

Lab

Analytical measurement loop: *Questions 91 and 92, completed objectives due by the end of day 5, section 3*

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Exam

*Day 6 of section 3*

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

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

- Electricity Review: Design a simple circuit to achieve a stated objective
  - Balancing a chemical reaction
  - Explain the operating principle of a specified analyzer type
  - Calculate temperatures or voltages in thermocouple and RTD circuits given access to thermocouple and RTD tables
  - Solve for a specified variable in an algebraic formula (may contain exponents or logarithms)
  - Determine the possibility of suggested faults in a 4-20 mA loop circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
  - Motor/relay/3phase/PLC Review: Determine status of PLC output given input conditions and RLL program
  - INST252 Review: Identify cause of poor loop performance from a trend graph
  - INST262 Review: Use decibels to calculate power gains and losses
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**Recommended daily schedule**

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Day 1

**Theory session topic:** Conductivity measurement

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

Discuss the upcoming Capstone Assessment due by the end of the course (*Question 93*)

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Day 2

**Theory session topic:** pH and pH measurement

Questions 21 through 40; answer questions 21-30 in preparation for discussion (remainder for practice)

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Day 3

**Theory session topic:** Potentiometric pH measurement

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

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Day 4

**Theory session topic:** Chromatography

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.

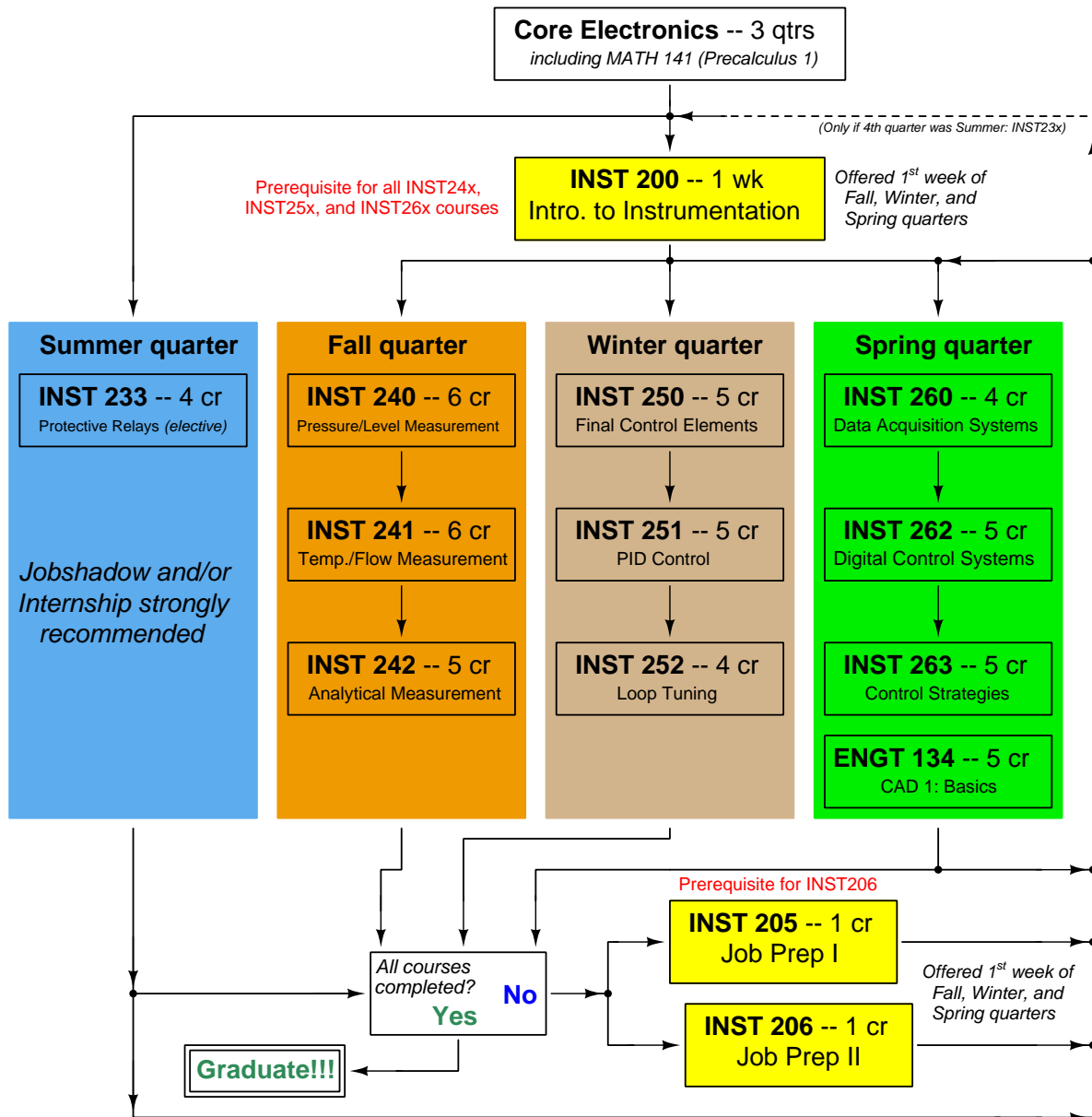
file outcomes\_program

## INST 242 Course Outcomes

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

- 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 analytical loop consisting of a chemical analyzer, signal wiring, and indicator. [Ref: Program Learning Outcome #5]
- Generate an accurate loop diagram compliant with ISA standards documenting your team's analytical measurement system. [Ref: Program Learning Outcome #8]
- Calibrate analyzer to specified accuracy using industry-standard calibration equipment. [Ref: Program Learning Outcome #7]
- Design and build a circuit to fulfill a function randomly selected by the instructor (voltage divider, passive filter, capacitive time-delay, or phase shift network) and demonstrate its proper operation using a signal generator and oscilloscope. [Ref: Program Learning Outcome #5]
- Diagnose a random fault placed in another team's analytical measurement system by the instructor within a limited time using no test equipment except a multimeter, logically justifying your steps in the instructor's direct presence. [Ref: Program Learning Outcome #4]
- Construct a working control loop consisting of a pre-made process unit with transmitter and final control element, properly connected to a controller, within a limited time. Both the process and the controller are randomly selected by the instructor, with measurement range values specified by the instructor. [Ref: Program Learning Outcomes #5 and #9]

## 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> ( $\text{W/m}^2 \cdot \text{K}^4$ )

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

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

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

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

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

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

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

### Properties of Dry Air at sea level

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

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

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 “Terms and Definitions” section of the “Chemistry” 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 i04121

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## Question 2

Each element on the periodic table has its own preferred state of ionization in liquid solutions. Hydrogen, Sodium, and Potassium atoms, for instance, “want” to ionize with a single positive charge ( $\text{H}^+$ ,  $\text{Na}^+$ , and  $\text{K}^+$ , respectively). Magnesium, Calcium, and Barium atoms “want” to ionize with a double positive charge ( $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ , and  $\text{Ba}^{2+}$ , respectively). Oxygen atoms “prefer” to ionize with a double negative charge ( $\text{O}^{2-}$ ). The “halogen” elements (Fluorine, Chlorine, Bromine, Iodine, etc.) tend to ionize with a single negative charge ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ , respectively). Nitrogen atoms readily take on a triple negative charge ( $\text{N}^{3-}$ ).

Just as the individual elements have their own ionization preferences, certain molecular combinations of elements also have preferred ionization states.

Shown here is a list of some common polyatomic ions:

- Ammonium =  $\text{NH}_4^+$
- Hydroxide =  $\text{OH}^-$
- Hydronium =  $\text{H}_3\text{O}^+$
- Cyanide =  $\text{CN}^-$
- Nitrite =  $\text{NO}_2^-$
- Nitrate =  $\text{NO}_3^-$
- Phosphate =  $\text{PO}_4^{3-}$
- Hydrogen phosphate =  $\text{HPO}_4^{2-}$
- Sulphite =  $\text{SO}_3^{2-}$
- Sulphate =  $\text{SO}_4^{2-}$
- Hydrogen sulphide =  $\text{HS}^-$
- Hydrogen sulphite =  $\text{HSO}_3^-$
- Hydrogen sulphate =  $\text{HSO}_4^-$
- Carbonate =  $\text{CO}_3^{2-}$
- Hypochlorite =  $\text{ClO}^-$
- Chlorate =  $\text{ClO}_3^-$
- Borate =  $\text{BO}_3^{3-}$

Identify which of these ions are *cations* and which are *anions*, and then explain the meanings of the subscript and superscript numbers.

<b>Suggestions for Socratic discussion</b>
--

- Note that the hydrogenated versions of sulphur ions have one less negative charge (one more positive charge) than the unhydrogenated versions. Explain this pattern!
- Compare all the ions whose names end in “-ide” versus “-ite” versus “-ate”. Do you see any pattern to the naming of ions?

file i03078

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### Question 3

Read and outline the “Ions In Liquid Solutions” section of the “Chemistry” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i04122](#)

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### Question 4

Read and outline the introduction, the “Dissociation and Ionization in Aqueous Solutions” subsection, and the “Two-Electrode Conductivity Probes” subsection of the “Conductivity Measurement” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i04124](#)

## Question 5

Bring the following materials to class to perform an experiment demonstrating conductivity and electrolysis in water. You may partner with one or two classmates to bring these materials, and perform the experiment together. You are also free to perform the experiment before class to get an advance-start on understanding the principles involved:

- Two paper clips
- Small drinking cup (to fill with water)
- At least two “alligator clip” jumper wires
- One 6-volt or 9-volt battery
- One or more packets of table salt (from the cafeteria)
- Stir-stick (or pencil) to mix salt into the water
- Multimeter capable of measuring current in the milliamp range

Bend the paperclips so they form two electrodes which will dip into water you put in the cup. Place each paperclip on opposite sides of the cup, maximizing the distance between them. Fill the cup with water, and connect the paper-clip electrodes to the battery and to your multimeter (forming a series circuit so the meter measures *current*) using the “alligator clip” jumper wires. Take one measurement of the battery’s voltage for reference later (you will need to know the voltage so you can calculate conductance:  $G = \frac{I}{V}$ ).

Document the meter’s current measurement indication. Add approximately one-quarter of the salt to the water and stir it until it completely dissolves, then document the meter’s indication and calculate the conductance ( $G$ ). Repeat this process over and over until you have added all the salt to the water. *Be careful to maintain the same amount of separation between the two paper-clip electrodes when taking measurements, and make absolutely sure they never touch each other!* Maintaining a constant separation is important for measurement accuracy, and avoiding contact prevents you from blowing a fuse in your meter.

<b>Battery voltage</b>	volts
------------------------	-------

<b>Salt content</b>	<b>Measured current (<math>I</math>)</b>	<b>Calculated conductance (<math>G = \frac{I}{V}</math>)</b>
No salt in the water		
$\approx 25\%$ of the salt added		
$\approx 50\%$ of the salt added		
$\approx 75\%$ of the salt added		
100% of the salt added		

Devise a method of determining when the water has become *saturated* with salt, and describe your procedure. Note: you may require more salt than used in your initial test in order to achieve saturation.

After running this experiment for a short while, you will probably notice a lot of bubbles collecting on the two electrodes. At least one of these gases will have a very distinctive odor. Identify which gas this is, and explain why it is being generated based on your knowledge of chemistry.

[file i04123](#)

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### Question 6

Read and outline the “Four-Electrode Conductivity Probes” subsection of the “Conductivity Measurement” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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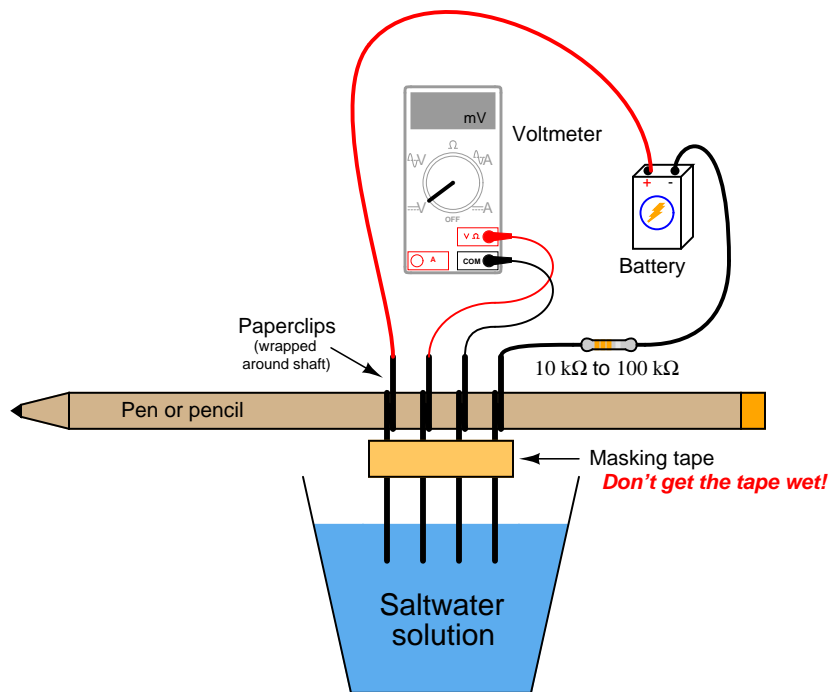
[file i04125](#)

### Question 7

Bring the following materials to class to build your own four-wire conductivity probe. Partner with several classmates ahead of time to bring these materials, and to perform the experiment together in class as a team:

- Four large paperclips
- Masking tape
- Small drinking cup (to fill with water)
- One pencil or plastic (non-metal) pen
- At least five “alligator clip” jumper wires (only three if multimeter has test clips)
- One 6-volt or 9-volt battery
- Resistor between  $10\text{ k}\Omega$  and  $100\text{ k}\Omega$  in value
- One or more packets of table salt (from the cafeteria)
- Multimeter capable of measuring DC millivolts

Bend the paperclips so they are straight, then wrap them around the pencil or pen to form a four-electrode conductivity probe, with the electrode spacing narrow enough for all four electrodes to easily fit into the opening of the cup. Fold a length of masking tape over the four wires to hold them in position, ensuring consistent spacing between the wires as the probe is used. *Do not get the masking tape wet with the sample water*, or else all subsequent conductivity measurements will be affected by electrical conductance within the wet tape. Be sure to use steel paperclips rather than copper wires, as steel is much less chemically reactive with saltwater than copper.



The large resistor in series with the battery forms a crude current source: current output by the battery will be relatively constant despite changes in water conductivity because the large series resistor value “swamps out” the relatively small amount of resistance presented by the saltwater. Your results will not be nearly as good without the resistor in series!



The instructor will take several cups and prepare random concentrations of saltwater, identifying each cup with a number written on the side. Your team's job is to use your conductivity probe to rank each solution in order from *greatest conductivity* to *least conductivity*. In order to minimize the "traffic congestion" of students at the cups, it is recommended that members from each team quickly insert their probe into each solution and gather the raw data (voltage measurements) for each numbered cup, then return to their seats to analyze the data and rank the solutions. When your team has agreed on a ranking, write your ranked results (from greatest to least) on a piece of paper and prepare to present your findings to the class.

#### Suggestions for Socratic discussion

- Explain how this 4-wire conductivity probe design is similar to the design of a 4-wire RTD temperature sensor. What is the purpose of using 4 wires instead of 2 wires in an RTD circuit, and how is this purpose similar to that in a 4-wire conductivity probe?
- Explain how your conductivity instrument's response will be affected by increasing the spacing between all four electrodes.
- Suppose we actually wished to *calibrate* a student-built conductivity probe so it measured solution conductivity in Siemens per centimeter. How would we go about calibrating it to ensure it read conductivity accurately?

[file i04126](#)

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#### Question 8

Read and outline the "Electrodeless Conductivity Probes" subsection of the "Conductivity Measurement" section of the "Continuous Analytical Measurement" chapter in your *Lessons In Industrial Instrumentation* textbook.

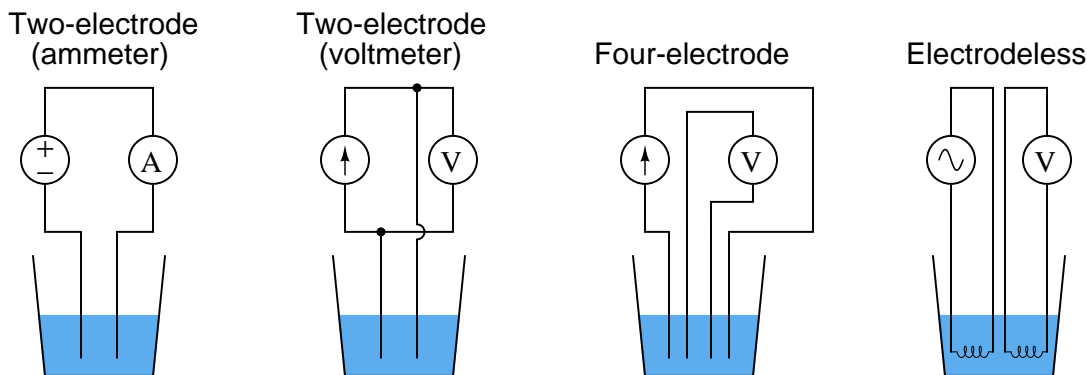
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[file i04127](#)

### Question 9

Compare the behaviors of these three conductivity probes to a steadily increasing liquid conductivity over time, noting whether the meter indication *increases*, *decreases*, or *remains the same* as the liquid's conductivity steadily increases:



Probe design	Meter indication
Two-electrode (ammeter)	
Two-electrode (voltmeter)	
Four-electrode	
Electrodeless	

Be prepared to explain *why* each meter's indication changes as it does!

Now, determine how the meter's indication will be affected by a steady accumulation of residue ("plating") on the probes over time, identifying whether the meter indication will *increase*, *decrease*, or *remain the same*:

Probe design	Meter indication
Two-electrode (ammeter)	
Two-electrode (voltmeter)	
Four-electrode	
Electrodeless	

### Suggestions for Socratic discussion

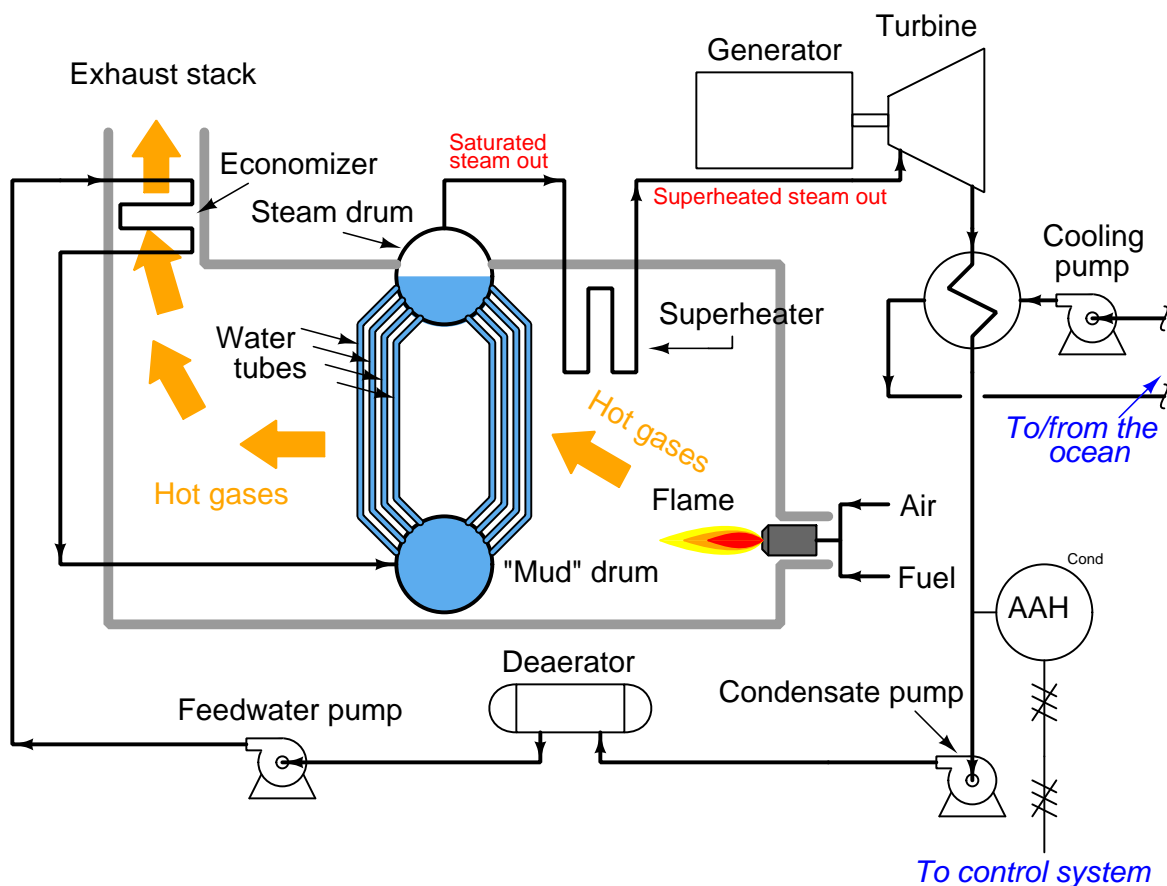
- Explain why we use a *voltage source* in the "ammeter" style of two-electrode cell, and a *current source* in the "voltmeter" style of two-electrode cell. What would happen if we mixed up the meter and source styles (e.g. ammeter with a current source; voltmeter with a voltage source)?
- Is it possible to use an AC excitation source rather than a DC source in either the 2-electrode or 4-electrode cell designs? Explain why or why not.
- Is it possible to use a DC excitation source rather than an AC source in the electrodeless cell design? Explain why or why not.
- Identify something we could do to the liquid solution to increase its conductivity.
- Identify something we could do to the liquid solution to decrease its conductivity.
- Imagine pouring liquid mercury into the sample cups rather than water. What effect will this have on each conductivity meter type?

- Imagine draining all liquid out of the sample cups. What effect will this have on each conductivity meter type?

file i04128

# Question 10

The following PFD shows the “loop” for steam and water in a power boiler system, where fuel is burnt to produce electricity. This particular power plant is located near the ocean, where saltwater is used to cool the steam turbine’s exhaust back into water:



The purpose of the “AAH” instrument is to detect any leaks that might develop inside the condenser (heat exchanger). What exactly is this analytical instrument measuring and what purpose does it serve in the context of the larger system? What would be bad about having a small leak in the heat exchanger, anyway?

## Suggestions for Socratic discussion

- Describe the difference between *saturated* steam and *superheated* steam.
- Would it be useful to place a conductivity sensor in either the saturated or superheated steam line? Explain why or why not.
- Would it be useful to place a conductivity sensor in the mud drum? Explain why or why not.
- One way to help avoid contamination due to leakage is to situate the heat exchanger with the proper pressure differential between the cooled and cooling fluids. Describe how this “pressure differential” approach might be applied to this process, so that a heat exchanger leak would not be so disruptive to power plant operations. Furthermore, identify where a differential pressure transmitter could be connected in this system to monitor the pressure difference.
- Identify how the piping arrangement could be altered from what is shown in this diagram to help maintain a pressure differential between the tube and shell sides of the heat exchanger.

