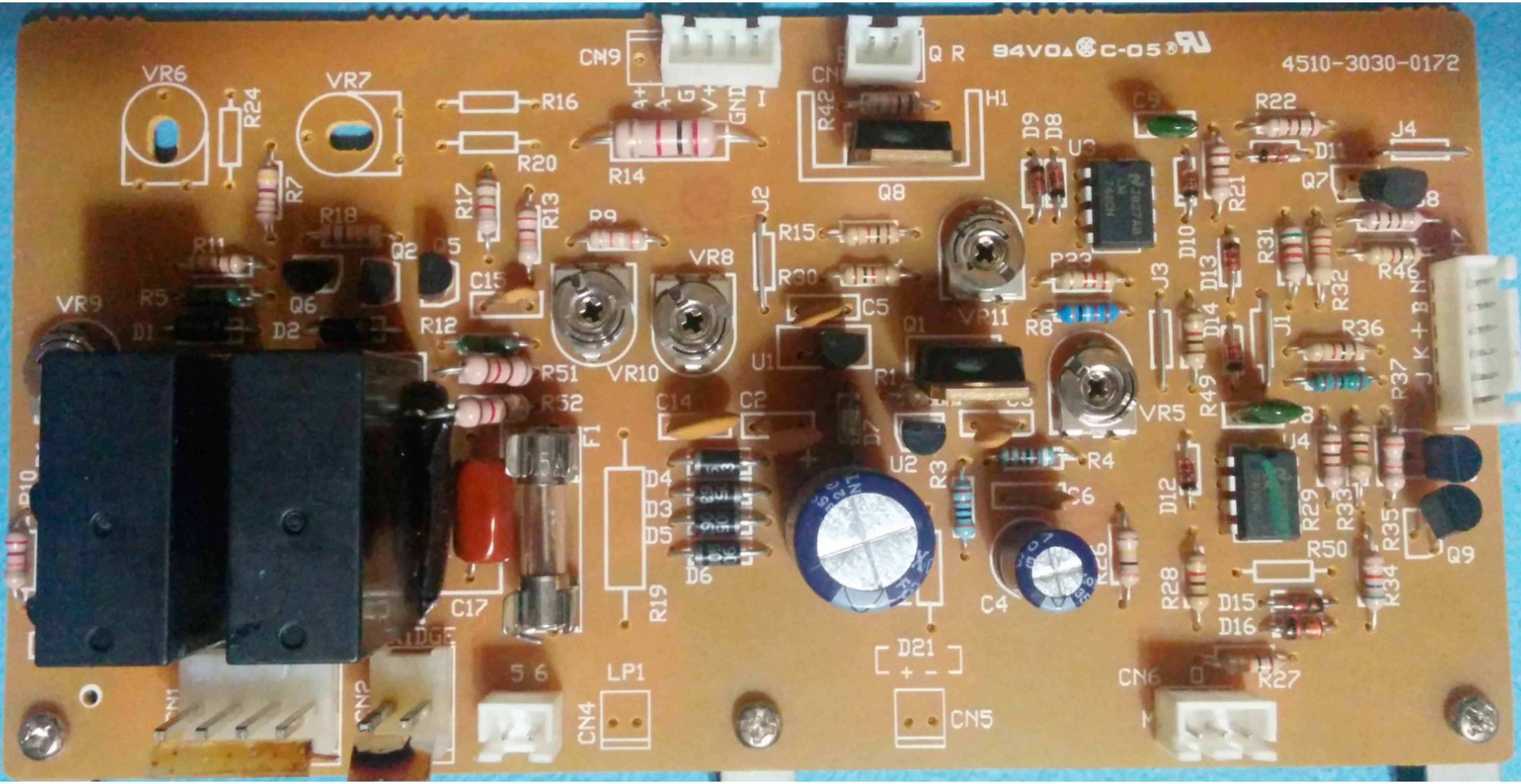
PHYS127AL Lecture 4

David Stuart, UC Santa Barbara

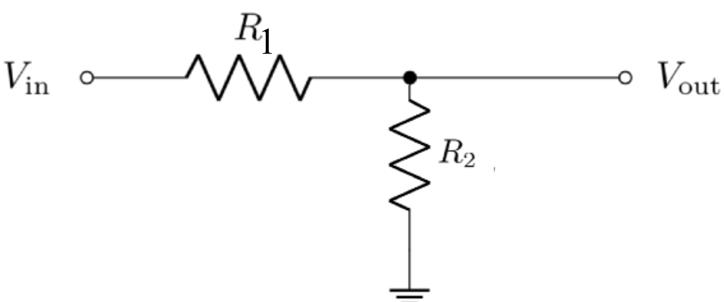
Transformers and diodes

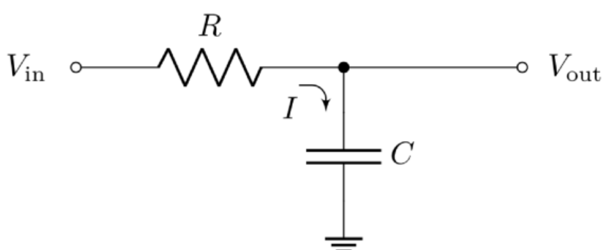


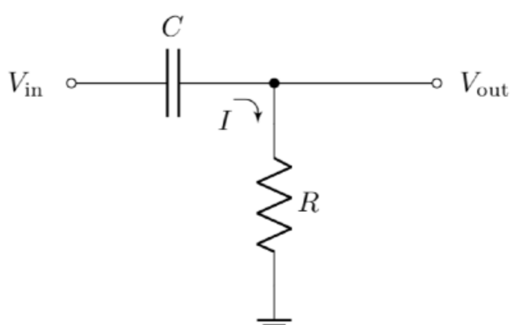
Review

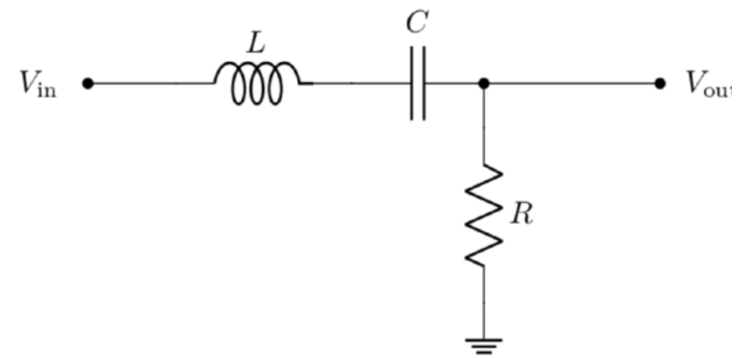
Review

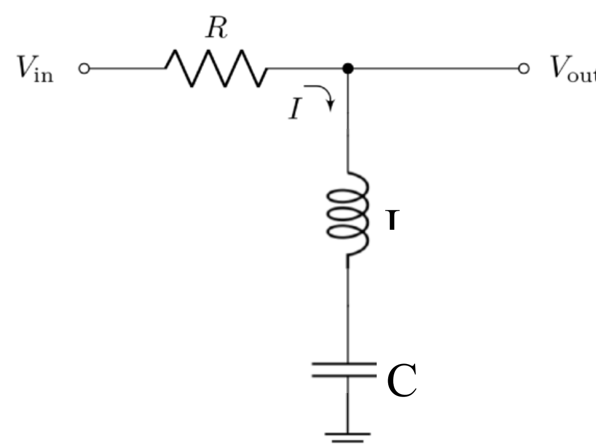
$$V = IR \Rightarrow \tilde{V} = \tilde{I}\tilde{X}$$

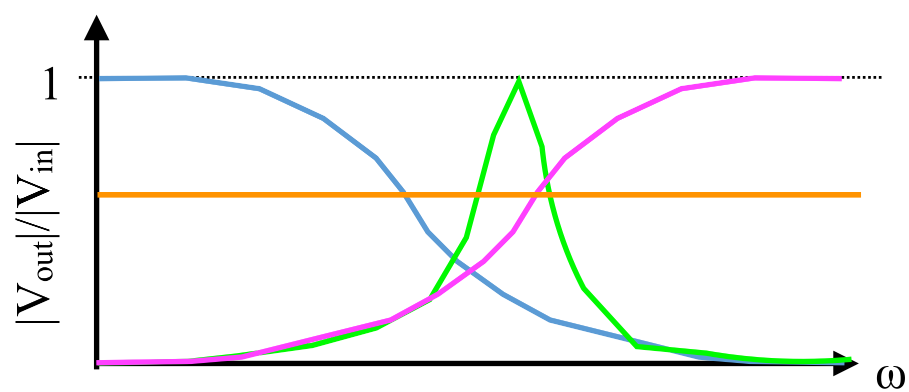












Outline

Transformers

Diode introduction

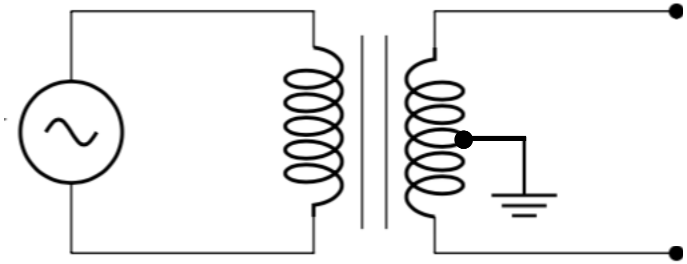
Solid-state physics view of semi-conductors

Diode circuits

DC Power supply

Transformers

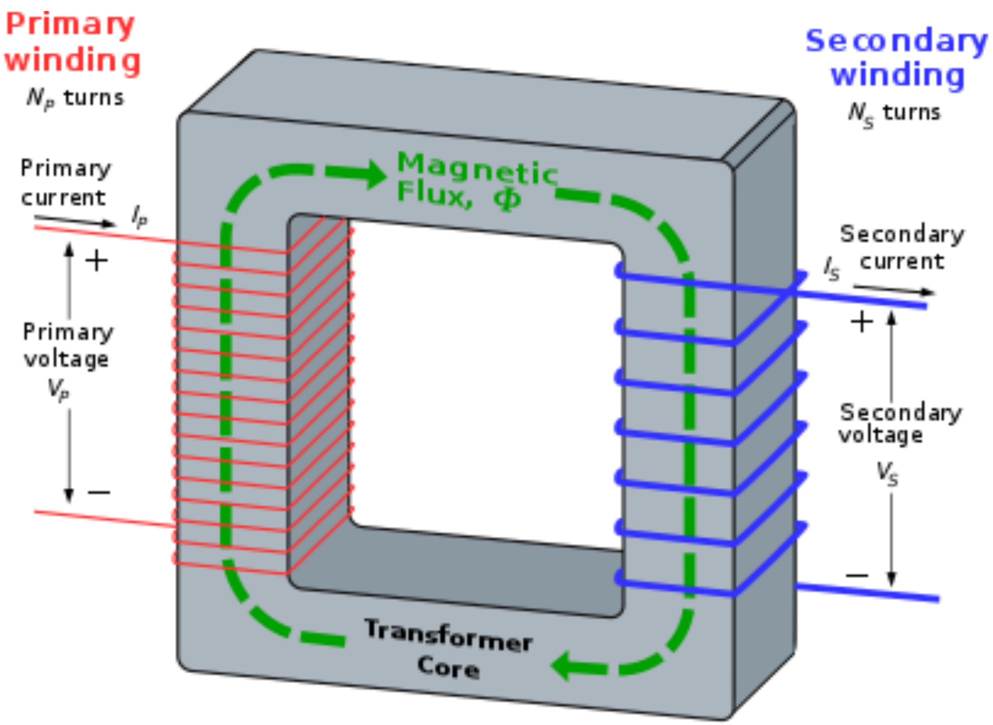
Two loops of wire can have mutual inductance; the common example of that is a transformer.

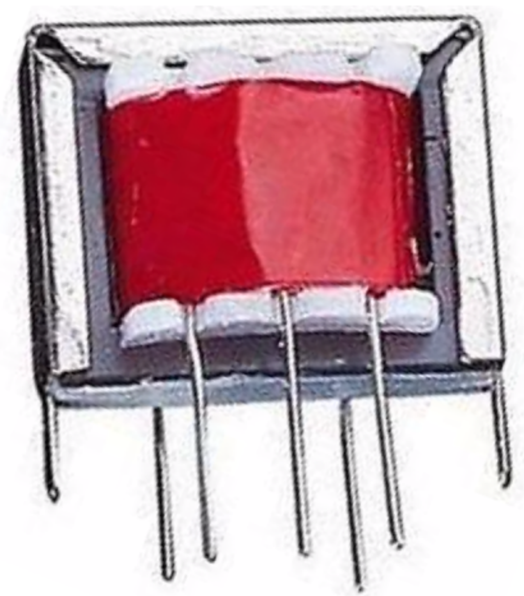


AC power transferred efficiently through B field.

$V_pI_p = V_sI_s$. $V_s/V_p = I_p/I_s = N_s/N_p$

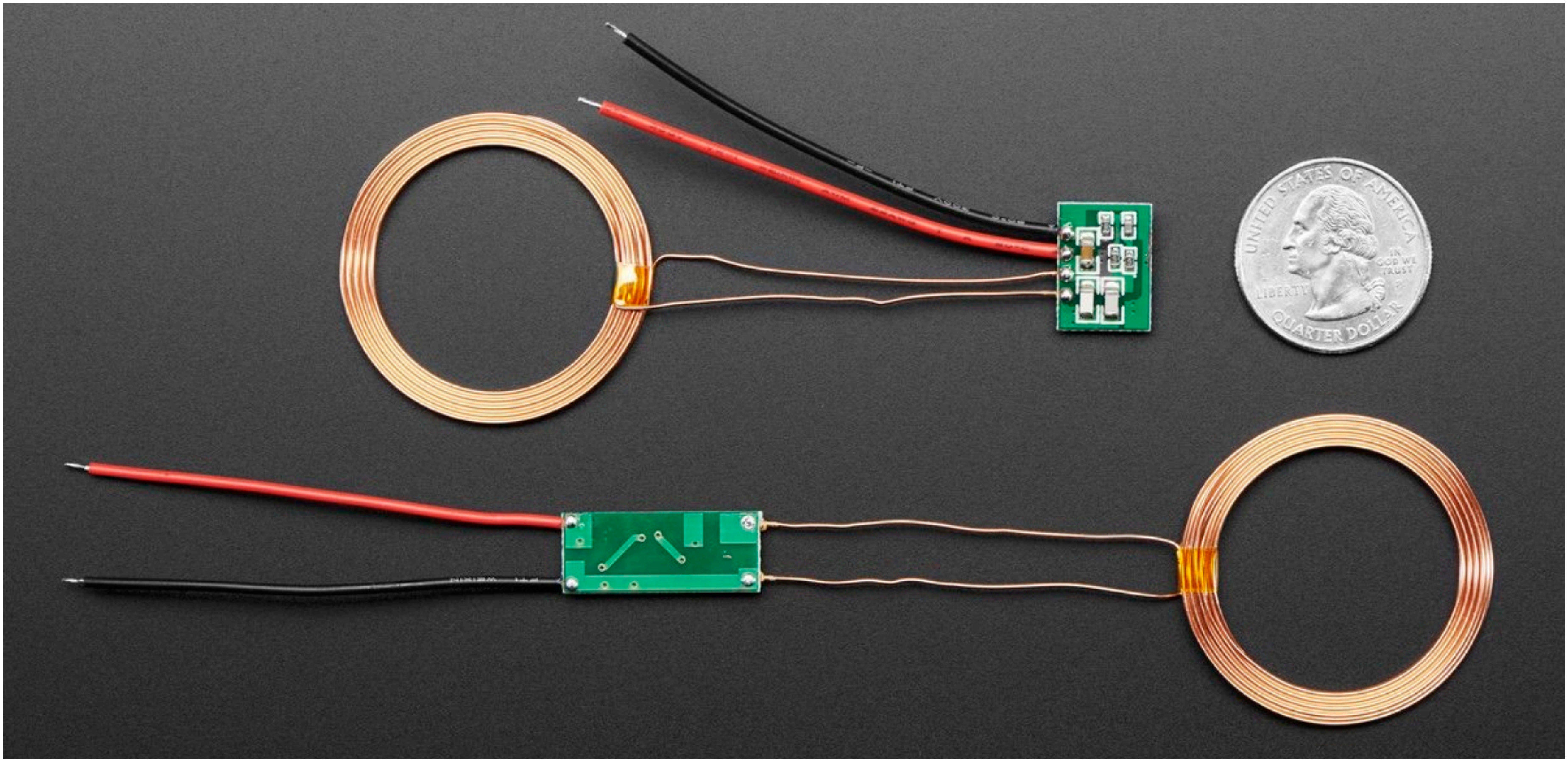
$V_s = V_pN_s/N_p$





Non-contact transformers

Can also have non-contact transformers for inductive charging.



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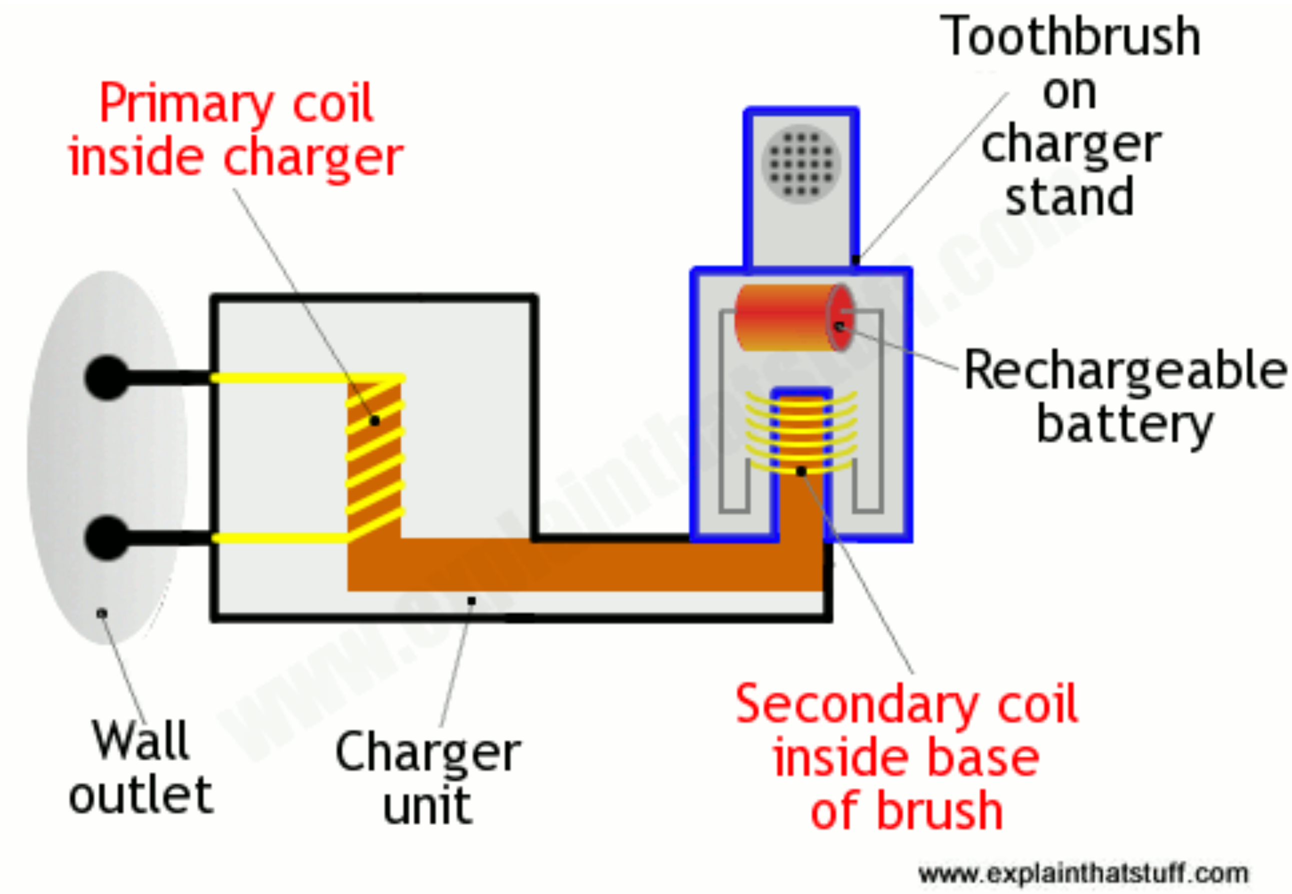
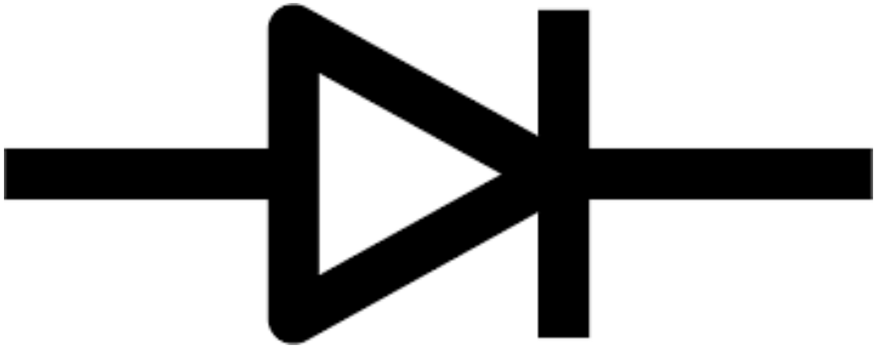


Diodes

A diode is approximately a one-way current valve, where current flows once there is enough voltage to overcome a threshold.

Called a check-valve in plumbing.



There are several ways to make an electronic version.
We'll focus on semiconductor diodes.

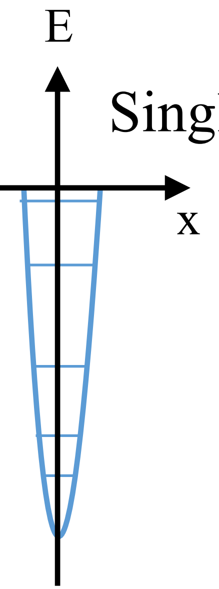
Conduction in metals

Current flows due to free charge carriers.

In copper, each atom contributes its valence electron, which is loosely bound, to a sea of free electrons.

$$I = n\,A\,q\,v_d$$

- v_d: drift velocity
- q: charge per carrier
- A: area of "pipe"
- n: number density of charge carriers



Single-atom energy levels

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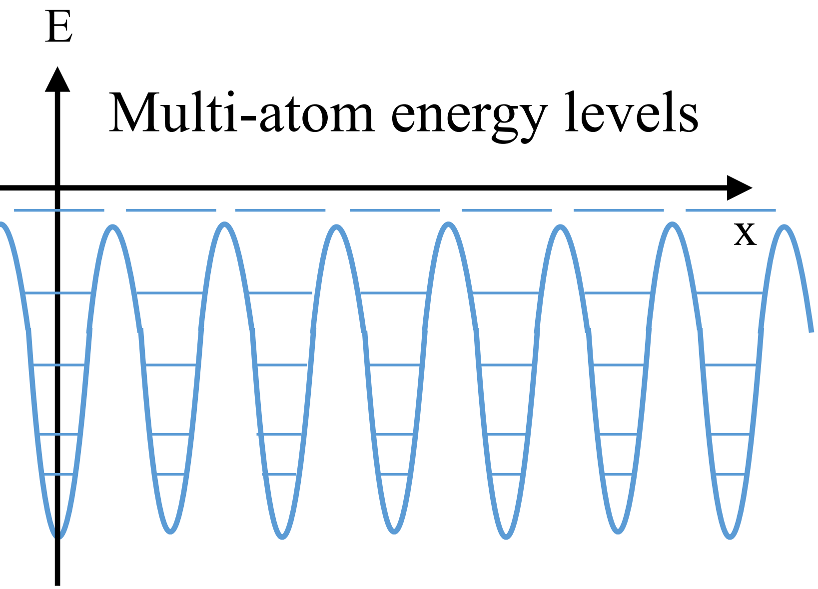

Valence electrons shared across crystal.

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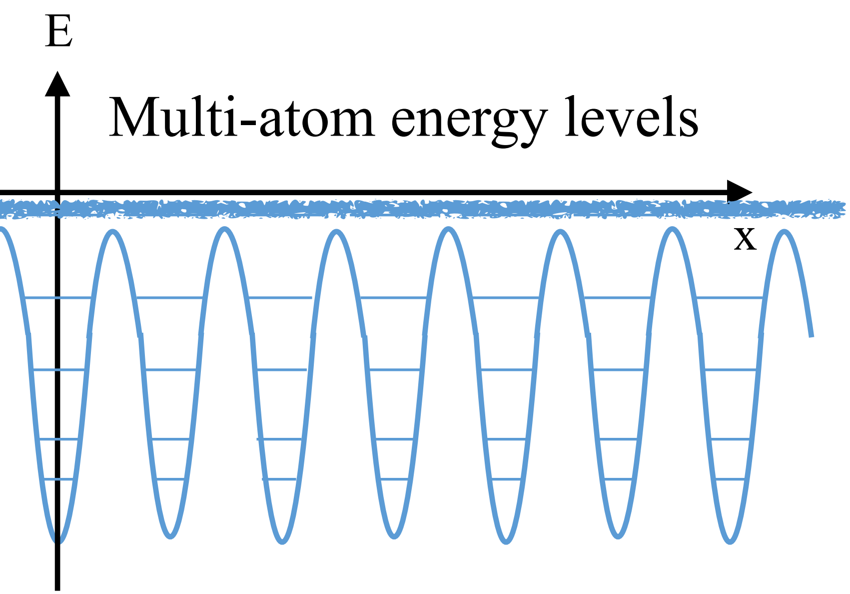

Valence electrons shared across crystal.
Form a “Fermi sea” of energy levels.
Have one free charge carrier per atom.
Large n gives high conductivity.

Conduction in semi-conductors

Current flows due to free charge carriers.

In a semiconductor, like silicon, each atom has its outer shell filled, without a valence electron.

