INST 150 (Digital 3), section 2

Recommended schedule

Day 1

Topics: *PWM power control with microcontrollers*
Questions: *1 through 10*
Lab Exercise: *Work on project prototype (progress report: Question 51)*

Day 2

Topics: *Servo systems*
Questions: *11 through 20*
Lab Exercise: *MCU DC motor speed control (question 52)*

Day 3

Topics: *Digital-to-Analog conversion*
Questions: *21 through 30*
Lab Exercise: *Work on project prototype (progress report: Question 53)*

Day 4

Topics: *Analog-to-Digital conversion*
Questions: *31 through 40*
Lab Exercise: *MCU analog voltage output (question 54)*

Day 5

Topics: *Review*
Questions: *41 through 50*
Lab Exercise: *Work on project prototype (progress report: Question 55)*
Demo: Set up digital oscilloscope to show aliasing

Day 6

Troubleshooting Assessment due: *project prototype*
Question 56: Troubleshooting log
Question 57: Sample troubleshooting assessment grading criteria
Project due at end of INST155, Section 2 (next course)

Skill standards addressed by this course section

EIA *Raising the Standard; Electronics Technician Skills for Today and Tomorrow*, June 1994

F Technical Skills – Digital Circuits

F.24 Understand principles and operations of types of digital to analog and analog to digital circuits.

F.25 Troubleshoot and repair types of digital to analog and analog to digital circuits.

B Basic and Practical Skills – Communicating on the Job

B.01 Use effective written and other communication skills. *Met by group discussion and completion of labwork.*

B.03 Employ appropriate skills for gathering and retaining information. *Met by research and preparation prior to group discussion.*

B.04 Interpret written, graphic, and oral instructions. *Met by completion of labwork.*

B.06 Use language appropriate to the situation. *Met by group discussion and in explaining completed labwork.*

B.07 Participate in meetings in a positive and constructive manner. *Met by group discussion.*

B.08 Use job-related terminology. *Met by group discussion and in explaining completed labwork.*

B.10 Document work projects, procedures, tests, and equipment failures. *Met by project construction and/or troubleshooting assessments.*

C Basic and Practical Skills – Solving Problems and Critical Thinking

C.01 Identify the problem. *Met by research and preparation prior to group discussion.*

C.03 Identify available solutions and their impact including evaluating credibility of information, and locating information. *Met by research and preparation prior to group discussion.*

C.07 Organize personal workloads. *Met by daily labwork, preparatory research, and project management.*

C.08 Participate in brainstorming sessions to generate new ideas and solve problems. *Met by group discussion.*

D Basic and Practical Skills – Reading

D.01 Read and apply various sources of technical information (e.g. manufacturer literature, codes, and regulations). *Met by research and preparation prior to group discussion.*

E Basic and Practical Skills – Proficiency in Mathematics

E.01 Determine if a solution is reasonable.

E.02 Demonstrate ability to use a simple electronic calculator.

E.06 Translate written and/or verbal statements into mathematical expressions.

E.07 Compare, compute, and solve problems involving binary, octal, decimal, and hexadecimal numbering systems.

E.12 Interpret and use tables, charts, maps, and/or graphs.

E.13 Identify patterns, note trends, and/or draw conclusions from tables, charts, maps, and/or graphs.

E.15 Simplify and solve algebraic expressions and formulas.

E.16 Select and use formulas appropriately.

E.18 Use properties of exponents and logarithms.

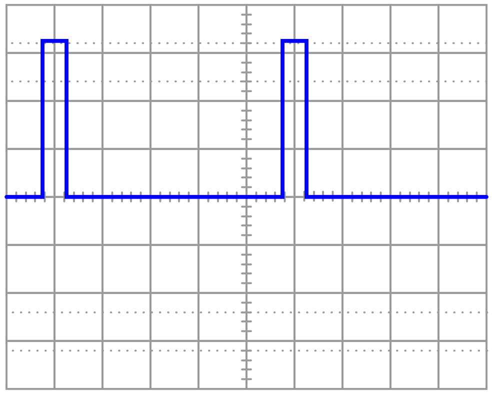
A Additional Skills – Communications

A.01 Transmission line applications.

A.04 Data communications.

Question 1

Determine the *duty cycle* of this square wave signal:



file 02611

Answer 1

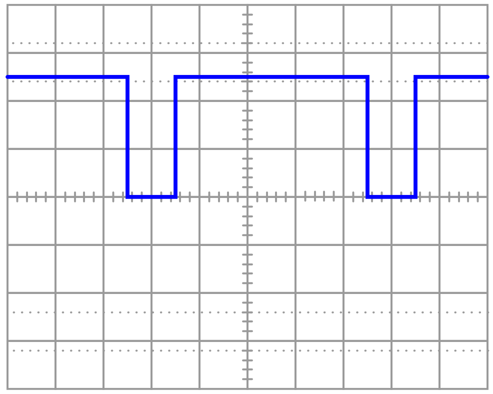
Duty cycle $\approx 10\%$

Notes 1

This question challenges students to apply their knowledge of duty cycle to a measurement scenario.

Question 2

Determine the *duty cycle* of this square wave signal:



file 02612

Answer 2

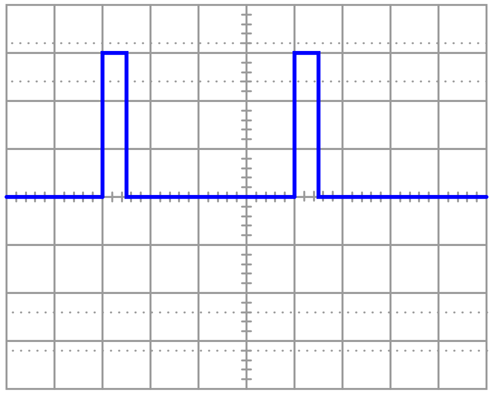
Duty cycle $\approx 80\%$

Notes 2

This question challenges students to apply their knowledge of duty cycle to a measurement scenario.

Question 3

A resistive DC load receives pulse-width modulated (PWM) power from a controller circuit, and an oscilloscope shows the load voltage waveform as such:



Vertical sensitivity = 20 volts/div
Probe ratio = 1:1
Coupling = DC
Timebase = 0.1 ms/div

Calculate the duty cycle of this waveform, and also the average power dissipated by the load assuming a load resistance of 1.8 Ω.

file 02349

Answer 3

Duty cycle ≈ 12.5%

$P_{average} \approx 250$ W

Follow-up question: which oscilloscope setup parameters (vertical sensitivity, probe ratio, coupling, and timebase) are necessary for performing these calculations? Which parameters are unnecessary, and why?

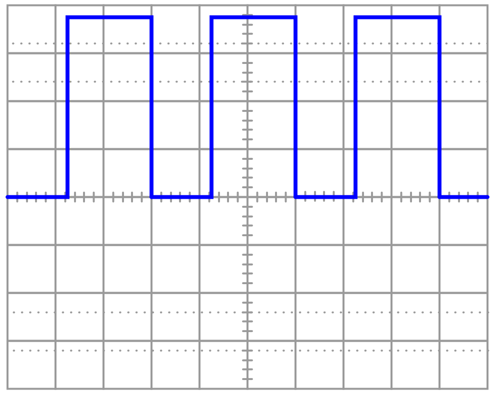
Notes 3

Calculating the duty cycle should be easy. Calculating load power dissipation requires some thought. If your students do not know how to calculate average power, suggest this thought experiment: calculating power dissipation at 0% duty cycle, at 100% duty cycle, and at 50% duty cycle. The relationship between duty cycle and average power dissipation is rather intuitive if one considers these conditions.

If a more rigorous approach is required to satisfy student queries, you may wish to pose another thought experiment: calculate the *energy* (in units of Joules) delivered to the load for a 50% duty cycle, recalling that Watts equals Joules per second. Average power, then, is calculated by dividing Joules by seconds over a period of one or more whole waveform cycles. From this, the linear relationship between duty cycle and average power dissipation should be clear.

Question 4

A resistive DC load receives pulse-width modulated (PWM) power from a controller circuit, and an oscilloscope shows the load voltage waveform as such:



Vertical sensitivity = 1 volt/div
Probe ratio = 10:1
Coupling = DC
Timebase = 20 µs/div

Calculate the duty cycle of this waveform, and also the average power dissipated by the load assuming a load resistance of 10.3 Ω.

file 02348

Answer 4

Duty cycle ≈ 58.3%
$P_{average} \approx 80$ W

Follow-up question: which oscilloscope setup parameters (vertical sensitivity, probe ratio, coupling, and timebase) are necessary for performing these calculations? Which parameters are unnecessary, and why?

Notes 4

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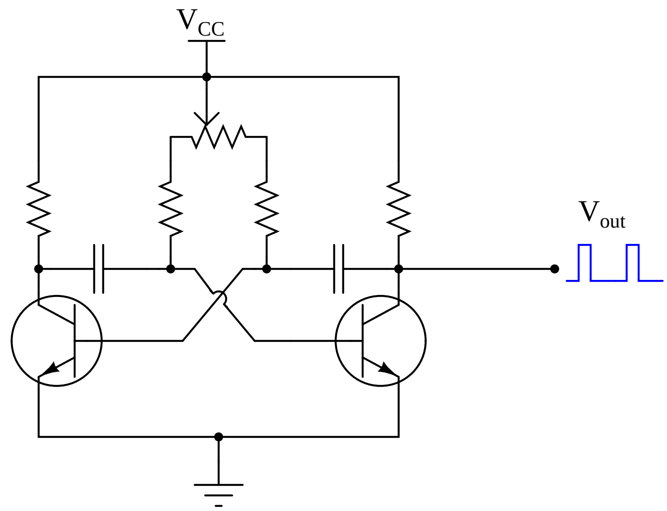
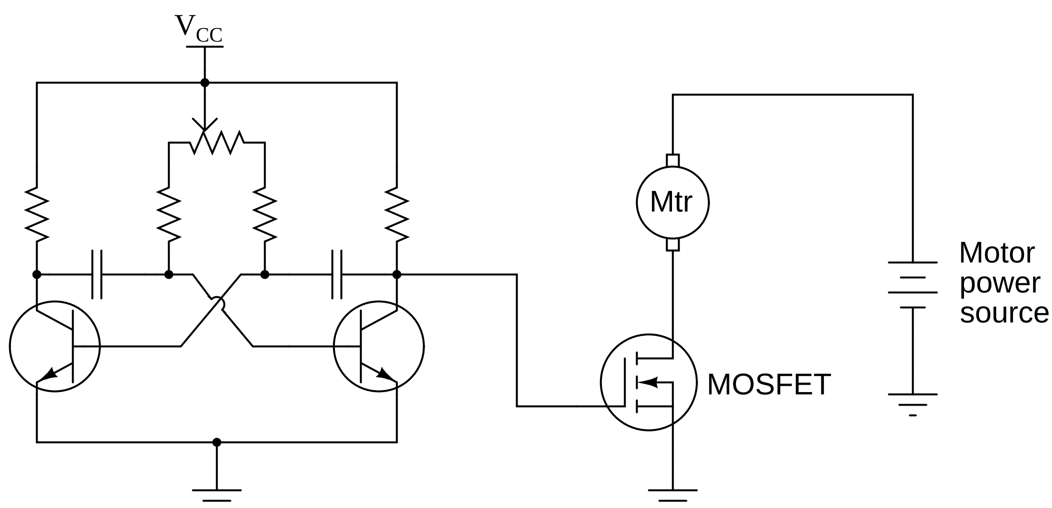
Question 5

The *oscillator* circuit in this diagram generates a square wave with an adjustable duty cycle:



A student desires to use this circuit as the basis for a *pulse-width modulation* (PWM) power controller, to vary the amount of power delivered to a DC load. Since the oscillator circuit is built to produce weak signals and not deliver power directly to a load, the student adds a power MOSFET to switch heavy load currents:



Correlate the duty cycle of the oscillator's output signal with motor power. In other words, describe how increases and decreases in signal duty cycle affect the amount of power delivered to the electric motor.

file 02152

Answer 5

The greater the duty cycle, the more power delivered to the motor.

Follow-up question: how do you recommend a suitable oscillator *frequency* be determined for this motor control circuit? Describe how you might experiment with the circuit to determine a suitable frequency without performing any calculations.

Notes 5

As review, ask your students to identify what type of MOSFET this is (type of channel, and either depletion or enhancement mode), and what the proper oscillator signal amplitude should be to drive the MOSFET alternately between cutoff and saturation.

Question 6

Explain why it is important for the final power transistor(s) in a PWM power control circuit to operate at full cutoff and full saturation, and not in the linear (active) mode in between those two extremes. What might happen if the power transistor(s) were to be less than cut-off or less than saturated when carrying load current?

file 02155

Answer 6

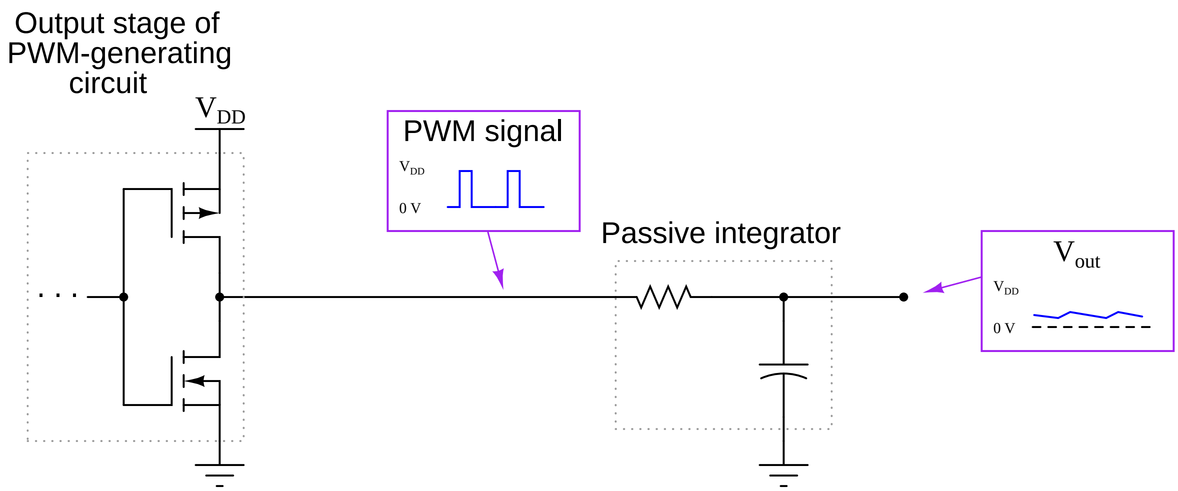
Transistor power dissipation will increase if operating in its "linear" range of operation rather than being completely cut off or saturated. This decreases its service life as well as the energy efficiency of the circuit.

Notes 6

Review with your students what it means for a transistor to be in "cutoff" or in "saturation," if they are not familiar with these terms or if it has been a while since they have studied this. A clear understanding of this concept is crucial to their being able to understand the efficiency of PWM power control.

Question 7

If a pulse-width modulated (PWM) signal is sent to a passive integrator circuit from a circuit capable of both sourcing and sinking current (as is the case with the dual-MOSFET output stage), the output will be a DC voltage (with some ripple):



Determine the relationship between the PWM signal's duty cycle and the DC voltage output by the integrator. What does this suggest about PWM as a means of communicating information, such as analog data from a measuring device?

file 02156

Answer 7

There is a direct-proportional relationship between duty cycle and DC output voltage in this circuit, making it possible for a PWM signal to represent analog data.

Follow-up question #1: why is it important that the circuit generating the PWM signal for the integrator be able to both source *and* sink current?

Follow-up question #2: what would have to be done to reduce the ripple voltage at the integrator's output?

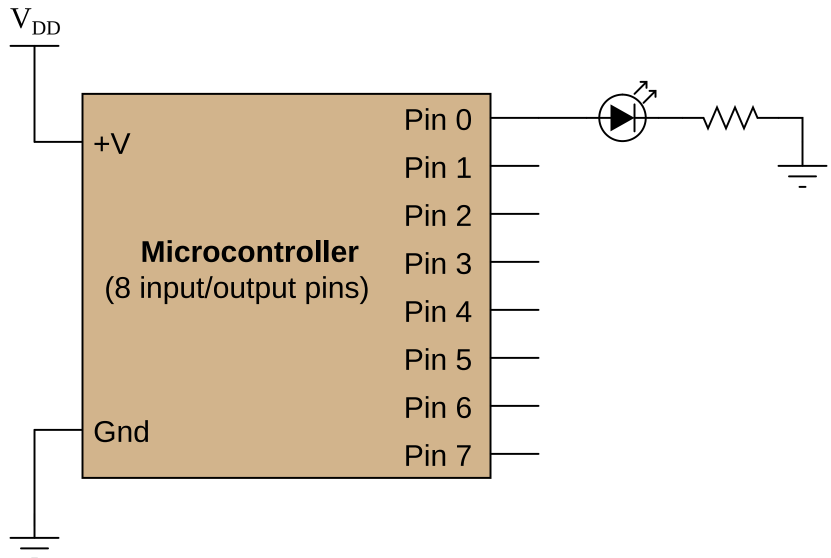
Notes 7

Although it should not be difficult for students to discern the relationship between duty cycle and DC output voltage, the application of this relationship to data communication might be difficult for some students to grasp, especially on their own. Further elaboration on your part may be necessary.

