Outline

• Overview of Physical Implementations
• CMOS devices
• CMOS transistor circuit functional behavior
  – basic logic gates
  – transmission gates
  – tri-state buffers
  – flip-flops
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

Chip in Package

- 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
- 1-20 in 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?
Integrated Circuits

- 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):
  ![Inverter Circuit Diagram]

- NAND gate
  ![NAND Gate Diagram]
  - Note:
    - out = 0 iff both a AND b = 1
    - therefore out = (ab)'
    - pFET network and nFET network are duals of one another.

How about AND gate?

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:
  ![NAND Gate Circuit Diagram]

Note: This rule is sometimes violated by expert designers under special conditions.
Transistor-level Logic Circuits

- **NAND gate**

- **NOR gate**

  ![NAND gate diagram](image)

  ![NOR gate diagram](image)

  **Note:**
  - out = 0 if 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)'

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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 Multiplexor

• 2-to-1 multiplexor:
  \[ c = s_0 \cdot a + s_1 \cdot b \]

• Switches simplify the implementation:

4-to-1 Pass-transistor Mux

• The series connection of pass-transistors in each branch effectively forms the AND of \( s_1 \) and \( s_0 \) (or their complement).

• 20 transistors
Alternative 4-to-1 Multiplexor

- 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

- Transistor circuit for inverting tri-state buffer:

- 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 Multiplexor

- Multiplexor
- Transistor Circuit for inverting multiplexor:

If $s=1$ then $c=a$ else $c=b$
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: