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Lab

Temperature measurement loop: *Questions 91 and 92, completed objectives due by the end of day 5, section 2*

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Exam

*Day 5 of next section* – only a simple calculator may be used! **Complete mastery of these objectives due by the next exam date**

*Specific objectives for the “mastery” exam:*

- Electricity Review: Calculate voltages and currents in an ideal AC transformer circuit
  - Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components
  - Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables
  - 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 Wheatstone bridge circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
  - Motor/relay/3phase/PLC Review: Calculate either the full-load current or the horsepower of an electric motor (either single- or three-phase) given the line voltage and one of the other parameters
  - INST250 Review: Calculate  $C_v$  rating of control valve for liquid (non-cavitating) service
  - INST263 Review: Determine effect of a fault in a selector or override control system
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**Recommended daily schedule**

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Day 1

**Theory session topic:** Temperature measurement technologies

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

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Day 2

**Theory session topic:** Principles of heat and temperature

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

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Day 3

**Theory session topic:** RTDs and thermistors

Questions 41 through 60; answer questions 41-50 in preparation for discussion (remainder for practice)

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Day 4

**Theory session topic:** Thermocouples

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

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

## How To . . .

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

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

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

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

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

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

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

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

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

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

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

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

file howto

## General Values, Expectations, and Standards

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

**Learning** is the top priority in this program. Every circumstance, every incident, every day 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. If your efforts do not yield the expected results, only you can make it right.

**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** means exercising self-discipline and persistence in your studies, 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.

**Mastery** 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 nearest deadline.

**Communication** means clearly conveying your thoughts and paying attention to what others convey. Remember that no one can read your mind, and so it is incumbent upon you to communicate any and all important information.

**Teamwork** means working constructively with your classmates so as to maximize their learning as well as your own.

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

**Representation** means your actions are a reflection of this program and not just of 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 hire.

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

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

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

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

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

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

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

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

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

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

**Academic Progress:** your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers provided you have signed the FERPA release form. You are welcome to see these records at any time, and are encouraged to track your own academic progress using the grade spreadsheet template.

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

**Grounds for Failure:** a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, or if any of the following behaviors are demonstrated: false testimony (lying) to your instructor, cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, intoxication, or destruction of property. Such 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.

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## INST 241 Course Outcomes

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

- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]
- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]
- Sketch proper wire connections showing how to simulate an RTD or thermocouple input to a temperature transmitter using simple electronic components. [Ref: Program Learning Outcome #5]
- Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables. [Ref: Program Learning Outcome #7]
- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]
- Determine suitability of different flow-measuring technologies for a given process fluid type. [Ref: Program Learning Outcome #4]
- Calculate instrument input and output values given calibrated ranges. [Ref: Program Learning Outcome #7]
- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]
- Identify specific instrument calibration errors (zero, span, linearity, hysteresis) from data in an “As-Found” table. [Ref: Program Learning Outcome #7]
- Determine the possibility of suggested faults in simple circuits and Wheatstone bridge circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]
- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]
- Construct and commission a working temperature-measurement loop consisting of an electronic temperature transmitter, signal wiring, and SCADA RTU programmed in a text-based programming language. [Ref: Program Learning Outcome #5]
- Construct and commission a working flow-measurement loop consisting of an electronic flow transmitter, signal wiring, and flow computer programmed in a text-based programming language. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team’s systems. [Ref: Program Learning Outcome #8]
- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

- Calibrate an electronic RTD temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Calibrate an electronic thermocouple temperature transmitter to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Accurately simulate a thermocouple signal using a millivoltage source. [Ref: Program Learning Outcome #7]
- Accurately simulate an RTD signal using a potentiometer. [Ref: Program Learning Outcome #7]
- Calculate flow rate and pressure drop for a nonlinear flow element given maximum flow specifications. [Ref: Program Learning Outcome #7]
- Edit text-based programming code for a flow computer. [Ref: Program Learning Outcome #5]
- Utilize command-line instructions in a Unix operating system environment. [Ref: Program Learning Outcome #5]

## Sequence of second-year Instrumentation courses





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

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

### 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.

## Methods of instruction (continued)

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

### Sample rubric for pre-assessments

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

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

### Sample rubric for post-assessments

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

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

## Methods of instruction (continued)

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

## Methods of instruction (continued)

### Lab sessions

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

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

### Troubleshooting assessments must meet the following guidelines:

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

## Distance delivery methods

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

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

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

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

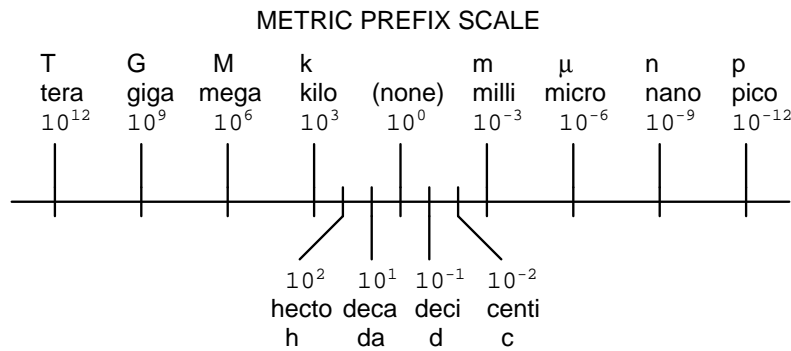
Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either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

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

## Metric prefixes and conversion constants

- **Metric prefixes**

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



- **Conversion formulae for temperature**

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

### Conversion equivalencies for distance

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

**Conversion equivalencies for volume**

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

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

**Conversion equivalencies for velocity**

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

**Conversion equivalencies for mass**

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

**Conversion equivalencies for force**

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

**Conversion equivalencies for area**

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

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

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

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

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

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

**Conversion equivalencies for energy or work**

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

**Conversion equivalencies for power**

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

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

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



### Physical constants

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

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

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

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

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

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

### Properties of Water

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

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

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

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

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

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

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

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

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

### Properties of Dry Air at sea level

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

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

file conversion\_constants

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

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

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

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

**How to manage your time:**

- Avoid procrastination. Work now and play later, or else you will create trouble for yourself. Schedule your work appropriate to the *place* you’re in as well: e.g. don’t waste lab time doing things that could be done anywhere else, when there is work to be done that requires the lab.
- Eliminate distractions. Kill your television and video games. Study in places where you can concentrate.
- Use your “in between” time productively. Don’t leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

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

file question0

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## Questions

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### Question 1

Read and outline the “Heat Versus Temperature”, “Temperature”, and “Heat” subsections of the “Elementary Thermodynamics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- Questions of your own and requests for clarification after reading the text
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- Images copied from the text (or sketched by you) to illustrate concepts
- Acknowledgement of previously learned concepts
- Descriptions of problem-solving strategies applied by the author

[file i03977](#)

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### Question 2

Skim the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain how a *bi-metal strip* works as a temperature-sensing device.

Explain how a *filled-bulb* system works to sense temperature.

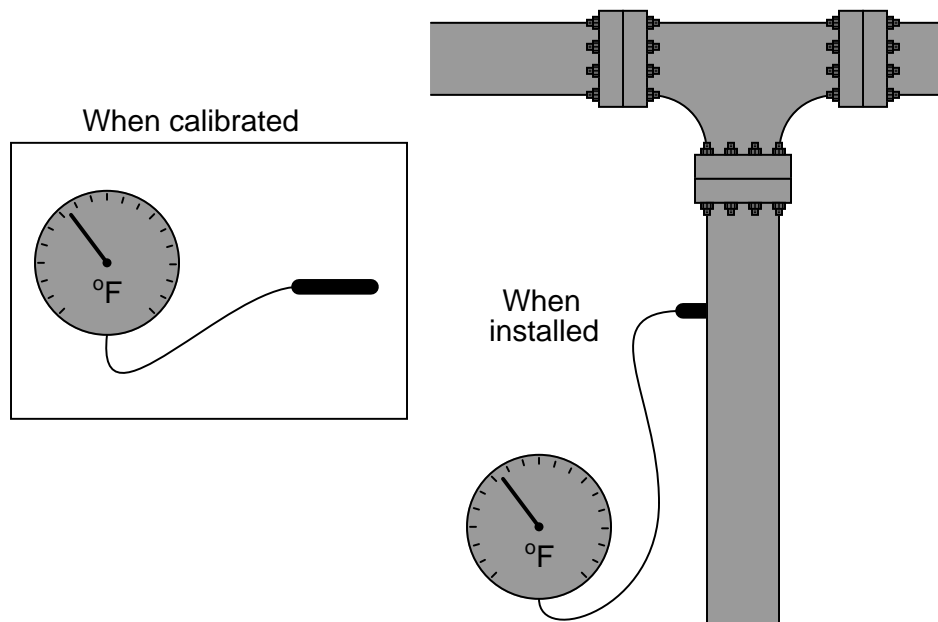
### **Suggestions for Socratic discussion**

- Identify different strategies for “skimming” a text, as opposed to reading that text closely. Why do you suppose the ability to quickly scan a text is important in this career?
- A common mechanic’s “trick” for slipping a metal bearing or ring over a metal shaft where the two parts would ordinarily make a very tight fit, is to either heat the ring and/or freeze the shaft prior to assembly. Explain why this “trick” works in light of what you know about coefficients of expansion.
- A ring made of copper tightly fitted over an iron shaft may be more easily removed from the shaft if both are first heated. However, a copper ring tightly fit over an aluminum shaft will not loosen up when both the ring and shaft are heated. Referencing the coefficients of thermal expansion for these metals, explain why. Then, explain how a copper ring fit tightly over an aluminum shaft *could* be loosened, if not by heating.

[file i03971](#)

### Question 3

A filled-system temperature indicator is calibrated in the instrument shop with the sensing bulb at the same level (height) as the bourdon tube indicating element. In the field, however, the sensing bulb is significantly elevated from the bourdon tube's height.



Will this cause a measurement error? If so, what type of error (zero or span shift) will it be?

#### Suggestions for Socratic discussion

- Will all classes of filled-bulb temperature gauges be affected the same way by an offset in height?
- Will a measurement error develop if the gauge is positioned *above* the sensing bulb?
- How is this phenomenon similar to issues faced inferring liquid level using hydrostatic pressure? Is there a term we use to describe it?

[file i00360](#)

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#### Question 4

Skim the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Both *thermistors* and *RTDs* are electrically-based temperature sensors. Identify the electrical property of each that changes with temperature.

Explain how you would use common electrical test equipment (such as that found in any electronics workshop or laboratory) to check whether or not a thermistor or an RTD is functional.

*Thermocouples* are also electrically-based temperature sensors, but different from RTDs. Identify the electrical property of a thermocouple that changes with temperature.

Explain how you would use common electrical test equipment (such as that found in any electronics workshop or laboratory) to check whether or not a thermocouple is functional.

#### **Suggestions for Socratic discussion**

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

[file i03973](#)

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#### Question 5

Skim the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook to specifically answer these questions:

Explain how the temperature of an object may be sensed *optically* (non-contact).

Identify some practical applications of non-contact temperature measurement, as well as some disadvantages (compared to direct-contact methods of temperature measurement).

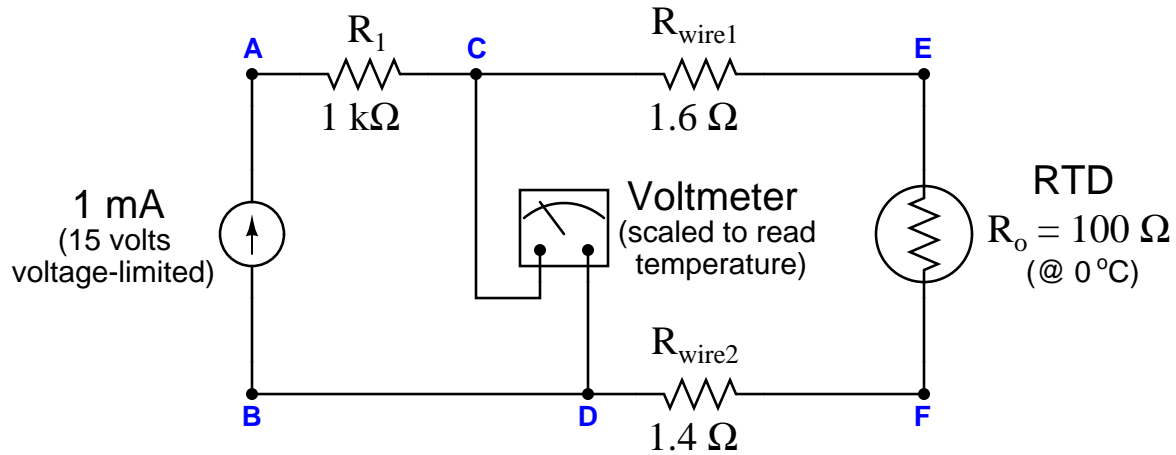
#### **Suggestions for Socratic discussion**

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

[file i03975](#)

### Question 6

Suppose this temperature-sensing circuit falsely registers a very low temperature (full downscale) when the RTD sensor is sensing room temperature (20 °C). A digital multimeter (DMM) connected between test points **A** and **C** registers 1 volt:



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

Fault	Possible	Impossible
$R_1$ failed open		
Voltmeter failed open		
Wire 1 failed open		
Wire 2 failed open		
RTD failed open		
$R_1$ failed shorted		
Voltmeter failed shorted		
RTD failed shorted		
Current source dead		

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

### Question 7

Program a computer spreadsheet (e.g. Microsoft Excel) application to automatically convert between the temperature units of Fahrenheit and Celcius:

	1	2	3	4	5
1	Enter deg F		Enter deg C		
2					
3					
4	Calculated deg C		Calculated deg F		
5					

The yellow and blue cell shading (color fill) shown in this example is entirely optional, but helps to distinguish number-entry fields from calculated-value fields.

I recommend placing the entered temperatures into cells R2C1 and R2C3, while the calculated values go into cells R5C1 and R5C3 (respectively). Then, test your spreadsheet program on the following conversions to see how well it works:

- $300^{\circ}\text{C} = ???^{\circ}\text{F}$
- $50^{\circ}\text{F} = ???^{\circ}\text{C}$
- $4^{\circ}\text{C} = ???^{\circ}\text{F}$
- $894^{\circ}\text{F} = ???^{\circ}\text{C}$
- $-250^{\circ}\text{F} = ???^{\circ}\text{C}$
- $-312^{\circ}\text{F} = ???^{\circ}\text{C}$
- $-150^{\circ}\text{C} = ???^{\circ}\text{F}$
- $-230^{\circ}\text{C} = ???^{\circ}\text{F}$
- $2600^{\circ}\text{F} = ???^{\circ}\text{C}$
- $3000^{\circ}\text{C} = ???^{\circ}\text{F}$

#### Suggestions for Socratic discussion

- How could you *test* your spreadsheet temperature conversion calculator for accuracy (to verify you haven't made any mistakes) once you've entered all your equations?
- Did you have to use parentheses in either formula (in cell R5C1 or in cell R5C3)? Why or why not?
- Explain how a spreadsheet is such a powerful mathematical tool for performing "tedious" calculations such as instrument input/output responses. Can you think of any other practical uses for a spreadsheet?

file i00339



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### Question 8

Read and outline the “Heat Transfer” subsection of the “Elementary Thermodynamics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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[file i03978](#)

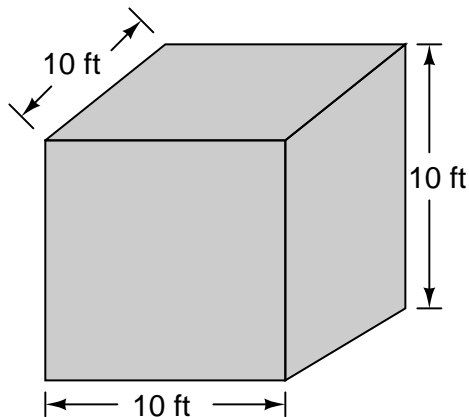
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**Question 9**

The  $R$ -value of an insulating material is defined as the quotient of length ( $l$ ) and thermal conductivity ( $k$ ), both from the heat conduction equation:

$$R = \frac{l}{k}$$
$$\frac{dQ}{dt} = \frac{kA\Delta T}{l}$$

Modify the heat conduction equation to incorporate  $R$  instead of  $k$ , and then use it to calculate the heat loss rate through the surfaces of the following box, insulated with R-30 insulation ( $R = 30 \text{ ft}^2 \cdot \text{h} \cdot \text{F}^\circ / \text{Btu}$ ), heated internally to a temperature of  $75^\circ \text{F}$ , and exposed to an outside (ambient) temperature of  $40^\circ \text{F}$ :



Challenge question: if the box is heated solely by an electric light bulb, how large would this light bulb have to be (i.e. its wattage rating) in order to maintain an internal box temperature of  $75^\circ \text{F}$  given an outside temperature of  $40^\circ \text{F}$ ?

**Suggestions for Socratic discussion**

- Describe the relationship between insulation R-value and energy efficiency for a heated building.
- Describe the relationship between insulation R-value and energy efficiency for a cooled (air-conditioned) building.
- Suppose this box were heated by an electric heating element with an on/off thermostat control to maintain air temperature at or near 75 degrees F. How would the *duty* cycle of this heater (it's on-time divided by the on+off time) vary with changes in outside temperature?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i00333](#)

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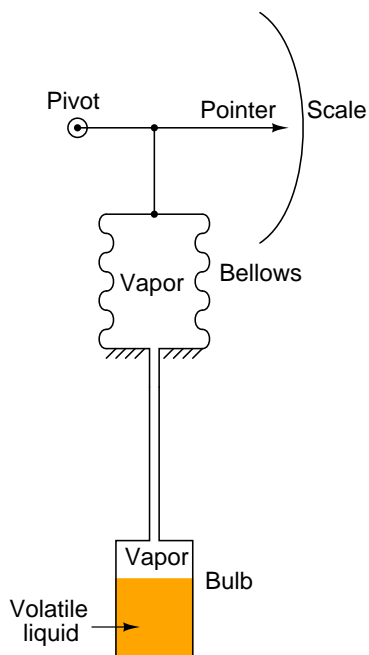
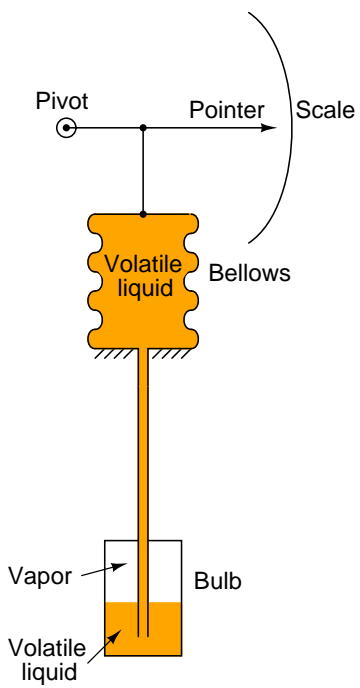
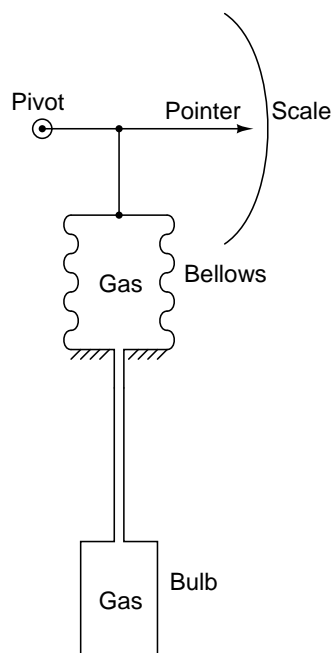
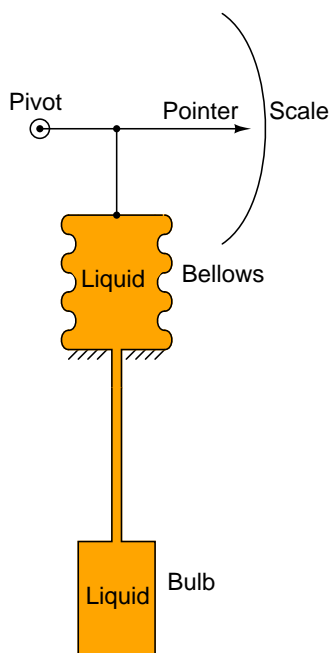
**Question 10**

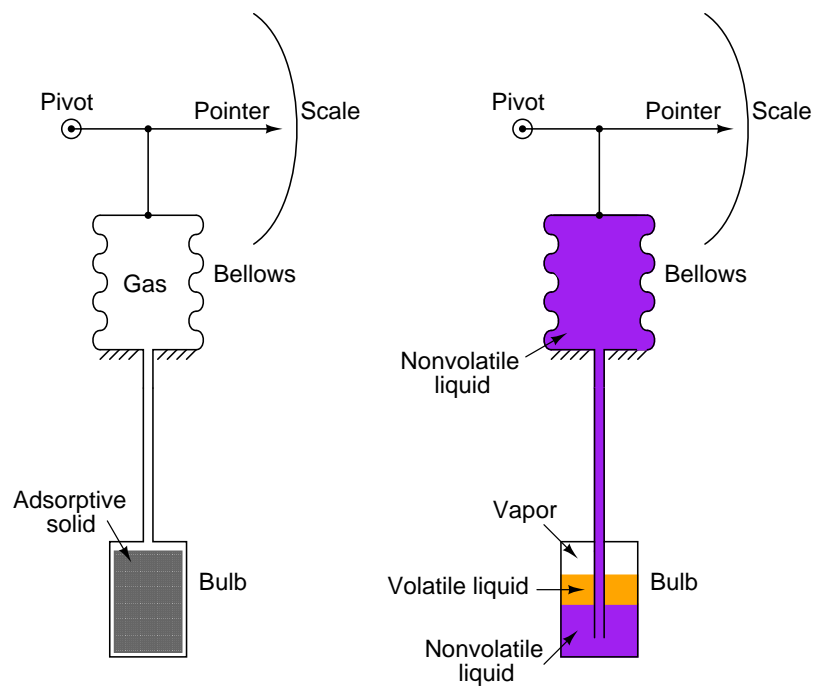
In a filled-system type of temperature instrument, why is it important to use a small-diameter (“capillary”) tube to connect the bulb to the bellows? Why not use regular, large-diameter tubing instead?

[file i00358](#)

Question 11

Identify the following filled-system types (be as specific as possible – each system shown here has a unique identifying name!).

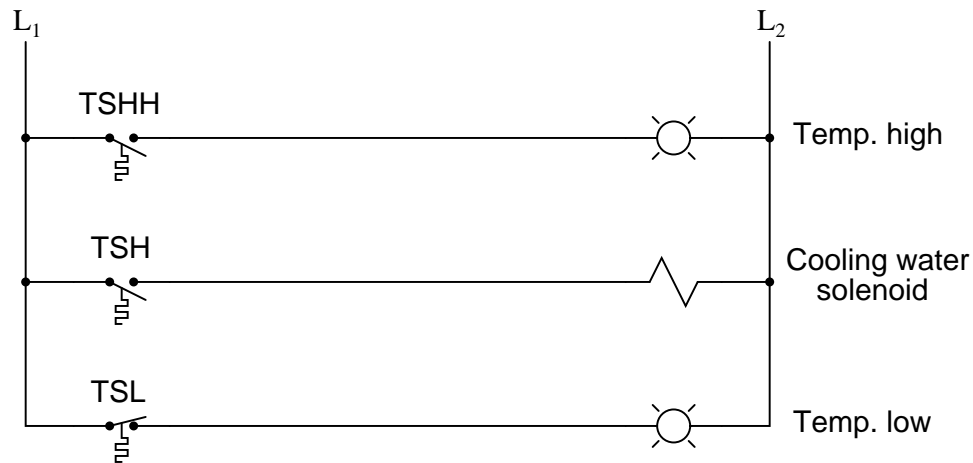




file i00359

### Question 12

Explain what the following “ladder-logic” circuit does, and identify the meaning of each symbol in the diagram:



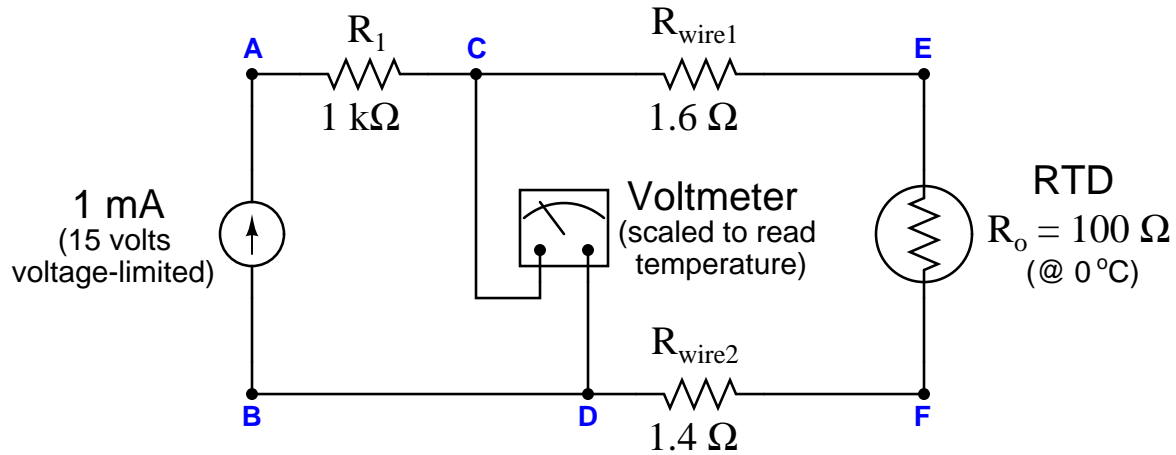
#### Suggestions for Socratic discussion

- Explain why the TSH uses a *normally-open* contact instead of a *normally-closed* contact.
- Explain why the TSL uses a *normally-closed* contact instead of a *normally-open* contact.
- Based on what we see in this diagram, determine whether the electric solenoid valve allows cooling water to flow when energized, or when de-energized.
- What do the designations “L1” and “L2” refer to in ladder-logic electrical diagrams?
- Suppose switch TSL has a trip setting of 105 °F (falling) and a deadband value of 2 °F. Explain how this switch will respond to a rising and falling temperature.
- Suppose we wished to have switch TSHH activate *two* different alarm lights instead of just one. Modify the circuit diagram accordingly.

[file i00364](#)

### Question 13

Suppose this temperature-sensing circuit falsely registers a very high temperature (full upscale) when the RTD sensor is sensing room temperature (20 °C). A digital multimeter (DMM) connected between test points **C** and **D** registers 14.99 volts:



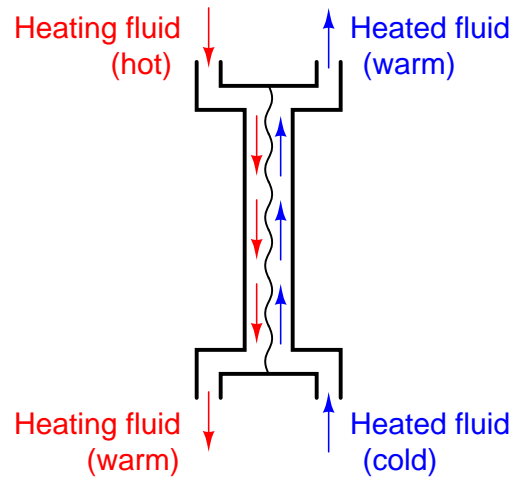
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
$R_1$ failed open		
Voltmeter failed open		
Wire 1 failed open		
Wire 2 failed open		
RTD failed open		
$R_1$ failed shorted		
Voltmeter failed shorted		
RTD failed shorted		
Current source dead		

#### Question 14

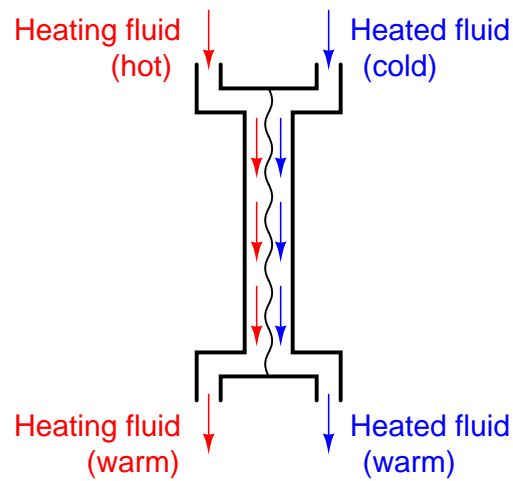
Steam heaters are almost always of the *contra-flow* design, where the two fluids pass by each other in opposing directions:

*Contra-flow heat exchanger*



This is very intentional. If we were to have the fluids moving in the same direction, the exchanger would not be nearly as effective:

*Fluids moving in same direction*



Explain why this is, making reference to the equation  $\frac{dQ}{dt} = \frac{kA\Delta T}{l}$  if possible.  
[file i00335](#)

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Question 15

The rate of heat transfer through *radiation* from a warm body may be expressed by the Stefan-Boltzmann equation:

$$\frac{dQ}{dt} = e\sigma AT^4$$

Where,

$\frac{dQ}{dt}$  = Rate of heat flow

$e$  = Emissivity factor

$\sigma$  = Stefan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ W} / \text{m}^2 \cdot \text{K}^4$ )

$A$  = Area of radiating surface

$T$  = Absolute temperature

Based on the unit of measurement given for the Stefan-Boltzmann constant, determine the proper units of measurement for heat flow, emissivity, area, and temperature.

file i00343



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### Question 16

Solids tend to expand when heated. The amount a solid sample will expand with increased temperature depends on the size of the sample and the material it is made of. A formula expressing linear expansion in relation to temperature is as follows:

$$l = l_0(1 + \alpha\Delta T)$$

Where,

$l$  = Length of material after heating

$l_0$  = Original length of material

$\alpha$  = Coefficient of linear expansion

$\Delta T$  = Change in temperature

Here are some typical values of  $\alpha$  for common metals:

- Aluminum =  $25 \times 10^{-6}$  per degree C
- Copper =  $16.6 \times 10^{-6}$  per degree C
- Iron =  $12 \times 10^{-6}$  per degree C
- Tin =  $20 \times 10^{-6}$  per degree C
- Titanium =  $8.5 \times 10^{-6}$  per degree C

We may also express the tendency for the *area* and the *volume* of a solid to expand when heated, not just its linear dimensions. If we imagine a square with original length  $l_0$  and original width  $l_0$ , the original area of the square must be  $l_0^2$ , which means the new area of the square after heating will be:

$$A = [l_0(1 + \alpha\Delta T)]^2$$

$$A = l_0^2(1 + \alpha\Delta T)^2$$

$$A = l_0^2(1 + \alpha\Delta T)(1 + \alpha\Delta T)$$

$$A = l_0^2[1 + 2\alpha\Delta T + (\alpha\Delta T)^2]$$

or

$$A = A_0[1 + 2\alpha\Delta T + (\alpha\Delta T)^2]$$

This equation may be simplified by approximation – a mathematical principle commonly applied in electrical engineering known as *swamping*:

$$A \approx A_0(1 + 2\alpha\Delta T)$$

Explain why it is okay to make this simplification, and extrapolate the principle to calculating the new *volume* of a solid material after heating.

file i00346

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**Question 17**

A very useful principle in physics is the *Ideal Gas Law*, so called because it relates pressure, volume, molecular quantity, and temperature of an ideal gas together in one neat mathematical expression:

$$PV = nRT$$

Where,

$P$  = Absolute pressure (atmospheres)

$V$  = Volume (liters)

$n$  = Gas quantity (moles)

$R$  = Universal gas constant (0.0821 L · atm / mol · K)

$T$  = Absolute temperature (K)

Note that temperature  $T$  in this equation must be in *absolute* units (Kelvin). Modify the Ideal Gas Law equation to accept a value for  $T$  in units of °C.

Then, modify the equation once more to accept a value for  $T$  in units of °F.

[file i00342](#)

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**Question 18**

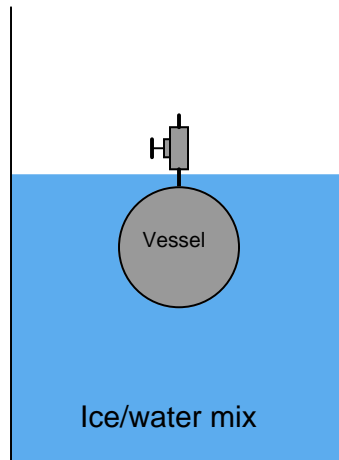
A block of iron and a block of copper are both heated to 200° F in an oven, then placed on a wooden table to cool down to room temperature. Assuming all other factors being equal (mass, surface area, etc.), which block will cool at a faster rate? Why??

[file i00330](#)

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**Question 19**

Suppose an empty test vessel of fixed volume is immersed in an ice-water mixture and allowed to stabilize at that temperature, with a bleed valve left open to equalize the vessel's air pressure with ambient (atmospheric) pressure at sea level:



Once stabilized, the valve is shut off and the vessel is taken out of the ice-water bath, then left to stabilize at room temperature (70° F). Calculate the pressure built up inside the vessel resulting from the increased temperature, in units of inches water column ("W.C.).

[file i02970](#)

Saturated Steam Table

Temperature (Deg F)	Pressure (PSIA)	Sensible heat of liquid (BTU/lb)	Latent heat of vapor (BTU/lb)	Total heat (BTU/lb)
32	0.0886	0.00	1073.4	1073.4
40	0.1217	8.05	1068.9	1076.9
50	0.1780	18.08	1063.3	1081.4
60	0.2562	28.08	1057.8	1085.9
70	0.3626	38.06	1052.3	1090.3
80	0.505	48.03	1046.7	1094.8
90	0.696	58.00	1041.2	1099.2
100	0.946	67.97	1035.6	1103.6
110	1.271	77.94	1030.0	1108.0
120	1.689	87.91	1024.4	1112.3
130	2.219	97.89	1018.8	1116.7
140	2.885	107.87	1013.1	1121.0
150	3.714	117.86	1007.4	1125.3
160	4.737	127.86	1001.6	1129.5
170	5.992	137.87	995.8	1133.7
180	7.51	147.88	989.9	1137.8
190	9.34	157.91	983.9	1141.8
200	11.52	167.94	977.8	1145.8
210	14.13	177.99	971.6	1149.6
212	14.70	180.00	970.4	1150.4
220	17.19	188.1	965.2	1153.3
230	20.77	198.2	958.7	1156.9
240	24.97	208.3	952.1	1160.4
250	29.82	218.5	945.3	1163.8
260	35.42	228.6	938.4	1167.0
270	41.85	238.8	931.4	1170.2
280	49.18	249.0	924.3	1173.3
290	57.55	259.3	916.9	1176.2
300	67.00	269.6	909.5	1179.1
310	77.67	279.9	901.9	1181.8
320	89.63	290.2	894.2	1184.4
330	103.0	300.6	886.3	1186.9
340	118.0	311.0	878.3	1189.3
350	134.6	321.4	870.1	1191.5
360	153.0	331.9	861.8	1193.7
370	173.3	342.4	853.4	1195.8
380	195.6	352.9	844.8	1197.7
390	220.2	363.5	836.1	1199.6
400	247.1	374.1	827.2	1201.3
410	276.4	384.7	818.2	1202.9
420	308.4	395.4	809.0	1204.4
430	343.2	406.2	799.6	1205.8
440	380.8	417.0	790.1	1207.1

**Saturated Steam Table (continued)**

<b>Temperature (Deg F)</b>	<b>Pressure (PSIA)</b>	<b>Sensible heat of liquid (BTU/lb)</b>	<b>Latent heat of vapor (BTU/lb)</b>	<b>Total heat (BTU/lb)</b>
450	422	428	780	1208
460	466	439	770	1209
470	514	450	760	1210
480	565	462	749	1211
490	620	473	738	1211
500	679	484	727	1211
510	743	496	715	1211
520	810	507	703	1210
530	883	519	690	1209
540	960	531	677	1208
550	1043	542	664	1206
560	1130	554	650	1204
570	1224	566	635	1201
580	1323	578	619	1197
590	1428	591	602	1193
600	1540	604	585	1189

file i00872

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## Question 21

Read and outline the “Specific Heat and Enthalpy” subsection of the “Elementary Thermodynamics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

- Questions of your own and requests for clarification after reading the text
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- Descriptions of problem-solving strategies applied by the author

### Suggestions for Socratic discussion

- Thermal energy, like voltage, is a *relative* quantity: always measured between two points. In the case of voltage, those two points are different physical locations between which electric charges might be moved. In the case of *enthalpy*, the two points in question are not physical locations, but rather something else. Identify what this “something else” is, and explain how enthalpy is a relative measurement (i.e. relative to what?).

[file i03979](#)

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### Question 22

Calculate the amount of heat one must add in order to raise the temperatures of the following substances by the amounts specified:

- Two pounds of iron from 80 °F to 110 °F  $Q =$  \_\_\_\_\_ BTU
- 15 grams of ice from  $-11$  °C to  $-3$  °C = \_\_\_\_\_ calories
- 0.0042 pounds of hydrogen gas from 50 °F to 220 °F = \_\_\_\_\_ BTU
- 47 kg of methanol from 10 °C to 35 °C = \_\_\_\_\_ calories

Calculate the amount of heat loss necessary for the following substances to cool down by the amounts specified:

- Five pounds of copper from 100 °F to 65 °F  $Q =$  \_\_\_\_\_ BTU
- 1 kilogram of ethanol from 30 °C to 4 °C = \_\_\_\_\_ calories
- 0.075 pounds of helium gas from 195 °F to 30 °F = \_\_\_\_\_ BTU
- 800 grams of steam from 150 °C to 108 °C = \_\_\_\_\_ calories

[file i03976](#)

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### Question 23

Suppose you own a large hot tub holding 700 gallons of water, with water weighing approximately 8.3 pounds per gallon. Calculate the amount of thermal energy (in units of BTUs) necessary to raise the temperature of the water in the hot tub from ambient (60 degrees Fahrenheit) to 100 degrees Fahrenheit, assuming no heat lost to the surrounding environment in the process.

Calculate the cost of initially heating this hot tub with propane gas, assuming a propane rate of \$2.20 per gallon, a heating value of 21,700 BTU per pound of propane, and a propane density of 4.2 pounds per gallon.

Calculate the cost of initially heating this hot tub with electricity, assuming an electrical power rate of 8.5 cents per kilowatt-hour.

### **Suggestions for Socratic discussion**

- Would it be possible to lower the calculated heating cost of this hot tub by insulating it better? Why or why not?
- What factor(s) affect the continuing energy cost of *maintaining* the hot tub at 100 degrees F? Is it possible, if only in theory, to maintain this temperature with no energy input over time?
- Describe the similarity between thermal energy input versus temperature (in this hot tub example), and *mechanical* energy input versus *speed* for a moving object such as an automobile.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i03980](#)

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#### Question 24

Read and outline the “Phase Changes” subsection of the “Elementary Thermodynamics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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- Descriptions of problem-solving strategies applied by the author

[file i03981](#)

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#### Question 25

Read and outline the “Phase Diagrams and Critical Points” subsection of the “Elementary Thermodynamics” section of the “Physics” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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[file i03610](#)

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### Question 26

An instrument technician wants to create a temperature reference for a thermocouple transmitter by freezing some water, knowing that the freezing point of water at sea level is  $32^{\circ}\text{ F}$  (or  $0^{\circ}\text{ C}$ ). He inserts the thermocouple into a cup of water, then sets the cup and thermocouple inside a freezer until the water is frozen solid. He then takes the cup out of the freezer and connects the thermocouple to the temperature transmitter for calibration.

What is wrong with the technician's procedure? What must be done differently to ensure a reference temperature of  $32^{\circ}\text{ F}$  ( $0^{\circ}\text{ C}$ ) at the thermocouple tip?

<b>Suggestions for Socratic discussion</b>
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- Refer to a *phase diagram* to identify points where  $\text{H}_2\text{O}$  maintains a very stable temperature despite changes in surrounding pressure.
- Explain how the *triple point* of water is used in metrology laboratories to maintain both stable temperature and stable pressure for instrument calibration purposes.

[file i00355](#)

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### Question 27

Suppose a process vessel containing only  $\text{H}_2\text{O}$  is equipped with both a temperature indicator and a pressure indicator. Consult a *steam table* to determine whether the conditions within this vessel are *water only*, *water and steam mixed*, or *steam only*:

- $T = 501^{\circ}\text{ F}$  and  $P = 810\text{ PSIG}$
- $T = 250^{\circ}\text{ F}$  and  $P = 75\text{ PSIG}$
- $T = 690^{\circ}\text{ F}$  and  $P = 1886\text{ PSIG}$
- $T = 369^{\circ}\text{ F}$  and  $P = 550\text{ PSIG}$
- $T = 274^{\circ}\text{ F}$  and  $P = 30\text{ PSIG}$
- $T = 471^{\circ}\text{ F}$  and  $P = 405\text{ PSIG}$

If you determine the process condition to be *steam only*, calculate the amount of superheat (i.e. the number of degrees F that the steam is heated beyond the boiling temperature).

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.

<b>Suggestions for Socratic discussion</b>
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- Plot where each of these temperature/pressure points falls on a *phase diagram* for ice, water, and steam.

[file i00347](#)



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**Question 28**

Convert between the following units of temperature:

- $235^{\circ}\text{C} = ???^{\circ}\text{R}$
- $567.2^{\circ}\text{F} = ???\text{K}$
- $0.004\text{K} = ???^{\circ}\text{F}$
- $830^{\circ}\text{R} = ???^{\circ}\text{C}$
- $-200^{\circ}\text{C} = ???^{\circ}\text{R}$
- $-98.25^{\circ}\text{F} = ???\text{K}$
- $992.8^{\circ}\text{C} = ???^{\circ}\text{F}$
- $-105.3^{\circ}\text{C} = ???^{\circ}\text{F}$
- $1040\text{K} = ???^{\circ}\text{R}$
- $5222.6^{\circ}\text{R} = ???^{\circ}\text{C}$

**Suggestions for Socratic discussion**

- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.

[file i00341](#)

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**Question 29**

Convert between the following units of temperature:

- $350\text{K} = ???^{\circ}\text{C}$
- $575^{\circ}\text{F} = ???^{\circ}\text{R}$
- $-210^{\circ}\text{C} = ???\text{K}$
- $900^{\circ}\text{R} = ???^{\circ}\text{F}$
- $-366^{\circ}\text{F} = ???^{\circ}\text{R}$
- $100\text{K} = ???^{\circ}\text{C}$
- $2888^{\circ}\text{C} = ???\text{K}$
- $4502^{\circ}\text{R} = ???^{\circ}\text{F}$
- $1000\text{K} = ???^{\circ}\text{R}$
- $3000^{\circ}\text{R} = ???\text{K}$

**Suggestions for Socratic discussion**

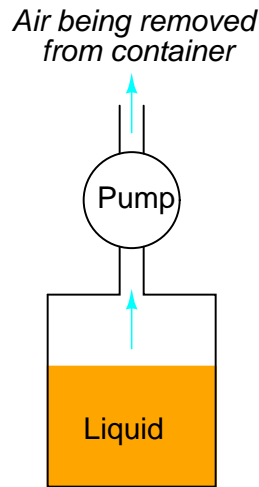
- Demonstrate how to *estimate* numerical answers for these conversion problems without using a calculator.
- What practical purpose does a temperature scale such as Kelvin or Rankine serve, especially since the scales of Celsius and Fahrenheit are so well-known and commonly used?

[file i00340](#)

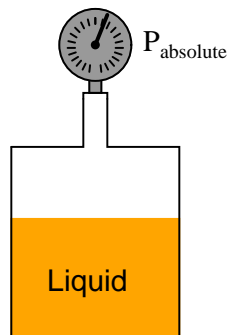
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Question 30

Suppose that a liquid is placed into a container, and then all the air is drawn out of that container using a vacuum pump:

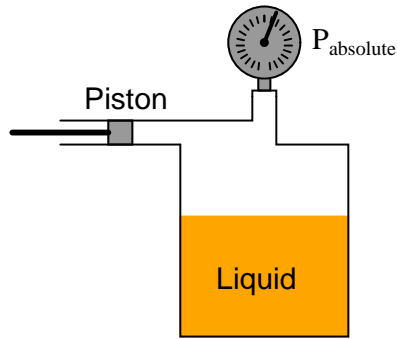


The container is then sealed, and the absolute pressure measured with some kind of pressure instrument:



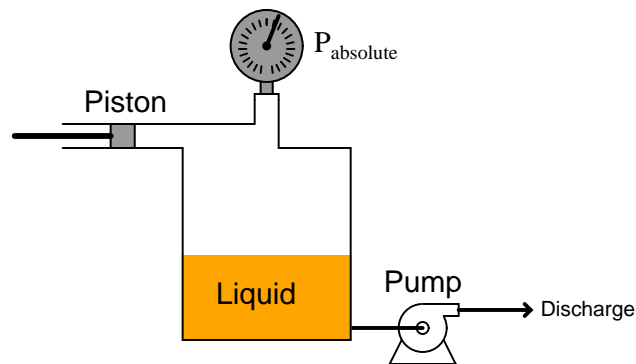
As the liquid is trapped inside the container, thermal energy liberates some of the molecules into the vacuum above, resulting in a vapor forming above the liquid. As some of these vapor molecules strike the walls of the container, they condense back into liquid and dribble down into the liquid pool below. When the rates of evaporation and condensation reach equilibrium, we say the liquid/vapor process is in a condition of *saturation*, and the amount of pressure inside this vessel as the *saturated vapor pressure* of the substance. “Saturated” simply refers to the condition where the rates of evaporation and condensation exactly match; when the space above the liquid can hold no more vapor molecules.

Suppose we now attach a piston to this container so we may change the volume of the vapor space:



If the system reaches a state of saturation (evaporation and condensation rates equal), and temperature remains the same, what will happen to the pressure in the container if the piston is moved inward, thus decreasing volume? Does the pressure increase, decrease, or stay the same?

Now suppose we attach a pump to the bottom of this container so we may remove some of the liquid without letting any air in:



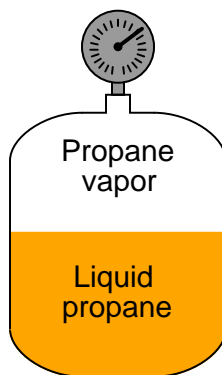
If the system reaches a state of saturation (evaporation and condensation rates equal), and temperature remains the same, what will happen to the pressure in the container as liquid is drawn out? Does the pressure increase, decrease, or stay the same?

[file i00348](#)

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**Question 31**

A propane tank holds both liquid propane and propane vapor at high pressure:



How may the pressure in the tank be altered? What physical variable must be changed in order to increase or decrease the vapor pressure inside the tank?

[file i00349](#)

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**Question 32**

Rank the following transitions according to the amount of heat energy input required:

- To heat a pound of water from  $60^{\circ}\text{F}$  to  $65^{\circ}\text{F}$ .
- To boil a pound of water completely into steam (warming it from  $211^{\circ}\text{F}$  to  $213^{\circ}\text{F}$ ).
- To melt a pound of ice completely into water (warming it from  $31^{\circ}\text{F}$  to  $33^{\circ}\text{F}$ ).

<b>Suggestions for Socratic discussion</b>
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- Which of these transitions involves *sensible heat* and which involve *latent heat*?

[file i00353](#)

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**Question 33**

Suppose exactly 1000 calories of heat energy is transferred to a 5-gram mass of water at  $20^{\circ}\text{C}$  and at atmospheric pressure (sea level). Calculate what will happen to the water (how far will its temperature be raised, and if it boils, how much steam will be liberated from the water?).

Hint: the specific heat of water is  $1\text{ calorie/gram-}^{\circ}\text{C}$ . The latent heat of fusion for water is  $80\text{ calories/gram}$ , and the latent heat of vaporization for water is  $540\text{ calories/gram}$ .

[file i01796](#)

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**Question 34**

Suppose a steam boiler is supposed to have a capacity of 300 pounds (of steam) per hour. How much heat energy (in BTUs per hour) will it take to boil this rate of steam, assuming that water enters the boiler at  $212^{\circ}\text{F}$ ?

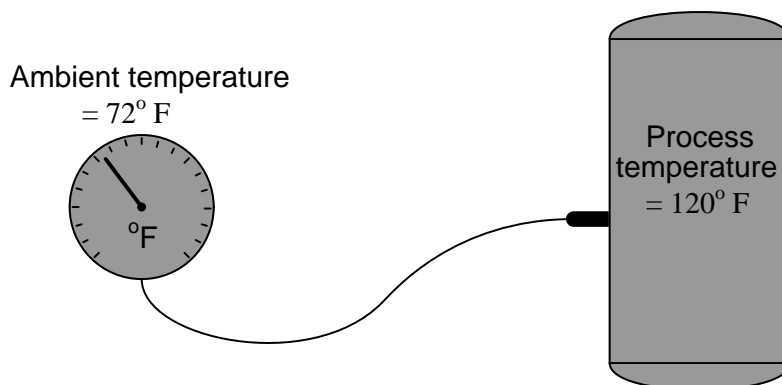
Hint: the specific heat of water is  $1\text{ BTU/lb}_m\text{-}^{\circ}\text{F}$ . The latent heat of fusion for water is  $144\text{ BTU/lb}_m$ , and the latent heat of vaporization for water is  $970\text{ BTU/lb}_m$ .

[file i01797](#)

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Question 35

In the following liquid/vapor filled system (Class II), where is the liquid located in the system, and where is the vapor located in the system?



What will happen to the liquid and vapor locations if the process temperature decreases to 60° F?  
[file i00361](#)

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Question 36

The scientific paper “Cavitation Pressure in Water” written by Eric Herbert, Sébastien Balibar, and Frédéric Caupin, and published in the October 16 (2006) edition of *Physical Review* opens with the following statement about material phases:

The liquid and vapor phases of a pure substance can coexist at equilibrium only on a well defined line relating pressure and temperature. Away from this coexistence line, one of the phases is more stable than the other. However, because of the existence of a liquid-vapor surface tension, if one phase is brought in the stability region of the other, it can be observed for a finite time in a metastable state; the lifetime of this metastable state decreases as one goes away from the coexistence line.

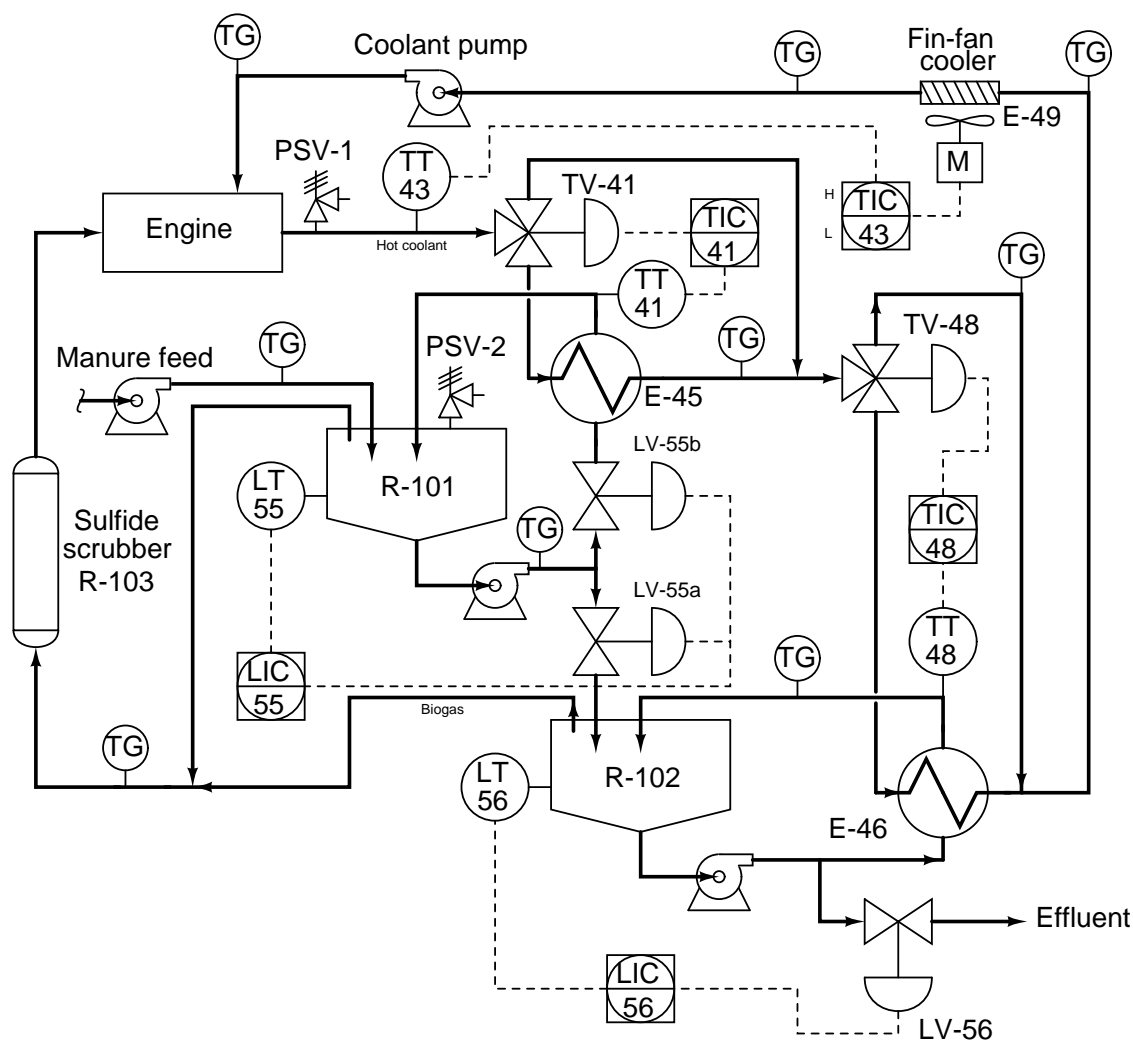
After reading this passage, reflect on it and try to answer the following questions based on what it says as well as what you have learned about phases and phase changes:

- What is meant by the phrase *coexistence line*? Does this refer to something you have already learned about, or is this a brand-new concept?
- What is meant by the phrase *stability region*? Again, does this refer to something you already know, or is the reference new to you?
- Describe an experiment by which we might produce the type of “metastable state” referred to in this passage, and measure its lifespan.

[file i00336](#)

Question 37

In this biogas generation system, cow manure is used as a feedstock to produce methane gas ( $\text{CH}_4$ ), which is then used to fuel an engine to turn a generator and make electricity. The waste heat from the engine is used to maintain the cascaded digesters ("reactors" R-101 and R-102) at optimal temperatures for anaerobic bacteria to digest the manure and produce biogas (approximately 105 °F):

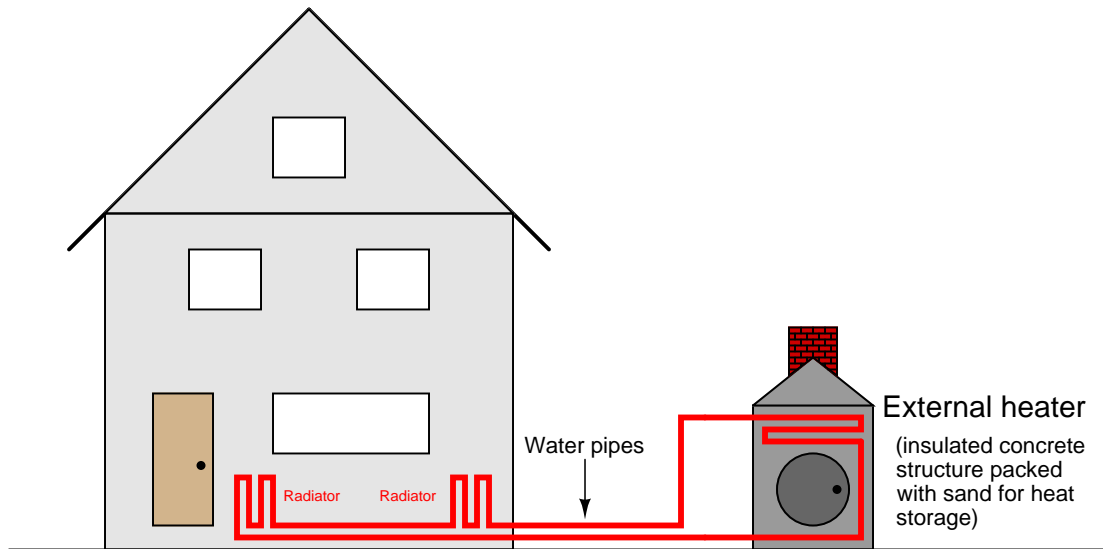


Suppose one day there is a high-temperature engine coolant alarm indicated by TIC-43. Determine some possible faults that could each independently account for this alarm, and also identify the first diagnostic test you would perform to troubleshoot the problem.

[file i03486](#)

### Question 38

A type of heating system developed to provide a measure of safety and convenience for self-sufficient homes is an *external heater*, where fuel such as wood is burned at high temperature for short durations in an outdoor furnace, and the heat from that furnace stored in a large “thermal reservoir” of sand. A fire is lit inside the furnace only once every few days, then the heat from that burn is transferred to the home by means of water pumped through heat exchangers:



Answer the following questions about this type of heating system:

- What advantages might there be with this design versus a furnace installed inside the home?
- Why is *sand* a good choice as a heat-storage medium inside the furnace structure?
- Is the heat storage in this system based on *specific heat* or *latent heat*?
- Is the heat transfer in this system (from heater to home) based on *specific heat* or *latent heat*?
- How may the home's temperature be thermostatically controlled?
- How to equip the system with an alarm prompting the user to light a new fire in the furnace?
- Calculate the enthalpy of the water as it enters the home (from the heater) at a temperature of 184 °F.
- Calculate the enthalpy of the water as it leaves the home (on its way to the heater) at a temperature of 127 °F.
- Calculate the rate of heat delivered to the home by this hot water assuming a water mass flow rate of 9.2 pounds per minute.

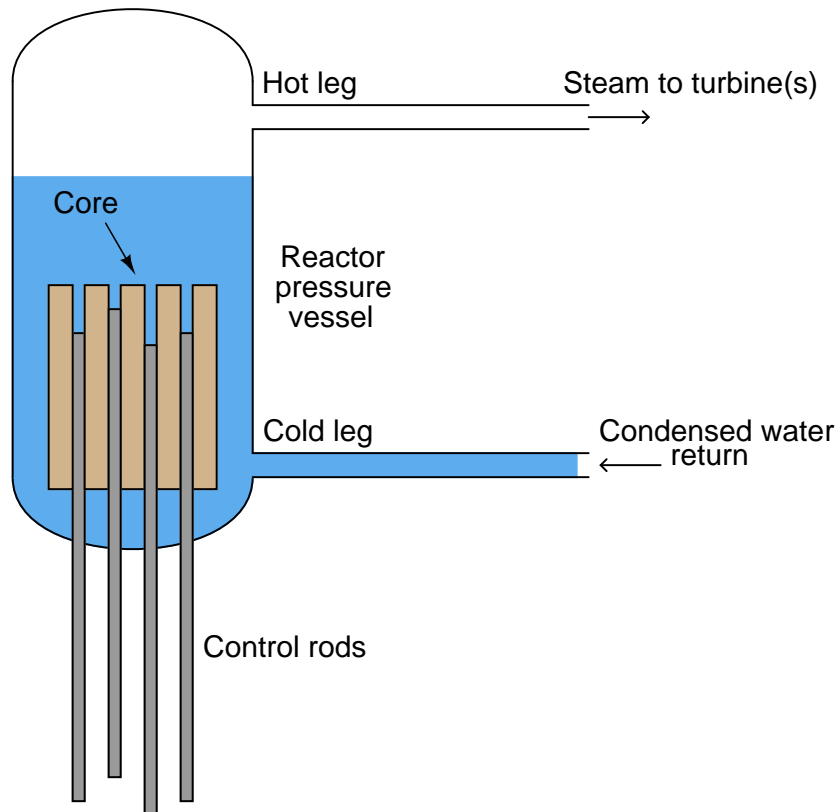
file i01017

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Question 39

A *boiling-water reactor* (BWR) in a nuclear power plant uses the heat emitted by the nuclear “core” to boil water into steam, which is then used to turn a steam turbine and drive an electrical generator to produce electricity:

**Boiling-water nuclear reactor (BWR)**



It is critically important that the nuclear core be kept completely submerged in water, lest it overheat.

Suppose the temperature and pressure measurements on a BWR are 780 °F and 495 PSIG, respectively. Reference a steam table and then determine whether the core is covered (submerged) or uncovered (exposed).  
[file i01018](#)

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Question 40

Suppose a steam turbine engine in a power plant receives steam from the boiler at a temperature of 583 °F and a pressure of 88 PSIG, and discharges steam at a temperature of 91 °F and a pressure of –14 PSIG. The mass flow rate of this steam is 2300 pounds per minute.

Assuming a turbine efficiency of 80%, calculate the mechanical power output by this steam turbine, in the unit of Watts.

[file i02855](#)



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#### Question 41

Read and outline the “Temperature Coefficient of Resistance ( $\alpha$ )” subsection of the “Thermistors and Resistance Temperature Detectors (RTDs)” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i03984](#)

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#### Question 42

A platinum RTD with an  $R_0$  of  $1000\ \Omega$  and an  $\alpha = 0.00392\ \Omega/\Omega^\circ\text{C}$  is heated to a temperature of  $120^\circ\text{C}$ . Calculate its resistance at that temperature.

Also, calculate the temperature of the same RTD if its resistance measures  $1043.8\ \Omega$ .

#### **Suggestions for Socratic discussion**

- Explain how an RTD may be constructed to have a different “base” resistance value (e.g. 1000 ohms versus 100 ohms). Specifically, what is it about the RTD’s physical construction that determines this resistance value?
- Explain why RTDs do not all have the same “alpha” ( $\alpha$ ) value.

[file i00406](#)

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#### Question 43

A  $100\ \Omega$  platinum RTD with an  $\alpha$  ( $\alpha$ ) of 0.00385 has a measured resistance of  $98\ \Omega$ . Calculate its temperature, expressing your answer both in degrees C and degrees F.

#### **Suggestions for Socratic discussion**

- Two common  $\alpha$  values for platinum RTDs are 0.00385 and 0.00392. Which of these is sometimes referred to as the “European” value and which as the “American” value? Are these labels accurate?

[file i00407](#)

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#### Question 44

Read and outline the “Two-Wire RTD Circuits”, “Four-Wire RTD Circuits”, “Three-Wire RTD Circuits”, and “Proper RTD Sensor Connections” subsections of the “Thermistors and Resistance Temperature Detectors (RTDs)” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

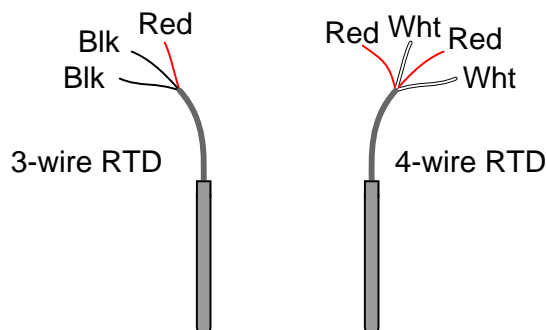
The purpose of your outline is to foster close reading of the text, to facilitate quick referencing of specific points within the text, to record questions of your own, and to practice clear writing. Your outline must meet the following standards for full credit: *every major idea contained in the text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

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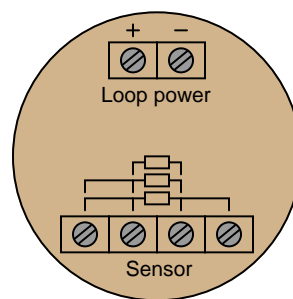
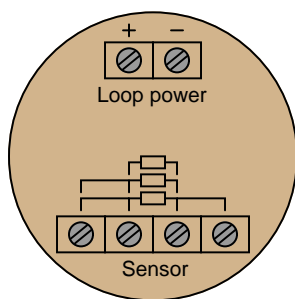
[file i03985](#)

# Question 45

Draw schematic diagrams for the following RTDs:



Then, show how each type of RTD would connect to the input terminals of an RTD-input temperature transmitter. Note how each transmitter is configurable for different types of RTDs, the different RTD types being shown symbolically on the face of the transmitter:



## Suggestions for Socratic discussion

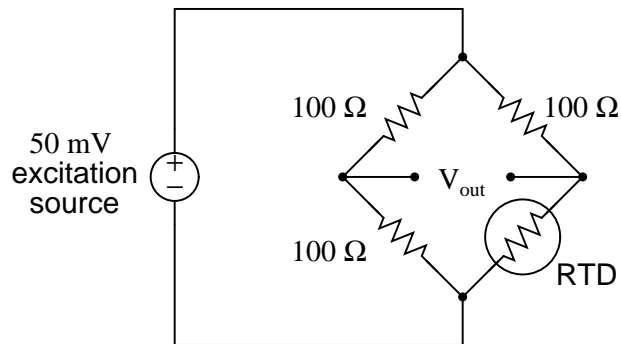
- What do common colors represent for RTD lead wires?
- What advantage is there to a four-wire RTD over a three-wire RTD to justify the extra expense and connections required for the fourth wire?
- Interpret the meaning of the box-shaped resistor symbols found on the faces of the RTD temperature transmitters. Do these symbols represent what gets connected to the terminals of the transmitter, or do they represent what is already built inside the transmitter?
- Is it possible to connect a four-wire RTD to a temperature transmitter intended for use with three-wire RTDs? How about connecting to a temperature transmitter intended for two-wire RTDs?
- How will the temperature measurement be affected if one of the “sense” wires breaks open on the 4-wire RTD?

- How will the temperature measurement be affected if one of the “excitation” wires breaks open on the 4-wire RTD?

[file i00404](#)

#### Question 46

Calculate the output voltage of this bridge circuit at the following RTD temperatures (assume the use of a  $100\ \Omega$  RTD with a European alpha value).



- $V_{out} = \underline{\hspace{2cm}}$  at  $T = 0^\circ\text{ C}$
- $V_{out} = \underline{\hspace{2cm}}$  at  $T = 35^\circ\text{ C}$
- $V_{out} = \underline{\hspace{2cm}}$  at  $T = -15^\circ\text{ C}$

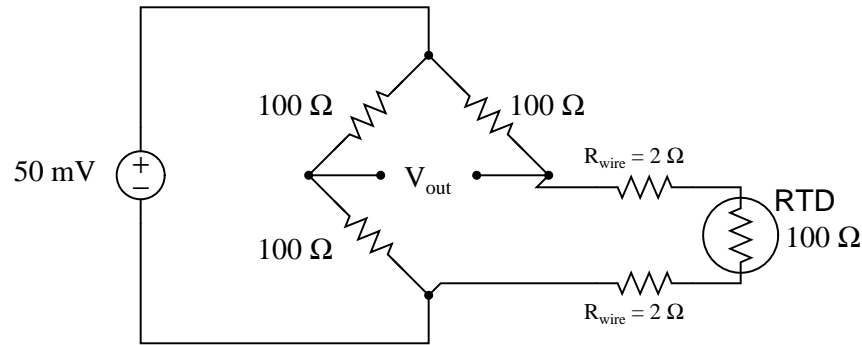
#### Suggestions for Socratic discussion

- The low voltage (50 mV) of the “excitation” source is not arbitrary, but rather serves a practical purpose. Explain why it is important for this voltage source to be small in magnitude rather than large (e.g. 5 volts or 24 volts).
- Suppose the only DC voltage source we had available for powering the RTD bridge was a fixed 24 volt source. How could we make this source work with the bridge circuit shown without encountering problems by over-powering the bridge?
- Choose a resistor at random in this circuit and imagine that it fails (either open or shorted). Would this electrical fault make the RTD appear hotter than it really is, or colder than it really is? Explain your answer in detail.

[file i00410](#)

### Question 47

Shown here is a typical 2-wire RTD bridge circuit, where the RTD is located a considerable distance away from the bridge circuit:

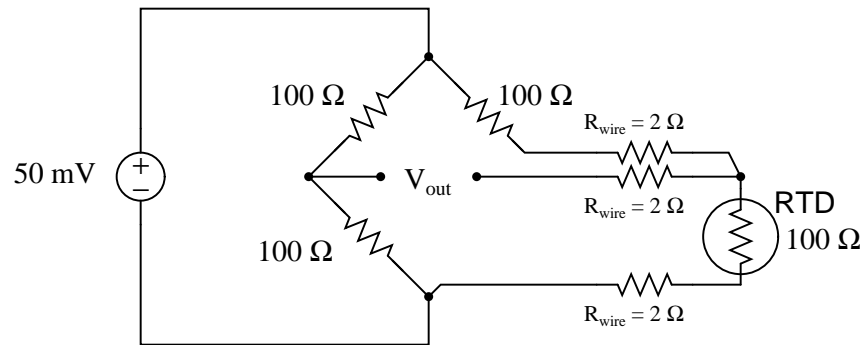


The two-wire cable connecting the RTD to the rest of the bridge circuit has resistance distributed along its length, shown in the schematic in “lumped” form as two “ $R_{\text{wire}}$ ” resistors. What effect will the presence of this cable resistance have on the temperature measurement system? Will it result in a zero shift, a span shift, or both? Why??

Calculate the output voltage of this bridge circuit when the  $100\ \Omega$  RTD is at its reference temperature of  $0^\circ\text{C}$ , and each  $R_{\text{wire}}$  resistance is equal to  $2\ \Omega$  (Hint: the alpha figure is irrelevant in this problem).

Also calculate how hot the RTD “appears” to be as indicated by the output voltage of the bridge circuit, given the added cable resistance. Assume a European  $\alpha$  value for this calculation.

Shown here is a typical 3-wire RTD bridge circuit, where the RTD is located a considerable distance away from the bridge circuit:



Calculate the output voltage of this bridge circuit when the  $100\ \Omega$  RTD is at its reference temperature of  $0^\circ\text{C}$ , and each  $R_{\text{wire}}$  resistance is equal to  $2\ \Omega$  (Hint: the alpha figure is irrelevant in this problem):

Comment on how this 3-wire RTD bridge circuit compares against a 2-wire RTD bridge circuit with the same amount of cable resistance.

### Suggestions for Socratic discussion

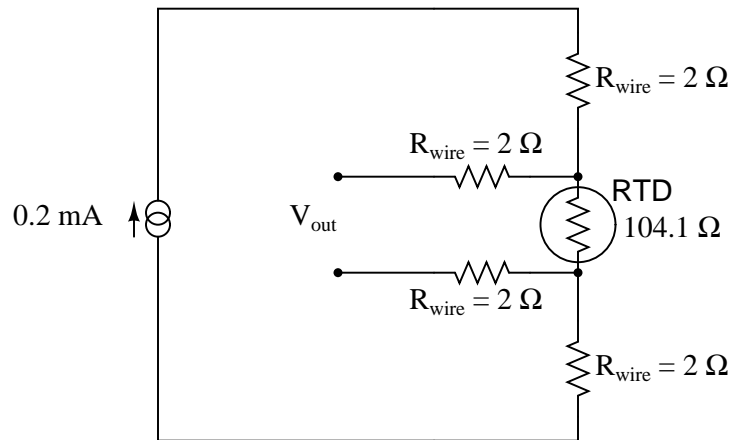
- Explain why the RTD’s alpha value is irrelevant when its temperature is  $0^\circ\text{C}$ .
- Identify some “open” faults in either of these circuits that would make the output voltage ( $V_{\text{out}}$ ) saturate “low” (as if the RTD were extremely cold!).
- Identify some “open” faults in either of these circuits that would make the output voltage ( $V_{\text{out}}$ ) saturate “high” (as if the RTD were extremely hot!).

- A good problem-solving technique to apply in cases where we need to determine the direction of a change is to consider *limiting cases*. Instead of asking ourselves what would happen if one of the resistances changed slightly, we ask ourselves what would happen if resistance in question changed *dramatically*. Explain how this problem-solving technique applies to this particular system.

[file i00413](#)

#### Question 48

Explain why this 4-wire RTD circuit is completely immune to calibration drift resulting from cable resistance:



Also, identify the magnitude and polarity of all voltage drops in this circuit.

#### Suggestions for Socratic discussion

- How will the temperature measurement be affected if the current source's value is increase?
- Will this circuit be immune to calibration drift even if the RTD wire resistances are not all equal to each other? Is this true for a three-wire RTD circuit as well?
- Explain the meaning of the DC source symbol used in this diagram. What type of source is this, and what is its polarity?
- Choose a resistor at random in this circuit and imagine that it fails (either open or shorted). Would this electrical fault make the RTD appear hotter than it really is, or colder than it really is? Explain your answer in detail.

[file i00415](#)

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### Question 49

Calculate the amount of heat energy released by two pounds of superheated steam (at atmospheric pressure) as it cools from 400 °F to 125 °F, in units of BTU. Be sure to separate your solution into three steps: the heat lost as the steam cools to the condensing temperature (212 °F), the latent heat released through condensation, and the heat lost as the condensed water cools to the final temperature of 125 °F.

In which step of this three-step heat loss process is *most* of the heat being released? What does this indicate about the heat-storing capabilities of water, steam, and phase changes between water and steam?

Next, use numbers taken from a *steam table* to calculate the same heat release: subtracting the enthalpy (also known as *total heat*, or *h*) of 400 °F steam from the enthalpy of 125 °F water. Assume the steam is at atmospheric pressure. How closely does this calculated value agree with your previous calculation?

Hint: the *Socratic Instrumentation* website contains a page where you may download public-domain textbooks, one of which is a set of steam tables published in 1920.

