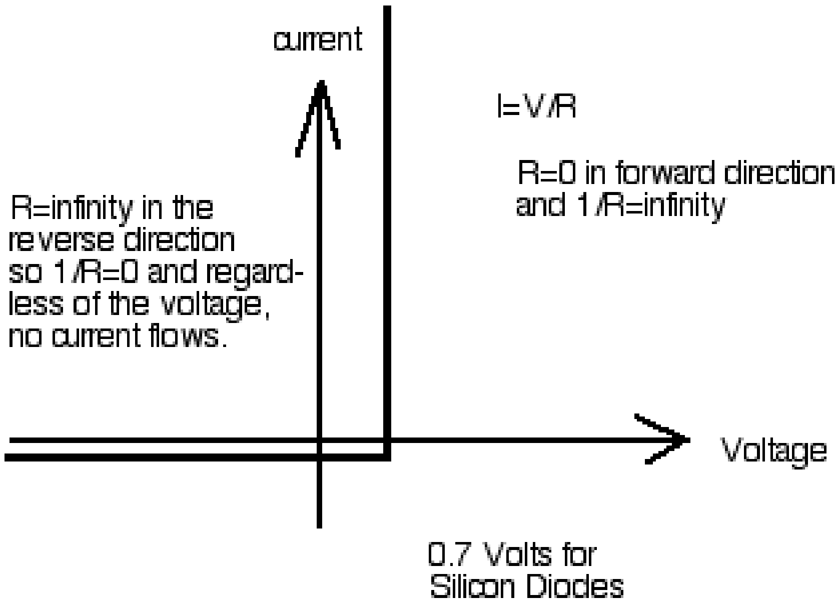
13. Diode Rectifiers, Filters, and Power Supplies

Introduction

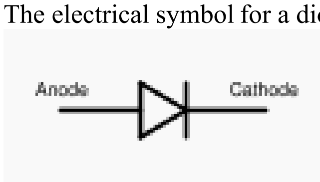
A power supply takes Alternating Current or A.C. power from your electric utility (Con Edison) and converts the A.C. electrical current into D.C. or Direct Current. Power supplies have several componets which are at first understood separatly and then they are joined together. First the transformer converts the A.C. from Con Edison into a lower or higher voltage and we have already had some experience using transformers. Next solid state diode are used to convert the A.C. from the transformer into D.C. albeit not with a constant voltage. At least after the power has gone through the diode rectifiers, the electric current is of only one sign either positive or negative. Next the fluctuating electric current is smoothed with a filter usually made of a resistor and capacitor. The resistor and capacitor act as alow pass filter and the high frequency electric current is blocked. Finally some more smoothing is done with a voltage regulator.

The Solid State Diode

The theory of the operation of the solid state diode is a bit complicated but we will just describe the solid state diode from an operations point of view. (By the way, there are two kinds of diodes: solid state and vacuum tube. We will only used solid state diodes so it will be understood that this is what is meant by the term diode.) The state diode is a device that doesnot obey ohm's law V=IR. If a voltage is applied to a diode in what is called the "forward direction" then electrical current flows easily in the circuit. (By the way, the forward direction is indicated by an arrow on the diode or sometimes a band is placed on one end of the diode in the forward direction.) When the diode is connected in the forward direction, there is only a small voltage drop across the diode of 0.7 volts is the diode is made of silicon. This voltage drop is independent of the size of the current in the circuit (and Ohm's law is not obeyed.) When a voltage is applied in the "reverse direction" across a diode then no current flows and again this is a non-Ohmic behavior. A graph of the voltage across the diode versus the current through it appears below:



