

**Metric Prefixes**

peta	P	$10^{15}$	1 000 000 000 000 000
tera	T	$10^{12}$	1 000 000 000 000
giga	G	$10^9$	1 000 000 000
mega	M	$10^6$	1 000 000
kilo	k	$10^3$	1 000
hecto	h	$10^2$	100
deca	da	$10^1$	10
one		$10^0$	1
deci	d	$10^{-1}$	0.1
centi	c	$10^{-2}$	0.01
milli	m	$10^{-3}$	0.001
micro	$\mu$	$10^{-6}$	0.000 001
nano	n	$10^{-9}$	0.000 000 001
pico	p	$10^{-12}$	0.000 000 000 001
femto	f	$10^{-15}$	0.000 000 000 000 001

**De Morgan's Laws**

- $\overline{AB} = \overline{A} + \overline{B}$
- $\overline{A + B} = (\overline{A})(\overline{B})$

**Silicon**

- Si
- P-type:
  - \* doped with material to remove electrons (add electron holes), usually Boron (B), Aluminum (Al), or Gallium (Ga)
- N-type:
  - \* doped with material to add electrons, usually Antimony (Sb), Arsenic (As), or Phosphorous (P)
- Silicon dioxide:  $\text{SiO}_2$
- Polysilicon is just silicon without the crystal structure

**Transistors**

- nMOS
  - \* no bubble
  - \* on when input is on, off when input is off
  - \* base (of whole chip) is p-substrate
  - \* spot of n+ for source and drain, joined by a small layer of oxide ( $\text{SiO}_2$ ) and polysilicon (gate). also has a spot of p+ (base) connected to ground
- pMOS:
  - \* has the bubble
  - \* on when input is 0, off when input is 1
  - \* whole thing sits in an n-well (inside the p-substrate base)
  - \* source and drain are spots of p+ connected by gate. Gate is polysilicon layer separated from rest of chip by thin layer of  $\text{SiO}_2$  on bottom. Also has a n+ spot for base (connected to VDD)
- CMOS: when you combine a nMOS and pMOS network together to make a gate, where one is the compliment of the other
- $V_t$ : Threshold voltage. Nominal voltage below which the transistor is off
  - \* below as in closer to 0, not less
  - \*  $V_t > 0$  for nMOS,  $V_t < 0$  for pMOS
  - \* this is compared to the gate to source voltage,  $V_{gs}$
- regions: (for nMOS)
  - \* accumulation: gate is negatively charged, attracts positive voids in p-substrate, which block flow in the channel
  - \* depletion: small positive charge on gate repels positive voids from channel, forming a depletion below the gate
  - \* inversion: higher positive charge ( $> V_t$ ) is applied to gate, attracting electrons to the channel and allowing

flow

**D Flip Flop vs Latch**

- latch is level triggered
- flip flop is edge triggered

**Fabrication**

- n-well: use diffusion or ion implantation
- positive lithography: expose to UV where you want to remove material
- negative lithography: expose to UV where you want to keep material

**Stick Diagram vs Boolean Function**

- TODO
- there is more than one way of making a stick diagram for an expression
  - \* stuff in series could be in different order, for instance
- if you do it manually, you need to check it with tools:
  - \* LVS: Layout Vs Schematic
  - \* DRC: Design Re-Check
  - \* These aren't really needed for designs automatically generated from verilog code, because of course that's correct

**Lithography**

- the process of printing onto a chip at nanometer scale
- generally uses UV light, wavelength around 150nm
  - \* must use fancy tricks to make 10nm features with 150nm light
  - \* would be nice to use even lower wavelength X-rays, but those are hard to focus
- negative lithography: use the lithography mask to cover what you want to keep.
- positive lithography: mask what you want to remove
- a lens is used to focus the light
  - \* ideally, want a point source for the light, but that is not practical
  - \* Optical Proximity Effect: what happens when your focus from the lens is not just right
  - \* results in rounded corners, inaccurate critical dimensions, and shorter wire ends
  - \* can use Optical Proximity Correction to fix: basically over-emphasize all the features, and/or add extra lines at outset