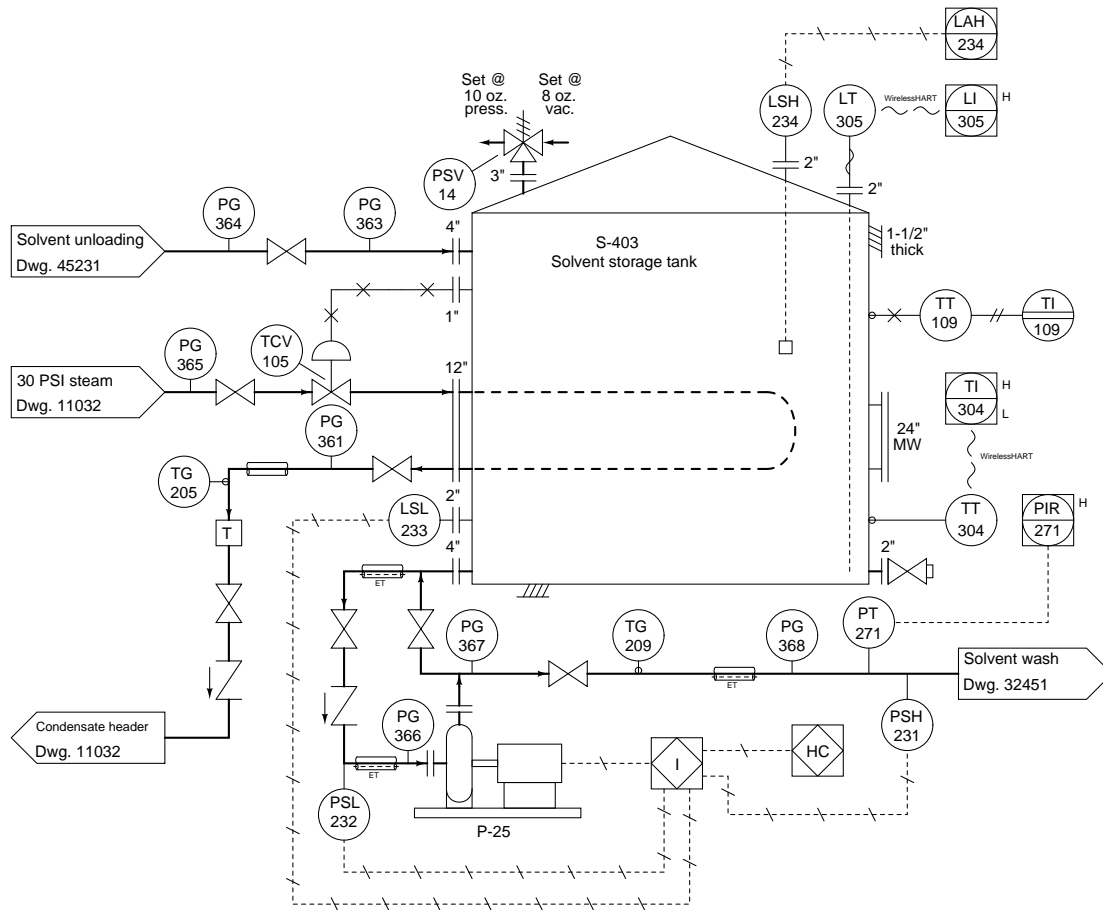
<b>Suggestions for Socratic discussion</b>
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- Be sure to discuss how to properly use a steam table to reference enthalpy values.
- Some superheated steam tables index their entries by the “total” temperature of the steam, while others list the amount of “superheat.” What exactly does *superheat* mean, and how do we calculate it?
- Which result do you think is more accurate: the one calculated in three steps, or the one calculated from steam table enthalpy?

[file i03982](#)

### Question 50

Calculate the heat loss rate through the surfaces of this solvent storage tank, which is a vertical cylinder in shape. Assume the wall insulation has an R-value of 5 per inch of thickness, the floor insulation has an R-value of 2, and the roof insulation has an R-value of 4. The tank's diameter is 10 feet, its wall height is 13 feet, and its conical roof has a total surface area of 101 square feet. The setpoint for solvent temperature inside the tank is 95 degrees Fahrenheit, and the ambient air temperature is 40 degrees Fahrenheit:



Next, calculate the heat value rate of the fuel needed to fire this boiler, to keep the solvent tank temperature at setpoint. Assume a steam boiler efficiency (fuel heat value in, to heat delivered at the tank) of 83%.

### Suggestions for Socratic discussion

- Calculate the “lift” pressures of PSV-14 in units of inches water column.
- Explain the purpose of each protective interlock (safety switch) on the pump P-25 control system.

[file i03485](#)



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Question 51

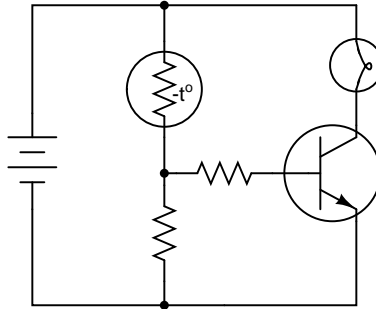
A typical RTD specification reads as such:  $100\ \Omega$  platinum @  $0^\circ\text{C}$ ,  $\alpha = 0.00385\ \Omega/\Omega\cdot^\circ\text{C}$ . What, exactly, does this statement mean?

[file i00405](#)

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Question 52

In this circuit, a thermistor is used to control power to a lamp:

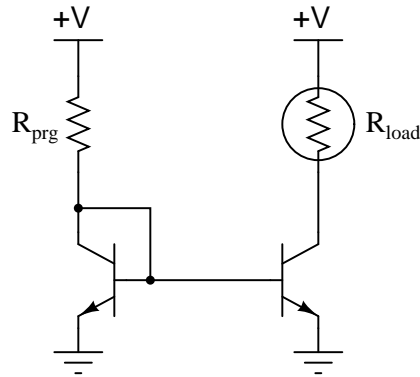


As the temperature increases, does the lamp become brighter or dimmer? Explain your answer.

[file i00417](#)

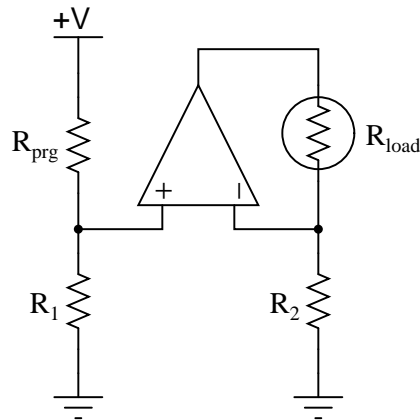
A basic circuit often used to regulate current through a variable-resistance load is the classic *current mirror*:

*Current mirror sourcing  
constant current to  
a varying load resistance*

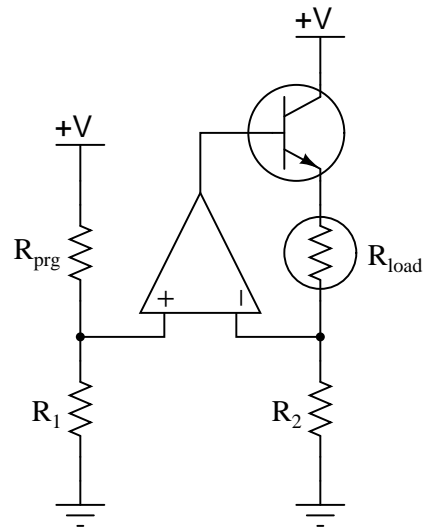


The “programming” resistor ( $R_{prg}$ ) establishes the current magnitude to be maintained through the varying-resistance load, in this case an RTD or a thermistor. For optimum performance, the two transistors should be precisely matched and also share the same heat sink (or be etched on the same semiconductor substrate).

However, we can do much better than this circuit if we use an operational amplifier. Consider this “modernized” current mirror circuit:



Here there is no need for matched transistors or special heat-sinking. So long as resistors  $R_1$  and  $R_2$  have equal resistance, the current through  $R_{load}$  will be maintained at the same value as the current through  $R_{prg}$ . If the intended current value is large, we may “boost” the output of the opamp with a single transistor:



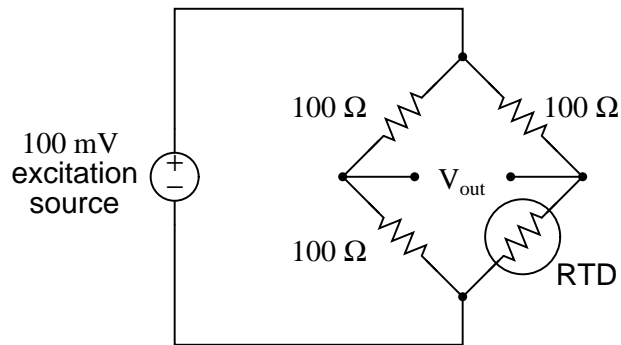
Explain how both of these operational amplifier circuits work, and why they function as “current mirrors.”

[file i00418](#)

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#### Question 54

Calculate the output voltage of this bridge circuit at the following RTD temperatures (assume the use of a  $100\ \Omega$  RTD with an American alpha value).

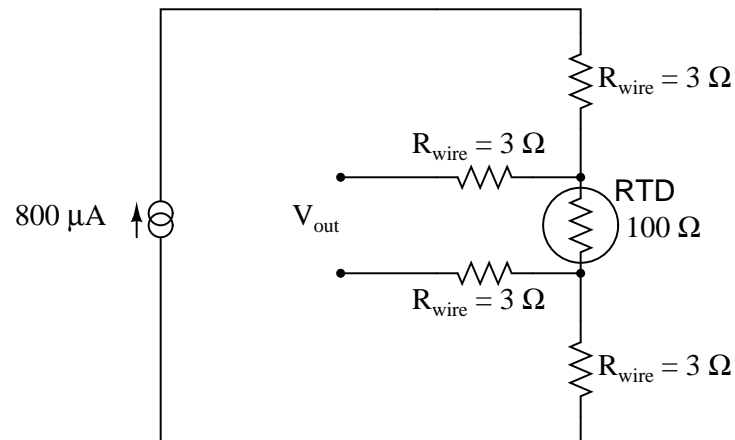


- $V_{out} = \underline{\hspace{2cm}}$  at  $T = -20^\circ\text{C}$
- $V_{out} = \underline{\hspace{2cm}}$  at  $T = 70^\circ\text{C}$
- $V_{out} = \underline{\hspace{2cm}}$  at  $T = 200^\circ\text{C}$

[file i00690](#)

Question 55

Calculate  $V_{out}$  in this 4-wire RTD circuit when the temperature of the RTD is  $135^{\circ}\text{F}$  (assume an American  $\alpha$  value):

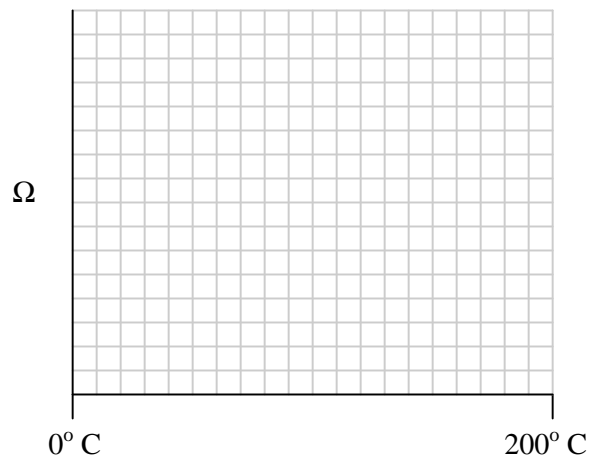


file i00691

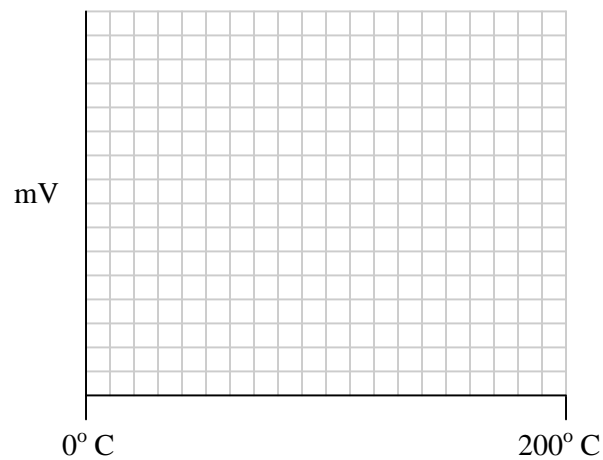
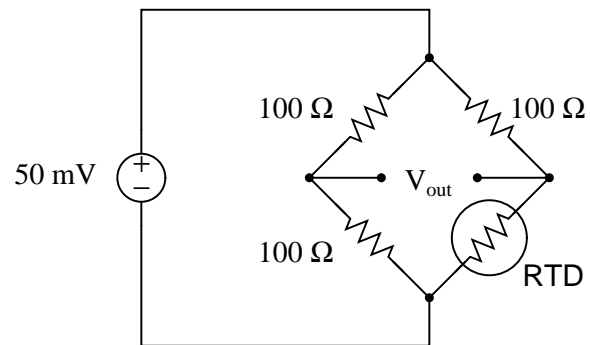
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Question 56

Plot a graph of an RTD's resistance over a temperature range of  $0^{\circ}\text{C}$  to  $200^{\circ}\text{C}$ . Assume a  $100\ \Omega$  RTD with an American alpha value.



Then, plot a graph of a bridge circuit's voltage output containing the same RTD ( $100\ \Omega$ , American  $\alpha$ ), as its temperature changes from  $0^{\circ}\text{C}$  to  $200^{\circ}\text{C}$ :



Compare these two graphs, then comment on the behavior of RTDs both inside and outside of a bridge circuit.

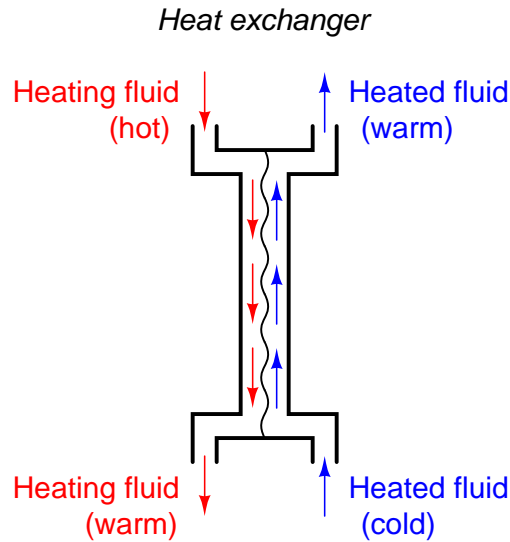
<b>Suggestions for Socratic discussion</b>
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- Explain how a *computer spreadsheet program* such as Microsoft Excel might be useful in graphing the results of this circuit.

file i00412

Question 57

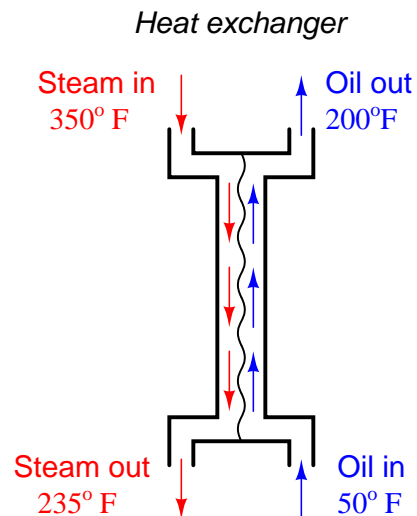
A *heat exchanger* is a metal device built to facilitate heat transfer between two fluids:



A *heating* fluid enters one side of the heat exchanger and gives up some of its thermal energy to the *heated* fluid on the other side of a thin, metal barrier. The heated fluid, meanwhile, absorbs the heat released by the heating fluid across the barrier, increasing its temperature before exiting.

There are many different types of heat exchangers, but they all function on the same basic principles: thermal convection (heat transfer between each fluid and the barrier), and thermal conduction (heat transfer through the barrier itself).

Suppose that a heat exchanger is being used to pre-heat fuel oil with steam prior to combustion in a boiler (this is common practice in boilers operating with heavy liquid petroleum fuel such as “bunker-C”):



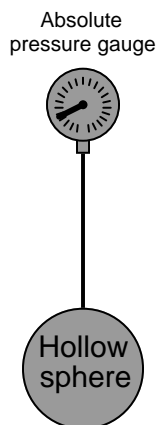
What will happen to the steam and oil outlet temperatures if the oil *flow* is decreased? I’m looking for qualitative answers here (increase, decrease, or stay the same).

file i00334

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**Question 58**

An absolute pressure gauge is connected to a hollow metal sphere containing a gas:



According to the Ideal Gas Law, the relationship between the gauge's pressure indication and the sphere's temperature is as follows:

$$PV = nRT$$

Unfortunately, though, we do not happen to know the volume of the sphere ( $V$ ) or the number of moles of gas contained within ( $n$ ). At best, all we can do is express the relationship between  $P$  and  $T$  as a proportionality, or as an equality with a *constant of proportionality* ( $k$ ) accounting for all the unknown variables and unit conversions:

$$P \propto T \qquad P = kT$$

Calculate the value of this constant ( $k$ ) if you happen to know that the pressure gauge registers 1.5 bar (absolute) at a temperature of 280 K. Then, predict the temperature when the pressure gauge reads 1.96 bar (absolute).

[file i02992](#)

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**Question 59**

While on a camping trip, Sally needs to collect enough firewood to fuel a campfire that will bring 5 gallons of water to a boil. Assuming a heat of combustion value of 9000 BTU per pound of dry wood, how much wood must Sally collect for the fire that will heat this water? Assume that the ambient air temperature is 51 degrees F, and that the boiling point of water at Sally's altitude is 205 degrees F.

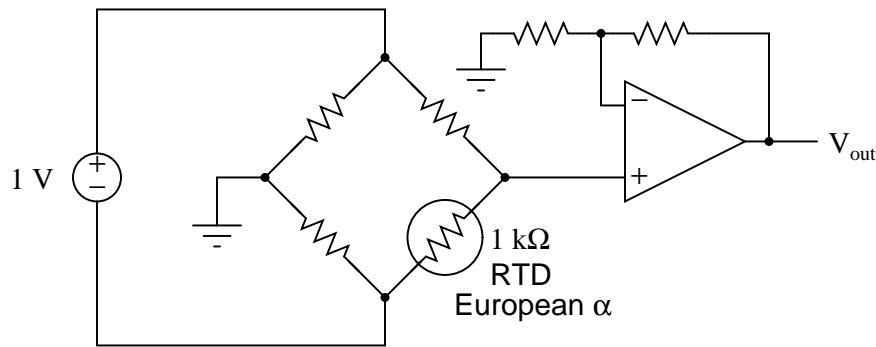
[file i00408](#)



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### Question 60

Choose proper resistor values so that the op-amp outputs a 0 to 5 volt voltage signal over a temperature measurement range of 0° C to 80° C. Assume the use of a 1000  $\Omega$  RTD with a European alpha.



$V_{out} = 0 \text{ to } 5 \text{ volts}$   
Temperature range = 0° C to 80° C

### Suggestions for Socratic discussion

- Do the operational amplifier's two feedback resistors affect this temperature circuit's *zero*, *span*, or *linearity*?
- How might we provide for *adjustable* zero and span calibrations in this circuit?
- Choose a resistor at random in this circuit and imagine that it fails (either open or shorted). Would this electrical fault make the RTD appear hotter than it really is, or colder than it really is? Explain your answer in detail.

[file i00411](#)

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### Question 61

Read and outline the “Dissimilar Metal Junctions” subsection of the “Thermocouples” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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- Descriptions of problem-solving strategies applied by the author

[file i03986](#)

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### Question 62

Read and outline the “Thermocouple Types” subsection of the “Thermocouples” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i03987](#)

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### Question 63

Read and outline the “Connector and Tip Styles” subsection of the “Thermocouples” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i03988](#)

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#### Question 64

Read and outline the “Manually Interpreting Thermocouple Voltages” subsection of the “Thermocouples” section of the “Continuous Temperature Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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- Descriptions of problem-solving strategies applied by the author

[file i03989](#)

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#### Question 65

Build your own thermocouple by taking a piece of thermocouple cable (type J or K works well) and twisting together the wires at one end to form a measurement junction. Clip the test leads of a sensitive millivoltmeter to the other wire ends (the reference junction). Heat the measurement junction using body heat or an open flame (e.g. butane lighter) and then use a thermocouple reference table to infer the temperature of the measurement junction.

A helpful feature of high-end digital multimeters is *high-resolution mode*, where the meter displays an extra digit on the screen at the expense of slower update times. This extra resolution will help you better read the small millivoltage signals output by your thermocouple.

Another helpful feature of most DMMs is *min/max mode*. Try engaging this mode on your multimeter and see how it might be helpful to you reading minimum and maximum millivoltage values, as well as potentially a troubleshooting tool!

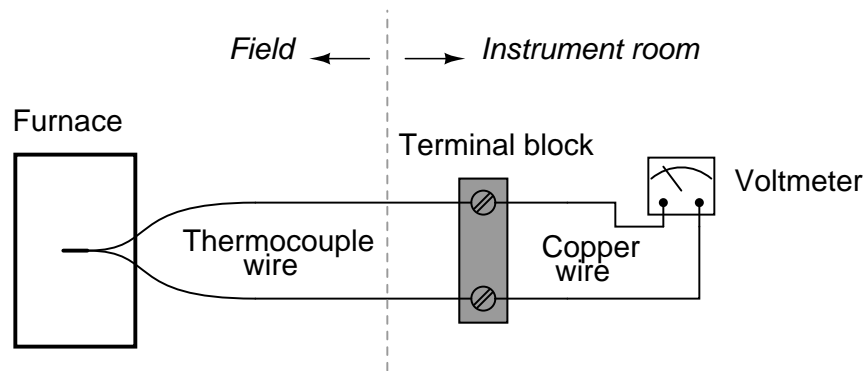
#### **Suggestions for Socratic discussion**

- Why is it important to know the ambient (room) temperature when calculating the temperature of the heated measurement junction?
- Based on what you know of *measurement* versus *reference* junctions in thermocouple circuits, explain the millivoltage measurement you obtain with your meter when the thermocouple is at ambient (room) temperature.
- What would happen if you touched the thermocouple’s measurement junction to an ice cube instead of a flame?
- What would happen if you warmed up the reference junction instead of the measurement junction?
- Research what a *thermopile* is, and try building one with thermocouple wire. Demonstrate with a heat source how a thermopile’s operation differs from that of a regular thermocouple’s.

[file i03629](#)

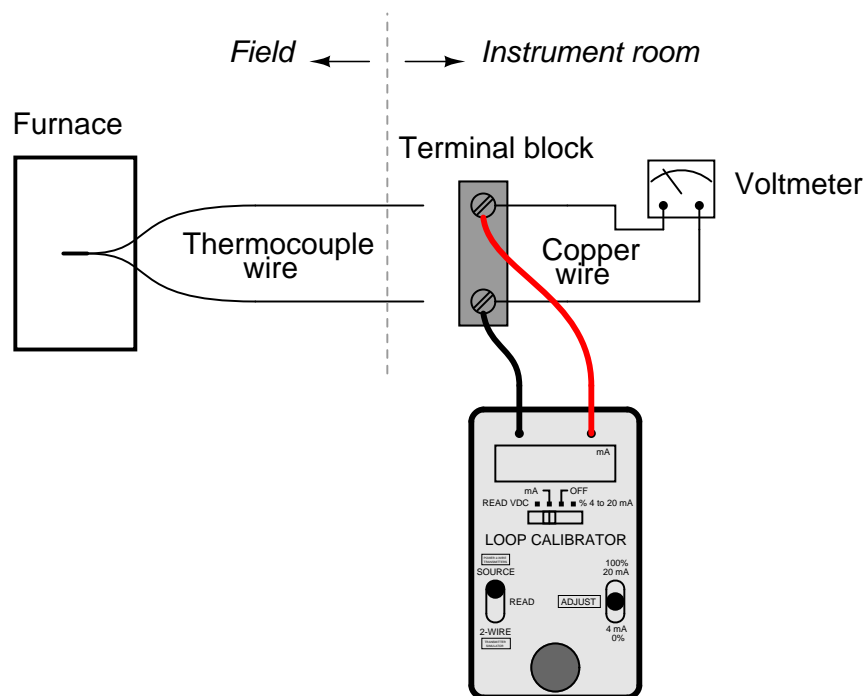
### Question 66

Suppose we use a thermocouple to measure the temperature of a furnace, a voltmeter to indicate the voltage generated, and we infer furnace temperature from that measured voltage:



Describe what will happen to the voltmeter's indication if the ambient temperature of the instrument room increases while the furnace temperature remains the same, and explain why.

Also, explain what would happen if an inexperienced instrument technician tried to check the calibration of the indicating meter by disconnecting the thermocouple from it and connecting a loop calibrator set to "Source" mode like this:



### Suggestions for Socratic discussion

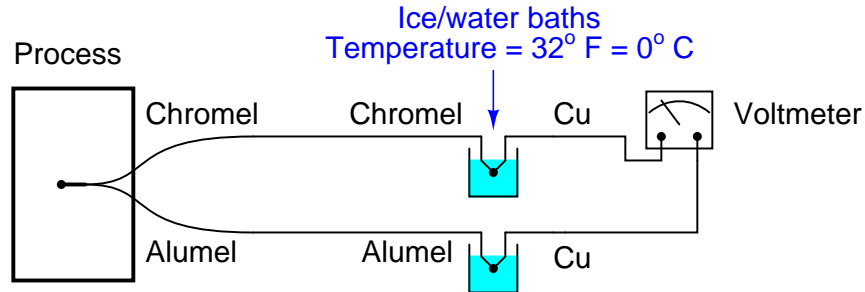
- Suppose a wire broke open in this particular thermocouple circuit. How would this affect the meter's indication of temperature?

- Suggest a better piece of test equipment for this task than a loop calibrator, and explain how it is supposed to function.

[file i00371](#)

#### Question 67

A type “K” thermocouple is made of the dissimilar metals Chromel (chromium-nickel alloy) and Alumel (aluminum-nickel alloy). Using a thermocouple table, determine the output voltages of a type “K” thermocouple at the following process temperatures:



- $T_{process} = 800^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = -163^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = 32^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = 2350^{\circ} \text{ F}$ ; Voltmeter voltage = ???

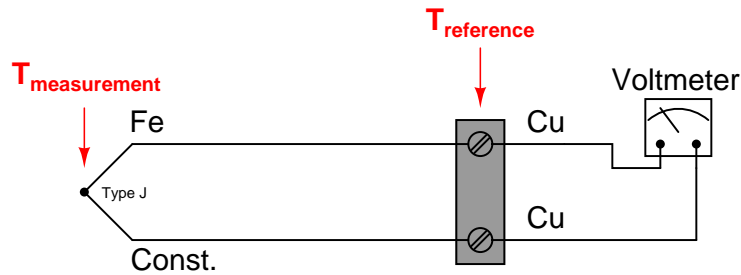
#### Suggestions for Socratic discussion

- Explain the rationale of using an ice-water bath for the reference junction. Also, explain why both of the reference junction connections are immersed in ice-water baths instead of just one of them.

[file i00368](#)

### Question 68

Determine the voltmeter's indication in this thermocouple circuit (type J) for the following temperatures:



- $T_{\text{measurement}} = 250^{\circ} \text{ F}$  ;  $T_{\text{reference}} = 60^{\circ} \text{ F}$  ; Voltmeter voltage = ???
- $T_{\text{measurement}} = 733^{\circ} \text{ F}$  ;  $T_{\text{reference}} = 72^{\circ} \text{ F}$  ; Voltmeter voltage = ???
- $T_{\text{measurement}} = -60^{\circ} \text{ F}$  ;  $T_{\text{reference}} = 49^{\circ} \text{ F}$  ; Voltmeter voltage = ???
- $T_{\text{measurement}} = -238^{\circ} \text{ F}$  ;  $T_{\text{reference}} = 80^{\circ} \text{ F}$  ; Voltmeter voltage = ???

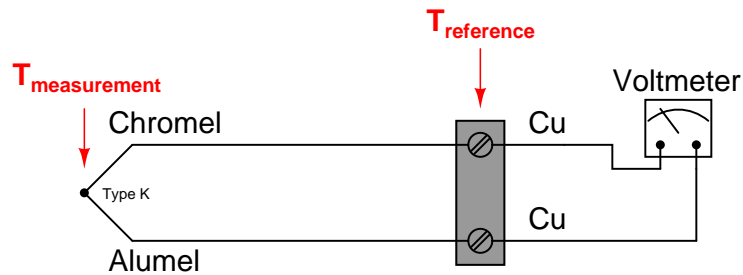
### Suggestions for Socratic discussion

- Students often get confused regarding the mathematical relationship between measurement junction voltage and reference junction voltage. Do these voltages aid each other (add), or do they oppose each other (subtract)? Devise a simple “thought experiment” whereby you may prove to yourself which of these stated relationships is correct.

[file i00380](#)

### Question 69

Determine the temperature of the measurement junction in this thermocouple circuit (type K), given the reference junction temperatures and the voltmeter indications. Round your answer to the nearest whole degree Fahrenheit:



- $T_{reference} = 70^{\circ} \text{ F}$  ; Voltmeter voltage = 20.018 mV ;  $T_{measurement} = ???$
- $T_{reference} = 65^{\circ} \text{ F}$  ; Voltmeter voltage = 5.833 mV ;  $T_{measurement} = ???$
- $T_{reference} = 52^{\circ} \text{ F}$  ; Voltmeter voltage = 31.420 mV ;  $T_{measurement} = ???$
- $T_{reference} = 73^{\circ} \text{ F}$  ; Voltmeter voltage = -2.027 mV ;  $T_{measurement} = ???$

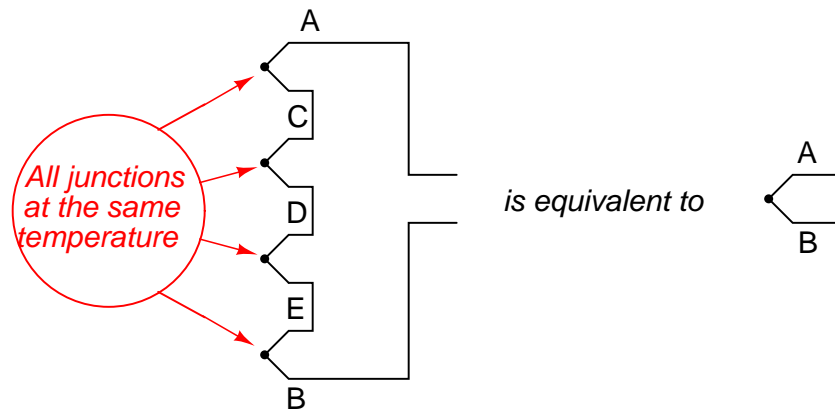
### Suggestions for Socratic discussion

- With RTDs, it is possible to use a *formula* to relate resistance with temperature rather than having to consult a table. Do you think this is possible for thermocouples as well? If so, what do you think the voltage/temperature formula describing a thermocouple might look like?

[file i00382](#)

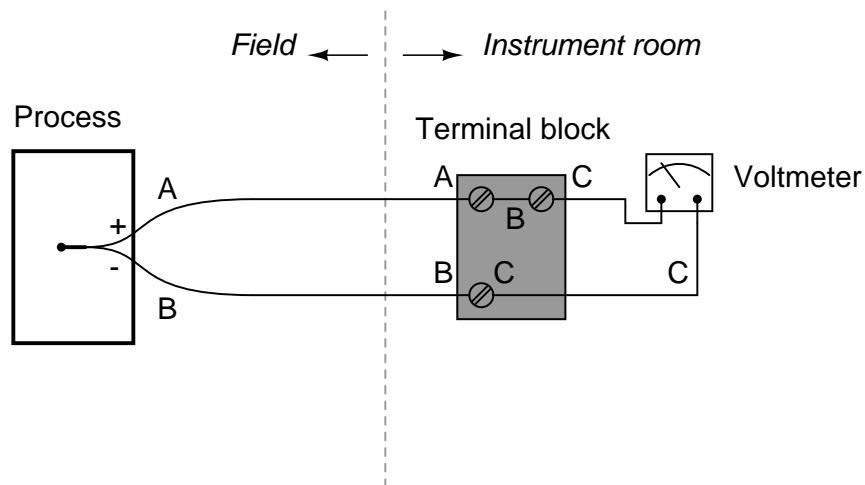
Question 70

It is a fundamental principle of thermocouple circuits that the voltage output by a junction will be the same as for a collection of isothermal ("same-temperature") junctions beginning and ending with the same metal types:



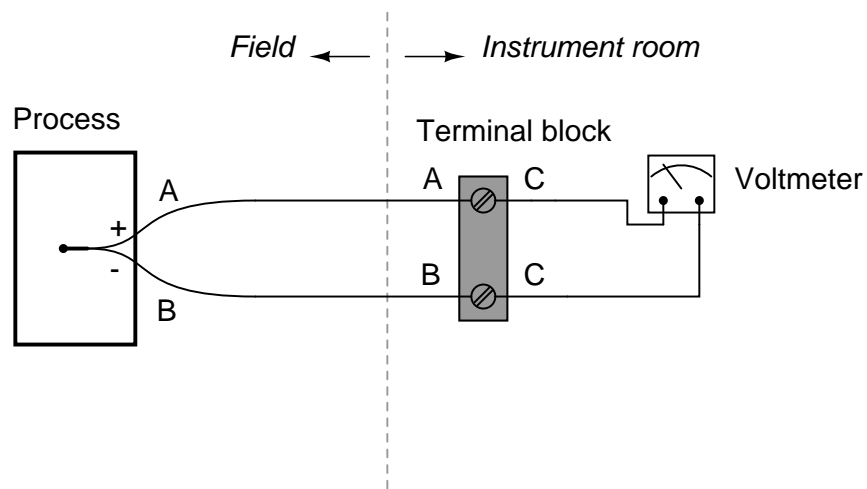
In other words, a junction comprised of metal **A** joining together with metal **B** will produce the same voltage as a collection of isothermal, series junctions **A-C**, **C-D**, **D-E**, and **E-B**. This is sometimes referred to as the Law of Intermediate metals.

Apply this equivalence principle to the following circuit, simplifying it so as to reduce the number of total junctions to an absolute minimum (assume that you can make the voltmeter wires out of any metal type you desire, so long as they're both the same):



Would the thermocouple work the same if we got rid of the metal **B** segment at the terminal block? Explain why or why not.

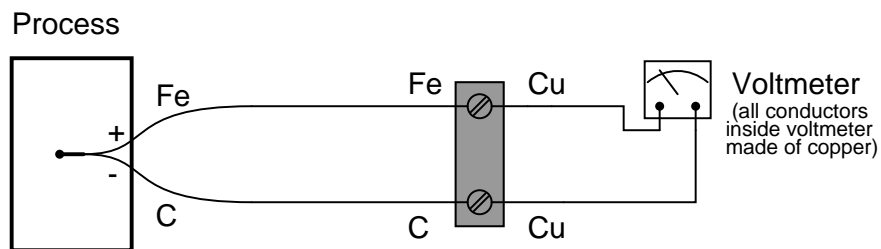
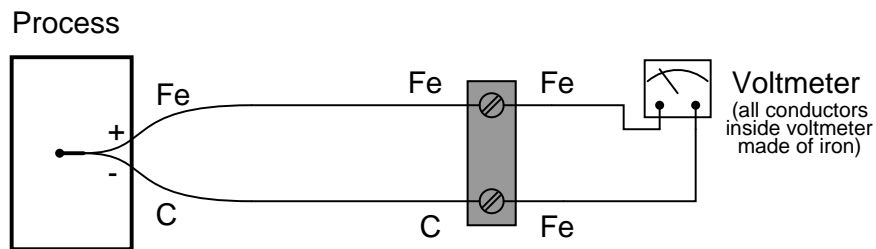




file i00373

#### Question 71

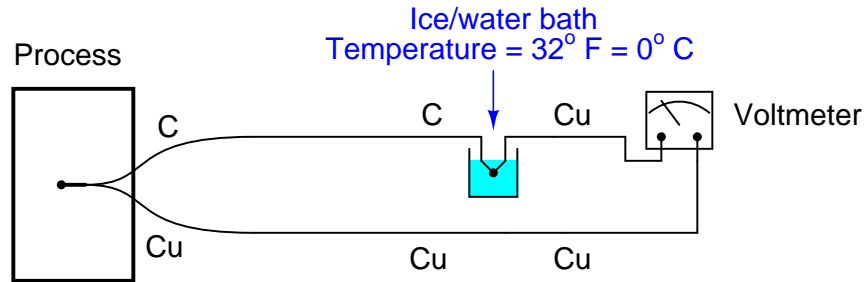
Are these two thermocouple circuits electrically equivalent? That is, will they produce the same voltmeter indication given the same temperatures? Why or why not? The abbreviations are as follows: Fe = Iron, C = Constantan, Cu = Copper.



file i00376

### Question 72

A type “T” thermocouple is made of the dissimilar metals copper (Cu) and Constantan (C). Copper is an element while Constantan is an alloy made up of copper and nickel. Thermocouple “tables” published by instrument manufacturers commonly give measurement junction output voltages for different temperatures for an assumed reference junction temperature of 32° F, or 0° C, the freezing point of pure water. Using such a table, determine the output voltages of a type “T” thermocouple constructed from 16 gauge solid wire at the following process temperatures:



- $T_{process} = 350^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = -65^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = 32^{\circ} \text{ F}$ ; Voltmeter voltage = ???
- $T_{process} = 100^{\circ} \text{ C}$ ; Voltmeter voltage = ???

Also determine the standard color codes for type T thermocouple wire:

- Positive conductor:
- Negative conductor:
- Thermocouple-grade jacket:
- Extension-grade jacket:

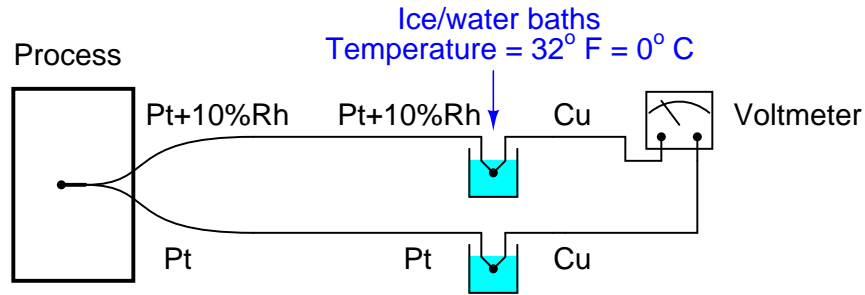
### Suggestions for Socratic discussion

- Explain the rationale of using an ice-water bath for the reference junction. Also, explain why only one of the reference junction connections is immersed in that bath, while the other (Cu/Cu) is not.
- If the ice-water mixture were to completely melt and rise in temperature, what effect would this have on the measurement accuracy of the thermocouple circuit? Would it result in a *zero* shift, a *span* shift, or a change in *linearity*?

file i00367

### Question 73

A type “S” thermocouple is made of the dissimilar metals Platinum and Platinum-Rhodium (10%) alloy. Using a thermocouple table, determine the output voltages of a type “S” thermocouple at the following process temperatures:



- Voltmeter voltage = 11.857 mV;  $T_{process} = ???^{\circ} \text{F}$
- Voltmeter voltage = 6.381 mV;  $T_{process} = ???^{\circ} \text{F}$
- Voltmeter voltage = 1.972 mV;  $T_{process} = ???^{\circ} \text{F}$
- Voltmeter voltage = 0 mV;  $T_{process} = ???^{\circ} \text{F}$

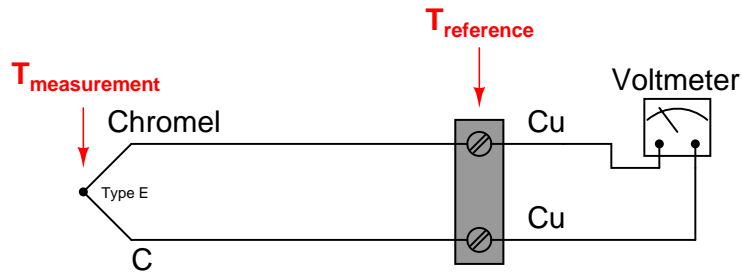
Also determine the standard color codes for type S thermocouple wire:

- Positive conductor:
- Negative conductor:
- Thermocouple-grade jacket:
- Extension-grade jacket:

[file i00369](#)

### Question 74

Determine the voltmeter’s indication in this thermocouple circuit (type E) for the following temperatures:

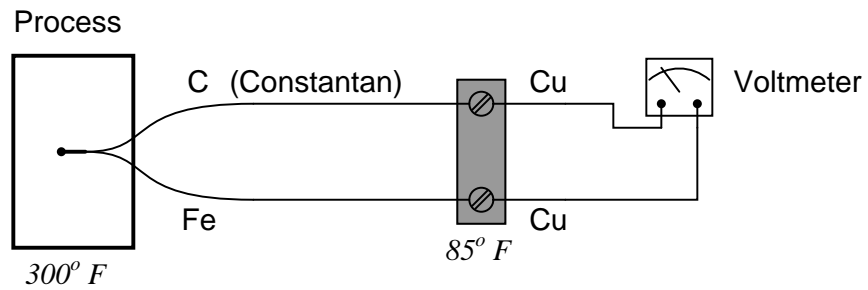
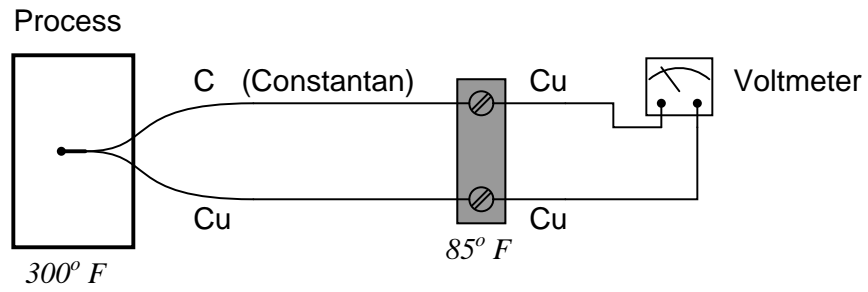


- $T_{measurement} = 1500^{\circ} \text{F}$  ;  $T_{reference} = 65^{\circ} \text{F}$  ; Voltmeter voltage = ???
- $T_{measurement} = 212^{\circ} \text{F}$  ;  $T_{reference} = 74^{\circ} \text{F}$  ; Voltmeter voltage = ???
- $T_{measurement} = -360^{\circ} \text{F}$  ;  $T_{reference} = 32^{\circ} \text{F}$  ; Voltmeter voltage = ???
- $T_{measurement} = -132^{\circ} \text{F}$  ;  $T_{reference} = -30^{\circ} \text{F}$  ; Voltmeter voltage = ???

[file i00381](#)

Question 75

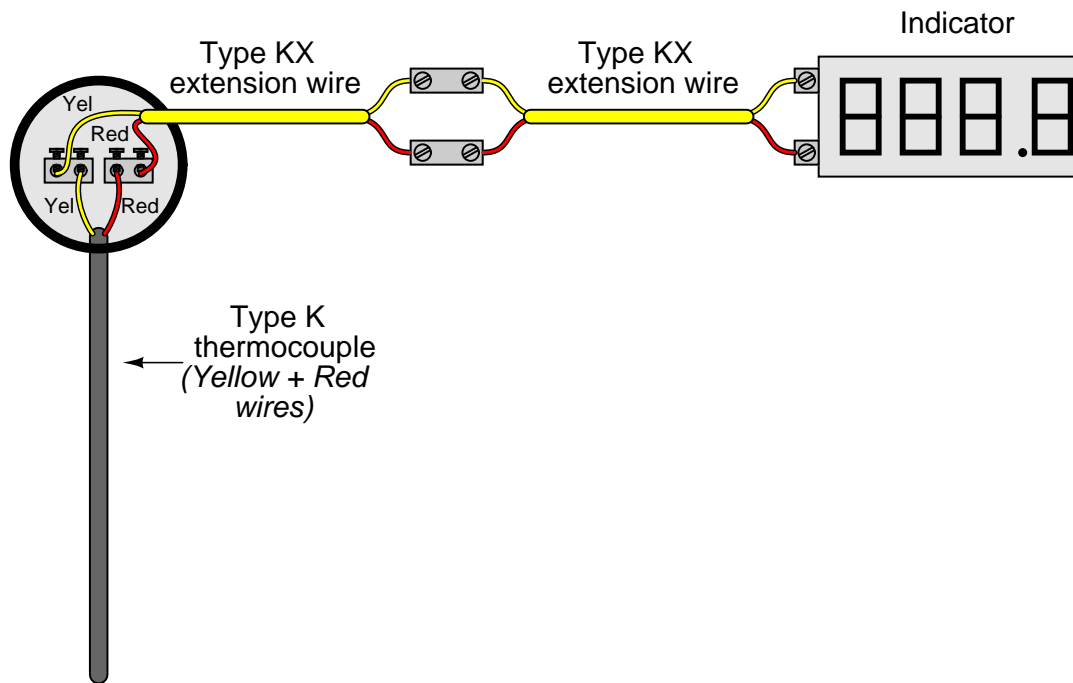
Determine the polarities of all voltage drops across all junctions made of dissimilar metal wires in the following thermocouple circuits:



file i00375

Question 76

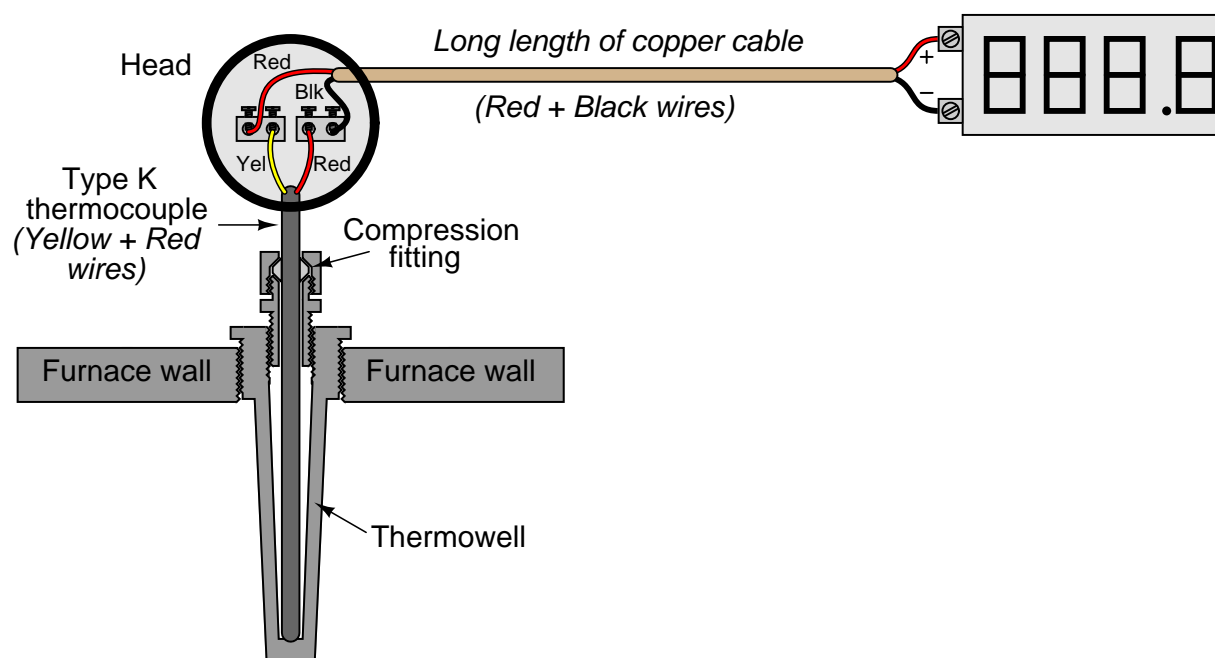
How many reference junctions does this thermocouple circuit have, and where exactly are they located?



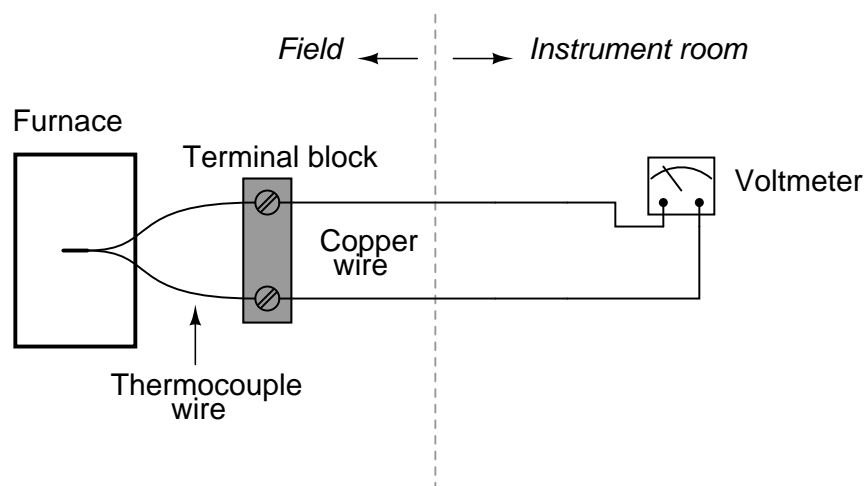
file i02972

Question 77

Thermocouple wire can be quite expensive in some cases. Suppose a technician is tempted to save money, and decides to use a copper wire pair to span the distance between the thermocouple “head” and the control room where the indicating instrument is located, instead of thermocouple wire or thermocouple extension wire:



Drawn in more of a schematic diagram form, the circuit looks like this:



Explain why this attempt to save money is a bad idea.

[file i00374](#)

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### Question 78

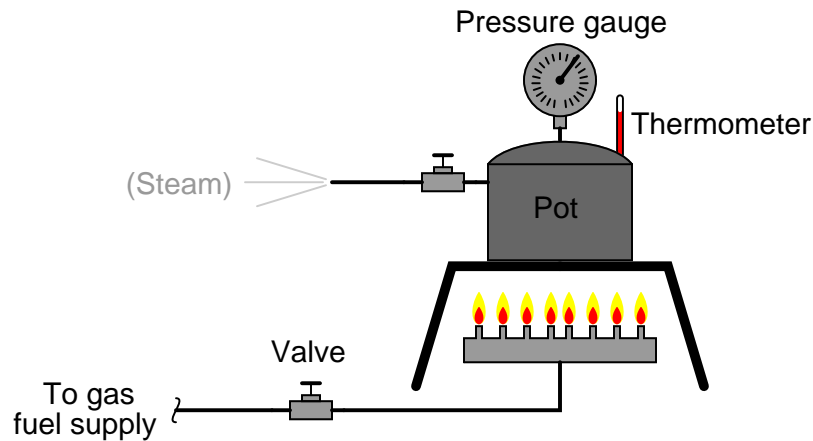
Is the temperature/resistance transfer function of an RTD more or less linear than the temperature/voltage transfer function of a thermocouple? What bearing does this have on the decision to choose a thermocouple versus an RTD for a temperature measurement application?

[file i00409](#)

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### Question 79

A student, weary of performing “thought experiments,” decides to perform a *real* experiment to better understand phase changes. She assembles a primitive steam boiler using a pressure cooker, a pressure gauge, a thermometer, a couple of valves, and a burner as a source of heat:



Her hypothesis is that boiler temperature may be controlled by fuel gas flow (burner heat rate output), and that boiler pressure may be controlled by steam flow out of the boiler. Two process measurements, and two control valves: what could be simpler?

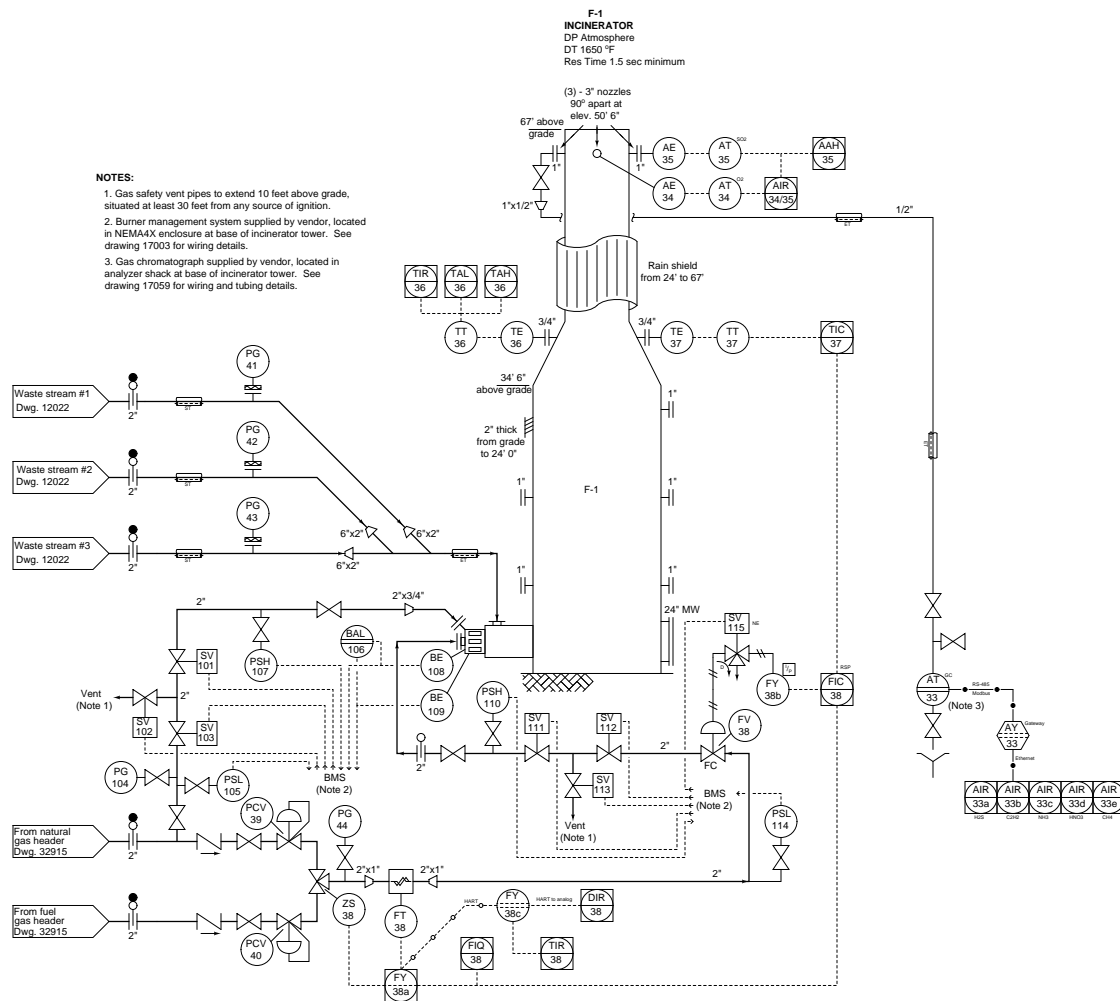
However, the student soon discovers that she cannot *independently* control boiler pressure and boiler temperature. When fuel flow is increased, *both* pressure and temperature rise; as the steam valve is opened, *both* pressure and temperature decrease.

Explain why this experiment did not go as planned, and what important lesson this student should learn about phase changes.

[file i01795](#)

## Question 80

This P&ID shows the controls for an incinerating flare, used to safely incinerate poisonous gas compounds from a chemical manufacturing process:



Suppose one day the operators tell you that the temperature of the flare stack is registering lower than it should. TIC-37 registers 1135 °F when the setpoint is 1400 °F. According to the operators, this low-temperature condition has persisted steadily for the last several hours, with stack temperature drifting around the 1140 °F mark.



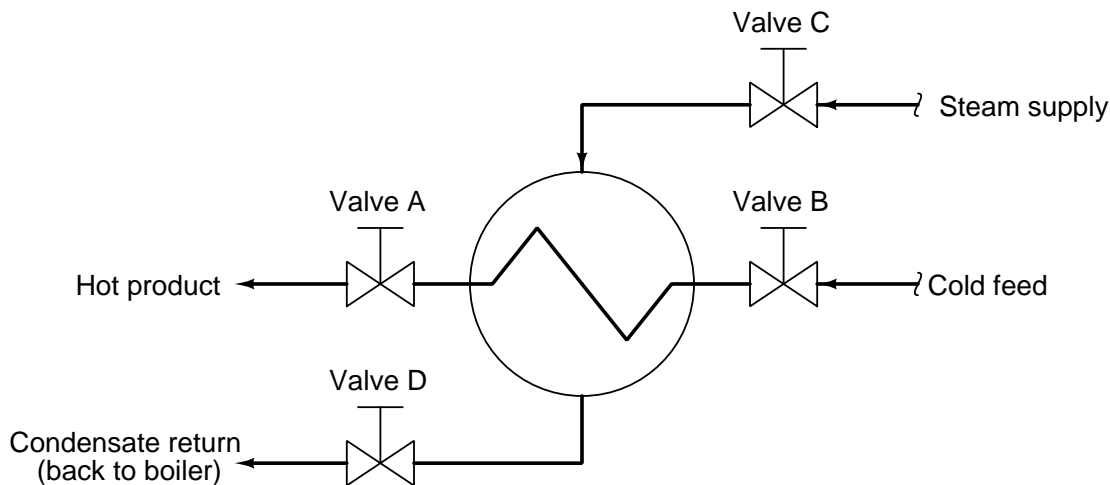
Identify the likelihood of each specified fault in this process. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this process.

<b>Fault</b>	<b>Possible</b>	<b>Impossible</b>
PCV-40 set too low		
Partial blockage in FT-38		
Burner management system tripped (shut down)		
Low air supply pressure to FY-38b		
Air leak in solenoid SV-115		
Solenoid SV-101 shut		
Solenoid SV-103 shut		
6 inch waste stream header line blocked		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.  
file i03487

Question 81

Determine all actions that will result in an *increased* product temperature in the “hot product” pipe (as it exits the heat exchanger), assuming the use of saturated steam (i.e. steam at its boiling/condensing temperature) as the heating fluid:



Identify the validity of each possible action in this list by checking boxes in the table – whether the action will result in an increased product temperature or whether it will not. Assume all valves are throttling (neither fully open nor fully closed, but each one working to restrict flow through it), and that the words “open” and “close” refer to incremental motion rather than extreme travel (i.e. opening or closing each valve just a bit, rather than *fully* opening or *fully* closing each valve):

Action	Will work	Will not work
Open valve A		
Close valve A		
Open valve B		
Close valve B		
Increase steam supply pressure		
Decrease steam supply pressure		
Increase incoming feed temperature		
Open valve C		
Close valve C		

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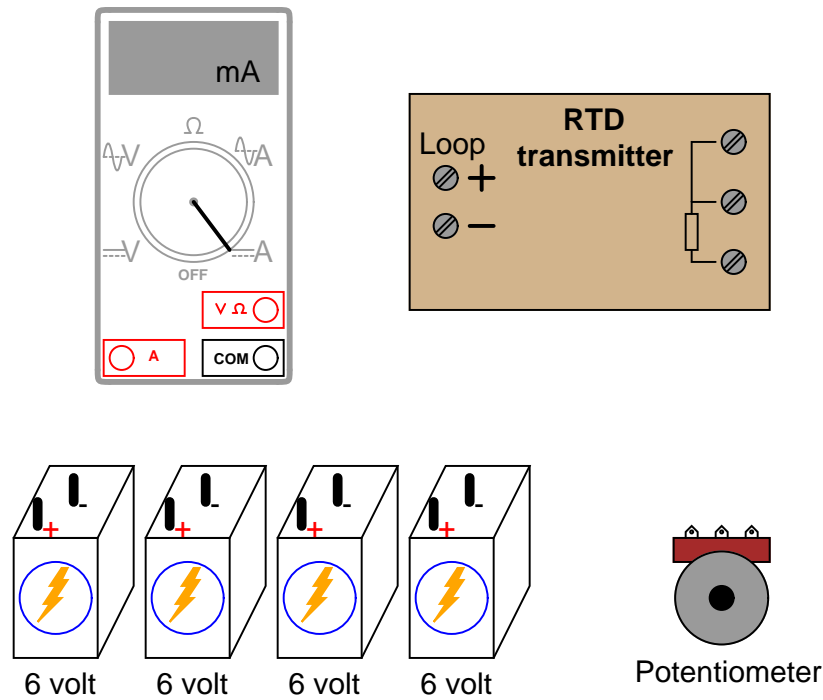
Question 82

Complete the following table of equivalent temperatures:

$^{\circ}\text{F}$	$^{\circ}\text{R}$	$^{\circ}\text{C}$	K
59			
		-10	
	560		
			307
-99			
			2
	1588		
		355	

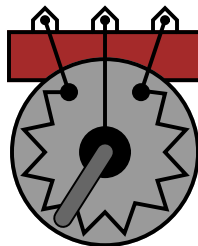
Question 83

Suppose you needed to simulate an RTD to the input of a temperature transmitter, using a  $\frac{3}{4}$ -turn potentiometer:



Sketch the necessary connecting wires so that the simulated RTD signal to the transmitter increases as the potentiometer's shaft is rotated *clockwise*, and so that the multimeter registers the transmitter's 4-20 mA signal (using the batteries as a 24 VDC loop power supply) as a positive numerical value.

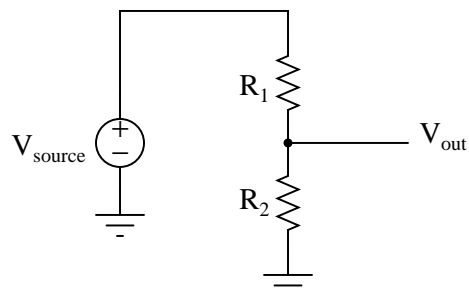
Note the internal construction of a typical  $\frac{3}{4}$ -turn potentiometer, as shown in this illustration:



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Question 84

Design a thermistor circuit that produces an increasing output voltage with increasing temperature.  
Hint: the topology of the circuit may be as simple as this:



You will need to choose which resistor ( $R_1$  or  $R_2$ ) to make the thermistor and which to make fixed, and also choose which type of temperature coefficient the thermistor will have (either *positive* or *negative*). After making these choices and drawing your circuit below, explain how it works (i.e. what happens to all the voltages and currents as temperature increases):

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Question 85

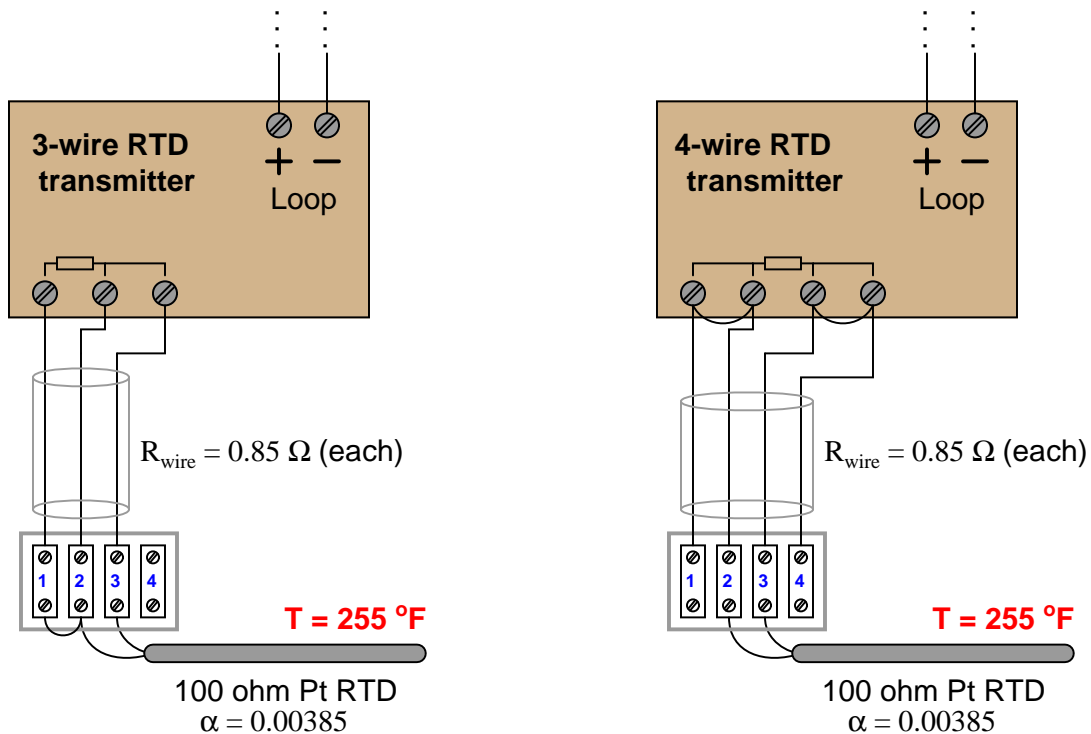
Calculate the following values involved with heating a pot of water (2.1 pound aluminum pot, 5.6 pounds of water) from 58 degrees Fahrenheit to boiling:

- Amount of heat necessary to achieve boiling temperature = \_\_\_\_\_ BTU
- Amount of time to achieve boil (assuming 10,000 BTU/hour heat input) = \_\_\_\_\_ minutes
- Amount of additional heat necessary to convert 2 pounds of water into steam = \_\_\_\_\_ BTU

Be sure to show all your work!

Question 86

Each of these illustrations shows an RTD connected improperly to a temperature transmitter. Correct the mis-wiring, and also calculate the temperature “seen” by the transmitter given the improper sensor connections:



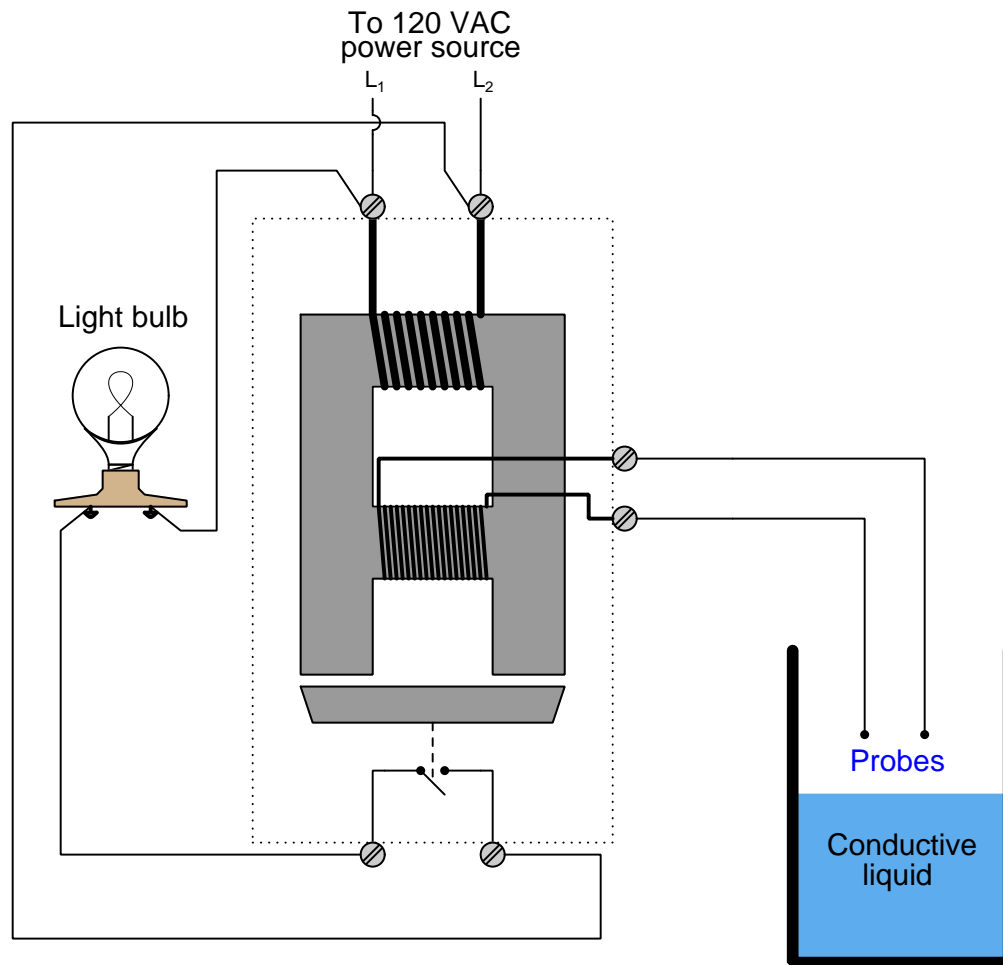
$T_{\text{indicated}}$  with incorrect 3-wire RTD wiring = \_\_\_\_\_

$T_{\text{indicated}}$  with incorrect 4-wire RTD wiring = \_\_\_\_\_

Identify whether or not these measurement errors could be compensated by recalibrating the transmitter. If so, identify which calibration adjustment (zero or span) would have to be changed on the analog transmitter.

Question 87

This inductive liquid level relay produces 800 volts between the sensing probes when no contact is made with the liquid, from a 120 volt AC power source:



Assuming 200 turns of wire in its primary winding, calculate the following parameters. Assume for the sake of simplicity that the relay's armature has not yet "picked up" when the liquid first contacts the probe tips:

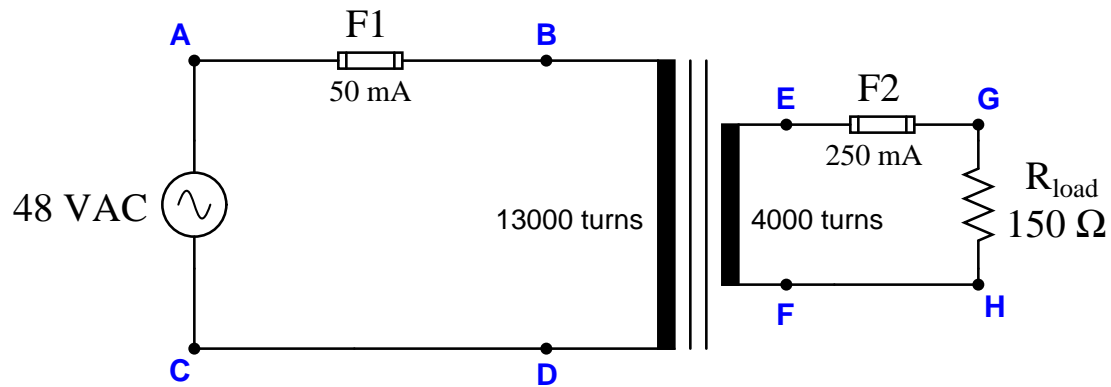
- Number of turns in the secondary winding = \_\_\_\_\_
- Primary winding current when liquid  $R$  is  $20,000\ \Omega$  = \_\_\_\_\_
- Secondary winding current when liquid  $R$  is  $20,000\ \Omega$  = \_\_\_\_\_

Also, explain why it is important to know that the armature is still in its "resting" position for the sake of these calculations.



Question 88

Suppose a voltmeter registers 0 volts between test points **E** and **F** in this step-down transformer circuit:



First, calculate the AC voltage and current we would expect to see at the load resistor. Then, 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
Fuse F1 blown		
Fuse F2 blown		
Primary windings failed open		
Secondary winding failed open		
$R_{load}$ failed shorted		
$R_{load}$ failed open		
Wire between F and H failed open		

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

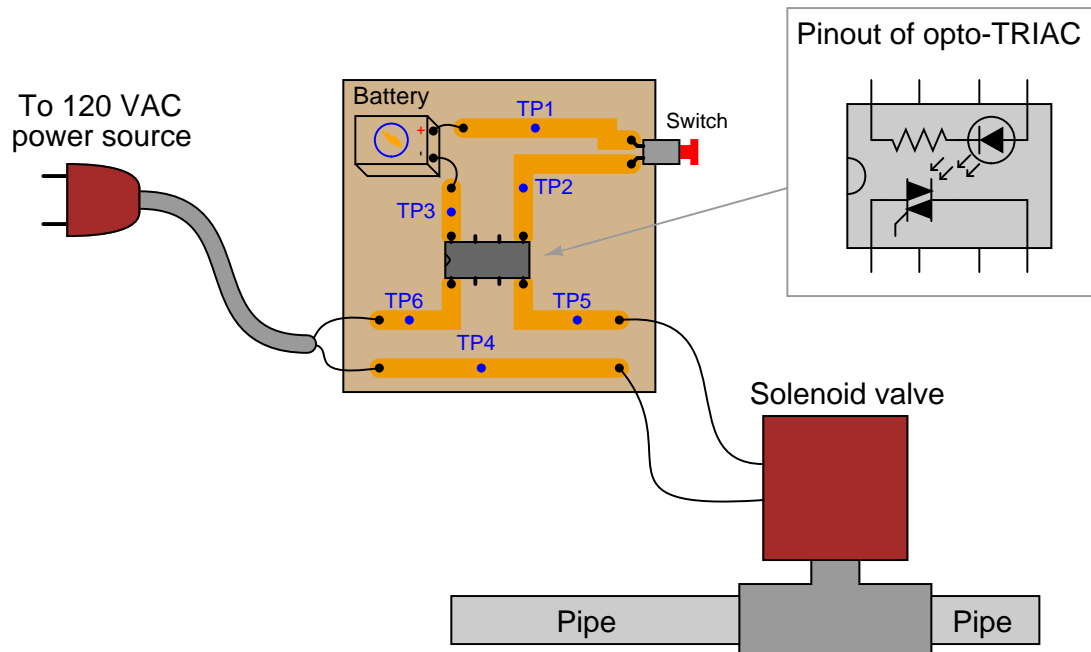
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Question 89

Suppose a farmer working hard in his field on a hot summer day loses 2 pounds of water due to sweat (evaporative body cooling). Use a *steam table* to calculate the heat lost due to the phase change from liquid (sweat droplets) to vapor (water vapor into the air) on his skin at a temperature of 90 degrees Fahrenheit. Express your answer in the unit of *dietary Calories* (the type of “Calorie” used to rate food energy).

