<u>Lab</u>

WirelessHART instrument loop: *Question 91*, **completed objectives due by the end of day 5**

<u>Exam</u>

Day 5 – **Complete mastery of these objectives due by the next exam date**

Specific objectives for the "mastery" exam:
- Electricity Review: Calculate voltages and currents in an ideal AC transformer circuit
- Determine proper AI block parameters to range a Fieldbus transmitter for a given application
- Use decibels to calculate power gains and losses
- Calculate instrument input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Determine status of PLC discrete output given input switch conditions and a simple RLL program listing
- INST241 Review: Determine suitability of different flow-measuring technologies for a given process fluid type
- INST251 Review: Determine the effect of a component change on the gain of a pneumatic controller mechanism

Recommended daily schedule

<u>Day 1</u>

Theory session topic: Radio communication systems

Questions 1 through 20; <u>answer questions 1-6</u> in preparation for discussion (remainder for practice)

<u>Day 2</u>

Theory session topic: WirelessHART systems

Questions 21 through 40; <u>answer questions 21-26</u> in preparation for discussion (remainder for practice)

<u>Day 3</u>

Theory session topic: Long-range wireless networks

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

<u>Day 4</u>

Theory session topic: Review for exam

Questions 61 through 80; <u>answer questions 61-68</u> in preparation for discussion (remainder for practice)

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

<u>Day 5</u>

Exam

How To . . .

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

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

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

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

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

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

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

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

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

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

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

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

<u>file `howto`</u>

General Values, Expectations, and Standards

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

file `expectations`

Program Outcomes for Instrumentation and Control Technology (BTC)

#1 | Communication

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

#2 | Time management

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

#3 | Safety

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

#4 | Analysis and Diagnosis

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

#5 | Design and Commissioning

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

#6 | System optimization

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

#7 | Calibration

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

#8 | Documentation

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

#9 | Independent learning

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

#10 | Job searching

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

file outcomes_program

INST 262 Course Outcomes

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

- Calculate voltages, currents, powers, and/or resistances in a DC series-parallel circuit. [Ref: Program Learning Outcome #4]

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

- Identify proper controller action for a given process. [Ref: Program Learning Outcome #5]

- Predict the response of a single-loop control system to a component fault or process condition change, given a pictorial and/or schematic illustration. [Ref: Program Learning Outcome #4]

- Determine proper AI block parameters to range a Fieldbus transmitter for a given application. [Ref: Program Learning Outcome #5]

- Use decibels to calculate power gains and losses. [Ref: Program Learning Outcome #4]

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

- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]

- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]

- Determine the possibility of suggested faults in a simple circuit given measured values (voltage, current), a schematic diagram, and reported symptoms. [Ref: Program Learning Outcome #4]

- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]

- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]

- Connect a loop controller to the electronic transmitter and final control element of a pre-constructed process, then commission all components to form a working feedback control loop. [Ref: Program Learning Outcome #5]

- Generate an accurate loop diagram compliant with ISA standards documenting your team's control system. [Ref: Program Learning Outcome #8]

- Commission and decommission a WirelessHART instrument. [Ref: Program Learning Outcome #5]

- Configure a digital indicator to poll instrument data via the Modbus/TCP protocol. [Ref: Program Learning Outcome #5]

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

- Build a circuit to sense either pressure or vacuum using a differential pressure transmitter with HART

communication capability, reporting the sensed variable on an analog meter chosen by the instructor, setting the range values according to instructor specifications, capturing peak signal value using a digital multimeter, and capturing binary 0 and 1 bits using a digital oscilloscope. [Ref: Program Learning Outcome #5]

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

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

file `outcomes_INST262`

Sequence of second-year Instrumentation courses

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

(Only if 4th quarter was Summer: INST23x)

INST 200 -- 1 wk
Intro. to Instrumentation

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

Prerequisite for all INST24x, INST25x, and INST26x courses

Summer quarter

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

Jobshadow and/or Internship strongly recommended

Fall quarter

INST 240 -- 6 cr
Pressure/Level Measurement

INST 241 -- 6 cr
Temp./Flow Measurement

INST 242 -- 5 cr
Analytical Measurement

Winter quarter

INST 250 -- 5 cr
Final Control Elements

INST 251 -- 5 cr
PID Control

INST 252 -- 4 cr
Loop Tuning

Spring quarter

INST 260 -- 4 cr
Data Acquisition Systems

INST 262 -- 5 cr
Digital Control Systems

INST 263 -- 5 cr
Control Strategies

ENGT 134 -- 5 cr
CAD 1: Basics

Prerequisite for INST206

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

INST 205 -- 1 cr
Job Prep I

INST 206 -- 1 cr
Job Prep II

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

Graduate!!!

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

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

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

file sequence
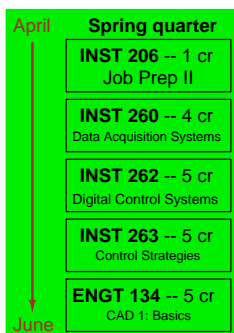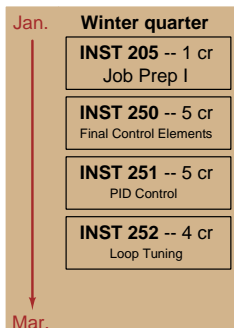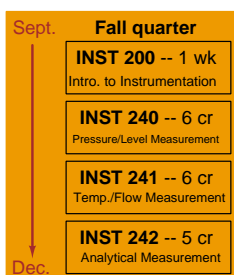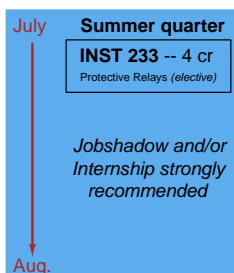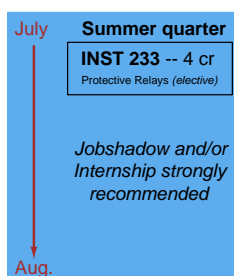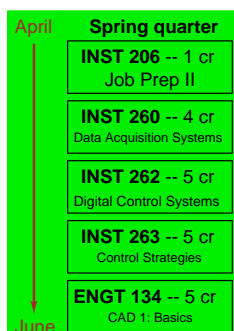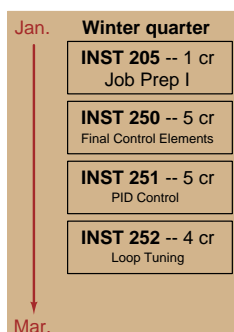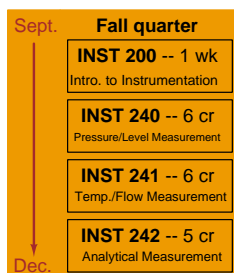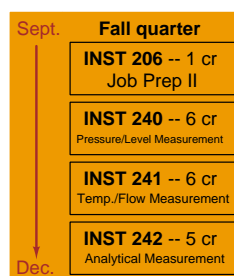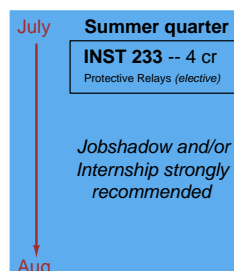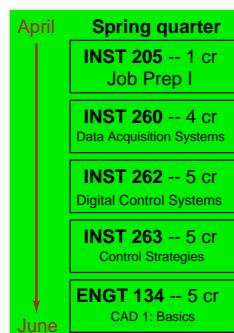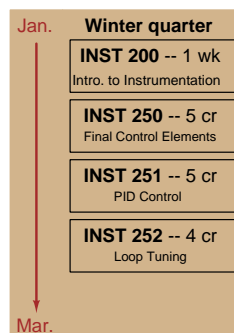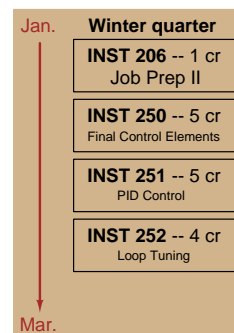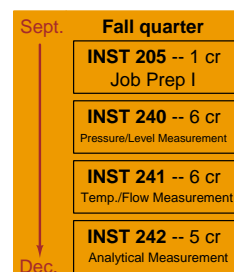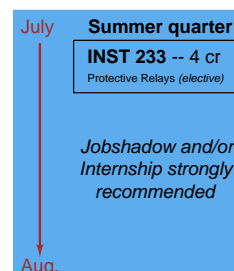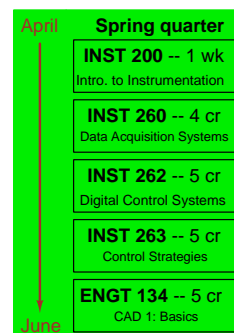
General tool and supply list

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

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

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

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

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

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

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

file `tools`

Methods of instruction

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

Inverted theory sessions

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

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

Small sessions

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

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

Large sessions

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

Correspondence

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

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

Sample rubric for pre-assessments

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

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

Sample rubric for post-assessments

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

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

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

Methods of instruction (continued)

Lab sessions

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

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

Troubleshooting assessments must meet the following guidelines:

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

file `instructional`

Distance delivery methods

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

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

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

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

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

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

file `distance`

Metric prefixes and conversion constants

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

METRIC PREFIX SCALE

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

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

- **Conversion formulae for temperature**
- ^{o}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 (W/m^2·K^4)

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

Properties of Water

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

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

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

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

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

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

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

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

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

Properties of Dry Air at sea level

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

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

file `conversion_constants`

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

<u>file `question0`</u>

Checklist when reading an instructional text

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

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

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

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

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

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

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

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

General challenges following a tutorial reading assignment

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

General follow-up challenges for assigned problems

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

file `license`

Question 1

Read and outline the "Antennas", "Decibels", "Antenna Radiation Patterns", "Antenna Gain Calculations", and "Effective Radiated Power" subsections of the "Radio Systems" section of the "Wireless Instrumentation" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

(1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A "Table of Contents" format works well for this.

(2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author's problem-solving strategies, etc.).

(3) General principles, especially physical laws, referenced in the text.

(4) Questions of your own you would pose to another reader, to challenge their understanding.

(5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.

(6) Any points of confusion, and precisely why you found the text confusing.

Suggestions for Socratic discussion

- A helpful "active reading" technique for technical texts is to work through every mathematical example presented, to ensure you understand the math as you read along. Apply this technique here, demonstrating how to work through at least one of the calculation examples presented in the textbook.

- A critically important step when learning any new mathematical procedure is the *meaning* of all the mathematical terms and concepts. Here, for example, we must identify what *decibels* really means in real-life terms. Do your best to define "dB" so that it has practical meaning.

file i00588

Question 2

Suppose a radio transmitter unit outputs 25 watts of RF power at a frequency of 900 MHz, into a half-wave dipole antenna. The radio energy radiates outward from the transmitting antenna, and is received by another antenna to send a signal of 1.8 microwatts into a radio receiver.

Calculate the transmitter's output power (P_{tx}) in both dBm and dBW, and also the receiver's input signal power (P_{rx}) in dBm and dBW. Then, calculate the total power loss between transmitter and receiver (P_{loss}), in dB.

$P_{tx} = $ _____ dBm = _____ dBW

$P_{rx} = $ _____ dBm = _____ dBW

$P_{loss} = $ _____ dB

Explain in your own words the meaning of the following units: *dBm*, *dBW*, and *dB*.

| Suggestions for Socratic discussion |

- Explain why the "decibel" is such a commonly used unit for power, and also for power gains and losses, in RF communications work.
- Does it matter if P_{loss} is calculated from the transmit and receive powers in units of watts, dBm, or dBW? Why or why not?
- If we wished to reduce the power loss from transmitter and receiver, how could we do so? Note: there are many different solutions to this problem!
- If the transmitting and receiving antennas were spaced farther apart, would P_{loss} increase, decrease, or remain the same?
- If the transmitting and receiving antennas were both located closer to ground level (i.e. not as high off the ground), would P_{loss} increase, decrease, or remain the same?
- Estimate these decibel values by first rounding the power ratio to the nearest product of 10 and/or 2, then applying the equivalence of 10 dB to a 10-fold ratio and 3 dB to a 2-fold ratio.

file i00561

Question 3

Read and outline the "RF Link Budget" subsection of the "Radio Systems" section of the "Wireless Instrumentation" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i00547

Question 4

Create a computer spreadsheet to calculate the required transmitter signal power given frequency, path distance, antenna gains, cable losses, and receiver sensitivity (the minimum signal power required at the receiver input). A sample layout is presented here, where yellow shading represents values to enter, and blue shading represents values calculated by the spreadsheet:

	1	2	3	4	5
1	Frequency (Hz)	Path distance (m)	Rx sensitivity (dBm)	Tx antenna gain (dB)	Rx antenna gain (dB)
2					
3				Tx cable loss (dB)	Rx cable loss (dB)
4					
5	Min. Tx power (dBm)	Min. Tx power (mW)		Other Tx losses (dB)	Other Rx losses (dB)
6					

Then, use your spreadsheet to calculate the minimum transmitter power for a radio system with the following parameters:

- Frequency = 900 MHz
- Path distance = 720 meters
- Receiver sensitivity = −109 dBm
- Transmitter cable = −0.25 dB per foot ; 12 feet long
- Transmitter lightning arrestor = −0.2 dB insertion loss
- Transmitter antenna = 6 dB gain
- Receiver lightning arrestor = −0.2 dB insertion loss
- Receiver cable = −0.25 dB per foot ; 16 feet long
- Receiver antenna = 13 dB gain

Suggestions for Socratic discussion

- Explain why it is important to have a practical example calculation ready to *test* your spreadsheet program.
- How could you alter your spreadsheet to calculate a *fade margin* to account for losses due to fade?

file i00331

Question 5

Read and outline the "Fresnel Zones" subsection of the "Radio Systems" section of the "Wireless Instrumentation" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i00549

Question 6

Create a computer spreadsheet to calculate the width of the *Fresnel zone* between two antennas given frequency, path distance, position from one antenna, and Fresnel zone number. A sample layout is presented here, where yellow shading represents values to enter, and blue shading represents values calculated by the spreadsheet:

	1	2	3	4	5
1	Frequency (Hz)	Path distance (m)	Position (m)	Fresnel zone number	
2					
3					
4		Width at position (m)	Max. width (m)		
5					
6					

Suggestions for Socratic discussion

- Explain how you may *test* your finished spreadsheet program to see that it correctly calculates the Fresnel zone widths.
- If we are concerned with the Fresnel zone clearing a space between two parallel trees to either side of the line-of-sight, do we need to calculate *radius* or *diameter*?
- If we are concerned with the Fresnel zone clearing the ground, do we need to calculate *radius* or *diameter*?

file i00332

Question 7

Decibels are a logarithmic representation of power ratios, with negative decibel values representing power attenuation and positive decibel values representing power gain. Every addition or subtration of 10 dB exactly represents a 10-fold multiplication or division of power ratio. A simple approximation that is useful in decibel calculations is that an addition or subtraction of 3 dB approximately represents a 2-fold multiplication or division of power ratio.

Here are some numerical examples based on the equivalence of $\pm$ 10 dB with orders of magnitude:

- Power ratio gain of 10 = **10 dB**
- Power ratio gain of 100 = **20 dB**
- Power ratio gain of 1000 = **30 dB**
- Power ratio gain of 10000 = **40 dB**
- Power ratio reduction of $\frac{1}{10}$ = **−10 dB**
- Power ratio reduction of $\frac{1}{100}$ = **−20 dB**
- Power ratio reduction of $\frac{1}{1000}$ = **−30 dB**
- Power ratio reduction of $\frac{1}{10000}$ = **−40 dB**

Here are some numerical examples based on the approximation of $\pm$ 3 dB being equivalent to doubling or halving of power ratio:

- Power ratio gain of $2 \approx$ **3 dB**
- Power ratio gain of $4 \approx$ **6 dB**
- Power ratio gain of $8 \approx$ **9 dB**
- Power ratio gain of $16 \approx$ **12 dB**
- Power ratio reduction of $\frac{1}{2} \approx$ **−3 dB**
- Power ratio reduction of $\frac{1}{4} \approx$ **−6 dB**
- Power ratio reduction of $\frac{1}{8} \approx$ **−9 dB**
- Power ratio reduction of $\frac{1}{16} \approx$ **−12 dB**

Based on these equivalents and approximations, estimate the following decibel values from the given power ratio values:

- Power ratio gain of $20 \approx$ _____
- Power ratio reduction of $\frac{1}{40} \approx$ _____
- Power ratio gain of $1600 \approx$ _____
- Power ratio reduction of $\frac{1}{800} \approx$ _____

file i00954

26

Question 8

Decibels are a logarithmic representation of power ratios, with negative decibel values representing power attenuation and positive decibel values representing power gain. Every addition or subtration of 10 dB exactly represents a 10-fold multiplication or division of power ratio. A simple approximation that is useful in decibel calculations is that an addition or subtraction of 3 dB approximately represents a 2-fold multiplication or division of power ratio.

Here are some numerical examples based on the equivalence of $\pm$ 10 dB with orders of magnitude:

- Power ratio gain of 10 = **10 dB**
- Power ratio gain of 100 = **20 dB**
- Power ratio gain of 1000 = **30 dB**
- Power ratio gain of 10000 = **40 dB**
- Power ratio reduction of $\frac{1}{10}$ = **−10 dB**
- Power ratio reduction of $\frac{1}{100}$ = **−20 dB**
- Power ratio reduction of $\frac{1}{1000}$ = **−30 dB**
- Power ratio reduction of $\frac{1}{10000}$ = **−40 dB**

Here are some numerical examples based on the approximation of $\pm$ 3 dB being equivalent to doubling or halving of power ratio:

- Power ratio gain of $2 \approx$ **3 dB**
- Power ratio gain of $4 \approx$ **6 dB**
- Power ratio gain of $8 \approx$ **9 dB**
- Power ratio gain of $16 \approx$ **12 dB**
- Power ratio reduction of $\frac{1}{2} \approx$ **−3 dB**
- Power ratio reduction of $\frac{1}{4} \approx$ **−6 dB**
- Power ratio reduction of $\frac{1}{8} \approx$ **−9 dB**
- Power ratio reduction of $\frac{1}{16} \approx$ **−12 dB**

Based on these equivalents and approximations, estimate the following decibel values from the given power ratio values:

- +26 dB = power ratio gain of _____
- −33 dB = power ratio gain of _____
- +50 dB = power ratio gain of _____
- −29 dB = power ratio gain of _____

file i00958

Question 9

Suppose a radio transmitter unit outputs 327 watts of RF power at a frequency of 1070 kHz, into a half-wave "whip" antenna. The radio energy radiates outward from the transmitting antenna, and is received by another antenna to send a signal of 9.5 microwatts into a radio receiver.

Calculate the transmitter's output power (P_{tx}) in both dBm and dBW, and also the receiver's input signal power (P_{rx}) in dBm and dBW. Then, calculate the total power loss between transmitter and receiver (P_{loss}), in dB.

$P_{tx} = $ _____ dBm = _____ dBW

$P_{rx} = $ _____ dBm = _____ dBW

$P_{loss} = $ _____ dB

| Suggestions for Socratic discussion |

- Explain why the "decibel" is such a commonly used unit for power, and also for power gains and losses, in RF communications work.
- Estimate these decibel values by first rounding the power ratio to the nearest product of 10 and/or 2, then applying the equivalence of 10 dB to a 10-fold ratio and 3 dB to a 2-fold ratio.

file i00285

Question 10

Suppose an RF signal cable receives 230 milliwatts of RF power at one end, but conveys only 89 milliwatts of RF power to its far end. Express each of these power figures in dBm, and then express the power loss of this cable in dB.

Also, calculate the loss of the cable in decibels per foot, assuming it is 170 feet long.

Finally, explain why the dB figure for a cable must always be a negative value and never a positive value.

| Suggestions for Socratic discussion |

- Estimate these decibel values by first rounding the power ratio to the nearest product of 10 and/or 2, then applying the equivalence of 10 dB to a 10-fold ratio and 3 dB to a 2-fold ratio.

file i00540

Question 11

Suppose a waveguide receives 0.83 megawatts of RF power from a radar transceiver at one end, and delivers 0.79 megawatts of RF power to a radar antenna at the other end. Express each of these power figures in dBW, and then express the power loss of this waveguide in dB.

Also, calculate the loss of the waveguide in decibels per foot, assuming it is 40 feet long.

What would the dB/foot rating be for a *perfect* waveguide?

Suggestions for Socratic discussion

- Estimate these decibel values by first rounding the power ratio to the nearest product of 10 and/or 2, then applying the equivalence of 10 dB to a 10-fold ratio and 3 dB to a 2-fold ratio.

  file i03259

Question 12

Do radio waves suffer more or less degradation in power as they spread out over long distances if they have higher frequencies or lower frequencies, or is frequency completely unrelated to power degradation? Defend your answer mathematically.