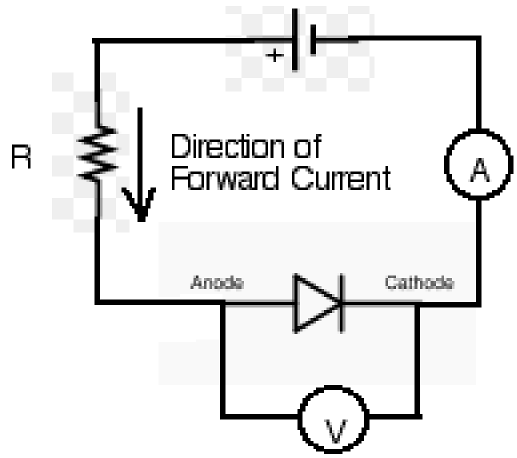
The electrical symbol for a diode is



and the arrow is in the forward direction which has a low resistance. Sometimes on the physical diode, all you see is a band and this represents the bar in the above symbol.

Laboratory Experiments for You

Identify a diode in you parts box and connect it in a circuit with a DC current supply and a resistor R so your circuit should look something like this:



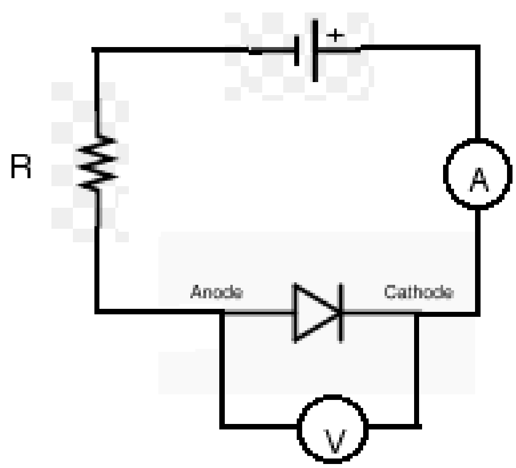
Notice the diode and battery are connected so the current flows in the forward direction. Choose a resistor R=5,000 Ω or so the current is relatively small when the battery voltage is V=12 volts. The current in this case is

```
V = 12.; R = 5000.;
```

$$\mathbf{I0} = \frac{\mathbf{V}}{\mathbf{R}}$$

```
0.0024
```

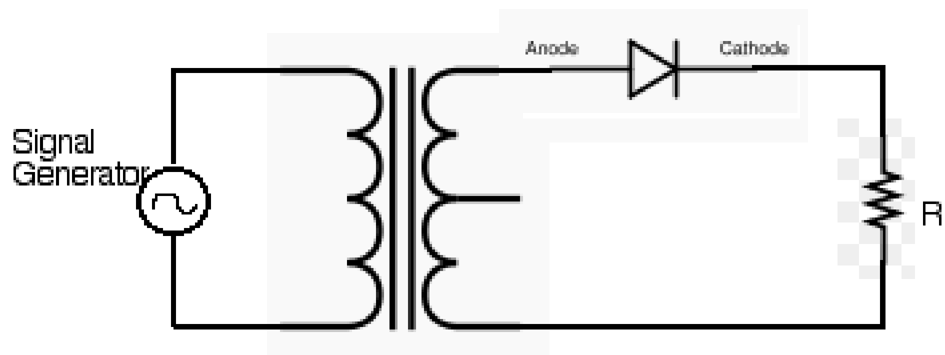
or I0=2.4 milliamps. Measure the voltage across the diode and make sure it is about 0.7 volts. Next change the direction of the battery or DC power supply as indicated below:



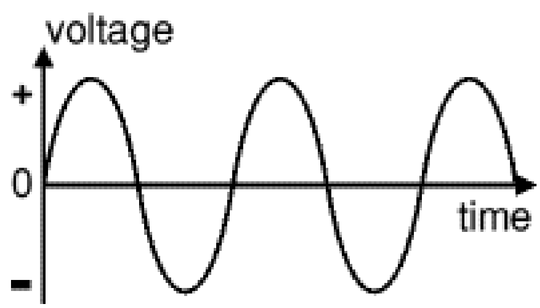
The battery would like the current to flow clockwise in the circuit and the current would do so if there were no diode in the circuit and a plain wire were in it stead. However, there is in fact a diode in the circuit and since it is in the "reverse direction" no current should flow. Check to make sure I0=0 in this case. Also, measure the voltage across the diode which should be zero also.