### Question 90

A technician is troubleshooting a faulty optically-isolated TRIAC power switching circuit. The solenoid valve is supposed to open up and pass liquid through it whenever the pushbutton switch is pressed, but it remains shut no matter what state the switch is in:



Leaving the switch in its normal (“unpressed”) position, the technician measures 120 volts AC between test points TP5 and TP6, and 9 volts DC (normal for the battery) between test points TP1 and TP3. Based on these voltage measurements, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted). The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

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

**Lab Exercise – introduction**

Your task is to build, calibrate, document, and program a temperature measurement system consisting of an electronic temperature transmitter connected to one of the analog inputs of a data acquisition module (DAQ) for a SCADA RTU (Remote Terminal Unit) node. The particular SCADA system we will be using has been designed specifically for BTC Instrumentation students. It is called *caSCADA* and it is based on a single-board computer running the Linux operating system. In this lab exercise you will be configuring the RTU node to receive a temperature transmitter's 4-20 mA analog signal and properly condition that data for visual display on a remote computer. This will involve editing some of the programming code written in the "C" language. Your instructor will assign the temperature to be measured, as well as the specific channel(s) to use on the *caSCADA* system for your loop.

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

Objective completion table:

Performance objective	Grading	1	2	3	4	Team
Team meeting and prototype sketch (do <i>first!</i> )	mastery	–	–	–	–	
Final loop diagram and system inspection	mastery					– – – –
T/C signal simulation ( $\pm 1\%$ of span accuracy)	mastery					– – – –
RTD signal simulation ( $\pm 1\%$ of span accuracy)	mastery					– – – –
Linux command-line usage	mastery					– – – –
Editing and running <i>caSCADA</i> code	mastery					– – – –
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

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

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

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

## Lab Exercise – objectives and expectations

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

### Team meeting and prototype sketch

Meet with your instructor prior to any project construction, presenting the design as a prototype sketch. *Analyze the circuit represented in your prototype sketch, being sure to annotate the diagram with all expected voltages and currents, and identifying all electrical sources and loads. Be prepared to identify the effects of specific faults your instructor may propose in this circuit, applying principles such as series and parallel network properties, Kirchhoff's Laws, and Ohm's Law.* Read the lab exercise documentation in its entirety and discuss with your teammates prior to this meeting, where you may ask questions and clarify expectations with the instructor. Be prepared to answer questions from your instructor about this lab exercise, especially regarding any unique safety or procedural details described in the documentation.

### Final loop diagram and system inspection

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

### T/C signal simulation

Simulate a thermocouple signal to the input of your transmitter for a temperature randomly selected by the instructor, based on thermocouple tables and measured ambient temperature, demonstrating that the system displays within  $\pm 1\%$  of that temperature.

### RTD signal simulation

Simulate an RTD signal to the input of your transmitter for a temperature randomly selected by the instructor, based on RTD tables or formulae, demonstrating that the system displays within  $\pm 1\%$  of that temperature.

### Linux command-line usage

Demonstrate proper use of Linux commands described in the lab exercise documentation as called upon by the instructor.

### Editing and running caSCADA code

Edit your team's caSCADA source code file and recompile to express your transmitter's output in a unique range (and/or unit) specified by the instructor.

## Lab Exercise – objectives and expectations (continued)

### Lab percentage score

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

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

### Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, 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 without the instructor's presence so long as that work does not disturb the learning environment for other students.

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

## Lab Exercise – team meeting, prototype sketch, and planning the system

An important first step in completing this lab exercise is to **meet with your instructor** as a team to discuss safety concerns, team performance, achievement expectations, 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. This team meeting will also be an opportunity to clarify expectations on all lab project objectives, so everyone on the team knows exactly what is being asked of them. *Completely read the lab exercise documentation and discuss it with your teammates prior to meeting with the instructor.*

An absolutely essential step in completing this lab exercise is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This diagram must show all connections between components. It need not be exhaustive in detail, but it must show enough for the instructor to determine if all components will function properly and safely. *Any team found constructing their system without a verified plan will be ordered to cease construction and not resume until a prototype plan has been drafted and approved!*

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

Your first step should be selecting proper field instruments from the instrument storage area to use in building your system. In this particular lab, you are looking for an electronic temperature transmitter, either “smart” or analog. The Rosemount model 644/3044/3144/3244 transmitters are good examples of smart transmitters, while the Rosemount model 444 is a good example of an analog transmitter. Note that analog transmitters are built *either* thermocouple or RTD input. Since you will need to calibrate *both* types in this lab activity, this will require two different analog transmitters! If you choose to use a “smart” transmitter, however, you need only select one because digital temperature transmitters are usually configurable for both RTD and thermocouple input.

The next step should be finding appropriate documentation for your temperature transmitter. Nearly every instrument in the lab is documented electronically at the manufacturer’s website, so your best resource is the Internet (and/or your Instrumentation Reference where a variety of instrument manuals have been downloaded for you). Use this documentation to identify how to properly connect and calibrate the transmitter.

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For an analog thermocouple transmitter, you may simply short (jumper) the thermocouple input terminals to make the transmitter “think” it is measuring ambient temperature. For an analog RTD transmitter, you may connect a 100  $\Omega$  resistor to the RTD input terminals to make it “think” it is measuring the freezing point of water. For a digital (“smart”) transmitter, first use a HART communicator to configure it for either 2-wire RTD or thermocouple input, then proceed with these tests. If the transmitter fails to respond properly, tag it with a label explaining what it does (or what it fails to do).

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

## Lab Exercise – loop diagram and system inspection

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

### Construction Standards

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

### Documentation Standards

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



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

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

#### **Common mistakes:**

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

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

## Lab Exercise – building the system

Each RTU contains power circuitry and terminal blocks set up to marshal analog signals from field instruments to a data acquisition device. A generic loop diagram (shown in the following question of this worksheet) shows how any field device may connect to the DAQ. Your final loop diagram will simply be a customized version of this generic diagram provided to you near the end of this worksheet.

Each loop has a pre-assigned loop number, kept on file by the instructor to ensure each loop is uniquely labeled. Your transmitter and its signal wiring should be labeled with the loop number to distinguish it from other loops.

### Common mistakes:

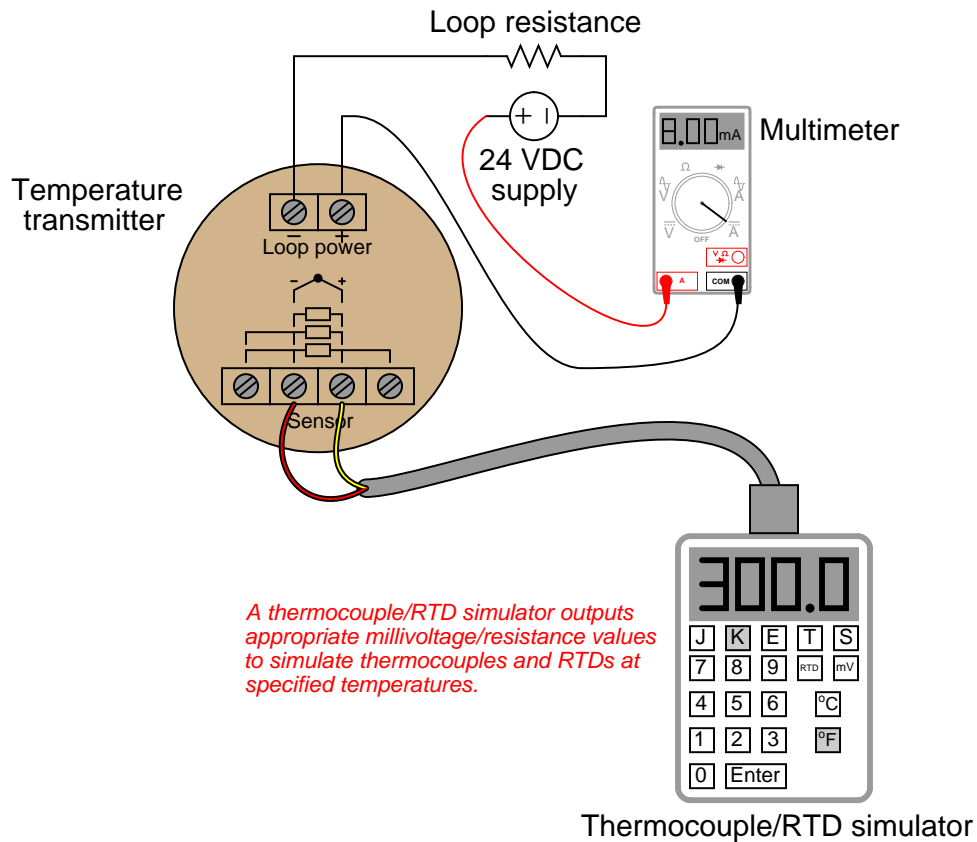
- Neglecting to consult the manufacturer's documentation for field instruments (e.g. how to wire them, how to calibrate them).
- Mounting the field instrument(s) in awkward positions, making it difficult to reach connection terminals or to remove covers when installed.
- Failing to tug on each and every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

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

## Lab Exercise – instrument calibration and signal simulation

Each team must calibrate the transmitter to ensure it interprets temperature accurately and outputs an accurate current, and also scale the SCADA system channel to register in the proper engineering units (e.g. a temperature transmitter ranged for 0 to 200 degrees F should actually register 0 to 200 deg F back at the SCADA system display). Instructions for programming the caSCADA system with the proper range for your measurement loop are explained later in this document. Each team should choose a temperature range that covers room temperature, but is something *other* than 0 to 100 degrees so they get practice setting range points on the controller to values other than the default (0 to 100%). Teams using a “smart” temperature transmitter may need to “trim” both the input and output of their transmitter, then set the range (LRV and URV points). Teams using an analog transmitter must apply LRV and URV electrical signals to the transmitter’s input while adjusting the “zero” and “span” potentiometers on the transmitter.

As in all cases where an instrument must be calibrated, you will need to check the instrument’s response against one or more *standards*. In this case, the standard we will use is either millivoltage (thermocouple) or resistance (RTD) applied to the input of the temperature transmitter using a thermocouple/RTD simulator, while we use a multimeter to measure the transmitter’s electronic output signal in DC milliamps:



This calibration may be performed at the calibration bench or other work-table, or in the field. Refer to the simulator’s documentation for more information on how to make proper wire connections to the transmitter being calibrated. This is especially helpful when simulating 3- or 4-wire RTD sensors.

Document the accuracy of your transmitter's sensor trim before and after adjustment in this table, at five different points throughout its sensing range using these two tables:

#### As-Found calibration table

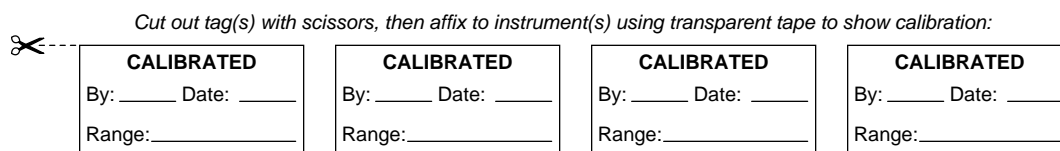
Applied temperature	Output signal (actual)	Output signal (ideal)	Error (% of span)

#### As-Left calibration table

Applied temperature	Output signal (actual)	Output signal (ideal)	Error (% of span)

$$\text{Error as \% of span} = \left( \frac{\text{Actual} - \text{Ideal}}{\text{Span}} \right) (100\%)$$

When finished calibrating your team's transmitter, be sure to place a calibration tag on it showing the range and the date it was calibrated. A set of calibration tags are shown here which you may cut out and tape to the transmitter after completing your calibration:

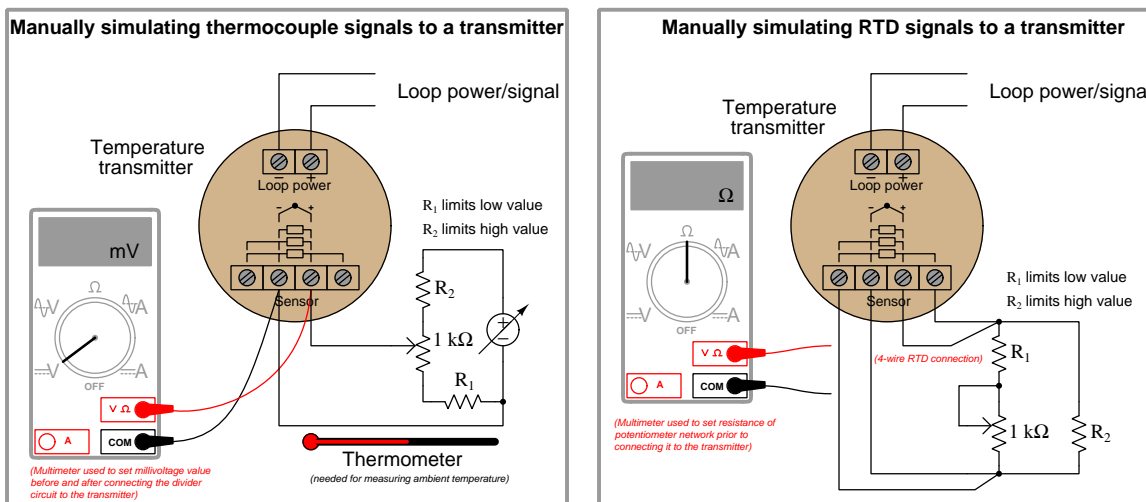


After each team calibrates their transmitter and installs it in the working system, each student on the team must then individually demonstrate their understanding of the electrical signals generated by thermocouples and RTDs by manually simulating appropriate signals at the input of the transmitter to make it register random temperatures called out by the instructor. The purpose of doing this is to ensure each student understands how thermocouples and RTDs actually work, and are familiar with the purpose and use of thermocouple and RTD tables.

For example, if a team calibrates and installs a type J thermocouple transmitter with a range of 0 to 150 degrees Fahrenheit, the instructor will choose a different temperature value within that range (e.g. 102, 93, 77, 128 °F) for each student on the team to simulate using simple electrical equipment (no thermocouple/RTD simulators allowed here!). Each student passes the "T/C signal simulation" objective when they are able to successfully simulate a specified temperature using nothing more than a multimeter and a low-voltage source (e.g. a DC power supply connected to a voltage divider circuit). Each student passes the "RTD signal simulation" objective when they are able to successfully simulate a specified temperature using nothing more than a multimeter and a low-range variable resistance (e.g. a potentiometer, or a decade resistance box). The instructor checks to see that the temperature value specified appears on the SCADA system display to within  $\pm 1\%$  of transmitter span.

The following illustrations show the general scheme of thermocouple (“T/C”) and RTD signal simulation. Resistor values shown in these illustrations are examples only, and may need to be modified for your particular application. *Invest the necessary time for all team members to thoroughly understand how and why these potentiometer networks function as thermocouple and RTD simulators.* A convenient way to determine necessary values for  $R_1$  and  $R_2$  is to set up a computer spreadsheet or use circuit simulation software to experiment with different  $R_1$  and  $R_2$  values to get the desired range of adjustment from your potentiometer. This adjustment range must be reasonable for your temperature transmitter, and be narrow enough that your potentiometer will yield sufficiently fine resolution which is especially important if it only has a 3/4 turn movement range:

**Please note that a thermocouple temperature transmitter is easily damaged by providing it with excessive signal voltage. These instruments are designed to receive MILLI-VOLT signals, and so your voltage divider circuit must be designed in such a way that it cannot generate any signal exceeding the transmitter’s maximum rating. Be sure to research your transmitter model’s maximum input signal voltage value before designing the voltage divider circuit!!**



It is recommended that you use a terminal strip rather than a solderless “breadboard” to construct your potentiometer networks, due to the unstable contact resistance typical of breadboards. Use the “relative” function on your DMM’s resistance scale to “zero out” the electrical resistance of your meter’s test leads when using it to set the resistance of your RTD-simulating network. If your DMM supports a “high resolution” mode for millivoltage measurement, you should use that mode when setting the voltage signal of your thermocouple-simulating network. For RTD and thermocouple simulation alike, adjustments should be made with the simulation circuit disconnected from the transmitter, to avoid interference between the transmitter and the multimeter.

Students typically find the accurate simulation of thermocouple signals to be more challenging than RTD signals, since RTDs simply manifest a certain amount of resistance at each temperature, while thermocouple signals vary with the process (measured) temperature *and* the ambient temperature at the transmitter terminals. For more information on the simulation of thermocouple signals, refer to the “Thermocouples” section of the “Continuous Temperature Measurement” chapter of *Lessons In Industrial Instrumentation*.

### Common mistakes:

- Applying excessive voltage to the input of a thermocouple or RTD transmitter. Remember that thermocouples only output small amounts of voltage, in the low millivolt range. I have seen students **destroy** thermocouple transmitters by applying as little as 1.5 volts to its input terminals, thinking that would be a safe amount of voltage for the transmitter!!! To avoid this mistake, set the millivolt signal of your simulating circuit *before* connecting it to the input of your transmitter.
- Neglecting to accurately measure the ambient temperature when manually simulating a thermocouple signal (in order to look up the correct reference junction millivoltage).
- Mis-interpreting rows and columns in the thermocouple/RTD table when looking up millivoltage or resistance values.
- Trying to make potentiometer adjustments while connected to the transmitter's input terminals. This is especially true for RTD simulation, where the transmitter's excitation current to the RTD interferes with the multimeter's resistance measurement.
- Choosing a calibration ("trim") range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Ignoring the mathematical signs (+ or -) of error calculations.
- Neglecting to place a calibration tag on the transmitter after calibrating it.

**Calibrating your team's transmitter should take no more than one full lab session (3 hours) if the team is working efficiently!**

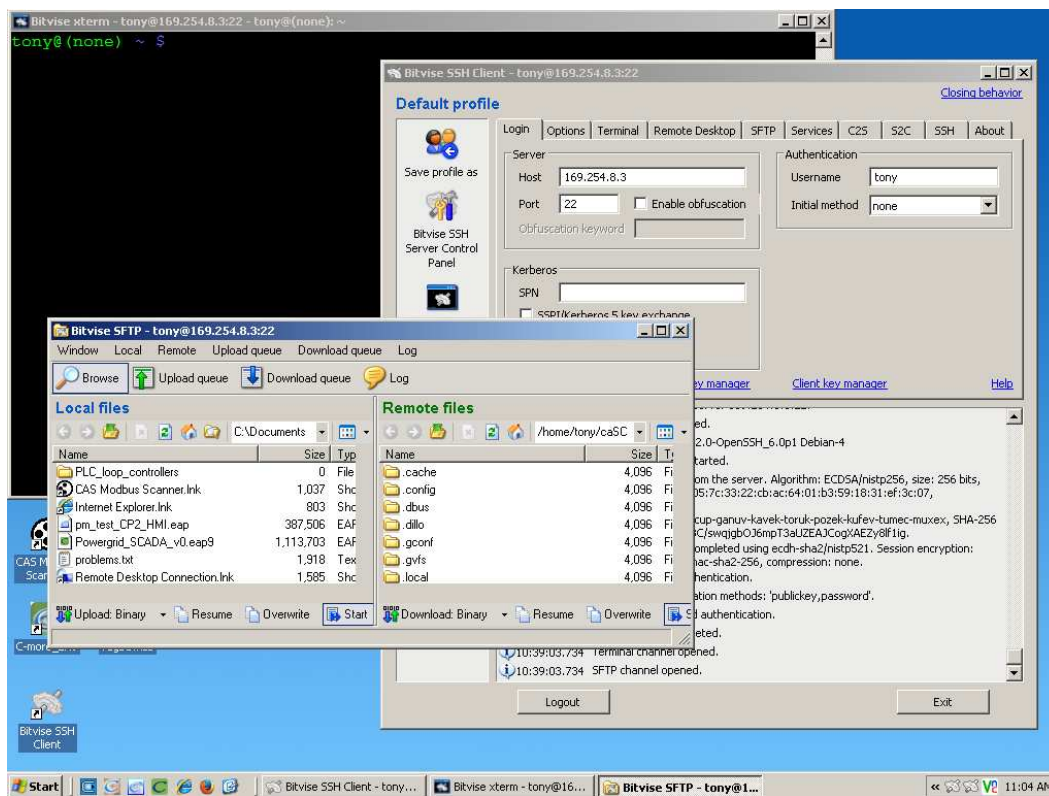
## Notes on using SSH for remote administration

Each caSCADA RTU is based on single-board computer running Linux operating system software, located inside an electrical enclosure without convenient physical access. Attaching a keyboard and monitor is impractical, therefore you will need to log in to this computer through some other means.

Fortunately, a digital communication protocol has been developed to permit remote access of Unix-based operating systems called *SSH*, which stands for *Secure SHell*. Any computer running an SSH client program is able to log into any Linux computer running an SSH server program. Any personal computers running a Unix-based operating system (e.g. FreeBSD, Linux, Apple's OS X) have SSH clients built in.

Microsoft Windows operating systems do not have native SSH client software, but one available for free download is **Bitvise**. Another one is called **PuTTY**. For the really ambitious there is even a complete Linux terminal emulation package for Microsoft Windows called **Cygwin**. Any of these programs will suffice, but the easiest to download, install, and use is **Bitvise**. Be sure you download and install the *client* software for **Bitvise**, and not the *server* software (which should already be installed and running on the single-board Linux computer)!

The following screenshot shows **Bitvise** running on a Windows XP machine, communicating with a model of single-board computer called a "Raspberry Pi":



Three windows appear in this screenshot: the **Bitvise** client through which the login connection is established (you must enter the RTU computer's IP address and Linux user name, then later enter the Linux password for that user account), the **Bitvise** SFTP window for file transfer between the two computers, and the **xterm** terminal window (the one with the black background and colorful prompt) where you may enter typed commands to the RTU computer. Since Linux is a multi-user operating system, many people can log into the RTU using their own individual Windows PCs, even under the same user name! All you need is a network connection to the RTU and its IP network address.

## Lab Exercise – Linux command-line usage

The caSCADA telemetry system is built on the foundation of a single-board computer running the Linux operating system. Linux is a very robust alternative to Microsoft Windows, and it happens to be entirely free. To use this operating system, you will need to become familiar with typing text-based commands into a *command-line interface* and reading the results given back to you by the computer, rather than pointing and clicking with a mouse. Linux does support mouse-based user interfaces, but the text-based interface is more efficient from the perspective of processing power and memory and so it is what we will use here.

If you have ever used the `cmd` (“command”) window on a Microsoft operating system to run utilities such as `ping` or `ipconfig` for network troubleshooting, you are already familiar with what a command-line interface is. Here is an example of the Linux command `ifconfig` (similar to the Windows command `ipconfig`) being run in the command-line interface:

```
tony@ (none) ~ $ ifconfig
eth0      Link encap:Ethernet  HWaddr b8:27:eb:ba:f9:0d
          inet addr:169.254.8.3  Bcast:169.254.255.255  Mask:255.255.0.0
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:77541 errors:0 dropped:385 overruns:0 frame:0
          TX packets:23178 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:10964517 (10.4 MiB)  TX bytes:4455164 (4.2 MiB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          UP LOOPBACK RUNNING  MTU:16436  Metric:1
          RX packets:2 errors:0 dropped:0 overruns:0 frame:0
          TX packets:2 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:100 (100.0 B)  TX bytes:100 (100.0 B)

tony@ (none) ~ $
```

The dark blue text (`~ $`) is called the *prompt*, which shows me which directory on the computer’s filesystem I’m currently viewing and working under. The green text to the left of the prompt tells me I’m logged into the Linux operating system under the username `tony` with an undefined domain name. In a fully configured system, the domain might be something like `btc.edu` or `RTU_MC1`. The white text `ifconfig` is the command I typed (pressing the Enter key at the end), and the two “paragraphs” of text following that line are the results of running the `ifconfig` command. In this particular example it tells me details about the two network interfaces operational on this computer: one Ethernet interface (`eth0`) and one called a “loopback” (`lo`).

There are a great multitude of typed commands available within the command-line environment of the Linux operating system. We will only need to use a few to do our work with the caSCADA system. The next several pages showcase those commands you should learn in order of their importance.



```
ls
```

The `ls` command lists the contents of a directory, or folder, on the computer's filesystem. Here is an example of the `ls` command being issued by myself (`tony`) while working in my “home” directory (`/home/tony` which is abbreviated as `~`):

```
tony@ (none) ~ $ ls
caSCADA Desktop letter.txt pistore.desktop
tony@ (none) ~ $
```

The two dark blue listings (`caSCADA` and `Desktop`) are both directories within my home directory (called “subdirectories”). Think of these as folders in which we may store files. The white listing (`letter.txt`) is a file. The light blue listing (`pistore.desktop`) is a *link* to a file of the same name located in a completely different directory. In the Microsoft Windows world, a link is called a *shortcut*.

```
ls -l
```

This is the same command, issued with the `-l` option. Many Linux commands have options you may specify, each one preceded by a dash. In this case, the `-l` option instructs the `ls` command to provide a *long* (i.e. more detailed) listing of the same files and directories. It should be noted that the `l` symbol is a lower-case letter L, and not the number 1.

```
tony@ (none) ~ $ ls -l
total 12
drwxr-xr-x 2 tony tony 4096 Oct  7 20:48 caSCADA
drwxr-xr-x 2 tony tony 4096 Jun 19  2013 Desktop
-rw-r--r-- 1 tony tony   39 Oct  9 20:29 letter.txt
lrwxrwxrwx 1 tony tony   44 Jun 19  2013 pistore.desktop -> /usr/share/indiecity/pistore/pistore.desktop
tony@ (none) ~ $
```

Here we see how the “long” listing provides much more detail. The series of 10 characters starting each line tell us what type of listing each line is and who has permission to use it (`d` for *directory*, `l` for *link*, a dash symbol for regular files, `w` for *write* permission, `r` for *read* permission, and `x` for *executable* permission). We can also tell the owner and group of each listing (`tony`), the size of the file in *bytes*, and the last date and time that listing was changed.

You will use the `ls` and `ls -l` commands frequently to see which files and directories are accessible to you.

## cd

The `cd` (“change directory”) command moves you from one directory to another. This is analogous to clicking on folder symbols in a Microsoft Windows environment. Here we see the `ls` command issued to list all the items in my home directory (`~`), then the `cd` command issued to descend into the `caSCADA` directory, then the `ls` command issued one more time to list all the files contained in the `caSCADA` directory:

```
tony@(none) ~ $ ls
caSCADA Desktop letter.txt pistore.desktop
tony@(none) ~ $ cd caSCADA
tony@(none) ~/caSCADA $ ls
cascada.h                f_channel_03.c  f_channel_12.c  f_channel_21.c  f_channel_30.c
cascada_poll.c           f_channel_04.c  f_channel_13.c  f_channel_22.c  f_channel_31.c
cascada_poll_simulate.c  f_channel_05.c  f_channel_14.c  f_channel_23.c  LICENSE.txt
cascada.tar              f_channel_06.c  f_channel_15.c  f_channel_24.c  Makefile
data.html               f_channel_07.c  f_channel_16.c  f_channel_25.c  poll
data.txt                f_channel_08.c  f_channel_17.c  f_channel_26.c  README.txt
f_channel_00.c           f_channel_09.c  f_channel_18.c  f_channel_27.c  simulate
f_channel_01.c           f_channel_10.c  f_channel_19.c  f_channel_28.c  write_datahtml.c
f_channel_02.c           f_channel_11.c  f_channel_20.c  f_channel_29.c  write_datatext.c
tony@(none) ~/caSCADA $
```

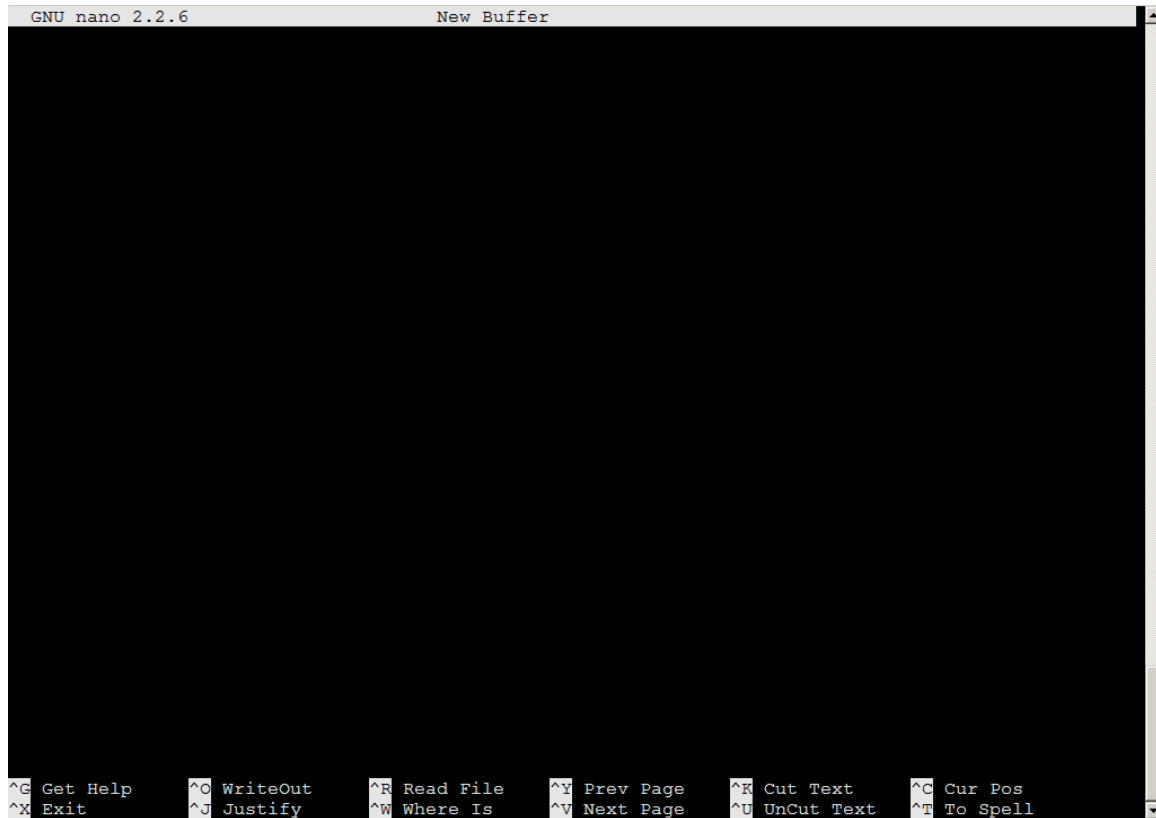
Note how the dark blue prompt changed from `~` to `~/caSCADA` after issuing the `cd` command. This is a reminder to you, the user, of which directory you are currently “in” as you do your work in the command-line environment.

If we wish to go back up one directory level, we invoke the command `cd ../` and it will take you there. If you wish to return to your home directory, simply invoke `cd` without any options or arguments and you will go back home regardless of your present location.

## nano

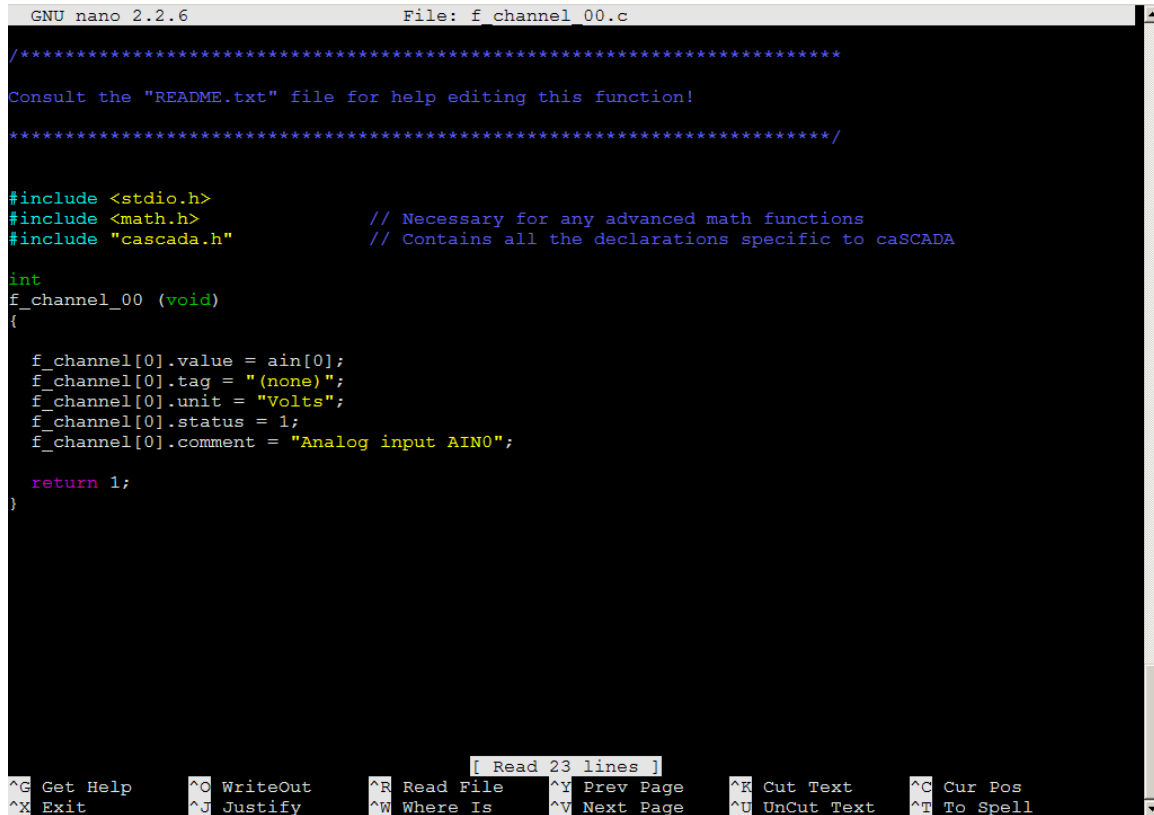
One of the most important applications you will use when using Linux is a *text editor*, used to create and modify plain-text files. You may think of a text editor as being a kind of simplified word processor because it doesn't offer any means of formatting the text to look nice on paper. However, text editors are powerful tools for programming because most offer *syntax-sensitive coloring* to render certain programming instructions in different colors to make them easier to identify.

**nano** is a popular text editor found on practically all Linux operating systems. It is fast and easy to learn, which is why I'm recommending it to you. To start this program, simply type **nano** at the command prompt and you will get a mostly blank screen with some key-command reminders at the bottom, like this:



Most of the screen is blank because **nano** hasn't been told to open any file, and therefore there is no content to view. This is like starting up Microsoft Word (a heinous monstrosity of a program) with a blank page, before we have typed anything. The inverse-colored symbols at the bottom of the screen show you common **nano** commands, such as viewing a help menu (**^G** which means holding the "Ctrl" key down while pressing the "G" key), or writing your edits to a file (**^O**), or exiting the **nano** text editor (**^X**) entirely.

If we wish to use **nano** to edit a particular file within our current directory instead, we would simply type **nano** at the prompt followed by the name of the file we wish to edit. Here we see the results of typing **nano f\_channel\_00.c** at the command-line prompt:



```
GNU nano 2.2.6 File: f_channel_00.c

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

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

int
f_channel_00 (void)
{
    f_channel[0].value = ain[0];
    f_channel[0].tag = "(none)";
    f_channel[0].unit = "Volts";
    f_channel[0].status = 1;
    f_channel[0].comment = "Analog input AIN0";

    return 1;
}

[ Read 23 lines ]
^G Get Help    ^O WriteOut    ^R Read File   ^Y Prev Page   ^K Cut Text    ^C Cur Pos
^X Exit        ^J Justify     ^W Where Is    ^V Next Page   ^U UnCut Text  ^T To Spell
```

The file named **f\_channel\_00.c** is one of the files containing programming code to instruct the caSCADA system what to do. This particular file controls the information for channel 0 in the caSCADA system. You will be editing a source file much like this one when you do your configuration work for the caSCADA system, just for a different channel number. The various colors rendered by **nano** as it views the contents of this file have different meanings in the *C* programming language, and make the code easier to comprehend than if it were all shown in white.

Once you are viewing the contents of a file, you may use the arrow keys, page up/down keys, Enter key, Delete key, Backspace key, and all the alpha-numeric keys on your keyboard to write and edit text into this file. When complete, you use the command **Ctrl-X** to save and exit from **nano**.

