Lecture A4: Sequential Circuits
Architecture


Lecture A3: Boolean logic and combinational circuits.
  • In principle, we could build TOY computer with one gigantic combinational circuit.
  
  • Each circuit element used (at most) once.

Today.
  • How to reuse circuit elements.
  • How to store bits in "memory."

Next time.
  • Glue these components together to make TOY computer.
Sequential vs. Combinational Circuits

Combinational circuits.
- Output determined solely by inputs.

Sequential circuits.
- Feedback loop.
- Output determined by inputs and previous outputs.
Flip-Flop

Flip-flop.
- A small and useful sequential circuit.
- "Remembers" one bit.

We will consider many flavors.
SR Flip-Flop

SR Flip-Flop.

- Pulse on S (set) ⇒ Flips "bit" on.
- Pulse on R (reset) ⇒ Flips "bit" off.
- S = R = 0 ⇒ Status quo.
- S = R = 1 ⇒ Not allowed.

Implementation
Truth Table and Timing Diagram (for SR Flip-Flop)

Truth table.
- Values vary over time.
- $S(t), R(t), Q(t)$ denote value at time $t$.

Characteristic equation.

$$Q(t+\varepsilon) = S(t) + R'(t)Q(t) \quad (SR = 0)$$

Sample timing diagram.
Clock

- Fundamental abstraction.
  - regular on-off pulse
- External analog device.
- Synchronize operations of different circuit elements.
- 800 MHz clock means 800 million pulses per second.
Clocked SR Flip-Flop

Clocked SR Flip-Flop.

- Like SR flip-flop but S and R only work if clock is on.

![SR flip-flop diagram](image)

**Implementation**

**Interface**

<table>
<thead>
<tr>
<th>Q</th>
<th>Cl</th>
<th>R</th>
<th>S</th>
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<td></td>
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</table>
Clocked D Flip-Flop

- On clock pulse: if $D = 1$, then set; if $D = 0$, then reset.
Master Slave Flip-Flop

Master-slave flip-flop (falling edge-trigger).

- Input can only change on falling edge.
Computer Architecture Perspective

Circuits needed to build a computer.

- Combinational circuit components.
  - adder, multiplexer, decoder

- Sequential circuit components (build from flip-flops).
  - counter
  - memory

All are built from AND, OR, NOT gates.
1-Bit Counter

1-bit counter.

- "Clock" whose cycle is twice as long as input.

Implementation Interface

Master-Slave

1-bit counter

Q

D

Cl

Q

Cl

Q
N-Bit Counter

N-bit counter.

- Chain N 1-bit counters together.
Memory Overview

Computers have many types of memory.
  - Registers.
  - Main memory.

Master-slave flip-flop implements 1 bit of memory.

Need mechanism to reference, store, and extract individual bits.
  - Multiplexer, decoder.

Bit-slice memory.
  - Word size in TOY is 16 bits.
  - First: design circuit for memory with 1 bit "words."
  - Then: implement 16-bit word memory with 16 copies.
Register File: 8 1-bit "words"

Register file: \( n = 2^t \) bits.
- \( n \) bits of memory.
- Address specifies which bit.
  - How many bits needed to specify address?

- If \( \text{write} = 1 \), input gets copied into addressed bit.
- If \( \text{write} = 0 \), addressed bit appears on output.

TOY registers.
- 8 16-bit words.
- Need 16 copies.

TOY main memory.
- 256 16-bit words.
- Need 16 copies of register file with 256 1-bit words.
Register File: n 1-bit "words"

Register file: n registers (words), 1 bit per register.
  - Decoder writes input to address bit.
  - Multiplexer copies address bit to output.
Register File: n k-bit words

Register file: n registers (words), k bits per register.
  - k copies of single bit register file (k = 16 for TOY).
Cheat Sheet

SR flip-flop

Clock SR flip-flop

Master-slave flip-flop

1-bit counter

Register File (8 bits)

Register File (8 16-bit words)