An excellent example of this principle applied is the generation of an analog voltage by a 1-bit digital circuit. This technique is useful in microcontroller systems where output ports may be scarce, provided that ripple voltage (or slow response) is not a problem.

Question 8

This microcontroller is programmed to vary the perceived brightness of an LED by means of pulse-width modulation (PWM) control of pin 0's output:



Pseudocode listing

```
Declare Pin0 as an output
Declare X as an integer variable
LOOP
  Set Pin0 LOW
  Pause for 100 - X microseconds
  Set Pin0 HIGH
  Pause for X microseconds
ENDLOOP
```

Determine what the value of `X` must be to set the LED's brightness at 80%, and also what the frequency of the PWM signal is.

file 03990

Answer 8

This question is probably best answered by drawing a timing diagram of Pin 0's output, noting the times of `100 - X` μs and `X` μs.

Follow-up question: what is the resolution of this PWM control, given that `X` is an integer variable? How might we improve the resolution of this PWM control scheme?

Notes 8

Pulse-width modulation (PWM) is a very common and useful way of generating an analog output from a microcontroller (or other digital electronic circuit) capable only of "high" and "low" voltage level output. With PWM, time (or more specifically, *duty cycle*) is the analog domain, while amplitude is the digital domain. This allows us to "sneak" an analog signal through a digital (on-off) data channel.

In case you're wondering why I write in pseudocode, here are a few reasons:

- No prior experience with programming required to understand pseudocode
- It never goes out of style
- Hardware independent
- No syntax errors

If I had decided to showcase code that would actually run in a microcontroller, I would be dooming the question to obsolescence. This way, I can communicate the spirit of the program without being chained to an actual programming standard. The only drawback is that students will have to translate my pseudocode to real code that will actually run on their particular MCU hardware, but that is a problem guaranteed for some regardless of which real programming language I would choose.

Of course, I could have taken the Donald Knuth approach and invented my own (imaginary) hardware and instruction set . . .

Question 9

Many microcontrollers come equipped with a built-in PWM function, so that you do not have to code a custom PWM algorithm yourself. This fact points to the popularity of pulse-width modulation as a control scheme. Explain why PWM is so popular, and give a few practical examples of how it may be used.

file 03991

Answer 9

I'll let you do your own research for this question! The answer(s) is/are not hard to find.

Notes 9

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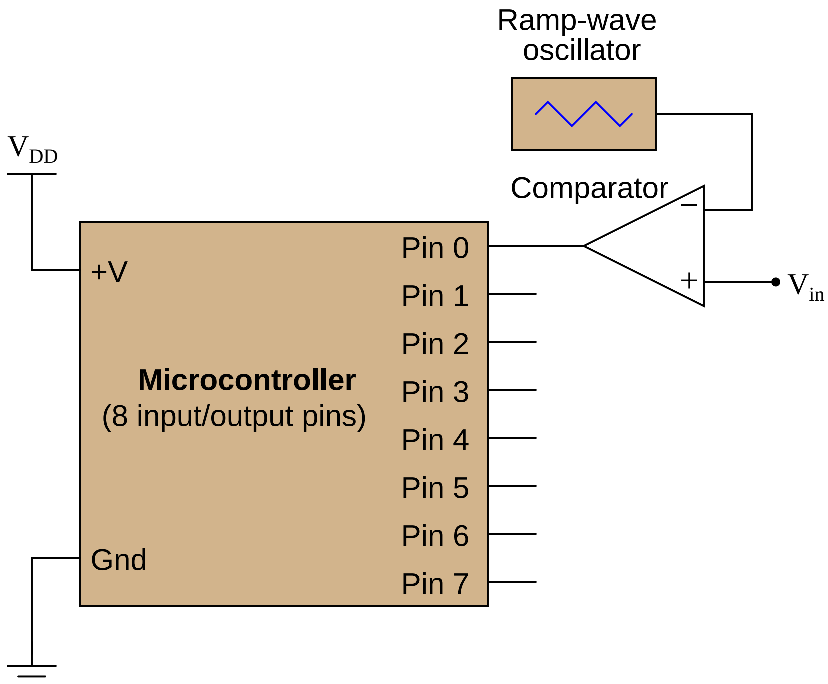
Question 10

Pulse-width modulation (PWM) is not only useful for generating an analog output with a microcontroller, but it is also useful for receiving an analog input through a pin that only handles on-off (high-low) digital voltage levels. The following circuit takes an analog voltage signal in to a comparator, generates PWM, then sends that PWM signal to the input of a microcontroller:



Pseudocode listing

```
Declare Pin0 as an input
Declare Last_Pin0 as a boolean variable
Declare Time_High as an integer variable
Declare Time_Low as an integer variable
Declare Duty_Cycle as a floating-point variable
Set Time_High and Time_Low both to zero
LOOP
  Set Last_Pin0 equal to Pin0
  If Pin0 is HIGH, increment Time_High by one
  If Pin0 is LOW, increment Time_Low by one
  If Last_Pin0 is not equal to Pin0, go to SUBROUTINE
ENDLOOP

SUBROUTINE
  Set Duty_Cycle equal to (Time_High / (Time_High + Time_Low))
  Set Time_High and Time_Low both to zero
  Return to calling loop
ENDSUBROUTINE
```

Explain how this program works. Hint: the `Last_Pin0` boolean variable is used to detect when the state of `Pin0` has changed from 0 to 1 or from 1 to 0.

file 03992

Answer 10

The trickiest part of this program is figuring out the `Last_Pin0` variable's function, and how it determines when to execute the subroutine. I strongly recommend you perform a "thought experiment" with a slow square-wave input signal to the microcontroller, examining how the `Time_High` and `Time_Low` variables become incremented with the square wave's state.

Notes 10

Pulse-width modulation (PWM) is a very common and useful way of generating an analog output from a microcontroller (or other digital electronic circuit) capable only of "high" and "low" voltage level output. Here, we also see it used as a form of *input* signal modulation. With PWM, time (or more specifically, *duty cycle*) is the analog domain, while amplitude is the digital domain. This allows us to "sneak" an analog signal through a digital (on-off) data channel.

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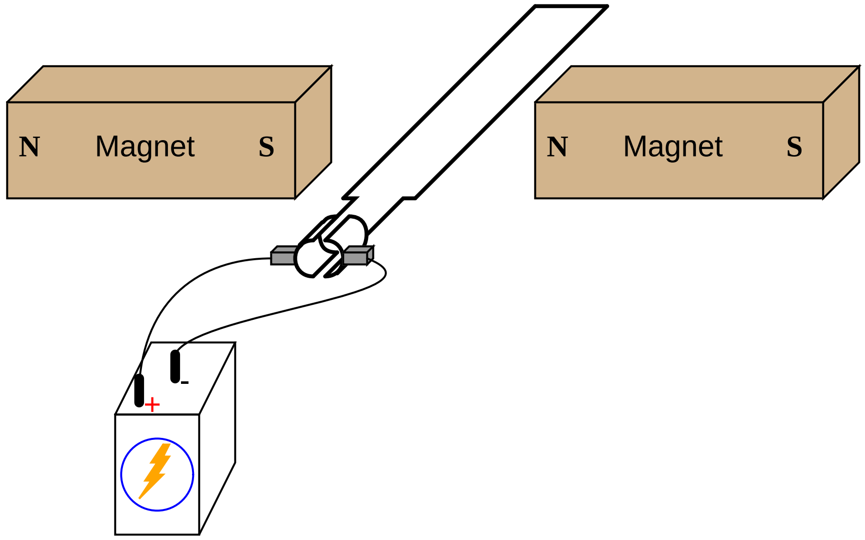
Question 11

If the ends of a wire loop are attached to two half-circular metal strips, arranged so that the two strips almost form a complete circle, and those strips are contacted by two "brushes" which connect to opposite poles of a battery, which way will the wire loop rotate?



file 00384

Answer 11

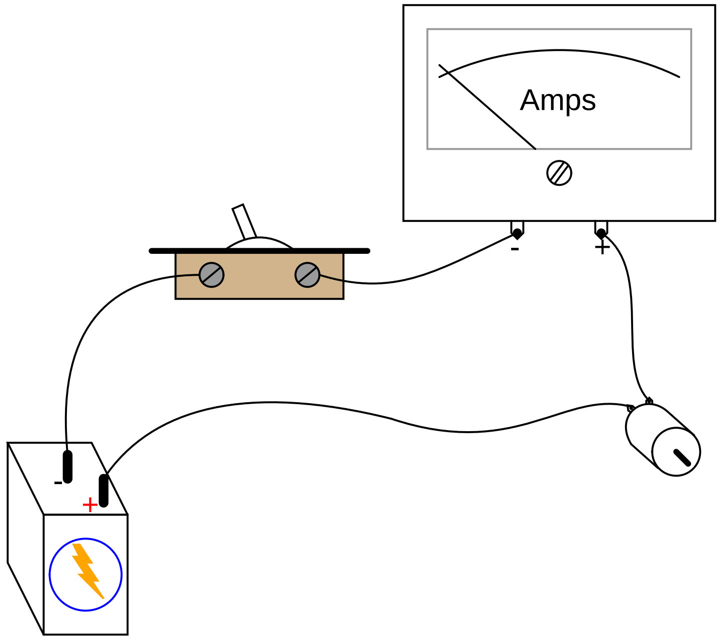
Clockwise, continuously.

Notes 11

Challenge your students with this question: is there any way we can get the wire loop to continuously rotate without using those half-circle metal strips to make and break contact with the battery? Ask your students what the two half-circle metal strips are called, in electric motor/generator terminology.

Question 12

When the switch closes, the ammeter will initially register a large amount of current, then the current will decay to a much lesser value over time as the motor speeds up:



In view of Ohm's Law, where current is supposed to be a direct function of voltage and resistance ($I = \frac{E}{R}$), explain why this happens. After all, the motor's winding resistance does not change as it spins, and the battery voltage is fairly constant. Why, then, does the current vary so greatly between initial start-up and full operating speed?

What do you think the ammeter will register after the motor has achieved full (no-load) speed, if a mechanical load is placed on the motor shaft, forcing it to slow down?

file 00395

Answer 12

Motor current is inversely proportional to speed, due to the counter-EMF produced by the armature as it rotates.

Follow-up question: draw a schematic diagram showing the equivalent circuit of battery, switch, ammeter, and motor, with the counter-EMF of the motor represented as another battery symbol. Which way must the counter-EMF voltage face, *opposed* to the battery voltage, or *aiding* the battery voltage?

Notes 12

The so-called "inrush" current of an electric motor during startup can be quite substantial, upwards of ten times the normal full-load current!

Question 13

A DC electric motor spinning at 4500 RPM draws 3 amps of current with 110 volts measured at its terminals. The resistance of the armature windings, measured with an ohmmeter when the motor is at rest, unpowered, is 2.45 ohms. How much counter-EMF is the motor generating at 4500 RPM?

How much "inrush" current will there be when the motor is initially powered up (armature speed = 0 RPM), once again assuming 110 volts at the terminals?

file 00398

Answer 13

$E_{counter} = 102.65$ V @ 4500 RPM

$I_{inrush} = 44.9$ A

Notes 13

This calculation helps students realize just how significant the "inrush" current of an electric motor is.

Question 14

Explain what a *servo* motor system is, in your own words.

file 03993

Answer 14

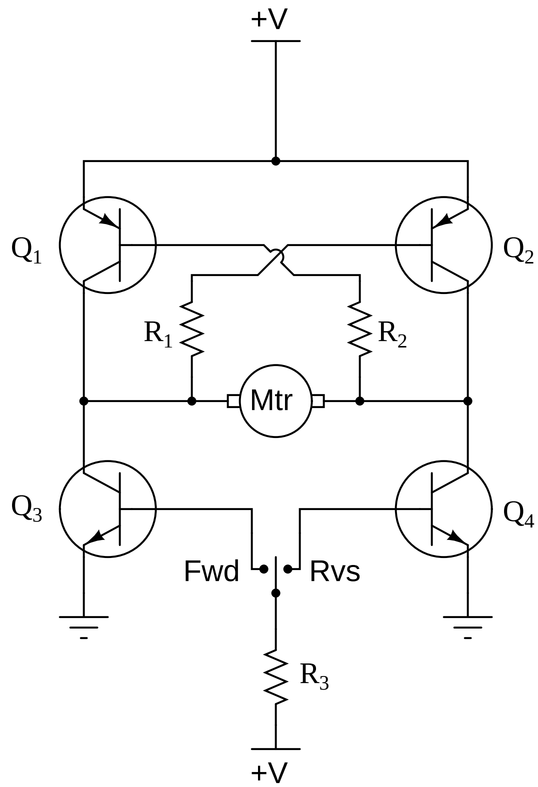
A servo motor is one whose position is controlled by a negative feedback system. I know, this definition is very minimal, but then I want you to express the answer *in your own words!*

Notes 14

Servos come in many different types and sizes, but they all share similar characteristics. Your students should have no problem at all finding information on them.

Question 15

Explain the operation of this "H-bridge" motor control circuit:



At any given moment, how many transistors are turned on and how many are turned off? Also, explain what would happen to the function of the circuit if resistor R1 failed open.

file 00449

Answer 15

Two transistors are on at any given time, and the other two are off. If R1 fails open, the motor will not be able to go in the "forward" (Fwd) direction.

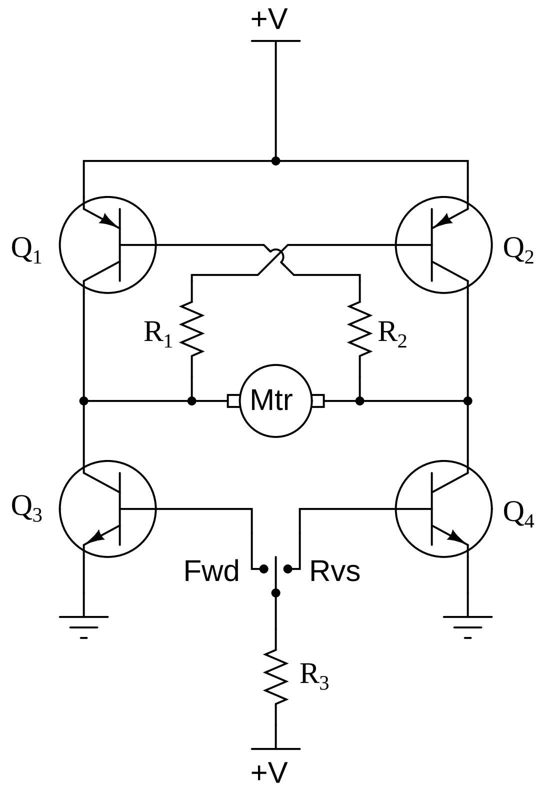
Challenge question: what type of DC motor is this drive circuit designed for? Shunt-wound, series-wound, compound, or permanent magnet? Explain your answer.

Notes 15

The "H-drive" circuit is a very common method of reversing polarity to a DC motor (or other polarity-sensitive load), using only a single-pole switch. Very, very large electric motor "drives" have been based on this same design.

Question 16

Predict how the motor function in this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Transistor Q_1 fails open (collector-to-emitter):
- Transistor Q_2 fails open (collector-to-emitter):
- Transistor Q_3 fails open (collector-to-emitter):
- Transistor Q_4 fails open (collector-to-emitter):
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Resistor R_3 fails open:
- Transistor Q_3 fails shorted (collector-to-emitter):
- Transistor Q_4 fails shorted (collector-to-emitter):

For each of these conditions, explain *why* the resulting effects will occur.
file 03714

Answer 16

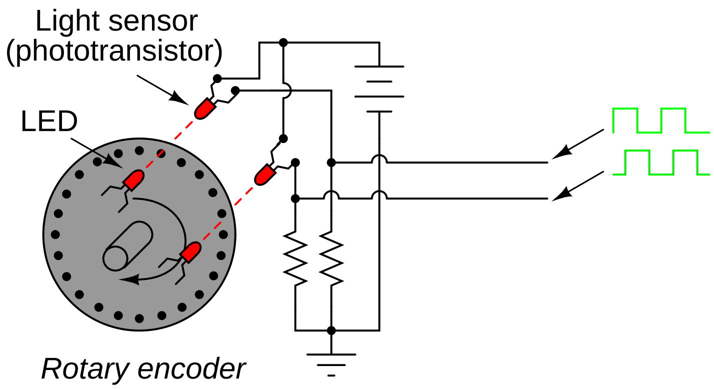
- Transistor Q_1 fails open (collector-to-emitter): *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*
- Transistor Q_2 fails open (collector-to-emitter): *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*
- Transistor Q_3 fails open (collector-to-emitter): *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*
- Transistor Q_4 fails open (collector-to-emitter): *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*
- Resistor R_1 fails open: *Motor fails to turn in "forward" direction, can still turn in "reverse" direction.*
- Resistor R_2 fails open: *Motor fails to turn in "reverse" direction, can still turn in "forward" direction.*
- Resistor R_3 fails open: *Motor cannot turn in either direction.*
- Transistor Q_3 fails shorted (collector-to-emitter): *Motor turns in "forward" direction even when the switch is in the center (off) position.*
- Transistor Q_4 fails shorted (collector-to-emitter): *Motor turns in "reverse" direction even when the switch is in the center (off) position.*

Notes 16

The purpose of this question is to approach the domain of circuit troubleshooting from a perspective of knowing what the fault is, rather than only knowing what the symptoms are. Although this is not necessarily a realistic perspective, it helps students build the foundational knowledge necessary to diagnose a faulted circuit from empirical data. Questions such as this should be followed (eventually) by other questions asking students to identify likely faults based on measurements.