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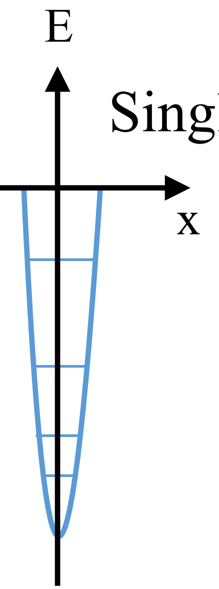
Single-atom energy levels



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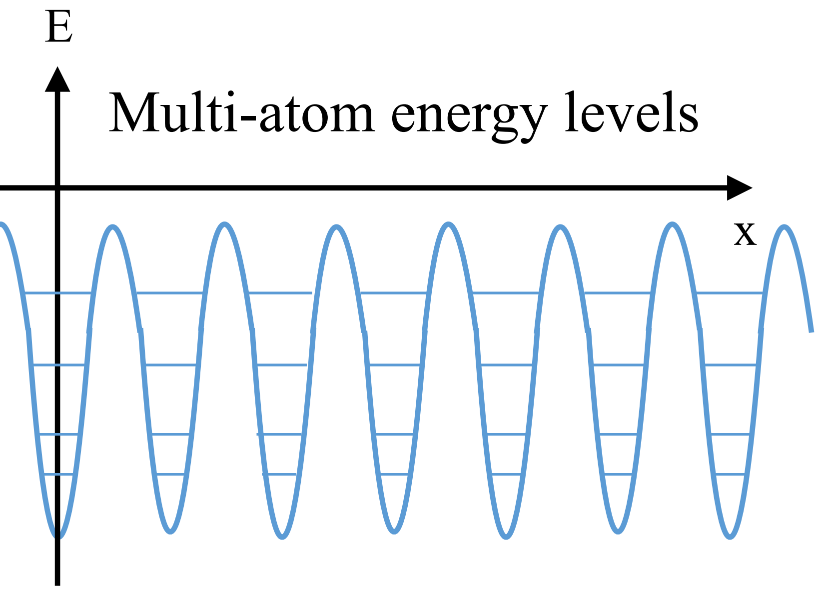


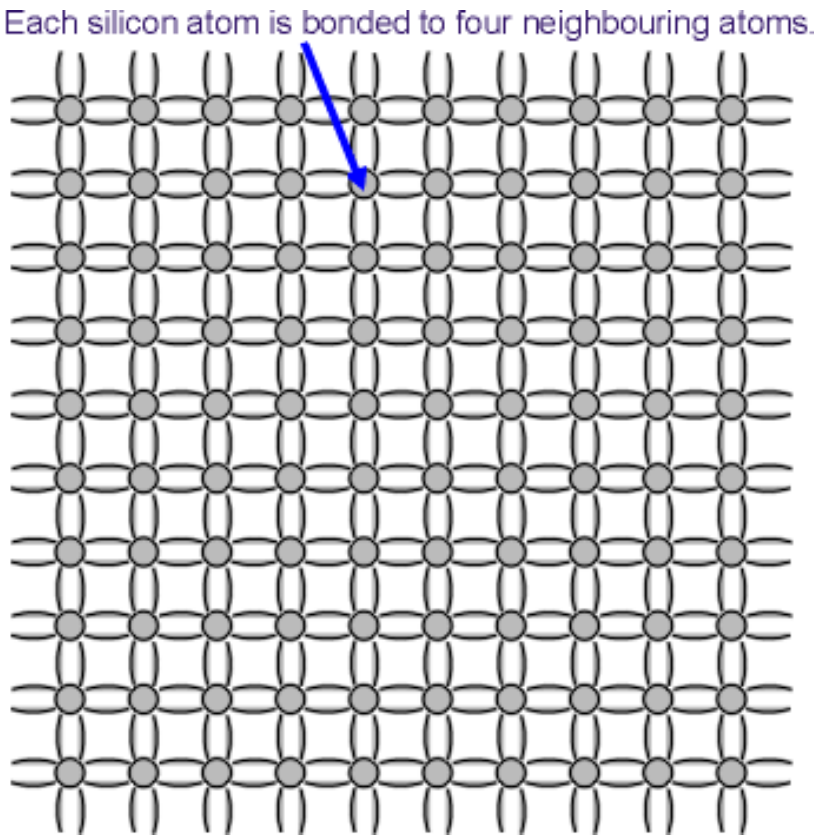
No valence electrons, so no conduction band, and no free charge carriers. n=0.

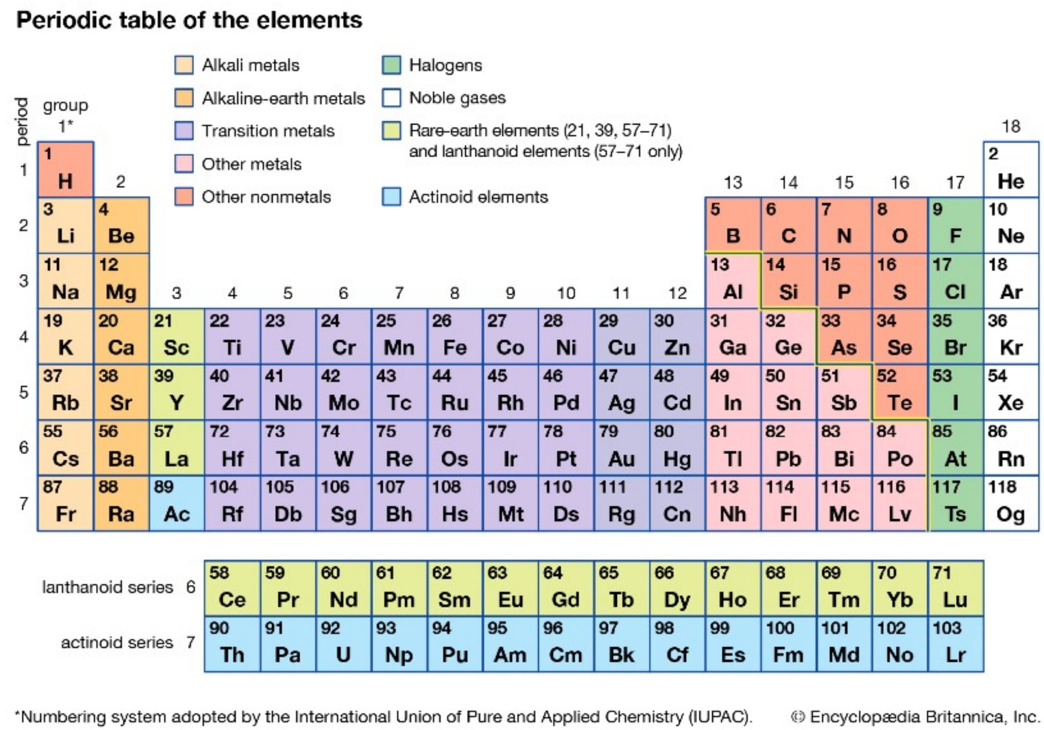
But we can implant charge carriers.

Conduction in semi-conductors

Silicon has atomic structure $1s^2 2s^2 2p^6 \underline{3s^2 3p^2}$

Four valence electrons share with four neighbors to fill outer shell.





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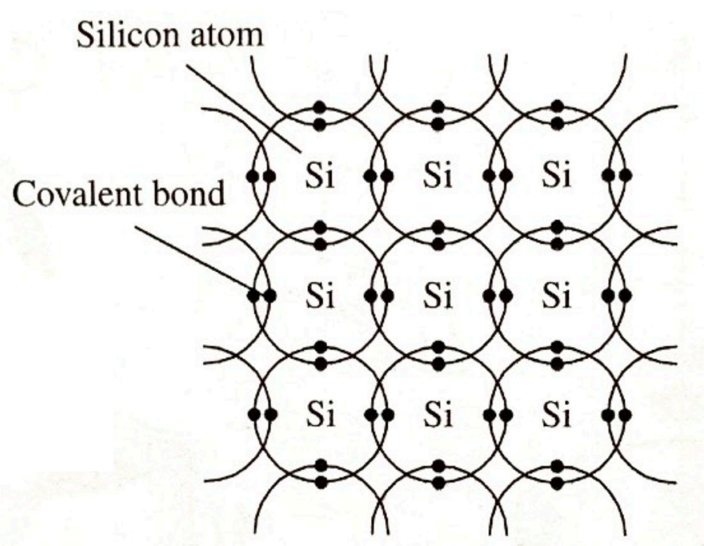
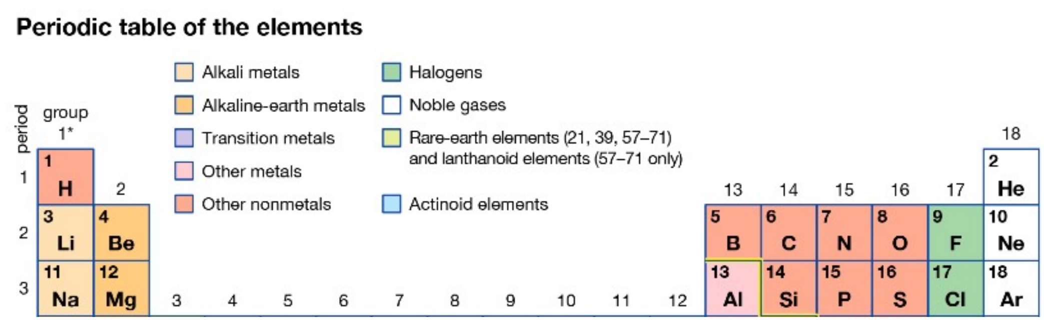
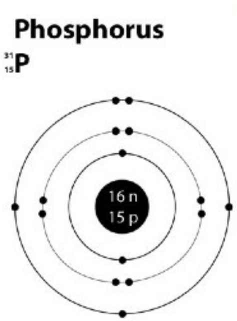
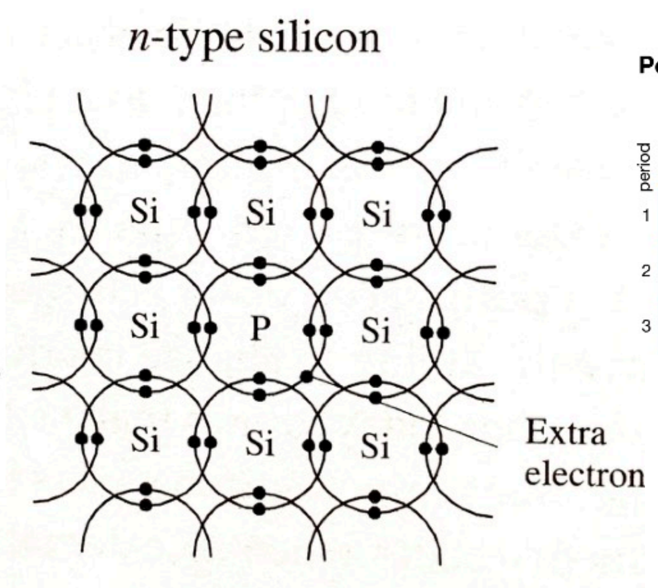


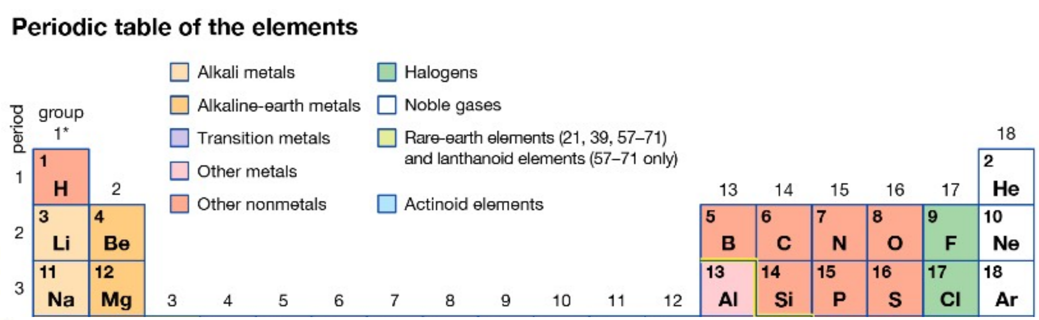


Conduction in semi-conductors

Now, let's replace one silicon atom with a phosphorus atom. It has an extra electron, which is very weakly bound. The crystal is still charge neutral, but it has one free charge carrier.



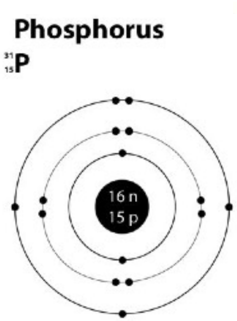


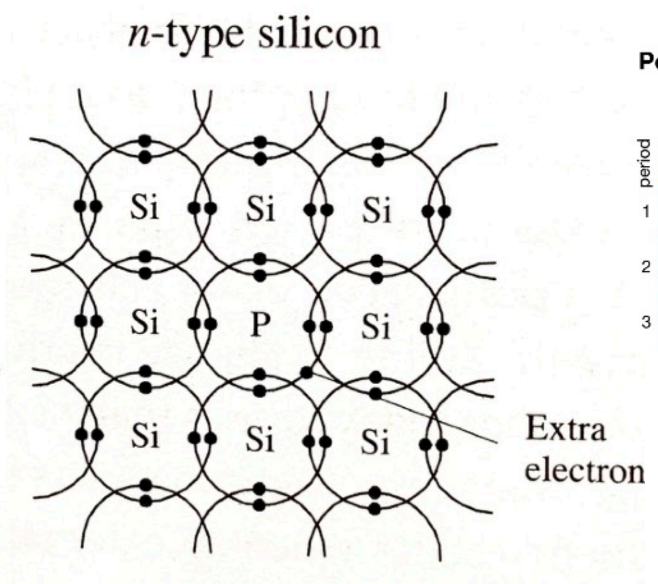


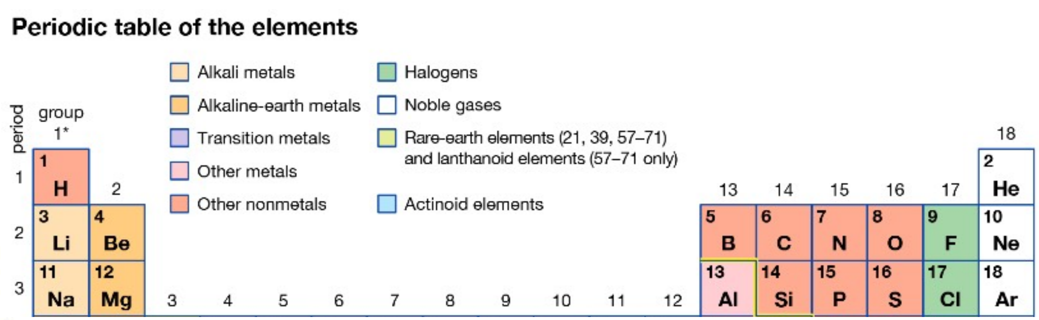
Conduction in semi-conductors

Now, let's replace one silicon atom with a phosphorus atom. It has an extra electron, which is very weakly bound. The crystal is still charge neutral, but it has one free charge carrier.

An electric field (voltage) across the silicon crystal will cause those charges to move, and never be bound. This is called n-type silicon since it has negative charge carriers.







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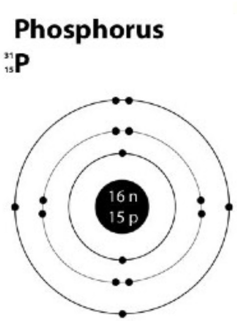
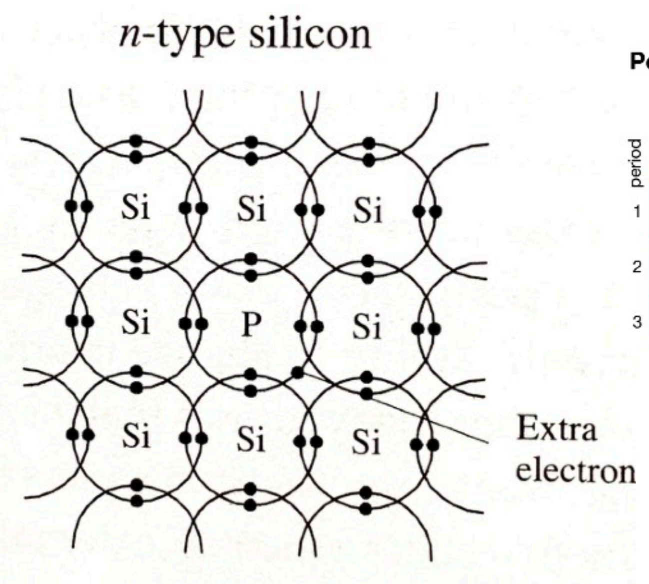
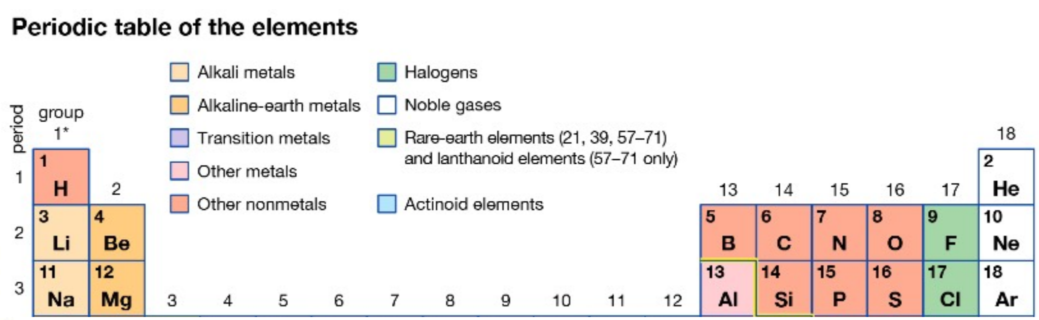
We can implant (dope) some controlled density of phosphorus, order 1 per 10^6 Si atoms, and get a controlled charge carrier density and hence resistivity. $I = n A q v_d$





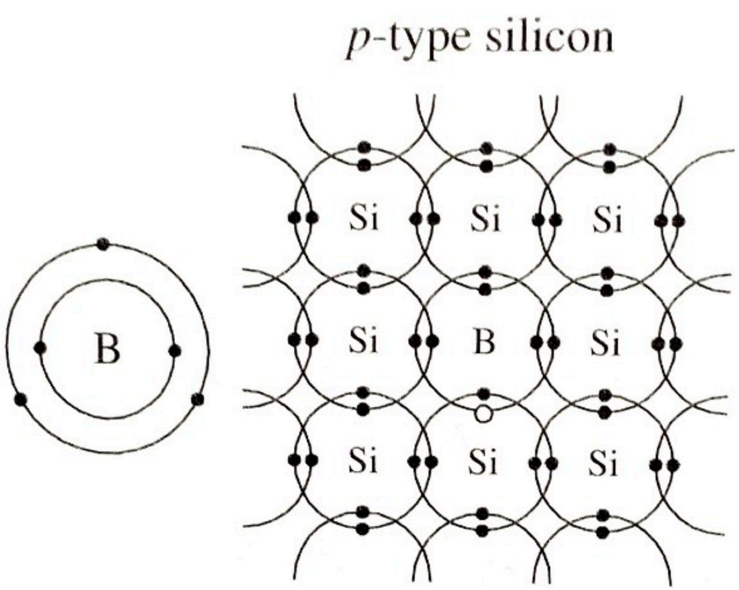


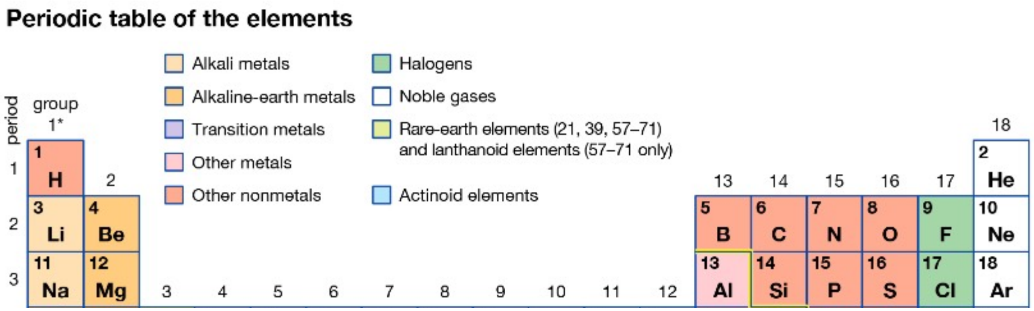
Conduction in semi-conductors

Alternatively, we could replace one silicon atom with a Boron atom. It has one less electron, so there is a "hole" in the covalent bonds.

An electric field (voltage) across the silicon crystal will cause electrons to move into the "hole", leaving another bond missing an electron. This is like a positive charge carrier, so this is called p-type silicon.

We can dope with some controlled density of boron and get a controlled charge carrier density and hence resistivity. $I = n A q v_d$

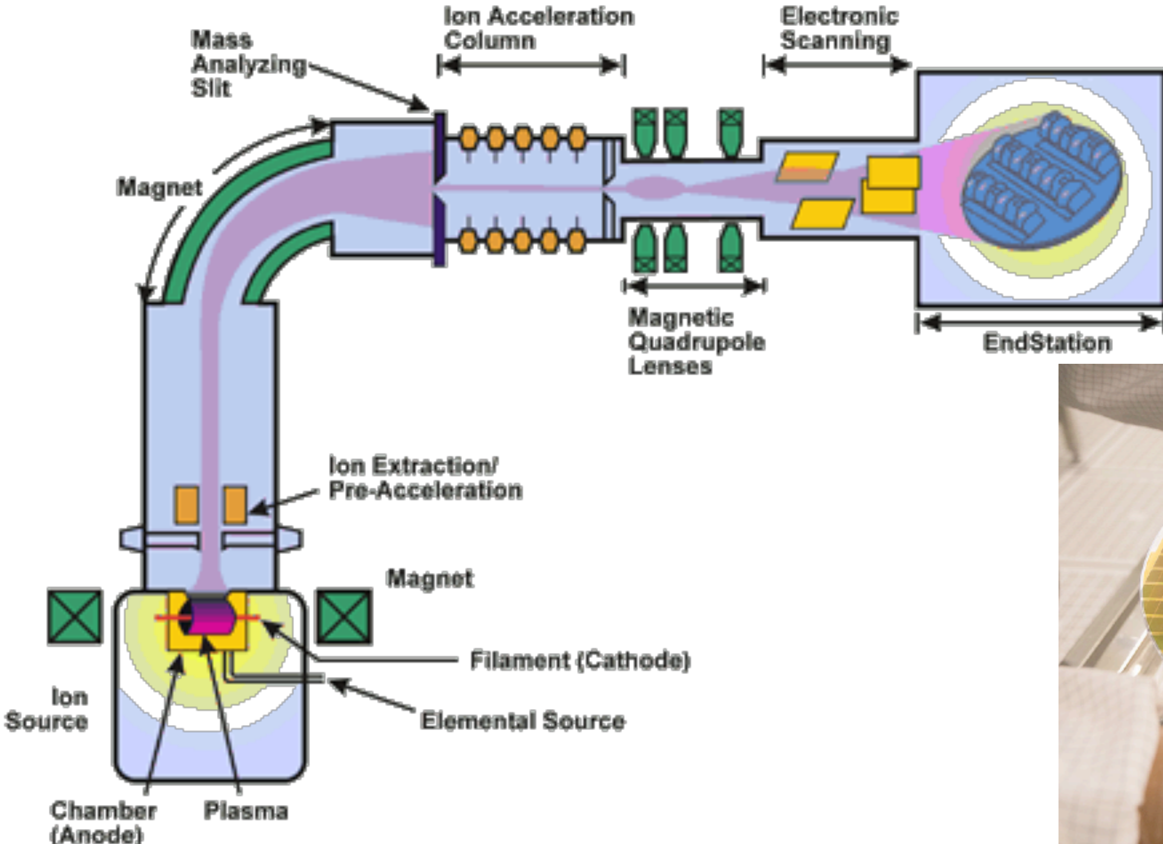


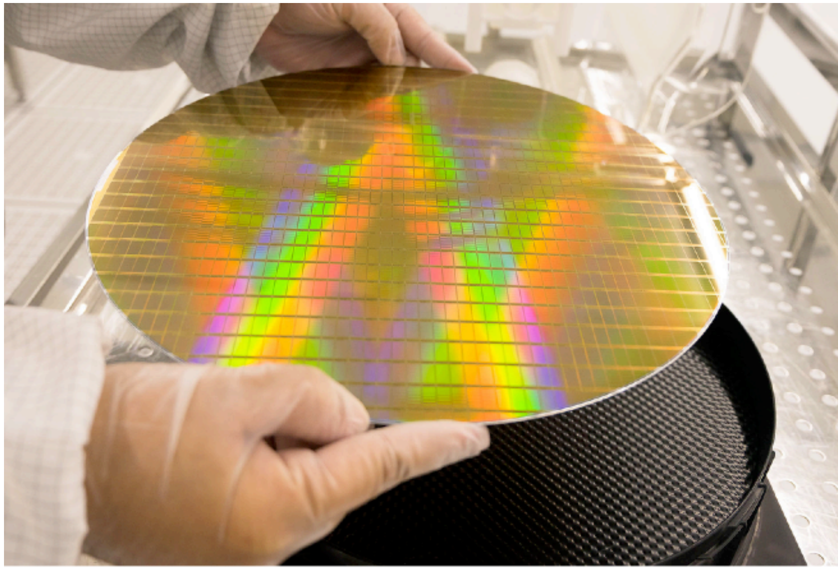


Conduction in semi-conductors

Doping (or implanting) is done with an ion-beam accelerator, usually on thin wafers of silicon 4, 6, 8, 12-inch diameter and 0.1 to 0.5 mm thick.

Then the wafer is heated so the implanted impurities settle into lattice sites.





