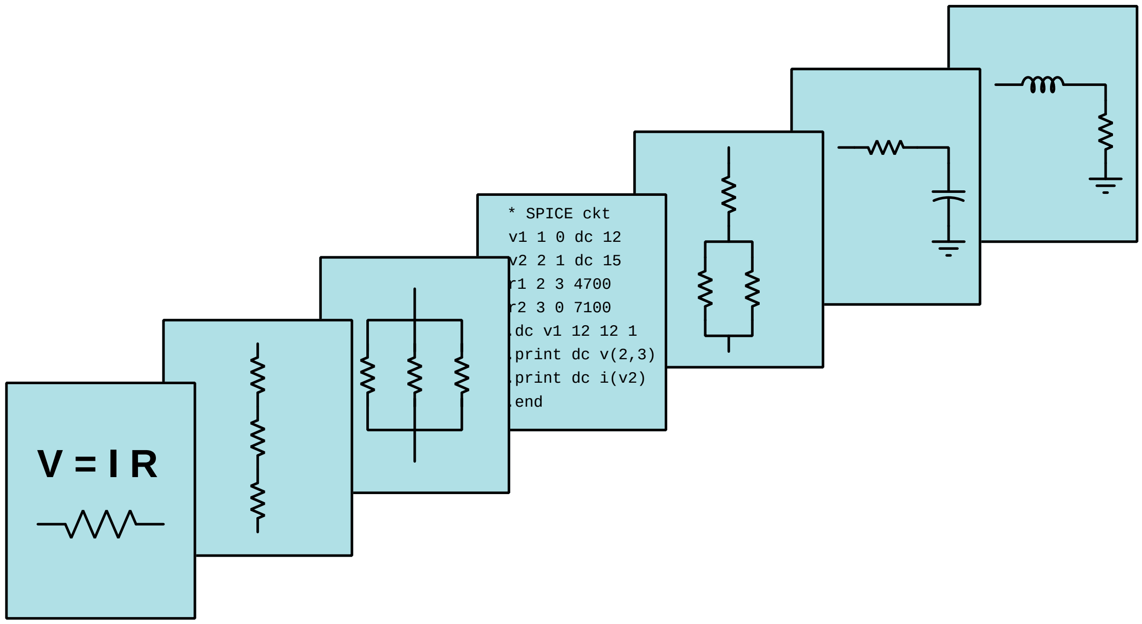
Modular Electronics Learning (ModEL) project



Oscillators

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Chapter 1

Introduction

1.1 Recommendations for students

An *oscillator* is any circuit designed to produce AC or pulsing signals from steady DC power. Some oscillators naturally produce sinusoidal waveforms, while others produce inverse-exponential "sawtooth" waveforms and/or square waves.

Applications for oscillator circuits are many. Digital circuits usually require a *clock pulse* signal to synchronize the operations of many logic "gate" circuits, and this "clock" signal is simply a high-frequency square-wave pulse train. Radio circuits usually require multiple oscillators: one to produce the high-frequency "carrier" waveform necessary to produce electromagnetic waves and others to "mix" with the carrier waveform for the purpose of *modulating* it (i.e. impressing information upon it at the transmitting end) and/or *demodulating* it (i.e. extracting information from it at the receiving end).

Important concepts related to oscillators include **resistor-capacitor time delays**, **reactance**, **resonance**, **tank circuits**, **hysteresis**, **Barkhausen criterion**, **gas discharge tubes**, **thyristors**, **avalanche breakdown**, **BJT behavior**, **multivibrators**, **555 timers**, **phase shift**, **feedback**, **gain**, **operational amplifiers**, **bridge** networks, **quartz crystals**, and **negative resistance**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to measure the frequency of an oscillator circuit's output signal? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to measure the stability of oscillator circuit's frequency over long spans of time? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What is the operating principle of a relaxation oscillator?
- Which components determine the operating frequency of an astable multivibrator circuit?

- What is the operating principle of a phase shift oscillator?
- What is the operating principle of a resonant oscillator?
- What is the operating principle of a negative resistance oscillator?
- What are some different examples of hysteresis?
- Why do resistor-capacitor networks exhibit inverse-exponential growth and decay of voltage/current?
- What is the Barkhausen criterion?
- Why is it challenging to achieve perfectly sinusoidal oscillations in a feedback-based oscillator?
- Why does phase shift vary with frequency in an RC network?
- Under what condition(s) will a Wein bridge circuit oscillate?
- What is the purpose of the incandescent lamp in William Hewlett's Wein-bridge oscillator design?
- Why do tank circuits naturally oscillate?
- How is the correct amount of phase shift for oscillation achieved in a Colpitts, Hartley, or Pierce oscillator design?
- What is negative resistance, and what sorts of devices exhibit this phenomenon?
- What is the purpose of a *crystal*?

1.2 Challenging concepts related to oscillators

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Hysteresis** – whenever a component or system tends to remain in its last state, we refer to that lagging tendency as *hysteresis*. There are many physical manifestations of hysteresis including *magnetic hysteresis* (where a magnetic material tends to remain magnetized after the magnetizing influence is removed), *thyristor devices* (electronic devices that tend to remain "on" even after the triggering stimulus is removed), and physical mechanisms having *friction* (where the mechanism's position tends to stay put after the influencing force is removed).
- **Bistable transistor circuits** – these circuits tend to be challenging to analyze because they actually will not work if their respective components are absolutely identical in performance! They only work when one side of the circuit preferentially turns on before the other. Therefore, these are best analyzed if one begins with the assumption that one of the two transistors (for some unstated reason) is already in its "on" state and the other is "off".

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

- **Outcome** – Identify the functions of components from a schematic diagram

  Assessment – Identify the purpose of each component within an oscillator circuit's schematic diagram; e.g. pose problems in the form of the "Identifying oscillator circuit sections" Conceptual Reasoning question.

- **Outcome** – Calculate oscillator frequencies from component values

  Assessment – Calculate the oscillating frequency of a Hartley oscillator; e.g. pose problems in the form of the "Hartley oscillator frequency" Quantitative Reasoning question.

  Assessment – Calculate the oscillating frequency of a Colpitts oscillator; e.g. pose problems in the form of the "Colpitts oscillator frequency" Quantitative Reasoning question.

  Assessment – Calculate the oscillating frequency of a Clapp oscillator; e.g. pose problems in the form of the "Clapp oscillator frequency" Quantitative Reasoning question.

- **Outcome** – Predict the effects of component faults in an oscillator circuit

  Assessment – Predict the effect(s) of a single component failing either open or shorted in a relaxation oscillator circuit; e.g. pose problems in the form of the "Effects of faults in a relaxation oscillator" and "Effects of faults in a strobe light circuit" and "Effects of faults in a JFET-UJT oscillator" and "Effects of faults in astable multivibrator" Diagnostic Reasoning questions.

- **Outcome** – Independent research

  Assessment – Locate IC oscillator datasheets and properly interpret some of the information contained in those documents including operating frequency, power supply voltage range, output power, output waveform type, etc.

Chapter 2

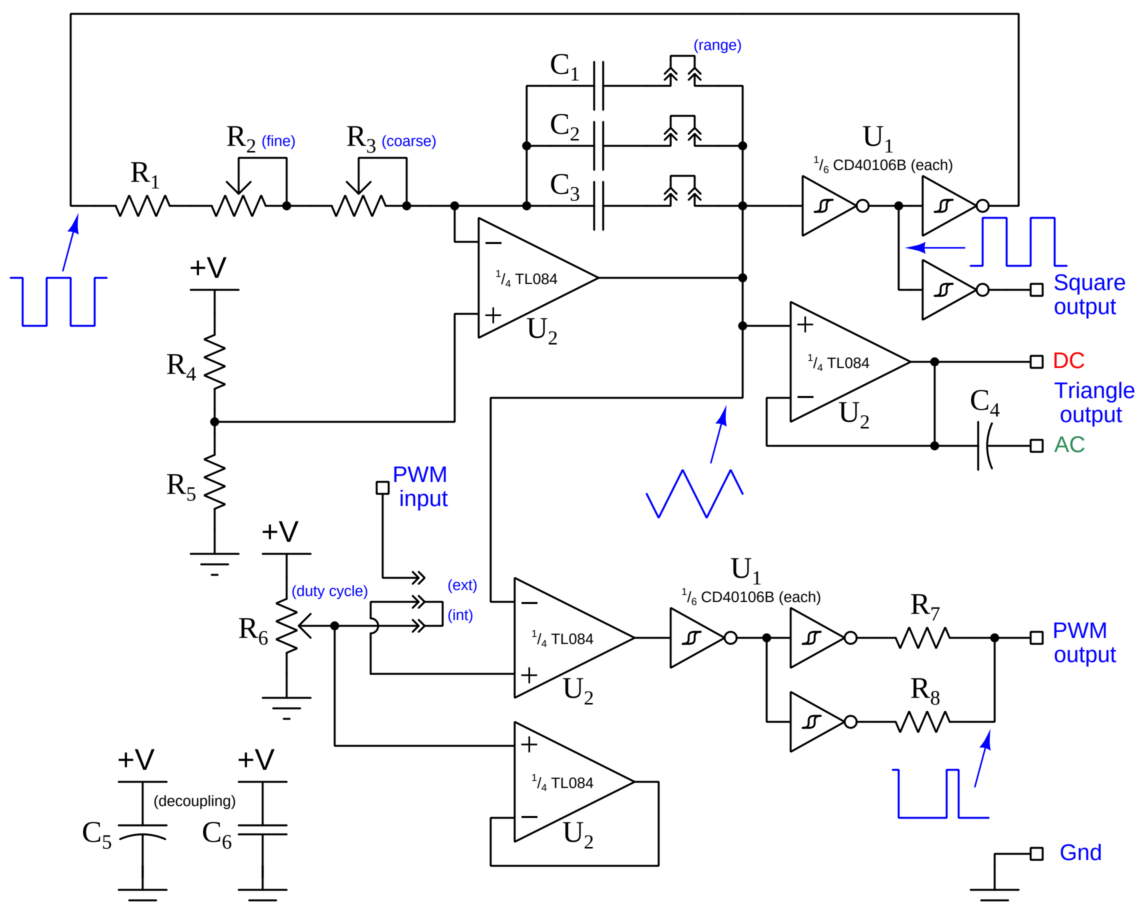
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: simple triangle/square/PWM oscillator

This simple oscillator circuit provides triangle wave output (both DC- and AC-coupled) as well as square wave output and pulse-width-modulated ("PWM") square wave output with an adjustable duty cycle. Jumpers select capacitor values for frequency range, while two potentiometers provide coarse and fine frequency adjustment:



DC power source voltage may range widely, given the advertised operating voltage ranges for the CD40106B and TL084 integrated circuits (3 to 18 Volts for the hex inverter and 10 to 30 Volts for the opamp). I have successfully tested this circuit at a supply voltage as low as 5 Volts and it seems to work well.

It is worth noting that the fairly close similarity between triangle and sine wave-shapes means students may use the triangle-wave output of this oscillator circuit as an AC voltage source to energize simple RLC networks rather than using a true sine-wave signal generator signal. The error between measured and calculated values of voltage and current are generally within the ± 5%

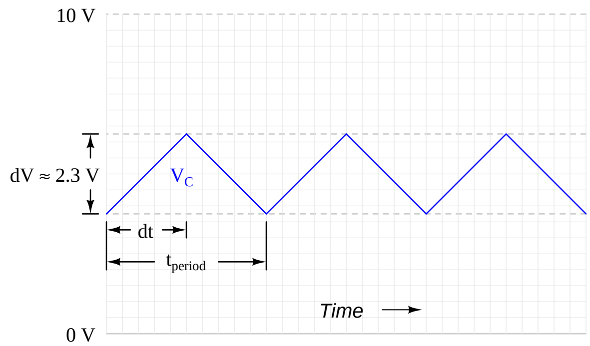
tolerance of common resistors, capacitors, and inductors when using a true-RMS multimeter to take the measurements.

Parts list:

- U_1 = CD40106B CMOS hex inverter with Schmitt trigger inputs
- U_2 = TL084 quad operational amplifier
- R_1 = 10 kΩ – *this sets the maximum frequency when both pots are at minimum resistance*
- R_2 = 10 kΩ potentiometer – *this is the "fine" frequency adjustment*
- R_3 = 100 kΩ potentiometer – *this is the "coarse" frequency adjustment*
- R_4 = 10 kΩ – *the values of R_4 and R_5 are not critical, so long as they are equal*
- R_5 = 10 kΩ
- R_6 = 10 kΩ potentiometer – *the values of R_6 is not critical*
- R_7 = 100 Ω – *R_7 and R_8 equalize load-sharing between inverters, the values being non-critical*
- R_8 = 100 Ω
- C_1 = 0.0047 μF ceramic (for oscillator timing)
- C_2 = 0.047 μF ceramic (for oscillator timing)
- C_3 = 0.47 μF ceramic (for oscillator timing)
- C_4 = 4.7 μF electrolytic (for output coupling – value not critical)
- C_5 = 47 μF electrolytic (for power supply decoupling – value not critical)
- C_6 = 1 μF ceramic (for power supply decoupling – value not critical)

The triangle wave signal begins to exhibit "ringing" at the positive and negative peaks if the total oscillator network resistance (i.e. $R_1 + R_2 + R_3$) becomes too low (approximately 20 kΩ or less). This is the major function of the fixed resistor R_1, to make sure this resistance never becomes unreasonably low.

The upper-most opamp functions as a current source for capacitors C_1 through C_3, driving a constant current through the capacitor(s) in order to produce a ramping voltage across them. The amount of current driven through the capacitor(s) is equal to the difference between the hex inverter's output voltage (square wave) and one-half supply voltage (set by divider R_4/R_5) divided by the resistance of $R_1 + R_2 + R_3$, which should be approximately $\pm\frac{V_{supply}}{2(R_1+R_2+R_3)}$. The capacitor voltage will ramp at a rate $\frac{dV}{dt}$ equal to that current divided by capacitance C. The CD40106B Schmitt-trigger inverter has a typical hysteresis value of approximately[1] 23% (e.g. 2.3 Volts for a 10-Volt V_{supply}), so the time duration of each half-cycle of the waveform is the amount of time it takes the capacitor voltage to ramp that 23% of supply voltage as opamp U_2 forces a constant current:



Here is a mathematical derivation for output frequency based on these conditions, where C represents the capacitance offered by C_1, C_2, and/or C_3 (depending on which jumpers are connected) and R represents the total series resistance of R_1, R_2, and R_3:

$$I_C = C\frac{dV}{dt} \text{ (``Ohm's Law'' for any capacitor)} \qquad I_C = \frac{V_{supply}}{2R} \text{ (Current forced by opamp)}$$

$$C\frac{dV}{dt} = \frac{V_{supply}}{2R}$$

$$\frac{dV}{dt} = \frac{V_{supply}}{2RC}$$

$$dV = \frac{V_{supply}}{2RC}dt$$

$$0.23V_{supply} \approx \frac{V_{supply}}{2RC}dt$$

$$(0.23)(2RC) \approx dt$$

[1] This figure of 23% is merely a rough estimate, and should not be relied upon for accuracy. Schmitt-trigger logic gates are designed for noise tolerance, not to function as precision comparators, and so it is unwise to assume this value will be stable from IC to IC or even between different operating frequencies in this circuit!

$$t_{period} \approx (2)(0.23)(2RC)$$

$$f \approx \frac{1}{(2)(0.23)(2RC)} \approx \frac{1.09}{RC}$$

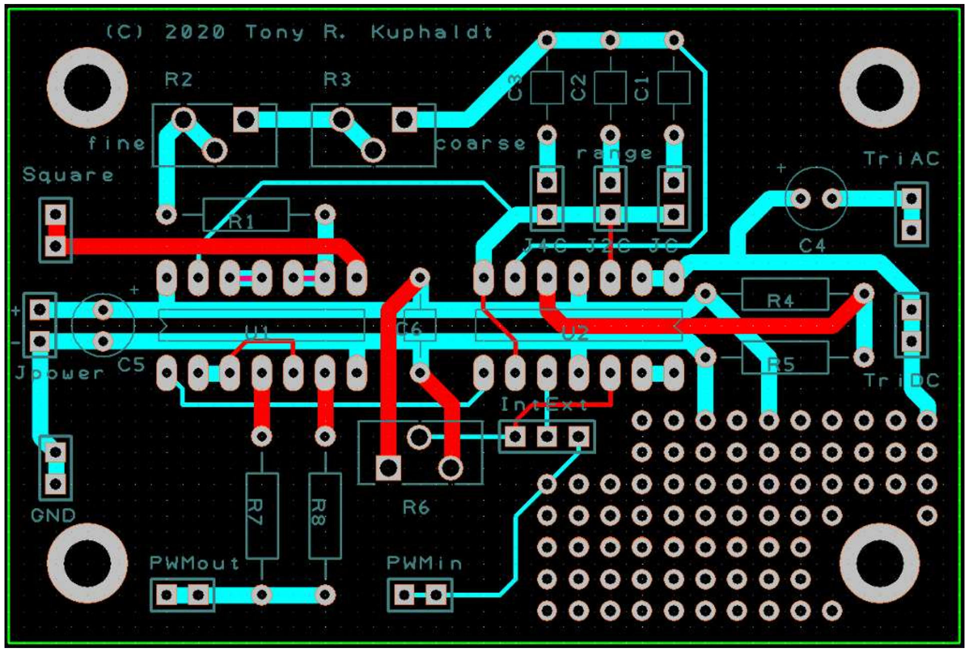
Assuming the component values shown in the parts list, with both potentiometers set to mid-position and only the middle capacitor (C_2) selected by jumper, the frequency should be approximately:

$$f \approx \frac{1.09}{(65 \times 10^3)(0.047 \times 10^{-6})} = 356 \text{ Hz}$$

I recommend choosing capacitor values of octave multiples (i.e. C, $2C$, $4C$) or decade multiples (i.e. C, $10C$, $100C$). With a large "coarse" potentiometer value (R_3), decade multiples make the most sense. Lower-valued frequency-adjust potentiometers would better suit octave-multiples of capacitor value, but then the total adjustment range of the oscillator will be more limited.

