INST 251 (PID control), section 2

Lab

Split-ranged valves with pneumatic positioners: *Questions 91 and 92*, **completed objectives due by the end of day 5**

Exam

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

Specific objectives for the "mastery" exam:

- Electricity Review: Calculate voltages and currents in an ideal AC transformer circuit
- Determine the effect of a component fault or condition change in a single-loop controlled process
- Determine the effect of a component change on the gain of a pneumatic controller mechanism
- Calculate instrument input and output values given calibrated ranges
- Solve for a specified variable in an algebraic formula
- Determine the possibility of suggested faults in a simple relay circuit given measured values (voltage, current), a schematic diagram, and reported symptoms
- Motor/relay/3phase/PLC Review: Determine status of PLC discrete output given input switch conditions and a simple RLL program listing
- INST241 Review: Calculate flow rate / pressure drop for a nonlinear flow element
- INST262 Review: Determine proper AI block parameters to range a Fieldbus transmitter for a given application

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Recommended daily schedule

Day 1

Theory session topic: Differential calculus

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

Day 2

Theory session topic: Integral calculus

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

Day 3

Theory session topic: Applications of calculus

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

Day 4

Theory session topic: Review for exam

Questions 61 through 80; answer questions 61-69 in preparation for discussion

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

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Day 5

Exam

How To . . .

Access the worksheets and textbook: go to the *Socratic Instrumentation* website located at `http://www.ibiblio.org/kuphaldt/socratic/sinst` to find worksheets for every 2nd-year course section organized by quarter, as well as both the latest "stable" and "development" versions of the *Lessons In Industrial Instrumentation* textbook. 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` 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 purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here will be treated as a learning opportunity, every mistake as a "teachable moment". Every form of positive growth, not just academic ability, will be regarded as real learning.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

file `expectations`

Program Outcomes for Instrumentation and Control Technology (BTC)

#1 | Communication

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

#2 | Time management

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

#3 | Safety

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

#4 | Analysis and Diagnosis

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

#5 | Design and Commissioning

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

#6 | System optimization

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

#7 | Calibration

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

#8 | Documentation

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

#9 | Independent learning

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

#10 | Job searching

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

file `outcomes_program`

INST 251 Course Outcomes

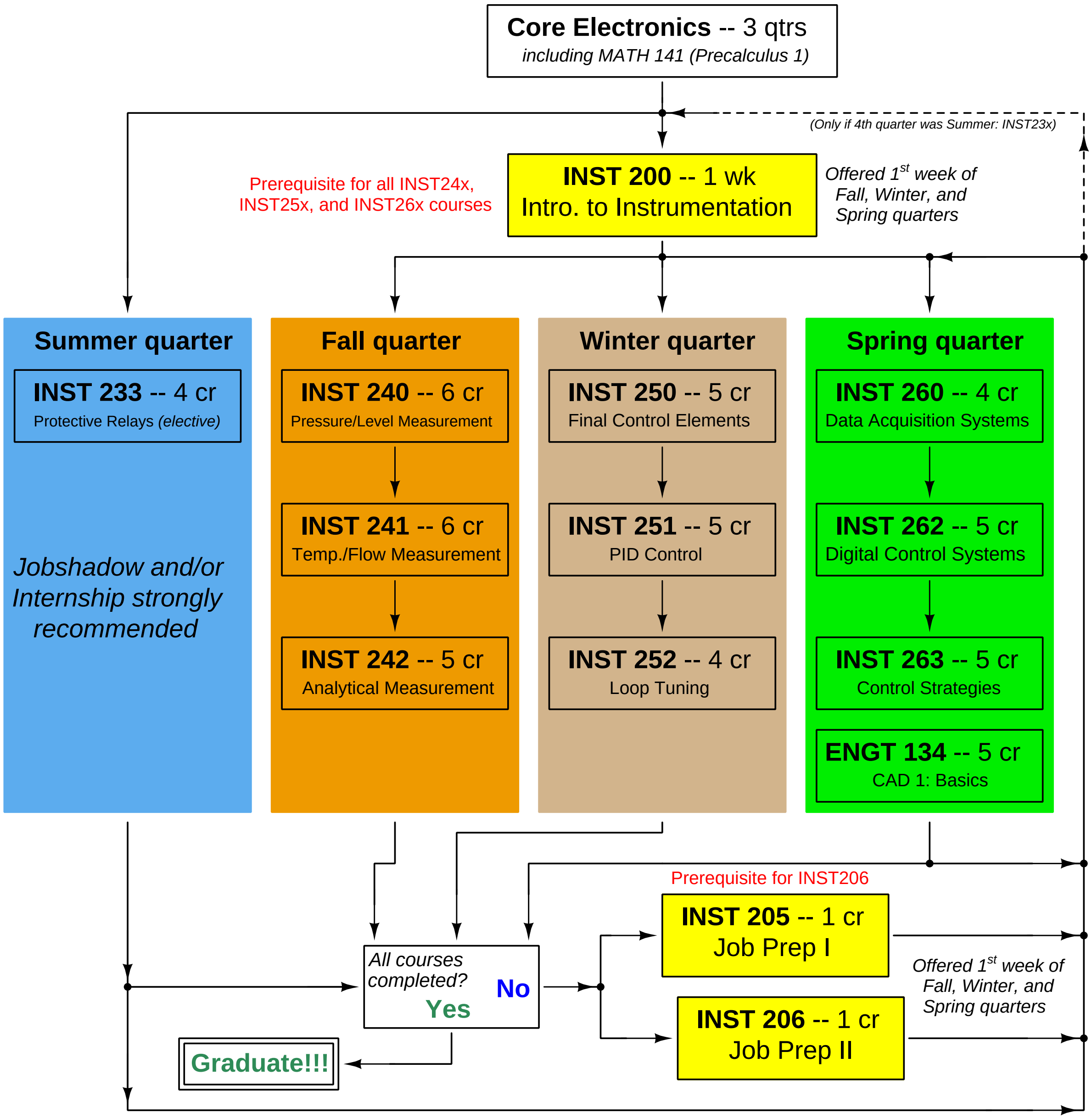
Each and every outcome in this course is assessed at a mastery level (i.e. 100% competence)

- Calculate voltages and currents in an ideal AC transformer circuit. [Ref: Program Learning Outcome #4]
- Calculate voltages, currents, and phase shifts in an AC reactive circuit. [Ref: Program Learning Outcome #4]
- Predict the response of an automatic control system to a component faults or process change, given pictorial and/or schematic illustrations. [Ref: Program Learning Outcome #4]
- Determine the effect of a component change on the gain of a pneumatic controller mechanism. [Ref: Program Learning Outcome #4]
- Compute the value of the numerical derivative at a single specified point on a graph. [Ref: Program Learning Outcome #4]
- Compute the value of the numerical integral over a specified interval on a graph. [Ref: Program Learning Outcome #4]
- Identify the response of a loop controller as being either P, I, or D based on a comparison of process variable, setpoint, and output trend graph recordings. [Ref: Program Learning Outcome #6]
- Solve for specified variables in algebraic formulae. [Ref: Program Learning Outcome #4]
- Determine the possibility of suggested faults in simple circuits given measured values (voltage, current), schematic diagrams, and reported symptoms. [Ref: Program Learning Outcome #4]
- Demonstrate proper use of safety equipment and application of safe procedures while using power tools, and working on live systems. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all lab work. [Ref: Program Learning Outcomes #1 and #2]
- Construct and commission a hand control loop using a pneumatic controller and pair of split-ranged pneumatic control valves. [Ref: Program Learning Outcome #5]
- Connect a loop controller to the electronic transmitter and final control element of a pre-constructed process, then commission all components to form a working feedback control loop. [Ref: Program Learning Outcome #5]
- Generate accurate loop diagrams compliant with ISA standards documenting your team's control systems. [Ref: Program Learning Outcome #8]
- Adjust the PID settings of your team's control loop for stable operating behavior. [Ref: Program Learning Outcome #6]
- Wire and program a VFD (Variable Frequency motor Drive) for remote starting and stopping of an AC induction motor using pushbutton switches, measuring motor line current with a clamp-on ammeter. [Ref: Program Learning Outcome #5]
- Research equipment manuals to sketch a complete circuit connecting a loop controller to either a 4-20 mA transmitter or a 4-20 mA final control element, with all DC voltages and currents correctly

annotated, all electrical sources and loads properly identified, given components randomly selected by the instructor. [Ref: Program Learning Outcomes #5 and #9]

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

file `outcomes_INST251`


Core Electronics -- 3 qtrs
including MATH 141 (Precalculus 1)
(Only if 4th quarter was Summer: INST23x)
Prerequisite for all INST24x, INST25x, and INST26x courses
INST 200 -- 1 wk
Intro. to Instrumentation
Offered 1st week of Fall, Winter, and Spring quarters
Summer quarter
INST 233 -- 4 cr
Protective Relays (elective)
Jobshadow and/or Internship strongly recommended
Fall quarter
INST 240 -- 6 cr
Pressure/Level Measurement
INST 241 -- 6 cr
Temp./Flow Measurement
INST 242 -- 5 cr
Analytical Measurement
Winter quarter
INST 250 -- 5 cr
Final Control Elements
INST 251 -- 5 cr
PID Control
INST 252 -- 4 cr
Loop Tuning
Spring quarter
INST 260 -- 4 cr
Data Acquisition Systems
INST 262 -- 5 cr
Digital Control Systems
INST 263 -- 5 cr
Control Strategies
ENGT 134 -- 5 cr
CAD 1: Basics
Prerequisite for INST206
INST 205 -- 1 cr
Job Prep I
INST 206 -- 1 cr
Job Prep II
Offered 1st week of Fall, Winter, and Spring quarters
All courses completed?
No
Yes
Graduate!!!

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

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

file sequence

General tool and supply list

Wrenches

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

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

Pliers

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

Screwdrivers

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

Electrical

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

Safety

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

Miscellaneous

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

file `tools`

Methods of instruction

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

Inverted theory sessions

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

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

Small sessions

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

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

Large sessions

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

Correspondence

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

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

Sample rubric for pre-assessments

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

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

Sample rubric for post-assessments

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

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

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

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.

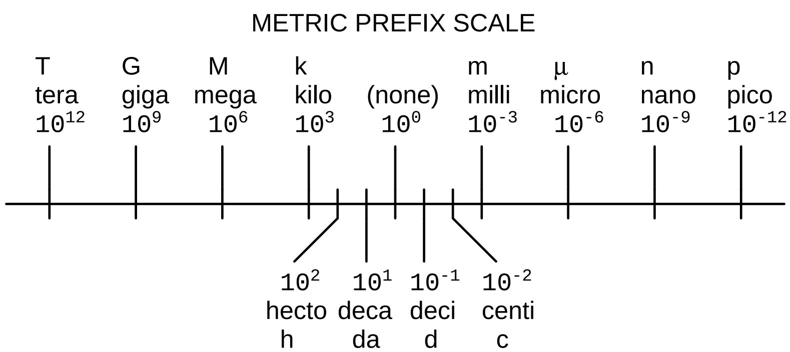
Labwork is perhaps the most difficult portion of the curriculum for a "distance" student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. "Distance" students must find a way to complete the required lab activities, either 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.

file `distance`

Metric prefixes and conversion constants

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



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

Conversion equivalencies for distance

1 inch (in) = 2.540000 centimeter (cm)

1 foot (ft) = 12 inches (in)

1 yard (yd) = 3 feet (ft)

1 mile (mi) = 5280 feet (ft)

Conversion equivalencies for volume

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

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

Conversion equivalencies for velocity

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

Conversion equivalencies for mass

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

Conversion equivalencies for force

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

Conversion equivalencies for area

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

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

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

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

Conversion equivalencies for absolute pressure units (only)

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

Conversion equivalencies for energy or work

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

Conversion equivalencies for power

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

Acceleration of gravity (free fall), Earth standard

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

Physical constants

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

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

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

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

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

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

Properties of Water

Freezing point at sea level = 32^{o}F = 0^{o}C

Boiling point at sea level = 212^{o}F = 100^{o}C

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

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

Specific heat of ice ≈ 0.5 calories/g·^{o}C

Specific heat of steam ≈ 0.48 calories/g·^{o}C

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

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

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

Properties of Dry Air at sea level

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

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

Question 0

How to get the most out of academic reading:

- Outline, don't highlight! Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.
- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.
- 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.
- Create your own questions based on what you read, as a teacher would to challenge students.

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 step 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). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.
- Check for exceptions – does your solution work for *all* conditions and criteria?
- 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, every single day.
- Consider the place you're in when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).
- Eliminate distractions. Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.
- 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, as this is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

file `question0`

Checklist when reading an instructional text

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

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

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

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

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

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

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

$\boxed{\surd}$ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

General challenges following a tutorial reading assignment

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

General follow-up challenges for assigned problems

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

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file `license`

Question 1

Read and outline the "Introduction to Calculus" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04270

Question 2

Read and outline Chapter 1 of the book *Calculus Made Easy* by Sylvanus P. Thompson, titled "To Deliver You From The Preliminary Terrors". Don't worry – it is a very short reading assignment!

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

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

file i04271

Question 3

Read and outline the "The Concept of Differentiation" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04272

Question 4

A bored child is traveling in a car with his parents, and decides to pass the time by writing mileage values displayed by the odometer at different times, and then noting those times next to the distances:

Odometer reading (miles)	Time (hour:minute)
60,344.1	2:14
60,346.3	2:17
60,347.1	2:18
60,351.7	2:25
60,353.9	2:27
60,357.4	2:30
60,359.5	2:35

Calculate the average speed of the car between the following times:

- Between 2:17 and 2:18, average speed = ________ MPH
- Between 2:18 and 2:25, average speed = ________ MPH
- Between 2:25 and 2:27, average speed = ________ MPH
- Between 2:17 and 2:27, average speed = ________ MPH

Then, compare the average speeds taken in the first three intervals with the average speed over the sum of those intervals (2:17 to 2:27). What does this tell us about the calculation of speed based on distance and time measurements?

Suggestions for Socratic discussion

- In parts of the country with *toll booths*, you can get a speeding ticket automatically issued to you based on the time it took you to drive from one toll station to another. Explain how this works, and if there is any way to "beat the system" (i.e. speed without getting a time-based speeding ticket).
- If we were to plot the odometer and time data on a graph, where would this plot be the steepest? What, exactly, would the steepness (or pitch) of the graph imply?
- If the bored child had recorded odometer readings more often (i.e. over shorter intervals of time), would it affect our speed calculations? Why or why not?
- Identify the arithmetic operations needed to compute rates of change, such as speed.
- This sort of repetitive calculation lends itself well to a programmable calculator, or to a *spreadsheet* program running on a personal computer. If you have some familiarity with spreadsheets, try building one to calculate average speeds given this table of distance values!

file i01502

Question 5

A bored operator is filling a large tank with water from different sources, the flow rates from those sources being variable over time. He decides to pass the time by writing water volume values displayed by the level indicator (calibrated in gallons) at different times, and then noting those times next to the volumes:

Level indicator (gallons)	Time (hour:minute)
120.7	9:17
1005.4	9:21
1377.8	9:23
2050.2	9:26
2944.6	9:30
4875.1	9:40
5101.8	9:45

Calculate the average flow rate of water into the tank between the following times:

- Between 9:17 and 9:21, average flow = __________ GPM
- Between 9:21 and 9:23, average flow = __________ GPM
- Between 9:23 and 9:26, average flow = __________ GPM
- Between 9:17 and 9:26, average flow = __________ GPM

Then, compare the average flow rates taken in the first three intervals with the average flow rate over the sum of those intervals (9:17 to 9:26). What does this tell us about the calculation of water flow based on volume and time measurements?

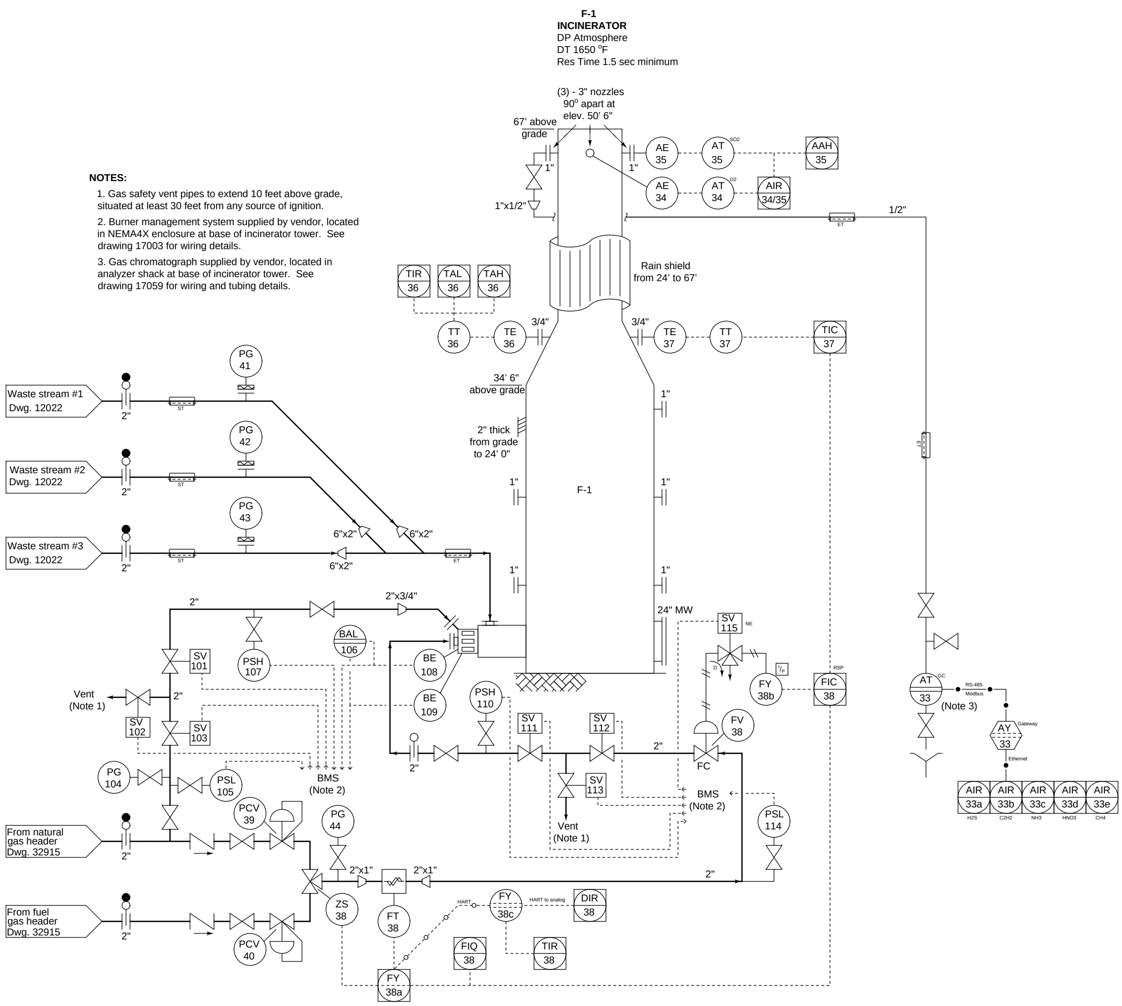
Suggestions for Socratic discussion

- Identify the arithmetic operations needed to compute rates of change, such as flow.
- If the bored operator had recorded level readings more often (i.e. over shorter intervals of time), would it affect our flow calculations? Why or why not?
- Suppose the operator's tank indication were expressed in *kilograms* of water mass rather than *gallons* of water volume. How would this change affect our computations (if at all)?
- Identify how this table of level readings would be affected if the tank developed a leak at 9:26.
- This sort of repetitive calculation lends itself well to a programmable calculator, or to a *spreadsheet* program running on a personal computer. If you have some familiarity with spreadsheets, try building one to calculate average flow rate given this table of volume values!

file i01503

Question 6

After the interior of this incinerator vessel is lined with brand-new refractory brick, it must be heated slowly to full temperature. This slow heating process is called *curing*. If heated too quickly, the steam pressure from the internal moisture in the brick cause the bricks to fracture or even explode. The most important limit to observe in the initial act of curing the new refractory brick is not maximum temperature, but rather maximum temperature *rate*.



If you were to observe the graph plotted by trend recorder TIR-36, what feature(s) of the graph would indicate to you the *rate* of temperature rise? Be as specific as you can in your answer, giving a numerical example if possible. Also, determine the unit of measurement for a temperature rate-of-change.

Also, identify the ISA tag letter used to represent an instrument measuring or acting upon the *rate-of-change* of some variable, and where you might install such an instrument in this system to help operations personnel monitor incinerator temperature rate.

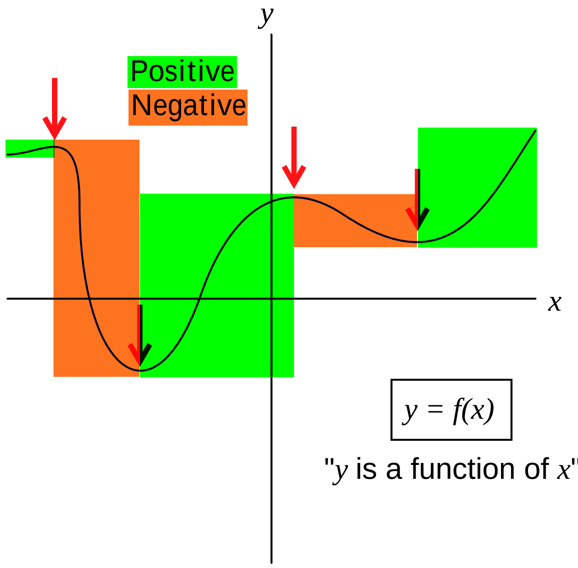
Suggestions for Socratic discussion

- Describe how one would program a control system such as a DCS to calculate *rate* of temperature change to warn personnel working near the furnace if this rate becomes excessive. Specifically, what mathematical steps must the control system do in order to calculate a rate-of-change value from successive temperature measurement values?

file i01507

Question 7

Define what "derivative" means when applied to the graph of a function. For instance, examine this graph:



Label all the points where the derivative of the function ($\frac{dy}{dx}$) is positive, where it is negative, and where it is equal to zero.

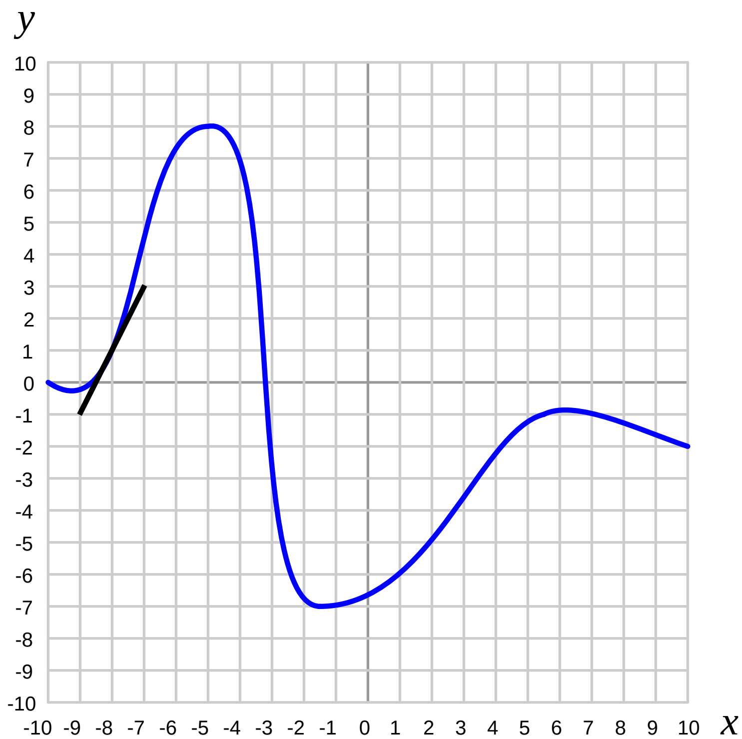
Suggestions for Socratic discussion

- Articulate a set of simple rules for determining whether a point on a curve has a derivative that is positive, negative, or zero. These rules should be simple enough for a child to comprehend and apply!
- Sometimes the slope of a curved function at any given point is graphically shown by something called a *tangent line*. Research what a "tangent line" is, and then draw tangent lines on this function to demonstrate the slope at some specified points.

file i01509

Question 8

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = -8$:



Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

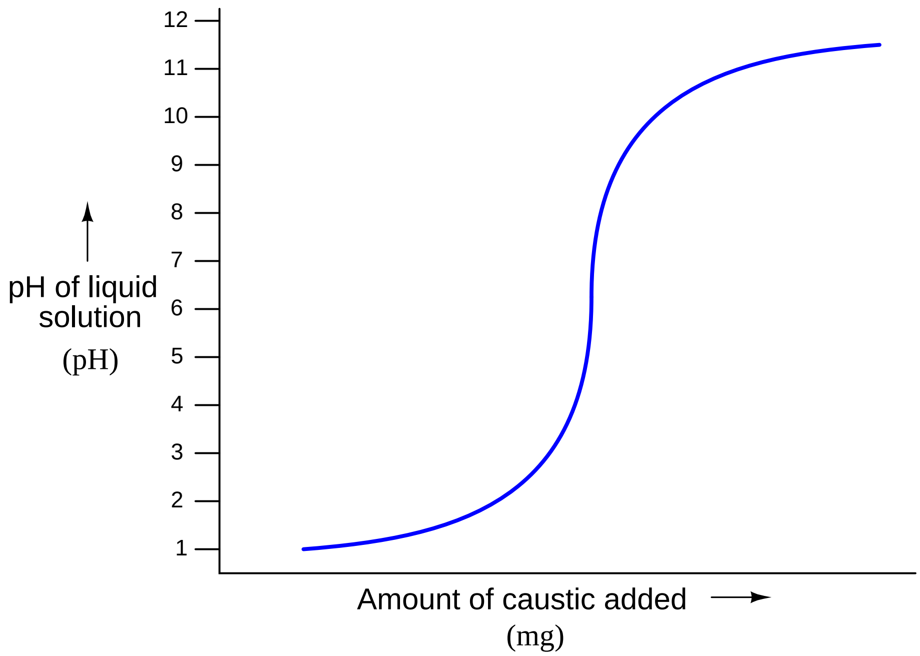
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of differentiation in your own words, as it applies to this particular problem.
- Sometimes the slope of a curved function at any given point is graphically shown by something called a *tangent line*. Research what a "tangent line" is, and then draw a tangent line on this function at the point where $x = -8$.

file i04369

Question 9

The *pH value* of an aqueous (water-based) solution can be a challenging process variable to control. When a caustic substance (high pH) is added to an acidic solution (low pH), the pH value of that solution will rise accordingly, but it often rises in a very non-linear way. If we are adding a strongly concentrated caustic to a strongly concentrated acid, what we initially see is a mild increase in pH, followed by a very rapid rise in pH, followed by another mild increase. This is called a *titration curve*, an example shown in this graph:



First, identify how the calculus concept of the *derivative* applies to a titration curve (i.e. what does "derivative" mean in this context?) and how you would write a mathematically-correct expression for this derivative. Next, identify where on this titration curve it will be "easiest" for an automatic control system to regulate the pH value of the liquid solution, and where it will be the most challenging (and also why!).

Suggestions for Socratic discussion

- A relevant concept to consider in this scenario is the idea of *process gain*: how responsive a process variable (i.e. the solution's pH value in this case) is to changes in the manipulated variable (i.e. the amount of caustic material the control system adds to the solution). Where along the titration curve is the process gain greatest? Where is the process gain minimal?
- How do you think the gain of a proportional loop controller should be set in relation to the gain of the process it is tasked with controlling? For example, if we wished to control pH at a point on the titration curve where the process gain is very high, should the controller be "tuned" with a high amount of gain or a low amount of gain? Why?

file i01695

Question 10

Read and outline Chapter 3 of the book *Calculus Made Easy* by Sylvanus P. Thompson, titled "On Relative Growings".

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

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

file i04273

Question 11

In areas of the United States where toll booths are used to monitor passenger vehicle travel, you can get a speeding ticket if your travel time between two toll booths is too short. Explain how this method of ticketing speeders is valid even if the exact speed of the vehicle at any specific time is unknown between toll booths. Also, explain how it is possible to exceed the speed limit between toll booths *without* getting ticketed based on elapsed time between tolls.

file i01505

Question 12

One of the first, and most fundamental, concepts you learn in calculus is something called the *derivative*. A "derivative" is an expression of the *rate of change* of two related variables, one of those variables often (but not always!) being *time*.

An example that everyone can relate to is *position* versus *speed* for an object. Speed, we say, is the *derivative* of position with respect to time. Using v to represent an object's speed, x to represent an object's position, and t to represent time, we may write express this calculus relationship as such:

$$v = \frac{dx}{dt}$$

In the following list of variables, determine which is the derivative of which, and express each relationship in the same form that you see here for speed, position, and time (one variable equal to a quotient of differentials).

- Mass of radioactive substance (m), decay rate (r), and time (t)
- Liquid volume (V), liquid flow (Q), and time (t)
- Speed (v), acceleration (a), and time (t)
- Work (W), power (P), and time (t)
- Voltage (V), current (I), and incremental resistance (R)
- Magnetizing force (H), magnetic flux density (B), and permeability (μ)
- Cost (C) to manufacture items, number of items (x), and marginal cost (C')

Note: for each of these, it may help to sketch a graph showing how two of the three variables normally relate to each other.

file i01510

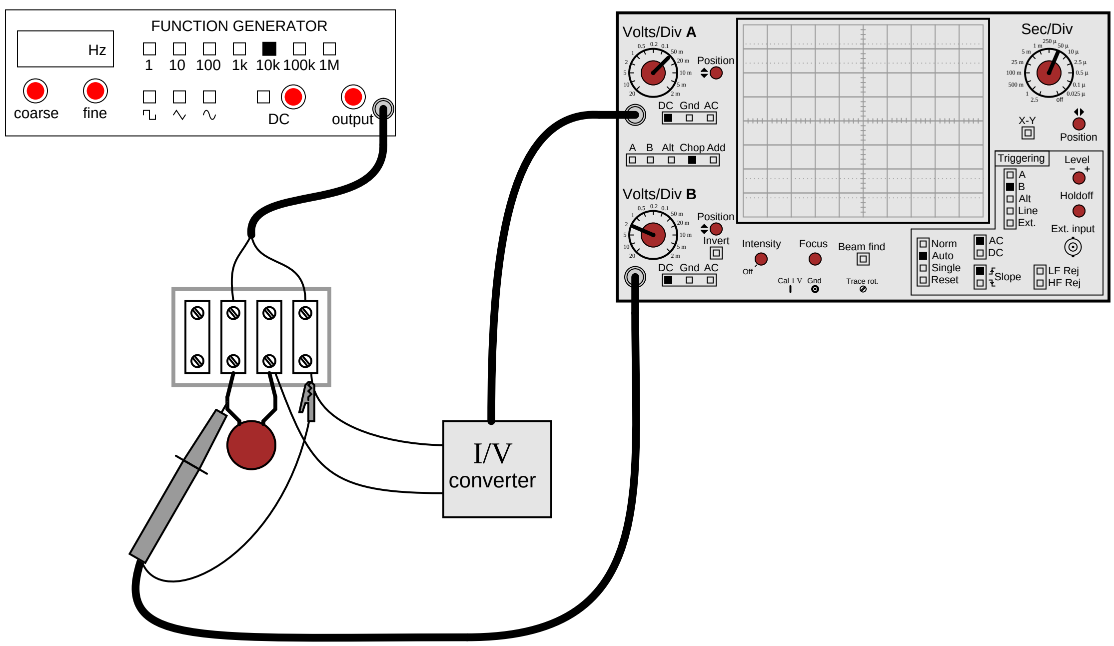
Question 13

According to the "Ohm's Law" formula for a capacitor, capacitor current is proportional to the *time-derivative* of capacitor voltage:

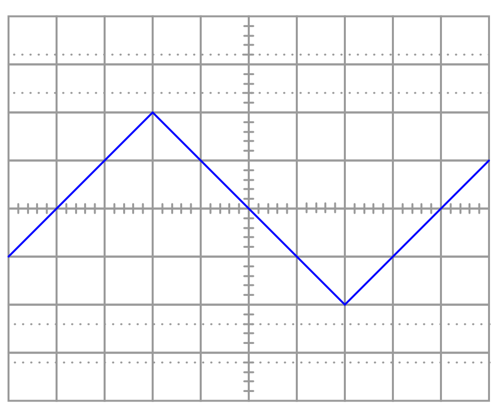
$$i = C\frac{dv}{dt}$$

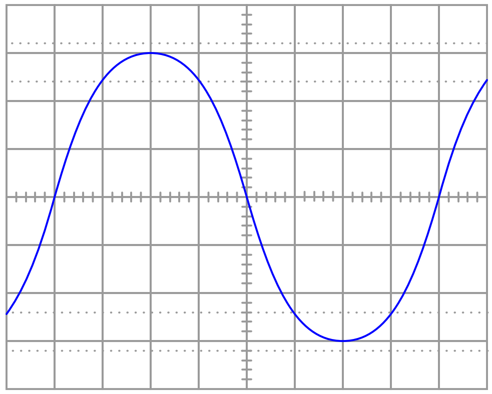
Another way of saying this is to state that the capacitors *differentiate* voltage with respect to time, and express this *time-derivative* of voltage as a current. Thus, the amount of current "through" a capacitor is an expression of how fast the voltage *changes* over time.

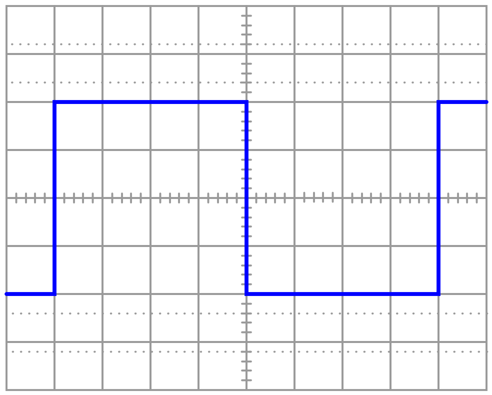
Suppose we had an oscilloscope capable of directly measuring current, or at least a current-to-voltage converter that we could attach to one of the probe inputs to allow direct measurement of current on one channel. With such an instrument set-up, we could directly plot capacitor voltage and capacitor current together on the same display:



For each of the following voltage waveforms (channel B), plot the corresponding capacitor current waveform (channel A) as it would appear on the oscilloscope screen:





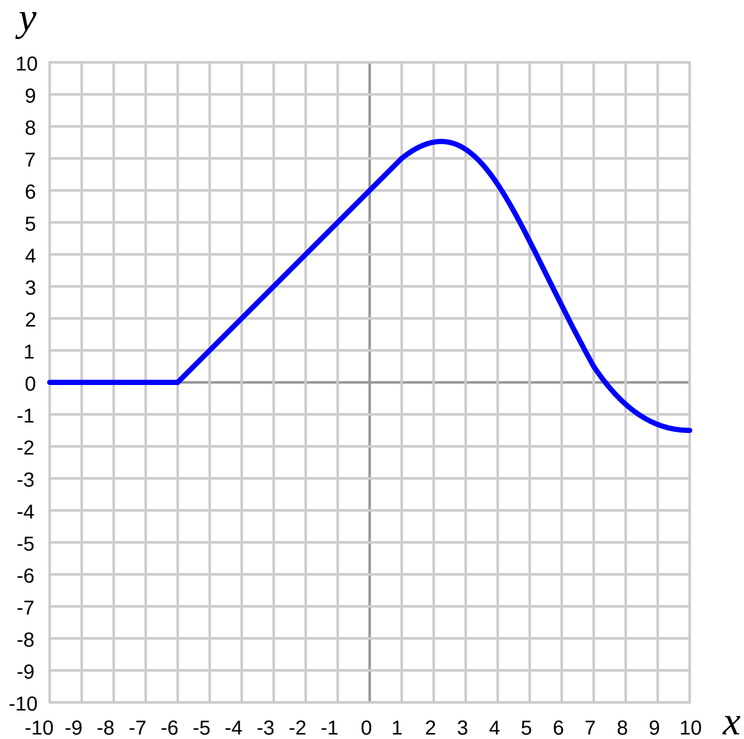


Note: the amplitude of your current plots is arbitrary, since I did not give you enough information (capacitor size, etc.) to actually *calculate* current through the capacitor at any given time. What I'm interested in here is the *shape* of each current waveform, as it compares to the *shape* of the voltage waveform.

file i01512

Question 14

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 5$:



Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

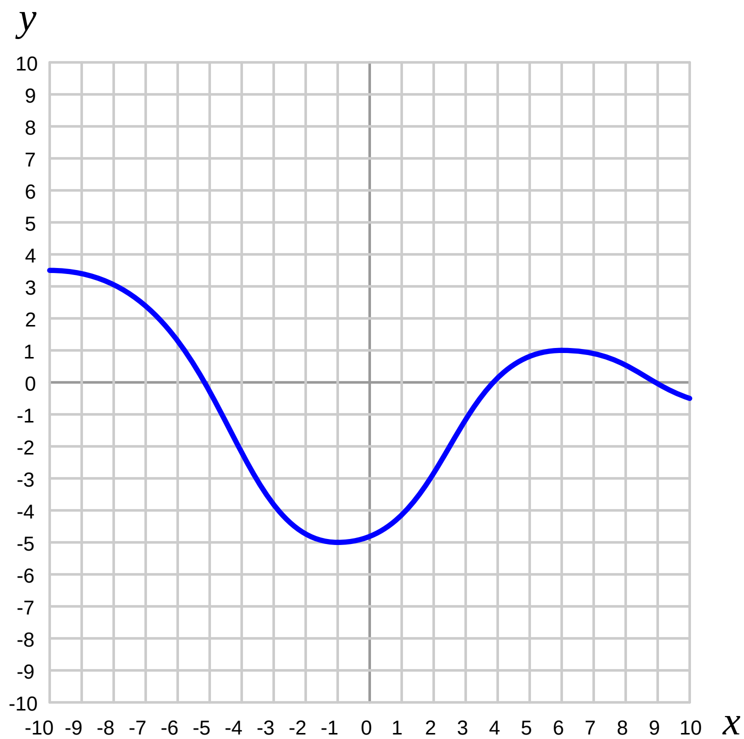
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of differentiation in your own words, as it applies to this particular problem.

file i04379

Question 15

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 6$:



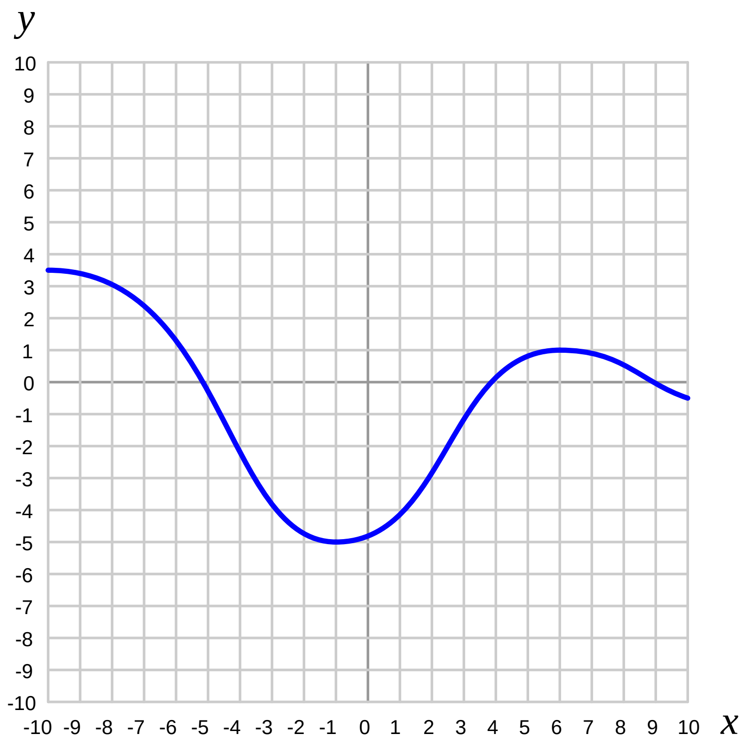
Choose the closest answer:

