Previously

• Three components of power
  – Static
  – Short circuit
  – Capacitive switching

\[ P_{\text{tot}} = P_{\text{static}} + P_{\text{sc}} + P_{\text{dyn}} \]

Static

• CMOS circuit in steady-state
  – Leaks subthreshold current determined by off device
  – \[ P_{\text{static}} = V_{dd} \times I_{\text{static}} \]

Switching (Charging)

• CMOS circuit switching output from 0→1
  – Spends energy \[ CV_{dd}^2 \] charging load

\[ Q = CV = \int I(t)dt \]

\[ E = CV_{dd}^2 \]

Switching (Short Circuit)

• \( P=IV \)
• When:
  \[ V_{in}=V_{dd}/2, \quad V_{th}<V_{in}<V_{dd}-|V_{thp}| \]

Today

• Power Sources
  – Static
  – Short Circuit
  – Capacitive Switching

• Reducing Switching Energy

• Energy-Delay tradeoffs (time permit)
Switching

Quick Review

Switching Currents

- $I_{\text{switch}}(t) = I_{\text{sc}}(t) + I_{\text{dyn}}(t)$
- $I(t) = I_{\text{static}}(t) + I_{\text{switch}}(t)$

Charging

- $I_{\text{dyn}}(t)$
  - $I_{ds} = f(V_{ds}, V_{gs})$
  - and $V_{gs}$, $V_{ds}$ changing

Energy to Switch

$$E = \int I(t) V_{dd} \, dt$$

$$E = V_{dd} \int I(t) \, dt$$

Look at Energy [focus on $I_{\text{dyn}}(t)$]

$$E = \int P(t) \, dt$$

$$P \approx E_{\text{dy}n} / t_{\text{switch}}$$

$$E = \int I(t) V_{dd} \, dt$$

Capacitor Charge

$$Q = CV = \int I(t) \, dt$$
Capacitor Charging Energy

\[ E = V_{dd} \int I(t)dt \]
\[ Q = CV = \int I(t)dt \]
\[ E = CV^2 \]

Switching Power

• Every time output switches 0 \( \rightarrow \) 1 pay:
  \[ E = CV^2 \]
• \( P_{\text{dyn}} = (# \ 0 \rightarrow 1 \text{ trans}) \times CV^2 / \text{time} \)
• \( # \ 0 \rightarrow 1 \text{ trans} = \frac{1}{2} \# \text{ of transitions} \)
• \( P_{\text{dyn}} = (# \text{ trans}) \times \frac{1}{2} CV^2 / \text{time} \)

Short Circuit Power

• Current flow during switching?

Short Circuit Power

• Between \( V_{TN} \) and \( V_{dd} - V_{TP} \)
  – Both N and P devices conducting
• Roughly:

\[ I_{DS} \approx \nu_{sat} C_{OX} W \left( V_{GS} - V_T - \frac{V_{DSAT}}{2} \right) \]
Short-Circuit Energy

\[ E = V_{dd} \int I(t) \, dt \]

\[ \int I(t) \, dt \approx I_{peak} \times t_{sc} \times \left( \frac{1}{2} \right) \]

Short Circuit Energy

- Looks like a capacitance
  - \( Q = I \times t \)
  - \( Q = CV \)
  
  \[ E = V_{dd} \times \left( I_{peak} \times t_{sc} \times \left( \frac{1}{2} \right) \right) \]

\[ E = V_{dd} \times Q_{sc} \]

\[ E = C_{sc} V_{dd}^2 \]

Short-Circuit Energy and Power

- Every time switch
  - Also dissipate short-circuit energy: \( E = CV^2 \)
  - Different \( C = C_{sc} \)
  - \( C_{sc} \) “fake” capacitance (for accounting)

- Largely same dependence as charging

Switching Energy

Reminder

- Output switches 0→1 charge output from Vdd

- Output switches 1→0 discharge output to ground
  - no current from Vdd
Data Dependent Activity

- Consider an 8b counter
  - How often do each of the following switch?
    - Low bit?
    - High bit?
  - Average switching across all 8 output bits?
- Assuming random inputs
  - Activity at output of nand4?
  - Activity at output of xor4?