The int/ext jumper sets the signal source for the PWM signal's adjustable duty cycle. When set for "internal" the duty cycle is adjusted by potentiometer R_6; when set for "external" a signal voltage input at the "PWM input" terminal controls the duty cycle.

One possible PCB layout for this circuit is shown below, the dimensions of the board being 3 inches by 2 inches. Red traces are on the top copper layer of the board, while blue traces are on the bottom. DC supply power comes into the board at the left-hand edge, at the `Jpower` terminals:



Note how two pads are provided for each of the I/O terminals. This was done to facilitate a small loop of bare wire soldered between the two pads, which makes an easy connection point for "grabber" hooks or "alligator" clips. The four large pads at the board's corners are intended for nylon stand-offs, for mounting this PCB to a larger panel. These mounting pads are spaced 2.5 inches horizontally and 1.5 inches vertically from each other.

An important detail to note on this layout is the orientation of the two integrated circuits. U_1 (the CMOS hex inverter) has its pin 1 located on the left side, while U_2 (the quad opamp) is "upside-down" with its pin 1 located on the right. This is due to the locations of the DC power pins on each of these integrated circuits. In order to avoid crossing the +V and Ground power traces on the board, these two chips had to be positioned opposite-facing.

A "prototyping" area with an array of unallocated pads exists at the lower-right corner of the PCB, provided so that you may add other components to the board (e.g. power amplifier, wave-shaping networks) to enhance its capabilities.

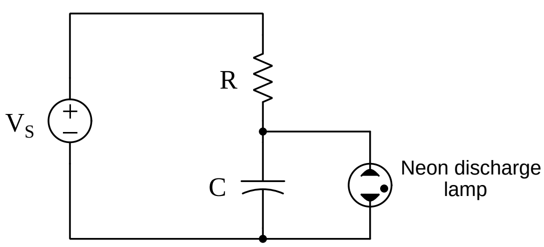
Chapter 3

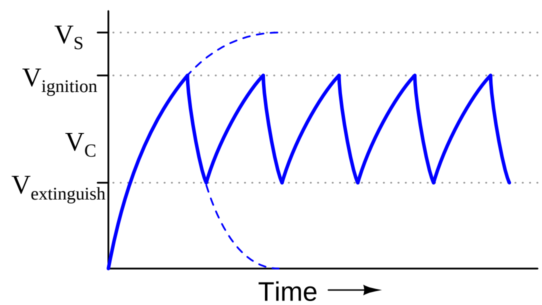
Tutorial

An *oscillator* is an electronic circuit designed to convert DC power into AC or pulse signals. This tutorial is divided into sections categorizing different types of oscillator circuits.

3.1 Relaxation oscillators

Perhaps the simplest type of oscillator circuit is the *relaxation oscillator*, based on the time-delayed energizing of a capacitor. A primitive relaxation oscillator is shown in the following diagram, using a resistor, capacitor, neon discharge lamp (requiring about 70 Volts to produce light), and a DC voltage supply of approximately 100 Volts:





One way to begin analyzing this oscillator circuit is to apply the problem-solving technique of *simplifying the system*. If we were to remove the neon lamp from the circuit, we would be left with just the DC supply, resistor, and capacitor, which of course would result in the capacitor's voltage rising over time to finally equal the supply voltage (approximately 100 Volts). The trajectory of the capacitor's voltage over time is traced by the first curve in the graph (rising asymptotically to supply voltage V_S).

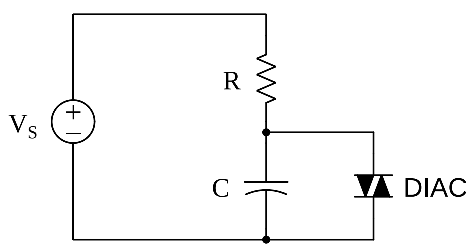
Neon lamps are quite unlike incandescent lamps, in that they conduct zero current unless and until the voltage impressed across their terminals exceeds the "ignition" voltage, which is the amount of voltage necessary to ionize the neon gas and make it electrically conductive. Once ionized, such a lamp will exhibit a relatively low resistance through the ionized gas, and will continue to conduct current until the voltage across its terminals falls to a much lower value (the "extinguishing" voltage) at which point the neon gas returns to a non-ionized state and becomes an electrical insulator once again.

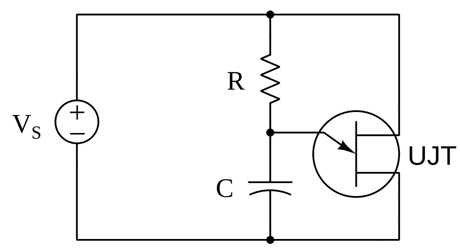
Now that we know how a neon lamp functions with different levels of applied voltage, we may form another simplified circuit to explore its behavior. Imagine letting the capacitor energize to the "ignition" voltage level, then removing the resistor from the circuit and inserting the neon lamp back into the circuit (in parallel with the capacitor). The lamp, of course, would immediately begin conducting current which would cause the capacitor to begin to de-energize, its voltage asymptotically descending toward 0 Volts. The capacitor's voltage would not actually fall all the way to zero, though, because the neon lamp would turn off at its "extinguishing" voltage. At this point the capacitor's voltage would remain at that level with the lamp off, but the second dashed line on the graph shows what the voltage *would* do if somehow the neon lamp were to remain lit all the way to zero.

Putting all these concepts together, we can imagine what would happen with all components connected: beginning at zero Volts, the capacitor's voltage rises asymptotically toward supply voltage with current limited by the resistor. Once the capacitor's voltage reaches the ignition level, the neon lamp turns on and provides a low-resistance load for the capacitor to dissipate its stored energy (even with the resistor still supplying current from the DC source). Once the capacitor's voltage falls down to the extinguishing level, the neon lamp turns off and the capacitor begins absorbing energy again. The result is a "sawtooth" voltage waveform measured across the capacitor. This is the cycle of a relaxation oscillator: a capacitor gradually energizes over time, then "relaxes" as some non-linear component (e.g. the neon lamp) switches to a conductive state to dissipate the capacitor's stored energy, the cycle repeating itself at some lower voltage value.

Some careful reflection reveals that the key property enabling any relaxation oscillator to function is a switching component containing *hysteresis*. Hysteresis is that property of any component or system which fails to return to its original state after the removal of stimulus. Neon lamps are hysteretic, in that they remain non-conducting as the applied voltage rises to the point of ignition, and then once ionized they remain conductive until the applied voltage falls down to the extinguishing value. This is why the relaxation oscillator circuit requires a *gas discharge* lamp rather than something more conventional such as an incandescent lamp or LED[1].

Any hysteretic, voltage-activated switching device may substitute for the neon lamp. Some alternatives are shown in this next set of schematic diagrams:

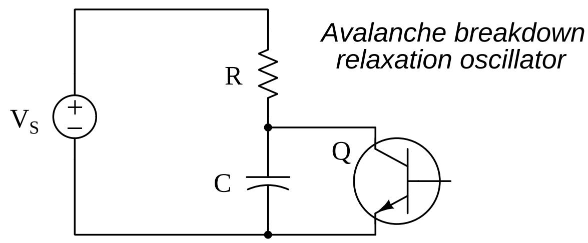




Both DIACs and unijunction transistors (UJTs) are classified as *thyristors*, defined as a semiconductor device built to exhibit hysteresis. In each case the device remains essentially non-conductive between the two terminals in parallel with the capacitor until voltage increases to some critical threshold value, at which point the device switches "on" and acts to discharge the capacitor. The device only turns back "off" when the capacitor voltage falls to a significantly lower value.

[1]Even though both incandescent lamps and LEDs are nonlinear devices (i.e. they do not obey Ohm's Law), neither one is hysteretic. If one were to exchange the neon lamp for an incandescent lamp or LED in the oscillator circuit, the circuit would never oscillate. Instead, the capacitor voltage would stabilize at some constant value allowing the lamp to output some amount of steady light.

Interesting, regular transistors may be used as a sort of thyristor by exploiting a property called *reverse avalanche breakdown*[2]. When used in this manner, unusually high voltages[3] become necessary for any given transistor model because it is being operated in a region beyond its usual ratings:

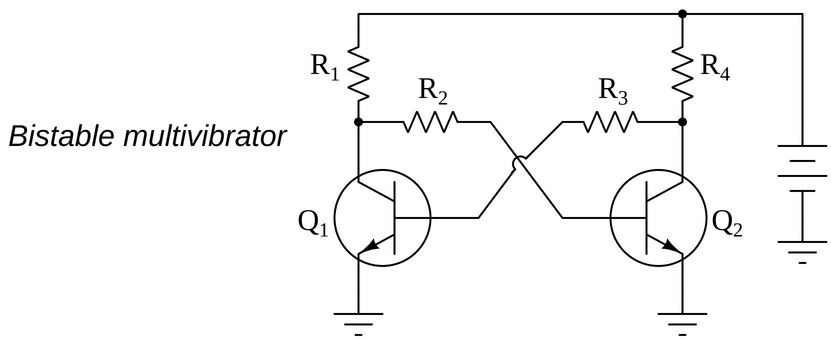


With unusually high voltage drop creating sudden surges of current through the transistor, breakdown is a mode of operation usually avoided in the design of transistor circuits. Careful selection of power supply voltage, capacitor size, and resistor size will be necessary to avoid damaging the transistor when used in this manner.

[2]This is where minority charge carriers drifting through a semiconductor material achieve a high enough velocity that they create more electron-hole pairs when colliding with stationary atoms. Those newly-liberated electrons and holes also accelerate until they move fast enough to do the same, resulting in a cascading liberation of new charge carriers.

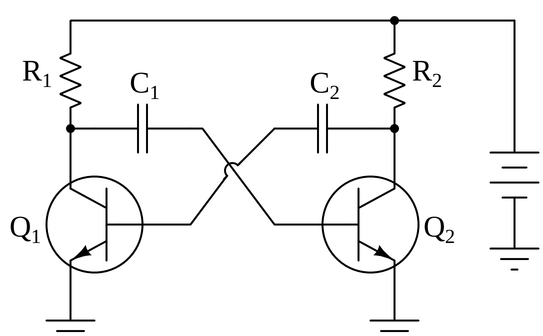
[3]For example, the common 2N2222 small-signal NPN transistor model breaks down between collector and emitter anywhere from 40 Volts to 50 Volts. It is for this very reason that transistor amplifier circuits must operate at lower voltages, to avoid breakdown. Here, we are intentionally exploiting breakdown as a mechanism for hysteretic behavior in order to fashion a relaxation oscillator.

An alternative to finding a single hysteretic component to form the basis of a relaxation oscillator, we may alternatively build a circuit of linear devices using *positive feedback*[4] to "latch" in one of two states. Such a "multivibrator" circuit may then be used to control the energization and de-energization of a capacitor. A typical "bistable" multivibrator circuit is shown below, comprised of two transistors cross-coupled to each other so that they tend to fall into opposite on/off states:



If we imagine transistor Q_1 turning fully on, we may see that its saturated collector-emitter voltage drop (approximately 0.3 Volts) will not be enough to activate the base-emitter junction of transistor Q_2, thereby keeping the latter transistor fully off. With Q_2 off, its collector-emitter voltage will be nearly equal to supply voltage, giving transistor Q_1 more than enough signal at its base terminal to remain fully on. If we imagine Q_2 starting in the full-on condition, the reverse occurs, with Q_1 turning fully off and holding Q_2 fully on. Thus, this circuit has two states in which it tends to stabilize ("bistable"), just like a gas-discharge lamp or a thyristor. Moreover, the circuit's positive feedback guarantees one of the transistors saturating soon after power-up, as even the slightest bias of one transistor over the other will cause the more-on transistor to saturate.

A relaxation oscillator requires capacitance, though, in order to create the necessary time delay. We may accomplish this by replacing the two inner resistors with capacitors:

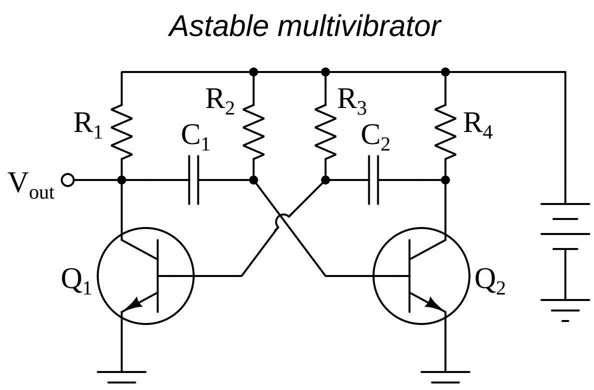


Unfortunately, this circuit has a design flaw: since the base terminal of an NPN transistor only *sinks* current, the direction of capacitor currents will always be the same which means the capacitors

[4]Positive feedback is the term given to that phenomenon by which an amplified signal is recycled back to the amplifier circuit to be amplified again, in such a manner that the signal reinforces itself.

can only energize but never de-energize. Somehow, we must provide a means for these two capacitors to de-energize when their respective transistor bases stop drawing current.

A solution to our dilemma is to add two more resistors, R_2 and R_3, to the circuit in such positions that they create a load path for the capacitors to de-energize. If the resistance values of these new resistors are substantially larger than that of R_1 and R_4, they will swamp both R_1 and R_4 in establishing the RC time constant values (τ) for the capacitors' timing. The multivibrator circuit is now *astable* (i.e. non-stable) rather than bistable, and as such it continually oscillates with the two transistors assuming opposite states at all times:

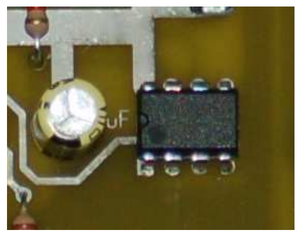


With the two transistors switching between fully-on and fully-off, the output signal voltages measured between collector terminals and ground will be square waves. The duty cycle[5] of these square waves will be 50% if the capacitors are of equal value and the timing resistor values symmetrical (i.e. $R_2 = R_3$).

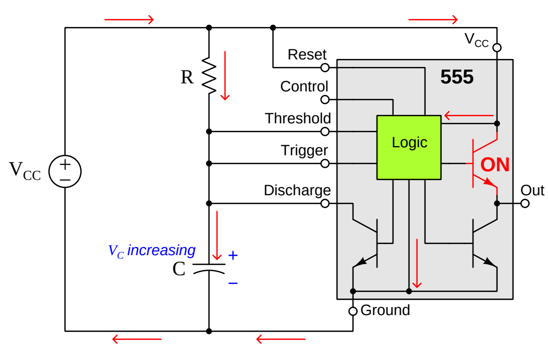
[5] "Duty cycle" is a measurement of on-time versus total waveform period for any pulse wave-shape. A symmetrical square wave spends half its time "high" and half its time "low" which equates to 0.5 or 50%.

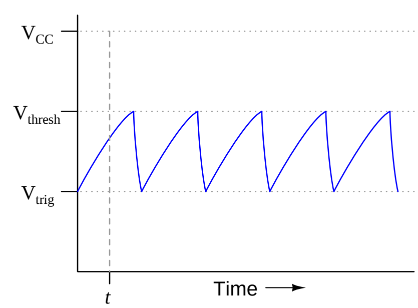
A very popular form of electronic relaxation oscillator is the model 555 timer integrated circuit (IC). This IC contains a *comparator* and resistive voltage divider network to compare capacitor voltage against a constant reference voltage, using the output of that comparator to trigger a digital *latch* circuit activating three transistor switches. One of these transistors serves to discharge the capacitor, while the other two source and sink current at the IC's output terminal where an on/off pulse signal appears. The capacitor and current-limiting resistor are external to the IC, chosen and connected by the end-user.

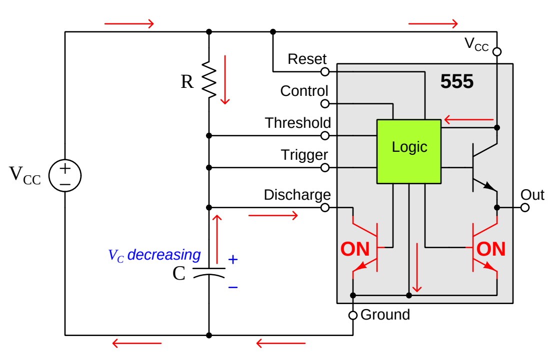
The basic 555 timer is an 8-pin IC, as shown in the following photograph:

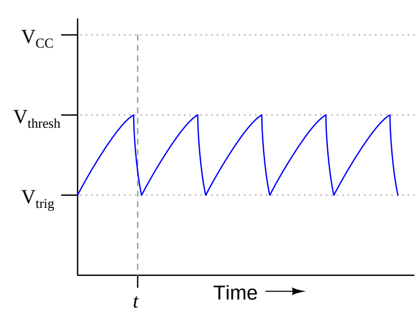


The next two diagrams show the 555 timer functioning as a simple relaxation oscillator, with all the necessary external components and connections. A graph showing the capacitor's "sawtooth" voltage waveform over time, with time markers (t) for each state of the 555 timer circuit, demonstrate the operation of this oscillator:









3.2 Phase-shift oscillators

A more sophisticated type of oscillator builds upon the circuitry of an *amplifier*, using the principle of *positive feedback* (also known as *regenerative feedback*) to produce self-sustaining oscillations. "Feedback" refers to the intentional coupling of an amplifier's input terminals to its output terminals, such that some (or all) of its output signal "feeds back" into the input of the amplifier where it becomes re-amplified.

Feedback is a very important concept in electronics because it grants new behaviors and characteristics to otherwise plain amplifier circuits. For example, instantaneous positive feedback tends to turn an amplifier into a *latch*, forcing it to saturate to one extreme signal state or another just like the bistable multivibrator circuit discussed previously. Time-delayed positive feedback tends to make an amplifier oscillate. Negative feedback (also known as *degenerative feedback*) is where the recycled signal acts to *cancel* its own effects, resulting in a condition of stability and of decreased gain.