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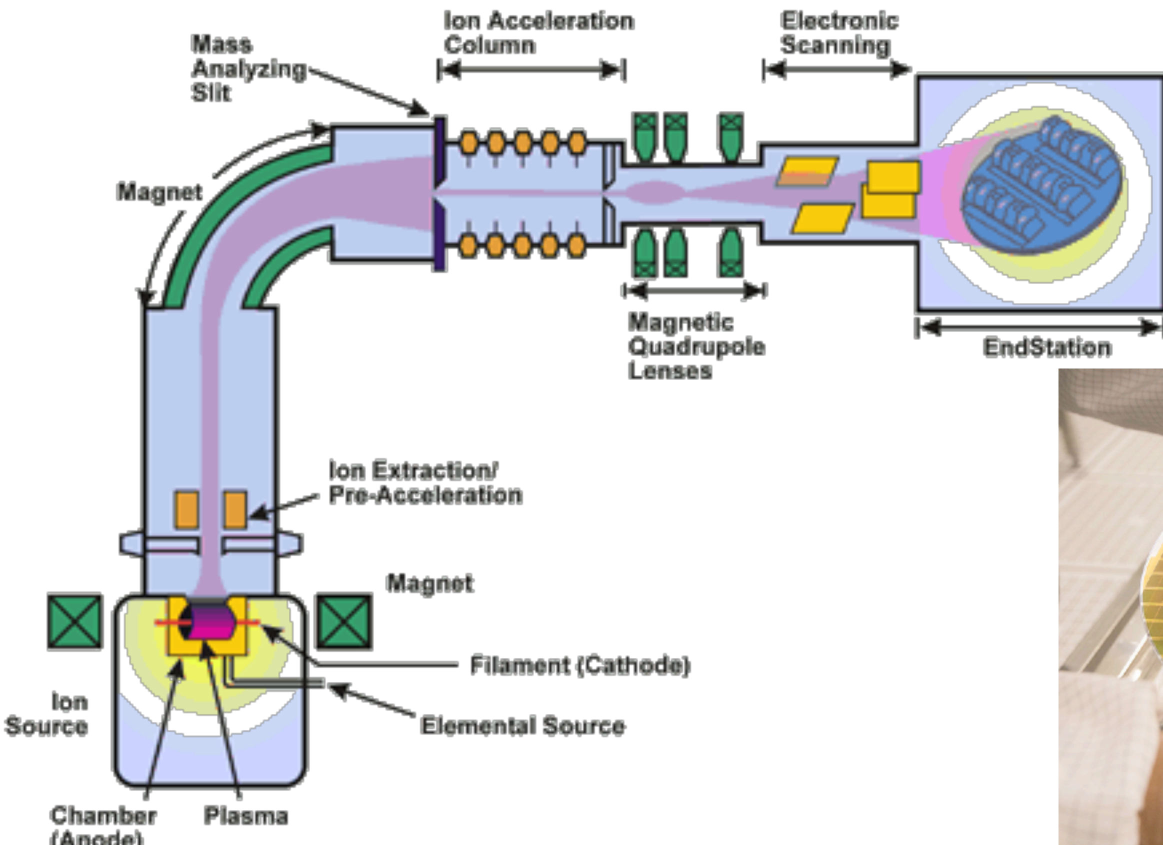
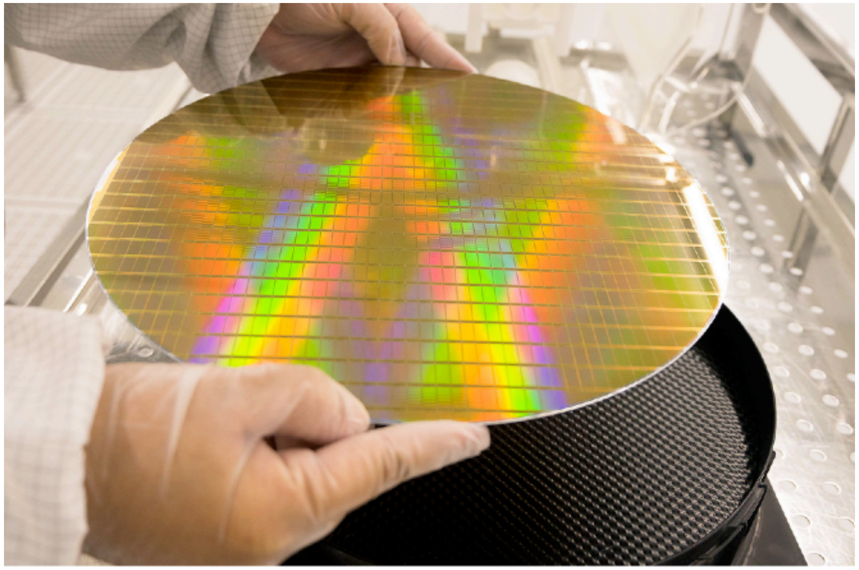
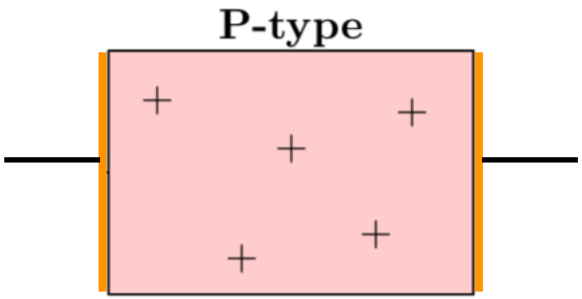
Deposit Al for connecting surfaces; called the Ohmic contact.

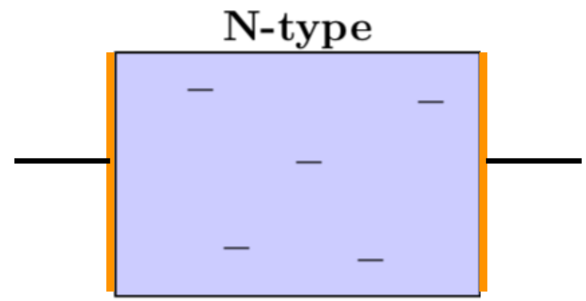




Conduction in semi-conductors

We then have a bulk crystal with an excess of charge carriers, either n-type or p-type.

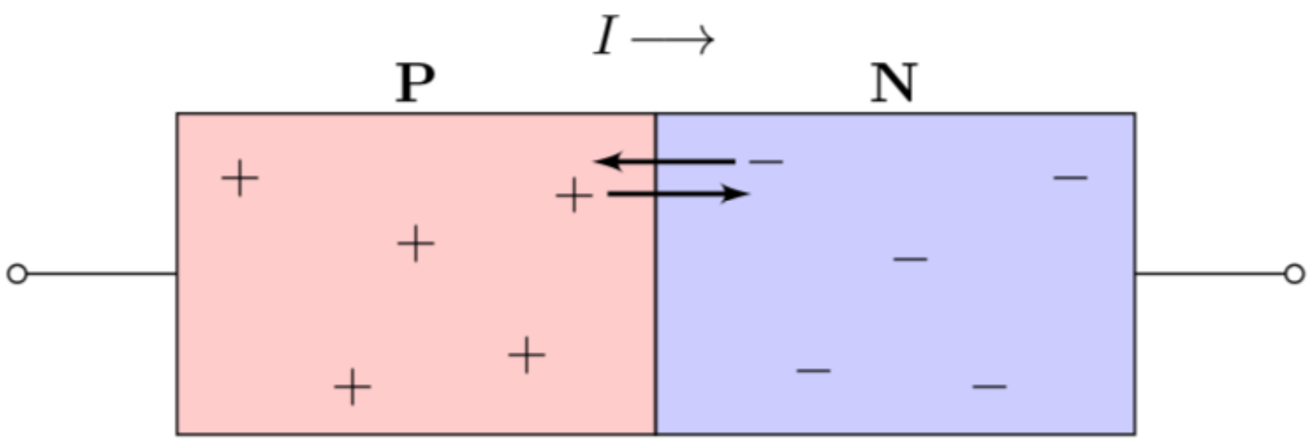




These are just resistors.

Conduction in semi-conductors

If I put a p-type piece in contact with an n-type piece, the opposite signed charge carriers can move to cancel either other.



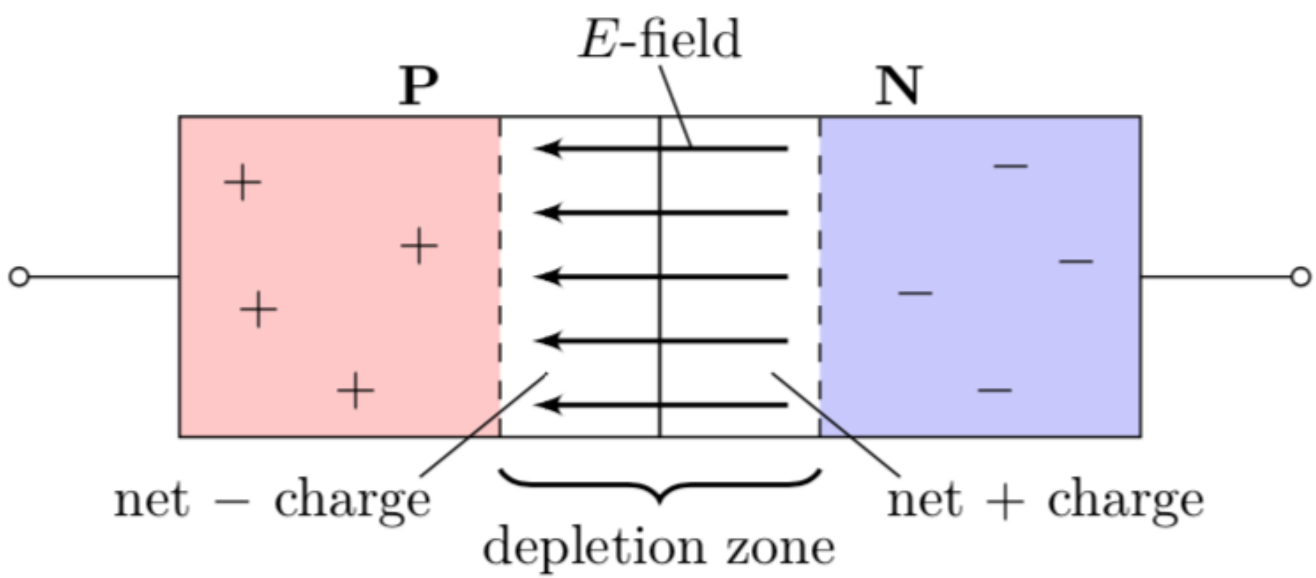
Conduction in semi-conductors

If I put a p-type piece in contact with an n-type piece, the opposite signed charge carriers can move to cancel either other.

As they do so, they will leave a region on either side of the junction that is *depleted* of charge carriers.

The bulk is charge neutral throughout, but the carriers are no longer *free charge carriers*.

And an intrinsic electric field develops in the depletion region. $V \cong 0.7$ Volts



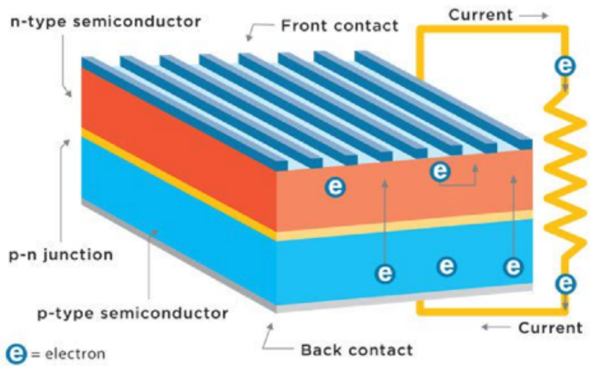
Conduction in semi-conductors

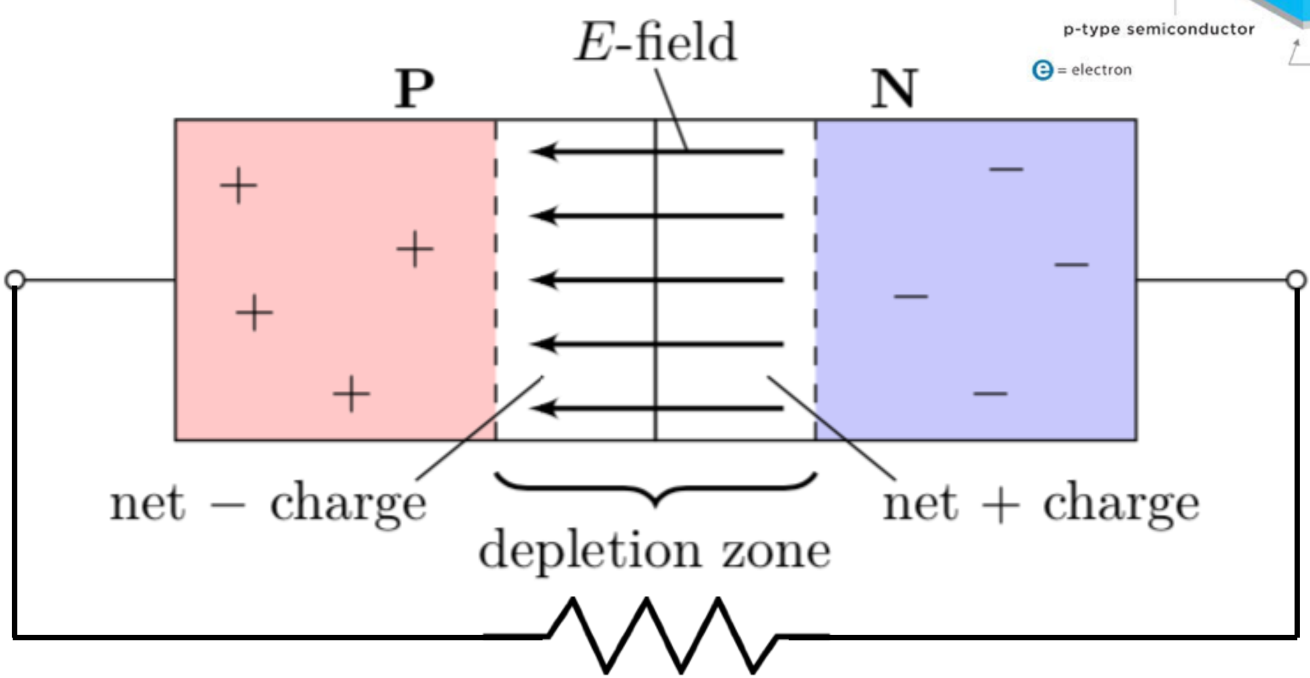
An intrinsic electric field develops in the depletion region. V ≅ 0.7 Volts

If we put a resistor across this, no current would flow because the depletion region has high resistivity (n=0).

Voltage, but no current, so no power. Unless we freed a charge carrier.

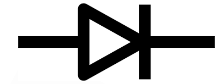
This is a photocell.

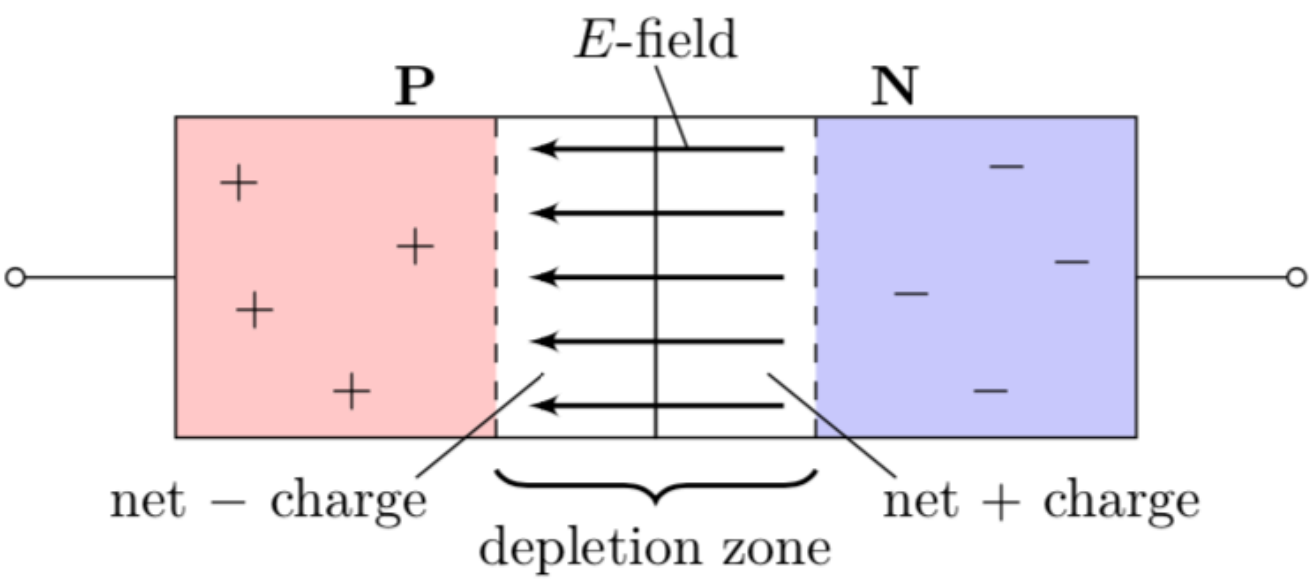




pn diode

This is a pn-diode, and its symbol matches that of a one-way valve.





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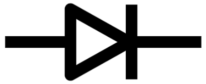
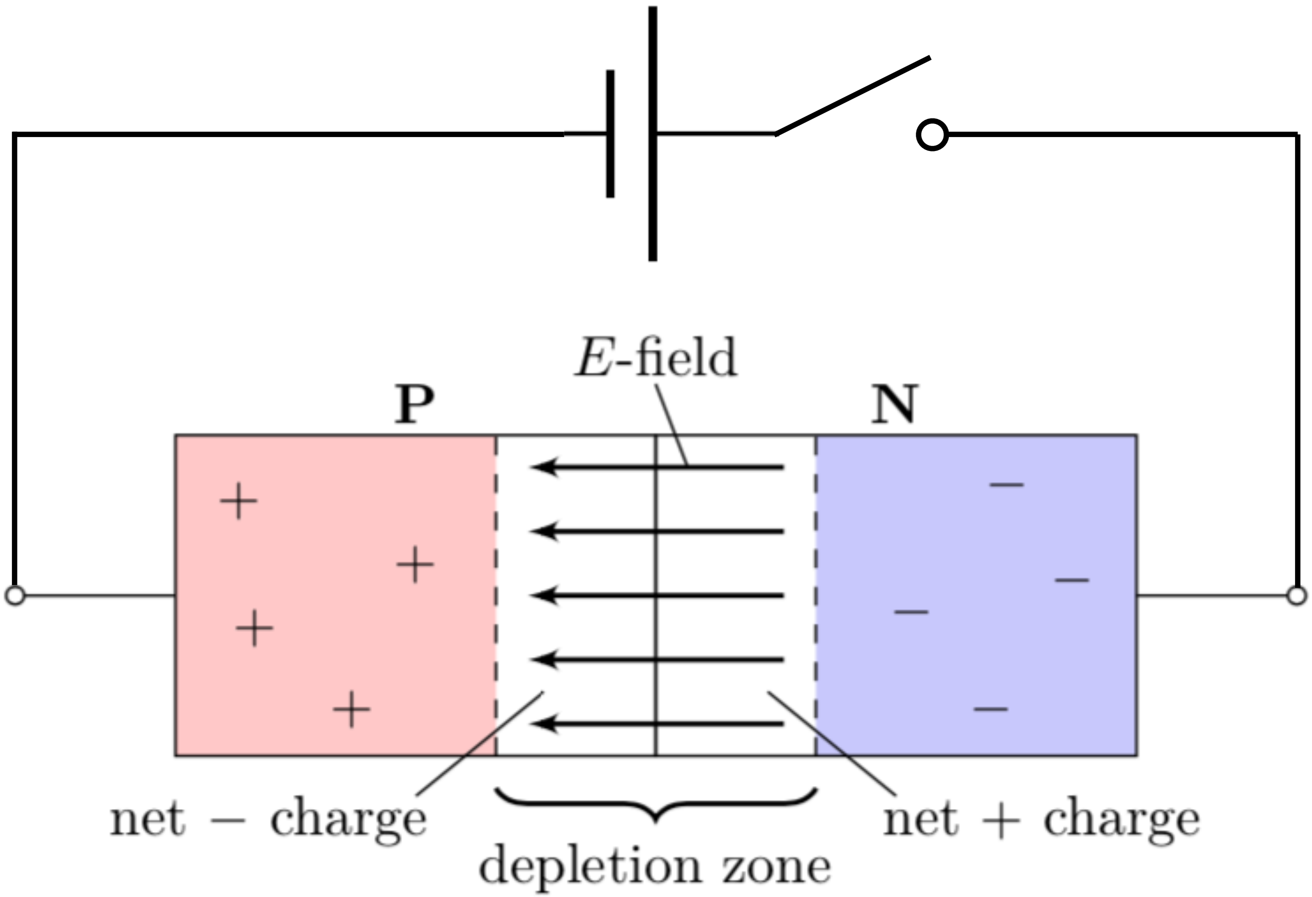
This is a pn-diode, and its symbol matches that of a one-way valve. 

We can see that one-way current behavior by applying an external voltage.



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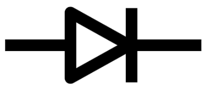
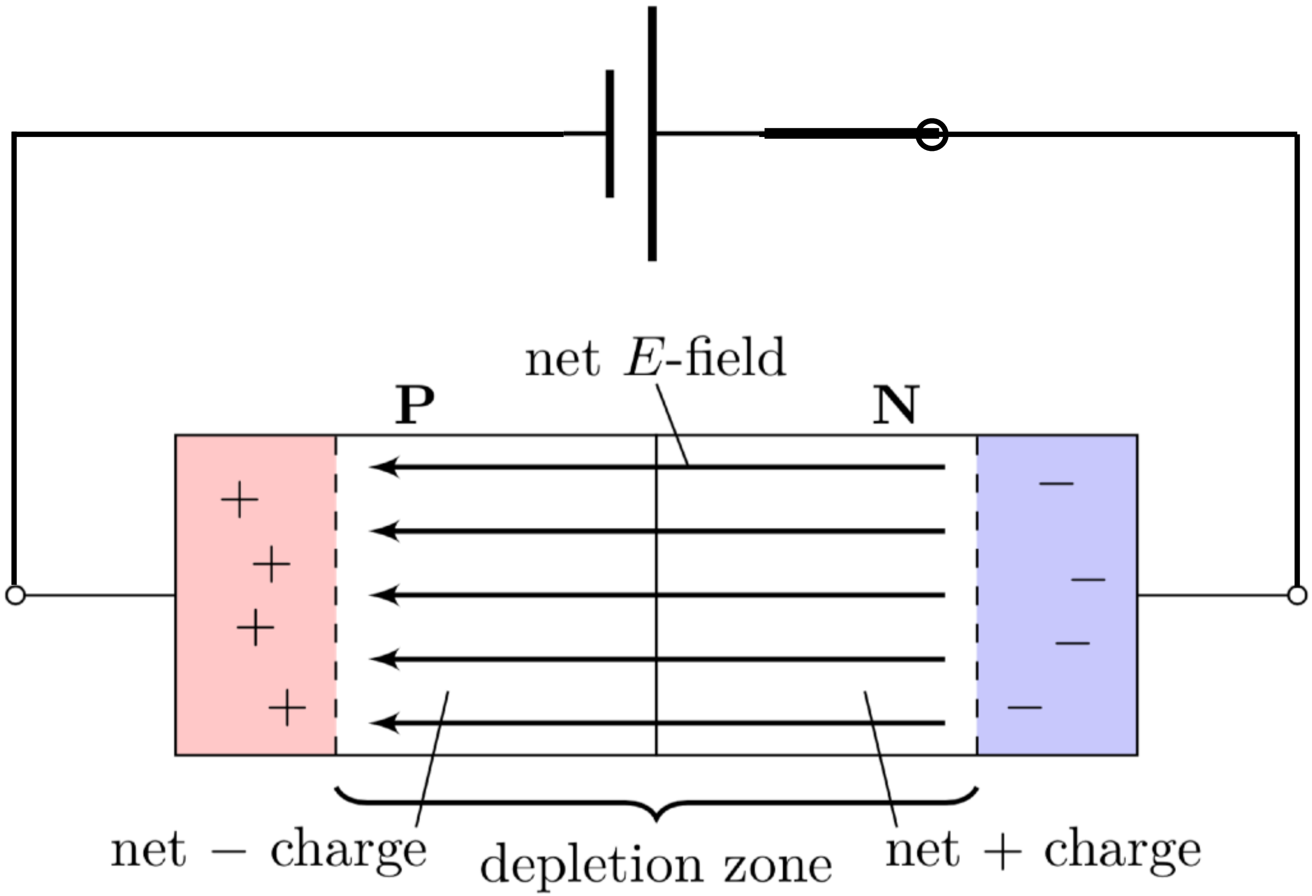
This is a pn-diode, and its symbol matches that of a one-way valve. 

We can see that one-way current behavior by applying and external voltage.

That widens the depletion region but current still won't flow through it.



