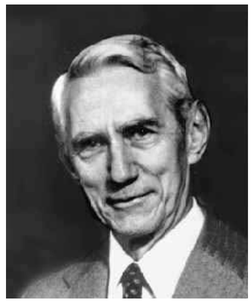
6.1 Combinational Circuits

George Boole (1815 – 1864)



Claude Shannon (1916 – 2001)

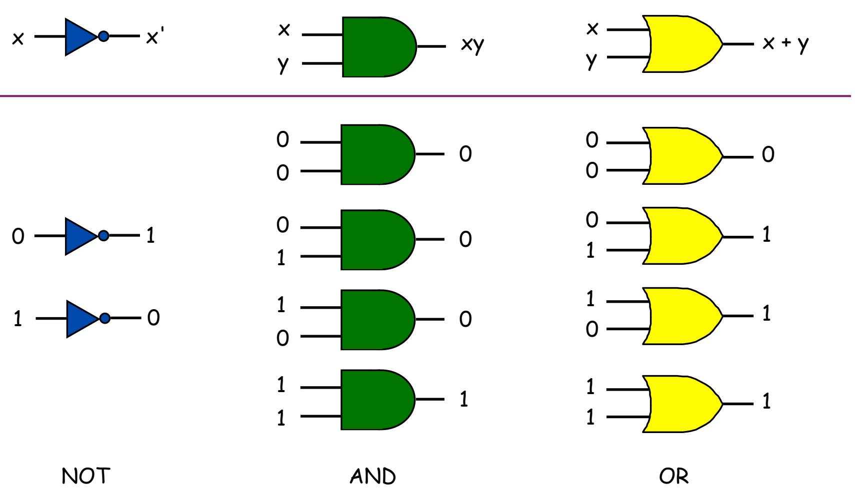
Signals and Wires

Digital signals
- Binary (or "logical") values: 1 or 0, on or off, high or low voltage

Wires.
- Propagate digital signals from place to place.
- Signals "flow" from left to right.
  - A drawing convention, sometimes violated
  - Actually: flow from producer to consumer(s) of signal

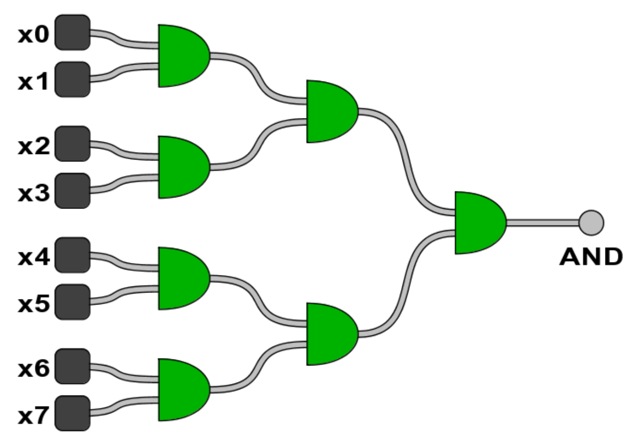
Logic Gates

Logical gates.
- Fundamental building blocks.



Multiway AND Gates

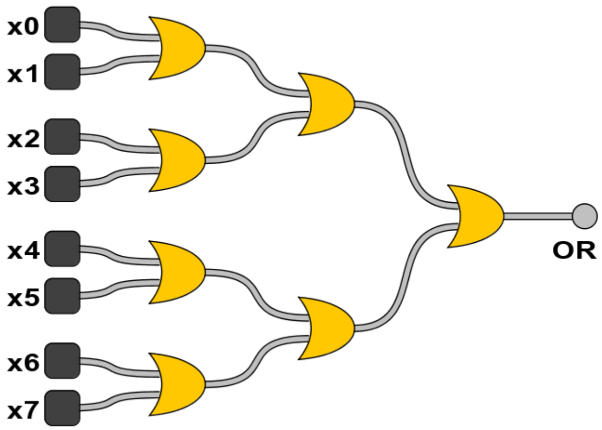
AND(x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7).
- 1 if all inputs are 1.
- 0 otherwise.