Do the Fresnel zones of radio waves occupy more or less space as their frequencies increase? Defend your answer mathematically.

  file i03241

Question 13

Calculate the RF power intercepted by a receiving antenna from a 350 kHz radio transmitter located 14 miles away, assuming no obstacles or other interference between the transmitter and receiver. Use the following parameters in your calculations:

- Frequency = 350 kHz
- Distance = 14 miles
- Transmitter output power = 15 watts
- Transmitter antenna gain = 3 dBi
- Receiver antenna gain = 8.7 dBi
- Transmitter cable loss = 0.11 dB per foot ; 72 feet long

Explain why we did not need to include the loss of the receiver cable in this problem.

Also, explain how it is possible to have *positive* dB values for passive elements such as antennas, when we know the Law of Energy Conservation forbids creation of energy from nothing.

  file i03622

Question 14

It is common practice to connect an antenna to a radio transceiver (transmitter/receiver) using a transmission line if the antenna must be located somewhere high up for good reception. In this particular example, a radio transceiver is used to communicate natural gas flow measurement data from a flow computer to some far-away location, as part of a SCADA system for the natural gas pipeline. The antenna is located at the top of a wooden pole for better signal strength than if it were located at ground level:
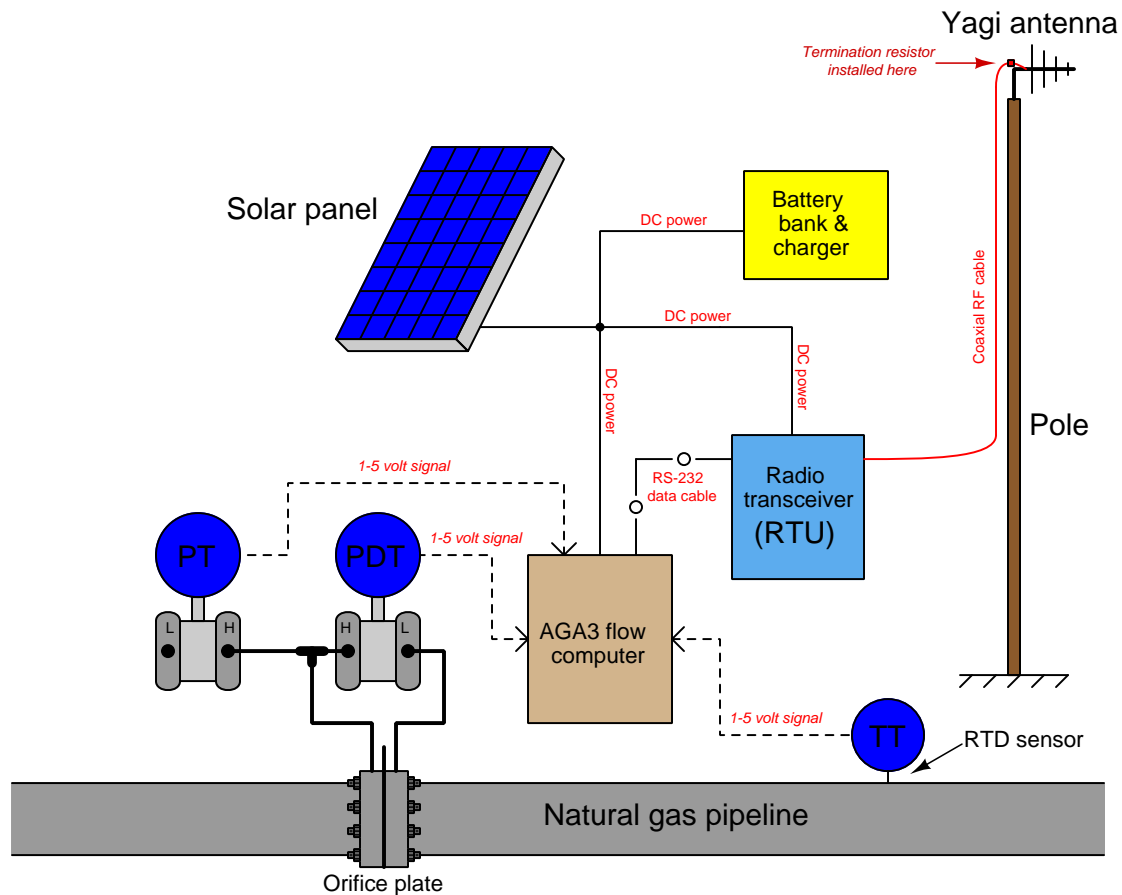
In this installation, the transmission line is a 20 foot length of 50 Ω coaxial cable. Knowing that reflected signals are bad in any transmission line system, the technician who installed this system also installed a 50 Ω *termination resistor* at the antenna-end of the cable, in parallel with the antenna.

Was the installation of this termination a good idea, or not? Explain your answer.

Suggestions for Socratic discussion

- Explain how a TDR could be used to check the transmission line for proper termination.
- For those who have studied gas flow measurement, what does *AGA3* mean, and why are there *three* process transmitters connected to the flow computer?
- Explain what a "SCADA" system is and what function it fulfills.
- It is quite common to find analog transmitters in solar-powered SCADA monitoring sites using *voltage* signal ranges rather than the *current* signals more commonly found in industrial (plant) applications. The reason for this is to reduce power consumption. Explain how the use of voltage signaling reduces power consumption compared to current signaling.

- Is this a true example of a "SCADA" node, or might it best be characterized as a *telemetry* node? Explain your answer.

file i01357

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Read and outline the "*Wireless*HART" section of the "Wireless Instrumentation" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i00537

Question 22

Search the Rosemount model 648 WirelessHART temperature transmitter Reference Manual (document 00809-0100-4648, revision BA) to answer the following questions:

Identify the necessary parameters within the *Wireless*HART device enabling it to communicate with a particular network gateway device. Where is this information stored at in a *Wireless*HART system?

How does one access and edit the parameters of a *Wireless*HART field instrument such as the model 648 temperature transmitter *before* it has been detected and incorporated into an active *Wireless*HART network?

How fast does a typical *Wireless*HART field instrument update its information to the network gateway? Does the total number of field devices in any one mesh network affect this update rate?

How should the antenna be oriented for each *Wireless*HART field instrument? Explain the reason why.

| Suggestions for Socratic discussion |

- What would happen if someone mounted a *Wireless*HART device with the antenna oriented incorrectly? Would the instrument be able to function at all? Would it be able to function in a limited capacity? Explain your reasoning thoroughly.
- What diagnostic data is available from the gateway to help you determine the integrity of the radio link for a particular *Wireless*HART device?
- Appendix page B-3 in this manual describes the device's radio transmit power as limited to "10 mW e.i.r.p.". Explain what this means.

file i00352

Question 23

Read portions of the reference manual for the Rosemount Smart Wireless THUM Adapter (document 00809-0100-4075, revision AA) and answer the following questions:

Explain what the purpose of the THUM device is. How would it typically be used in a *Wireless*HART network?

Does the THUM need to be programmed with a "network ID" and a "join key" just like a regular *Wireless*HART field device, or is it exempt from this because it is merely an *adapter*? Explain the rationale for your answer.

How much of a DC voltage drop does the THUM impart to the 4-20 mA loop circuit? More importantly, how could this voltage drop (potentially) affect the loop circuit? Also, *why* is a voltage drop across the THUM necessary for its operation?

Explain the purpose of the THUM having both a variable (default) and fixed voltage drop mode.

This manual recommends a certain power-up sequence when commissioning new devices in a *Wireless*HART mesh network. Explain how this sequence is supposed to go, and why it has any bearing on the operation of the mesh network.

The THUM may be connected to loop-powered (2-wire) instruments as well as self-powered (4-wire) instruments. Examine the connection diagrams for both types of configurations, and identify the pattern of wire connections to the THUM: which direction does current always flow through the THUM's wires?

Does the mounting orientation for a THUM device matter, since there is no external antenna as there is on other *Wireless*HART devices? If so, which way should the THUM be mounted?

| **Suggestions for Socratic discussion** |

- In this manual, a distinction is made between 2-wire HART instruments, 4-wire "passive" HART instruments, and 4-wire "active" HART instruments. Explain this distinction.

  file i00577

Question 24

Read selected portions of the *IEC 62591 WirelessHART System Engineering Guide* (revision 2.2) and answer the following questions:

Describe the "**Rule of 5 minimum**" articulated in this document and give one realistic example of a *Wireless*HART network not in compliance with the rule.

Describe the "**Rule of 3**" articulated in this document and give one realistic example of a *Wireless*HART network not in compliance with the rule.

Describe the "**Rule of 25%**" articulated in this document and give one realistic example of a *Wireless*HART network not in compliance with the rule.

Describe the "**Rule of 1**" articulated in this document (for *control* applications only) and give one realistic example of a *Wireless*HART network not in compliance with the rule.

Describe the important cyber-security provisions built into the *Wireless*HART standard.

Identify some common cyber-security precautions one could implement on the LAN side (i.e. the wired Ethernet side) of a *Wireless*HART Gateway to help ensure the security of the system as a whole.

| **Suggestions for Socratic discussion** |

- Explain the rationale for each one of these rules!
- Examine one of the *Wireless*HART network illustrations shown in your textbook and apply some these rules to that diagram. Which rules are met, and which are violated?
- Suppose the reported RSSI (Received Signal Strength Indication) value for a *Wireless*HART device is -40 dBm. Convert this decibel figure into *milliwatts* without using an electronic calculator.
- Suppose the reported RSSI (Received Signal Strength Indication) value for a *Wireless*HART device is -53 dBm. Convert this decibel figure into *milliwatts* without using an electronic calculator.
- Identify any cyber-vulnerabilities you see in the *Wireless*HART system. If you were a hacker bent on infiltrating a *Wireless*HART network, what would be the easiest "vector" (pathway) to pursue?

file i00542

Question 25

According to Rosemount recommendations, a *Wireless*HART instrument's antenna should be vertically oriented, and given plenty of space between it and any "objects in a parallel metal plane such as a pipe or a metal framework." Explain why there is a concern over metal objects lying *parallel* to the antenna, more so than metal objects *perpendicular* to the antenna.

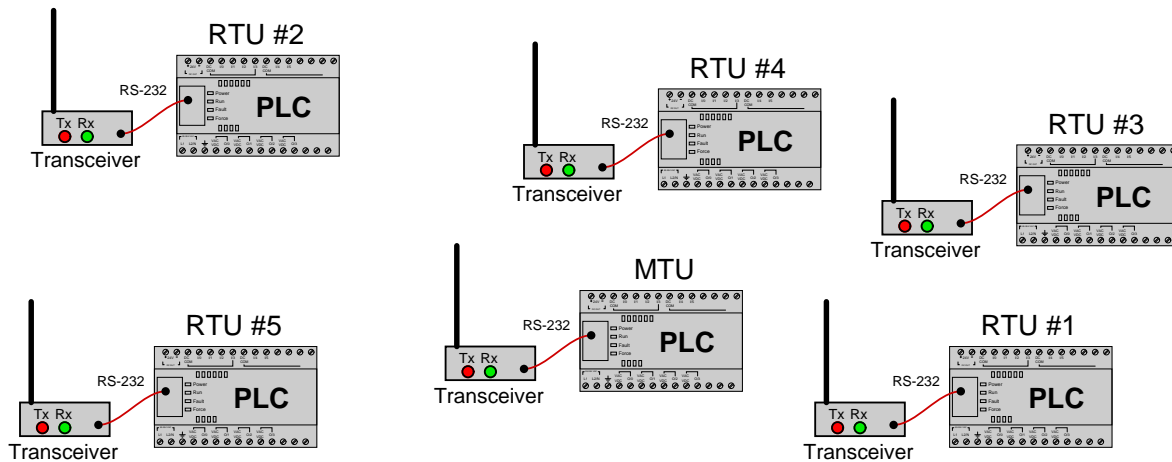Also, identify the major problem with this *Wireless*HART transmitter installation and suggest improvements for it:
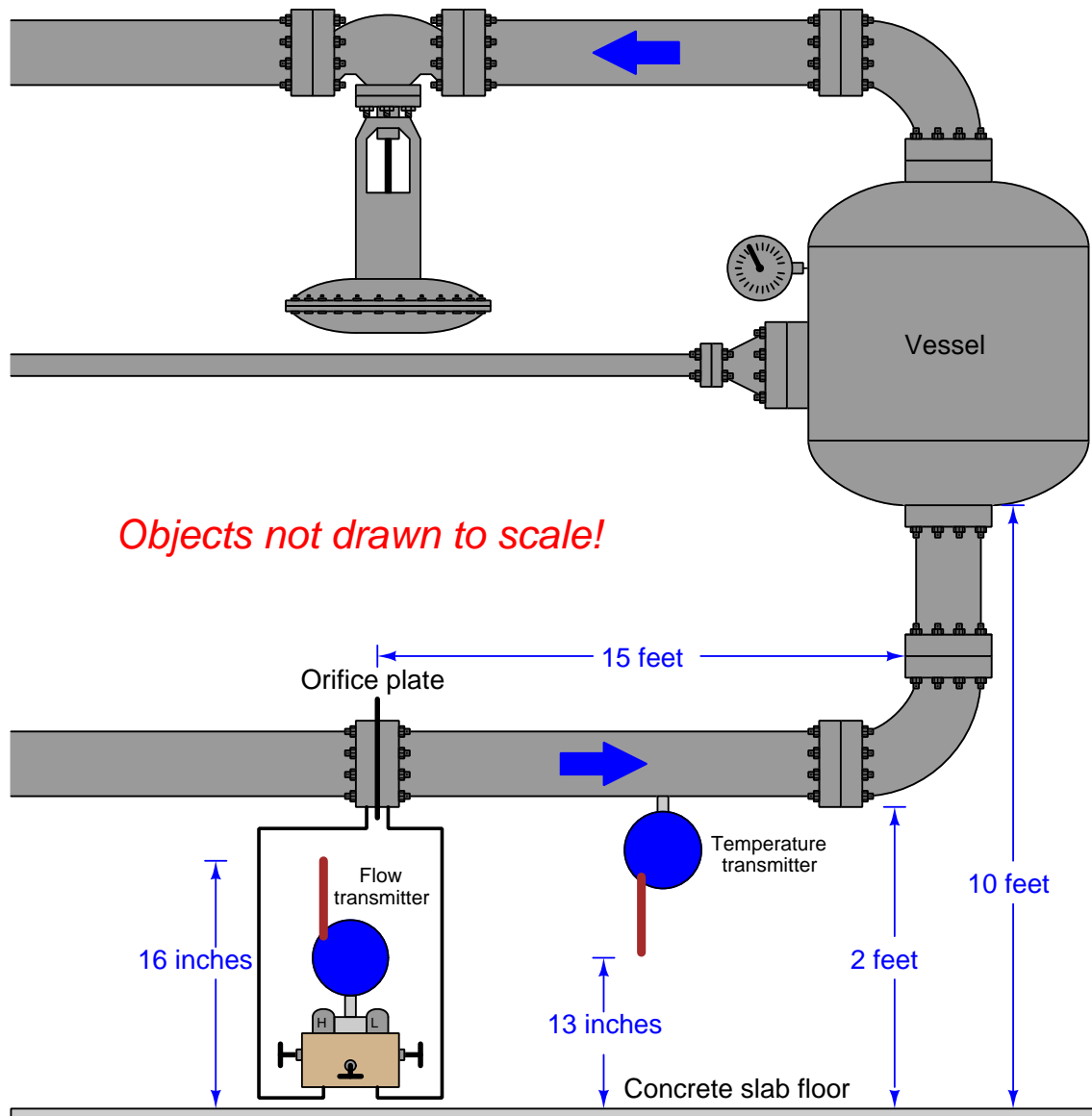
Suggestions for Socratic discussion

- Which information in this illustration is relevent to the question, and which is not?
- Suggest alterations in this system to improve the performance of the *Wireless*HART network.

Question 26

In this SCADA system, a "master" PLC (MTU) communicates with multiple "slave" PLCs (RTUs) via radio using Modbus protocol. Each PLC communicates with its radio transceiver via a short RS-232 serial cable. This illustration is approximately drawn to scale with regard to distances between the units:

RTU #2
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

RTU #4
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

RTU #3
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

RTU #5
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

MTU
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

RTU #1
RS-232
Tx Rx
Transceiver
PLC
Power Run Fault Force

Unfortunately, there is a problem with this system. RTU number 4 does not communicate with the MTU. Upon inspection, you see that the "Tx" and "Rx" LED indicators are blinking on all the RTU radio transceivers except for RTU #4: there, only the "Rx" LED blinks.

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

Fault	Possible	Impossible
Damaged antenna on MTU		■
Damaged antenna on RTU #4		■
PLC halted (not running) RTU #4	■	
Radio transceiver powered down on RTU #4		■
"TD" conductor broken inside RS-232 cable on RTU #4	■	
"RD" conductor broken inside RS-232 cable on RTU #4	■	
PLC baud rate set incorrectly on RTU #4	■	
PLC baud rate set incorrectly on MTU		■
Modbus mode (RTU/ASCII) set incorrectly on RTU #4	■	
Modbus mode (RTU/ASCII) set incorrectly on MTU		■
Fresnel zone interference between MTU and RTU #4		■

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


Suggestions for Socratic discussion

- A powerful troubleshooting technique is to *swap identical components* between elements of a system to see if and where the problem moves. Explain how this simple test could be applied to this SCADA system in order to diagnose the fault.
- An important question to answer is whether the "Tx" and "Rx" LED indicators on the radio transceivers refer to transmission and reception over the wireless network or over the RS-232 serial network. Explain

how we may conclusively answer this question based on the information given and our knowledge of serial Modbus networks.

file i00713

Question 27

Calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB). Also, write a general equation for calculating the voltage gain of such an amplifier, given the resistor values of R_1 and R_2:
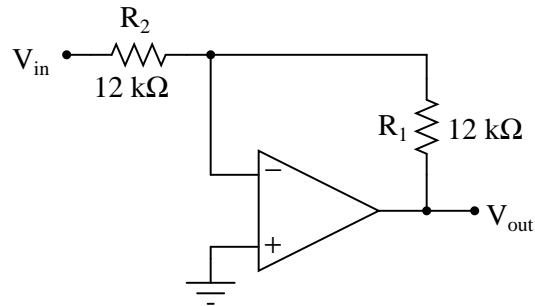
file i03266

Question 28

Calculate all voltage drops and currents in this circuit, complete with arrows for current direction and polarity markings for voltage polarity. Then, calculate the overall voltage gain of this amplifier circuit (A_V), both as a ratio and as a figure in units of decibels (dB):
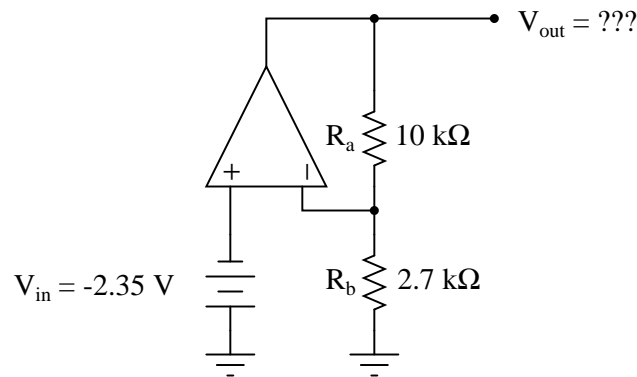
Suggestions for Socratic discussion

- Identify the "simplifying assumptions" we generally use when analyzing DC opamp circuits. Hint: one has to do with the effect of negative feedback on the input voltages, and another has to do with the input terminal currents.
- Trace the direction of current at the opamp's output terminal, and determine whether the opamp is *sourcing* current or *sinking* current.
- Explain how this circuit would respond if the 10 kΩ resistor failed open.
- Explain how this circuit would respond if the 10 kΩ resistor failed shorted.
- Explain how this circuit would respond if the 2.7 kΩ resistor failed open.
- Explain how this circuit would respond if the 2.7 kΩ resistor failed shorted.
- Explain how this circuit would respond if the (+) and (−) opamp inputs were swapped.

file i03261

Question 29

Yagi antennas are sometimes used in radio SCADA systems at remote terminal units (RTUs) for stronger signal reception and transmission. Explain why Yagi antennas are so effective, and also identify the proper antenna type to use at the master terminal unit (MTU), and the proper antenna orientation to use at both points.

Do you think Yagi antennas would be good to use in a mesh-network such as *Wireless*HART? Why or why not?

file i00476

Question 30

Question 31

Question 32

Question 33

Question 34

Question 35

Question 36

Question 37

Question 38

Question 39

Question 40

Question 41

Suppose a radio transmitter sends 0.75 watts of power into one end of a twin-lead cable, the other end connected to an antenna. The cable is 20 feet long, and exhibits a power loss of −0.033 dB/foot. Calculate the power received by the antenna, in both units of watts and units of dBm.