A Diode Connected to A.C.: Half-Wave Power Supply

The above two circuits would never appear in an actual circuit since for one thing the power source is DC and a major role of diodes is to convert AC into DC. Connect your transformer to you signal generator in the Sine wave mode at about 100 Hz and 5 volts as indicated below:

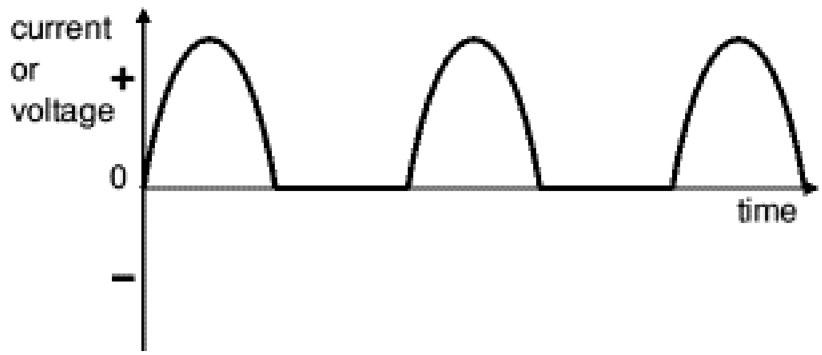


You can use your transformer in a voltage stepup mode. Again use a resistor something like R=5,000 Ω to make the current in the milliampere range. Connect channel #1 of your oscilloscope across the secondary of the transformer and you should see something like the diagram below:



Notice the shape of the Sine wave you measure in channel #1. The frequency should be the same as the signal generator and make sure you understand the amplitude of the voltage you measure across the secondary of the transformer in terms of the turns ratio of the transformer and the amplitude of the input voltage applied to the primary.

Connect channel #2 of your oscilloscope across the resistor and you should see something like the diagram below:



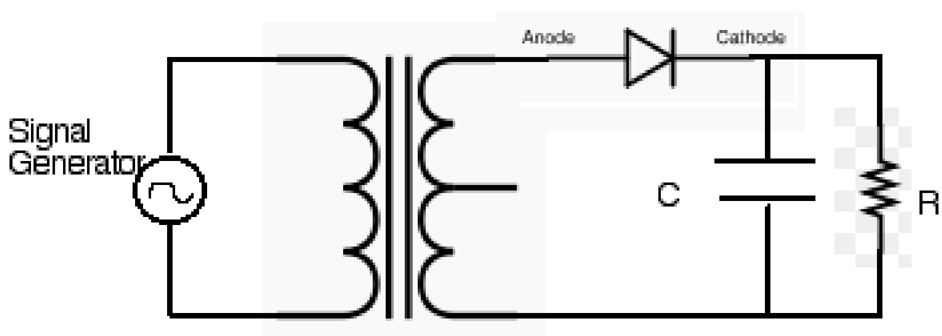
Notice that the current or voltage across the resistor is only in one direction (called positive). Only half of the original wave appears across the resistor and this kind of power supply is called a Half Wave Power Supply.

Compare the amplitude of the voltage across the resistor to the amplitude of the voltage across the secondary of the transformer. Are these amplitudes the same? What is the frequency of the voltage across the resistor? Is it the same as the frequency of the signal generator?

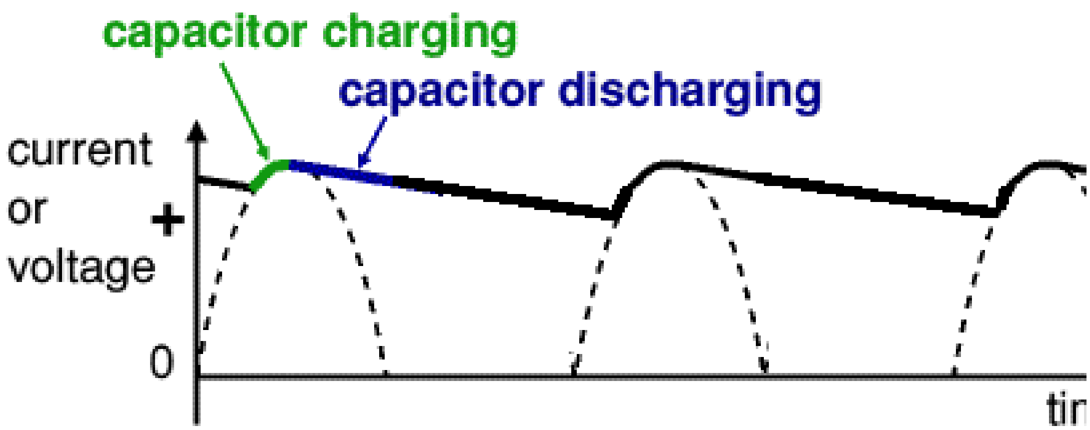
Reverse the direction of the diode in the above circuit. What happens to the voltage you measure with channel #2 across the resistor?

A RC Filter to Smooth the Output of the Power Supply

Next add a capacitor to the power supply circuit above obtaining



The purpose of the capacitor is to smooth the output voltage (and current) of the power supply. If you choose the proper value for the capacitor C, then the voltage (and current) across the resistor should appear aas below:



The frequency of the signal generator should be something like f=100 Hz so the corresponding period T=1/f is

```
f = 100.;
T = 1 / f
```

```
0.01
```

which is a period of 10 milliseconds. You should design your power supply filter so T is also about the decay time τ=RC of your the resistor R and capacitor in your circuit. Actually in one time constant, the voltage will decay e^{-1} of the original value. If you want the voltage to fall less than this (say $e^{-0.5}$) you should calculate the time from T/τ=0.5 or τ = T/0.5 = 2T. Again τ=RC so eliminating τ between these two equations we get

```
R = 5000.;
T = 0.01;
C0 = 2 * T / R
```

$4. \times 10^{-6}$

So you should pick your capacitor C= 4μF to get this degree of filtering.

Experiments You Should Do

Build a circuit like that above. You may use different values of R and C as well as V_0 the amplitude of the voltage on the transformer secondary. However make sure your R is not too small as the currents should be in the milliampere range in order to not overload the signal generator. Do not add the diode yet Record the voltage on the primary and the turns ratio of the transformer and make sure you understand how these things aree relataed.

Sketch the voltage across the resistor before adding the capacitor. Indicate the amplitude fo this voltage and the period. Again set the signal generator at about 100 Hz. Add the diode and sketch the voltage across the resistor once again. Next add the capacitor and sketch the voltage across the resistor indicating the period and the amplitude.

The "ripple voltage" is the variation of the voltage across the resistor even though the diode and capacitor are present. How big is the ripple voltage across the capacitor? Does making the capacitor bigger or smaller make the amplitude of the ripple voltage smaller?

The Ripple Voltage

The voltage across a resistor in an RC circuit where the capacitor has been initially charged to a voltage V_0 is