**MOS transitive  $I$ - $V$  Characteristics and Parasitics**

- $I$ - $V$ : current-voltage relationship
- Transistors are not really ideal switches, they have 3 zones of operation: cutoff, linear, saturation
- definitions:
  - $V_{gs}$ : voltage gate to source
  - $V_{gd}$ : voltage gate to drain
  - $V_{ds}$ : voltage source to drain (across the channel)
  - $V_t$ : critical voltage at which transistor is saturated
  - channel: space between the source and drain, where the electrons flow
- remember that the gate is insulated from the area under it by a thin layer of Silicon Dioxide ( $\text{SiO}_2$ )
- by convention, the source is the terminal at lower voltage
- **cutoff**:
  - \* when  $V_{gs} < 0$
  - \* electrons on the gate attract positive voids in the silicon below, and inhibit current flow. Therefore, the transistor is closed.
  - \*  $I_{ds} = 0$
- **linear**:
  - \*  $V_{gs} > V_t, V_{gd} = V_{gs}, V_{ds} = 0$  or  $V_{gs} > V_t, V_{gs} > V_{gd} > V_t, 0 < V_{ds} < V_{gs} - V_t$
  - \*  $I_{ds}$  linearly proportional to  $V_{ds}$
  - \* channel of electrons forms, allowing current to flow

- **saturated:**

- \*  $V_{gs} > V_t, V_{gd} < V_t, V_{ds} > V_{gs} - V_t$
- \* channel pinches off due to electrons attracting to source
- \*  $I_{ds}$  is independent of  $V_{ds}$

- **capacitor effect**

- gate and channel can have a parallel plate capacitor effect, with the thin layer of  $\text{SiO}_2$  acting as the insulator
- $C = \frac{Q}{V} = \epsilon_{\text{SiO}_2} w l / t_{\text{SiO}_2}, V = V + g_c - V_t = (v_{gs} - V_{ds}/2) - V_t$ 
  - \*  $l, w$ : length, width of section of gate above channel
  - \*  $\epsilon_{\text{SiO}_2}$ : permittivity of  $\text{SiO}_2$  layer
  - \*  $t_{\text{SiO}_2}$ : thickness of  $\text{SiO}_2$  layer
- general capacitance per unit area:  $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$ 
  - \*  $\epsilon_{ox}$ : permittivity of oxidation layer
  - \*  $t_{ox}$ : thickness of oxidation layer
- carrier velocity: velocity of the electrons?
  - \* proportional to the electric field running horizontally between source and drain
  - \*  $v = \mu E, E = V_{ds}/L, t = L/v = L/(\mu E) = L/(\mu \frac{V_{ds}}{L})$ 
    - $\mu$ : mobility. electrons move about twice as fast as positive voids
    - $L$ : length of channel
- actual velocity of electrons is the speed of light, but they don't travel in a straight line, they travel atom-to-atom
  - \* this slowdown is called the **scattering** effect

- **Shockley model of transistor**

- $V_{dsat} = V_{gs} - V_t$
- 1st order model:  $\beta = \mu C_{\text{SiO}_2} \frac{w}{l}$ 

$V_{gs} < V_t$	$I_{ds} = 0$	cutoff
$V_{ds} < V_{dsat}$	$I_{ds} = \beta(V_{gs} - V_t - \frac{V_{ds}}{2})V_{ds}$	linear
$V_{ds} > V_{dsat}$	$I_{ds} = \frac{\beta}{2}(V_{gs} - V_t)^2$	saturation
- Must be able to derive this model on exam!

- **Non-Ideal I-V Effects**

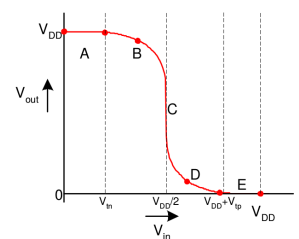
- velocity saturation (due to scattering)
  - \* also called short channel effect
  - \* this is hard to make into a mathematical formula
- sub-threshold leakage, junction leakage, gate tunneling
- **Body Effect**
  - \* affected by  $V_{sb}$ : voltage of the p-substrate (which should be ground)
    - \*  $V_t = V_{t0} + \lambda(\sqrt{|-2\phi_F + V_{sb}|} - \sqrt{|-2\phi_F|})$ 
      - $V_{t0}$ : threshold without body bias
      - $\phi_F$ : Fermi potential
        - negative for nMOS, positive for pMOS
      - $\lambda$ : body effect coefficient
        - positive for nMOS, negative for pMOS (reversed)
  - \* generally fixed/caused by biasing
  - \* Forward Body Bias (FBB):
    - $V_{sb} < 0, V_t < V_{s0}$
    - gates switch faster, but leak more current
  - \* Reverse Body Bias (RBB):
    - $V_{sb} > 0, V_t > V_{s0}$
    - gates switch slower, but consume less power (because less leakage)
- **Temperature**
  - \* higher temperature means higher electron mobility, more leakage, and threshold decreases
- **Diffusion Capacitance**
  - \* capacitance on the source/drain:  $C_{sb}, C_{db}$ 
    - source/drain are diffusion nodes
    - $C$  is comparable to  $C_g$  (gate) for connected nodes,  $\frac{1}{2}C_g$  for unconnected
    - (depends on process)

- \* this is the capacitance we care most about (because we must fill it every time the gate switches?)
- \* if two capacitors share a source/drain, that reduces diffusion capacitance (reducing this is a good thing)
- \* also, you can remove unconnected diffusion spots

- **DC Response**

- example: inverter
- must settle to  $I_{dsn} = |I_{dsp}|$
- $V_{tn}, V_{tp}$ : threshold voltages for nMOS and pMOS (defined in Non-Ideal I-V Effects)
- $V_{in} = V_{DD} \rightarrow V_{out} = 0, V_{in} = 0 \rightarrow V_{out} = V_{DD}$
- nMOS
  - \*  $V_{gsn} = V_{in}, V_{dsn} = V_{out}$
  - \* cutoff:  $V_{in} < V_{tn}$
  - \* linear:  $V_{in} > V_{tn}, V_{out} < V_{in} - V_{tn}$
  - \* saturated:  $V_{in} > V_{tn}, V_{out} > V_{in} - V_{tn}$
- pMOS
  - \*  $V_{gsp} = V_{in} - V_{DD}, V_{dsp} = V_{out} - V_{DD}, T_{tp} < 0$
  - \* cutoff:  $V_{in} > V_{DD} + V_{tp}$
  - \* linear:  $V_{in} < V_{DD} + V_{tp}, V_{out} > V_{in} - V_{tp}$
  - \* saturated:  $V_{in} < V_{DD} + V_{tp}, V_{out} < V_{in} - V_{tp}$
- to calculate actual output voltage, balance  $I_{dsn} = I_{dsp}$  (easiest to do graphically)
- \* end up with a graph of  $V_{out}$  as function of  $V_{in}$

Region	nMOS	pMOS
A	Cutoff	Linear
B	Saturation	Linear
C	Saturation	Saturation
D	Linear	Saturation
E	Linear	Cutoff



- \* don't want to switch nMOS and pMOS because then nMOS would saturate at far end of graph (and vice versa for pMOS)
- \* horizontal position of graph can be varied by tuning  $\beta_p/\beta_n$ 
  - called beta ratio, or skewed gate
  - $\beta_p/\beta_n > 1 \rightarrow$  right,  $\beta_p/\beta_n \rightarrow$  left
- \* unity gain slope: part of response graph where the slope is  $-1$ 
  - want to tune  $\beta_p/\beta_n$  to put logic levels at these regions to maximize noise margins
- \* Noise Margins:
  - $NM_H = |V_{OH} - V_{IH}|, NM_L = |V_{OL} - V_{IL}|$
  - that's just the higher/lower of the two axes

- **Transient Analysis**

- for instance, find step response of gate to determine rise time.
- rise/fall delay: time from when  $V_{in}$  crosses  $\frac{V_{DD}}{2}$  to when  $V_{out}$  crosses it
- rise/fall time: (of  $V_{in}$  or  $V_{out}$ ): time for that signal to go from  $0.1V_{DD}$  to  $0.9V_{DD}$  (or reverse)
- TODO many equations and such for inverter step response (from slides)
- TODO pass transistors (from slides)

- **Pass Transistors**

- for nMOS trying to pass  $V_{DD}$  or pMOS trying to pass 0
- nMOS can pull no higher than  $V_{DD} - V_{tn}$  if  $V_g = V_{DD}$ 
  - \* more generally,  $V_g - V_{tn}$
  - \* called degraded 1
- pMOS can pull no lower than  $|V_{tp}|$

- **Delay**

- generally estimated with RC models
  - \* for nMOS with width  $k$ :
  - \* resistance of  $R/k$

