EE273 Lecture 17
Off-Chip Power Distribution
November 23, 1998

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Today's Assignment

- Term Project
  - checkpoint 2 due on Wednesday 11/25
- Reading
  - Sections 5.3 and 5.4

A Quick Overview

- The Power-Distribution Problem
  - DC supply voltage with small tolerance
  - AC current, large di/dt
  - Inductive and resistive supply components
- Inductive Power Supply Noise
  - L supplies low-frequency current, C supplies high frequency
  - ripple due to current variation within each cycle
  - transient at start/stop of load current
- Bypass Capacitors
  - parasitic L and R in capacitors make them effective only below a certain frequency
- Local Regulation
  - series and parallel (shunt)
  - clip voltage ripple
  - ‘subtract’ AC current
  - distribute at a more convenient voltage

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The Power Distribution Problem

- Modern digital systems operate at small DC voltages
  - 1.5 to 3.3V
  - must be held to within ±10% (or less)
- and draw large AC currents
  - 10A or more per chip, 100A per board, KA in a system
  - may go from 0 to full current in less than one clock cycle
- over a supply network with parasitic elements
  - Inductance of bus bars, PC boards, packages,and bond wires
  - Resistance of on-chip wires

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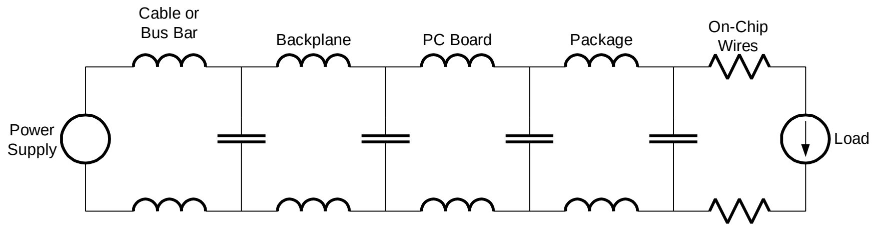
A Typical Power Supply Network



- Actually a tree with branching at each level
- Parasitic inductance (off-chip) and resistance (on-chip)
- Power and ground networks are usually symmetric
- Capacitance added to give a *tapered* frequency response

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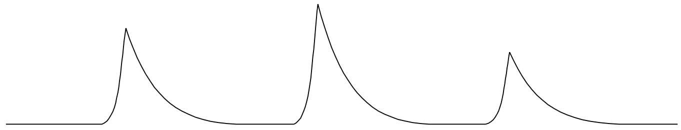
Typical Load Current

- For a given clock domain, load is usually periodic with the clock
- May stop or start in a single clock cycle
- With multiple clock domains, they may drift into phase reinforcing one another
- Load is often *resistive*, varying linearly with supply voltage
- Some loads are *high impedance,* constant independent of supply voltage



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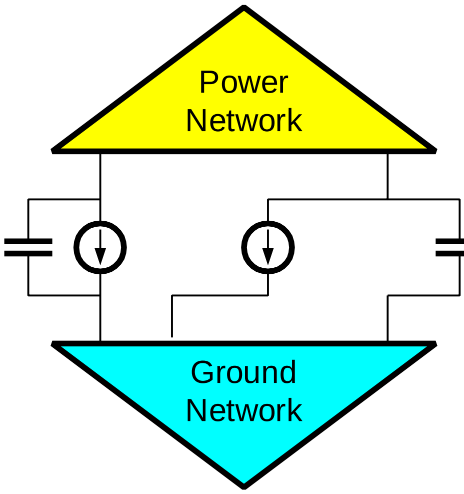
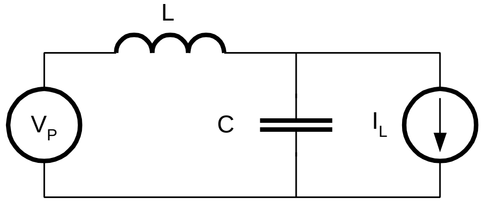
Local Loads and Signal Loads

- Logic loads connect a point in the power network to a corresponding point in the ground network
  - current can be supplied from a nearby bypass capacitor
- Signal loads connect a point in the power network to a distant point in the ground network
  - usually due to unbalanced signaling
  - current must return over a *long* path
  - bypass capacitors are not effective