- $\frac{dy}{dx} = +3$
- $\frac{dy}{dx} = -3$
- $\frac{dy}{dx} = -9$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = 0$
- $\frac{dy}{dx} = +1$

file i04365

Question 16

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 2.5$:



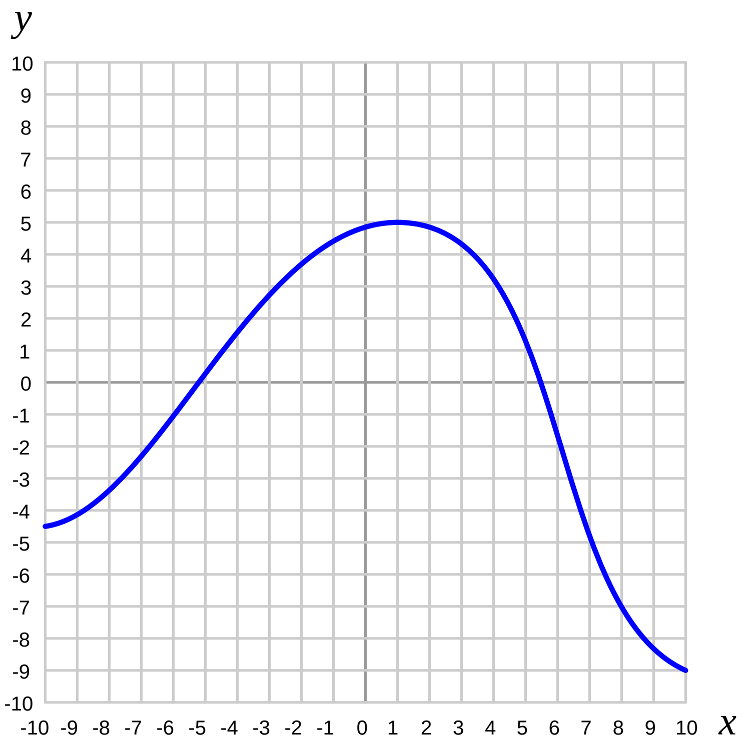
Choose the closest answer:

- $\frac{dy}{dx} = +3$
- $\frac{dy}{dx} = -3$
- $\frac{dy}{dx} = -9$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = 0$
- $\frac{dy}{dx} = +1$

file i04366

Question 17

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 3$:



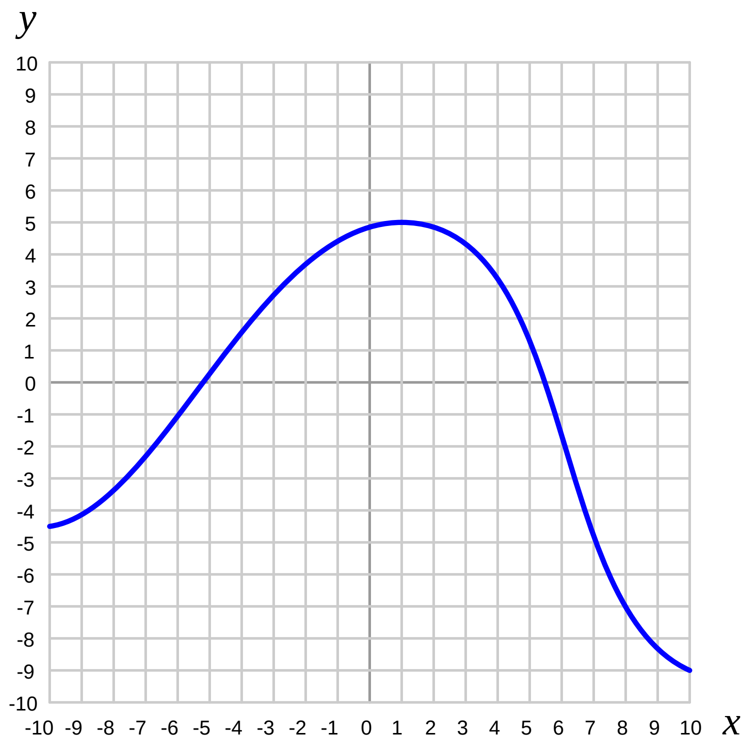
Choose the closest answer:

- $\frac{dy}{dx} = +2.4$
- $\frac{dy}{dx} = -3.3$
- $\frac{dy}{dx} = -10$
- $\frac{dy}{dx} = -0.7$
- $\frac{dy}{dx} = +10.4$
- $\frac{dy}{dx} = 0$
- $\frac{dy}{dx} = +1$

file i04363

Question 18

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = -8$:



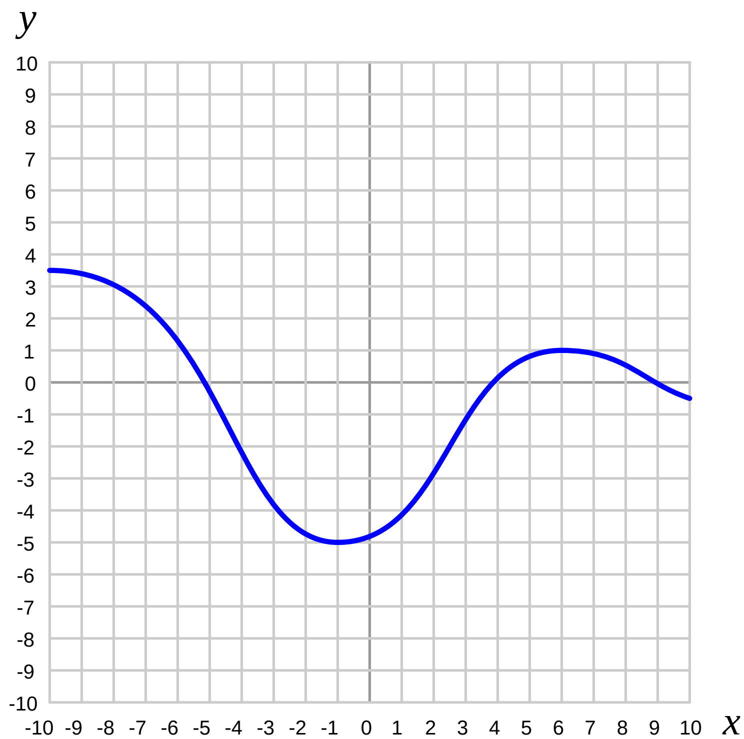
Choose the closest answer:

- $\frac{dy}{dx} = +2.4$
- $\frac{dy}{dx} = -3.3$
- $\frac{dy}{dx} = -10$
- $\frac{dy}{dx} = -0.7$
- $\frac{dy}{dx} = +10.4$
- $\frac{dy}{dx} = 0$
- $\frac{dy}{dx} = +1$

file i04364

Question 19

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = -7$:



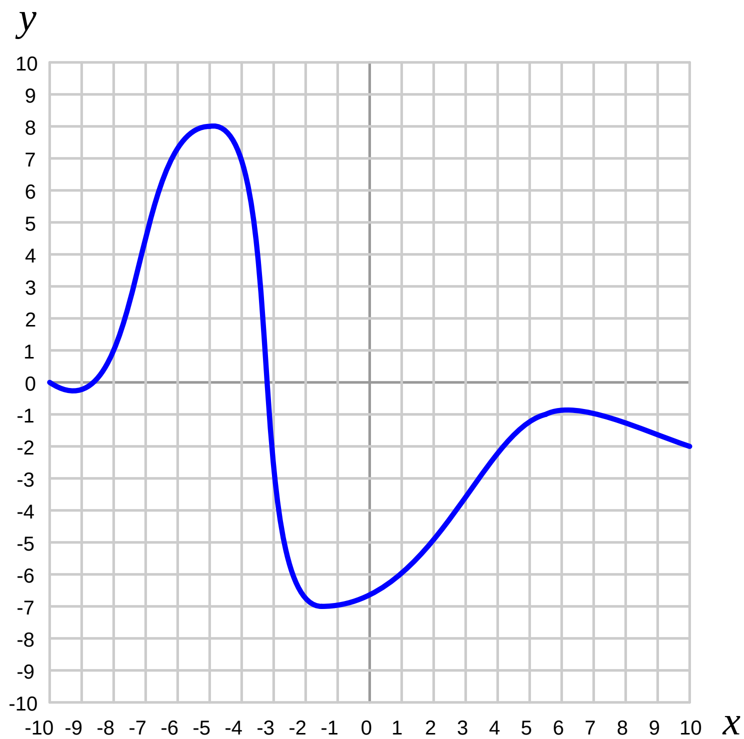
Choose the closest answer:

- $\frac{dy}{dx} = +3$
- $\frac{dy}{dx} = -3$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = 0$
- $\frac{dy}{dx} = +1$

file i04367

Question 20

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 1$:



Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

file i04368

Question 21

Read and outline the "The Concept of Integration" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04274

Question 22

A bored child is traveling in a car with his parents, and decides to pass the time by writing speed values displayed by the speedometer at different times, and then noting those times next to the distances:

Speedometer reading (miles/hour)	Time (hour:minute)
55	2:14
57	2:17
60	2:18
61	2:25
58	2:27
55	2:30
60	2:35

Describe how you may calculate the distance traveled by this car between 2:14 and 2:35 based on speed values from this table.

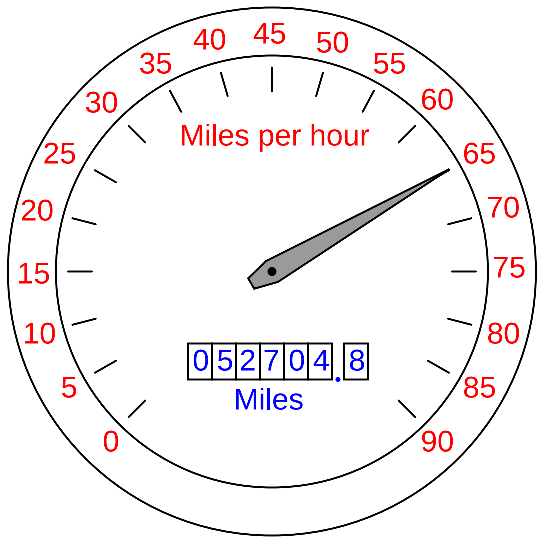
Suggestions for Socratic discussion

- This sort of repetitive calculation lends itself well to a programmable calculator, or to a *spreadsheet* program running on a personal computer. If you have some familiarity with spreadsheets, try building one to calculate distance traveled given this table of speeds!
- If the bored child had recorded speedometer readings more often (i.e. over shorter intervals of time), would it affect our distance calculations? Why or why not?
- Identify more than one way to calculate distance traveled from the speed and time values given.

file i01570

Question 23

Calculus is believed to be inscrutable by many people. Yet, anyone who has ever driven a car has an intuitive grasp of calculus' most basic concepts: *differentiation* and *integration*. These two complementary operations may be seen at work on the instrument panel of every automobile:



On this one instrument, two measurements are given: speed in miles per hour, and distance traveled in miles. In areas where metric units are used, the units would be kilometers per hour and kilometers, respectively. Regardless of units, the two variables of speed and distance are related to each other over time by the calculus operations of integration and differentiation. My question for you is, *which operation goes which way?*

We know that speed is the rate of change of distance over time. This much is apparent simply by examining the units (miles *per hour* indicates a rate of change over time). Of these two variables, speed and distance, which is the *derivative* of the other, and which is the *integral* of the other? Also, determine what happens to the value of each one as the other maintains a constant (non-zero) value.

Suggestions for Socratic discussion

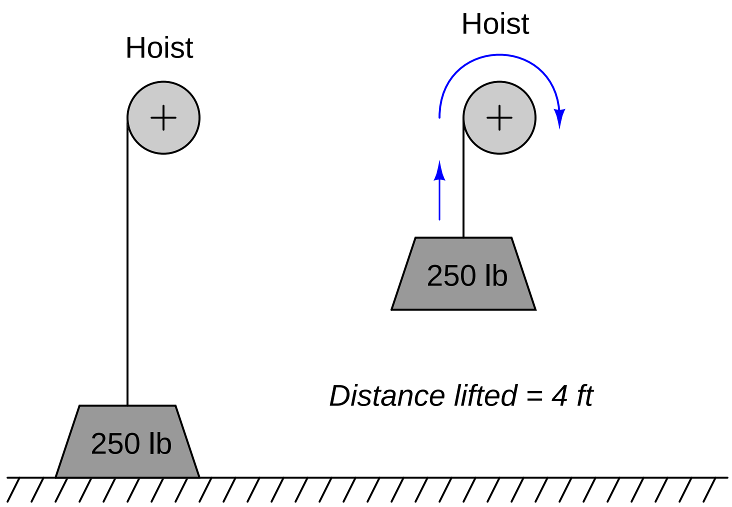
- The relationship of speed to distance traveled, as recorded by a speedometer/odometer, lends itself well to exploration through *thought experiments*. Try using a thought experiment to explain the operation of an odometer in terms simple enough for someone who has never seen an odometer before to understand (a child, perhaps). What does the odometer do when the automobile is traveling along at a constant speed? What changes when the automobile's speed increases or decreases? How does the speedometer needle position on the scale relate to the odometer's digits over time?
- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.

file i01560

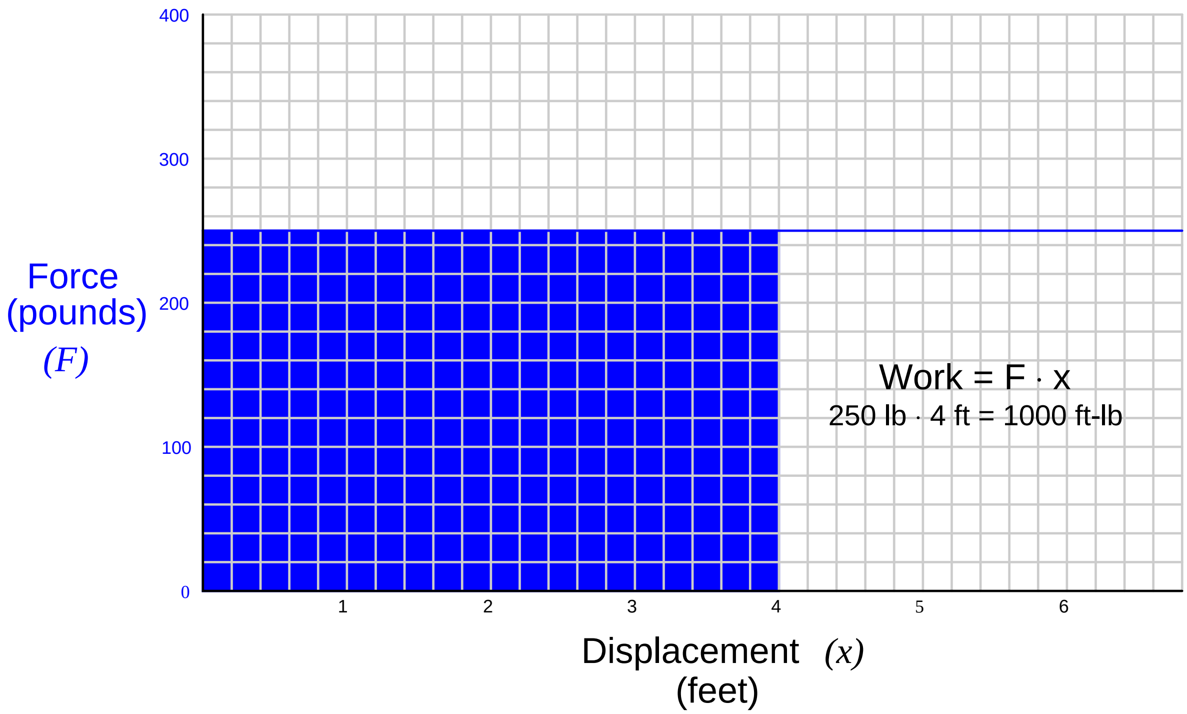
Question 24

In the study of physics we find sets of variables related to one another by differentiation and integration *with respect to time*. Position, velocity, and acceleration are one such set. Voltage and current in reactive circuits is another set. Such examples are often given to illustrate differentiation and integration, because most people find it easier to grasp these complex operations in a familiar context. However, exploring these common relationships makes it easy for new students of calculus to think that differentiation and integration must always have something to do with time, when they in fact this is not necessarily true.

Here is a non-time-related application of integration that is relatively easy to understand and apply: the physics concept of *work*. "Work" is the gainful expenditure of energy, calculated in physical terms by the magnitude of applied force multiplied by the displacement (travel) in the direction of that force ($W = Fx$). For example, lifting a 250 pound weight 4 feet off the ground constitutes 1000 foot-pounds of work:



If we graph force and distance to obtain a geometric understanding of work, we see that the multiplication of force and distance may be interpreted as the *area* bounded by the graph:



Lifting this weight higher does not change the force required, but it does change the distance, leading to a new calculation of work (a greater area bounded on the graph).

Express work (W) as a calculus equation, in terms of the variables force (F) and displacement (x). Specifically, express the work calculation for this particular weight-lifting problem.

Suggestions for Socratic discussion

- Is the hoist in this problem functioning as an energy *source* or an energy *load*? How can you tell based on directions of force and displacement vectors?
- How could you use calculus notation to express the energy *released* as the weight is lowered from a height of 4 feet back down to ground level? Calculate this energy quantity.
- How could you use calculus notation to express the energy required to hoist the weight from a height of 2 feet up to a height of 4 feet? Calculate this energy quantity.
- Identify the mathematical sign (positive or negative) of force (F), differentials of distance (dx), and work (W) while the weight is being *lifted* by the hoist.
- Identify the mathematical sign (positive or negative) of force (F), differentials of distance (dx), and work (W) while the weight is being *lowered* by the hoist.
- Modern electric elevators use motors powered via VFDs (Variable Frequency Drives) to precise control the starting, stopping, and speed of the motor for smooth elevator positioning. Large VFDs provide a very useful feature called *regenerative braking* which makes the motor act as a generator when the elevator descends. Explain why regenerative braking is a useful feature for elevator control. Is it possible to build an electrically-powered elevator without this feature?
- Compare the amount of energy required to hoist this load 4 feet upwards in 10 seconds, versus the amount of energy required to hoist the load the same distance (4 feet) in half the time (5 seconds). Explain your analysis of the two energy quantities.

- Define *power* as it applies to this scenario, and identify the appropriate calculus function (i.e. either differentiation or integration) for calculating power given the variables available to us.

  <u>file i01574</u>

Question 25

Energy is required to compress or stretch a mechanical spring, because there is a force exerted over a parallel distance. Calculating the work done in compressing or stretching a spring is more complicated than calculating work done when lifting a weight, because the force (F) is not constant. Most springs exhibit a linear relationship between force and displacement (distance compressed or stretched) over short distances which is known as *Hooke's Law*:

$$F = kx$$

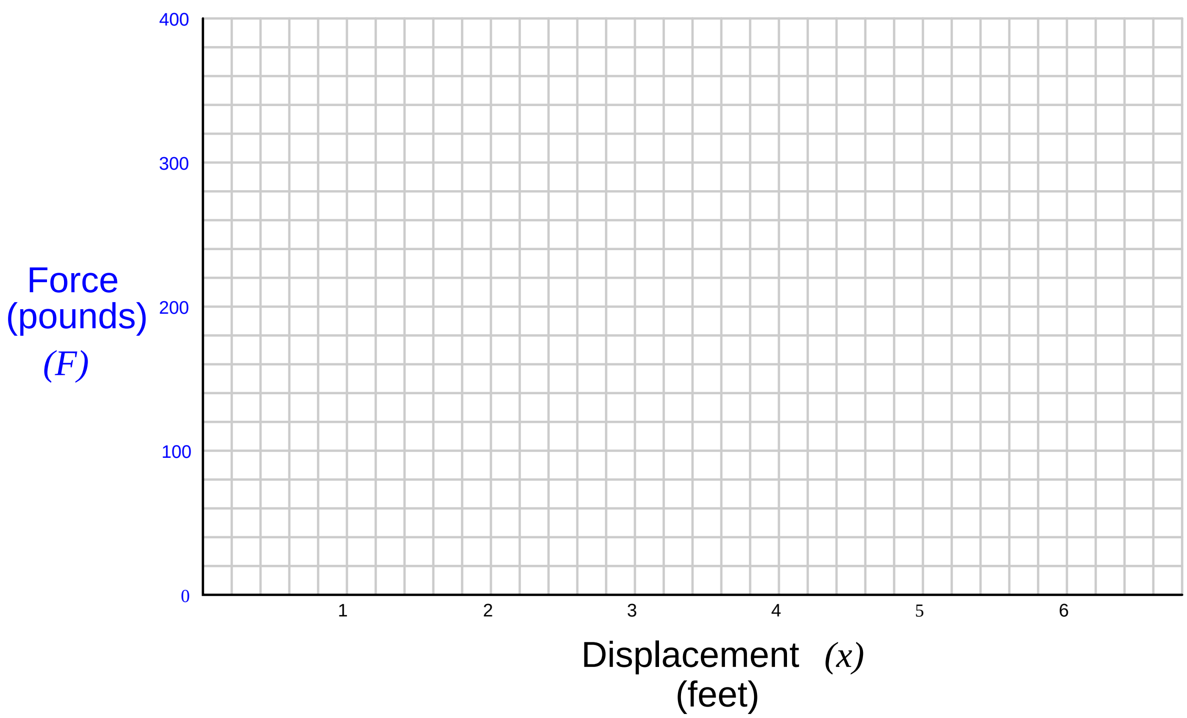
Where,

F = Force required to compress or stretch a spring by x amount, in pounds (lb), or Newtons (N)
x = Distance that the spring is compressed or stretched, in feet (ft), or meters (m)
k = Constant of the spring, in pounds per foot (lb/ft), or Newtons per meter (N/m)

Spring-operated weight scales exploit this principle of linearity: doubling the weight applied to a spring scale doubles the motion of the needle as it registers weight on a linear scale.

To calculate the amount of *work* done in compressing or stretching a spring, we must somehow account for the fact that force is *not* constant as the spring deforms. Here, graphing force versus displacement is a helpful tool for calculating work.

Graph the force required to compress a spring with a constant (k) of 60 pounds per foot, then calculate the amount of work required to compress that spring by 3 feet:



Suggestions for Socratic discussion

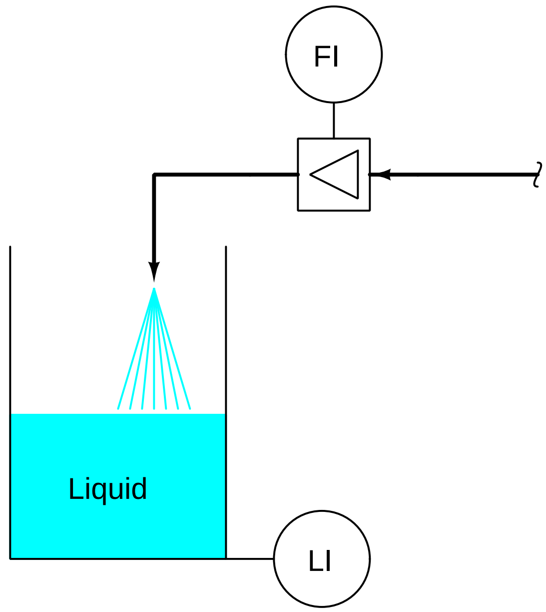
- At which end of the spring's motion (0 feet of stretch, or 3 feet of stretch) does the spring store the most energy *per inch* of additional stretch?
- If you were to plot a graph of stored energy per inch of spring motion, what shape would that graph exhibit?

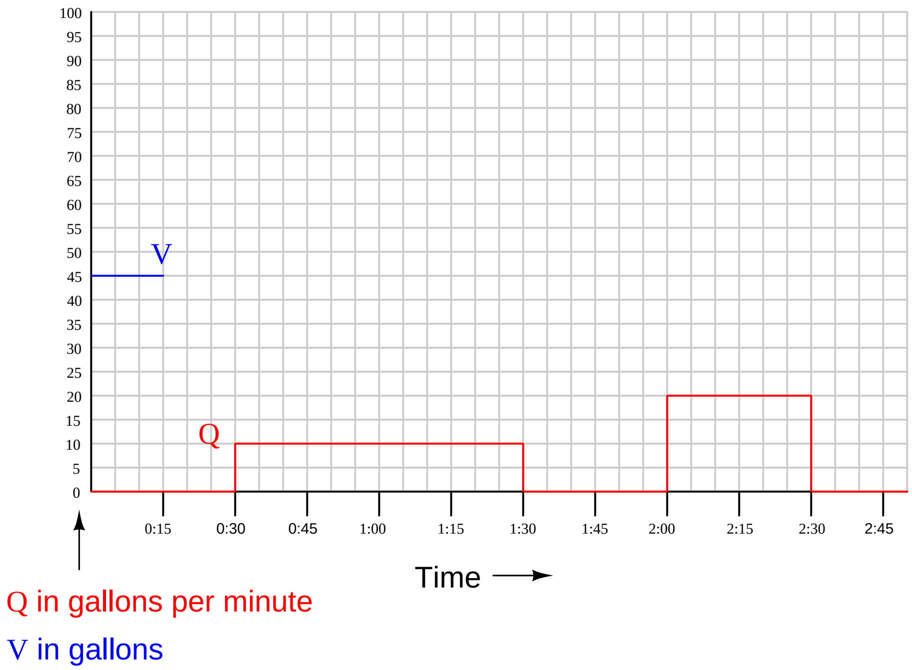
- Identify the mathematical sign (positive or negative) of force (F), differentials of distance (dx), and work (W) while the spring is being *loaded* by an external force.
- Identify the mathematical sign (positive or negative) of force (F), differentials of distance (dx), and work (W) while the spring is being *unloaded* towards its relaxed state.
- Suppose this spring resided inside of an air-to-open pneumatic control valve. If the control loop is oscillating – thus making the valve's stem move up and down periodically – what does the calculated work of spring compression represent in terms of compressed air consumption? Would this quantity of work be significant in any way to us, or is it academic?
- Suppose an air-to-open pneumatic control valve is cycling $\pm 10\%$ near the fully-shut position. Now suppose that same valve is cycling $\pm 10\%$ near the fully-open position. In which condition does the control valve consume the greatest rate of compressed air? Explain why.

file i01575

Question 26

Given the liquid flowmeter and storage vessel shown here, determine the accumulated volume in the vessel at the following times, for the flow rates shown on the graph:





As indicated on the graph, the vessel holds 45 gallons of liquid at time = 0:00. Note that the unit of time for the graph's horizontal axis is minutes:seconds, not hours:minutes.

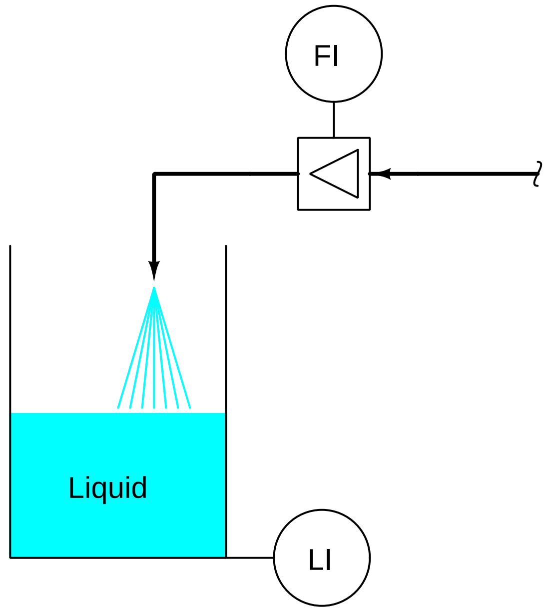
Suggestions for Socratic discussion

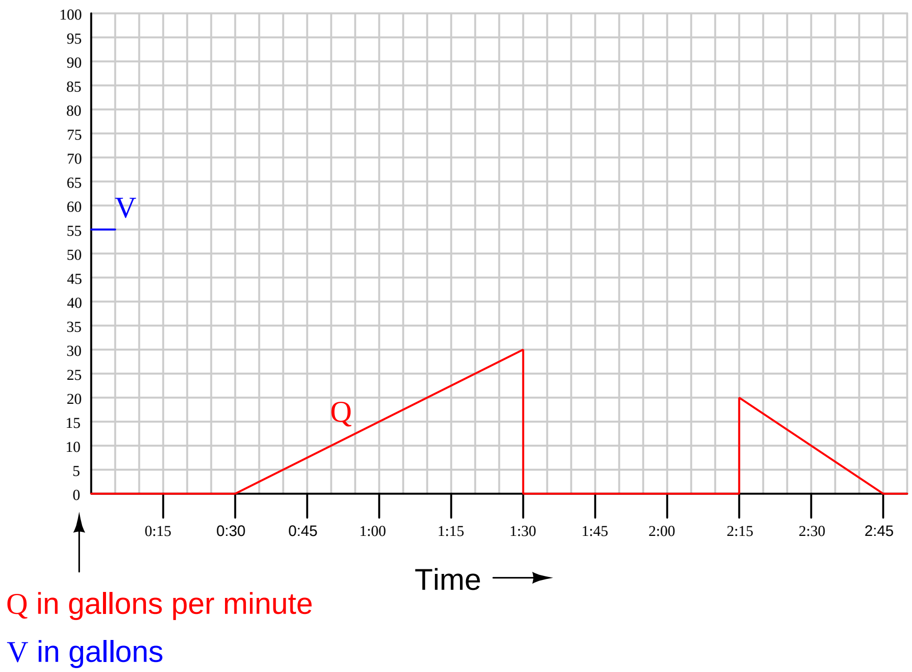
- If you were standing in view of the pipe discharging water into this vessel, what would the liquid flow rate shown by the graph *look* like? Would the flow vary over time, or would it remain steady? Would it start and stop, or be continuous?
- Suppose you were given a graph of water volume in the tank, and asked to calculate flow rate in or out of the tank. What principle of calculus would you apply to solve this problem?
- Suppose the flow rate (Q) shown on the graph represented flow *out* of the tank rather than flow *in* to the tank. How would this difference affect the shape of the V graph?
- A tank being filled with water is analogous to an electrical capacitor being "filled" with charge. Identify the appropriate variables for a graph showing the "filling" of a capacitor.

file i01580

Question 27

Given the liquid flowmeter and storage vessel shown here, determine the accumulated volume in the vessel at the following times, for the flow rates shown on the graph:





- Time = 0:15; Volume = __________
- Time = 1:30; Volume = __________
- Time = 1:45; Volume = __________
- Time = 2:45; Volume = __________

As indicated on the graph, the vessel holds 55 gallons of liquid at time = 0:00. Note that the unit of time for the graph's horizontal axis is minutes:seconds, not hours:minutes.

Also, calculate the accumulated volume in the liquid storage vessel at time = 1:00 and time = 2:30. Use this information to sketch a plot of accumulated liquid volume over time.

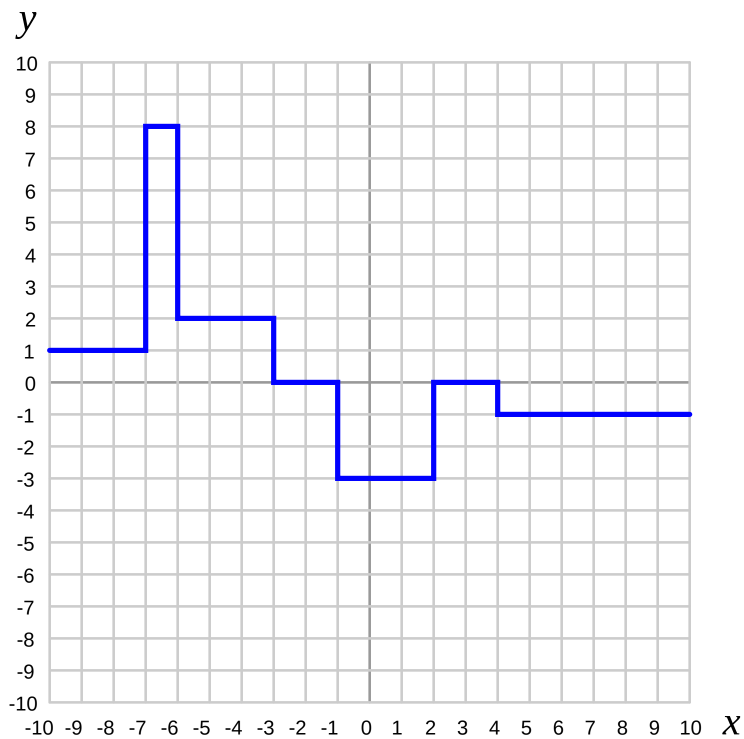
Suggestions for Socratic discussion

- If you were standing in view of the pipe discharging water into this vessel, what would the liquid flow rate shown by the graph *look* like? Would the flow vary over time, or would it remain steady? Would it start and stop, or be continuous?
- Suppose you were given a graph of water volume in the tank, and asked to calculate flow rate in or out of the tank. What principle of calculus would you apply to solve this problem?
- Suppose the flow rate (Q) shown on the graph represented flow *out* of the tank rather than flow *in* to the tank. How would this difference affect the shape of the V graph?
- A tank being filled with water is analogous to an electrical capacitor being "filled" with charge. Identify the appropriate variables for a graph showing the "filling" of a capacitor.

file i01581

Question 28

Determine the value of the specified *integral* for this function:



$$\int_{-3}^{+4} f(x)\, dx$$

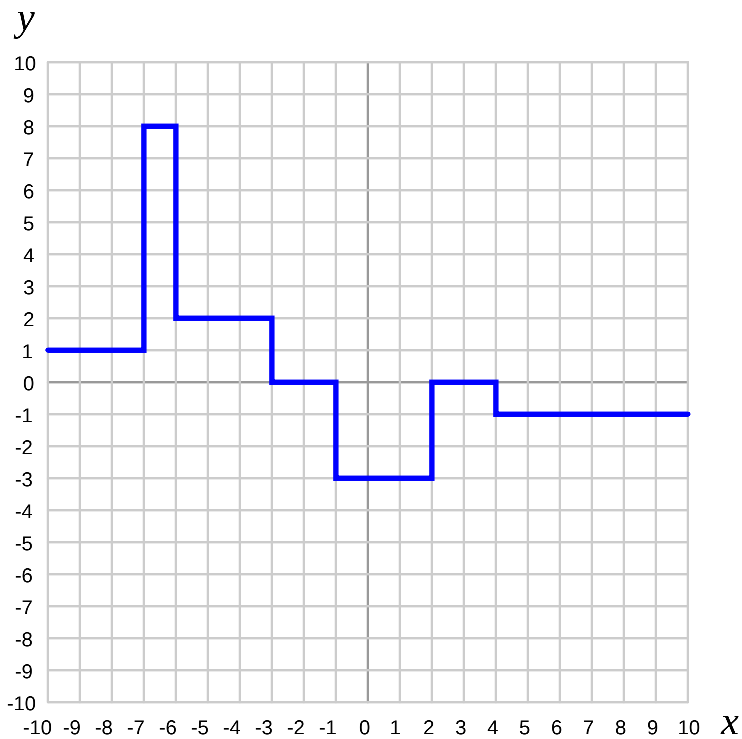
Suggestions for Socratic discussion

- A helpful hint when evaluating integrals is to determine the *sign* of the terms within the integrand over the specified interval. Here, where the interval begins at $x = -3$ and continues to $x = +4$, what is the mathematical sign of dx? Over this same interval, what is the mathematical sign of $f(x)$?
- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- Identify a practical, real-life example this graph might apply to. Identify what the horizontal axis would represent, and what the vertical axis would represent, complete with units of measurement.

file i04370

Question 29

Determine the value of the specified *integral* for this function:



$$\int_{+3}^{-5} f(x)\, dx$$

Suggestions for Socratic discussion

- A helpful hint when evaluating integrals is to determine the *sign* of the terms within the integrand over the specified interval. Here, where the interval begins at $x = +3$ and continues to $x = -5$, what is the mathematical sign of dx? Over this same interval, what is the mathematical sign of $f(x)$?
- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- Identify a practical, real-life example this graph might apply to. Identify what the horizontal axis would represent, and what the vertical axis would represent, complete with units of measurement.
- Identify intervals of integration that will yield a result of 6.
- Identify intervals of integration that will yield a result of 10.

file i04372

Question 30

Read and outline the "How Derivatives and Integrals Relate to One Another" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04275

Question 31

Calculus is a branch of mathematics that originated with scientific questions concerning *rates of change*. The easiest rates of change for most people to understand are those dealing with time. For example, a student watching their savings account dwindle over time as they pay for tuition and other expenses is very concerned with rates of change (*dollars per day* being spent).

Rates of change are symbolically expressed in mathematical equations using the "derivative" notation. For example, if the variable S represents the amount of money in the student's savings account and t represents time, the rate of change of dollars over time (the *time-derivative* of the student's account balance) would be written as $\frac{dS}{dt}$. The process of calculating this rate of change from a record of the account balance over time, or from an equation describing the balance over time, is called *differentiation*.