Multiway OR Gates

$OR(x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7)$.

- 1 if at least one input is 1.
- 0 otherwise.



Boolean Algebra

History.

- Developed by Boole to solve mathematical logic problems (1847).
- Shannon master's thesis applied it to digital circuits (1937).

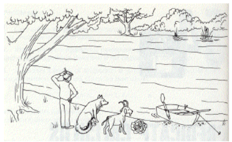
"possibly the most important, and also the most famous, master's thesis of the [20th] century" --Howard Gardner

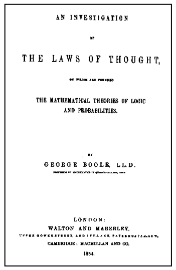
Basics.

- Boolean variable: value is 0 or 1.
- Boolean function: function whose inputs and outputs are 0, 1.

Relationship to circuits.

- Boolean variables: signals.
- Boolean functions: circuits.



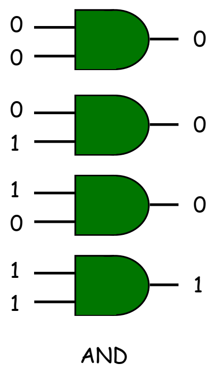


Truth Table

Truth table.

- Systematic method to describe Boolean function.
- One row for each possible input combination.
- N inputs $\Rightarrow$ 2^N rows.

AND Truth Table		
x	y	AND(x, y)
0	0	0
0	1	0
1	0	0
1	1	1



Truth Table for Functions of 2 Variables

Truth table.

- 16 Boolean functions of 2 variables.
  - every 4-bit value represents one

Truth Table for All Boolean Functions of 2 Variables									
x	y	ZERO	AND		x		y	XOR	OR
0	0	0	0	0	0	0	0	0	0
0	1	0	0	0	0	1	1	1	1
1	0	0	0	1	1	0	0	1	1
1	1	0	1	0	1	0	1	0	1

Truth Table for All Boolean Functions of 2 Variables									
x	y	NOR	EQ	y'		x'		NAND	ONE
0	0	1	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1
1	0	0	0	1	1	0	0	1	1
1	1	0	1	0	1	0	1	0	1

Truth Table for Functions of 3 Variables

Truth table.

- 16 Boolean functions of 2 variables.
  - every 4-bit value represents one
- 256 Boolean functions of 3 variables.
  - every 8-bit value represents one
- 2^(2^N) Boolean functions of N variables!

Some Functions of 3 Variables						
x	y	z	AND	OR	MAJ	ODD
0	0	0	0	0	0	0
0	0	1	0	1	0	1
0	1	0	0	1	0	1
0	1	1	0	1	1	0
1	0	0	0	1	0	1
1	0	1	0	1	1	0
1	1	0	0	1	1	0
1	1	1	1	1	1	1

Universality of AND, OR, NOT

Any Boolean function can be expressed using AND, OR, NOT.

- "Universal"
- Example: XOR(x,y) = xy' + x'y

Notation	Meaning
x'	NOT x
x y	x AND y
x + y	x OR y

Expressing XOR Using AND, OR, NOT							
x	y	x'	y'	x'y	xy'	x'y + xy'	XOR
0	0	1	1	0	0	0	0
0	1	1	0	1	0	1	1
1	0	0	1	0	1	1	1
1	1	0	0	0	0	0	0

Exercise. Show {AND, NOT}, {OR, NOT}, {NAND}, {AND, XOR} are universal.

Hint. Use DeMorgan's Law: (xy)' = (x' + y') and (x + y)' = (x'y')

Sum-of-Products

Any Boolean function can be expressed using AND, OR, NOT.