$P_{antenna} = \underline{\hspace{2cm}}$ watts

$P_{antenna} = \underline{\hspace{2cm}}$ dBm

Explain in your own words the meaning of the following units: *dBm*, *dBW*, and *dB*.

| Suggestions for Socratic discussion |

- A technique highly recommended for word-problems is to *sketch a picture* of the problem and label elements of that picture with the given information. Do this, and compare your sketch with those of your classmates. How, specifically, does this aid your problem-solving?
- Solve this problem more than one way, and explain how these multiple solutions work.
- Explain what "dBm" actually *means*. Simple numerical examples may be helpful here:
  → How much power is 0 dBm?
  → How much power is +3 dBm?
  → How much power is −3 dBm?
  → How much power is +10 dBm?
  → How much power is −10 dBm?
- Explain what "dBW" actually *means*. Simple numerical examples may be helpful here:
  → How much power is 0 dBW?
  → How much power is +3 dBW?
  → How much power is −3 dBW?
  → How much power is +10 dBW?
  → How much power is −10 dBW?

file i01204

Question 42

Suppose a radio antenna receives 0.52 watts of power from the end of a twin-lead cable connected to an RF transmitter. The cable is 30 feet long, and exhibits a power loss of −0.041 dB/foot. Calculate the output power of the transmitter, in both units of watts and units of dBm.

P_{xmtr} = _____ watts

P_{xmtr} = _____ dBm

Determine if your calculations for transmitter power would be any different if you knew the antenna had a gain of +6.8 dBi.

Suppose the output power of an RF transmitter were rated at 0 dBW. Convert this figure into watts (W) without the use of a calculator.

Suggestions for Socratic discussion

- A technique highly recommended for word-problems is to *sketch a picture* of the problem and label elements of that picture with the given information. Do this, and compare your sketch with those of your classmates. How, specifically, does this aid your problem-solving?
- If the operating frequency of this radio system were increased, would cable loss increase, decrease, or remain the same as before?
- If the operating frequency of this radio system were increased, would the antenna need to be lengthened, shortened, or would the same antenna work just as well as before?

file i02533

Question 43

Suppose a radio antenna receives 7.5 watts of power from the end of a coaxial cable connected to an RF transmitter outputting 8.5 watts. The cable is rated to have a power loss of −0.015 decibels per foot. Calculate the output power of the transmitter in units of dBW and dBm, and also the length of the cable in inches.

P_{xmtr} = _____ dBW

P_{xmtr} = _____ dBm

Cable length = _____ inches

Suggestions for Socratic discussion

- A technique highly recommended for word-problems is to *sketch a picture* of the problem and label elements of that picture with the given information. Do this, and compare your sketch with those of your classmates. How, specifically, does this aid your problem-solving?

file i02998

Question 44

Suppose a radio transmitting antenna radiates 120 kW of RF power into space, and that only 30 milliwatts of this power reaches a receiving antenna some distance away. Calculate the path loss in decibels *without using a calculator*. Note that an addition or subtraction of 10 dB is exactly equal to a 10-fold multiplication or division ratio (respectively), and that an addition or subtraction of 3 dB is approximately equal to a 2-fold multiplication or division ratio.

$L_{path} =$ _____ dB

Suggestions for Socratic discussion

- Explain what creates path loss. Is this something that can be overcome or at least mitigated by applying the correct technology? Why or why not?
- Explain what *fade loss* is, what creates it, and how it differs from path loss.
- Is path loss affected by the type of antenna used to transmit the RF energy? Explain why or why not.
- Is path loss affected by the type of antenna used to receive the RF energy? Explain why or why not.
- Is path loss affected by the frequency of the RF energy transmitted?

file i00957

42

Question 45

Calculate the minimum required transmitter power for a FreeWave I2-IOS industrial data radio (2.4 GHz) assuming the following parameters:

- BER (bit error rate) = 10^{-6}
- Distance = 3 miles
- EAN2400NR 1/2 wave whip transmitting antenna
- ASC0032SF transmitting cable (3 feet long)
- EAN2414CR Corner Reflector receiving antenna
- ASC0102SN receiving cable (10 feet long)

Next, show where all these figures fit into the following link budget graph. Note that this is a generic graph, and is not necessarily tailored to this particular application:
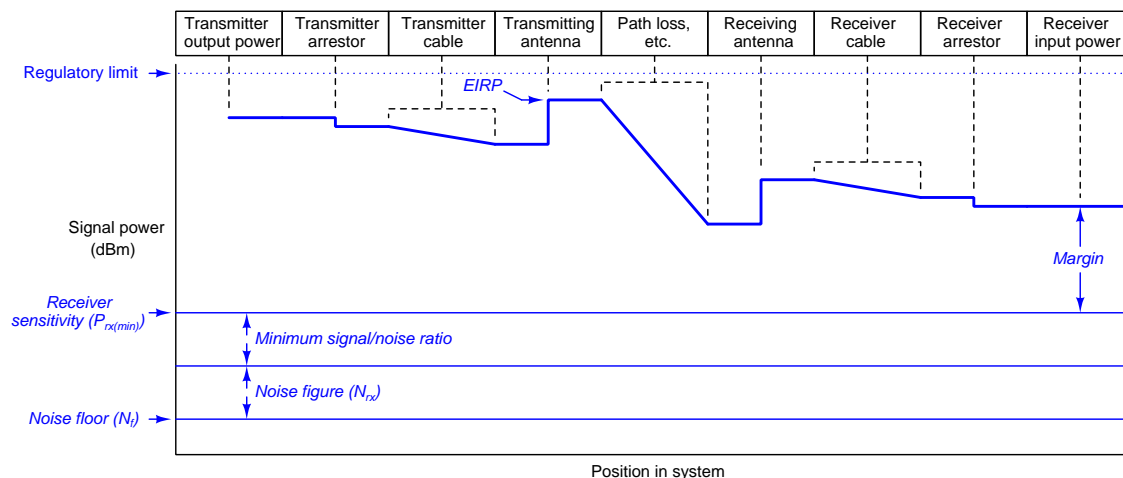
Suggestions for Socratic discussion

- Explain why the *bit error rate* is an important factor in this calculation. If we desire a lower (smaller) bit error rate, what must change?
- Define "sensitivity" for a radio receiver unit.
- Explain why one should always incorporate some *fade loss* into the minimum transmitter power calculation for any realistic radio application.
- After calculating the minimum transmitter power for this application, calculate the amount of margin (for fade and other losses) based on this particular transmitter's rated power output.

file i03521

43

Question 46

Calculate the maximum width of the (first) Fresnel zone between two *Wireless*HART instruments separated by a distance of 50 feet.

Question 47

Calculate the necessary height the radio antennas (assume the same height for each) in order that the first Fresnel zone will have no interference. Assume a signal frequency of 900 MHz, and that the two objects shown lie exactly along the line-of-site path between the two antennas:
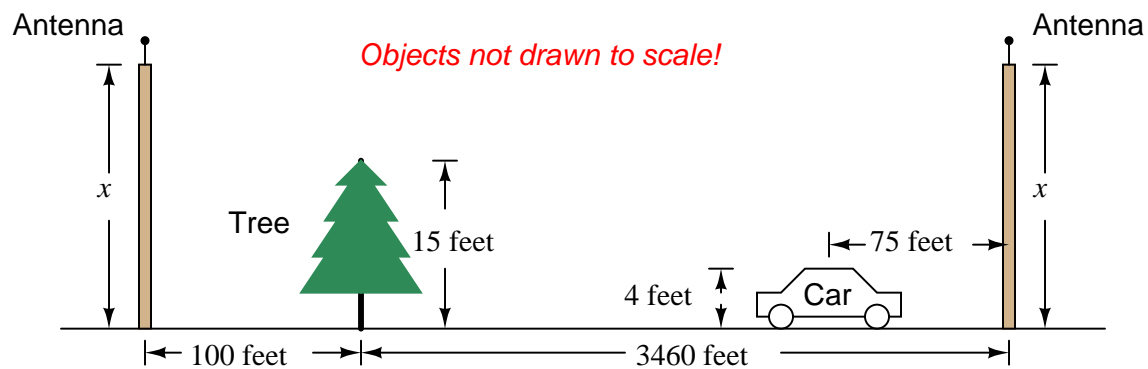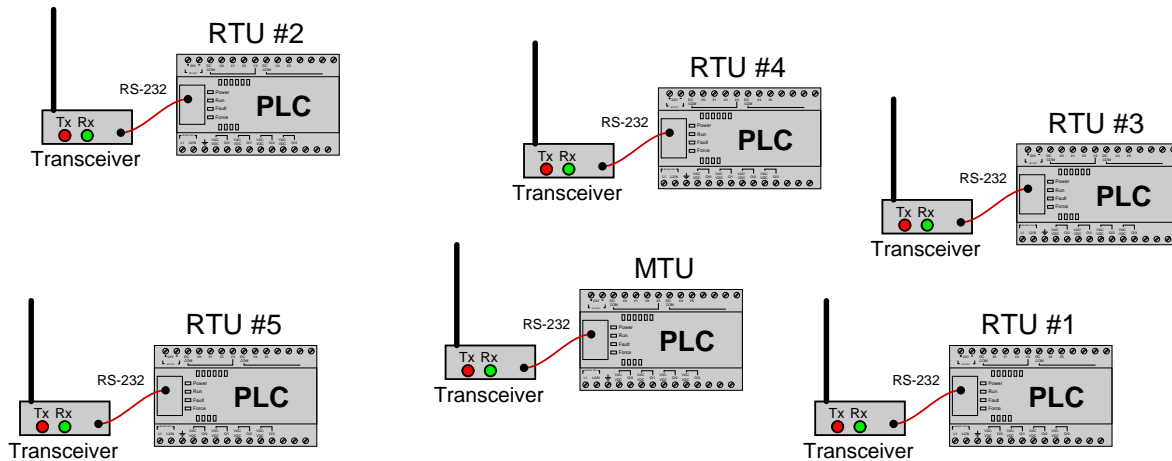
44

Question 48

In this SCADA system, a "master" PLC (MTU) communicates with multiple "slave" PLCs (RTUs) via radio using Modbus protocol. Each PLC communicates with its radio transceiver via a short RS-232 serial cable. This illustration is approximately drawn to scale with regard to distances between the units:

Unfortunately, there is a problem with this system. None of the RTUs are communicating with the MTU. Upon inspection, you see that the "Tx" indicator is blinking on the MTU's transceiver unit but not the "Rx" indicator.

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

Fault	Possible	Impossible
Damaged antenna on MTU		
Damaged antenna on RTU #4		
PLC halted (not running) on MTU		
Radio transceiver powered down on RTU #4		
"TD" conductor broken inside RS-232 cable on MTU		
"RD" conductor broken inside RS-232 cable on MTU		
PLC baud rate set incorrectly on RTU #4		
PLC baud rate set incorrectly on MTU		
Modbus mode (RTU/ASCII) set incorrectly on RTU #4		
Modbus mode (RTU/ASCII) set incorrectly on MTU		
Fresnel zone interference between MTU and RTU #4		

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

Suggestions for Socratic discussion

- Identify some practical modifications we could make to this SCADA system in order to make it more secure, guarding against potential cyber-attacks.

  file i00220

45

Question 49

Suppose a radio transmitter sends 80 watts of power into one end of a twin-lead cable, the other end connected to an antenna. The cable is 200 feet long, and exhibits a power loss of -0.03 dB/foot. Calculate the power received by the antenna, in both units of watts and units of dBm, *without using a calculator*. Note that an addition or subtraction of 10 dB is exactly equal to a 10-fold multiplication or division ratio (respectively), and that an addition or subtraction of 3 dB is approximately equal to a 2-fold multiplication or division ratio.

$P_{antenna} = $ _____ watts

$P_{antenna} = $ _____ dBm

Suggestions for Socratic discussion

- A technique highly recommended for word-problems is to *sketch a picture* of the problem and label elements of that picture with the given information. Do this, and compare your sketch with those of your classmates. How, specifically, does this aid your problem-solving?

  file i00956

Question 50

Is it possible for a radio antenna to have a *negative* dBi value? Why or why not?

Is it possible for a radio antenna to have a *negative* dBd value? Why or why not?

file i03840

Question 51

Suppose a radio receiver unit is equipped with a lightning arrestor that presents a signal power attenuation of -0.4 dB. During a storm, this arrestor is damaged. Lacking a replacement on hand, you decide to remove it from the system and re-connect the antenna directly to the receiver with no lighting arrestor at all, at least until you can purchase and install a new arrestor.

Supposing this receiver was able to gather an RF signal of 0.8 microwatts with the arrestor in place, calculate the new signal power level without the arrestor, assuming all other factors remain the same as before (e.g. same transmitter power, same path loss, same environmental conditions, etc.):

$P_{rx} = $

file i03429

Question 52

Suppose an RTU in a radio SCADA system is able to receive an RF signal strength of 0.17 microwatts from the MTU using a standard "whip" antenna with a gain of 5.8 dBi. If you were to replace this whip antenna with a Yagi having a gain of 11.4 dBi, how much signal power would the RTU receive?

$P_{rx} = $

file i03415

Question 53

Suppose you are asked to install lightning arrestors at both the MTU and the RTU in a two-station radio SCADA system. Each arrestor has an advertised power loss of -0.55 dB. If the current transmitter output power is 3.2 milliwatts, how much more powerful will it need to be in order to overcome the new losses resulting from the installation of these lightning arrestors and achieve the exact same performance as it did without the arrestors in place?

$P_{tx} =$

file i03414

Question 54

Suppose a radio transmitting antenna radiates 45 watts of RF energy in a particular direction, and a receiving antenna intercepts 1.4 microwatts of RF energy from it. Calculate the *path loss* between these two antennas, and also calculate the approximate distance between them assuming the frequency of the RF signal is 700 kHz.

$L_{path} =$ _____ dB

$D =$ _____ meters

Suggestions for Socratic discussion

- Explain what creates path loss. Is this something that can be overcome or at least mitigated by applying the correct technology? Why or why not?
- Explain what *fade loss* is, what creates it, and how it differs from path loss.

file i03140

Question 55

Electrical power distribution "grids" were early-adoption platforms for SCADA technology, given the need to communication mission-critical information quickly over long distances. With modern (digital) protective relay devices, measurement instrumentation, and substation automation controllers in popular use throughout electric power grids, the need to communicate large amounts of system data over reliable channels is more pressing than ever.

Three forms of system data communication are prevalent in the field of electric power distribution, listed in order of their historical introduction (from earliest to latest):

- **Power Line Carrier** (high-frequency AC signals used to encode data along existing power line conductors)

- **Microwave radio** (point-to-point communication between parabolic dish antennas)

- **Fiber optic cables** (pulses of light used to communicate digital 1's and 0's between locations, along glass fiber cables)

Identify why these forms of data communication are each well-suited to the task of critical system data communication between substations and other centers of an electric power grid. One criterion to keep in mind when assessing these modes is resistance to disruption from natural disasters.

Suggestions for Socratic discussion

- One of these communication modes bears a striking resemblance to the HART standard of instrument data communication. Identify which one it is, and explain the similarity.
- Identify what a malicious person would have to do to intercept data communicated along these three different modes. In other words, how *secure* is each form of data communication?
- Identify what a malicious person would have to do to interrupt data communicated along these three different modes. In other words, how *robust* is each form of data communication?
- Compare the *bandwidth* (i.e. the data transmission rate) of these three communication modes.
- Can you think of any alternate modes of communication that could be used as alternatives to any of these three, to communicate critical data between power generating stations, substations, and large industrial load centers?

file i01240

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

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

Identify any knowledge and/or skill areas in which you would like to become stronger, and describe practical steps you can take to achieve that goal. Don't limit yourself to just technical knowledge and skills, but consider behavioral habits (e.g. patience, attention to detail, time management) and general academic abilities (e.g. reading, writing, mathematics) as well. If you find yourself struggling to achieve a goal, don't just say "I'll work harder" as your plan of action – identify something *different* you can do to achieve that goal.
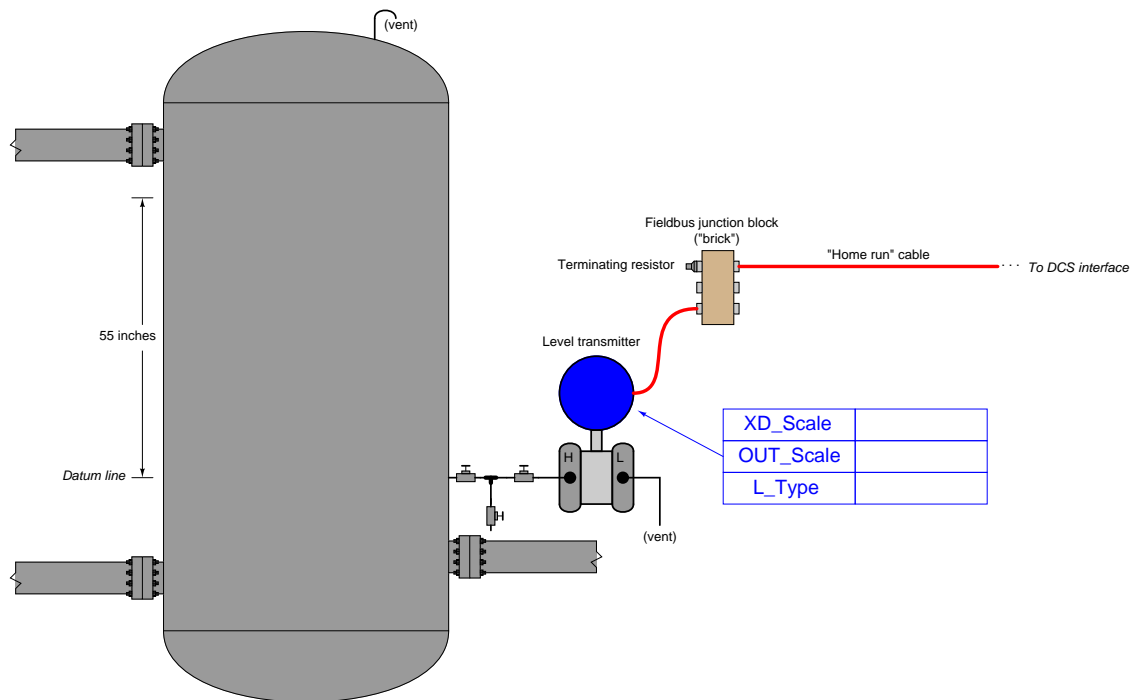
Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

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

file i00999

Question 62

Suppose a FOUNDATION Fieldbus level transmitter will be used to measure the volume of water stored in a process vessel above the datum line. The transmitter is connected to the vessel through an impulse tube connected to the "High" port of the DP sensor, sensing liquid level directly in units of *inches water column*. The operator, in turn, expects to be able to read liquid volume in *gallons*. The vessel is cylindrical in shape, with a diameter of 40 inches:

(vent)

55 inches

Datum line

H L

(vent)

Fieldbus junction block
("brick")

Terminating resistor

"Home run" cable

To DCS interface

Level transmitter

XD_Scale	
OUT_Scale	
L_Type	

Complete the configuration table in the above illustration, showing the proper XD_Scale, OUT_Scale, and L_Type parameter values to make the transmitter function as it should in this application.

Also, determine the proper settings (open or shut) for the three hand valves between the process vessel and the transmitter while the system is operating normally.

