Reverse Engineering the 6502: we exposed the silicon die, photographed its surface at high resolution and also photographed its substrate...we created...models of each of the chip's physical components...complete digital model and surface at high resolution and also photographed its substrate...we created...

---

What is Machine Structures?

Coordination of many levels of abstraction
ISA is an important abstraction level: contract between HW & SW

---

Synchronous Digital Systems

**Hardware of a processor, such as the MIPS, is an example of a Synchronous Digital System**

**Synchronous:**
- All operations coordinated by a central clock
  - “Heartbeat” of the system!

**Digital:**
- All values represented by discrete values
- Electrical signals are treated as 1s and 0s; grouped together to form words
Switches: Basic Element of Physical Implementations

- Implementing a simple circuit (arrow shows action if wire changes to “1”):
  - Close switch (if A is “1” or asserted) and turn on light bulb (Z)
  - Open switch (if A is “0” or unasserted) and turn off light bulb (Z)

Switches (cont’d)

- Compose switches into more complex ones (Boolean functions):
  - AND
  - OR

Transistor Networks

- Modern digital systems designed in CMOS
  - MOS: Metal-Oxide on Semiconductor
  - C for complementary: normally-open and normally-closed switches

- MOS transistors act as voltage-controlled switches

http://youtu.be/ZaBLiciesOU
MOS Transistors

- Three terminals: Drain, Gate, and Source
  - Switch action:
    - n-channel: open when voltage at G is low closes when: voltage(G) > voltage (S) + ε
    - p-channel: closed when voltage at G is low opens when: voltage(G) < voltage (S) – ε

MOS Networks

- “1” (voltage source)
- “0” (ground)

Transistor Circuit Rep. vs. Block diagram

- Chips are composed of nothing but transistors and wires.
- Small groups of transistors form useful building blocks.
- Block are organized in a hierarchy to build higher-level blocks: ex: adders.
  (You can build AND, OR, NOT out of NAND!)
How many hours $h$ on Project 2a?

a) $0 \leq h < 10$

b) $10 \leq h < 20$

c) $20 \leq h < 30$

d) $30 \leq h < 40$

e) $40 \leq h$

Other administrivia?

Signals and Waveforms: Clocks

- Signals
  - When digital is only treated as 1 or 0
  - Is transmitted over wires continuously
  - Transmission is effectively instant
    - Implies that any wire only contains 1 value at a time

Signals and Waveforms: Grouping

Signals and Waveforms: Circuit Delay

Sample Debugging Waveform
Type of Circuits

• Synchronous Digital Systems are made up of two basic types of circuits:
  • Combinational Logic (CL) circuits
    • Our previous adder circuit is an example.
    • Output is a function of the inputs only.
    • Similar to a pure function in mathematics, \( y = f(x) \). (No way to store information from one invocation to the next. No side effects)
  • State Elements: circuits that store information.

Circuits with STATE (e.g., register)

Peer Instruction

1) SW can peek at HW (past ISA abstraction boundary) for optimizations
2) SW can depend on particular HW implementation of ISA

And in conclusion...

• ISA is very important abstraction layer
  • Contract between HW and SW
• Clocks control pulse of our circuits
• Voltages are analog, quantized to 0/1
• Circuit delays are fact of life
• Two types of circuits:
  • Stateless Combinational Logic (\&,\|,\sim)
  • State circuits (e.g., registers)