$$V[t] = V_0 \left(1 - e^{-\frac{t}{\tau}}\right) \tag{1}$$

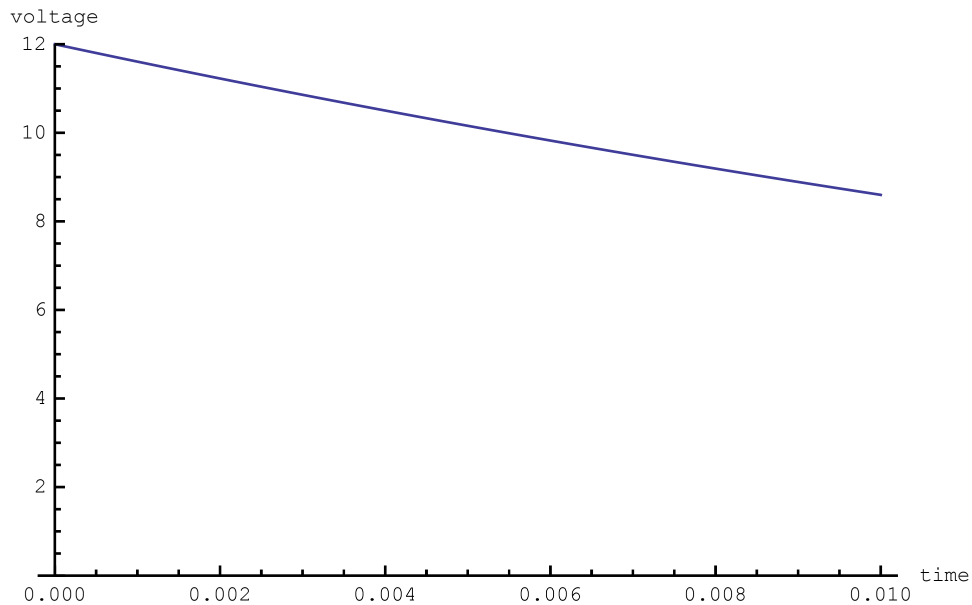
For example, using

```
Clear[V];
R = 5000.;
C0 = 4 * 10^-6;
V0 = 12.;
Print["Time Constant ", τ = R * C0]
Print["The period is ", T]
V[t_] := V0 * e^(-t/τ)
```

```
Time Constant 0.02

The period is 0.01
```

The voltage across the resistor in one period is

```
Plot[V[t], {t, 0, T}, AxesLabel → {"time", "voltage"}, PlotRange → {0, V0}]
```



The ripple voltage in one time constant τ is

```
V0 - 8.
```

```
4.
```

and the percent ripple is

$$\frac{V0 - 8.}{V0}$$

```
0.333333
```

or 33% which is huge. You can decrease the ripple by making the time constant longer. Remember we picked the value of C so that the time constant would be twice the period. Suppose you make the capacitor so the time constant is three times the period:

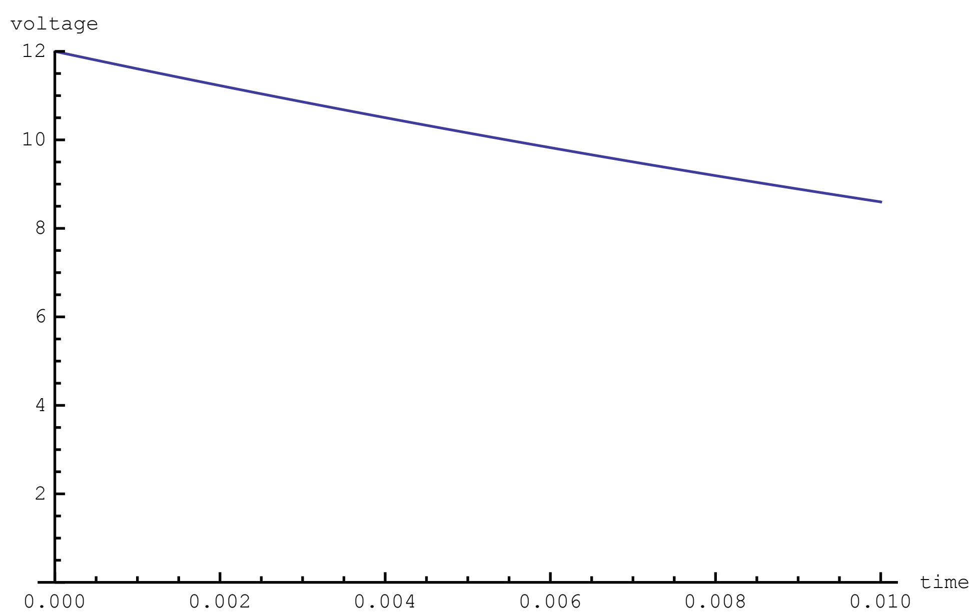
```
f = 100.;
T = 1 / f;
τ = 3 * T;
R = 5000.;
V0 = 12.;
Print["Time Constant ", τ]
Print["The period is ", T]
Print["The capacitor is  ", C0 = τ / R];
V[t_] := V0 * ⅇ^(-t/τ) // N
```

```
Time Constant 0.03

The period is 0.01

The capacitor is  6. × 10^-6
```