- \* caps of  $kC$  on all terminals
- \* pMOS same except resistance is  $2R/k$
- depends on effective  $R$  and  $C$  of transistors
  - \* exactly what parasitic caps depends on exact layout (which stuff is shared between transistors)
- width:
  - \*  $C$  proportional to width (approx  $2\text{ fF}/\mu\text{m}$ )
  - \*  $R$  inversely proportional to width (approx  $6\text{ k}\Omega/\mu\text{m}$ )
  - \* TODO unity transistors
- find widths necessary for rise and fall resistance to be same as standard inverter
  - \* pMOS is about half as conductive as nMOS, so the inverter has nMOS=1, pMOS=2
  - \* larger width  $\rightarrow$  smaller  $R$
  - \* transistors in series: delay adds, so double the width
  - \* transistors in parallel: same as a single transistor (because we assume worst case of only one being active)
- use effective resistance in RC model:  $I_{ds} = V_{ds}/R$  (just good enough for a RC model, not for current at arbitrary time)
- find delay of circuit
  - \* decompose to RC model (take into account widths of each transistor)
    - replace transistors with resistors
    - add parasitic caps on either side of every transistor (cap value = width of transistor)
      - caps with both pins short to ground don't count, are never charged
      - caps from  $V_{DD}$  to ground don't count, always charged
  - \* add together all  $R$  and  $C$ 's to get delay
    - don't count  $R$  of nMOS and pMOS at the same time, because they're never on at the same time
- **Delay**  $d = f + p$
- **Effort Delay**  $f = gh$ 
  - \*  $g$ : logical effort: relative ability of gate to deliver current
    - $g = 1$  for standard inverter
  - \*  $h$ : electrical effort: ratio of input to output capacitance
    - also called fanout
- **Parasitic Delay**  $p$ 
  - \* independent of load (represents delay of gate driving no load)
  - \* set by internal parasitic capacitance
- Elmore Delay:
  - \* ON transistors look like resistors, so pullup/pulldown network is modeled as RC ladder
  - \*  $t = \sum_{i \in \text{nodes}} R_{i \rightarrow \text{source}} C_i$   
 $= R_1 C_1 + (R_1 + R_2) C_2 + \dots + (R_1 + \dots + R_n) C_n$
- Ideal number of stages for inverter driving large load
  - \* delay  $= \left(\frac{C_{load}}{C_{inv}}\right)^{\frac{1}{k}} k R_{inv} C_{inv}$
  - \*  $k$ : number of stages
  - \* stage size ratio:  $\left(\frac{C_{load}}{C_{inv}}\right)^{\frac{1}{k}}$

### Static Timing Analysis

- worst case at each step
- in form arrival time / required arrival time / slack
- arrival time: input to output, take max
- required arrival time: output to input, take min
  - \* work backward
  - \* if a gate drives only one gate on it's output, this is trivial
- slack: required arrival time - arrival time
- Contamination delay: just best case delay (smallest delay)

- \* in this case, you'll count parallel transistors as parallel resistors
- not sure about this stuff, Peter just said to not worry about this question on the homework
- Power Estimation**
- Dynamic Power
  - \* power required to charge the load capacitor
  - \* only counted when transistor switches
    - therefore this power usage is data dependent
    - therefore, you have to count the falling transitions in the output per time period
  - \*  $P_{dynamic} = \frac{1}{T} \int_0^T i_{DD}(t) V_{DD} dt$
  - \* for any gate:  $P_{dynamic} = C V_{DD}^2 f_{sw}$
- Activity Factor  $\alpha$ 
  - \*  $\alpha$ : how often this gate switches in terms of the base clock frequency
  - \*  $\alpha = 1$ : clock;  $\alpha = 0.5$ : every other cycle, etc...
  - \* for system clock at frequency  $f$ ,  $P_{dynamic} = \alpha C V_{DD}^2 f$
- Short Circuit Current
  - \* nMOS and pMOS may both be on for a short instant during switching, leading to a short instant of short circuit current (from  $V_{DD}$  to ground)
  - \*  $P_s \propto (V_{DD} - 2V_t)^3 t_r f_p$   
 assume  $t_r = t_f$  for input  
 $f_p$ : frequency of input
  - \* this is less than 10% of dynamic power if the rise/fall times are comparable
- Static Power
  - \* leakage when gate is off
  - \*

$$I_{ds} = I_{ds0} e^{\frac{V_{gs} - V_t}{n v T}} \left(1 - e^{\frac{-V_{ds}}{v T}}\right)$$

$$V_t = V_{t0} - \eta V_{ds} + \gamma \left(\sqrt{\phi_s + V_{sb}} - \sqrt{\phi_s}\right)$$