If you have ever experienced the "howling" or "shrieking" sound of a public-address amplifier system whenever the microphone gets too close to the loudspeaker, you have heard positive-feedback oscillation in action. Oscillations may occur in any amplifier system if the following criteria[6] are met:

- The total phase-shift of the amplifier and feedback network must be 360^o or some whole multiple thereof
- The total gain of the amplifier and feedback network must be at least unity (1, or 0 dB)

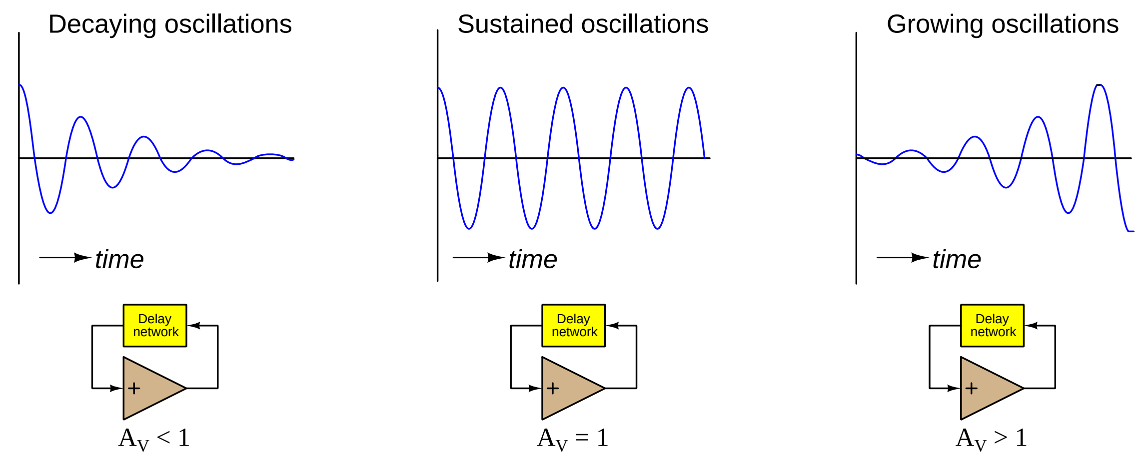
These criteria make sense once we grasp why positive feedback works to produce oscillations. In a positive-feedback system, any disturbance of the amplifier's output signal gets fed back to its input in such a way as to reinforce that original disturbance. If this positive feedback is instantaneous, the amplifier's output will simply saturate to one of its power supply rails (limits) and remain there. However, if the feedback is delayed by a full 360^o, it means the positive-feedback reinforcement will continue along all points of the waveform to reproduce that waveform in its entirety[7]. As the signal's voltage rises, the amplifier will act to make it rise even more; once the delayed signal begins to fall, the amplifier will act to make it fall even further.

Negative feedback also plays a role in these oscillator circuits by allowing us to control the voltage gain of the circuit to the desired ratio of unity (1).

[6]These conditions are often referred to as the *Barkhausen criterion* in honor of German physicist Georg Barkhausen.

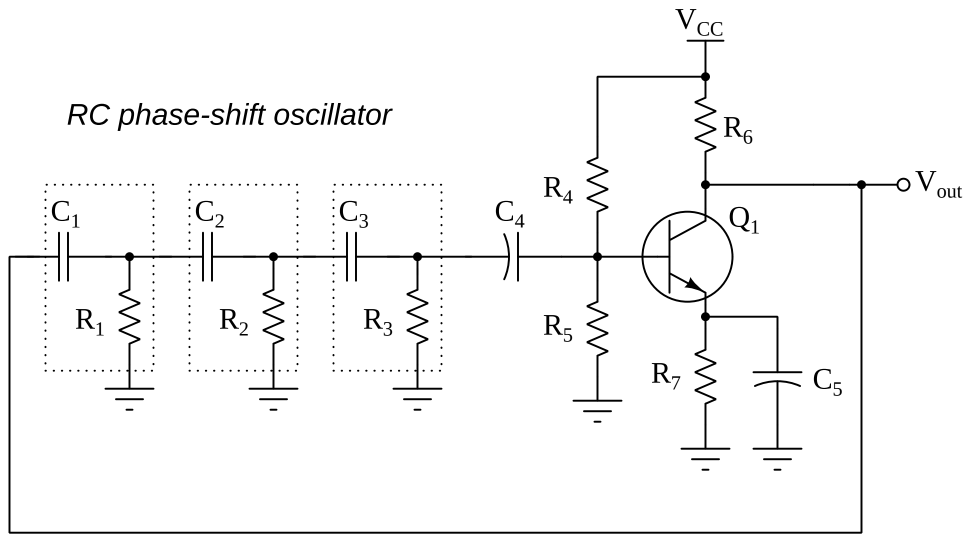
[7]This scenario evokes the image of a dog chasing its own tail: the fact that the dog must reach *back* to its own tail with its mouth leads it to spin in circles, that reach being the necessary "delay" to sustain a circular trajectory. A dog would never chase a stationary object lying straight ahead.

This cyclic process continues as long as the amplifier's gain is large enough to overcome all attenuation in the feedback-delay network. If the gain is not quite high enough, the oscillations will decay with every cycle until they die out completely. If the gain is exactly the right amount, the oscillations will continue with steady AC amplitude. If the gain is greater than necessary, the oscillations will grow in amplitude until the amplifier begins to "clip" and distort the wave-shape.



Self-oscillation by amplified positive feedback can be a useful phenomenon, or a problem to be avoided. If your design goal is to make a *stable* amplifier, then you want to avoid the conditions that will lead to self-oscillation. If your design goal is to make a sinusoidal oscillator from an amplifier circuit, then you want to create the necessary conditions that will cause that amplifier to continuously oscillate. The latter is our goal for the purposes of this section.

One way to produce the necessary phase-shift is to use multiple RC networks as part of a feedback loop for an amplifier, as shown in the following schematic:



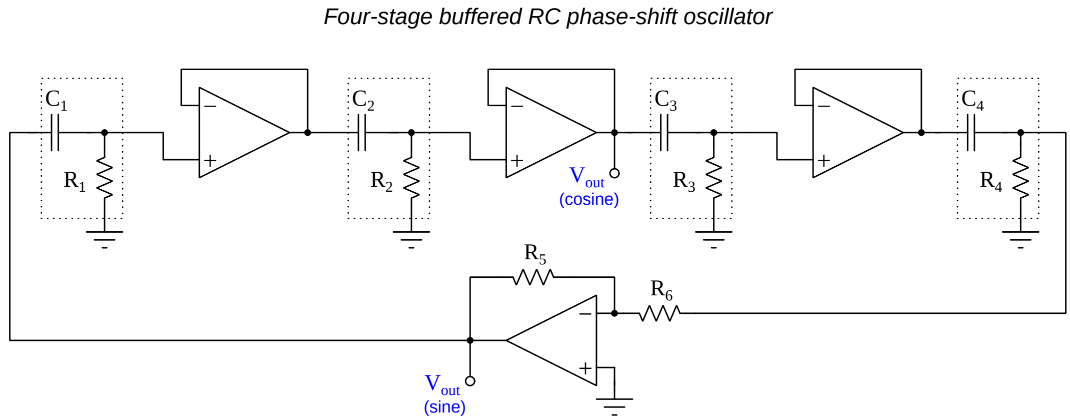
This common-emitter amplifier is naturally inverting (i.e. has a 180 degree phase shift from input to output), and so the three RC networks need only provide a total[8] of 180 degrees of phase shift in order to make the loop's total feedback phase shift 360 degrees. A common-emitter amplifier stage provides voltage gain, easily adjusted by varying the value of resistor R_6.

The wave-shape output by this phase-shift oscillator will be sinusoidal, because only at one frequency will the RC networks exhibit the 180 degrees of phase shift necessary to sustain oscillations in this circuit. Non-sinusoidal wave-shapes are always mathematically equivalent to multiple sinusoids summed together[9], and so if a non-sinusoidal oscillation were ever to occur in this circuit we would find that those harmonic frequencies *not* producing the required phase shift would quickly decay leaving only the (pure) frequency of interest.

[8] It is tempting to think of each RC network in this oscillator circuit providing 60 degrees of phase shift, with the three networks together creating 180 degrees of shift. However, in practice it is not as simple as this because these are all passive networks and as such each one "loads" the one before it. This loading effect – similar in principle to the loading of a voltage divider – affects not only the attenuation of each stage but its phase shift as well.

[9] This is the basis of *Fourier analysis*, and is a very important general concept in electronics. The fact that all wave-shapes may be decomposed into a series of sinusoids explains a great many phenomena.

An interesting variation on the simple one-transistor RC oscillator circuit is to use operational amplifiers[10] (also known as *opamps*), with one opamp per RC network for buffering:



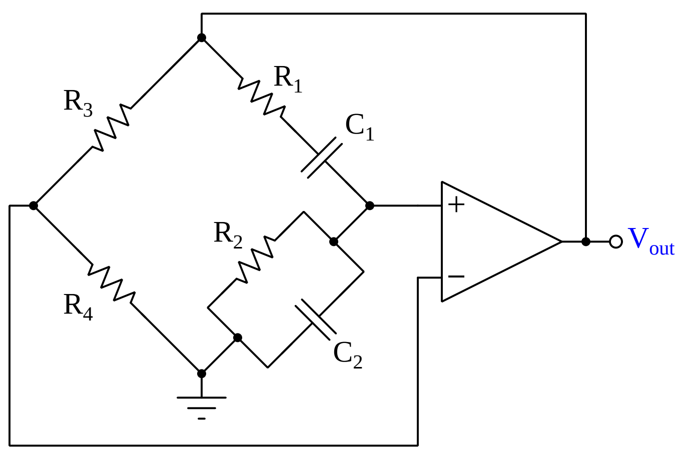
Each operational amplifier having its output terminal directly connected to its "inverting" (−) input terminal functions as a *voltage follower* which means it exhibits a voltage gain of unity (1). The purpose of these voltage-follower stages is to prevent each successive RC network from loading the previous stage, so that each of them will yield equal amounts of phase shift (assuming identical R and C values for each). That same buffering also provides the very useful feature of multiple amplified outputs. With four RC phase-shifting stages, the amount of phase shift exhibited by each RC stage will be 45 degrees in order to create 360 degrees of total shift (4×45^o from the RC networks + 180^o from the feedback opamp = 360^o total). This means every two RC stages will yield 90 degrees of phase shift, permitting the output of sine and cosine waves from the same oscillator circuit. Frequency is set by the R and C values of each stage: for a four-stage oscillator such as this, we will obtain 45 degrees of shift in each RC stage at the frequency where $X_C = R$. Voltage gain necessary for sustaining oscillations comes from the single operational amplifier at the bottom of this circuit, using resistors R_5 and R_6 to establish a voltage gain[11] value great enough to overcome all signal losses throughout the rest of the circuit, mostly arising from the attenuation created by each RC phase-shifter network.

Designing an RC phase shift oscillator circuit to have *adjustable* frequency is a challenge, because there are multiple RC phase-shifting networks contributing to the overall phase shift. We could make *one* of the resistors variable, but since this would only adjust one of the four RC networks it would have a relatively small impact on the overall phase shift, and therefore on the frequency necessary to obtain 360 degrees of total shift. Some manufacturers make *ganged potentiometers* where multiple (identical) potentiometers share a common shaft, enabling a single knob to simultaneously adjust multiple resistances, and such a device having four potentiometers could be used to make adjustments to all four RC stages. However, such devices are uncommon and expensive.

[10] An "operational amplifier" is a differential-input amplifier with an extremely high gain, noted for its ease of use in constructing amplification systems based on signal feedback.

[11] In the configuration shown, the opamp will have a voltage gain equal to $\frac{R_5}{R_6}$.

A more practical phase-shift oscillator design utilizing an operational amplifier for voltage gain is the *Wein bridge* oscillator, shown in the following schematic diagram. This oscillator uses an RC bridge network to create a 360 degree phase shift as well as a non-shifted feedback signal. The phase-shifted signal gets sent to the opamp's "noninvertering" (+) input terminal for positive feedback, while the non-shifted signal gets sent to the "inverting" (−) input terminal for negative feedback:



With equal resistor values $R_1 = R_2$ and equal capacitor values $C_1 = C_2$ in the phase-shifting side of the bridge network, that side of the bridge achieves 360 degrees of phase shift and an attenuation factor of $\frac{1}{3}$ when $X_C = R$. This means a Wein bridge oscillator circuit built with equal-value resistors and equal-value capacitors will oscillate at a frequency predicted by the formula $f = \frac{1}{2\pi RC}$, which happens to be the same formula used to predict the cutoff frequency for a simple RC filter network, and for the same reason[12]: a simple resistor-capacitor filter network is said to be in a state of "cutoff" when $X_C = R$. The non-shifting side of the bridge (R_3 and R_4) must be designed to feed back $\frac{1}{3}$ of the opamp's output voltage to the inverting input, which is the necessary condition to prompt the opamp to exhibit the voltage gain of 3 necessary to overcome the shifted signal's attenuation and sustain oscillations.

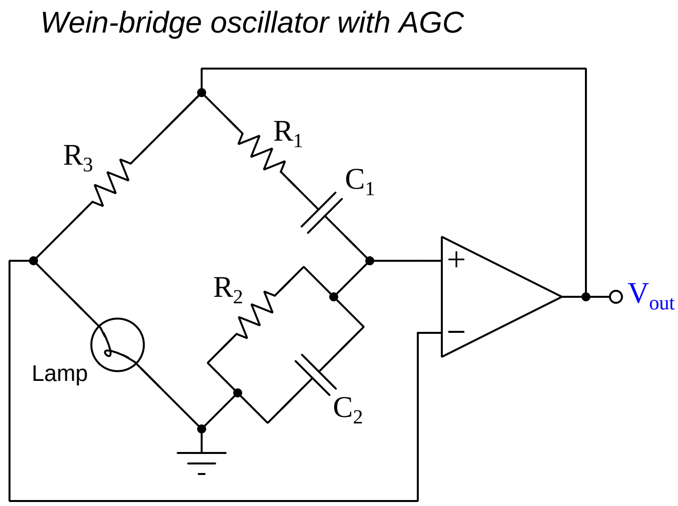
The Wein bridge oscillator circuit requires fewer components than the staged RC-network oscillator, and therefore making its frequency adjustable by the user is an easier design feat. A weakness of all feedback oscillator circuits, though, is the necessity of maintaining *precisely* the right amount of amplifier gain to ensure proper oscillation. Too little gain, and any oscillations will decay over time until the circuit no longer oscillates; too much gain, and the oscillations grow in amplitude until the waveform "clips" at the amplifier's power supply rail limits. This "clipping" distorts the wave-shape from its ideal (sinusoidal) form, which may lead to poor results (e.g. unwanted harmonics[13]).

[12] We know that $X_C = \frac{1}{2\pi fC}$, so if a simple RC filter's cutoff point is defined by that frequency where $X_C = R$, then we may solve for f in the formula $R = \frac{1}{2\pi fC}$ to arrive at $f = \frac{1}{2\pi RC}$.

[13] Recall that any non-sinusoidal waveform is mathematically equivalent to multiple sinusoids at different frequencies (called *harmonics*) and amplitudes. Thus, an oscillator outputting a non-sinusoidal waveform is equivalent to

A practical solution to this problem is to equip the oscillator circuit with *automatic gain control* (abbreviated *AGC*). A feedback oscillator circuit able to automatically adjust its own voltage gain will not only produce sinusoidal signals of higher purity, but will also exhibit greater tolerance to loading when connected to other circuits.

An ingenious[14] implementation of AGC in the Wein bridge oscillator design was invented by William Hewlett (of Hewlett-Packard fame) in 1939. Instead of relying on fixed-value resistors to set his amplifier's voltage gain, he used an *incandescent lamp* as one of the resistive elements. The glowing metal filament of an incandescent lamp has a positive resistivity coefficient, which means its resistance rises as it becomes hotter. As V_{out} grows in magnitude, the lamp glows brighter (i.e. hotter filament) thereby increasing the voltage-division ratio $\frac{R_{lamp}}{R_{lamp}+R_3}$ and *automatically* reducing output voltage V_{out} through the action of negative feedback:



Modern variations on this theme use JFETs or other variable-resistance electronic devices in place of a lamp, the conductivity of that component usually adjusted by the output of another opamp.

outputting a *series* of sinusoidal signals, some of which may result in undesired effects in the circuit being excited by the oscillator.

[14]This really is an excellent example of creative engineering: exploiting the voltage/current characteristics of a component intended for a completely different purpose. For more detail on this design, refer to the Historical References chapter of this module.

3.3 Resonant oscillators

Feedback oscillators are only as stable as their feedback networks are *selective*. This means, the more sensitive the feedback network is with regard to variations in frequency, the "tighter" the oscillator circuit will lock onto one frequency and remain at that value despite external influences (e.g. loading). If we view the feedback network as a *filter* designed to screen out all frequencies except for the one resulting in a total phase shift of 360 degrees, this means we ideally want a filter network with high *roll-off rate*[15].

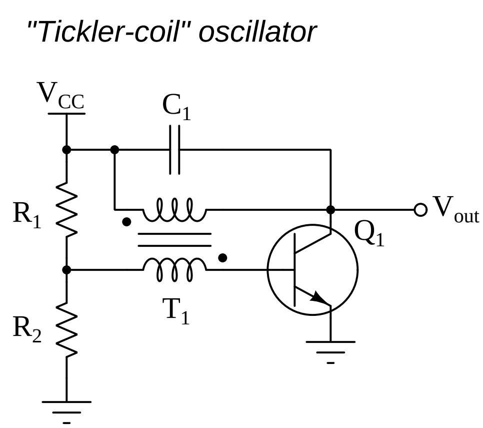
Resonant networks exploiting the complementary properties of inductance and capacitance yield sharper roll-off rates than resistor-capacitor networks, and so it makes sense to explore LC networks for feedback oscillator circuits. Furthermore, the resonant frequency of an LC "tank circuit" may be altered simply by varying either L or C which potentially means easier user-adjustment of oscillator frequency than any RC phase-shift design.