Suggestions for Socratic discussion

- Describe the purpose of the XD_Scale and OUT_Scale parameters in a Fieldbus instrument.
- Explain what will happen if the L_Type parameter is set to *Direct*.

file i00354

Question 63

The following P&ID shows a FOUNDATION Fieldbus *cascade* control system for regulating liquid level in a tank – a level controller provides a "remote setpoint" signal to a flow controller, which then regulates how rapidly liquid flows out of the tank:
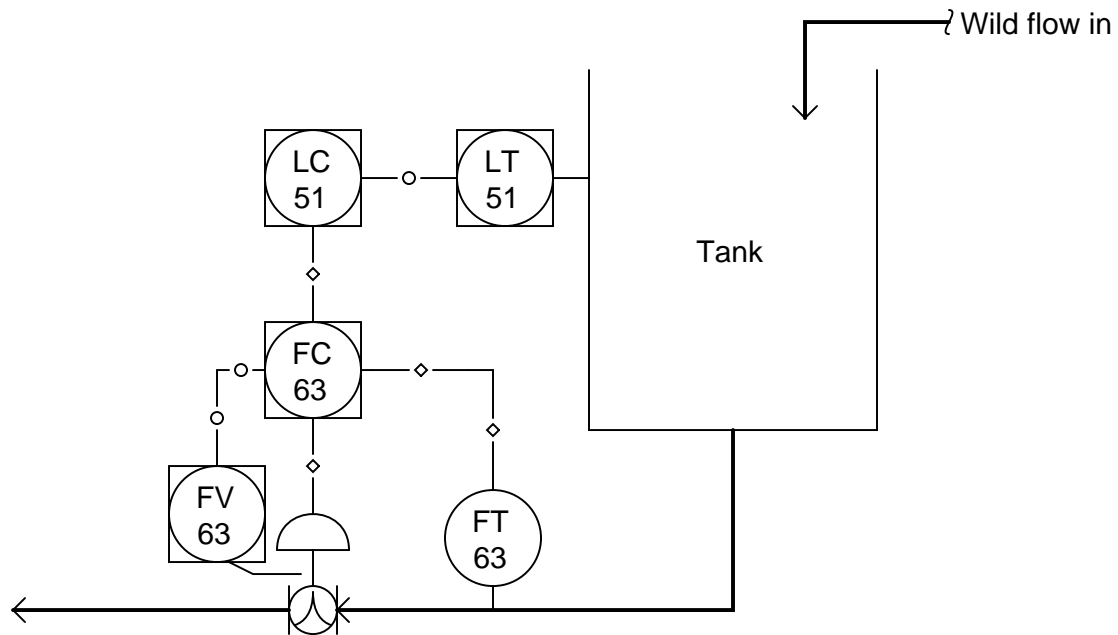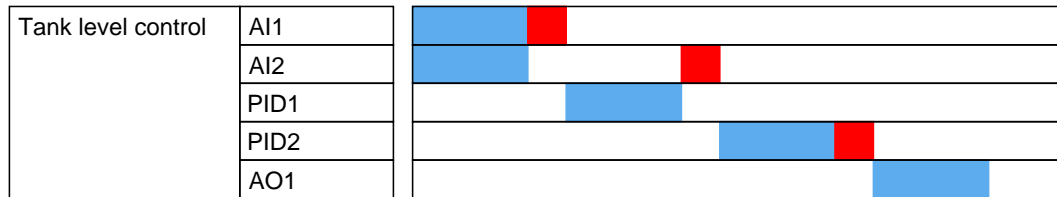

A function block diagram shows how the signals interconnect in this Fieldbus control system:
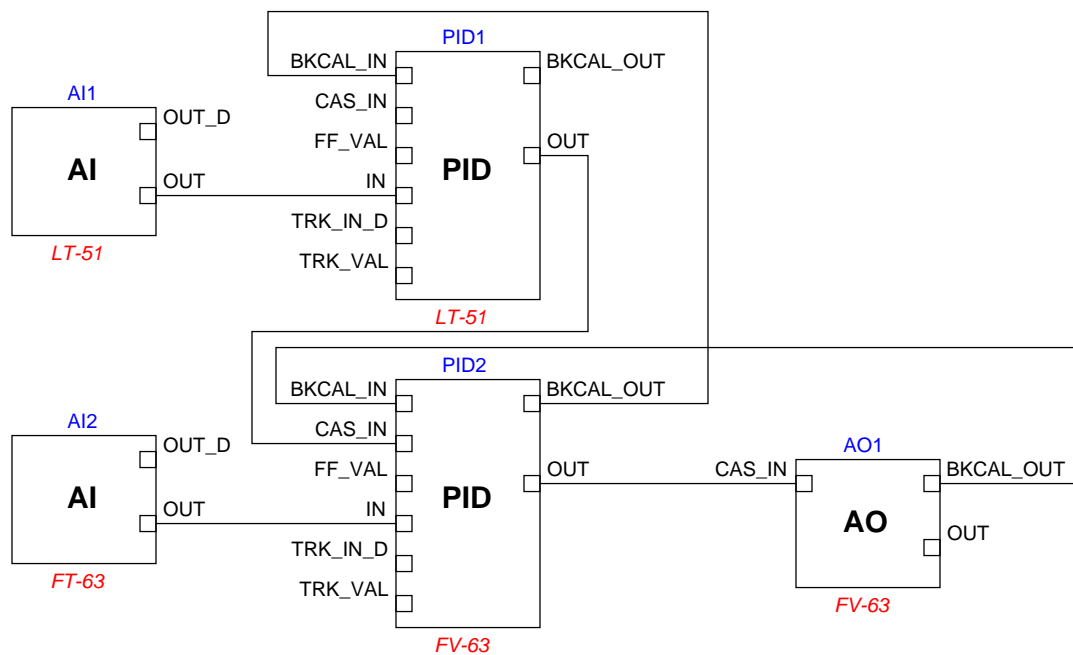
Based on the information presented, determine which of the following *timing diagrams* matches this Fieldbus segment:
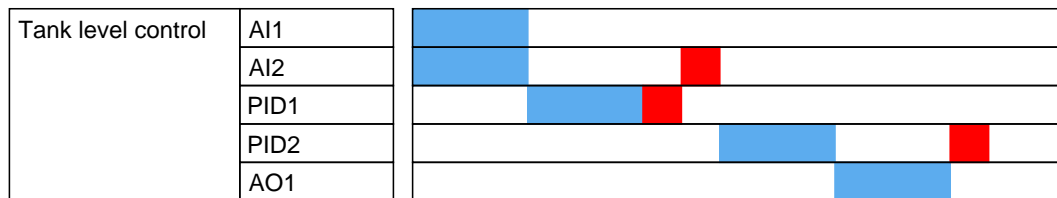

= Function block execution time
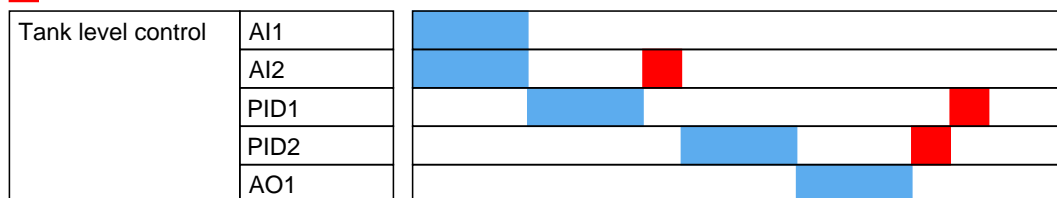
= Scheduled communications

Tank level control	AI1	
	AI2	
	PID1	
	PID2	
	AO1	

= Function block execution time

= Scheduled communications

Tank level control	AI1	
	AI2	
	PID1	
	PID2	
	AO1	

= Function block execution time

= Scheduled communications

Tank level control	AI1	
	AI2	
	PID1	
	PID2	
	AO1	

= Function block execution time

= Scheduled communications

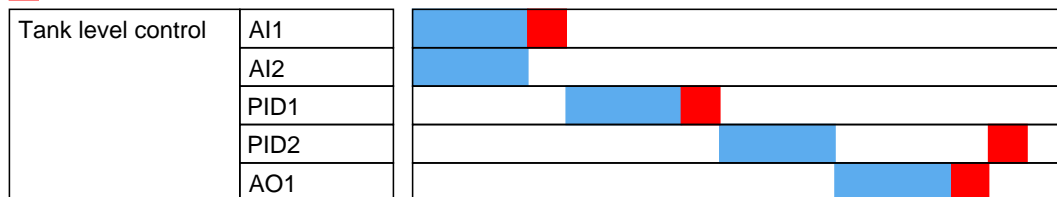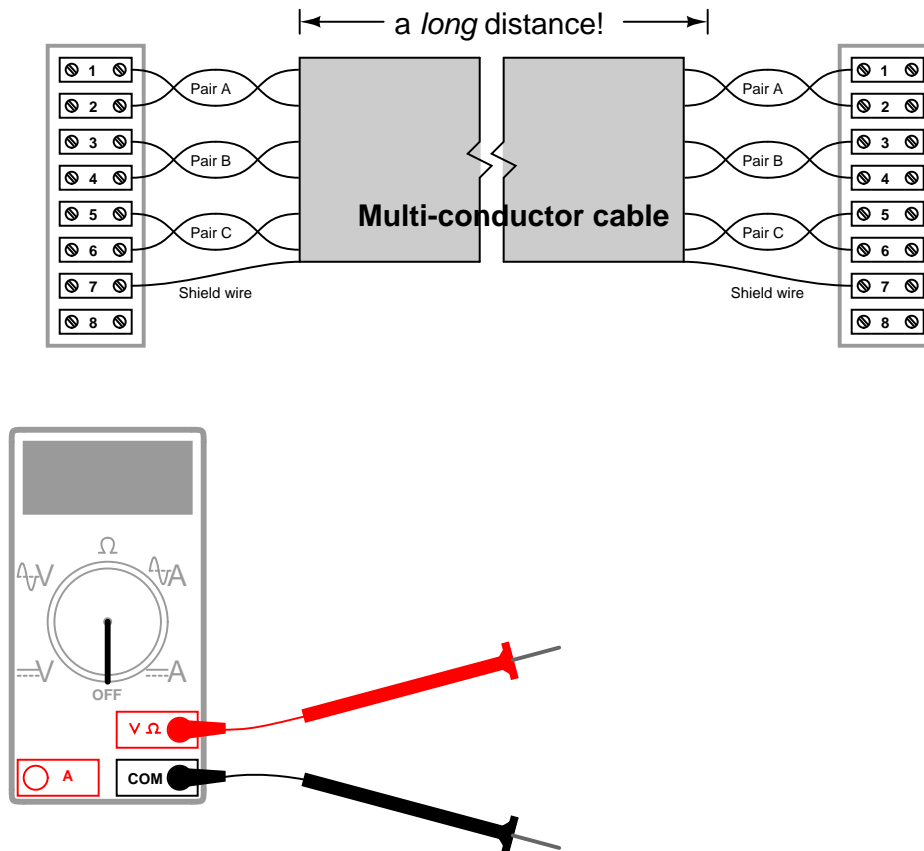| Tank level control	AI1	
	AI2	
	PID1	
	PID2	
	AO1	

file i00437

52

Question 64

Suppose you need to test a multi-pair electrical cable before it is used as part of a FOUNDATION Fieldbus H1 network. The cable ends are terminated at terminal blocks too far away to permit a multimeter's test leads to stretch from one end to the other:

Devise a series of measurements that a technician could take using a multimeter located at one end of the cable, to test for each of the following cable faults. Be sure to specify which setting the multimeter should be configured for, and which terminals the test leads should touch. Also, be sure to specify what range of measurements would indicate "good" versus "bad" for each test:

- Test for pair "B" wires shorted together in cable

- Test for either conductor of Pair "B" being broken (open)

- Test for either conductor of Pair "B" shorted to cable shield

- Test for either conductor of Pair "B" shorted to either conductor of pair "A"

Suggestions for Socratic discussion

- What purpose does the *shield* conductor serve in a multi-conductor cable?

  file i00448

Question 65

A newly-constructed H1 Fieldbus segment seems to have a problem. The host system (an Emerson DeltaV DCS) recognizes the pressure transmitter, but fails to recognize the control valve positioner when it is connected to the segment. The positioner does not even come up on the Emerson system as a "decommissioned" device – there simply isn't any ackowledgement from the DCS at all that another device exists on the segment. A diagram of the system appears here:
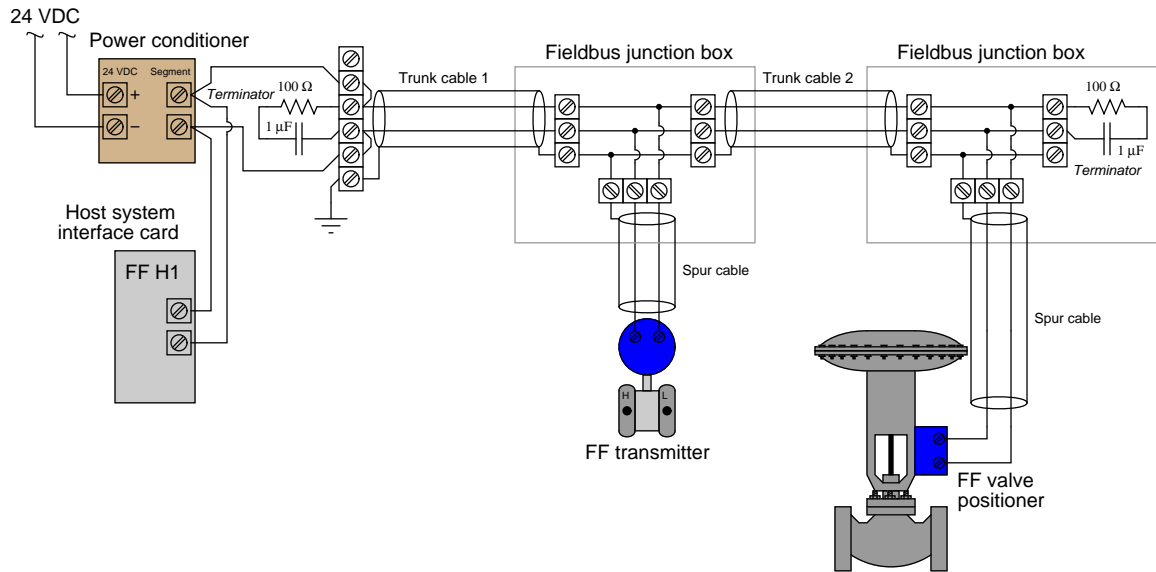
The first step you take in diagnosing this problem is to measure DC voltage with your voltmeter at the terminals of the valve positioner. There, you measure a steady 23.1 volts DC.

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
Trunk cable 1 failed open		
FF transmitter failed open		
FF positioner failed open		
Transmitter spur cable failed open		
Positioner spur cable failed open		
Trunk cable 1 failed shorted		
FF transmitter failed shorted		
Transmitter spur cable failed shorted		
Positioner spur cable failed shorted		
Terminator failed open		

Also, identify one fault not included on this list that is capable of independently accounting for all measurements and symptoms.

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

<u>file i00477</u>

Question 66

In many microwave radio systems, hollow rectangular tubes known as *waveguides* are often used in lieu of cables to serve as transmission lines between the transceiver and the antenna. These hollow metal tubes acts as "pipes" to convey GHz-range electromagnetic waves with great efficiency, far exceeding the efficiency of coaxial cables:

RF energy in

Flange

Flange

Waveguide

RF energy out
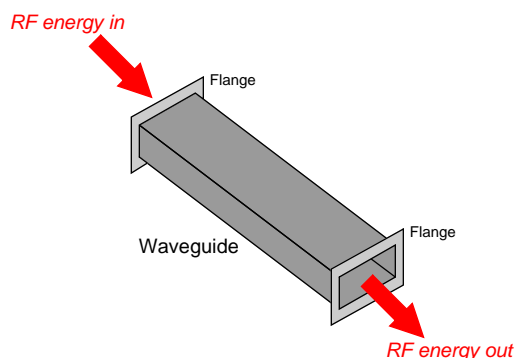
The following table shows a comparison between RG-49/U waveguide and RG-9/U flexible cable:

Parameter	RG-49/U waveguide	RG-9/U coaxial cable
External dimensions	2 inch × 1 inch	0.420 inch diameter
Dielectric	air	polyethylene (plastic)
Weight	1.4 lb per foot	0.15 lb per foot
Attenuation at f = 5 GHz	0.011 dB per foot	0.23 dB per foot
Power rating	1.2 MW	66 W

Suppose an RG-49/U waveguide is used to transfer RF energy from a 300 watt radar transceiver to a dish antenna. Calculate the RF power (in watts) available at the antenna, assuming the waveguide is 8 feet long and that there are no other power losses between the transceiver and the antenna.

Now suppose that radar transceiver's power is increased to 800 watts. Calculate the RF power (in watts) available at the antenna, assuming the same waveguide length.

Now suppose that radar transceiver's power is increased to 3 kilowatts. Calculate the RF power (in watts) available at the antenna, assuming the same waveguide length.

Does the waveguide power loss remain constant as transmitter power increases, or does it change with the amount of transmitted power? How does the "lost" RF energy manifest itself through the waveguide (given that the Law of Energy Conservation tells us energy cannot be created or destroyed)?

| Suggestions for Socratic discussion |

- Explain why the waveguide shown has such a greater power rating than the coaxial cable, based on their respective dB/foot loss ratings.
- Why aren't waveguides used for all GHz-frequency radio applications, given that their power losses are so much less than the losses exhibited by coaxial cable?
- For those who have studied level measurement technologies, explain how the concept of a *waveguide* relates to guided-wave radar (GWR) level transmitters.
- Is is possible for a waveguide to experience *reflected signals* as in the case of improperly terminated transmission line cables? Why or why not?
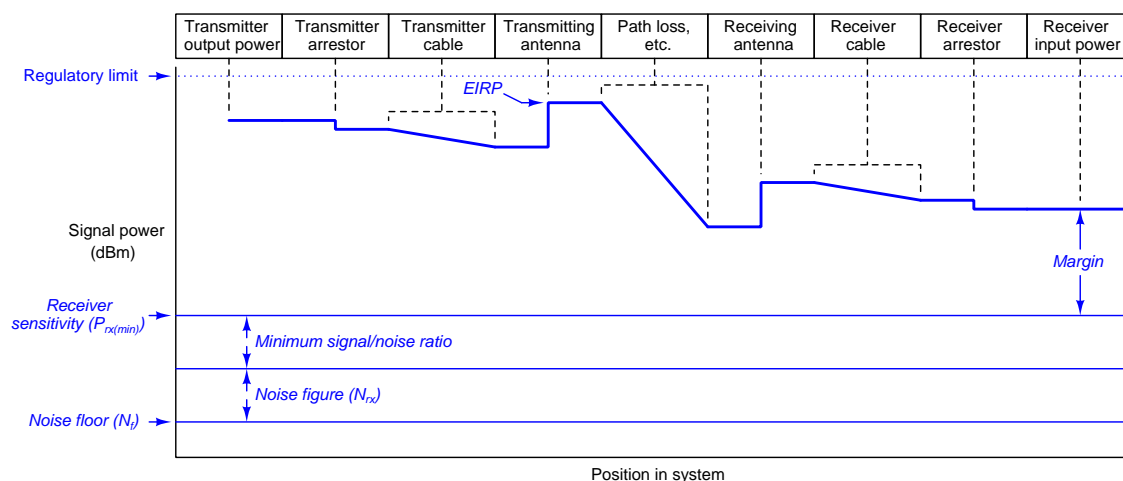
file i00791

Question 67

Perform a link budget analysis of the following radio communication system, using a FreeWave FGR2 industrial data radio (900 MHz) transmitting at 5 mW with the following components and parameters:

- BER (bit error rate) = 10^{-4}
- Distance = 8.5 miles
- EAN0900YC Yagi transmitting antenna
- ASC0202SN transmitting cable (20 feet long)
- EAN0906YA Yagi receiving antenna
- ASC0302SN receiving cable (30 feet long)

Specifically, calculate the amount of *margin* (i.e. safety factor) between the 5 mW transmitter power and the bare-minimum transmitter power you calculate from the link budget.

Next, show where all these figures fit into the following link budget graph. Note that this is a generic graph, and is not necessarily tailored to this particular application:

Question 68

This control system measures and regulates the differential pressure across a large motor-driven gas compressor by "recycling" gas from the compressor's discharge line back to its suction line. It uses an air-to-close control valve so that the valve will fail open in the event of air pressure or signal loss. The controller's output indication, however, is reverse-responding so that 0% (20 mA) represents a fully shut valve while 100% (4 mA) represents a wide-open valve:
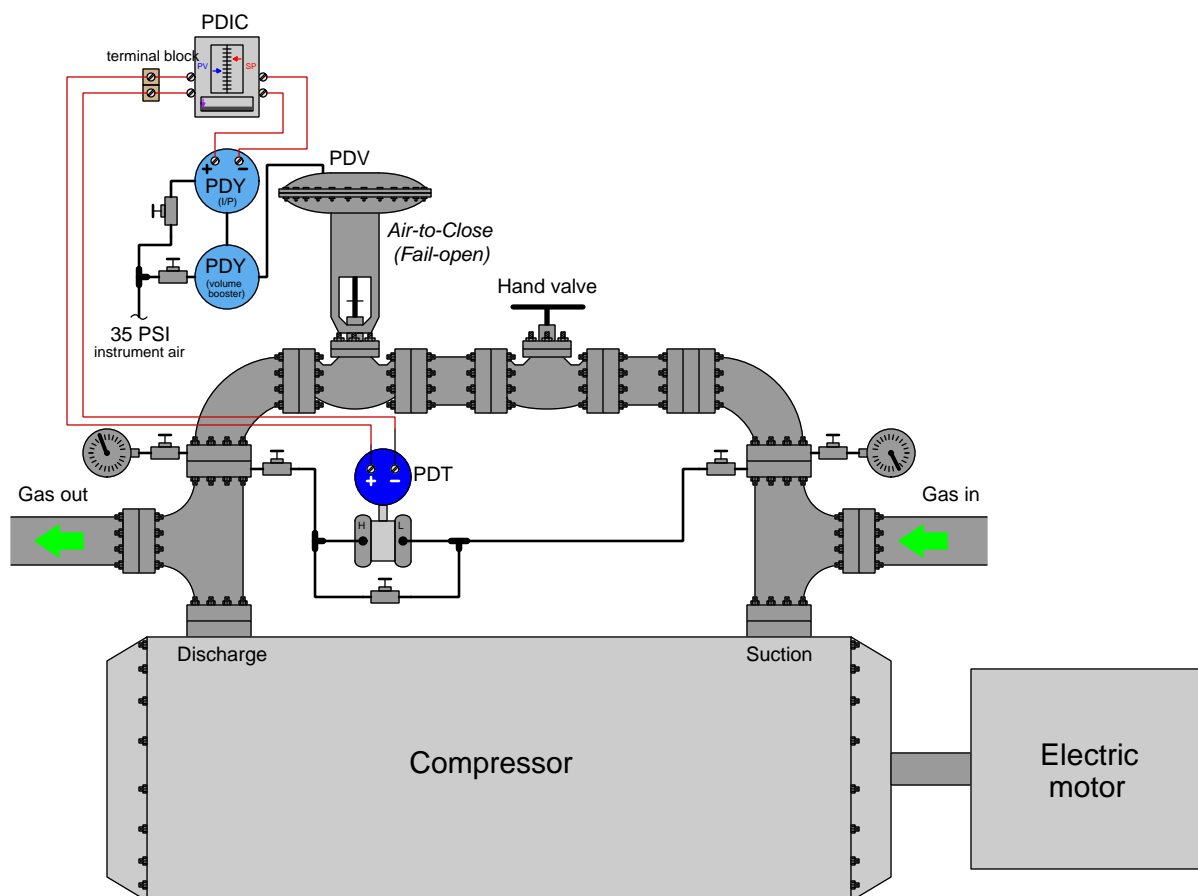
Unfortunately, this system has a problem. The pressure differential indicating controller (PDIC) shows the process variable (PV) being about 50% of range, while the setpoint (SP) is adjusted to 70%. The controller's output indication shows 0%.