## After exam 1

- exam 1 was on March 8 (2017.03.08)
- nothing specifically from previous exam
- Propagation vs Contamination delay**
- contamination delay ( $t_{cd}$ ): time from input change to **any** output changing value
  - \* kind of a best-case delay or smallest possible delay
  - \* time counted when input crosses 50% of logical high voltage level
- propagation delay: time from when all inputs are stable to when all outputs are stable
  - \* kind of like a worst-case delay
- Latch vs Flip Flop**
- Latch is level-sensitive, flip-flop is edge-sensitive
- register is flip-flop
- Latch/flip flop designs**
- pass transistor latch
  - \* pros: tiny, low clock load
  - \* con: voltage drop across is  $V_t$ , it's non-restoring
  - \* con: not really a latch because doesn't hold signal
- transmission gate
  - \* pro: no  $V_t$  drop
  - \* con: requires inverted clock
- inverting buffer
  - \* TODO
- tristate feedback
  - \* first complete latch here
  - \* risk of backdriving: downstream could change state if it is very strong
- buffered output
  - \* no backdriving problem
  - \* widely used

- \* rather large and slow though, and large load on clock
- a flip-flop is just two latches back-to-back

### Metastability

- stable works if it's not at a strong high or low but will settle somewhere
- metastable is where it might sit there, but if it must settle, you don't know which one it will settle to when perturbed

### Sequential Circuits

- sequential means that the circuit holds state: the output depends on both current and past input
- to model a state machine, you can unroll it to [register]  $\rightarrow$  [combinational]  $\rightarrow$  ...
  - \* this way you can use regular timing stuff for it: arrival time, slack, etc...
- Mealy FSM: output of circuit is from combinational logic
- Moore FSM: output is from registers
- pipelined circuit: uses registers to hold state between clock cycles, because not all of the combinational logic can happen fast enough to work in a single clock cycle
  - \* pipelined circuits can use flip-flops or latches?
- the clock consumes 20-30% of the power on a chip
- the whole reason that registers are needed is because data (signals) moves through components at non-constant speed
- reset
  - \* can be sync or async
  - \* force low output when reset is high
- sequencing: it is (generally) equivalent to split the sequential logic in two, and then use two latches (one halfway through) instead of one large section of sequential logic with flip-flops at either end
  - \* this is called two phase clocking
  - \* you have to make sure the middle latch operates on clock-bar instead of clock
- timing:
  - $t_{pd}$  logic propagation delay
  - $t_{cd}$  logic contamination delay
  - $t_{pcq}$  Clk $\rightarrow$ Q propagation delay
  - $t_{ccq}$  Clk $\rightarrow$ Q contamination delay
  - $t_{pdq}$  D $\rightarrow$ Q propagation delay
  - $t_{setup}$  setup time of flip-flop/latch
  - $t_{hold}$  hold time of flip-flop/latch
  - \* D $\rightarrow$ Q delay only makes sense for latches, since for flip-flops it is simply one clock cycle
- sequencing overhead and max delay:
  - \*  $T_c$ : cycle time
  - \* need for combinational logic to be fast enough
  - \* for single phase flip flop:  $t_{pd} < T_c - (T_{setup} + T_{pcq})$
  - \* for two-phase latch:  $t_{pd} = t_{pd1} + t_{pd2} < T_c - 2t_{pdq}$
  - \* max delay is dictated by cycle time and sequencing overhead; sequencing overhead does not effect minimum delay
- minimum delay:
  - \* for single phase flip flop:  $t_{cd} > t_{hold} - t_{ccq}$ 
    - combinational stuff must be slow enough that it doesn't violate hold time of second flip flop
  - \* for two-phase latch:
    - $t_{cd1}, t_{cd2} > t_{hold} - t_{ccq} - t_{non-overlap}$
    - hold time applies twice each cycle, once per each combinational circuit
    - $t_{non-overlap}$ : phase between clock signals?
- time borrowing: for two-phase latch-based system, you can borrow time from one segment to the other while the latch is transparent
  - \* works (is possible) as long as the total circuit still completes within one clock cycle

- clock skew:
  - \* when uncertain: causes tighter required CL propagation delay and minimum CL contamination delay, and reduces opportunity for time borrowing.
  - \* when know constant skew: can help with same effect as time borrowing, except can also have effect for flip-flop based systems
- skew tolerance:
  - \* flip-flop circuits are not very skew tolerant because the setup and hold times define a specific window of time in which the data must arrive
  - \* latch circuits are more hold-time-tolerant because the data can arrive any time that the latch is transparent
- if setup times are violated, you can reduce clock speed to fix it
- if hold times are violated, it won't work at any clock speed