The resonant frequency of a simple LC "tank" circuit is that which causes inductive reactance and capacitive reactance to be equal ($X_L = X_C$), predicted by the following formula:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

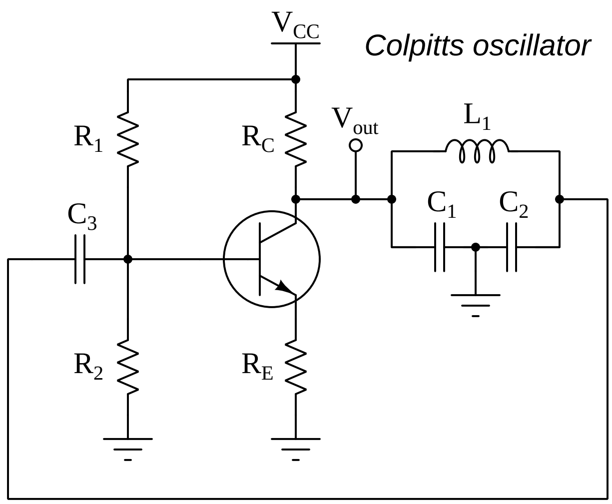
Where,
f = Resonant frequency, Hertz
L = Inductance, Henrys
C = Capacitance, Farads

An example of an oscillator using a "tank" circuit is the so-called *tickler-coil* oscillator circuit shown in the next schematic, using the primary winding of a transformer as an inductance to resonate with a capacitor, while the secondary winding provides positive feedback to the base of a transistor:



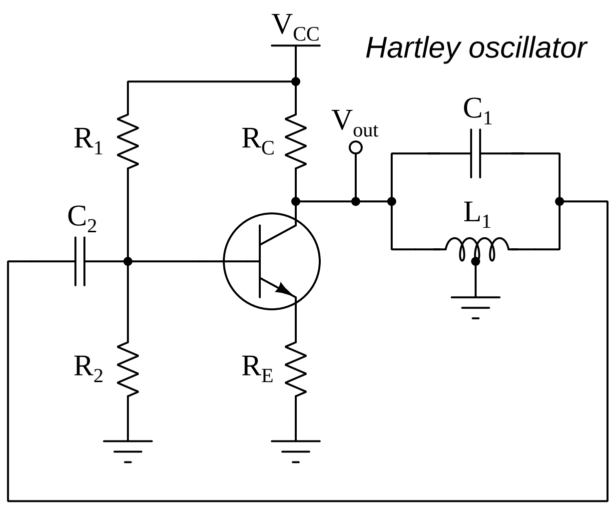
[15]The degree to which a filter circuit "cuts off" undesired frequencies lying outside of its "pass-band" is its *roll-off rate*, typically expressed in units of decibels per octave (dB/octave) or decibels per decade (dB/decade) in honor of the fact that filter cut-off usually approaches a straight-line plot on a graph having logarithmically-scaled axes (decibels for signal amplitude and octaves or decades for frequency).

The *Colpitts* oscillator design uses one inductor and two capacitors for its tank circuit:



In this tank circuit, the equivalent capacitance is the series combination of C_1 and C_2, which of course is $\frac{1}{\frac{1}{C_1}+\frac{1}{C_2}}$.

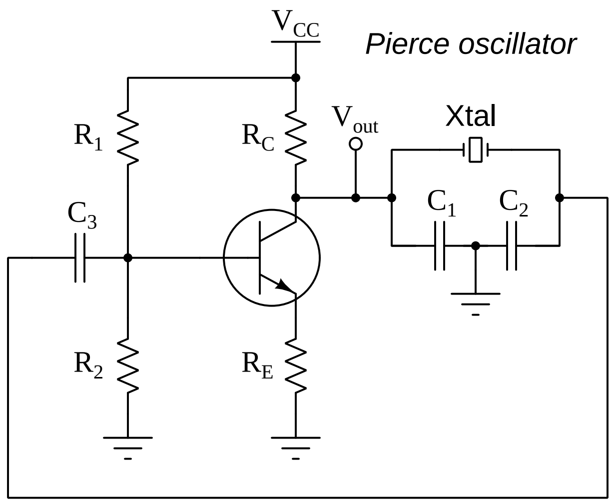
The *Hartley* oscillator is similar, using a tapped inductor rather than a pair of capacitors:



In both designs, the "center-tap" feature of the tank circuit provides a 180 degree phase shift[16] necessary to complement the common-emitter amplifier's inverting characteristic to make 360 degrees of total phase shift.

[16]For any direction of current oscillating within the tank circuit, the voltage polarities across each half of the center-tapped element will be series-aiding, which means when the left-hand side of the tank circuit is positive with respect to ground the right-hand side will be negative, and vice-versa.

The *Pierce* oscillator design follows the Colpitts model, replacing the inductor with a *quartz crystal*:



Quartz is one of many different types of naturally-occurring crystalline materials exhibiting *piezoelectricity*: such a crystal produces voltage when physically strained (compressed or stretched), and also strains with the application of voltage. When cut into specific shapes, a quartz crystal will resonate mechanically, and its piezoelectric properties makes it a suitable analogue[17] for an LC tank circuit.

Crystals happen to have an extremely sharp frequency response – far more selective than most LC tank circuits – and therefore the frequency stability of the Pierce oscillator is exceptional.

As with RC phase-shift oscillators, resonant oscillators output sinusoidal wave-shapes for the same basic reason: only one frequency produces the necessary phase shift for the oscillator to function. It is worth noting that one of the frustrations of electronic amplifier design is the *prevention* of unwanted oscillations, since parasitic inductance, capacitance, and/or resistance is unavoidable in real circuits. An amplifier with sufficiently high gain and bandwidth will *find* the necessary frequency to produce a 360 degree (total) phase shift, and start oscillating whether you want it to or not!

[17] One might think of a quartz crystal as akin to a mechanical pendulum with a solenoid coil for magnetic "pickup" of motion as well as for producing a driving force on the pendulum. The crystal's mechanical resonance acts to stabilize the oscillator circuit at that same frequency, just as an electromagnetic pendulum would do the same. The idea of an electromagnetic resonator for an electronic oscillator circuit is not hypothetical either: a type of fluid flowmeter called a *Coriolis effect mass flowmeter* uses a positive-feedback oscillator to shake a steel tube filled with moving fluid, the tube's elasticity and the fluid's mass acting together to form a resonant mechanical assembly. As the fluid's density varies, the tube's effective mass varies with it, altering the assembly's resonant frequency and thereby shifting the frequency of the oscillator circuit driving and sensing the tube's motion. This frequency becomes an inverse-proportional representation of fluid density in the Coriolis flowmeter.

Many electronic circuit applications require *square-wave* oscillations, most notably *digital electronic circuits* which use these square-wave signals as "clock" pulses to synchronize the operations of the various digital elements. For this purpose *integrated circuit oscillator modules* are manufactured. These packaged oscillator units typically use quartz crystals as the resonant element, and also contain all the other circuitry necessary to provide positive feedback and to generate a square-wave pulse signal from the crystal's naturally sinusoidal resonance. A photograph of such an oscillator module appears below:

This particular crystal oscillator module has a resonant frequency of 1.000 MHz (1 million cycles per second), output as a square-wave signal with a peak value of 5 Volts. It is powered by 5 Volts DC, which is a standard source voltage rating for many digital integrated circuits. Its frequency stability is ± 100 parts per million, which means $\frac{100}{1{,}000{,}000}$ and is equivalent to ± 0.01 percent[18].

While typical quartz-crystal oscillator frequency is remarkably stable, it may be slightly adjusted by the capacitance connected to the crystal (e.g. C_1 and C_2 in the Pierce oscillator schematic). If one of these capacitances takes the form of a *varactor diode*, it may be adjusted by the application of a DC control voltage, making the circuit a *Voltage Controlled Crystal Oscillator* or *VCXO*. Since ambient temperature is the most significant environmental variable influencing a crystal's resonant frequency, it is possible to achieve outstanding frequency stability by supplying a control voltage to a VCXO from a temperature-sensing circuit, the idea being to compensate for the effects of changing ambient temperature on the crystal by adjusting the adjacent capacitance by just the right amount. When built as such, the circuit becomes a *Temperature-Compensated Crystal Oscillator* or *TCXO*.

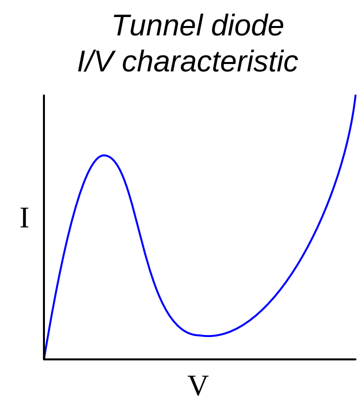
An even more direct method of stabilizing the resonant frequency of a quartz crystal is to control its temperature by placing it inside a tiny electrically-heated oven, and thermostatically regulating that oven's temperature slightly above ambient. This arrangement is called an *Oven-Controlled Crystal Oscillator* or *OCXO*. For even greater frequency stability some crystal oscillators use a *double oven*, the crystal being inside of one tiny oven which itself is inside yet another tiny oven. Of course, providing a stable operating temperature for the crystal requires additional electric power to run the oven, but for some high-precision applications this extra power requirement is a small price to pay. These *Double Oven-Controlled Crystal Oscillator* (*DOCXO*) modules achieve both short- and long-term frequency stabilities less than ± 1 part per billion (ppb).

[18] "Percent" literally means "per cent" or "parts per hundred". Parts per million (ppm) is merely a similar method for expressing very small quantities, like a version of percent that is ten thousand times smaller! For high-precision applications it is actually more common to see tolerances and uncertainties expressed as ppm (or even ppb, parts per *billion*!) than percent.

3.4 Negative resistance oscillators

Relaxation oscillators function on the basis of hysteresis: some component or network of components having the ability to "latch" into one of two states, alternately energizing and de-energizing one or more capacitors to produce oscillations. Phase-shift and resonant oscillators make use of non-hysteretic, linear components such as transistors to perform basic amplification, and use the principle of positive feedback (i.e. feedback with 360 degrees of total phase shift) to create an inherently unstable system that breaks into oscillations.

Another type of component characteristic exists which may be used to form oscillator circuits, and that is *negative resistance*. This is a phenomenon observed with a few different types of electronic components whereby current *decreases* with increasing voltage. A device called a *tunnel diode* exhibits negative resistance over a portion of its operating range:

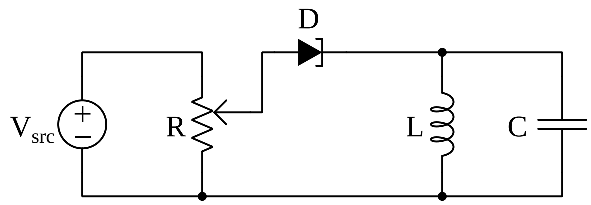


That portion of the tunnel diode's curve having a *negative slope* is where the device exhibits negative resistance[19]: instead of current increasing as voltage increases (like a normal resistance), over that specific range of voltage we can see the current *decreasing* as voltage increases. Within this region of negative resistance the tunnel diode behaves much like a positive-feedback system when connected in series with a voltage source and a load: as load voltage increases, the tunnel diode's voltage decreases, causing it to pass *more* current rather than less, and this tends to make load voltage rise even more. Conversely, when load voltage decreases it increases voltage across the tunnel diode and makes it pass less current, resulting in even less voltage for the load.

With a resonant load (e.g. a tank circuit) rather than a resistive load, the result will be that the tunnel diode's behavior helps sustain oscillations.

[19]It may be tempting to equate negative resistance with hysteresis, but these are two distinctly different phenomena. A hysteretic device such as a gas-discharge lamp does exhibit a sudden decrease in resistance as voltage rises, but when voltage is subsequently reduced below the trigger value the lamp's resistance remains low because the ionized state of the gas persists. A tunnel diode, by contrast, *retraces the exact same curve* when voltage decreases as when voltage increases. Negative resistance and hysteresis (latching) are therefore not the same concept.

We may build a resonant oscillator around a tunnel diode with very few accessory components:

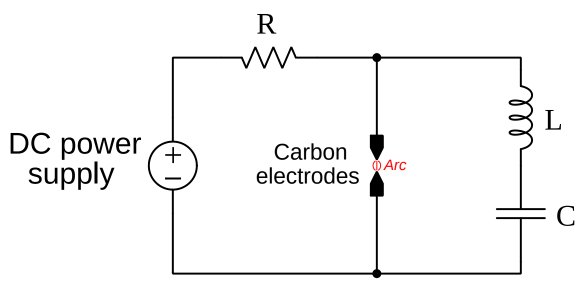


As the operation of this oscillator circuit depends critically on the diode's voltage lying within the narrow range of negative resistance, a potentiometer provides the user with a means to adjust until the circuit oscillates reliably. As with all oscillators built around a resonant LC "tank" circuit, this oscillator's frequency is also predicted by the LC resonance formula:

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Where,
f = Resonant frequency, Hertz
L = Inductance, Henrys
C = Capacitance, Farads

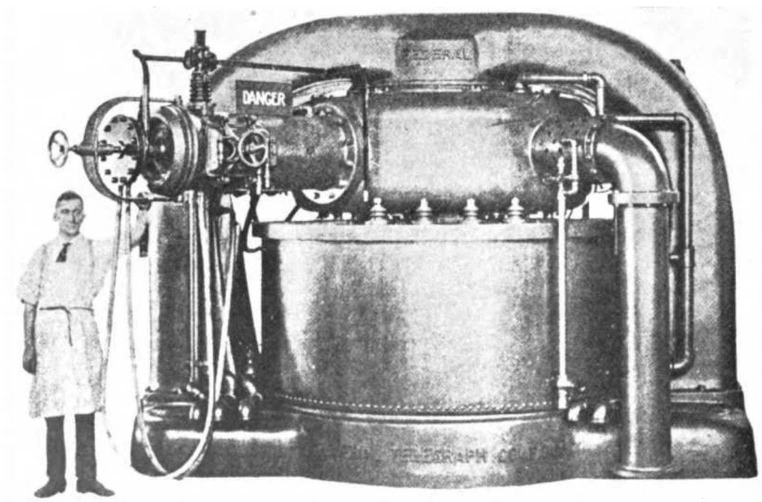
Interestingly, continuous electric arcs occurring in gas also exhibit this phenomenon of negative resistance, and in fact were used for a number of years to create radio-frequency oscillations before the advent of high-power vacuum tube technology. A simple example of this technology is shown in the following schematic diagram:



An experimenter named William Duddell demonstrated in the year 1900 that such an apparatus could be made to produce oscillations in the audio-frequency range, the arc itself functioning as a loudspeaker such that these tones could be heard by the human ear when the circuit was functioning. Another researcher, named Valdemar Poulsen, improved upon this basic technique just two years later in 1902 to create frequencies high enough to transmit radio waves. Poulsen's arc circuit enclosed the carbon electrodes in a vessel filled with hydrogenous gases rather than air, used a strong magnetic field to periodically extinguish the arc, and employed auxiliary systems[20] to make high-power operation practical.

[20]The carbon electrodes were slowly rotated to ensure even "burning" as they wore with use, and the anode was made of water-cooled copper to draw away the heat produced by the arc.

As high-power oscillators for radio broadcasting applications, these *arc converters* were manufactured in impressively large sizes. Though it was more common to encounter arc-based radio transmitters rated in the tens of kiloWatts, these were manufactured for even greater power levels than this. The following photograph shows a Federal Telegraph Company arc converter rated at one *megaWatt*[21], circa 1923:



The prominent "DANGER" sign affixed to this arc chamber was well-justified, as these devices were known for causing minor explosions if operated improperly because the gases used inside these converters were flammable – if any air was introduced into the arc chamber it would virtually guarantee combustion.

[21]This was the total DC load of the arc transmitter at full power. It's efficiency was only about 50%, which meant approximately 500 kW of energy was broadcast as electromagnetic radiation at the antenna and 500 kW of energy had to be dissipated in the form of heat!

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

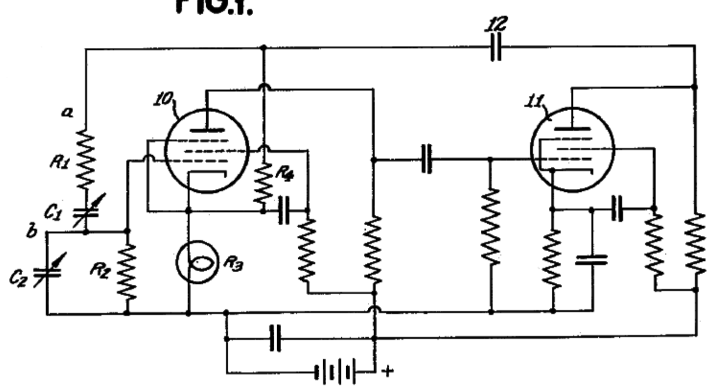
> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 William Hewlett's oscillator

One of the founders of the famous electronics manufacturer *Hewlett-Packard*, William Hewlett, filed for a US patent in early July of 1939 for a reliable sine-wave oscillator. This patent (number 2,268,872) was granted on the 6th of January 1942, and it shows a Wein-bridge design using vacuum tubes (*pentodes*, to be precise) as amplifying elements:

FIG.1.