Identify which of these four areas of the system the problem may be located in, and then describe a good test you could do in or to this system to narrow the problem location even further:

- Problem with the measurement side (transmitter, wiring, controller analog input)?
- Problem with the controller's control action (its "decision-making")?
- Problem with the final control element side (valve, I/P, booster, controller analog output)?
- Problem with the compressor itself (or other portions of the process)?

Suggestions for Socratic discussion

- Could a shut recycle line hand valve account for what we're seeing here? Explain why or why not.

  file i00294

Question 69

Suppose a Rosemount model 3244MV (FOUNDATION Fieldbus) temperature transmitter is used as an electric current sensor, the transmitter configured for millivolt input and connected in parallel with a shunt resistor carrying load current in a DC power system. The shunt resistor has a resistance of 35 milliohms:
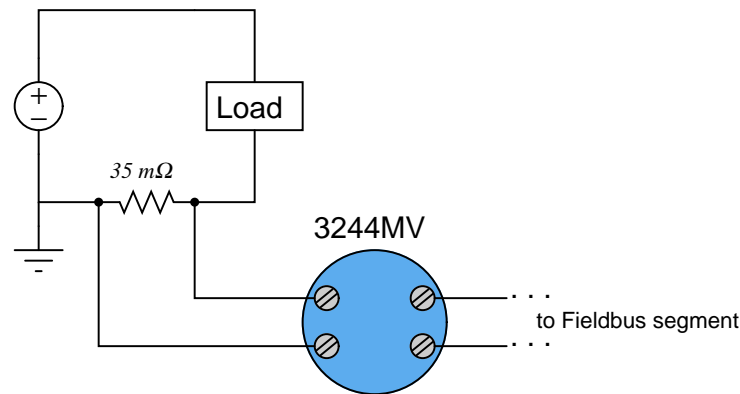
Determine the proper XD_Scale, OUT_Scale, and L_Type parameter values to make the transmitter functional over a DC load current range of 0 to 2.5 amps.

file i03642

Question 70

A FOUNDATION Fieldbus pressure transmitter is used to sense hydraulic fluid pressure applied to a cylinder with a piston diameter of 3 inches. Recall that the force/pressure/area formula is $F = PA$.

Determine the proper XD_Scale, OUT_Scale, and L_Type parameter values to make the transmitter report the cylinder's *force* over a range of pressure 0 to 2000 PSI.

file i03647

Question 71

A FOUNDATION Fieldbus pressure transmitter is used to sense the mass of liquid stored inside a cylindrical vessel having a diameter of 70 inches and a height of 115 inches. The liquid's density is 54 pounds per cubic foot (equivalent to 86.5% the density of water):
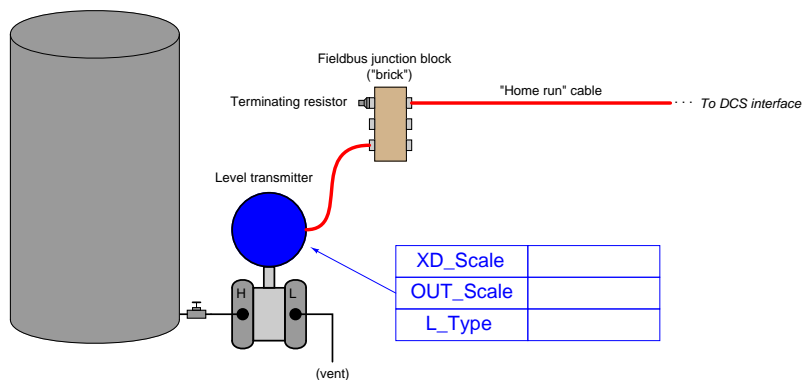
Determine the proper XD_Scale, OUT_Scale, and L_Type parameter values to make the transmitter functional over the entire height of the tank.

file i03646

A FOUNDATION Fieldbus pressure transmitter is used as part of a *hydraulic load cell* system to measure the weight applied to a platform scale: the platform's weight presses against a piston, which exerts pressure in a hydraulic fluid according to the force/pressure/area formula $F = PA$. The transmitter then senses this fluid pressure as a representative proportion of platform weight:

Assuming the circular piston has a diameter of 4 inches, determine the proper XD_Scale, OUT_Scale, and L_Type parameter values to make the transmitter functional over a platform weight range of 0 to 25,000 pounds.
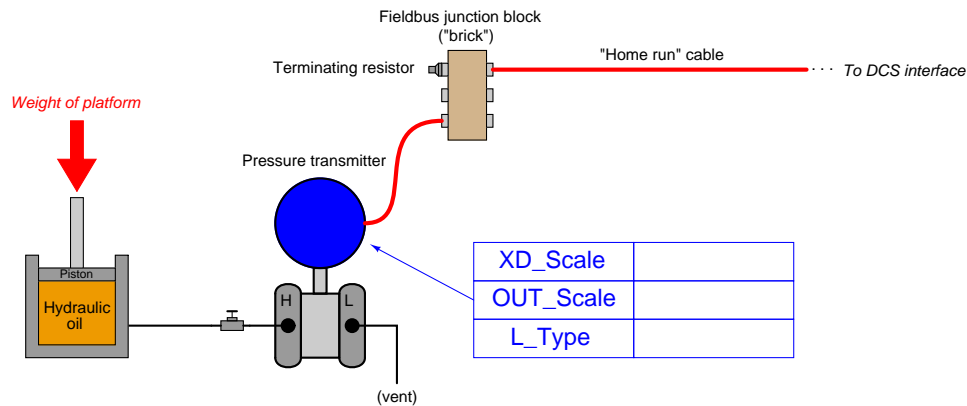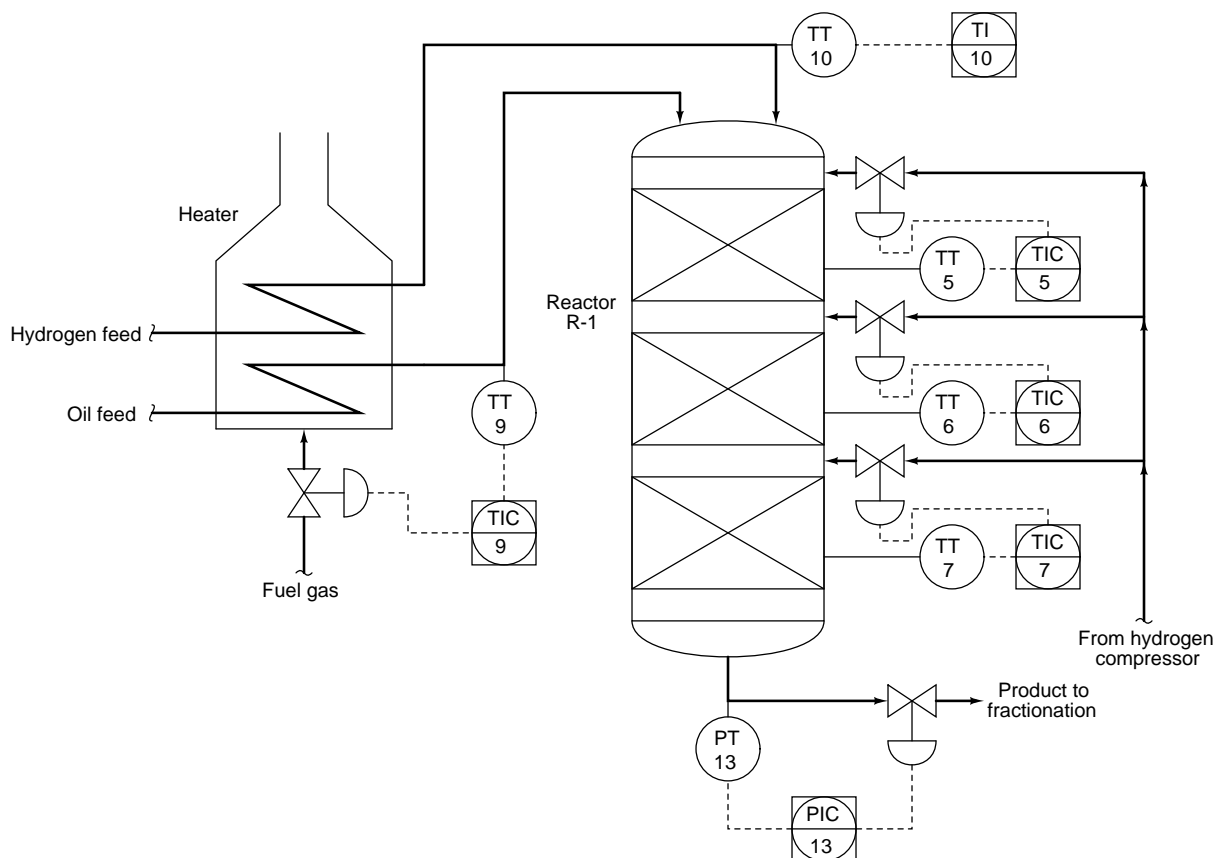
<u>file i03385</u>

Question 73

One of the chemical processes used in some petroleum oil refineries to convert heavy oils into more marketable products such as jet fuel is called *hydrocracking*, where hydrogen gas is added to hot oil at very high pressure to "crack" the oil molecules into smaller (shorter-length) molecules that make lighter oils:

The hydrocracking reaction is exothermic, which means it produces (rather than absorbs) heat. In order to control the reaction temperature and prevent it from "running away," cool hydrogen gas is added to each catalyst bed inside the reactor to *quench* the reaction and regulate its temperature.

Assuming all transmitters are direct-acting, determine the necessary actions of each controller in this system so that each control loop will be stable. Note the valve actions for each loop:

- TV-5 = signal-to-open ; TIC-5 = *direct* or *reverse* action?
- TV-6 = signal-to-open ; TIC-6 = *direct* or *reverse* action?
- TV-7 = signal-to-open ; TIC-7 = *direct* or *reverse* action?
- TV-9 = signal-to-open ; TIC-9 = *direct* or *reverse* action?
- PV-13 = signal-to-close ; PIC-13 = *direct* or *reverse* action?

| Suggestions for Socratic discussion |

- For those who have studied chemistry, what property of hydrogen gas makes it such a good coolant?

file i00433

Question 74

This heat exchanger's outlet temperature is controlled by a PID controller, regulating the amount of steam admitted to the exchanger to impart heat to the process fluid:
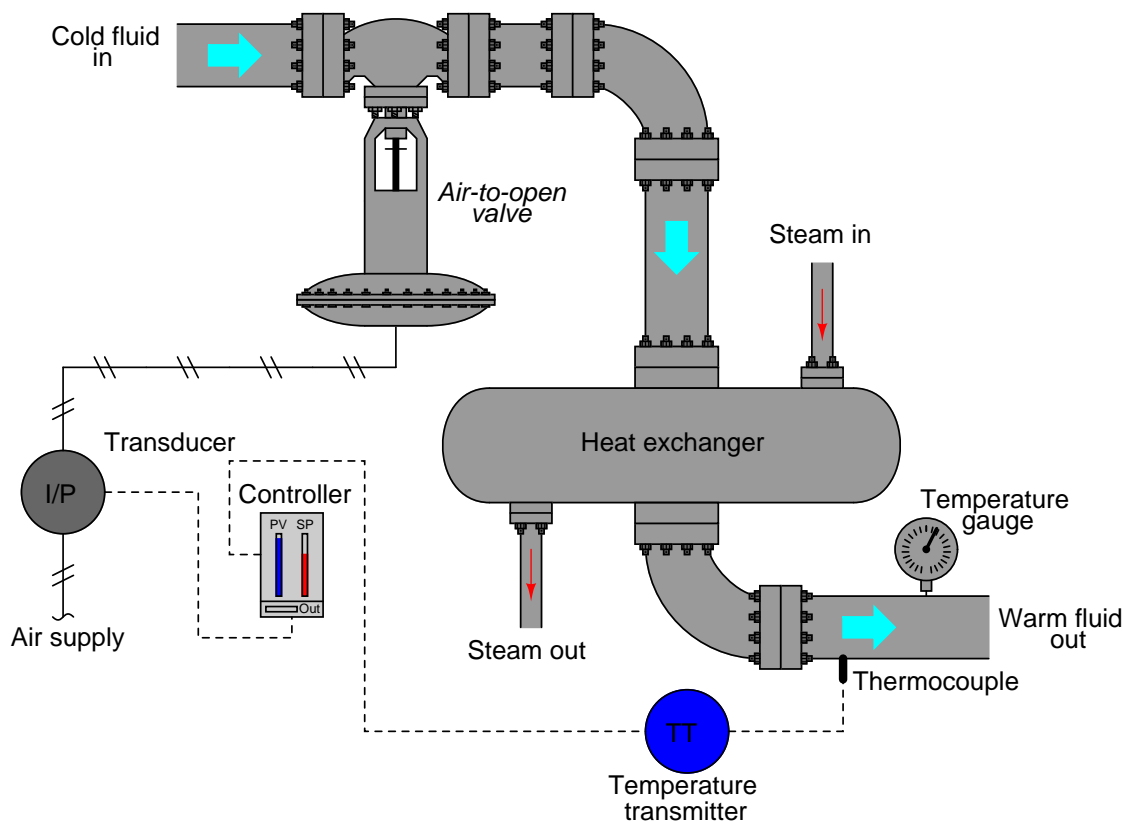
An operator tells you there is a problem with this system, though: the controller faceplate shows the temperature well above setpoint. You happen to notice that the bargraph on the controller faceplate showing output is at 0%. Another operator in the field (near the exchanger) reports via radio that the control valve stem is at the "closed" position.

Another instrument technician happens to be with you, and recommends the controller be placed in manual mode for a quick stroke-test of the control valve (i.e. making sure it responds to the controller's output). Explain why this test would be a waste of time, and propose a better test for helping to pinpoint the location of the fault.

| Suggestions for Socratic discussion |

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which field variables correspond with their respective controller faceplate displays, and which do not. Apply this comparative test to the scenario described, and use it to explain why the technician's proposed test was probably not the best first step.

file i00297

61

Question 75

Suppose two radio antennas are located on 12-foot towers, with free and open space in between. If their operating frequency is 900 MHz, calculate the distance between these towers where the first Fresnel zone contacts the ground in between. Is this tower-to-tower distance a *minimum* or a *maximum* value for practical radio operation?

Antenna

Antenna

12 feet

12 feet
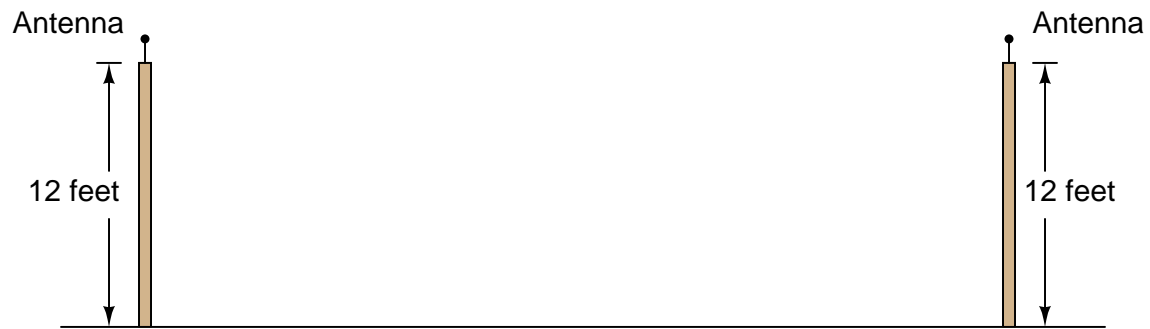
| Suggestions for Socratic discussion |

- Identify at least one practical factor which would change the distance value allowable between the two antennas. In other words, what could change in the system to permit a different distance between antennas?

  file i00449

Question 76

Question 77

Question 78

Question 79

Question 80

Question 81

Suppose you are tasked with building a control system using *Wireless*HART transmitters to sense a variety of process variables. The central component of the wireless network, of course, is the *gateway* device. Your particular network gateway provides Modbus access to the data received from all those transmitters via an RS-485 (serial) network port.

The challenge is this: five programmable logic controllers (PLCs) require access to the measurement variables of five different *Wireless*HART transmitters. Each PLC has an RS-485 serial port, meaning they may be all "daisy-chained" on one RS-485 wired network connecting also to the wireless network gateway device. What is not so easy is figuring out how all five of the PLCs will be able to read data from the gateway, since Modbus is fundamentally a *master/slave* protocol (one "master" device sending data to and receiving data from multiple "slave" devices). In our system, we need five different PLCs to get data from the one gateway, which itself is a "slave" device.

Explain how it is possible to configure a single PLC as the Modbus "master" device, and still have the other four PLCs receive data from the wireless network gateway ("slave") device.

Determine whether or not it is possible to configure *all* five of the PLCs as Modbus "master" devices on the RS-485 network, yet avoid "bus contention" issues as they all attempt to query the wireless gateway ("slave") device. Explain why this proposed solution is (or is not!) possible!

Question 82

Suppose two PLCs use Modbus TCP protocol to read data registers inside a *Wireless*HART network, populated by live data from *Wireless*HART temperature transmitters at various locations:
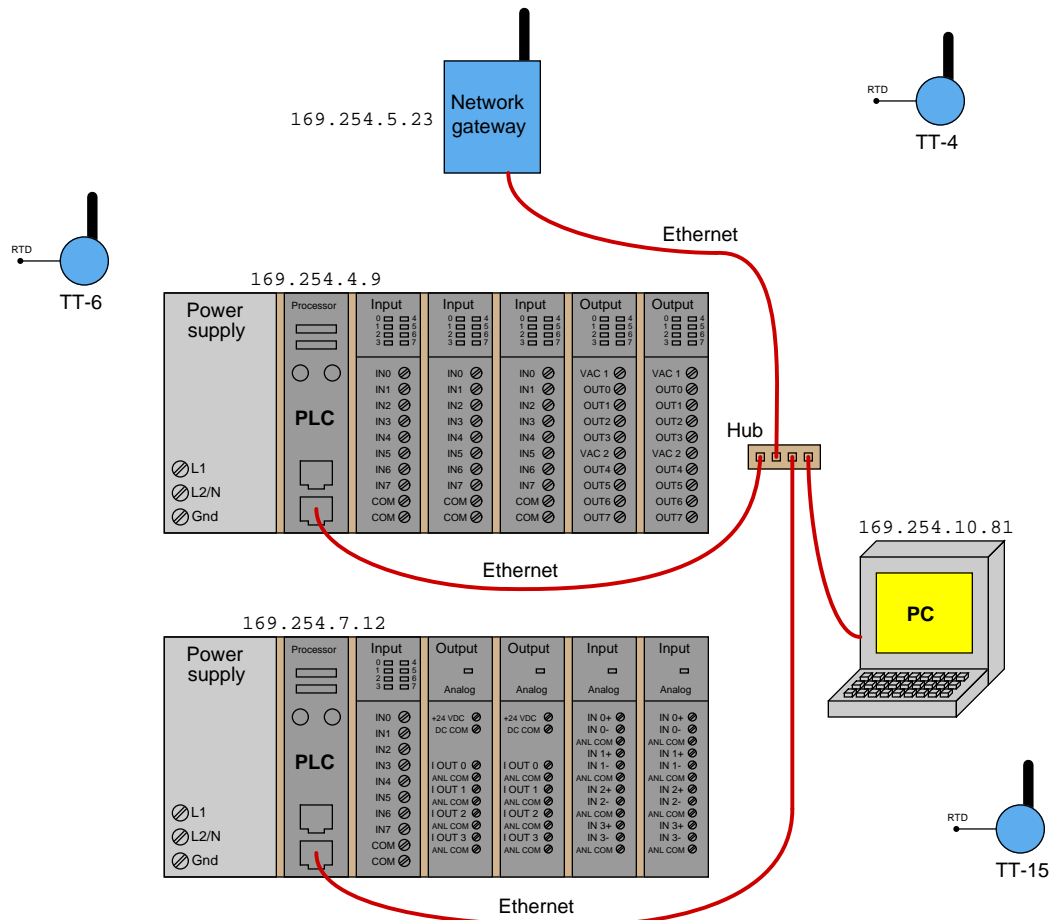
Unfortunately, there is a problem in this system. One PLC (IP = 169.254.4.9) cannot seem to read the temperature sensed by transmitter TT-15. We happen to know that the other PLC (IP = 169.254.7.12) can read the temperatures of the other two *Wireless*HART transmitters (TT-4 and TT-6) just fine, but we don't know if this other PLC can read TT-15's data.

