ECEN454 Ref Sheet © Josh Wright May 6, 2017

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	μ	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: 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 (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 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 (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 SiO_2 acting as the insulator
- $C = \frac{Q}{V} = \epsilon_{SiO_2} wl/t_{SiO_2}, V = V + gc - V_t = (v_{gs} - Vds/2) - V_t$
  - l, w: length, width of section of gate above channel
  - ϵ_{SiO_2}: permittivity of SiO_2 layer
  - t_{SiO_2}: thickness of SiO_2 layer
- general capacitance per unit area: $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$
  - ϵ_{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
  - $v = \mu E, E = V_{ds}/L, t = L/v = L/(\mu E) = L/(\mu \frac{V_{ds}}{L})$
    μ: 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: $\beta = \mu C_{SiO_2} \frac{w}{l}$

$V_{gs} < V_t$	$I_{ds} = 0$	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

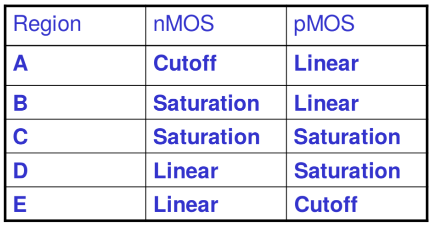
- Must be able to derive this model on exam!

Non-Ideal I-V Effects

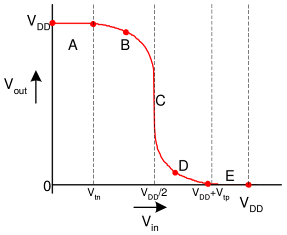
- velocity saturation (due to scattering)
  - also called short channel effect
  - this is hard to make into a mathematical formula
- sub-threshold leakage, junction leakage, gate tunneling
- **Body Effect**
  - affected by V_{sb}: voltage of the p-substrate (which should be ground)
  - $V_t = V_{t0} + \lambda(\sqrt{|-2\phi_F + V_{sb}|} - \sqrt{|-2\phi_F|})$
    - V_{t0}: threshold without body bias
    - ϕ_F: Fermi potential
      - · negative for nMOS, positive for pMOS
    - λ: 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 β_p/β_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 β_p/β_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 (form 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 fF/μm)
  - R inversely proportional to width (approx 6kΩ*μm)
  - 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 → 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
  - $t = \sum_{i \in nodes} R_{i-to-source} C_i$
    $= R_1C_1 + (R_1 + R_2)C_2 + \ldots + (R_1 + \ldots + R_n)C_n$
- Ideal number of stages for inverter driving large load
  - delay $= \left(\frac{C_{load}}{C_{inv}}\right)^{\frac{1}{k}} kR_{inv}C_{inv}$
  - 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: $P_{dynamic} = CV_{DD}^2 f_{sw}$
- Activity Factor α
  - α: 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, $P_{dynamic} = \alpha CV_{DD}^2 f$
- 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
  - $$I_{ds} = I_{ds0} e^{\frac{V_{gs}-V_t}{nv_T}} \left(1 - e^{\frac{-V_{ds}}{v_T}}\right)$$
    $$V_t = V_{t0} - \eta V_{ds} + \gamma\left(\sqrt{\phi_s + V_{sb}} - \sqrt{\phi_s}\right)$$

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 backdrifing 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 [regieter] → [combinational] → ...
  - 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→Q propagation delay
t_{ccq}	Clk→Q contamination delay
t_{pdq}	D→Q propagation delay
t_{setup}	setup time of flip-flop/latch
t_{hold}	hold time of flip-flop/latch

  - D→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: TODO

Wire Delay

- n-segment π 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 $C_{eff} = C_{gnd} + MCF \cdot C_{adj}$
- MCF:

behavior of B	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: clockCycle - Clk→Q - FlipFlopSetup - WorstSkew
  - minimum circuit delay: HoldTime - Clk→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: $\Delta T = \theta_{jaa} P$
    - ΔT: temperature rise in chip
    - θ_{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?