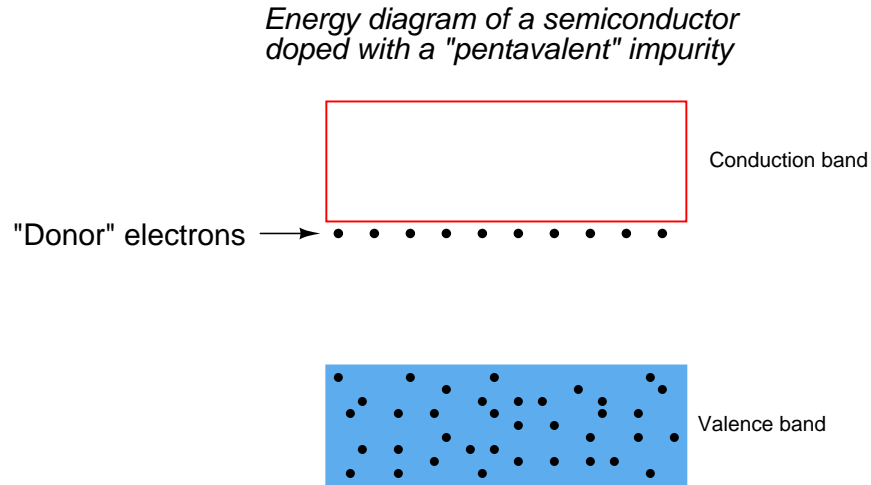
- Examining this diagram, identify the purpose of the “economizer” in a boiler feedwater system.
- Examining this diagram, describe the difference between “saturated” and “superheated” steam, and explain how both types of steam are produced.
- Identify suitable level transmitter technologies for installation in the steam drum.
- Identify suitable flowmeter technologies for installation in the feedwater line, and also the most desirable location(s). Assume we need to know the *mass* flow rate for boiler feedwater, in units of pounds per minute.
- Identify suitable flowmeter technologies for installation in the saturated steam line, and also the most desirable location(s). Assume we need to know the *mass* flow rate for boiler steam output, in units of pounds per minute.
- Identify suitable flowmeter technologies for installation in the burner’s air line.
- Identify suitable flowmeter technologies for installation in the burner’s fuel line, assuming a liquid fuel.
- Identify suitable flowmeter technologies for installation in the burner’s fuel line, assuming a gaseous fuel.

file i03727

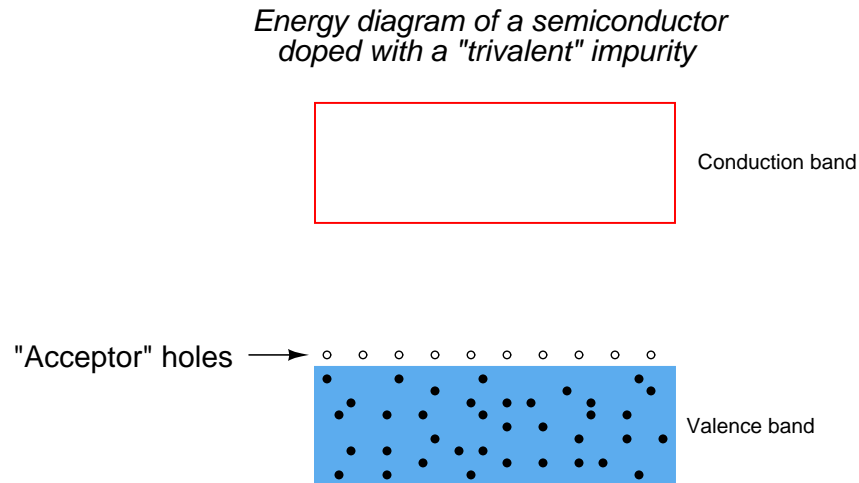
### Question 11

Electrical conductivity in metals is a function of free electrons. That is to say, free electrons are the *charge carriers* for electricity in metallic substances.

Electrical conductivity in semiconductors is a function of either conduction-band electrons or valence-band holes. Pentavalent dopants add electrons at an energy level just beneath the conduction band of a semiconductor crystal, allowing ambient thermal energy to boost those electrons into the conduction band and serve as charge carriers like free electrons in metals. This makes an *N-type* semiconductor:



Trivalent dopants add “vacancies,” or “holes,” for valence-band electrons to leap in to with the help of ambient thermal energy. This makes room for motion of electrons within the valence band, and we call the resulting substance a *P-type* semiconductor:



To differentiate the valence-band electron motion in P-type semiconductors from the conduction-band electron motion in N-type semiconductors, we commonly refer to the valence-band electrons’ motion in terms of the “holes” they leave behind, and treat these holes as positive charge carriers.

Conduction within liquids is another thing entirely. Since the molecules are free to move about within liquids (and not within solids), entire molecules may act as electrical charge carriers if they are *ionized*. Explain what “ionization” is, and distinguish between *anions* and *cations*.

[file i00603](#)

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### Question 12

Any substance that enhances electrical conductivity when dissolved in water is called an *electrolyte*. When “table” salt is mixed with water to become a solution, an interesting thing happens called *dissociation*. A similar process called *ionization* occurs when hydrogen chloride (HCl) enters a solution. Explain what these processes are.

Then, identify how the following electrolytes will separate into cations and anions when dissolved in water. In other words, identify which part of each electrolyte molecule will become an anion, and which part will become a cation:

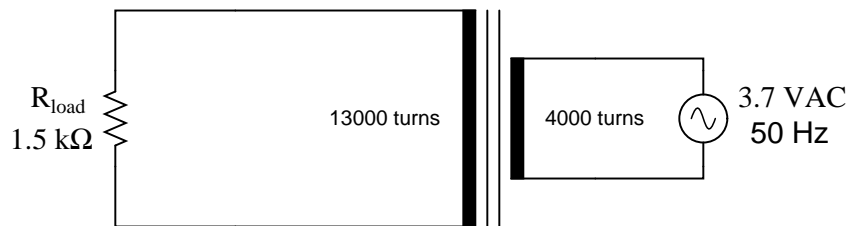
- Sodium Chloride (NaCl) →
- Hydrogen Chloride (HCl) →
- Sodium Hydroxide (NaOH) →
- Calcium Sulfate (CaSO<sub>4</sub>) →
- Potassium Sulfate (K<sub>2</sub>SO<sub>4</sub>) →
- Sulfuric Acid (H<sub>2</sub>SO<sub>4</sub>) →

Hint: you might find a *Periodic Table of the Ions* helpful in determining how these compounds dissociate.  
[file i00604](#)

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### Question 13

Calculate all listed values for this transformer circuit:



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

Explain whether this is a *step-up*, *step-down*, or *isolation* transformer, and also explain what distinguishes the “primary” winding from the “secondary” winding in any transformer.

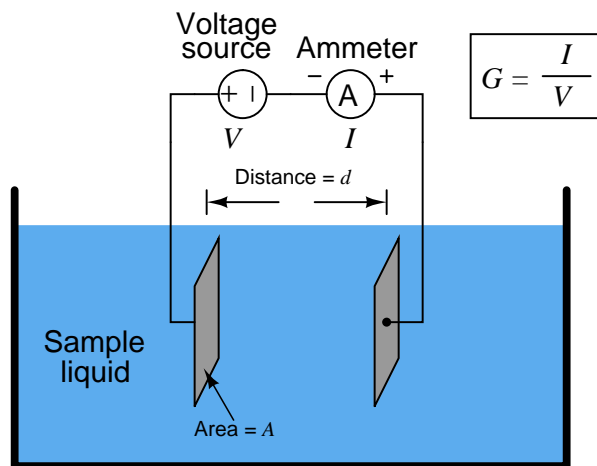
[file i00611](#)

# Question 14

Conductance of an aqueous (water-based) solution is usually expressed in units of Siemens per centimeter (S/cm). The unit of Siemens, of course, is nothing more than the reciprocal of Ohms, given that conductance ( $G$ ) and resistance ( $R$ ) are inverse quantities:

$$G = \frac{1}{R}$$

We may measure the conductivity of a liquid by immersing two electrodes of known area into that liquid, separating them by a known distance, and then measuring the electrical conductance between the electrodes. We call such a device a *conductivity cell*:



Assuming the conductivity of the liquid does not change, how will the conductance measurement be affected by changes in electrode area and distance? The following equation may be helpful in answering this question:

$$G = k \frac{A}{d}$$

Where,

$G$  = Conductance, in Siemens (S)

$k$  = Specific conductivity of liquid, in Siemens per centimeter (S/cm)

$A$  = Electrode area (each), in square centimeters (cm<sup>2</sup>)

$d$  = Electrode separation distance, in centimeters (cm)

Also, show how the unit of “Siemens per centimeter” comes directly from this equation.

file i00606



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#### Question 15

Conductivity cells are rated in terms of a *cell constant*, often denoted by the Greek letter  $\theta$  (“theta”) in conductivity equations. The proper unit of measurement for this cell constant is inverse centimeters, or  $\text{cm}^{-1}$ .

Take the following two equations and combine them using algebraic substitution to form a new equation solving for the specific conductivity of a liquid ( $k$ ) given raw conductance ( $G$ ) and the cell constant ( $\theta$ ):

$$G = k \frac{A}{d} \qquad \theta = \frac{d}{A}$$

Where,

$G$  = Conductance, in Siemens (S)

$\theta$  = Conductivity cell constant, inverse centimeters ( $\text{cm}^{-1}$ )

$k$  = Specific conductivity of liquid, in Siemens per centimeter (S/cm)

$A$  = Electrode area, in square centimeters ( $\text{cm}^2$ )

$d$  = Electrode separation distance, in centimeters (cm)

[file i00607](#)

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#### Question 16

A conductivity probe is used to measure the conductivity of a water sample. Supposing the drive (excitation) current to the probe is  $150 \mu\text{A}$ , the sensed (output) voltage is 1.64 volts, and the cell constant ( $\theta$ ) is 1.2, calculate the specific conductivity ( $k$ ) of the water sample.

Relevant formulae:

$$G = k \frac{A}{d} \qquad \theta = \frac{d}{A} \qquad k = G\theta$$

Where,

$G$  = Conductance, in Siemens (S)

$k$  = Specific conductivity of liquid, in Siemens per centimeter (S/cm)

$A$  = Electrode area (each), in square centimeters ( $\text{cm}^2$ )

$d$  = Electrode separation distance, in centimeters (cm)

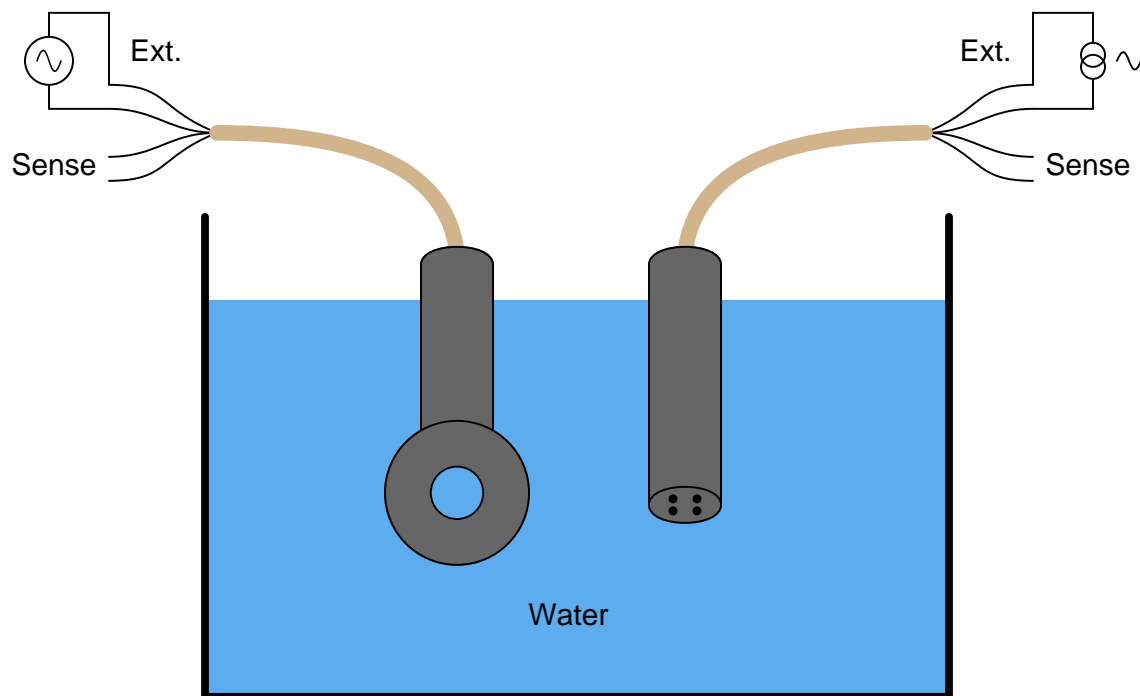
$\theta$  = cell constant

[file i03074](#)

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### Question 17

Imagine a situation where two different conductivity probes are immersed in the same container of water. One probe is toroidal, while the other is a 4-electrode “contact” style:



In both cases, the excitation signal (Ext.) is alternating current (an AC voltage source for the toroidal probe and an AC current source for the contact probe). In both cases, the probe has a pair of wires outputting the “Sense” signal (normally going to an electronic amplifying circuit for conditioning and conversion into a 4-20 mA DC instrument signal).

As table salt (NaCl) is added to the water, one probe’s “sense” signal will grow stronger while the other probe’s “sense” signal will diminish. Identify which is which, and explain why in each case.

[file i03073](#)

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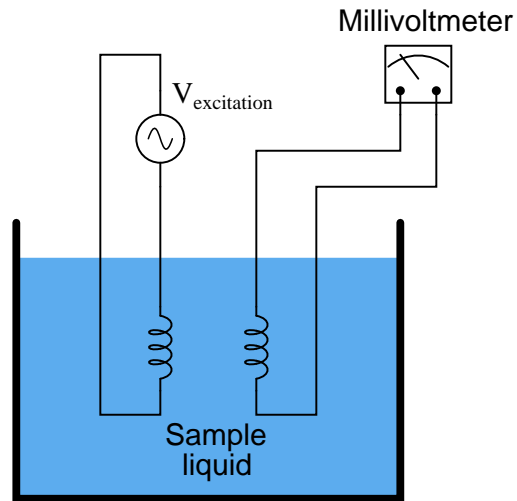
### Question 18

A toroidal conductivity sensor may suffer from calibration error if located too close to the wall of a metal pipe. Explain why.

[file i03075](#)

Question 19

Examine the following toroidal conductivity analyzer circuit, then answer the questions that follow:



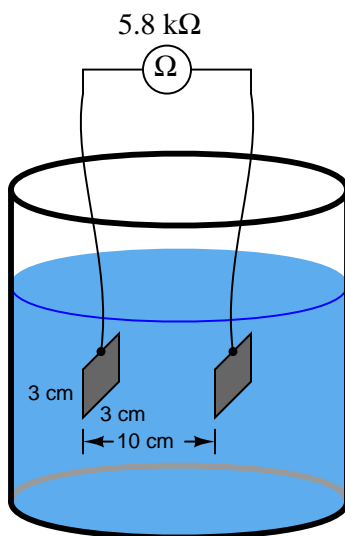
- If  $V_{excitation}$  were to increase, would the millivoltmeter's reading *increase*, *decrease*, or *stay the same*?
- If the conductivity of the liquid were to increase, would the millivoltmeter's reading *increase*, *decrease*, or *stay the same*?
- If the liquid were to completely drain out of the sample holder, would the millivoltmeter's reading *increase*, *decrease*, or *stay the same*?
- If the sampled liquid is tap water, identify something you could do to the water to increase its conductivity.

file i04305

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Question 20

An ohmmeter registers a resistance of  $5.8\text{ k}\Omega$  when connected between two metal plates immersed in a sample of water. The metal plates each measure 3 centimeters by 3 centimeters, and are separated by a distance of 10 centimeters:



Calculate the specific conductivity of this water, expressed in units of microsiemens per centimeter ( $\mu\text{S}/\text{cm}$ ):

Specific conductivity = \_\_\_\_\_  $\mu\text{S}/\text{cm}$

[file i00923](#)

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Question 21

Read and outline the “pH” section of the “Chemistry” 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
- Page numbers from the source text for quick reference during discussion
- 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 i04129](#)

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**Question 22**

What is the difference between an *acid*, a *base*, and a *salt*?

Determine whether the following compounds are acids, bases, or salts, based on their formulae:

- NaOH
- KCl
- H<sub>2</sub>SO<sub>4</sub>
- HNO<sub>3</sub>
- KOH
- HCN
- NaCl
- ZnSO<sub>4</sub>

**Suggestions for Socratic discussion**

- A helpful reference to consult is a *periodic table of the ions*, showing the “preferred” ionic states of elements and common compounds.
- Explain why the addition of O<sup>2-</sup> ions to a solution increases pH just as the addition of OH<sup>-</sup> ions will.
- All other factors being equal, does the electrical conductivity of any electrolyte vary depending on if it is an acid, a base, or a salt?

[file i00612](#)

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**Question 23**

Suppose two chemistry students decide to engage in a “pH battle,” where one tries to make a bucket of water more acidic by adding hydrochloric acid (HCl), while the other tries to make the same water more alkaline by adding sodium hydroxide (NaOH).

Identify the reaction products resulting from the mixing of these two substances in water, and why you would be wise to stay clear of this experiment.

**Suggestions for Socratic discussion**

- What conditions would make this neutralization safer to execute? What conditions would make it more dangerous?
- Would you expect a pH neutralization process to be *endothermic* or *exothermic*? Explain your reasoning.
- Identify the reaction products from mixing calcium hydroxide with sulfuric acid in a similar “pH battle”.
- Identify the reaction products from mixing hydrofluoric acid with magnesium hydroxide in a similar “pH battle”.

[file i04131](#)

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#### Question 24

Read and outline the “Colorimetric pH Measurement” subsection of the “pH Measurement” section of the “Continuous Analytical 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 i04134](#)

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### Question 25

Research how to use *litmus paper* to measure pH, and prepare to measure the pH values of several different solutions in class. Plan with some of your classmates to bring some of these substances to class:

- Small drinking cup (no more than one per person necessary)
- Carbonated beverage
- Milk
- Orange juice
- Cranberry juice
- Bottled water
- Water from home
- Water from a public drinking fountain at school
- Antacid pills
- Drain cleaner powder (do not let the powder contact your skin!)
- Vinegar

The instructor will take several cups and partially fill them with the liquid samples you bring to class. Your team's job is to use strips of litmus paper (also supplied by the instructor) to rank each sample in order from *highest pH* to *lowest pH*. In order to minimize the “traffic congestion” of students at the cups, it is recommended that each team member quickly dip one litmus paper strip into one solution (each of their teammates dipping their strips into different solution cups) and return to their desks for analysis of the paper and to rank the solutions. When your team has agreed on a ranking, write your ranked results (from greatest to least) on a piece of paper and prepare to present your findings to the class.

<b>Suggestions for Socratic discussion</b>
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- Identify some of the disadvantages of measuring pH with litmus paper.
- Devise a way in which this colorimetric method of pH sensing could be automated, to provide a 4-20 mA electronic signal representing pH based on the color change of a litmus strip.

[file i04133](#)

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#### Question 26

Calculate the pH values of the following solutions, given the hydrogen ion concentrations shown. Based on the pH values you obtain, determine whether each solution is *acidic*, *alkaline*, or *neutral*:

- $[\text{H}^+] = 0.0007 \text{ M}$  ; pH = \_\_\_\_\_
- $[\text{H}^+] = 0.0000032 \text{ M}$  ; pH = \_\_\_\_\_
- $[\text{H}^+] = 0.000000085 \text{ M}$  ; pH = \_\_\_\_\_
- $[\text{H}^+] = 0.0000000012 \text{ M}$  ; pH = \_\_\_\_\_

#### Suggestions for Socratic discussion

- Which of these solutions has the greatest concentration of hydrogen ions, and which of these solutions has the least?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- As hydrogen ion concentration increases in a solution, does the solution become more acidic or more alkaline?
- Does a sample of water become more acidic, more alkaline, or does its pH value remain stable as it is *electrolyzed* to produce hydrogen and oxygen gases?
- Explain why we cannot calculate the ionization constant ( $K_w$ ) of the solution from just this information given.

[file i04135](#)

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#### Question 27

Calculate the hydrogen ion molarities of the following solutions, given the pH values shown:

- 8.15 pH ;  $[\text{H}^+] = \text{_____ } \text{M}$
- 2.71 pH ;  $[\text{H}^+] = \text{_____ } \text{M}$
- 6.08 pH ;  $[\text{H}^+] = \text{_____ } \text{M}$
- 10.62 pH ;  $[\text{H}^+] = \text{_____ } \text{M}$

#### Suggestions for Socratic discussion

- Which of these solutions has the greatest concentration of hydrogen ions, and which of these solutions has the least?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.
- Demonstrate how to display all possible non-zero digits on your calculator when you are presented with a number such as 0.000000007 (i.e. when significant figures are hidden from view owing to limitations in the calculator's display width).
- How much must the hydrogen ion molarity of a solution change in order to experience a pH increase of 1?
- How much must the hydrogen ion molarity of a solution change in order to experience a pH decrease of 1?

[file i04136](#)



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### Question 28

Read the “Sodium hydroxide” (caustic soda) entry in the *NIOSH Pocket Guide To Chemical Hazards* (DHHS publication number 2005-149) and answer the following questions:

Write the chemical formula for sodium hydroxide, and identify its constituent elements. Is this considered an acid, a base, or a salt?

Calculate the molecular weight for this compound, and also the mass that 13 moles of pure sodium hydroxide will have.

Interpret the respirator recommendations given for sodium hydroxide in the NIOSH guide. Is a filter-style respirator sufficient, or must a person work with a “supplied air” apparatus to ensure they do not inhale sodium hydroxide?

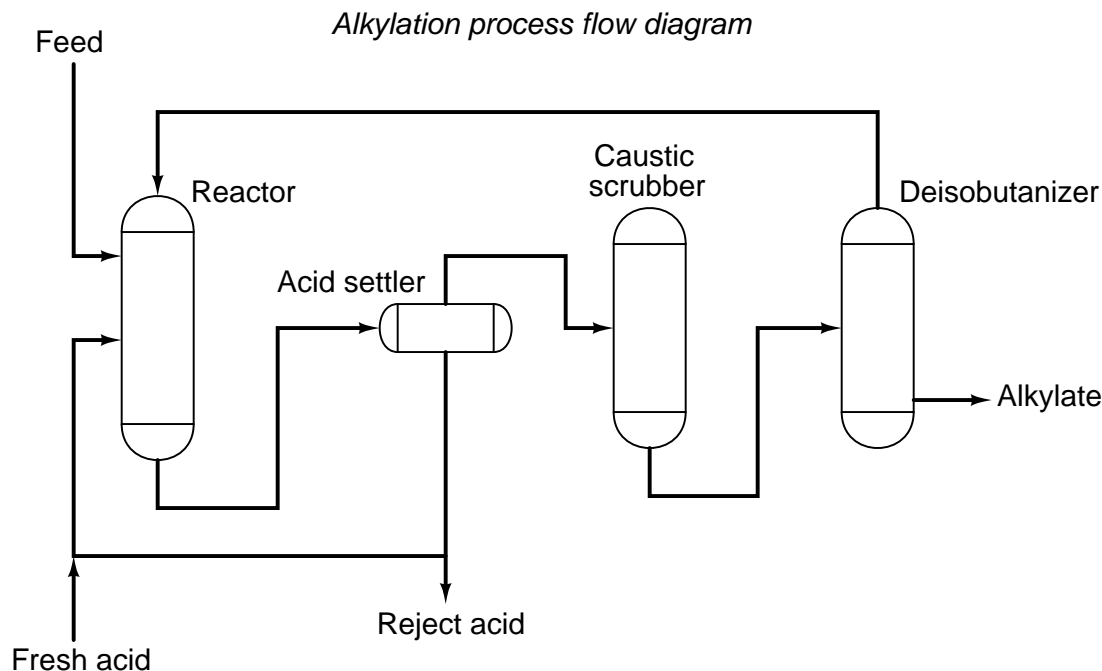
<b>Suggestions for Socratic discussion</b>
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- Explain *why* a filter-style respirator is or is not sufficient protection against inhalation of this chemical substance, based on what you know about its physical properties.
- Identify why sodium hydroxide powder might be added to drinking water in a water purification process.

[file i04138](#)

## Question 29

A process used in the oil refining industry to make high-octane gasoline feedstock is called *alkylation*. So-called “alky” units employ a concentrated acid as the catalyst for the alkylation reaction, usually sulfuric acid:



The “acid settler” vessel is a separator, allowing the reaction products and acid catalyst to separate according to their respective densities (concentrated sulfuric acid being denser than any hydrocarbon). The interface level between hydrocarbon liquid and acid must be tightly controlled for the process to work well. It is bad for acid to “carry over” to the caustic scrubber (if the interface rises too high), and it is also bad for hydrocarbon liquids to leave the system through the “reject acid” line (if the interface falls too low).