Suppose student **A** banks at Humongous Savings and Loan where daily account balances are documented to customers, while student **B** banks at Isaac Newton Credit Union, where only rates of account balance *change* are shown in each statement. These rates of change are always in units of dollars per day, calculated at the close of every day. If both students began with exactly the same amount of money in each account, and withdrew exactly the same amount from each account at the same times, the two statements would compare as follows:

Normal bank statement
from Humongous Savings & Loan

May 4	S = $12,340.75
May 5	S = $12,129.28
May 6	S = $12,103.98
May 9	S = $12,041.55
May 10	S = $11,836.32

"Differentiated" bank statement
from the Isaac Newton Credit Union

May 4	
May 5	dS/dt = -$211.47 per day
May 6	dS/dt = -$25.30 per day
May 9	dS/dt = -$20.81 per day
May 10	dS/dt = -$205.23 per day

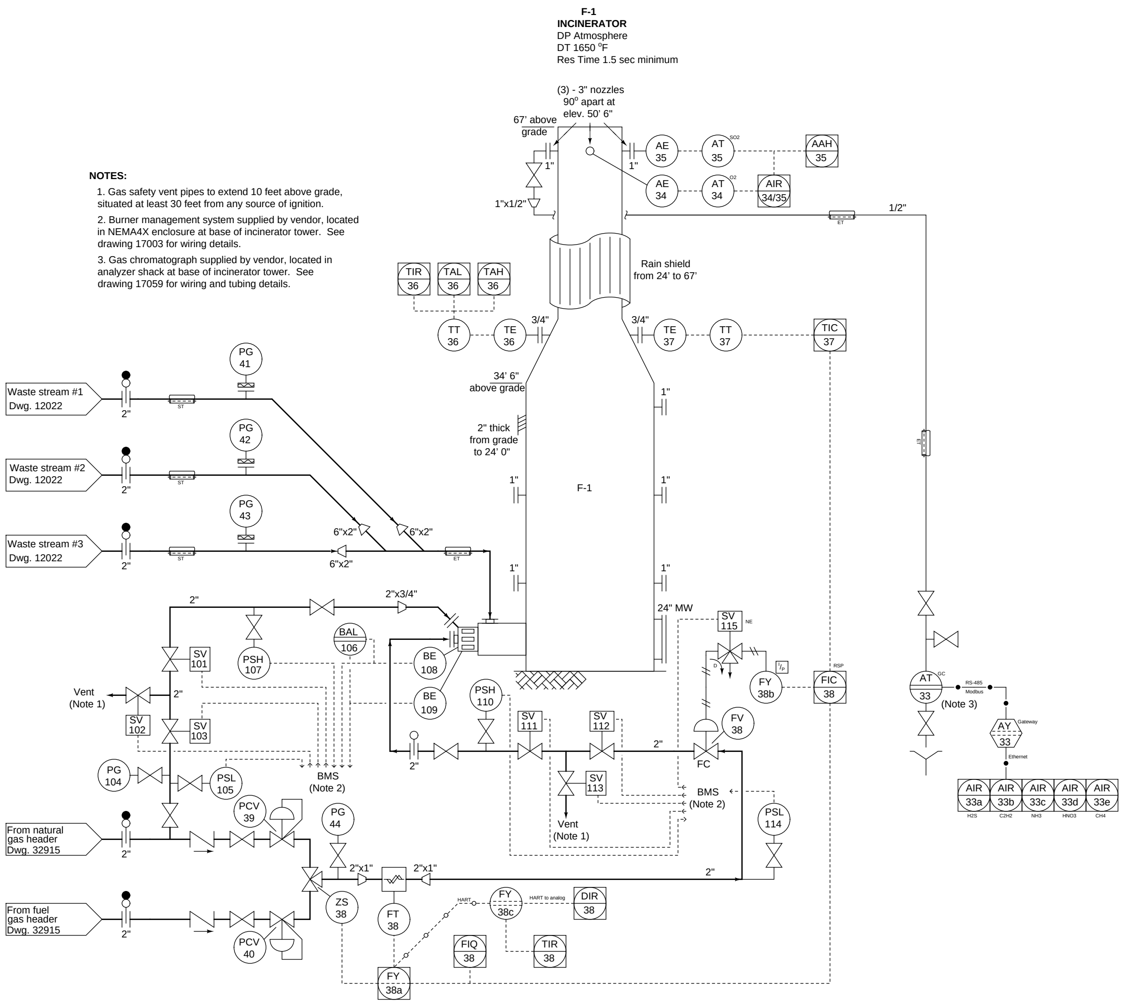
Explain how the Isaac Newton Credit Union calculates the derivative ($\frac{dS}{dt}$) from the balance numbers (corresponding to S in the Humongous Savings & Loan statement), and then explain how the student who banks at Isaac Newton Credit Union could figure out how much money is in their account at any given time lacking such balance figures.

Hint: the process of calculating a variable's value from rates of change is called *integration* in calculus. It is the opposite (inverse) function of differentiation.

file i01563

Question 32

This P&ID shows an incinerator stack used to safely burn poisonous gases. The high temperature of the gas flame reduces the poisonous compounds to relatively harmless water vapor, carbon dioxide, and oxides of sulfur and nitrogen:



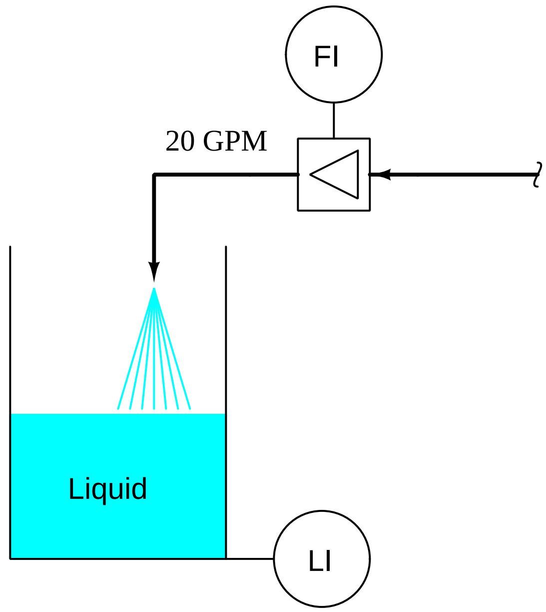
Identify where the measurement/control system is performing *integration* to "totalize" a quantity over time. If possible, identify realistic units of measurement for the integrated value(s).

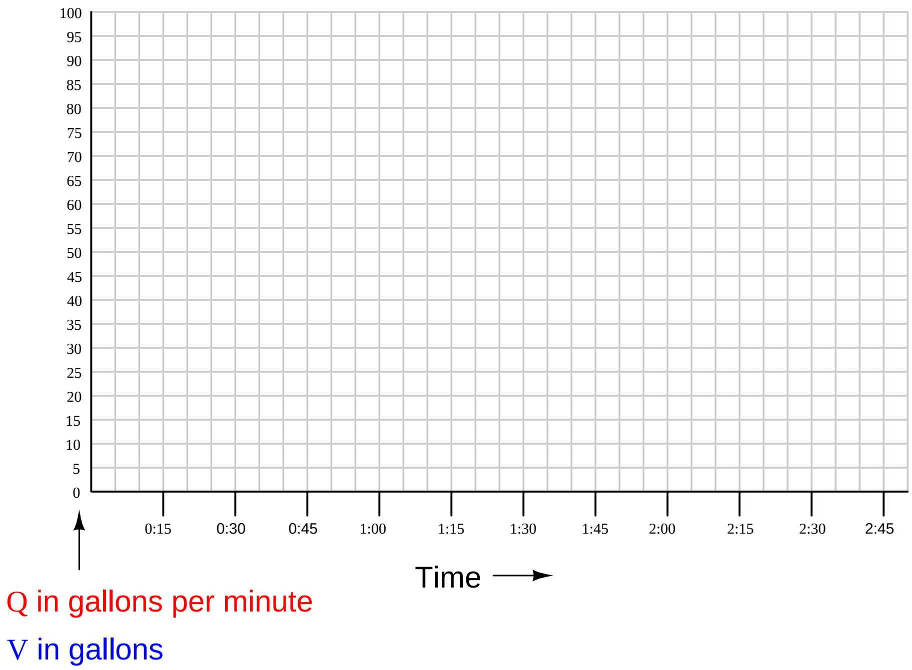
Suppose an environmental regulatory agency required that the emissions monitoring system (loop number 33 in the P&ID) calculate the *total volume* of pollutants emitted each month, rather than just provide measurements of pollutant concentration (e.g. percent or parts-per-million). How would it be possible to do this, and what additional field instrumentation would be required?

file i03507

Question 33

Suppose a constant flow rate of 20 gallons per minute enters the vessel through the pipe. Graph this constant value of flow over time, as well as the accumulating volume of liquid inside the vessel over time:





Assume the vessel is completely empty when the liquid begins to flow at start time (0:00). Note that the unit of time for the graph's horizontal axis is minutes:seconds, not hours:minutes. Also, explain why the assumption of an empty vessel at 0:00 is important for predicting total stored volume in the vessel.

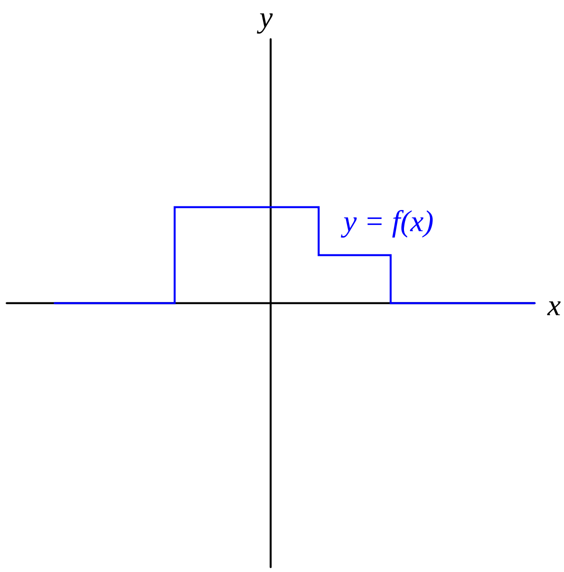
Calculate the accumulated liquid volume at the following times:

- Time = 1:00; Volume = ________
- Time = 1:30; Volume = ________
- Time = 2:00; Volume = ________
- Time = 2:30; Volume = ________
- Time = 2:45; Volume = ________

file i01579

Question 34

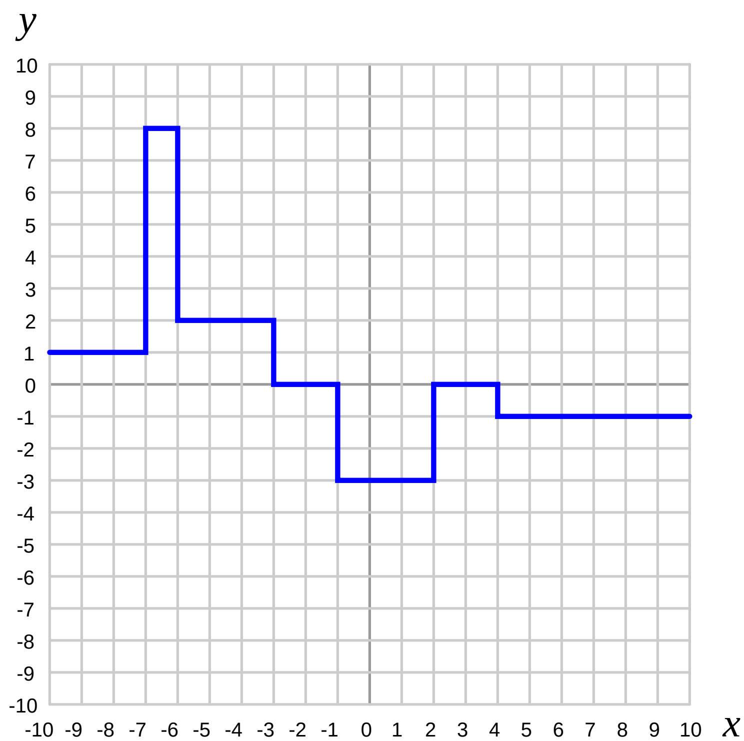
Define what "integral" means when applied to the graph of a function. For instance, examine this graph:



Sketch an approximate plot for the integral of this function.
file i01561

Question 35

Determine the value of the specified *integral* for this function:

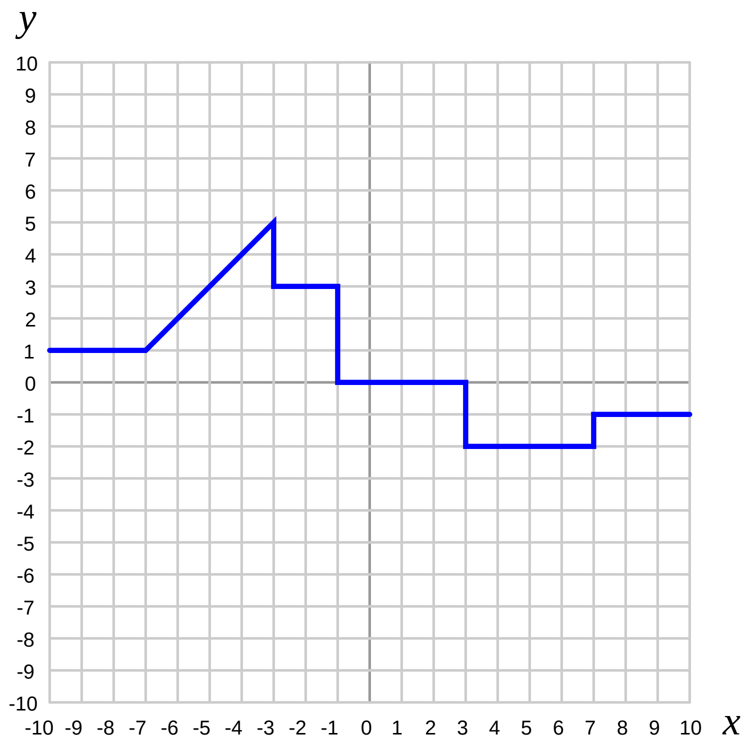


$$\int_{-8}^{-4} f(x)\, dx$$

file i04371

Question 36

Determine the value of the specified *integral* for this function:

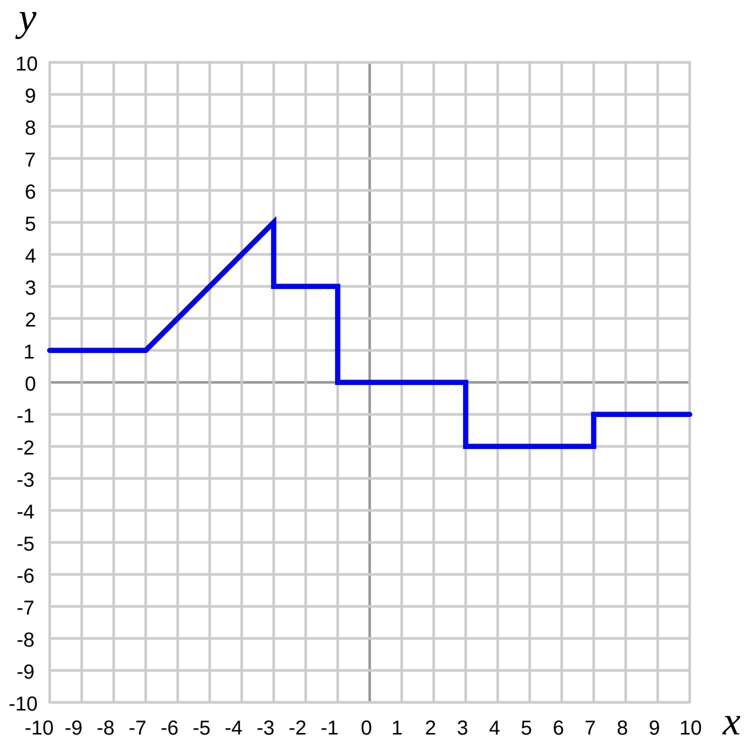


$$\int_{-3}^{+10} f(x)\, dx$$

file i04373

Question 37

Determine the value of the specified *integral* for this function:

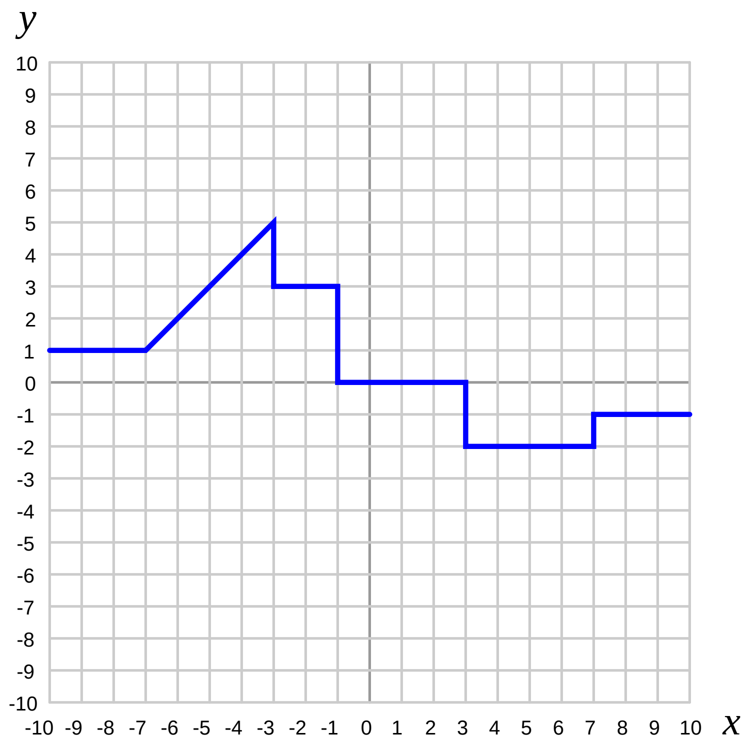


$$\int_{+2}^{-2} f(x)\, dx$$

file i04374

Question 38

Determine the value of the specified *integral* for this function:

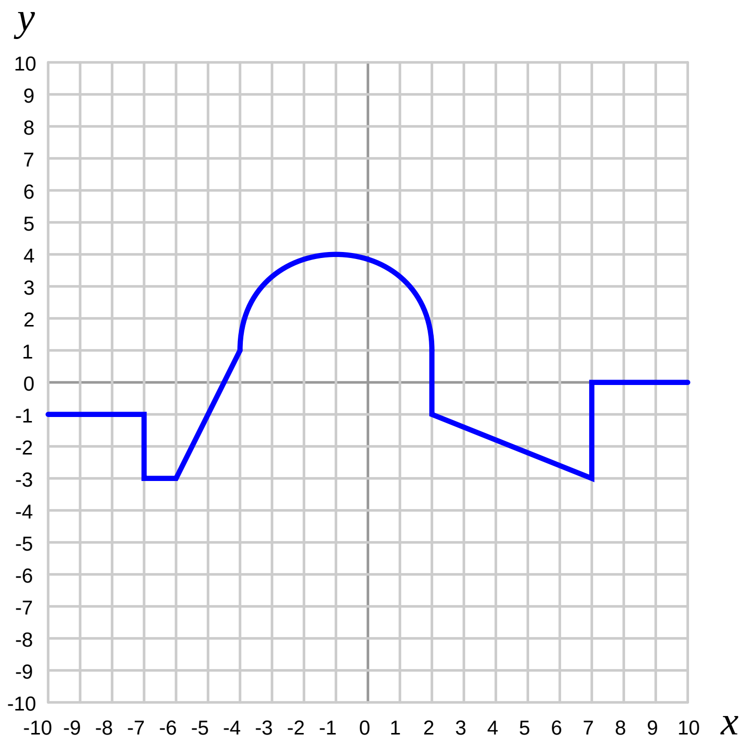


$$\int_{-10}^{0} f(x)\, dx$$

file i04375

Question 39

Determine the value of the specified *integral* for this function:

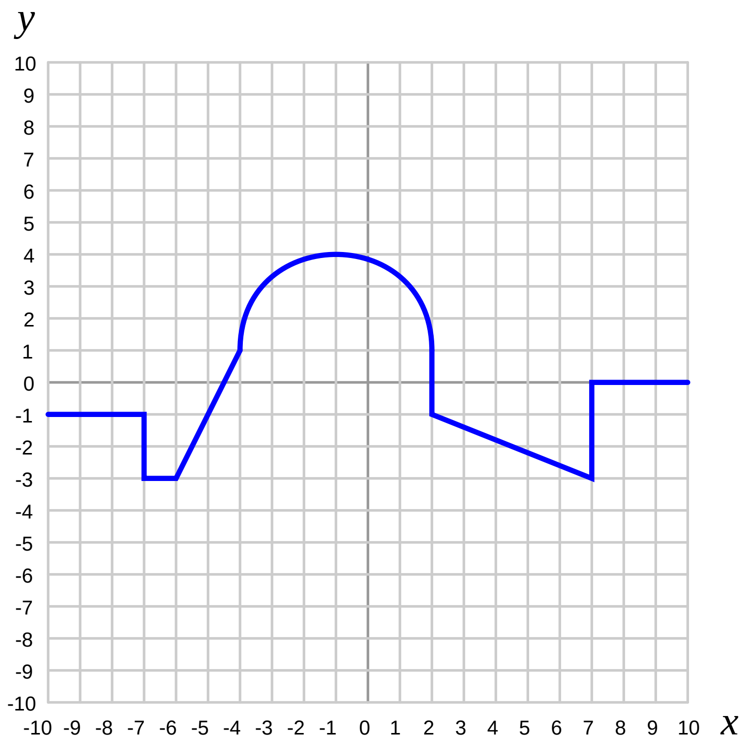


$$\int_{-1}^{+2} f(x)\,dx$$

file i04376

Question 40

Determine the value of the specified *integral* for this function:



$$\int_{8}^{-4} f(x)\, dx$$

file i04377

Question 41

Read and outline the "Numerical Differentiation" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

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

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

file i04277

Question 42

Read and outline the "Numerical Integration" section of the "Calculus" chapter in your *Lessons In Industrial Instrumentation* textbook.

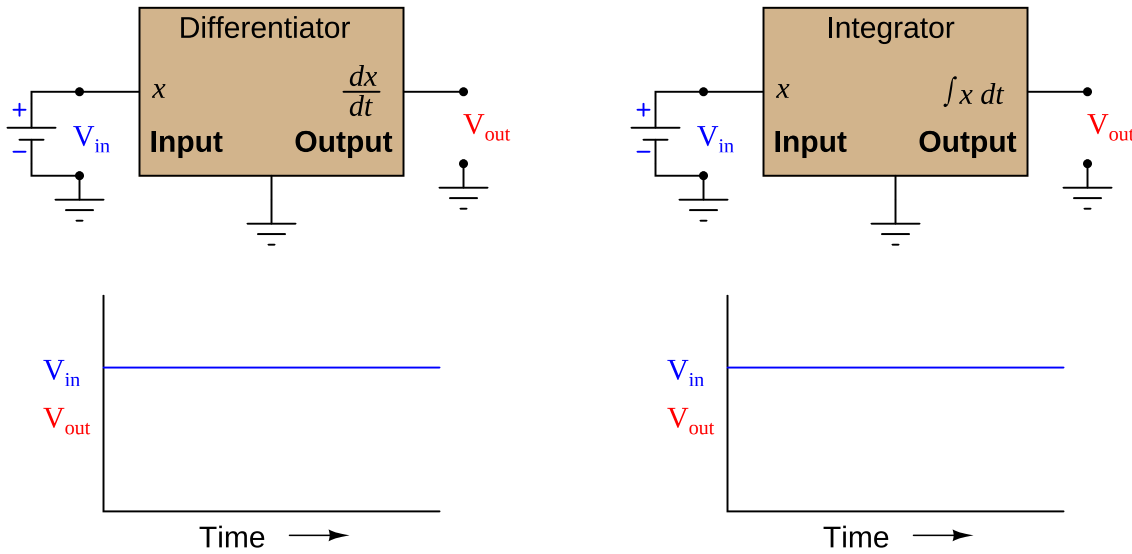
After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

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

file i04278

Question 43

Determine what the output response will be to a constant DC voltage applied at the input of these (ideal) circuits:



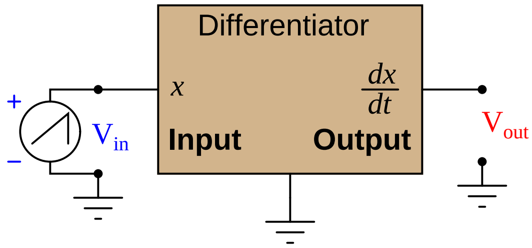
Suggestions for Socratic discussion

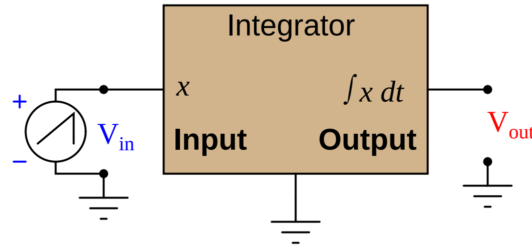
- Identify practical applications in industry for circuits such as these.
- Explain how each of these circuits would respond to a square-wave input signal of constant frequency.
- Explain how each of these circuits would respond to a square-wave input signal of increasing frequency.
- Explain what would happen if the output of the integrator were connected to the input of the differentiator, and then a signal was input to the integrator. What kind of signal would come out of the differentiator?
- Explain what would happen if the output of the differentiator were connected to the input of the integrator, and then a signal was input to the differentiator. What kind of signal would come out of the integrator?

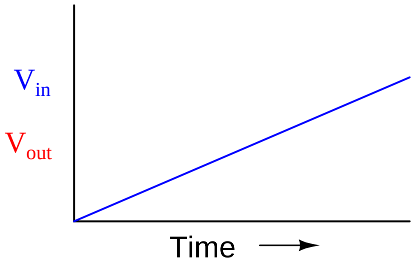
file i01562

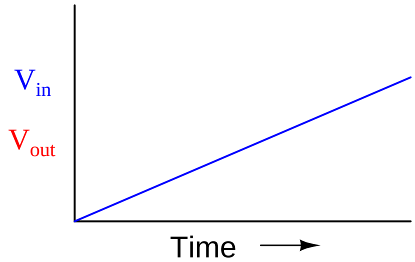
Question 44

Determine what the output response will be to a positive-ramping voltage applied at the input of these (ideal) circuits:









Suggestions for Socratic discussion

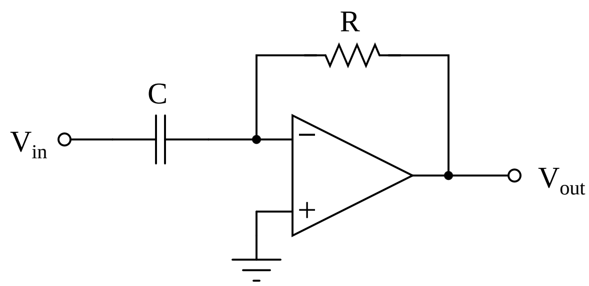
- Identify practical applications in industry for circuits such as these.
- Identify what would have to be different about the input signal to each circuit in order to generate a *negative* output voltage.
- Explain how each of these circuits would respond to a sinusoidal input signal of constant frequency.
- Explain how each of these circuits would respond to a sinusoidal input signal of increasing frequency.
- Explain what would happen if the output of the integrator were connected to the input of the differentiator, and then a signal was input to the integrator. What kind of signal would come out of the differentiator?
- Explain what would happen if the output of the differentiator were connected to the input of the integrator, and then a signal was input to the differentiator. What kind of signal would come out of the integrator?

file i01571

Question 45

Differentiator circuits output a voltage proportional to the *rate of change over time* of the input voltage. That is, the output of a differentiator circuit reflects how *quickly* the input voltage changes.

An electronic differentiator circuit



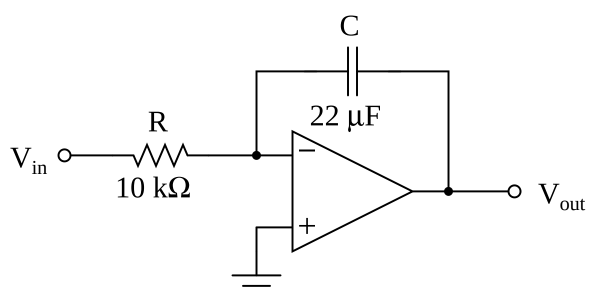
$$V_{out} = -\tau_d \frac{dV_{in}}{dt}$$

Every differentiator circuit has a *time constant* (τ_d), sometimes called the *characteristic time*, which is a proportionality constant between the input rate-of-change (measured in volts per second) and the output voltage (measured in volts). For instance, a differentiator circuit like the one shown having a time constant of 3 seconds will output a constant voltage of -15 volts if it sees an input voltage rising at a rate of 5 volts per second:

$$-15 \text{ [V]} = -(3 \text{ [s]}) \left(\frac{5 \text{ [V]}}{\text{[s]}} \right)$$

Integrator circuits also have time constants (τ_i), expressing a proportionality between one voltage and another voltage's rate-of-change. Explain how the time constant of an electronic integrator circuit may be calculated from component values, and then formulate a "thought experiment" to apply your explanation to the following integrator circuit, illustrating what the time constant means in practical terms:

An electronic integrator circuit



Suggestions for Socratic discussion

- A useful problem-solving technique for answering qualitative or conceptual questions is to insert numerical quantities into the problem to give yourself something concrete to calculate. Try applying this technique here.
- Identify multiple ways to *lengthen* the time constant of either circuit.

- Of those multiple ways, which do you think is easier to implement in a practical circuit? Explain why.
- Suppose a constant DC voltage signal of 2 volts was applied to the input of this integrator circuit, for a period of 1.5 seconds. After that, the input signal goes to zero and remains there. What will the output of this opamp circuit do, assuming it began at 0 volts before we first applied any DC input?
- Assuming a constant DC voltage signal of 2 volts applied to the input of this integrator circuit, calculate all currents and voltage drops in this circuit, being sure to mark all directions of current and polarities of voltage.

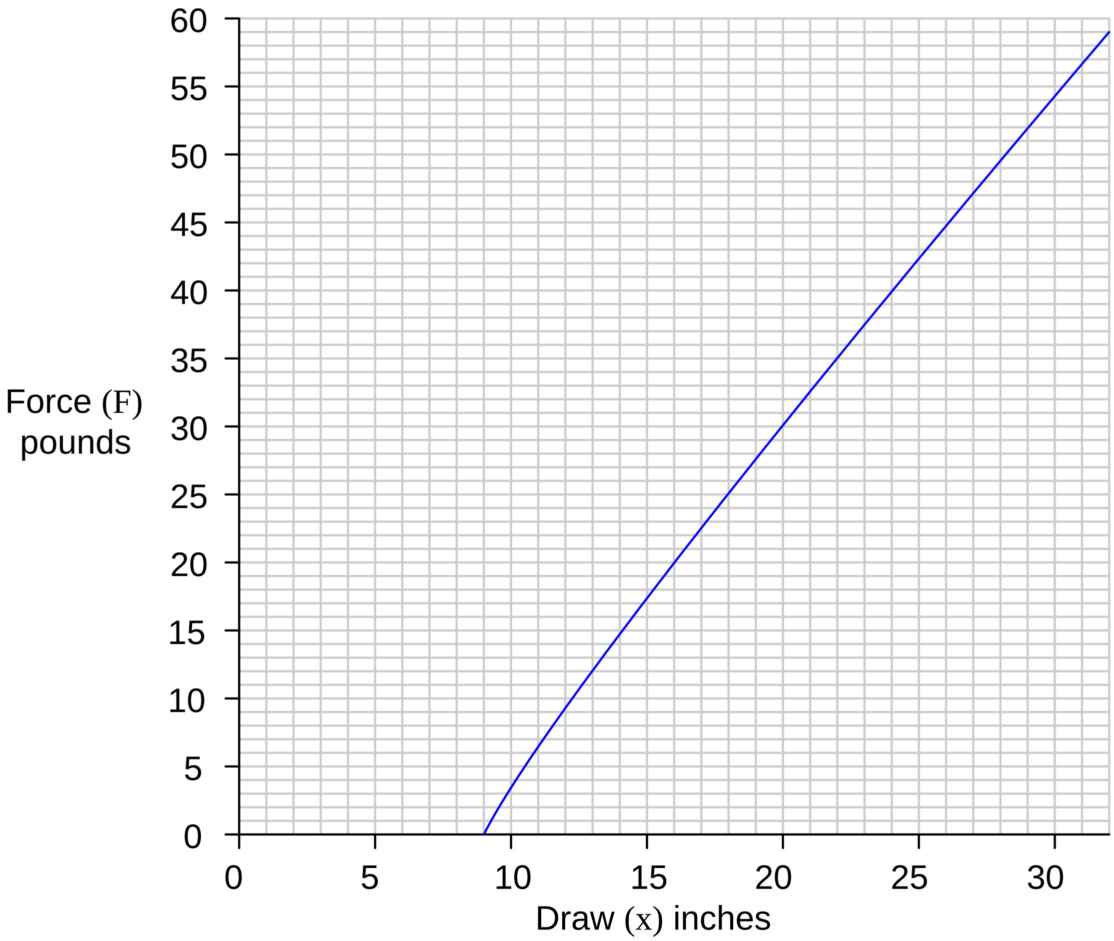
  file i01577

Question 46

The energy stored in an archer's bow when fully drawn is equal to the amount of mechanical work invested by the archer in drawing the string back. This potential energy is the integral of force (F) over increments of distance (dx) over an interval of distance beginning at x_0 and finishing at x_f:

$$E_p = \int_{x_0}^{x_f} F \, dx$$

Approximately calculate the amount of energy stored in a longbow drawn to 30 inches, given the following force-draw curve:



Express your answer in units of *foot-pounds*.

Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- How does the amount of work done between 10 and 15 inches of draw compare with the amount of work done between 25 and 30 inches of draw?

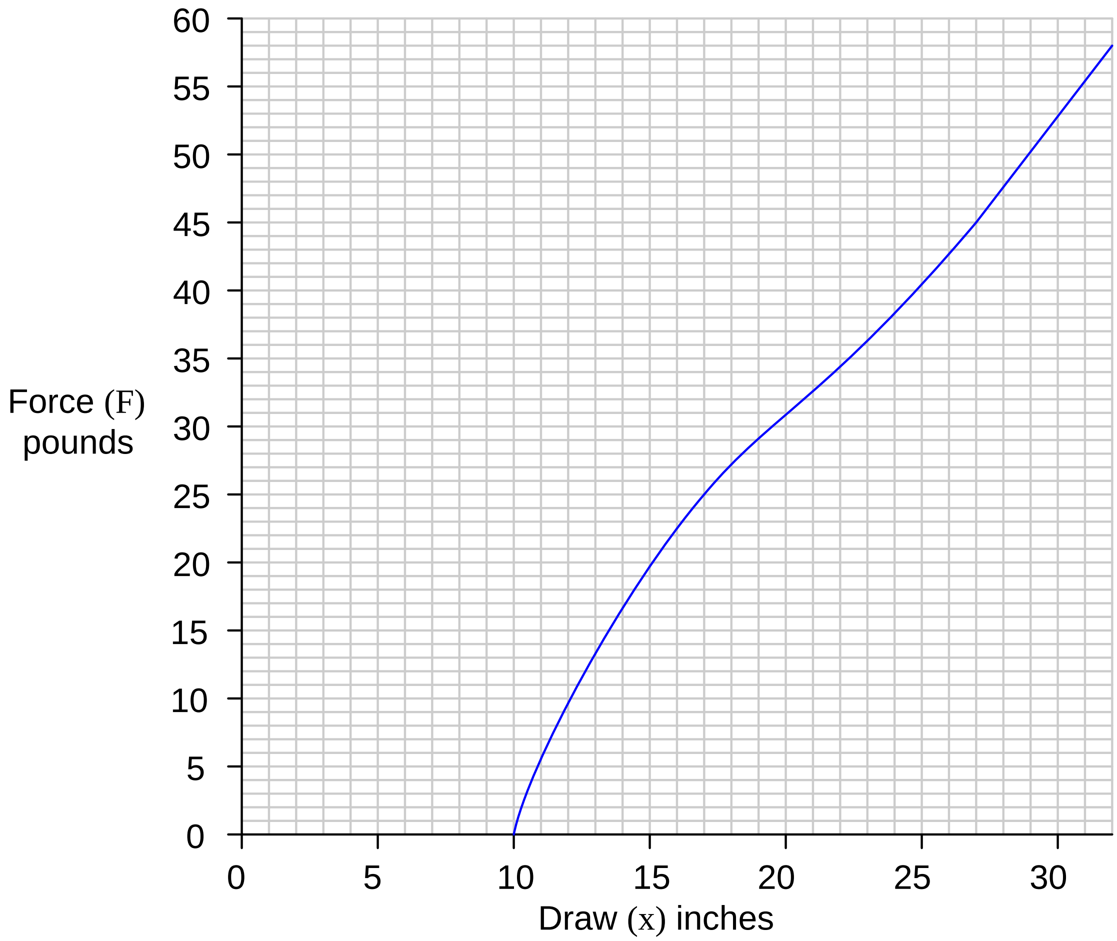
file i04279

Question 47

The energy stored in an archer's bow when fully drawn is equal to the amount of mechanical work invested by the archer in drawing the string back. This potential energy is the integral of force (F) over increments of distance (dx) over an interval of distance beginning at x_0 and finishing at x_f:

$$E_p = \int_{x_0}^{x_f} F \, dx$$

Approximately calculate the amount of energy stored in a recurve bow drawn to 30 inches, given the following force-draw curve:



Express your answer in units of *foot-pounds*.

Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- How does the amount of work done between 10 and 15 inches of draw compare with the amount of work done between 25 and 30 inches of draw?

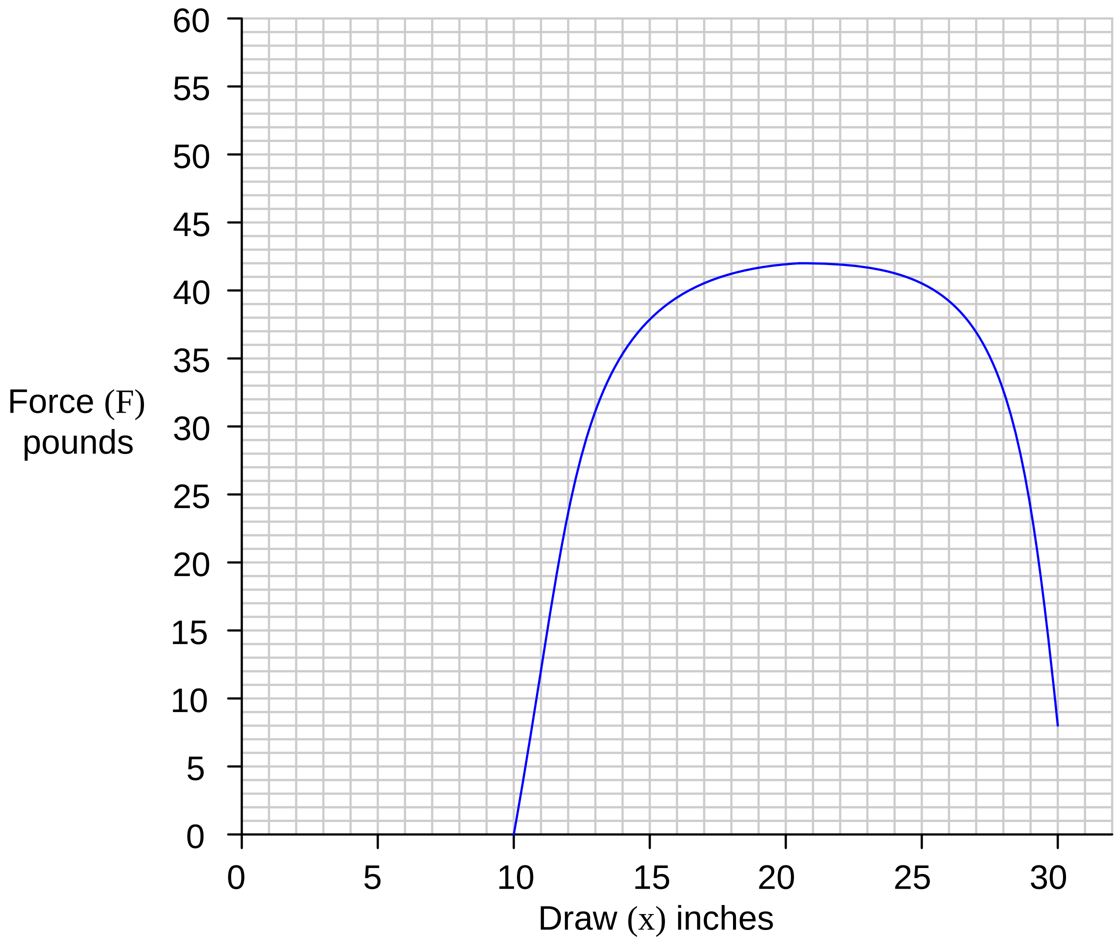
file i04280

Question 48

The energy stored in an archer's bow when fully drawn is equal to the amount of mechanical work invested by the archer in drawing the string back. This potential energy is the integral of force (F) over increments of distance (dx) over an interval of distance beginning at x_0 and finishing at x_f:

$$E_p = \int_{x_0}^{x_f} F \, dx$$

Approximately calculate the amount of energy stored in a compound bow drawn to 30 inches, given the following force-draw curve:



Express your answer in units of *foot-pounds*.