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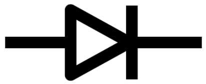

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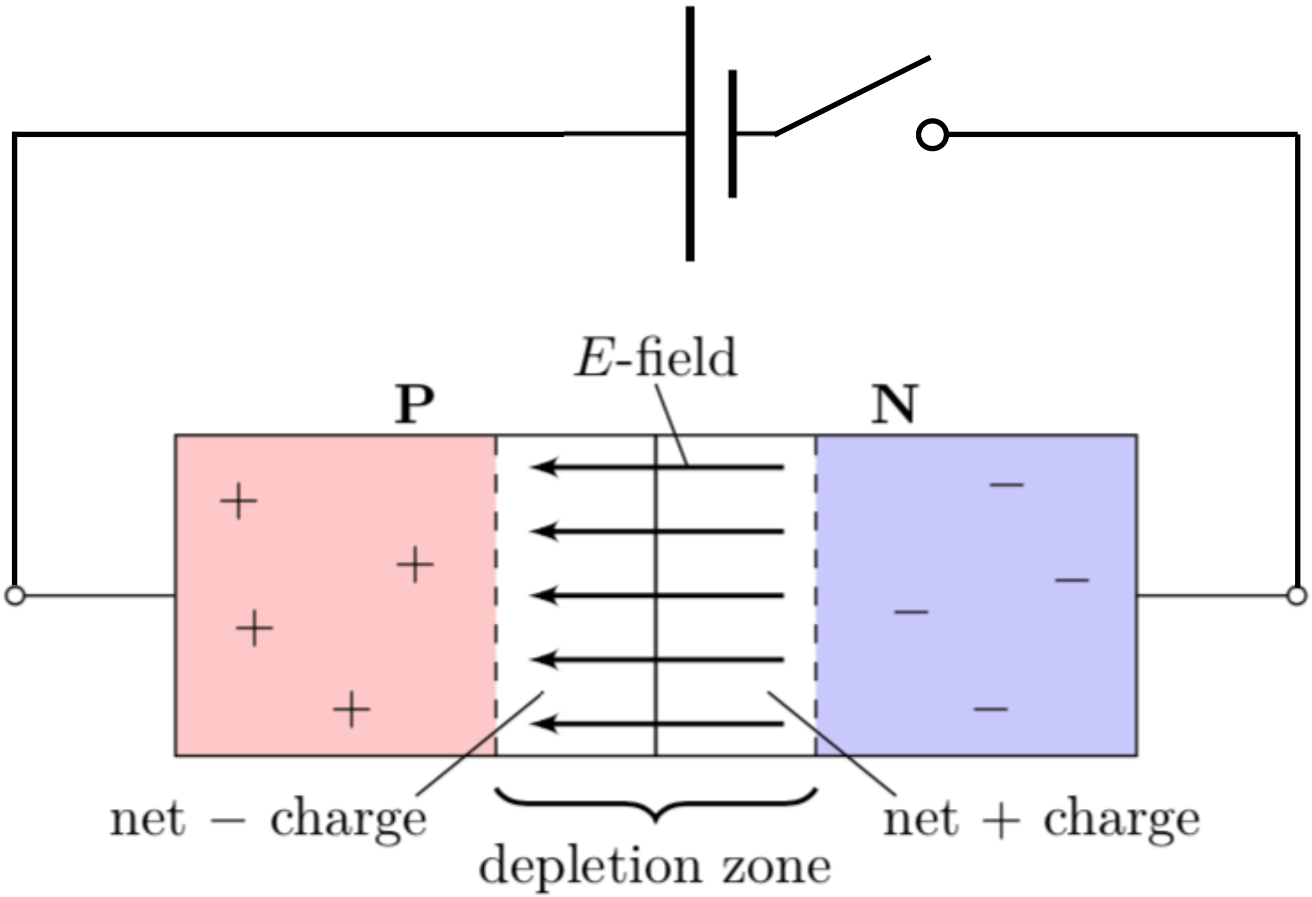
Flip the battery's polarity.



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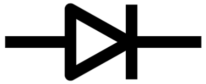

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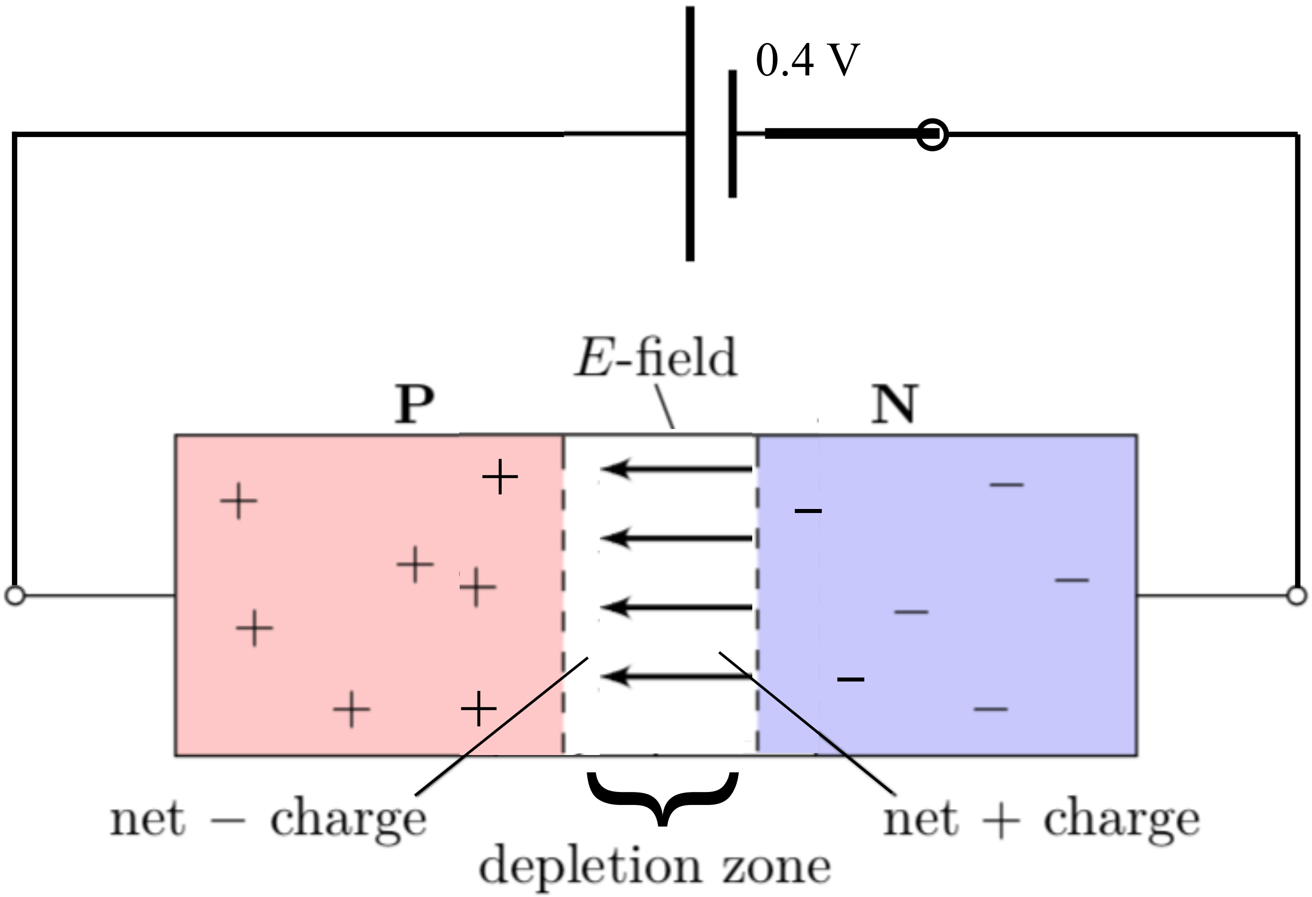

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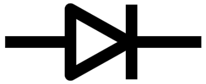
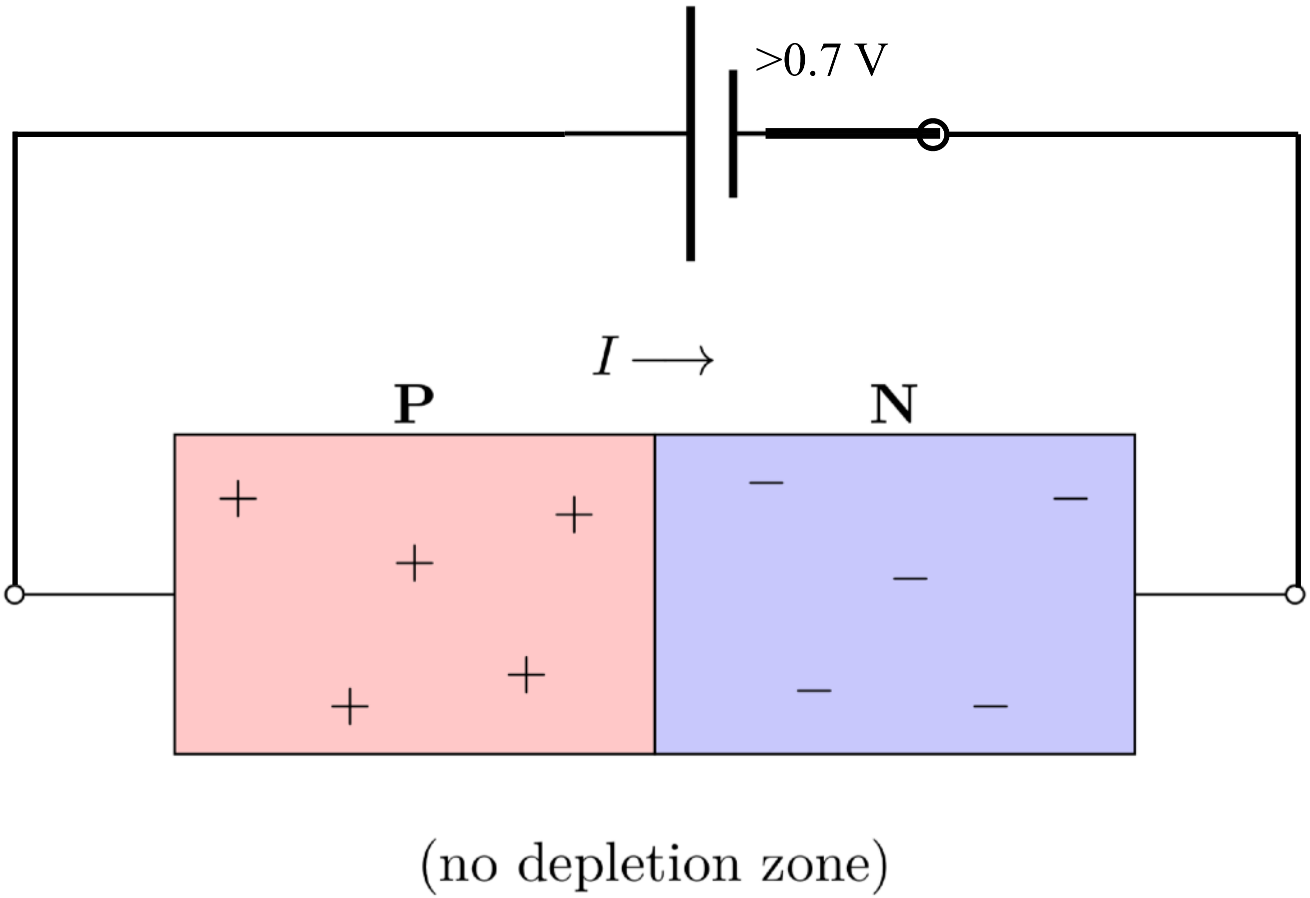


We can see that one-way current behavior by applying an external voltage.

Flip the battery's polarity. Once we overcome the 0.7 V internal voltage, current flows through continuous charge carriers.



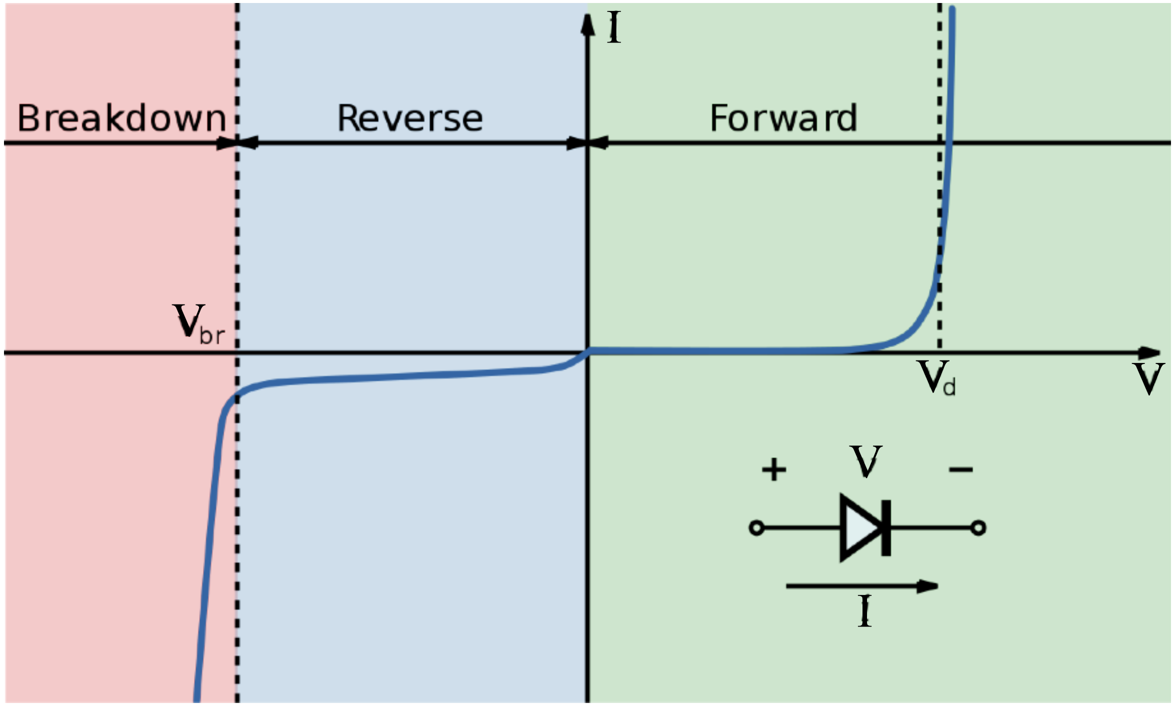
Diode IV curve

The IV relation depends on polarity.

Forward biased above $V_d \Rightarrow \; I = I_s(e^{V/nV_T} - 1)$ due to injected carriers. $V_T = kT/e$

Reverse biased $\Rightarrow$ small leakage from thermally excited carriers.

Reverse biased below breakdown gives exponential increase.

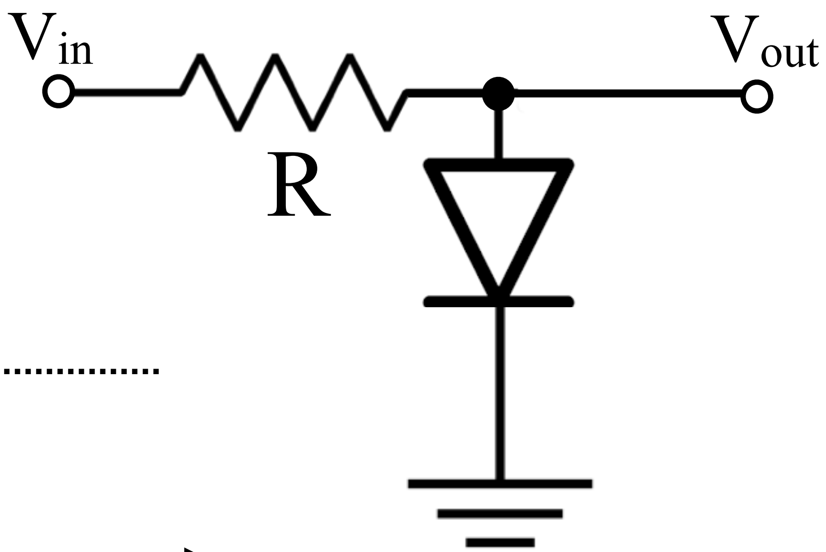


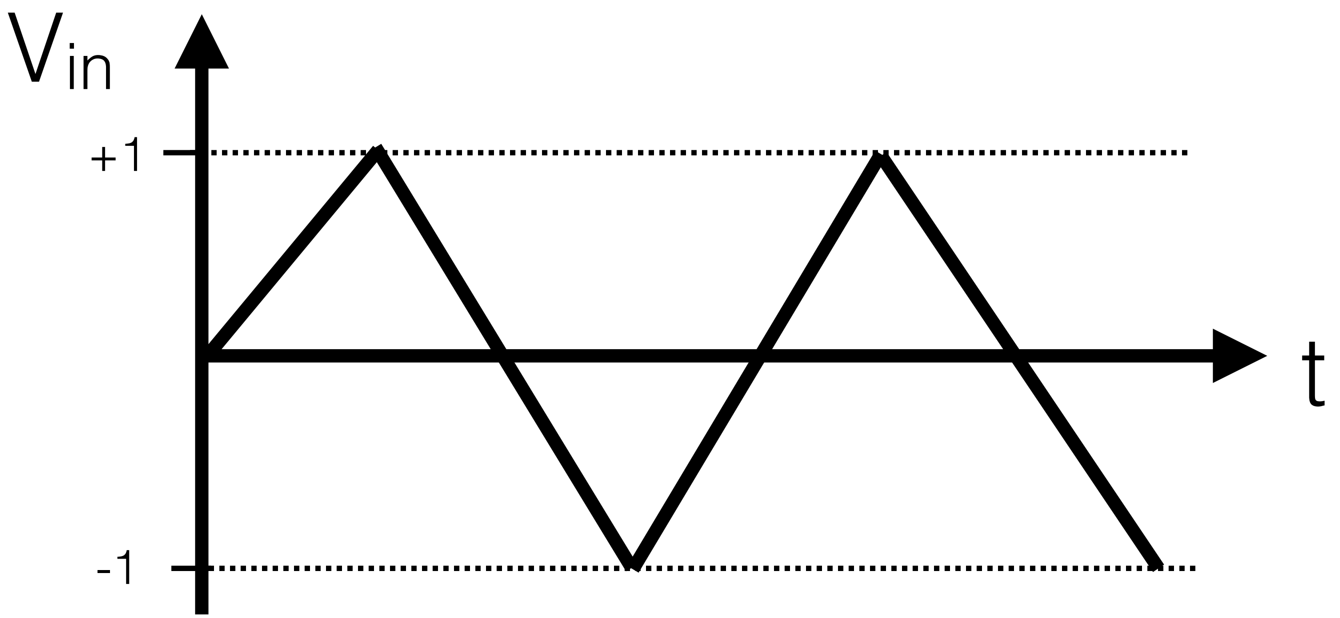
Diode circuits

We can analyze diode circuits with a simpler IV model:

Zero current if less than 0.7 V across diode.

Short circuit if more than 0.7 V across diode.





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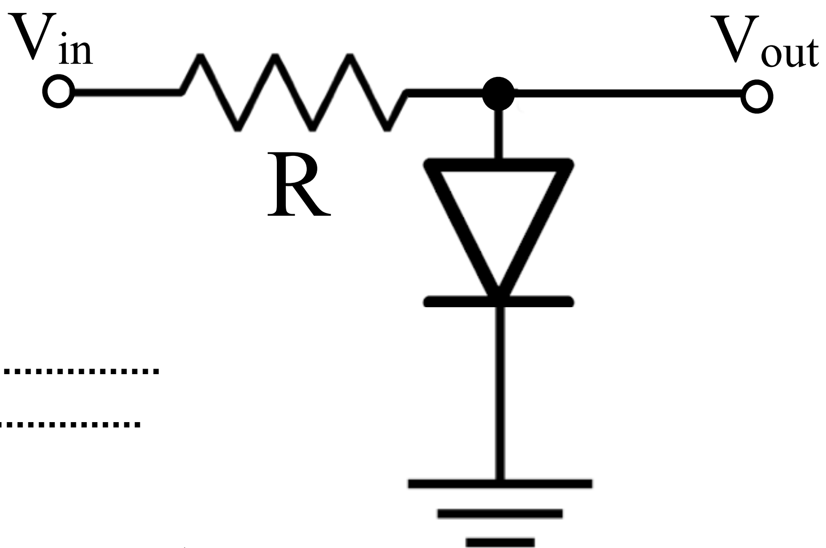

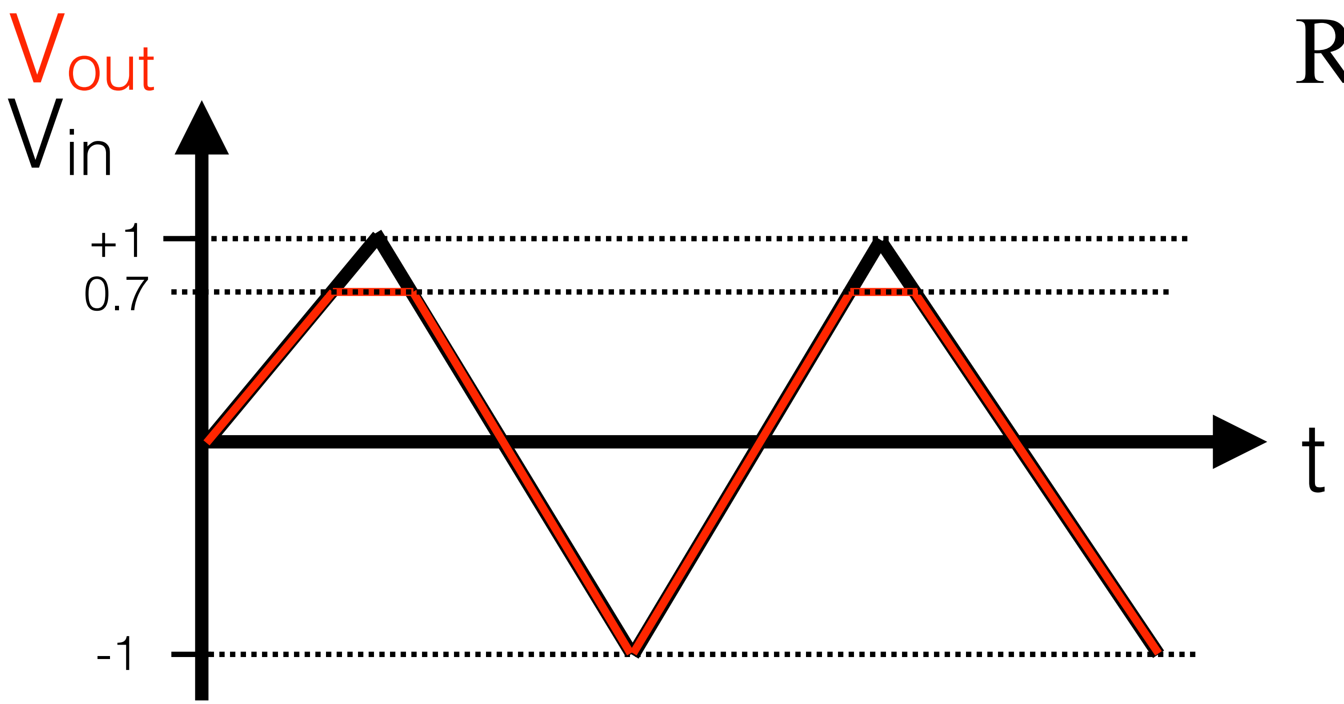

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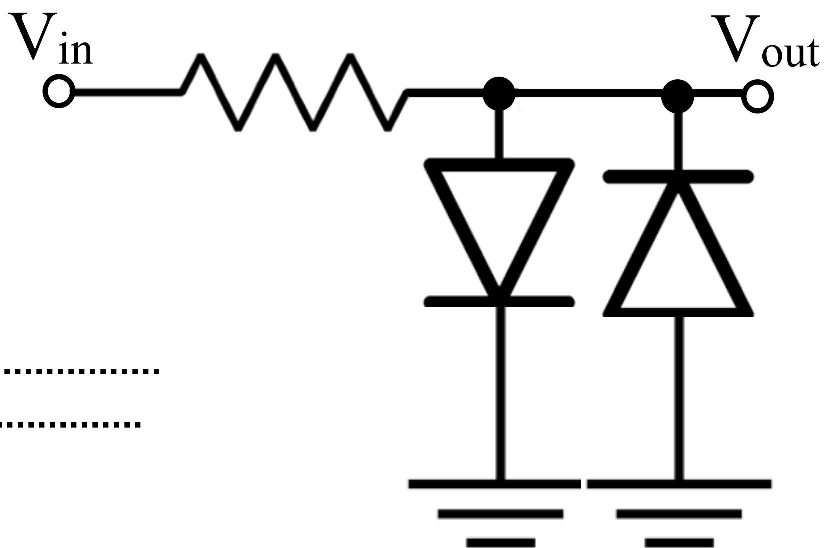

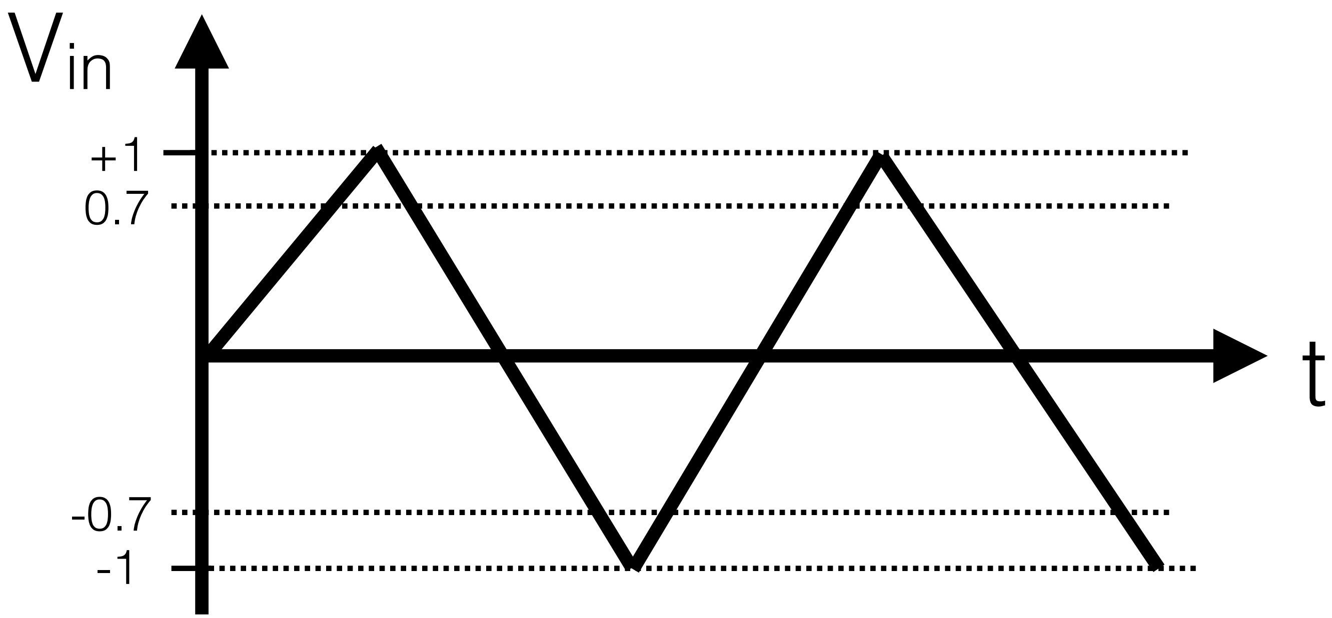

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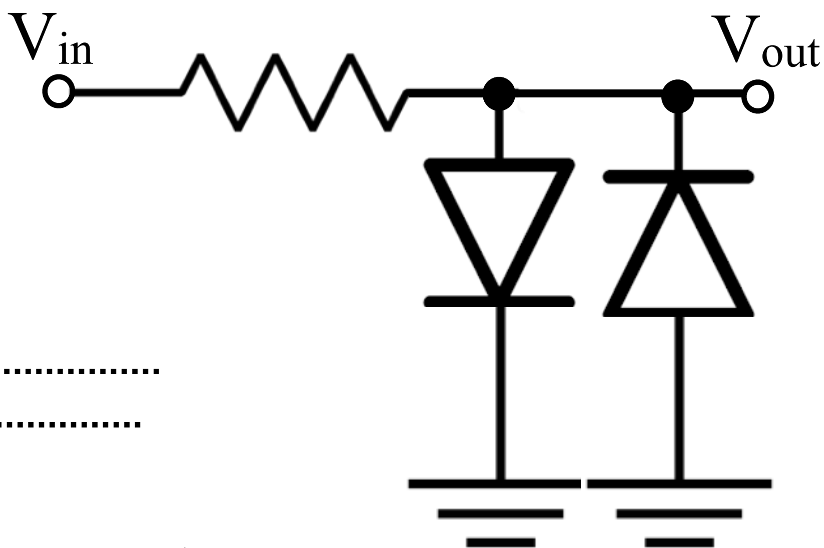