The major problem here is that the sulfuric acid is highly corrosive, creating a challenge for interface level measurement. Identify a few different level-measurement technologies that might be appropriate for sensing the settler’s interface level.

### Suggestions for Socratic discussion

- By contrast, can you think of some level-measurement technologies that would *not* be appropriate for highly corrosive solutions?
- Identify some of the different *flowmeter* technologies appropriate to various process lines shown for this alkylation unit.
- What types of *personal protective equipment* (PPE) do you think an instrument technician might need to wear before working on a instrument contacting this highly concentrated acid?
- How much fresh acid needs to be sent to the reactor, compared to the hydrocarbon feed rate? Explain your answer based on what a *catalyst* does in a chemical reaction.
- Older alkylation units used *hydrofluoric acid* instead of sulfuric acid because HF is a more effective catalyst for the alkylation reaction than  $\text{H}_2\text{SO}_4$ . Unfortunately, while sulfuric acid at this concentration is quite dangerous, hydrofluoric acid is far worse. HF tends to penetrate skin easier than many other acids, and when inside the body it dissolves bones! Explain why the first-aid for topical HF exposure is to apply (or sometimes inject) a calcium gluconate ( $\text{C}_{12}\text{H}_{22}\text{CaO}_{14}$ ) solution.

### Question 30

When the sugar *glucose* ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) ferments, the result is the production of carbon dioxide ( $\text{CO}_2$ ) and ethanol ( $\text{C}_2\text{H}_5\text{OH}$ ). This is the chemical reaction on which all alcohol beverage industries are founded: the conversion of sugar into ethanol. The following chemical equation shows the conversion of glucose into carbon dioxide and ethanol:



Unfortunately, this equation is incomplete. Although it does indicate the *identities* of the reaction products (carbon dioxide and ethanol), it does not indicate their *relative quantities*. Re-write this chemical equation so that it is balanced.

<b>Suggestions for Socratic discussion</b>
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- Fermentation is a process strongly influenced by pH. Is this evident from the balanced equation, or not?
- Is fermentation an endothermic or exothermic process? How may we tell by this chemical equation?

[file i00572](#)

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### Question 31

Calculate the sodium ion molarity of a solution made from 0.05 moles of table salt ( $\text{NaCl}$ ) completely dissolved in 30 cups of water.

Calculate the chlorine ion molarity of a solution made from 0.05 moles of table salt ( $\text{NaCl}$ ) completely dissolved in 30 cups of water.

[file i04130](#)

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### Question 32

Many liquid substances undergo a process whereby their constituent molecules split into positively and negatively charged ion pairs. Liquid *ionic* compounds split into ions completely or nearly completely, while only a small percentage of the molecules in a liquid *covalent* compound split into ions. The process of neutral molecules separating into ion pairs is called *dissociation* when it happens in ionic compounds, and *ionization* when it happens to covalent compounds.

Molten salt ( $\text{NaCl}$ ) is an example of the former, while pure water is an example of the latter. The large presence of ions in molten salt explains why it is a good conductor of electricity, while the comparative lack of ions in pure water explains why it is often considered an insulator.

However, while the ionization process in water is very slight, it is not zero. Research the molarity (how many moles per liter of volume –  $M$ ) for both anions and cations in pure water at  $25^\circ\text{C}$ .

Hint: the best sources to research for this question may be found in tutorials on *pH* and *pH measurement*.  
[file i00613](#)

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### Question 33

Dilute (or pure) water at 25° C has an ionization constant of  $1.00 \times 10^{-14}$ , meaning that the product of the hydrogen ion molarity and the hydroxyl ion molarity is constantly equal to this value:

$$K_W = [\text{H}^+][\text{OH}^-] = 1.00 \times 10^{-14}$$

The *pH* value of an aqueous (water-based) solution is a way to express the molarity of hydrogen ions  $[\text{H}^+]$  in solution. Specifically, it is the negative logarithm of hydrogen ion molarity:

$$\text{pH} = -\log[\text{H}^+]$$

Given this definition of pH, calculate the pH value of absolutely pure water, where the number of hydrogen ions  $[\text{H}^+]$  exactly equals the number of hydroxyl ions  $[\text{OH}^-]$ .

Challenge question: while pH is often defined as the negative logarithm of hydrogen ion activity (nearly equal to the negative log of hydrogen ion molarity  $-\log[\text{H}^+]$  in dilute solutions), it is more properly defined as the negative log of *hydronium ion* activity. Explain what this distinction means.

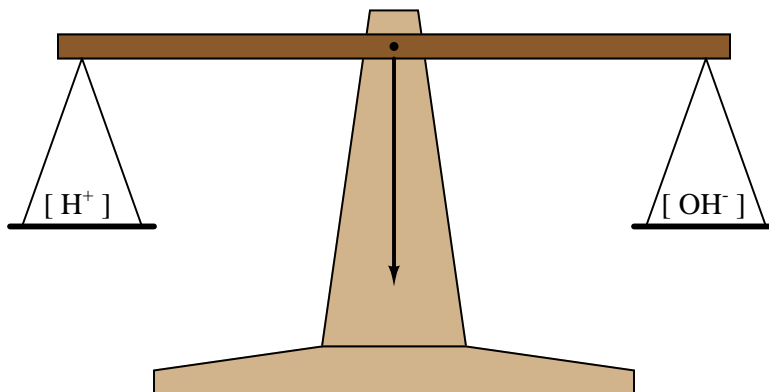
file i00614

### Question 34

When an acid substance is added to water, some of the acid molecules dissociate into positive hydrogen ions ( $\text{H}^+$ ) and negative ions (the type of negative ions depending on what type of acid it is). This increases the molarity of hydrogen ions (the number of moles of  $\text{H}^+$  ions per liter of solution). The addition of hydrogen ions to the solution also decreases the molarity of hydroxyl ions (the number of moles of  $\text{OH}^-$  ions per liter of solution) because some of the water's  $\text{OH}^-$  ions combine with the acid's  $\text{H}^+$  ions to form deionized water molecules ( $\text{H}_2\text{O}$ ).

If an alkaline substance (otherwise known as a *caustic*, or a *base*) is added to water, some of the alkaline molecules dissociate into negative hydroxyl ions ( $\text{OH}^-$ ) and positive ions (the type of positive ions depending on what type of alkaline it is). This increases the molarity of  $\text{OH}^-$  ions in the solution, as well as decreases the molarity of hydrogen ions (again, because some of the caustic's  $\text{OH}^-$  ions combine with the water's  $\text{H}^+$  ions to form deionized water molecules,  $\text{H}_2\text{O}$ ).

One way to envision these processes is to think of a laboratory balance scale, balancing the number of hydrogen ions in a solution against the number of hydroxyl ions in the same solution:



When the solution is pure water, this imaginary scale is balanced, with  $[\text{H}^+] = [\text{OH}^-]$ . Adding an acid to the solution tips the scale one way, while adding a caustic to the solution tips it the other way.

Interestingly, the product of these two molarities is roughly constant for any dilute water solution at a constant temperature. This is called the *ionization constant of water*, symbolized as  $K_W$ :

$$K_W = [\text{H}^+][\text{OH}^-] = 1.00 \times 10^{-14} \text{ at } 25^\circ \text{ C}$$

Suppose we add an acid substance to a sample of pure water until the molarity of hydrogen ions in solution is  $[\text{H}^+] = 0.00027 \text{ M}$ . Calculate the pH value for this solution, assuming a temperature of  $25^\circ \text{ C}$ .

Suppose we add an alkaline substance to a sample of pure water until the molarity of hydroxyl ions in solution is  $[\text{OH}^-] = 0.0081 \text{ M}$ . Calculate the pH value for this solution, assuming a temperature of  $25^\circ \text{ C}$ .

As a general rule, how do the pH values of acidic solutions, alkaline solutions, and pure water relate to

one another? In other words, what are the numerical ranges for each type of solution?

[file i00615](#)

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#### Question 35

It is commonly said that the pH value of pure, or “neutral” water is always 7.0. This is not completely true. While the pH of pure water is indeed 7.0 at 25° C, it is not at other temperatures!

What follows is a table of ionization constants for pure water at different temperatures:

Temperature	$K_W$
0° C	$1.139 \times 10^{-15}$
5° C	$1.846 \times 10^{-15}$
10° C	$2.920 \times 10^{-15}$
15° C	$4.505 \times 10^{-15}$
20° C	$6.809 \times 10^{-15}$
25° C	$1.008 \times 10^{-14}$
30° C	$1.469 \times 10^{-14}$
35° C	$2.089 \times 10^{-14}$
40° C	$2.919 \times 10^{-14}$
45° C	$4.018 \times 10^{-14}$
50° C	$5.474 \times 10^{-14}$
55° C	$7.296 \times 10^{-14}$
60° C	$9.614 \times 10^{-14}$

Calculate the pH values of pure water at some of these temperatures, noting which direction pH changes as temperature increases and as temperature decreases.

#### Suggestions for Socratic discussion

- High-accuracy pH probes often have *temperature compensating sensors* (RTDs) installed to measure the temperature of the probe as it is immersed in the solution. Contrary to popular belief, this temperature probe does not compensate for changes in the water’s pH value, but rather it compensates for something else. Identify what this “something else” is, and why it needs to be compensated in high-accuracy applications.

[file i00616](#)

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#### Question 36

Why is pH measurement important in industry? Who cares what the pH value of a solution is, anyway? Identify some applications where we absolutely *do* care, and explain why.

[file i00617](#)

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#### Question 37

What does it mean if a particular sample of ethyl alcohol has a *molarity* of 0.1 *M*, or 0.1 molar?

[file i03004](#)

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#### Question 38

If a 2 kilogram sample of pure water is mixed with 1 gram of pure H<sub>2</sub>SO<sub>4</sub>, what will the resulting sulfuric acid’s *molality* be? Note: I am asking you to calculate molality (*m*), not molarity (*M*), of the acid solution!

[file i03005](#)

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Question 39

What is pH *neutralization*? In what types of processes is this procedure relevant to, and why is it important (from an environmental perspective)?

Is there any chemical byproduct of the pH neutralization process?

[file i03079](#)

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Question 40

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Question 41

Read and outline the “Potentiometric pH Measurement” subsection of the “pH Measurement” section of the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i04140](#)

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## Question 42

One of the technical challenges inherent to potentiometric pH measurement is how to measure a small voltage when the measuring circuit contains an enormously large resistance (the glass bulb of the pH-sensing electrode). To better understand this electrical principle, we may perform a simple experiment using a voltmeter to measure the voltage of a battery through resistors of various size.

Bring the following materials to class:

- Assortment of resistors from 1 k $\Omega$  to 10 M $\Omega$
- Multimeter
- At least two “alligator clip” jumper wires
- Small battery (any voltage)

Use your voltmeter to measure the battery’s voltage, inserting different amounts of resistance in series with your meter as you do. Your first voltage measurement will be with no resistor, connecting the meter’s test leads directly to the battery terminals. This is the “true” voltage measurement against which all the others will be compared:

Resistor value	Measured battery voltage
0 $\Omega$ (no resistor)	
100 k $\Omega$	
10 M $\Omega$	

Identify the effect increased resistance has on the voltmeter’s indication.

Explain how the results of this experiment demonstrate the voltage-measurement problem inherent to glass pH electrodes. Also, use your experimental data to determine how much larger than the circuit impedance the voltmeter’s internal impedance must be in order to obtain a reasonably accurate voltage measurement. Note: in order to calculate a ratio, you must know the approximate input impedance of your voltmeter. Assuming a glass measurement electrode impedance of 300 M $\Omega$ , how high must the input impedance of the pH transmitter be?

### Suggestions for Socratic discussion

- How do modern pH measuring instruments reliably measure the millivoltage produced by pH probes, given this problem of glass electrode resistance?
- Explain how the experimental results also confirm the fact that magnetic flowmeters are not greatly affected by changes in liquid conductivity, so long as the liquid’s conductivity value does not fall below a certain limit rated by the manufacturer.
- Explain how the traditional “null-balance” laboratory technique may be used to measure signal voltages originating from extremely high-resistance sources with negligible error.

[file i04144](#)



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#### Question 43

Read relevant portions of the “Rosemount Model 389 Combination pH/ORP Sensor” instruction manual (publication PN 51-389, revision 1), and answer the following questions:

Identify whether this is a preamplified probe or a “passive” (unamplified) probe.

Based on the wiring diagrams showing how to connect this probe to various pH transmitter instruments, identify which wire colors on the model 389 cable connect to which sensing elements:

- Measurement electrode: \_\_\_\_\_
- Reference electrode: \_\_\_\_\_
- RTD (2 wires): \_\_\_\_\_ and \_\_\_\_\_

#### Suggestions for Socratic discussion

- Explain how we can tell the model 389-01 (“option 01”) probe has a built-in preamplifier circuit, just by examining the screw terminal labels on the pH instruments it is designed to connect to.
- Discuss ideas for identifying “relevant portions” of a text so you do not have to read the whole thing.

[file i04145](#)

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#### Question 44

Read relevant portions of the “Rosemount Model 389 Combination pH/ORP Sensor” instruction manual (publication PN 51-389, revision 1), and answer the following questions:

Identify the page in this manual describing the buffer calibration procedure for the pH probe.

Identify the calibrated slope values indicating a pH probe in need of replacement.

This manual describes a “standardization” procedure in addition to a full “calibration” procedure. Explain the difference between the two procedures.

#### Suggestions for Socratic discussion

- Explain the rationale for each step of the two-buffer calibration procedure.
- During a two-buffer calibration procedure, which calibration parameter(s) get adjusted within the pH instrument: *zero*, *span*, or *both*?
- During a standardization procedure, which calibration parameter(s) get adjusted within the pH instrument: *zero*, *span*, or *both*?
- When a technician performs a “standardization” on a pH instrument, as opposed to a full calibration, is the technician adjusting the instrument’s *zero*, its *span*, its *linearity*, or its *hysteresis*?
- The instructions on page 19 of this manual tell you to “. . . check the pH buffer manufacturer specifications for millivolt values at various temperatures since it may affect the actual value of the buffer solution mV/pH value.” This warning is actually referring to two different phenomena: the effect of temperature on the probe’s slope, and the effect of temperature on the buffer solution’s pH value. If the pH probe being calibrated is equipped with an RTD temperature sensor, which of these two phenomena is accounted for?

[file i04146](#)

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**Question 45**

Suppose a pH probe is immersed in a solution of 98% water having a hydrogen ion activity of  $0.0000032\text{ M}$ . Calculate the pH value of this solution, and also the (ideal) voltage generated by a pH probe assuming a probe resistance of  $125\text{ M}\Omega$  and a solution temperature of 30 degrees Celsius.

**Suggestions for Socratic discussion**

- Identify factors influencing the voltage output by a glass electrode, other than the pH of the liquid it's immersed in.
- Explain why you chose the value you did for  $n$  in the Nernst equation.
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i04147](#)

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**Question 46**

Calculate the ideal “slope” values for a glass pH electrode at the following temperatures:

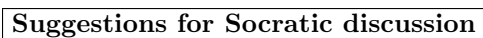
- $T = 15\text{ }^{\circ}\text{C}$  ; slope = \_\_\_\_\_ mV/pH
- $T = 33\text{ }^{\circ}\text{C}$  ; slope = \_\_\_\_\_ mV/pH
- $T = 110\text{ }^{\circ}\text{F}$  ; slope = \_\_\_\_\_ mV/pH
- $T = 40\text{ }^{\circ}\text{F}$  ; slope = \_\_\_\_\_ mV/pH

**Suggestions for Socratic discussion**

- Do changes in a pH instrument's slope represent a *zero* shift, a *span* shift, or a change in *linearity*?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i04148](#)

Determine the proper control action (*direct* or *reverse*) for the controller in this pH neutralization system, assuming direct action on the part of the transmitter (i.e. increasing pH = increasing mA signal) and an air-to-open (ATO) control valve:



- If the pH transmitter in this control system were mis-calibrated so that it always registered 0.5 pH units too high, how would this affect the real pH value of the treated water?
- If the control valve in this control system were mis-calibrated so that it always opened up 7% more than it was supposed to, how would this affect the real pH value of the treated water?
- If the controller were configured for the wrong action (e.g. direct instead of reverse, or vice-versa), what would likely be the result in this process?
- If the neutralizing reagent were switched from acid to caustic, would this require a change in the controller's action? Why or why not?
- Will changes in acid density affect the accuracy of the acid flowmeter? Why or why not?
- If the water temperature happens to increase but there is no RTD in the pH probe to compensate for temperature changes, will the pH transmitter register too high, too low, or will the change be impossible to predict?
- Is the influent water *acidic* or *alkaline*, based on this neutralization system design?

51

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Question 48

Two instrument technicians are arguing over the suitability of a magnetic flowmeter (“magflow”) in a process line carrying highly concentrated sodium hydroxide (caustic soda). One technician claims a magflow meter will not work because it requires a lot of ions in the liquid for conductivity, and as we all know caustic solutions have very low hydrogen ion concentrations. The other technician does not agree.

Which technician is correct, and why?

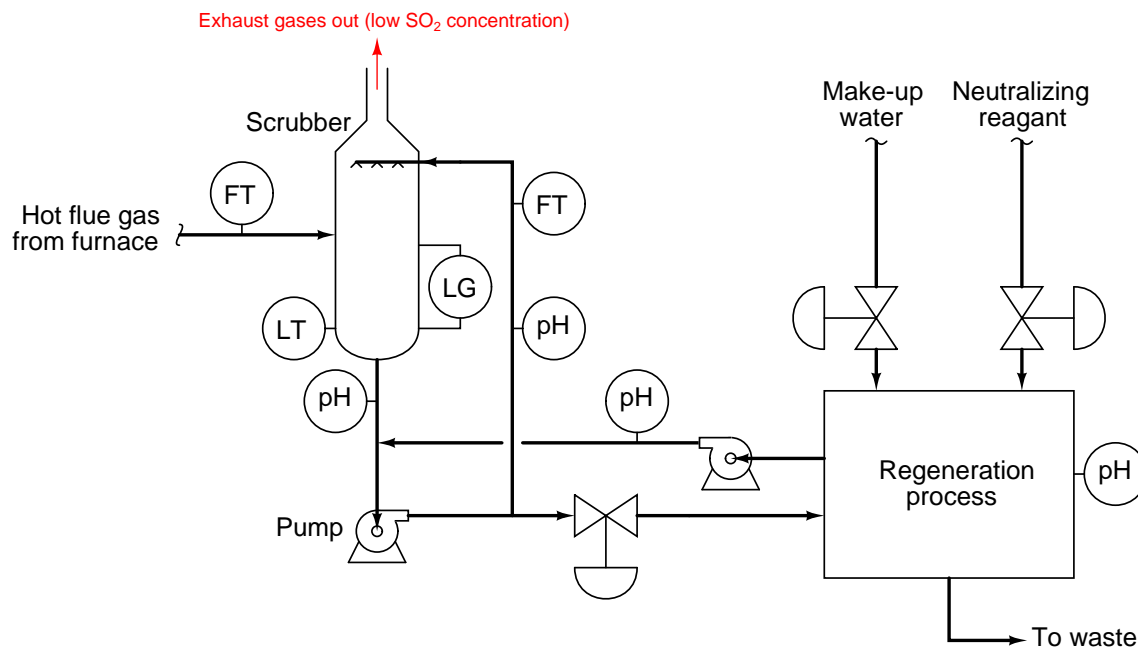
<b>Suggestions for Socratic discussion</b>
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- If the pH value of an industrial flow stream is liable to change over time, will this affect the suitability of a magflow meter?
- One of the challenges posed by the measurement of some caustic solution flow rates is clogging of the flowmeter by crystals forming in the caustic solution. Identify specific flowmeter technologies that would be affected more by plugging than others.

file i04143

# Question 49

When sulfur-containing fuels are burned, one of the reaction products is sulfur dioxide ( $\text{SO}_2$ ), which is an atmospheric pollutant. Fortunately,  $\text{SO}_2$  is relatively easy to “scrub” out of hot flue gases by spraying water down on the rising gases and then chemically treating (regenerating) the resulting solution:



The reaction product formed between water and  $\text{SO}_2$  gas has a strongly corrosive pH value. Identify what this reaction product is, based on your knowledge of chemistry, and then explain what happens in the “regenerating” process to remove this product so that the water may be returned to the scrubber for re-use.

Suppose the sulfur content of the fuel being burned were to increase. How would this change in fuel chemistry affect the various pH measurements shown in the scrubber process, all other conditions being unchanged?

Specifically, what kind of “neutralizing reagent” must be added to the solution to regenerate it, and what kind of “waste” product is generated as a result?

## Suggestions for Socratic discussion

- Rank the four pH transmitters in order of their expected pH measurements, from lowest (acid) to highest (alkaline).
- Explain what would happen to the four pH transmitters’ indications if the regenerator process shut down, merely passing water through it without neutralizing pH.
- Explain what would happen to the process if the control valve failed in the shut position.
- Explain what would happen to the process if the control valve failed in the full-open position.
- Identify what kind of pollution hazard is posed by  $\text{SO}_2$  stack emissions.
- Identify suitable flowmeter technologies for the flow measurement points shown in this diagram.
- Would it be worthwhile to install a pH analyzer on the flue gas line? Explain why or why not.

[file i03042](#)

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#### Question 50

Calculate the voltage generated by a pH probe given the following solution pH and glass electrode temperature values:

- pH = 5.82 ;  $T = 25\text{ }^{\circ}\text{C}$  ; Nernst voltage = \_\_\_\_\_ mV
- pH = 8.75 ;  $T = 43\text{ }^{\circ}\text{C}$  ; Nernst voltage = \_\_\_\_\_ mV
- pH = 11.23 ;  $T = 95\text{ }^{\circ}\text{F}$  ; Nernst voltage = \_\_\_\_\_ mV
- pH = 3.29 ;  $T = 122\text{ }^{\circ}\text{F}$  ; Nernst voltage = \_\_\_\_\_ mV

Calculate the pH of a solution given the following Nernst potential and glass electrode temperature values:

- Nernst voltage = 105 mV ;  $T = 25\text{ }^{\circ}\text{C}$  ; Solution = \_\_\_\_\_ pH
- Nernst voltage = 233 mV ;  $T = 12\text{ }^{\circ}\text{C}$  ; Solution = \_\_\_\_\_ pH
- Nernst voltage = -40 mV ;  $T = 77\text{ }^{\circ}\text{F}$  ; Solution = \_\_\_\_\_ pH
- Nernst voltage = -185 mV ;  $T = 131\text{ }^{\circ}\text{F}$  ; Solution = \_\_\_\_\_ pH

file i04303

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#### Question 51

Sketch a simple schematic diagram showing the essential components of a pH measurement system. Be sure to include these elements:

- Measurement electrode
- Reference electrode
- Voltmeter (pH meter)
- Chemical solution (to be measured by the electrodes)

file i00619

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### Question 52

The *Nernst equation* is the primary formula used to predict voltage generated across *any* ion-selective membrane, pH measurement electrodes included. The general form of the equation is as follows:

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

Where,

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

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

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

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

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

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

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

We may also write the Nernst equation using of common logarithms instead of natural logarithms, which is usually how we see it written in the context of pH measurement:

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

Calculate the pH values for the following solution concentrations, assuming a temperature of 25° C, and also use the Nernst equation to calculate the amount of voltage produced across the thickness of a glass pH measurement electrode. Keep in mind that the measurement electrode's internal potassium chloride (KCl) reference solution is buffered to maintain a hydrogen ion molarity of  $[H^+] = 1.00 \times 10^{-7} M$  under all conditions. The proper value for  $n$  is 1, because we are dealing with hydrogen ions:

$[H^+]$ in solution	pH	V
$5.83 \times 10^{-5} M$		
$1 \times 10^{-5} M$		
$1 \times 10^{-6} M$		
$1 \times 10^{-7} M$		
$1 \times 10^{-8} M$		
$7.02 \times 10^{-9} M$		
$1 \times 10^{-9} M$		
$1 \times 10^{-10} M$		

After calculating some voltage values, you will begin to notice a pattern. There is a proportionality between voltage generated and the pH value of the measured solution. See if you can detect this pattern, and express the relationship in simple terms.

