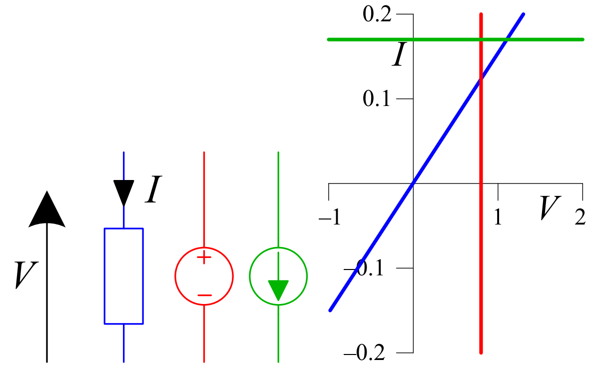
8: Nonlinear Components

Ideal Diode

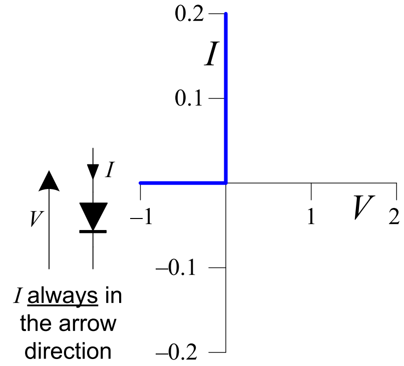
The *characteristic* of a component is a plot of I against V using the passive sign convention.

All our components have had straight-line characteristics.



An ideal *diode* allows current to flow in one direction only.

Its characteristic is not a straight line, but is made from two straight line segments: *piecewise-linear*. Each segment is a *mode of operation*.



Each mode applies only when a particular condition is true:

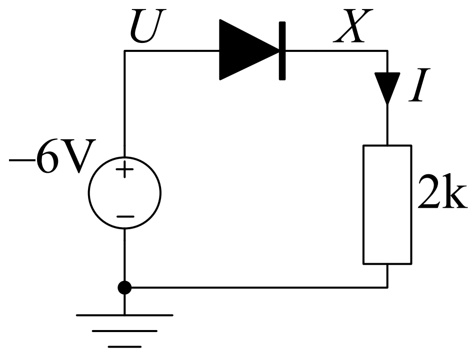
Mode	Condition	Equation
Conducting (or "forward bias" or "on")	$I > 0$	$V = 0$
Non-conducting (or "reverse bias" or "off")	$V < 0$	$I = 0$

Operating modes

To analyse a circuit with a diode in it, you first guess which mode it is operating in, solve the circuit and then check the condition.
If you guessed wrongly, the condition will not be met.

Mode	Condition	Equation
Conducting	$I > 0$	$V_D = 0$
Non-conducting	$V_D < 0$	$I = 0$

Voltage across diode is $V_D = U - X$.
Current through diode is $I = \frac{X}{2}\text{ mA}$.

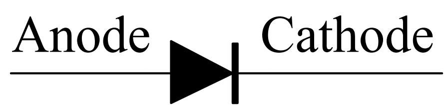


Assume Conducting Mode $\Rightarrow V_D = 0$

$V_D = 0 \Rightarrow X = U = -6 \Rightarrow I = -3$
but condition is $I > 0$ so bad guess

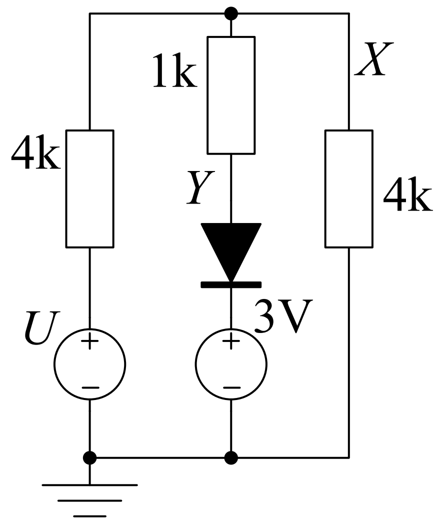
Assume Non-conducting Mode $\Rightarrow I = 0$

$I = 0 \Rightarrow X = 2I = 0 \Rightarrow V_D = U - X = -6$
condition is $V_D < 0$ so good guess



Current flows from *anode* to *cathode*.

How does X change with U ?

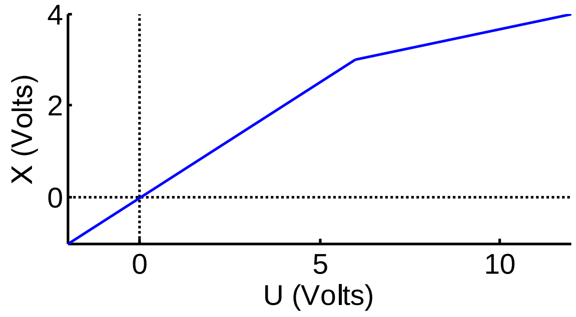


Voltage across diode is $V_D = Y - 3$.
Current through diode is $I_D = \frac{X-Y}{1}$ mA.