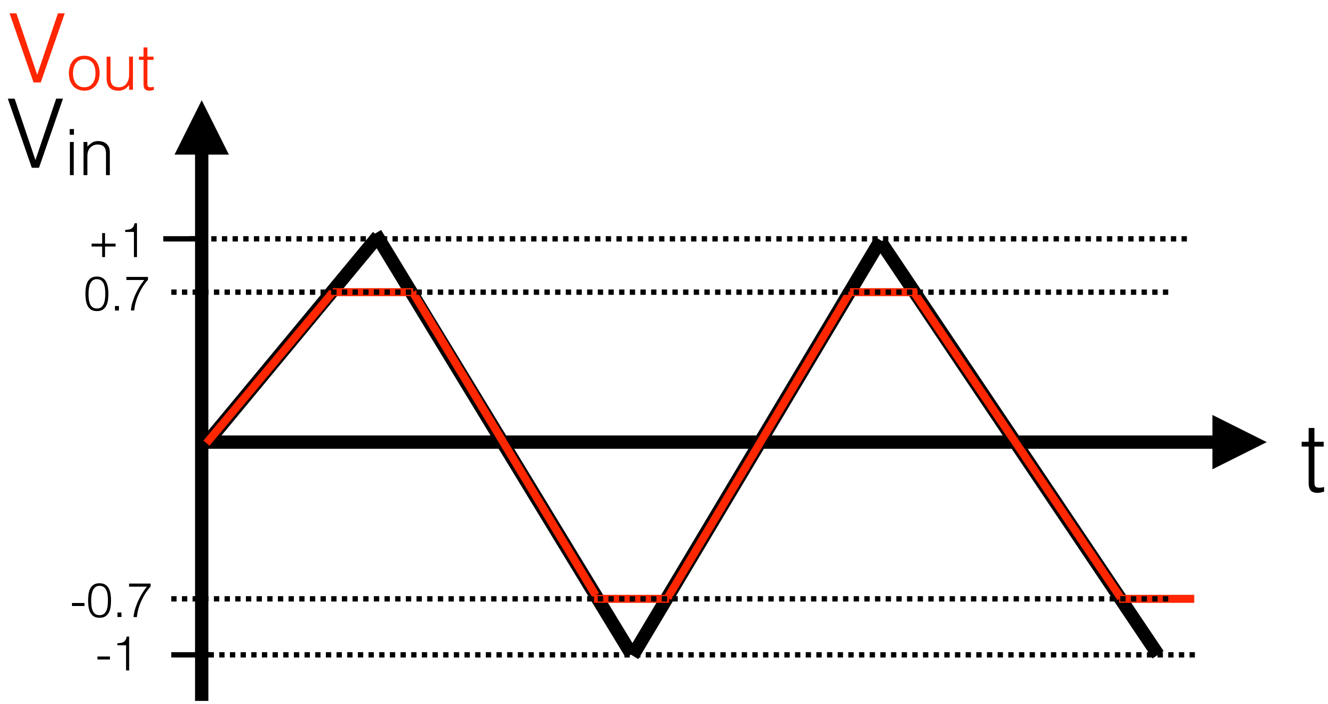

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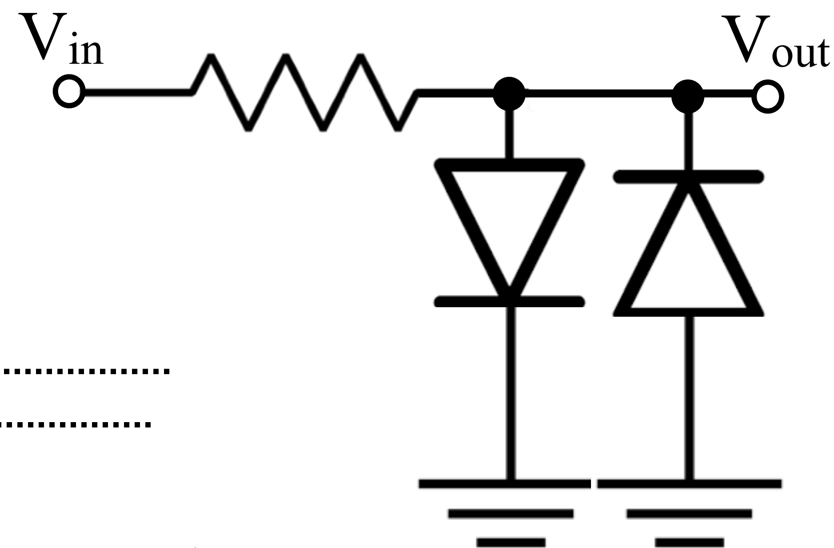

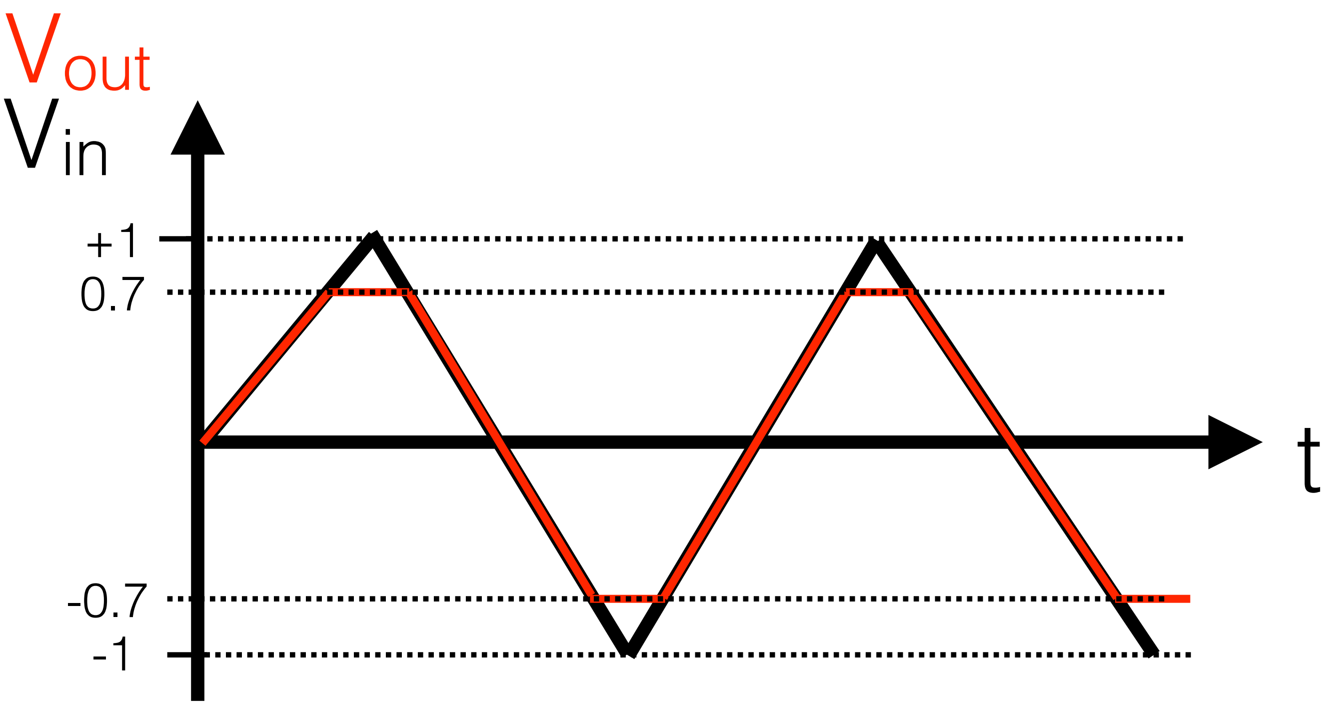

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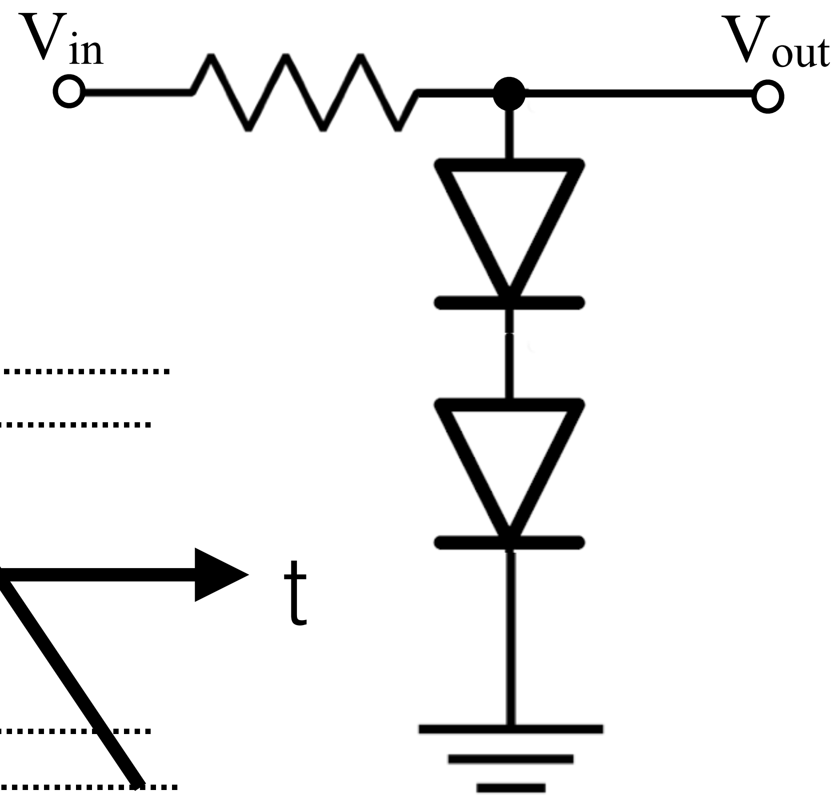

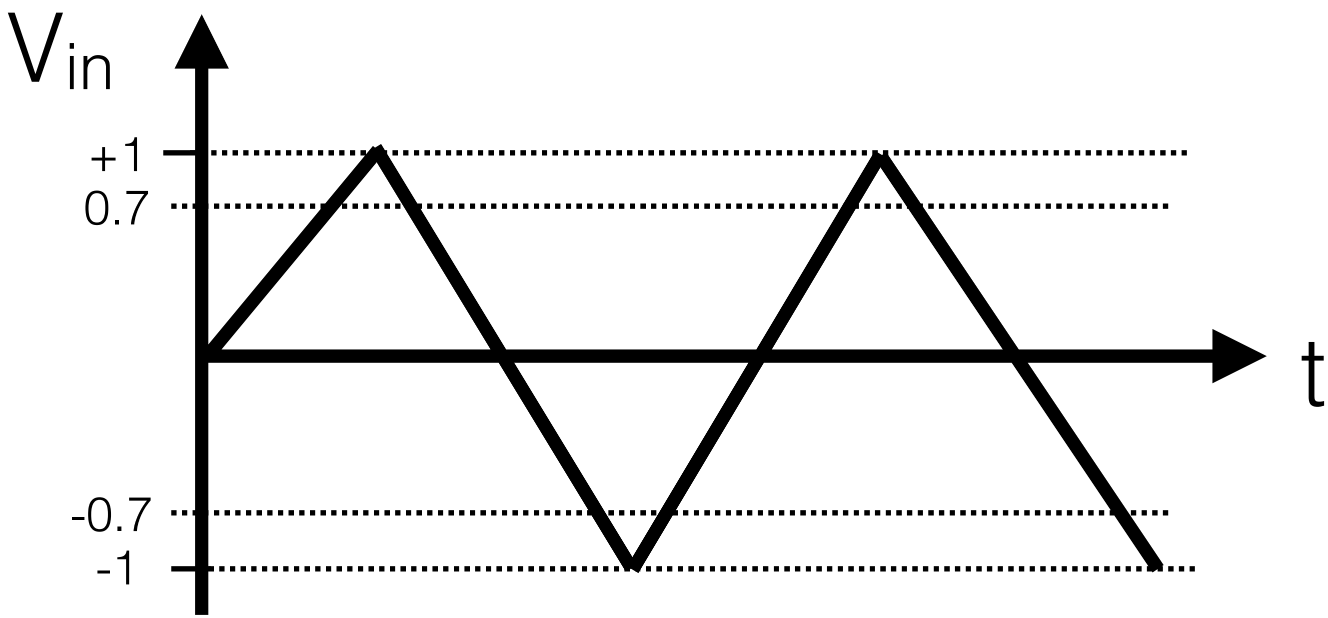

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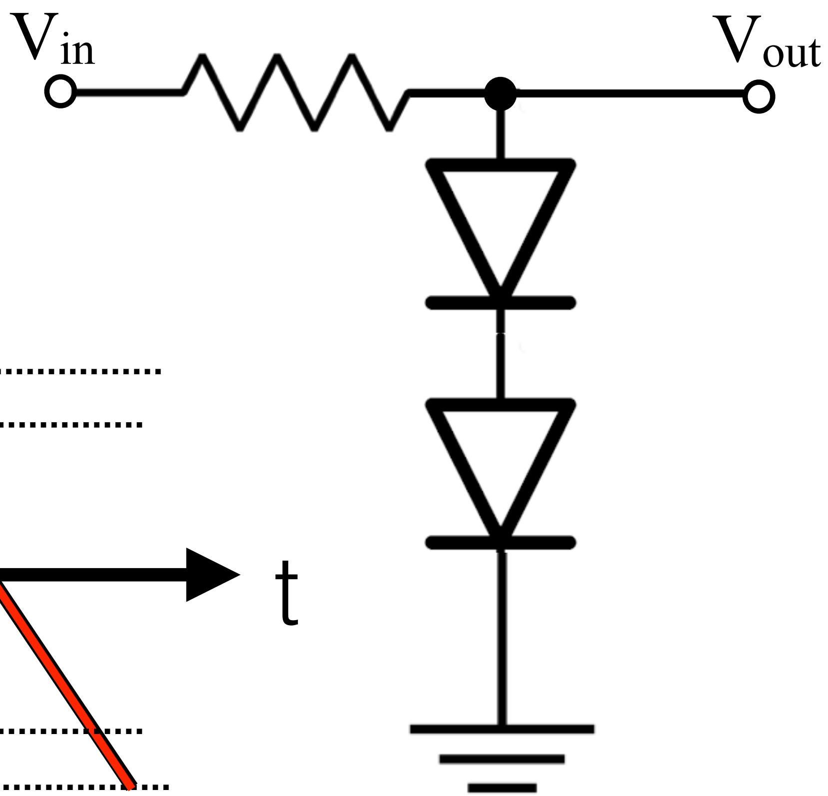
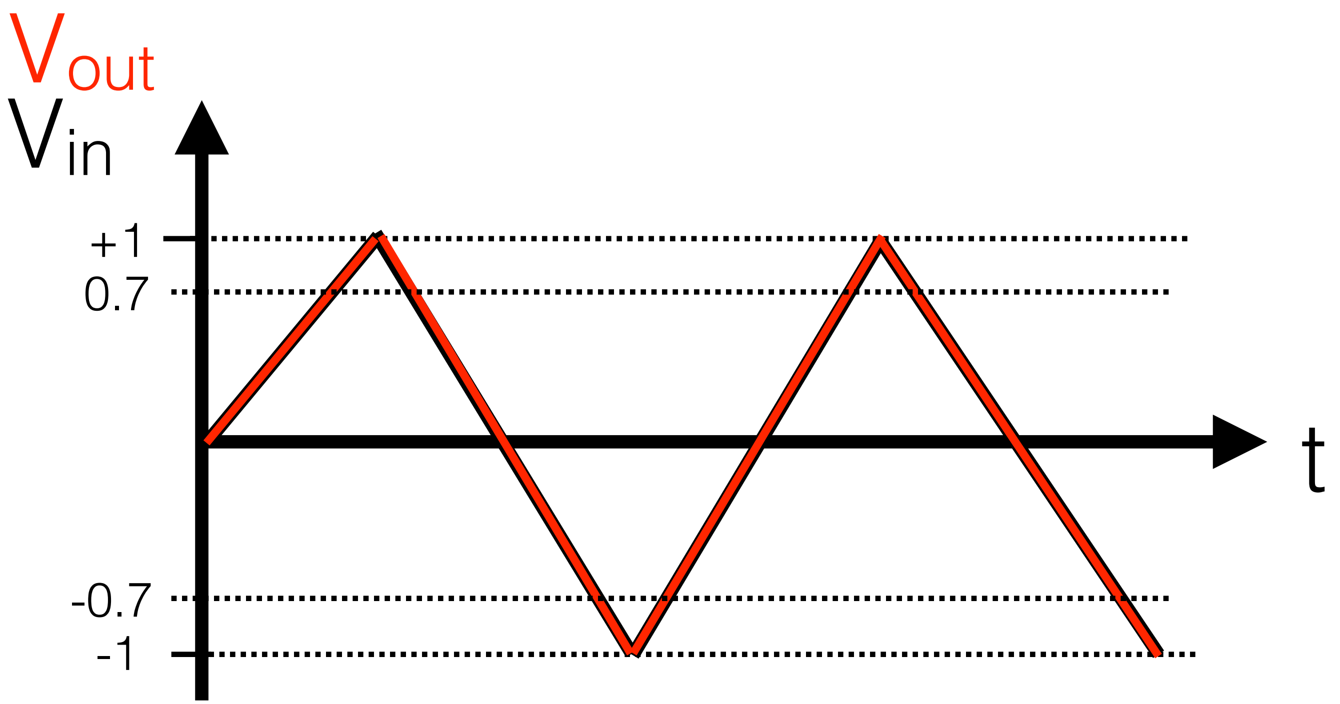
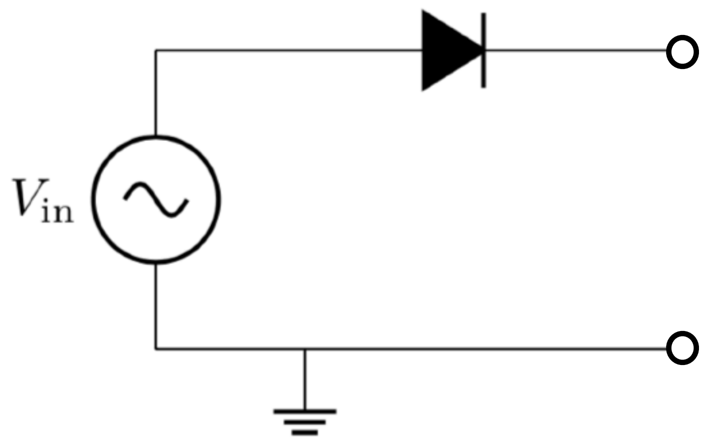




Diode circuits

If diodes are in-line, they just drop 0.7 Volts — if current is flowing—otherwise they act like an open circuit.

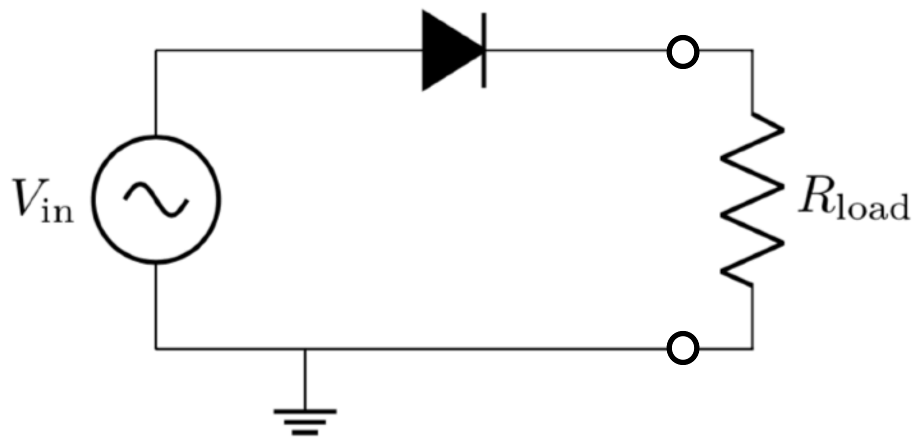


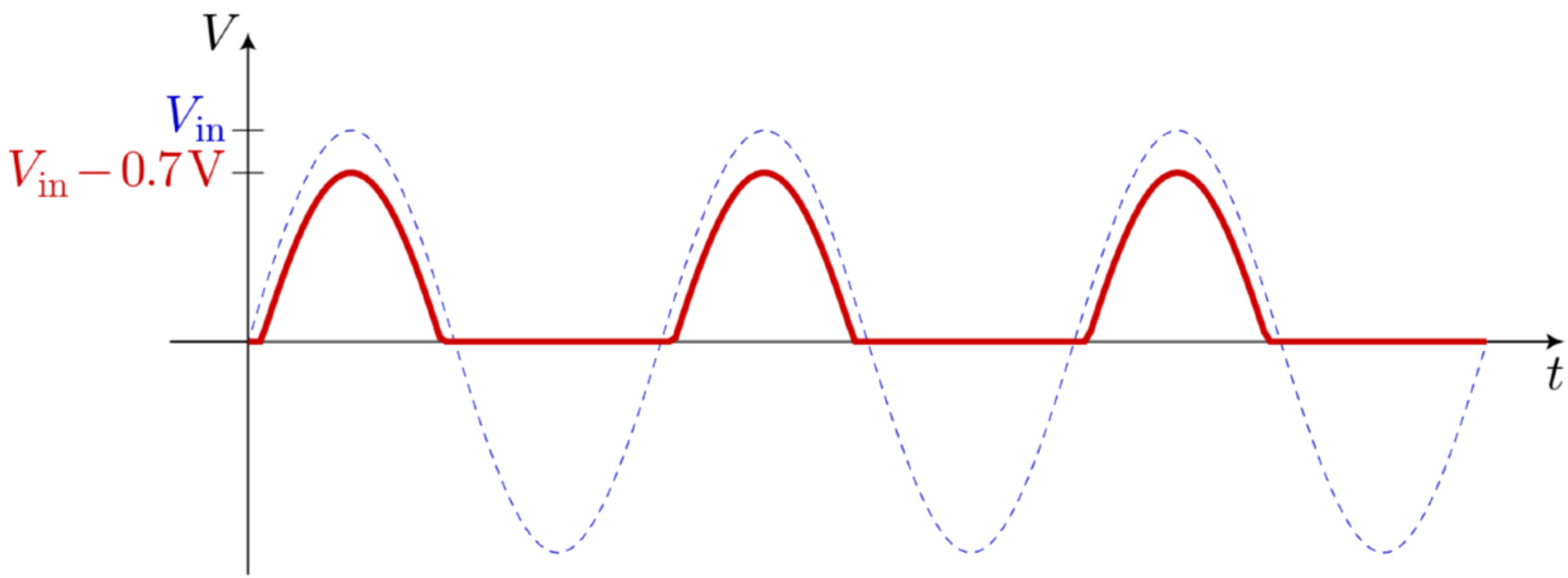
No output because no current flows.

But, can always imagine some load resistance.

Diode circuits

If diodes are in-line, they just drop 0.7 Volts — if current is flowing—otherwise they act like an open circuit. "Rectifier circuit."