[file i00618](#)

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### Question 53

Explain why the glass measurement electrode if a pH sensor must always be kept wet, ideally with a potassium chloride (KCl) solution, when in storage.

[file i00620](#)

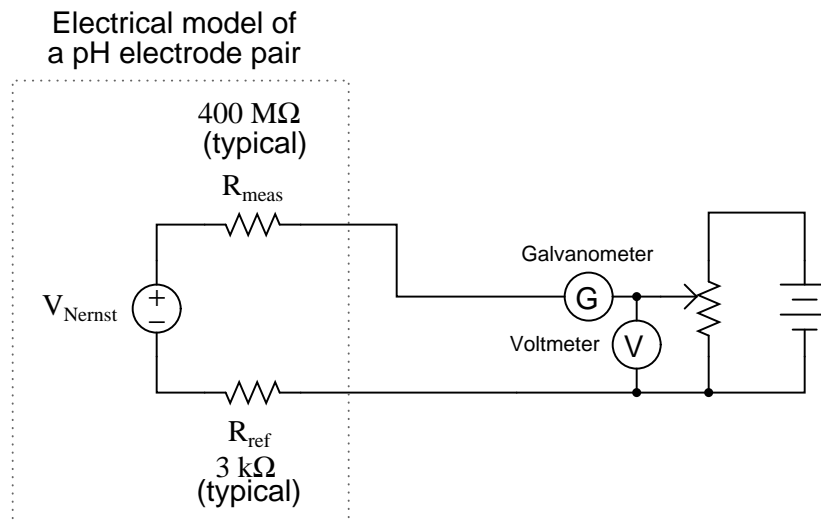
#### Question 54

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

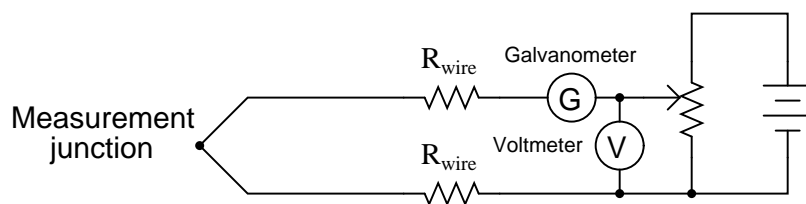
In the days before the advent of solid-state digital multimeters with their operational amplifier (high impedance) inputs, a technique called *null-balance* was used to accurately measure small voltages such as those produced by thermocouple junctions and pH probes. This “potentiometric” technique allowed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

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

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



#### Null-balance measurement of thermocouple voltage



[file i00621](#)



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**Question 55**

Calculate the pH of the following aqueous solutions and the voltage (ideally) generated by a pH electrode pair, given the hydrogen ion molarity of each solution. Assume a solution temperature of 25° C:

$[H^+]$	pH	$V_{probe}$
0.001995 M		
$6.309 \times 10^{-7}$ M		
$7.943 \times 10^{-13}$ M		
$3.881 \times 10^{-5}$ M		
$1.452 \times 10^{-11}$ M		

**Suggestions for Socratic discussion**

- How does a pH instrument tell the difference between a pH value above 7 versus one below 7?
- Demonstrate how to *estimate* numerical answers for this problem without using a calculator.

[file i03006](#)

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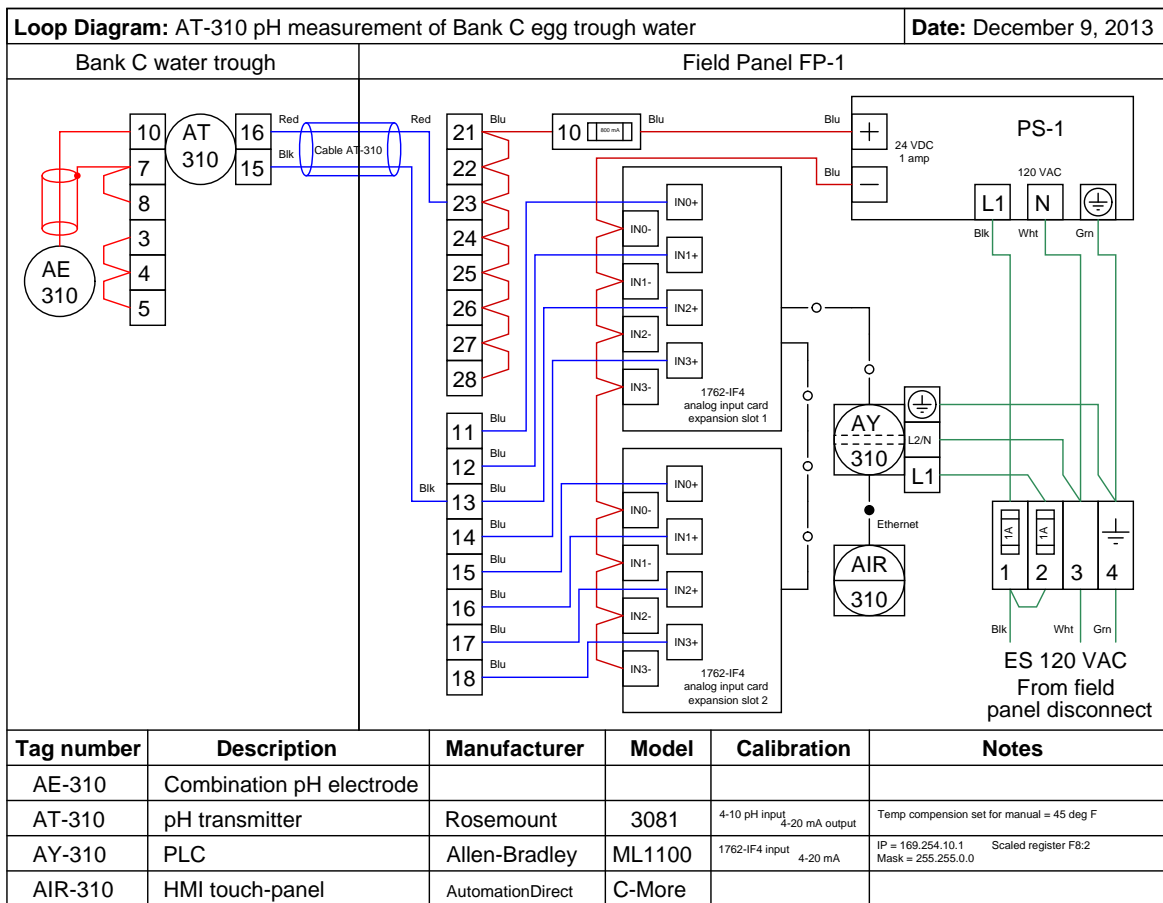
**Question 56**

What should happen if you electrically short the input of a pH transmitter (i.e. short the two wires normally connected to the pH sensing electrodes)? Why?

[file i03085](#)

# Question 57

Suppose an operator tells you that the pH reads below 4.0 in this system, despite having checked the actual pH of the process water as approximately 7.3 pH using a “grab sample” tested with a benchtop pH meter. Identify possible faults which could account for this incorrect reading:



file i03082

# Question 58

The Nernst equation yields a “slope” figure of 59.17 millivolts per pH unit for a perfect pH electrode probe pair. Explain where this numerical value comes from.

file i03071

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**Question 59**

The ideal “slope” for a pH electrode pair at 25° C is 59.17 mV per pH unit. Calculate the ideal slope for a pH electrode pair at the following temperatures:

Temperature (°C)	Slope (mV/pH)
5° C	
20° C	
60° C	
100° C	

[file i03072](#)

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**Question 60**

Is it physically possible for a solution to have a pH of less than zero or greater than 14?

[file i03076](#)

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**Question 61**

Read and outline the introduction to the “Chromatography” section as well as the “Automated Chromatographs” subsection of that same section, found within the “Continuous Analytical 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:

- Questions of your own and requests for clarification after reading the text
- Page numbers from the source text for quick reference during discussion
- 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 i04149](#)

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## Question 62

Read and outline the “Species Identification”, “Chromatograph Detectors”, and “Measuring Species Concentration” subsections of the “Chromatography” section in the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

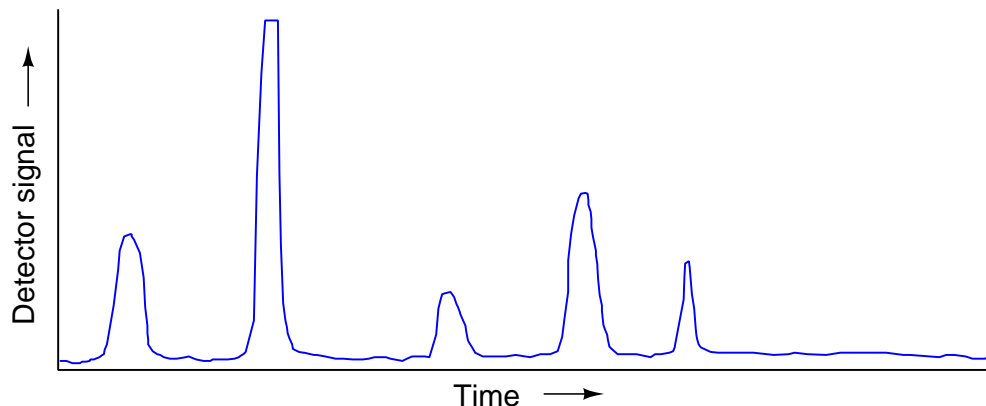
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file i00230

### Question 63

Examine this chromatogram showing five unique paraffinic hydrocarbon compounds (methane through pentane), and determine which peaks most likely belong to which compounds:



Use the label “C1” to refer to methane ( $\text{CH}_4$ ), “C2” to refer to ethane ( $\text{C}_2\text{H}_6$ ), “C3” to refer to propane ( $\text{C}_3\text{H}_8$ ), etc.

Identify which compound experiences the greatest *retention time*, and explain this is so.

Suppose the source of ethane (C3) in this mixture were suddenly cut off, so that only four paraffinic hydrocarbon compounds remain (e.g. C1, C2, C4, and C5). How would this process change affect the chromatogram?

#### Suggestions for Socratic discussion

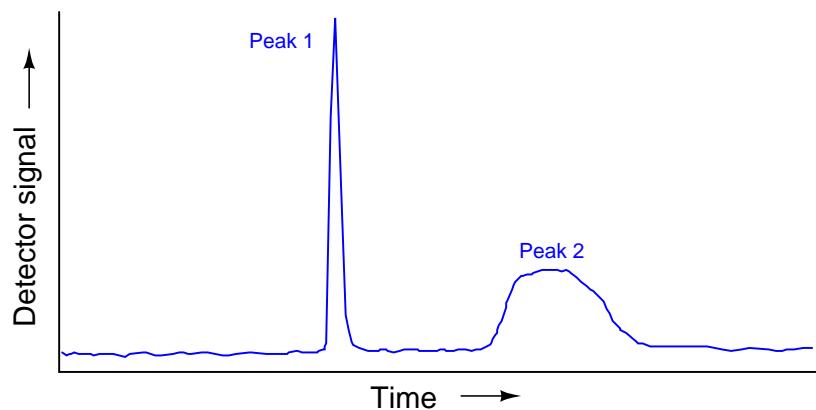
- Identify a practical application for using a chromatograph to separate hydrocarbon compounds in a fluid stream.
- Explain the significance of the “flat-top” peak shown in this chromatogram.
- Assuming this chromatogram was generated by a GC column at constant temperature, describe how it would change if *temperature programming* were included in the GC’s configuration.

file i04153

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Question 64

Examine this chromatogram showing two peaks, and determine which peak represents the greatest quantity of substance:



Explain *why* you interpreted the peaks as you did.

Now suppose the concentration of substance causing peak 1 suddenly increases in the sample stream, while the concentration of the other substance does not change. How would this change in the sample's composition affect the appearance of subsequent chromatograms?

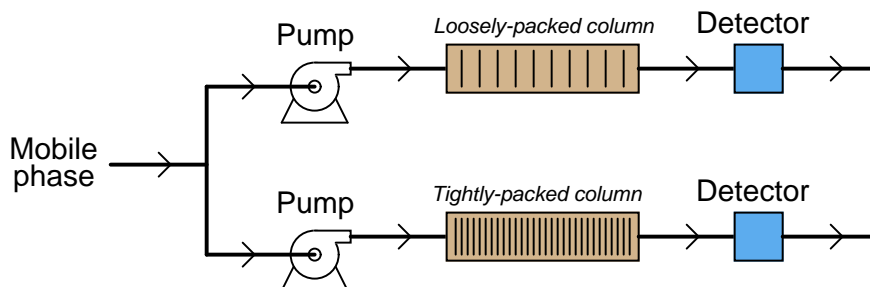
**Suggestions for Socratic discussion**

- Explain how the calculus concept of *integration* applies to this question.
- Suppose you were informed this chromatogram was taken off the detector's raw signal, unscaled by any *response factors*. Would your interpretation of the chromatogram be any different with this knowledge?

file i04156

### Question 65

Suppose we were to inject the same mobile phase into two different columns, each with a different density of stationary phase material (“packing”):



Assuming all other factors being equal, which column will do a better job separating different components of the mobile phase (i.e. different chemical substances mixed together in the same input sample)? Which column will do a *faster* job separating the components?

#### Suggestions for Socratic discussion

- Chromatography is analogous to a marathon race, where groups of runners become further separated over time by their relative speeds. By the end of the race, it is easy to identify who is fast, who is slow, and how many of each type of runner there was in the starting group at the beginning of the race. Relate this question of comparing two columns to the analogy of a marathon race: what does a tightly-packed column represent, versus a loosely-packed column?
- An important variable affecting the retention time of a compound inside a chromatograph column is *temperature*. Explain how an increase in column temperature would affect the propagation of a *gaseous* compound. Then, explain how an increase in column temperature would affect the propagation of a *liquid* compound.
- Identify other variables affecting the retention time of a compound inside a chromatograph column besides packing density.

[file i00667](#)

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#### Question 66

Read and outline the “Industrial Applications of Chromatographs” subsection of the “Chromatography” section in the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i00777](#)

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#### Question 67

Read and outline the “Chromatograph Sample Valves” and “Improving Chromatograph Analysis Time” subsections of the “Chromatography” section in the “Continuous Analytical Measurement” chapter in your *Lessons In Industrial Instrumentation* textbook.

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[file i00778](#)



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#### Question 68

Read the Emerson Gas Chromatograph application note “BTU Analysis Using a Gas Chromatograph” (document EPMGC-AN-004 R0608) in its entirety and answer the following questions:

Explain in general terms what a gas chromatograph does to analyze the composition of natural gas fuel.

Identify some of the more prevalent compounds found in natural gas, as listed in this document, interpreting the “shorthand” notation used in the industry (C2, IC5, etc.) used to represent different substances.

#### Suggestions for Socratic discussion

- Explain the significance of the *response factor* described for each chromatogram peak, and how it is calculated.
- Are there any components of natural gas that have zero heating value? If so, what are they?
- Natural gas pipeline stations employing gas chromatographs for online gas analysis usually also employ AGA3 or similar custody-transfer flow metering technology for precision measurement of natural gas flow. Explain how the data provided by the chromatograph might also be useful in maintaining optimum accuracy for AGA3 gas flowmeters.

[file i04154](#)

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#### Question 69

Read the Emerson Gas Chromatograph application note “BTU Analysis Using a Gas Chromatograph” (document EPMGC-AN-004 R0608) in its entirety and answer the following questions:

One of the challenges of chromatography is to perform an analysis of a complex mixture *swiftly*. The gas chromatograph (GC) schematic shown on page 2 of this document achieves fast analysis by using a complex series of valves and columns. Study the analysis sequence described on this page, and then explain how these multiple columns achieve a faster analysis than if a single column were used.

#### Suggestions for Socratic discussion

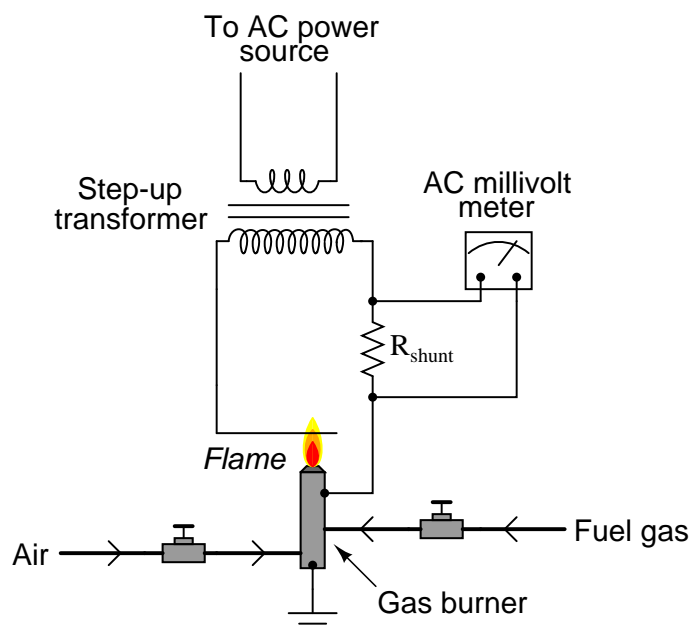
- The genius of using multiple columns in a chromatograph is the ability to accelerate the separation and detection of certain component in the sample while giving other components the time needed to adequately separate. Is there some other method we may alternatively use to achieve this end, rather than adding complexity with additional columns and switching valves?
- How does the presence of multiple columns, switching valves, and sequencing affect the order that components appear at the detector? How would this alter our interpretation of the analyzer’s chromatogram?
- Explain why the C6+ “heavy” molecules all exit the chromatograph in one bunch, rather than being separated (e.g. C6, C7, C8, etc.) like the lighter molecules. Hint: it has to do with the “backflush” valve and how that routes the C6+ molecules through the columns.
- If we were to modify column 4 for finer separation of the heavy molecules (C6+), in what order would those compounds exit? What specific modifications would we need to make to column 4 in order to achieve better separation at the end? Would these alterations speed up or slow down the analysis?

[file i04155](#)

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### Question 70

It has been known for a long time that ions (electrically charged atoms or molecules) exist in most flames. This means a flame can act as a weak conductor of electricity. Given a large enough voltage, we can push a measurable current through the flame:



Not all fuels generate the same amount of ions when burned. Hydrogen, for instance, burns very clean and generates negligible ionic activity. Carbon, on the other hand, easily ionizes in flame, and so hydrocarbon fuels such as methane ( $\text{CH}_4$ ), ethane ( $\text{C}_2\text{H}_6$ ), and propane ( $\text{C}_3\text{H}_8$ ) generate ions in approximate proportion to their carbon content.

Explain how the circuit shown above functions, and how it would respond to the combustion of different fuel types.

Explain how this circuit would respond if the “fuel gas” happened to be the discharge of a chromatograph column using hydrogen gas as the “carrier,” and the chromatograph were sampling a mixed-hydrocarbon stream.

[file i00656](#)

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### Question 71

Chromatographs work by passing a fluid through a narrow length of tubing called a *column* and measuring what comes out the other end. This fluid consists of a *carrier* mixed with the sample to be analyzed.

Explain (in more detail) what happens inside the “column” of a chromatograph, and how this relates to the analysis of chemicals in the sample stream.

[file i00670](#)

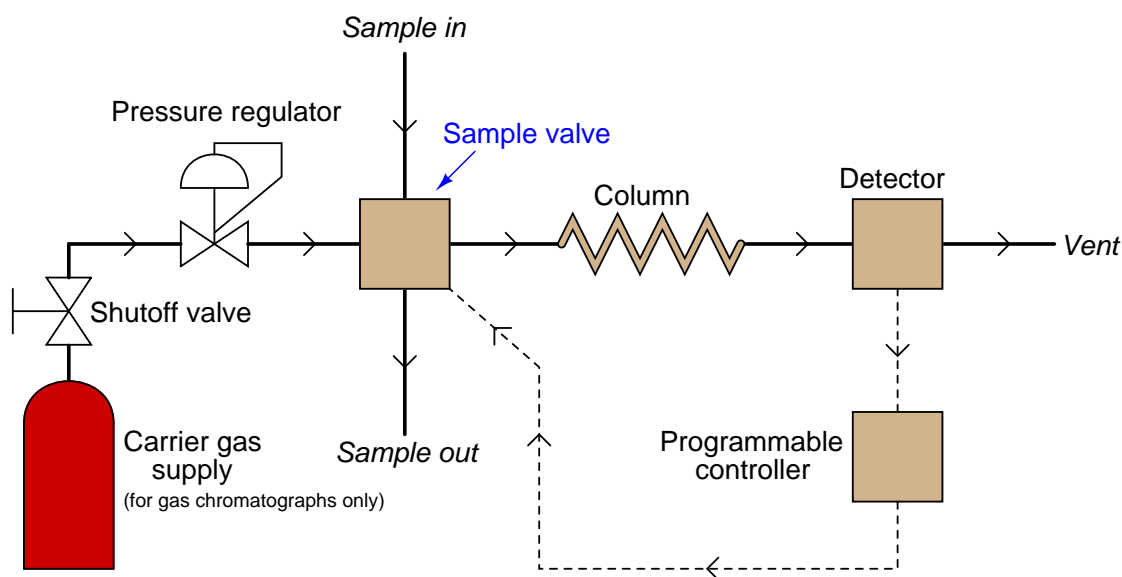
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### Question 72

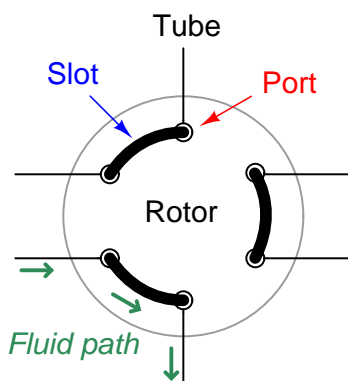
In both gas chromatography and liquid chromatography, there must always be two “phases” at work: a *mobile phase* and a *stationary phase*. Explain what each of these phases is, and give examples for both gas and liquid chromatography.

[file i00666](#)

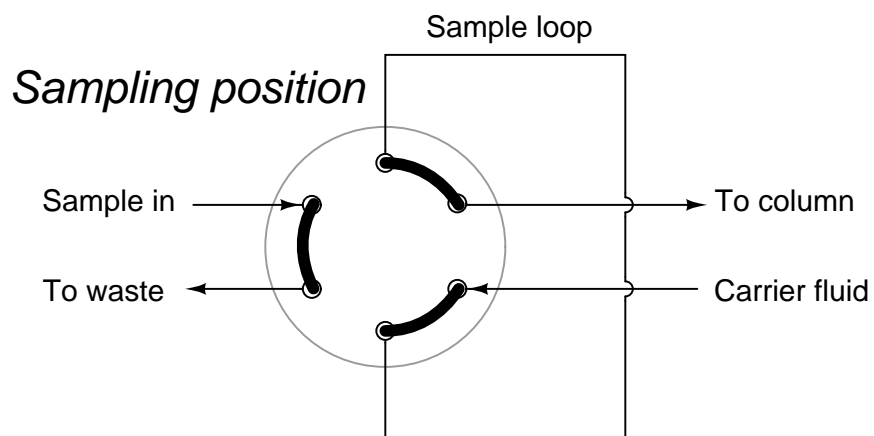
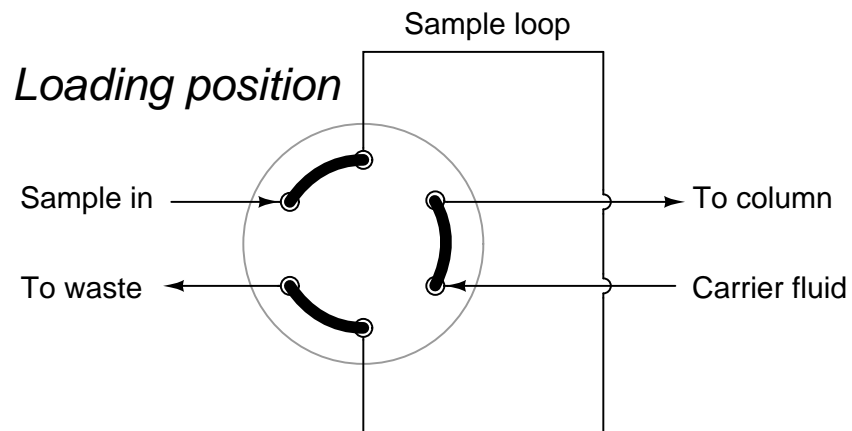
The sample valve in a gas chromatograph plays an extremely important role: it must inject a precise volume of sample gas to be analyzed, in a precise amount of time. The following diagram shows the components of a basic gas chromatograph. Liquid chromatographs differ only slightly from this:



Given the importance of this function, the sample valve is constructed quite differently from ordinary valves. Most chromatograph sample valves are rotary in nature, with slots cut into a metal rotor for directing fluid flows along different paths. A common sample valve design uses six ports and three slots, like this:



The following illustration shows a typical sample valve with a rotary valve element, in two different positions. The *loading* position prepares the sample loop for injection while the column is flushed with carrier gas. The *sampling* position injects a precise volume of sample into the column followed by carrier gas.



