**Counter**

Counter increments an unsigned binary value from 0 to N.

Consider a T flip-flop with hardwired input of 1:

The behavior can be represented by a timing diagram:

Value of Q toggles at each positive clock edge.

Notice that if the clock period is $t$, the period of the output $Q$ is exactly double the clock period, or $2t$. 
Counter

Now use the output of the first flip-flop as the clock input of another T flip-flop:

1 \rightarrow T \rightarrow Q \rightarrow Q_1 \rightarrow Q'_1

1 \rightarrow T \rightarrow Q \rightarrow Q_0 \rightarrow Q'_0

CLK

What will be the period of the second flip-flop output Q_1?
If we keep repeating this N times, the period of the Nth output will be 2^N \cdot t
How does this help build a counter?
Consider what it means to count in binary:

<table>
<thead>
<tr>
<th>$x_2$</th>
<th>$x_1$</th>
<th>$x_0$</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>7</td>
</tr>
</tbody>
</table>

The sequence of $x_0$ values looks like a clock with period 1: 0 1 0 1 0 1 0 1
The sequence of $x_1$ values looks like a clock with period 2: 0 0 1 1 0 0 1 1
The sequence of $x_2$ values looks like a clock with period 4: 0 0 0 1 1 1 1

However, notice when $x_1$ changes relative to $x_0$:
- $x_1$ goes from 0 to 1 (for example, value 1 to 2) when $x_0$ goes from 1 to 0
- $x_1$ goes from 1 to 0 (for example, value 3 to 4) when $x_0$ goes from 1 to 0

This means that we need to toggle $x_1$ when $x_0$ is on a negative edge, but we want to use positive-edge flip-flops.
Counter

Toggling $Q_1$ on a negative edge of $Q_0$ is the same as toggling $Q_1$ on a positive edge of $Q_0'$, so connect the negated output $Q'$ of each flip flop to the input of the next flip-flop.
Timing diagram for this 3-bit counter:

Read values in each column from left to right:

000, 001, 010, . . .

Variation: how would we use D flip-flops instead of T flip-flops?