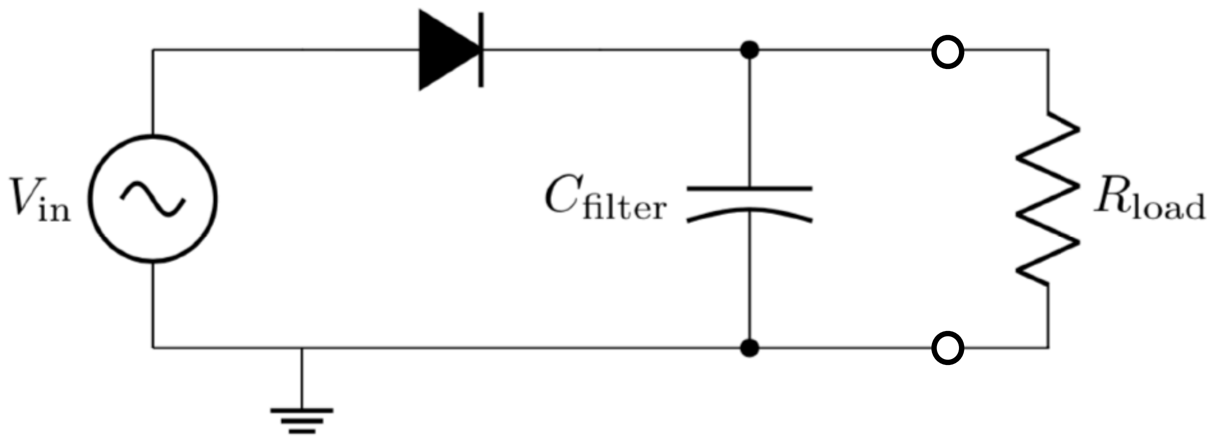


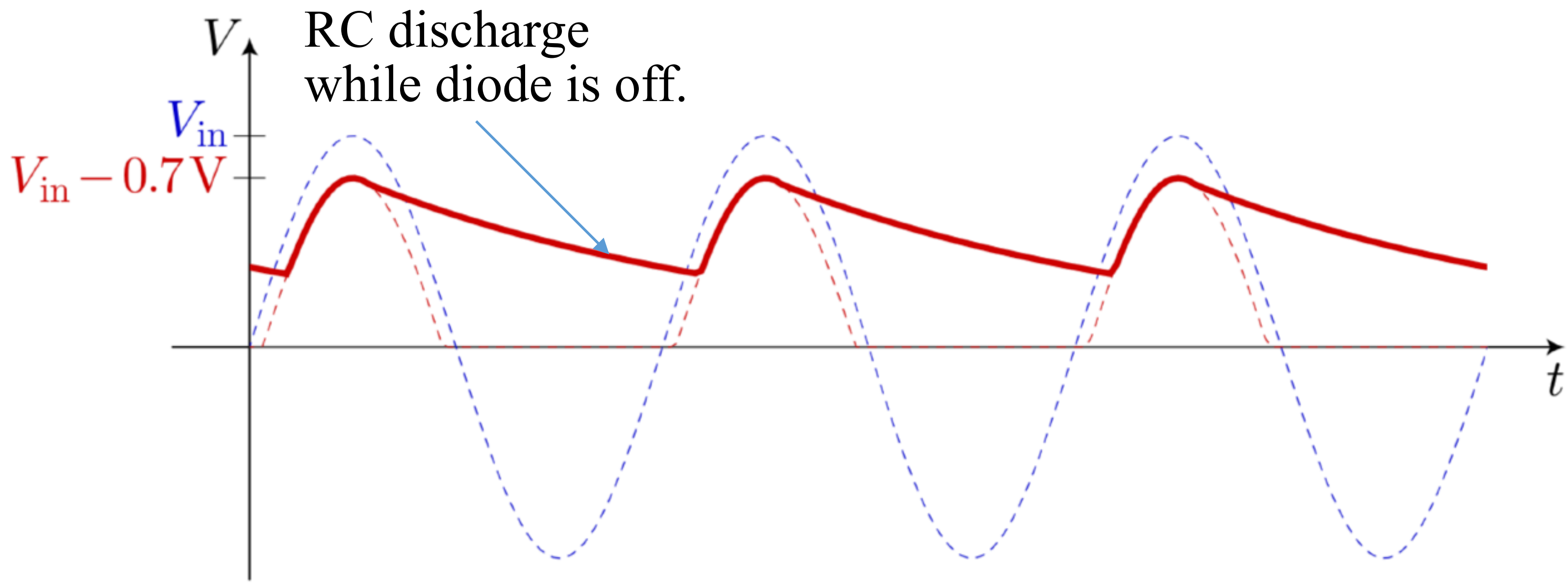


When V_{in} goes negative, diode is reverse biased ⇒ open circuit.

Diode power supply circuits

Can use this to convert an AC signal to a DC signal, e.g., in a power supply, with a capacitor to provide current between swings.





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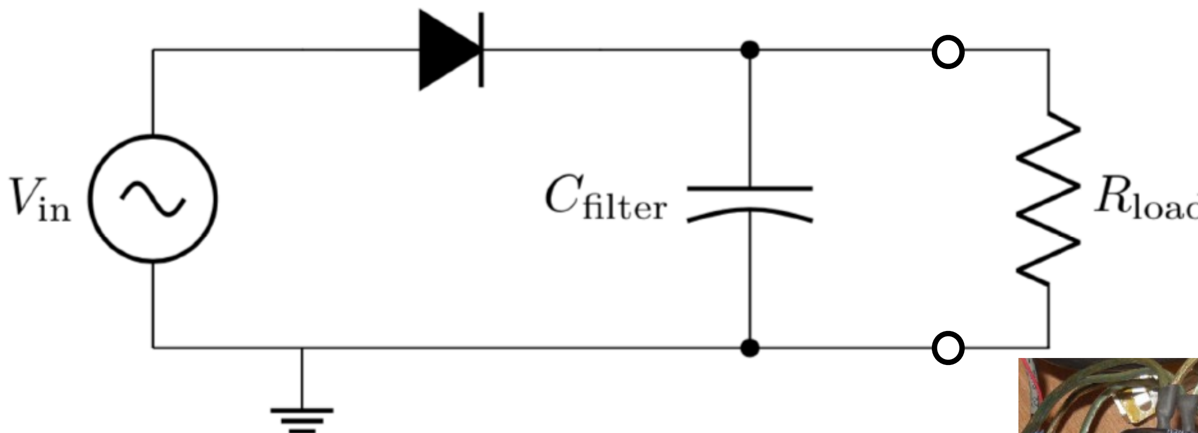

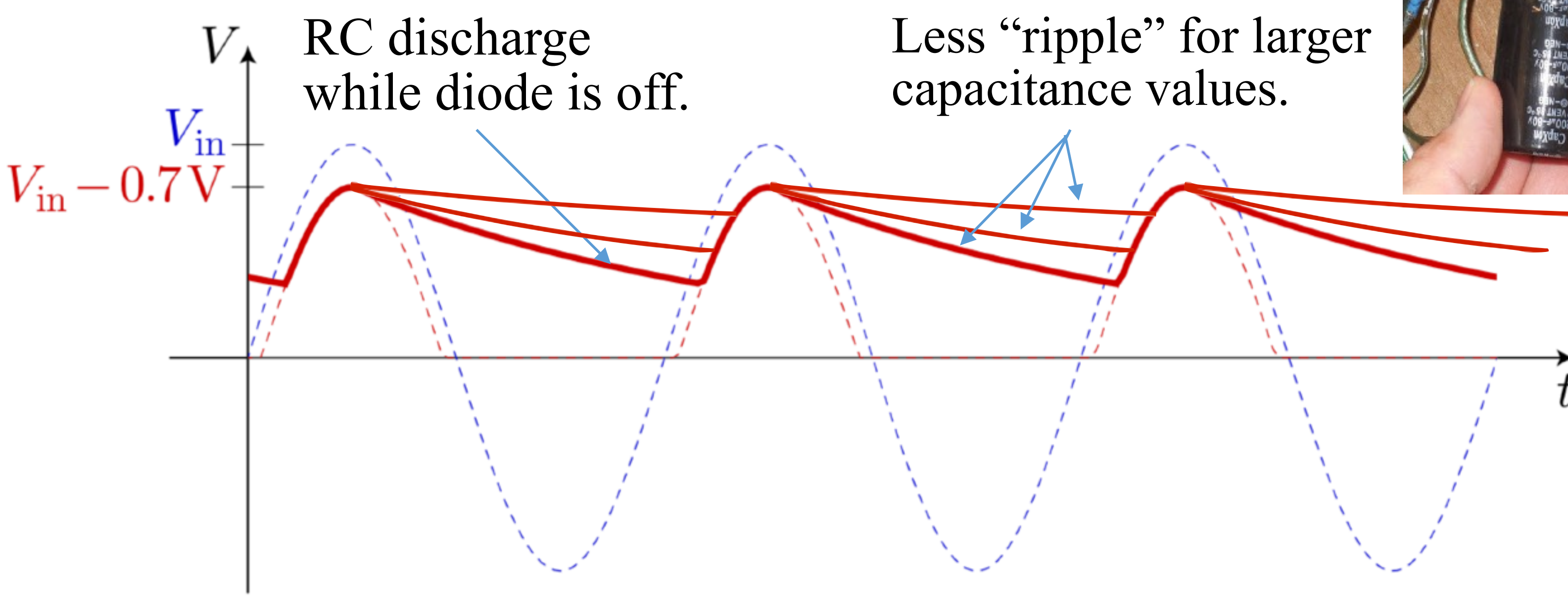

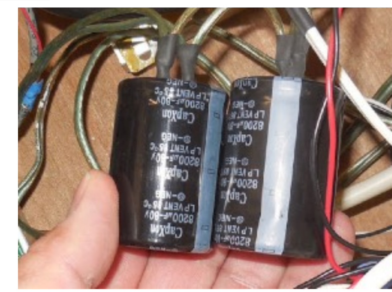

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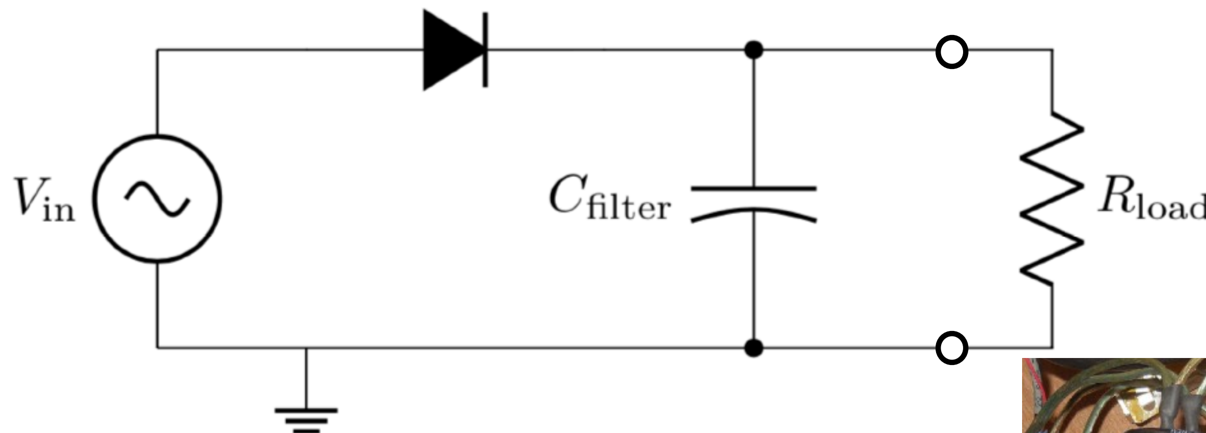
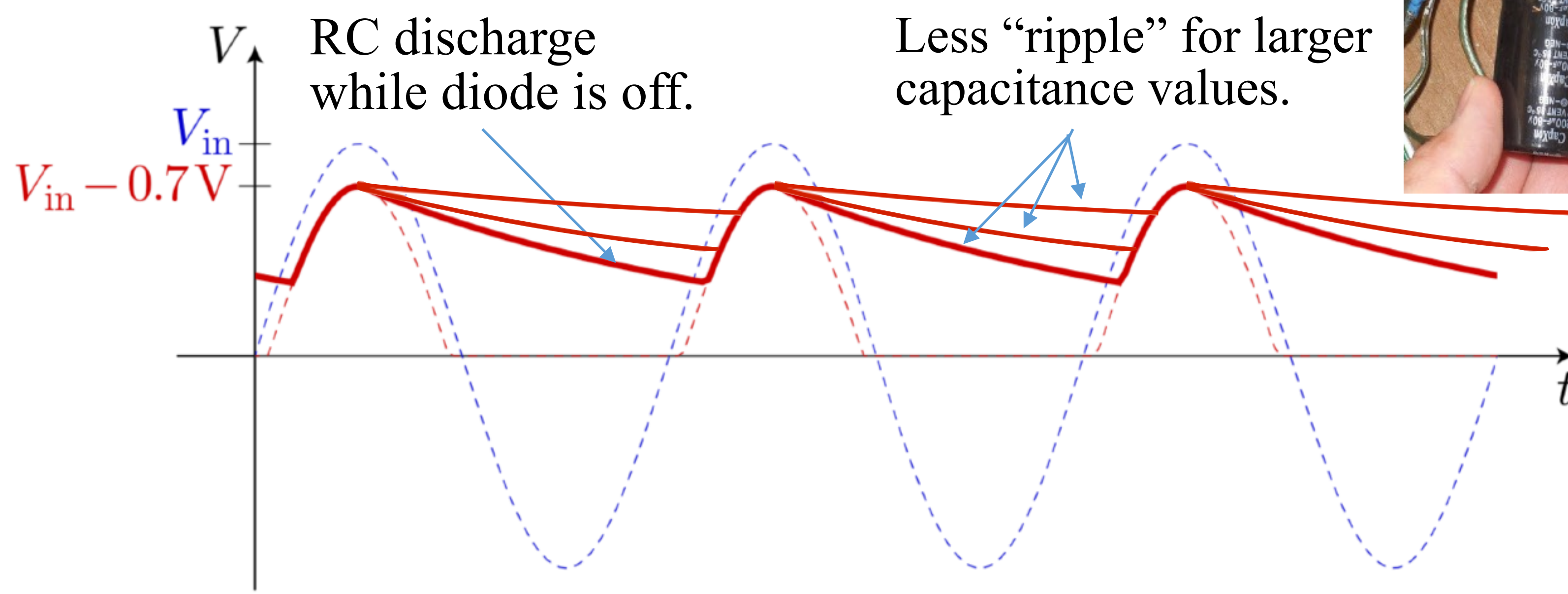
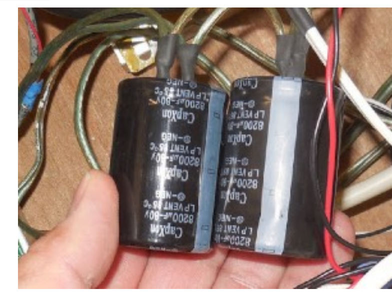


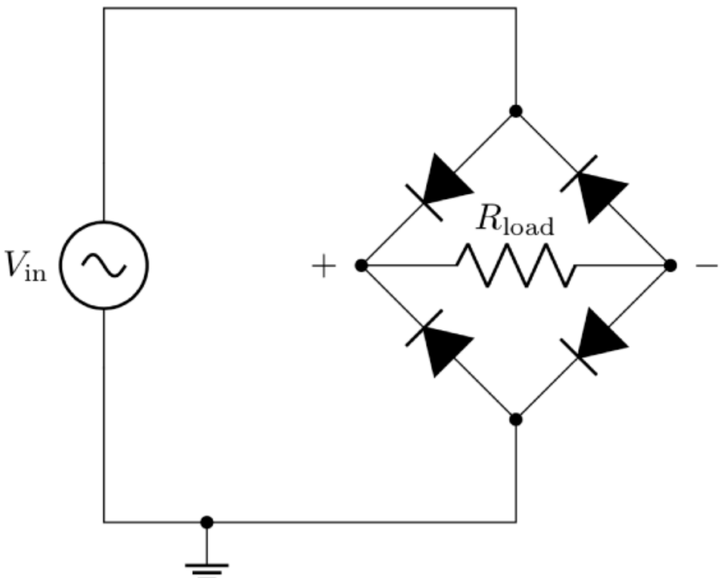


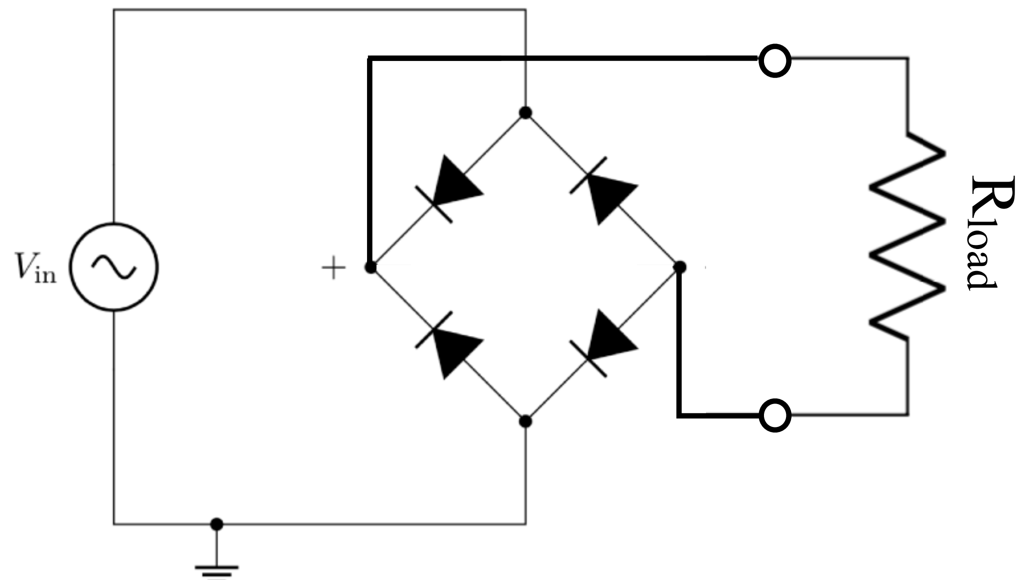


But the negative swings are wasted.

Diode power supply circuits

Can use the negative swing with four diodes in a “full-wave rectifier” circuit.





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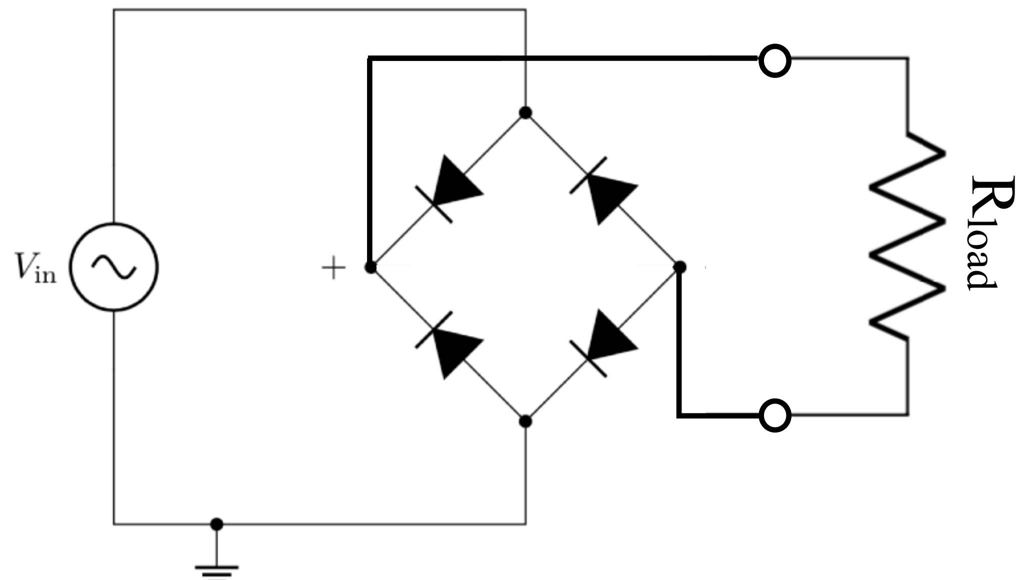

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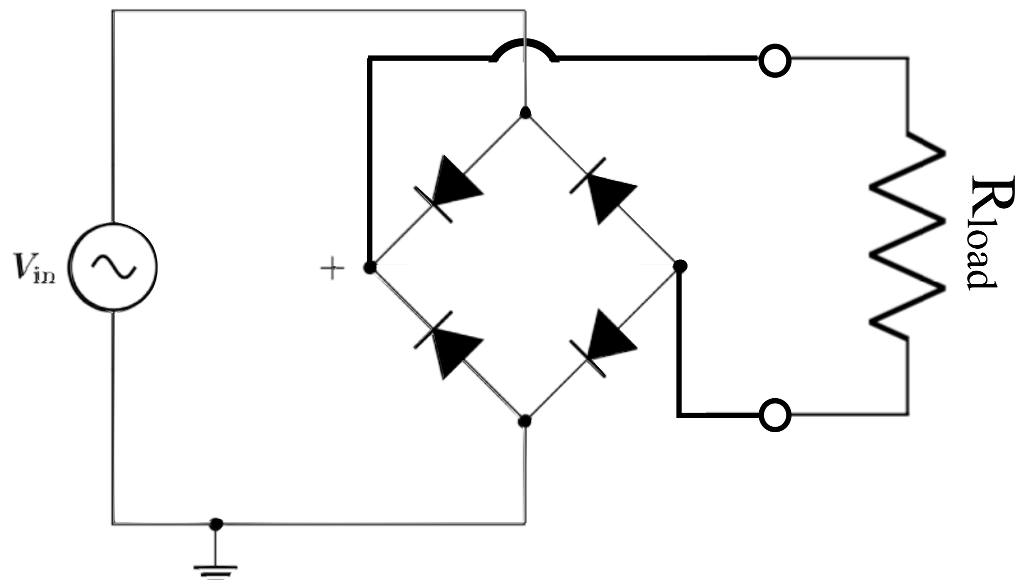

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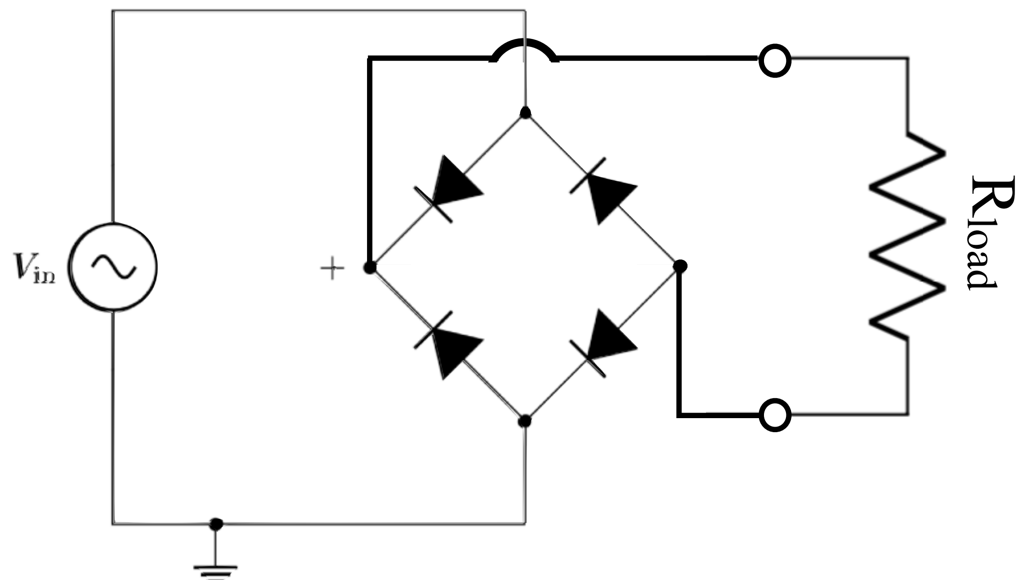

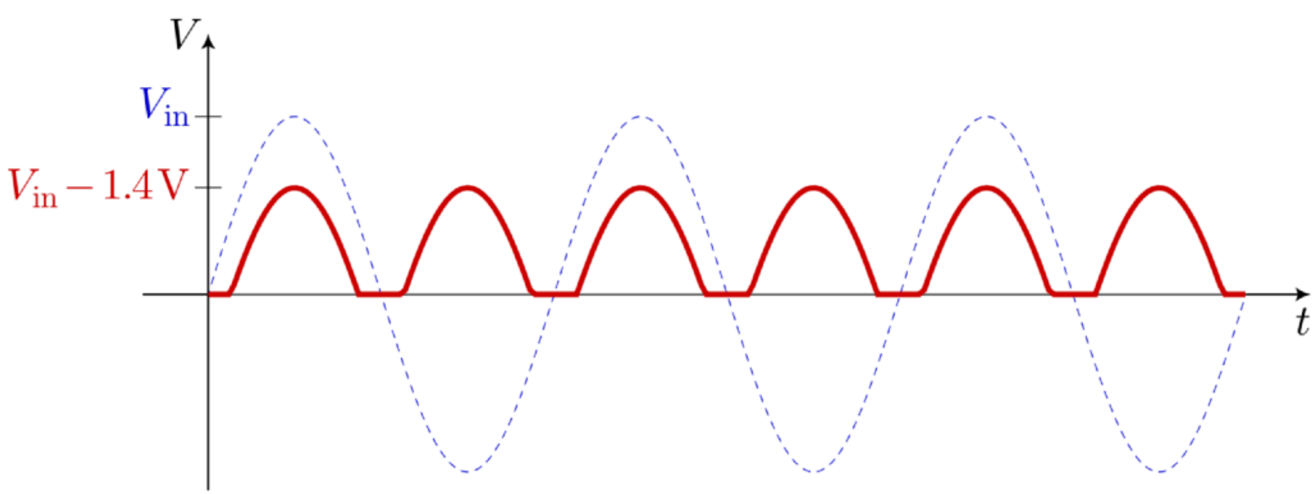

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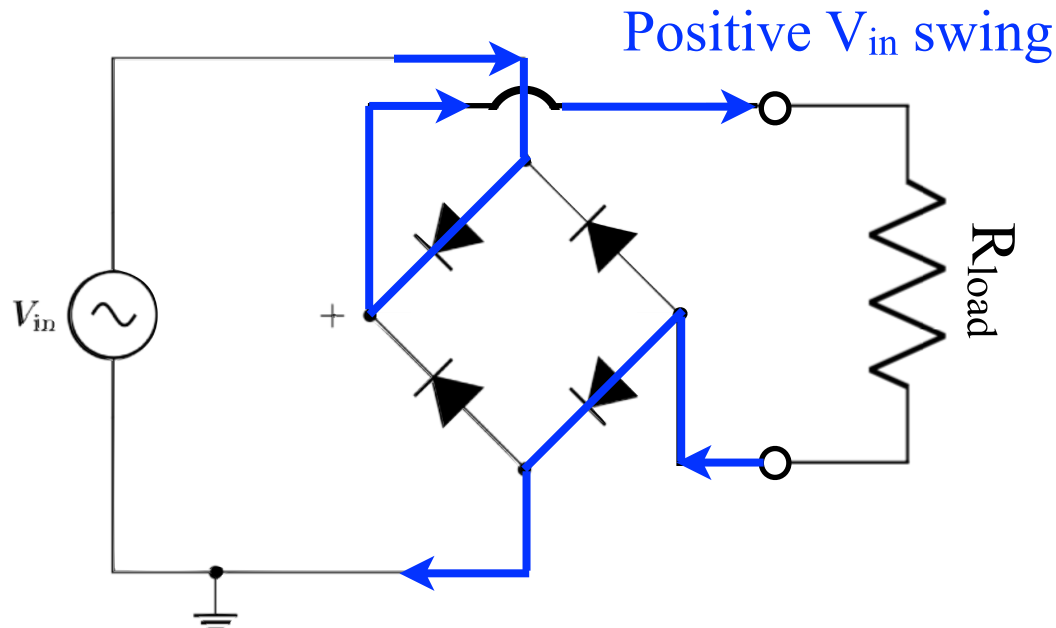