So now the capacitor is 6 μF which is larger than before. The voltage across the resistor in one time constant is

The voltage across the resistor in one period is

```
Plot[Tooltip[V[t]], {t, 0, T},
 AxesLabel → {"time", "voltage"}, PlotRange → {0, V0}]
```



The ripple voltage in one time constant τ is

```
V[T]
```

```
8.59838
```

```
V0 - 8.6
```

```
3.4
```

and the percent ripple is

$$\frac{V0 - 8.6}{V0}$$

```
0.283333
```

The percent ripple is given by

$$r = \frac{V_0 - V_0\, e^{-\frac{T}{\tau}}}{V_0} = 1 - e^{-\frac{T}{\tau}} \cong 1 - \left(1 - \frac{T}{\tau}\right) = \frac{T}{\tau} \tag{2}$$

Remember that τ=RC so solving for the capacitor necessary for a certain ripple percent we obtain

$$r = \frac{T}{RC} \quad \text{and} \quad C = \frac{T}{rR} \tag{3}$$

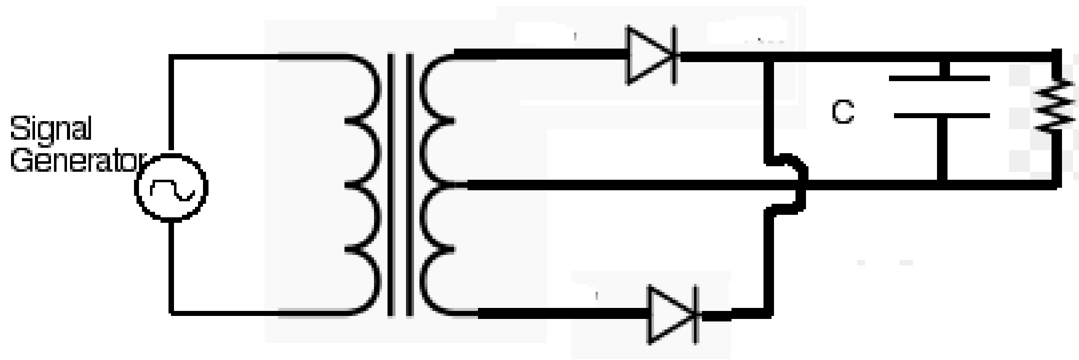
So for example, if you want a small ripple r, you can increase C.

Laboratory Experiment

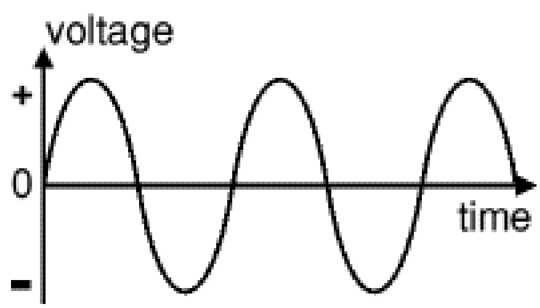
So increasing C had the effect of decreasing the percent ripple. Determine C so that the ripple is 1%. Check your calculation by using this new C in your circuit and measure the percent ripple voltage across the resistor.

