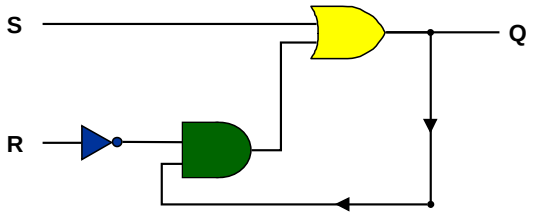
Lecture A4: Sequential Circuits



Overview

Lecture A1 – A3: TOY machine.

Lecture A4: Boolean logic and combinational circuits.

- Basic abstraction = controlled switch.
- In principle, we could build TOY computer with one gigantic combinational circuit.

- Each circuit element used (at most) once.

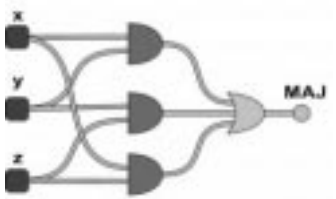
Today: reuse circuit elements by storing bits in "memory."

Next time: glue components together to make TOY computer.

Sequential vs. Combinational Circuits

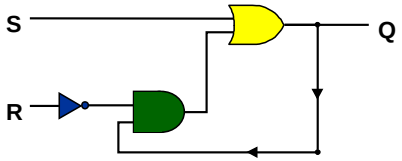
Combinational circuits.

- Output determined solely by inputs.
- You can draw it with all left-to-right signal paths



Sequential circuits.

- Feedback loop.
- Output determined by inputs and previous outputs.
- You cannot draw it with all left-to-right signal paths



Flip-Flop

Flip-flop.

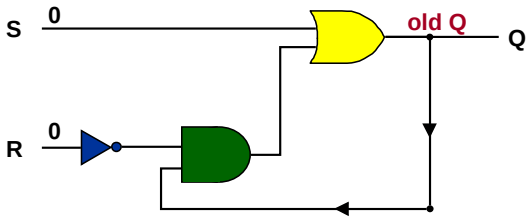
- A small and useful sequential circuit.
- Abstraction that "remembers" one bit.
- Basis of important computer components:
  - memory
  - counter

We will consider several flavors.

SR Flip-Flop

What is the value of Q if:

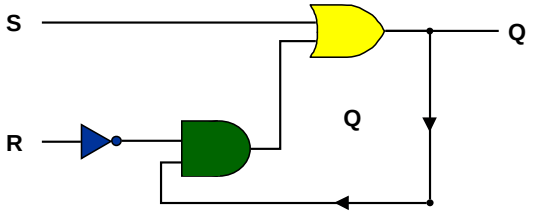
- S = 1 and R = 0 ? ⇒ Q is surely 1.
- S = 0 and R = 1 ? ⇒ Q is surely 0.
- S = 0 and R = 0 ? ⇒ Q is possibly 0. . .or possibly 1.
- *While S = 0 and R = 0, Q "remembers" what it was the last time S or R was 1.*



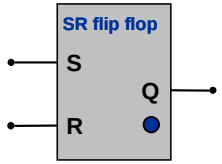
SR Flip-Flop

SR Flip-Flop.

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



Implementation



Interface

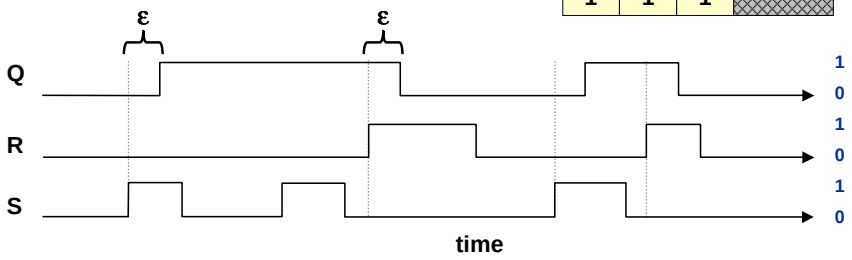
Truth Table and Timing Diagram

Truth table.

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

SR Flip Flop Truth Table			
S(t)	R(t)	Q(t)	Q(t+ε)
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	1
1	1	0	
1	1	1	

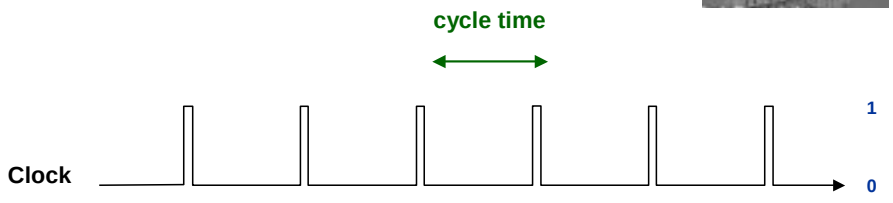
Sample timing diagram for SR flip-flop.



Clock

Clock.

- Fundamental abstraction.
  - regular on-off pulse
- External analog device.
- Synchronize operations of different circuit elements.
- 1 GHz clock means 1 billion pulses per second.