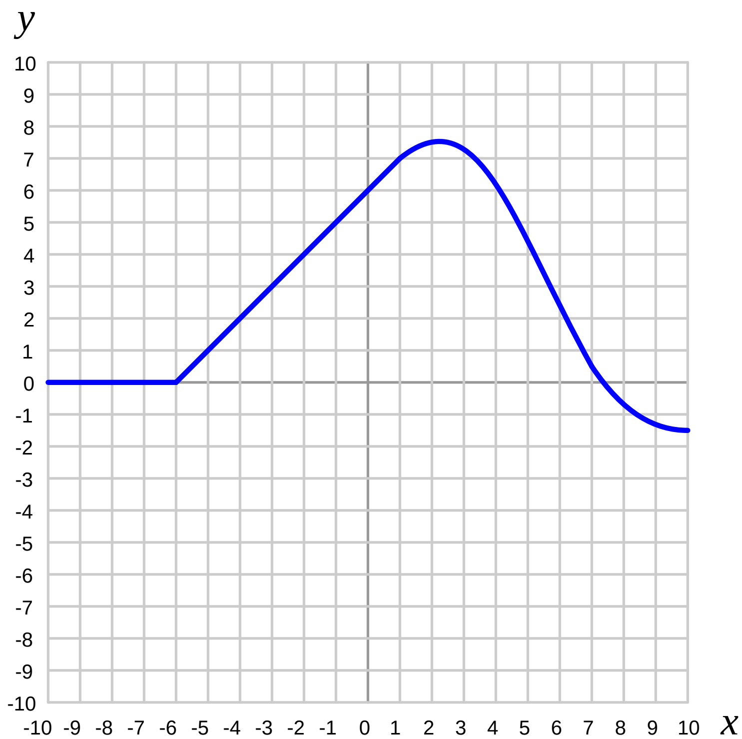
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- How does the amount of work done between 10 and 15 inches of draw compare with the amount of work done between 25 and 30 inches of draw?

file i04281

Question 49

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = -3$:



Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +3$
- $\frac{dy}{dx} = -3$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

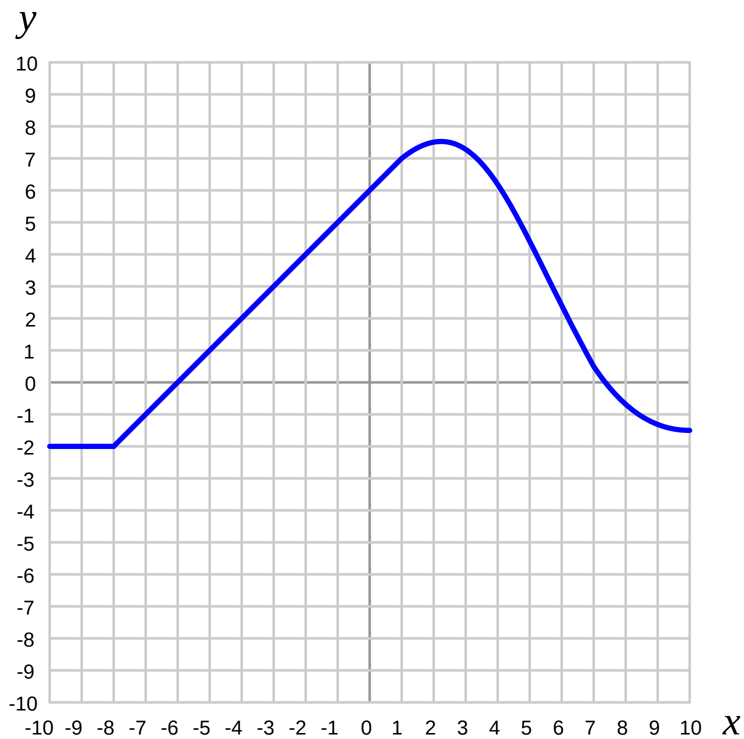
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of differentiation in your own words, as it applies to this particular problem.
- Identify what would have to be different about this function for the derivative at $x = -3$ to have the opposite sign that it does now.

file i04378

Question 50

Determine the value of the specified *integral* for this function:



$$\int_{-9}^{-3} y \, dx$$

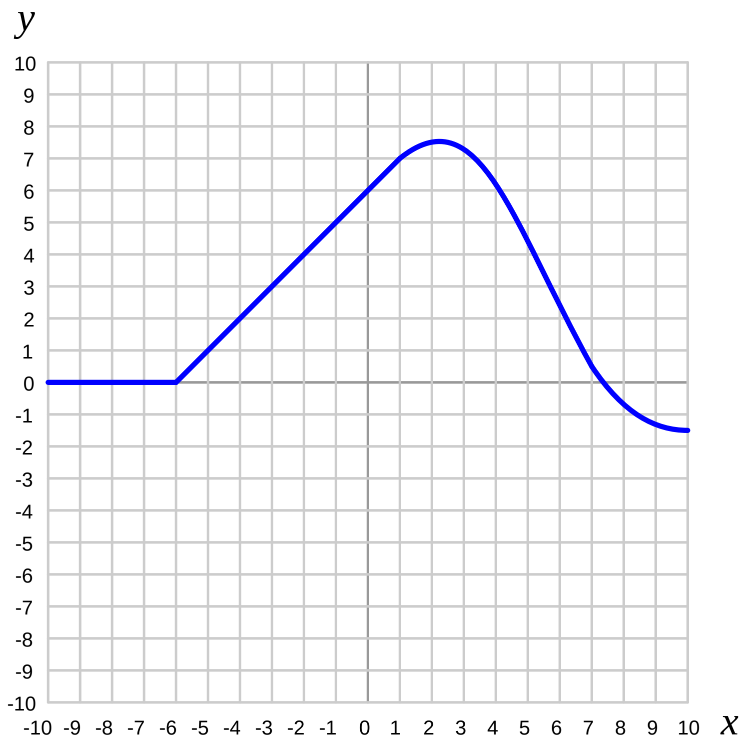
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- Identify the mathematical sign of the function (y) and of the differential (dx) over various portions of the integration interval (as x varies between -9 and -3). Are there places where y changes sign? Are there places where dx changes sign?

file i04382

Question 51

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = 7.5$:



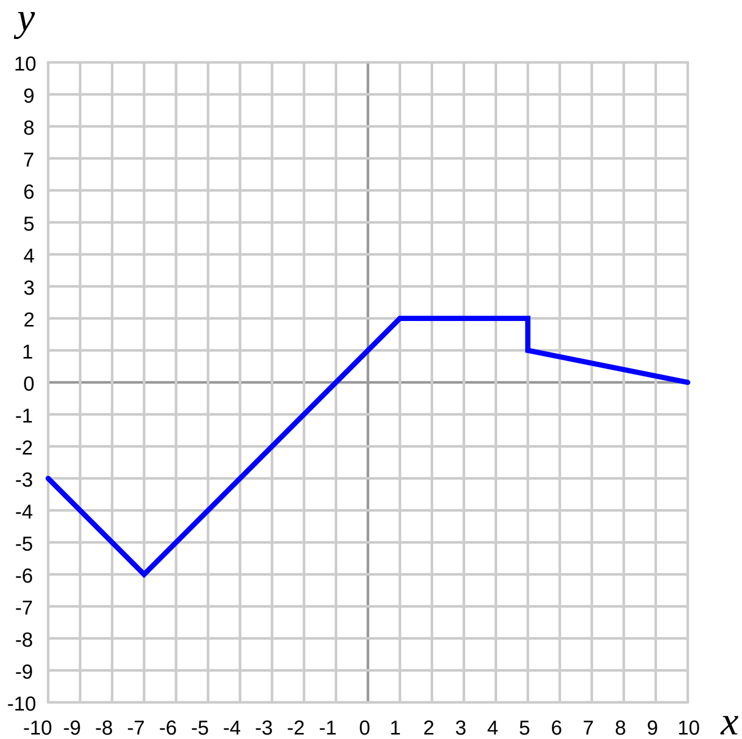
Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

file i04381

Question 52

Determine the value of the specified *integral* for this function:

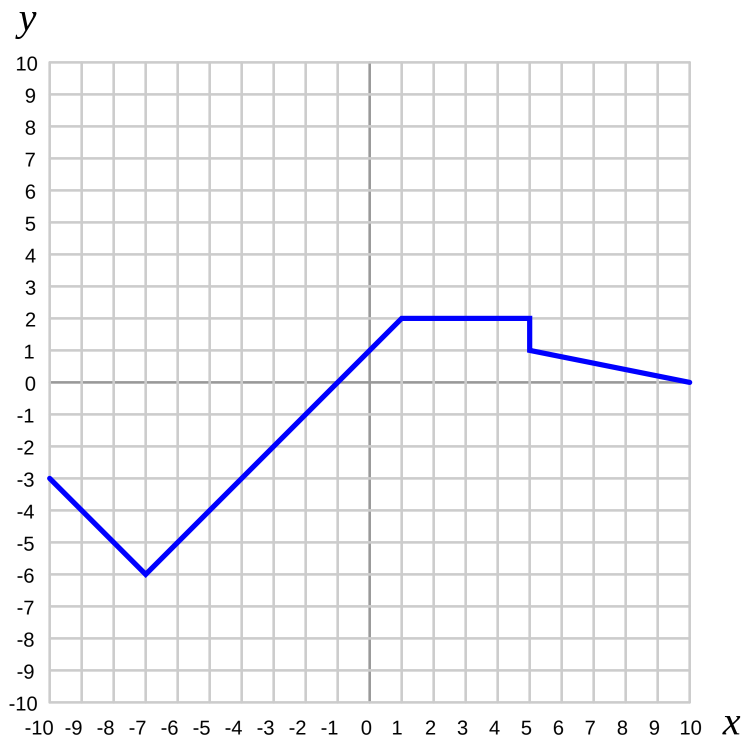


$$\int_{+10}^{-1} f(x)\, dx$$

file i04385

Question 53

Determine the value of the specified *integral* for this function:



$$\int_{-5}^{+4} f(x)\, dx$$

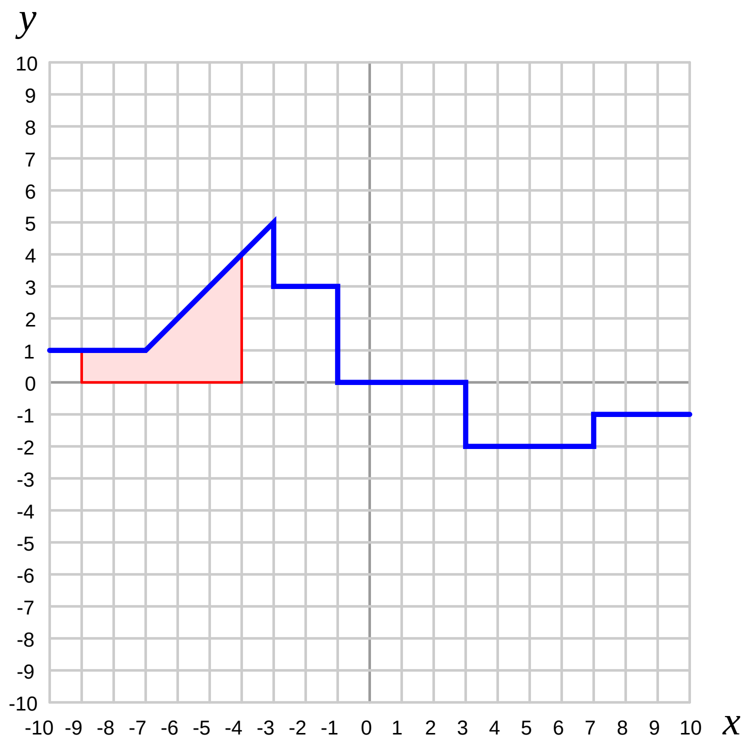
Suggestions for Socratic discussion

- A helpful hint when evaluating integrals is to determine the *sign* of the terms within the integrand over the specified interval. Here, where the interval begins at $x = -5$ and continues to $x = +4$, what is the mathematical sign of dt? Over this same interval, what is the mathematical sign of $f(x)$?
- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.

file i04384

Question 54

Write a mathematical expression using proper calculus notation for the shaded area in this graph:

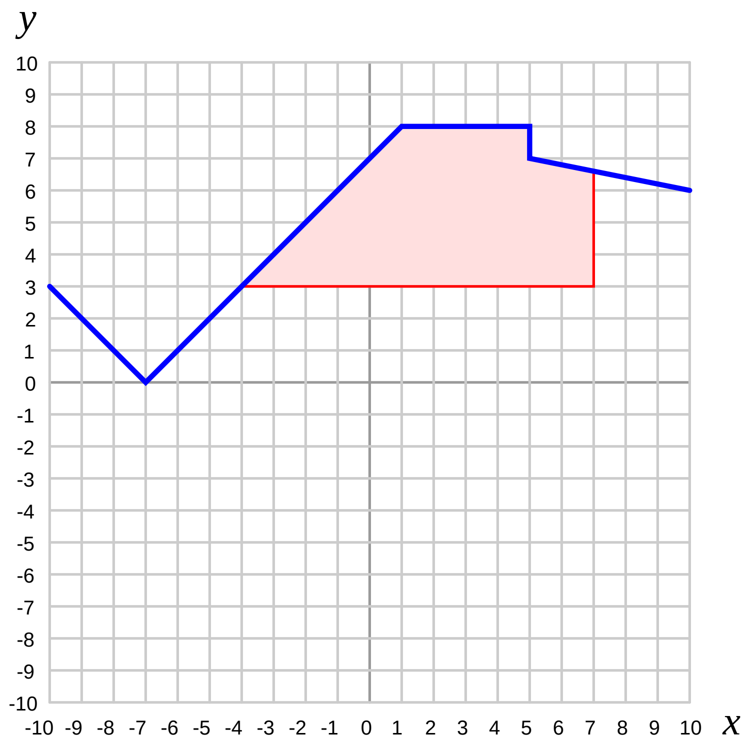


Assume this area has a *positive* value.

file i01900

Question 55

Write a mathematical expression using proper calculus notation for the shaded area in this graph:

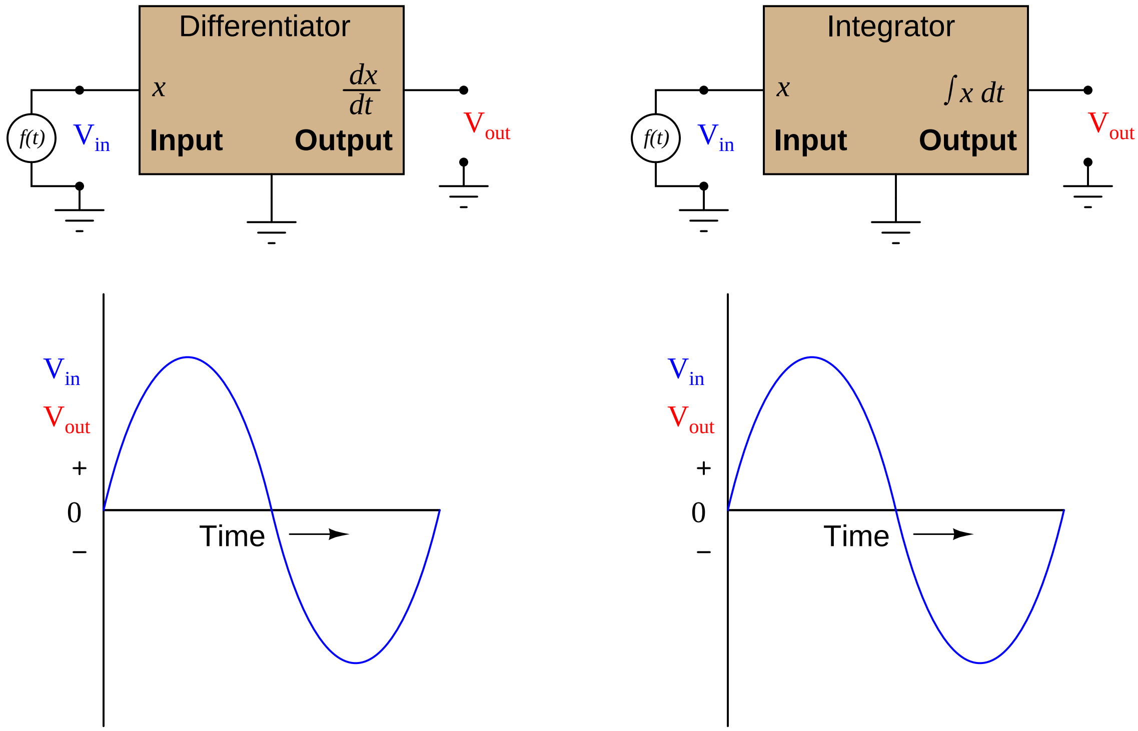


Assume this area has a *positive* value.

Next, re-write the expression so as to make the value of the integral *negative* rather than positive.
file i01904

Question 56

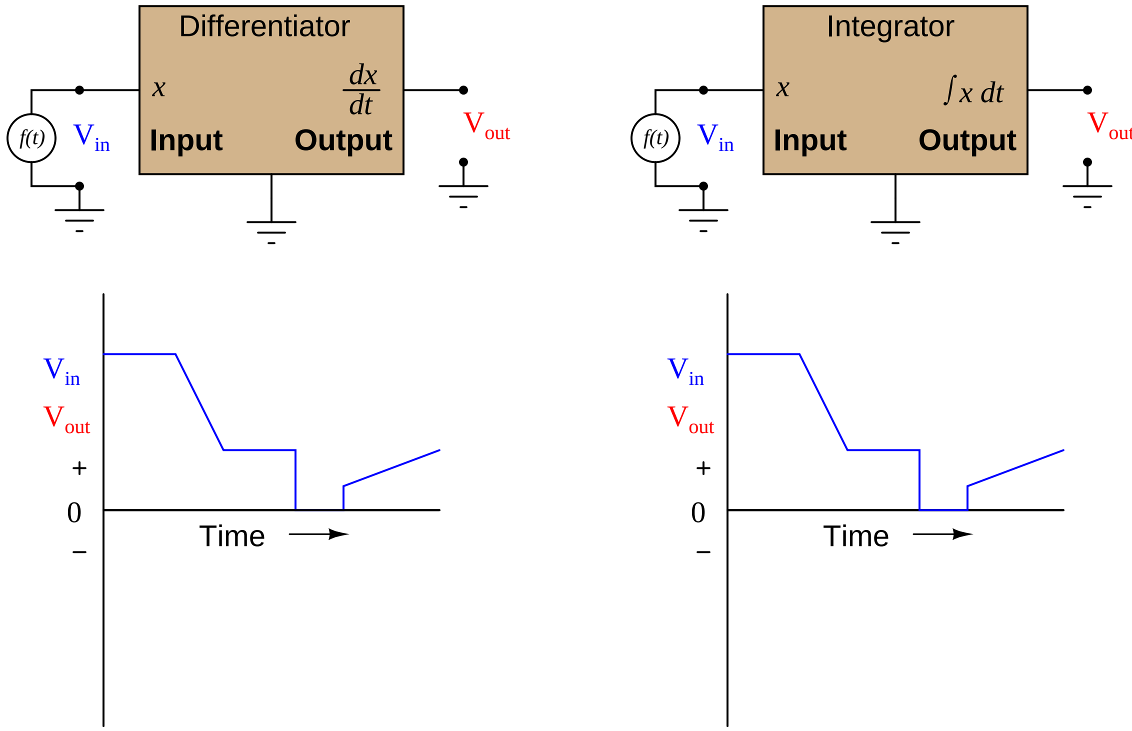
Determine what the output response will be to a varying voltage applied at the input of these (ideal) circuits:



file i01804

Question 57

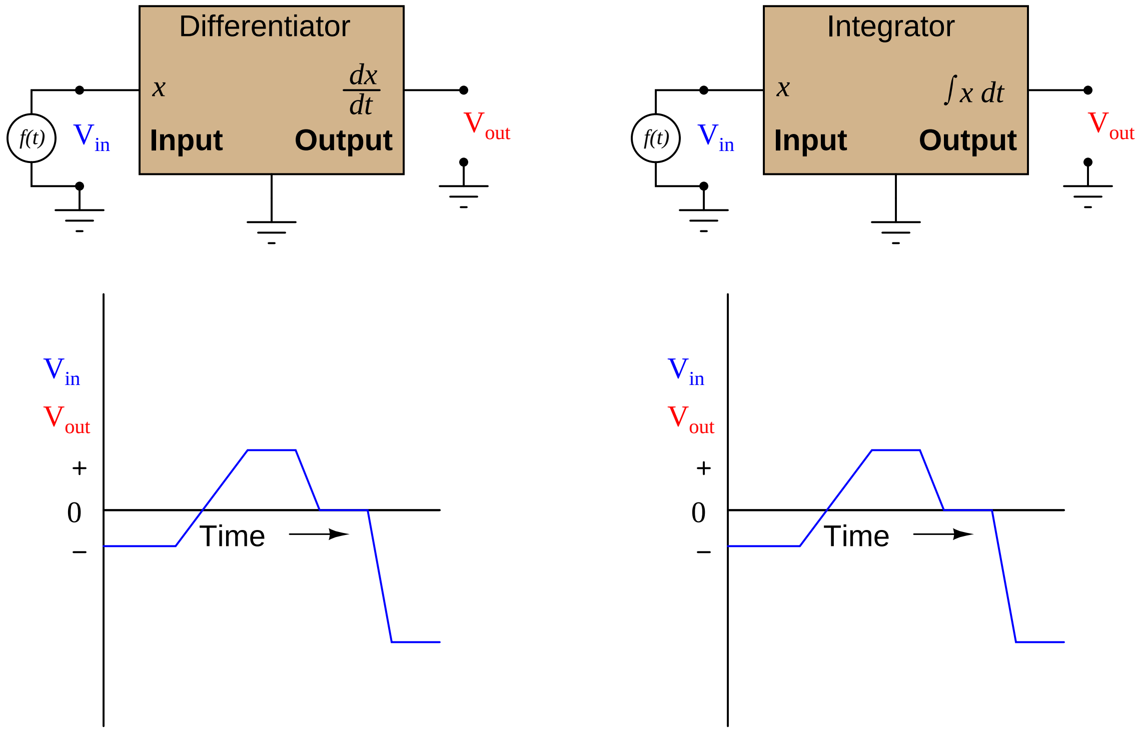
Determine what the output response will be to a varying voltage applied at the input of these (ideal) circuits:



file i01803

Question 58

Determine what the output response will be to a varying voltage applied at the input of these (ideal) circuits:



file i01805

Question 59

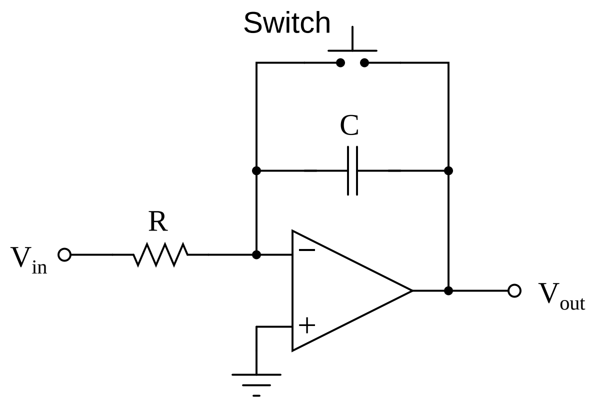
How much force will be required to compress a spring (from its relaxed state) a displacement of 3 inches, given a spring constant of 150 pounds per inch? How much energy (in foot-pounds) will be stored in the spring after compressing it this much?

Write a mathematical expression (using proper calculus notation) representing the energy invested in this spring by compressing it by 3 inches.

file i03778

Question 60

Identify the purpose of the pushbutton switch in this integrator circuit:



Then, give a practical example of this switch's use, in an application where the integrator circuit is integrating some real-life measurement signal.

file i01582

Question 61

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

Identify any knowledge and/or skill areas in which you would like to become stronger, and describe practical steps you can take to achieve that goal. Don't limit yourself to just technical knowledge and skills, but consider behavioral habits (e.g. patience, attention to detail, time management) and general academic abilities (e.g. reading, writing, mathematics) as well. If you find yourself struggling to achieve a goal, don't just say "I'll work harder" as your plan of action – identify something *different* you can do to achieve that goal.

Note: your responses to these questions will not be shared in Socratic discussion with classmates without your consent. Feel free to maintain these as private notes between yourself and your instructor.

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

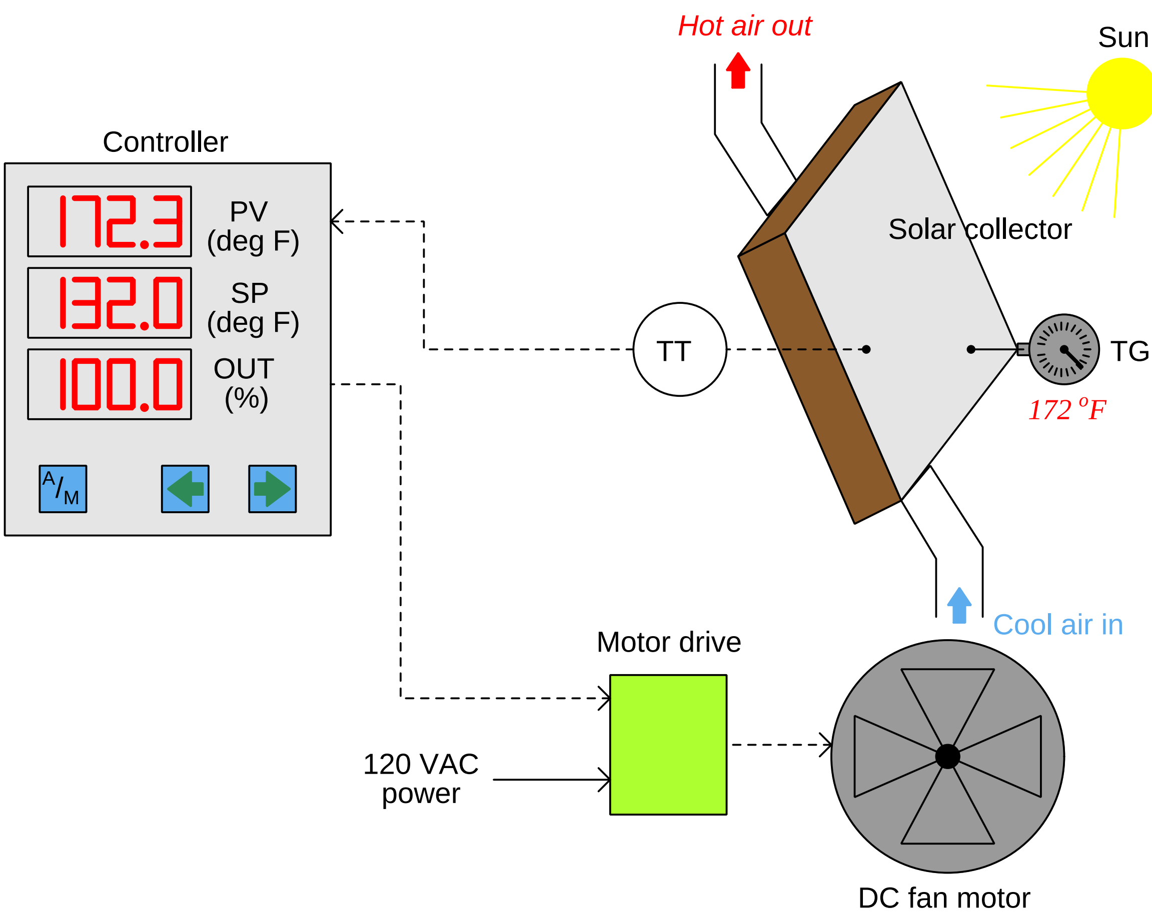
file i00999

Question 62

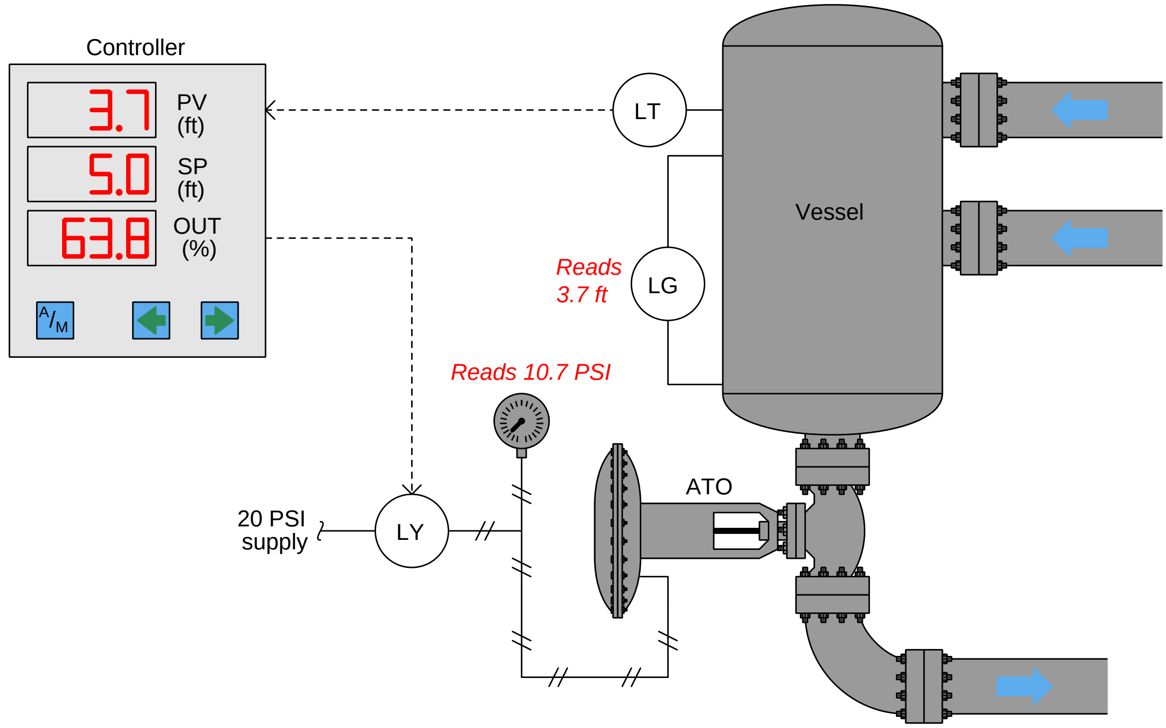
The following processes all have some problem, which may be diagnosed by careful observation of the controller's faceplate display (PV, SP, and Output values) and/or indications given by gauges in the field. Examine each control system and determine possible faults in each system from the information given.

Assume that the conditions shown have existed for quite some time, long enough for the control system to have brought the process variable back to setpoint if everything were operating correctly:

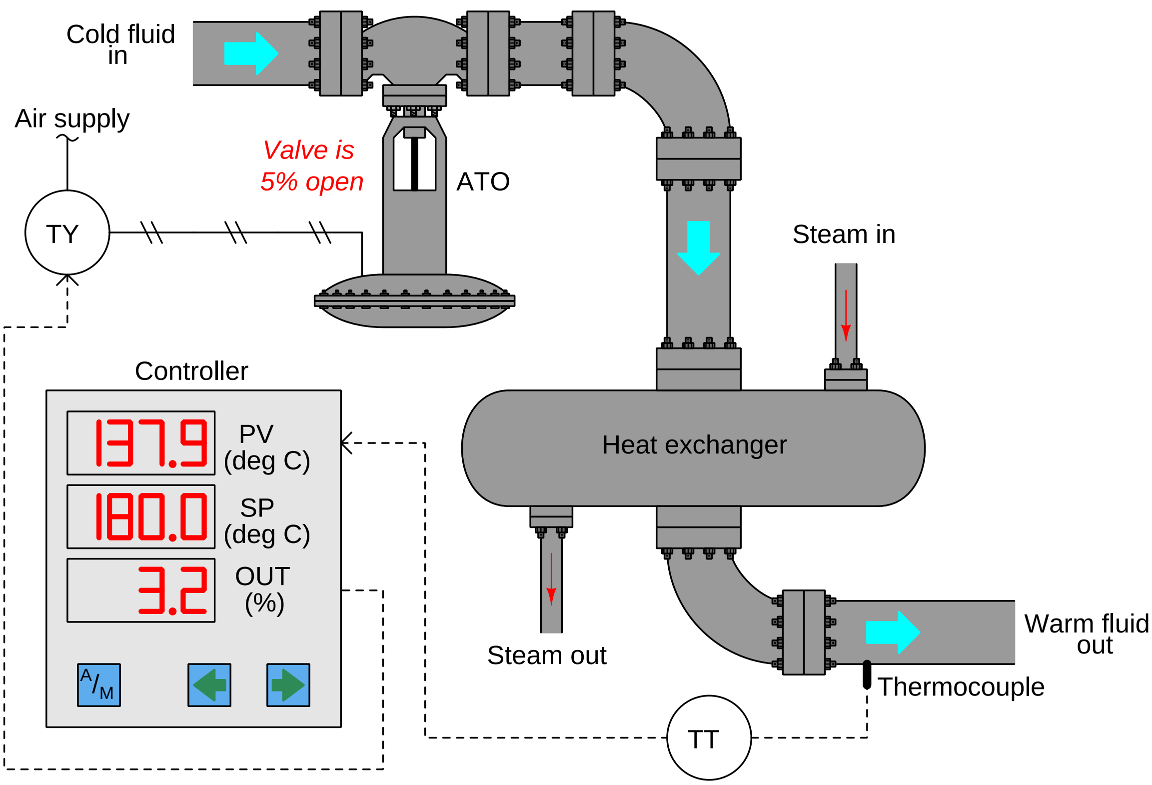
Example 1:



Example 2:



Example 3:



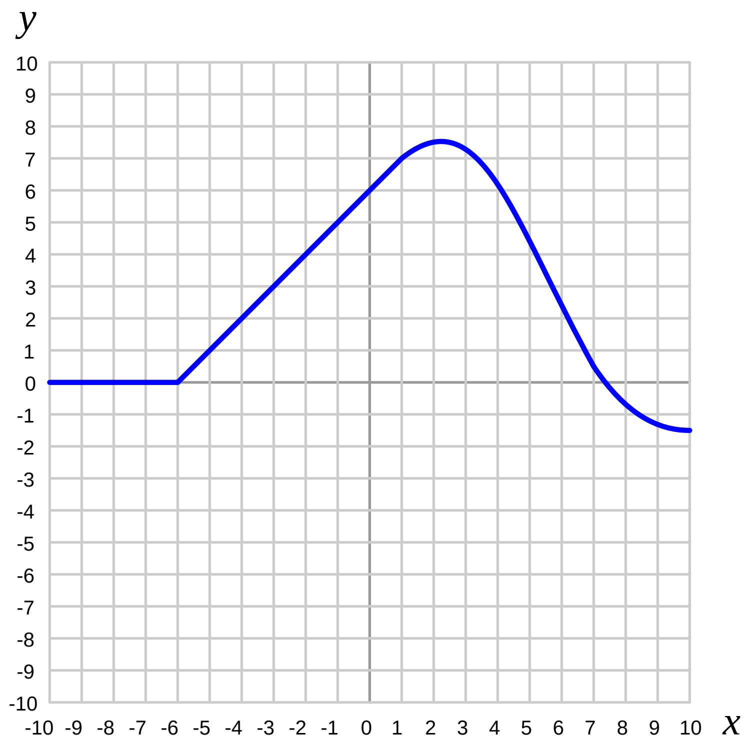
Suggestions for Socratic discussion

- A valuable principle to apply in a diagnostic scenario such as this is *correspondence*: identifying which values agree with each other. Explain how a check of correspondence tells us which instrument is at fault in any of these control loops.
- For each of these scenarios, determine what your next diagnostic test might be to further pinpoint the location and nature of the problem.

file i01353

Question 63

Determine the approximate value of the *derivative* ($\frac{dy}{dx}$) for this function where $x = -8$:



Choose the closest answer:

- $\frac{dy}{dx} = +1$
- $\frac{dy}{dx} = -1$
- $\frac{dy}{dx} = +2$
- $\frac{dy}{dx} = -2$
- $\frac{dy}{dx} = +5$
- $\frac{dy}{dx} = -5$
- $\frac{dy}{dx} = 0$

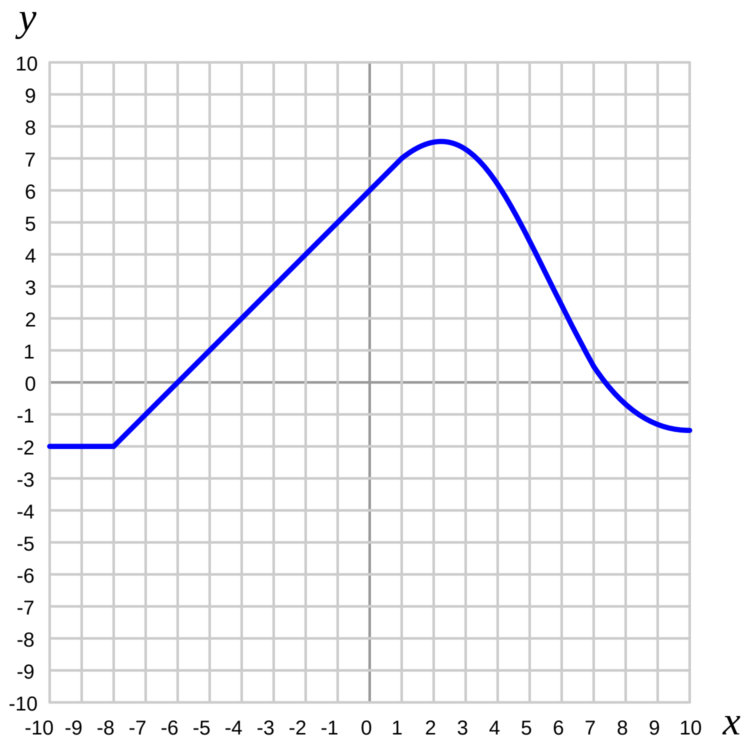
Suggestions for Socratic discussion

- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of differentiation in your own words, as it applies to this particular problem.
- Suppose the unit of measurement for y is *dollars*, and the unit of measurement for x is *hours*. Identify the proper unit of measurement for $\frac{dy}{dx}$, and a possible real-world application with these units that would fit the graph.

file i04380

Question 64

Determine the value of the specified *integral* for this function:



$$\int_{0}^{-7} f(x)\, dx$$

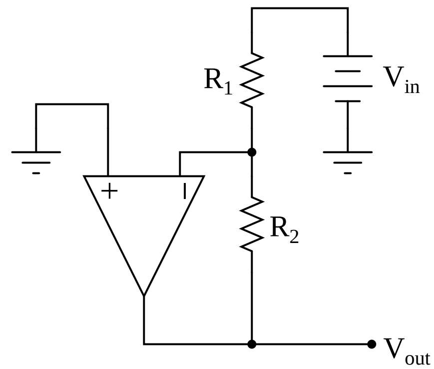
Suggestions for Socratic discussion

- A helpful hint when evaluating integrals is to determine the *sign* of the terms within the integrand over the specified interval. Here, where the interval begins at $x = 0$ and continues to $x = -7$, what is the mathematical sign of dt? Over this same interval, what is the mathematical sign of $f(x)$?
- What is most important when solving problems such as this is to be able to explain *why* (not just *how*) to arrive at the correct value. Try explaining the process of integration in your own words, as it applies to this particular problem.
- Suppose the unit of measurement for y is *volts*, and the unit of measurement for x is *seconds*. Identify the proper unit of measurement for $\int y\, dx$, and a possible real-world application with these units that would fit the graph.

file i04383

Question 65

Predict how the operation of this operational amplifier circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no coincidental faults):



- Resistor R_1 fails open:
- Solder bridge (short) across resistor R_1:
- Resistor R_2 fails open:
- Solder bridge (short) across resistor R_2:
- Broken wire between R_1/R_2 junction and inverting opamp input:

For each of these conditions, explain *why* the resulting effects will occur.