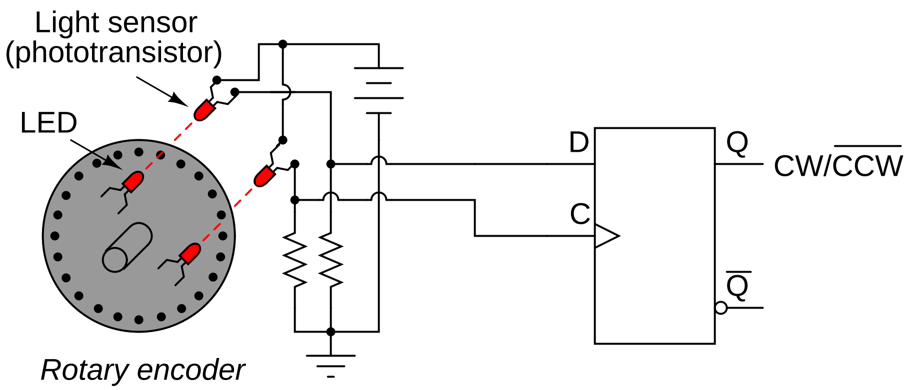
Question 17

A common type of rotary encoder is one built to produce a *quadrature* output:



The two LED/phototransistor pairs are arranged in such a way that their pulse outputs are always 90^o out of phase with each other. Quadrature output encoders are useful because they allow us to determine direction of motion as well as incremental position.

Building a quadrature direction detector circuit is easy, if you use a D-type flip-flop:



Analyze this circuit, and explain how it works.

file 01384

Answer 17

The operation of this circuit is quite easy to understand if you draw a pulse diagram for it and analyze the flip-flop's output over time. When the encoder disk spins clockwise, the Q output goes high; when counterclockwise, the Q goes low.

Follow-up question: comment on the notation used for this circuit's output. What does the label "$CW/\overline{CCW}$" tell you, without having to analyze the circuit at all?

Notes 17

Quadrature direction-detection circuits such as this become important when encoders are linked to digital counter circuits. The complemented notation is also very common in counter circuits.

Students may show a reluctance to draw a timing diagram when they approach this problem, even when they realize the utility of such a diagram. Instead, many will try to figure the circuit out just by looking at it. Note the emphasis on the word "try." This circuit is much more difficult to figure out without a timing diagram! Withhold your explanation of this circuit until each student shows you a timing diagram for it. Emphasize the fact that this step, although it consumes a bit of time, is actually a time-saver in the end.

Question 18

Radio-controlled toy cars, airplanes, and boats use small servo motors for positioning of the steering mechanisms, engine throttle position, and such. These servos have the motor, position sensor, and control electronics housed in the same plastic package, making them very compact.

Research the type(s) of control signals used to command these servo units. In other words, find out what sort of electronic signal they require to "command" them to go to certain positions. Then, suggest a circuit that could generate these signals.

file 03994

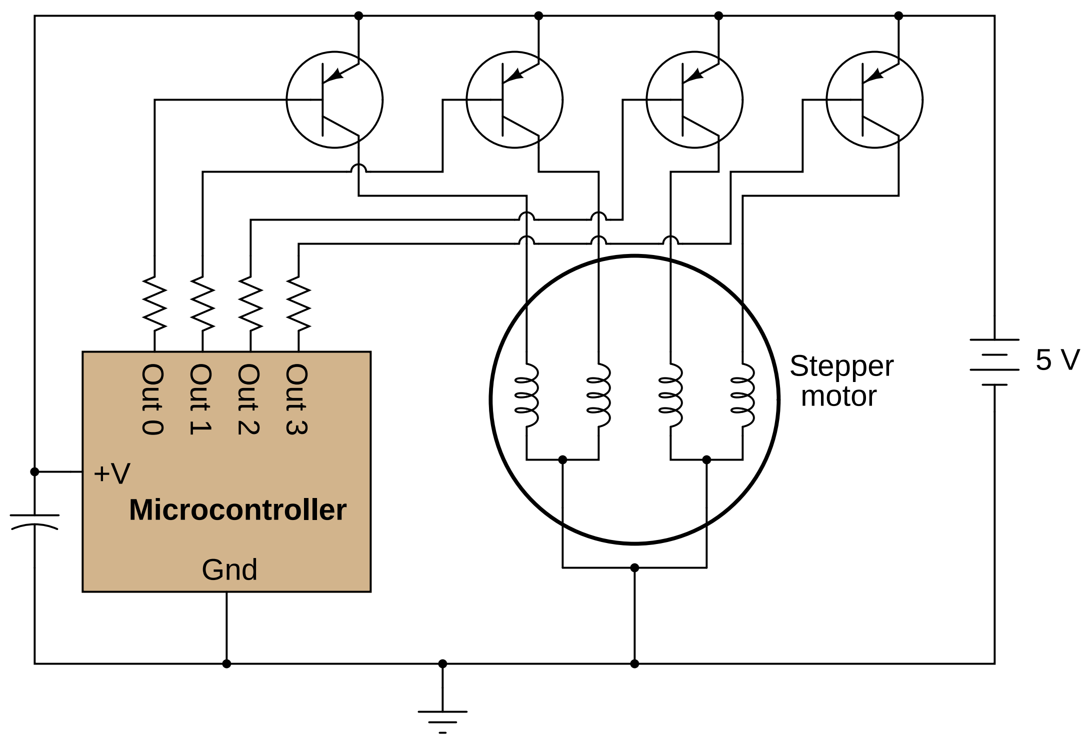
Answer 18

I will not give an answer here, not just because I want you to do all the research and thinking for yourself, but also because RC servo technology may have changed changed since I wrote this question!

Notes 18

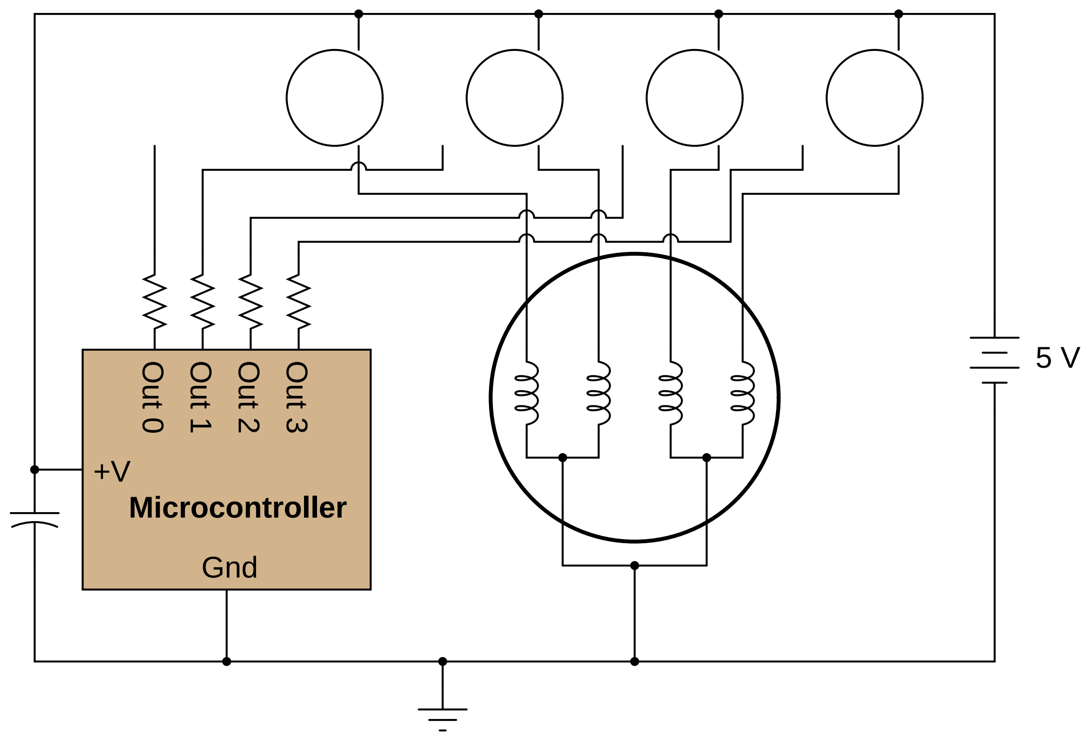
The availability of inexpensive RC servos makes them ideal for use in lab experiments and student projects. It is well worth your students' time (and yours!) to find out how these amazing little devices are controlled!

In this circuit, a microcontroller controls the rotation of a special type of motor known as a *stepper motor* by sequentially activating one transistor at a time (thus, energizing one motor coil at a time). With each step in the sequence, the motor rotates a fixed number of degrees, typically 1.8 degrees per step:



Each motor coil draws a relatively heavy current when energized, necessitating transistors to "interpose" between the microcontroller outputs and the motor coils.

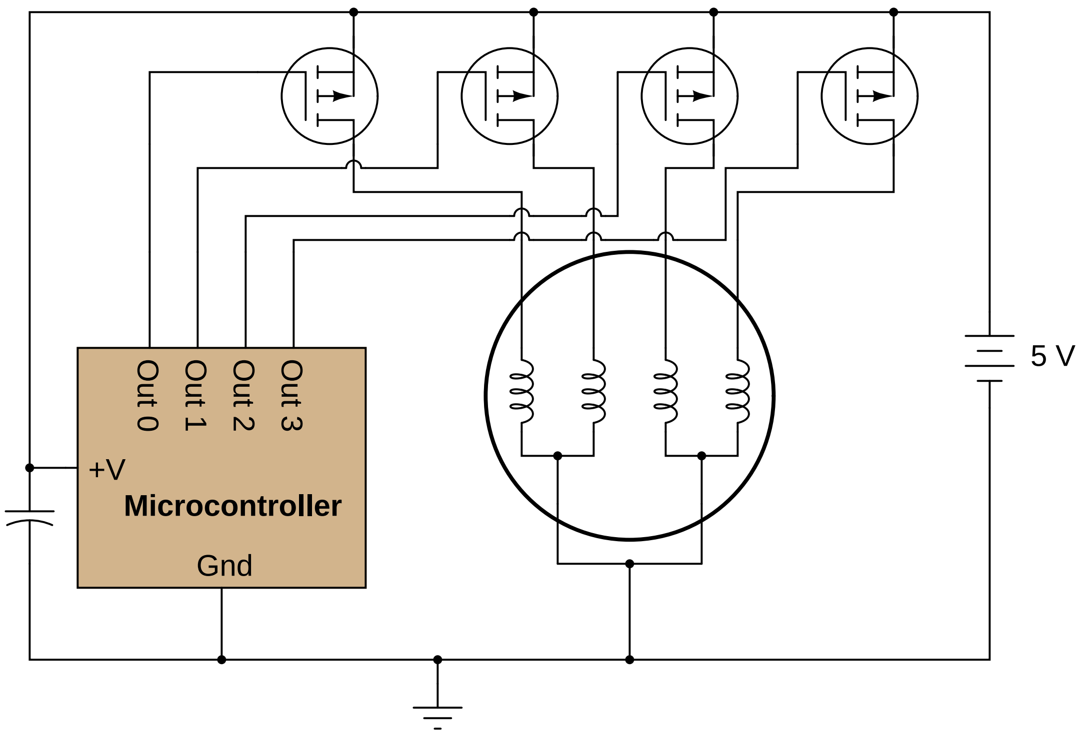
Identify what type of logical signal ("high" or "low") from the output ports of the microcontroller is needed to energize each transistor. Also, show how the power losses and parts count may be reduced by replacing each bipolar junction transistor with a suitable MOSFET in the following diagram:



file 02423

Answer 19

Each stepper motor coil becomes energized when the respective microcontroller output goes to a "low" (Ground potential) state.



Follow-up question: if the resistors had to be left in place, would the modified (MOSFET instead of BJT) circuit still function properly?

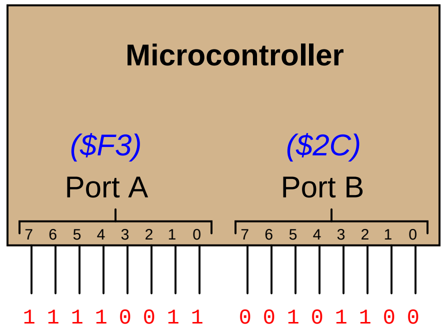
Notes 19

The purpose of this long-winded question is not just to have students figure out how to replace a BJT with a MOSFET, but also to introduce them to the concept of the microcontroller, which is a device of increasing importance in modern electronic systems.

No commutating diodes have been shown in this circuit, for simplicity's sake. If any students ask about this, commend them for noticing!

Question 20

Digital computers communicate with external devices through *ports*: sets of terminals usually arranged in groups of 4, 8, 16, or more (4 bits = 1 *nybble*, 8 bits = 1 *byte*, 16 bits = 2 bytes). These terminals may be set to high or low logic states by writing a program for the computer that sends a numerical value to the port. For example, here is an illustration of a microcontroller being instructed to send the hexadecimal number `F3` to port A and `2C` to port B:



Suppose we wished to use the upper four bits of port A (pins 7, 6, 5, and 4) to drive the coils of a stepper motor in this eight-step sequence:

Step 1: `0001`
Step 2: `0011`
Step 3: `0010`
Step 4: `0110`
Step 5: `0100`
Step 6: `1100`
Step 7: `1000`
Step 8: `1001`

As each pin goes high, it drives a power MOSFET on, which sends current through that respective coil of the stepper motor. By following a "shift" sequence as shown, the motor will rotate a small amount for each cycle.

Write the necessary sequence of numbers to be sent to port A to generate this specific order of bit shifts, in hexadecimal. Leave the lower four bit of port A all in the low logic state.

file 02895

Answer 20

Step 1: 10_{16}
Step 2: 30_{16}
Step 3: 20_{16}
Step 4: 60_{16}
Step 5: 40_{16}
Step 6: $C0_{16}$
Step 7: 80_{16}
Step 8: 90_{16}

Follow-up question: write the same sequence in decimal rather than hexadecimal:

Step 1:
Step 2:
Step 3:
Step 4:
Step 5:
Step 6:
Step 7:
Step 8:

Notes 20

Although the root of this question is nothing more than binary-to-hexadecimal conversion, it also introduces students to the concept of controlling bit states in microcomputer ports by writing hex values. As such, this question is *very* practical!

In case students ask, let them know that a dollar sign prefix is sometimes used to denote a hexadecimal number. Other times, the prefix 0x is used (e.g., $F3 and 0xF3 mean the same thing).

Question 21

Explain what the purpose of a *digital-to-analog converter*, or *DAC* circuit is, in your own words.
file 03997

Answer 21

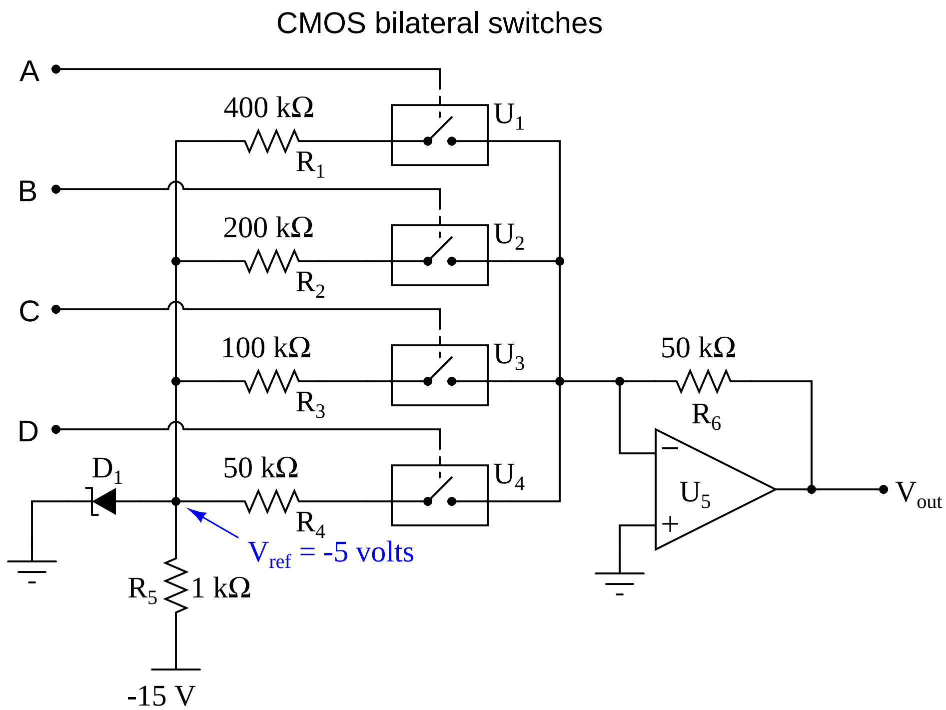
The most basic definition for this device should be obvious: a circuit that takes a digital input and creates an analog output. What I'm looking for, though, is something a little less obvious. In your own words, explain what it means for a circuit to have a "digital input" and an "analog output." You may give an example of such a circuit if you find it easier to answer the question in context.