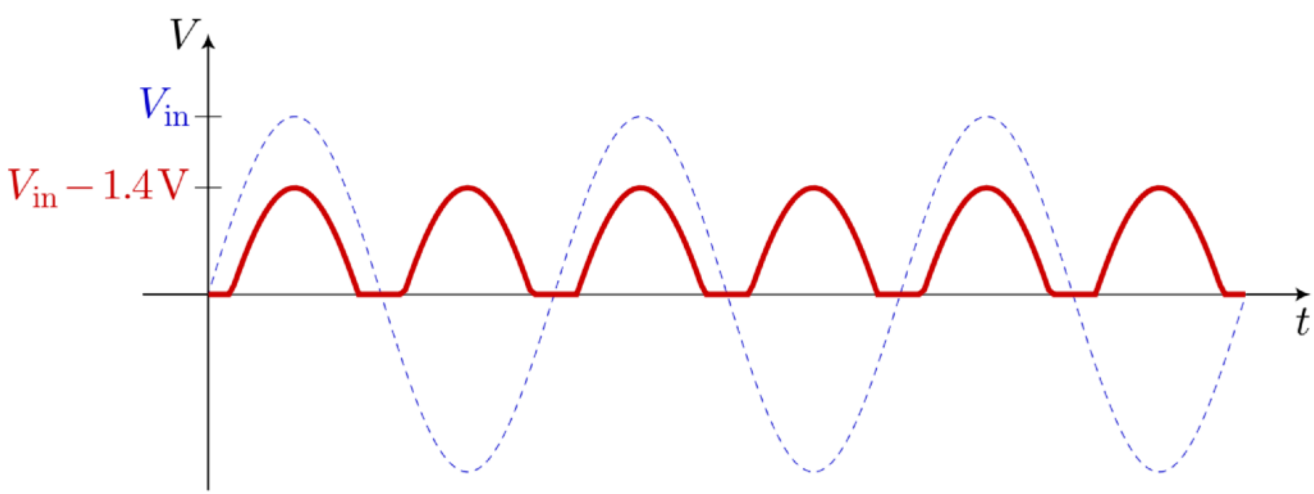

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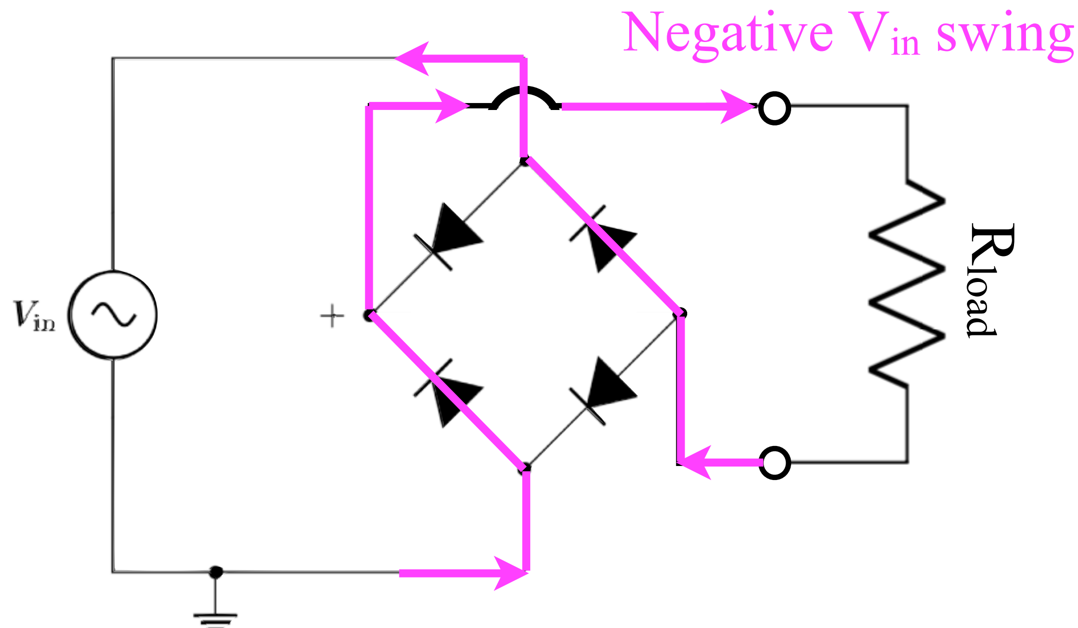
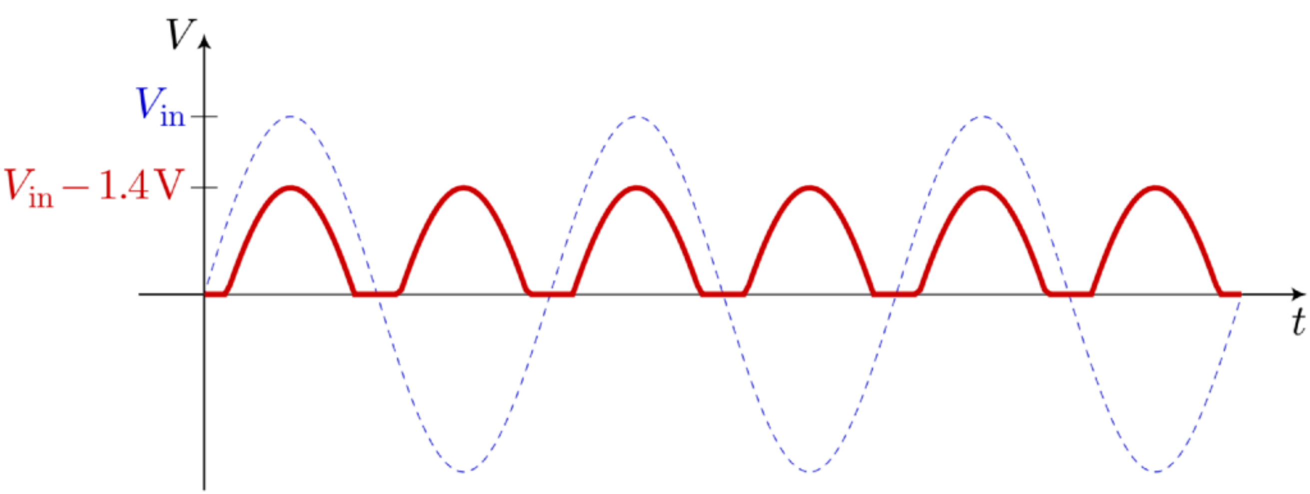
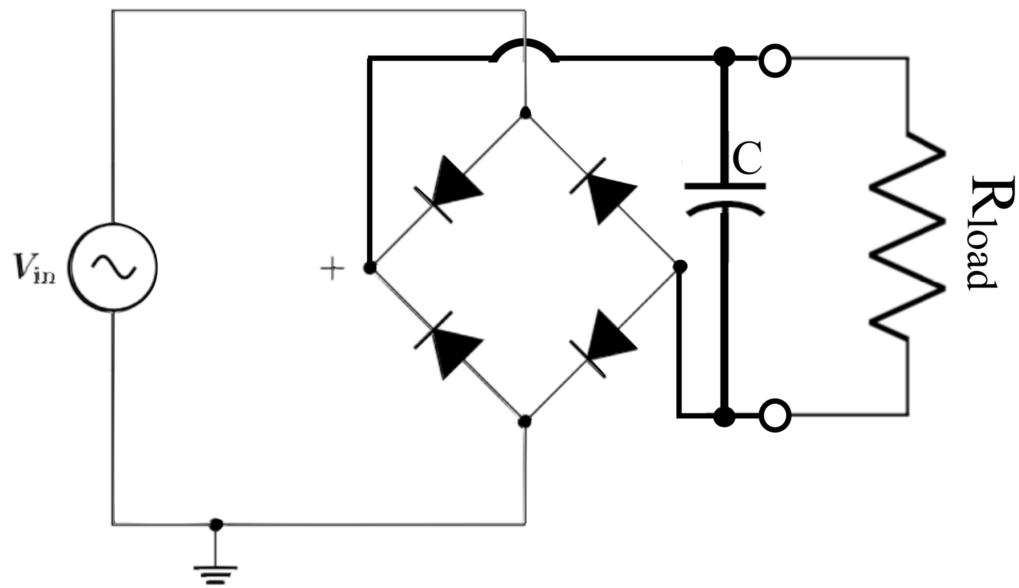


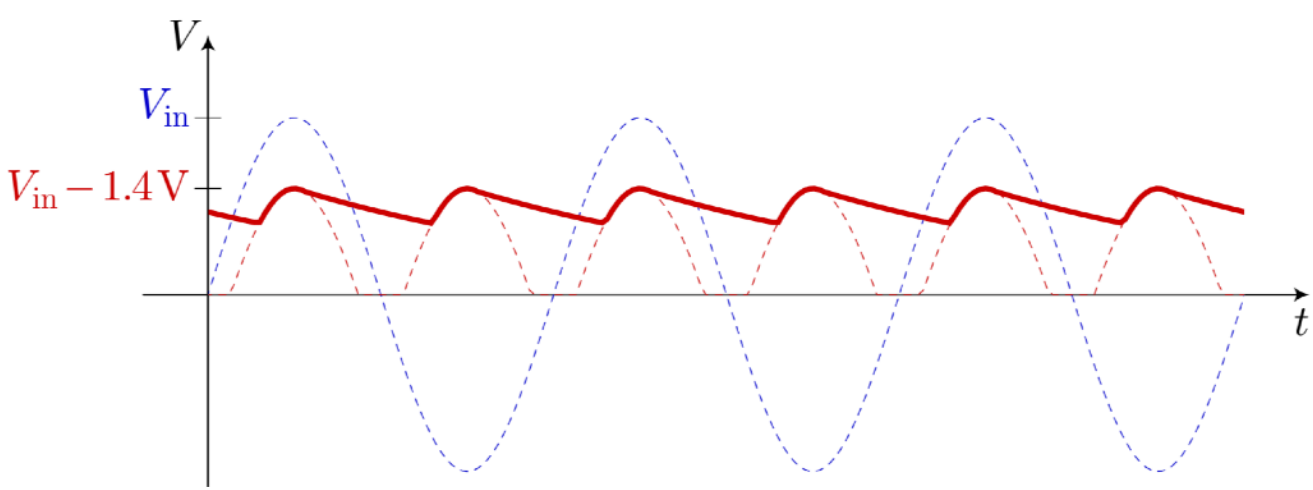


Voltage across R_{load} is positive for both half-cycles, but we have two diode drops, 1.4 V, given up in the rectifier.

Diode power supply circuits

Can use the negative swing with four diodes in a "full-wave rectifier" circuit.





Again, a capacitor can smooth the ripple between peaks.

Note use of electrolytic cap here.

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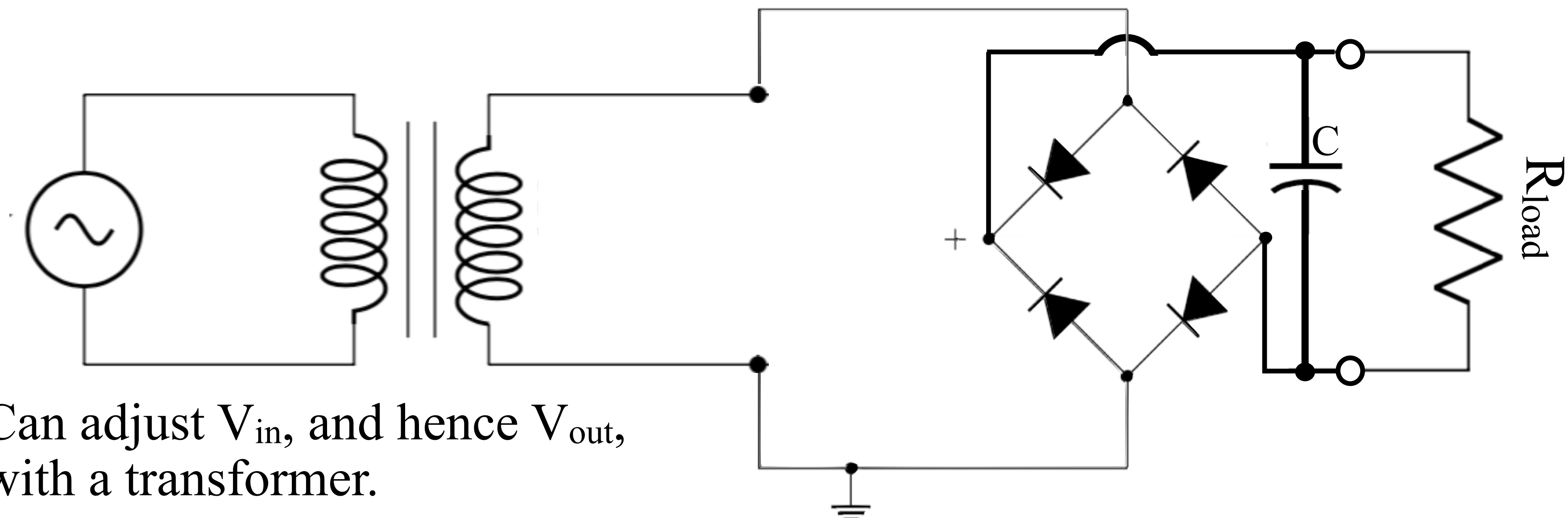
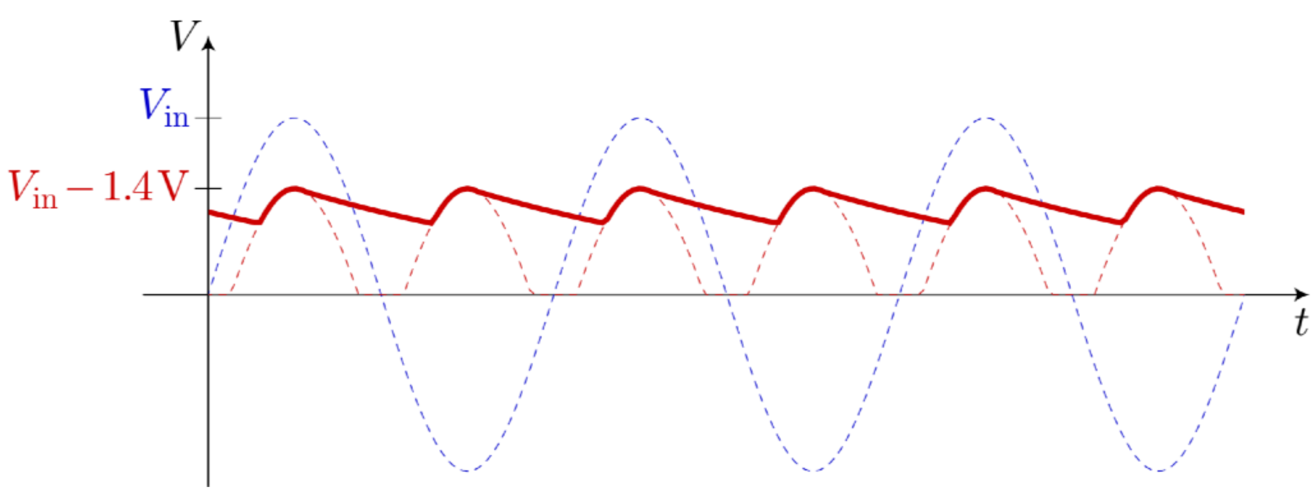


Can adjust V_{in}, and hence V_{out}, with a transformer.



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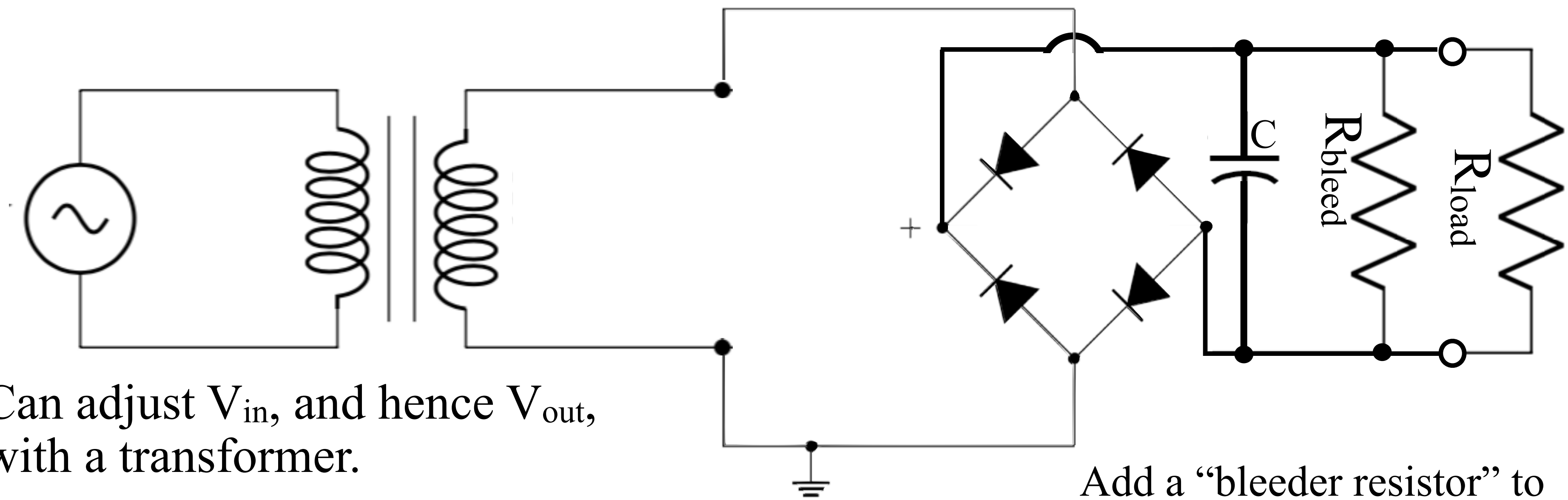

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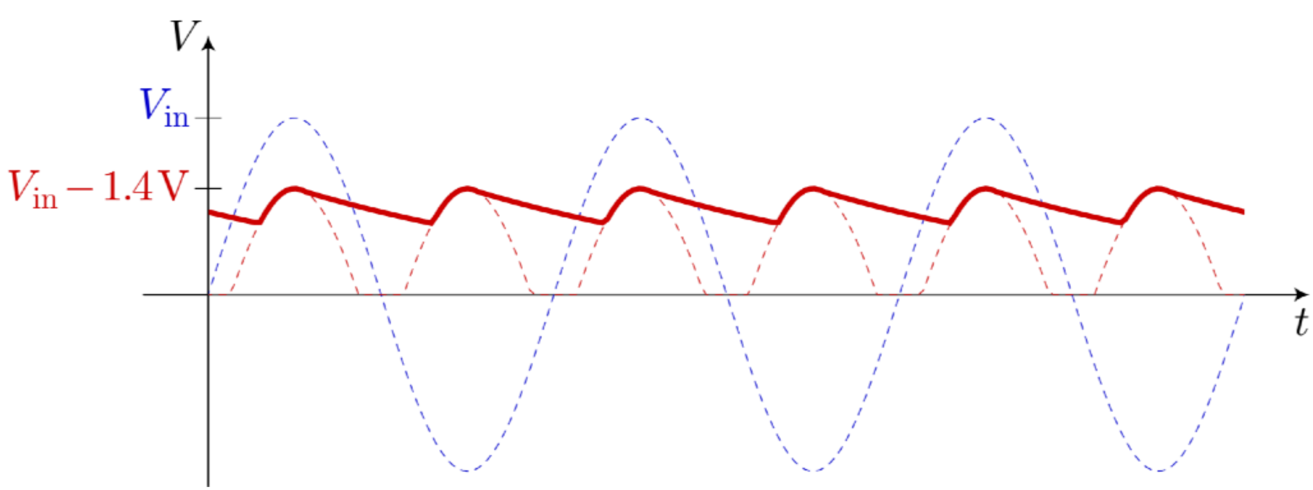

Add a "bleeder resistor" to discharge the large capacitor and avoid a shock if load is disconnected and power turned off.

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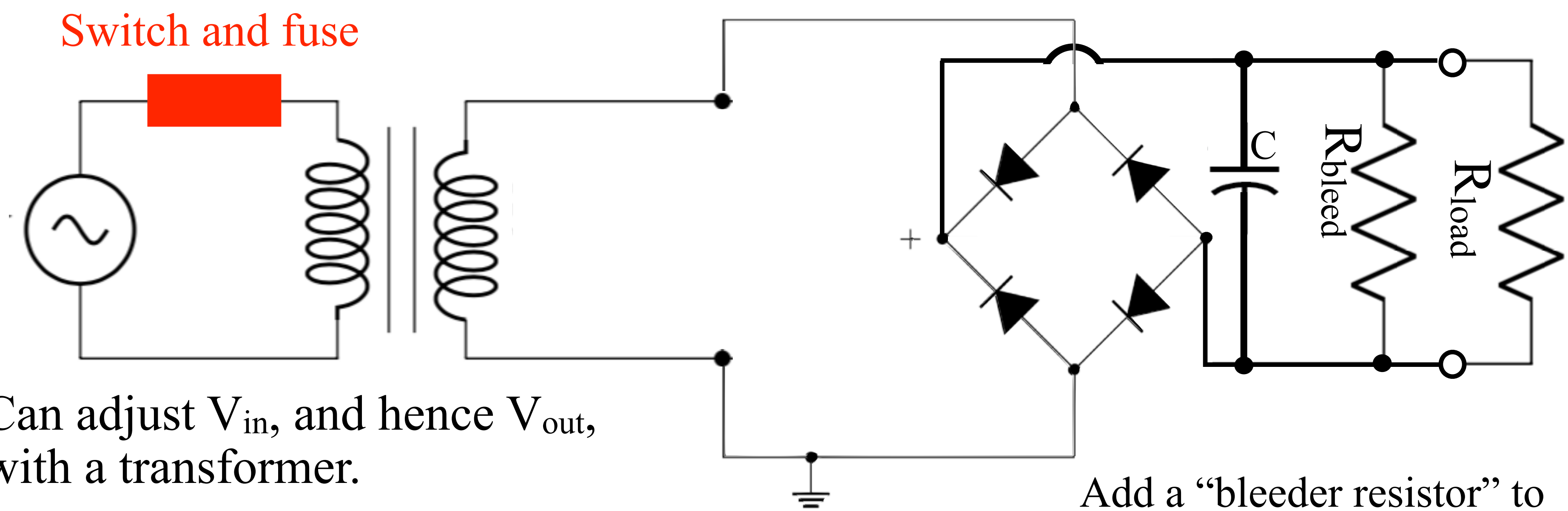

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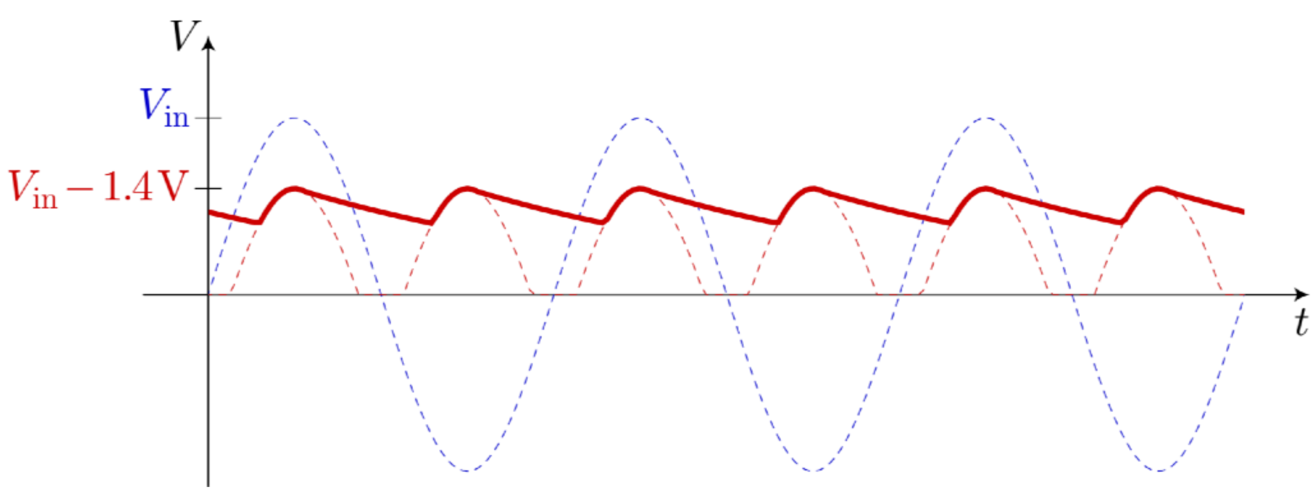