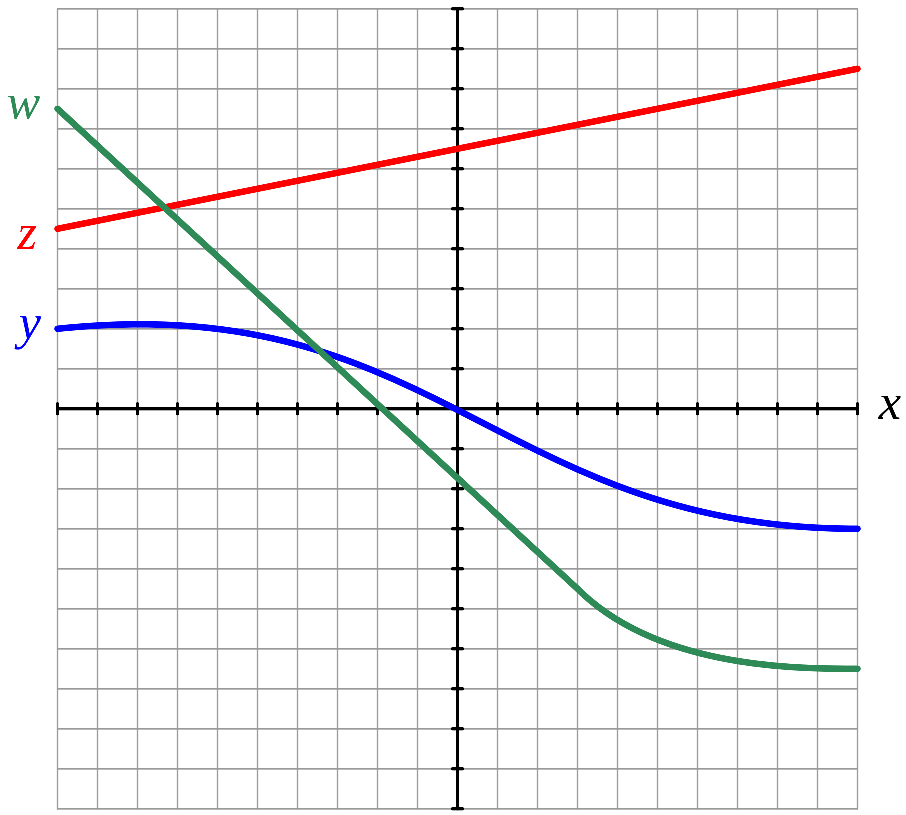
Suggestions for Socratic discussion

- When performing fault analyses of opamp circuits, it is helpful to bear in mind the simplifying assumptions of negative-feedback opamp circuits. Identify some of these assumptions, especially the one regarding input voltages to the opamp when negative feedback is in effect.

file i03269

Question 66

Shade the area(s) on this graph representing the following integral (assuming each horizontal and vertical division on the graph has an incremental value of 1):



$$\int_{-5}^{2} (z - y)\, dx$$

Also, determine whether the numerical value of this integral is *positive* or *negative*.

Suggestions for Socratic discussion

- Identify some possible units of measurement for z, y, and x that might fit the given integral. Given the units you choose, which unit of measurement would go with the interval limits -5 and 2?
- Challenge yourself by identifying *any other area* bounded by two of the functions on this graph and then writing an integral expression for that area.
- Challenge yourself by writing an arbitrary integral expression using any one function (y, w, or z) or the difference between any *two* of those functions, and any two starting and ending points on the x axis (interval limits), then shade the area on the graph represented by that expression.

file i01342

Question 67

A challenging concept for many students is determining whether the calculus concept of *differentiation* or *integration* needs to be applied to a particular problem. What follows here is a list of real-life applications for one or the other of these two calculus operations. Consider each application, then choose which calculus operation is proper to obtain the desired result, expressing your answer as a mathematical formula using proper calculus notation. Note that there is not enough information given to actually calculate a numerical answer – you will only be able to write a formula for each case:

A radiation sensor outputs a signal corresponding to the intensity of nuclear radiation (I) measured in *millirem per hour*. You need to be able to calculate the total dosage of radiation (D) measured in *millirem* received over one work shift (8:00 AM to 5:00 PM).

An open water storage reservoir loses water due to evaporation on hot, dry days. A level sensor on the reservoir outputs a volume signal (V) in units of *gallons*. You need to be able to calculate the loss rate (L) in *gallons per hour*.

A new business is about to open, and its proprietor wants to know how many advertising fliers to print and distribute. A local marketing firm provides statistics on the rate of new customer visits per flier (v) typically generated given different numbers of fliers (n) distributed within a month. For low numbers of fliers, very few customers will notice. For large numbers of fliers, the rate tends to go down as you saturate the advertising space. Therefore, the function of v plotted over n tends to be a bell curve: low at first, then peaking, then dropping off with increasing n. The proprietor wants to know how many fliers to print within the first month in order to have a certain minimum number of new customer visits (C).

A piston of area A is moved distance x to compress a gas inside of a cylinder. When compressed, the gas pressure (P) rises. You need to calculate the amount of work (W) done compressing the gas.

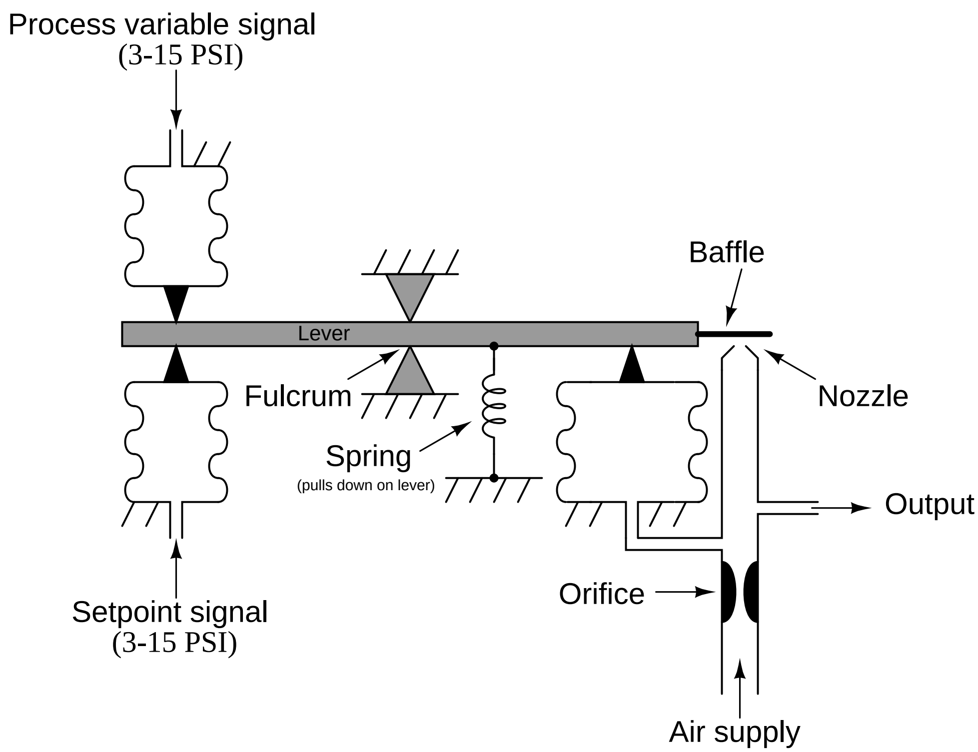
Suggestions for Socratic discussion

- A good problem-solving strategy for quantitative problems such as this one is to first identify what it is you need to solve, then identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and finally identify any "missing pieces" to a solution. Demonstrate how to do all these steps on this problem.
- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.
- Explain how *units of measurement* are especially in determining when to apply differentiation, versus when to apply integration.
- Graphically interpret each application, showing how the given variables could be represented in a graph, and then how the calculus operation could be applied to each graph.

file i01111

Question 68

Write the equation describing the behavior of this pneumatic controller, assuming the PV and SP bellows are equal area (1.3 in^2), the output bellows has an area of 2.6 in^2, the fulcrum is precisely mid-point on the lever, and the supply pressure is 22 PSI:



Next, identify at least two different ways to *increase the gain* of this proportional-only pneumatic controller, if you could change any aspect of its construction:

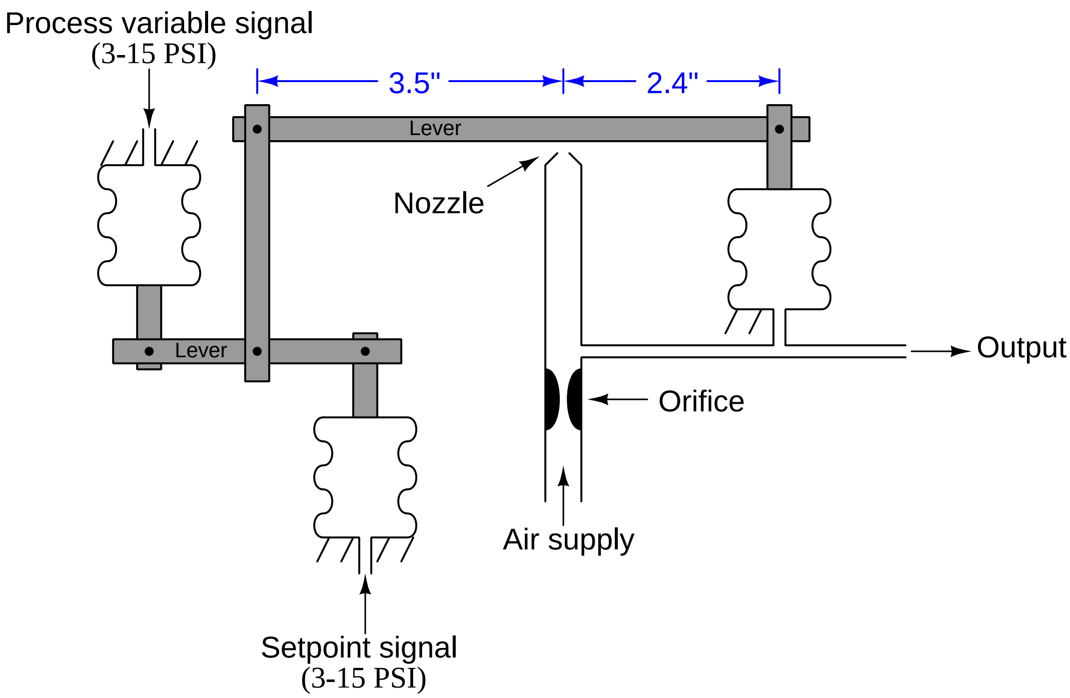
Suggestions for Socratic discussion

- Explain why it is important to determine whether the mechanism is *force-balance* or *motion-balance* in your analysis.
- Suppose someone suggested to you that the gain of this controller might be increased by enlarging the orifice. Explain why this would have no effect on gain.
- Suppose someone suggested to you that the gain of this controller might be increased by lengthening the lever (equally on both sides of the fulcrum) "so that the baffle was more sensitive to motion." Explain why this would have no effect on gain.
- Write a mathematical expression for the gain of this controller, using calculus notation.

file i03756

Question 69

Write the equation describing the behavior of this pneumatic controller, assuming identical bellows all around:



Next, identify at least two different ways to *adjust the bias* of this proportional-only pneumatic controller, if you could change any aspect of its construction:

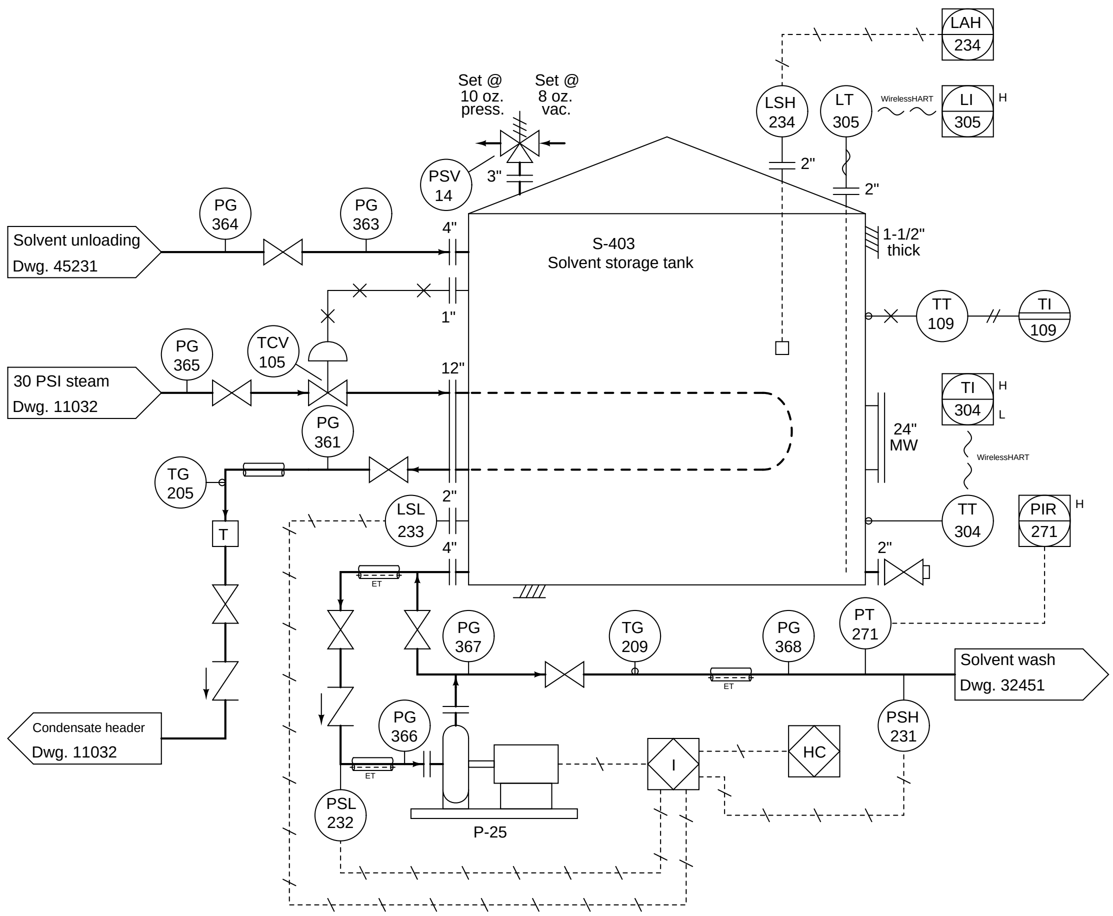
Suggestions for Socratic discussion

- Explain why it is important to determine whether the mechanism is *force-balance* or *motion-balance* in your analysis.
- A common mistake students make when sketching a pneumatic mechanism is to place the orifice (restrictor) between the output tube and the nozzle. Explain why this is wrong.

file i01666

Question 70

This solvent storage tank is filled from the truck unloading rack, and emptied by pump P-25 pumping solvent at a constant flow rate to the solvent wash process:



Level transmitter LT-305 monitors the volume of solvent stored in this tank. Over a period of several hours, an operator makes a log of solvent volumes and times:

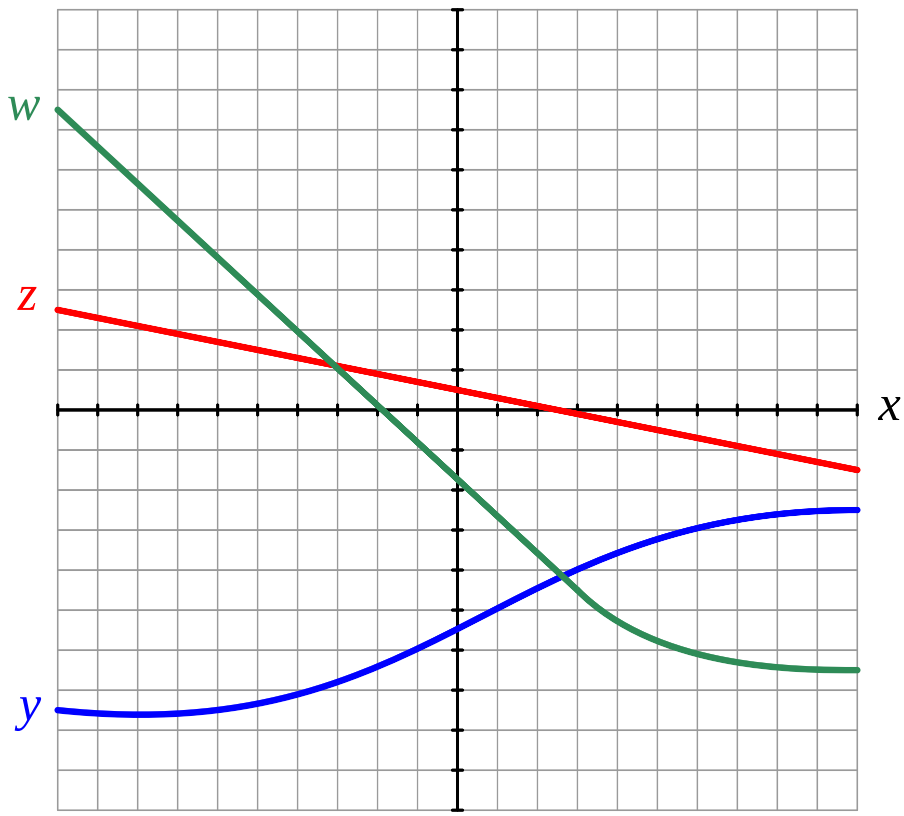
Solvent volume (gallons)	Time (hour:minute)
2951 gallons	2:45
2897 gallons	3:05
2843 gallons	3:25
2789 gallons	3:45
2735 gallons	4:05
3140 gallons	4:25
3086 gallons	4:45
3032 gallons	5:05

Your task is to determine the flow rate of solvent to the solvent wash process, the approximate time when the tank was re-filled, and the approximate re-fill flow rate from the supply truck. Sketch the graphical interpretation of this calculus problem, showing how a graph makes visual sense of the given information as well as the final result.

file i01922

Question 71

Shade the area(s) on this graph representing the following integral (assuming each horizontal and vertical division on the graph has an incremental value of 1):



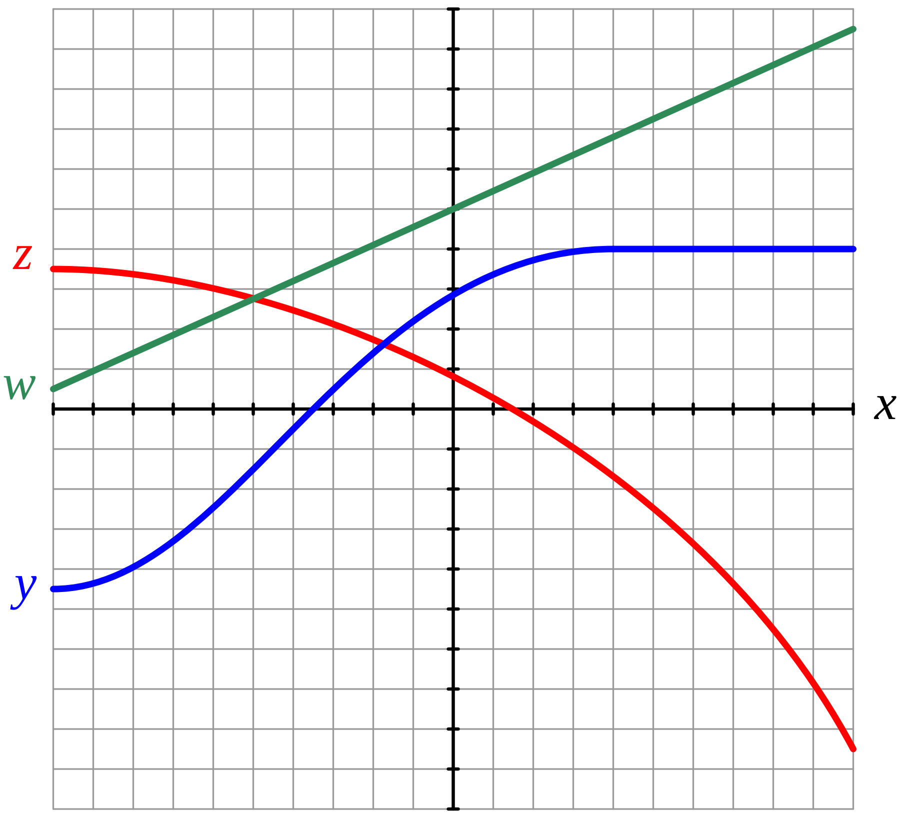
$$\int_{-6}^{6} (5 - z)\, dx$$

Also, determine whether the numerical value of this integral is *positive* or *negative*.

file i01920

Question 72

Shade the area(s) on this graph representing the following integral (assuming each horizontal and vertical division on the graph has an incremental value of 1):



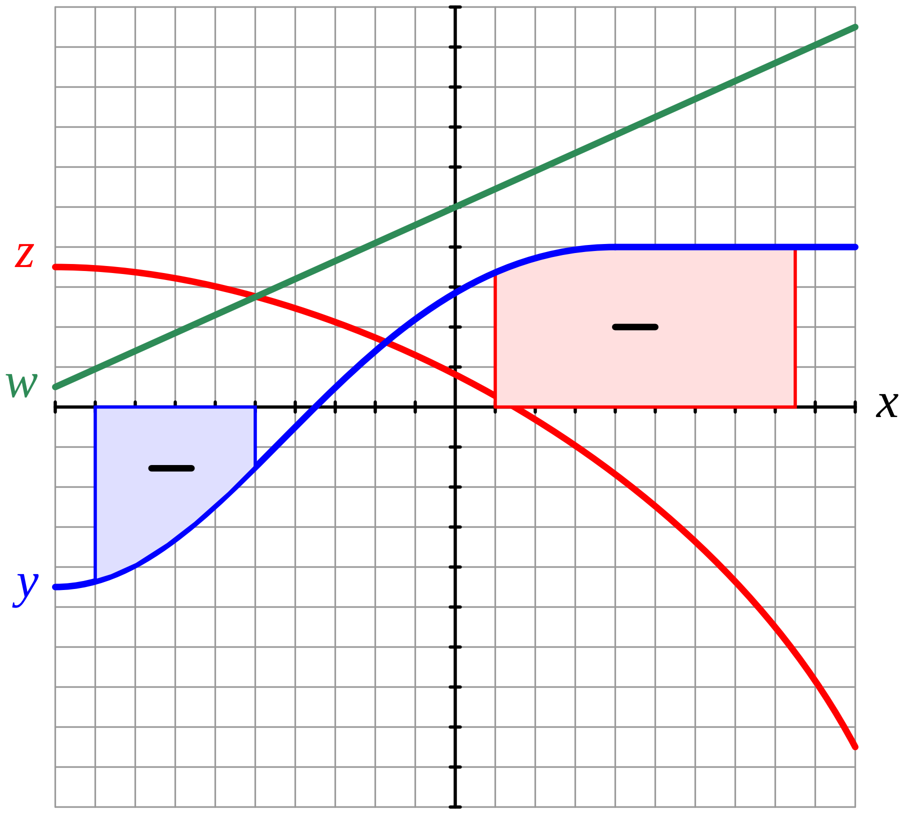
$$\int_{-7}^{0} (z - y)\, dx$$

Also, determine whether the numerical value of this integral is *positive* or *negative*.

file i01919

Question 73

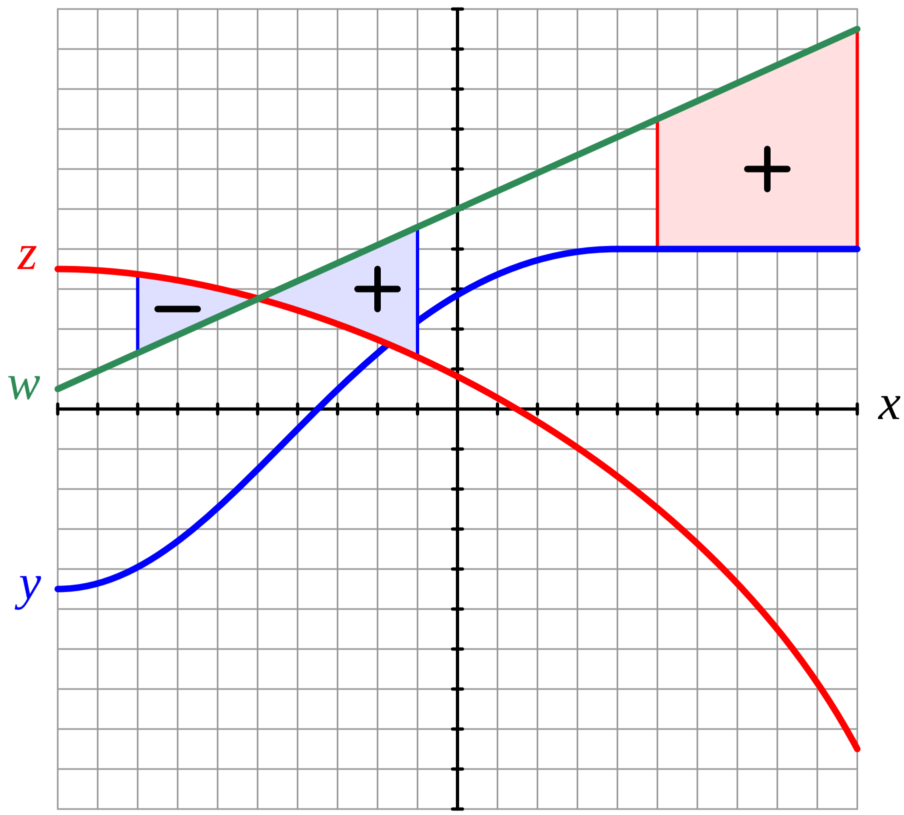
Write integral expressions for each of the shaded areas on this graph, assuming both areas have *negative* values:



file i01908

Question 74

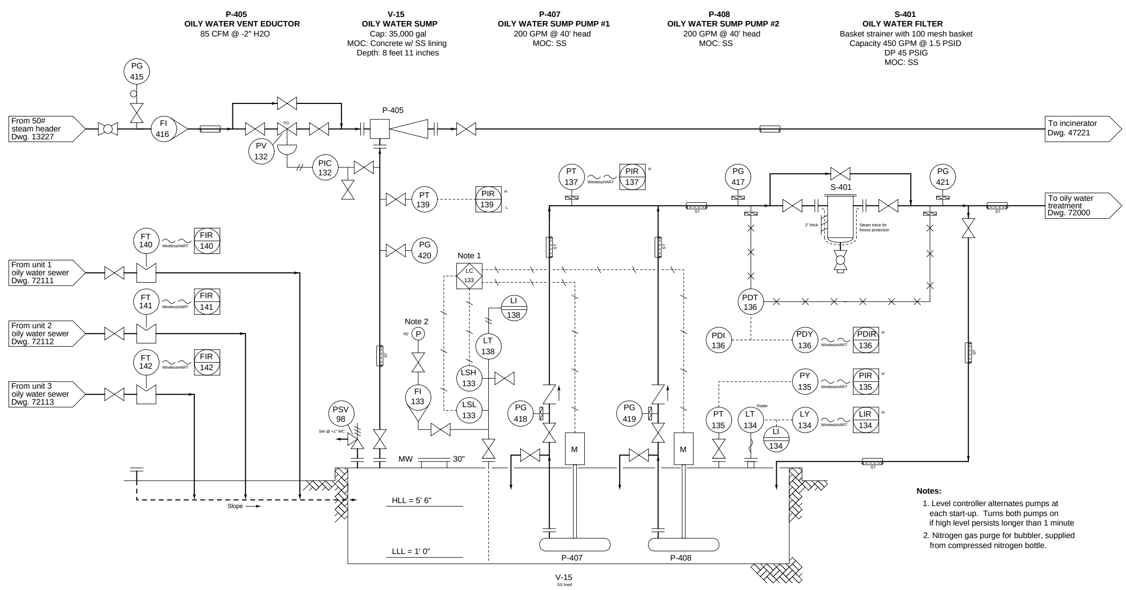
Write integral expressions for each of the shaded areas on this graph, assuming the mathematical signs (positive vs. negative) shown for each of the areas:



file i01918

Question 75

The flow of oily water from unit #3 is shut off, but units #1 and #2 are still sending oily water at constant flow rates to this sump:



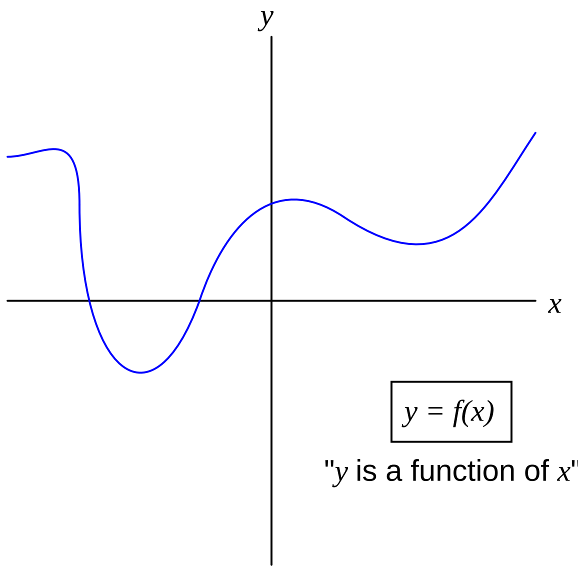
FIR-140 shows a constant flow rate of 3.5 gallons per minute, and FIR-141 shows a constant flow rate of 4.1 gallons per minute. At these flow rates, determine how long it will take for the oily water level inside the sump to accumulate from the low-level mark to the high-level mark, expressing the calculation using calculus notation.

Sketch the graphical interpretation of this calculus problem, showing how a graph makes visual sense of the given information as well as the final result.

file i01907

Question 76

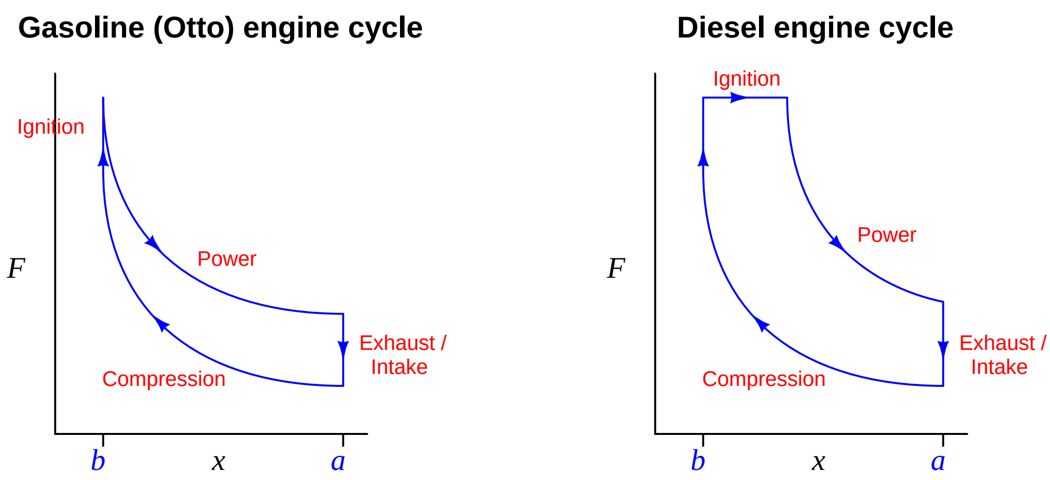
Qualitatively sketch the *derivative* of the function shown here. In other words, draw another function that describes how *quickly* the given curve changes:



file i01528

Question 77

Gasoline and diesel engines differ in their thermodynamic cycles. The Force/Stroke graphs of each engine type are shown here for comparison:



The prolonged ignition cycle of the diesel cycle is a consequence of how diesel fuel burns when it is injected into the hot, compressed air inside the cylinder: it burns in stages rather than all at once as is the case with a gasoline engine where the entire cylinder's volume is filled with an optimal mix of fuel and air.

Assuming all other factors are equal, which type of engine will deliver more net energy per cycle? Explain your reasoning.

file i04433

Question 78

Suppose an archer's longbow has a draw of 0.8 meters and a holding force of 340 newtons. Assuming a perfectly linear force-draw function, calculate the maximum speed of a 17 gram arrow shot by this bow.

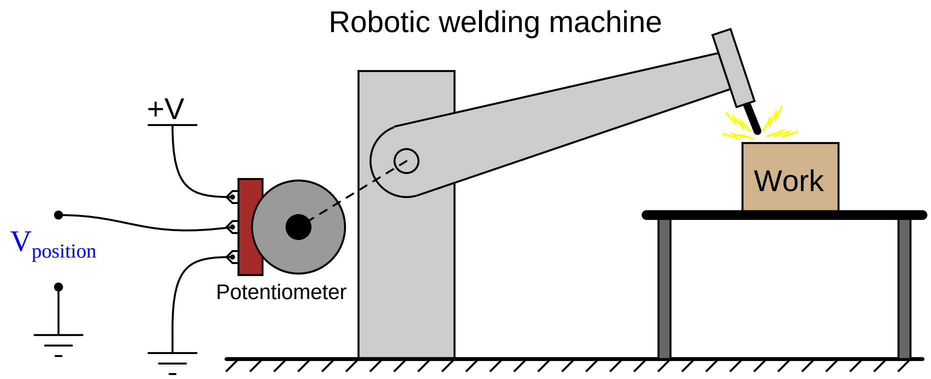
Suggestions for Socratic discussion

- A good problem-solving strategy for quantitative problems such as this one is to first identify what it is you need to solve, then identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and finally identify any "missing pieces" to a solution. Demonstrate how to do all these steps on this problem.

file i02149

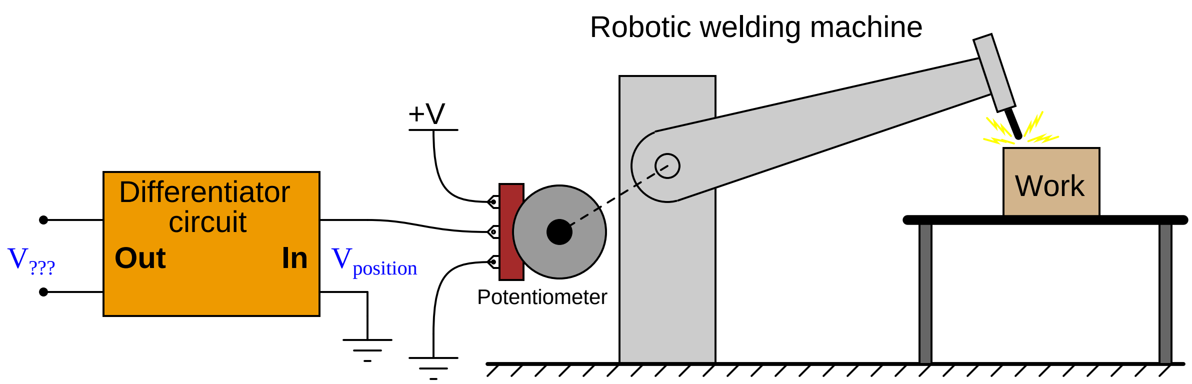
Question 79

Potentiometers are very useful devices in the field of robotics, because they allow us to represent the position of a machine part in terms of a voltage. In this particular case, a potentiometer mechanically linked to the joint of a robotic arm represents that arm's angular position by outputting a corresponding voltage signal:



As the robotic arm rotates up and down, the potentiometer wire moves along the resistive strip inside, producing a voltage directly proportional to the arm's position. A voltmeter connected between the potentiometer wiper and ground will then indicate arm position. A computer with an analog input port connected to the same points will be able to measure, record, and (if also connected to the arm's motor drive circuits) control the arm's position.

If we connect the potentiometer's output to a *differentiator* circuit, we will obtain another signal representing something else about the robotic arm's action. What physical variable does the differentiator output signal represent?



Suggestions for Socratic discussion

- Sketch an operational amplifier circuit capable of performing this differentiation on the position signal.
- What physical variable would we be calculating if we differentiated the output of the first differentiator circuit?

file i01513

Question 80

You are part of a team building a rocket to carry research instruments into the high atmosphere. One of the variables needed by the on-board flight-control computer is velocity, so it can throttle engine power and achieve maximum fuel efficiency. The problem is, none of the electronic sensors on board the rocket has the ability to directly measure velocity. What is available is an *altimeter*, which infers the rocket's altitude (its position up from ground in *meters*) by measuring ambient air pressure; and also an *accelerometer*, which infers acceleration (rate-of-change of velocity in *meters per second squared*) by measuring the inertial force exerted by a small mass.

The lack of a "speedometer" for the rocket may have been an engineering design oversight, but it is still your responsibility as a development technician to figure out a workable solution to the dilemma. How do you propose we obtain the electronic velocity measurement the rocket's flight-control computer needs?