Notes 21

Informational sources abound which your students can research. Be sure to ask them to answer specifically, explaining what it means for a circuit to have a "digital input" and an "analog output."

Question 22

Explain how this *digital-to-analog* converter (DAC) circuit is supposed to function:



file 03996

Answer 22

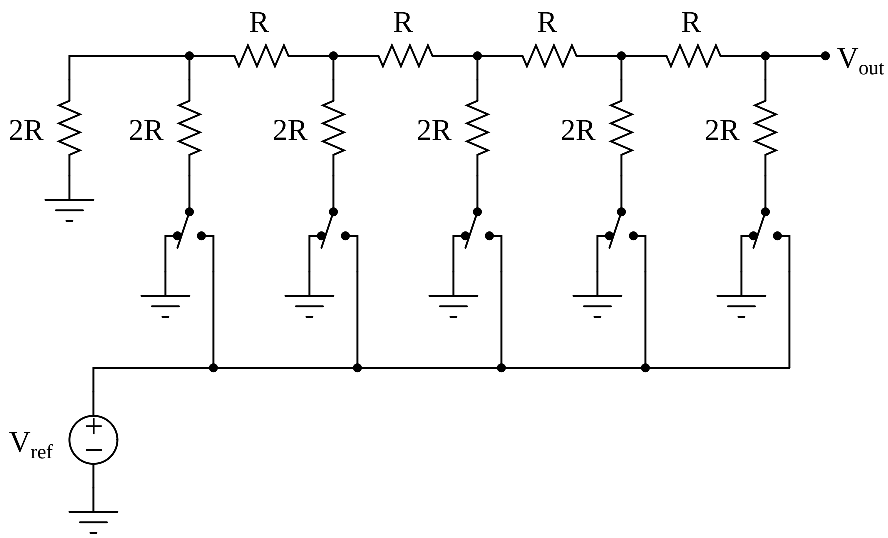
I'll let you figure out the operation of this circuit on your own!

Notes 22

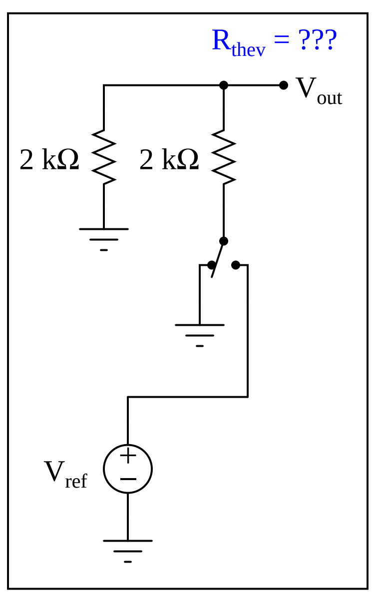
This question is a good review of op-amp theory, especially for students who might not have studied operational amplifiers in a while.

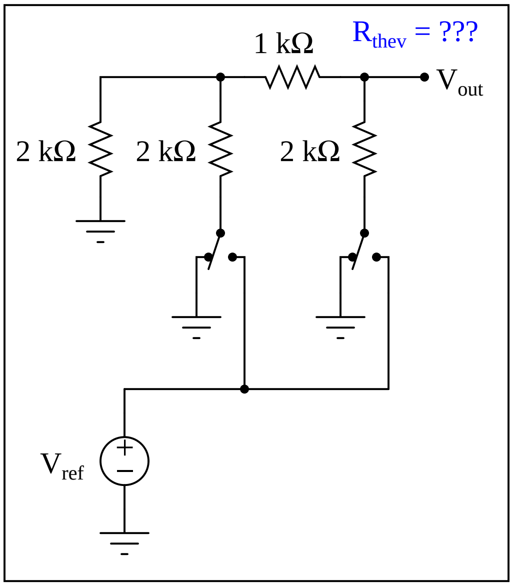
Question 23

A type of resistor network known as an *R-2R ladder* is often used in digital-to-analog conversion circuits:

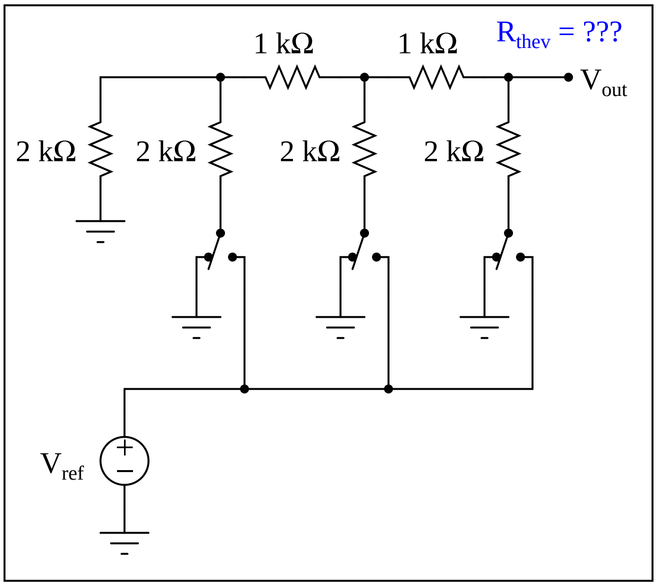


When all switches in the R-2R ladder are in the "ground" position, the network has a very interesting property regardless of its size. Analyze the Thévenin equivalent resistance (as seen from the output terminal) of the following R-2R ladder networks, then comment on the results you obtain:

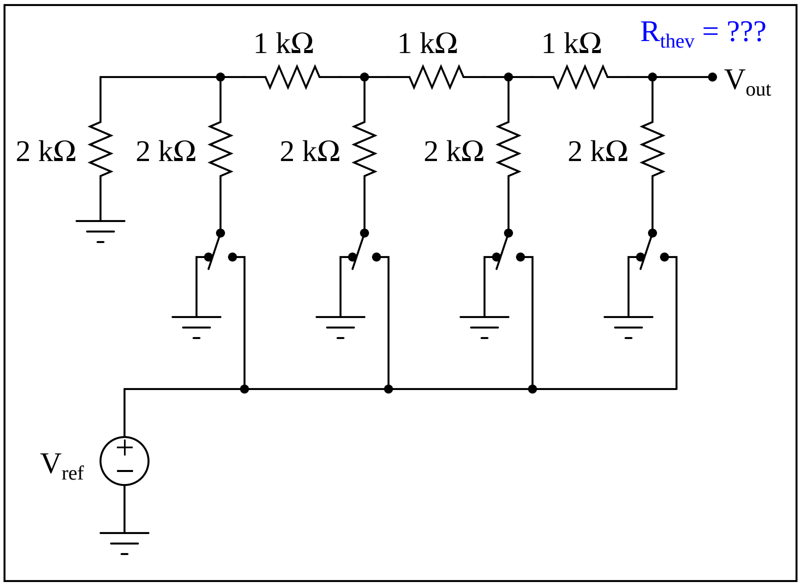


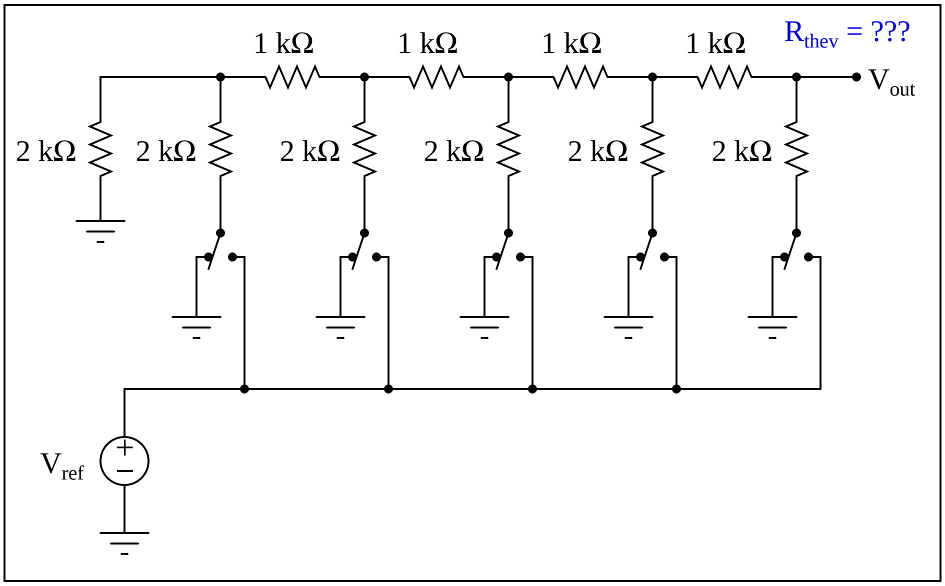


1 kΩ
R_{thev} = ???
V_{out}
2 kΩ
2 kΩ
2 kΩ
V_{ref}



1 kΩ
1 kΩ
R_{thev} = ???
V_{out}
2 kΩ
2 kΩ
2 kΩ
2 kΩ
V_{ref}





file 03999

Answer 23

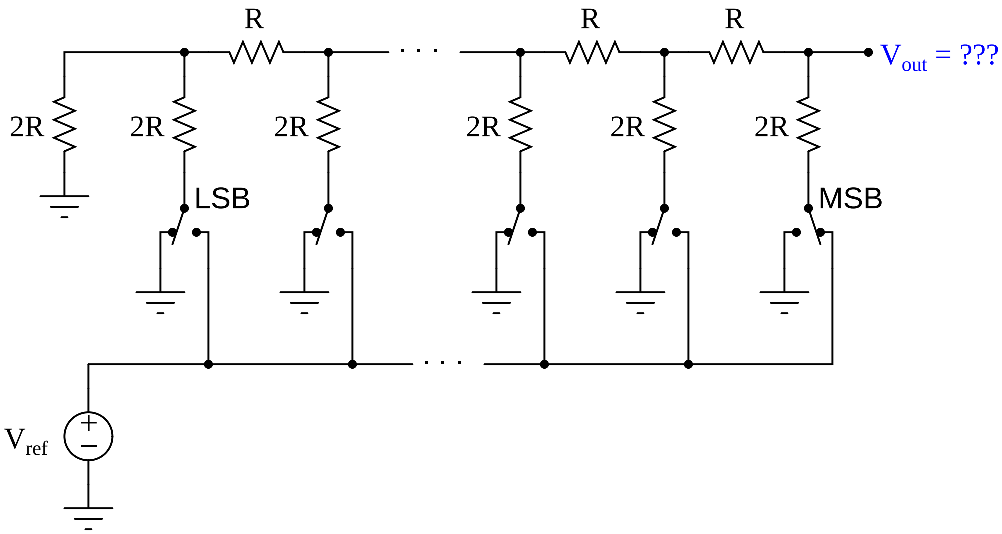
Did you honestly think I'd do all the work for you and just give you the answer?

Notes 23

The answer is not difficult to obtain if you use each Thévenin equivalent resistance to model the left-hand portion of each successive R-2R ladder network as they become more complex! Those students who do not take this problem-solving step are doomed to perform a *lot* of series-parallel calculations!

Question 24

When only the most significant bit (MSB) of an R-2R ladder resistor network is activated (all other bits inactive, their switches connecting to ground), the output voltage will be the same, regardless of how many bits the network has:



Explain why this output voltage magnitude stands independent of the number of bits (sections) in the R-2R ladder network.

file 04000

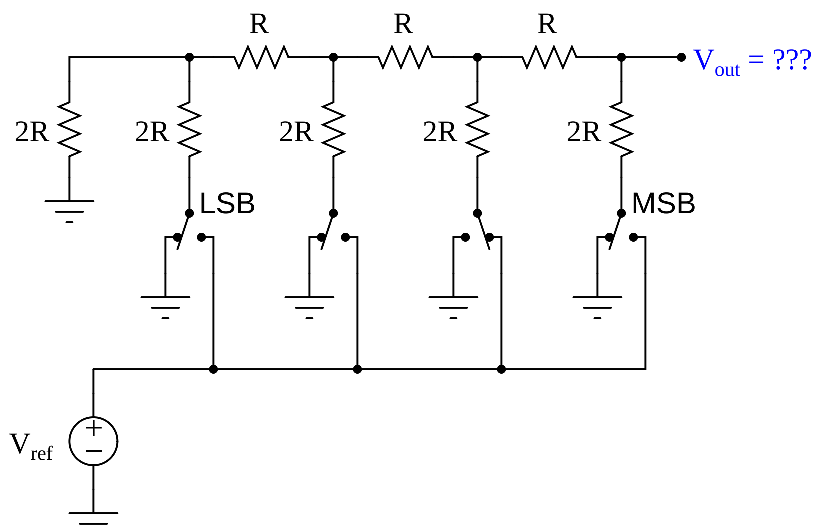
Answer 24

$$V_{out} = \frac{V_{ref}}{2}$$

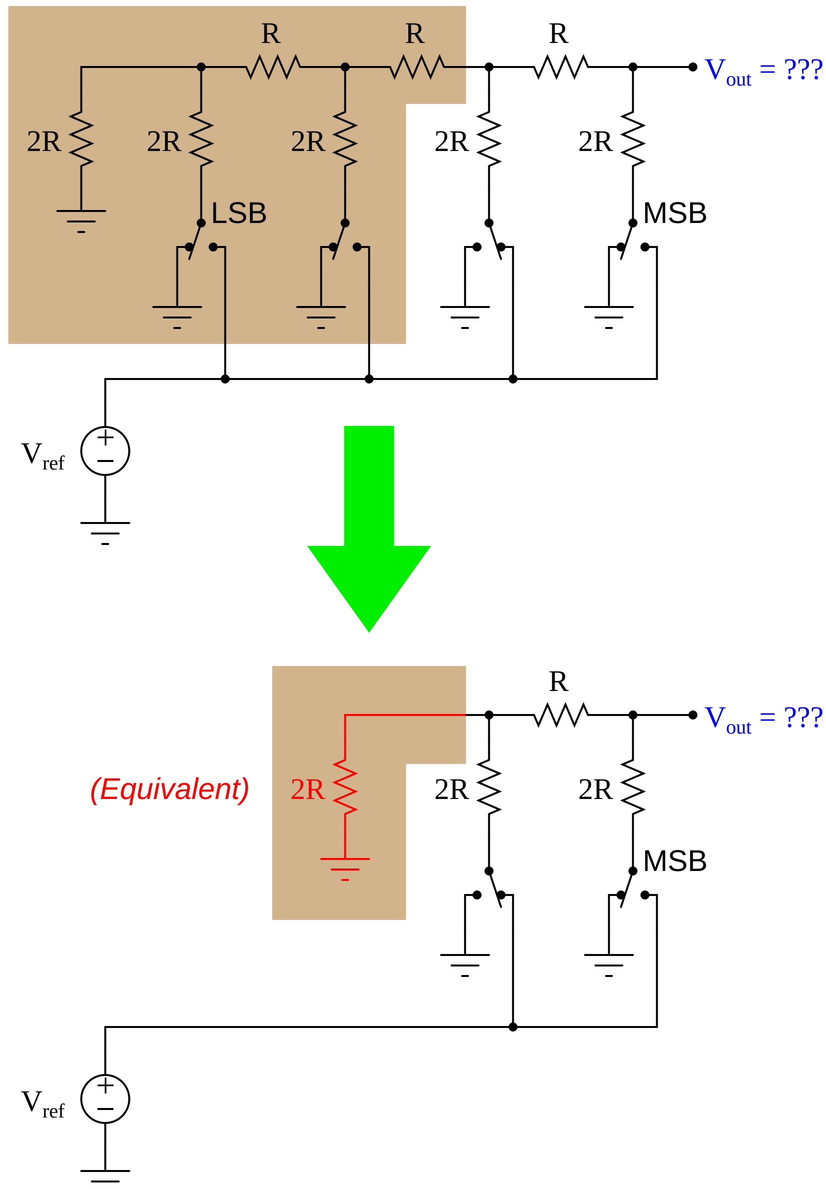
Notes 24

The key to understanding the answer is to apply Thévenin's theorem to the "inactive" sections of the network. Here, the unique property of constant output impedance for an R-2R network yields a useful feature when applied to DAC circuitry.

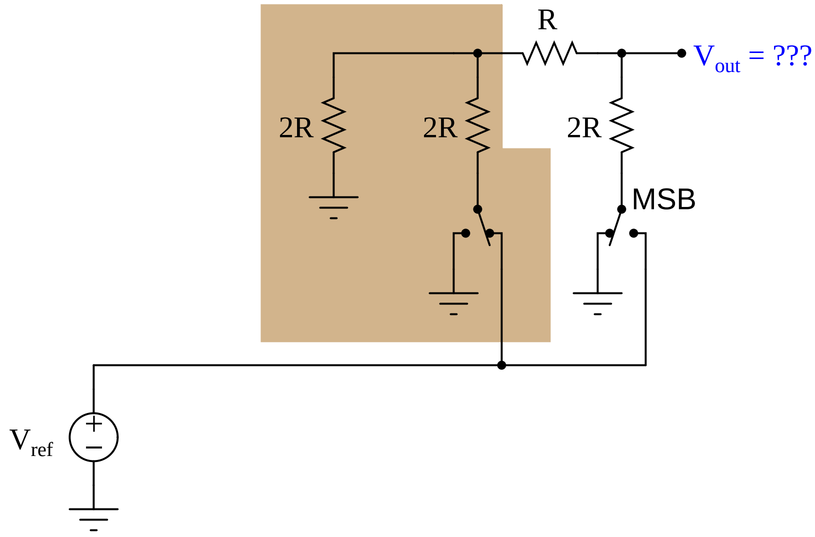
Thévenin's theorem is a powerful tool for analyzing R-2R ladder networks. Take for instance this four-section network where the next-to-most-significant "bit" is activated, while all the other "bits" are inactive (switched to ground):



If we Thévenize all sections to the left of the activated section, replacing it with a single resistance to ground, we see the network becomes far simpler:



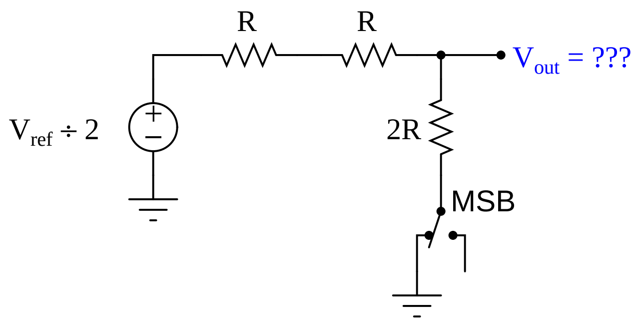
Explain how we may apply Thévenin's theorem once again to the shaded section of this next circuit (simplified from the previous circuit shown above) to simplify it even more, obtaining a final result for V_{out}:



file 04001

Answer 25

Once you get to this point, solving for V_{out} in terms of V_{ref} is trivial:

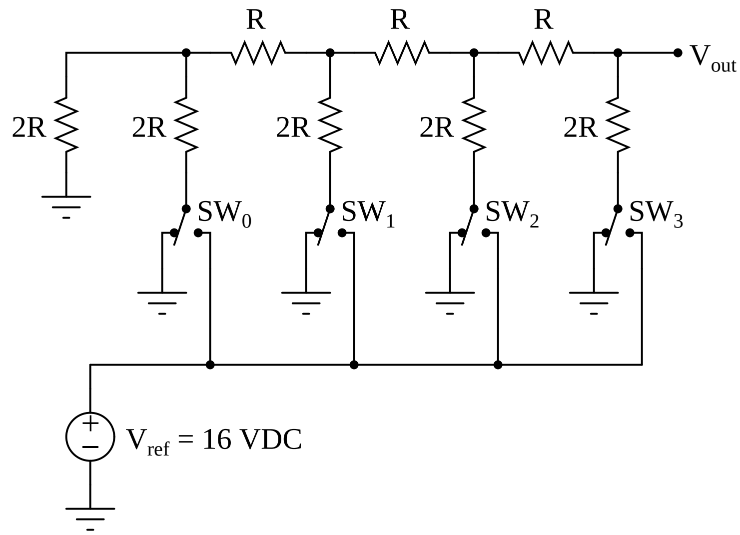


Notes 25

Students might not realize it is valid to iteratively apply Thévenin's theorem to the solution of a circuit problem. You can, and this stands as a good example of how (and why!) you should do it.

Question 26

Determine the voltage output by the following R-2R ladder network given the switch states shown in the table:



SW_0	SW_1	SW_2	SW_3	V_{out}
Ground	Ground	Ground	V_{ref}	
Ground	Ground	V_{ref}	Ground	
Ground	V_{ref}	Ground	Ground	
V_{ref}	Ground	Ground	Ground	
Ground	Ground	Ground	Ground	

file 04007

Answer 26

SW_0	SW_1	SW_2	SW_3	V_{out}
Ground	Ground	Ground	V_{ref}	8 volts
Ground	Ground	V_{ref}	Ground	4 volts
Ground	V_{ref}	Ground	Ground	2 volts
V_{ref}	Ground	Ground	Ground	1 volt
Ground	Ground	Ground	Ground	0 volts

Follow-up question: the fact that an R-2R resistor network is inherently linear, we may readily apply the *Superposition Theorem* to figure out what happens when more than one switch is moved to the V_{ref} position. Explain how you would apply Superposition to determine all output voltages for all possible combinations of switch positions.

Notes 26

As you can see, the reference voltage value of 16 volts was not chosen at random! I wanted students to see the pattern between single switch closures and binary place-weights for a four-bit number. The actual electrical analyses for each condition are best expedited by applying Thévenin's theorem repeated to the circuit, condensing sections to single resistances and voltage sources until a simple voltage divider circuit is obtained at the output terminal.

The follow-up question is quite important. Be sure to ask your students about it, for it holds the key to figuring out all output voltage values for all binary input possibilities.

Question 27

Explain why DAC circuits based on R-2R ladder networks are more popular than binary-weighed resistor networks. Either one will work well if properly designed and built, so why would one design be more widely manufactured?

file 04009

Answer 27

The answer to this question has to do with business and production-line priorities. Just because two designs work equally well in theory does not mean they are equally easy to mass-produce!

Notes 27

It is important for your students to grasp basic principles and practices of business, because that is the arena their technical skills will most likely find challenge and value. This question is a way to get your students thinking about real-life, practical manufacturing concerns that go beyond basic principles of electrical theory.

Question 28

Explain what a *digital potentiometer* is, and give one example of a digital potentiometer in integrated-circuit (IC) form.

file 02817

Answer 28

Analog Devices manufactures a 64-position digital potentiometer under the part number AD5227, for example. This is by no means the only digital potentiometer in production!

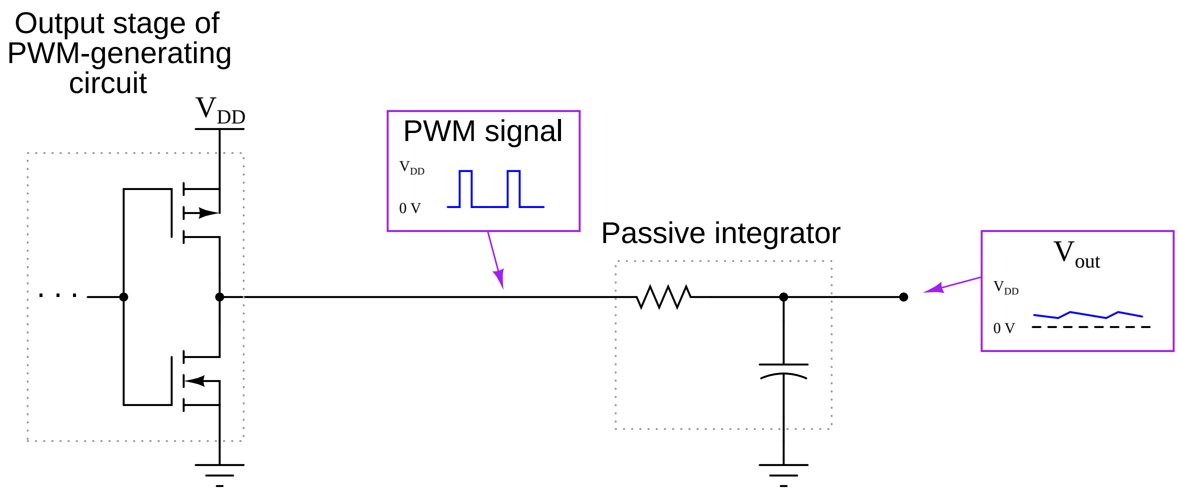
Follow-up question: would you classify a digital potentiometer as an ADC (analog-to-digital converter) or as a DAC (digital-to-analog converter)?

Notes 28

Rarely is the digital potentiometer mentioned in introductory textbooks as a digital-to-analog converter device, but it is!

Question 29

If a pulse-width modulated (PWM) signal is sent to a passive integrator circuit from a circuit capable of both sourcing and sinking current (as is the case with the dual-MOSFET output stage), the output will be a DC voltage (with some ripple):



Determine the relationship between the PWM signal's duty cycle and the DC voltage output by the integrator. What does this suggest about PWM as a means of communicating information, such as analog data from a measuring device?

file 02156

Answer 29

There is a direct-proportional relationship between duty cycle and DC output voltage in this circuit, making it possible for a PWM signal to represent analog data.

Follow-up question #1: why is it important that the circuit generating the PWM signal for the integrator be able to both source *and* sink current?

Follow-up question #2: what would have to be done to reduce the ripple voltage at the integrator's output?

Notes 29

Although it should not be difficult for students to discern the relationship between duty cycle and DC output voltage, the application of this relationship to data communication might be difficult for some students to grasp, especially on their own. Further elaboration on your part may be necessary.

An excellent example of this principle applied is the generation of an analog voltage by a 1-bit digital circuit. This technique is useful in microcontroller systems where output ports may be scarce, provided that ripple voltage (or slow response) is not a problem.

Question 30

What is meant by the word *resolution* in reference to an ADC or a DAC? Why is resolution important to us, and how may it be calculated for any particular circuit knowing the number of binary bits?

file 04008

Answer 30

The *resolution* of either a digital-to-analog converter (DAC) or an analog-to-digital converter (ADC) is the measure of how *finely* its output may change between discrete, binary steps. For instance, an 8-bit DAC with an output voltage range of 0 to 10 volts will have a resolution of 39.22 mV.

Notes 30

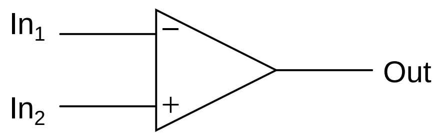
Note that I did not hint how to calculate the resolution of a DAC or an ADC, I just gave the answer for a particular example. The goal here is for students to inductively "work backwards" from my example to a general mathematical statement about resolution.

There are actually two different ways to calculate the resolution, depending on the actual range of the converter circuit. For the answer given, I assumed that a digital value of 0x00 = 0.00 volts DC and that a digital value of 0xFF = 10.00 volts DC. If a student were to calculate the resolution for a circuit where 0xFF generated an output voltage just shy of 10.00 volts DC (e.g. an R-2R ladder network where $V_{ref} = 10$ volts DC, and a full-scale binary input generates an output voltage just one step less than V_{ref}), the correct answer for resolution would be 39.06 mV.

You may want to bring up such practical examples of resolution as the difference between a handheld digital multimeter and a lab-bench digital multimeter. The number of digits on the display is a sure clue to a substantial difference in ADC resolution.

Question 31

A *comparator* may be thought of as a one-bit analog-to-digital converter:



Explain why this description of a comparator is appropriate. What exactly is meant by the term "analog-to-digital converter," or ADC?

file 03847

Answer 31

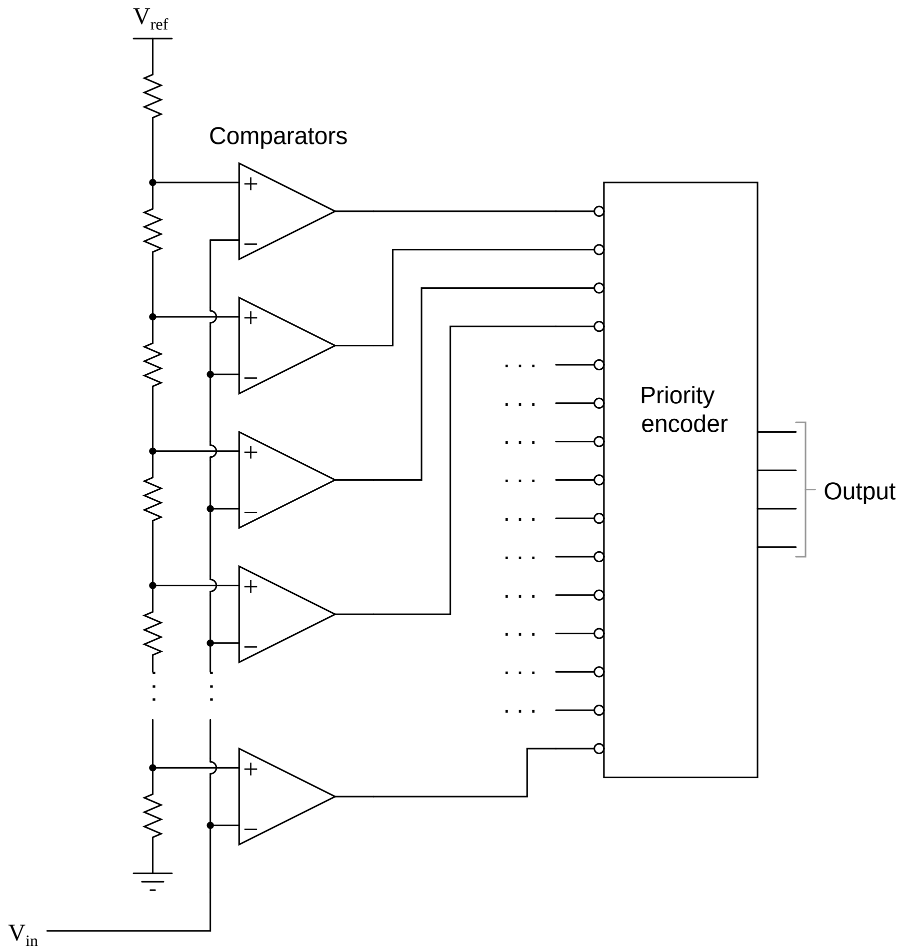
All ADCs input one or more analog signals and output a discrete signal.

Notes 31

This description of a comparator is not just theoretical. In many practical ADC circuits, a comparator is actually used as the primary analog-to-digital conversion device. This is particularly true for *oversampling* or *Sigma-Delta* converters, which may be built around a single (1-bit) comparator.

Question 32

The circuit shown here is a four-bit analog-to-digital converter (ADC). Specifically, it is a *flash* converter, so named because of its high speed:



Explain why we must use a *priority* encoder to encode the comparator outputs into a four-bit binary code, and not a regular encoder. What problem(s) would we have if we were to use a non-priority encoder in this ADC circuit?

file 01413

Answer 32

I won't directly answer this question, but instead pose a "thought experiment." Suppose the analog input voltage (V_{in}) were slowly increased from 0 volts to the reference voltage (V_{ref}). What do the outputs of the comparators do, one at a time, as the analog input voltage increases? What input conditions does the encoder see? How would a primitive "diode network" type of encoder (which we know does *not* encode based on priority) interpret the comparator outputs?

Notes 32

Here, I show students a very practical application of a priority encoder, in which the necessity of priority encoding should be apparent after some analysis of the circuit.

Question 33

Flash analog-to-digital converters are easy to understand, but are not practical for many applications. Identify some of the drawbacks of the "flash" circuit design.

file 04010

Answer 33

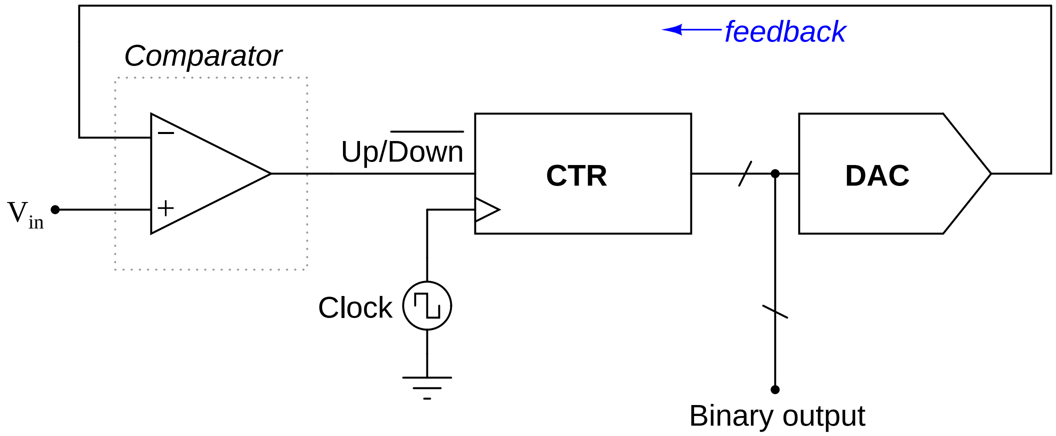
Flash converter circuits have too many components! Actually, the answer is a bit more detailed than this, but easy enough to find on your own that I'll leave the task of research to you.

