<table>
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<th>Nonlinear Components</th>
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<tr>
<td>Non-Ideal Diode</td>
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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.
The *characteristic* of a component is a plot of $I$ against $V$ using the passive sign convention.

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Ideal Diode

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

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<td>$V &lt; 0$</td>
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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.

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Voltage across diode is $V_D = U - X$. Current through diode is $I = \frac{X}{2} \text{ mA}$. 
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Assume Conducting Mode $\Rightarrow V_D = 0$
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![Circuit Diagram]
Operating modes

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$V_D = 0 \Rightarrow X = U = -6$
Operating modes

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$V_D = 0 \Rightarrow X = U = -6 \Rightarrow I = -3$
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Operating modes

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Voltage across diode is \( V_D = U - X \).
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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 \( \Rightarrow I = 0 \)
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condition is \( V_D < 0 \) so **good guess**
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.

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

**Assume Conducting Mode** ⇒ $V_D = 0$

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but condition is $I > 0$ so bad guess

**Assume Non-conducting Mode** ⇒ $I = 0$

$I = 0 \Rightarrow X = 2I = 0 \Rightarrow V_D = U - X = -6$

condition is $V_D < 0$ so good guess

Current flows from anode to cathode.
Switching Point

How does $X$ change with $U$?
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.
Switching Point

How does $X$ change with $U$?

Voltage across diode is $V_D = Y - 3$.

Current through diode is $I_D = \frac{X-Y}{1} \text{ mA}$.

Assume Conducting Mode $\Rightarrow Y = 3$
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: $\frac{X - U}{4} + \frac{X - 3}{1} + \frac{X}{4} = 0$
$\Rightarrow X = \frac{1}{6}U + 2$
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 $\Rightarrow Y = 3$

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$$I_D = \frac{X - 3}{1} = \frac{1}{6}U - 1$$
Switching Point

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Voltage across diode is $V_D = Y - 3$.
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$I_D = \frac{X-3}{1} = \frac{1}{6}U - 1$
$I_D > 0 \Leftrightarrow U > 6$
How does $X$ change with $U$?

Voltage across diode is $V_D = Y - 3$.
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Assume Non-conducting Mode
$\Rightarrow I_D = 0$
Switching Point

8: Nonlinear Components

- Ideal Diode
- Operating modes
- Switching Point
- Bridge Rectifier
- Non-Ideal Diode
- Halfwave Rectifier
- Precision Halfwave Rectifier
- Summary

How does $X$ change with $U$?

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

Assume Conducting Mode $\Rightarrow Y = 3$

\[
\text{KCL: } \frac{X-U}{4} + \frac{X-3}{1} + \frac{X}{4} = 0 \Rightarrow X = \frac{1}{6}U + 2
\]
\[
I_D = \frac{X-3}{1} = \frac{1}{6}U - 1
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I_D > 0 \iff U > 6
\]

Assume Non-conducting Mode

$\Rightarrow I_D = 0$

Potential Div: $X = Y = \frac{1}{2}U$
Switching Point

How does $X$ change with $U$?

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

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: $X = Y = \frac{1}{2}U$
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How does $X$ change with $U$?

Voltage across diode is $V_D = Y - 3$.

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Assume Non-conducting Mode

$\Rightarrow I_D = 0$

Potential Div: $X = Y = \frac{1}{2}U$

$V_D = Y - 3 = \frac{1}{2}U - 3$

$V_D < 0 \Leftrightarrow U < 6$
How does $X$ change with $U$?

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

**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
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$I_D = \frac{X-3}{1} = \frac{1}{6}U - 1$
$I_D > 0 \iff U > 6$

**Assume Non-conducting Mode**

$\Rightarrow I_D = 0$

Potential Div: $X = Y = \frac{1}{2}U$

$V_D = Y - 3 = \frac{1}{2}U - 3$
$V_D < 0 \iff U < 6$

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 $U = B - A$. 
Bridge Rectifier

**Bridge Rectifier:** 4 diodes:

- $D_1$ and $D_2$ both point towards node $X$.
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The input voltage is $U = B - A$.

**Case 1:** $U > 0$. 
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The input voltage is $U = B - A$.

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

*Bridge Rectifier:* 4 diodes:

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

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

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

*Note:* $I_n, V_n$ apply to diode $n$
**Bridge Rectifier**

*Bridge Rectifier:* 4 diodes:

- $D_1$ and $D_2$ both point towards node $X$.
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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 $D_2, D_3$: $V_2 = V_3 = -U < 0$

Note: $I_n, V_n$ apply to diode $n$
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All diodes OK

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**Bridge Rectifier**

*Bridge Rectifier:* 4 diodes:

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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

**Case 2:** $U < 0$.

---

*Note: $I_n, V_n$ apply to diode $n$*
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 $\Rightarrow X = U$

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

All diodes OK

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

**Note:** $I_n, V_n$ apply to diode $n$
Bridge Rectifier

**Bridge Rectifier:** 4 diodes:
- $D_1$ and $D_2$ both point towards node $X$.
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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