Determine the diagnostic value of each of the following tests. Assume only one fault in the system, including any single component or any single wire/cable/tube connecting components together. If a proposed test could provide new information to help you identify the location and/or nature of the one fault, mark "yes." Otherwise, if a proposed test would not reveal anything relevant to identifying the fault (already discernible from the measurements and symptoms given so far), mark "no."

Diagnostic test	Yes	No
Use PC to log into Gateway and check RSSI of TT-15		
Use PC to "ping" PLC 169.254.4.9		
Use PC to "ping" PLC 169.254.7.12		
Use PC to "ping" Gateway 169.254.5.23		
Inspect status LEDs on hub ports		

file i01703

Suppose two radio transceivers must communicate with each other over a long distance. Each one uses a half-wave "whip" antenna with 6 dBi gain, a lightning arrestor at the transceiver (−0.5 dB loss at each transceiver), and each one has 25 feet of coaxial cable connecting the transceiver to the antenna (−0.2 dB loss per foot). Each transceiver transmits 350 mW of RF power, and has a receiving sensitivity of −103 dBm.

Assuming a 900 MHz signal frequency, no fade loss, and absolutely clear line-of-sight between the two antennas, how far away may these transceivers be separated and still fall within the RF budget for good communication?

Question 84

This level-control system does not appear to be regulating vessel liquid level correctly. The SP is set for 2.5 feet (out of a 0-5 foot range), but the PV display on the controller faceplate registers 3.74 feet. You happen to notice that the controller output reads 100% on the faceplate:
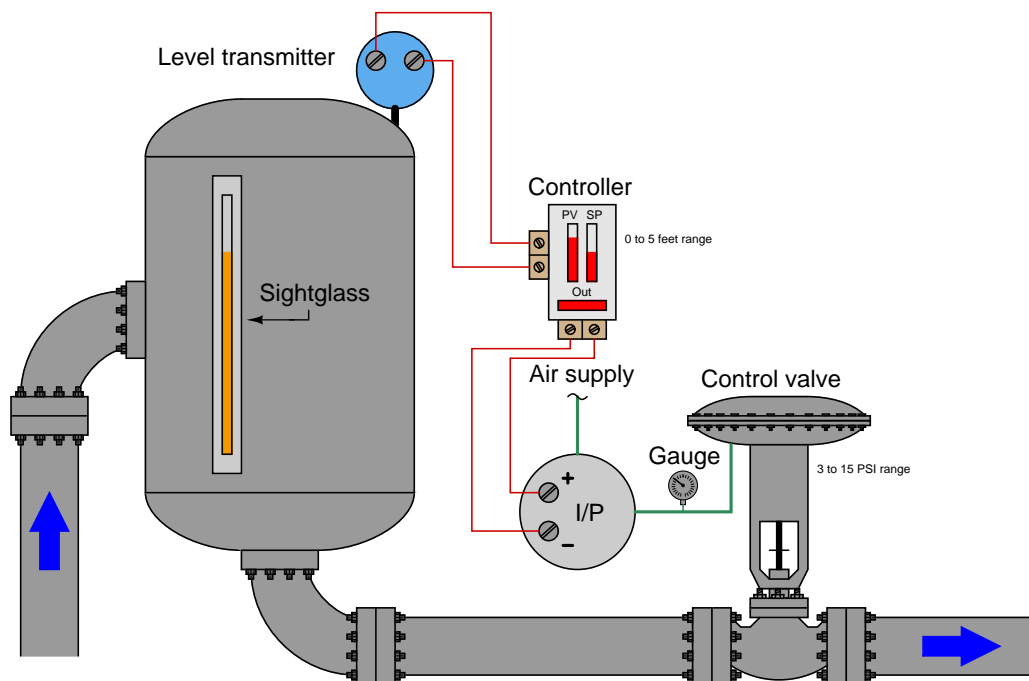
A field operator informs you that a sightglass on this vessel reads 3 feet 9 inches, and the control valve stem position is approximately 40% open.

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

Fault	Possible	Impossible
LT out of calibration (outputting wrong current)		
LIC input out of calibration (not interpreting signal properly)		
LIC output out of calibration (not sending correct mA signal to I/P)		
I/P out of calibration (not outputting correct pressure)		
Control valve is oversized		
Control valve is undersized		
LIC is poorly tuned (not making good control "decisions")		
Instrument air supply not at full pressure		

Also, explain how the principle of *correspondence* may be used to determine which portion of this control system (measurement, controller, output) the problem is located in.

file i00337

Question 85

The Rosemount 3244MV FOUNDATION Fieldbus temperature transmitter is capable of receiving input signals from thermocouples, RTDs, and also generic millivoltage sources (over a range of −10 mV to +100 mV). The option to input a millivoltage and digitally scale that analog signal into whatever range is desired is very useful. Take for instance this application where we will use a Rosemount 3244MV transmitter to convert the signal from a tachogenerator into a speed indication for the motor (in units of RPM):
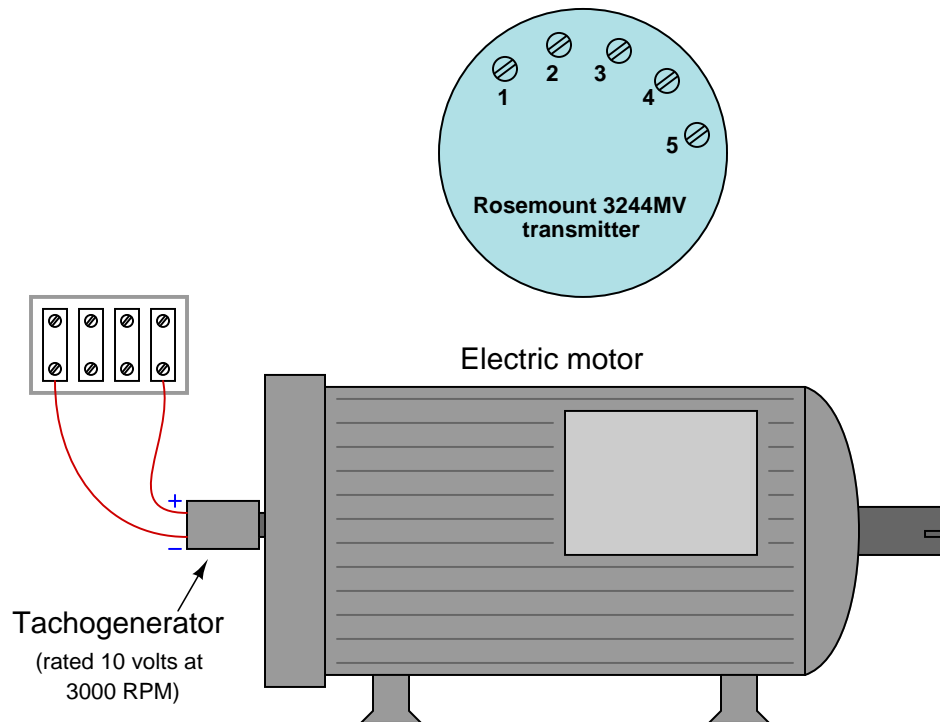
The tachogenerator is nothing more than a small, permanent-magnet DC generator whose output voltage is directly proportional to shaft speed (this one rated 10 volts output at 3000 RPM).

Sketch a circuit connecting this tachogenerator to the 3244MV transmitter, ensuring the transmitter will never see more than 100 mV signal strength, and also determine the proper configuration parameters for this Fieldbus instrument's Analog Input (AI) block to scale the output so that it reports 0 to 2500 RPM:

L_Type	
XD_Scale	
OUT_Scale	

Question 86

The flow rate of a fluid measured by a *counterpropagation* ("transit-time") ultrasonic flowmeter is given by the following formula:

$$Q = k\frac{t_{up} - t_{down}}{(t_{up})(t_{down})}$$
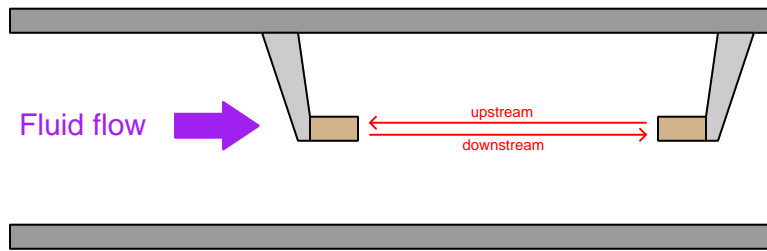
Knowing that the time for a sound wave to propagation upstream is equal to the length of the travel path divided by the difference in sound wave and fluid velocities ($t_{up} = \frac{L}{c-v}$) and that the time for a sound wave to propagation downstream is equal to the length of the travel path divided by the sum of sound wave and fluid velocities ($t_{down} = \frac{L}{c+v}$), prove that the flow rate measurement (Q) does not depend on the speed of sound through the fluid (c). In other words, substitute these mathematical definitions for t_{up} and t_{down} into the flowmeter equation and simplify to show that c is eliminated (canceled out) in the end.

file i03522

Question 87

Calculate all voltages and all currents in this transformer circuit, assuming the source supplies 4.5 amps to the transformer's primary winding:
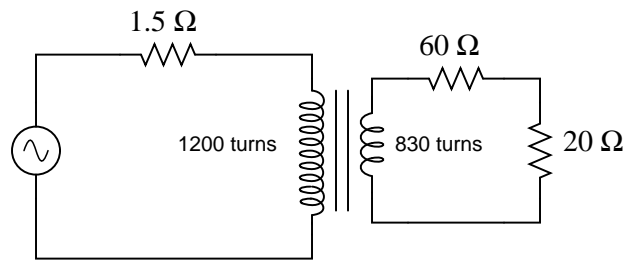
- $V_{source} =$
- $V_{primary} =$
- $V_{secondary} =$
- $I_{primary} =$
- $I_{secondary} =$

<u>file i01268</u>

Question 88

The formula for calculating *path loss* in a radio system (the power lost due to spreading of RF energy from the transmitting antenna) looks like this:

$$L_p = -20 \log \left(\frac{4\pi D}{\lambda} \right)$$

Where,

L_p = Loss of power (decibels)

D = Distance between transmitting and receiving antennas

λ = Wavelength of radio wave

Why does this formula have a multiplier of *20* instead of the more customary 10 we are used to seeing in decibel formulae?

file i03636

Question 89

Calculate the minimum required transmitter power for an FM radio broadcast station, assuming we wish an FM radio receiver with a sensitivity of −90 dBm be able to receive the signal. Assume the following gains, losses and other parameters in the system:

- Frequency = 104.5 MHz

- Distance = 120 km

- Transmitter antenna gain = 6 dBi

- Receiver antenna gain = 0 dBi

- Transmitter cable loss = 0.09 dB per foot ; 300 feet long

- Receiver cable loss = 0.12 dB per foot ; 3 feet long

After calculating the required (minimum) transmitter power, re-calculate to include a *fade margin* of 20 dB for good measure. Explain what "fade margin" is, and why it might be a good idea to include it in an RF link budget calculation.

Question 90

Something is wrong with this building security alarm system circuit. The alarm siren energizes even when all the windows and doors are shut. The only way to silence the alarm is to use the "override" key switch:
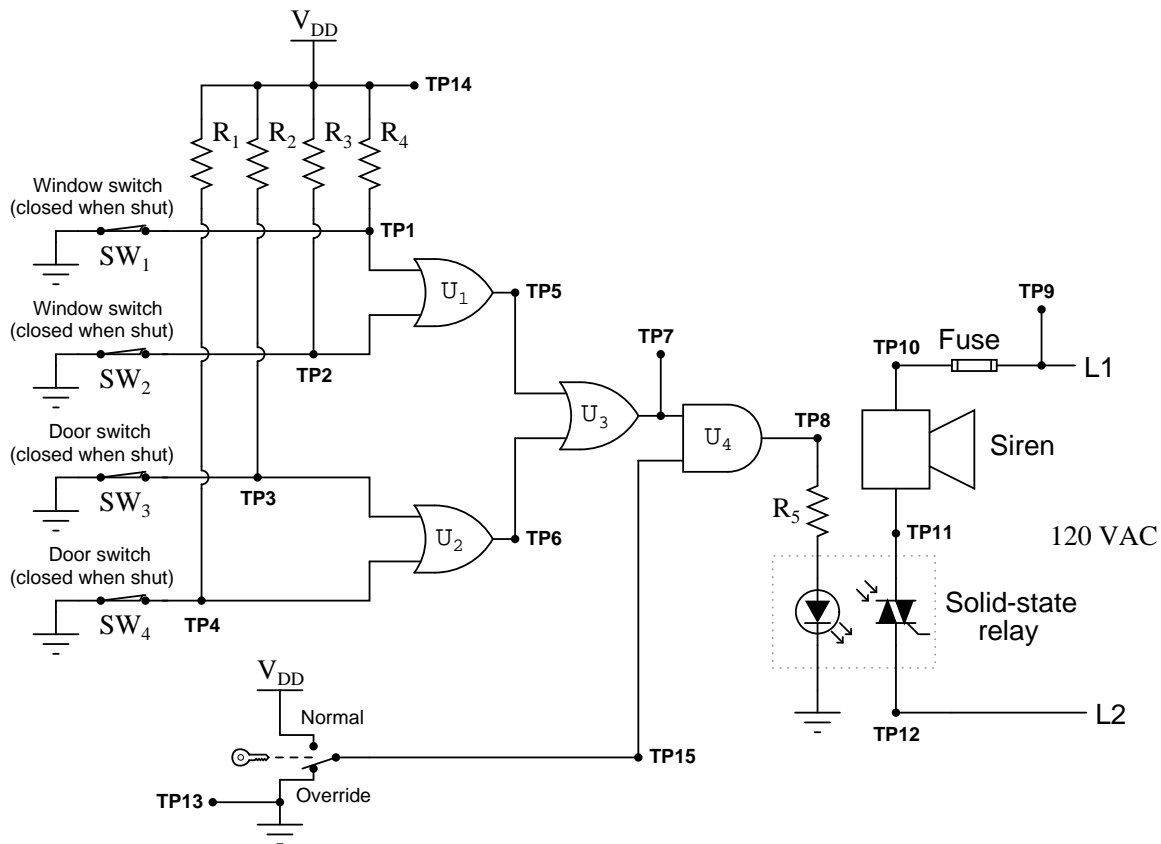
Using your logic probe, you measure a high signal at TP7 and a low signal at TP6 with all windows and doors shut, and with the key switch in the "override" position. From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit). Then, choose one of those possible faults and explain why you think it could be to blame. The circuit elements you identify as possibly faulted can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted
1.
2.

- Explanation of *why* you think one of the above possibilities could be to blame

<u>file i03195</u>

Lab Exercise – introduction

Your task is to commission and de-commission a *Wireless*HART field instrument, recording and/or controlling variables within that instrument using the Modbus protocol. Each lab team will commission one *Wireless*HART instrument (field device), and each person on that team will read or write one variable within that device. Troubleshooting will be done on a PID-controlled process commissioned during a previous lab exercise, which may or may not be related at all to the *Wireless*HART instrument you commission in this exercise.

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
Record serial number of device	(ungraded)	–	–	–	–	
Team meeting	mastery	–	–	–	–	
*Wireless*HART instrument commissioned	mastery	– –	– –	– –	– –	
Data displayed/controlled via Modbus	mastery					– – – –
Circuit design challenge	mastery					– – – –
Troubleshooting	mastery					– – – –
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –
Decommission and lab clean-up	(ungraded)	– –	– –	– –	– –	

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

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

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

Lab Exercise – objectives and expectations

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

Record serial number of device

Your *Wireless*HART device is portable and will likely be moved to different locations during the commissioning process. For this reason it is important to track which team is responsible for which device, and having the instructor record the serial number from your team's device is a good way to do this. This same serial number will be verified when you decommission the device and return it to storage.

Team meeting and prototype sketch

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

WirelessHART instrument commissioned

Establish wireless (i.e. radio) communication between a *Wireless*HART field instrument and the Gateway using the appropriate *Network ID* and *Join Key* (both unique to the Gateway) as well as a *HART long tag* name unique to your team. The instrument's *update rate* should be appropriately set as well.

Data displayed/controlled via Modbus

Each student must configure the *Wireless*HART Gateway and data display device (e.g. HMI) to either display or control one variable within the field instrument, a task requiring *mapping* of that instrument variable to a specified Modbus register. Both the variable and the Modbus register must be unique to each student.

Circuit design challenge

Build a circuit with a HART differential pressure transmitter responding properly to applied pressure/vacuum, using an analog multimeter to register the transmitter's analog signal and a digital oscilloscope to register the transmitter's digital (HART) signal.

Troubleshooting

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

Lab Exercise – objectives and expectations (continued)

Lab percentage score

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

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

Safety and professionalism (deduction)

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

General format and philosophy

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

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

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

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

Lab Exercise – team meeting

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.

For example, if a team member lacks experience using personal computers, this lab exercise is an excellent opportunity to gain those skills. It is *strongly* recommended that those team members with the least computer experience be the people to do all the initial configuration work while those with more experience merely supervise.

Remember, the purpose of this lab exercise is not to complete it in the least amount of time, but rather for every team member to gain new knowledge and skill. This is why tasks should not necessarily be assigned with *maximum efficiency* in mind as they would at a workplace, but rather with *maximum learning* in mind because this is a school.

Lab Exercise – circuit design challenge

Connect a loop-powered "smart" differential pressure transmitter (4-20 mA output with HART communication ability) to a DC voltage source and an analog meter such that the meter will indicate a increasing signal when a certain stimulus is applied to the transmitter, setting the transmitter's pressure measurement range as specified by the instructor. Additionally, connect a digital oscilloscope to this circuit and use it to capture one of the digital messages communicated between the transmitter and the HART communicator. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, etc.) "Alligator" clips are permitted for making connections to battery terminals only.

This exercise tests your ability to correctly identify pressure port functions on a differential pressure transmitter, to navigate a "smart" instrument's parameters using a communicator, to properly interpret terminal connections on a field instrument for signal and power, to use an analog multimeter to measure 4-20 mA loop current, to use a DMM to capture peak signal amplitude, to use a digital oscilloscope to capture FSK data, and to interpret that FSK-encoded digital data.
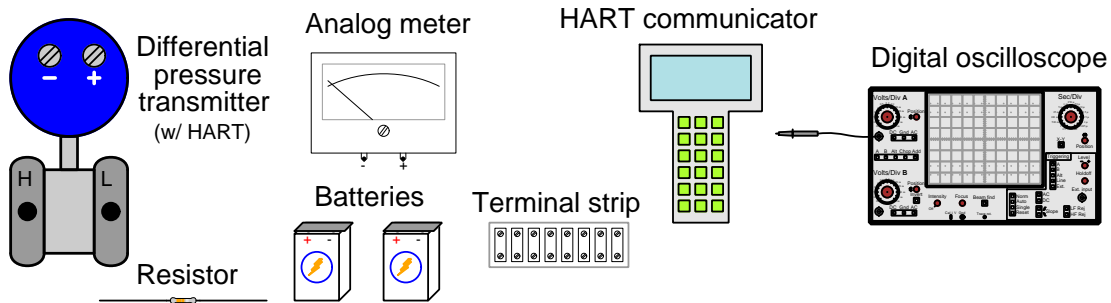
The following components and materials will be available to you: assorted 2-wire 4-20 mA HART differential pressure **transmitters** calibrated to ranges 0-30 PSI or less, equipped with Swagelok compression tube connectors at the "high" and "low" ports ; lengths of **plastic tube** with ferrules pre-swaged ; **terminal strips** ; lengths of **hook-up wire** ; 250 Ω (or approximate) **resistors** ; analog **meters** ; **batteries** ; **HART communicator** ; digital **oscilloscope**. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

SEQUENCE: (1) Instructor chooses criteria; (2) You build, power, and test circuit; (3) Instructor verifies all objectives satisfied.