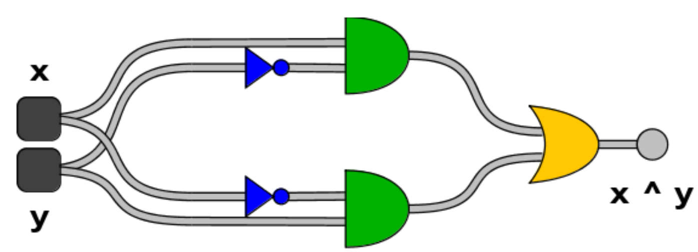
- Sum-of-products is systematic procedure.
  - form AND term for each 1 in truth table of Boolean function
  - OR terms together

Expressing MAJ Using Sum-of-Products								
x	y	z	MAJ	x'yz	xy'z	xyz'	xyz	x'yz + xy'z + xyz' + xyz
0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0
0	1	1	1	1	0	0	0	1
1	0	0	0	0	0	0	0	0
1	0	1	1	0	1	0	0	1
1	1	0	1	0	0	1	0	1
1	1	1	1	0	0	0	1	1

Translate Boolean Formula to Boolean Circuit

Use sum-of-products form.

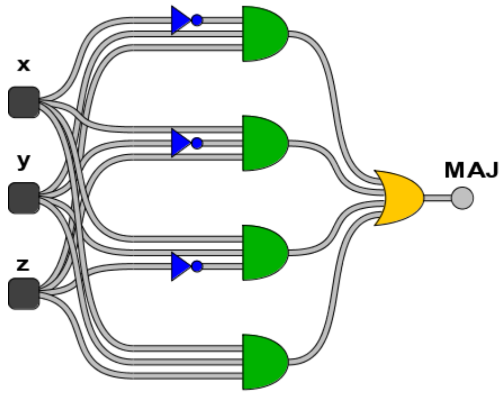
- XOR(x, y) = xy' + x'y.



Translate Boolean Formula to Boolean Circuit

Use sum-of-products form.

- MAJ(x, y, z) = x'yz + xy'z + xyz' + xyz.

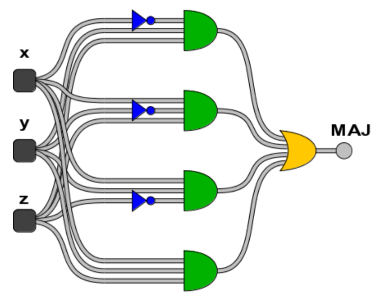


Simplification Using Boolean Algebra

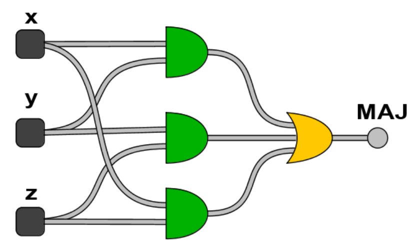
Many possible circuits for each Boolean function.

- Sum-of-products not necessarily optimal in:
  - number of gates (space)
  - depth of circuit (time)

- MAJ(x, y, z) = x'yz + xy'z + xyz' + xyz = xy + yz + xz.



size = 8, depth = 3



size = 4, depth = 2

Expressing a Boolean Function Using AND, OR, NOT

Ingredients.

- AND gates.
- OR gates.
- NOT gates.
- Wire.

Instructions.

- Step 1: represent input and output signals with Boolean variables.
- Step 2: construct truth table to carry out computation.
- Step 3: derive (simplified) Boolean expression using sum-of products.
- Step 4: transform Boolean expression into circuit.

ODD Parity Circuit

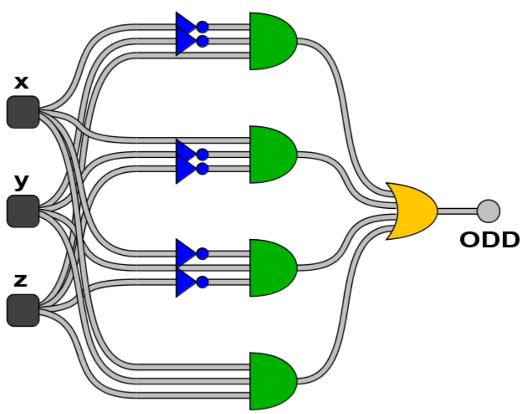
ODD(x, y, z).

- 1 if odd number of inputs are 1.
- 0 otherwise.