Notes 33

It is a shame that flash converter circuits suffer the disadvantage(s) that they do. They are so simple to understand and have such an inherent speed advantage over other circuit designs! Discuss with your students why the weaknesses of the flash design make the other ADC types necessary, and even preferable in most applications.

Question 34

Explain the operating principle of this analog-to-digital converter circuit, usually referred to as a *tracking* converter:



file 04014

Answer 34

The binary counter will count up or down as necessary to "track" the analog input voltage, resulting in a binary output that continuously represents the input.

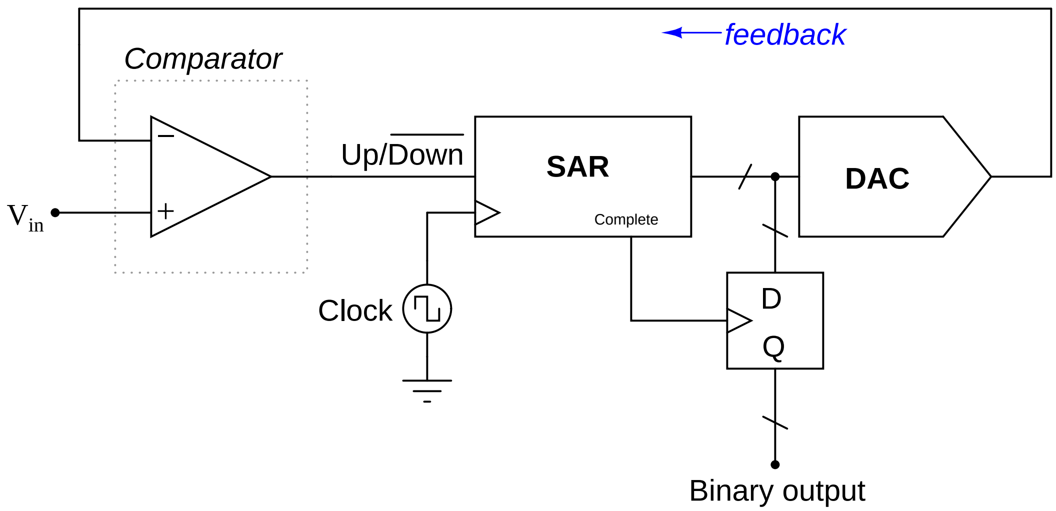
Follow-up question: this form of ADC is not very effective at following fast-changing input signals. Explain why.

Notes 34

Have your students express the answer to this question in their own words, not just copying the answer I provide. Aside from the flash converter, the tracking converter is one of the easiest ADC circuits to understand.

Question 35

Explain the operating principle of this analog-to-digital converter circuit, usually referred to as a *successive-approximation* converter:



Note: the successive-approximation register (SAR) is a special type of binary counting circuit which begins counting with the most-significant bit (MSB), then the next-less-significant bit, in order all the way down to the LSB. At that point, it outputs a "high" signal at the "Complete" output terminal. The operation of this register may be likened to the manual process of converting a decimal number to binary by "trial and fit" with the MSB first, through all the successive bits down to the LSB.

file 04015

Answer 35

The successive approximation register counts up and down as necessary to "zero in" on the analog input voltage, resulting in a binary output that locks into the correct value once every n clock cycles, where n is the number of bits the DAC inputs.

Follow-up question: this form of ADC is much more effective at following fast-changing input signals than the *tracking* converter design. Explain why.

Notes 35

Have your students express the answer to this question in their own words, not just copying the answer I provide. Aside from the flash converter, the tracking converter is one of the easiest ADC circuits to understand.

Question 36

Explain the operating principle of a *single-slope* ADC circuit, in your own words.

file 04016

Answer 36

I won't give away all the details here, but the single-slope converter uses an integrator and a binary counter, the binary output determined by how long the counter is allowed to count.

Notes 36

Tutorials abound on simple ADC strategies, so your students should have little problem locating an adequate explanation for the operation of a single-slope ADC.

Question 37

Explain the operating principle of a *dual-slope* ADC circuit, in your own words.

file 04017

Answer 37

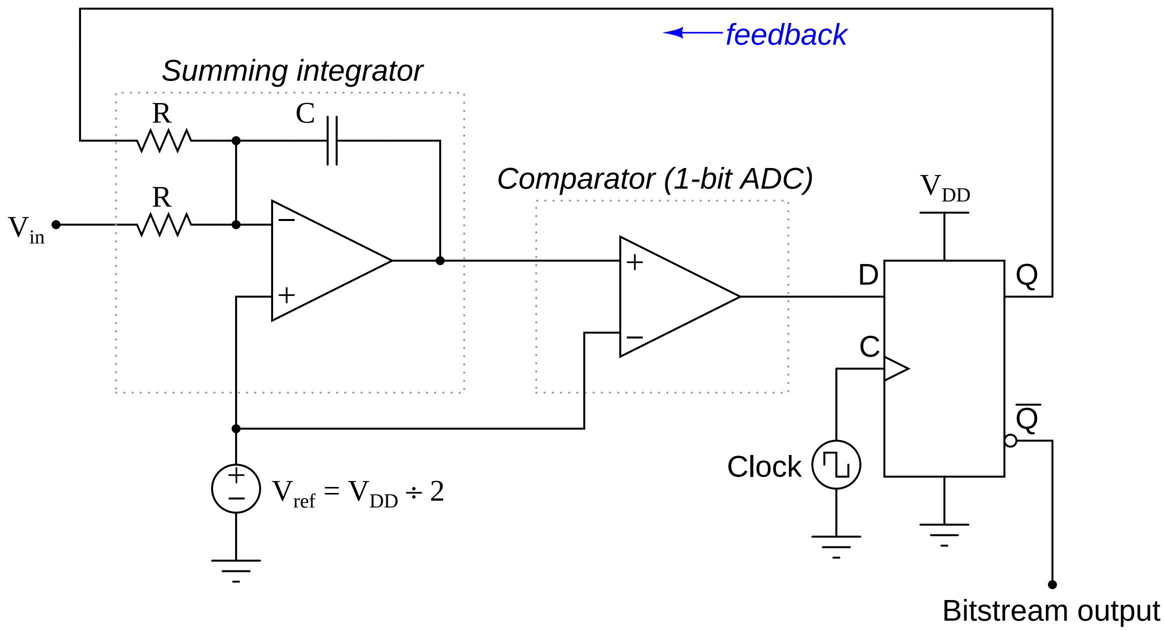
I won't give away all the details here, but the dual-slope converter uses the same integrator and binary counter that the single-slope ADC does. However, the integrator is used a bit differently in the dual-slope design, the benefits being greater immunity to high-frequency noise on the input signal and greater accuracy due to relative insensitivity to integrator component values.

Notes 37

Tutorials abound on simple ADC strategies, so your students should have little problem locating an adequate explanation for the operation of a dual-slope ADC.

Question 38

The *Delta-Sigma* or *Sigma-Delta* analog-to-digital converter works on the principle of *oversampling*, whereby a low-resolution ADC repeatedly samples the input signal in a feedback loop. In many cases, the ADC used is nothing more than a comparator (a 1-bit ADC!), the output of this ADC subtracted from the input signal and integrated over time in an attempt to achieve a balance near 0 volts at the output of the integrator. The result is a *pulse-density modulated* (PDM) "bitstream" of 1-bit digital data which may be filtered and *decimated* (converted to a binary word of multiple bits):



Explain what this PDM bitstream would look like for the following input voltage conditions:

- $V_{in} = 0$ volts
- $V_{in} = V_{DD}$
- $V_{in} = V_{ref}$

file 04011

Answer 38

- $V_{in} = 0$ volts ; bitstream = `00000000` . . .
- $V_{in} = V_{DD}$; bitstream = `11111111` . . .
- $V_{in} = V_{ref}$; bitstream = `01010101` . . .

Notes 38

In order to answer this question, students must have a good grasp of how the summing integrator works. Discuss with them how the feedback loop's "goal" is to maintain the integrator output at the reference voltage (V_{ref}), and how the 1-bit ADC can only make adjustments to the integrator's output by driving it upward or downward by the same analog quantity every clock pulse.

Question 39

The pulse-density modulation (PDM) of a 1-bit oversampled Delta-Sigma modulator circuit may be "decimated" into a multi-bit binary number simply by counting the number of "1" states in a bitstream of fixed length.

Take for example the following bitstreams. Sample the first seven bits of each stream, and convert the equivalent binary numbers based on the number of "high" bits in each seven-bit sample:

- `001001001001001`
- `101101101101101`
- `010010001100010`
- `010001100010001`
- `111011101110111`

Then, take the same five PDM bitstreams and "decimate" them over a sampling interval of 15 bits.
file 04012

Answer 39

Sampling interval = 7 bits

- `001001001001001` ; Binary value = 010_2
- `101101101101101` ; Binary value = 101_2 or 100_2
- `010010001100010` ; Binary value = 010_2 or 011_2
- `010001100010001` ; Binary value = 011_2 or 001_2
- `111011101110111` ; Binary value = 110_2 or 101_2

Sampling interval = 15 bits

- `001001001001001` ; Binary value = 0101_2
- `101101101101101` ; Binary value = 1010_2
- `010010001100010` ; Binary value = 0101_2
- `010001100010001` ; Binary value = 0101_2
- `111011101110111` ; Binary value = 1100_2

Follow-up question: what relationship do you see between *sampling speed* and *resolution* in this "decimation" process, and how does this relate to the performance of a Delta-Sigma ADC?

With little effort, your students should be able to see that sampling twice as many bits in the PDM bitstream adds one more bit of resolution to the final binary output. Such is the nature of so many circuits: that optimization of one performance parameter comes at the expense of another.

Students may question how two (or more!) different decimation results can occur from the same bitstream, especially as shown in the answer for the 7-bit groupings. The answer is two-part: first, the bitstreams I show are not all perfectly repetitive. Some change pattern (slightly) mid-way, which leads to different pulse densities in different sections. The second part to this answer is that the nature of decimation by grouping will inevitably lead to differing results (even when the pattern is perfectly repetitive), and that this is the converter's "way" of resolving an analog quantity lying *between* two discrete output states. In other words, a pair of decimated values of "4" and "5" (100_2 and 101_2, respectively) from a perfectly repetitive bitstream suggests an analog value lying somewhere between the discrete integer values of "4" and "5". Only by sampling groups of bits equal to the period of the PDM repetition (or integer multiples of that repetition) can the digital output precisely and constantly equal the analog input.

Question 40

Suppose an analog-digital converter IC ("chip") inputs a voltage ranging from 0 to 5 volts DC and converts the magnitude of that voltage into an 8-bit binary number. How many discrete "steps" are there in the output as the converter circuit resolves the input voltage from one end of its range (0 volts) to the other (5 volts)? How much voltage does each of these steps represent?

file 02951

Answer 40

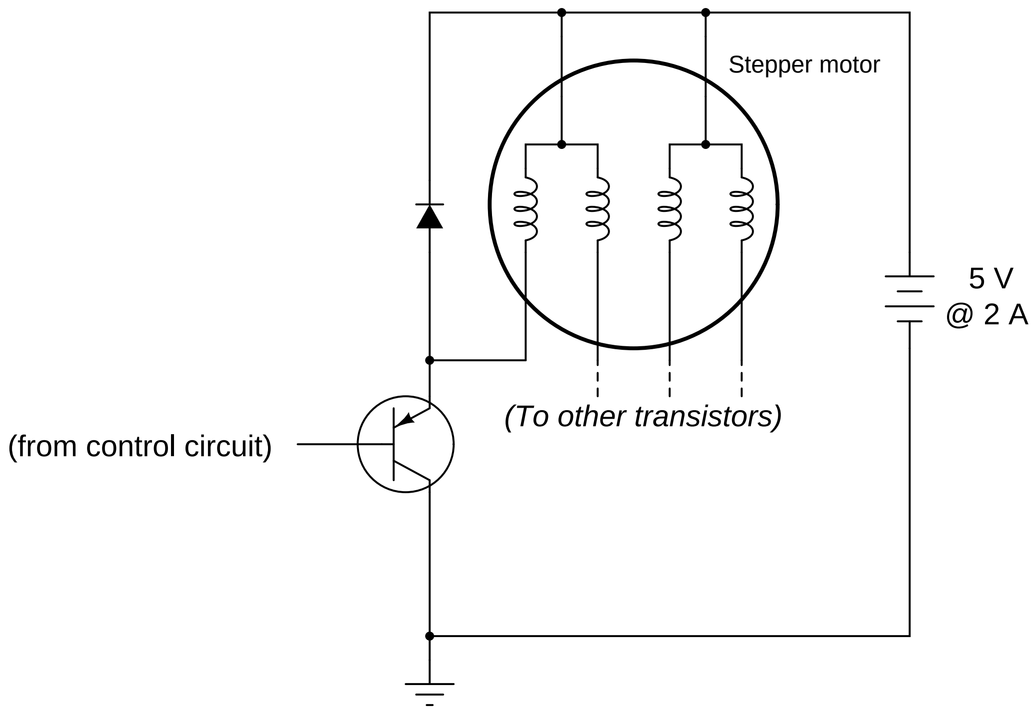
This ADC (Analog-to-Digital Converter) circuit has 256 steps in its output range, each step representing 19.61 mV.

Notes 40

This question is not so much about ADC circuitry as it is about digital resolution in general. Any digital system with a finite number of parallel bits has a finite range. When representing analog variables in digital form by the limited number of bits available, there will be a certain minimum voltage increment represented by each "step" in the digital output. Here, students get to see how the discrete nature of a binary number translates to real-life measurement "rounding."

Question 41

Stepper motor coils typically draw a lot of current, requiring the use of power transistors to "buffer" the control circuitry to the motor. A typical stepper motor final drive circuit looks something like this (only one of the four output transistors is shown, for brevity):

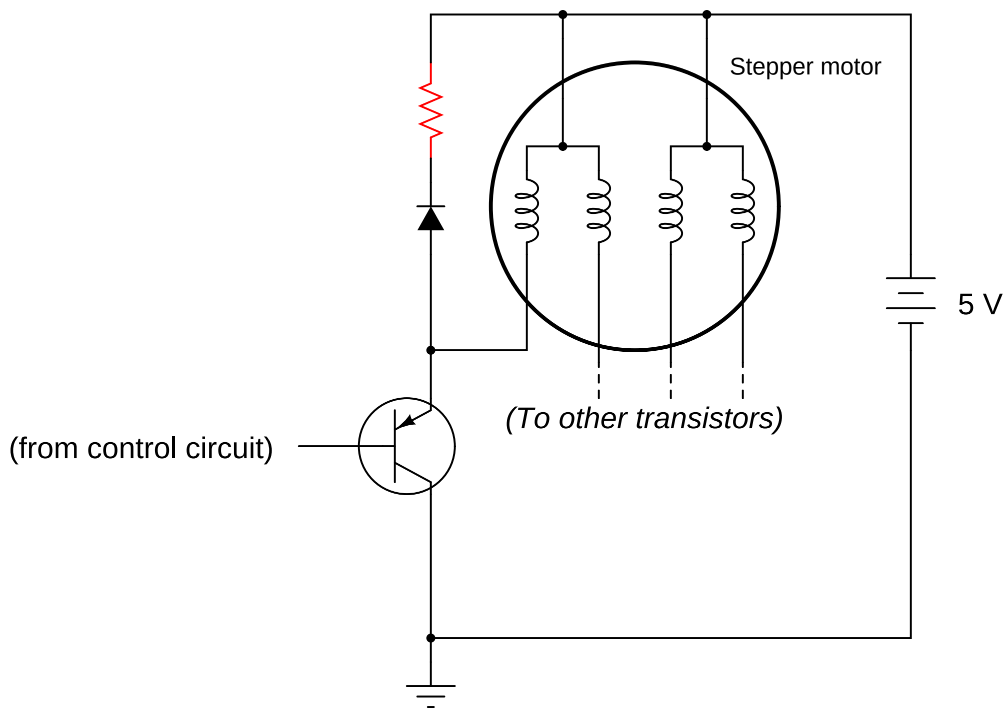


The diode is installed, of course, to prevent high-voltage surges from destroying the output transistor each time it turns off. However, this causes a different problem: with the free-wheeling diodes in place, the magnetic field formed in each coil takes longer to "decay" when its respective transistor turns off. This delay in time imposes a maximum rotational speed on the stepper motor, because the motor will not move to the next step until the magnetic field(s) from the previous step have dissipated.