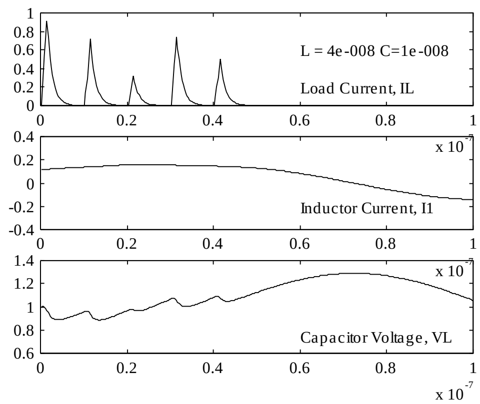


Inductive Supply Noise

- Each section of the supply network is an LC circuit
  - has a resonant frequency, $\omega_{LC} = (LC)^{-1/2}$
  - inductor carries DC current ($<< \omega_{LC}$)
  - capacitor supplies AC current ($>> \omega_{LC}$)
- Size capacitor to
  - supply cycle to cycle AC current with acceptable ripple
  - handle inductor start/stop transient



Response of an LC Section to Typical Supply Current



Magnitude of Ripple within a Cycle

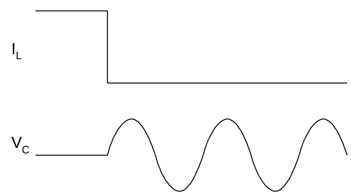
- Over a clock cycle, inductor current is essentially constant, I_{avg}
- Load current varies considerably
- Capacitor current is the difference
- Capacitor voltage *ripples* due to this AC current

$$\Delta V = \frac{k_i I_{\text{avg}} t_{ck}}{C_B}$$

$$C_B > \frac{k_i I_{\text{avg}} t_{ck}}{\Delta V_{\max}}$$

Starting and Stopping on a Dime

- When circuit is *off*, inductor current is 0.
- During startup, the capacitor must supply current to the load while the inductor current ramps up
- Similarly, when the circuit shuts down, the capacitor must absorb the inductor current while it ramps down
- In either case, the situation is that of a step current into an LC circuit
- Response is a sine-wave

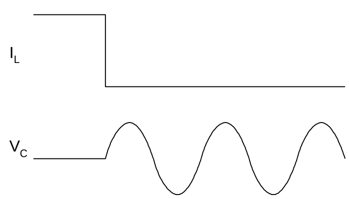


$$\Delta V = \frac{I_{avg}}{C_B w_C} \sin(w_C t)$$

$$= I_{avg} \sqrt{\frac{L}{C}} \sin(w_C t)$$

$$\Delta V_{max} = I_{avg} \sqrt{\frac{L}{C}}$$

Bypass Capacitor to Handle Start/Stop Transient



$$\Delta V_{max} = I_{avg} \sqrt{\frac{L}{C_B}}$$

$$C_B > \left(\frac{I_{avg}}{\Delta V_{peak}}\right)^2 L$$

Sizing Bypass Capacitors

- Bypass capacitor must be sized to handle both types of inductive power supply noise
  - ripple due to non-uniform current within a clock cycle
  - start/stop transients
  - maximum ripple can happen at peak or trough of transient
- Approximate capacitance requirement by summing the independent requirements

$$\Delta V_{\max} = I_{\text{avg}}\sqrt{\frac{L}{C_B}} + \frac{k_i I_{\text{avg}} t_{ck}}{C_B}$$

$$C_B > \left(\frac{I_{\text{avg}}}{\Delta V_{\max}}\right)^2 L + \frac{k_i I_{\text{avg}} t_{ck}}{\Delta V_{\max}}$$

$$C_B > \left(\frac{I_{\text{avg}}}{\Delta V_{\max}}\right)\left(k_i t_{ck} + \left(\frac{I_{\text{avg}}}{\Delta V_{\max}}\right)L\right)$$

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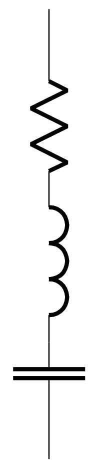
The Truth about Bypass Capacitors