## cat

The *concatenate* command, abbreviated **cat**, simply reads the contents of a text file and prints it all to the screen in the command-line environment. In this example we see the **cat** command used to print the contents of a file named **data.txt** residing within the **caSCADA** directory we have navigated to:

```
tony@ (none) ~/caSCADA $ cat data.txt
F_CH #   TAG          VALUE          UNIT          COMMENT
0        (none)       4.2372        Volts          Analog input AIN0
1        (none)       3.8622        Volts          Analog input AIN1
2        (none)       1.6518        Volts          Analog input AIN2
3        (none)       1.5448        Volts          Analog input AIN3
4        (none)       2.1167        Volts          Analog input AIN4
5        (none)       1.6125        Volts          Analog input AIN5
6        (none)       2.9682        Volts          Analog input AIN6
7        (none)       1.3455        Volts          Analog input AIN7
8        (none)       1.6593        Volts          Analog input AIN8
9        (none)       3.5525        Volts          Analog input AIN9
10       (none)       1.8980        Volts          Analog input AIN10
11       (none)       1.4140        Volts          Analog input AIN11
12       (none)       4.6203        Volts          Analog input AIN12
13       (none)       3.9976        Volts          Analog input AIN13
14       (none)       0.0000        (none)         (none)
15       (none)       0.0000        (none)         (none)
16       (none)       0.0000        (none)         (none)
17       (none)       0.0000        (none)         (none)
18       (none)       0.0000        (none)         (none)
19       (none)       0.0000        (none)         (none)
20       (none)       0.0000        (none)         (none)
21       (none)       0.0000        (none)         (none)
22       (none)       0.0000        (none)         (none)
23       (none)       0.0000        (none)         (none)
24       (none)       0.0000        (none)         (none)
25       (none)       0.0000        (none)         (none)
26       (none)       0.0000        (none)         (none)
27       (none)       0.0000        (none)         (none)
28       (none)       0.0000        (none)         (none)
29       (none)       0.0000        (none)         (none)
30       (none)       0.0000        (none)         (none)
31       (none)       0.0000        (none)         (none)
tony@ (none) ~/caSCADA $
```

We could have easily viewed the contents of the **data.txt** file using a text editor program such as **nano**, but **cat** is faster and more convenient if all we want to do is *look* at what the file contains and not edit (change) it. While **cat** is useful for viewing **caSCADA**'s **data.txt** file, it may be used to view the contents of *any* plain-text file.

If you choose to learn more about the Linux, you will find that a great many details of the operating system are represented by and controlled by plain-text files. Knowing how to edit those files with a text editor and view those files using **cat** are nothing less than survival skills for Linux users.

Using the **cat** command to display the contents of the **data.txt** file is something you will undoubtedly find yourself doing as you work with the **caSCADA** system: this file happens to show all the conditioned data in the **caSCADA** system. As you can see here, the **data.txt** file shows us the last-recorded view of all analog input voltages being read by the data acquisition unit (DAQ), and later when we've customized the C programming code for our instrument loops this same file will show us the signals scaled and presented as real-world measurements.

who

Linux is a *multi-user* operating system, which means multiple people may log into one computer at any given time, either with individual login names or even under the same name! Microsoft Windows, by contrast, was designed to support only one user at a time. The **who** command gives a listing of all the users logged into the Linux operating system:

```
tony@ (none) ~ $ who
root      tty2      2015-10-09 21:28
tony      pts/0      2015-10-09 21:29 (169.254.15.90)
tony@ (none) ~ $
```

Here we see two users logged in: one named **root** and the other named **tony**. The green text preceding each command-line prompt tells us who we are (**tony**). If we had any doubt, we could issue the command **whoami** which will reply back with *our* user name.

The **root** user is sometimes called the *super-user* because of their unlimited privileges. The **root** user can delete or edit any file, in any directory, at any time. As far as the Linux operating system is concerned, **root** is God. Therein lies a lesson: never sign into a Linux system as **root** unless you are absolutely, one hundred percent sure of what you are doing.

The text **tty2** tells us that the **root** user is logged into the system at a keyboard that is directly plugged into the RTU computer. “**tty**” comes from the old days of *teletype* machines which were the equivalent of modern computer keyboards. The text **pts/0** (which stands for “pseudo terminal slave”) tells us that the user (**tony**) is logged into the system through a *network* connection. The four dot-separated numbers shown in parentheses (**169.254.15.90**) shows the IP network address of the other computer from which **tony** is logging in.

You will probably do most of your work on the caSCADA system via network connection to your own personal computer. Free software is available for your download that lets any Microsoft Windows PC remotely log into any Linux computer using the *SSH* (Secure SHell) protocol. This detail will be discussed later in this document.

All the work you will be doing on the caSCADA system will be through the user account **btc** (password also **btc**). This account will already be set up for you on each RTU’s computer.

```
ps
```

Linux is also a *multi-tasking* operating system, like Microsoft Windows. This means it has the ability to execute multiple programs at once. Single-processor computers manage this feat by switching attention really fast between all the running programs, giving the illusion that they're all running simultaneously.

Each running program is called a *process* (not to be confused with the term “process” as it applies to industrial instrumentation). Any user may view running processes on a Linux system by invoking the `ps` command, although this command (without any options) doesn't provide much information.

```
ps -e
```

If we run the command `ps -e` we will see a very long list of *every* process running in the operating system, including the `ps` command itself:

```
1909 ?      00:00:00 dbus-daemon
1970 ?      00:00:38 ntpd
1975 ?      00:00:01 ntpd
2034 ?      00:00:04 thd
2045 tty1    00:00:00 getty
2046 tty2    00:00:00 getty
2047 tty3    00:00:00 getty
2048 tty4    00:00:00 getty
2049 tty5    00:00:00 getty
2050 tty6    00:00:00 getty
2051 ?      00:00:00 getty
2053 ?      00:00:00 console-kit-dae
2120 ?      00:00:00 polkitd
2151 ?      00:00:03 flush-179:0
2266 ?      00:10:06 simulate
3340 ?      00:00:00 kworker/0:2
3903 ?      00:00:00 kworker/0:1
3964 ?      00:00:00 sshd
3972 ?      00:00:00 sshd
3979 ?      00:00:00 sshd
3980 ?      00:00:00 sshd
3987 ?      00:00:00 sshd
3988 ?      00:00:00 sftp-server
3989 pts/1    00:00:01 bash
4074 pts/1    00:00:00 ps
tony@ (none) ~ $
```

The list shown here is so long that it doesn't even fit the whole screen!

```
ps -u username
```

A more useful invocation of the `ps` command shows us all the processes that have been run under a specified user name. Here, we will view all the processes running under the user name `tony` by entering the command as `ps -u tony` (using the `-u` “user” option):

```
tony@ (none) ~ $ ps -u tony
  PID TTY          TIME CMD
 2266 ?      00:10:06 simulate
 3979 ?      00:00:00 sshd
 3987 ?      00:00:00 sshd
 3988 ?      00:00:00 sftp-server
 3989 pts/1    00:00:01 bash
 4076 pts/1    00:00:00 ps
tony@ (none) ~ $
```

Each line displayed by the `ps` command begins with a number, which is the *Process ID number*, or *PID* (not to be confused with “PID” control for industrial instrumentation!). This number will become very useful to us for the next command.

## kill

From time to time it may be necessary for a user to halt a running process, especially one that runs without a live user interface. This is done using the `kill` command, which works by specifying the process ID number (PID) of the process you wish to terminate.

The following illustration shows how to kill a running process called `simulate`, which happens to be one of the processes used in the caSCADA telemetry system. First, we see the `ps` command being used to list all the processes started by the user `tony` so we can identify its PID, then the `kill` command being invoked to halt that one process, then the `ps` command used again to prove the `simulate` process is no longer running:

```
tony@(none) ~/caSCADA $ ps -u tony
  PID TTY          TIME CMD
 2266 ?            00:10:07 simulate
 3979 ?            00:00:00 sshd
 3987 ?            00:00:01 sshd
 3988 ?            00:00:00 sftp-server
 3989 pts/1        00:00:02 bash
 4183 pts/1        00:00:00 ps
tony@(none) ~/caSCADA $ kill 2266
tony@(none) ~/caSCADA $ ps -u tony
  PID TTY          TIME CMD
 3979 ?            00:00:00 sshd
 3987 ?            00:00:01 sshd
 3988 ?            00:00:00 sftp-server
 3989 pts/1        00:00:02 bash
 4184 pts/1        00:00:00 ps
tony@(none) ~/caSCADA $
```

You will be doing this many times as you work with the caSCADA system, because processes such as `simulate` run in the “background” (i.e. they don’t prompt the user for any input, nor do they report any information to the command-line display). When you make changes to the caSCADA software, you will need to “compile” those edits into an executable file that Linux can run, kill the version of that program currently running, and start up your newly modified version.

As part of this lab exercise you will be asked to demonstrate the use of several of these commands, to ensure you are fluent enough in their use to work with the caSCADA system.

### Common mistakes:

- Not practicing the use of these commands.



## Lab Exercise – editing and running caSCADA code

The caSCADA system has been developed for the express purpose of teaching students how to write their own programming code in the C computer language, while at the same time building a working telemetry (SCADA) system measuring real-world data.

Each student team will be given a different piece of the caSCADA software (called a *function*) to modify for their own purposes. Each team's function resides in its own file ending with the extension `.c` which identifies it as a source code file written in the C language, just like a filename extension of `.txt` identifies the contents of a file as ASCII *text*, or a filename ending in `.pdf` identifies that file as an *Adobe PDF* document. Students will use a text editor to modify their source file, then they will use another program in the Linux operating system called a *compiler* to translate that source code into instructions that Linux can directly execute. After that, they will run their compiled program and monitor how well it performs the intended task.

Like much of the software found on Linux (including all the essential parts of the Linux operating system itself), caSCADA is an *open-source* project. This means all the source code files are available for perusal and modification. This is very different from most of the software that Microsoft Windows users are familiar with, which is generally “closed” and therefore cannot be modified by the end-user.

Most open-source software projects provide a text file called **README** or **README.txt** describing details about the project. caSCADA is no exception to this rule: in the caSCADA directory you will find such a file describing how the system works, complete with examples of how to modify the function code to perform practical conditioning on real-world data.

Here is a step-by-step summary of your program development cycle:

- (1) Use a text editor (one easy-to-use editor is named **nano**) to modify the source file for the channel you've been assigned. For example, if you are assigned caSCADA channel number 6, then you will need to edit the file named **f\_channel\_06.c** and then save those changes before exiting the text editor.
- (2) Next, re-compile the executable file by issuing a **make** command followed by the name of the executable you wish to create. The **make** command invokes the compiler software for you, handling a bunch of technical details along the way, to make this task simpler. You have only two options here: either run **make poll** to compile the executable called **poll** which gathers real data from the LabJack DAQ unit, or run **make simulate** to compile the executable called **simulate** which generates random data (useful in the absence of a LabJack DAQ) for your function to process.
- (3) Use the **ps** command to check for currently-running instances of the executable. If your user name is *btc*, for example, you will want to run **ps -u btc**. If one or more are running, halt them using the **kill** command. *There should never be more than one of poll or simulate running at any given time, and neither should you have poll and simulate running at once – just one or the other, that's all!*
- (4) Start up a new instance of that process by typing the name of the executable (either **poll** or **simulate** depending on what you want to do) preceded by **./** and followed by an ampersand symbol (**&**). For example, if you just compiled the **simulate** executable file, you would run it by typing **./simulate &** at the command prompt. To run the **poll** executable, type **./poll &** at the command prompt. Remember, you only need *one* of these running at any given time. Running multiple instances of **poll** and/or **simulate** will write possibly conflicting data to the data files.
- (5) Read the contents of the **data.txt** file to see how the data is being displayed. I recommend typing **cat data.txt** to do this. If a console-based web browser such as **lynx** is installed in the Linux computer, you may alternatively use it to view the contents of the **data.html** file which will produce results that are better-formatted for easier viewing than the plain text file. Both the **poll** and the **simulate** process updates both data files with fresh values once per second. If everything is working as planned, you're done! If not, go back to step 1 to fix your function and repeat all these steps.

You will find the caSCADA channel functions to be fairly easy to understand, even if you have never done any computer programming before. For example, here is a listing of the default code for the source file `f_channel_10.c`:

```
/******  
Consult the "README.txt" file for help editing this function!  
*****/  
  
#include <stdio.h>  
#include <math.h> // Necessary for any advanced math functions  
#include "cascada.h" // Contains all the declarations specific to caSCADA  
  
int  
f_channel_10 (void)  
{  
  
    f_channel[10].value = ain[10];  
    f_channel[10].tag = "(none)";  
    f_channel[10].unit = "Volts";  
    f_channel[10].status = 1;  
    f_channel[10].comment = "Analog input AIN10";  
  
    return 1;  
}
```

The only code you'll have to edit here is what falls between the curly brace characters (`{` and `}`): that is to say, the lines of code assigning values to each element of the `f_channel[10]` data structure. The first of these lines assigns `f_channel[10].value` to be equal to analog input 10 on the LabJack. If AIN10 on the LabJack happens to measure 4.307 volts, another portion of caSCADA will place that value into the external variable `ain[10]`, and when the `f_channel[10]` function is called by the main program the first line copies that value 4.307 into the variable `f_channel[10].value` where another portion of the caSCADA program will display it a file named `data.txt` (as well as in another file named `data.html`). The lines assigning text (between quotation marks) to the `.tag`, `.unit`, and `.comment` elements are for free-form text. The `.status` element is normally set to a value of 1 (which means "good" status), but may be set to other values at your discretion.

As written, this default function doesn't do much other than directly display channel 10's value in volts and applies some text labels. This is where your work becomes important: your task will be to modify the code for your channel to make it do something more useful, like scale the analog input's voltage value into a real-world measurement complete with appropriate units. This lab exercise is focused on *temperature*, and so your modified channel function will have to scale the received voltage signal into a temperature measurement expressed in *degrees* F, C, R, or Kelvin.

You are welcome to make your function code as simple or as sophisticated as you desire. Multiple examples are shown in the `README.txt` file located with the other source files on the RTU computer. The following code segment shows a simple version of the `f_channel_10.c` source file written to scale analog input number 3's 1-to-5-volt DC signal into a *pressure* measurement range of 0 to 75 PSI using a  $y = mx + b$  equation where  $m = 18.75$  and  $b = -18.75$ :

```
int
f_channel_10 (void)
{

    f_channel[10].value = (ain[3] * 18.75) - 18.75;
    f_channel[10].tag = "PT-42";
    f_channel[10].unit = "PSI";
    f_channel[10].status = 1;
    f_channel[10].comment = "Receiver tank pressure";

    return 1;
}
```

A good way for each student on a team to get experience programming a different mathematical function without having to re-range their team's transmitter each time is to re-program the function for a different unit of temperature measurement on the exact same calibrated range. For example, one student programs caSCADA to read out in degrees Fahrenheit, another in degrees Celsius, another in degrees Rankine, and another in Kelvin, but each and every one of these uses the exact same transmitter range. This objective could even be checked by the instructor at the same time as the RTD or thermocouple simulation objective, with the student applying a simulated RTD/thermocouple signal to the transmitter and showing that simulated temperature displayed in a unique unit on the caSCADA display (i.e. the contents of the live `data.txt` or `data.html` file).

If you would like to learn more about the mathematical and algorithmic capabilities offered by the C programming language, an excellent resource is the book *The C Programming Language* written by the inventors of C: Brian W. Kernighan and Dennis M. Ritchie. Many other C programming tutorials and references may be found on the internet as well. Suffice it to say, you can program each function to do almost *anything* to and with the channel data. You may even program your function to read the values, statuses, and text fields of other channels, since all default channel variables are “global” (also called *external*) and therefore accessible to all portions of the caSCADA software.

C is a professional-grade programming language, which means that although the caSCADA system was written for use as a student learning system, anyone wishing to extend the capabilities of caSCADA beyond its intended use is welcome and able to do so because the C language is sufficiently capable for practically any task. The fact that caSCADA is an *open-source* software project means anyone has the freedom to sample the C programming code and modify it to their heart's content without the need to request permission from the original developer. This is the real beauty of open-source software: it gives you both the right and the means to *learn* from the code and *extend* that code well beyond its original intent.

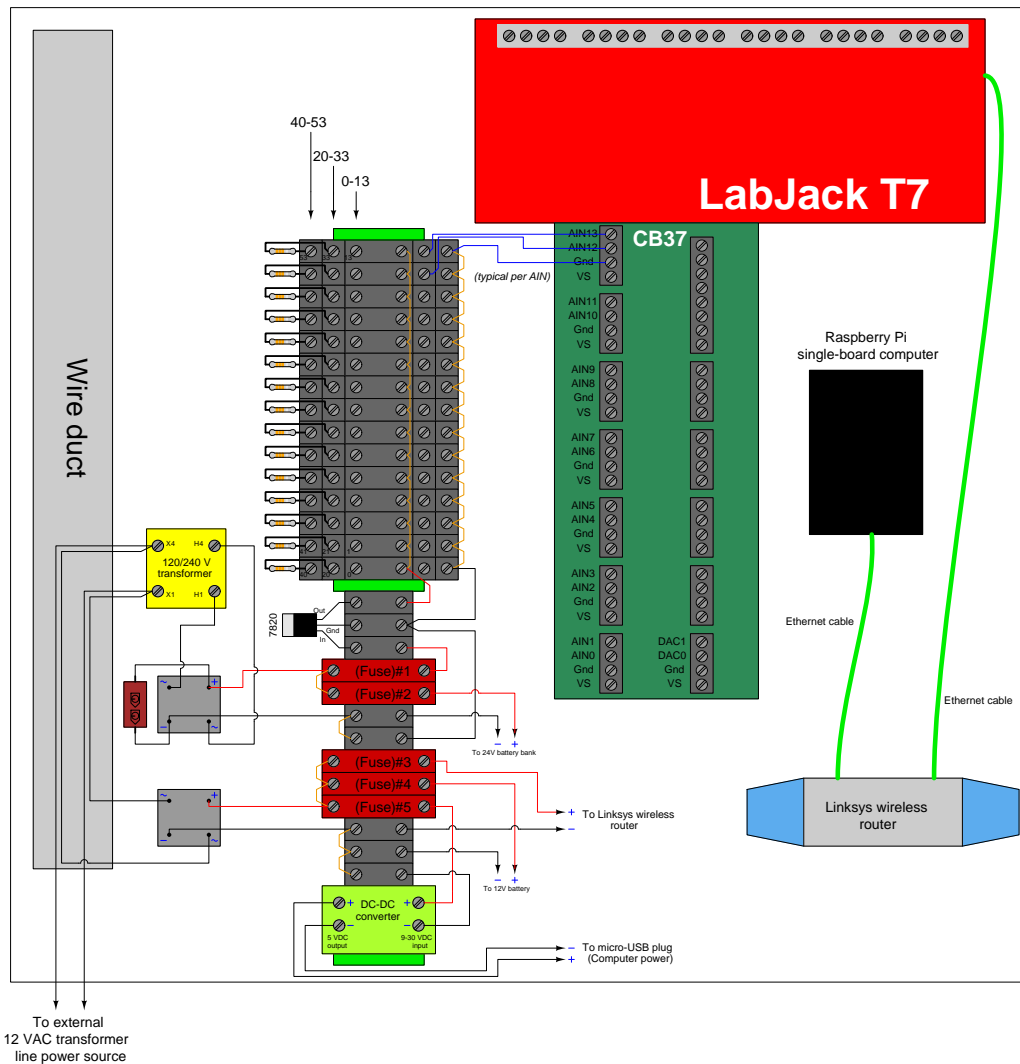
### Common mistakes:

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

file i00378

## RTU component layout

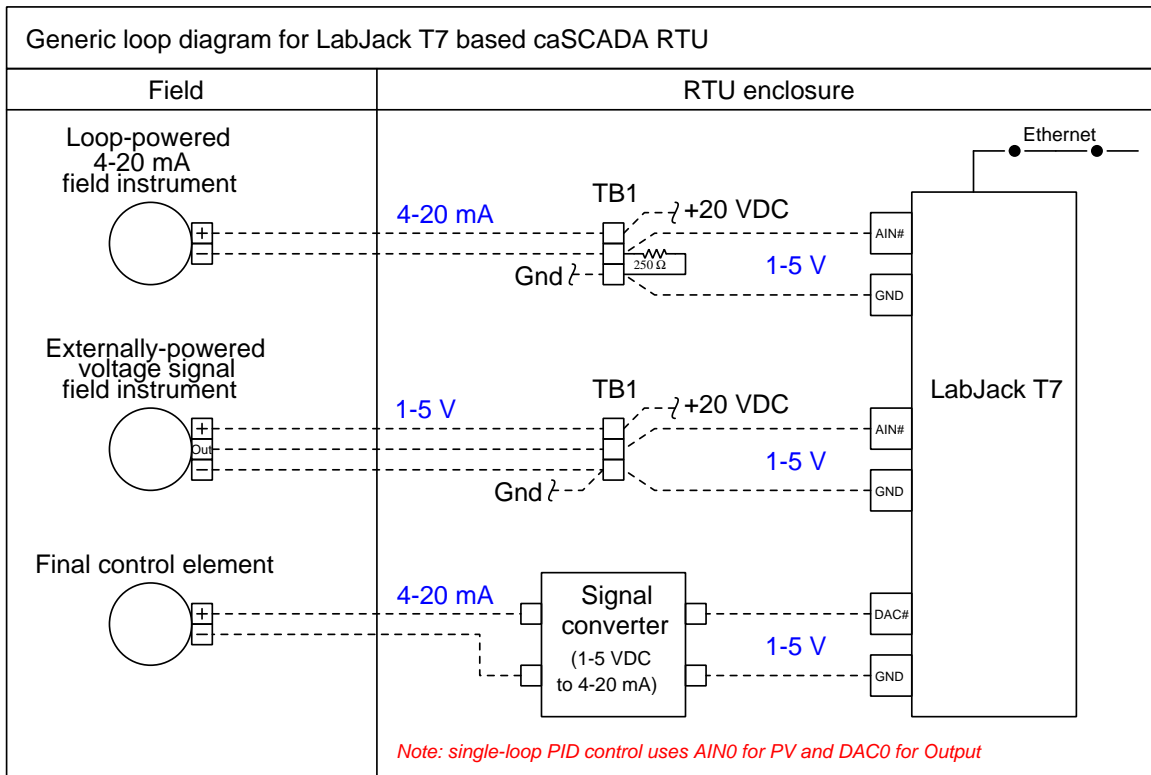
An “RTU” is a *Remote Terminal Unit* in a SCADA system serving as the interface between field instruments and a central control/display unit called the “MTU” (*Master Terminal Unit*). In our caSCADA system, the MTU is just a laptop computer viewing data generated by the single-board Linux computer in each RTU. Each RTU uses a LabJack data acquisition unit to sense analog signals sent by field transmitters and a single-board computer to condition and present that data in the form of digital data files readable by the MTU. Communication takes place via a wireless access point (WAP) router:



Each RTU enclosure is weatherproof, and equipped with a set of batteries to maintain DC power to all the system components in the event of an external AC power failure.

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

## Sample loop diagrams

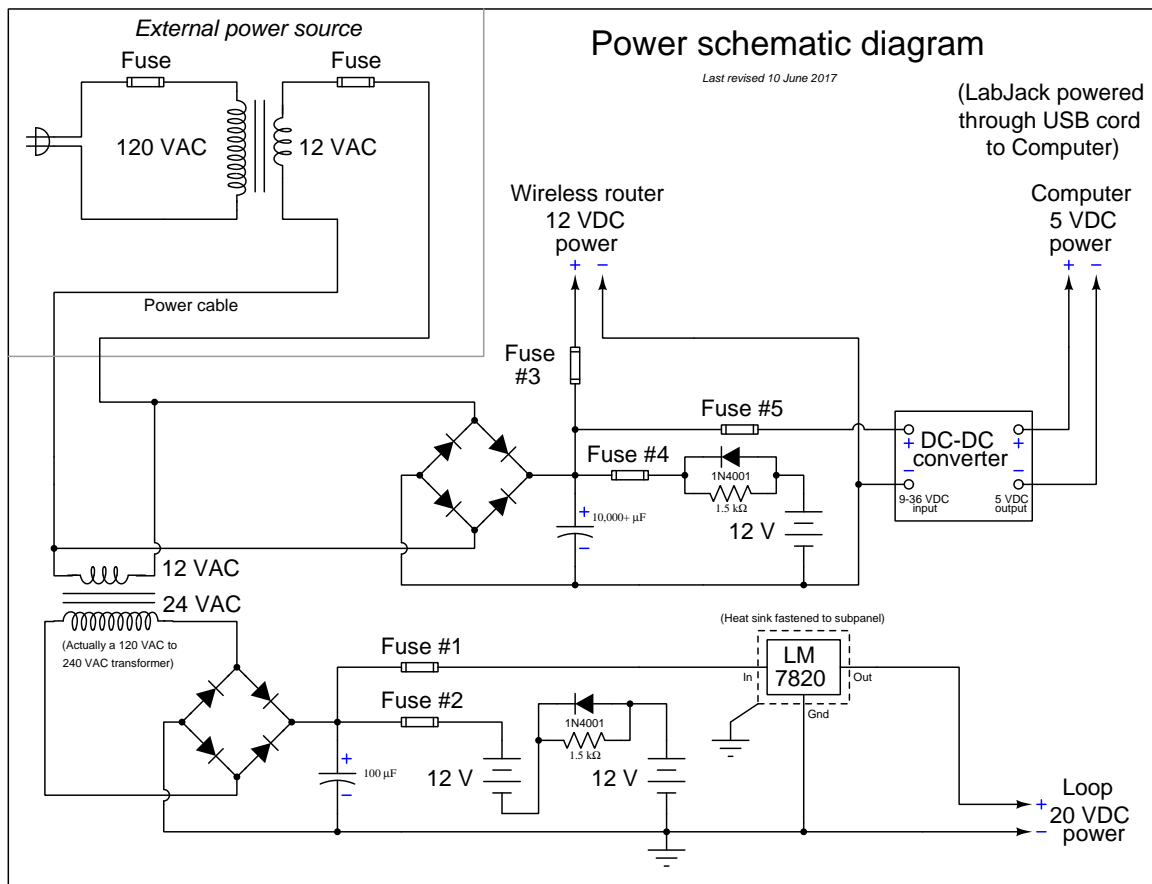


A set of triple-height terminal blocks marshall field instrument signals to the DAQ input terminals, with the three terminals of each block represented in the above diagram. The top-most terminal is the + DC power supply bus, the middle terminal connects to the LabJack DAQ input channel, and the bottom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

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

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

## Electrical power diagram



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

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

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

## RTU power system testing procedure

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

- (1) Test the external 12 VAC transformer by itself: when plugged into a 120 volt AC source, does it output at least 12 volts AC?
- (2) Open up all fuses (#1 through #5) to ensure no device will become powered until you intend so.
- (3) Connect this external 12 VAC transformer's output to the RTU as shown in the diagrams and apply power. Check the output of both bridge rectifiers for proper DC voltage magnitude and polarity. Due to the filter capacitors the DC voltage magnitudes will register greater than the AC voltage magnitudes feeding each of the bridge rectifiers.
- (4) Ensure the batteries are wired to the proper terminal blocks and fuse holders, and measure DC voltage magnitudes and polarities at the battery-side of each open fuse. This ensures the batteries are properly connected.
- (5) Close fuses #2 and #4. This connects the two battery banks to their respective charging sources. Re-measure the voltage magnitudes at the battery-side of each closed fuse. You should read slightly higher voltage now than in the previous step, because the batteries are charging.
- (6) Ensure all power plugs are removed from the caSCADA electronic devices: the LabJack DAQ unit, the RTU computer, and the Linksys wireless router. Prepare to measure DC voltage at the ends of those power plugs.
- (7) Close fuse #3 and measure DC voltage magnitude and polarity at the Linksys router's power plug. Check the router's documentation for the proper DC polarity of the plug's shell and tip to see that the polarity is correct. If all is well, plug the power cable into the router and check to see that it powers up. Re-measure voltage magnitude at fuse #3 to see that the router is receiving adequate voltage while powered (i.e. under load).
- (8) Close fuse #5 and measure DC voltage magnitude and polarity at the RTU computer's micro-USB power plug. Check online for the "pinout" specification of a micro-USB power plug to see that the polarity is correct. If the pins on the micro-USB plug are too small to safely probe using your multimeter, you may check DC voltage at the stripped end of that cable where it lands at the terminal block, and verify correct voltage and polarity according to the colors of that cable's wires. If all is well, plug the power cable into the RTU computer and check to see that it powers up.
- (9) Plug the B-style USB cable into the LabJack. It receives power through the RTU computer and should power up immediately. Re-measure voltage magnitude at fuse #5 to see that both the RTU computer and LabJack units are receiving adequate voltage while powered (i.e. under load).
- (10) Close fuse #1 to apply 20 VDC power to the field instrument terminal blocks. Measure DC voltage magnitude and polarity between terminals 13 and 53 to ensure 20 VDC is supplied all the way to the end of the terminal block section.
- (11) At this point in time you may initialize the caSCADA system MTU (a laptop PC) and test the system for proper data. A procedure for this is given on the following page.
- (12) Unplug the external 12 VAC transformer from its line power source, and re-measure all DC supply voltages to ensure all devices are receiving adequate voltage under battery power alone.
- (13) Repeat these DC voltage measurements at one-hour intervals to check the health of the batteries.



## RTU data system testing

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

- (1) Ensure that the proper IP addresses are all written on labels affixed to each of the networked devices in the RTU: the LabJack DAQ unit, the Linksys wireless router, and the single-board computer.
- (2) Set the IP address and subnet mask of your personal computer to appropriate values for the Ethernet device you wish to connect to. For each octet of the subnet mask with the value “255” the octet of your PC’s IP address must match the IP addresses of all devices in the RTU. For each octet of the subnet mask with the value of “0” the octet of your PC’s IP address must be different from any device in the RTU. This will prepare your PC for direct Ethernet cable connection to the device you intend to configure.
- (3) Plug your computer into the Linksys router using an Ethernet cable, and set the router’s IP address and subnet mask and name using a web browser. Follow the instructions given in the manual for the router. The router’s name should make sense to any user of the system. In an area with multiple RTUs, the name should be specific enough to clearly identify which RTU it is.
- (4) Plug your computer into the LabJack DAQ using an Ethernet cable, and set the DAQ’s IP address and subnet mask using the software provided by LabJack for this task. Follow the instructions given in the LabJack manual.
- (5) Plug an HDMI monitor and USB keyboard into the single-board computer, and log in directly to set its IP address and subnet mask. To check its current settings, use the `ifconfig` command (similar to the `ipconfig` command in Microsoft Windows). If the settings are not correct, you may change them by editing the file `/etc/network/interfaces`. This requires “root” privileges. Lines of text in this `interfaces` file follow this pattern:
  - The line specifying the `eth0` interface must read `iface eth0 inet static`
  - Prior to the `eth0` line must be a line that reads `auto eth0`
  - The “address” line contains the IP address (e.g. `address 169.254.8.3`)
  - The “netmask” line contains the subnet mask (e.g. `netmask 255.255.0.0`)
- (6) Unplug the Ethernet cable from your personal computer and wirelessly connect to the Linksys router. The router will automatically assign an appropriate IP address to your computer’s wireless card, as routers are designed to do.
- (7) Use the `ping` command in your computer to test network connectivity with each device in the RTU. This command is simply the word “ping” followed by the IP address of the device you wish to ping. For example, `ping 169.254.8.1` will test to see whether your computer has connectivity with the device bearing the IP address 169.254.8.1.
- (8) Once all devices have been proven to ping successfully, you may use an SSH client program in your personal computer (e.g. `Bitvise`) to log into the RTU computer. The login account is simply `btc` with the password `btc`.
- (9) Once you are logged in to the Linux operating system, you may try compiling the `caSCADA` code and then running it (either `poll` process or the `pid` process) to test its ability to communicate with the DAQ unit.

