Overview of Physical Implementations

The stuff out of which we make systems

- Integrated Circuits (ICs)
  - Combinational logic circuits, memory elements, analog interfaces
- Printed Circuits (PC) boards
  - Substrate for ICs and interconnection, distribution of CLK, Vdd, and GND signals, heat dissipation
- Power Supplies
  - Converts line AC voltage to regulated DC low voltage levels
- Chassis (rack, card case, ...)
  - Holds boards, power supply, fans, provides physical interface to user or other systems
- Connectors and Cables
Integrated Circuits

- Primarily Crystalline Silicon
- 1mm - 25mm on a side
- 100 - 200M transistors
- (25 - 50M "logic gates")
- 3 - 10 conductive layers
- 2005 - feature size ~ 90nm = 0.09 x 10^-6 m
- "CMOS" most common - complementary metal oxide semiconductor

Package provides:
- spreading of chip-level signal paths to board-level
- heat dissipation.
- Ceramic or plastic with gold wires

Printed Circuit Boards

- fiberglass or ceramic
- 1-25 conductive layers
- 1-20in on a side
- IC packages are soldered down

Multichip Modules (MCMs)

- Multiple chips directly connected to a substrate (silicon, ceramic, plastic, fiberglass) without chip packages
Integrated Circuits

Moore's Law has fueled innovation for the last 3 decades

“Number of transistors on a die doubles every 18 months.”

What are the consequences of Moore’s law?

Uses for digital IC technology today:

- Standard microprocessors
  - Used in desktop PCs, and embedded applications (ex: automotive)
  - Simple system design (mostly software development)
- Memory chips (DRAM, SRAM)
- Application specific ICs (ASICs)
  - Custom designed to match particular application
  - Can be optimized for low-power, low-cost, high-performance
  - High-design cost / relatively low manufacturing cost
- Field programmable logic devices (FPGAs, CPLDs)
  - Customized to particular application after fabrication
  - Short time to market
  - Relatively high part cost
- Standardized low-density components
  - Still manufactured for compatibility with older system designs
CMOS Devices

- MOSFET (Metal Oxide Semiconductor Field Effect Transistor)

Top View

Cross Section

The gate acts like a capacitor. A high voltage on the gate attracts charge into the channel. If a voltage exists between the source and drain a current will flow. In its simplest approximation, the device acts like a switch.

Transistor-level Logic Circuits

- Inverter (NOT gate):
- NAND gate

How about AND gate?

Note:
- \( \text{out} = 0 \) iff both \( a \) AND \( b = 1 \)
- therefore \( \text{out} = (ab)' \)
- pFET network and nFET network are duals of one another.
Transistor-level Logic Circuits

Simple rule for wiring up MOSFETs:

- nFET is used only to pass logic zero
- pFet is used only to pass logic one
- For example, NAND gate:

Note: This rule is sometimes violated by expert designers under special conditions

Transistor-level Logic Circuits

- NAND gate
- NOR gate

Note:

- out = 0 iff both a OR b = 1 therefore out = (a+b)'
- Again pFET network and nFET network are duals of one another

Other more complex functions are possible. Ex: out = (a+bc)'
Transmission Gate

- Transmission gates are the way to build "switches" in CMOS
- In general, both transistor types are needed:
  - nFET to pass zeros
  - pFET to pass ones
- The transmission gate is bi-directional (unlike logic gates)
- Does not directly connect to Vdd and GND, but can be combined with logic gates or buffers to simplify many logic structures

Pass-Transistor Multiplexer

- 2-to-1 multiplexer:
  \[ c = s \cdot a + s' \cdot b \]
- Switches simplify the implementation:
4-to-1 Pass-transistor Mux

- The series connection of pass-transistors in each branch effectively forms the AND of s1 and s0 (or their complement)

- 20 transistors

Alternative 4-to-1 Multiplexer

- This version has less delay from in to out

- Care must be taken to avoid turning on multiple paths simultaneously (shorting together the inputs)

- 36 Transistors
Tri-state Buffers

Tri-state Buffer:

Transistor circuit for inverting tri-state buffer:

“high impedance” (output disconnected)

Variations

Inverting buffer
Inverted enable

“transmission gate”

Tri-state Buffers

Tri-state buffers are used when multiple circuits all connect to a common bus. Only one circuit at a time is allowed to drive the bus. All others “disconnect”.

Bidirectional connections:

Busses:
Tri-state Based Multiplexer

- **Multiplexer**

  If \( s=1 \) then \( c=a \) else \( c=b \)

- **Transistor Circuit for inverting multiplexer:**

D-type Edge-triggered Flip-flop

- The edge of the clock is used to *sample* the "D" input & send it to "Q" (positive edge triggering)
- At all other times the output Q is independent of the input D (just stores previously sampled value)
- The input must be stable for a short time before the clock edge.
Transistor-level Logic Circuits

Positive Level-sensitive latch:

Latch Transistor Level:

Positive Edge-triggered flip-flop built from two level-sensitive latches:

State Machines in CMOS

- Two Phase Non-Overlapping Clocking