Assume Conducting Mode $\Rightarrow Y = 3$

KCL: $\frac{X-U}{4} + \frac{X-3}{1} + \frac{X}{4} = 0$
$\Rightarrow X = \frac{1}{6}U + 2$
$I_D = \frac{X-3}{1} = \frac{1}{6}U - 1$
$I_D > 0 \Leftrightarrow U > 6$

Assume Non-conducting Mode
$\Rightarrow I_D = 0$



Potential Div: $X = Y = \frac{1}{2}U$
$V_D = Y - 3 = \frac{1}{2}U - 3$
$V_D < 0 \Leftrightarrow U < 6$

Diode switches between regions where the graphs intersect $(U = 6)$.
At this point both the diode equations, $V_D = 0$ and $I_D = 0$, are true.

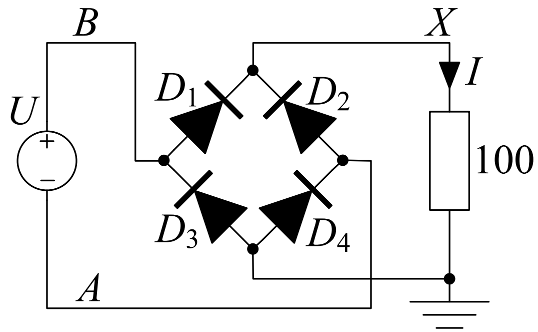
Bridge Rectifier

Bridge Rectifier: 4 diodes:

D_1 and D_2 both point towards node X.

D_3 and D_4 both point away from ground.

The input voltage is $U = B - A$.



Case 1: $U > 0$. D_1,D_4 on $\Rightarrow X = U$

Check D_1, D_4: $I_1 = I_4 = I = \frac{U}{100} > 0$

Check D_2, D_3: $V_2 = V_3 = -U < 0$

All diodes OK

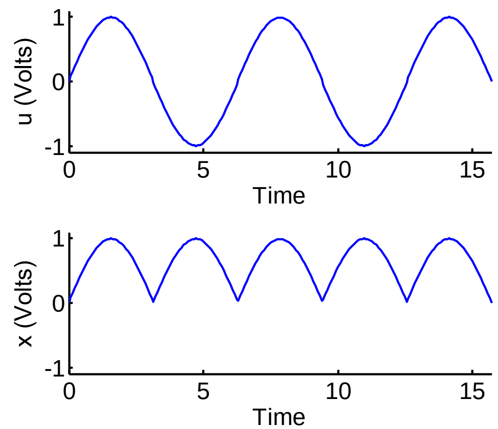
Note: I_n,V_n apply to diode n

Case 2: $U < 0$. D_2,D_3 on $\Rightarrow X = -U$

Check D_2, D_3: $I_{2,3} = I = \frac{-U}{100} > 0$

Check D_1, D_4: $V_1 = V_4 = U < 0$

All diodes OK

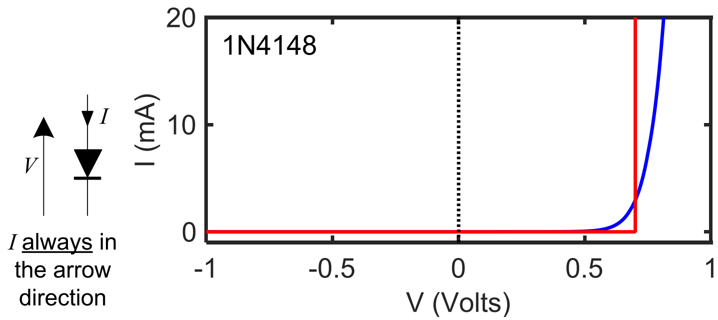


X is always equal to $|U|$: this is an absolute value circuit.

If U is a sine wave, then X is a *full-wave rectified* sine wave with twice the frequency.

Non-Ideal Diode

An *ideal* diode allows has $V = 0$ whenever it is “on”.



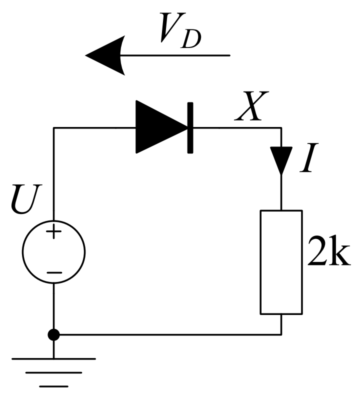
A *real* diode has a voltage drop that depends approximately logarithmically on the current: it increases by about $0.1\,\text{V}$ for every 50-fold increase in current.

For a wide range of currents we can treat V as almost constant:
(a) For low-current circuits (e.g $I < 20\,\text{mA}$): $V \simeq 0.7\,\text{V}$.
(b) For high-current circuits: $V \simeq 1.0\,\text{V}$.

