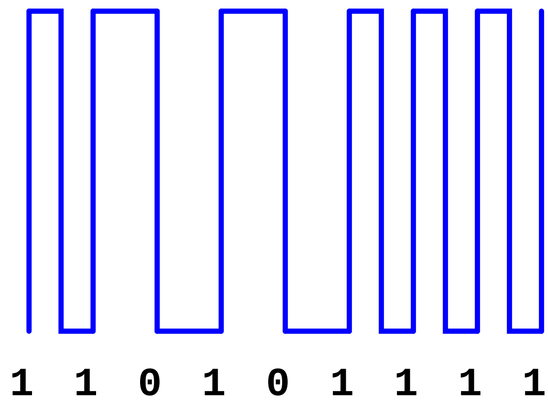
Follow-up question: research an example of a UART IC available for purchase today.

Answer 78

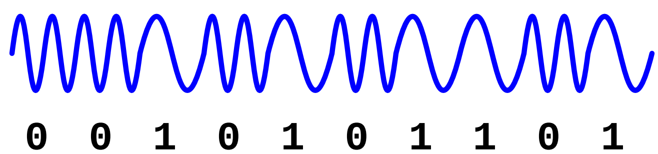
This is a graded question – no answers or hints given!

Answer 79

(Manchester encoding)



(FSK encoding)



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.