Lecture 19: Packaging, Power, & Clock
Outline

- Packaging
- Power Distribution
- Clock Distribution
Packages

- Package functions
  - Electrical connection of signals and power from chip to board
  - Little delay or distortion
  - Mechanical connection of chip to board
  - Removes heat produced on chip
  - Protects chip from mechanical damage
  - Compatible with thermal expansion
  - Inexpensive to manufacture and test
Package Types

- Through-hole vs. surface mount
Traditionally, chip is surrounded by *pad frame*
- Metal pads on 100 – 200 µm pitch
- Gold *bond wires* attach pads to package
- *Lead frame* distributes signals in package
- Metal *heat spreader* helps with cooling
Advanced Packages

- Bond wires contribute parasitic inductance
- Fancy packages have many signal, power layers
  - Like tiny printed circuit boards
- *Flip-chip* places connections across surface of die rather than around periphery
  - Top level metal pads covered with solder balls
  - Chip flips upside down
  - Carefully aligned to package (done blind!)
  - Heated to melt balls
  - Also called *C4* (Controlled Collapse Chip Connection)
Package Parasitics

- Use many $V_{DD}$, GND in parallel
  - Inductance, $I_{DD}$
Heat Dissipation

- 60 W light bulb has surface area of 120 cm$^2$
- Itanium 2 die dissipates 130 W over 4 cm$^2$
  - Chips have enormous power densities
  - Cooling is a serious challenge
- Package spreads heat to larger surface area
  - Heat sinks may increase surface area further
  - Fans increase airflow rate over surface area
  - Liquid cooling used in extreme cases ($$$)
Thermal Resistance

- \( \Delta T = \Theta_{ja} P \)
  - \( \Delta T \): temperature rise on chip
  - \( \Theta_{ja} \): thermal resistance of chip junction to ambient
  - \( P \): power dissipation on chip

- Thermal resistances combine like resistors
  - Series and parallel

- \( \Theta_{ja} = \Theta_{jp} + \Theta_{pa} \)
  - Series combination
Example

- Your chip has a heat sink with a thermal resistance to the package of 4.0°C/W.
- The resistance from chip to package is 1°C/W.
- The system box ambient temperature may reach 55°C.
- The chip temperature must not exceed 100°C.
- What is the maximum chip power dissipation?

- \( (100-55 \, \text{C}) / (4 + 1 \, \text{C/W}) = 9 \, \text{W} \)
Temperature Sensor

- Monitor die temperature and throttle performance if it gets too hot
- Use a pair of pnp bipolar transistors
  – Vertical pnp available in CMOS

\[ I_c = I_s e^{\frac{qV_{BE}}{kT}} \rightarrow V_{BE} = \frac{kT}{q} \ln \frac{I_c}{I_s} \]

\[ \Delta V_{BE} = V_{BE1} - V_{BE2} = \frac{kT}{q} \left( \ln \frac{I_{c1}}{I_s} - \ln \frac{I_{c2}}{I_s} \right) = \frac{kT}{q} \left( \ln \frac{I_{c1}}{I_{c2}} \right) = \frac{kT}{q} \ln m \]

- Voltage difference is proportional to absolute temp
  – Measure with on-chip A/D converter
Power Distribution

- Power Distribution Network functions
  - Carry current from pads to transistors on chip
  - Maintain stable voltage with low noise
  - Provide average and peak power demands
  - Provide current return paths for signals
  - Avoid electromigration & self-heating wearout
  - Consume little chip area and wire
  - Easy to lay out
Power Requirements

- $V_{DD} = V_{DD\text{nominal}} - V_{\text{droop}}$
- Want $V_{\text{droop}} < +/ - 10\%$ of $V_{DD}$
- Sources of $V_{\text{droop}}$
  - IR drops
  - $L$ di/dt noise
- $I_{DD}$ changes on many time scales
A chip draws 24 W from a 1.2 V supply. The power supply impedance is 5 mΩ. What is the IR drop?

\[ I_{DD} = \frac{24 \text{ W}}{1.2 \text{ V}} = 20 \text{ A} \]

\[ \text{IR drop} = (20 \text{ A})(5 \text{ mΩ}) = 100 \text{ mV} \]
A 1.2 V chip switches from an idle mode consuming 5W to a full-power mode consuming 53 W. The transition takes 10 clock cycles at 1 GHz. The supply inductance is 0.1 nH. What is the L di/dt droop?