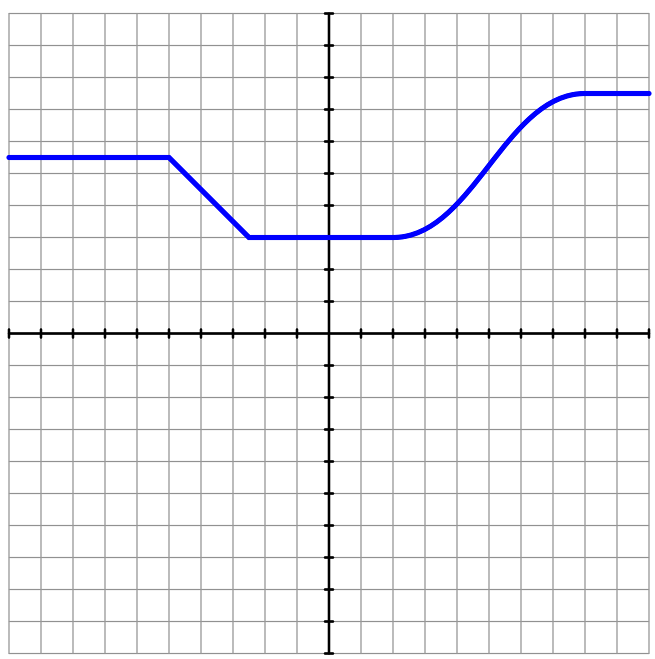
Suggestions for Socratic discussion

- A useful problem-solving technique for calculus-based problems is to sketch a graph of the variables being considered. The *derivative* of a function is the slope of the graph, while the *integral* of a function is the area bound by the graph. Apply this problem-solving technique to the problem at hand in this question.
- Suppose a ground-based radar is used to continuously track the rocket's altitude. Explain how data taken from this radar could be used to calculate rocket velocity.
- Explain how *units of measurement* are especially in determining when to apply differentiation, versus when to apply integration.

file i01568

Question 81

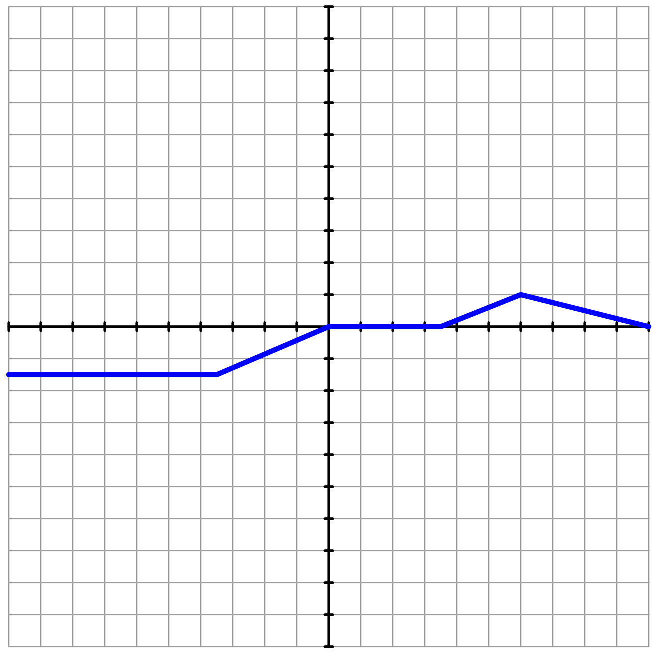
Sketch the curve of a function that is the *derivative* of the function shown on the graph:



file i04276

Question 82

Sketch the curve of a function that is the *integral* of the function shown on the graph:

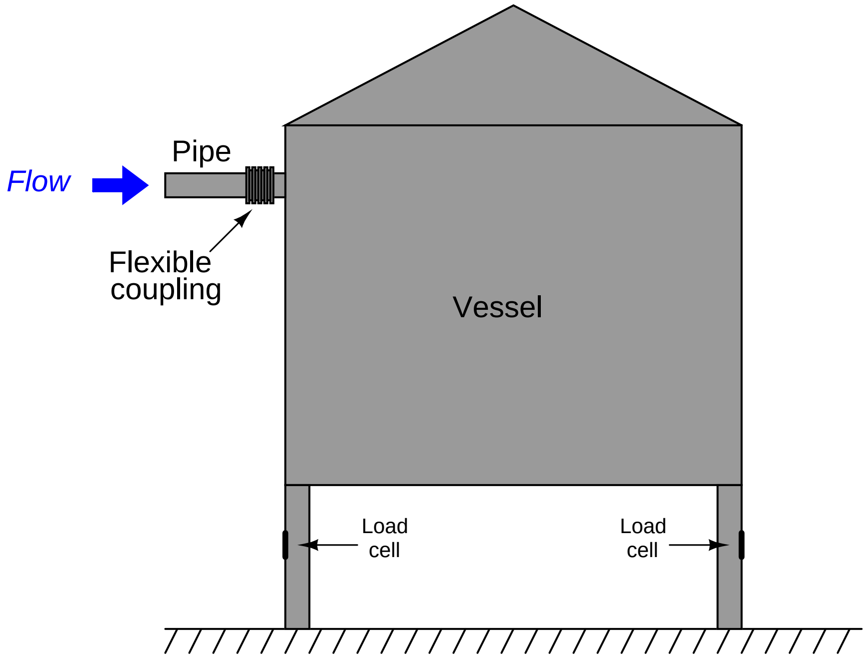


Note: the starting location of your sketch is arbitrary, making possible a multitude of correct answers for this question.

file i01632

Question 83

A liquid flows into a storage vessel:



Load cells installed on the vessel support legs provide a means of measuring accumulated liquid mass. A computer logs the gross weight of the vessel at 5 minute intervals:

Gross weight (pounds)	Time (hour:minute)
1342	4:55
2003	5:00
2624	5:05
3255	5:10
3927	5:15

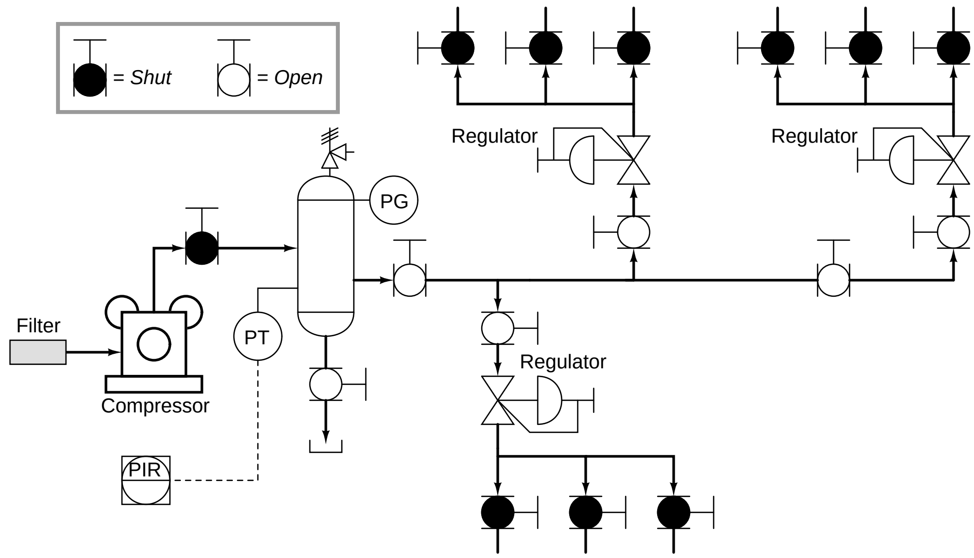
Calculate the following:

- The mass flow rate of the liquid (in units of pounds per hour) at 5:07
- The average mass flow rate of the liquid (in units of pounds per hour) since the beginning of the hour

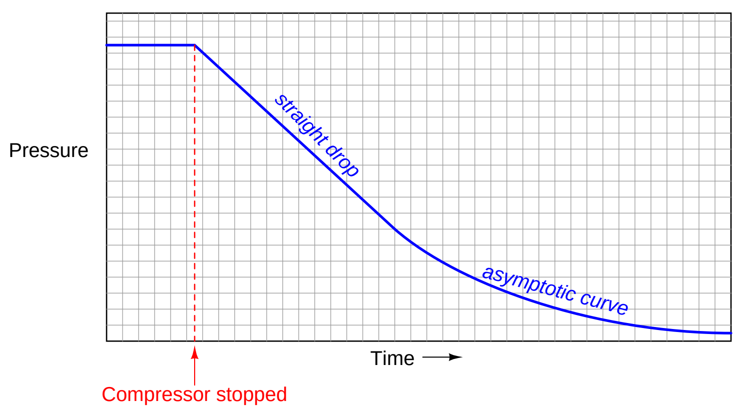
file i01552

Question 84

A compressed air system has a leak, and you are part of a group of technicians asked to locate the leak. A pressure transmitter measuring receiver tank pressure is connected to a trend recorder, offering a way for you monitor tank pressure over time. Setting up for the leak test, one of the technicians on your team runs the compressor until the receiver tank gauge registers normal (full) pressure, then she shuts off the compressor and begins shutting off all the valves shown (dark) in this P&ID:



After waiting a few hours, you examine the trend of the receiver tank pressure, shown here:



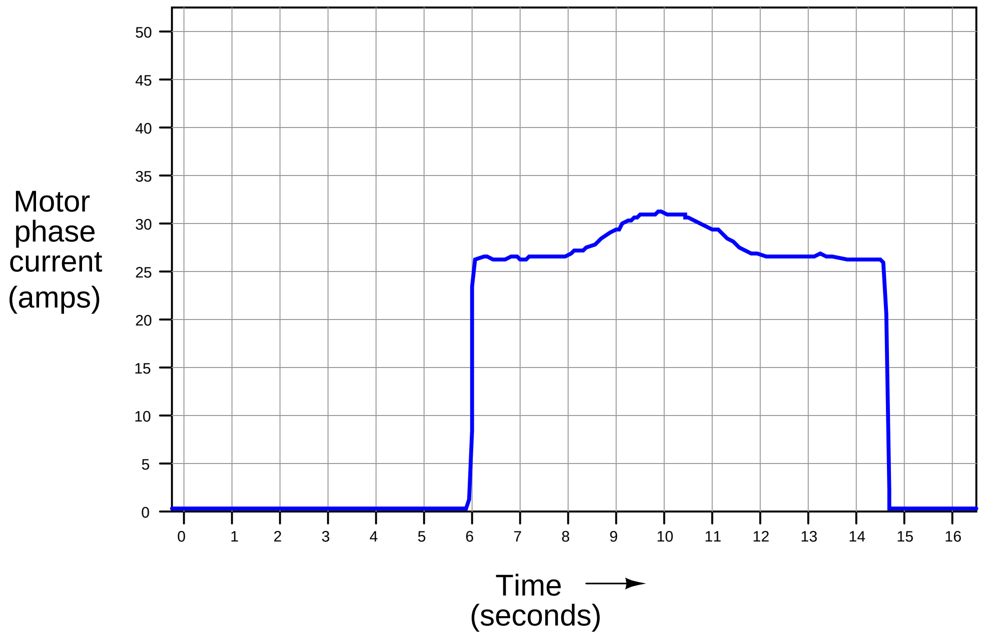
Another technician on your team sees this trend and exclaims, "Ah-Ha!! We know the leak is downstream of a pressure regulator, not upstream!" Puzzled by this, you ask your teammate to explain. "Look at the shape of the trend: a straight line sloping down, followed by a curve asymptotically approaching zero PSI. If the leak were upstream of a regulator, the whole downward trend would be asymptotic with no straight portions. If you take the Ideal Gas Law ($PV = nRT$) and express it as a differential equation over time ($\frac{dP}{dt}V = \frac{dn}{dt}RT$), you see that the rate of pressure fall ($\frac{dP}{dt}$) is proportional to the rate of air molecule leakage ($\frac{dn}{dt}$)."

Explain what your teammate is trying to say, in your own words. *Why* would the location of an air leak in this system make a difference in the *shape* of the trend? Furthermore, what would you do to isolate the location of the leak, now that you know it is downstream of a regulator?

file i01553

Question 85

A trend recorder is connected to a *current transformer*, which is clamped around one of the power conductors leading to the three-phase electric motor powering a utility elevator. As the elevator lifts a load, the motor's torque translates into line current which is measured and plotted by the trend recorder. The heavier the load lifted, the more torque output by the motor, and the more current drawn by the motor.



Calculate the approximate amount of *work* done by this elevator (in the unit of joules), knowing that the power of a three-phase electric motor is equal to line voltage (480 volts) times line current (graphed) times the square root of 3, and also knowing that one *watt* is equivalent to one *joule* of work performed each *second* (watts = joules per seconds):

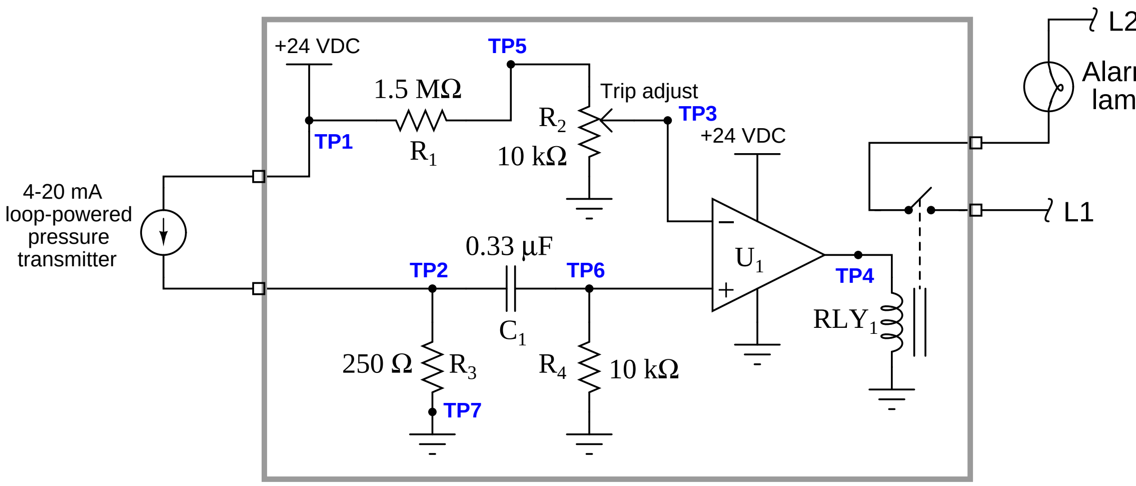
$$P = V_{line} I_{line} \sqrt{3}$$

Also, explain the significance of the "hump" appearing mid-way in the elevator's travel. What does this odd shape suggest about the elevator?

file i01613

Question 86

This is a simple rate-of-change detector circuit, designed to produce an alarm if the input signal rate-of-change becomes excessive:



Unfortunately, though, this circuit has a problem. The alarm light never comes on, no matter how rapidly the pressure rises at the pressure transmitter. Your first diagnostic measurement is to check for AC voltage between L1 and L2: there, you measure 116 volts AC.

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
C_1 failed open		
R_1 failed open		
R_3 failed open		
R_4 failed open		
C_1 failed shorted		
R_1 failed shorted		
R_3 failed shorted		
R_4 failed shorted		
RLY_1 coil failed open		
U_1 output failed to low supply rail		
U_1 output failed to high supply rail		

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

file i03616

Question 87

Suppose you construct a spring catapult to launch a projectile straight up into the air. Your catapult uses a winch to tense the spring, and a release mechanism to unleash the spring's stored energy to launch the projectile. While building this catapult, you are interested in predicting the velocity of the projectile as it leaves the catapult, as well as the maximum height the projectile can attain if shot vertically.

First, identify all the relevant variables you would need to determine the values of in order to calculate both projectile velocity and projectile apogee.

Next, write an equation solving for the velocity of the projectile (v) as it leaves the catapult, as a function of the spring's initial compression distance (x):

$v = f(x) =$

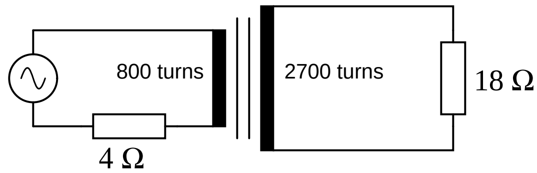
Finally, write an equation solving for the maximum height (apogee) the projectile is able to attain (h) as it leaves the catapult, as a function of the spring's initial compression distance (x):

$h = f(x) =$

file i01110

Question 88

Calculate all voltages and all currents in this transformer circuit, assuming the resistor in the primary side of the circuit drops 9 volts:

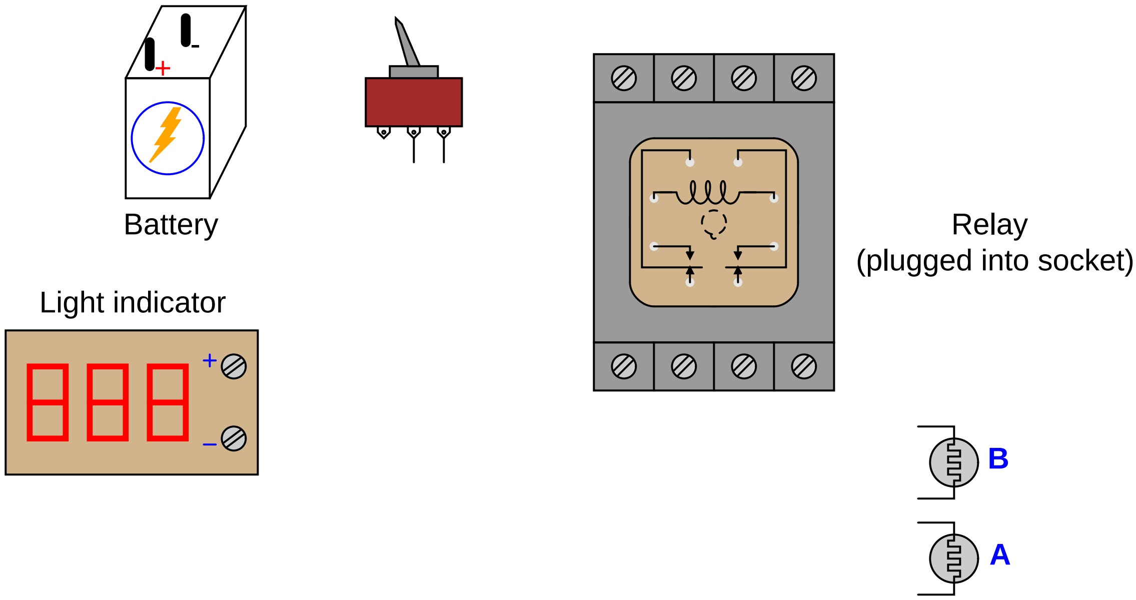


- V_{source} =
- $V_{primary}$ =
- $V_{secondary}$ =
- $I_{primary}$ =
- $I_{secondary}$ =

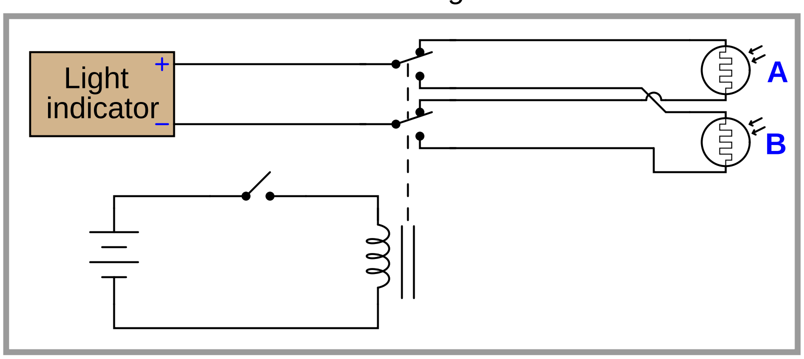
file i01270

Question 89

Sketch connecting wires such that the relay will select one of two different photocells to send signals to a light indicator. Use the following schematic diagram as a guide:



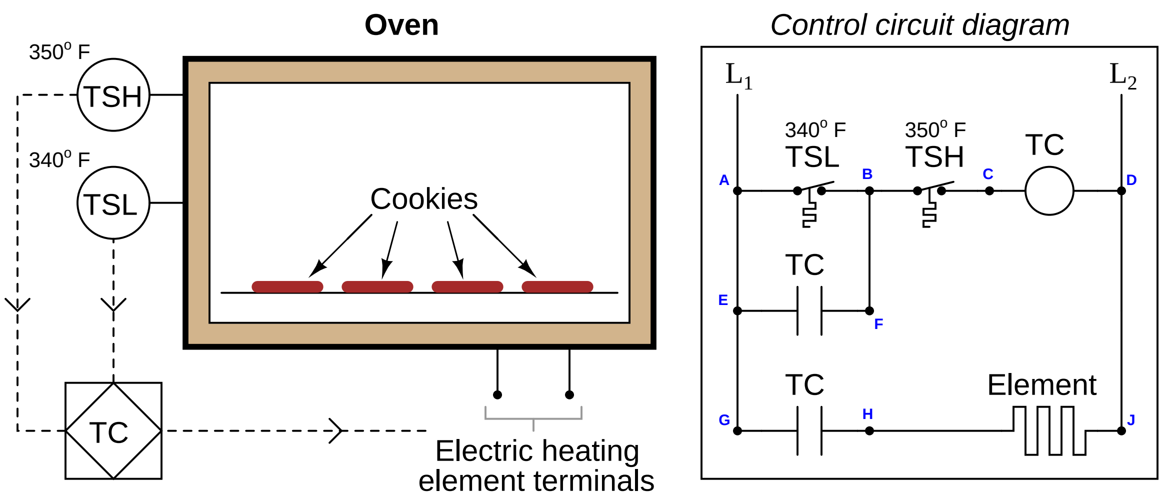
Schematic diagram



file i01420

Question 90

This oven temperature control system has a problem: the oven refuses to heat up when power to the control circuit is turned on:



A voltmeter registers 117 volts AC between test points **G** and **H** in the control circuit with the power applied and the oven cold, and registers 0 volts AC between test points **E** and **F** under the same conditions.

From this information, identify two possible faults (either one of which could account for the problem and all measured values in this circuit), and also identify two circuit elements that could not possibly be to blame (i.e. two things that you know *must* be functioning properly, no matter what else may be faulted). The circuit elements you identify as either possibly faulted or properly functioning can be wires, traces, and connections as well as components. Be as specific as you can in your answers, identifying both the circuit element and the type of fault.

- Circuit elements that are possibly faulted

1.
2.

- Circuit elements that must be functioning properly

1.
2.

file i03536

Question 91

Lab Exercise – introduction

Your task is to build, document, and calibrate a *split range* valve system with another team, where a pair of control valves are controlled by the output of a single pneumatic controller in its "manual" mode. Each control valve will use a pneumatic positioner (not an electronic positioner!) to implement the split-ranges. Each instrument in the loop should be labeled with a proper tag name (e.g. "HV-78a" and "HV-78b" for two split-ranged, hand-controlled valves), with all instruments in each loop sharing the same loop number. Write on pieces of masking tape to make simple labels for all the instruments and signal lines.

An additional objective of this lab is to properly cut, bend, and fit metal instrument tubing. Each student is to bend a length of copper or stainless-steel tubing somewhere in their pneumatic controller/valve system and demonstrate to the instructor that the tubes all fit neatly (right-angle corners, proper offsets, level and plumb). Instrument tube bending is something of an art, and requires practice to master.

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

Objective completion table:

Performance objective	**Grading**	**1**	**2**	**3**	**4**	**Team**
Team meeting and prototype sketch (do *first!*)	mastery	–	–	–	–	
Circuit design challenge	mastery					– – – –
Alignment of positioner to valve	mastery					– – – –
Split-range calibration (with saturation)	mastery					– – – –
Final loop diagram and system inspection	mastery					– – – –
Metal tubing properly fitted	mastery					– – – –
Demonstration of working system	mastery	–	–	–	–	
Safety and professionalism	deduction					
Lab percentage score	proportional					– – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

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

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

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

Lab Exercise – objectives and expectations

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

Team meeting and prototype sketch

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

Circuit design challenge

Wire a VFD to a single-phase power source and a three-phase electric motor, then configure the VFD to control the starting and stopping of that motor according to criteria randomly chosen by the instructor.

Final loop diagram and system inspection

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

Alignment of positioner to valve

Correctly mount, connect, and mechanically align a positioner to the control valve following all instructions given in the manufacturer's documentation.

Split-range calibration

Calibrate the positioner to fulfill its portion of the split-range scheme agreed upon by all participating teams. The positioner should be fully "saturated" at its signal end-points to ensure full valve stem travel and seat loading.

Metal tube fitting

Bent and fit a short length of metal tubing to connect two devices together, as randomly chosen by the instructor.

Demonstration of working system

Show that the control valve operates correctly over its portion of the split range, using the controller's manual mode to set the 4-20 mA "manipulated variable" signal value.

Lab percentage score

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

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

Safety and professionalism (deduction)

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

General format and philosophy

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

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

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

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

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

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

An absolutely essential step in completing this lab exercise is to work together as a team to **sketch a prototype diagram** showing what you intend to build. This usually takes the form of a simple diagram showing all tubing used to connect pneumatic instruments together. This prototype sketch need not be exhaustive in detail, but it does need to show enough detail for the instructor to determine if all components will be correctly connected for their safe function.

You should practice good problem-solving techniques when creating your prototype sketch, such as consulting equipment manuals for information on component functions and marking directions of air flow. 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.

You team will need to install a pneumatic positioner on a control valve, and then split-range this positioner in conjunction with another team's valve. While valves lacking positioners can be split-ranged, the task of split-ranging is greatly simplified by using a positioner because it is relatively easy to change zero and span settings. The Fisher model 3582 valve positioner is highly recommended for this lab exercise. Consult documentation from the manufacturer's website to identify how to properly mount, align, and tube the valve positioner.

The control valve should have mounting holes on its actuator assembly for receiving a positioner bracket. This metal bracket will serve as the mounting "platform" for the positioner once attached to the valve actuator. Brackets and positioners are not universal in design – that is, they are made to match each other.

Positioners act as "position controllers" for control valves, sending enough air pressure as necessary to move the valve to match the signal given by the controller's output. As controllers in their own right, positioners require a supply of compressed air to "power" them. This air supply often needs to be of a different (greater) pressure than the air supply of an I/P signal converter. For piston-actuated valves, the positioner often runs on 100 PSI compressed air, while a typical I/P converter typically runs on only 20 PSI. As always, consult the manufacturer's manual for air supply specifications.

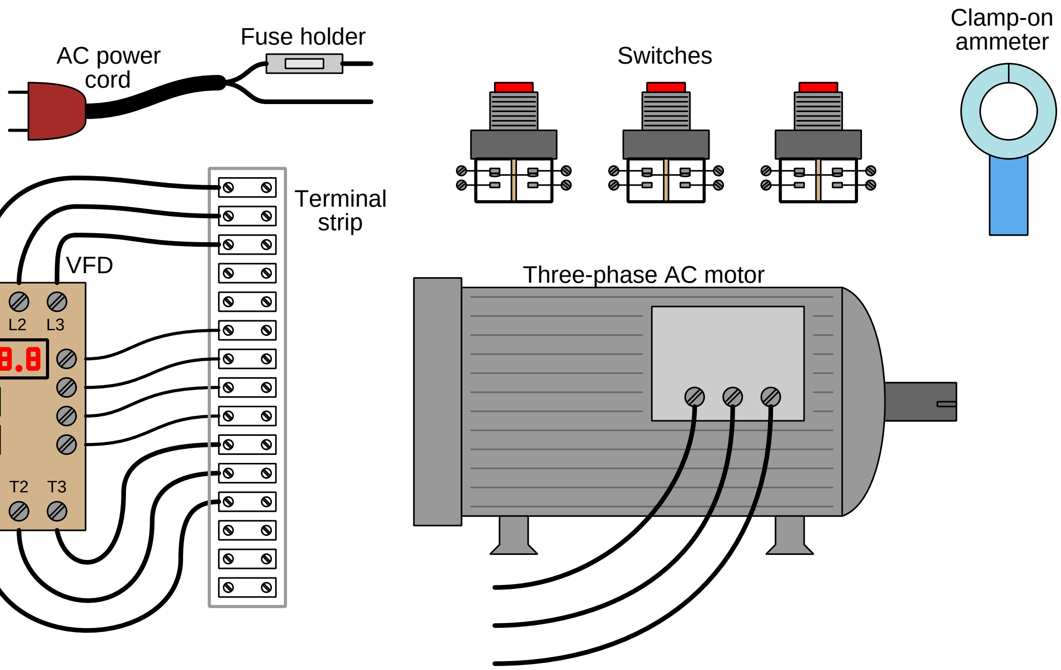
Common mistakes:

- Not checking valve stroke length for proper configuration before installing the positioner.
- Improper pipe/tube fitting installation (e.g. trying to thread tube fittings into pipe fittings and vice-versa).
- Applying Teflon tape to tube fitting threads; failing to apply Teflon tape to pipe fitting threads.

Lab Exercise – circuit design challenge

Connect a variable-frequency motor drive (VFD) to a source of single-phase 120 VAC power and a three-phase electric motor, then demonstrate remote start and stop control over that motor using two or more switches. The motor's speed control will be set by the knob or buttons (keypad) on the VFD, and the motor's acceleration/deceleration rates will be configured for gentle starts and stops. All electrical connections must be made using a terminal strip (no twisted wires, crimp splices, wire nuts, spring clips, or "alligator" clips permitted). The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to correctly wire a VFD to a power source and to a three-phase induction motor, reset VFD parameters to their default values, program correct parameters in a VFD to control it per specified criteria, and to use a clamp-on ammeter to measure motor line current.



The following components and materials will be available to you: **variable-frequency motor drive**, with input, control, and motor power wires pre-wired to a terminal strip (this reduces wear and tear on the drive's screw terminals) ; 120 VAC **power cord** with **fuse assembly** ; **three-phase electric motor** ; lengths of **hook-up wire** ; assorted **switches**, and a **clamp-on ammeter** or adapter for use with a multimeter.. You must provide your own tools and digital multimeter (DMM) as well as a copy of this page for your instructor to mark objectives.

You are not allowed to apply power to the VFD, nor start the motor. The instructor will do both, following inspections of your work.

SEQUENCE: (1) Instructor chooses control parameters; (2) You wire and test while unpowered; (3) Instructor verifies wiring is safe for energization; (4) Instructor energizes VFD for the first time and observes you resetting VFD parameters; (5) You program VFD with all necessary parameters; (6) Instructor verifies safe parameters programmed in VFD; (7) Instructor starts and stops motor; (8) You demonstrate correct use of clamp-on ammeter to measure motor line current.

Control options (instructor chooses): ____ SW1 = Forward/Stop, SW2 = Reverse/Stop
____ SW1 = Start, SW2 = Stop, SW3 = Forward/Reverse

Acceleration/Deceleration rate (instructor chooses): ____ seconds (*5 seconds minimum!*)

Maximum motor speed (instructor chooses): __________ RPM

How to reset the VFD to factory defaults (you research and describe):

Instructor inspects wiring and powers up VFD, you reset VFD ____ (completed)

Base motor parameters (from nameplate):
V_{line} = __________ Volts
I_{line} = __________ Amps @ full load
Speed = __________ RPM @ 60 Hz

Instructor inspects critical VFD parameters and starts motor, you measure I_{line} ____ (completed)

Study reference: the "Variable Frequency AC Motor Drives" learning module in the *Modular Electronics Learning Project* (ModEL) collection provides general information on VFD parameters. The manual for your specific model of VFD will be absolutely necessary to reference!

Lab Exercise – aligning the positioner

Perhaps the most tedious detail in this lab exercise is properly aligning the mechanical components of the positioner such that the positioner receives accurate and linear feedback of the valve stem's position throughout the range of the control valve. Improper linkage alignment will result in non-linear valve travel (i.e. if 0% and 100% is accurate, 25%, 50% and/or 75% will not be). The manufacturer's documentation is your ultimate guide to proper alignment of the positioner-to-stem linkage.

Additionally, your positioner will likely need to have its internal components aligned with each other. For example, on the Fisher model 3582 positioner, there is a full "beam alignment" procedure which must be followed in order to ensure consistent positioning behavior throughout the range of the valve stem's travel and also throughout the range of the positioner's span adjustment.

For rotary control valves where the positioner receives its feedback from a cam follower, there is less to align than on a sliding-stem control valve. However, other internal alignments to the positioner such as the "crossover" adjustment must still be checked and adjusted. Once again, the manufacturer's documentation will step you through any and all procedures necessary.

After successful alignment, the instructor will mis-adjust the alignment to make the positioner ready for the next person to re-align it.

A detail important for both safety and time management is to make sure you do not disturb the coupling of the valve body and actuator stems when connecting the positioner to the stem. On Fisher sliding-stem valves, particularly, the stem connector bolts must be un-done to attach the positioner's feedback linkage. If the stem connector is loosened with full spring force applied to the valve seat (as is the case with any sliding-stem, air-to-open valve when no air pressure is applied), the actuator stem will slip loose and suddenly shift. This will not only hurt your fingers if they are in the way of the actuator stem when it slips, but it will also necessitate a re-setting of the coupling between the valve body and actuator stems which can be time-consuming.

To avoid this problem on air-to-open valves, first apply enough air pressure to the actuator to raise the plug off the seat and relieve the seating force before loosening the stem coupling! With the valve plug held off the seat by air pressure, you may loosen the stem coupling with no risk of harm to yourself and little risk of disturbing the coupling position.

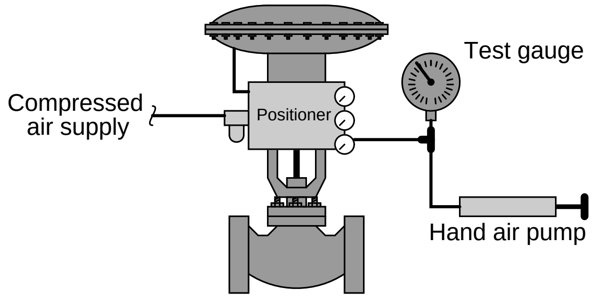
Another important safety tip is that the positioner's feedback linkage must not be adjusted while the positioner is powered and active. Remember that the positioner's function is to apply as much or as little force to the valve stem as needed to achieve the desired stem position, and the only way the positioner "knows" what that stem position is, is via the feedback linkage assembly. If you make adjustments to this feedback linkage while the positioner is powered, it will "think" the valve stem is moving when it should not, and rapidly act to re-position the valve. This is dangerous when your fingers are touching the feedback linkage, because the valve's rapid movement may pinch your fingers. Furthermore, any such adjustments will be counter-productive because the valve stem will not remain still as you are attempting to make those adjustments.

Common mistakes:

- Disturbing the valve body/actuator stem coupling by disassembling the coupling when the actuator spring pressure is still seating the plug.
- Incorrect installation and/or alignment of the linkage coupling the positioner to the valve stem: *consult the manual when installing your team's positioner to see exactly how it should attach!*
- Failing to follow all manufacturer instructions *precisely*, failing to reference figures on different pages than the text, etc.
- Attempting to adjust the feedback linkage while the positioner is powered, which is both futile and dangerous.

Lab Exercise – calibrating the positioner

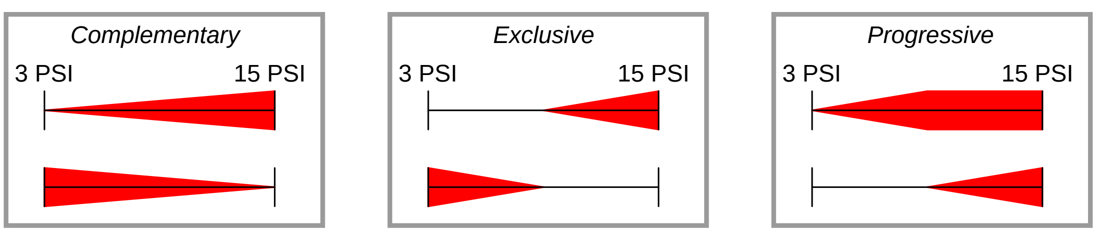
When finished installing the positioner, you should test it prior to building the rest of the loop system. Simply simulate the output signal of a pneumatic loop controller by using a hand air pump and a test gauge indicating the 3-15 PSI signal pressure:



One of the criteria for a successful positioner calibration is that the positioner must "saturate" its output pressure(s) when the valve reaches full stroke. For example, on a simple air-to-open valve calibration (i.e. 3 PSI = valve at 0% position ; 15 PSI = valve at 100% position), the positioner should saturate beyond bench-set pressure at full signal (15 PSI) and saturate at 0 PSI at minimum signal (3 PSI) to ensure full seat loading. Note that the valve's bench-set range may be completely different from the positioner's input signal range of 3-15 PSI, for example 10-30 PSI. In such applications the positioner will automatically adapt to the valve's bench set because that is what positioners do: apply as much or as little actuating pressure to the valve as necessary to move the stem to where it needs to be (as directed by the 3-15 PSI input signal). The requirement of full saturation at 3 and 15 PSI input is in addition to accurate positioning at all points between 0% and 100%.

Mechanical positioners have interactive "zero" and "span" calibration adjustments much like analog transmitters, requiring multiple adjustments to get right. Calibrating a mechanical positioner for a given range is therefore more tedious than doing so with a digital electronic "smart" positioner. As always, you should consult the manufacturer's documentation to determine the proper calibration procedure for your valve's positioner.

You will need to agree with the other team on a particular split-ranging scheme (e.g. complementary, exclusive, or progressive), then calibrate each valve accordingly:



Be sure to note the limitations of your team's valve when deciding on a split range: some positioners are limited in the ranges they can handle (e.g. some positioner models cannot be configured for reverse action)!

When you are done calibrating the positioner, attach a calibration tag to it:

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

CALIBRATED	CALIBRATED	CALIBRATED	CALIBRATED
By: ____ Date: ____	By: ____ Date: ____	By: ____ Date: ____	By: ____ Date: ____
Range:________	Range:________	Range:________	Range:________

Common mistakes:

- Not learning about the *other* positioner (different model) in your split-range loop, but rather focusing exclusively on your team's positioner
- Incorrect supply pressure given to positioner
- Assuming the positioner's input signal pressure needs to match the actuating pressure

Installing and roughly calibrating a positioner should take no more than one full lab session (3 hours) if all components are readily available and the student is working efficiently!

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.

After getting your prototype sketch approved by the instructor, you are cleared to begin building the split-ranged valve system. This will consist of a pneumatic loop controller placed into "manual" mode to allow direct control over the position of your team's valve as well as the valve of one more team.

There will be no transmitter installed in this loop. Feel free to use 1/4 inch plastic tubing for all pneumatic signal connections, and be sure not to exceed the rated supply pressure for any instrument.

Select a specific loop controller to act as a "hand control" station for the valves. This may be a rack-mounted pneumatic controller (e.g. Foxboro model 130) or a field-mounted pneumatic controller (e.g. Foxboro model 43AP or Fisher Multi-Trol). The controller itself should be labeled "HC-" or "HIC-" because it is a "hand" controller, allowing a human operator manual control over the valve's position.

Finally, your split-range valve 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 form a two-digit number from the equivalent resistor color-code values for your teams' colors. For example, if you are the "Red" team, and the partnering team is "Blue," your loop number could be "26". The two valves will then be distinguished by suffix letters (e.g. HV-26a and HV-26b).

Common mistakes:

- Applying Teflon tape to tube fitting threads.
- Failing to apply Teflon tape to pipe fitting threads.
- Failing to properly tighten each tube 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 from two working valves 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 simulaneous 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 seperation 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 tube fitting

An additional objective of this lab is learn how to properly bend instrument tubing. Each student is to bend a length of copper or stainless-steel tubing somewhere in their pneumatic controller/valve system and demonstrate to the instructor that the tubes all fit neatly (right-angle corners, proper offsets, no gradual bends, all straight sections level and plumb). Instrument tube bending is something of an art, and requires practice to master!

An ideal application for tube bending are the lines to and from a valve positioner. Alternatively, you may bend and fit tubes for the pneumatic controller's air supply line, the line connecting controller to positioner, etc. Which ever run of tubing you plan to bend, the work should be coordinated with those team members aligning and calibrating the positioner, so as to not create interference in the work schedule.

Rolls of soft copper tubing will be provided by the instructor to use in this lab exercise. Each student's tube run should be relatively short (less than 2 feet) in order to conserve the amount of tubing used. Expect to make at least two attempts when fitting your tube run!

Videos are available on the BTC Instrumentation YouTube channel showing some of the basic procedures of tube cutting, bending, and compression fitting make-up. Each team has a professional-quality 1/4-inch tube bender in their locker, to be used for this exercise. Your Instrumentation Reference also contains manuals from both Swagelok and Parker describing how instrument tube fittings work, and how to properly fit tubing.

Common mistakes:

- Applying Teflon tape or other sealant to tube fitting threads (not necessary!).
- Forgetting to apply Teflon tape or other sealant to pipe fitting threads (necessary!).
- Throwing away used tube fittings when done with the job. Remember than although tube *ferrules* cannot be re-used, the nuts and fitting bodies can!
- Over-tightening compression fittings (only 1-1/4 turns past initial contact are necessary when *first* "making-up" the tube connection!). When re-making tube connections, you need only "snug" the nut, not re-swage with another 1-1/4 turns!
- Trying to straighten a piece of tubing that has already been bent.