What modification may be made to this circuit to allow the transistors to switch faster, driving the stepper motor at a higher rotational speed? Explain in detail why your solution will work.

file 01527

Answer 41



I won't explain exactly why this solution works, but I'll let Michael Faraday give you a mathematical "hint:"

$$v = N \frac{d\phi}{dt}$$

Follow-up question: what factors determine the resistance value of the new resistor shown in the diagram?

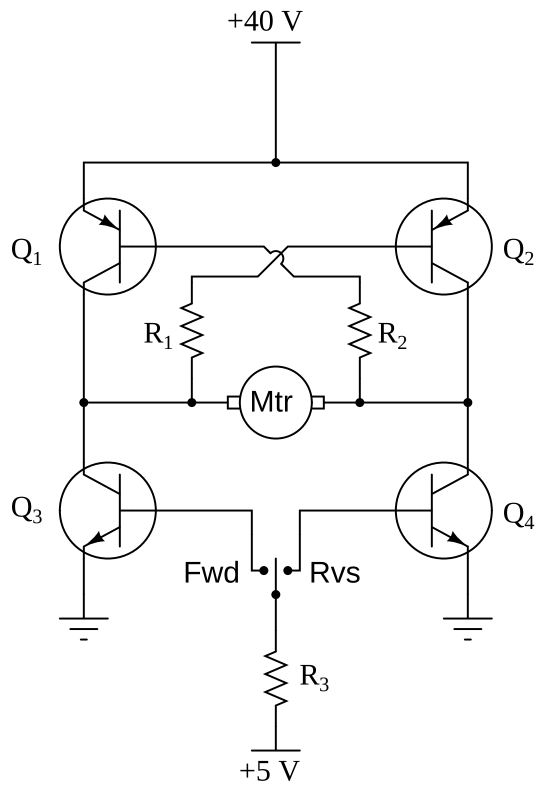
Challenge question: determine how to calculate the magnitude of the voltage "spike" seen at the transistor's collector terminal given a certain resistance value, diode specifications, and full-load motor coil current.

Notes 41

Ask your students to describe the rate-of-change of magnetic flux in each coil upon transistor turn-off, with no commutating diodes in place (assuming the transistor could withstand the transient voltages produced by the inductor). It should become clear to your students that the inclusion of diodes to prevent the high-voltage "spikes" literally creates the problem of magnetic field decay time.

Question 42

Determine all component voltage drops in this circuit when the motor is operating in the reverse direction. Be sure to explain how you performed all the analyses! Assume 0.7 volts as the standard forward voltage drop for a forward-biased PN junction, and 0.3 volts as the standard collector-to-emitter voltage drop for a saturated BJT.



file 04033

Answer 42

I'll give you a hint: use *Kirchhoff's Voltage Law*.

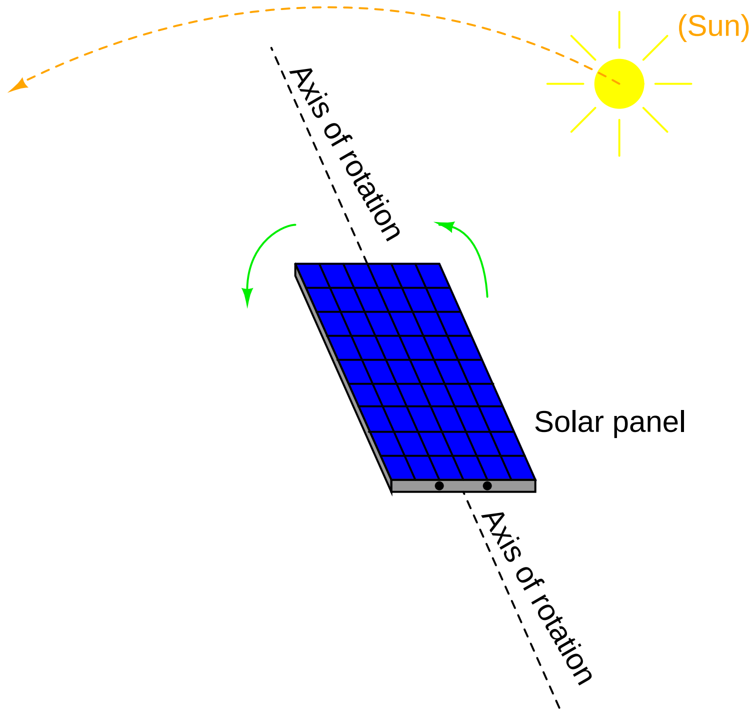
Challenge question: what type of DC motor must this be, to be reversed in rotational direction by a reversal of polarity?

Notes 42

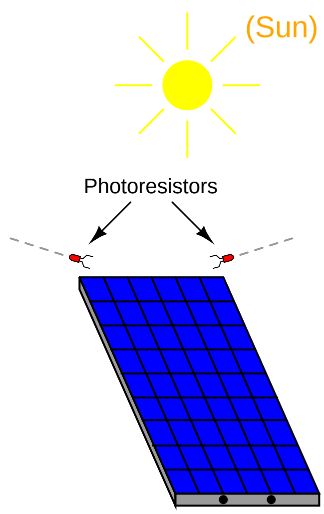
The primary purpose of this question is to give students more practice using Kirchhoff's Voltage Law. Be sure to work through the analysis of *all* component voltage drops.

Question 43

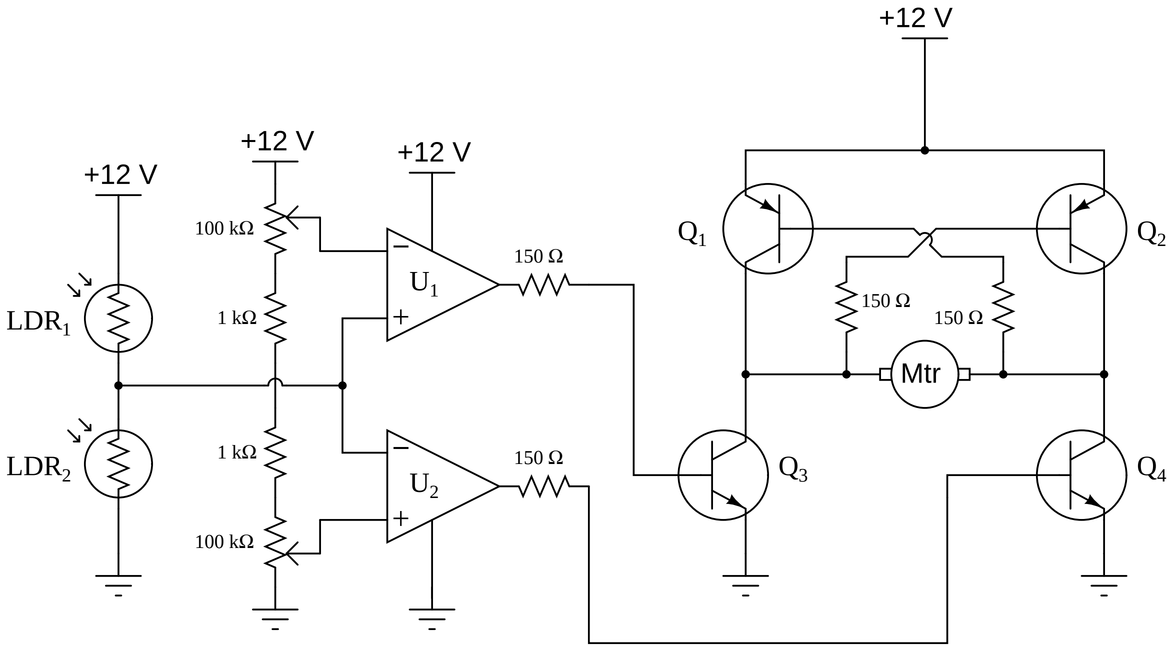
Photovoltaic solar panels produce the most output power when facing directly into sunlight. To maintain proper positioning, "tracker" systems may be used to orient the panels' direction as the sun "moves" from east to west across the sky:



One way to detect the sun's position relative to the panel is to attach a pair of Light-Dependent Resistors (LDR's) to the solar panel in such a way that each LDR will receive an equal amount of light only if the panel is pointed directly at the sun:



Two comparators are used to sense the differential resistance produced by these two LDR's, and activate a tracking motor to tilt the solar panel on its axis when the differential resistance becomes too great. An "H-drive" transistor switching circuit takes the comparators' output signals and amplifies them to drive a permanent-magnet DC motor one way or the other:



In this circuit, what guarantees that the two comparators never output a "high" (+V) voltage simultaneously, thus attempting to move the tracking motor clockwise and counter-clockwise at the same time?

file 00881

Answer 43

With the potentiometers connected in series like this, the upper comparator's reference voltage will always be greater than the lower comparator's reference voltage. In order for both comparators to saturate their outputs "high," the voltage from the photoresistor divider would have to be greater than the upper potentiometer's voltage *and* less then the lower potentiometer's voltage at the same time, which is an impossibility. This comparator configuration is commonly known as a *window comparator* circuit.

Notes 43

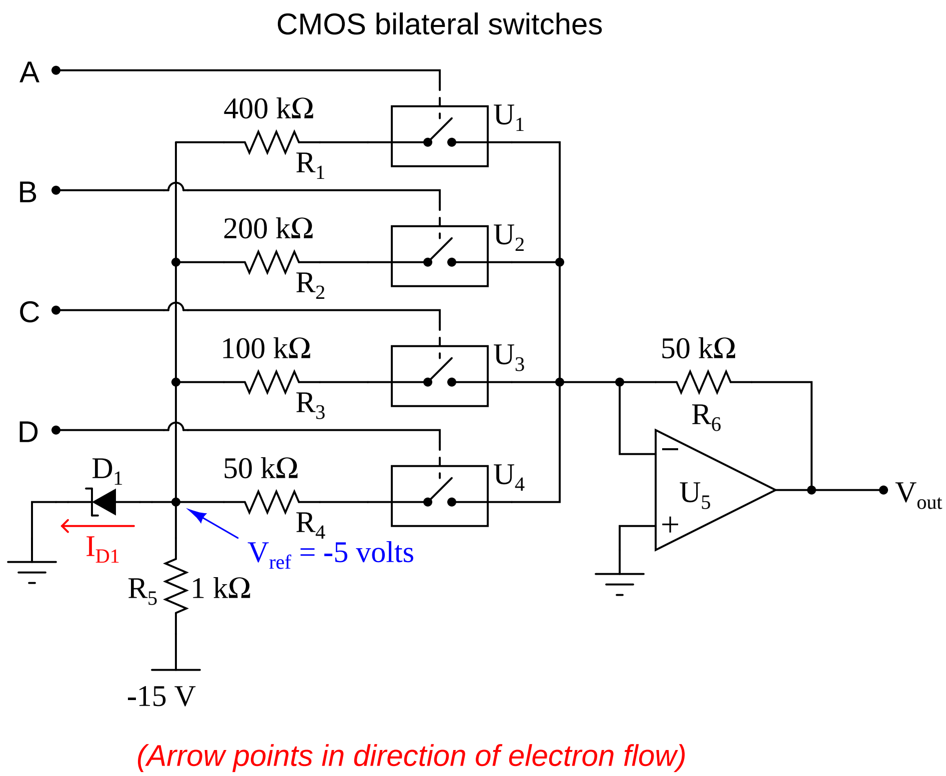
There is a lot going on in this comparator circuit for you and your students to discuss. Take time to talk about the operation of the entire circuit in detail, making sure students understand how every bit of it works.

If any of your students point out that there seem to be some power supply connections missing from the comparators (U_1 and U_2), discuss the fact that this notation is often used when multiple opamps or comparators are contained in the same integrated circuit. Often, the power supply connections will be omitted entirely for the sake of simplicity! Since everyone understands that opamps *need* DC power in order to function, the +V and -V (or ground) connections are simply assumed.

One misunderstanding I've seen with beginning students is to assume that signal input connections and power connections to an opamp are equivalent. That is, if an opamp does not receive +V/-V power through the normal power terminals, it will operate off of whatever voltages appear at its inverting and noninverting inputs. Nothing could be further from the truth! An "input" connection to a circuit denotes a signal to be detected, measured, or manipulated. A "power" connection is completely different. To use a stereo analogy, this is confusing the audio patch cable connections with the power cord.

Question 44

This *digital-to-analog* converter (DAC) circuit takes a four-bit binary input (input terminals A through D) and converts it to an analog voltage (V_{out}). Predict how the operation of this circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



- Bilateral switch U_1 fails open:
- Zener diode fails shorted:
- Solder bridge (short) past resistor R_1:
- Resistor R_6 fails open:

file 03849

Answer 44

- Bilateral switch U_1 fails open: *V_{out} same for all odd numbered input conditions as it is for next lowest even-numbered input condition (e.g. input value of 5 gives same output as input value of 4).*
- Zener diode fails shorted: *V_{out} is nearly zero volts for any input condition.*
- Solder bridge (short) past resistor R_1: *V_{out} saturates positive for any given odd-valued input condition.*
- Resistor R_6 fails open: *V_{out} always saturated.*

Follow-up question #1: is the arrow showing zener diode current drawn in the direction of electron flow or conventional flow?

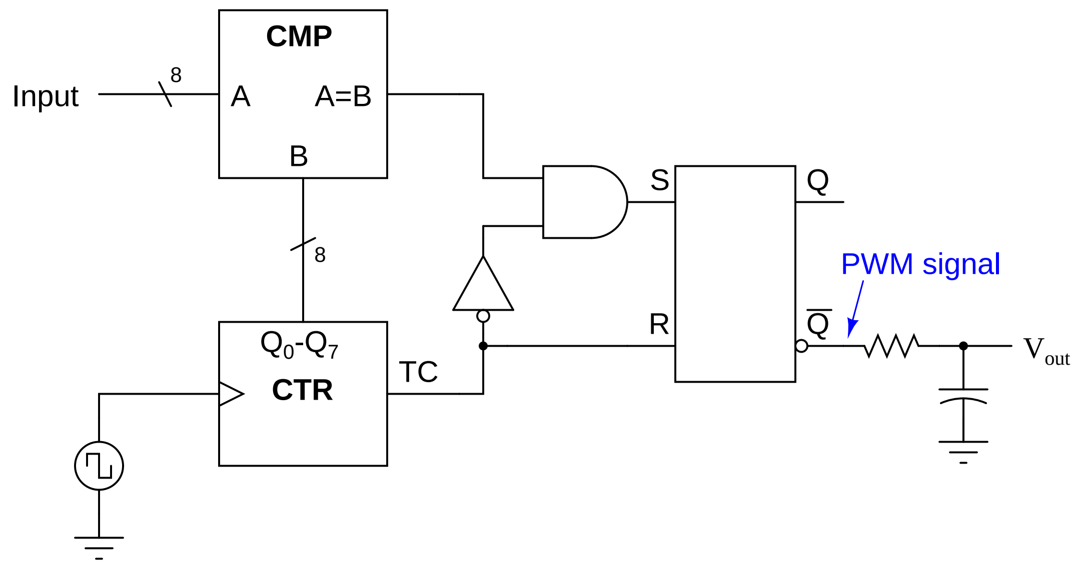
Follow-up question #2: which input bit is the most significant (MSB) and which is the least significant (LSB)?

Notes 44

Questions like this help students hone their troubleshooting skills by forcing them to think through the consequences of each possibility. This is an essential step in troubleshooting, and it requires a firm understanding of circuit function.