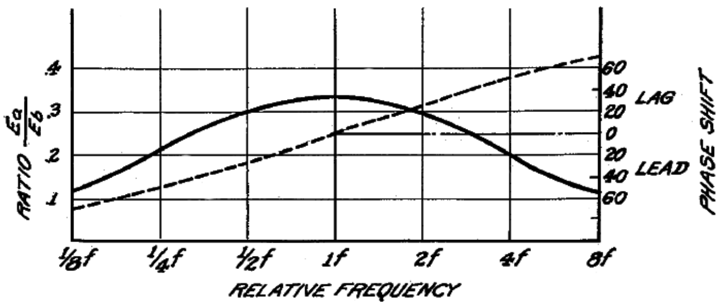
The text of Hewlett's patent begins as such on page 2 of the patent document:

> My invention relates to variable frequency oscillation generators and more particularly to oscillation generators wherein the frequency is determined by means of resistance capacity networks.
>
> Oscillation generators capable of tuning over a wide range of frequencies are useful for many purposes, for example, as test oscillation generators in place of beat frequency generators. In general such oscillation generators have been provided with a variably tuned resonant circuit to maintain the oscillations at a frequency to which the tuned circuit is adjusted.
>
> According to my invention, I provide an oscillation generator with a variable resistance capacity network forming a positive feedback path for the purpose of determining the frequency of oscillation.
>
> According to another feature of my invention an oscillation generator with resistance capacity frequency determining arrangements and with a negative feedback circuit for reducing distortion caused in the amplifier circuit, is provided.
>
> According to a further feature of my invention I provide an automatic amplitude control arrangement in a negative feedback path of an oscillation generator to maintain the amplitude of the generated oscillations constant despite changes in the supply voltages for the tubes. `[page 2]`

Hewlett continues, on the same page, making reference to the illustrations:

> Other advantages and features of my invention will be apparent from the particular description thereof made in connection with the accompanying drawing, in which
>
> Fig.1 shows a diagrammatic circuit of the preferred form of an oscillation generator in accordance with my invention, and
>
> Fig. 2 shows curves for the purpose of illustrating the operation of the circuit.
>
> In Fig. 1 is shown an oscillation generator comprising two amplifying tubes 10 and 11, coupled together by resistance capacity means in a known manner. The voltage supply sources and the cathode heating supply are omitted for simplifying the circuit. The anode of tube is coupled to the input grid of tube and the anode of tube is then connected to a circuit which provides a feedback path through a coupling condenser 12 and series connected resistance R_1 and variable capacity C_1, and a second circuit comprising R_2 and variable condenser C_2, to the input of tube 10. The circuit including R_1, C_1, R_2, C_2, provides a regenerative or positive coupling between the output and input circuits of the amplifiers 10 and 11, so that feedback occurs sufficient to maintain oscillations in the circuit. By properly proportioning the value of the resistance capacity networks R_1, C_1, R_2, C_2, the desired frequency may be obtained. If R_1, and C_1, respectively, equal R_2, and C_2, the ratio of the voltage E_b at point b to the voltage at point a varies with frequency in a manner similar to a resonance curve. In Fig. 2 this curve is shown in solid lines with voltage ratios of E_a and E_b plotted as ordinates against the relative frequency. At the maximum of this curve, the frequency
>
> $$f_o = \frac{1}{2\pi\sqrt{R_1, R_2, C_1, C_2}}$$
>
> and the voltages at points a and b have the same phase. Accordingly, oscillations tend to occur at the frequency f_o for this circuit. `[page 2]`

FIG. 2.



In Fig. 2 the broken line curve indicates the phase shifts as ordinates with the change in relative frequency. It can be seen that at zero phase shift, the maximum of the E_a, E_b ratio occurs. If the various condensers and resistances are not made equal as they were for plotting this curve, the maximum would occur at some other point and a symmetrical curve would not be obtained. However, the principles of my invention apply to the circuit regardless of equality of these elements. In practical construction, however, it is generally desirable to make the separate elements equal.

As shown in Fig. 1, frequency shift in the oscillation generator is accomplished by adjusting variable capacities C_1 and C_2. It is clear, however, that since the resistances as well as the capacities serve to control the frequency of the oscillator, either the resistances alone or both the resistances and capacities may be adjustable for varying the tuning.

For the type of oscillators illustrated in Fig. 1, it is necessary in order to obtain satisfactory operation that the amplifiers comprising tubes 10 and 11 have phase shift independent of changes in supply, etc., and furthermore, there should be provided some means for controlling the amplitude of the oscillations so that they do not exceed the range over which tubes 10 and 11 will operate as class A amplifiers. A constant amplifier phase shift is necessary to insure a constant frequency, because the phase angle of the transfer impedance of the resistance capacity network from point *a* to point *b* varies only slowly with frequency. Accordingly, a small change in amplifier phase shift such as might be produced by a variation in voltage supply requires a comparatively large change in the frequency of opera- `[page 2]`

tion to produce a compensating phase shift in the resistance capacity Coupling System. `[page 3]`

After explaining the basic operation of the oscillator circuit, Hewlett begins to describe some of the more advanced features of his design. He begins by explaining how his circuit is stabilized against variations such as tube parameters, temperature, and supply voltage (using negative feedback):

> In the circuit of Fig. 1, I provide a negative feedback arrangement for stabilizing the amplifier. This feedback is made from the output of amplifier 11 over coupling condenser 12 and the resistance R_3, R_4 to the cathode of tube 10. The potential drop across the resistance produces a negative feedback to the input of amplifier 10. This negative feedback operates in a manner known per se to reduce the amplification of the system and at the same time to stabilize the amplifier gain in magnitude and phase with respect to variations occurring within the amplifier, such as tube changes, temperature variations and changes caused by fluctuation in the voltage supplies to the electrodes of the amplifier system. `[page 3]`

Next, he explains what is perhaps the most innovative feature of his oscillator's design, a method for automatically controlling gain for the purpose of reducing waveform distortion:

> Amplitude control to prevent the oscillations from building up to such a large value that distortion occurs, is obtained according to my invention by non-linear action in the amplifier circuit. In order to produce this non-linear variation, I provide for resistance R_3 a small incandescent lamp, or similar device in which the resistance increases rapidly with increased current flow, the lamp being heated by the plate current of the tubes 10 and 1l or by an auxiliary means, so such a temperature that its resistance will vary rapidly with a small change in current. Thus, when the oscillation amplitudes tend to increase, the temperature of the lamp R_3 increases with a resulting increase in resistance thereby causing a greater negative feedback, thus reducing the amplification. Similarly, as the oscillations decrease in amplitude, the current through the lamp is reduced permitting the lamp to cool with an accompanying decrease in resistance and reduction of the negative feedback, thus increasing the amplitude of the generated oscillations. As a result the system operates at substantially a constant amplitude which is preselected to be below the value at which grid current flows. As a result no distortion of the wave form takes place.
>
> While I have described the amplitude control system in connection with my particular resistance capacity tuned oscillation generator, it is clear that this feature of my invention is similarly applicable to various types of oscillation generators, wherein frequency stabilization is obtained by means of negative feedback. Since the lamp itself responds relatively slowly to current changes it tends to average out the voltage peaks and does not cut off the peaks of the generated waves, maintaining the amplitude constant without producing distortions in wave form. `[page 3]`

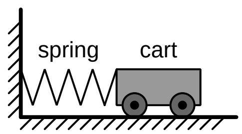
Chapter 5

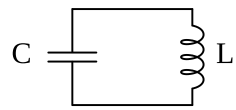
Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 LC resonance

A phenomenon known as *resonance* occurs when capacitance and inductance are coupled together. Capacitors and inductors absorb, store, and release energy in complementary forms. This is analogous to springs and masses, which store mechanical energy in complementary forms as well: springs storing potential energy in the form of tension and displacement, and masses storing kinetic energy in the form of motion. Any mass connected to a spring will exhibit resonance: an ability to sustain alternating motion for sometime after being stimulated. A spring-loaded mass moves to and fro because the spring and mass exchange energy back and forth with each other.



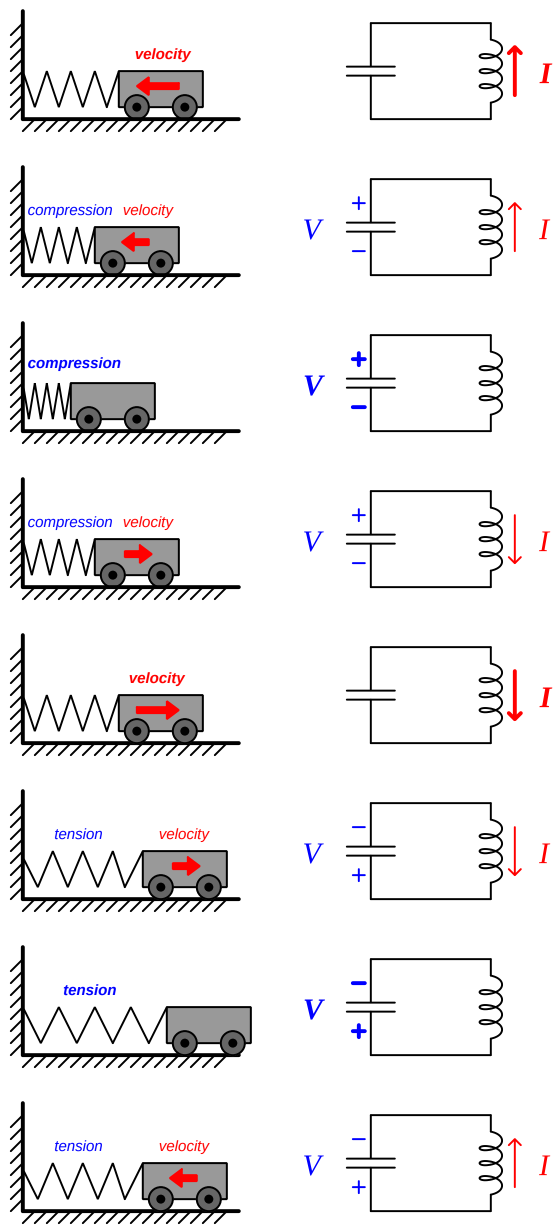


A cart with mass stores energy in kinetic form, while a spring with elasticity stores energy in potential form. Similarly, an inductor stores energy in its magnetic field as a function of current (kinetic charge carriers), while a capacitor stores energy in its electric field as a function of voltage (potential energy per charge). Coupling these complementary devices together means they now have the ability to exchange energy back and forth, and will do so if initially energized by some external source. For the spring-coupled cart it means the assembly will tend to move back and forth cyclicly; for the capacitor-inductor network it means the circuit will *oscillate* (i.e. produce alternating current, or AC).

The rate at which systems like this will oscillate depends on the characteristics of its elements. A stiffer spring will cause the cart to move back and forth more rapidly. A more massive cart will cause the cart to alternate more slowly. With capacitors and inductors it is simpler: increasing the size of either component will slow down the rate of oscillation[1].

[1]Resonant frequency for a simple capacitor-inductor network is predicted by the formula $f = \frac{1}{2\pi\sqrt{LC}}$ where L is inductance in Henrys, C is capacitance in Farads, and f is the frequency of oscillation in cycles per second or Hertz.

The following series of illustrations show a step-by-step sequence of events for an oscillating spring-and-cart mechanism alongside an oscillating capacitor-inductor circuit:



The spring's ability to store potential energy is analogous to the capacitor's ability to store energy in an electric field. The cart's ability to store kinetic energy is analogous to the inductor's ability to store energy in a magnetic field. Compression and tension within the mechanical spring is analogous to voltage across the capacitor; velocity of the cart is analogous to current through the inductor.

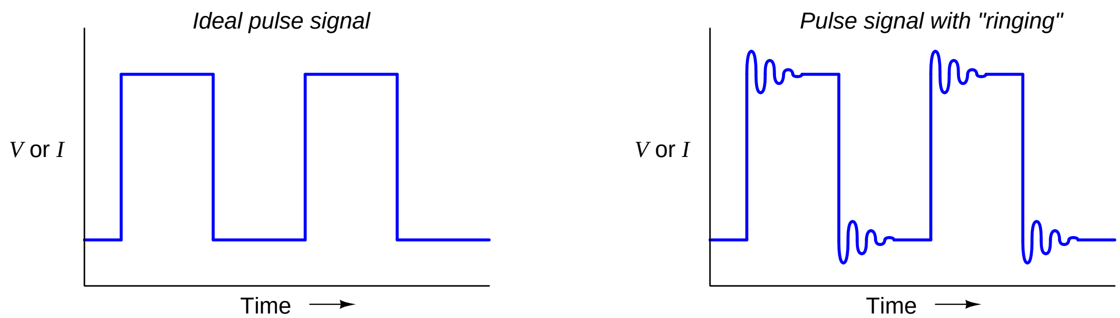
Even the mathematical expressions of stored energy for the spring and cart resemble the formulae for energy stored in the capacitor and inductor:

Potential energy (measured in Joules)	**Kinetic energy** (measured in Joules)
Potential energy stored in a tensed spring: $$E_p = \frac{1}{2}kx^2$$ where k is spring stiffness (measured in Newtons per meter) and x is spring displacement (measured in meters)	Kinetic energy stored in a moving mass: $$E_k = \frac{1}{2}mv^2$$ where m is mass (measured in kilograms) and v is velocity (rate of mass motion, measured in meters per second)
Energy stored in a capacitor: $$E_C = \frac{1}{2}CV^2$$ where C is capacitance (measured in Farads) and V is voltage (measured in Volts)	Energy stored in an inductor: $$E_L = \frac{1}{2}LI^2$$ where L is inductance (measured in Henrys) and I is current (rate of charge motion, measured in Amperes)

In the absence of any friction (resistance), both systems will oscillate ceaselessly as they exchange energy back and forth without losses. Mechanical systems made of springs and masses are used to create vibrations, an example being the string of a musical instrument such as a guitar: the elasticity and mass of the spring serves both roles in one component, so that the assembly *resonates* at a desired pitch. Capacitor-inductor circuits (often called *tank circuits*) are similarly used to create alternating current (AC) signals of a specific frequency[2].

[2] *Frequency* is the rate at which oscillations occur over time, generally measured in *cycles per second* (Hertz).

Capacitance and inductance, like elasticity and mass in mechanical systems, are intrinsic phenomena and therefore exist in *every* circuit whether desired or not. The existence of such "parasitic" capacitance and inductance in circuits means resonance may occur where it is unintended, just as unintended resonance may occur in mechanical assemblies[3]. An example of unintended electrical resonance called *ringing* is often encountered in *pulse* circuits where voltage or current is suddenly switched on and off to some load: instead of the graph of this voltage or current over time resembling a square-edge as desired, some oscillations will be seen at the leading edges of the pulse.



Whether the unintended resonance is electrical or mechanical, the solution is the same: insert enough energy dissipation into the system to dampen any oscillations that may otherwise occur. For mechanical systems this means incorporating sufficient *friction*[4]; for electrical circuits this means incorporating sufficient *resistance*.

For most electric circuits lacking capacitors and inductors, the amount of capacitance present between wires and the amount of inductance along the length of wires is so small compared to the energy-dissipating elements that these effects are negligible, and unintended resonance is simply not possible. However, for some specific types of circuits, especially those dealing with extremely high-frequency (fast-alternating) AC signals such as *radio* circuits, special care must be taken positioning all conductors to mitigate parasitic capacitance and inductance.

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[3]Perhaps the most obvious example of resonance in a mechanical assembly is undesirable "bouncing" in a suspension system, but in fact nearly every mechanical assembly is capable of resonance. Rotating machines exhibit *critical speeds* where the shaft rotation period matches the resonance period of the rotating element, causing vibration to naturally occur at these speeds. Struts and other supporting members for some mass will tend to oscillate at a natural frequency, the mass acting to store kinetic energy and the strut's elasticity acting to store potential energy. The infamous Tacoma Narrows bridge was a spectacular example of unintended resonance in a mechanical structure, earning it the nickname "Galloping Gertie" by motorists due to wind-induced oscillations prior to its catastrophic collapse on the seventh of November in the year 1940.

[4]The so-called *shock absorber* is a component designed to do exactly this in vehicle suspension systems, to prevent bouncing (oscillations) that would otherwise result as a consequence of the vehicle's elastic suspension system and its mass.

Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1]Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2]Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- 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, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- 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. Annotate any diagrams or illustrations with these calculated values.
- 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.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

6.1.1 Reading outline and reflections

"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, journal their own 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:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve 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.

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

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

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

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

6.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Conservation of Energy

Simplification as a problem-solving strategy

Capacitor

Time constant

Simplification as a problem-solving strategy

Hysteresis

Breakdown

Avalanche effect

Positive feedback

Swamping

Multivibrator

Astable

Bistable

Duty cycle

Phase angle

Gain

Feedback oscillation criteria

Filter

Automatic Gain Control

Roll-off

Inductance

Resonance

Piezoelectricity

Quantum tunneling

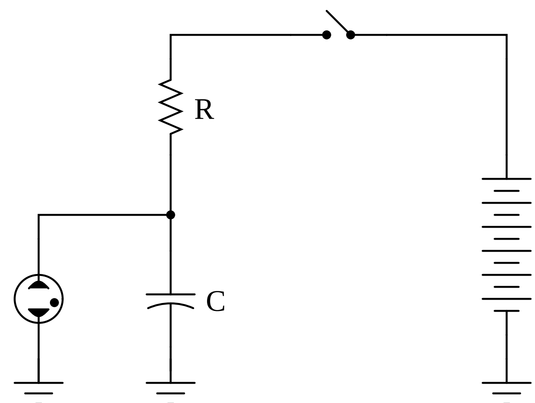
Negative resistance

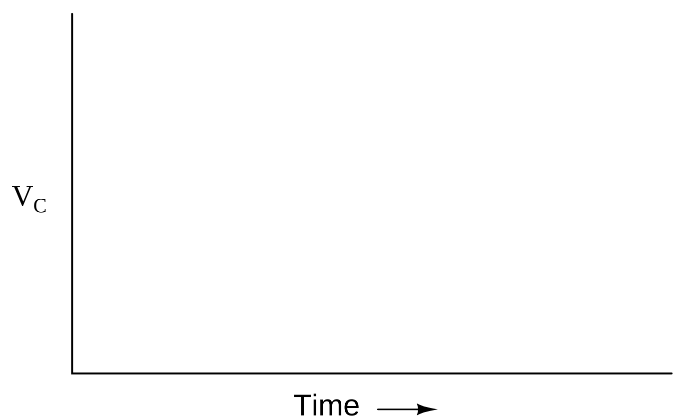
Sinusoidal decomposition (i.e. Fourier's Theorem)

6.1.3 Neon lamp relaxation oscillator

The circuit shown here is called a *relaxation oscillator*. It works on the principles of capacitor charging over time (an RC circuit), and of the *hysteresis* of a gas-discharge lamp: the fact that the voltage required to initiate conduction through the lamp is significantly greater than the voltage below which the lamp ceases to conduct current.