Lab Exercise – decommissioning and clean-up

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

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

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

Return the following components to their proper storage locations:

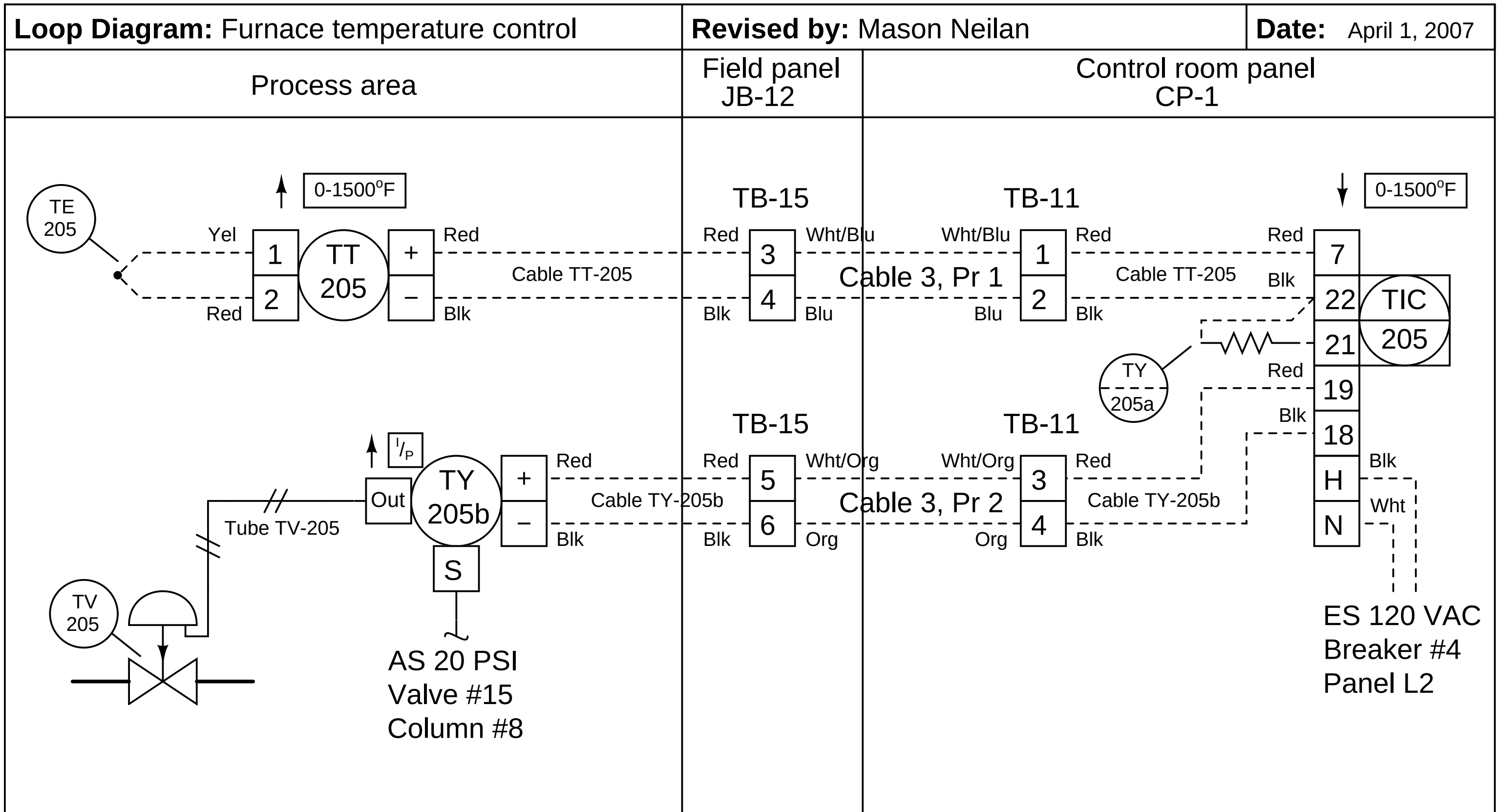
- Sensing elements (e.g. thermocouples, pH probes, etc.)
- Process transmitters
- "Jumper" cables used to connect terminal blocks within a single junction box
- Plastic tubing and tube fittings (disconnect compression-style tube fittings)
- Power cables and extension cords
- Adjustment (loading station)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

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

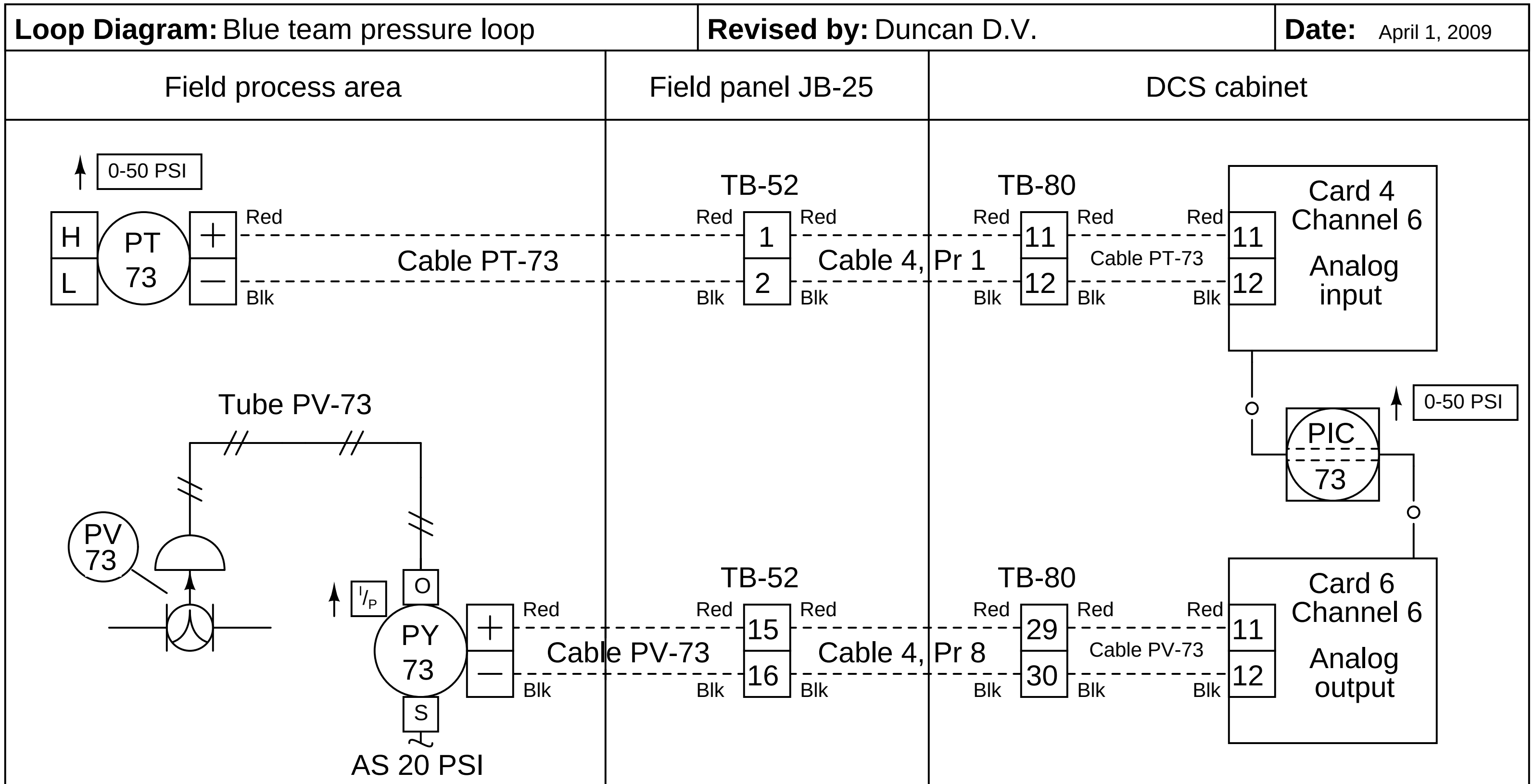
file i02584

Question 92

Sample Loop Diagram (using a single-loop controller)

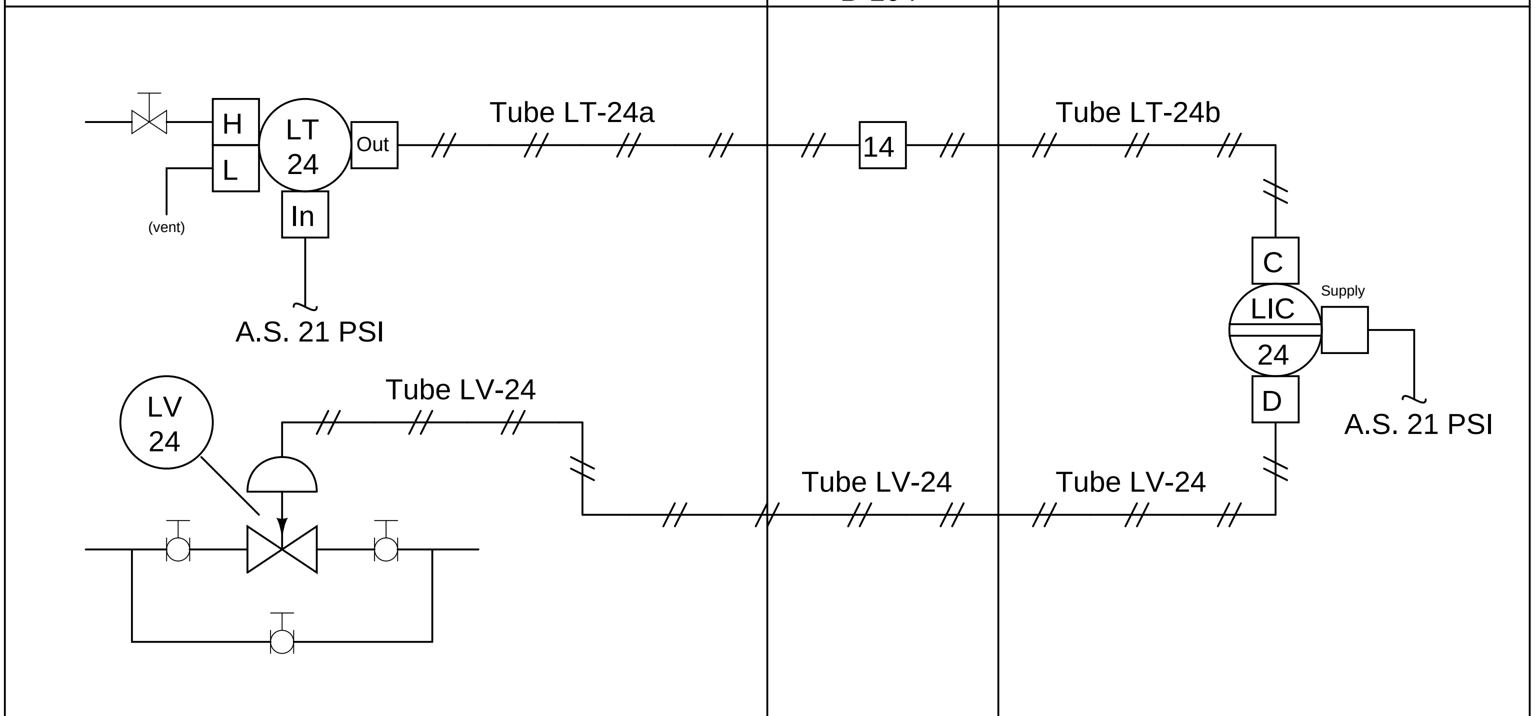


Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
TE-205	Thermocouple	Omega			Type K	Ungrounded tip
TT-205	Temperature transmitter	Rosemount	444	0-1500° F	4-20 mA	Upscale burnout
TY-205a	Resistor	Vishay			250 Ω	
TIC-205	Controller	Siemens	PAC 353	1-5 V	0-1500° F	Reverse-acting control
TY-205b	I/P transducer	Fisher	546	4-20 mA	3-15 PSI	
TV-205	Control valve	Fisher	Easy-E	3-15 PSI	0-100%	Fail-closed



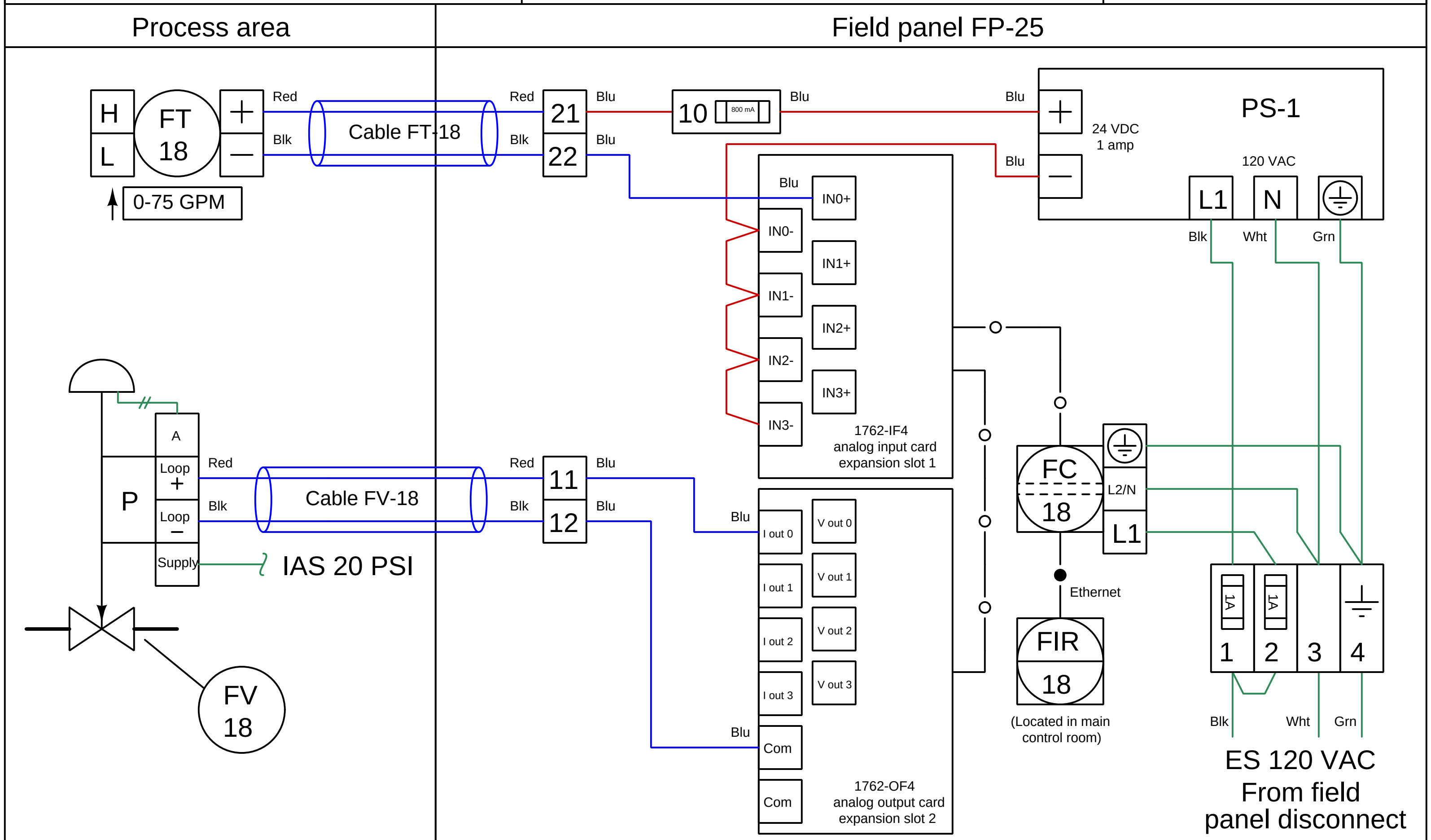
Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
PT-73	Pressure transmitter	Rosemount	3051CD	0-50 PSI	4-20 mA	
PIC-73	Controller	Emerson	DeltaV	4-20 mA	4-20 mA	HART-enabled input Direct-acting control
PY-73	I/P transducer	Fisher	846	4-20 mA	3-15 PSI	
PV-73	Control valve	Fisher	Vee-ball	3-15 PSI	0-100%	Fail-open

Loop Diagram: Sludge tank level control	**Revised by:** I. Leaky	**Date:** April 1, 2008
Process area	Bulkhead panel B-104	Control panel CP-11



Tag #	Description	Manufacturer	Model	Input range	Output range	Notes
LT-24	Level transmitter	Foxboro	13A	25-150 "H_2O	3-15 PSI	
LIC-24	Controller	Foxboro	130	3-15 PSI	3-15 PSI	
LV-24	Control valve	Fisher	Easy-E / 667	3-15 PSI	0-100%	Fail closed

Loop Diagram: Unit feed flow control	**Revised by:** A. Bradley	**Date:** April 1, 2013



Tag number	Description	Manufacturer	Model	Calibration	Notes
FT-18	Flow transmitter	Rosemount	3051S	0-100" WC input 4-20 mA output	Square-root characterization
FC-18	PLC	Allen-Bradley	ML1100	1762-IF4 input 4-20 mA 1762-OF4 output 4-20 mA	IP = 169.254.10.9 Mask = 255.255.0.0
FIR-18	HMI touch-panel	AutomationDirect	C-More		
FV-18	Flow valve with positioner	Fisher	ED / 667 DVC6010	4 mA = fully closed 20 mA = fully open	Fail-closed

Lab Exercise – loop diagram and system inspection

Each team's system will undergo an inspection simulaneous 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 seperation lines on the diagram.
- Each diagram must be sufficiently detailed so that no other student will have difficulty locating components (e.g. *"Where is the controller for this loop?"*) or determining important configuration parameters (e.g. range settings).

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

Common mistakes:

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

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

file i00654

Answer 1

Answer 2

Answer 3

Answer 4

- Between 2:17 and 2:18, average speed = **48.0** MPH
- Between 2:18 and 2:25, average speed = **39.4** MPH
- Between 2:25 and 2:27, average speed = **66.0** MPH
- Between 2:17 and 2:27, average speed = **45.6** MPH

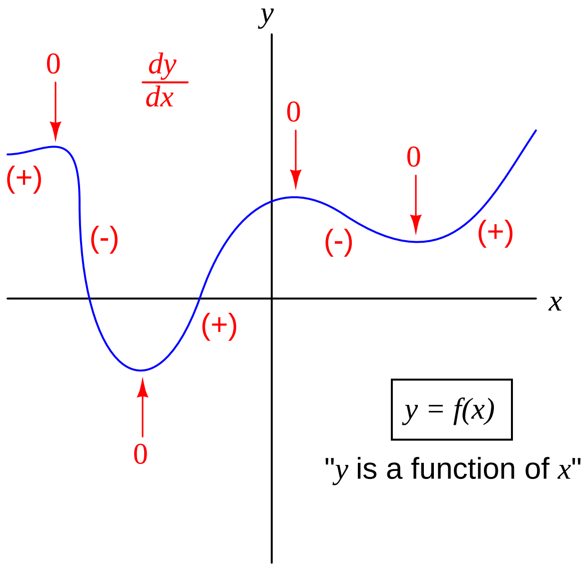
Answer 5

- Between 9:17 and 9:21, average flow = **221.18** GPM
- Between 9:21 and 9:23, average flow = **186.2** GPM
- Between 9:23 and 9:26, average flow = **224.13** GPM
- Between 9:17 and 9:26, average flow = **214.39** GPM

Answer 6

Answer 7

The graphical interpretation of "derivative" means the *slope* of the function at any given point.



Answer 8

$\frac{dy}{dx} = +2$

Answer 9

A mathematically-correct expression for this derivative:

$$\frac{d\text{pH}}{dm}$$

Answer 10

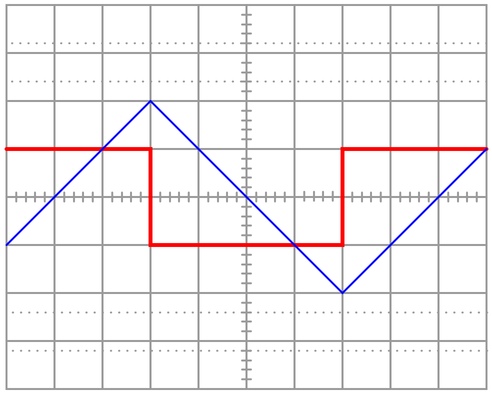
Answer 11

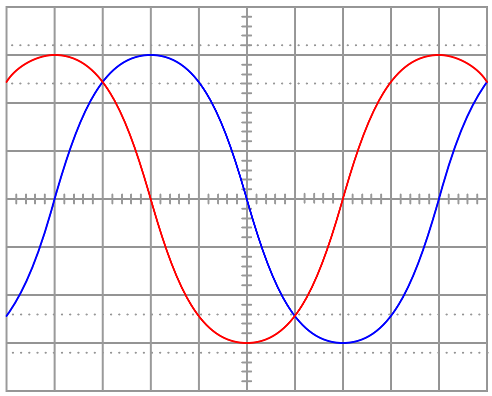
In order to reach the next toll booth in "too short" of time, the driver *must* have exceeded the speed limit. However, it is possible to exceed the speed limit for relatively short periods of time and still not reach the next toll booth "too soon."

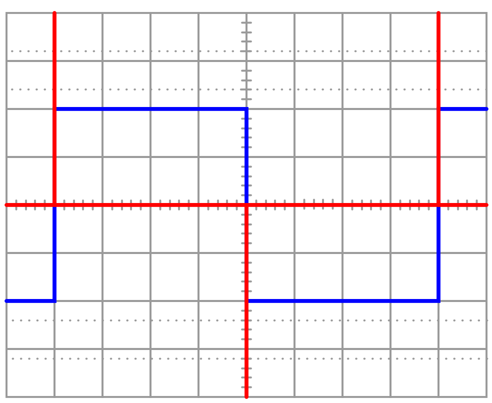
Answer 12

- Mass of radioactive substance (m), decay rate (r), and time (t) $r = \frac{dm}{dt}$
- Liquid volume (V), liquid flow (Q), and time (t) $Q = \frac{dV}{dt}$
- Speed (v), acceleration (a), and time (t) $a = \frac{dv}{dt}$
- Work (W), power (P), and time (t) $P = \frac{dW}{dt}$
- Voltage (V), current (I), and incremental resistance (R) $R = \frac{dV}{dI}$
- Magnetizing force (H), magnetic flux density (B), and permeability (μ) $\mu = \frac{dB}{dH}$
- Cost (C) to manufacture items, number of items (x), and marginal cost (C') $C' = \frac{dC}{dx}$

Answer 13







Follow-up question: what electronic device could perform the function of a "current-to-voltage converter" so we could use an oscilloscope to measure capacitor current? Be as specific as you can in your answer.

Answer 14

$\frac{dy}{dx} = -2$

Answer 15

$\frac{dy}{dx} = 0$

Answer 16

$\frac{dy}{dx} = +2$

Answer 17

$\frac{dy}{dx} = -0.7$

Answer 18

$\frac{dy}{dx} = +1$

Answer 19

$\frac{dy}{dx} = -1$

Answer 20

$\frac{dy}{dx} = +1$

Answer 21

Answer 22

I will let you explain the procedure for doing this! The approximate distance traveled by this car between 2:14 and 2:35 is somewhere between 20.22 miles and 20.65 miles, depending on your procedure.

Answer 23

Speed is the derivative of distance. In other words, if the speedometer broke, we could calculate the vehicle's speed by differentiating the odometer's reading (distance traveled) with respect to time.

Distance is the integral of speed. In other words, if the odometer broke, we could calculate the distance traveled by integrating the speedometer's reading with respect to time.

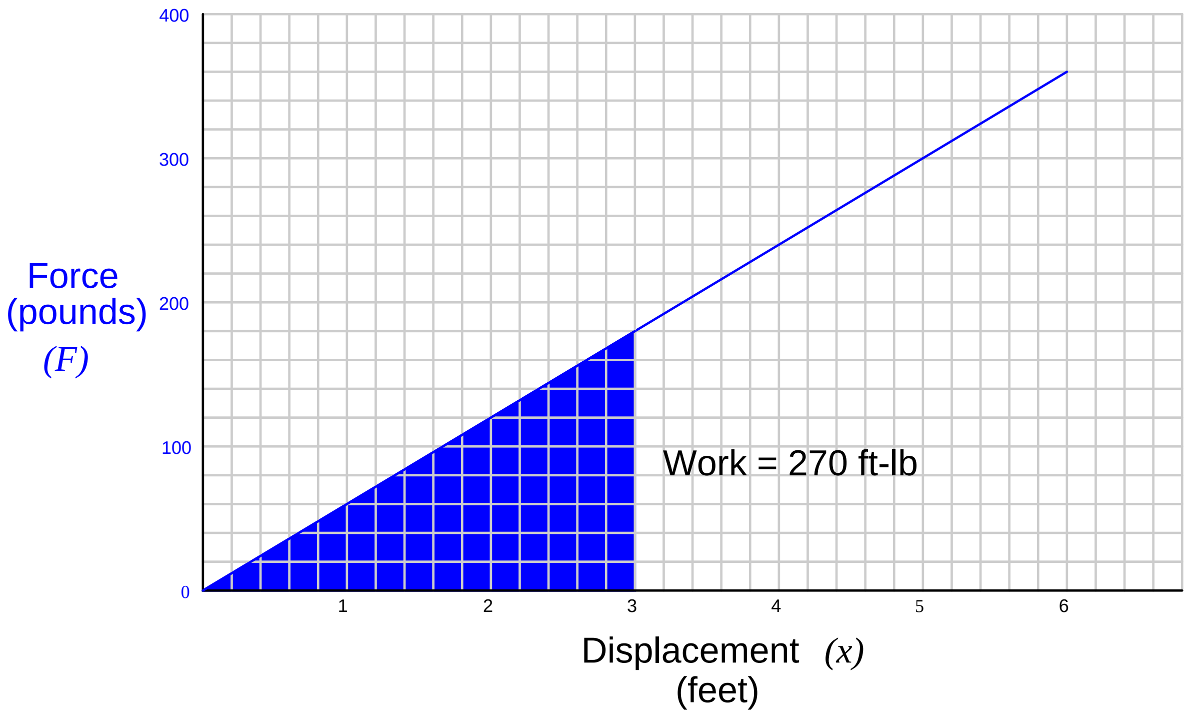
If the speed holds steady at some non-zero value, the distance will accumulate at a steady rate. If the distance holds steady, the speed indication will be zero because the car is at rest.

Answer 24

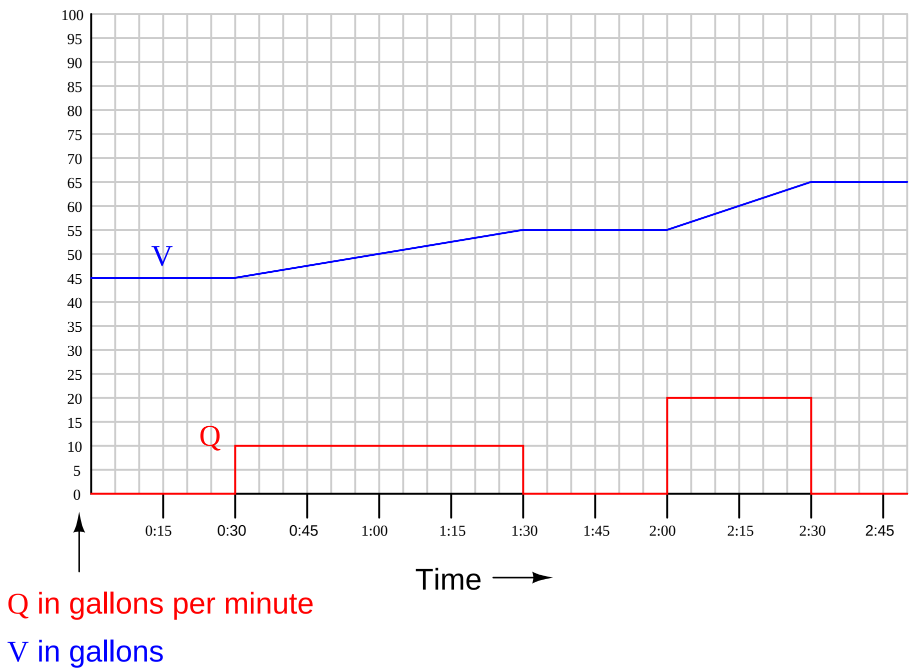
$$W = \int F \, dx$$

$$1000 \text{ ft-lb} = \int_{0 \text{ ft}}^{4 \text{ ft}} 250 \text{ lb} \, dx$$

Answer 25



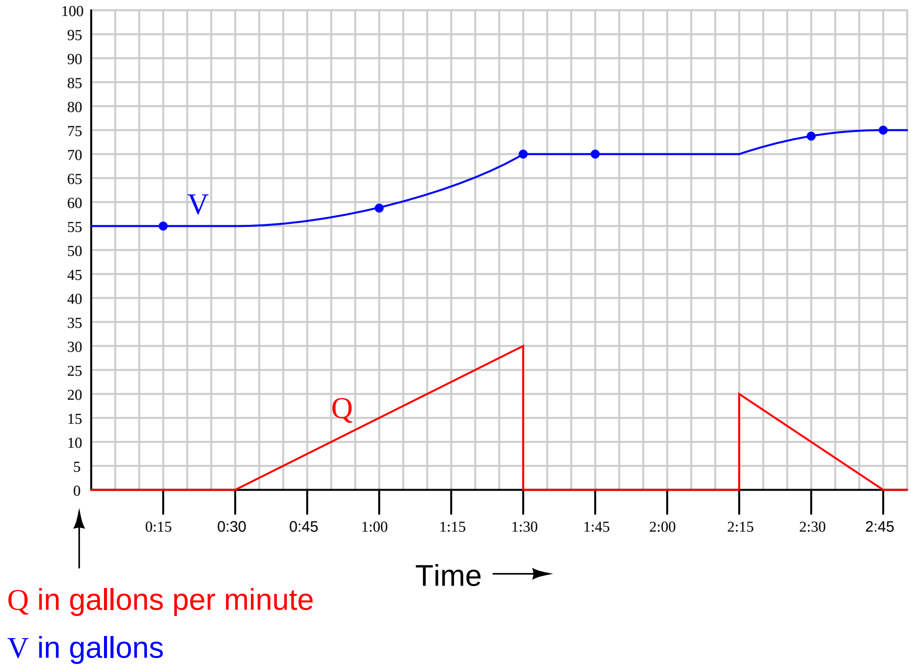
Answer 26



Answer 27

- Time = 0:15; Volume = 55 gallons
- Time = 1:30; Volume = 70 gallons
- Time = 1:45; Volume = 70 gallons
- Time = 2:45; Volume = 75 gallons

- Time = 1:00; Volume = 58.75 gallons
- Time = 2:30; Volume = 73.75 gallons



Answer 28

-9

Answer 29

$+5$

Answer 30

Answer 31

The Isaac Newton Credit Union differentiates S by dividing the difference between consecutive balances by the number of days between those balance figures. Differentiation is fundamentally a process of division.

To integrate the $\frac{dS}{dt}$ values shown on the Credit Union's statement so as to arrive at values for S, we must either repeatedly add or subtract the days' rate-of-change figures, beginning with a starting balance. Thus, integration is fundamentally a process of multiplication.

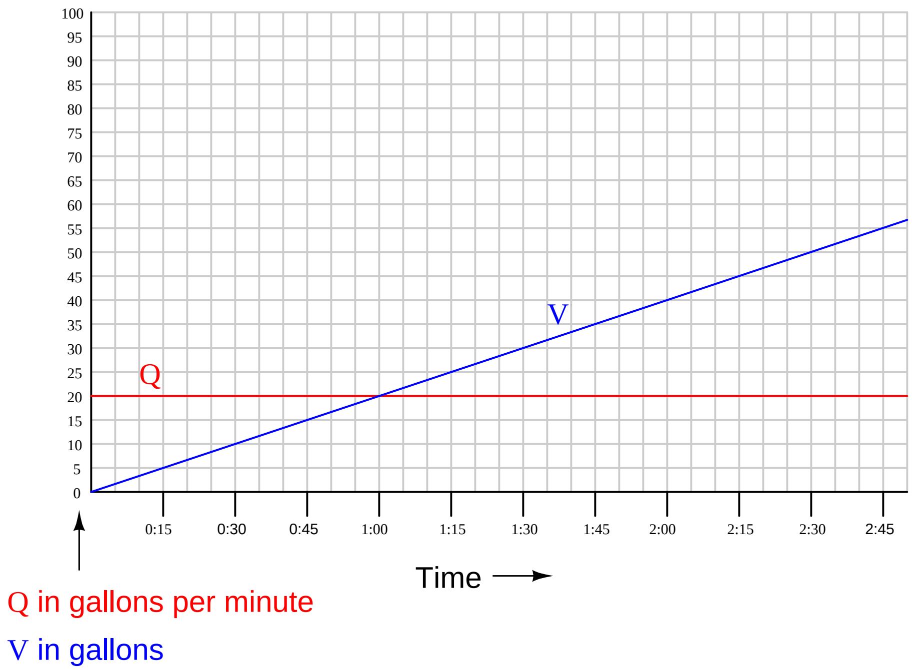
Follow-up question: explain why a starting balance is absolutely necessary for the student banking at Isaac Newton Credit Union to know in order for them to determine their account balance at any time. Why would it be impossible for them to figure out how much money was in their account if the only information they possessed was the $\frac{dS}{dt}$ figures?

Answer 32

FIQ-38 is a mass flow totalizer, integrating the mass *flow rate* signal coming from flow transmitter FT-38 to arrive at a total mass of fuel gas burned over time. Realistic units of measurement would be kilograms or pounds (mass).

In order to do the same for stack emissions, we would need to measure the flow rate of exhaust through the incinerator stack, then multiply that flow rate signal by each pollutant's measured concentration (to arrive at flow rate for each pollutant), then integrate each of those pollutant gas flow rates over time to calculate pollutant volumes.

Answer 33

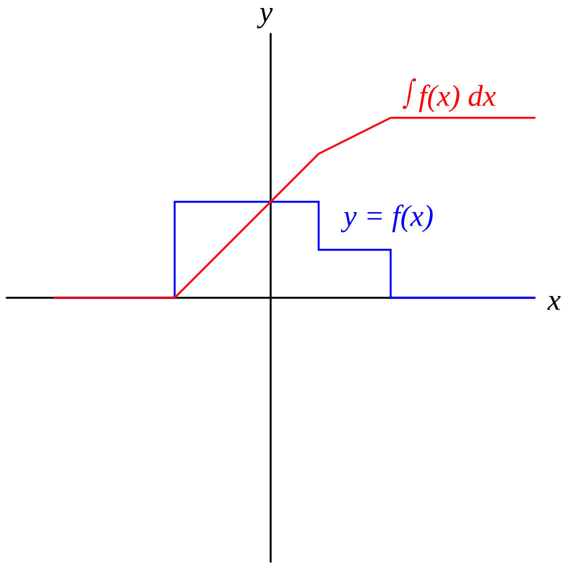


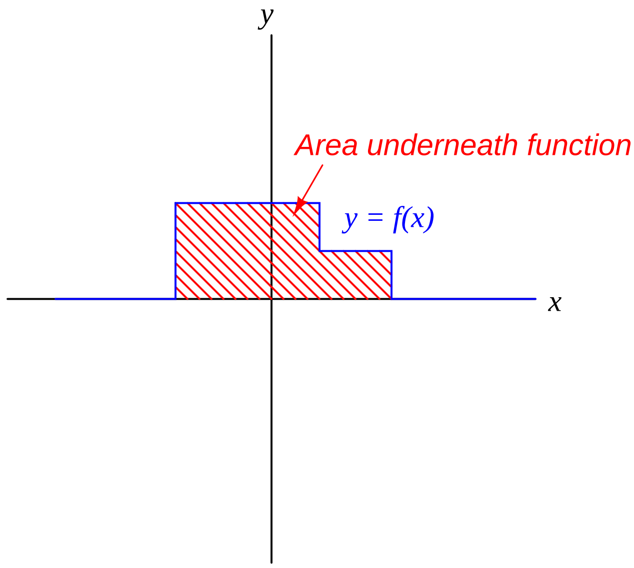
I will let you explain the importance of assuming an empty vessel to start!

- Time = 1:00; Volume = 20 gallons
- Time = 1:30; Volume = 30 gallons
- Time = 2:00; Volume = 40 gallons
- Time = 2:30; Volume = 50 gallons
- Time = 2:45; Volume = 55 gallons

Answer 34

The graphical interpretation of "integral" means the *area* accumulated underneath the function for a given domain.





Answer 35

+13

Answer 36

−5

Answer 37

-3

Note how the interval of integration starts at $x = +2$ and proceeds to $x = -2$. This means the integration proceeds in a negative direction, from $+2$ to -2 on the horizontal axis. Another way of saying this is that each differential of x is a negative quantity ($dx < 0$). This explains why the integral value is a negative quantity (-3) despite the fact that y never goes below zero during the entire interval of integration.

Answer 38

$+21$

Answer 39

$+10.07$

Answer 40

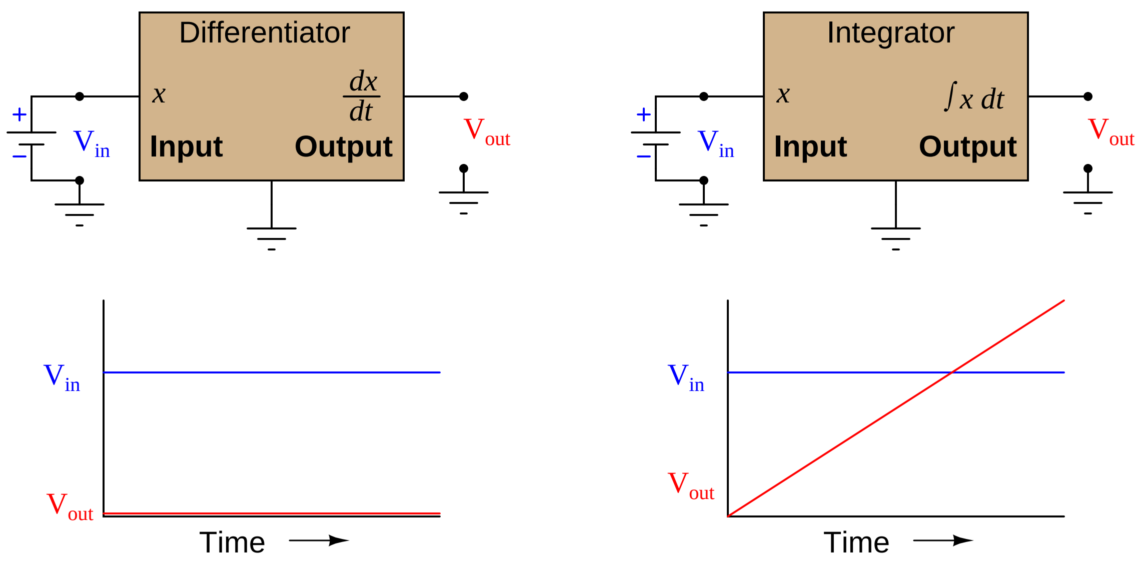
-10.14

This is another example where the interval of integration specifies a negative direction (i.e. each differential dx is a negative quantity). This explains why the integral value is *negative* 10.14 rather than positive, even though the enclosed area above the zero line exceeds the enclosed area below the zero line.