Expressing ODD Using Sum-of-Products								
x	y	z	ODD	x'y'z	x'yz'	xy'z'	xyz	x'y'z + x'yz' + xy'z' + xyz
0	0	0	0	0	0	0	0	0
0	0	1	1	1	0	0	0	1
0	1	0	1	0	1	0	0	1
0	1	1	0	0	0	0	0	0
1	0	0	1	0	0	1	0	1
1	0	1	0	0	0	0	0	0
1	1	0	0	0	0	0	0	0
1	1	1	1	0	0	0	1	1

ODD Parity Circuit

ODD(x, y, z).
- 1 if odd number of inputs are 1.
- 0 otherwise.



Let's Make an Adder Circuit

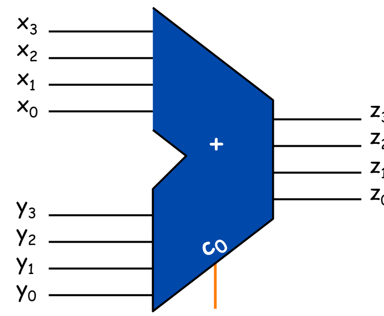
Goal: $x + y = z$ for 4-bit integers.
- We build 4-bit adder: 9 inputs, 4 outputs.
- Same idea scales to 128-bit adder.
- Key computer component.

	1	1	1	0
	2	4	8	7
+	3	5	7	9
	6	0	6	6

Step 1.
- Represent input and output in binary.

	1	1	0	0
	0	0	1	0
+	0	1	1	1
	1	0	0	1

	x_3	x_2	x_1	x_0
+	y_3	y_2	y_1	y_0
	z_3	z_2	z_1	z_0



Let's Make an Adder Circuit

Goal: $x + y = z$ for 4-bit integers.

Step 2. (first attempt)
- Build truth table.
- Why is this a bad idea?
  - 128-bit adder: 2^{256+1} rows > # electrons in universe!

				c_0
	x_3	x_2	x_1	x_0
+	y_3	y_2	y_1	y_0
	z_3	z_2	z_1	z_0

4-Bit Adder Truth Table

c_0	x_3	x_2	x_1	x_0	y_3	y_2	y_1	y_0	z_3	z_2	z_1	z_0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	1	0	0	0	1
0	0	0	0	0	0	0	1	0	0	0	1	0
0	0	0	0	0	0	0	1	1	0	0	1	1
0	0	0	0	0	0	1	0	0	0	1	0	0
0	0	0	0	0	0	1	0	1	0	1	0	1
.	.	.	.	.	.	.	.	.	.	.	.	.
1	1	1	1	1	1	1	1	1	1	1	1	1

$2^{8+1} = 512$ rows!

Let's Make an Adder Circuit

Goal: $x + y = z$ for 4-bit integers.

Step 2. (do one bit at a time)
- Build truth table for carry bit.
- Build truth table for summand bit.

	c_3	c_2	c_1	$c_0 = 0$
	x_3	x_2	x_1	x_0
+	y_3	y_2	y_1	y_0
	z_3	z_2	z_1	z_0

Carry Bit

x_i	y_i	c_i	c_{i+1}
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Summand Bit

x_i	y_i	c_i	z_i
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

Let's Make an Adder Circuit

Goal: $x + y = z$ for 4-bit integers.

Step 3.
- Derive (simplified) Boolean expression.