Gate Output Switching (random inputs)

\[ P_{\text{switch}} = P(0@i) \cdot P(1@i+1) + P(1@i) \cdot P(0@i+1) \]

Charging Power

- \( P_{\text{dyn}} = (# \text{trans}) \times \frac{1}{2} CV^2 / \text{time} \)
- Often like to think about switching frequency
  - Useful to consider per clock cycle
    - Frequency \( f = \frac{1}{\text{clock-period}} \)
  - \( P_{\text{dyn}} = (#\text{trans}/\text{clock}) \times \frac{1}{2} CV^2 f \)

Switching Power

- \( P_{\text{dyn}} = (\text{#trans/clock}) \times \frac{1}{2} CV^2 f \)
- Let \( a = \text{activity factor} \)
  - \( a = \text{average #tran/clock} \)
  - \( P_{\text{dyn}} = a \times \frac{1}{2} CV^2 f \)
  - \( P_{\text{sc}} = aC_{\text{sc}}V^2 f \)

Total Power

- \( P_{\text{tot}} = P_{\text{static}} + P_{\text{sc}} + P_{\text{dyn}} \)
- \( P_{\text{dyn}} + P_{\text{sc}} = a(\frac{1}{2}C_{\text{load}} + C_{\text{sc}})V^2f \)
- \( P_{\text{tot}} = a(\frac{1}{2}C_{\text{load}} + C_{\text{sc}})V^2f + VI'_{\text{s}}(W/L)e^{VI'/nKT/q} \)

Dynamic Power

- \( I_{DS} = \int \left( \frac{W}{L} \right) \left( \frac{1}{2} \frac{V - V_T}{nKT/q} \right) \left( 1 - e^{-\frac{V_{DS}}{L(VT/q)}} \right) \left( 1 + \lambda V_{DS} \right) \)
Reduce Dynamic Power?

- \( P_{\text{dyn}} = a \times \frac{1}{2} CV^2 f \)

- How do we reduce dynamic power?

Slow Down

- What happens to power contributions as reduce clock frequency?

- What suggest about \( V_{\text{th}} \)?

Reduce V

- What happens as reduce V?
  - Delay?
  - Energy?
  - Static
  - Switching

Old Reduce V (no vsat)

- \( \tau_{\text{gd}} = \frac{Q}{I} = \frac{(CV)}{I} \)
- \( I_d = \left( \frac{\nu_{\text{sat}} C_{\text{ox}}}{2} \right) (W)(V_{g_s} - V_{\text{th}})^2 \)
- \( \tau_{\text{gd}} \) impact?
- \( \tau_{\text{gd}} \propto \frac{1}{V} \)

Saturation Observe

- Ignoring leakage

\[
E \tau^2 \approx \text{Const}
\]

\[
E \propto V^2 \quad \tau \propto V^{-1}
\]

Reduce V (velocity saturation)

- \( \tau_{\text{gd}} = \frac{Q}{I} = \frac{(CV)}{I} \)
- \( I_d = \left( \frac{\nu_{\text{sat}} C_{\text{ox}}}{2} \right) (W)(V_{g_s} - (V_{\text{th}} - V_{\text{DSAT}}))^2 \)
Reduce Short-Circuit Power?

- $P_{sc} = aC_{sc}V^2f$

\[
E = V_{dd} \times \left( I_{peak} \times t_{sc} \times \left( \frac{1}{2} \right) \right)
\]

Energy vs. Power?

- Which do we care about?
  - Battery operated devices?
  - Desktops?
  - Pay for energy by kW-Hr?

Increase $V_{th}$?

- What is impact of increasing threshold on
  - Delay?
  - Leakage?

Increase $V_{th}$

- $\tau_{gd} = Q/I = (CV)/I$
- $I_{ds} = (\nu_{sat}C_{OX})(W)(V_{gs} - V_{TH} - V_{DSAT}/2)$

Idea

- Short circuit energy looks like more capacitance for switching energy
- Tradeoff
  - Speed
  - Switching energy
  - Leakage energy
- Energy-Delay tradeoff: $E \tau^2$? $E \tau$

Admin

- HW6 Due tomorrow
- Project 1 out
  - Milestone piece due in one week
  - Full Report in two weeks
  - That means you need to be starting on it now…and working on it all next week
    - Read assignment today
- Lecture Friday