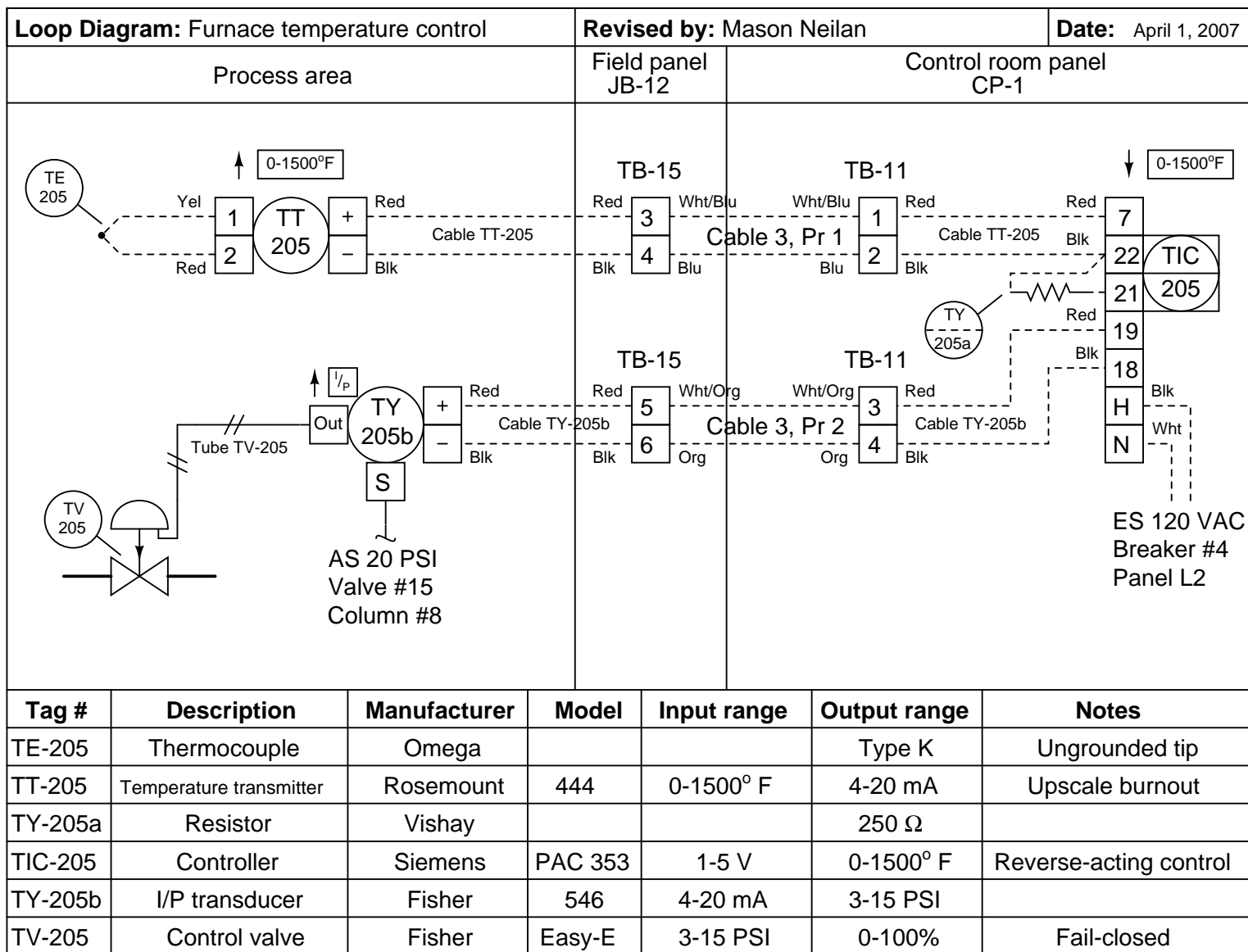
## Preparing the “Raspberry Pi” single-board computer for use in the caSCADA system

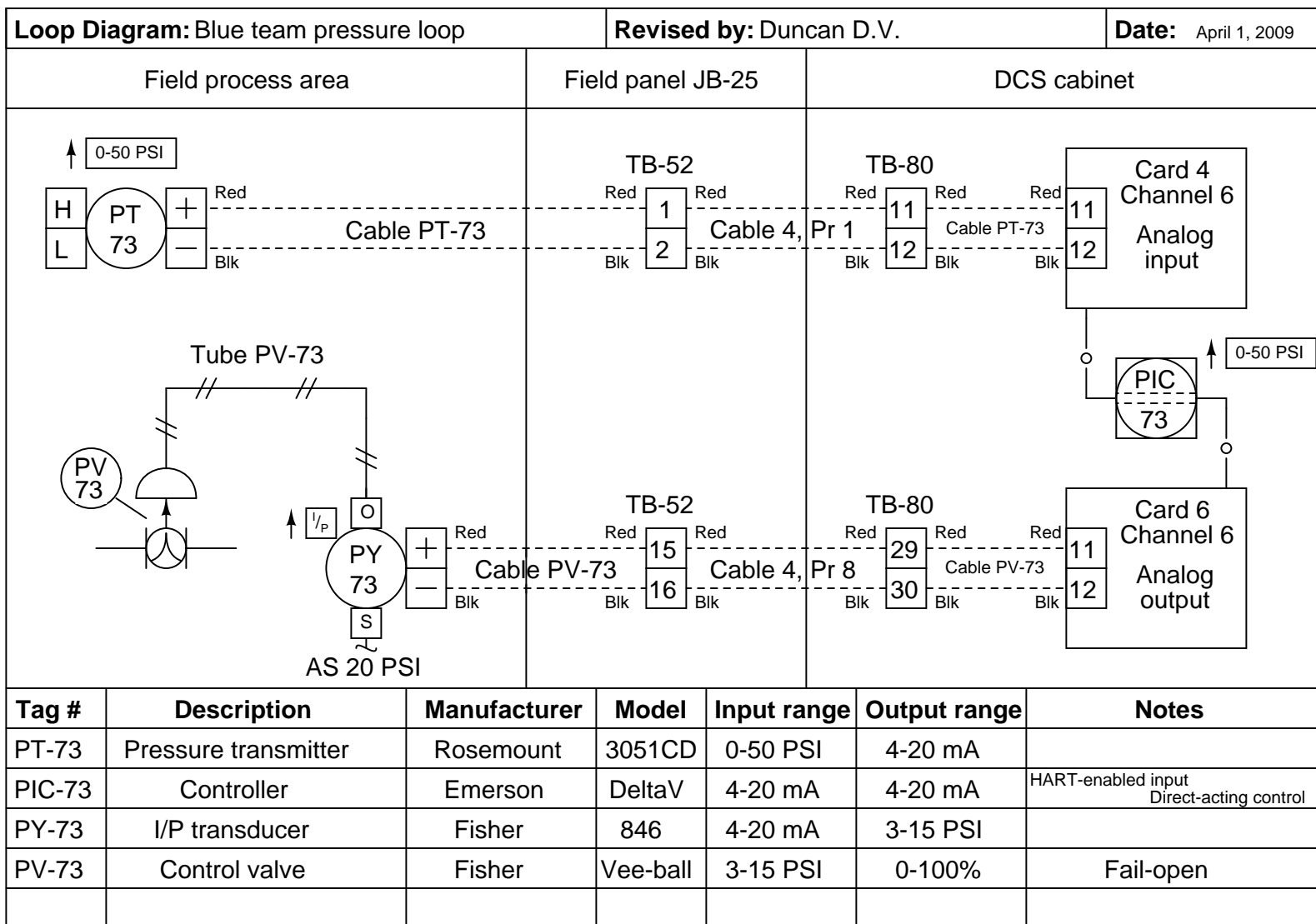
To initially configuring a Raspberry Pi to be used in the caSCADA system, there are several things which must be done:

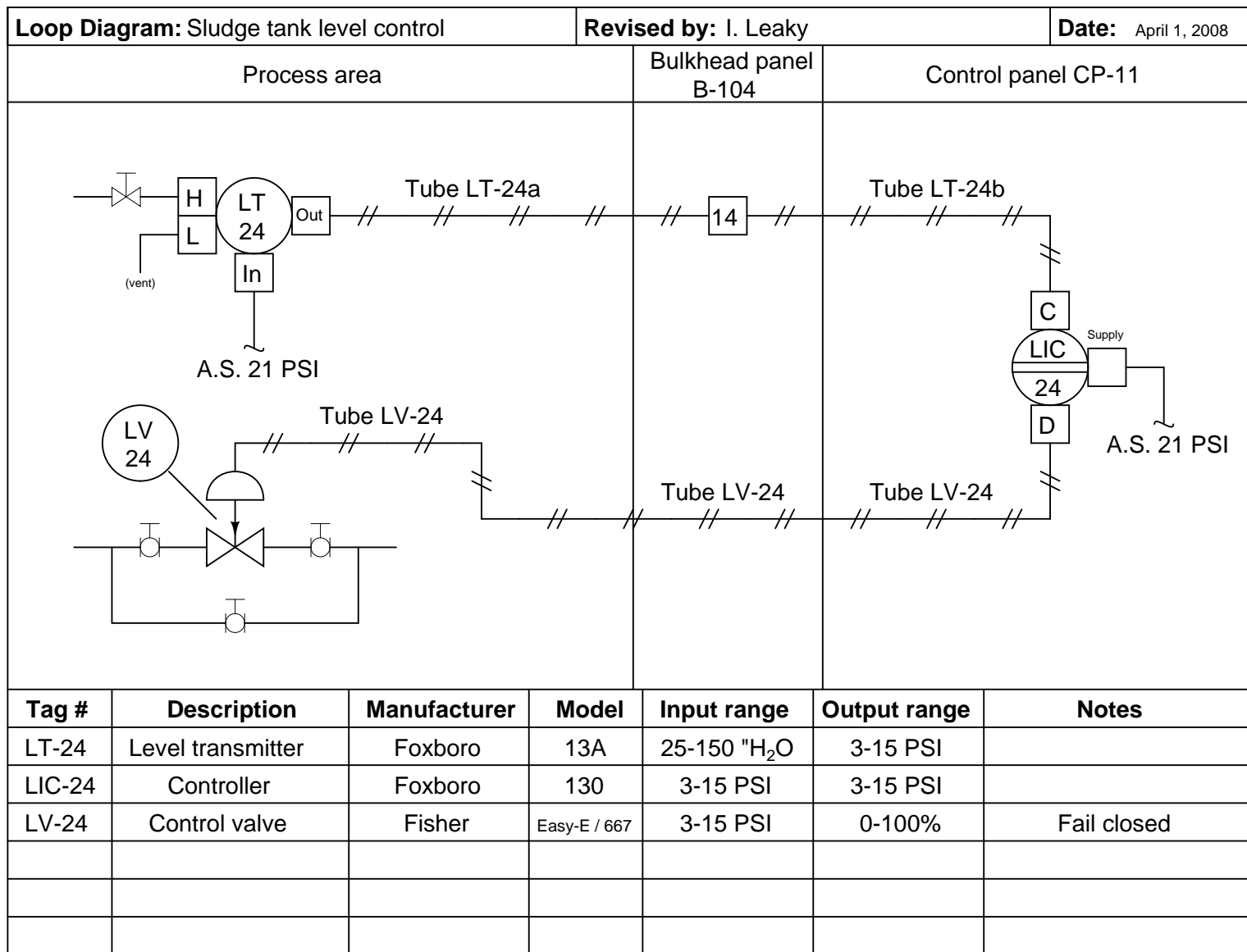
- Log in as the default user (name = `pi` and password = `raspberrypi`)
- Use the `sudo` and `passwd` commands to reset the root account’s password to your liking (e.g. `sudo passwd root`). There are several tasks for which root privileges are necessary, so it’s convenient to be able to log into the root account and do that work there, rather than have to preface all those commands typed under the `pi` login user with the “`sudo`” qualifier.
- Use the `raspi-config` utility to set the system’s hostname, configure the keyboard for US mapping (as British “UK” mapping is the default!), and also enable the `ssh` server which will be essential for remote login and system administration.
- Add a new user account called `btc`.
- Feel free to edit the hidden file named `.profile` in the `/home/btc` directory with any special instructions to be executed at login. For example, you may add lines containing the `echo` shell command to print messages to the screen for the user once they log in (e.g. `echo "Welcome to the fish hatchery RTU"`).
- Set the current time and date using the `date` command. The format is `MMDDhhmmCCYY`. For example, 3:21 PM on November 5, 2016 would be set by issuing the command `date 110515212016`.
- Navigate to the `/etc/network` directory and edit the file named `interfaces` to set all the required IP address and netmask information to give the Raspberry Pi a static IP address for use in the caSCADA system. Lines of text in this `interfaces` file follow this pattern:
  - The line specifying the `eth0` interface must read `iface eth0 inet static`
  - Prior to the `eth0` line must be a line that reads `auto eth0`
  - The “address” line contains the IP address (e.g. `address 169.254.8.3`)
  - The “netmask” line contains the subnet mask (e.g. `netmask 255.255.255.0`)
- Install the `cascada.tar` archive file in the `/home/btc` directory, and then use the command `tar xvf cascada.tar` to unpack that archive file.
- Install the latest `libmodbus` library archive file in the `root` directory, then uncompress it (`gunzip libmodbus*.gz`) and unpack the archive (`tar xvf libmodbus*tar`) and then descend into the new `libmodbus` directory to build it. This library is absolutely necessary for caSCADA to run, as it contains all the code necessary to read and write Modbus device registers over a TCP/IP network. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`. Check the general header file repository (located in the directory `/usr/include/`) to see if the installation script successfully copied the file named `modbus.h` there. In the versions of `libmodbus` I’ve installed, I have had to copy the `modbus.h` file to the `/usr/include` directory manually.
- Install the latest `ncurses` library archive file in the `root` directory, then uncompress it (`gunzip ncurses*.gz`) and unpack the archive (`tar xvf ncurses*tar`) and then descend into the new `ncurses` directory to build it. This library is necessary to run the `lynx` web browser, as well as the graphic interface for the caSCADA `pid` controller process. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.
- Install the latest `lynx` text-based web browser software archive file in the `root` directory, then uncompress it (`gunzip lynx*.gz`) and unpack the archive (`tar xvf lynx*tar`) and then descend into the new `lynx` directory to build it. Build and install the new software using the commands `./configure ; make ; make install ; ldconfig`.

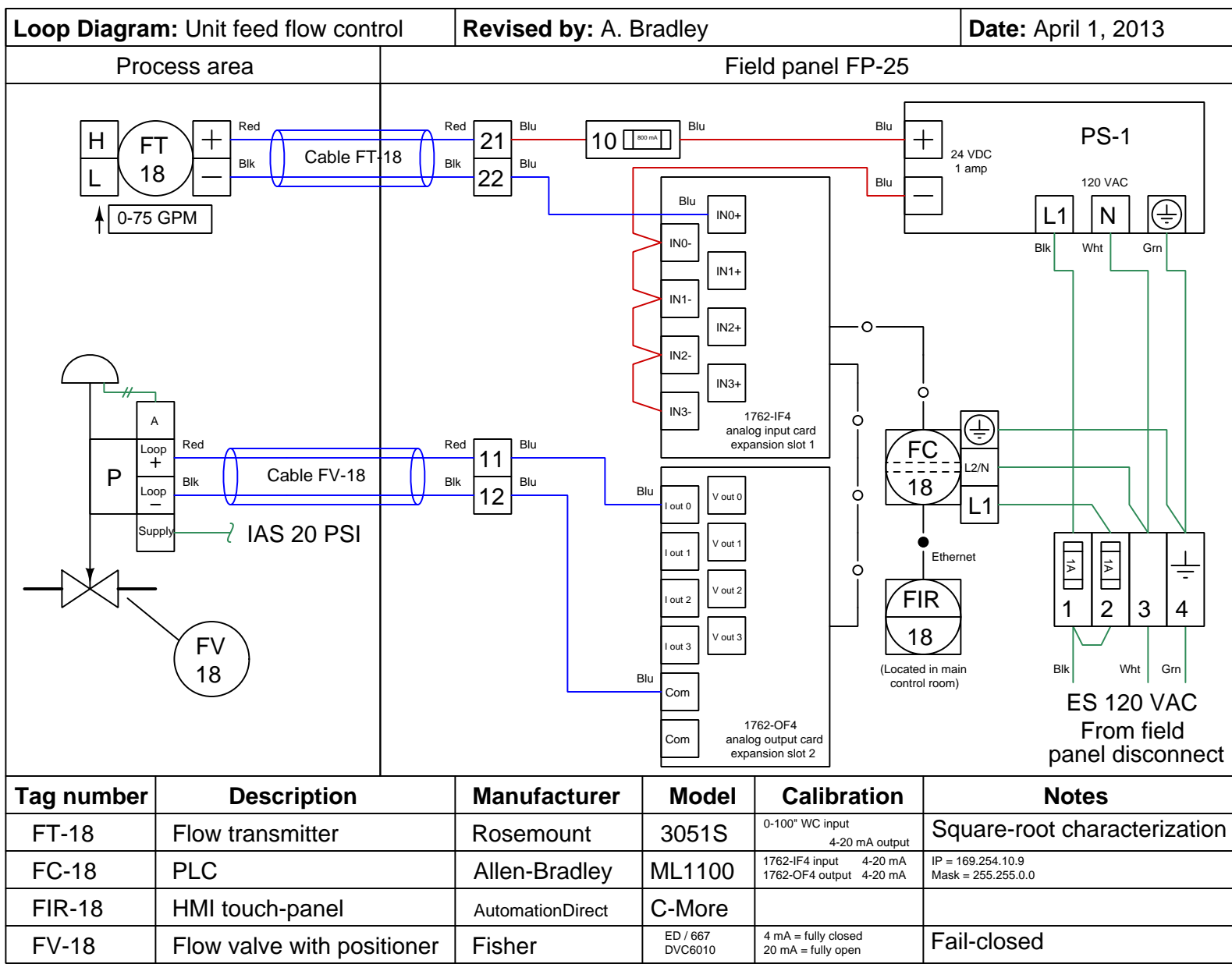
- Navigate to the `/home/btc` directory and edit the file `cascada_poll.c` with the correct IP address to establish a Modbus/TCP connection with the LabJack DAQ unit in your RTU. The function establishing the address will be easy to find in this file, as it calls out the IP address in standard four-octet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

[file i02566](#)









## Lab Exercise – loop diagram and system inspection

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

### Construction Standards

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

### Documentation Standards

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



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

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

#### **Common mistakes:**

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

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

[file i00654](#)

## Answers

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Answer 1

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Answer 2

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Answer 3

Differences in elevation between the sensing bulb and the indicating element only affect some classes of filled-bulb systems, not all. For these systems, the elevation will create a zero shift.

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Answer 4

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Answer 5

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Answer 6

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Answer 7

- $300^{\circ}\text{ C} = 572^{\circ}\text{ F}$
  - $50^{\circ}\text{ F} = 10^{\circ}\text{ C}$
  - $4^{\circ}\text{ C} = 39.2^{\circ}\text{ F}$
  - $894^{\circ}\text{ F} = 478.89^{\circ}\text{ C}$
  - $-250^{\circ}\text{ F} = -156.67^{\circ}\text{ C}$
  - $-312^{\circ}\text{ F} = -191.11^{\circ}\text{ C}$
  - $-150^{\circ}\text{ C} = -238^{\circ}\text{ F}$
  - $-230^{\circ}\text{ C} = -382^{\circ}\text{ F}$
  - $2600^{\circ}\text{ F} = 1426.67^{\circ}\text{ C}$
  - $3000^{\circ}\text{ C} = 5432^{\circ}\text{ F}$
- 

Answer 8

The following images were taken with an infra-red imaging camera, which shows the surface temperature(s) of an object by means of analyzing the infra-red light emitted by that object via *radiative* heat transfer. It is interesting to note where each object is hottest, and to relate that to heat transfer not only with regard to the thermal images obtained but also to the regular thermodynamic behavior of that object. Questions you may wish to pose include:

- Where is each object appear to be the hottest? Why?
- Where is each object appear to be the coldest? Why?
- How does each object shed heat during its ordinary day-to-day function?
- Is there more than one mode of heat transfer at work here?

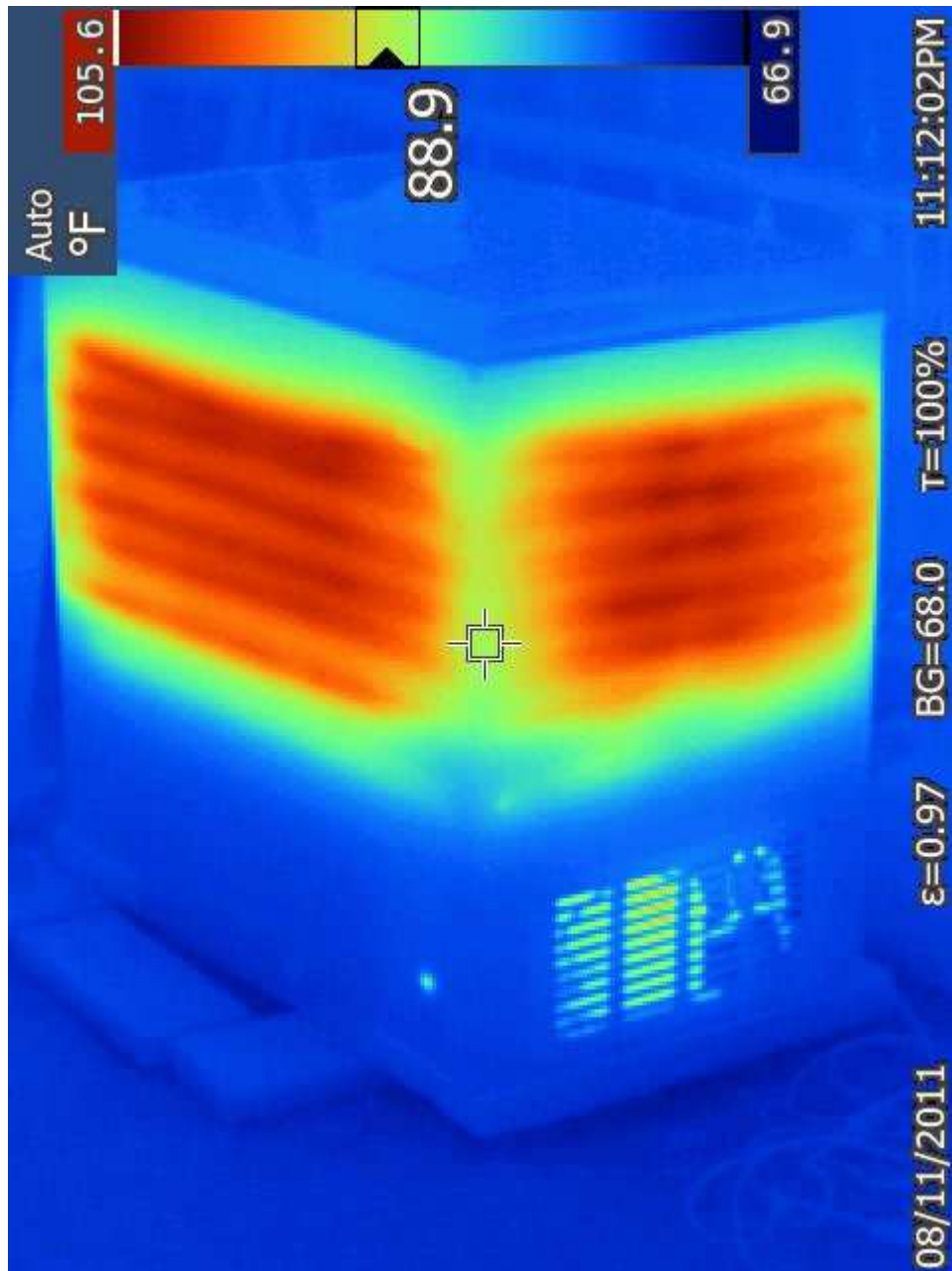
Heat transfer example – infrared thermal image of a Jeep vehicle after being driven:



Internal combustion engines are *heat engines*, developing mechanical power by heating a gas (air) to high temperatures and forcing the resulting expansion of that gas to press against a surface (called a *piston*) to do useful work. In the process, a lot of “waste” heat is created, which the engine must shed or else suffer damage from overheating.

This is why engines have *radiators*: to shed the excess heat energy to the surrounding environment. Can you see where the radiator is in this thermal image?

Heat transfer example – infrared thermal image of a chest freezer as it is running:



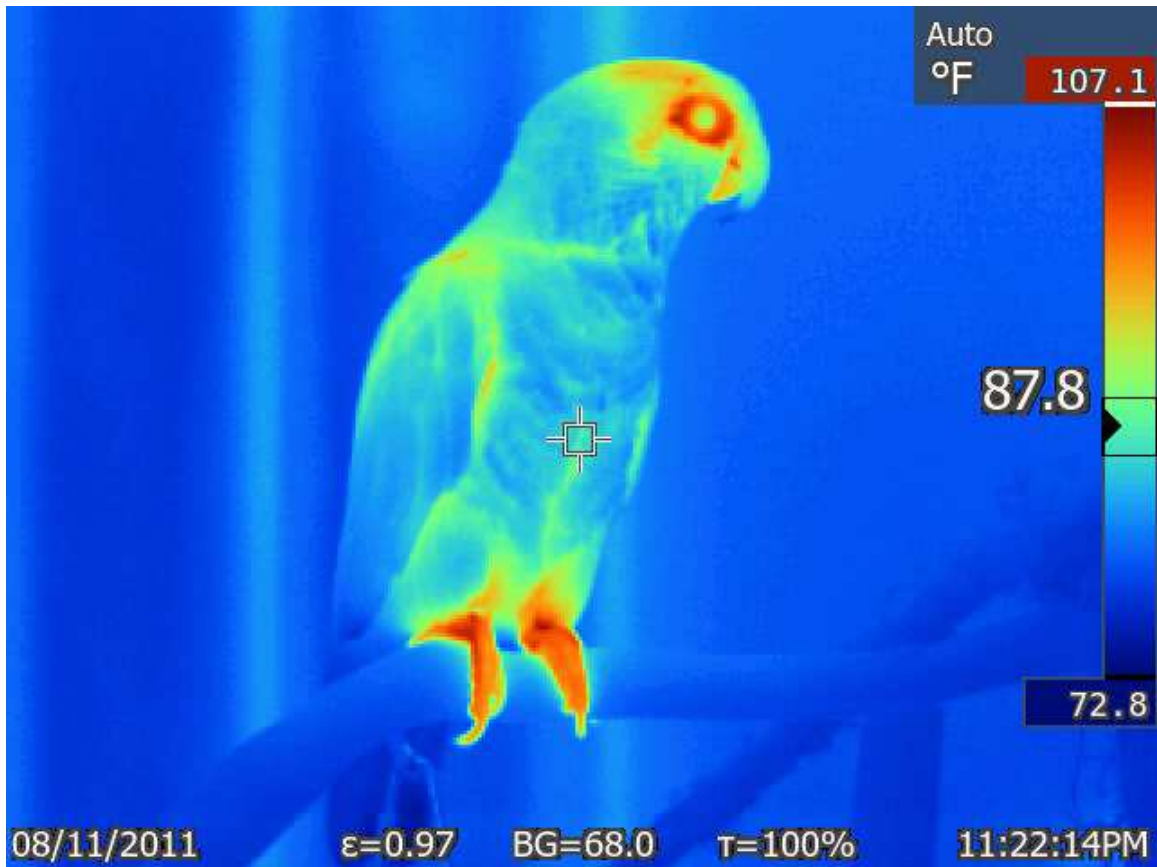
Refrigerators and freezers do not magically “make cold,” but rather force heat transfer to occur where it usually would not. Recall that heat spontaneously flows from areas of high temperature to areas of low temperature. This means a refrigeration unit must somehow force heat to flow “backwards” from a cold area to a warmer area. In a compressed-gas refrigerator unit, this happens because a compressor compresses a gas to a high pressure (which also causes that gas to rise in temperature), then sends that gas through a series of tubes called a *condensor* where the hot gas naturally loses heat energy to the (cooler) outside air. After losing heat, this high-pressure gas condenses into a high-pressure liquid. This liquid is then sent to another series of tubes called an *evaporator* where the liquid experiences a sharp drop in pressure and re-boils into a gas. This change of phase from liquid to gas requires an input of thermal energy, which takes the form of the boiling liquid (and boiled vapor) becoming much colder.

Thus, heat flows naturally as it always does from a warmer area to a colder area at both the condensor

and the evaporator. At the condensor, hot gas loses heat to the outside air and condenses into liquid at the same time. At the evaporator, cold liquid gains heat from the inside of the refrigerator/freezer unit and boils into gas at the same time. The “magic” of a refrigeration unit is that heat energy is carried from the cold evaporator to the hot condensor by the working fluid when forced to flow that way by the compressor.

The condensor may be seen in this thermal image as a series of lines along the side of the freezer unit, giving off heat to the surrounding air. The evaporator lies just underneath the inside walls of the freezer, absorbing heat from the interior of the freezer to make that space cold.

Heat transfer example – infrared thermal image of a parrot:

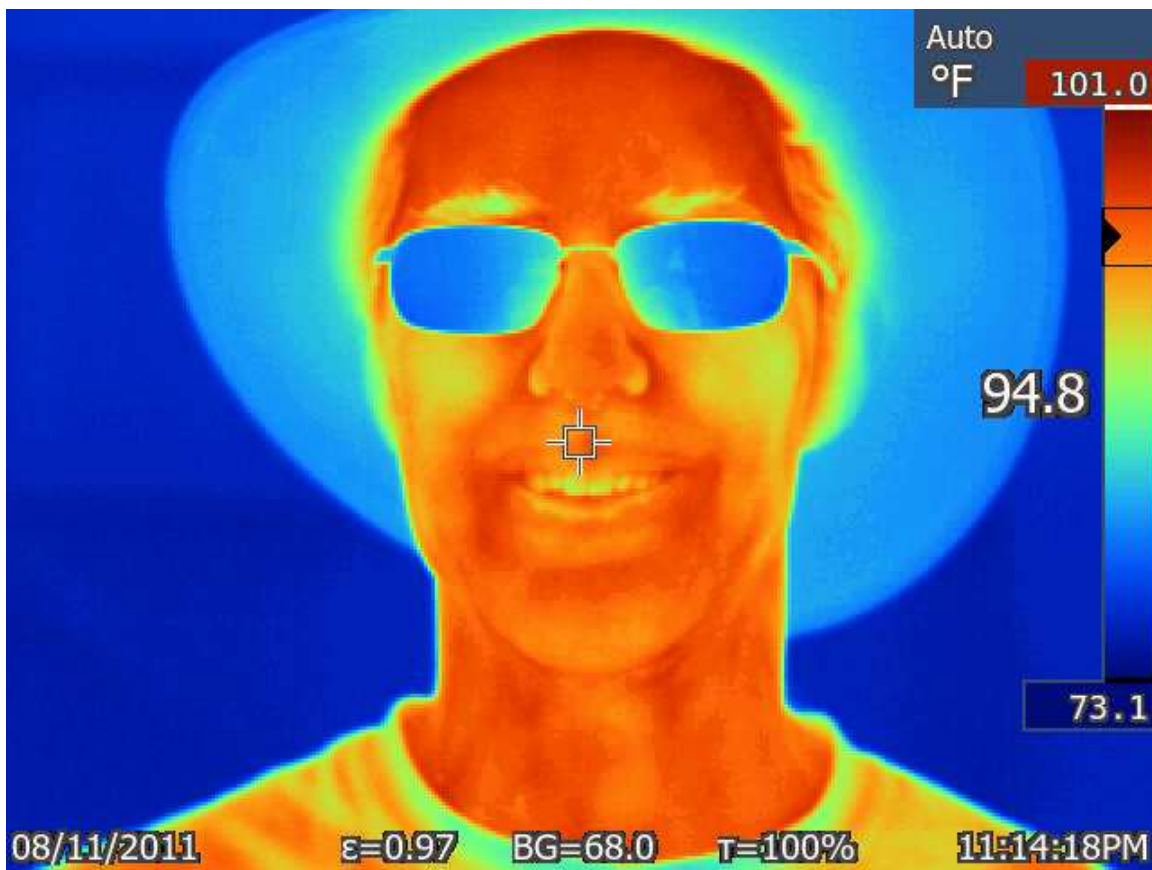


All animals live by metabolizing food. This is essentially a slow, low-temperature form of *combustion*, where carbohydrate and fat molecules (primarily) in the food combine with oxygen to form carbon dioxide gas and heat. Like the internal combustion engine in a vehicle, there is a lot of “waste” heat generated in this process, which must be shed lest the animal overheat.

Here, you can see areas on the parrot’s skin that appear warm. Most of the parrot’s body, however, appears much colder because it is insulated by a thick layer of feathers. This is the primary function of feathers: to provide thermal insulation. This is why even flightless birds (such as penguins) have feathers.

Can you see an area on this bird’s perch that has become warmer due to contact with the bird’s feet? What form of heat transfer is this?

Heat transfer example – infrared thermal image of the author wearing a hat:



Here we see a thermal image of the author, showing just how hot his head is. This explains a lot, perhaps more than the author is prepared to admit.

Compare the surface temperature of this person against the surface temperature of the parrot. Why do the two bodies appear so different?

An interesting artifact of infra-red thermal imaging is apparent in this image: note how the eyeglass lenses appear cold (blue). Most glasses and plastic materials are opaque to infra-red light, which means the author's warm eyes are invisible to the infra-red camera so long as he is wearing his glasses.

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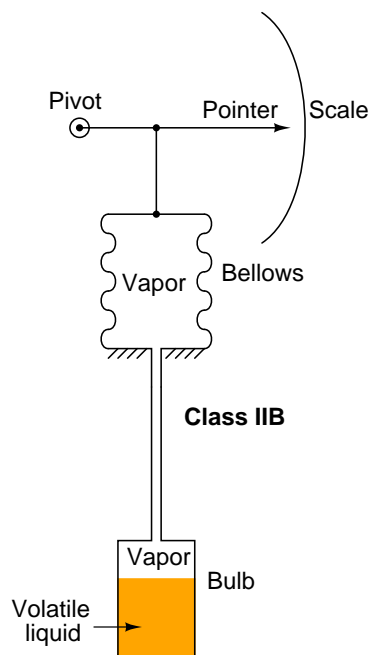
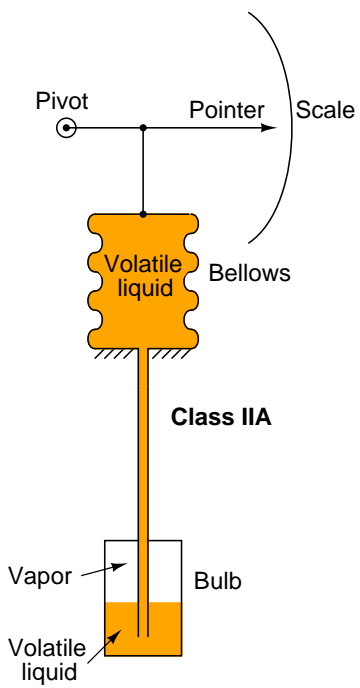
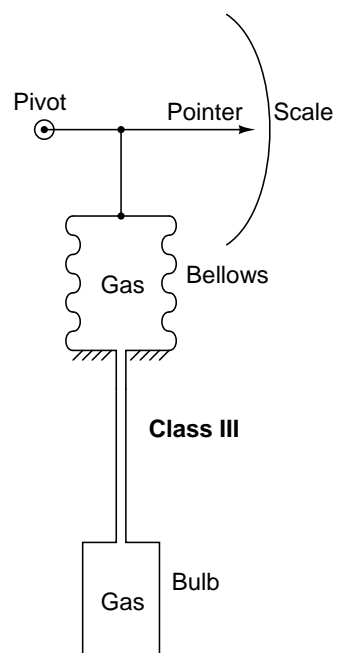
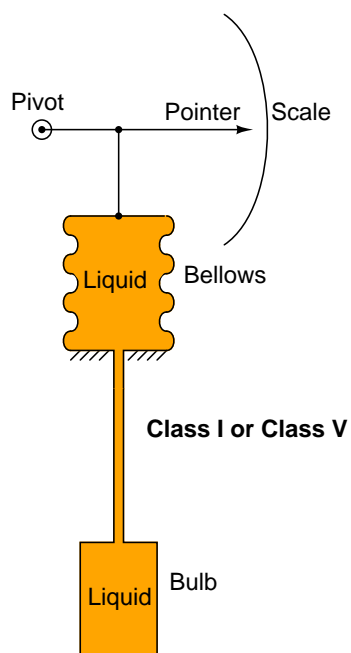
Answer 9

Answer to challenge question: the light bulb would have to be 205 watts (two 100-watt bulbs operating together would come close!).

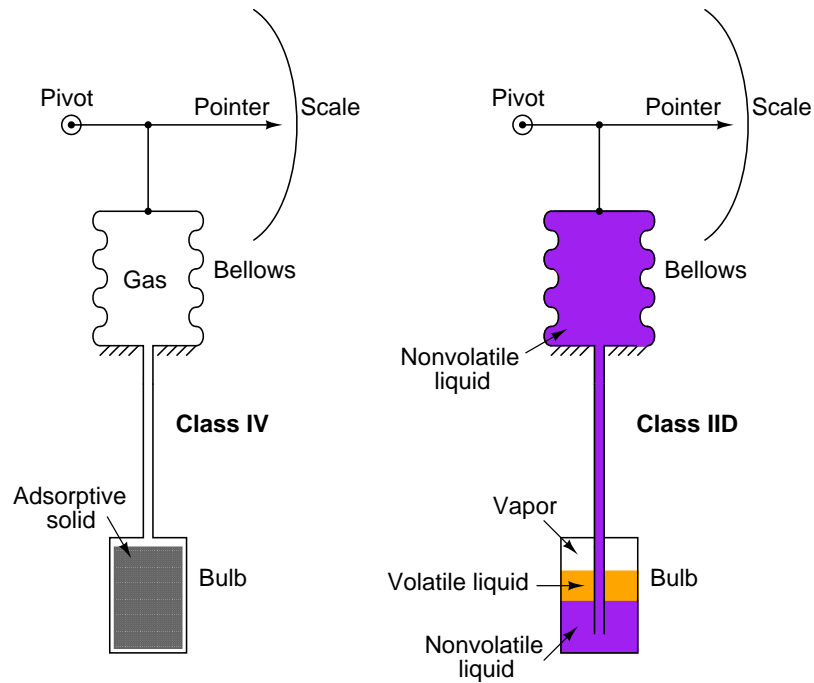
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Answer 10

Think about what would happen if the connecting tubing were the same inside diameter as the bulb itself. Would this not act like one, long bulb? If this were the case, the entire length of tubing would act as a temperature sensor, rather than just the bulb. In other words, the measurement provided by the instrument would be an aggregate of all temperatures between the process and the instrument itself, rather than a single measurement of process temperature!







Follow-up question: note that a Class IIC system is not shown. Explain why.

Answer 12

This is an automatic cooling system with high and low temperature alarms.

Answer 13

Fault	Possible	Impossible
$R_1$ failed open		✓
Voltmeter failed open		✓
Wire 1 failed open	✓	
Wire 2 failed open	✓	
RTD failed open	✓	
$R_1$ failed shorted		✓
Voltmeter failed shorted		✓
RTD failed shorted		✓
Current source dead		✓

Answer 14

In the heat exchanger where the two fluids move in the same direction, the heated fluid can never exit the exchanger at a warmer temperature than the heating fluid exits. With the contra-flow design, it can!

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Answer 15

$\frac{dQ}{dt}$  = Rate of heat flow (Watts)

$e$  = Emissivity factor (*unitless*)

$A$  = Area of radiating surface (square meters)

$T$  = Absolute temperature (Kelvin)

Challenge question: a more complete expression of the Stefan-Boltzmann equation takes into account the temperature of the warm object's surroundings:

$$\frac{dQ}{dt} = e\sigma A(T_1^4 - T_2^4)$$

Where,

$T_1$  = Temperature of the object

$T_2$  = Ambient temperature

Explain why this second  $T$  term is necessary for the equation to make sense.

---

Answer 16

$$V \approx V_0(1 + 3\alpha\Delta T)$$

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Answer 17

$$PV = nR(T + 273.15) \quad \text{Temperature in degrees C}$$

$$PV = nR \left( \frac{5}{9}(T - 32) + 273.15 \right) \quad \text{Temperature in degrees F}$$

It should be noted that the behavior of real gases departs significantly from the Ideal Gas Law model at temperatures near absolute zero, especially when phase changes (liquefaction and/or solidification) take place. Still, it is possible through intuition to tell the intended unit of temperature measurement for  $T$  in this equation must be absolute and not elevated, and this is the thrust of the challenge question.

---

Answer 18

The copper block will cool at a faster rate, because copper has less specific heat than iron, meaning that any given amount of heat energy lost will decrease its temperature more than it will iron for the same amount of heat energy loss. Another way of saying this is that the copper contains less heat energy than the iron, even though they both start out at the same temperature.

$$c_{Cu} = 0.093 \text{ cal/g}\cdot^\circ\text{C}$$

$$c_{Fe} = 0.113 \text{ cal/g}\cdot^\circ\text{C}$$

---

Answer 19

Assuming volume ( $V$ ), molecular gas quantity ( $n$ ), and the Gas Constant ( $R$ ) never change, the Ideal Gas Law may be reduced as follows:

$$P_1 V = nRT_1$$

$$P_2 V = nRT_2$$

$$\frac{P_1 V}{P_2 V} = \frac{nRT_1}{nRT_2}$$

$$\frac{P_1}{P_2} = \frac{T_1}{T_2}$$

$$P_2 = P_1 \frac{T_2}{T_1}$$

$$P_1 \text{ at } 0^\circ \text{ C} = 1 \text{ atm} = 14.7 \text{ PSIA}$$

$$T_1 \text{ at } 0^\circ \text{ C} = 273.15 \text{ K}$$

$$T_2 \text{ at } 70^\circ \text{ F} = 21.11^\circ \text{ C} = 294.26 \text{ K}$$

$$P_2 = 14.7 \text{ PSIA} \left( \frac{294.26 \text{ K}}{273.15 \text{ K}} \right)$$

$$P_2 = 15.84 \text{ PSIA} = 1.136 \text{ PSIG} = 31.5 \text{ "W.C.}$$

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Answer 20

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Answer 21

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Answer 22

- Two pounds of iron from  $80^\circ \text{F}$  to  $110^\circ \text{F}$   $Q = \mathbf{6.48}$  BTU
- 15 grams of ice from  $-11^\circ \text{C}$  to  $-3^\circ \text{C} = \mathbf{60}$  calories
- 0.0042 pounds of hydrogen gas from  $50^\circ \text{F}$  to  $220^\circ \text{F} = \mathbf{2.435}$  BTU
- 47 kg of methanol from  $10^\circ \text{C}$  to  $35^\circ \text{C} = \mathbf{715,575}$  calories

Note: heat losses shown as negative numbers, as compared to heat gains as positive numbers . . .