Transmitter range (instructor chooses): LRV = _____ URV = _____

Meter options (instructor chooses): ____ Voltmeter (1-5 VDC) *or* ____ Ammeter (4-20 mA)

Signal increases with... (instructor chooses): ____ Positive pressure *or* ____ Vacuum (suction)

HART signal captured (instructor verifies): ____ (peak FSK signal voltage read on DMM)
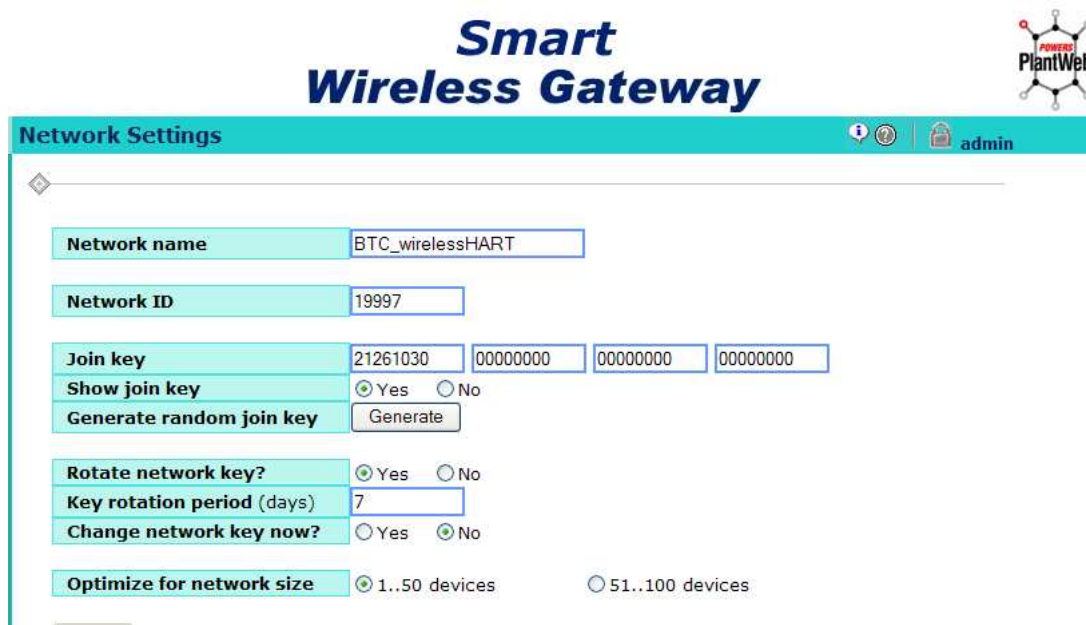
HART signal captured (instructor verifies): ____ (correctly read FSK "0" and "1" bits on scope)

Study references: the "Analog Electronic Instrumentation" chapter of *Lessons In Industrial Instrumentation*, particularly the sections on loop-powered transmitters and current loop troubleshooting. Also, the "Basic Concept of HART" subsection of the "The HART Digital/Analog Hybrid Standard" section of the "Digital Data Acquisition and Networks" chapter of the same book. Your DMM manual will provide instructions on capturing peak signal values.

Lab Exercise – commissioning a *Wireless*HART instrument

Detailed instructions for commissioning a *Wireless*HART instrument are found in the manuals for that instrument and/or in the manual for the Gateway device. You will need a HART communicator connected directly to the field instrument to configure it, and then web browser software pointed to the IP address of the Gateway (on the Ethernet network) to monitor the status of the field instrument. No special software is needed on your personal computer to access the Gateway's parameters – any web browser will do, because the Gateway has a built-in web server.

An essential step in the commissioning of a *Wireless*HART field device is to program it with the appropriate *Network ID* and *Join Key*. The Network ID is a number unique to each *Wireless*HART radio Gateway, and the Join Key is another (much larger!) number used to authenticate each field device. You may think of the Network ID as a "login name" and the Join Key as the "password" for a *Wireless*HART device to connect to the Gateway.

Network ID numbers are very important in applications where multiple *Wireless*HART networks coexist: where groups of field devices are assigned to different Gateways despite being close enough to each other to form a single "mesh" network. The unique Network ID number for each Gateway keeps their respective radio networks separate from each other.

Join Keys are an important security feature of *Wireless*HART, ensuring a new device cannot join the mesh network unless it is supposed to. Without the proper Join Key, a new *Wireless*HART device will be rejected from a Gateway's mesh network even if strong radio communication exists. The Join Key is more than just a password, though: it serves as the encryption key to secure all data communicated between the field device and the Gateway during the commissioning process. The Network Key is another 128-bit encryption key used to secure data communications on the mesh network. Whereas the Join Key is required to initially connect with a Gateway and thereby join the Gateway's mesh radio network, the Network Key is required to stay connected with that Gateway over time. The Network Key is updated to the field device after successful commissioning, and may be periodically randomized to ensure even better security.

It should be noted that the Join Key is a very long hexadecimal number, and is shown as *four different numerical fields* rather than as one long number (similar to the way credit card numbers are typically shown as four groups of four digits each, to make it more readable to humans). Be sure to note the Join Key as it appears on the web page of the Gateway (in four fields), and then enter those four number groups into the *Wireless*HART device in that same order.

You will also need to assign a *HART long tag* to uniquely identify your field device on the network. This is the "tagname" used to identify the device on the *Wireless*HART network. Note that the "short" HART tag is not referenced by the Gateway, and so you must be sure to set the "long" HART tag instead. You must choose an ISA-standard tag for your instrument (e.g. `PT-25` for a pressure transmitter in loop #25). This tag will not only identify your field device on the *Wireless*HART network, but also form the first portion of each variable name within that device.

Another important parameter to set is the *Update Rate*, which tells the device how often it should transmit data to the Gateway. It is recommended you set this rate to the quickest value (i.e. shortest time) during commissioning because fast updates make troubleshooting easier. The update rate may be adjusted at any time after commissioning through the Gateway, and does not require the use of a hand-held HART communicator.

After setting the instrument's HART long tag, Update Rate, Network ID, and Join Key parameters, the instrument is ready to be commissioned. It is recommended that you bring the instrument to its field location and then power it up (i.e. plug the battery into the instrument) while the instrument has a clear radio pathway to the Gateway antenna. Powering up the *Wireless*HART instrument enables it for acceptance into the Gateway's radio network. When setting up multiple field devices, the device with the best pathway to the Gateway antenna should be powered up first, so it may be commissioned first and thereby act as a repeater for commissioning the other field devices. If you have a HART communicator connected to the field device during commissioning, you may monitor certain parameters such as *Join Status*, *Radio State*, *Join Mode*, *Number of Advertisements Heard*, and *Number of Join Attempts* to check its progress. You may also issue a "Force Join" command through the HART communicator to any field device struggling to join the network.

To optimize the radio pathway between the field device and the Gateway antenna, you should mount it at least several feet above ground level, away from any metal objects (especially those parallel to the antenna), and be sure to maintain the device's antenna parallel to the Gateway's antenna (vertical up or vertical down) for optimum RF signal coupling.

Common mistakes:

- Neglecting to consult the manufacturer's documentation for field instruments (e.g. how to commission them).
- Failing to set the HART long tag in the device prior to commissioning. The result will be that the device comes up on the network (displayed on the Gateway web page) as a cryptic MAC address rather than an intelligible instrument tag.
- Using invalid characters (such as periods) in the HART long tag. HART long tags should be limited to letters, numbers, and dash symbols (e.g. `TT-36` for Temperature Transmitter number 36).
- Trying to commission the field device while not in clear sight of the Gateway antenna.
- Mounting the device in an area where good communication is hindered (e.g. blocked by metal objects, located too close to ground, device antenna not parallel with Gateway antenna).
- Failing to set the Update Rate to a quick value, thereby impeding diagnosis of problems.
- Not waiting long enough (several minutes) for the device to commission, once powered up in the field.
- Not enabling "Active Advertising" on the Gateway for fast commissioning of devices.
- Trying to commission a collection of field-mounted transmitters in the wrong order (i.e. beginning with the transmitter farthest from the Gateway, rather than beginning with the nearest transmitter as you should to build the strongest "mesh" network).

Commissioning a new WirelessHART instrument should take no more than an hour for a team doing it for the very first time, assuming they follow the instructions shown in the manual.

Lab Exercise – exchanging data using Modbus

The *Wireless*HART Gateway device provides a user-defined "map" between field instrument data points and standard Modbus registers, configured within the Gateway device using a web browser pointed to the Gateway's IP address. Since every *Wireless*HART instrument is a multi-variable device, each team member will choose their own variable within that instrument to read or write via Modbus.

First, you will need to identify the variable within the field instrument that you wish to monitor or control. A list of those variables may be browsed using the maintenance- or administrative-level access functions within the Gateway. Once the variable's name is identified, you may enter that variable name and its associated Modbus address in the Modbus mapping table. *Wireless*HART variable names typically follow the convention of the device HART tag (user-defined) followed by a "period" symbol and then additional characters specifying the variable within that device (e.g. `TT-37.PV` represents the "primary variable" within temperature transmitter 37; `FT-4.SV` represents the "secondary variable" within flow transmitter 4). Since the Gateway uses the period symbol as a delimiter between the device tagname and the variable name within the device, the device tagname cannot contain any periods.

Next, you will need to choose a Modbus register to "map" to the chosen *Wireless*HART device variable. Modbus register addresses are decimal values which you may freely choose within these ranges:

Address range (decimal)	Purpose
00001 to 09999	Discrete output bits ("coils"), *read/write*
10001 to 19999	Discrete input bits ("contacts"), *read-only*
30001 to 39999	16-bit analog input registers, *read-only*
40001 to 49999	16-bit "holding" registers, *read/write*

When reading or writing your variable from a Modbus master device connected to the Gateway, that device will reference the Modbus register address you chose and entered into the Gateway's mapping table. For example, if you assigned your temperature transmitter's primary variable (`TT-37.PV`) to Modbus register 30005, the Modbus master device tasked with reading that variable will read Modbus register 30005 within the Gateway to find that data.

Finally, you will need to program a Modbus master device to read or write data over a wired network to the Modbus register mapped to the *Wireless*HART variable in the Gateway's mapping table. For this you may choose to program one of the networked PLCs in the lab, or one of the networked HMI (Human-Machine Interface) "touch panels" in the lab. Both types of Modbus master devices require specialized software to program, which has been pre-loaded into various computer workstations in the lab.

For students seeking additional challenge, I recommend programming a general-purpose computer to read or write Modbus data rather than programming a PLC or an HMI to do the same. PLCs and HMIs are made to be fairly easily programmed, but writing code to instruct a general-purpose computer is a more challenging task. If you have coding experience, you may wish to program a computer in C or C++ using the free `libmodbus` library of Modbus access functions. A recommended computing platform to do this is the *Raspberry Pi* single-board computer running the Linux operating system, or a regular personal computer running the same OS. Your *Lessons In Industrial Instrumentation* textbook provides sample code (in the C language) showing how multiple 16-bit integer numbers may be read from a Modbus device using libmodbus function calls. Both lab exercises (temperature and flow measurement) for the INST241 course include information on how to use the Raspberry Pi computing platform (including many common command-line instructions useful for manipulating files).

Note: when writing code to read or write Modbus registers, you will have to contend with an idiosyncrasy of Modbus called *relative addressing*. Your *Lessons In Industrial Instrumentation* textbook also explains this in detail.

Some important details about Modbus communication and variable mapping are listed here:

- Every Modbus slave device is programmed with a Modbus address (not to be confused with the *register* address for device variables). This is how the Modbus master is able to distinguish one Modbus device from another on a broadcast network. The *Wireless*HART Smart Wireless Gateway is a Modbus slave, and as such is assigned a Modbus address to identify it to any Modbus master devices. You will need to reference this Modbus slave address when programming your Modbus master device to read or write data.

- The Emerson Smart Wireless Gateway provides two different Modbus communication paths: one through Ethernet (Modbus/TCP protocol) and another through RS-485 (Modbus RTU). You may use either path for your lab exercise. All networked PLCs and HMI panels in our lab use Ethernet communications (i.e. Modbus/TCP). A single PLC or HMI with an RS-485 serial port may be wired to the Gateway for Modbus RTU communication.

- Modbus registers suitable for process variables are 16 bits in length. If you are accessing a 32-bit variable inside a *Wireless*HART device, *two* consecutive Modbus registers will be occupied. The Modbus mapping table will only show the first of the two registers, however. For example, if `TT-37.PV` is a 32-bit floating-point value mapped to Modbus register 30005, the register pair 30005 and 30006 will be used. This means the next free Modbus register will be 30007. This, obviously, becomes very important when multiple people are configuring the Gateway to map their individual variables. It is also important when configuring a Modbus master device to read from or write to these registers, because that device will have to deal with two Modbus registers at a time.

- The Smart Wireless Gateway provides multiple options for formatting field device data into 16-bit Modbus registers. The field device's Primary, Secondary, Tertiary, and Quaternary Variables (`.PV`, `.SV`, `.TV`, and `.QV`, respectively) are all 32-bit floating-point numbers in their native form, but the Gateway provides the option of representing those values as 32-bit integers. This option is found on the Gateway's "Modbus Communication" page as a one-of-three choice, that choice being global for the entire Gateway:
  - → **Float** Floating-point numbers maintained in their original 32-bit floating-point form.
  - → **Round** Floating-point numbers rounded to the nearest 32-bit integer value.
  - → **Scale** Floating-point numbers scaled as 32-bit integers using the formula $y = Ax - (B - 32768)$. The values of A (gain) and B (offset) may be set globally on the Modbus Communication page (not recommended), or individually for each variable on the Modbus Mapping page.

- Primary, Secondary, Tertiary, and Quaternary Variables (`.PV`, `.SV`, `.TV`, and `.QV`, respectively) are mapped to real-world variables within the HART instrument, using the HART communicator. *Wireless*HART exploits the multi-variable nature of the HART communication standard, allowing a wide range of variables to be communicated between the Gateway and the *Wireless*HART field device. You are not limited, however, to these four variables (`.PV` through `.QV`) in a HART device. If you take the time to explore the commissioned device through the Gateway's web page, you will see a great multitude of variables accessible within it, each variable specified by name and data type (e.g. floating-point, integer, boolean, etc.). To map any of these HART variables to a Modbus register, you will need to prepend the HART tag to that variable name so as to distinguish it from the same variable within another HART device on the same wireless network.

Common mistakes:

- Crowding Modbus registers, by not allowing enough space between them. If the variable to be read is floating-point (32-bit) or a long integer (32 bit), it will require *two* consecutive Modbus registers, so the next Modbus register needs to be numbered at least 2 greater than the previous register.
- Incorrect byte-swapping at the Modbus master device polling the Gateway. The Modbus standard does not specify exactly how the 32 bits of a floating-point number are to be divided amongst two 16-bit Modbus registers, and so some manufacturers do weird byte-ordering (e.g. CDAB instead of ABCD) of their floating-point variables. Check the byte-swapping options on your master device to make sure it matches that of the Gateway, or else all floating-point data will appear scrambled.

Notes on troubleshooting feedback control loops

Recall that every feedback control loop consists of four basic elements: an element that *senses* the process variable (e.g. primary sensing element, transmitter), an element that *decides* what how to regulate this process variable (e.g. a PID controller), an element that *influences* the process variable (e.g. a control valve, motor drive, or some other final control device), and finally the process itself which *reacts* to the final control device's actions:
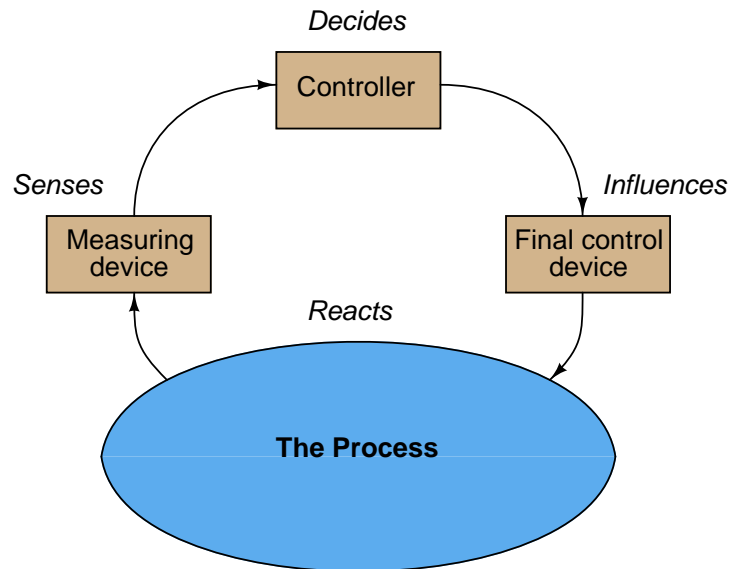
You can check each element of your feedback control loop by comparing its input with its output to see if each element is doing what it should:

(1) **Decision-making:** Carefully examine the controller faceplate, looking at the values of PV, SP, and Output. Is the controller taking appropriate action to force PV equal to SP? In other words, is the Output signal at a value you would expect if the controller were functioning properly to regulate the process variable at setpoint? If so, then the controller's action and tuning are most likely not at fault. If not, then the problem definitely lies with the controller.

(2) **Sensing:** Compare the controller's displayed value for PV with the actual process variable value as indicated by local gauges, by feel, or by any other means of detection. If there is good correspondence between the controller's PV display and the real process variable, then there probably isn't anything wrong with the measurement portion of the control loop (e.g. transmitter, impulse lines, PV signal wiring, analog input of controller, etc.). If the displayed PV disagrees with the actual process variable value, then something is definitely wrong here.

(3) **Influencing:** Compare the controller's displayed value for Output with the actual status of the final control element. If there is good correspondence between the controller's Output display and the FCE's status, then there probably isn't anything wrong with the output portion of the control loop (e.g. FCE, output signal wiring, analog output of controller, etc.). If the controller Output value differs from the FCE's state, then something is definitely wrong here.

(3) **Reacting:** Compare the process variable value with the final control element's state. Is the process doing what you would expect it to? If so, the problem is most likely not within the process (e.g. manual valves, relief valves, pumps, compressors, motors, and other process equipment). If, however, the process is not reacting the way you would expect it to given the final control element's state, then something is definitely awry with the process itself.

Lab Exercise – decommissioning and clean-up

The final step of this lab exercise is to decommission only the *Wireless*HART portions of your team's system and re-stock those components back to their proper storage locations, the purpose of which being to prepare the system for the next lab exercise. Leave all the analog (4-20 mA) instruments in place, so that the system operates as it did before this lab exercise. 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

Finally, you shall return all *Wireless*HART system components to the configurations at the start of this lab exercise. This includes transmitter ranges, Gateway Modbus mapping, etc.

file i03627

Answers

Answer 1

Answer 2

Partial answer:

$$P_{tx} = \underline{13.98} \text{ dBW}$$

$$P_{rx} = \underline{-57.45} \text{ dBW}$$

$$P_{loss} = \underline{-71.43} \text{ dB}$$

Regarding the meaning of terms, here is a starting point: the unit of the Bel, and therefore also the decibel, is simply a comparison of two power values. The distinction between dBm, dBW, and dB is thus a question of *which two powers are being compared?*

Answer 3

Answer 4

The minimum transmitter power required in this application is -31.92 dBm which is equal to 0.643 microwatts.

Answer 5

Answer 6

Answer 7

- Power ratio gain of $20 \approx$ **+13 dB**
- Power ratio reduction of $\frac{1}{40} \approx$ **$-$16 dB**
- Power ratio gain of $1600 \approx$ **+32 dB**
- Power ratio reduction of $\frac{1}{800} \approx$ **$-$29 dB**

Answer 8

- $+26$ dB = power ratio gain of **400**
- -33 dB = power ratio gain of **0.0005**
- $+50$ dB = power ratio gain of **100,000**
- -29 dB = power ratio gain of **0.00125**

Answer 9

$$P_{tx} = \underline{55.15} \text{ dBm} = \underline{25.15} \text{ dBW}$$

$$P_{rx} = \underline{-20.22} \text{ dBm} = \underline{-50.22} \text{ dBW}$$

$$P_{loss} = \underline{-75.37} \text{ dB}$$

Answer 10

$P_{in} = 230$ mW $= 23.617$ dBm

$P_{out} = 89$ mW $= 19.494$ dBm

Cable loss $= -4.123$ dB

Cable loss $= -0.02426$ dB per foot

A passive cable can only dissipate, and never generate, electrical energy. Therefore, P_{out} must always be *less than* P_{in}, and the decibel figure calculated from the ratio of $\frac{P_{out}}{P_{in}}$ will always be a negative quantity. A positive dB figure would mean that the cable somehow managed to output more power than it received.