How much does it Hert?

Frequency is expressed in hertz.

- Frequency of 1 Hz means that there is 1 cycle per second.
- Hence:
  - 1 kilohertz (kHz) means 1000 cycles/sec.
  - 1 megahertz (MHz) means 1 million cycles/sec.
  - 1 gigahertz (GHz) means 1 billion cycles/sec.

Unit named in honor of the German physicist Heinrich Rudolf Hertz.

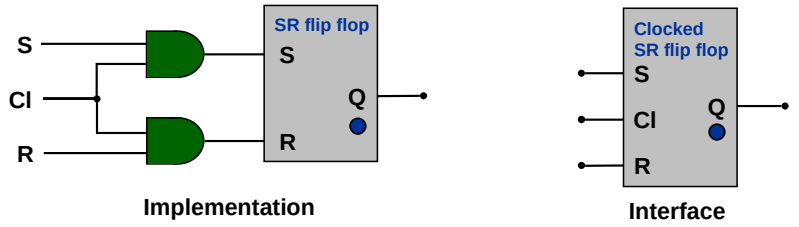
By the way, no such thing as 1 "hert" !

H. Hertz (1857-1894)

Clocked SR Flip-Flop

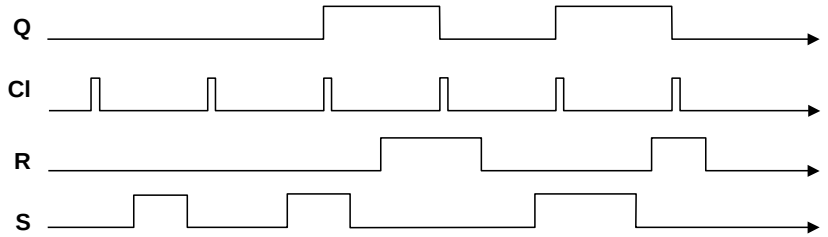
Clocked SR Flip-Flop.

- Same as SR flip-flop except S and R only active when clock is 1.



Implementation

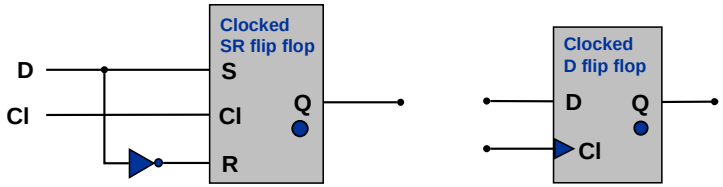
Interface



Clocked D Flip-Flop

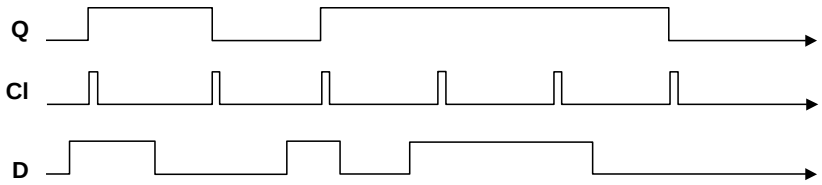
Clocked D Flip-Flop.

- Output follows D input while clock is 1.
- Output is remembered while clock is 0.



Implementation

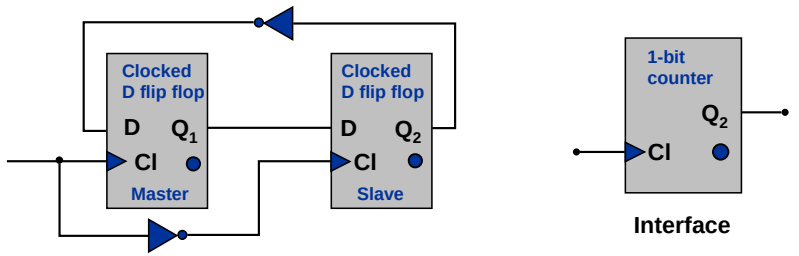
Interface



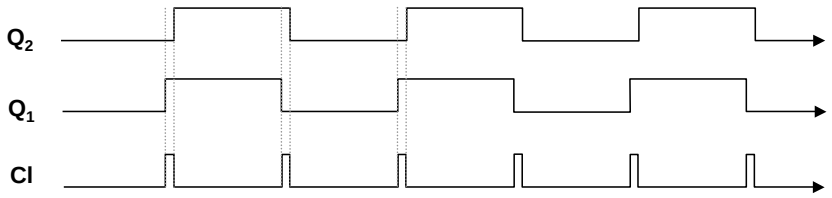
1-Bit Counter

1-bit counter ("edge-triggered").

- Circuit that oscillates between 1 and 0.



