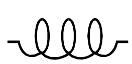
The Big Idea

Modern circuitry depends on much more than just resistors and capacitors. The circuits in your computer, cell phone, Ipod depend on circuit elements called diodes, inductors, transistors, operational amplifiers and other chips. In particular the invention of the transistor made the small size of modern devices possible. Transistors and op amps are know as *active* circuit elements. An active circuit element needs an external source of power to operate. This differentiates them from diodes, capacitors, inductors and resistors, which are *passive* elements.

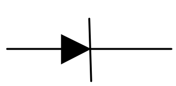
Key Concepts

- *Inductors* are made from coiled wires, normally wrapped around ferromagnetic material and operate according to the principles of magnetic induction presented in Chapter 14. Inductors generate a *back-emf*. Back-emf is essentially an induced negative voltage which opposes changes in current. The amount of back-emf generated is proportional to how quickly the current changes. They can be thought of as automatic flow regulators that oppose any change in current. Thus electrical engineers call them *chokes*.



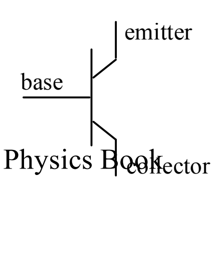
In a circuit diagram, an inductor looks like a coil. The resistance R and capacitance C of an inductor are very close to zero. When analyzing a circuit diagram, assume R and C are precisely zero.

- *Diodes* are passive circuit elements that act like one-way gates. Diodes allow current to flow one way, but not the other. For example, a diode that "turns on" at 0.6 V acts as follows: if the voltage drop across the diode is less than 0.6 V, no current will flow. Above 0.6 V, of current flows with essentially no resistance. If the voltage drop is negative (and not extremely large), no current will flow.



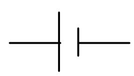
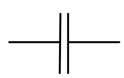
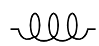
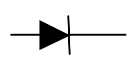
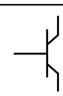
Diodes have an arrow showing the direction of the flow.

- *Transistors* are active circuit elements that act like control gates for the flow of current. Although there are many types of transistors, let's consider just one kind for now. This type of transistor has three electrical leads: the base, the emitter, and the collector.

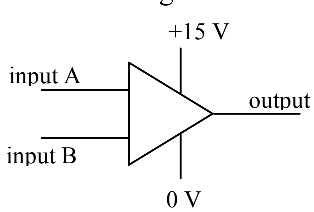


The voltage applied to the base controls the amount of current which flows from the emitter to the collector.

- For example, if the base voltage is more than 0.8 V above the collector voltage, then current can freely flow from the emitter to the collector, as if it were just a wire. If the base voltage is less than 0.8 V above the collector voltage, then current does not flow from the emitter to the collector. Thus the transistor acts as a switch. (This 0.8 V is known as a "diode drop" and varies from transistor to transistor.)
- Transistors have an infinite *output resistance.* If you measure the resistance between the collector and the base (or between the emitter and the base), it will be extremely high. Essentially no current flows into the base from either the collector or the emitter; any current, if it flows, flows from the emitter to the collector..
- Transistors are used in *amplifier* circuits, which take an input voltage and magnify it by a large factor. Amplifiers typically run on the principle of positive and negative *feedback*. Feedback occurs when a small portion of an output voltage is used to influence the input voltage.

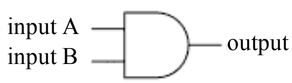
Circuit element	*Symbol*	*Electrical symbol*	*Unit*	*Everyday device*
Voltage Source	□**V**		Volts (V)	Batteries, electrical outlets, power stations
Resistor	**R**		Ohm (Ω)	Light bulbs, toasters, hair dryers
Capacitor	**C**		Farad (F)	Computer keyboards, timers
Inductor	**L**		Henry (H)	Electronic chokes, AC transformers
Diode	varies by type		none	Light-emitting diodes (LEDs)
Transistor	varies by type		none	Computer chips, amplifiers

- An *operational amplifier* or op-amp is an active circuit element that performs a specific function. The most common op-amp has five leads: two input leads, one output lead, and two fixed-voltage leads.



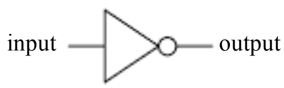
The job of an op-amp is to use the voltage it is supplied to adjust its output voltage. The op-amp will adjust its output voltage until the two input voltages are brought closer together. In other words, the output voltage will change as it needs to until $V_A - V_B = 0$. This won't happen unless the output voltage is somehow "fed back" into one of the inputs.

- *Digital circuits* only care about two voltages: for example, +5 V (known as "on") and 0 V (known as "off"). *Logic devices,* which are active circuit elements, interpret voltages according to a simple set of mathematical rules known as Boolean logic. The most basic logic devices are the AND, OR, and NOT gates:



For an AND gate, the output will always be at an electric potential of 0 V (off) unless *both* the inputs are at 5 V (on), in which case the output will be at 5 V (on) as well.

For an OR gate, the output will always be at an electric potential of 0 V (off) unless *either* of the inputs are at 5 V (on), in which case the output will be at 5 V (on) as well.