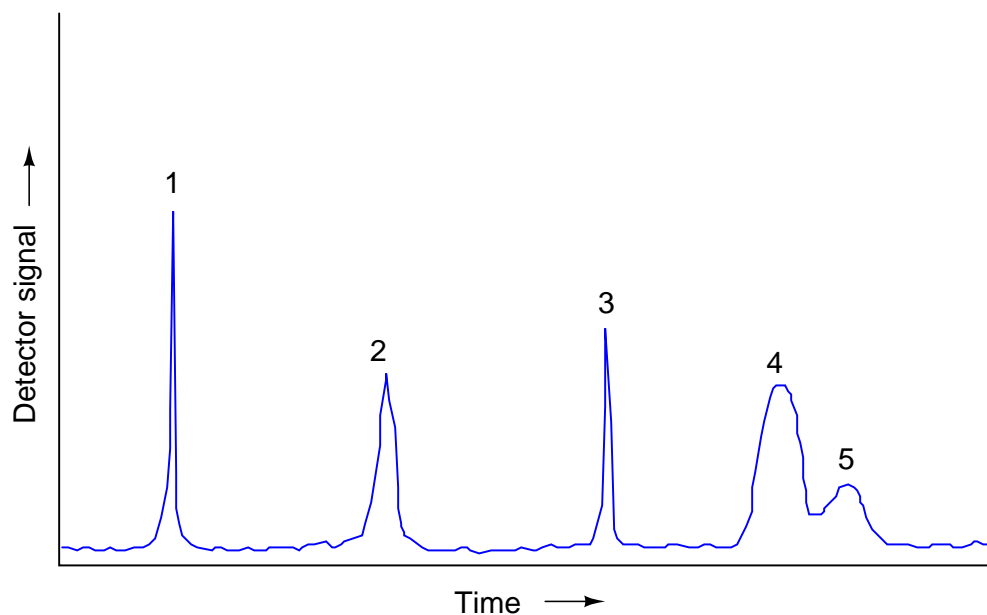
Explain how this valve and tubing arrangement provides a consistent, measured sample volume during each injection cycle. Also, identify what would have to change in order to double the amount of injected volume into the column for each injection cycle.

file i00675

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Question 74

This *chromatogram* shows the separation of five different substances over time:

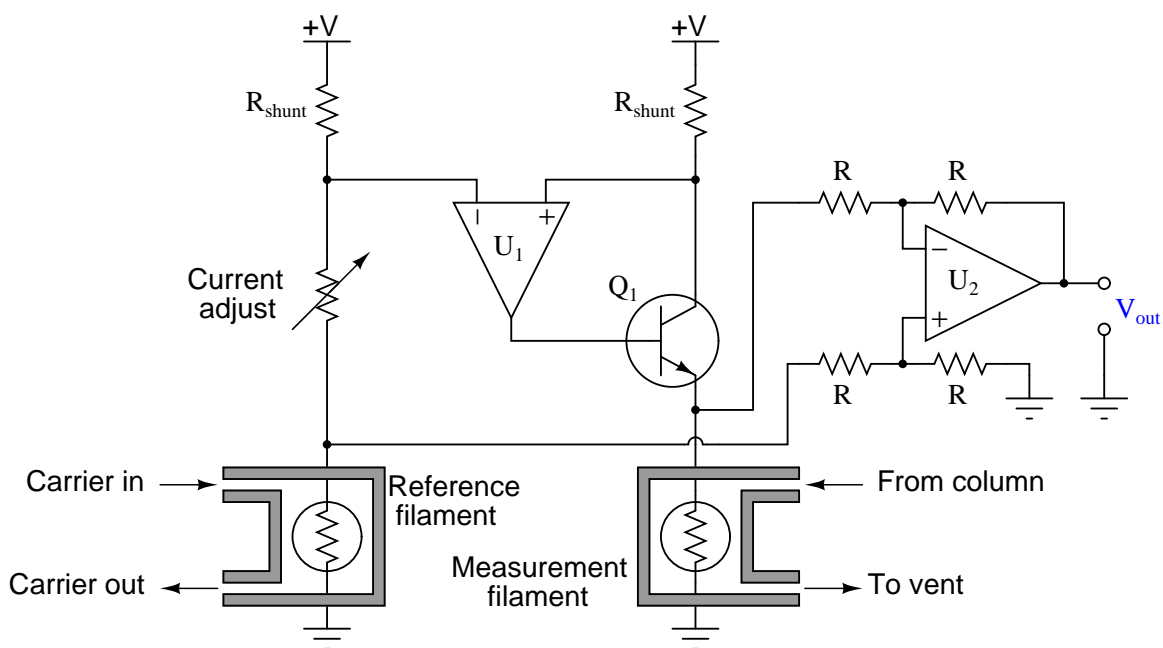


Note how components 4 and 5 are not clearly differentiated in the chromatogram. Identify at least one way the chromatograph could be altered to obtain clearer separation (better *resolution*) of these last two components.

file i00672

Question 75

Analyze the following electronic thermal conductivity sensor, used to detect different chemical components exiting the column of a chromatograph. Both the measurement and reference filaments are heated by the electric current going through them, and a varying voltage will develop across each one as each is cooled differently by the gases:



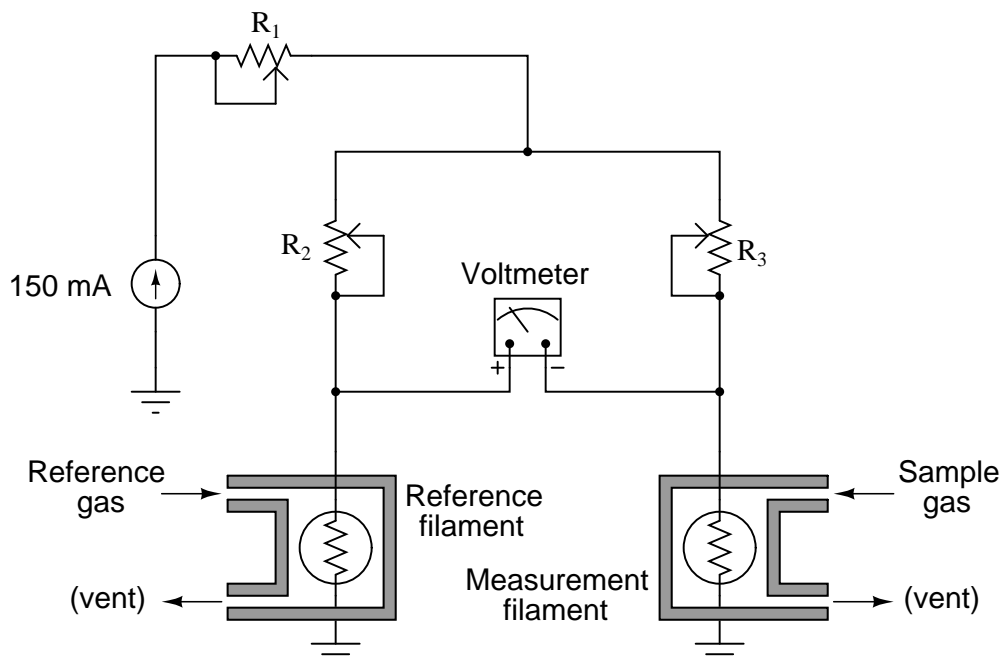
Explain the following things about this circuit:

- How does the rheostat adjust current equally through *both* filaments?
- How do opamp  $U_1$  and transistor  $Q_1$  work together to regulate current through the measurement filament?
- How can we tell that opamp  $U_1$  is truly functioning in negative-feedback mode, since at first glance it looks like positive feedback with the  $R_{shunt}$  voltage signal connecting to the noninverting (+) input?
- What is the function of opamp  $U_2$  and its four equal-value resistors?
- Where would an output voltage signal be measured in this circuit?
- Which direction does the output voltage signal go when the measurement filament heats up to a greater temperature, assuming a positive temperature coefficient of resistance ( $\alpha$ ) for the filament metal?

[file i00678](#)

# Question 76

This is an electronic thermal conductivity sensor, used to detect different chemical components exiting the column of a chromatograph. Both the measurement and reference filaments are heated by the electric current going through them, and a varying voltage will develop across each one as each is cooled differently by the gases:



Suppose a technician is setting up this detector for the very first time, and notes the voltmeter registers an abnormally large signal (in the polarity shown) even with the same test gas passed through each cell.

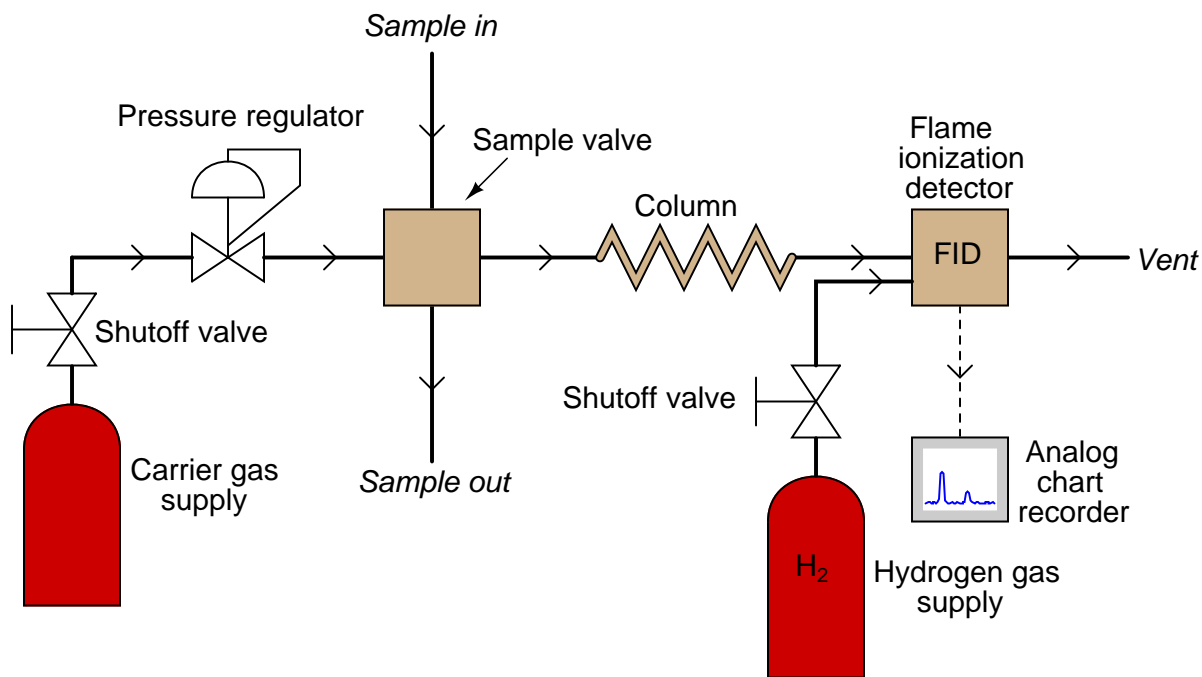
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
$R_1$ resistance set too low		
$R_1$ resistance set too high		
$R_2$ resistance set too low		
$R_2$ resistance set too high		
$R_3$ resistance set too low		
$R_3$ resistance set too high		
Reference filament burned open		
Measurement filament burned open		
Voltmeter failed open		
Voltmeter failed shorted		

file i00909

Question 77

Suppose we tried to build a very simple gas chromatograph, where the output voltage of the flame ionization detector (FID) connects directly to an analog chart recorder:



This chart recorder will produce a chromatogram, but it will be a rather strange one: we will not be able to accurately interpret it in its raw form. The height of the peaks on this chromatogram will *not* necessarily indicate the flow rates of the separated components exiting the column.

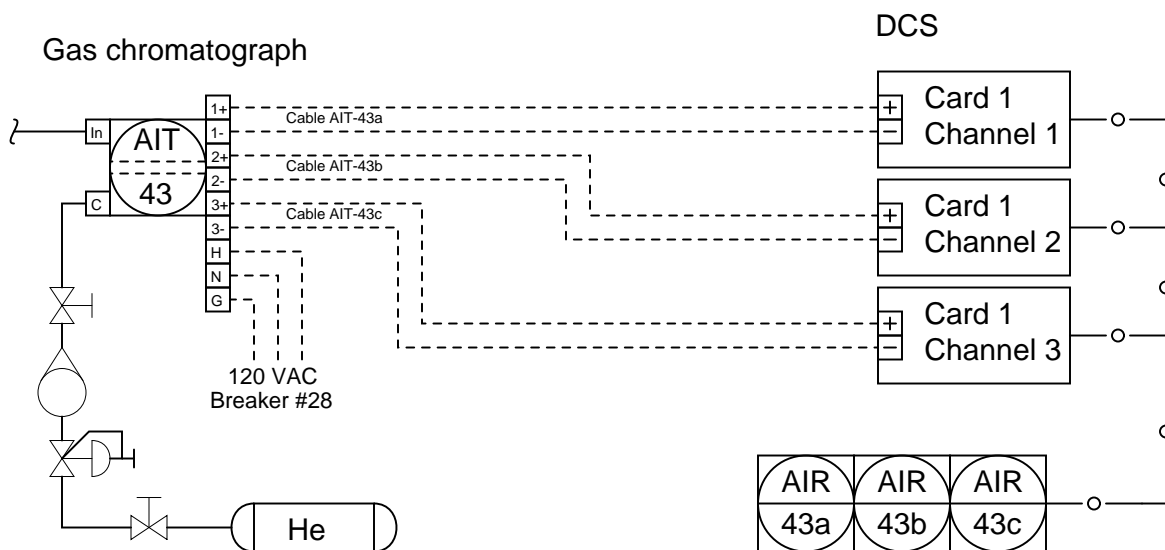
Explain why this chromatogram will not be accurate as displayed, and explain what is required to correct it (i.e. how modern process chromatographs solve this problem).

[file i01356](#)



# Question 78

Process chromatographs are *multi-variable* instruments, and so analog versions are often equipped with multiple 4-20 mA outputs to transmit concentration data for each measured component:



Inspecting this loop diagram, answer the following questions:

- What is the purpose of the vessel labeled “He”?
- Do the DCS input cards supply 24 VDC loop power or not?
- How would you connect a loop calibrator to simulate a 50% signal to AIR-43c?
- Can you think of any way we could reduce the number of cables needed to convey the data from the chromatograph to the DCS?

[file i00669](#)

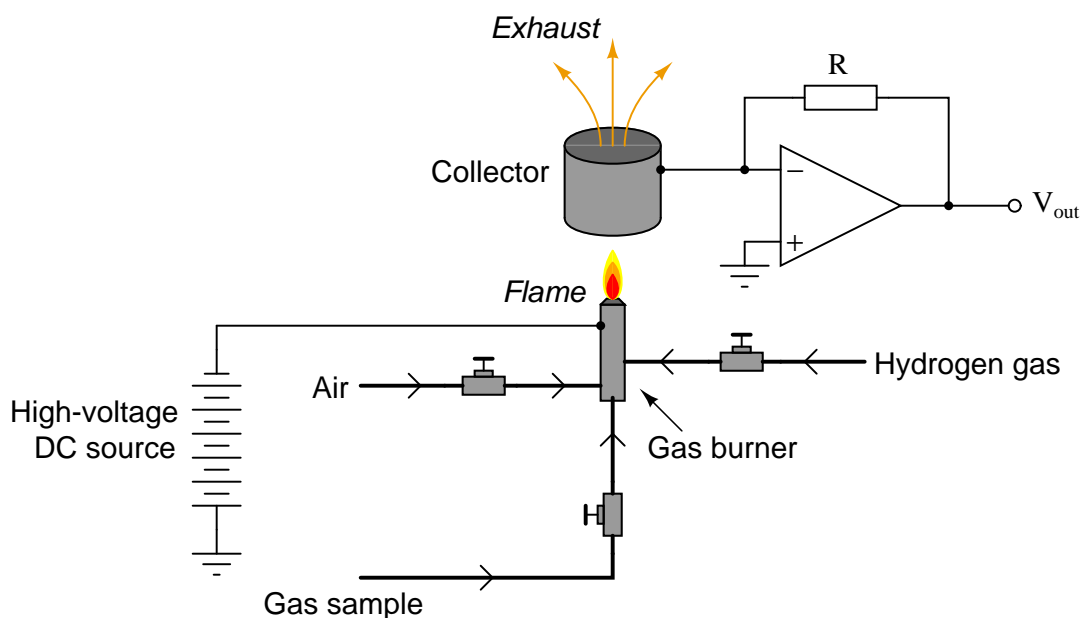
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**Question 79**

*Flame ionization detectors*, often referred to as *FIDs*, exploit the principle of electrical conductivity in a flame to detect the presence of trace substances in a hydrogen gas stream. FIDs are often used as detectors on industrial gas chromatographs, especially in the petrochemical industries where most compounds of interest contain carbon.

Hydrogen, when burned, does not create ions in the flame. However, quantities of hydrocarbon compounds mixed with hydrogen gas will generate ions in the flame, which may then be detected electrically. The strength of the electrical signal will be in proportion to the concentration of carbon atoms mixed in the hydrogen gas stream.

A simplified FID is shown here, the “exhaust” gases from the burner passing through a hollow metal ring acting as a “collector” for ions generated in the flame:



Explain how the operational amplifier in this circuit works to convert the small ionic current into an output voltage. Also, determine whether the resistor in the feedback loop of the opamp circuit should be of a large, small, or modest resistance value.

<b>Suggestions for Socratic discussion</b>
--

- Describe how an FID placed at the tail-end of a gas chromatograph column will respond as a complex hydrocarbon sample passes through the column.
- Explain why a flame ionization detector may be classified as an *amperometric* sensor, as opposed to a *potentiometric* sensor such as a pH glass electrode.
- Identify a fault in this system that could cause the output of this detector to always be zero (i.e. indicate no ions when in fact there are ionizable species in the sample).

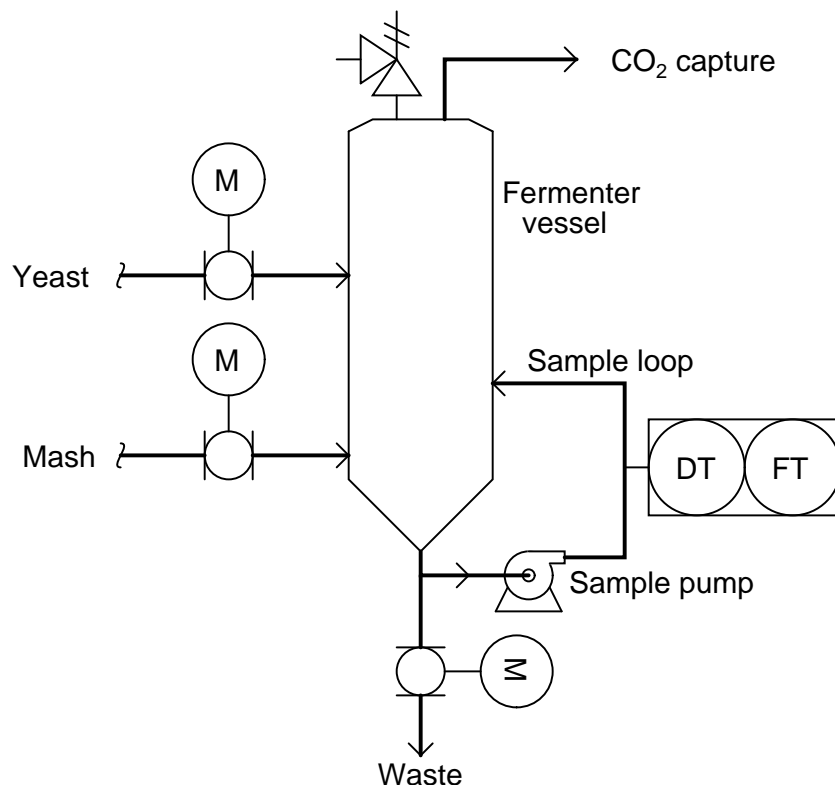
[file i00657](#)

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**Question 80**

Question 81

One of the central processes in manufacturing ethyl alcohol from sugar is *fermentation*, where yeast bacteria convert the sugar *glucose* ( $C_6H_{12}O_6$ ) into *ethanol* ( $C_2H_5OH$ ) with carbon dioxide ( $CO_2$ ) as a gaseous by-product. This reaction typically takes place in a vessel called a *fermenter*, with the carbon dioxide gas captured for re-use in carbonation:



First, write a balanced equation for the fermentation process, showing glucose as the sole reactant, and ethanol plus carbon dioxide as the two reaction products.

Next, calculate the mass flow rate of carbon dioxide gas produced when the fermentation reaction inside a fermenter vessel is proceeding at a rate of 2.7 kilograms of ethanol per minute.

Next, identify which is easiest to heat from room temperature to 90 °F: a gallon of water or a gallon of ethanol.

Finally, comment on the use of a combination density/flow transmitter to measure the alcohol content of the fermenting batch. What type of instrument is ideally suited for this purpose, and explain how alcohol content may be inferred from this instrument's measurement(s).

---

**Question 82**

Suppose a technician opens the door of a junction box and connects a DMM (digital multimeter) to a pair of thermocouple wires landed to a terminal strip inside the box. The thermocouple junction at the other end of this wire pair is installed in a hot process pipe about 50 feet away, measuring the temperature of a process fluid. Noting the ambient temperature inside the junction box being 58 degrees Fahrenheit, the technician measures a thermocouple signal of 29.34 millivolts. Calculate the temperature of this type E thermocouple.

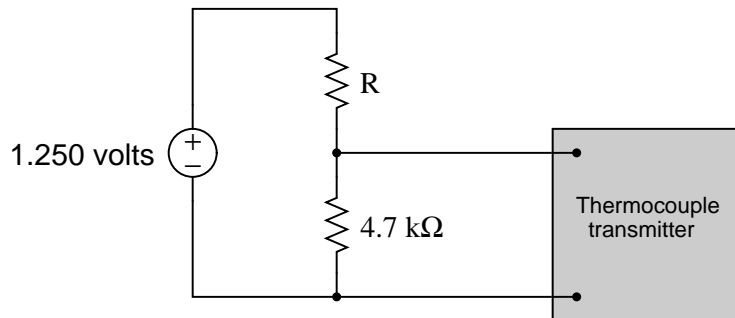
$$T = \underline{\hspace{2cm}} \text{ degrees Fahrenheit}$$

Be sure to show your work in calculating this temperature!