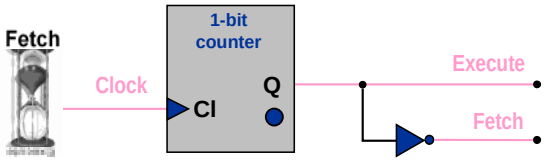
Interface

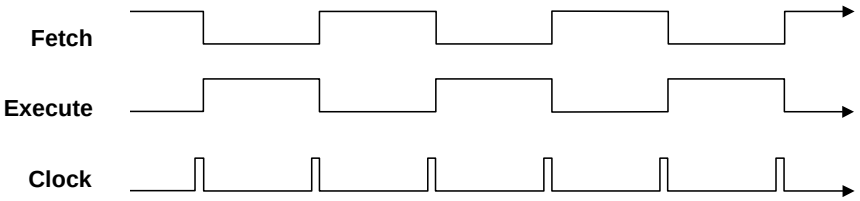


Fetch-Execute Cycle

Fetch-execute cycle.

- Use 1-bit counter.





Memory Overview

Computers have many types of memory.

- Program counter.
- Registers.
- Main memory.

We implement each bit of memory with a clocked D flip-flop.

Need mechanism to organize and manipulate groups of related bits.

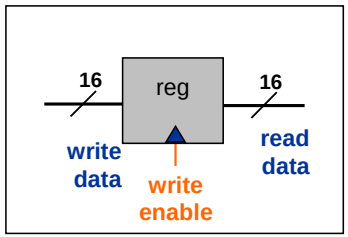
- TOY has 16-bit words.
- Memory hierarchy make architecture manageable.

Stand-Alone Register

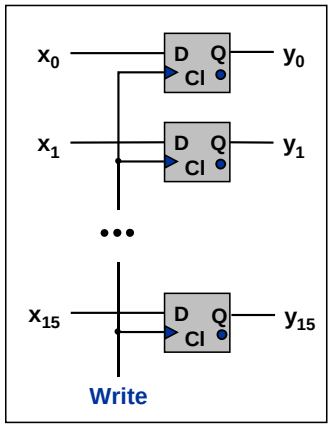
k-bit register.

- Stores k bits.
- Register contents always available on output.
- If write enable is asserted, k input bits get copied into register.

Ex: Program Counter, 16 TOY registers, 256 TOY memory locations.



16-bit Register Interface



16-bit Register Implementation

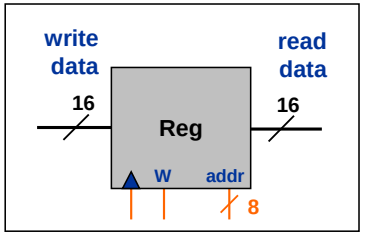
Register File Interface

n x k register file.

- Bank of n registers; each stores k bits.
- Read and write information to ONE of n registers.
  - address inputs specifies which one
  - how many bits needed to specify address?
- Addressed bits always appear on output.
- If write enable and clock are asserted, k input bits get copied into addressed register.

Examples.

- TOY registers: n = 16, k = 16.
- TOY main memory: n = 256, k = 16.
- Real computer: n = 256 million, k = 32.
  - 1 GB memory
  - 1 byte = 8 bits

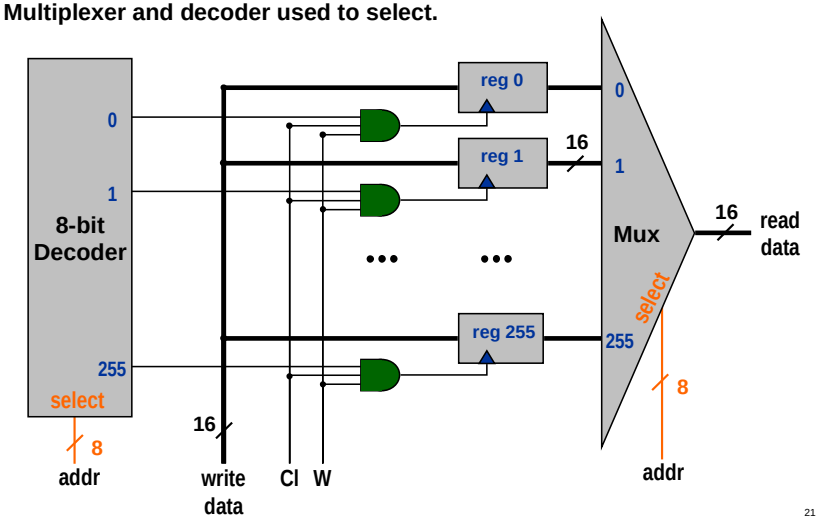


256 x 16 Register File Interface

Register File Implementation

Implementation.

- Use n k-bit registers.
- Multiplexer and decoder used to select.



Summary

Sequential circuits add "state" to digital hardware.

- Flip-flop (1 bit).
  - SR flip-flop
  - Clocked SR FF
  - Clocked D FF
- Register (k D flip-flops).
- Register file (16 registers for TOY).
- Memory (many, many registers).

Actual technologies for "register file" and "memory" are quite different.

- Register files are small and fast (and expensive per bit).
- Memories are large and pretty fast (and amazingly cheap per bit).

Next time: we build a complete TOY computer.