- Five pounds of copper from  $100^\circ \text{F}$  to  $65^\circ \text{F}$   $Q = \mathbf{-16.1}$  BTU
- 1 kilogram of ethanol from  $30^\circ \text{C}$  to  $4^\circ \text{C} = \mathbf{-15,262}$  calories
- 0.075 pounds of helium gas from  $195^\circ \text{F}$  to  $30^\circ \text{F} = \mathbf{-15.345}$  BTU
- 800 grams of steam from  $150^\circ \text{C}$  to  $108^\circ \text{C} = \mathbf{-15,993.6}$  calories

---

Answer 23

**Partial answer:**

Heat required to warm water from ambient to 100 °F = 232,400 BTU

Cost of initially heating the hot tub with electricity = \$5.79

The cost of initially heating the hot tub with propane gas is very nearly the same as with electricity!

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Answer 24

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Answer 25

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Answer 26

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Answer 27

**Partial answer:**

- $T = 501\text{ }^{\circ}\text{F}$  and  $P = 810\text{ PSIG}$  :
- $T = 250\text{ }^{\circ}\text{F}$  and  $P = 75\text{ PSIG}$  : **water only**
- $T = 690\text{ }^{\circ}\text{F}$  and  $P = 1886\text{ PSIG}$  : **steam only**, approximately **61 deg F** superheat
- $T = 369\text{ }^{\circ}\text{F}$  and  $P = 550\text{ PSIG}$  :
- $T = 274\text{ }^{\circ}\text{F}$  and  $P = 30\text{ PSIG}$  : **water and steam mixed**
- $T = 471\text{ }^{\circ}\text{F}$  and  $P = 405\text{ PSIG}$  :

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Answer 28

- $235^{\circ}\text{ C} = 914.67^{\circ}\text{ R}$
- $567.2^{\circ}\text{ F} = 570.48\text{ K}$
- $0.004\text{ K} = -459.663^{\circ}\text{ F}$
- $830^{\circ}\text{ R} = 187.96^{\circ}\text{ C}$
- $-200^{\circ}\text{ C} = 131.67^{\circ}\text{ R}$
- $-98.25^{\circ}\text{ F} = 200.79\text{ K}$
- $992.8^{\circ}\text{ C} = 1819.04^{\circ}\text{ F}$
- $-105.3^{\circ}\text{ C} = -157.54^{\circ}\text{ F}$
- $1040\text{ K} = 1872^{\circ}\text{ R}$
- $5222.6^{\circ}\text{ R} = 2628.29^{\circ}\text{ C}$

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Answer 29

- $350\text{ K} = 76.85^\circ\text{ C}$
- $575^\circ\text{ F} = 1034.67^\circ\text{ R}$
- $-210^\circ\text{ C} = 63.15\text{ K}$
- $900^\circ\text{ R} = 440.33^\circ\text{ F}$
- $-366^\circ\text{ F} = 93.67^\circ\text{ R}$
- $100\text{ K} = -173.15^\circ\text{ C}$
- $2888^\circ\text{ C} = 3161.15\text{ K}$
- $4502^\circ\text{ R} = 4042.33^\circ\text{ F}$
- $1000\text{ K} = 1800^\circ\text{ R}$
- $3000^\circ\text{ R} = 1666.67\text{ K}$

---

Answer 30

In both cases (piston moving in, and pump pulling liquid out) there will be an initial change in pressure. However, the pressure will stabilize at the exact same quantity it was at before once equilibrium is re-established. Saturated vapor pressure does not depend on the quantity of liquid or vapor, or the volume of the enclosed space!

Initially, the pressure will increase because the vapor will be forced into a smaller volume (remember  $PV = nRT$ ). This will cause the rate of condensation (vapor-to-liquid) to increase and the rate of evaporation (liquid-to-vapor) to decrease. As excess vapor re-condenses into liquid, the pressure will decrease due to a lesser molar quantity of vapor (the  $n$  in  $PV = nRT$ ) in the space above the liquid. Eventually, the pressure will stabilize at the exact same quantity it was at before, when the system reaches a state of saturation again.

---

Answer 31

The only factor able to alter the saturated vapor pressure inside the tank is *temperature*. Increasing the tank's temperature will cause the pressure to likewise increase.

This principle is put to use in Class II filled systems for measuring temperature: the vapor pressure of the volatile fill fluid indicates its temperature. Since this pressure does not depend on volume, any changes in volume resulting from expansion or contraction of the liquid or the vapor at the indicator end of the system will be absorbed by either condensation or evaporation (respectively), until the pressure again stabilizes at the value determined by the liquid/vapor interface's temperature.

---

Answer 32

In order of most heat required to least heat required:

- To boil a pound of water completely into steam (warming it from  $211^\circ\text{ F}$  to  $213^\circ\text{ F}$ ).
- To melt a pound of ice completely into water (warming it from  $31^\circ\text{ F}$  to  $33^\circ\text{ F}$ ).
- To heat a pound of water from  $60^\circ\text{ F}$  to  $65^\circ\text{ F}$ .

---

**Answer 33**

To raise the water's temperature from 20° C to 100° C will require this much heat energy:

$$Q = mc\Delta T$$

$$Q = (5 \text{ g})(1 \text{ cal/g-C}^\circ)(100^\circ \text{ C} - 20^\circ \text{ C})$$

$$Q = (5 \text{ g})(1 \text{ cal/g-C}^\circ)(80^\circ \text{ C})$$

$$Q = 400 \text{ cal}$$

This leaves 600 calories remaining from the original 1000 calorie heat dose to boil water into steam. Since the latent heat of vaporization is 540 calories/gram, 600 calories will vaporize this many grams of water:

$$L_v = \frac{Q}{m}$$

$$m = \frac{Q}{L_v}$$

$$m = (600 \text{ cal})/(540 \text{ cal/g})$$

$$m = 1.111 \text{ g}$$

Thus, 1.111 grams of water will boil into steam, and then the 1000 calories of heat energy will be spent.

---

**Answer 34**

Since the latent heat of vaporization for water is 970 BTU/lb<sub>m</sub>, and we wish to boil 300 pounds of steam per hour, this equates to the following number of BTUs each and every hour:

$$Q = mL_v$$

$$Q = (300 \text{ lb}_m)(970 \text{ BTU/lb}_m)$$

$$Q = 291,000 \text{ BTU}$$

Thus, the required heat input to the boiler (assuming 100% efficiency) is 291,000 BTU/hour. Since no boiler is perfectly efficient, though, the actual required heat input will be greater than this.

---

**Answer 35**

In the illustrated scenario, the liquid will move to the colder location (the indicator mechanism), while the vapor will move to the hotter location (the sensing bulb). This is typical for Class II filled systems: the liquid portion of the fill will try to migrate to the colder end, while the vapor portion will try to migrate to the warmer end. Only the Class IID type of system eliminates this problem, by using a non-volatile fill liquid to constantly occupy the capillary tube and sensing element (bourdon tube or bellows), thus confining the volatile liquid and vapor to the bulb.

As the process temperature cools below the indicator element's ambient temperature of 72° F, the liquid will try to migrate to the bulb and the vapor to the indicator. As this transfer is taking place, the pressure in the system will become unstable, creating unpredictable changes in temperature measurement at the indicator. This is commonly known as the *cross-ambient* problem.

For this reason, Class II filled systems should be avoided when measuring process temperatures ranging above and below ambient (indicator) temperature.

---

Answer 36

The “coexistence line” is simply the curve found in any phase diagram: the boundary(ies) delineating stable states of solid, liquid, and/or vapor.

The “stability region” is that area within a phase diagram where the substance in question exists in one phase only. For example, the “liquid” region of a phase diagram would be one of the “stability regions” for that substance.

Practical examples of metastable states are supercooled water, and superheated water. In each case, the temperature of a substance is varied under controlled conditions until the sample exists at a temperature where it “should” have changed states, but has not yet.

---

Answer 37

Possible faults include (but are not limited to):

- TE-43 failed open
- TT-43 failed with high output signal
- Motor driving cooling fan lost power
- Variable frequency drive for cooling fan is tripped
- Fin-fan heat exchanger fins plugged with farm debris
- Coolant pump motor lost power
- Coolant line plugged

- What advantages might there be with this design versus a furnace installed inside the home? *Safety (no fire hazard or smoke hazard inside the home), Efficiency (wood fires are very efficient and practically smokeless when burned at full intensity as is permitted with a heat-storage system like this), Convenience (the fire need not be tended for hours each day, but rather is lit and forgotten until the next fire needs to be lit)*
- Why is *sand* a good choice as a heat-storage medium inside the furnace structure? *Sand does not melt, freeze, corrode, or leak. It has a high density and a reasonable heat capacity (approximately 0.19).*
- Is the heat storage in this system based on *specific heat* or *latent heat*? *Since the sand does not change phase with the temperature of the furnace, this system is based on specific heat.*
- Is the heat transfer in this system (from heater to home) based on *specific heat* or *latent heat*? *Since the water does not boil in the heater, the transfer is strictly a function of specific heat. If the water was boiled into steam and then sent to the house, the energy transfer would involve latent heat as well as specific heat!*
- How may the home's temperature be thermostatically controlled? *A pump circulating the water between the furnace and the house may be cycled by a thermostat control.*
- How to equip the system with an alarm prompting the user to light a new fire in the furnace? *A low-temperature alarm with a sensor embedded in the sand reservoir would suffice.*
- Calculate the enthalpy of the water as it enters the home (from the heater) at a temperature of 184 °F. *Enthalpy is simply the amount of heat energy released per pound of mass based on the temperature falling down to 32 °F (0 °C).  $Q = mc\Delta T = (1 \text{ lb})(1 \text{ BTU/lb-degF})(184 \text{ deg F} - 32 \text{ deg F}) = 152 \text{ BTU}$ . Therefore, the enthalpy of the water entering the home is 152 BTU/lb.*
- Calculate the enthalpy of the water as it leaves the home (on its way to the heater) at a temperature of 127 °F. *Enthalpy is simply the amount of heat energy released per pound of mass based on the temperature falling down to 32 °F (0 °C).  $Q = mc\Delta T = (1 \text{ lb})(1 \text{ BTU/lb-degF})(127 \text{ deg F} - 32 \text{ deg F}) = 95 \text{ BTU}$ . Therefore, the enthalpy of the water exiting the home is 95 BTU/lb.*
- Calculate the rate of heat delivered to the home by this hot water assuming a water mass flow rate of 9.2 pounds per minute. *For every pound of heating water that circulates through the home, the amount of energy it delivers to the home is simply the difference between the incoming and outgoing enthalpy values.  $152 \text{ BTU/lb} - 95 \text{ BTU/lb} = 57 \text{ BTU/lb}$ . At a water flow rate of 9.2 pounds per minute, this equates to a heating rate of 524.4 BTU per minute, or 31,464 BTU per hour.*

---

Answer 39

The saturation temperature of steam at 505 PSIG (greater than 495 PSIG) is 471 °F. Since 780 °F is much greater than this, we may deduce that the steam in the hot leg is superheated, and thus the core must be adding heat to the steam after it has boiled away from the water. Thus, the core is uncovered.

This is a very bad situation!!



---

Answer 40

We may calculate the heat rate input to this turbine by subtracting enthalpy values ( $h_{in} - h_{out}$ ) and multiplying by the mass flow rate of the steam:

$$\text{Input enthalpy (from steam table; } 583^\circ\text{F and } 88 \text{ PSIG)} = 1314.4 \text{ BTU/lb}$$

$$\text{Output enthalpy (from steam table; } 91^\circ\text{F and } -14 \text{ PSIG)} = 1099.6 \text{ BTU/lb}$$

$$\text{Difference in enthalpy values from inlet to discharge of turbine} = 1314.4 \text{ BTU/lb} - 1099.6 \text{ BTU/lb} = 214.8 \text{ BTU/lb}$$

$$\text{Heat rate} = (214.8 \text{ BTU/lb})(2300 \text{ lb/min}) = 494,040 \text{ BTU/min} = 29,642,400 \text{ BTU/h}$$

We may convert this heat rate (power) into watts by using the conversion equivalence of 745.7 watts and 2544.43 BTU/h:

$$(29,642,400 \text{ BTU/h}) (745.7 \text{ W} / 2544.43 \text{ BTU/h}) = 8,687,343.6 \text{ W} = 8.69 \text{ MW}$$

Since the turbine is 80% efficient, only 80% of this heat rate gets converted into mechanical shaft power. Therefore,

$$(8.69 \text{ MW})(0.80) = \mathbf{6.95 \text{ MW}} \text{ shaft power}$$

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Answer 41

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Answer 42

**Partial answer:**

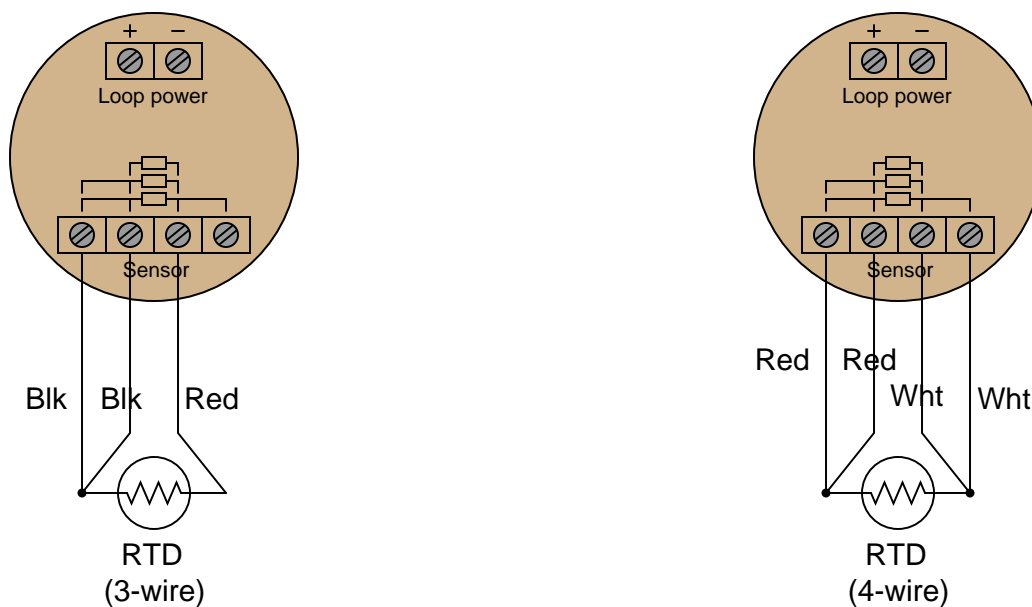
$$R_T = 1470.4 \, \Omega \text{ at } 120^\circ \text{ C}$$

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Answer 43

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Answer 44



**Partial answer:**

- $V_{out} = 0.000 \text{ mV}$  at  $T = 0^\circ \text{ C}$
- $V_{out} = 1.578 \text{ mV}$  at  $T = 35^\circ \text{ C}$

**Partial answer:**

Extra resistance introduced into the RTD arm of the 2-wire RTD bridge circuit by the cable wires will definitely cause temperature measurement errors, because it makes the RTD “appear” to have more resistance than it really does. This will result in an upward zero shift (a falsely high temperature indication).

This same effect will *not* happen in the 3-wire RTD version of the bridge circuit.

**Calculation in three steps:**

*Heat lost as steam cools from 400 °F to 212 °F:*

$$Q = mc\Delta T = (2 \text{ lb})(0.476 \text{ BTU/lb} \cdot ^\circ \text{F})(400^\circ \text{F} - 212^\circ \text{F}) = 178.98 \text{ BTU}$$

*Heat lost as steam condenses to water:*

$$Q = mL = (2 \text{ lb})(970.3 \text{ BTU/lb}) = 1940.6 \text{ BTU}$$

*Heat lost as water cools from 212 °F to 125 °F:*

$$Q = mc\Delta T = (2 \text{ lb})(1 \text{ BTU/lb} \cdot ^\circ \text{F})(212^\circ \text{F} - 125^\circ \text{F}) = 174 \text{ BTU}$$

$$\text{Total Heat Lost} = 178.98 + 1940.6 + 174 = \mathbf{2293.58 \text{ BTU}}$$

**Calculation using enthalpy values (from a steam table):**

Enthalpy of 400 °F superheated steam at 1 atm = 1239.9 BTU/lb = 2479.8 BTU for two pounds steam

Enthalpy of two pounds 125 °F water (heat lost cooling down to 32 °F):

$$Q = mc\Delta T = (2)(1)(125 - 32) = 186 \text{ BTU}$$

$$\text{Total Heat Lost} = 2479.8 - 186 = \mathbf{2293.8 \text{ BTU}}$$

---

Answer 50

Heat loss equation given temperature difference, surface area, and R value:

$$\frac{dQ}{dt} = \frac{A\Delta T}{R}$$

A good problem-solving approach is to neatly organize the given values and calculate surface areas before plugging these values into the heat transfer equations:

- Tank roof = 101 square feet with R-value of 4
- Tank floor =  $\pi r^2 = 78.54$  square feet with R-value of 2
- Tank walls =  $2\pi rh = 408.4$  square feet with R-value of 5 per inch (1.5 inches thick)

*Heat loss through the roof:*

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(101)(95 - 40)}{4} = 1388.75 \text{ BTU/hr}$$

*Heat loss through the floor:*

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(78.54)(95 - 40)}{2} = 2159.84 \text{ BTU/hr}$$

*Heat loss through the walls:*

$$\frac{dQ}{dt} = \frac{A\Delta T}{R} = \frac{(408.4)(95 - 40)}{(5)(1.5)} = 2995.0 \text{ BTU/hr}$$

**Total heat loss rate = 6543.6 BTU/hour**

**Total fuel demand rate = 7883.8 BTU/hour** (at 83% boiler efficiency)

---

Answer 51

The statement means that the RTD is made of platinum wire, with a resistance of  $100 \Omega$  at a reference temperature ( $R_{ref}$ ) of  $0^\circ \text{C}$ . The temperature coefficient of resistance ( $\alpha$ ) at this reference temperature of  $0^\circ \text{C}$  is 0.00385.

---

Answer 52

As temperature increases, the thermistor's resistance decreases because it has a negative  $\alpha$  (note the  $-t^\circ$  symbol inside the thermistor bubble). Less thermistor resistance means that the voltage at the base of the transistor (with respect to the emitter) becomes more positive. This forward-biases the base-emitter PN junction, turning the NPN transistor on. As the transistor turns on more, the lamp receives more current, making it brighter.

---

Answer 53

I'll let you explain the working principle of both circuits!

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Answer 54

- $V_{out} = \underline{-2.04 \text{ mV}}$  at  $T = -20^\circ \text{ C}$
- $V_{out} = \underline{6.032 \text{ mV}}$  at  $T = 70^\circ \text{ C}$
- $V_{out} = \underline{14.08 \text{ mV}}$  at  $T = 200^\circ \text{ C}$

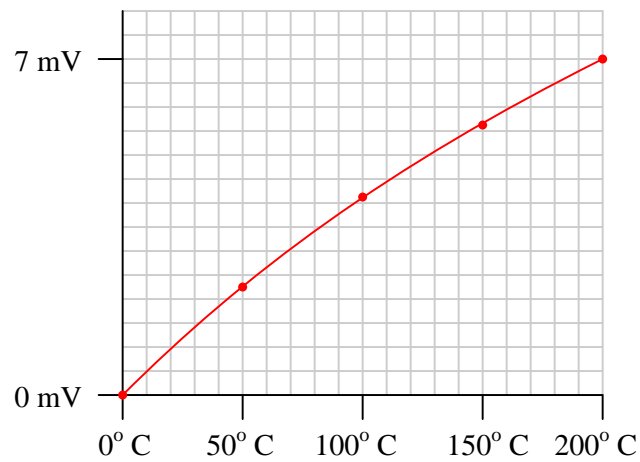
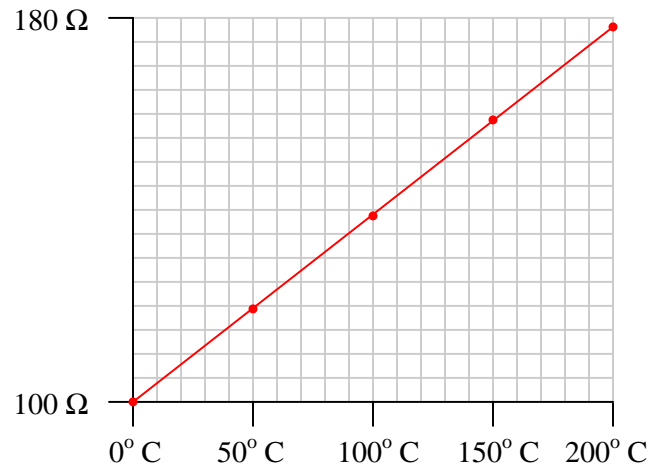
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Answer 55

$$V_{out} = 97.95 \text{ mV}$$

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Answer 56



The contrast is obvious. I'll let you reach your own conclusions!

---

Answer 57

If the oil flow rate decreases, its outlet temperature will increase because each oil molecule spends more time inside the heat exchanger, and thus has more time to absorb heat energy from the steam.

The steam outlet temperature will increase as well, because the decreased flow of oil is not removing as much heat from the steam as it passes through. One way to envision this is to think of the oil as cooling the steam, rather than the steam heating the oil. With less oil entering the exchanger to cool the steam, the outgoing steam will be at a higher temperature than before.

---

Answer 58

$$k = 0.00536$$

$$T = 365.9 \text{ K at } P = 1.96 \text{ bar}$$

---

Answer 59

This is a calorimetry problem, where we must use the specific heat of water (1 BTU per pound-degree F) to calculate the necessary heat for raising its temperature a specified amount (from 51 °F to 205 °F):

$$Q = mc\Delta T$$

Before we may use this formula, however, we need to figure out the mass (in pounds) for 5 gallons of water:

$$\left(\frac{5 \text{ gal}}{1}\right) \left(\frac{231 \text{ in}^3}{1 \text{ gal}}\right) \left(\frac{1 \text{ ft}^3}{1728 \text{ in}^3}\right) \left(\frac{62.4 \text{ lb}}{\text{ft}^3}\right) = 41.71 \text{ lb}$$

Now we are ready to plug all the values into our specific heat formula:

$$Q = mc\Delta T$$

$$Q = (41.71 \text{ lb})(1 \text{ BTU/lb} \cdot ^\circ \text{F})(205^\circ \text{F} - 51^\circ \text{F}) = 6423 \text{ BTU}$$

If dry wood has a fuel value of 9000 BTU per pound, Sally should only (theoretically) need 0.713 pounds (11.4 ounces) of dry wood for this fire.

However . . . we know that not all the heat from an open campfire gets transferred to the water kettle. Given the many forms of heat loss (radiation away from the kettle, convection up into the open air, evaporation of the heating water, etc., etc.), we can count on only a small fraction of the wood fire's heat going into useful heating of the 5 gallons of water. Therefore, Sally will probably need to gather at least several pounds of wood to do the job.

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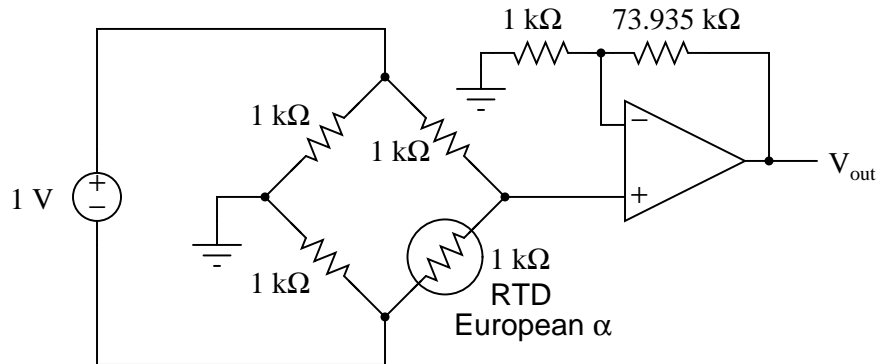
Answer 60

At 0 degrees C,  $R_{RTD} = 1000\ \Omega$  and  $V_+ = 0$  volts

At 80 degrees C,  $R_{RTD} = 1308\ \Omega$  and  $V_+ = 0.06672$  volts (assuming all other resistors in the bridge are  $1\text{ k}\Omega$  each)

In order to achieve a 5 volt opamp output given a 66.72 mV input, we need a voltage gain of exactly 74.935. Given the fact that this opamp circuit is noninverting, and its voltage gain is the ratio of feedback resistors plus one, we need a resistor ratio of 73.935:1.

The following resistor values are suggested, but are not the *only* correct values that may be used to obtain the same calibration:



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Answer 61

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Answer 62

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Answer 63

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Answer 64

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Answer 65

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Answer 66

The voltage output by a milliamp calibrator (in Source mode) would likely ruin the sensitive voltmeter indicator, because that indicator is designed to operate on nothing more than tens of *millivolts*. The calibrator likely outputs at least 12 volts in its attempt to force a 4 to 20 mA current through the meter!

**This is a very common way that students have destroyed thermocouple-input instruments in past classes! A few volts might not seem to harbor any hazards, but it is most definitely destructive to an instrument designed to function on mere millivolt-range signals.**

---

Answer 67

**Partial answer:**

- $T_{process} = -163^\circ\text{ F}$ ; Voltmeter voltage =  $-3.803\text{ mV}$
- $T_{process} = 2350^\circ\text{ F}$ ; Voltmeter voltage =  $51.982\text{ mV}$

---

Answer 68

**Partial answer:**

- $T_{measurement} = 250^{\circ} \text{ F}$  ;  $T_{reference} = 60^{\circ} \text{ F}$  ; Voltmeter voltage = 5.630 mV
- $T_{measurement} = -238^{\circ} \text{ F}$  ;  $T_{reference} = 80^{\circ} \text{ F}$  ; Voltmeter voltage = -7.864 mV

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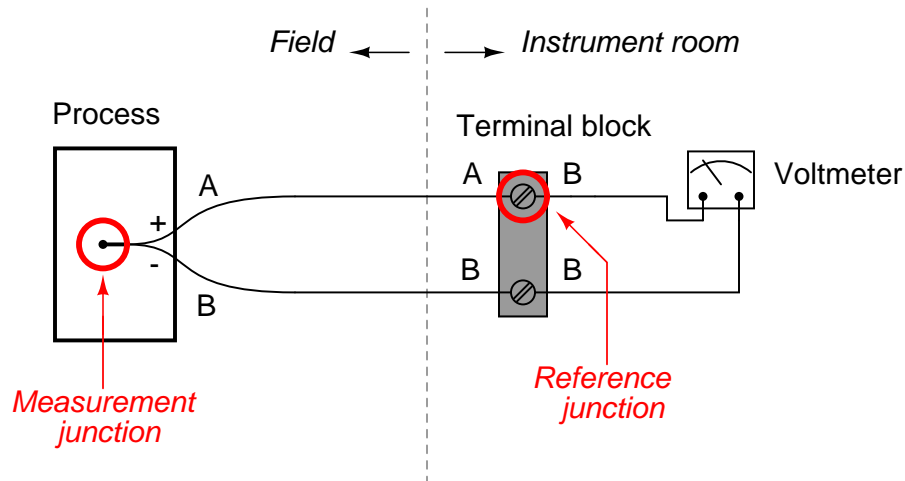
Answer 69

**Partial answer:**

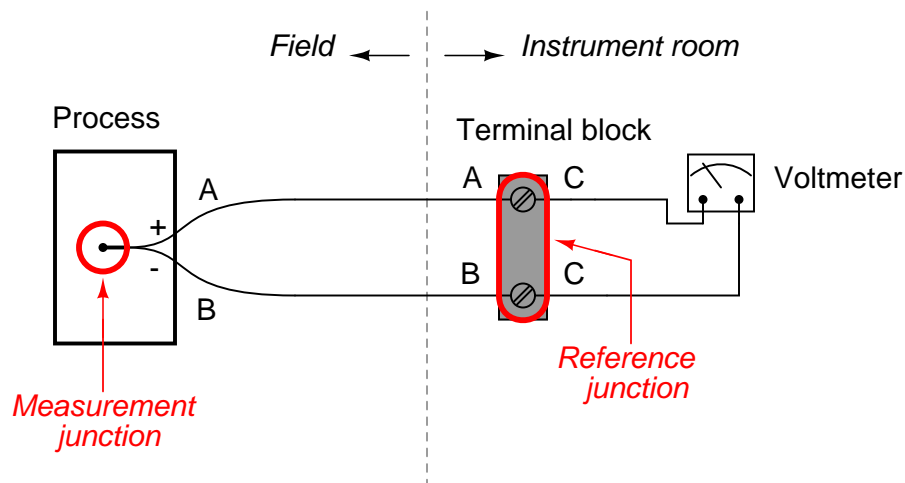
- $T_{reference} = 70^{\circ} \text{ F}$  ; Voltmeter voltage = 20.018 mV ;  $T_{measurement} = 941^{\circ} \text{ F}$
- $T_{reference} = 73^{\circ} \text{ F}$  ; Voltmeter voltage = -2.027 mV ;  $T_{measurement} = -20^{\circ} \text{ F}$



Making both voltmeter wires out of metal **B** allows this simplification of junctions:



Getting rid of metal **B** completely works just as well! Now the **A-C** and **B-C** junctions act as a single reference junction, because they are held at the same temperature by the thermal conductivity of the terminal block:



The upper thermocouple circuit only has two junctions formed by dissimilar metals (the process junction, and the lower terminal block junction), and the lower thermocouple circuit has three, but they are equivalent circuits. Imagine the voltmeter's copper wires shrinking in length until the two terminal block screws touch each other directly, and you will see that the same two Fe-C (Iron-Constantan) junctions exist in the same two circuits – the voltmeter's copper wires are merely an intermediary step in a composite Fe-Cu-C junction, that behaves the same as an Fe-C junction (assuming both screw terminals are at the same temperature).

---

Answer 72

(From ITS-90 thermocouple table:)

- $T_{process} = 350^{\circ} \text{ F}$ ; Voltmeter voltage = 8.064 mV
- $T_{process} = -65^{\circ} \text{ F}$ ; Voltmeter voltage = -1.950 mV
- $T_{process} = 32^{\circ} \text{ F}$ ; Voltmeter voltage = 0 mV
- $T_{process} = 100^{\circ} \text{ C}$ ; Voltmeter voltage = 4.279 mV

Color codes:

- Positive conductor: *Blue*
- Negative conductor: *Red*
- Thermocouple-grade jacket: *Brown*
- Extension-grade jacket: *Blue*

The last temperature was a “trick” question! You had to convert  $100^{\circ} \text{ C}$  into degrees Fahrenheit ( $212^{\circ} \text{ F}$ ), or else look up the answer in a Celsius-indexed table.

The wire size (16 gauge) is extraneous information, included for the purpose of challenging students to identify whether or not information is relevant to solving a particular problem.

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Answer 73

- Voltmeter voltage = 11.857 mV;  $T_{process} = 2178^{\circ} \text{ F}$
- Voltmeter voltage = 6.381 mV;  $T_{process} = 1310^{\circ} \text{ F}$
- Voltmeter voltage = 1.972 mV;  $T_{process} = 502^{\circ} \text{ F}$
- Voltmeter voltage = 0 mV;  $T_{process} = 32^{\circ} \text{ F}$

Color codes:

- Positive conductor: *Black* (extension grade – no standard color for thermocouple grade)
- Negative conductor: *Red* (extension grade – no standard color for thermocouple grade)
- Thermocouple-grade jacket: (no standard color for thermocouple grade)
- Extension-grade jacket: *Green*

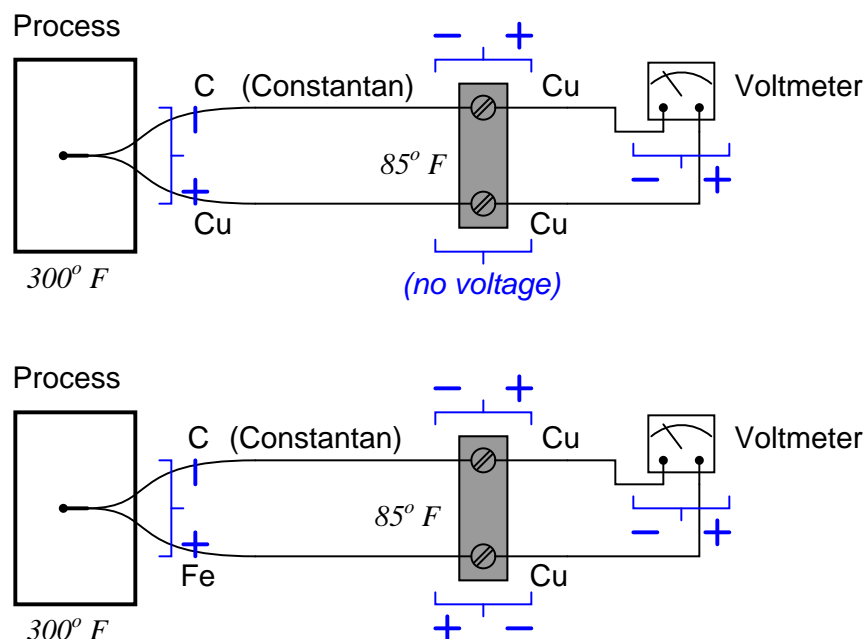
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Answer 74

- $T_{measurement} = 1500^{\circ} \text{ F}$ ;  $T_{reference} = 65^{\circ} \text{ F}$ ; Voltmeter voltage = 61.145 mV
- $T_{measurement} = 212^{\circ} \text{ F}$ ;  $T_{reference} = 74^{\circ} \text{ F}$ ; Voltmeter voltage = 4.925 mV
- $T_{measurement} = -360^{\circ} \text{ F}$ ;  $T_{reference} = 32^{\circ} \text{ F}$ ; Voltmeter voltage = -9.229 mV
- $T_{measurement} = -132^{\circ} \text{ F}$ ;  $T_{reference} = -30^{\circ} \text{ F}$ ; Voltmeter voltage = -2.876 mV

Answer 75

Hint: in order to answer this question, you are going to have to research what standard thermocouple types each dissimilar-metal junction forms, and the reference book(s) will tell you which metal is positive and which is negative.



Answer 76

This circuit only has one reference junction, if you count the two terminal connections at the indicator as a single junction. The junction mid-way between the thermocouple head and the indicator is not a reference junction because it is not a junction of dissimilar metals.

Answer 77

The connections made inside the thermocouple head form a reference junction, the temperature of which will subtract from the furnace's temperature to yield the total voltage registered by the instrument room indicator.

Answer 78

RTDs are more linear than thermocouples. This means that RTDs tend to be more precise within their rated temperature ranges than thermocouples within their rated temperature ranges when interpreted by a linear transmitter circuit, all other factors being equal.

Answer 79

The *saturated vapor pressure* of a substance is a direct function of temperature. If we increase the heat rate so as to boil water faster, we will build up more pressure in the vessel, causing the boiling point to rise. Continued heat flow into the water from the burner will then cause the temperature to rise to match the rising boiling point.

If we try to vent more steam, we cause the pressure in the vessel to decrease. More water begins to boil, which removes heat energy from the water, causing its temperature to drop.

A sophisticated way of stating the problem is that the student assumed *two degrees of freedom* in this process, where there in fact is only one degree of freedom.

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Answer 80

<b>Fault</b>	<b>Possible</b>	<b>Impossible</b>
PCV-40 set too low	✓	
Partial blockage in FT-38	✓	
Burner management system tripped (shut down)		✓
Low air supply pressure to FY-38b	✓	
Air leak in solenoid SV-115	✓	
Solenoid SV-101 shut		✓
Solenoid SV-103 shut		✓
6 inch waste stream header line blocked		✓

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Answer 81

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

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Answer 82

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

---

Answer 83

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

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Answer 84

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

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Answer 85

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

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Answer 86

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

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Answer 87

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

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Answer 88

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

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Answer 89

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

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Answer 90

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

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Answer 91

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Answer 92

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Answer 93

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