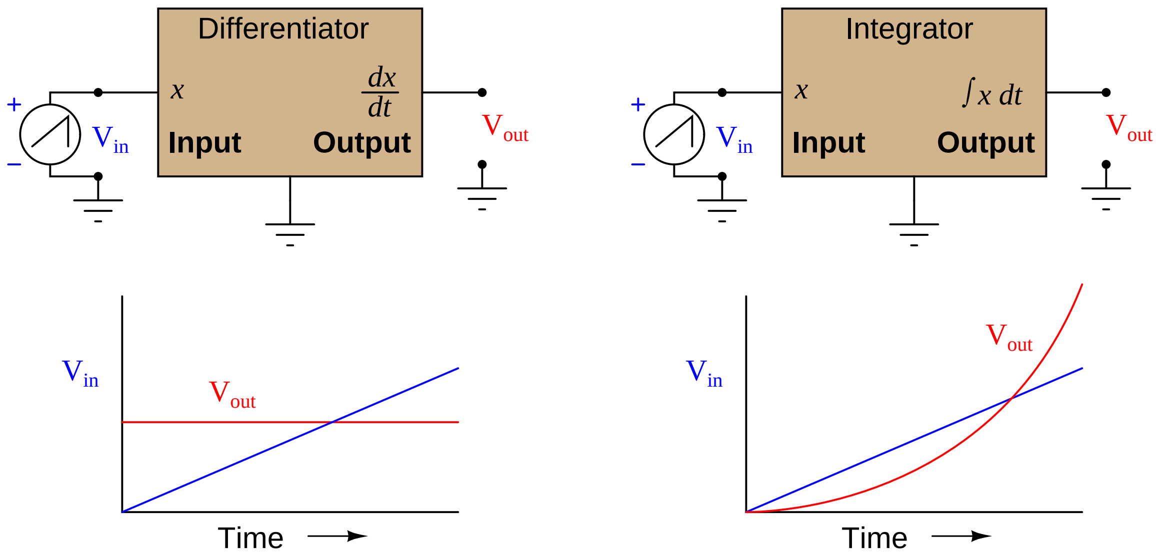
Answer 41

Answer 42

Answer 43



Answer 44



Answer 45

$\tau_i = RC$, just as $\tau_d = RC$ in a differentiator circuit.

$$V_{in} = -\tau_i \frac{dV_{out}}{dt} \qquad \text{or} \qquad \frac{dV_{out}}{dt} = -\frac{V_{in}}{\tau_i} \qquad \text{or} \qquad V_{out} = -\frac{1}{\tau_i} \int V_{in}\, dt$$

What the "time constant" (τ_i) means in practical terms for an integrator circuit is the amount of time it takes for the output to climb (or fall) by the amount of voltage present at the input. Another way of saying this is that the time constant is the amount of time is takes for the circuit to *repeat* the input voltage.

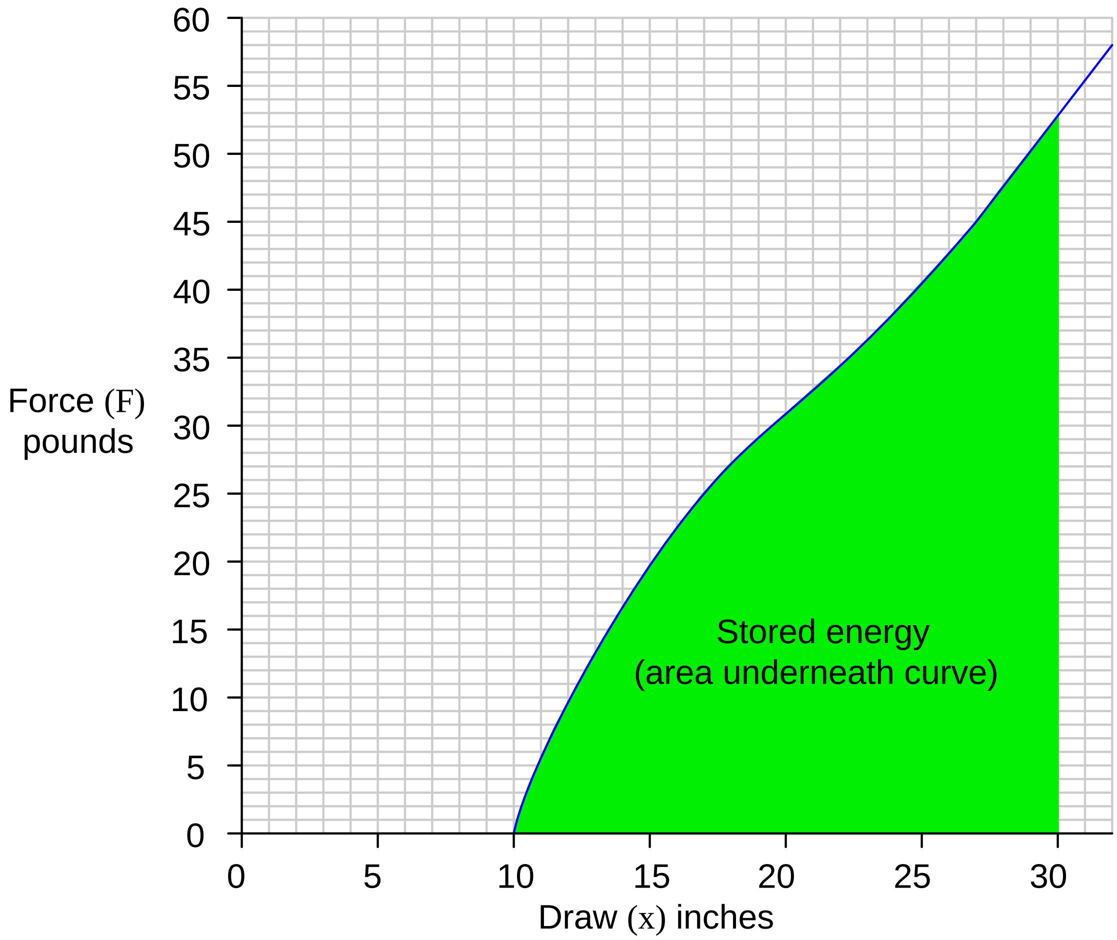
Answer 46

Hint:

$$E_p = \int_9^{30} F\, dx$$

Note that each rectangle on the graph has a height of 1 lb (force) and a width of 1 inch (draw), giving each rectangle's area an energy value of 1 inch-pound ($\frac{1}{12}$ foot-pound).

Answer 47



Answer 48

$$E_p \approx 57.17 \text{ ft} \cdot \text{lb}$$

Answer 49

$\frac{dy}{dx} = +1$

Answer 50

$+0.5$

Answer 51

$\frac{dy}{dx} = -1$

Answer 52

-12.5

Note how the interval of integration starts at $x = +10$ and proceeds to $x = -1$. This means the integration proceeds in a negative direction, from +10 to -1 on the horizontal axis. Another way of saying this is that each differential of x is a negative quantity ($dx < 0$). This explains why the integral value is a negative quantity (-12.5) despite the fact that y never goes below zero during the entire interval of integration.

Answer 53

0

Answer 54

$$\int_{-9}^{-4} y \, dx$$

Answer 55

$$\int_{-4}^{+7} (y - 3) \, dx$$

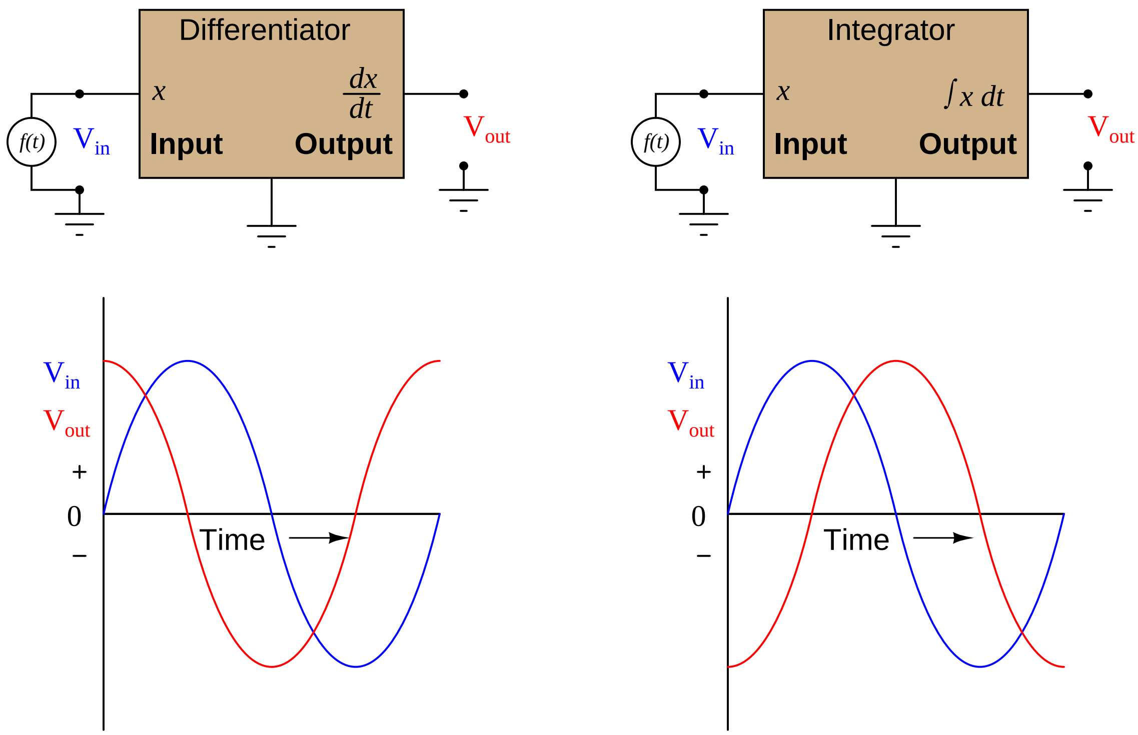
To make this integral negative, we have two options. The first option is to reverse the interval limits, so that we are integrating "backwards" along the x axis from +7 to -4 rather than "forwards" along the x axis from -4 to +7:

$$\int_{+7}^{-4} (y - 3) \, dx$$

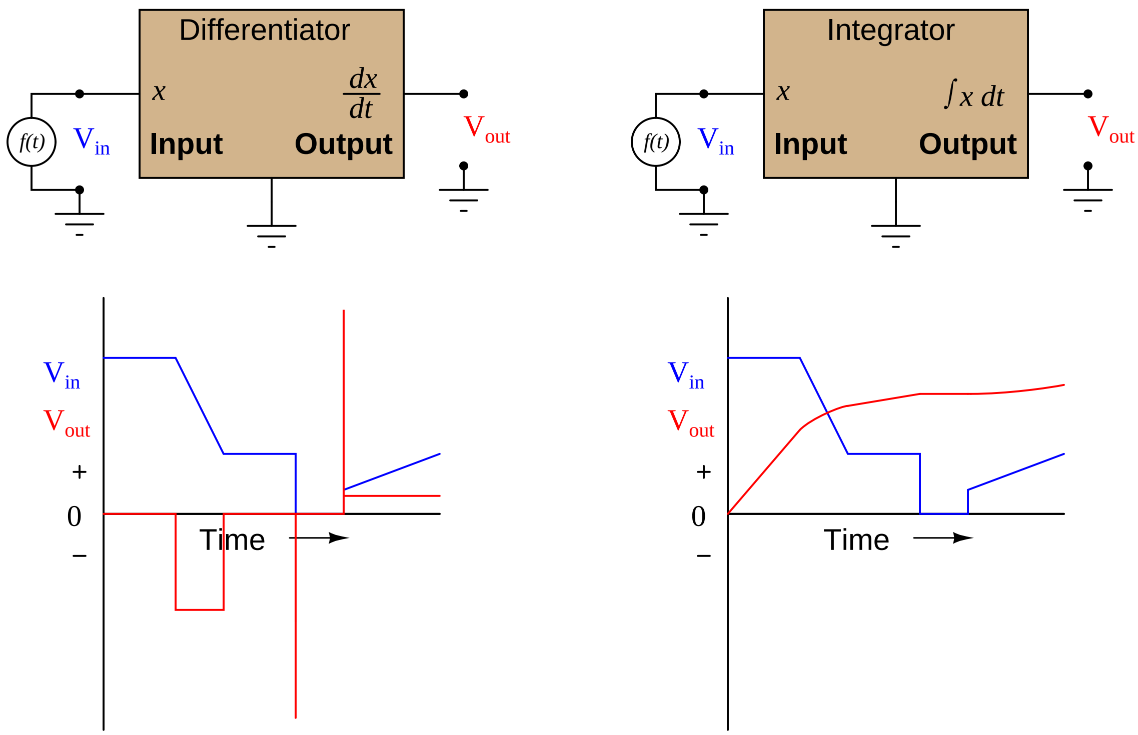
Alternatively, we could reverse the sign of the function being integrated (the "integrand"):

$$\int_{-4}^{+7} (3 - y) \, dx$$

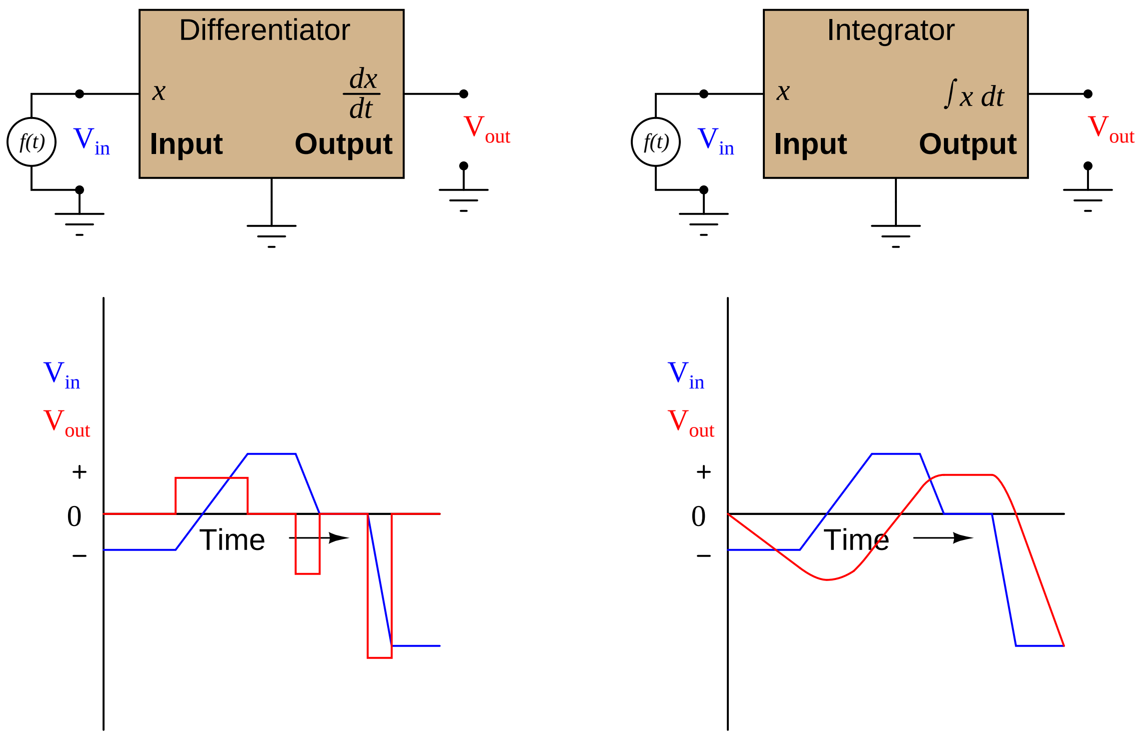
Either of these modifications will yield a negative value for the integral.


Differentiator
x
dx/dt
Input
Output
f(t)
Vin
Vout
Integrator
x
∫x dt
Input
Output
f(t)
Vin
Vout
Vin
Vout
+
0
−
Time
Vin
Vout
+
0
−
Time

Answer 57


Differentiator
x
dx/dt
Input
Output
f(t)
Vin
Vout
Integrator
x
∫x dt
Input
Output
f(t)
Vin
Vout
Vin
Vout
+
0
−
Time
Vin
Vout
+
0
−
Time

Answer 58



Answer 59

450 pounds of force will be required to compress this spring 3 inches ($F = kx$). After being compressed this much, the spring will be storing 675 inch-pounds of energy, which is equal to 56.25 foot-pounds.

$$E = \int_0^3 150x\,dx$$

Answer 60

If this integrator were used to "totalize" the number of gallons of liquid stored in a vessel from a flowmeter signal, the switch could be used to reset the totalized quantity to zero after each time the vessel is emptied.

Answer 61

Answer 62

Answer 63

$\frac{dy}{dx} = 0$

Answer 64

-17.5

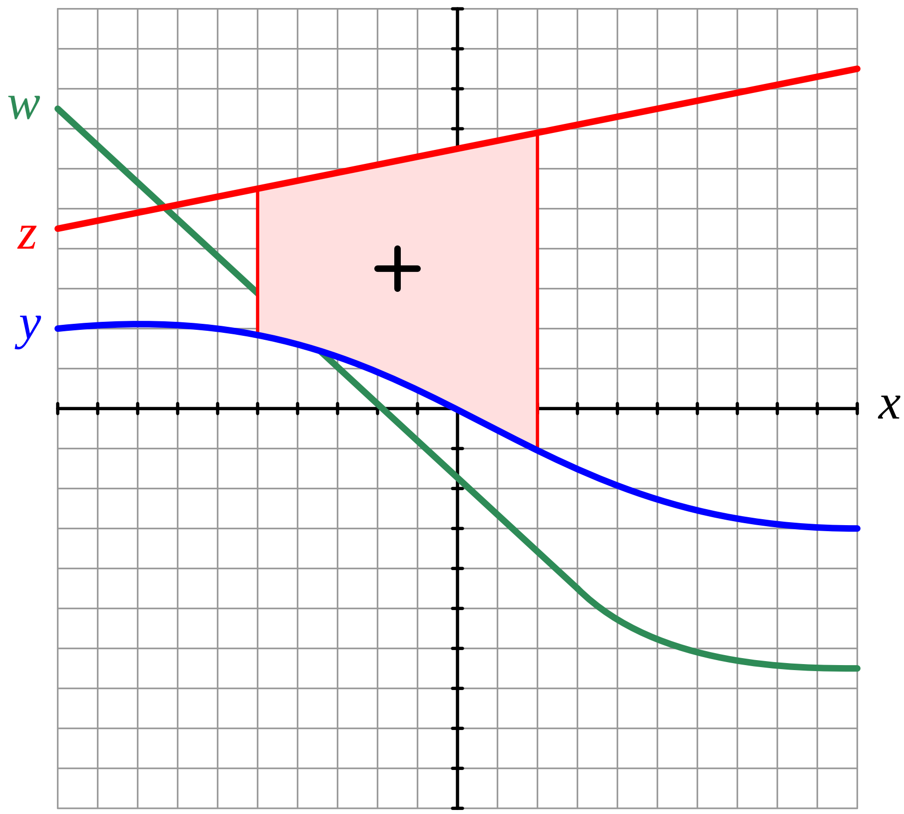
Answer 65

Partial answer:

- Solder bridge (short) across resistor R_1: *Output saturates negative.*
- Broken wire between R_1/R_2 junction and inverting opamp input: *Output voltage unpredictable.*

Answer 66

This integral has a *positive* value:



Answer 67

Answer 68

One way to increase gain is to move the fulcrum to the right (closer to the output bellows).

Answer 69

Based strictly off the dimensions shown in the diagram, it would first appear that the controller's gain should be 0.6875 (equal to $\frac{2.4}{3.5}$) and that therefore the controller equation should be:

$$m = 0.6857(\mathrm{PV} - \mathrm{SP}) + b$$

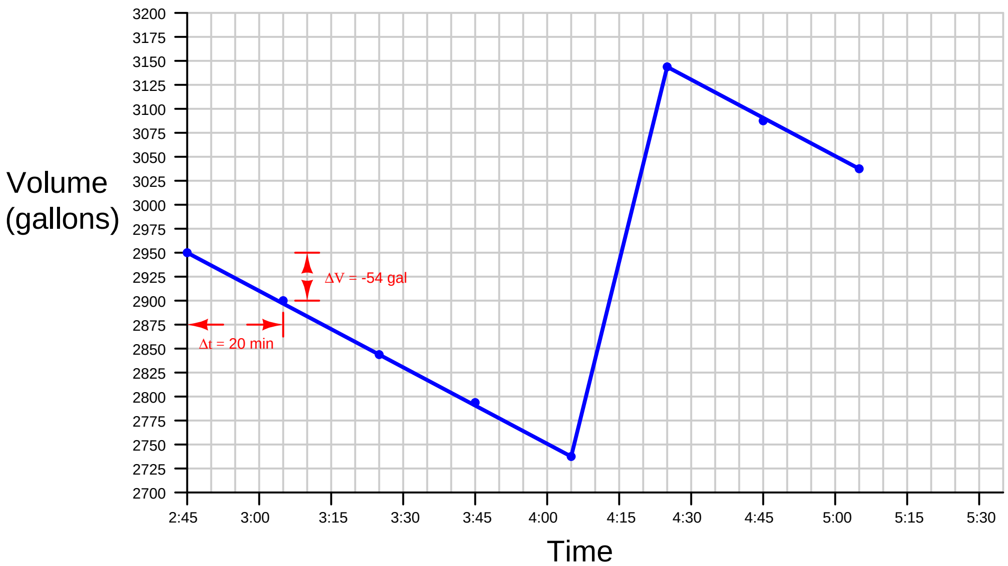
However, on closer analysis and inspection of the shorter lever coupling the PV and SP bellows together, it is possible to see that the gain is only *half* this amount:

$$m = 0.3429(\mathrm{PV} - \mathrm{SP}) + b$$

Explain why this is!

Answer 70

A graph shows the volume over time to look something like this:



The flow rate out of the tank to solvent wash may be found by calculating the rise-over-run of the slope prior to filling:

$$\frac{dV}{dt} \approx \frac{\Delta V}{\Delta t} = \frac{2897 \text{ gal} - 2951 \text{ gal}}{3{:}05 - 2{:}45} = \frac{-54 \text{ gal}}{20 \text{ min}} = -2.7 \text{ gallons per minute}$$

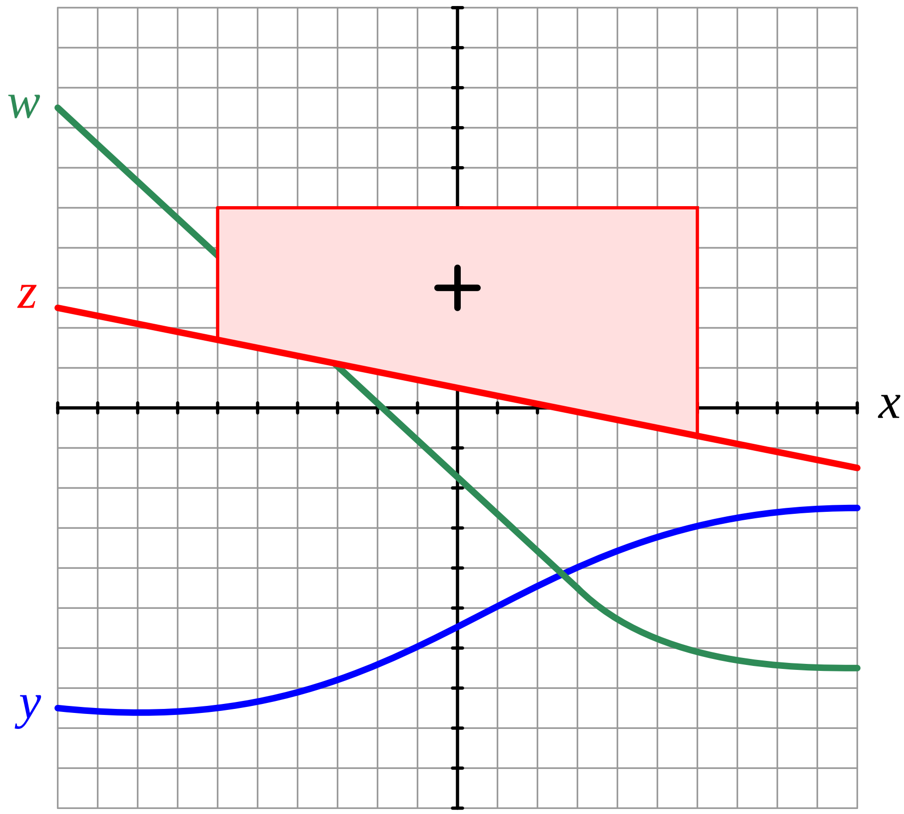
The tank is obviously filled at some time between 4:05 and 4:25. The exact slope (derivative) of volume over time is unknown to us, since the only data points we have are at 4:05 and 4:25 exactly, and it would be sheer coincidence if these times just happened to be the exact start and finish times of the truck's unloading operation. However, we can estimate the average (net) flow rate into the tank during these two times using the same numerical differentiation procedure:

$$\frac{dV}{dt} \approx \frac{\Delta V}{\Delta t} = \frac{3140 \text{ gal} - 2735 \text{ gal}}{4{:}25 - 4{:}05} = \frac{405 \text{ gal}}{20 \text{ min}} = 20.25 \text{ gallons per minute}$$

We must remember that estimations of flow into or out of a vessel based on changes in liquid volume within that vessel only yield *net* flow. During the time this tank was being filled, it was probably still feeding the solvent wash process at -2.7 gallons per minute. Therefore, the net flow rate we just calculated of 20.25 gallons per minute is the combination of the truck's unloading rate and the out-flow rate to solvent wash. Therefore, the truck's average unloading rate is actually 20.25 GPM + 2.7 GPM = 22.95 gallons per minute.

Answer 71

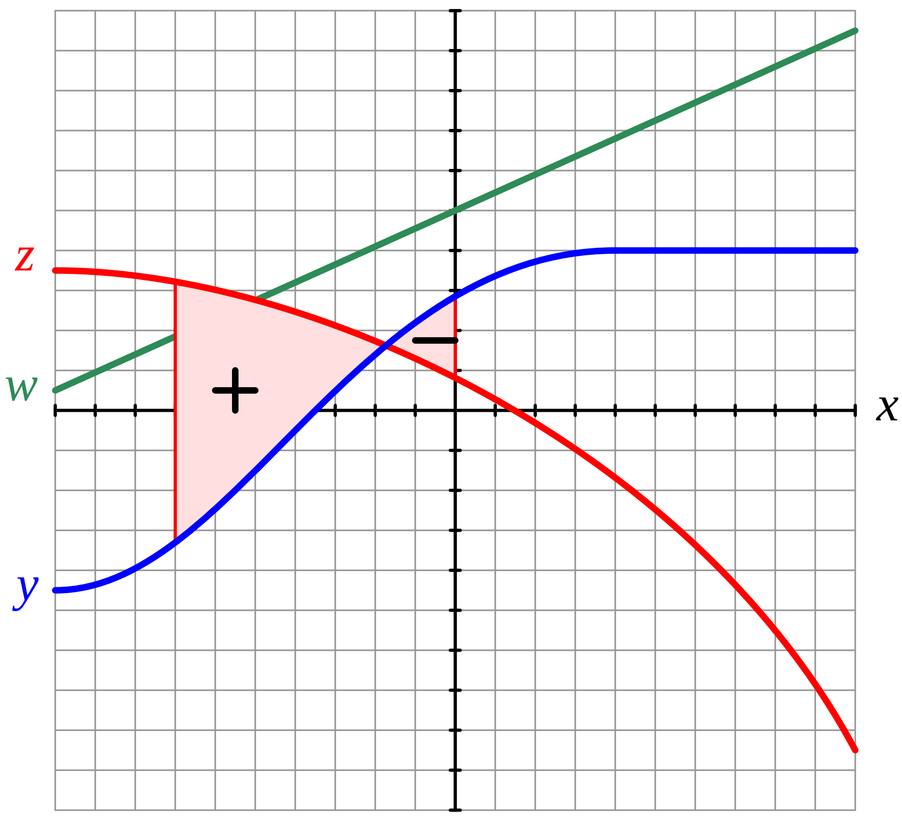
This integral has a *positive* value:



Over the entire interval from $x = -6$ to $x = 6$, the integral accumulates a positive value because it has positive dx increments and 5 remains larger than z.

Answer 72

This integral has a *positive* value:



From $x = -7$ to approximately $x = -1.75$, the integral accumulates a positive value because it has positive dx increments and z is larger than y. From approximately $x = -1.75$ to $x = 0$ the integral accumulates a negative value because y is larger than z (a negative integrand) while dx increments still remain positive. Overall, the positive area is greater than the negative area, and so the integral from $x = -7$ to $x = 0$ has a net positive value.

Answer 73

Blue-shaded area:

$$\int_{-9}^{-5} y\,dx \qquad \ldots \text{ or } \ldots \qquad \int_{-5}^{-9} -y\,dx$$

Red-shaded area:

$$\int_{1}^{8.5} -y\,dx \qquad \ldots \text{ or } \ldots \qquad \int_{8.5}^{1} y\,dx$$

Answer 74

Blue-shaded area:

$$\int_{-8}^{-1} (w - z)\, dx \qquad \text{. . . or . . .} \qquad \int_{-1}^{-8} (z - w)\, dx$$

Red-shaded area:

$$\int_{5}^{10} (w - y)\, dx \qquad \text{. . . or . . .} \qquad \int_{10}^{5} (y - w)\, dx$$

Answer 75

We know we are given flow *rate* values in gallons per minute, and that the rise in liquid inside the sump equates to a certain volume in *gallons*. We also are told to solve for time. From this we know we can use *integration* to relate the variables together, because the time-integral of flow rate is volume (gallons per minute times minutes equals gallons).

Let us set up a calculus expression using the variables Q_1 for FT-140's value of 3.5 GPM, Q_2 for FT-141's value of 4.1 GPM, ΔV for the accumulation of volume inside the sump, and x for the unknown amount of time it will take for that much liquid to accumulate:

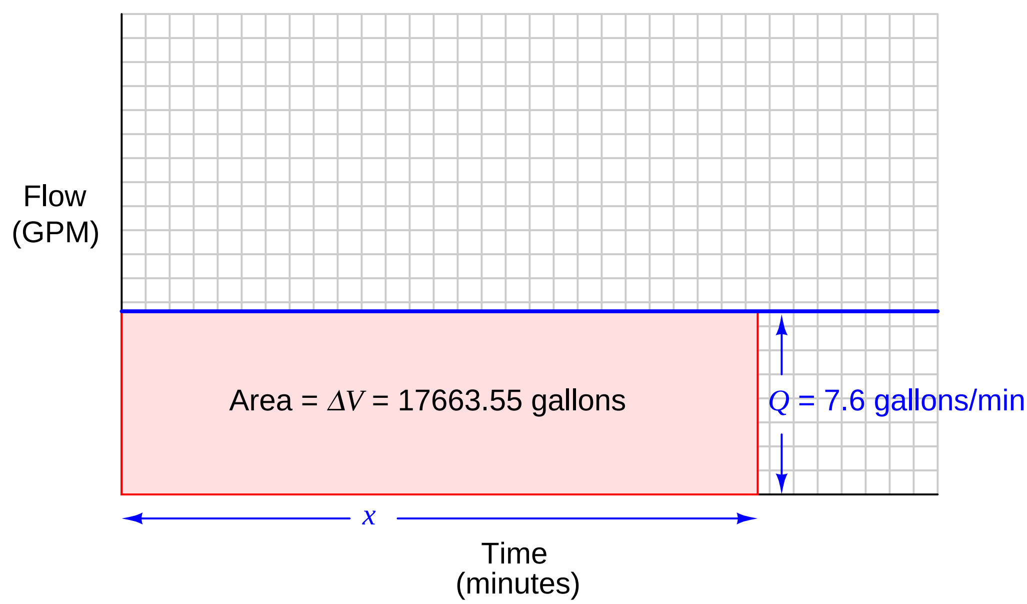
$$\Delta V = \int_0^x (Q_1 + Q_2) \, dt$$

We know the total volume of the sump is 35000 gallons, and that is at a liquid height of 8 feet 11 inches (8.91667 feet). This means each foot of depth is equivalent to 3925.23 gallons (assuming a constant width and length of the sump at all liquid levels. The difference in depth between the high and low level marks is 4 feet 6 inches (4.5 feet), which equates to 17663.55 gallons. This will be our ΔV value.

Combining the flow rates Q_1 and Q_2 (3.5 GPM + 4.1 GPM = 7.6 GPM) and plugging in our known value of 17663.55 gallons for ΔV:

$$17663.55 \text{ gal} = \int_0^x (7.6 \text{ gal/min}) \, dt$$

The graphical interpretation of integration is the *area* bounded by a function. In this case, the function being integrated is a constant total flow rate of 7.6 GPM (a horizontal line on a graph, with flow as the vertical axis and time as the horizontal axis):



Simple division tells us the required width of this area: **2324.15 minutes**, or **38 hours and 44.15 minutes**.

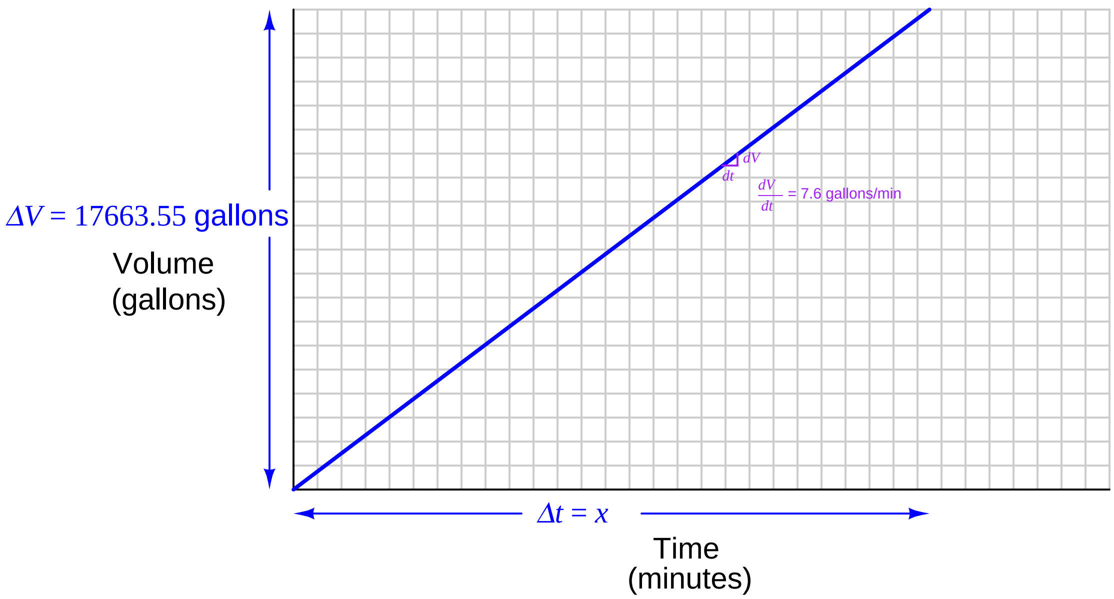
Another way we could have solved for the unknown time is to use *differentiation*. The total flow rate of liquid into the sump (7.6 GPM) could be expressed as a *derivative* of volume with respect to time:

$$\frac{dV}{dt} = 7.6 \text{ gallons per minute}$$

Since we happen to know this flow rate is constant (not changing), we may conclude that the *difference quotient* of the entire change in volume over the span of time it takes to accumulate that volume will also have the same value:

$$\frac{\Delta V}{\Delta t} = \frac{17663.55 \text{ gallons}}{x \text{ minutes}} = 7.6 \text{ gallons per minute}$$

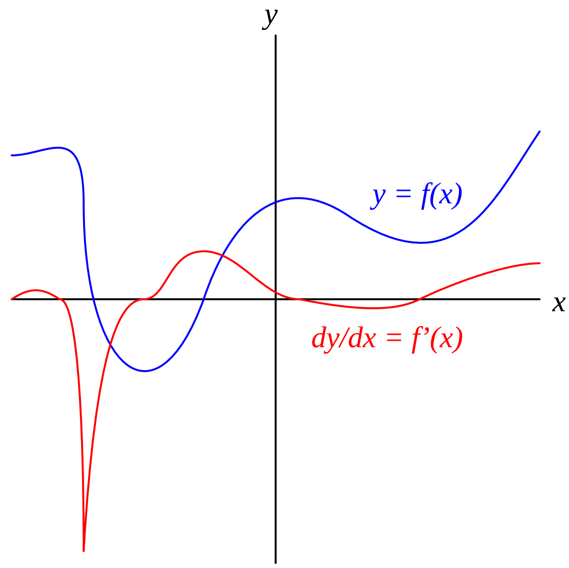
The graphical interpretation of differentiation is the *slope* of a function. In this case, the function being integrated is a constant total flow rate of 7.6 GPM (a horizontal line on a graph, with flow as the vertical axis and time as the horizontal axis):



$$\frac{\Delta V}{\Delta t} = \frac{dV}{dt} = \frac{17663.55 \text{ gallons}}{x \text{ minutes}} = \frac{7.6 \text{ gallons}}{1 \text{ minute}}$$

Once gain, simple division tells us the required Δt or x value: **2324.15 minutes**, or **38 hours and 44.15 minutes**.

Answer 76



Answer 77

The diesel cycle delivers more net energy: although the energy "invested" in the compression stroke is the same for both engines in this example, the diesel's power stroke constitutes a greater amount of energy because the area under the power curve is greater (owing to the prolonged ignition cycle).

This is the main reason why diesel engines are so much more efficient than gasoline engines, all other factors being equal.

Drawing this bow stores potential energy in it. Releasing the bowstring transfers that potential energy to the arrow, where it becomes kinetic energy. Thus, this is really a work/energy problem. If we calculate the amount of work done drawing this bow, we will know how much kinetic energy the arrow possesses when it is shot from the bow, and from that energy value we may calculate the arrow's velocity.

First, calculating the work done drawing the bow:

$$W = \int_{0 \text{ m}}^{0.8 \text{ m}} F \, dx$$

Since we know this longbow has a perfectly linear force-draw function, we know its graphical plot will look like a perfect right-triangle, with force starting at 0 newtons at 0 draw, linearly climbing to 340 newtons at a draw of 0.8 meters. Thus, the work done (i.e. the area under this force-draw triangle) will be one half times the peak height (340 newtons) times the peak draw (0.8 meters):

$$W = \left(\frac{1}{2}\right)(340 \text{ N})(0.8 \text{ m}) = 136 \text{ Nm}$$

Now that we know the fully-drawn bow stores 136 newton-meters of potential energy at full draw, we may set this quantity equal to the kinetic energy of the flying arrow and solve for velocity:

$$W = E_k = 136 \text{ Nm}$$

$$E_k = \frac{1}{2}mv^2$$

$$2E_k = mv^2$$

$$\frac{2E_k}{m} = v^2$$

$$v = \sqrt{\frac{2E_k}{m}}$$

$$v = \sqrt{\frac{(2)(136 \text{ Nm})}{0.017 \text{ kg}}}$$

$$v = 126 \text{ m/s}$$

This calculated velocity of 126 meters per second translates to approximately 411 feet per second. It is the speed of the arrow as it leaves the bow, assuming no energy lost in friction (i.e. 100% of the bow's potential energy gets transferred to the arrow).

Answer 79

The differentiator circuit's output signal represents the angular *velocity* of the robotic arm, according to the following equation:

$$\omega = \frac{d\theta}{dt}$$

Where,
ω = angular velocity, in degrees or radians
θ = angular position, in degrees/second or radians/second
t = time, in seconds

Answer 80

One possible solution is to use an electronic *integrator* circuit to derive a velocity measurement from the accelerometer's signal. However, this is not the only possible solution! Another solution would be to differentiate the altimeter signal. Differentiation assumes straight-line, vertical travel for the rocket.

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

Answer 87

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

Answer 88

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

Answer 89

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

Answer 90

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

Answer 91

Answer 92

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