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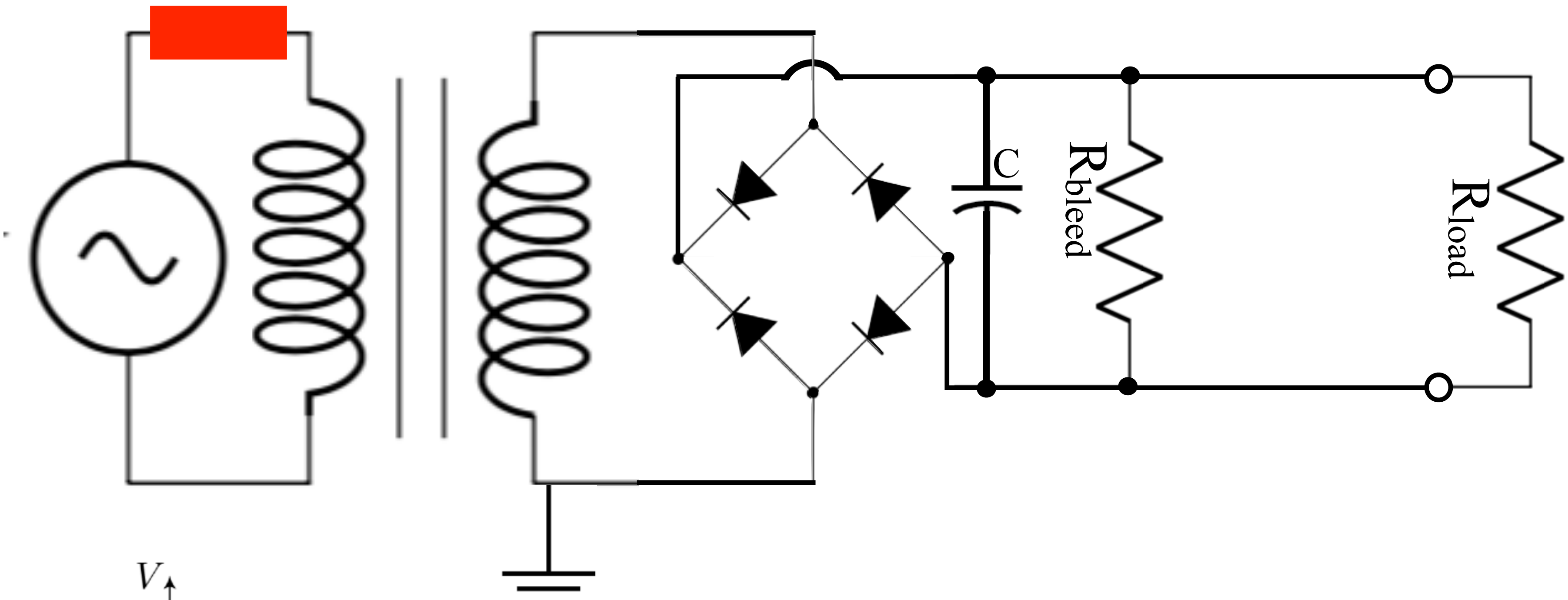
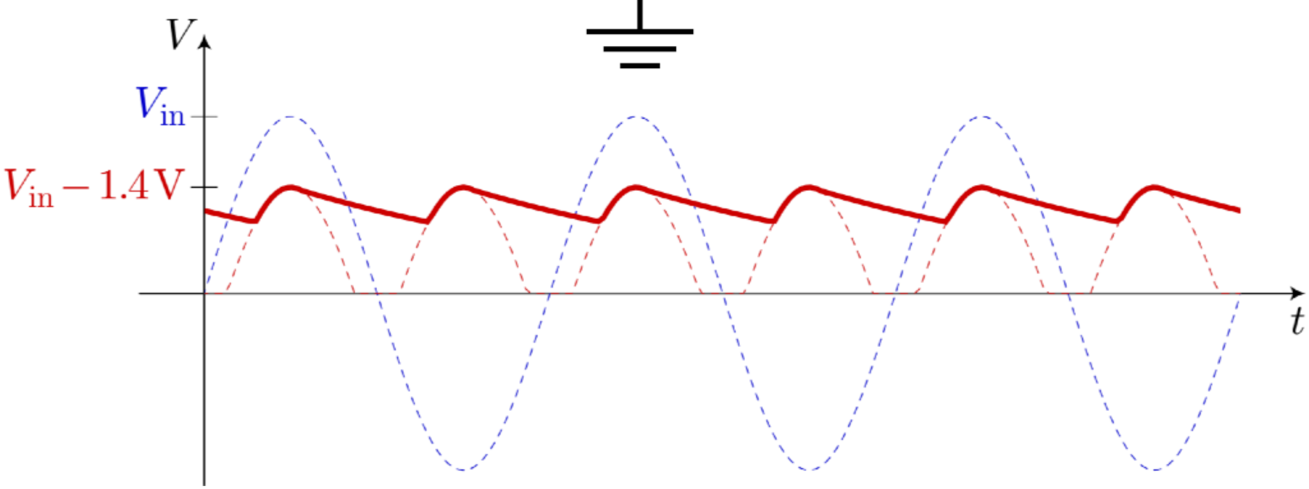
Diode power supply circuits

Full DC power supply circuit





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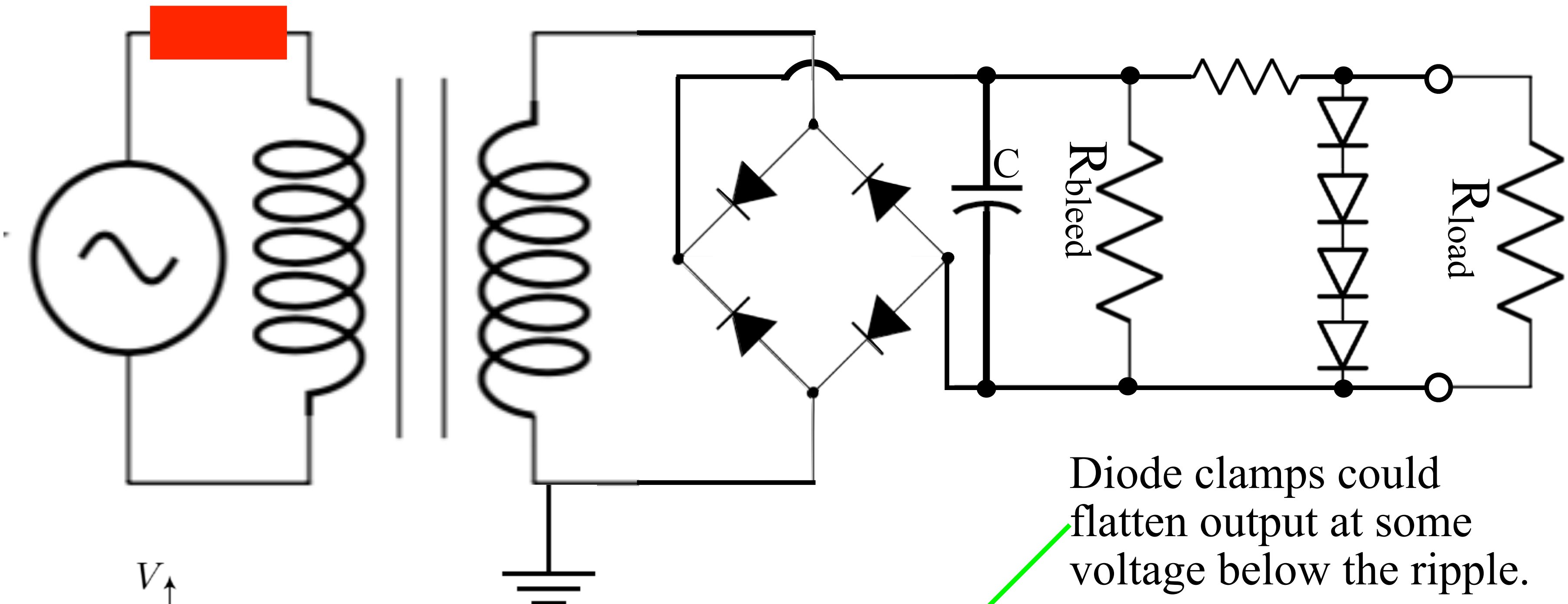
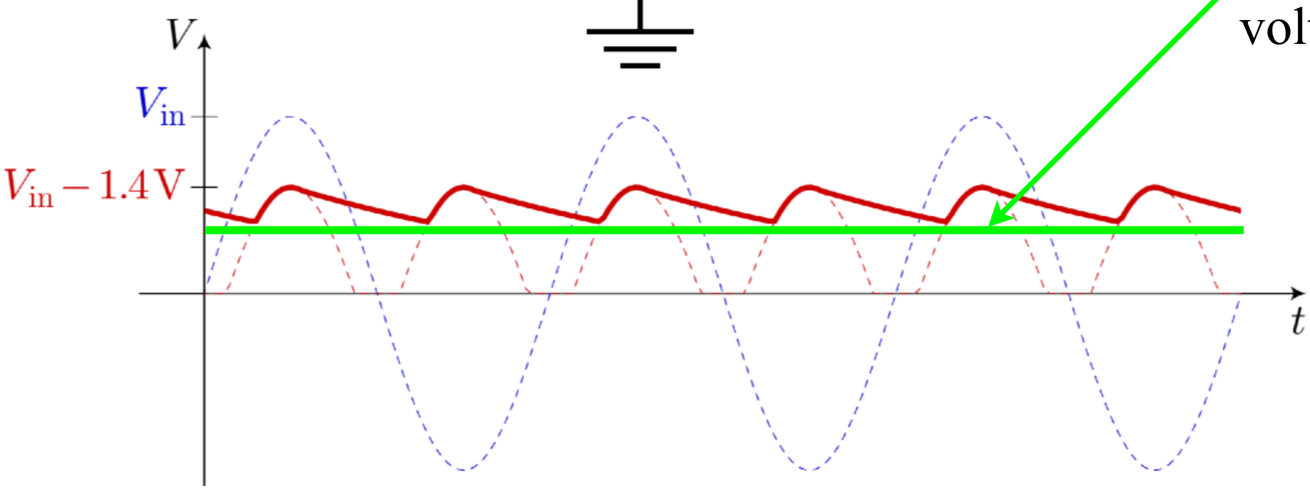


Diode clamps could flatten output at some voltage below the ripple.



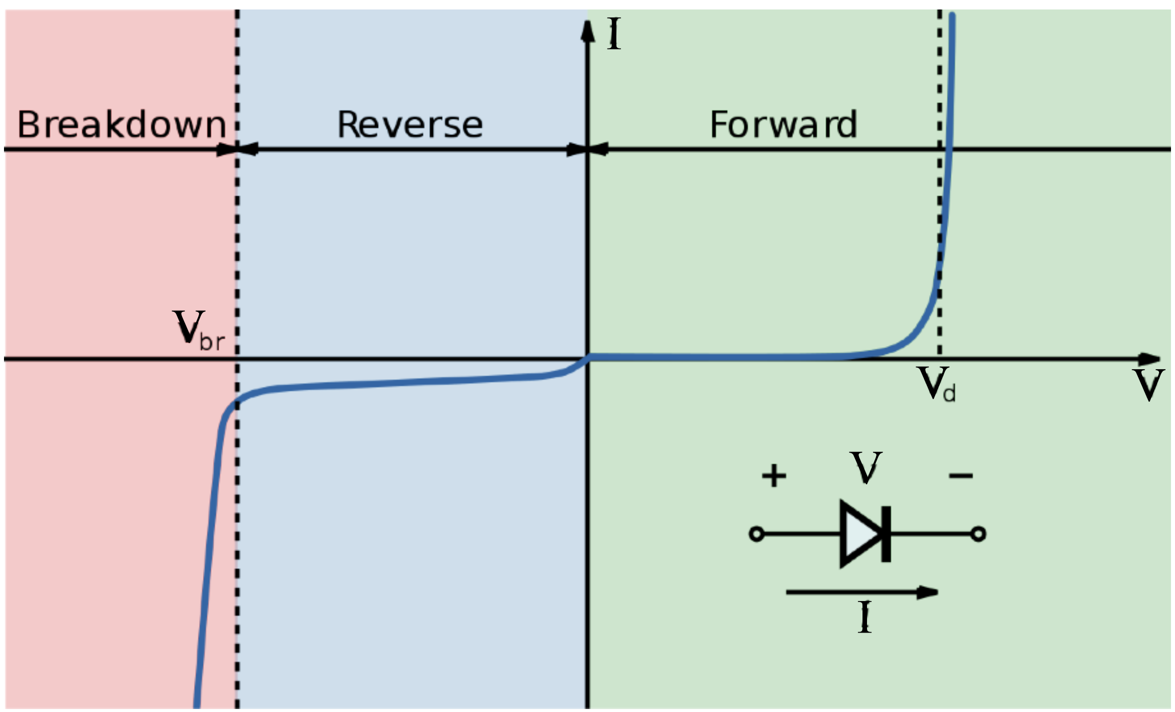
But chaining a large number of diodes, N*0.7 V, is inefficient.

Zener diodes

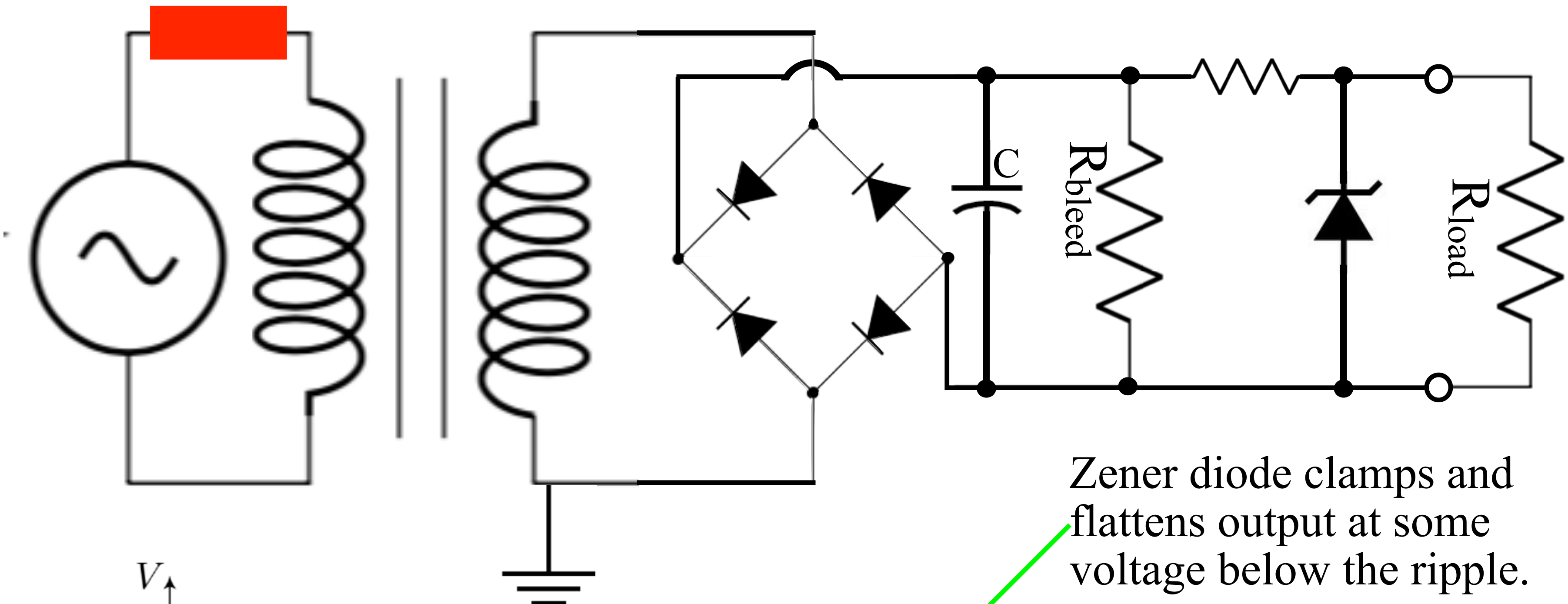
Diodes can be engineered to have a specific breakdown voltage.

Then we can run them reverse biased to clamp at their V_{br}.

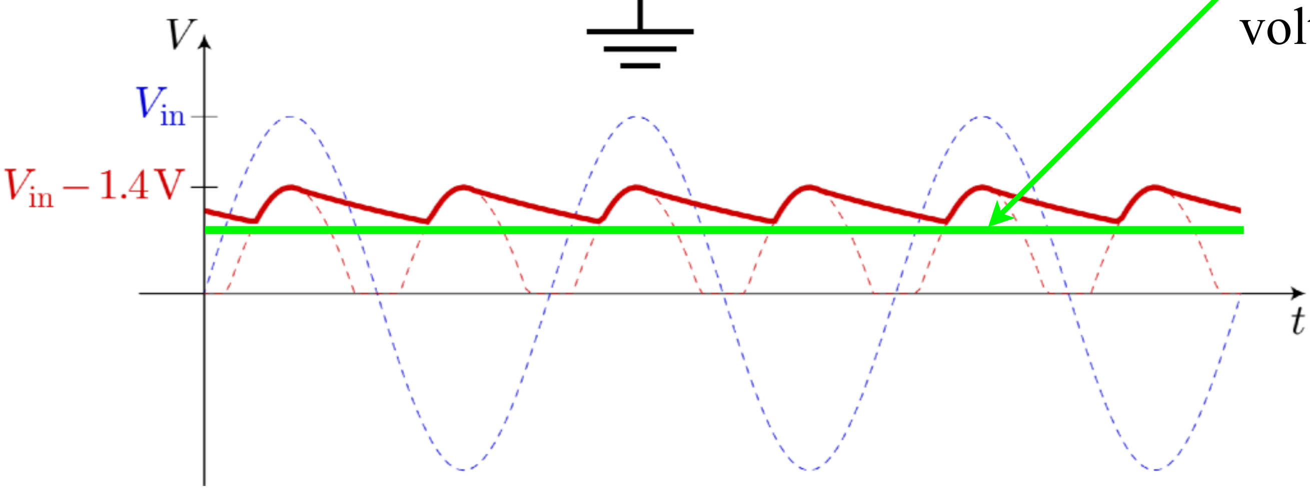
These are called Zener diodes.



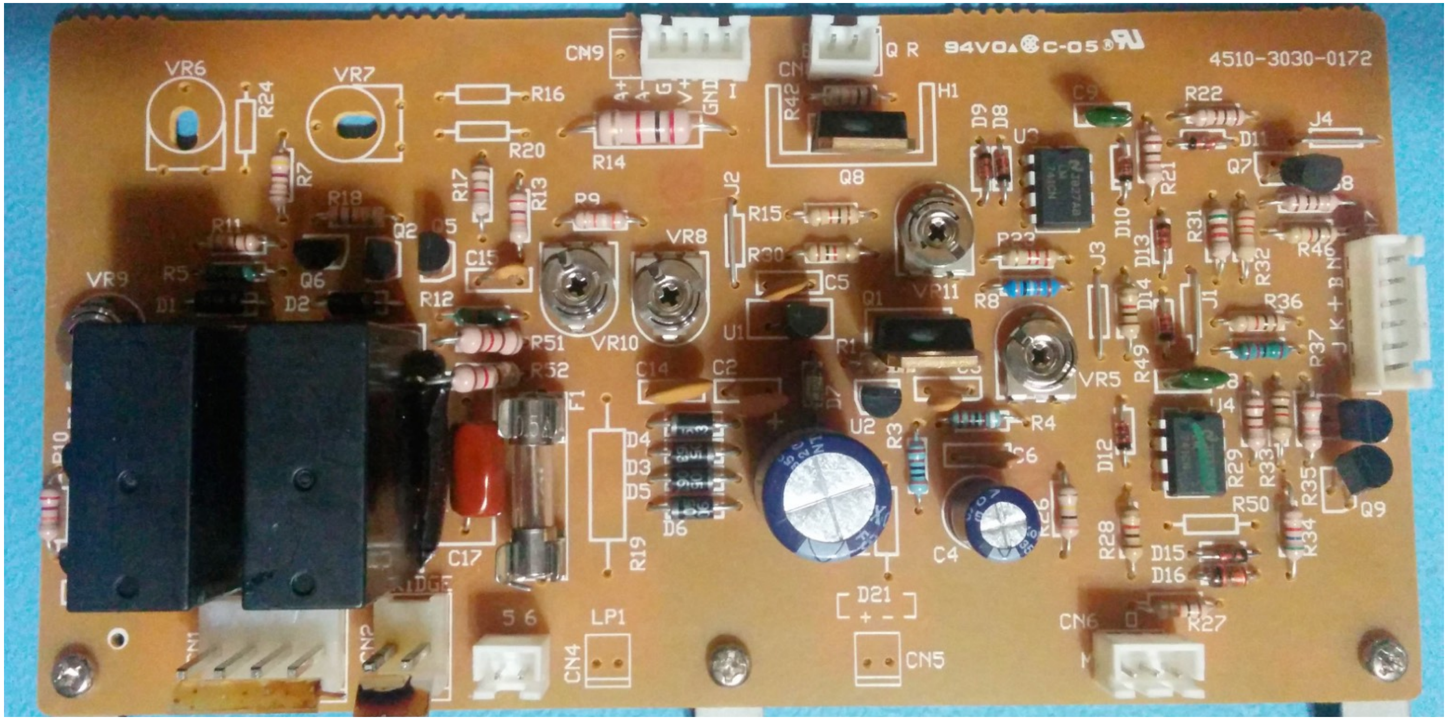
Final diode power supply circuits

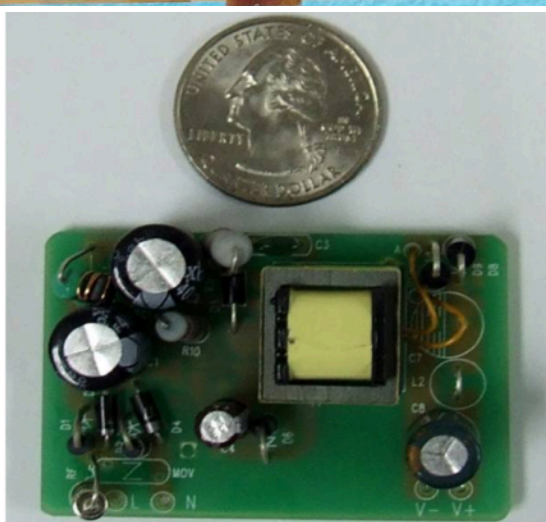


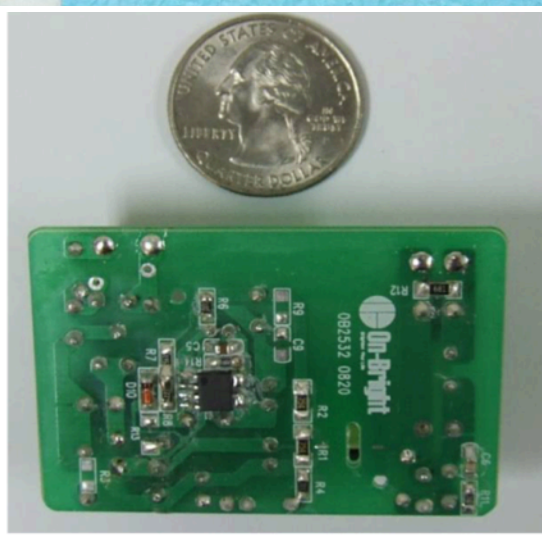
Zener diode clamps and flattens output at some voltage below the ripple.



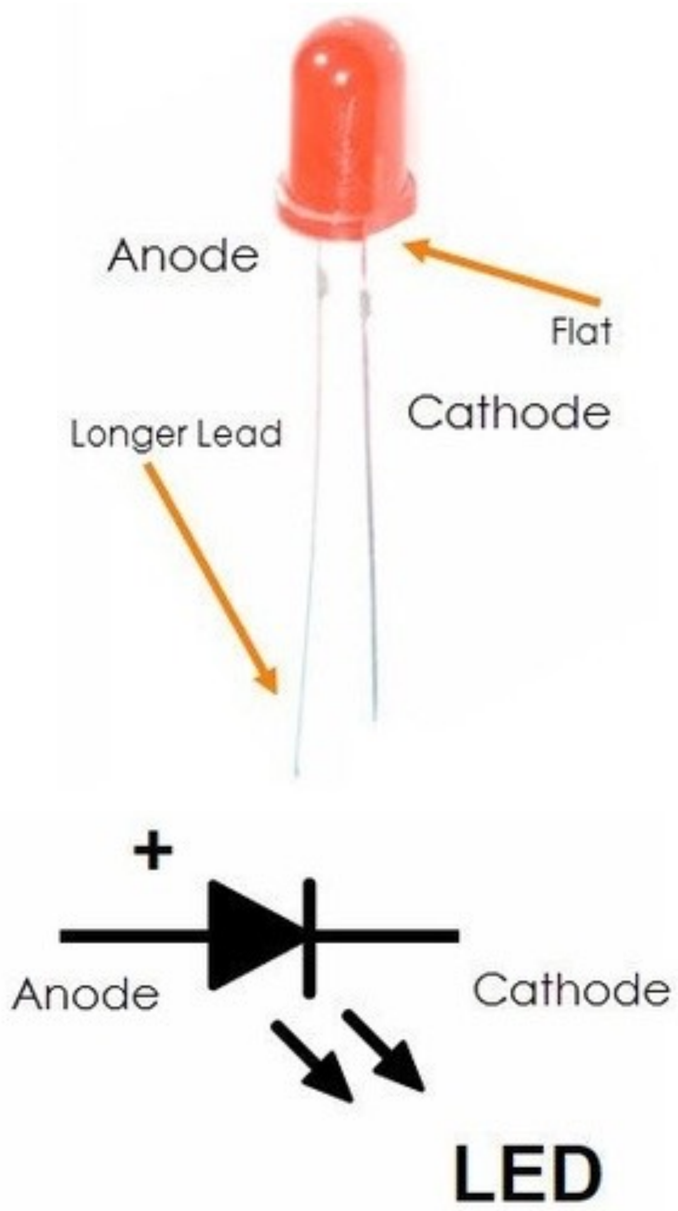
AC to DC power supply examples

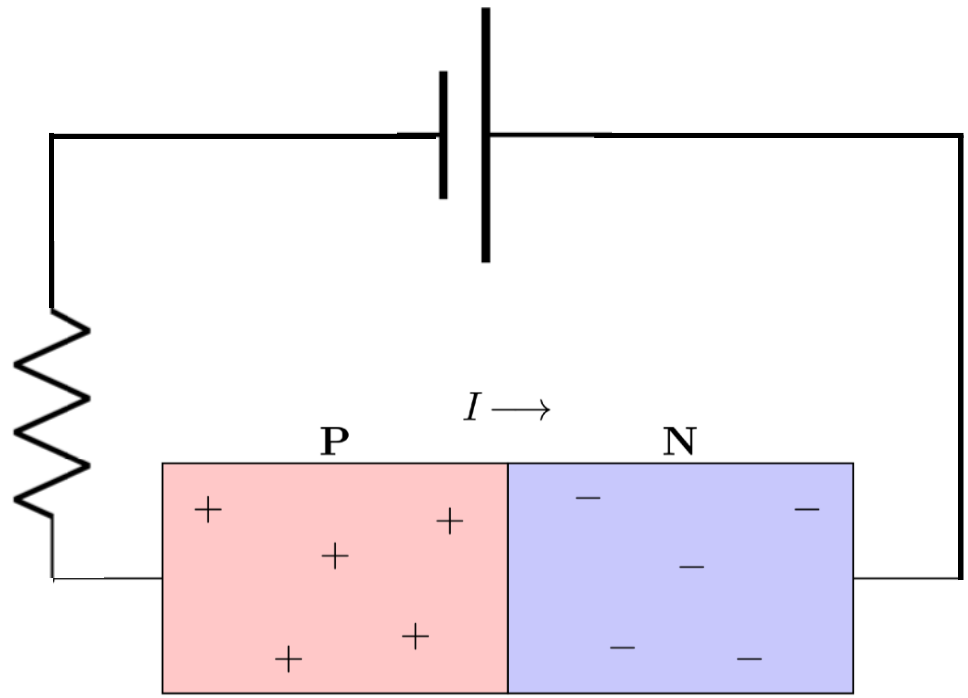






Light Emitting Diodes





(no depletion zone)

Photo Diodes