Lecture 16: October 24, 2001

Logic with Complementary State Devices
A) Discovering a Pull-Up Device
B) Designing a Pull-Up Device
C) EE 42 Pull-Up Device Model (42PU)
D) Composite $I_{OUT}$ vs. $V_{OUT}$
E) Voltage Transfer Function and $V_M$

Reading:
Schwarz and Oldham pp. 607-611 (read for graphs and not device equations) and lecture viewgraphs
Composite Current Plot for the 42PD Circuit with 200kΩ Load to Ground

Problem #1
Current when $V_{OUT}$ Low

Problem #2
Poor $V_{OUT}$ High with Load

$V_{THEVENIN}$ (200KΩ Load) = 3.3 V

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Problems and Opportunities in Logic Circuit Design

Problem #1: Significant wasted current and power when \( V_{OUT} \) is low.

Problem #2: High value of \( V_{OUT} \) is adversely affected by a load resistor.

Missed Opportunity: The value of the input control signal is not used to adjust the state of the pull-up device.

What if: If the pull-up device could be a state-dependent device what kind of device would we want?
**Pull-Up Device Design: Trial 1**

**Similar pull-up and pull-down states**

Problem #1 is worse! There is even more wasted current and power than before when $V_{OUT}$ is low because both devices are on at the same time.

Look for a more Complementary approach.

State 1

State 3

State 5

$I_{OUT}(\mu A)$

$V_{OUT}(V)$
Pull-Up Device Design: Trial 2

Complementary pull-up and pull-down states

Note that in the pull-down case the current increases with the state number and in the pull-up case it decreases.

Problem #1 is solved. There is essentially no wasted current or power when $V_{OUT}$ is low.

State 1

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Pull-Down and Pull-Up Must Complement Rather Than Fight Each Other

Input for State Control Signal

Share Same Signal

Input for State Control Signal

Reduce the Short-Circuit Current by making either one or the other device off.

Charging Current

Discharging Current

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Desirable Complementary Device Characteristics

We desire characteristics that are **complementary** for the pull-down and pull-up state-dependent devices.

<table>
<thead>
<tr>
<th>$V_{IN}$</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pull-Down Current</td>
<td>Low not leak</td>
<td>High Discharge Output</td>
</tr>
<tr>
<td>Pull-Up Current</td>
<td>High Charge Output</td>
<td>Low not leak</td>
</tr>
</tbody>
</table>
Designing the Complementary Device

The curve sets are very similar but have two key changes.

The creation of current with input State \( V_{IN} \) is reverse ordered (and also shifted).

The dependence on \( V_{OUT} \) is reverse ordered and shifted by \( V_{DD} \).
42 Pull-Down Device Equations

Describe $I_{OUT}$ as function of $V_{IN}$ and $V_{OUT}$

Cut-off

$V_{IN} \leq V_{TD}$

$I_{OUT-PD} = 0$

Linear (with $V_{OUT}$)

$V_{IN} \geq V_{TN}$  \hspace{1cm} $V_{OUT} \leq V_{TD}$

$I_{OUT-PD} = k_{D} (V_{IN} - V_{TD}) V_{OUT}$

Saturation (with $V_{OUT}$)

$V_{IN} \geq V_{TD}$  \hspace{1cm} $V_{OUT} \geq V_{TD}$

$I_{OUT-PD} = k_{D} (V_{IN} - V_{TD}) V_{TD}$
Drawing $I_{\text{OUT}}$ as function of $V_{\text{IN}}$ and $V_{\text{OUT}}$

for the 42Pull-Down Device Equations

The equations are expressly designed for EE42 to make it very simple to draw $I_{\text{OUT}}$ vs. $V_{\text{OUT}}$

1) For $V_{\text{IN}} < V_{\text{TD}}$, the current is zero.

2) For $V_{\text{IN}} > V_{\text{TD}}$, first evaluate the current $I_{\text{OUT}}$ at $V_{\text{OUT}} = V_{\text{TD}}$ and plot the single point $(I_{\text{OUT}}, V_{\text{OUT}})$

3) Draw a line from this point to the origin to create the linear region.

4) Draw a horizontal line from this point to create the saturation region
$V_{DD}-V_X$ Gives Complementary Characteristics

Physical Interpretation as device related rather than logic circuit related voltages.

$V'_{IN} = V_{DD}-V_{IN}$

$V'_{OUT} = V_{DD}-V_{OUT}$

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42 Pull-Up Device Equations

$I_{OUT}$ as function of $V_{IN}$ and $V_{OUT}$ in the Logic Circuit

Cut-off \[ V_{DD} - V_{IN} \leq V_{TU} \]

\[ I_{OUT-PU} = 0 \]

Linear (with $V_{OUT}$) \[ V_{DD} - V_{IN} \geq V_{TU} \]

\[ V_{DD} - V_{OUT} \leq V_{TU} \]

\[ I_{OUT-PU} = k_u (V'_{IN} - V_{TU})V'_{OUT} = k_u (V_{DD} - V_{IN} - V_{TU})(V_{DD} - V_{OUT}) \]

Saturation (with $V_{OUT}$) \[ V_{DD} - V_{IN} \geq V_{TU} \]

\[ V_{DD} - V_{OUT} \geq V_{TU} \]

\[ I_{OUT-PU} = k_u (V'_{IN} - V_{TU})V'_{TU} = k_u (V_{DD} - V_{IN} - V_{TU})V_{TU} \]

Note: \[ V_{IN}' = V_{DD} - V_{IN} \]
42 Pull-UP Device Model

$I_{OUT}$ vs. $V_{OUT}$

Evaluating the point where $V_{OUT} = V_{DD} - V_{TU}$ for a given $V_{IN}$ allows the entire curve to be sketched.
Composite \( I_{\text{OUT}} \) vs. \( V_{\text{OUT}} \) to Find Points That Satisfies Both Devices for Each \( V_{\text{IN}} \)
Voltage Transfer Function for the Complementary Logic Circuit

Vertical section due to zero slope of $I_{OUT}$ vs. $V_{OUT}$ in the saturation region of both devices.

Complete this VTC for the 42PD device in the Homework.
Method for Finding $V_M$

At $V_M$,

1) $V_{OUT} = V_{IN} = V_M$

2) Both devices are in saturation

3) $I_{OUT\_PD} = I_{OUT\_PU}$

\[ I_{OUT\_PD} = k_D (V_{IN} - V_{TD}) V_{TD} = I_{OUT\_PU} = k_U (V_{DD} - V_{IN} - V_{TU}) V_{TU} \]

Substitute $V_M$

Solve for $V_M$

Example Result: When $k_D = k_P$ and $V_{TD} = V_{TU}$, $V_M = V_{DD}/2$