For a NOT gate, the output will always be the *opposite* of the input. Thus, if the input is 5 V (on), the output will be 0 V (off) and vice-versa.

- *Alternating current* changes direction of current flow. The frequency is the number of times the current reverses direction in a second. Household AC is 60 Hz. In AC circuits the current is impeded but not stopped by elements like capacitors and inductors.
- *Capacitive Reactance* is a measure of how a capacitor impedes the current flow from a given voltage in an AC circuit and is inversely proportional to capacitance. *Inductive Reactance* is a measure of how an inductor in an AC circuit impedes the current flow from a given voltage and is directly proportional to inductance.
- *The total impedance of an AC circuit* depends on resitance, capacitive reactance and inductive reactance.
- If the capacitive reactance and inductive reactance are both zero or unequal the voltage and current are *out of phase.* That is they peak at different times in the cycle. The *phase angle* measures the lag or lead of current over voltage.

Key Equations

- $Emf = -L(\square I/\square t)$; the emf across an inductor is proportional to the rate of change of the current through it; the emf is negative, meaning that it opposes current flow.
- $L = \square_0 N^2 A/\ell$; the inductance of a solenoid depends on the number of turns in the solenoid, the cross-sectional area, and the length; the *SI* unit of inductance is the Henry (H).
- $X_L = \square f$; the inductive reactance equals the inductance times ω where $\omega = 2\pi f$
- $X_C = 1/\square C$; the capacitive reactance is the reciprocal of ωC
- $Z = \sqrt{R^2 + (X_L - X_C)^2}$; the impedance of an AC circuit is given by the Pythagorean Theorem, when R and $X_L - X_C$ are plotted on opposite axes.
- $V_m = I_m Z$; Ohm's Law for AC circuits; relating the peak voltages and currents
- $\tan\square = X_L - X_C / R$; formula for the phase angle between peak currents and voltages

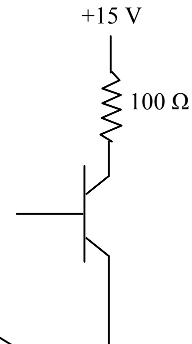
Advanced Topics Problem Set

1. You purchase a circular solenoid with 100 turns, a radius of 0.5 cm, and a length of 2.0 cm.

   a. Calculate the inductance of your solenoid in Henrys.
   b. A current of 0.5 A is passing through your solenoid. The current is turned down to zero over the course of 0.25 seconds. What voltage is induced in the solenoid?

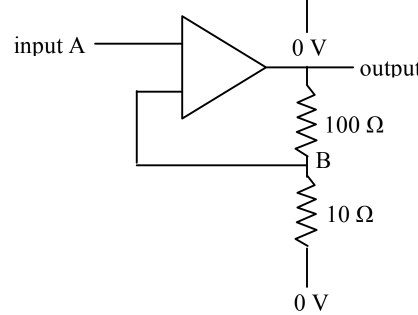
2. What is the voltage drop across an inductor if the current passing through it is not changing with time? Does your answer depend on the physical makeup of the inductor? Explain.

3. Consider the transistor circuit diagram shown here. The resistor is a light bulb that shines when current passes through it.



   a. If the base is raised to a voltage of 5 V, will the light bulb shine?
   b. If the base is lowered to a voltage of 0 V, will the light bulb shine?
   c. Why are transistors sometimes called electronic switches?

4. Consider the op-amp circuit diagram shown here. Note the fixed-voltage leads are omitted for clarity. (This is typical.)



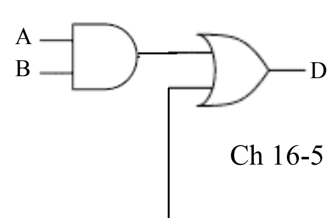
   Let's begin with an input voltage at point A of 0.5 V.

   a. If the op-amp is "doing its job," what is the electric potential at point B?
   b. What current is flowing through the 10 Ω resistor?
   c. Recall that no current ever flows *into* an op-amp. What current must be flowing through the 100 Ω resistor?
   d. What *must* the output voltage be?

   Now let's adjust the input voltage at point A to 0.75 V.

   e. What is the output voltage now?
   f. By what factor is the op-amp amplifying the input voltage?
   g. What are some practical applications for such a device?

5. Consider the logic circuit shown here.



a. If A, B, and C are all off, what is the state of D?
b. If A, B, and C are all on, what is the state of D?
c. Fill out the entire "logic table" for this circuit.

State of A	*State of B*	*State of C*	*State of D*
on	on	on	
on	on	off	
on	off	on	
on	off	off	
off	on	on	
off	off	on	
off	on	off	
off	off	off	

6. A series circuit contains the following elements: a 125 Ω resistor, a 175 mH inductor, two 30.0 μF capacitors and a 40.0 μF capacitor. Voltage is provided by a 235 V_m generator operating at 75.0 Hz.

a. Draw a schematic diagram of the circuit.
b. Calculate the total capacitance of the circuit.
c. Calculate the capacitive reactance.
d. Calculate the impedance.
e. Calculate the peak current.
f. Calculate the phase angle.
g. Resonance occurs at the frequency when peak current is maximized. What is that frequency?