In this circuit, the neon lamp ionizes at a voltage of 70 Volts, and stops conducting when the voltage falls below 30 Volts:





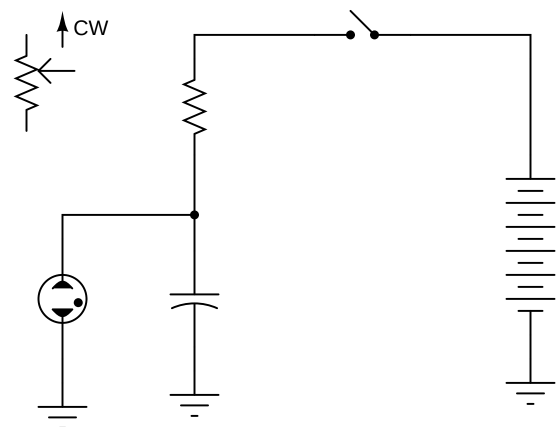
Graph the capacitor's voltage over time as this circuit is energized by the DC source. Note on your graph at what times the neon lamp is lit.

Challenges

- Assuming a source voltage of 100 Volts, a resistor value of 27 kΩ, and a capacitor value of 22 μF, calculate the amount of time it takes for the capacitor to charge from 30 Volts to 70 Volts (assuming the neon lamp draws negligible current during the charging phase).

6.1.4 Adjustable blinking rate

Replace the fixed-value resistor with a potentiometer to adjust the blinking rate of the neon lamp, in this *relaxation oscillator* circuit. Connect the potentiometer in such a way that clockwise rotation of the knob makes the lamp blink faster:

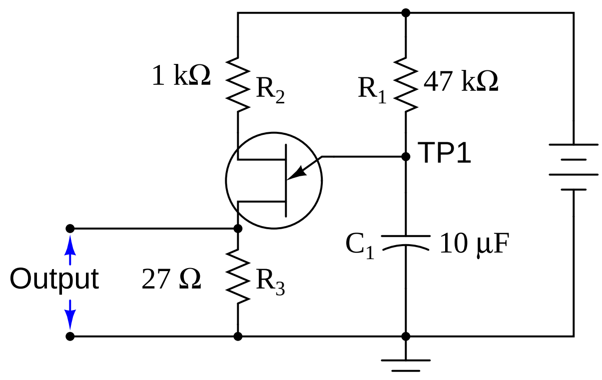


Challenges

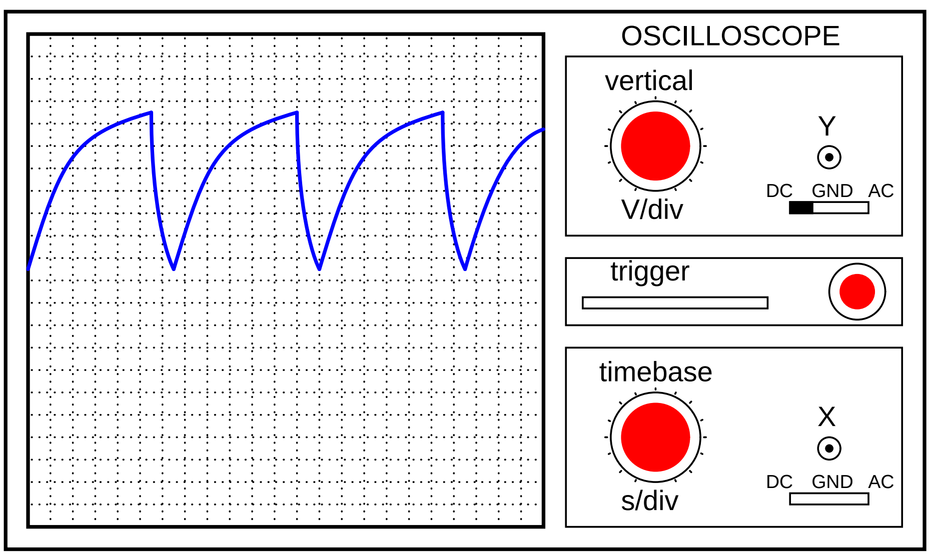
- Identify an alternative method for varying the flash rate, other than using a potentiometer.
- Explain how the circuit will function when the potentiometer's wiper is set to the "full up" position.
- Explain how the circuit will function when the potentiometer's wiper is set to the "full down" position.

6.1.5 JFET-UJT oscillator

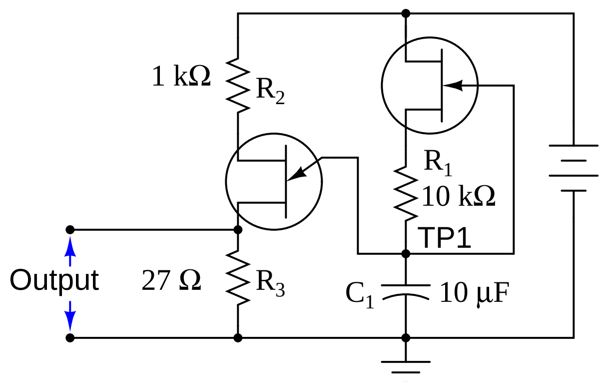
This relaxation oscillator circuit uses a resistor-capacitor combination (R_1 - C_1) to establish the time delay between output pulses:



When measured by an oscilloscope, the voltage between TP1 and ground looks like this:



A slightly different version of this circuit adds a JFET to the capacitor's charge current path:



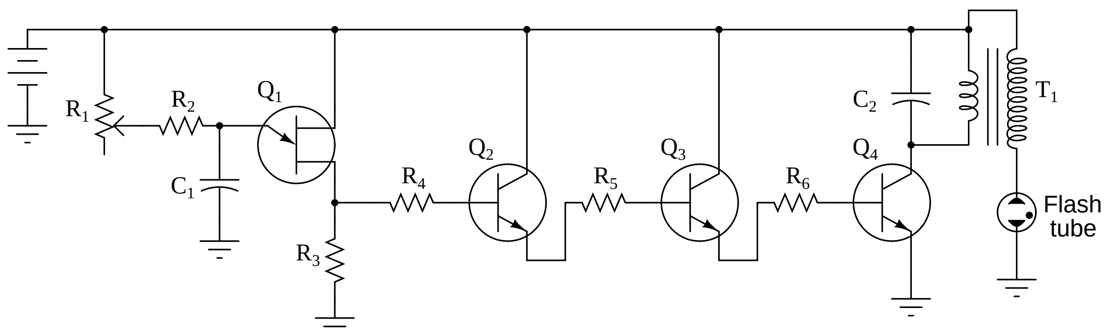
What function does this JFET serve, and how will the oscilloscope's display of TP1 voltage now appear?

Challenges

- Write a formula describing the *slope* of the JFET circuit's TP1 voltage waveform.

6.1.6 Strobe light circuit

This circuit shown here is for a *strobe light*: a device that uses a pulsed strobe lamp to "freeze" the motion of an object in periodic motion:



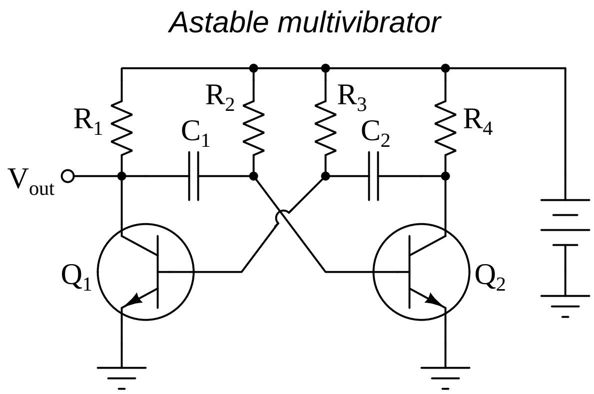
Which component(s) in this circuit form the oscillator section? What type of oscillator is used in this circuit? Which component values have a direct influence on the frequency of the flash tube's output?

Challenges

- What purpose does resistor R_2 serve? It would seem at first glance that it serves no useful purpose, as potentiometer R_1 is capable of providing any desired amount of resistance for the RC time constant circuit on its own – R_2's resistance is simply added to it. However, there is an important, practical reason for including R_2 in the circuit. Explain what that practical purpose is.
- The bipolar transistors serve a purpose very different from the UJT. Explain what that purpose is.

6.1.7 Astable multivibrator

Explain the principle of operation in this *astable multivibrator* circuit:



Also, identify where you would connect to this circuit to obtain an output signal. What type of signal would it be (sine wave, square wave, ramp or triangle wave, etc.)?

Challenges

- This circuit produce square-wave signals of 50% duty cycle (i.e. on-time = off-time) when $R_1 = R_4$, $R_2 = R_3$, $C_1 = C_2$, and the two transistors are identical. Identify a means of altering the *duty cycle* of this oscillator circuit's square-wave output to be more or less than 50%.

6.1.8 Clock pendulum

Spring- and weight-driven clock mechanisms always use a *pendulum* as an integral part of their workings. What function does a pendulum serve in a clock? What would a mechanical clock mechanism do if the pendulum were removed?

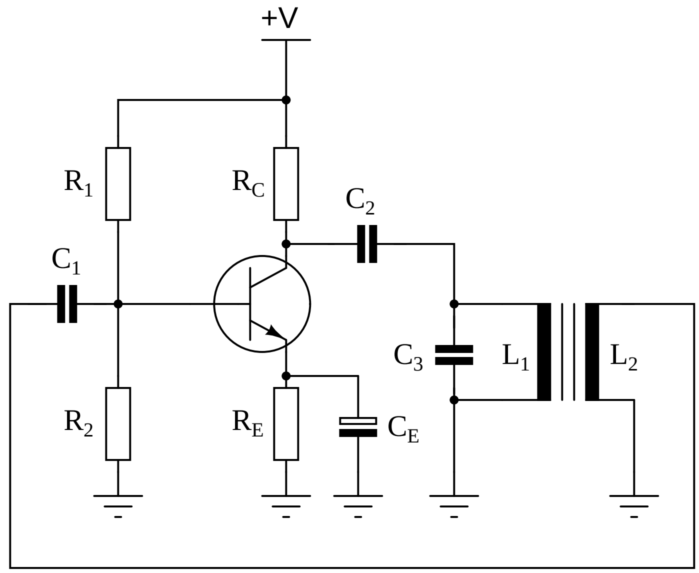
Describe what the electrical equivalent of a mechanical pendulum is, and what purpose it might serve in an oscillator circuit.

Challenges

- Suppose you were faced with a weight-driven clock that was running too fast. What exactly would you do to the mechanism to slow it down?

6.1.9 Armstrong oscillator transformer polarity

Draw the transformer phasing dots in the right places to ensure regenerative feedback:



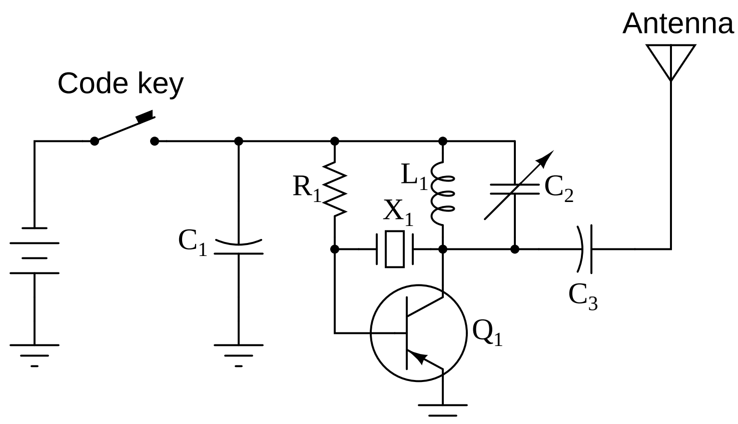
Also, identify the components most directly responsible for establishing the oscillating frequency for this circuit.

Challenges

- What would happen if the transformer phasing were incorrect?

6.1.10 Carrier-wave radio transmitter

Two technicians are arguing over the function of a component in this oscillator circuit. Capacitor C_1 has failed, and they are debating over the proper value of its replacement.



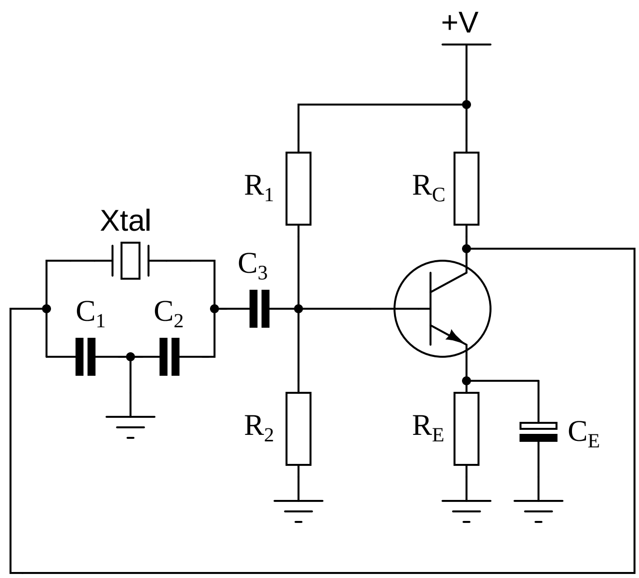
One technician argues that the value of capacitor C_1 helps set the oscillation frequency of the circuit, and that the value of the replacement capacitor therefore must be precisely matched to the value of the original. The other technician thinks its value is not critical at all, arguing that all it does is help to provide a stable DC power supply voltage. What do you think?

Challenges

- This radio transmitter circuit has no microphone to accept speech input. How do you suppose it is intended to function?

6.1.11 Pierce oscillator

Explain the purpose of the quartz crystal ("Xtal") in the *Pierce* type of oscillator circuit:



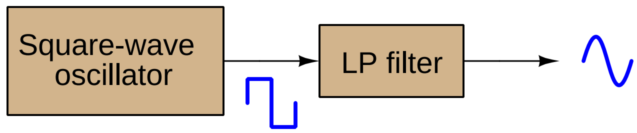
This type of oscillator circuit is usually limited to lesser power output levels than either the Colpitts or the Hartley designs. Explain why.

Challenges

- What must be done to this oscillator circuit to alter its frequency of operation?

6.1.12 Converting a square wave into a sine wave

A clever way to produce sine waves is to pass the output of a square-wave oscillator through a low-pass filter circuit:



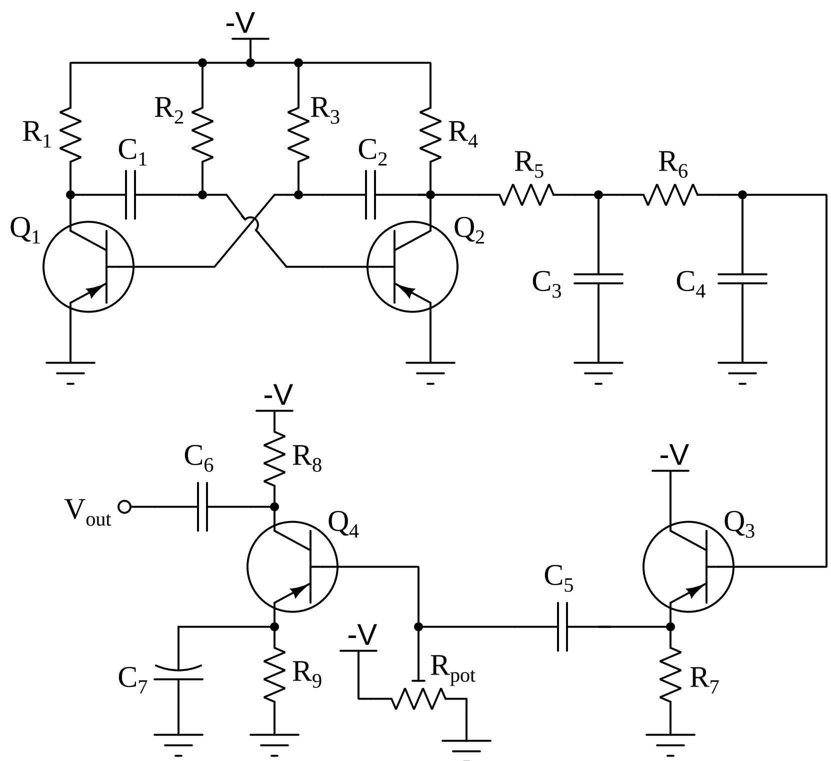
Explain how this principle works, based on your knowledge of Fourier's theorem.

Challenges

- How steep must the *rolloff* of this low-pass filter be in order to be most effective at converting the square wave into a sine wave?

6.1.13 Identifying oscillator circuit sections

This circuit generates output waveforms that are very close to being true sine waves:



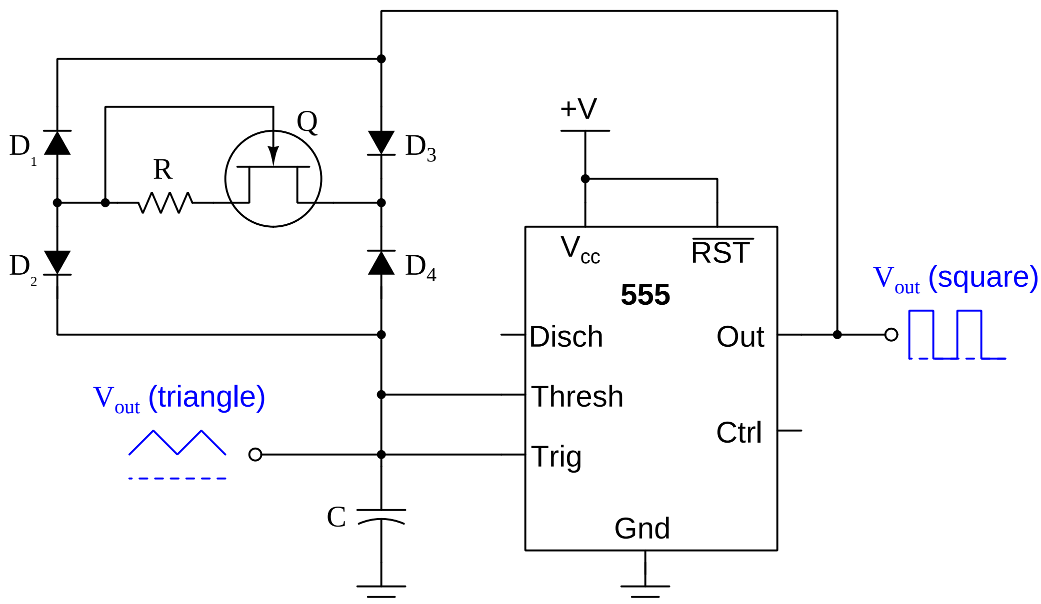
Divide this circuit into distinct sections, and describe how each of those sections contributes to the generation of a sinusoidal output signal.