Full Wave Rectifier Circuit

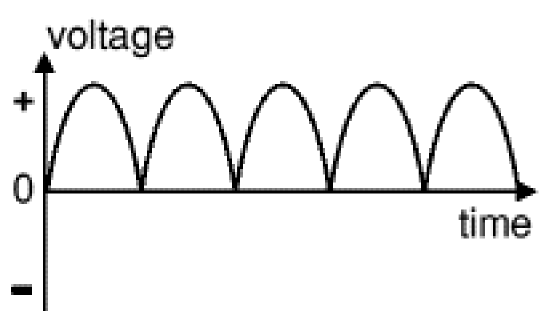
You can use two diodes in a circuit that will rectify on both half waves of the AC. See below:



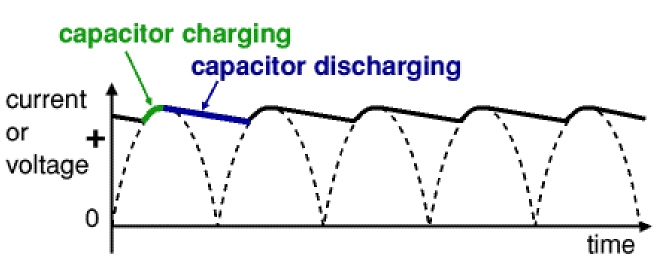
The input AC voltage is as before



but now the diodes conduct on both half waves and the output voltage across the resistor appears (if the capacitor C is not present)



If you add the capacitor back in for smoothing you obtain as output voltage across the resistor



Note the effective period is now T/2 so the ripple percent is given by

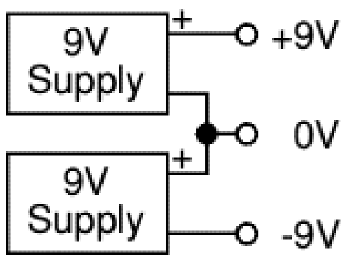
$$r = \frac{T/2}{RC} \quad \text{and} \quad C = \frac{T}{2\,rR} \quad \text{Full Wave Rectifier} \tag{4}$$

Laboratory Exercise

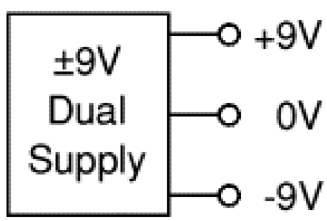
Construct a full wave rectifier and measure the output voltage and percent ripple. Make sure you understand that the percent ripple is half the size of the ripple for the half wave rectifier for the same R and C.

Dual Power Supplies

Some circuit like transistor amplifiers require a power supply with both negative and positive voltagees output. This kind of power supply is called "dual supply" because it is like two ordinary supplies connected together as indicated below:



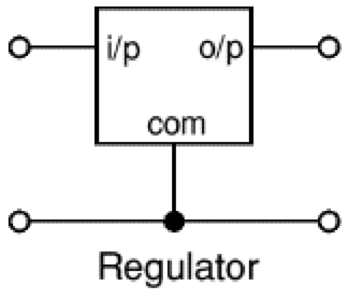
What you actually see is a power supply with three output terminals as indicated by the diagram below:



Here the three output terminals are +9 volts, 0 volts, and -9 volts. The 0 volt terminal is not necessarily grounded.

Voltage Regulators

You can add a final component called a "regulator" to your power supply after the filter. This provides an output at a voltage specified by the manufacturer say 5 volts. The regulator is an integrated circuit and the symbol for the regulator is



The bottom lead is common to both the input and output to the regulator. The i/p terminal is connectd to the filter of the power supply and the regulated output appears at 0/p. The actual regulator can appear as below

Typically voltage regulators are available as 5, 12, and 15 volts or even variable output voltages. Some regulators keep the output current fixed.