The two regions of operation are now:

Region	Condition	Equation
Conducting Mode (“on”)	$I > 0$	$V = 0.7$
Non-conducting Mode (“off”)	$V < 0.7$	$I = 0$

A halfwave rectifier aims for $X = \max(U, 0)$



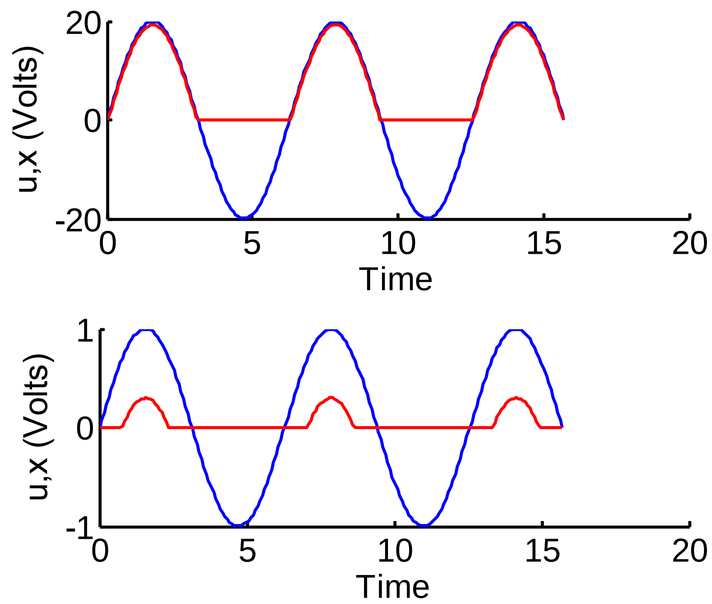
(a) $U > 0.7$
Diode on, $X = U - 0.7$, $I = \frac{U-0.7}{2\,\text{k}} > 0$

(b) $U < 0.7$
Diode off, $I = 0$, $X = 0$, $V_D = U < 0.7$

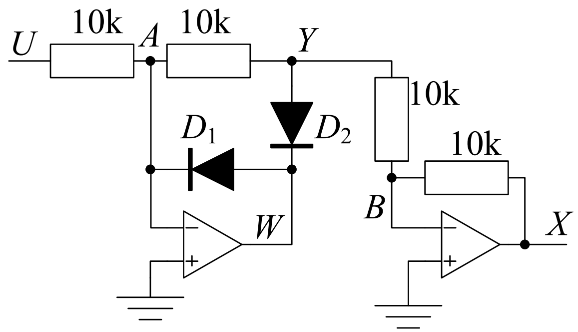
We actually have $X = \max(U - 0.7, 0)$

(1) $u(t) = 20\sin\omega t$
The $0.7\,\text{V}$ drop makes little difference.

(2) $u(t) = \sin\omega t$
The $0.7\,\text{V}$ drop makes a big difference.



Both op-amps have negative feedback, so $A = B = 0$.
Second op-amp is an inverting amplifier so $X = -Y$.



Note: I_n, V_n apply to diode n

Case 1: $U > 0$. D_2 on $\Rightarrow W = Y - 0.7$

KCL @ A: $\frac{0-U}{10} + \frac{0-Y}{10} = 0$

$\Rightarrow Y = -U$

KCL @ Y: $\frac{Y-0}{10} + \frac{Y-0}{10} + I_2 = 0$

$\Rightarrow I_2 = \frac{U}{5} > 0$

Check D_1: $V_1 = -U - 0.7 < 0.7$

Both diodes OK

Output: $X = -Y = U$

Case 2: $U < 0$. D_1 on $\Rightarrow W = 0.7$

KCL @ Y: $\frac{Y-0}{10} + \frac{Y-0}{10} = 0 \Rightarrow Y = 0$

KCL @ A: $\frac{0-U}{10} + \frac{0-0}{10} + -I_1 = 0$

$\Rightarrow I_1 = -\frac{U}{10} > 0$

Check D_2: $V_2 = Y - W = -0.7 < 0.7$

Both diodes OK

Output: $X = -Y = 0$

So $X = \max(U, 0)$

Putting diodes in a feedback loop allows their voltage drops to be eliminated.

- Beware: a nonlinear circuit does not obey superposition
- Ideal diode:
  - Two regions of operation:
    - ▷ Conducting Mode (= "on"): $V = 0$ and $I > 0$
    - ▷ Non-conducting Mode (= "off"): $I = 0$ and $V < 0$
- Solving a diode circuit:
  - (a) Guess region
  - (b) Solve circuit: assuming $V = 0$ or $I = 0$
  - (c) Check condition: either $I > 0$ or $V < 0$
- Real diode: $V \simeq 0.7$ in Conducting Mode ($\simeq 1.0$ for high currents)
- Fullwave and halfwave rectifier circuits
- Precision Rectifier Circuit
  - Use an opamp to eliminate the $0.7\,\mathrm{V}$ diode drop.

For further details see Irwin Ch 17.