Challenges

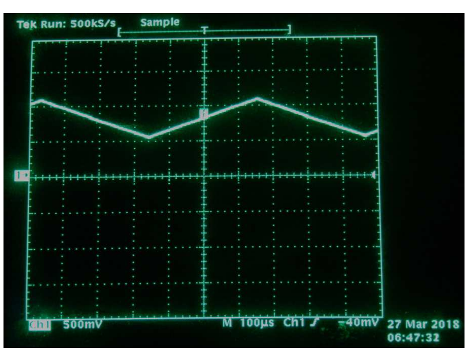
- Modify this circuit to provide an output amplitude adjustment.

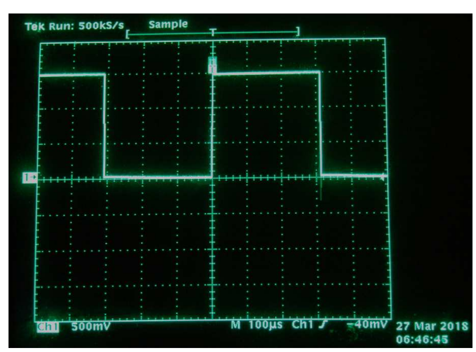
6.1.14 555-based triangle and square wave oscillator

The following circuit outputs both triangle-wave and square-wave voltage signals, using a 555 timer:



Screenshots of an oscilloscope showing the triangle and square wave outputs appear below, using a 10:1 probe. For this test $R = 7$ kΩ, $C = 0.015$ μF, +V = 16 V, an MPF102 was used as the transistor, and 1N4148 diodes were used throughout:





Based on your analysis of the schematic diagram, answer the following questions:

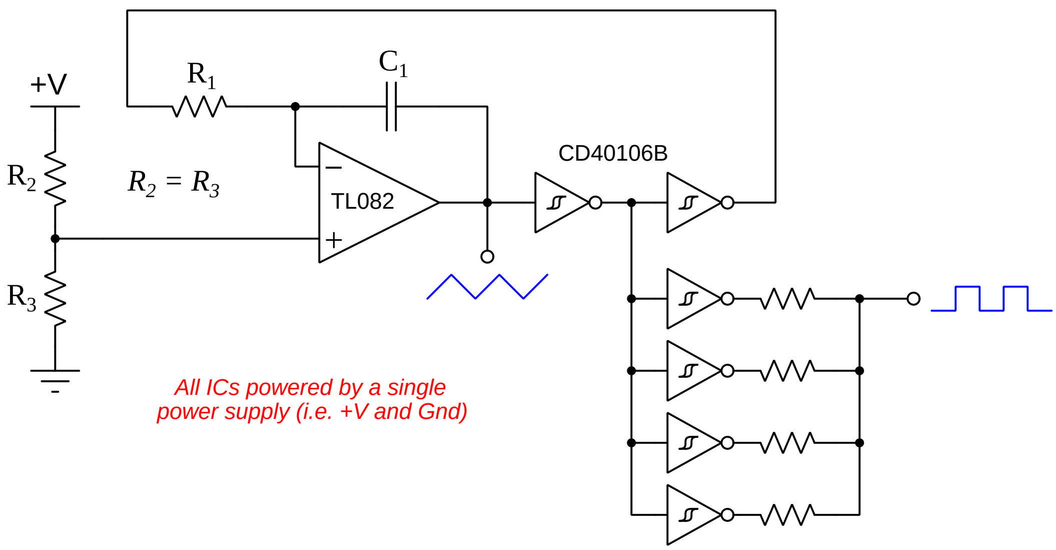
- What purpose do the four diodes serve?
- What purpose does the JFET serve?
- If the DC power supply voltage is 15 Volts, what will be the peak values of the triangle wave?
- If the DC power supply voltage is 15 Volts, what will be the peak values of the square wave?
- What will happen to output frequency if C is made smaller?
- What will happen to output frequency if R is made smaller?
- Modify this circuit to make its frequency easily adjustable by the user.
- Will the duty cycle of the triangle and square waves be symmetrical (i.e. 50%) or not?

Challenges

- Will signal amplitude vary as frequency is adjusted?

6.1.15 Opamp/inverter-based triangle and square wave oscillator

This simple circuit outputs very clean triangle-wave and square-wave signals using just two integrated circuits, an 8-pin TL082 operational amplifier and a 14-pin hex CMOS inverter:



Explain how this circuit functions.

Challenges

- Modify this circuit to provide an output amplitude adjustment.

6.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4]In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5]This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers.* Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($\text{m}^3/\text{kg-s}^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($\text{W/m}^2\cdot\text{K}^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

6.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6]Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (+)
- Subtraction (-)
- Multiplication (*)
- Division (/)
- Powers (^)
- Square roots (sqrt())
- Logarithms (ln() , log10())

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells B3, B4, and B5, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells B3 through B5. The numerical values appearing in cells B1 and B2 will be automatically updated by the computer immediately following any changes made to the coefficients.

[7]Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8]Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9]Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial $(9x^2 + 5x - 2)$ the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells B1 and B2, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

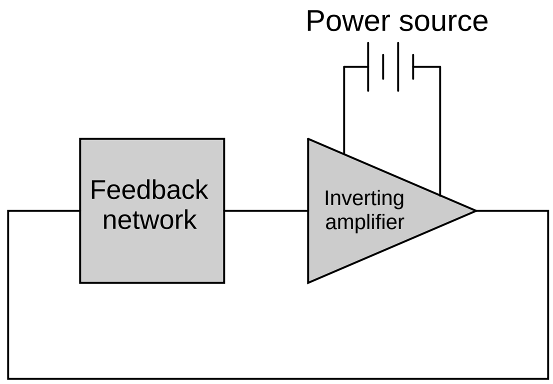
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

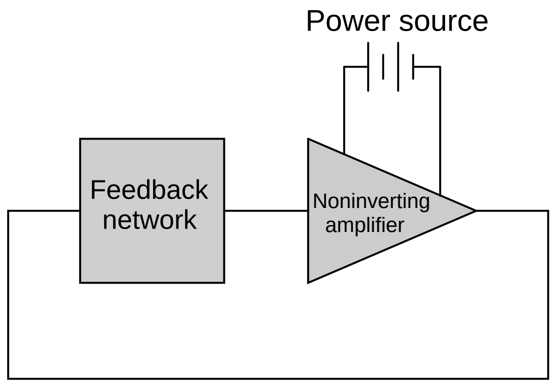
[10]My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

6.2.3 Phase shift requirements

How many degrees of phase shift must the feedback circuit (the square box in this schematic) introduce to the signal in order for this inverting amplifier circuit to oscillate?



How many degrees of phase shift must the feedback circuit (the square box in this schematic) introduce to the signal in order for this inverting amplifier circuit to oscillate?

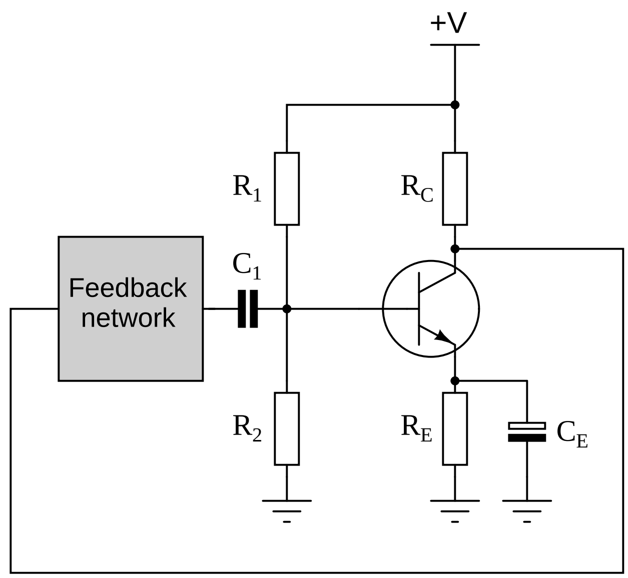


Challenges

- Other than phase shift, what other criterion must be met in order for a system such as either one of these to oscillate.

6.2.4 Common-emitter feedback oscillator

How many degrees of phase shift must the feedback circuit (the box in this schematic) introduce to the signal in order for this common-emitter amplifier circuit to oscillate?



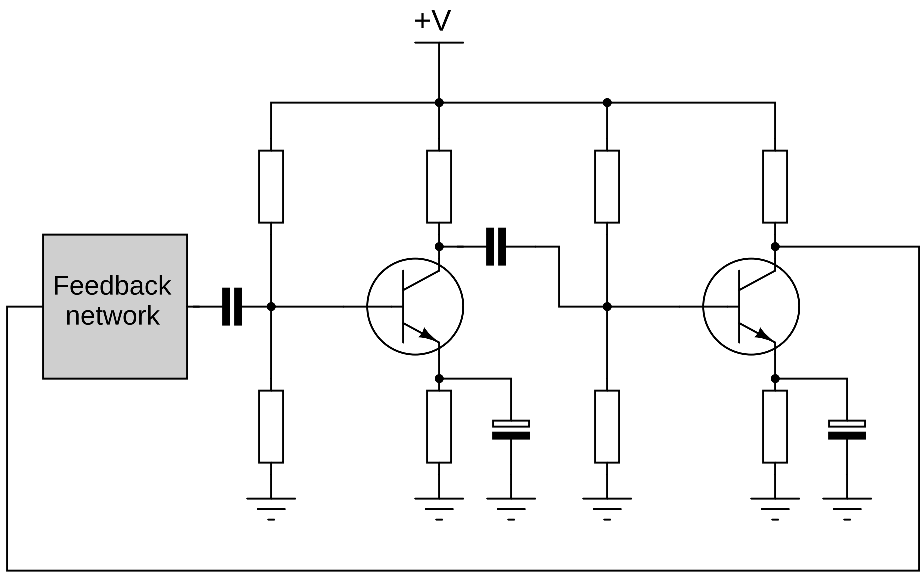
We know that oscillator circuits require "regenerative" feedback in order to continuously sustain oscillation. Explain how the correct amount of phase shift is *always* provided in the feedback circuit to ensure that the nature of the feedback is always regenerative, not degenerative. In other words, explain why it is not possible to incorrectly choose feedback network component values and thus fail to achieve the proper amount of phase shift.

Challenges

- Does the gain of the amplifier stage matter for this circuit's ability to oscillate?

6.2.5 Two-stage amplified oscillator

How many degrees of phase shift must the feedback circuit (the box in this schematic) introduce to the signal in order for this two-stage common-emitter amplifier circuit to oscillate?



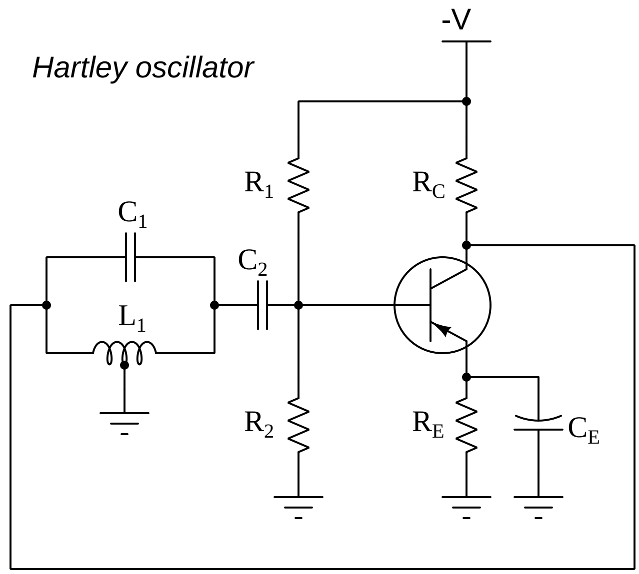
Why is this amount of phase shift different from that of a single-stage transistor oscillator?

Challenges

- Suppose one of these two stages were made to be common-collector instead of common-emitter. How would this affect the oscillation, if at all?

6.2.6 Hartley oscillator frequency

Calculate the operating frequency of this oscillator circuit, given the following values for C_1 and L_1:



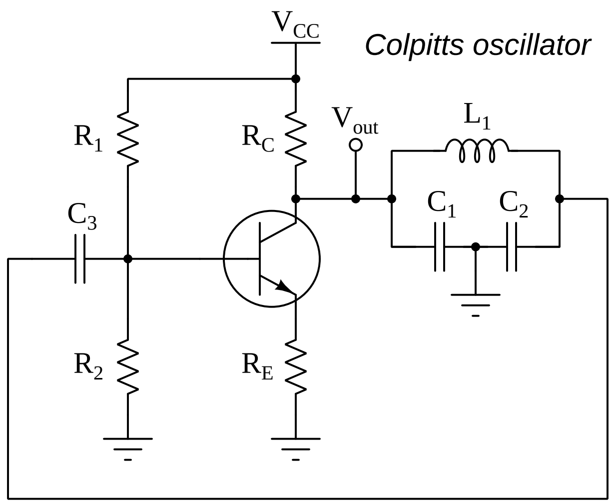
- $C_1 = 0.047\ \mu$F and $L_1 = 150$ mH; $f =$
- $C_1 = 0.033\ \mu$F and $L_1 = 175$ mH; $f =$
- $C_1 = 0.027\ \mu$F and $L_1 = 105$ mH; $f =$

Challenges

- Re-design this circuit to use an NPN instead of a PNP transistor.

6.2.7 Colpitts oscillator frequency

Calculate the operating frequency of this oscillator circuit, given the following values for C_1, C_2, and L_1:

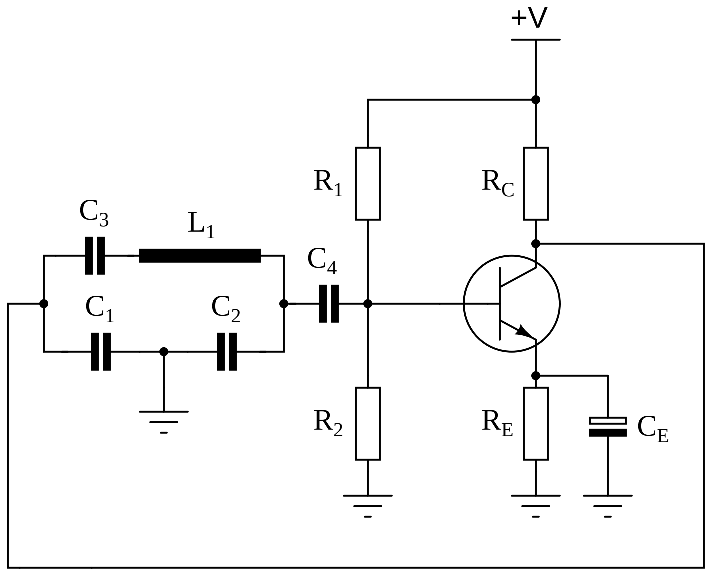


- $C_1 = 0.027\ \mu$F, $C_2 = 0.027\ \mu$F, and $L_1 = 220$ mH; $f =$
- $C_1 = 0.003\ \mu$F, $C_2 = 0.003\ \mu$F, and $L_1 = 50$ mH; $f =$
- $C_1 = 0.005\ \mu$F, $C_2 = 0.005\ \mu$F, and $L_1 = 80$ mH; $f =$

Challenges

- Re-design this circuit to use an NPN instead of a PNP transistor.
- Suppose a student mistakenly calculates $f = 2.065$ kHz for the case with $0.027\ \mu$F capacitors and a 220 mH inductor. What did they do wrong?
- Suppose a student mistakenly calculates $f = 1.460$ kHz for the case with $0.027\ \mu$F capacitors and a 220 mH inductor. What did they do wrong?

6.2.8 Clapp oscillator frequency



The frequency of oscillation for this type of circuit is given by the following formula:

$$f = \frac{1}{2\pi\sqrt{L_1\left(\frac{1}{\frac{1}{C_1}+\frac{1}{C_2}+\frac{1}{C_3}}\right)}}$$

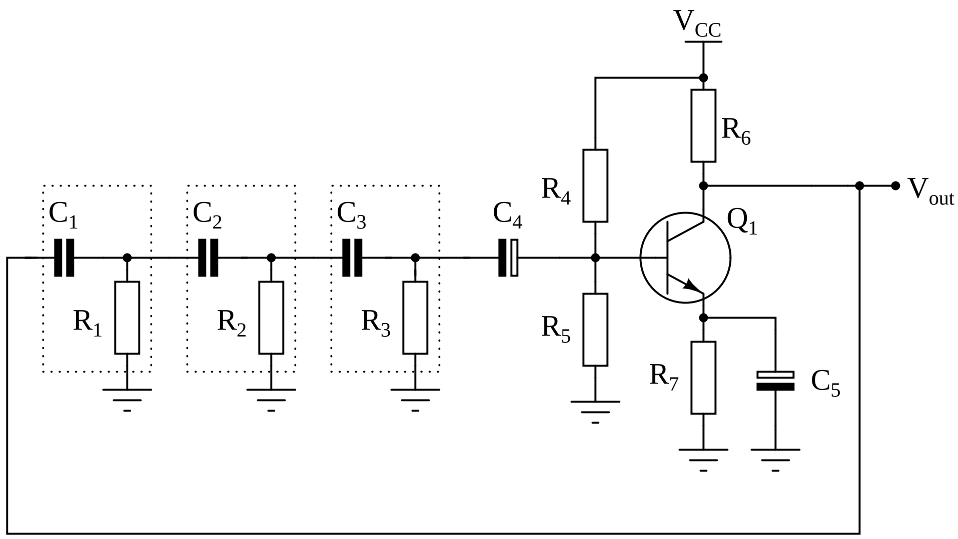
Explain why this formula makes sense, in light of what you know about inductors, capacitors, and resonance.

