**Announcements**

Homework 10 (LAST!!) due TODAY by 5 pm
Final Project: Card Game
  - Due December 12 – In-class Demos

Intermediate Deadlines
  - Wed (11/30): Find project partner — TODAY
    - Google Doc to find others (email to cs202-tas@cs.wisc.edu)
  - Fri (12/2): Project proposal
    - At least 1 sentence email to cs202-tas@cs.wisc.edu (cc partner)
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**EXTRA Instructor Office Hours**
Tuesday and Thursday — 1:30 – 4:30

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**Review: Combinational Circuits**

Combinational Circuit
  - Always gives same output for given set of inputs
    - ex: adder always generates sum and carry, regardless of previous inputs
  - Cycles are not allowed
    - Cannot have feedback from output back to input

- Useful for many, but not all, aspects of computation
  - Arithmetic Logic Unit (ALU)

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**Today’s Challenge**

How can we remember information with just
  - AND
  - OR
  - NOT

?????????
Quick Review: Boolean Logic

How to express:
Matt will go to party if and only if Sue goes to party?

Two boolean variables: M and S

\[ M = S \]

S \[ \rightarrow \] M

More Complicated Expression

Matt doesn’t like changing his mind...

Matt will go to the party if Sue goes or if he already wanted to go

Enumerate ALL Scenarios in Truth Table

\[
\begin{array}{ccc}
S & M & M' \\
0 & 0 & 0 \\
0 & 1 & 1 \\
1 & 0 & 1 \\
1 & 1 & 1 \\
\end{array}
\]

Sequential Circuits

Sequential Circuit (vs. Combinational)
- Stores information: state
- Output depends on state + input
  - Given same input might produce different output, depending on stored information
  - Example: ticket counter
    - Advances when push button, output depends on previous state
- Cycles are allowed
  - Can have feedback from output to input
- Useful for building memory!

More Complicated Expression

Matt doesn’t like changing his mind...

Matt will go to the party if and only if Sue goes or if he already wanted to go

Problem with this circuit (or Matt)?
Once going, can’t change mind! Once \( M = 1 \), always \( M = 1 \)
How can Matt change his Mind?

Matt will go to the party if and only if Sue goes OR (he already wanted to go AND Rita does not go)

How would you express?

\[ M' = S \text{ OR } (M \text{ AND NOT R}) \]

R, S: "control" inputs

What is S doing?
- Setting state (to 1)

What is R doing?
- Resetting state (to 0)

R-S Flip-Flop

(Caution: Simplified !!)

If Set = 1 (and Reset = 0), M = 1
If Reset = 1 (and Set = 0), M = 0
If Set = 0, Reset = 0, M keeps old value!

Not best if both Set and Reset = 1 (who wins?)

How can Matt change his Mind?

Matt will go to the party if Sue goes OR if the following holds:
(he already wanted to go AND Rita does not go)

Random Access Memory (RAM)

Memory: Remembers lots of bits, not just 1 bit
- Logical \( k \times m \) array of stored bits

Two operations:

Write: Specify n-bit address and m-bits of data; remember that data at that address

Read: Specify n-bit address and see m-bits of data stored there
Convenient 1-Bit Memory

Two inputs: D (data) and WE (write enable)
- when WE = 1, latch is set to value of D
- when WE = 0, latch holds previous value (ignores D)

Mystery Circuit

What does this combinational circuit do?
### Decoder Circuit

- **n** inputs, 2^n outputs
- exactly one output is 1 for each input pattern

![Decoder Circuit Diagram](image)

- 1, if \( AB = 00 \)
- 1, if \( AB = 01 \)
- 1, if \( AB = 10 \)
- 1, if \( AB = 11 \)

### Example RAM Operation

What happens when:

![RAM Operation Diagram](image)

### Other Components that Remember?

**Cache Analogy: Inefficient Library**

- 1000 checkouts/returns per day
- 50 ft x 2 x 1000 = 100,000 feet = ~ 20 miles

Please help, she’s worn down and customers are waiting too long!!

Ideas?

![Cache Analogy](image)
**Better Arrangement: Popular Books Nearby**

- **Reserves**: Hold 80% of collection, Handles 20% of requests
- **"Most popular" shelf**: Hold 20% of collection, Handles 80% of requests

Reduces distance walked each day

**Distance with Popular Objects Nearby?**

- **Reserves**: Hold 80% of collection, Handles 20% of requests
- **"Most popular" shelf**: Hold 20% of collection, Handles 80% of requests

Distance covered per day?

- \[ \text{Distance covered per day} = 1000 \times (1 - P_{hit}) \times 100 \text{ ft} + P_{hit} \times 10 \text{ ft} \]
- \[ = 1000 \times (0.20 \times 100 + 0.80 \times 10) = 28,000 \text{ ft instead of 100,000} \]

**How can we improve?**

- **Reserves**: Hold 80% of collection, Handles 20% of requests
- **"Most popular" shelf**: Hold 20% of collection, Handles 80% of requests

**Even better arrangement?**

- **Reserves**: Hold 80% of collection, Handles 20% of requests
- **"Most popular" shelf**: Hold 20% of collection, Handles 80% of requests
- Top 4%
Computer arrangement

- Reserves
- Disk
- "Most popular" shelf: 20% most popular books
- Memory (RAM)

"Most popular" shelf: 20% most popular books

Top 4%

Cache

CPU

Often, today’s computers have even more levels of caching
Level 1: Closest to CPU
Level 2: Next closest...

Memory Hierarchy

Leverage memory hierarchy of machine architecture

- Registers
- Cache
- Main memory (RAM)
- Non-volatile storage (disk)

Examples of Non-Volatile Storage

- Hard disk drive
- Tapes
- RAID
- Flash drives
- NVRAM

Disk in Action
Modern Libraries

Today’s Summary

Sequential circuits (vs. combinational)
- Can remember values using feedback loops in circuits!
- Implement Random Access Memory (RAM)

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