Now, suppose the technician removes the temperature transmitter connected to this type E thermocouple, taking the transmitter back to the calibration lab. Assuming a lab room temperature of 73 degrees F and “cold junction compensation” activated inside this transmitter, determine the number of DC millivolts the technician would need to input to the transmitter’s terminals to simulate a process (thermocouple) temperature of 925 degrees Fahrenheit.

$$V_{in} = \underline{\hspace{2cm}} \text{ mV}$$

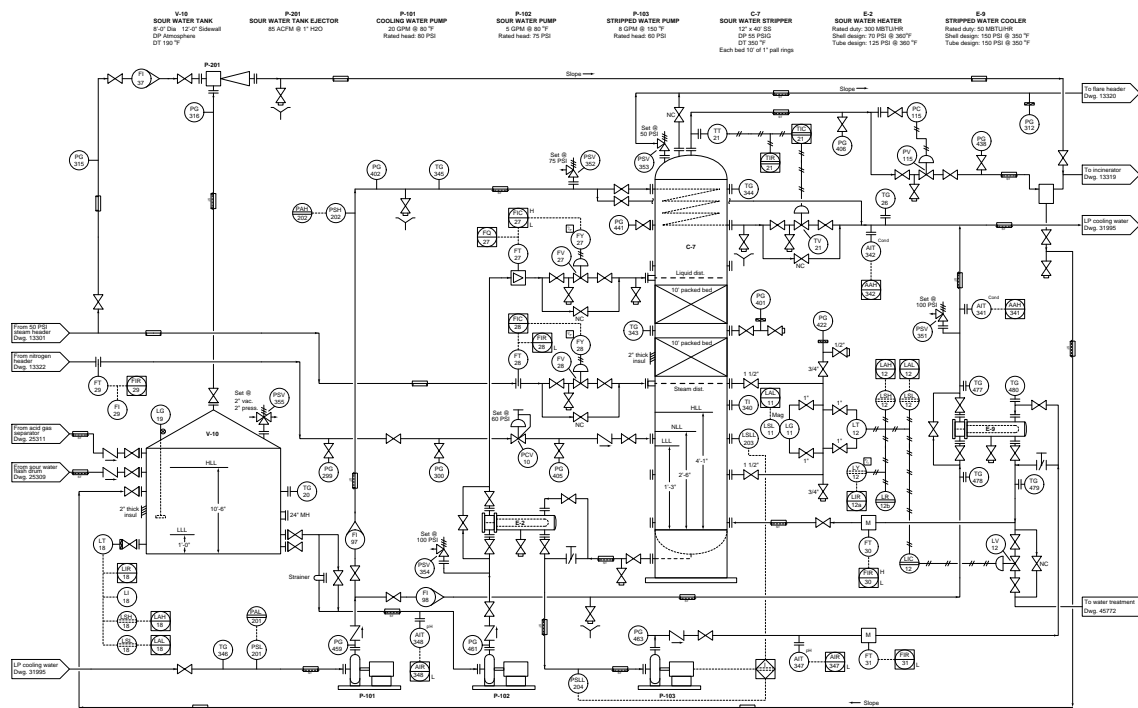
Next, calculate the necessary resistance in this voltage divider circuit to produce this required millivoltage signal (to simulate a temperature of 925 degrees F):



$$R = \underline{\hspace{2cm}} \text{ ohms}$$

### Question 83

Explain the purpose served by conductivity transmitters AIT-341 and AIT-342 in this sour water stripping tower unit (where sulfide-laden water is “stripped” of sulfur compounds by the addition of hot steam):.

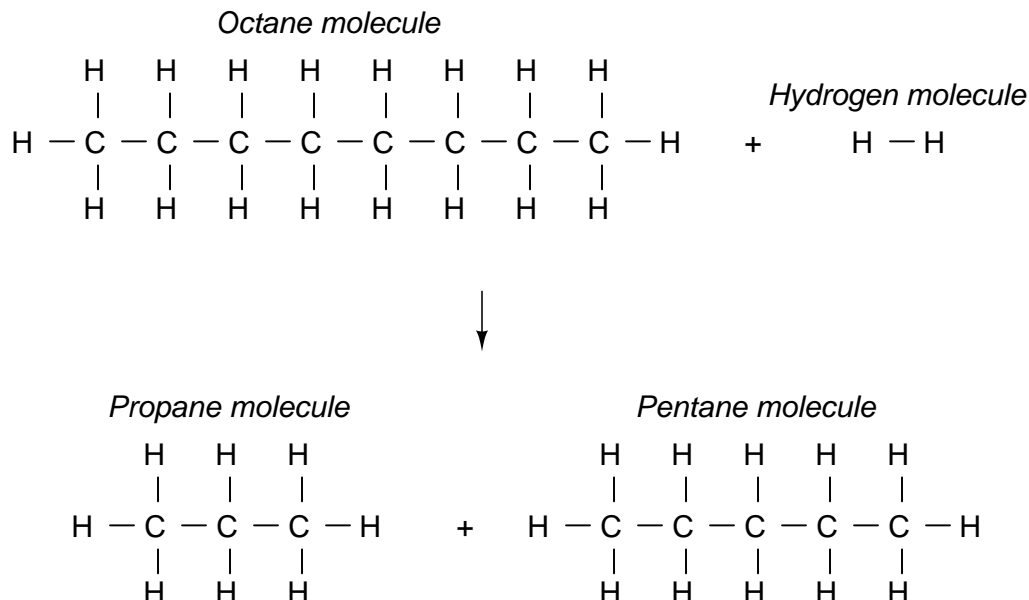


Also, calculate the heat exchange rate through exchanger E-9 given a flow indication of 18.5 GPM at FI-98, a temperature indication of 63 degrees F at TG-478, and a temperature indication of 189 degrees F at TG-477:

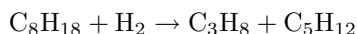
$$\frac{dQ}{dt} = \text{_____ BTU/hour}$$

Question 84

*Hydrocracking* is a petroleum refining process whereby heavy oils are converted into lighter oils for use as jet fuel and feedstock for gasoline production. In a hydrocracker reactor, heavy oils such as octane ( $\text{C}_8\text{H}_{18}$ ) are mixed with hydrogen gas ( $\text{H}_2$ ) at high temperatures and pressures to form lighter compounds such as propane ( $\text{C}_3\text{H}_8$ ) and pentane ( $\text{C}_5\text{H}_{12}$ ):



Expressed in formula form, this reaction is as follows:



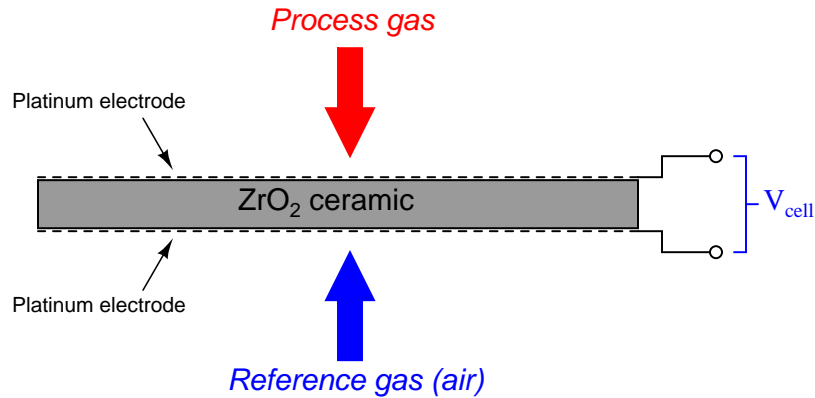
Overall, such reactions are exothermic. However, not every *portion* of the reaction is exothermic. Identify the endothermic and exothermic processes at work in a typical hydrocracking reaction, and comment on their relative energies given the knowledge that the overall reaction is exothermic.

Given the exothermic nature of hydrocracking reactions, some form of cooling is needed to prevent a “runaway” condition. In modern hydrocracker reactors, excess hydrogen gas is injected at the catalyst beds to “quench” the reaction and thereby control temperature. Based on what you know about hydrogen, explain why it is an effective coolant for this process.

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Question 85

The *Nernst equation* finds application in many different chemical analyzer technologies, not just pH measurement. One of these analytical technologies is *oxygen concentration* in mixed gas streams, such as the exhaust from a combustion process where oxygen content is usually maintained at about 2% (instead of the normal 20.9% oxygen concentration of Earth's atmosphere). A common oxygen sensor is made of a “sandwich” of platinum electrodes on either side of a solid zirconium oxide membrane. One side of this electrochemical cell is exposed to the exhaust gas (process), while the other side is exposed to heated air which serves as a reference:



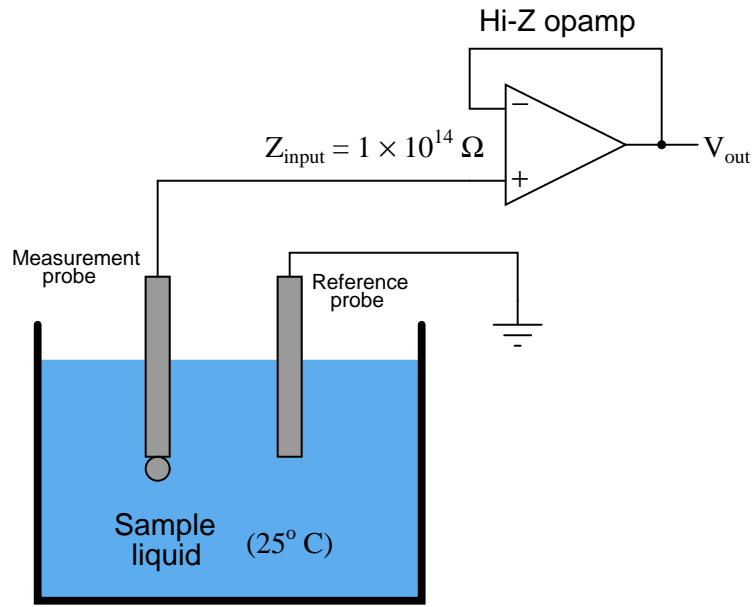
Voltage output by the cell is predicted by the Nernst equation:

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

Explain why temperature must be precisely controlled at the zirconium oxide cell in order to maintain accurate calibration of this instrument. Also, identify the relationship between measured oxygen content and cell output voltage (i.e. is voltage *directly* or *inversely* related to oxygen content?) for applications such as furnace exhaust oxygen measurement.

Question 86

Examine the following pH measurement circuit, then answer the questions that follow:

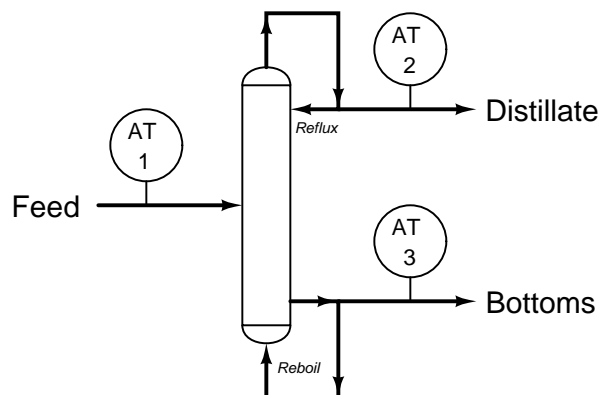


- Calculate the ideal output voltage of the two pH measurement probes if the solution's hydrogen ion molarity is 0.0065 M.  $V_{probe} = \underline{\hspace{2cm}}$  volts
- Will the output voltage *increase*, *decrease*, or *stay the same* as what you just calculated if a very small amount of acidic substance is added to the liquid?
- Will the output voltage *increase*, *decrease*, or *stay the same* if the resistance of the measurement probe increases greatly due to coating?
- Calculate the actual output voltage of the opamp if the measurement electrode's resistance is  $9.5 \times 10^{12}$  ohms and the probes are generating a voltage of 130 mV. Assume that the reference probe's resistance is low enough to be ignored.  $V_{output} = \underline{\hspace{2cm}}$  volts

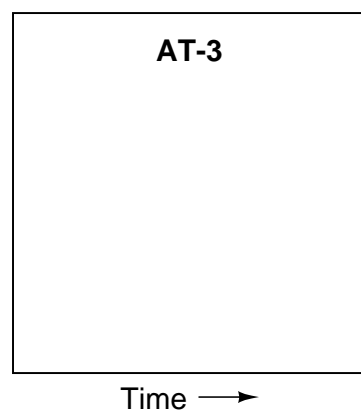
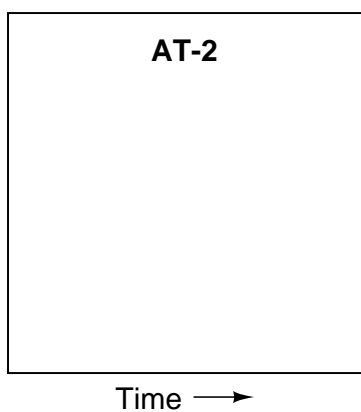
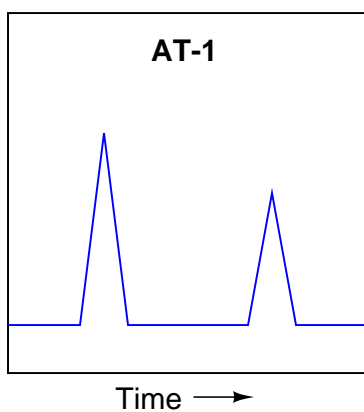


Question 87

Suppose three chromatographs are used to measure the composition of feed and separated products in and out of a simple distillation tower:

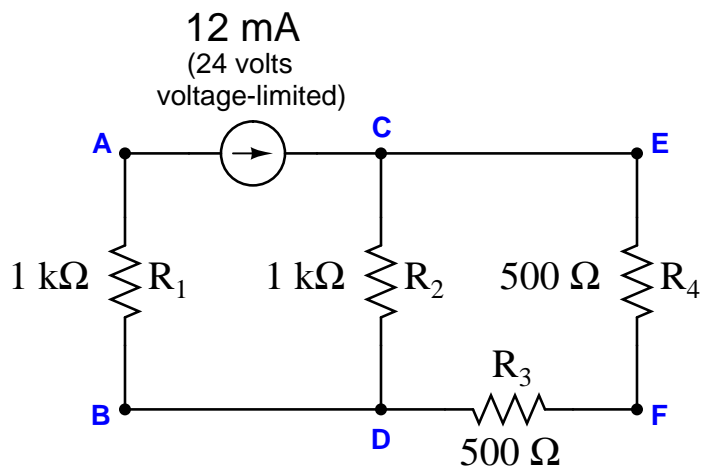


Based on the chromatogram shown for AT-1, sketch approximate chromatograms for the other two (product) analyzers:



Question 88

Suppose a voltmeter registers 0 volts between test points **F** and **B** in this series-parallel circuit:



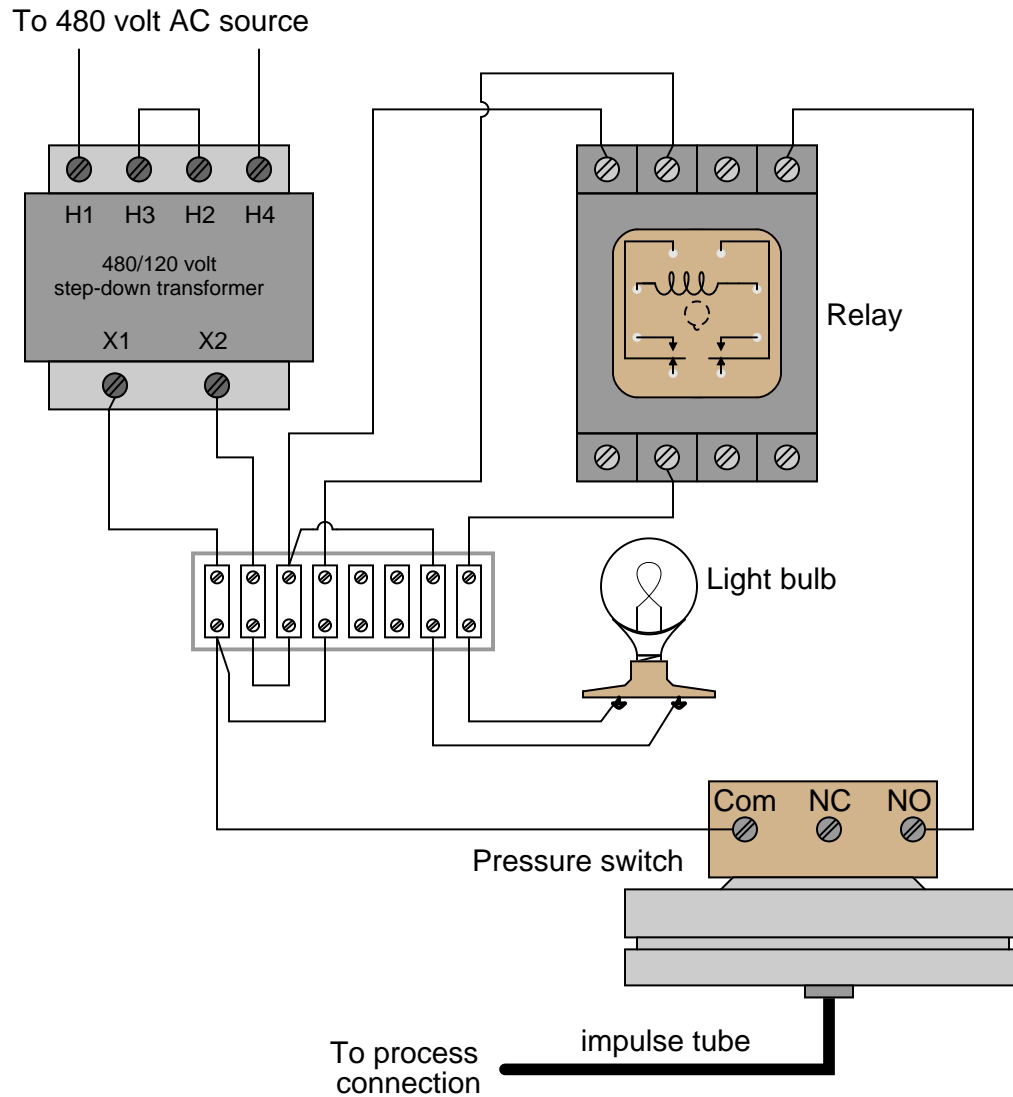
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

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

Now suppose a technician breaks the connection between test points **B** and **D** and measures voltage again between test points **F** and **B**. Explain how this voltage measurement would help further identify the location and/or nature of the fault.

Question 89

Identify the state of the light bulb when the normally-open pressure switch contact *closes*:



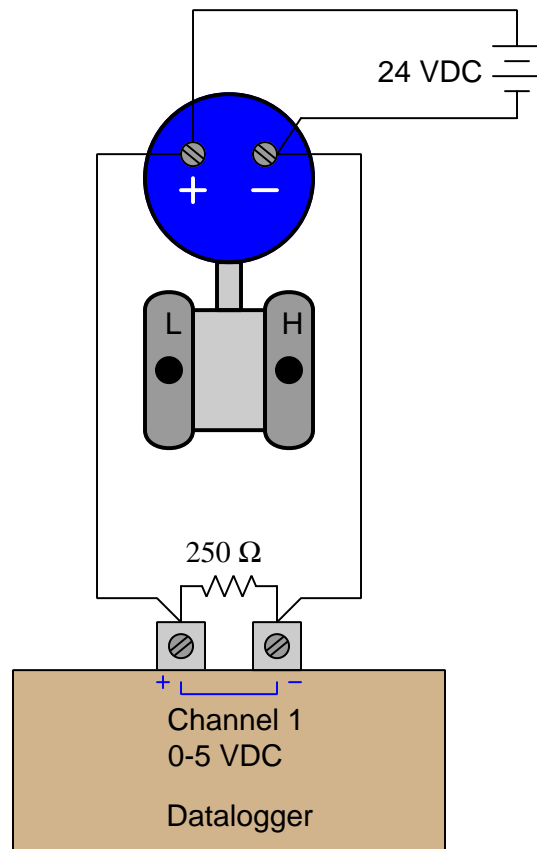
Assuming the light bulb functions as a pressure alarm to alert operators to an unsafe condition, determine whether this is a *low-pressure* alarm or a *high pressure* alarm.

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

file i03203

### Question 90

A technician connected a loop-powered pressure transmitter to a datalogger, but made a mistake in doing so. Identify the mistake in this circuit, and re-draw it (complete with all polarity markings) so that it will function correctly:



**Lab Exercise – introduction**

Your task is to build, document, and troubleshoot an analytical measurement system consisting of a digital electronic analytical transmitter connected to an electronic indicator or recorder (I recommend something other than an indicating controller, just to make this system different). Process variable options include pH measurement, conductivity measurement, or any other analyzer available in the lab's collection.

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	–	–	–	–	
Circuit design challenge	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Calibration (using chemical standard)	mastery	–	–	–	–	
Loop ranging ( $\pm 1\%$ of span accuracy)	mastery					– – – –
Troubleshooting	mastery					– – – –
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	
Team tool locker inspection	(ungraded)	–	–	–	–	

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

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

### Circuit design challenge

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

### Final loop diagram and system inspection

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

### Instrument calibration

Calibrate an analytical transmitter against a trusted chemical standard, using a trusted test instrument for verifying signal current values. Complete both As-Found and As-Left calibration tables, and tag when complete.

### Loop ranging

Set the lower- and upper-range values (LRV and URV) in both the transmitter and indicator as randomly selected by the instructor, demonstrating accurate measurement of the process variable to within  $\pm 1\%$  of span.

### Troubleshooting

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

## Lab Exercise – objectives and expectations (continued)

### Lab percentage score

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

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

### Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, 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 instrument selection

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

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

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

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

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

When selecting field instruments for this lab exercise, choose a *process analyzer* (a pH analyzer is recommended) with electronic (4-20 mA) signal output. Many analyzer types, pH included, use remotely-mounted sensing elements along with the transmitter unit. Be sure to locate the appropriate sensing elements for your analyzer. For a pH analyzer, this takes the form of a *combination electrode* stored with its glass sensing bulb immersed in a liquid to prevent dehydration.

Consult documentation from the manufacturer’s website to identify how to properly wire, power, and calibrate the transmitter. Your instructor will check to see you have located and are familiar with the equipment manual(s).

After locating a suitable instrument and its associated documentation, you should qualitatively test it prior to installing it in your system. For a pH transmitter, this entails inserting the sensing electrode in a cup of tap water to see that it registers a pH value somewhere near 7.0 (it may be as low as 5.0 or as high as 8.0, depending on the water quality and the condition of the sensing electrode). If the transmitter fails to respond properly, consult the instructor for assistance before tagging it with a label explaining what it does (or what it fails to do). Be sure not to let the pH electrode become dry, as dehydration will very quickly ruin it!

Bear in mind that analyzers powered by their own (non-loop) power source typically behave as current *sources*, and must be connected to the indicating instrument differently than a loop-powered device! Consult the manufacturer’s documentation for wiring details.

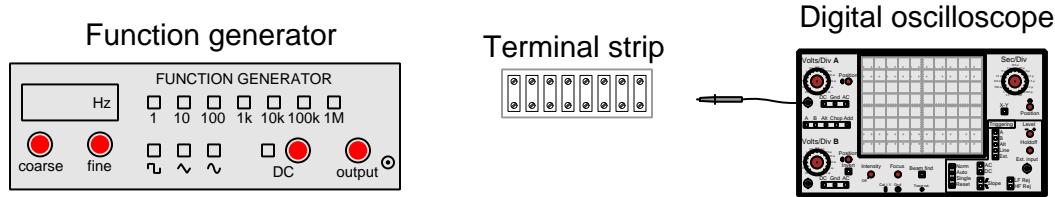
**Planning a functioning system should take no more than an hour if the team is working efficiently, and will save you hours of frustration (and possible component destruction!).**



## Lab Exercise – circuit design challenge

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

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



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

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

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

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

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

## Lab Exercise – building the system

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

After getting your prototype sketch approved by the instructor, you are cleared to begin building your system. Many analyzers are designed to be panel-mounted rather than field-mounted (attached to 2-inch pipes using special brackets and U-bolts). Feel free to set your panel-mount analyzer on a table or shelf in lieu of mounting it in an actual panel.

Select a specific loop controller or indicator to act as a display for the measured chemical concentration. Your instructor may choose the indicator for your team.

Finally, your analyzer system needs to have a loop number, so all instruments may be properly labeled. This loop number needs to be unique, so that another team does not label their instruments and cables the same as yours. One way to make your loop number unique is to use the equivalent resistor color-code value for your team’s color in the loop number. For example, if you are the “Red” team, your loop number could be “2”.

### 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 – 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 – instrument calibration

Each team must calibrate the transmitter to ensure it interprets chemical composition accurately and outputs an accurate current. Then, each team member must configure the transmitter for a unique range (set the LRV and URV parameters) and scale the indicator to register in the proper engineering units (e.g. a pH analyzer ranged for 4 to 12 pH should actually register 4 to 12 pH back at the control room display). The accuracy of this ranging will be checked by the instructor stimulating the analyzer with a random sample while each student verifies the indicator display.

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 ideal standard to use for an analyzer is a chemical solution of precisely known composition. For pH instruments, this takes the form of *pH buffer solutions*, easily mixed from distilled water and pH buffer powder. For gas analyzers, this takes the form of either ambient air (21% oxygen content) or more likely bottled *calibration gases*. Chemical calibration standards will be made available by the instructor, and should be used sparingly as they tend to be expensive.

Document the accuracy of your transmitter's measurement at two (minimum) different points throughout its sensing range using these two tables:

**As-Found calibration table**

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

**As-Left calibration table**

Applied concentration	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:

*Cut out tag(s) with scissors, then affix to instrument(s) using transparent tape to show calibration:*

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

**CALIBRATED**

By: \_\_\_\_\_ Date: \_\_\_\_\_

Range: \_\_\_\_\_

Each student, however, must individually re-range the transmitter and the receiving instrument (indicator, controller, and/or recorder). Re-ranging an analyzer is usually done using a keypad and display on the transmitter unit, following the manufacturer's instructions. Each student's ranging is confirmed by the instructor by applying a random chemical concentration to the sensing element and verifying that the indicating controller reads the same (to within  $\pm 1\%$  of span).

**Common mistakes:**

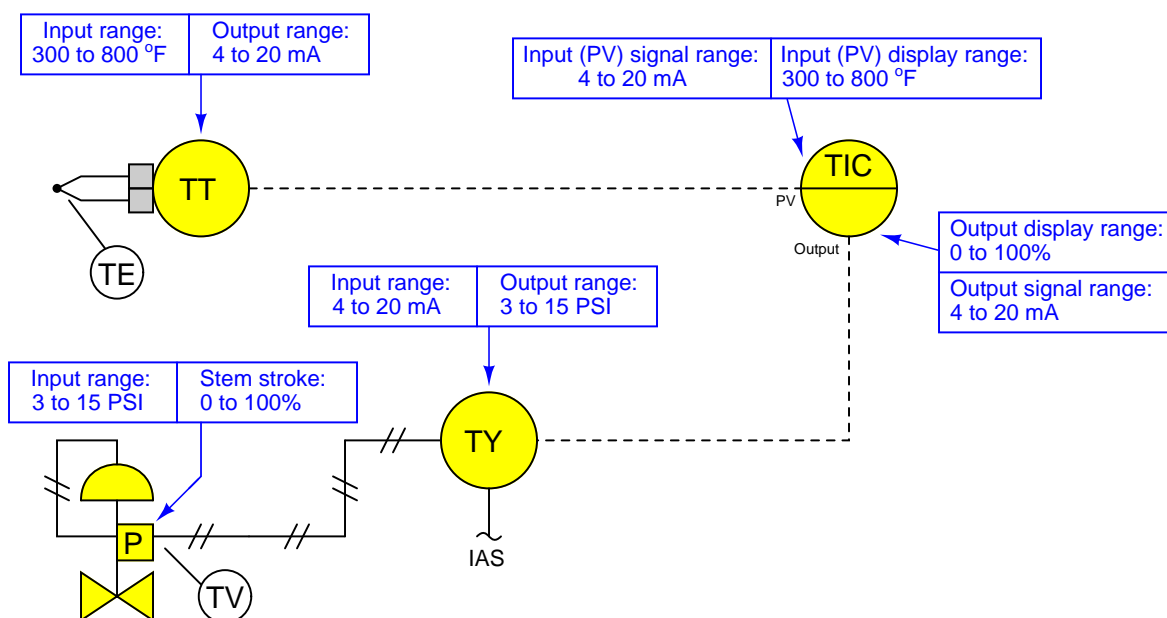
- Choosing a calibration ("trim") range that is substantially less than the final range of measurement when installed. As a general rule, you should trim the sensor of the transmitter to cover the broadest range of measurement possible with your calibration equipment.
- Neglecting to place a calibration tag on the transmitter after "trimming" it.

**Trimming and individually ranging your transmitter should take no more than one full lab session (3 hours) if the team is working efficiently!**

## Notes on instrument ranging

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

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



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

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

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

## Notes on instrument ranging (continued)

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



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

## Lab Exercise – troubleshooting

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

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

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

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

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

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

### Common mistakes:

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

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

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

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

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

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

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

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

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

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

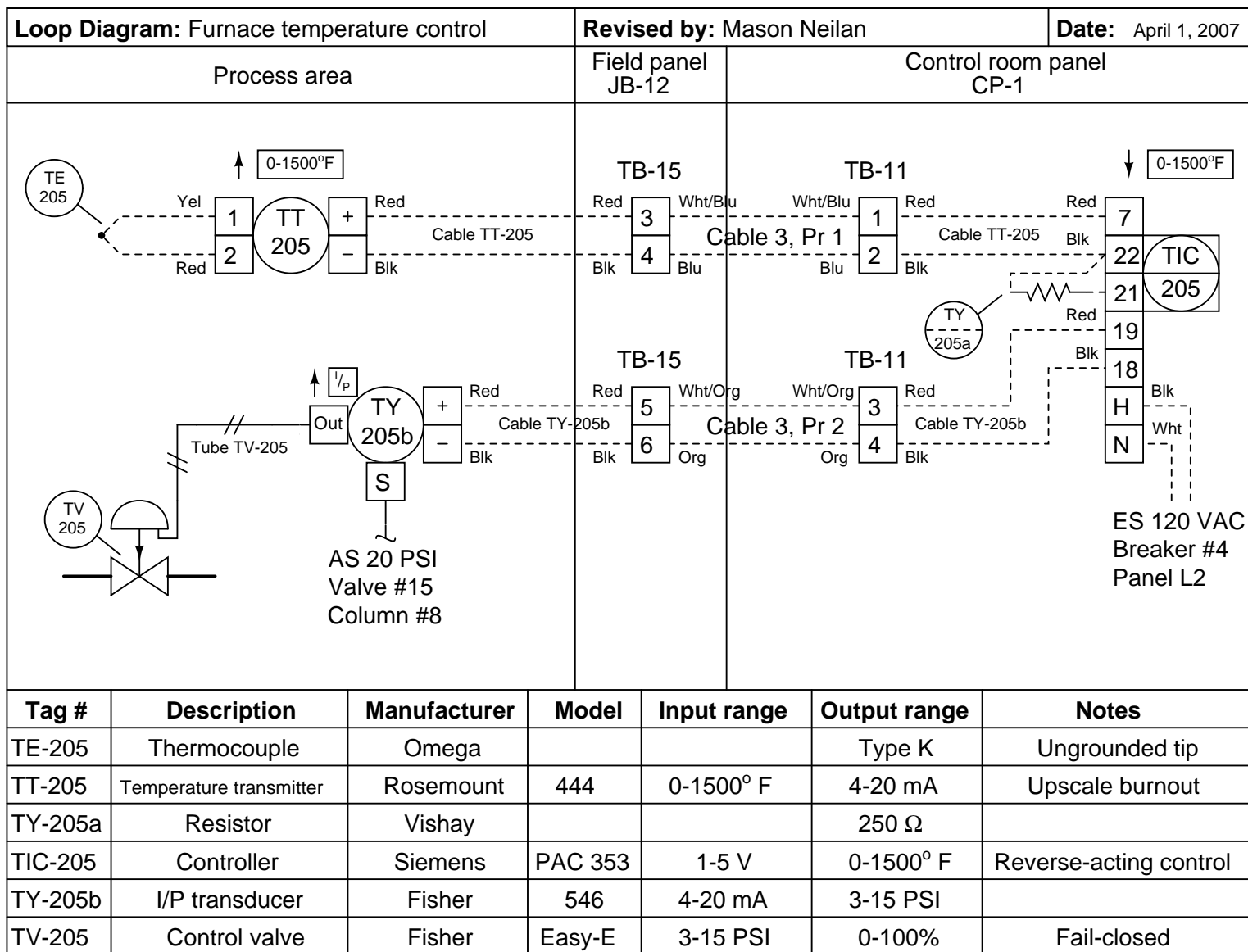
**Lab Exercise – team tool locker inspection**

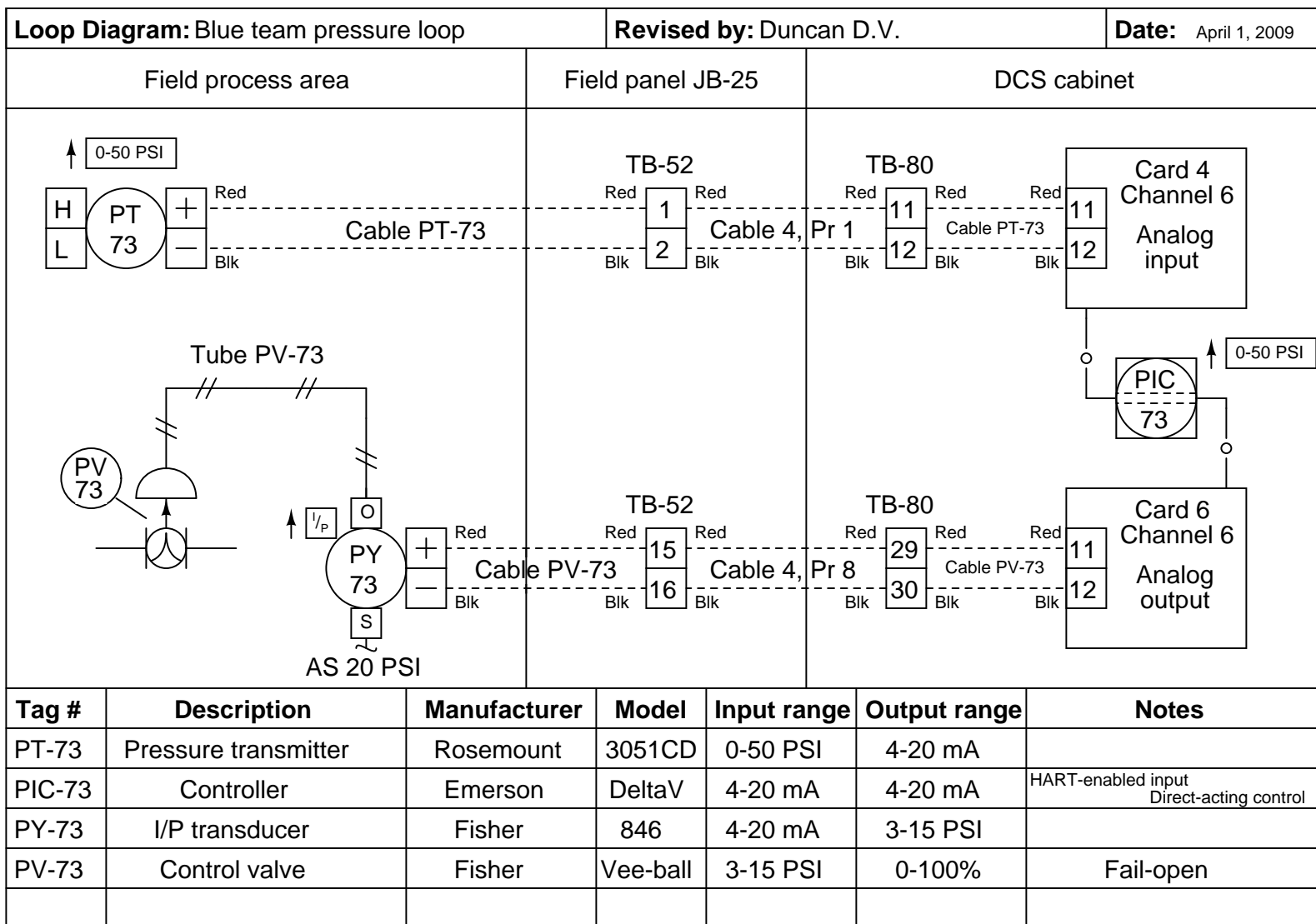
The instructor will work with each team to inspect their tool locker for all required items, and also to ensure nothing else is being stored there.

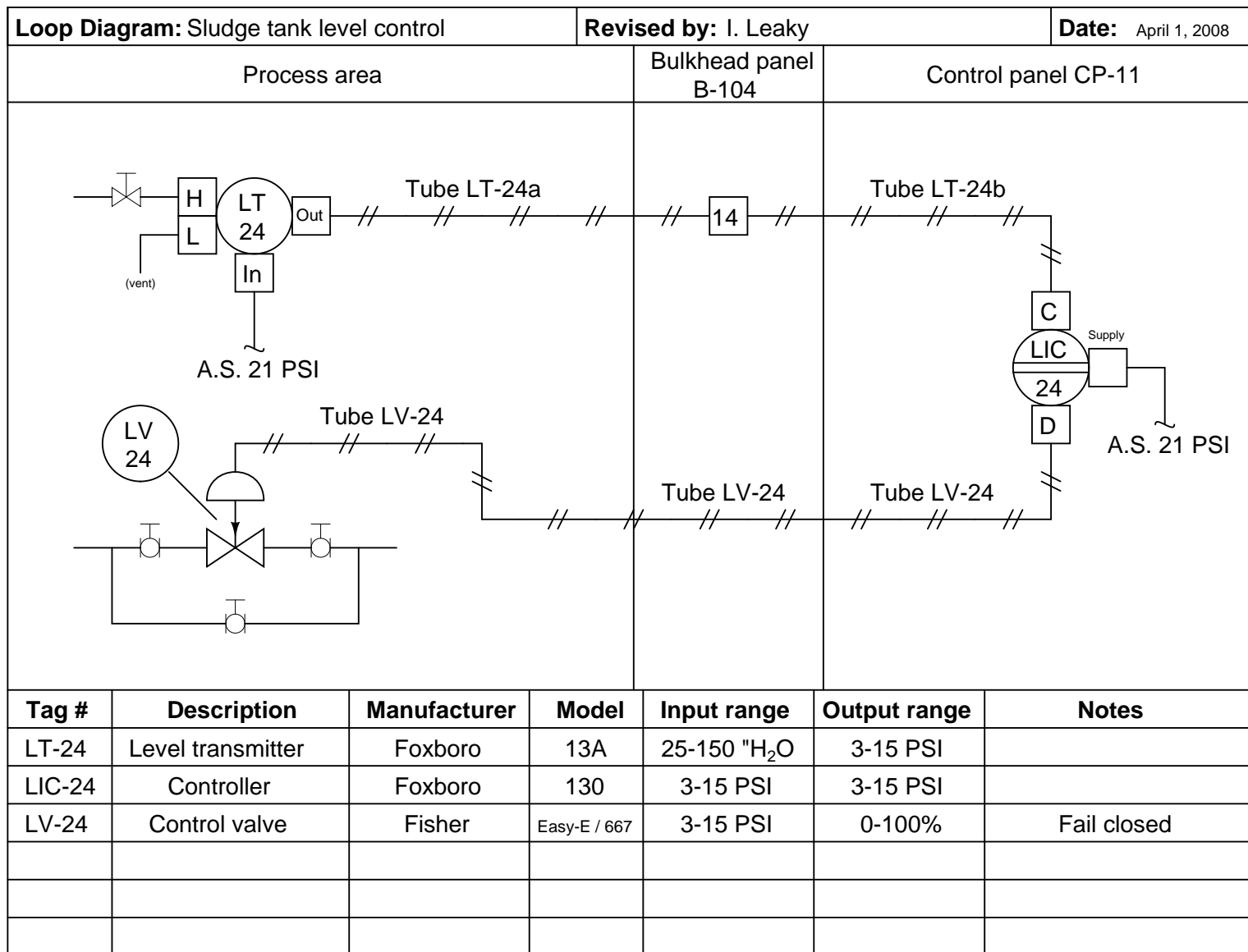
First, the locker will be entirely emptied. Next, the instructor will inspect each tool before placing it in the locker, following the order of the inventory list taped to the inside of the locker door. The team is responsible for finding or replacing any missing items. Any items not on the inventory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

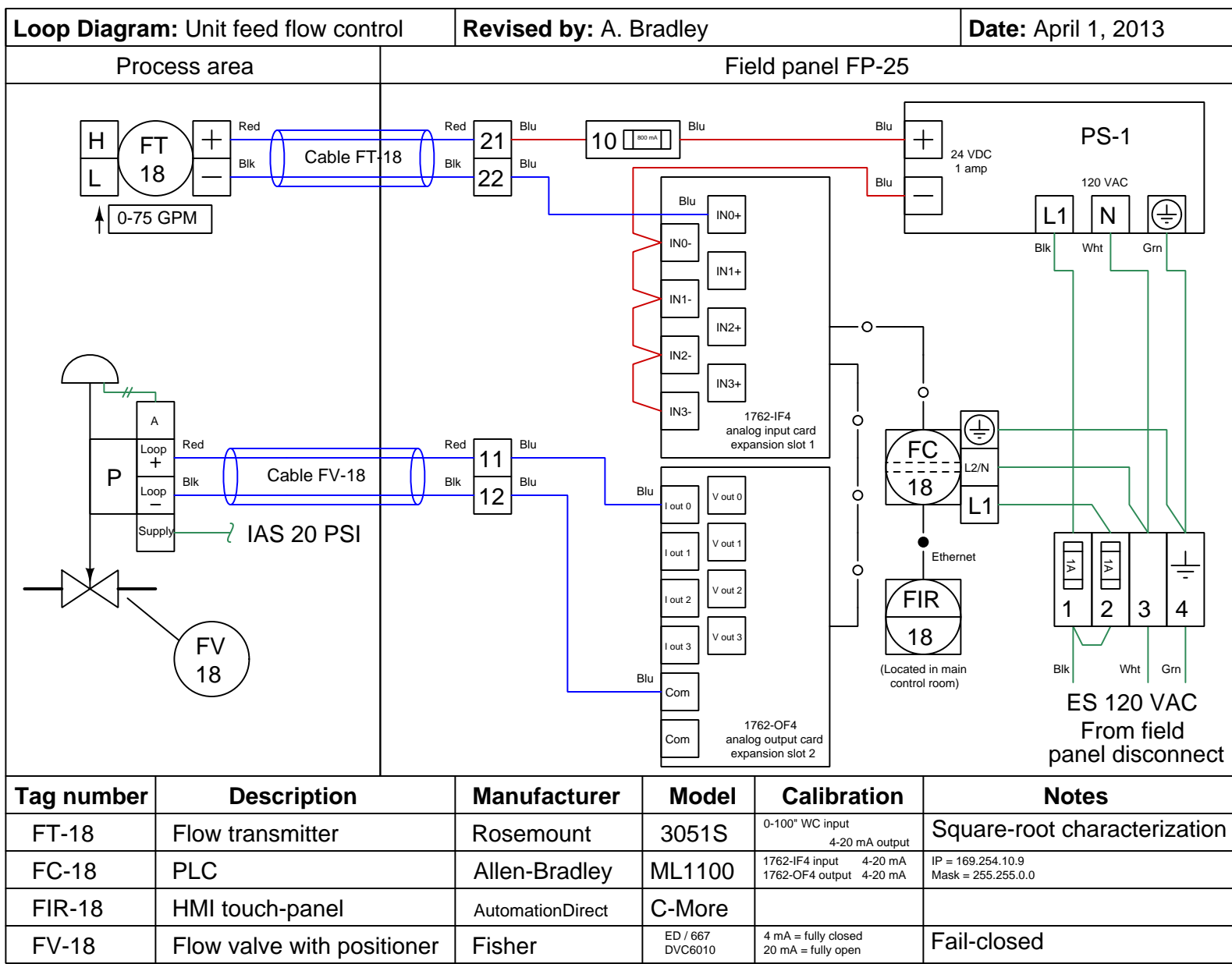
Any damaged or worn components will be replaced. Inexpensive items such as drill bits and taps will be replaced at student expense. More expensive items will be replaced at the school's expense, with students doing research to identify the replacement cost of the item(s) in question.

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## Lab Exercise – loop diagram and system inspection

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

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- 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).

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#### **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](#)

**Capstone Assessment** (end of quarter)

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

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

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

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

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

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

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

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

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

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

**The time clock starts now!**

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

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

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

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

**The time clock stops now!**

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

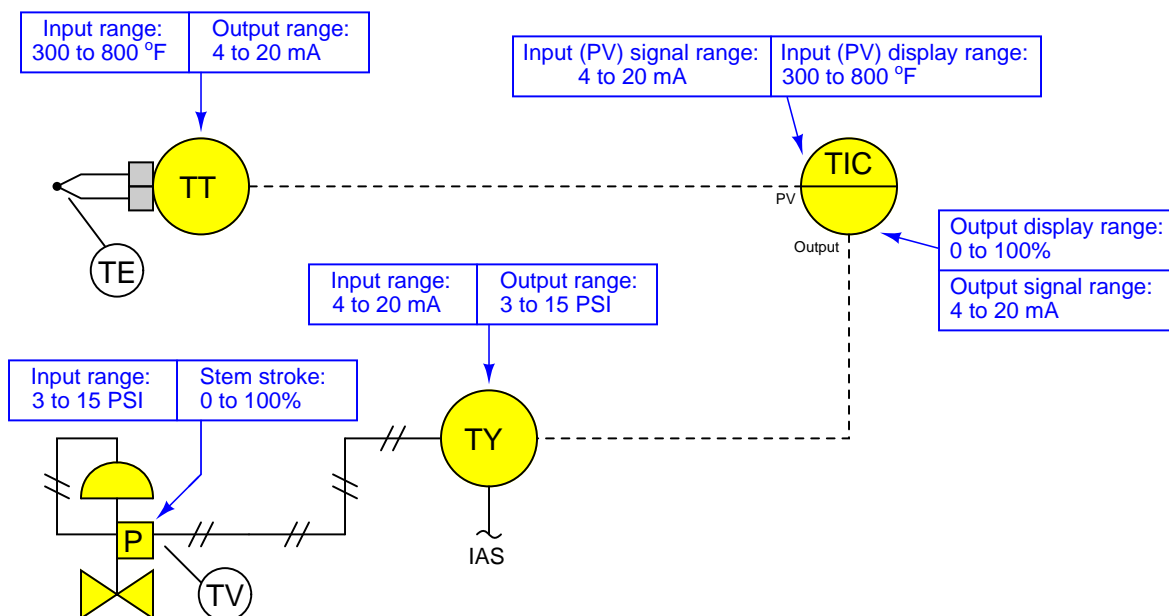
Criterion	(Instructor verifies)
Instructor verifies all signal wires/tubes disconnected	
Instructor verifies controller reset to original configuration	
Instructor verifies DAQ is returned to team tool locker	
Instructor collects your diagrams	

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

## Notes on instrument ranging

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

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



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

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

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

## Notes on instrument ranging (continued)

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

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

## Notes on controller action

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

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

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



## Notes on controller action (continued)

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

## Notes on controller tuning

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

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

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



## Answers

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Answer 1

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Answer 2

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Answer 3

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Answer 4

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Answer 5

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Answer 6

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Answer 7

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Answer 8

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Answer 9

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Answer 10

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Answer 11

An *ion* is any atom or molecule that is electrically imbalanced; i.e., its total number of electrons do not equal its total number of protons.

---

**Answer 12**

Both *dissociation* and *ionization* refer to the separation of formerly joined atoms upon entering a solution. The difference between these terms is the type of substance that splits: “dissociation” refers to the division of ionic compounds (such as table salt), while “ionization” refers to covalent-bonded (molecular) compounds such as HCl which are not ionic in their pure state.