Challenges

- Identify at least two different methods for increasing the frequency of this oscillator.

6.2.9 Necessary voltage gain

One way to achieve the phase shift necessary for regenerative feedback in an oscillator circuit is to use multiple RC phase-shifting networks:



How much voltage gain must the common-emitter amplifier have if the total voltage attenuation for the three phase-shifting RC networks is −29.25 dB?

Challenges

- If the maximum phase shift achievable by a single RC phase-shifting network is 90 degrees, why do we need *three* of these networks? Why not just `two` of them to achieve 180 degrees of phase shift?

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

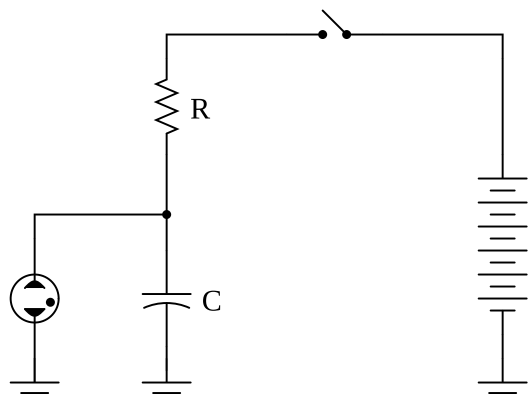
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

6.3.1 Effects of faults in a relaxation oscillator

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



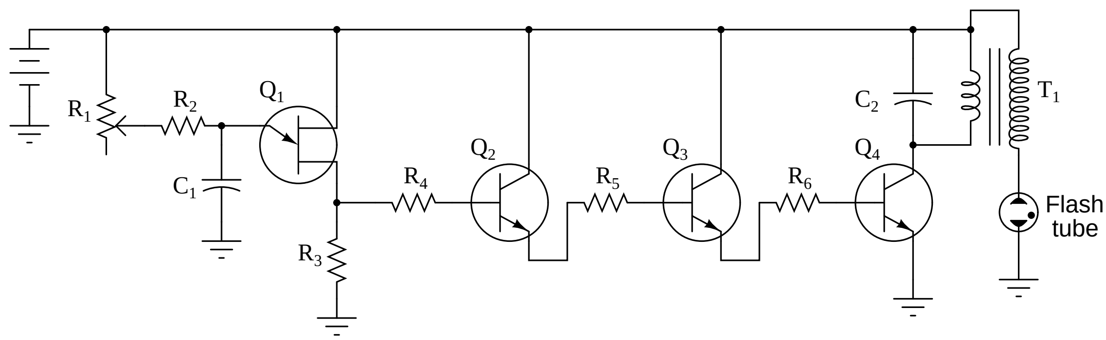
- Capacitor C_1 fails open:
- Capacitor C_1 fails shorted:
- Resistor R_1 fails open:
- Solder bridge (short) past resistor R_1:

Challenges

- Identify at least one more fault that would result in the lamp not blinking, that is not already listed.

6.3.2 Effects of faults in a strobe light circuit

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



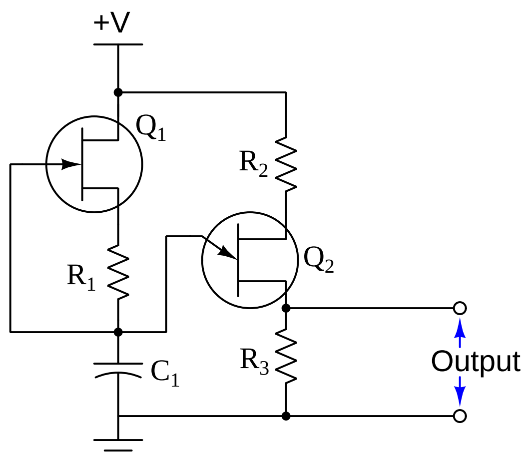
- Capacitor C_1 fails open:
- Capacitor C_1 fails shorted:
- Resistor R_2 fails open:
- Solder bridge (short) past resistor R_2:
- Resistor R_4 fails open:
- Transistor Q_4 fails open (collector-to-emitter):
- Capacitor C_2 fails open:
- Capacitor C_2 fails shorted:

Challenges

- How exactly is a strobe light used to "freeze" the apparent motion of a rotating object?

6.3.3 Effects of faults in a JFET-UJT oscillator

Predict how the operation of this sawtooth-wave oscillator circuit will be affected as a result of the following faults. Consider each fault independently (i.e. one at a time, no multiple faults):



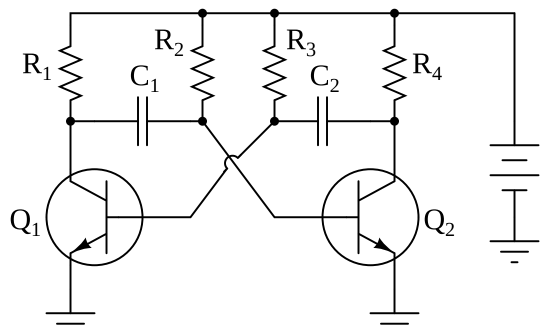
- Capacitor C_1 fails shorted:
- Resistor R_1 fails open:
- JFET fails shorted (drain-to-source):
- Resistor R_3 fails open:

Challenges

- Identify at least two different ways to decrease the frequency of this oscillator.

6.3.4 Effects of faults in astable multivibrator

Predict how the operation of this astable multivibrator circuit will be affected as a result of the following faults. Specifically, identify the final states of the transistors (on or off) resulting from each fault. Consider each fault independently (i.e. one at a time, no multiple faults):



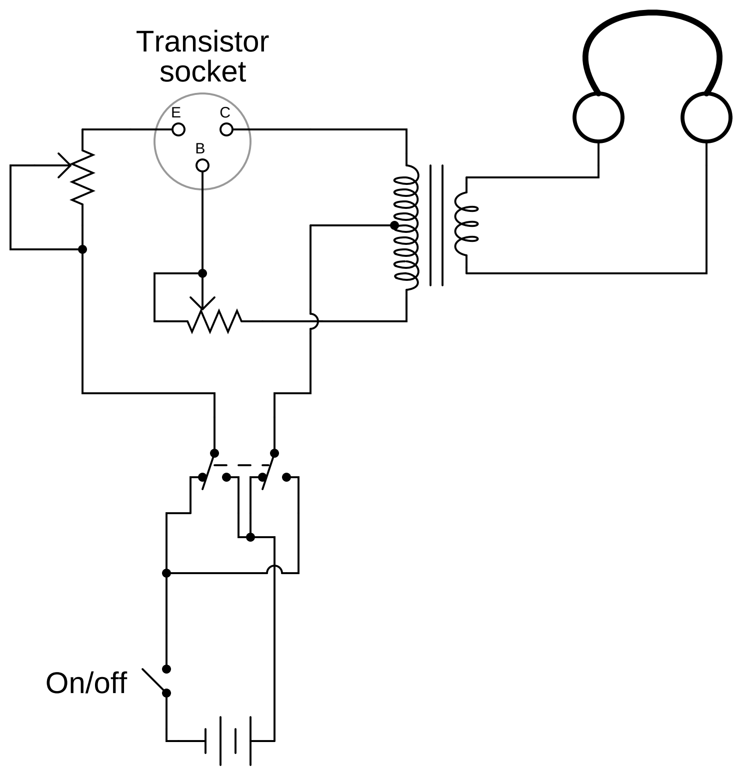
- Capacitor C_1 fails open:
- Capacitor C_2 fails open:
- Resistor R_1 fails open:
- Resistor R_2 fails open:
- Resistor R_3 fails open:
- Resistor R_4 fails open:

Challenges

- An interesting fact about this multivibrator circuit is that it will not oscillate if its two transistors and associated components are all *perfectly* matched. Explain why.

6.3.5 Missing switch label

A technician is given a transistor testing circuit to repair. This simple circuit is an audio-frequency oscillator, and has the following schematic diagram:



After repairing a broken solder joint, the technician notices that the DPDT switch has lost its label. The purpose of this switch is to allow polarity to be reversed so as to test both PNP and NPN transistor types. However, the label showing which direction is for NPN and which direction is for PNP has fallen off. And, to make matters worse, the schematic diagram does not indicate which position is which.

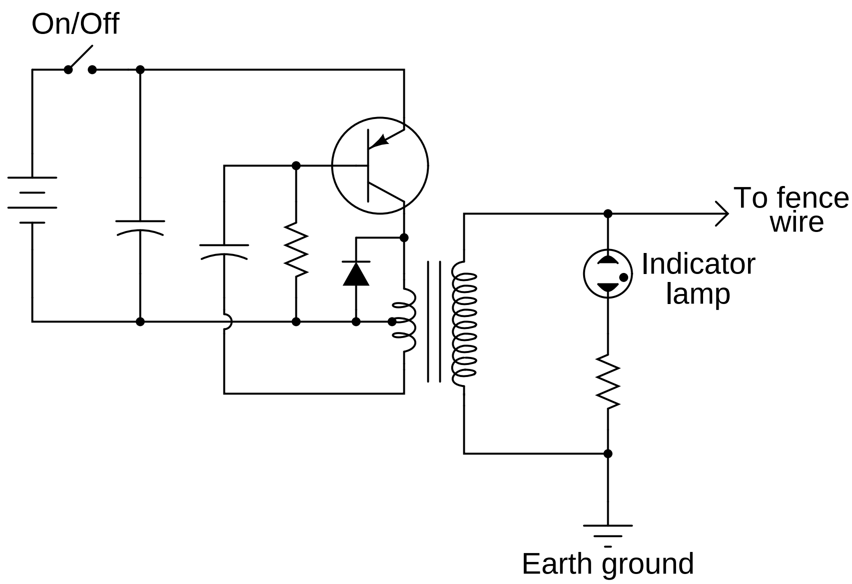
Determine what the proper DPDT switch label should be for this transistor tester, and explain how you know it is correct.

Challenges

- Identify the component factors determining this oscillator's frequency.

6.3.6 Failing electric fence charger circuit

This electric fence-charging circuit, which is designed to produce short, high-voltage pulses on its output, has failed. Now, it produces no output voltage at all:



A technician does some troubleshooting and determines that the transistor is defective. She replaces the transistor, and the circuit begins to work again, its rhythmic output pulses indicated by the neon lamp.

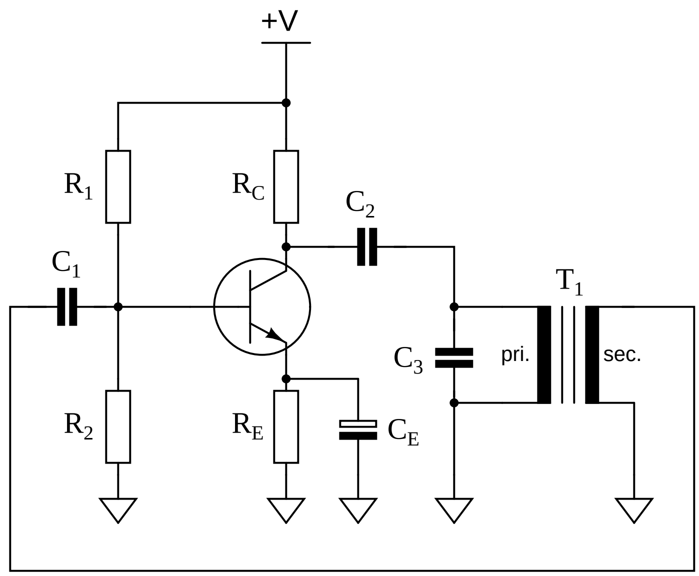
But after producing only a few pulses, the circuit stops working. Puzzled, the technician troubleshoots it again and finds that the transistor has failed (again). Both the original and the replacement transistor were of the correct part number for this circuit, so the failure is not due to an incorrect component being used. Something is causing the transistor to fail prematurely. What do you suppose it is?

Challenges

- Explain why *root-cause analysis* is an important goal in all diagnostic work.

6.3.7 Transformer fault in Armstrong oscillator

Suppose some of the turns of wire (but not all) in the primary winding of the transformer were to fail shorted in this Armstrong oscillator circuit:



How would this effective decreasing of the primary winding turns affect the operation of this circuit?

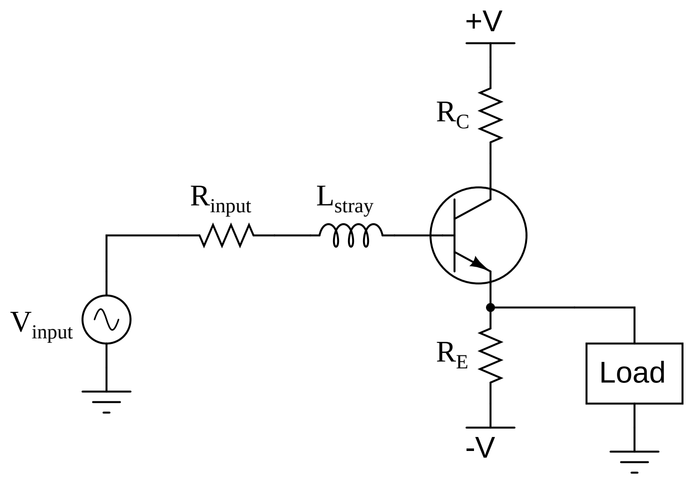
Would the effect(s) be the same or different if it were the secondary winding of the transformer to suffer this fault instead of the primary?

Challenges

- Redesign this circuit to use an NPN instead of a PNP transistor.

6.3.8 Unwanted oscillations

This simple one-transistor voltage amplifier circuit may oscillate if the base-emitter capacitance and load capacitance are sufficient:



Explain how this is possible. You may find it helpful to draw C_{BE} and C_{load} into the diagram.

Challenges

- Identify a design modification to this circuit that will help avoid oscillation even with these parasitic capacitances present in the circuit.

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- 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.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[1] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[2] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[3] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[1]In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[2]Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[3]This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told *again* how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to *require* those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students' thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this "inverted" format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the "inverted" session instructor in order that students never feel discouraged by having their errors exposed. *Everyone* makes mistakes from time to time, and learning is a lifelong process! Part of the instructor's job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.

To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student's responsibility to do that hard work ultimately limits that student's potential and thereby does real harm.

- It is not only permissible, but encouraged, to answer a student's question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.

- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one's own reasoning.

- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an "Outline and reflections" question as well as a "Foundational concepts" question in the Conceptual reasoning section, to prompt reflective reading.

- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple "Challenges" suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own "Challenges" as they are able, in order to have a multitude of ways ready to probe students' understanding.

- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples.*
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[4] effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge[5] one another.

To high standards of education,

Tony R. Kuphaldt

[4]As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

[5]Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one's life through the improvement of clear and independent thought, literacy, expression, and various practical skills.

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TeX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

4 November 2024 – re-worded one sentence in the Tutorial for better clarity, courtesy of Ron Felix.

17 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors. Also added a footnote on current mirrors prior to the section in which they are thorougly discussed.

22 February 2024 – typographical error correction courtesy of Jacob Stormes.

28 September 2023 – minor clarifying edits made to the Tutorial.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

13 April 2022 – moved Historical Reference on William Hewlett's oscillator design into its own file, and shared this among multiple modules.

24 February 2022 – added more questions to the Introduction chapter, and made minor edits to the Tutorial.

3 November 2021 – minor edits to the Tutorial regarding resonant oscillator circuits, and also some index entries.

30 September 2021 – added some comments in the "Phase-shift oscillators" section of the Tutorial discussing the frequency of a Wein bridge oscillator, and how that formula resembles the cutoff frequency formula for a simple RC filter network.

6 September 2021 – edits made to the "Phase-shift oscillators" section of the Tutorial for the benefit of readers who have not yet studied operational amplifiers.

10-11 May 2021 – commented out or deleted empty chapters. Also added more commentary to the Case Tutorial example showing the square/triangle/PWM oscillator circuit.

3 May 2021 – minor edits to the Tutorial commenting on the explosion hazards of legacy arc converters.

29 April 2021 – added another page of text to the Case Tutorial "Example: simple triangle/square/PWM oscillator" explaining how to estimate output frequency based on resistor and capacitor values.

26 March 2021 – added content to the Tutorial about integrated crystal oscillator circuits.

18 March 2021 – corrected multiple instances of "volts" that should have been capitalized "Volts".

6 December 2020 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions. Also added some commentary in the "Negative resistance oscillators" section of the Tutorial on arc oscillator circuits.

26 November 2020 – added commentary in the Tutorial about self-oscillation in amplifier circuits, and also the Barkhausen criterion.

17 November 2020 – added Case Tutorial chapter with section showing simple triangle/square/PWM oscillator circuit.

5 November 2020 – added new Conceptual question on an oscillator circuit based on an opamp and Schmitt-trigger CMOS logic inverters.

26 July 2020 – minor edit to one of the Foundational Concepts.

7 July 2020 – minor edits to some of the oscillator schematic diagrams.

6-7 May 2020 – minor edits to Tutorial and Quantitative Reasoning problems.

26 March 2020 – added oscilloscope screenshots for the simple triangle-wave oscillator circuit based on a 555 timer and a JFET current regulator.

25 March 2020 – added Conceptual Reasoning problem showing a simple triangle-wave oscillator circuit based on a 555 timer and a JFET current regulator.

3 February 2020 – continued writing Tutorial chapter.

1 February 2020 – continued writing Tutorial chapter.

31 January 2020 – continued writing Tutorial chapter.

22 January 2020 – begin writing Historical Reference on William Hewlett's lamp-stabilized oscillator.

21 January 2020 – began writing Introduction and Tutorial chapters.

15 January 2020 – continued adding questions.

14 January 2020 – added questions.

13 January 2020 – document first created.

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