Answer 11

$P_{in} = 59.19$ dBW

$P_{out} = 58.98$ dBW

Waveguide loss $= -0.2145$ dB

Waveguide loss $= -0.00536$ dB per foot

A perfect waveguide, if there ever could be such a device, would lose no power whatsoever, but instead would convey 100.0% of the power to its destination without any dissipation at all. This would be a $\frac{P_{out}}{P_{in}}$ ratio of 1:1, which would be a dB loss figure of zero per foot.

Answer 12

According to the formula for calculating *path loss* of an RF signal, the amount of attenuation over distance *increases* with increasing signal frequency. This is because a greater frequency (greater f) results in a shorter wavelength (smaller λ), which makes L_p a more negative value (greater loss):

Path loss formula:

$$L_p = -20 \log \left(\frac{4\pi D}{\lambda} \right)$$

Where,
   L_p = Path loss, a negative dB value
   D = Distance between transmitting and receiving antennas
   λ = Wavelength of transmitted RF field, in same physical unit as D

The formula for calculating wavelength is shown here. For radio waves, the propagation velocity is the speed of light (2.99792×10^8 meters per second, commonly represented as c), and the frequency is expressed in Hertz:

$$\lambda = \frac{c}{f}$$

Conversely, the Fresnel zone of a radio wave "tightens" to occupy a smaller space as signal frequency increases. This is due to wavelength (λ) being in the numerator of the fraction used to calculate Fresnel zone radius, with that wavelength parameter decreasing in magnitude as signal frequency increases:

$$r = \sqrt{\frac{n\lambda d_1 d_2}{D}}$$

Answer 13

   $P_{rx} = -4.8438$ dBm $= 327.8$ microwatts

The receiver cable is irrelevant because we were only asked to calculate the amount of power intercepted by the receiving antenna, not the amount of power that antenna actually delivers to the receiver unit.

An antenna may be rated at a positive dB value only in comparison to another antenna with a more uniform radiation pattern. A positive dB value only means more power output (in one direction) compared to another style of antenna, not the creation of energy from nothing.

Answer 14

There is absolutely no need for a termination resistor at the end of a transmission line terminating in an antenna.

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

Answer 23

Answer 24

Answer 25

Answer 26

Partial answer:

Fault	Possible	Impossible
Damaged antenna on MTU		
Damaged antenna on RTU #4		
PLC halted (not running) RTU #4	$\checkmark$	
Radio transceiver powered down on RTU #4		
"TD" conductor broken inside RS-232 cable on RTU #4		
"RD" conductor broken inside RS-232 cable on RTU #4	$\checkmark$	
PLC baud rate set incorrectly on RTU #4		
PLC baud rate set incorrectly on MTU		
Modbus mode (RTU/ASCII) set incorrectly on RTU #4	$\checkmark$	
Modbus mode (RTU/ASCII) set incorrectly on MTU		
Fresnel zone interference between MTU and RTU #4		$\checkmark$

Answer 27

$A_V = 1 = 0$ dB

$$A_V = \frac{R_1}{R_2} \qquad \text{(expressed as a ratio, not dB)}$$

87

Answer 28

V_{out} = -11.054 V

V_{Ra} = 8.704 V

10 kΩ

I_{Ra} = I_{Rb} = 870.4 µA

V_{in} = -2.35 V

2.7 kΩ

V_{Rb} = 2.35 V
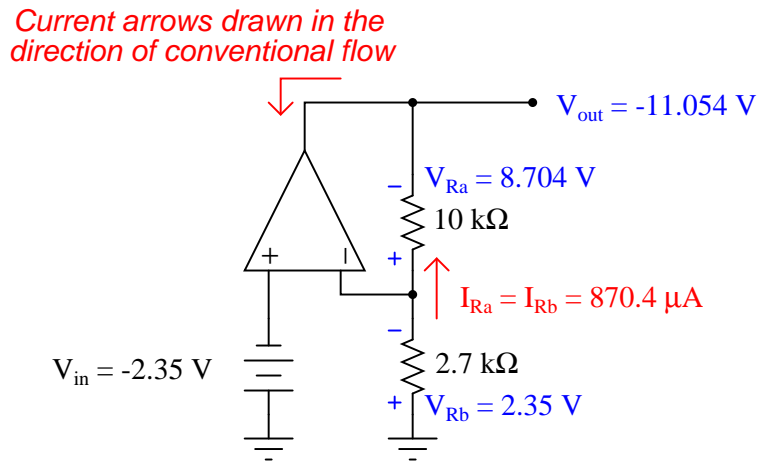
$A_V = 4.704 = 13.449$ dB

Follow-up question: how much input impedance does the -2.35 volt source "see" as it drives this amplifier circuit?

Answer 29

Yagi antennas are highly directional, giving them high gain. Used in conjunction with a vertical whip antenna at the MTU, the elements of the RTU Yagi antennas should likewise be oriented vertically.

Yagi antennas are not good for mesh-networking systems such as *Wireless*HART because they do not facilitate communication with neighboring devices out of the line-of-site path with the gateway. Omnidirectional antennas are best here, ideally a 1/2 wave whip or dipole for maximum gain.

Answer 30

Answer 31

Answer 32

Answer 33

Answer 34

Answer 35

Answer 36

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

$P_{antenna} = \underline{\textbf{0.644}}$ watts

$P_{antenna} = \underline{\textbf{28.09}}$ dBm

Answer 42

Partial answer:

$P_{xmtr} = \underline{\textbf{0.6902}}$ watts

Answer 43

Partial answer:

$P_{xmtr} = \underline{\textbf{39.294}}$ dBm

Answer 44

The ratio of 30 milliwatts to 120 kilowatts may be expressed in fractional form and then reduced into a product of halves and tenths:

$$\frac{30 \text{ mW}}{120 \text{ kW}} = \frac{0.030}{120000} = \frac{3}{12000000} = \left(\frac{3}{12} \times \frac{1}{1000000} \right) = \left(\frac{1}{4} \times \frac{1}{1000000} \right)$$

$$\frac{30 \text{ mW}}{120 \text{ kW}} = \left(\frac{1}{4} \times \frac{1}{1000000} \right) = \left(\frac{1}{2} \times \frac{1}{2} \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} \right)$$

$$\frac{30 \text{ mW}}{120 \text{ kW}} \approx (-3 \text{ dB} - 3 \text{ dB} - 10 \text{ dB} - 10 \text{ dB} - 10 \text{ dB} - 10 \text{ dB} - 10 \text{ dB} - 10 \text{ dB})$$

$$L_{path} = \frac{30 \text{ mW}}{120 \text{ kW}} \approx -\textbf{66 dB}$$

Answer 45

P_{tx} (minimum) $= -4.173$ dBm $= 0.383$ mW

The FreeWave I2-IOS transceiver has a minimum output power of 5 milliwatts, giving this system a healthy margin ("budget") on which to operate.

Answer 46

The Fresnel zone is 1.38 meters (4.527 feet) wide at its "fattest" point between the two *Wireless*HART instruments.

Answer 47

If you calculated a minimum antenna height of approximately 26 feet high, you forgot to perform one very important Fresnel zone radius calculation! The minimum height for both antennas is actually in excess of 31 feet!

Answer 48

Partial answer:

Fault	Possible	Impossible
Damaged antenna on MTU		
Damaged antenna on RTU #4		
PLC halted (not running) on MTU		
Radio transceiver powered down on RTU #4		√
"TD" conductor broken inside RS-232 cable on MTU		
"RD" conductor broken inside RS-232 cable on MTU		
PLC baud rate set incorrectly on RTU #4		√
PLC baud rate set incorrectly on MTU		
Modbus mode (RTU/ASCII) set incorrectly on RTU #4		√
Modbus mode (RTU/ASCII) set incorrectly on MTU	√	
Fresnel zone interference between MTU and RTU #4		

Answer 49

The 200 foot cable with a loss of -0.03 dB per foot will exhibit a total loss of -6 dB along its whole length. We know that every -3 dB loss is approximately equal to a halving of power, and so -6 dB loss is $\frac{1}{2} \times \frac{1}{2} = \frac{1}{4}$. Therefore, only one-quarter of the transmitter's power makes it to the far end of the cable where the antenna attaches. One-quarter of 80 watts is **20 watts**, which is our first answer.

In order to convert 20 watts into dBm, we must understand what "dBm" actually means: the number of dB a certain power value is compared to 1 milliwatt. In this case, 20 watts is 20,000 times greater than 1 milliwatt, and therefore the dBm value must be the equivalent of 20,000 (in dB). Since we know every $+10$ dB is a 10-fold multiplication, and every $+3$ dB is a 2-fold multiplication, all we need to do is express 20,000 as a product of 10's and 2's which will then tell us the dB value as a sum of 10's and 3's:

$$20000 = 2 \times 10 \times 10 \times 10 \times 10$$

$$20000 = 3 \text{ dB} + 10 \text{ dB} + 10 \text{ dB} + 10 \text{ dB} + 10 \text{ dB}$$

$$20000 = 43 \text{ dB}$$

$$20000 \times 1 \text{ mW} = \textbf{43 dBm}$$

Answer 50

In order for any antenna to have a negative gain, it must be *more* omnidirectional (less directional) than the reference antenna it's being compared to. An isotropic antenna is perfectly omnidirectional, and so no antenna could ever have a negative dBi value (i.e. be less directional than an isotropic antenna). However, since an isotropic antenna is less directional than a dipole, an isotropic antenna (if it existed) would have a negative *dBd* value.

Of course, poor performance may be realized by other means: damage, mis-operation (e.g. operating at the wrong frequency), etc.

Answer 51

Removing the arrestor from the system essentially added a +0.4 dB gain compared to the performance of the old system (with the arrestor in place). This much gain expressed as a ratio is:

$$10^{\frac{0.4}{10}} = 1.096$$

Therefore, the new receiver signal power will be 1.096 times stronger than the old receiver signal power:

$$1.096 \times 0.8 \, \mu W = 0.8772 \, \mu W$$

$P_{rx} = 0.8772$ microwatts

Answer 52

Replacing the low-gain antenna (5.8 dBi) with a high-gain antenna (11.4 dBi) adds 5.6 more decibels of gain to the overall system. This equates to a power ratio of:

$$10^{\frac{5.6}{10}} = 3.631$$

Therefore, the new receiver signal power will be 3.631 times stronger than the old receiver signal power:

$$3.631 \times 0.17 \, \mu W = 0.617 \, \mu W$$

$P_{rx} = 0.617$ microwatts

Answer 53

Adding lightning arrestors to the system makes the signal path suffer an addition power loss of -1.1 dB. This equates to a power ratio of:

$$10^{\frac{-1.1}{10}} = 0.7762$$

Therefore, the new transmitter output power will need to be $\frac{1}{0.7762}$ times stronger than the old transmitter output power:

$$\frac{1}{0.7762} \times 3.2 \text{ mW} = 4.122 \text{ mW}$$

$P_{tx} = 4.122$ milliwatts

Answer 54

Dividing RF power received by RF power transmitted gives us the total path loss as a ratio:

$$L_{path} = \frac{1.4 \, \mu\text{W}}{45 \text{ W}} = 3.111 \times 10^{-8}$$

Taking the common logarithm of this figure and multiplying by ten yields the same path loss as a decibel figure:

$$L_{path} = 10 \log(3.111 \times 10^{-8}) = -75.07 \text{ dB}$$

Now, we know path loss in decibels is related to path distance through empty space by the following formula:

$$L_{path} = -20 \log \left(\frac{4\pi D}{\lambda} \right)$$

All we need to do now is solve for the wavelength of the RF signal (λ) and then manipulate the path loss formula to solve for distance (D):

$$v = \lambda f$$

$$\lambda = \frac{v}{f} = \frac{2.9979 \times 10^8 \text{ m/s}}{700000 \text{ Hz}} = 428.27 \text{ m}$$

$$L_{path} = -20 \log \left(\frac{4\pi D}{\lambda} \right)$$

$$\frac{L_{path}}{-20} = \log \left(\frac{4\pi D}{\lambda} \right)$$

$$10^{\frac{L_{path}}{-20}} = \frac{4\pi D}{\lambda}$$

$$\lambda 10^{\frac{L_{path}}{-20}} = 4\pi D$$

$$D = \frac{\lambda 10^{\frac{L_{path}}{-20}}}{4\pi}$$

$$D = \frac{(428.27) \left(10^{\frac{-75.07}{-20}} \right)}{4\pi} = 193,219.7 \text{ m} = 193.22 \text{ km}$$

Note: the wavelength of this RF signal (428.27 meters) is typical of AM radio transmissions, which is why the transmitting antennas for AM radio stations must be so tall! Antenna size is a direct function of signal wavelength, in order that the signal will resonate with the physical length of an antenna the same way that acoustic (sound) waves resonate inside the length of a wind instrument such as a saxophone or trumpet.

Answer 55

Power line carrier ("PLC") is the form most closely resembling HART communication, as AC signals are carried simultaneously along the same conductors as the power. This early technology makes a lot of sense, because the path of communication is the power lines themselves. If any natural disaster is severe enough to knock power lines down to the ground, then communication for that power route is a moot point.

Microwave radio communication and fiber optic lines both enjoy tremendous bandwidth for signals (much higher than power line carrier!). Microwave antennas will work well provided their high-gain dish antennas are precisely aimed at each other. Earthquakes, tornados, and other forces of nature might knock dish antennas out of alignment, but otherwise this is an extremely reliable and secure mode of communication. Fiber optic lines are typically buried underground, where they are immune to things like tornados, but might be severed in extreme earthquakes. Like microwave communication, fiber optic is extremely secure as well.

Answer 56

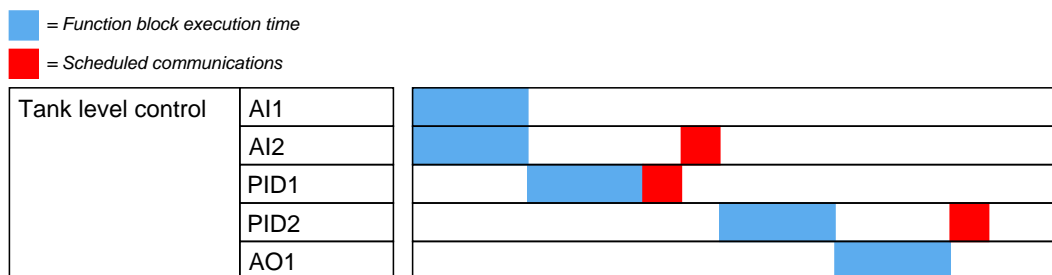Answer 57

Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Probably the trickiest portion of this problem is how to calculate the volume in gallons, based on nothing but the *height* of water as measured by the level transmitter. Suffice to say, this is fundamentally a geometry problem, followed by a units-conversion problem!

Answer 63

Answer 64

Partial answer:

You must perform *continuity* tests using the multimeter set to its "resistance" (ohms) measuring function. Low resistance indicates continuity, while high resistance indicates lack of continuity.

The *real* question in each case is which terminals we must measure between with the multimeter in order to test for each possible cable fault! This I leave to you to figure out.

Answer 65

Partial answer:

Fault	Possible	Impossible
Trunk cable 1 failed open		
FF transmitter failed open		$\checkmark$
FF positioner failed open	$\checkmark$	
Transmitter spur cable failed open		
Positioner spur cable failed open		
Trunk cable 1 failed shorted		
FF transmitter failed shorted		$\checkmark$
Transmitter spur cable failed shorted		
Positioner spur cable failed shorted		$\checkmark$
Terminator failed open		

Answer 66

$P_{antenna} = 293.98$ W at a transmitted power of 300 W.

$P_{antenna} = 783.95$ W at a transmitted power of 800 W.

$P_{antenna} = 2.9398$ kW at a transmitted power of 3 kW.

Answer 67

P_{tx} (minimum) $= -11.696$ dBm

With the transmitting power set to 5 milliwatts (6.99 dBm), the RF link budget margin – the difference between this actual transmitting power and the bare-minimum required to get the job done – is 18.69 dB.

Answer 68

The problem is clearly *not* with the controller's action, because according to the faceplate displays it is trying to do the right thing (i.e. shut the control valve to build up differential pressure).

Answer 69

L_Type = Indirect

XD_Scale = 0 to 87.5 mV

OUT_Scale = 0 to 2.5 amps

Answer 70

L_Type = Indirect

XD_Scale = 0 to 2000 PSI

OUT_Scale = 0 to 14,137.2 pounds

Answer 71

`XD_Scale` = 0 to 99.47 inches of water

`OUT_Scale` = 0 to 13,830.4 pounds

`L_Type` = Indirect

Hint: with a density 86.5% that of water, a full tank (115 inches) will generate 86.5% as much pressure as if it were filled with water. This is why a height of 115 inches only generates 99.47 inches of water pressure.

Answer 72

`XD_Scale` = 0 to 1989.4 PSI

`OUT_Scale` = 0 to 25,000 pounds

`L_Type` = Indirect

Answer 73

- TIC-5 = **direct** action
- TIC-6 = **direct** action
- TIC-7 = **direct** action
- TIC-9 = **reverse** action
- PIC-13 = **reverse** action

Answer 74

The reason that the technician's proposed test would have been a waste of time is because the control valve is already doing what the controller is telling it to: go to the 0% (closed) position. In other words, the valve stem position corresponds with the controller's output indication, suggesting there is no problem in that (output) portion of the control system.

The controller's "decision" to shut the valve makes no sense from the perspective of PV > SP. What the controller should be doing is opening the cold feed valve in order to reduce the temperature of the process. We do not know if the PV indication corresponds with the temperature gauge, but this is actually a moot point right now because we know for certain that the controller is not taking the correct action for what it "sees" in terms of PV and SP. Fault possibilities include:

- Controller left in manual mode (not automatic)
- Very poor controller tuning
- Incorrect controller action

A good "next step" would be to check to see if the controller is in automatic mode. If it is, then there is a problem with the controller's configuration or tuning.

Answer 75

The formula for calculating the radius of the Fresnel zone is:

$$r = \sqrt{\frac{n\lambda d_1 d_2}{D}}$$

Since we are interested in finding the radius of the Fresnel zone at its mid-point where $d_1 = d_2 = \frac{D}{2}$, we may make this substitution within the formula:

$$r = \sqrt{\frac{n\lambda \left(\frac{D}{2}\right)^2}{D}}$$

Simplifying:

$$r = \sqrt{\frac{n\lambda \frac{D^2}{4}}{D}}$$

$$r = \sqrt{\frac{n\lambda D^2}{4D}}$$

$$r = \sqrt{\frac{n\lambda D}{4}}$$

Solving for wavelength (λ) at the operating frequency of 900 MHz and then solving for the distance given a first Fresnel zone radius of 12 feet (3.6576 meters):

$$\lambda = \frac{v}{f} = \frac{2.9979 \times 10^8 \text{ m/s}}{900 \times 10^6 \text{ Hz}} = 0.3331 \text{ m}$$

$$r = \sqrt{\frac{\lambda D}{4}}$$

$$r^2 = \frac{\lambda D}{4}$$

$$4r^2 = \lambda D$$

$$D = \frac{4r^2}{\lambda} = \frac{(4)(3.6576 \text{ m})^2}{0.3331 \text{ m}} = 160.65 \text{ m}$$

$$\left(\frac{160.65 \text{ m}}{1}\right)\left(\frac{100 \text{ cm}}{1 \text{ m}}\right)\left(\frac{1 \text{ in}}{2.54 \text{ cm}}\right)\left(\frac{1 \text{ ft}}{12 \text{ in}}\right) = 527.06 \text{ ft}$$

This distance figure is a *maximum*, not a minimum. Exceeding 160.65 meters will result in the first Fresnel zone contacting the ground mid-way between the antennas.

Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

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

Students choosing the Emerson "THUM" *Wireless*HART adapter will encounter extra challenges. Here are some things to know about the THUM as a HART device:

- **HART addressing** – The THUM's HART address is 63, whereas the wired HART device it connects to is HART address 0. You may communicate with either device using a HART communicator connected to the same location in the circuit (across the loop resistance works well) simply by specifying the polling address in the communicator (63 = talk with THUM ; 0 = talk with wired HART device).

- **Appearance on the Gateway** – if the THUM wirelessly connects to the Gateway as a sole device (i.e. no wired HART device connected to the THUM), the THUM appears on the Gateway's device list under its own long HART tag name. If the THUM wirelessly connects to the Gateway while connected to a wired HART device, the THUM's HART tag name appears nowhere, replaced instead by the wired HART device's *Message* text field. I'm assuming the use of the "Message" field as a tag name stems from the fact that old HART devices didn't support a long HART tag name, and so the THUM exploits the long-form Message field as a place to write a long tag name.

- **Voltage drop** – the THUM is very thrifty on power, passing the 4-20 mA current signal to the wired HART device while only dropping a couple of volts to "scavenge" power off that signal! This may take students by surprise as they measure DC voltage in the wired circuit during troubleshooting.