### Clocking

- H-Tree (clock distribution network)
  - \* laid out in such a way that the delay from the center to any leaf node is equal
- Grid clock distribution
  - \* grid on two or more levels
  - \* ensures low local skew, but there could still be larger chip-wide skew
- generally, the longer the delay between two point, the larger the worst-case clock skew
- Domino circuit: TODO
  - \* a kind of dynamic logic

### Memory

- random access or sequential access, or content addressable
- CAM: content-addressable memory
  - \* basically like an associative array, or database
  - \* designed to search all memory at once in a single operation (wikipedia)
- DRAM: TODO
- SRAM: TODO
  - \* 12T and 6T cell designs
  - \* 12T design: just a latch connected to a bitline
  - \* 6T design: cross-coupled inverters (3T each) +2T for bit and bit-bar lines
    - read: pre-charge bit and bit-bar, raise wordline, read result
      - (need to pre-charge or else read is destructive?)
    - write: drive data onto bit and bit-bar and raise wordline to write

### Wire Delay

- $n$ -segment  $\pi$  model:
  - to model, find total R and C of wire; then split up according to  $n$  segment model, then combine adjacent caps

### Miller Effect

- AKA crosstalk; it's when one wire affects another
- it's dynamic; depends on what signal the wires are carrying
- MCF: Miller factor (or something)
- for two wires A and B, model as
 
$$C_{eff} = C_{gnd} + MCF \cdot C_{adj}$$

	behavior of B	MCF
• MCF:	constant	1
	with A	0
	opposite A	2

### Timing

- setup time: minimum time that signal must remain stead **before** clock edge
- hold time: minimum time that signal must remain stead **after** clock edge

- propagation delay: when driving another gate? largest (worst case) delay?
- contamination delay: best case delay (smallest delay)?
- parasitic delay: independent of load
- effort delay: proportional to load capacitance (nothing to do with the thing that is doing the driving of the load capacitance)
- maximum possible logic propagation delay for combinational circuit buffered on either side by flip-flops:  $\text{clockCycle} - \text{Clk} \rightarrow \text{Q} - \text{FlipFlopSetup} - \text{WorstSkew}$
- \* minimum circuit delay:  $\text{HoldTime} - \text{Clk} \rightarrow \text{Q}$

## Memory

- serial access memory (SAM): accessed in a sequence, not randomly
  - \* ex. shift register, queue, stack, etc...
  - \* often implemented using random access memory
- Shift Register
  - \* serial in, parallel out
  - \* large number of transistors per cell when implemented using flip flop
  - \* tapped delay line: shift register with variable number of stages
    - useful for allowing chips at different clock frequencies to communicate (apparently)
- queue or stack can be built using SRAM block with pointers to first/last and stuff
- SRAM
  - \* static ram
  - \* can be dual ported: means you can write to a cell while reading the old value from it
  - \* designed in a cell grid, MUXes for input and then decoders for output connected to bit lines that run across the cells
  - \* TODO note about pre charging bit line
- DRAM
  - \* stores bits using capacitors
- decoders
  - \* needed to switch to the right bit-line
  - \* need to be pitch-matched to RAM cell width for efficiency
  - \* TODO note about twisted bit lines
- ROM: read only memory
  - \* used to be custom masked chips for data
  - \*
- PROM

## Packaging

- flip chip: put connection pads on the surface of the die instead of the edges
  - \* then flip the chip over and affix it directly to the package
  - \* means the die must be positioned in the package more precisely
- Heat
  - \* Thermal Resistance:  $\Delta T = \theta_{ja} P$ 
    - $\Delta T$ : temperature rise in chip
    - $\theta_{ja}$ : thermal resistance of chip junction to ambient; units:  $C/W$
    - $P$ : power dissipation on chip
- IO
  - \* ESD Protection: TODO
  - \* output pads:
    - must drive large off-chip loads (2-50pF) do that using successively larger buffers
    - surround with guard ring to protect against lockup
  - \* input pads:
    - may need level converters
    - Schmitt trigger: allow signal to cross high/low edge

- only after it goes a little over the tipping point
- \* bidirectional pads:
  - combine input and output
  - use tristate driver to set pin direction
- \* analog:
  - no buffering
  - any protection circuitry must be careful to not distort the signal at all
  - RF pads?