\[ \Delta I = \frac{53 \text{ W} - 5 \text{ W}}{1.2 \text{ V}} = 40 \text{ A} \]

\[ \Delta t = 10 \text{ cycles} \times \frac{1 \text{ ns}}{\text{ cycle}} = 10 \text{ ns} \]

\[ L \frac{\Delta I}{\Delta t} \text{ droop} = (0.1 \text{ nH}) \times \frac{40 \text{ A}}{10 \text{ ns}} = 0.4 \text{ V} \]
Bypass Capacitors

- Need low supply impedance at all frequencies
- Ideal capacitors have impedance decreasing with $\omega$
- Real capacitors have parasitic R and L
  - Leads to resonant frequency of capacitor

![Graph showing impedance vs. frequency]

- Impedance:
  - $0.03 \, \Omega$
  - $1 \, \mu F$
  - $0.25 \, nH$

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Power System Model

- Power comes from regulator on system board
  - Board and package add parasitic R and L
  - Bypass capacitors help stabilize supply voltage
  - But capacitors also have parasitic R and L
- Simulate system for time and frequency responses
Frequency Response

- Multiple capacitors in parallel
  - Large capacitor near regulator has low impedance at low frequencies
  - But also has a low self-resonant frequency
  - Small capacitors near chip and on chip have low impedance at high frequencies
- Choose caps to get low impedance at all frequencies
Example: Pentium 4

- Power supply impedance for Pentium 4
  - Spike near 100 MHz caused by package L

- Step response to sudden supply current chain
  - 1\textsuperscript{st} droop: on-chip bypass caps
  - 2\textsuperscript{nd} droop: package capacitance
  - 3\textsuperscript{rd} droop: board capacitance

[Xu08] [Wong06]
Charge Pumps

- Sometimes a different supply voltage is needed but little current is required
  - 20 V for Flash memory programming
  - Negative body bias for leakage control during sleep
- Generate the voltage on-chip with a charge pump

\[
V_{\text{out}} = N \left[ CV_{DD} - \frac{I_{\text{out}}}{f} - V_t \right]
\]
Energy Scavenging

- Ultra-low power systems can scavenge their energy from the environment rather than needing batteries
  - Solar calculator (solar cells)
  - RFID tags (antenna)
  - Tire pressure monitors powered by vibrational energy of tires (piezoelectric generator)
- Thin film microbatteries deposited on the chip can store energy for times of peak demand
Clock Distribution

- On a small chip, the clock distribution network is just a wire
  - And possibly an inverter for clkb
- On practical chips, the RC delay of the wire resistance and gate load is very long
  - Variations in this delay cause clock to get to different elements at different times
  - This is called clock skew
- Most chips use repeaters to buffer the clock and equalize the delay
  - Reduces but doesn’t eliminate skew
Example

- Skew comes from differences in gate and wire delay
  - With right buffer sizing, clk\(_1\) and clk\(_2\) could ideally arrive at the same time.
  - But power supply noise changes buffer delays
  - clk\(_2\) and clk\(_3\) will always see RC skew
Review: Skew Impact

- Ideally full cycle is available for work
- Skew adds sequencing overhead
- Increases hold time too

\[ t_{pd} \leq T_c - \left( t_{pcq} + t_{setup} + t_{skew} \right) \]

sequencing overhead

\[ t_{cd} \geq t_{hold} - t_{ccq} + t_{skew} \]
Solutions

- Reduce clock skew
  - Careful clock distribution network design
  - Plenty of metal wiring resources

- Analyze clock skew
  - Only budget actual, not worst case skews
  - Local vs. global skew budgets

- Tolerate clock skew
  - Choose circuit structures insensitive to skew
Clock Dist. Networks

- Ad hoc
- Grids
- H-tree
- Hybrid
Clock Grids

- Use grid on two or more levels to carry clock
- Make wires wide to reduce RC delay
- Ensures low skew between nearby points
- But possibly large skew across die
Alpha Clock Grids

![Alpha Clock Grids](image-url)
H-Trees

- Fractal structure
  - Gets clock arbitrarily close to any point
  - Matched delay along all paths
- Delay variations cause skew
- A and B might see big skew
Itanium 2 H-Tree

- Four levels of buffering:
  - Primary driver
  - Repeater
  - Second-level clock buffer
  - Gater
- Route around obstructions
Hybrid Networks

- Use H-tree to distribute clock to many points
- Tie these points together with a grid

- Ex: IBM Power4, PowerPC
  - H-tree drives 16-64 sector buffers
  - Buffers drive total of 1024 points
  - All points shorted together with grid