**Case 2:** $U < 0$. $D_2, D_3$ on $\Rightarrow X = -U$
- Check $D_2, D_3$: $I_{2,3} = I = \frac{-U}{100} > 0$

Note: $I_n, V_n$ apply to diode $n$
**Bridge Rectifier**

*Bridge Rectifier:* 4 diodes:

- $D_1$ and $D_2$ both point towards node $X$.
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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

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

*Note:* $I_n, V_n$ apply to diode $n$
**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

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

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

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

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If $U$ is a sine wave,
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Check $D_2, D_3$: $I_2, I_3 = I = -\frac{U}{100} > 0$

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

$I$ always in the arrow direction.
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A *real* diode has a voltage drop that depends approximately logarithmically on the current: it increases by about $0.1 \, V$ for every $50$-fold increase in current.
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For a wide range of currents we can treat $V$ as almost constant:
Non-Ideal Diode

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

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- (b) For high-current circuits: $V \simeq 1.0 \text{ V}$.
An *ideal* diode allows has \( V = 0 \) whenever it is “on”.

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For a wide range of currents we can treat \( V \) as almost constant:

- (a) For low-current circuits (e.g \( I < 20 \text{ mA} \)): \( V \approx 0.7 \text{ V} \).
- (b) For high-current circuits: \( V \approx 1.0 \text{ V} \).

The two regions of operation are now:

<table>
<thead>
<tr>
<th>Region</th>
<th>Condition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conducting Mode (“on”)</td>
<td>( I &gt; 0 )</td>
<td>( V = 0.7 )</td>
</tr>
<tr>
<td>Non-conducting Mode (“off”)</td>
<td>( V &lt; 0.7 )</td>
<td>( I = 0 )</td>
</tr>
</tbody>
</table>
A halfwave rectifier aims for $X = \max(U, 0)$
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(a) $U > 0.7$

Diode on, $X = U - 0.7$, $I = \frac{U - 0.7}{2k} > 0$
A halfwave rectifier aims for \( X = \max(U, 0) \)

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   We actually have $X = \max(U - 0.7, 0)$
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(1) $u(t) = 20 \sin \omega t$
   The 0.7 V drop makes little difference.
Halfwave Rectifier

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

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

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(1) \( u(t) = 20 \sin \omega t \)
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(2) \( u(t) = \sin \omega t \)
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Both op-amps have negative feedback, so $A = B = 0$. Second op-amp is an inverting amplifier so $X = -Y$. 
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Note: \( I_n, V_n \) apply to diode \( n \)
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Output: $X = -Y = U$

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Both op-amps have negative feedback, so \( A = B = 0 \).

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\text{KCL @ A: } \frac{0-U}{10} + \frac{0-Y}{10} = 0 \Rightarrow Y = -U
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Check \( D_1 \): \( V_1 = -U - 0.7 < 0.7 \)
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Output: \( X = -Y = U \)

**Case 2: \( U < 0 \).** \( D_1 \) on \( \Rightarrow W = 0.7 \)

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Note: \( I_n, V_n \) apply to diode \( n \)

So \( X = \max(U, 0) \)
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Both diodes OK
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Note: $I_n, V_n$ apply to diode $n$

Putting diodes in a feedback loop allows their voltage drops to be eliminated.
Beware: a nonlinear circuit does not obey superposition
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Ideal diode:
  - Two regions of operation:
    - Conducting Mode ("on"): $V = 0$ and $I > 0$
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 \( V < 0 \)
Beware: a nonlinear circuit does not obey superposition

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- Two regions of operation:
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Solving a diode circuit:
- (a) Guess region
- (b) Solve circuit: assuming $V = 0$ or $I = 0$
- (c) Check condition: either $I > 0$ or $V < 0$
**Summary**

- **Beware:** a nonlinear circuit does not obey superposition

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- **Real diode:** $V \simeq 0.7$ in Conducting Mode ($\simeq 1.0$ for high currents)
8: Nonlinear Components

- Ideal Diode
- Operating modes
- Switching Point
- Bridge Rectifier
- Non-Ideal Diode
- Halfwave Rectifier
- Precision Halfwave Rectifier
- Summary

- **Beware:** a nonlinear circuit does not obey superposition

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- **Solving a diode circuit:**
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- Fullwave and halfwave rectifier circuits
Summary

- **Beware:** a nonlinear circuit does not obey superposition

- **Ideal diode:**
  - Two regions of operation:
    - **Conducting Mode** (= “on”): $V = 0$ and $I > 0$
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- **Solving a diode circuit:**
  - (a) Guess region
  - (b) Solve circuit: assuming $V = 0$ or $I = 0$
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  - Use an opamp to eliminate the 0.7 V diode drop.
Summary

• **Beware:** a nonlinear circuit does not obey superposition

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• Fullwave and halfwave rectifier circuits

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For further details see Irwin Ch 17.