Question 45

The following circuit generates an analog output voltage proportional to the value of the binary input, using pulse-width modulation (PWM) as an interim format. An eight-bit binary counter (**CTR**) continually counts in the "up" direction, while an 8-bit magnitude comparator (**CMP**) checks when the 8-bit binary input value matches the counter's output value. The AND gate and inverter simply prevent the S-R latch from being "set" and "reset" simultaneously (when both A and B are maximum, both at a hex value of $FF), which would cause the output to be "invalid" when S and R were both active, and unpredictable when both S and R inputs returned to their inactive states:

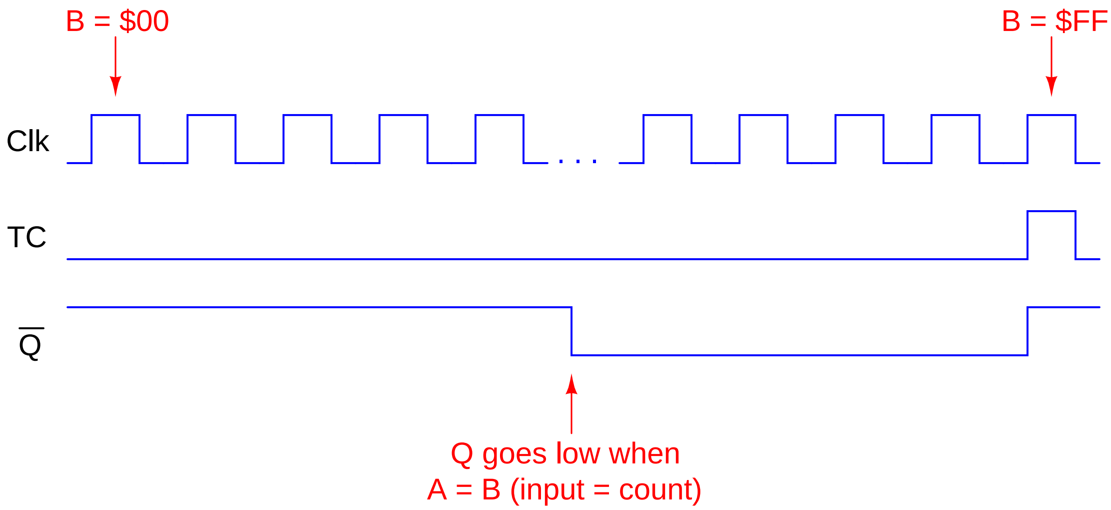


Explain how this circuit works, using timing diagrams if necessary to help show the PWM signal at $\overline{Q}$ for different input values.

file 03998

Answer 45

Here is a timing diagram to help get you started on a complete answer:



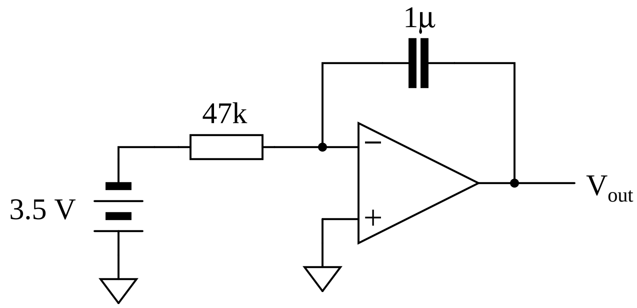
I'll leave it to you to explain the relationship between the input value (A), the PWM duty cycle, and the analog output voltage.

Notes 45

This circuit provides students with an interesting exercise in timing analysis, as well as being a simple means of converting large binary values into analog output voltages without resorting to using *large* resistor networks.

Question 46

Calculate the output voltage rate-of-change ($\frac{dv}{dt}$) for this active integrator circuit, being sure to explain all the steps involved in determining the answer:



file 04037

Answer 46

$\frac{dv}{dt} = +74.47$ volts/second

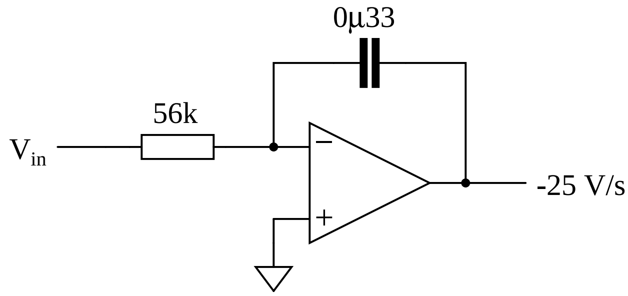
Notes 46

Ask your students to relate the capacitive "Ohm's Law" equation to their solutions:

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

Question 47

Calculate the input voltage needed to produce an output voltage rate-of-change ($\frac{dv}{dt}$) of -25 volts per second in this active integrator circuit:



file 04038

Answer 47

$V_{in} = +462$ mV

Notes 47

Ask your students to relate the capacitive "Ohm's Law" equation to their solutions:

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

Question 48

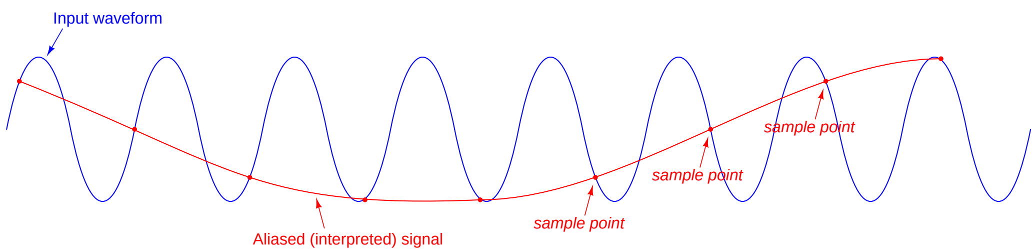
One of the idiosyncrasies of analog-to-digital conversion is a phenomenon known as *aliasing*. It happens when an ADC attempts to digitize a waveform with too high of a frequency.

Explain what aliasing is, how it happens, and what may be done to prevent it from happening to an ADC circuit.

file 04040

Answer 48

As the saying goes, a picture is worth a thousand words:



Notes 48

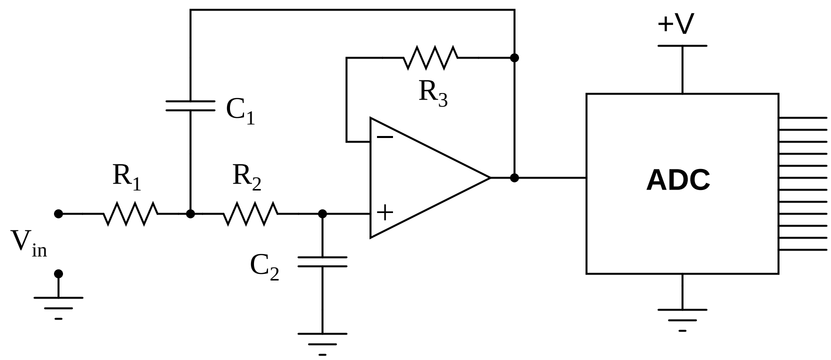
The point of this question (and of the answer given) is to have students put this important concept into their own words.

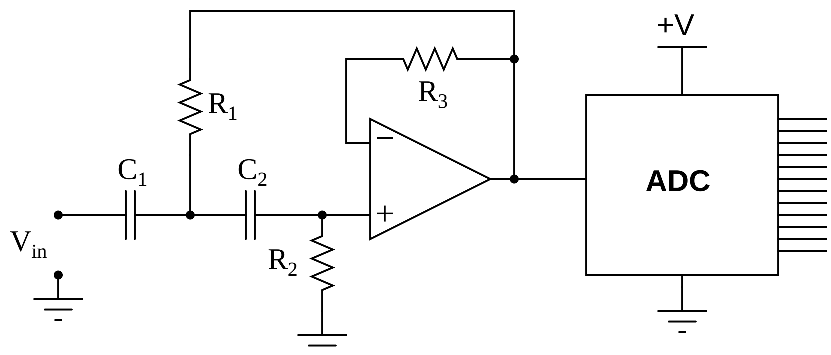
Something noteworthy for students and instructors alike is that aliasing may be visually experienced using digital oscilloscopes. Setting the timebase (seconds/division) control too slow may result in a false (aliased) waveform displayed in the oscilloscope. Not only does this make a good classroom demonstration, but it also is a great lesson to learn if one expects to use digital oscilloscopes on a regular basis!

Question 49

Analog-to-digital converter circuits (ADC) are usually equipped with analog low-pass filters to pre-condition the signal prior to digitization. This prevents signals with frequencies greater than the sampling rate from being seen by the ADC, causing a detrimental effect called *aliasing*. These analog pre-filters are thus known as *anti-aliasing filters*.

Determine which of the following Sallen-Key active filters is of the correct type to be used as an anti-aliasing filter:





file 04039

Answer 49

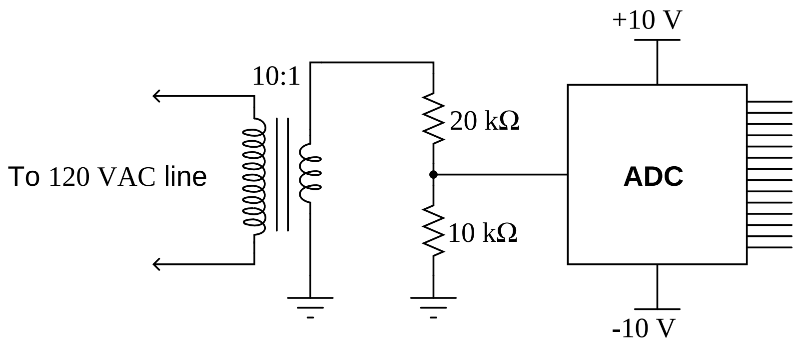
The low-pass Sallen-Key filter, of course! What's the matter? You're not laughing at my answer. What I'm doing here is asking you to some research on Sallen-Key filters to confirm your qualitative analysis. And yes, I do expect you to be able to *figure out* which of the two filters is low-pass based on your knowledge of capacitors and op-amps, not just look up the answer in an op-amp reference book!

Notes 49

Discuss with your students various ways of identifying active filter types. What clues are present in these two circuits to reveal their filtering characteristics?

Question 50

Suppose a particular ADC has an input voltage range of +5 volts to -5 volts, and therefore is suitable for digitizing AC input signals. A technician wants to use this ADC to digitize AC line voltage (120 volts RMS), and builds the following conditioning circuit to safely connect the ADC to the AC line:



Unfortunately, this ADC is not able to fully sample the AC waveform when tested. It "overflows" and "underflows" at the waveform's peaks, as though the input waveform is too large (outside of the +5/-5 volt ADC chip range). The technician re-checks his calculations, but still thinks the voltage division ratio provided by the potential transformer and resistor network should be sufficient for this task.

What is wrong with this circuit? Why does it "over-range" at the waveform peaks instead of sampling the 120 volt waveform with range to spare? Then, once having identified the problem, recommend a solution to fix the problem.

file 04041

Answer 50

The technician failed to consider the *peak* voltage of the AC line!

Challenge question: one thing the technician did right in this circuit was use a transformer as the front-end of his signal conditioning network. Explain why this was a smart idea. In other words, why would it possibly be worse to simply use a resistive voltage divider to do *all* the attenuation, instead of using a step-down transformer to do part of it and a resistive divider to do the rest?

Notes 50

The given answer is purposefully minimal, but should contain enough information that anyone familiar with RMS versus peak sinusoidal values should realize what the problem is. There is more than one practical solution for fixing this problem, so be sure to allow time for discussion into the various options.

Project progress report (1 day)
Date:
Description of progress made on this day

file 03995

Answer 51

Be sure to note *everything* accomplished for each day, so your instructor has a complete record of your progress.

Notes 51

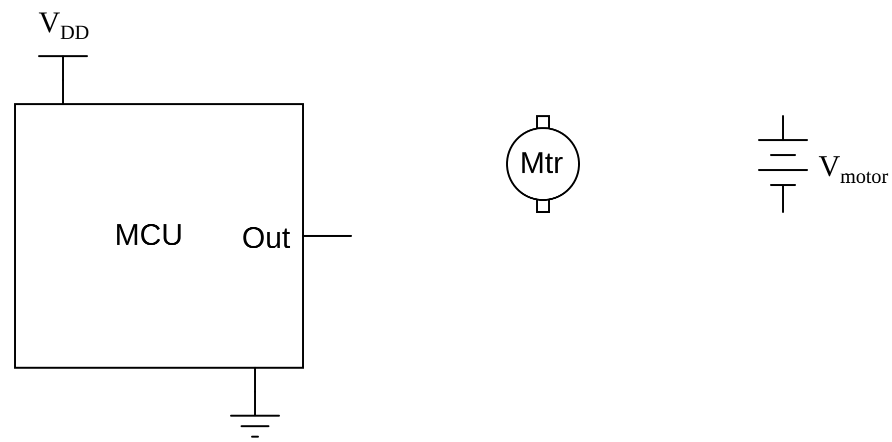
The purpose of this report form is to familiarize students with the concept of time management as it relates to project completion. Too many students have a tendency to do little or nothing until just before their project is due. By assigning a grade value for progress made each day, you help them learn time management skills and also help them complete their projects sooner (and better!).

Competency: **Motor speed control using MCU** Version:

Description

Use the Pulse-Width Modulation (PWM) capability of a microcontroller to set the speed of a DC motor.

Schematic



Given conditions

V_{motor} =

D (duty cycle) =

Program

file 04018

Answer 52

Use circuit simulation software to verify your predicted and actual truth tables.

Notes 52

Here, I let students design and build their own transistor drive circuit to interpose between the MCU and the DC motor.

Project progress report (1 day)
Date:
Description of progress made on this day

file 03995

Answer 53

Be sure to note *everything* accomplished for each day, so your instructor has a complete record of your progress.

Notes 53

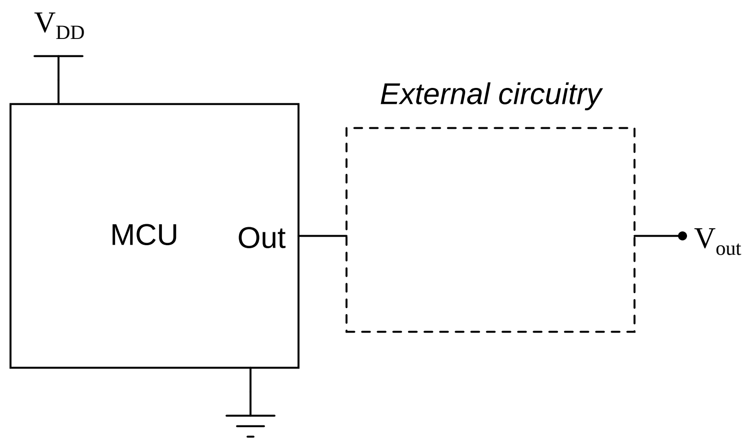
The purpose of this report form is to familiarize students with the concept of time management as it relates to project completion. Too many students have a tendency to do little or nothing until just before their project is due. By assigning a grade value for progress made each day, you help them learn time management skills and also help them complete their projects sooner (and better!).

Competency: **MCU analog voltage output** Version:

Description

Generate an analog output voltage using an MCU.

Schematic



Given conditions

V_{out} =

Program

file 04019

Answer 54

Use circuit simulation software to verify your predicted and actual truth tables.

Notes 54

One method that is convenient for generating an analog output voltage with many microcontrollers is to program the MCU to generate a PWM output, then build an analog filter circuit to capture just the average DC value of that PWM waveform.

Project progress report (1 day)
Date:
Description of progress made on this day

file 03995

Answer 55

Be sure to note *everything* accomplished for each day, so your instructor has a complete record of your progress.

Notes 55

The purpose of this report form is to familiarize students with the concept of time management as it relates to project completion. Too many students have a tendency to do little or nothing until just before their project is due. By assigning a grade value for progress made each day, you help them learn time management skills and also help them complete their projects sooner (and better!).

Troubleshooting log

Actions / Measurements / Observations (i.e. *What I did and/or noticed . . .*)	**Conclusions** (i.e. *What this tells me . . .*)

file 03933

Answer 56

I do not provide a grading rubric here, but elsewhere.

Notes 56

The idea of a troubleshooting log is three-fold. First, it gets students in the habit of documenting their troubleshooting procedure and thought process. This is a valuable habit to get into, as it translates to more efficient (and easier-followed) troubleshooting on the job. Second, it provides a way to document student steps for the assessment process, making your job as an instructor easier. Third, it reinforces the notion that each and every measurement or action should be followed by reflection (conclusion), making the troubleshooting process more efficient.

Question 57

NAME: ________________ **Troubleshooting Grading Criteria**

You will receive the highest score for which *all* criteria are met.

100 % *(Must meet or exceed all criteria listed)*
A. Absolutely flawless procedure
B. No unnecessary actions or measurements taken

90 % *(Must meet or exceed these criteria in addition to all criteria for 85% and below)*
A. No reversals in procedure (i.e. changing mind without sufficient evidence)
B. Every single action, measurement, and relevant observation properly documented

80 % *(Must meet or exceed these criteria in addition to all criteria for 75% and below)*
A. No more than one unnecessary action or measurement
B. No false conclusions or conceptual errors
C. No missing conclusions (i.e. at least one documented conclusion for action / measurement / observation)

70 % *(Must meet or exceed these criteria in addition to all criteria for 65%)*
A. No more than one false conclusion or conceptual error
B. No more than one conclusion missing (i.e. an action, measurement, or relevant observation without a corresponding conclusion)

65 % *(Must meet or exceed these criteria in addition to all criteria for 60%)*
A. No more than two false conclusions or conceptual errors
B. No more than two unnecessary actions or measurements
C. No more than one undocumented action, measurement, or relevant observation
D. Proper use of all test equipment

60 % *(Must meet or exceed these criteria)*
A. Fault accurately identified
B. Safe procedures used at all times

50 % *(Only applicable where students performed significant development/design work – i.e. not a proven circuit provided with all component values)*
A. Working prototype circuit built and demonstrated

0 % *(If any of the following conditions are true)*
A. Unsafe procedure(s) used at any point

file 03932

Answer 57

Be sure to document all steps taken and conclusions made in your troubleshooting!

Notes 57

The purpose of this assessment rubric is to act as a sort of "contract" between you (the instructor) and your student. This way, the expectations are all clearly known in advance, which goes a long way toward disarming problems later when it is time to grade.