- Sodium Chloride ( $\text{NaCl}$ )  $\rightarrow \text{Na}^+ + \text{Cl}^-$
- Hydrogen Chloride ( $\text{HCl}$ )  $\rightarrow \text{H}^+ + \text{Cl}^-$
- Sodium Hydroxide ( $\text{NaOH}$ )  $\rightarrow \text{Na}^+ + \text{OH}^-$
- Calcium Sulfate ( $\text{CaSO}_4$ )  $\rightarrow \text{Ca}^{2+} + \text{SO}_4^{2-}$
- Potassium Sulfate ( $\text{K}_2\text{SO}_4$ )  $\rightarrow 2\text{K}^+ + \text{SO}_4^{2-}$
- Sulfuric Acid ( $\text{H}_2\text{SO}_4$ )  $\rightarrow 2\text{H}^+ + \text{SO}_4^{2-}$

The distinguishing characteristic of an ionic compound is that it is a conductor of electricity in its pure, liquid state. That is, it readily separates into anions and cations all by itself. Even in its solid form, an ionic compound is already ionized, with its constituent atoms held together by an imbalance of electric charge. Being in a liquid state simply gives those atoms the physical mobility needed to dissociate.

Molecular (covalent) compounds, in contrast, do not readily separate into anions and cations in their pure, liquid states. Covalent bonds are formed by *shared* electrons, not electrostatic attraction between ionized atoms. An electron must be exchanged from one atom to another in order for a covalent compound to break into ionized parts, and so this process is called ionization. Water is an excellent example of a covalent compound. Although some molecules in water do ionize with no impurities added, it is a *very* small proportion and so we treat pure (deionized) water as an electrical insulator.

Other examples of covalently-bonded molecular compounds exist, such as hydrogen chloride. HCl ionizes into hydrogen cations and chlorine anions when dissolved in water, making HCl an electrolyte even though HCl is not conductive in its pure, liquid state.

In the electrolysis of saltwater, oxygen and chlorine gas will both be liberated at the anode (+), while hydrogen gas will be liberated at the cathode (−). Sodium accumulates on the cathode. The proportion of chlorine to oxygen liberated at the anode depends on the concentration of the saltwater. If you use enough current, you will dissolve copper ions into the water, turning it bluish-green in color.

---

**Answer 13**

- $V_{\text{primary}} = 3.7$  volts
- $V_{\text{secondary}} = 12.0$  volts
- $I_{\text{primary}} = 26.1$  mA
- $I_{\text{secondary}} = 8.02$  mA

This is a *step-up* transformer.

---

**Answer 14**

Here is a version of the conductivity cell equation showing units instead of variables:

$$[\text{S}] = \left[ \frac{\text{S}}{\text{cm}} \right] \frac{[\text{cm}^2]}{[\text{cm}]}$$

Follow-up question: identify the unit of conductance popular before Siemens. Hint: it actually makes *sense* as opposed to being someone’s (arbitrary) name!

---

Answer 15

$$k = G\theta$$

---

Answer 16

$$k = 110 \mu\text{S}/\text{cm}$$

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Answer 17

With increasing conductivity, the toroidal probe generates an increasing AC current circulating through the salty water. This increased electric current through the water passes through the center of both toroidal coils, inducing a stronger voltage in the sensing coil.

With increasing conductivity, the water becomes less resistive. This results in less voltage drop between the sensing electrodes for any given amount of current between the excitation electrodes.

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Answer 18

The pipe provides a higher-conductance current path than the liquid, making it seem (from the probe's perspective) as though the liquid is more conductive than it really is.

In a sense, a metal pipe wall "shorts out" part of the normal current pathway through the liquid. Electric current must still travel through the liquid as it goes through the center of the toroids, but the outer (return) path of the electric current which normally flows through liquid as well may be shunted through a metal pipe wall.

Solutions to the problem include use of non-metal pipes, plastic-lined metal pipes, and/or oversizing the pipe so that the probe is far from the walls.

---

Answer 19

- If  $V_{excitation}$  were to increase, the millivoltmeter's reading would **increase**
- If the conductivity of the liquid were to increase, the millivoltmeter's reading would **increase**
- If the liquid were to completely drain out of the sample holder, the millivoltmeter's reading would **decrease** (all the way to zero)
- You could add salt or some other ionic compound to the water to increase its conductivity. You could also heat the water to a greater temperature.

---

Answer 20

$$\text{Specific conductivity} = \underline{\mathbf{191.57}} \mu\text{S}/\text{cm}$$

---

Answer 21

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Answer 22

**Partial answer:**

An *acid* is a substance that produces positive hydrogen ions (hydrogen cations,  $\text{H}^+$ ) when mixed with water. A *base* (often called a *caustic* or an *alkaline*) is a substance that produces negative hydroxyl ions (hydroxyl anions,  $\text{OH}^-$ ) when mixed with water. A *salt* is a substance that contains a cation other than  $\text{H}^+$  and an anion other than  $\text{OH}^-$  or  $\text{O}^{2-}$ .

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Answer 23

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Answer 24

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Answer 25

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Answer 26

**Partial answer:**

- $[\text{H}^+] = 0.0000032 \text{ M}$  ; pH = 5.49 pH
- $[\text{H}^+] = 0.0000000012 \text{ M}$  ; pH = 9.92 pH

---

Answer 27

**Partial answer:**

- 2.71 pH ;  $[\text{H}^+] = \underline{0.00195} \text{ M}$
- 6.08 pH ;  $[\text{H}^+] = \underline{0.000000832} \text{ M}$

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Answer 28

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Answer 29

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Answer 30

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Answer 31

Molarity of sodium ions in the saltwater solution =  $0.05 \text{ mol} / 7.098 \text{ liters} = 0.007045 \text{ M}$

Molarity of chlorine ions in the saltwater solution =  $0.05 \text{ mol} / 7.098 \text{ liters} = 0.007045 \text{ M}$

The molarities are equal because sodium chloride (NaCl) completely dissociates into  $\text{Na}^+$  and  $\text{Cl}^-$  ions in solution, with equal molecular quantities. For every mole of  $\text{Na}^+$  originating from the salt, there will be one mole of  $\text{Cl}^-$  in the solution as well.

---

Answer 32

In pure water at  $25^\circ \text{C}$ :

$$[\text{H}^+] = 1.00 \times 10^{-7} \text{ M}$$

$$[\text{OH}^-] = 1.00 \times 10^{-7} \text{ M}$$

For pure water and also for dilute solutions of water at  $25^\circ \text{C}$ , the product of these two molarities is always (very nearly) equal to  $1.00 \times 10^{-14}$ . This is known as the *ionization constant of water*, or  $K_W$ :

$$K_W = [\text{H}^+][\text{OH}^-] = 1.00 \times 10^{-14}$$

---

Answer 33

Pure water at  $25^\circ \text{C}$  = 7.0 pH

Free hydrogen ions rarely exist in solution, but more commonly are found attached to water molecules ( $\text{H}_2\text{O}$ ) where they form the positive ion  $\text{H}_3\text{O}^+$  called hydronium.

---

**Answer 34**

For the first solution:  $-\log 0.00027 = 3.57$  pH

For the second solution:  $-\log \frac{1 \times 10^{-14}}{0.0081} = 14 - (-\log 0.0081) = 11.91$  pH

Acids have pH values below 7, caustics (alkalines) have pH values above 7, and pure water has a pH of 7.0 (at least at 25° C).

In the laboratory balance scale analogy, a balanced condition (where the scale shows equal “weights,”  $[\text{H}^+] = [\text{OH}^-]$ ) is analogous to a *neutral* pH solution. Incidentally, this does not necessarily mean a pH of 7.0 – all it means is that hydrogen and hydroxyl ion activities are balanced. Given the changing ionization constant of water at different temperatures, it is entirely possible to have a neutral solution that does *not* have a pH value of 7.

---

**Answer 35**

pH = 7.47 at 0° C and pH = 6.51 at 60° C, so pH decreases with increasing temperature.

The definition of “neutral” is worth exploring a bit. For all the different scenarios represented by the table of  $K_W$  values, the water is still neutral. The definition of a “neutral” solution in the context of pH is that hydrogen and hydroxyl ion activity is exactly equal ( $[\text{H}^+] = [\text{OH}^-]$ ). Given the changing ionization constant of water at different temperatures, it is entirely possible to have a neutral solution that does *not* have a pH value of 7, as your calculations should show here!

This trend may be explained in terms of Conservation of Energy. Remember that it takes energy to break a chemical bond. Ionization of a compound is an example of this, separating atoms that were formerly joined by either covalent bonding or electrostatic attraction. As heat energy is added to a sample of water, more water molecules are able to separate. A very cold sample of water has minimal energy, and so we find the molecules in a low energy state (hydrogen bonded with oxygen, rather than separating into ions).

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**Answer 36**

pH measurement and control is important for wastewater treatment, because extreme pH values (either too acidic or too caustic) can adversely affect both flora and fauna in the water body that the treated wastewater is discharged to.

In biopharmaceutical production, pH measurement and control is absolutely critical. Batches of cells will not grow, or grow properly, if the pH is not kept within tight bounds.

Food production (especially brewing) is another process where pH measurement (and control) is critical. Poor pH control leads to bad beer, and no one wants that.

---

**Answer 37**

For a solution of 0.1 molar (0.1  $M$ ) concentration, there are 0.1 moles of solute (pure ethyl alcohol) for every 1 liter of total solution volume. It should be noted that the molarity of a solution changes with temperature, because a solution’s volume will change with temperature even though the quantity of solute in moles does not!



---

Answer 38

*Molality* is defined as the number of moles of solute per kilograms of solvent (not of the total solution!). We were given the solvent mass in kilograms (2 kg) already. All we need to know is the molar quantity of the pure acid and we can solve for molality.

First, let's tally the number of grams per mole for  $\text{H}_2\text{SO}_4$ , based on the atomic mass units (amu) for the constituent elements:

For  $\text{H}_2\text{SO}_4$ , each molecule contains:

- 2 atoms of H at 1.01 amu each
- 1 atom of S at 32.06 amu each
- 4 atoms of O at 16 amu each

This gives a total of 98.08 grams per mole of pure  $\text{H}_2\text{SO}_4$ .

This figure may be used as a unity fraction to convert moles into grams, or grams into moles. For our application, we need to convert the given mass of 1 gram into moles:

$$(1 \text{ g})(1 \text{ mol} / 98.08 \text{ g}) = 0.0102 \text{ mol}$$

Taking this quantity in moles and dividing by the mass of solvent (2 kg) gives us the molality of the acid solution:

$$0.0102 \text{ mol} / 2 \text{ kg} = 0.0051 \text{ } m$$

---

Answer 39

pH neutralization is the minimization of either excessive acidity or alkalinity of aqueous liquids, usually prior to discharge into a natural body of water. In plain language, this means controlling the pH of process water to a range usually between 6 and 9. A pH value equal to exactly 7 is considered "neutral."

Wastewater treatment processes almost always involve some form of pH neutralization. It is important for the pH of treated water to be within a range close to that of natural bodies of water, so as not to disturb the habitat of flora and fauna there.

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Answer 40

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Answer 41

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Answer 42

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Answer 43

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Answer 44

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Answer 45

**Partial answer:**

$$V = 90.56 \text{ mV}$$

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Answer 46

**Partial answer:**

- $T = 33 \text{ } ^\circ\text{C}$  ; slope = **60.76** mV/pH
- $T = 40 \text{ } ^\circ\text{F}$  ; slope = **55.09** mV/pH

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Answer 47

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Answer 48

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Answer 49

The reaction product of water and  $\text{SO}_2$  gas is  $\text{H}_2\text{SO}_3$  – *sulfurous acid*.

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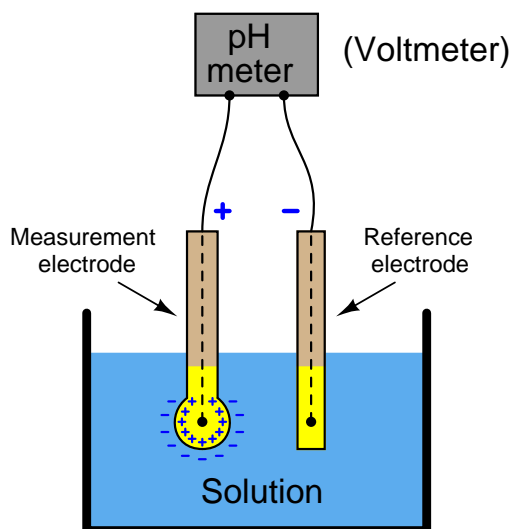
Answer 50

**Partial answer:**

- $\text{pH} = 5.82$  ;  $T = 25\text{ }^\circ\text{C}$  ; Nernst voltage = **69.83** mV
- $\text{pH} = 11.23$  ;  $T = 95\text{ }^\circ\text{F}$  ; Nernst voltage = **-258.7** mV
  
- Nernst voltage = 233 mV ;  $T = 12\text{ }^\circ\text{C}$  ; Solution = **2.88** pH
- Nernst voltage = -185 mV ;  $T = 131\text{ }^\circ\text{F}$  ; Solution = **9.84** pH

---

Answer 51



$[\text{H}^+]$ in solution	pH	V
$5.83 \times 10^{-5} M$	4.23	163.6 mV
$1 \times 10^{-5} M$	5	118.3 mV
$1 \times 10^{-6} M$	6	59.16 mV
$1 \times 10^{-7} M$	7	0 mV
$1 \times 10^{-8} M$	8	-59.16 mV
$7.02 \times 10^{-9} M$	8.15	-68.25 mV
$1 \times 10^{-9} M$	9	-118.3 mV
$1 \times 10^{-10} M$	10	-177.5 mV

Note that the difference in pH between the measured solution and the internal reference solution is indicated by a simple DC voltage!

Slope = 59.17 mV per pH unit deviation from 7.0 pH

Temperature compensation is required for high-accuracy pH measurement, to compensate for the temperature term in the Nernst equation. This temperature term strictly relates to the ion-permeable membrane, and not the solution. In other words, using an RTD to sense and correct for temperature merely compensates for changes in the pH/voltage proportionality of the measurement electrode, and does not (indeed, it *cannot*) compensate for actual ion activity changes in the solution. In order to do the latter (i.e. provide a temperature-corrected measurement of pH telling you what the pH of the solution *would* be at a fixed reference temperature rather than what it actually is at the real temperature), one would have to know the solution's unique temperature/ $[\text{H}^+]$  relationship, which will be unique for every different solution.

Incidentally, the true version of the Nernst equation is as follows:

$$V = \frac{RT}{nF} \ln \left( \frac{a_1}{a_2} \right)$$

Where,

$a_1$  = Activity of ion in measured solution

$a_2$  = Activity of ion in reference solution (on other side of membrane)

In the absence of chemical reactions that “tie up” ions, activity ( $a$ ) and concentration ( $C$ ) are directly proportional to one another ( $a = \gamma C$ ). However, the activity coefficient ( $\gamma$ ) may be subject to change in some situations, in which case the Nernst equation becomes even uglier.

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### Answer 53

The function of this electrode depends on the glass having internal and external *hydrated* layers. If the electrode becomes dried on the outside, ions cannot permeate it, and it becomes useless.

The hydrated layers of a glass electrode slowly dissolve over time, exposing new layers of (dry) glass underneath which hydrate and function anew. The maintenance of this hydrated layer is critical to proper measurement probe operation.

This also explains why pH measurement probe life is finite, and why it shortens with elevated temperature. As solution temperature increases, the speed of glass dissolution increases, eating away the electrode at a faster rate.

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**Answer 54**

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

The “null-balance” technique works like this:

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

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

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**Answer 55**

$[H^+]$	pH	$V_{probe}$
0.001995 M	2.7 pH	254.4 mV
$6.309 \times 10^{-7}$ M	6.2 pH	47.32 mV
$7.943 \times 10^{-13}$ M	12.1 pH	−301.7 mV
$3.881 \times 10^{-5}$ M	4.41 pH	153.2 mV
$1.452 \times 10^{-11}$ M	10.84 pH	−227.1 mV

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**Answer 56**

According to the Nernst equation, the voltage output by a pH probe immersed in 7 pH solution should be zero volts. Therefore, a pH transmitter reading exactly zero volts input should interpret that as a pH value of 7.

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**Answer 57**

This symptom is indicative of an open wire somewhere in the 4-20 mA loop circuit. Many faults are possible here.

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Answer 58

From the common logarithm version of the Nernst equation:

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

Where,

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

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

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

$n$  = Number of electrons transferred per ion exchanged (1 for  $H^+$  ions)

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

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

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

$$\frac{2.303RT}{nF} = 59.17 \text{ mV}$$

Since the common logarithm of hydrogen ion concentration is the very definition of pH, the logarithm term of the Nernst equation may be re-written as the difference between the solution pH and the measurement probe's internal buffer pH (7.0):

$$V = \frac{2.303RT}{nF} (7 - \text{pH})$$

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Answer 59

Temperature (°C)	Slope (mV/pH)
5° C	55.20
20° C	58.18
60° C	66.12
100° C	74.06

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Answer 60

Yes. Concentrated acids may have *negative* pH values, while concentrated bases can exceed 14 pH. In such extreme cases, where standard pH probe life is extremely short, a toroidal conductivity probe may be the best way to infer acid or base concentration.

Toroidal conductivity probes are encased in non-reactive plastic, and so can withstand very harsh pH conditions. Given that additional concentrations of either acid or caustic both increase solution conductivity to the point of “swamping” other sources of conductivity (such as mineral or salt concentration), extreme levels of pH may be reliably inferred from conductivity measurements.

Conductivity measurement is definitely *not* a reliable method for measuring pH in weak (or even most strong) acid or base solutions, because the effect of pH changes on conductivity is not strong enough in these cases to overshadow the effect of other conductivity factors (such as salt concentration).

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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

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Answer 67

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Answer 68

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Answer 69

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Answer 70

Fuel gases with greater carbon content will generate greater voltage readings on the AC meter.

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Answer 71

As the mix of carrier and sample fluids travels through the column, the packing material inside the column delays the travel of some sample components, resulting in different chemical components exiting the column at different times. The basic principle of a chromatograph is that a mix of flowing chemicals becomes separated over time, allowing for individual, quantitative measurement of each chemical by a single detector device.

The column itself is usually just a long metal tube with a very small inside diameter. Sometimes the length to diameter ratio of the column tubing is enormous: take for example a packed column used for the separation of components in gasoline, with a column length of 100 meters and an inside diameter of only 250  $\mu\text{m}$  (micro-meters!).

As a side note, this spectacularly long column example comes from Raymond P.W. Scott's excellent book, *Principles and Practice of Chromatography*, available for free download on the Internet. In this particular example of chromatographic gasoline analysis, the packing material was Petrocol DH with a thickness of 0.5  $\mu\text{m}$  on the inside of the column tube wall, and the sample volume was 0.1  $\mu\text{l}$ . The complete analysis took about 100 minutes, the long time due chiefly to the long length of the column. The carrier gas was helium, and the detector was an FID (flame ionization) type. Temperature programming was used to achieve good separation of the heavier components, starting at 35° C near the beginning of the analysis and ending at 200° C. This being gas chromatography, higher temperatures mean higher gas viscosity (the very opposite temperature relation of liquid viscosity!), so the higher temperatures at the end resulted in greater retardation of the heavier gas components at the end of the run, allowing better separation.

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Answer 72

**Gas chromatography:**

Stationary phase = a solid material, and/or a liquid held stationary by a solid material, all held in a chamber known as the “column.”

Mobile phase = sample (gas) mixed with an inert gas that “carries” the sample through and past the stationary phase.

**Liquid chromatography:**

Stationary phase = a solid material, and/or a liquid held stationary by a solid material, all held in a chamber known as the “column.”

Mobile phase = sample (liquid) mixed with an inert liquid that “carries” the sample through and past the stationary phase.

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Answer 73

The injected volume for a chromatograph’s sample is determined by the internal volume of the sample loop tubing *plus* the volume of one valve slot. Thus, to exactly double the injected volume, one must increase the sample loop tube length by a factor of a little more than two.

Process chromatographs use very small sample volumes. To put things into perspective, the typical sample volume for a chromatograph is in the order of tens of *micro*-liters!

The amount of time the sample valve spends in the sampling position has no effect whatsoever on the injected sample volume *so long as it exceeds the minimum amount of time required to completely flush the sample loop and valve slot of their contained volumes*. Any time greater than this is irrelevant. If the valve spends less than this minimum amount of time in the sampling position, however, the sample loop will not get completely emptied of sample, and the injected sample volume will be less than desired.

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Answer 74

- Use a denser stationary phase in the column.
- Use a stationary phase with better adsorptivity (and/or solubility).
- Use temperature or flow “programming” to slow down the elution of that last two components to achieve better separation

- How does the rheostat adjust current equally through *both* filaments? *The rheostat adjusts current through the reference filament, which then acts as a setpoint for the measurement filament circuit.*
- How do opamp  $U_1$  and transistor  $Q_1$  work together to regulate current through the measurement filament? *Opamp  $U_1$  senses the voltage dropped by both shunt resistors and tries to keep them equal, resulting in equal current through both filaments.*
- How can we tell that opamp  $U_1$  is truly functioning in negative-feedback mode, since at first glance it looks like positive feedback with the  $R_{shunt}$  voltage signal connecting to the noninverting (+) input? *If the current through the measurement filament grows too large, the voltage drop across the right-hand  $R_{shunt}$  will exceed the voltage drop across the other shunt resistor. This will make the noninverting input less positive than the inverting input, driving the output of  $U_1$  in the negative direction. This will tend to turn  $Q_1$  off, decreasing the measurement filament's current and bringing it closer to equality with the reference filament current.*
- What is the function of opamp  $U_2$  and its four equal-value resistors? *This is a differential voltage amplifier with a voltage gain of 1 (0 dB).*
- Where would an output voltage signal be measured in this circuit? *At the output of  $U_2$ .*
- Which direction does the output voltage signal go when the measurement filament heats up to a greater temperature, assuming a positive temperature coefficient of resistance ( $\alpha$ ) for the filament metal? *Assuming identical filaments, the output voltage will be zero when both filaments are at the same temperature, and it will drive negative when the measurement filament grows hotter than the reference filament.*

Fault	Possible	Impossible
$R_1$ resistance set too low		✓
$R_1$ resistance set too high		✓
$R_2$ resistance set too low	✓	
$R_2$ resistance set too high		✓
$R_3$ resistance set too low		✓
$R_3$ resistance set too high	✓	
Reference filament burned open	✓	
Measurement filament burned open		✓
Voltmeter failed open		✓
Voltmeter failed shorted		✓

The problem is that the different compounds exiting the chromatograph column will not all ionize equally in a flame. This means the heights of the chromatogram peaks vary with component flow rate *and* with relative ionization ability.

This is a fundamental problem for all chromatographs, regardless of detector type. The solution to the problem is to “program” the gain of the detector according to what component is expected to exit the column at any given time. This by itself makes it clear why all process chromatographs are microprocessor-controlled.



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Answer 78

- What is the purpose of the vessel labeled “He”? *This is the carrier gas tank, filled with helium.*
- Do the DCS input cards supply 24 VDC loop power or not? *Most likely not, since the chromatograph has its own 120 VAC power connections, it is most likely the loop power source and not the DCS.*
- How would you connect a loop calibrator to simulate a 50% signal to AIR-43c? *Disconnect cable AIT-43c from either the chromatograph terminals or the DCS input channel terminals, then set the loop calibrator to “source” mode (not “simulate” mode!) and use it to drive 12 mA of current into the DCS channel.*
- Can you think of any way we could reduce the number of cables needed to convey the data from the chromatograph to the DCS? *Use some form of digital communication rather than analog between the chromatograph and the DCS. One option is multi-drop HART, another is FOUNDATION Fieldbus (or some other fieldbus standard such as Profibus). Another option yet is to remote-mount the DCS I/O near the chromatograph, then use the DCS network cable to bring the data to the main control room. A similar option would be to remote-mount a PLC near the chromatograph, then run a network cable from the PLC to the DCS, possibly using a “bridge” device to translate the PLC’s network protocol into a form the DCS can interpret.*

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Answer 79

Current carried by the flame is pulled through the resistor by the opamp’s negative feedback action, thus producing a measurable voltage at the output of the opamp. The more carbon in the flame, the more current, and the more voltage output by the opamp.

Since the amount of current through the flame is exceedingly small, the resistor needs to be very large in order to develop a respectable amount of voltage.

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Answer 80

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Answer 81

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

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Answer 82

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

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Answer 83

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

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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

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

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Answer 93

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