- Most capacitors are only capacitors at low frequencies
- Capacitors have parasitic series resistance and inductance
- Every pico-Farad has its very own nano-Henry
- Two key breakpoints
  - LC frequency
  - RC frequency
- Capacitors are ineffective at bypassing currents above *either* of these frequencies



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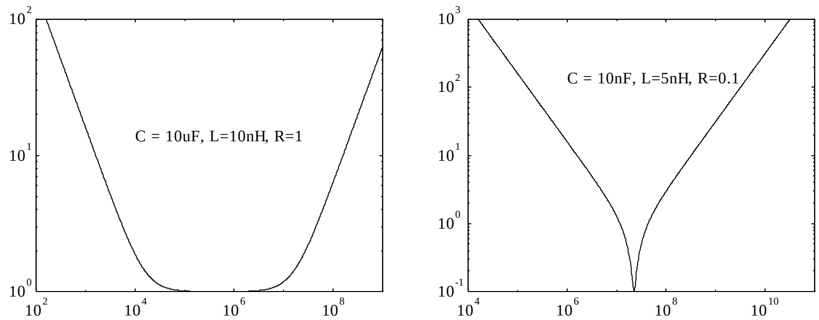
Impedance vs. Frequency for some Typical Capacitors



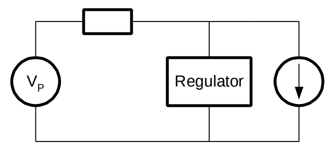
Capacitor Properties

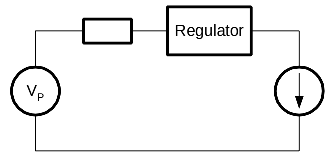
Type	C	R	L	f_{RC}	f_{LC}	f_{LR}
On-chip MOS	250fF	10	0	64GHz		
On-chip MOS	1pF	40	0	4GHz		
SMT ceramic	1pF	0.1	1nH		160MHz	
SMT ceramic	1nF	0.1	1nH		50MHz	
Ceramic disk	10nF	0.1	5nH		23MHz	
Al Electrolytic	10μF	1	10nH	160KHz		16MHz
Al Electrolytic	1mF	0.05	10nH	3KHz		800KHz

- High frequency is only achieved with small capacitors
- Many capacitors can be used in parallel to increase capacitance without reducing frequency

Local Power Supply Regulation

- Can put a regulator in series or parallel with the power supply
- Parallel or *shunt* regulators control current
  - add a current to the AC load current to make it look more like a DC current
- Series regulators control voltage
  - clip off the top of the voltage ripple and transient response
  - distribute power at a higher voltage (or AC voltage)





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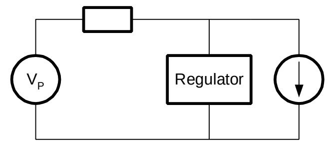
Shunt Regulators and Clamps

- Shunt regulators maintain a steady current draw from the distribution network
  - Measure the load current, I_L
  - Generate a shunt current $I_R = I_{max} - I_L$
  - Current is now DC
    - but large
- A clamp handles the turn-off transient to avoid overvoltage
  - measure the load voltage, V_C
  - draw current when V_C exceeds a threshold



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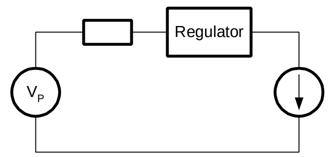
Series Linear Regulators

- Think of the regulator as a variable series resistor
  - drop distribution voltage (e.g., 3.3V) down to a load voltage (e.g., 2.5V)
- Can *clip* off the top of the voltage ripple by resistively dropping it
- Limited by
  - frequency response of the regulator (can't track fast transients)
  - series nature of regulator, can't divert transient inductor current



Switching Regulators

- A *switching* regulator uses a reactive element (usually a transformer or inductor) to convert the supply from one voltage to another with only a small loss in power
- Distributing power at a high voltage improves things quadratically
  - less current to distribute
  - more voltage to tolerate ripple
- Often advantageous to make this distribution voltage AC (at 0.1kHz to 1MHz)

$$V_D = kV_P$$

$$I_D = \frac{I_P}{k}$$

$$\frac{\Delta V_D}{V_D} = \frac{Z_D I_D}{V_D} = \frac{Z_D I_P}{k^2 V_P}$$

Next Time

- On-Chip Power Distribution