	c_3	c_2	c_1	$c_0 = 0$
	x_3	x_2	x_1	x_0
+	y_3	y_2	y_1	y_0
	z_3	z_2	z_1	z_0

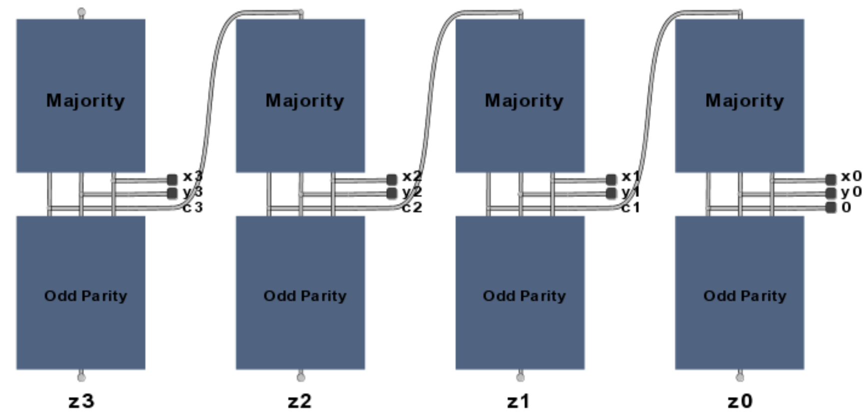
Carry Bit				
x_i	y_i	c_i	c_{i+1}	MAJ
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	1	1
1	0	0	0	0
1	0	1	1	1
1	1	0	1	1
1	1	1	1	1

Summand Bit				
x_i	y_i	c_i	z_i	ODD
0	0	0	0	0
0	0	1	1	1
0	1	0	1	1
0	1	1	0	0
1	0	0	1	1
1	0	1	0	0
1	1	0	0	0
1	1	1	1	1

Let's Make an Adder Circuit

Goal: $x + y = z$ for 4-bit integers.

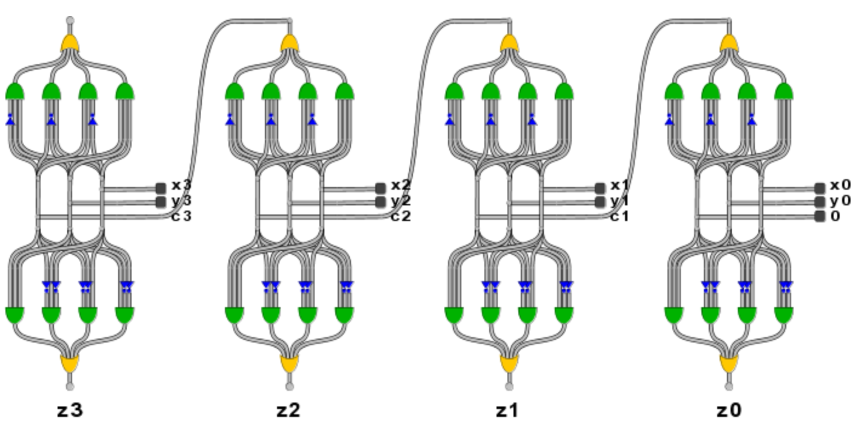
Step 4.
- Transform Boolean expression into circuit.
- Chain together 1-bit adders.



Let's Make an Adder Circuit

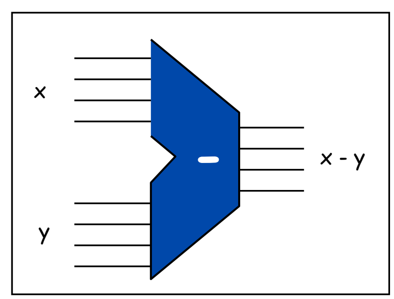
Goal: $x + y = z$ for 4-bit integers.

Step 4.
- Transform Boolean expression into circuit.
- Chain together 1-bit adders.

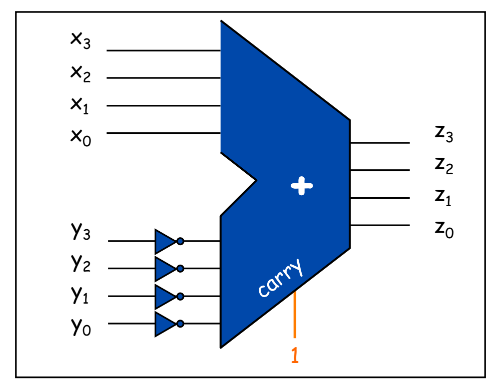


Subtractor

Subtractor circuit: $z = x - y$.
- One approach: design like adder circuit.
- Better idea: reuse adder circuit.
  - 2's complement: to negate an integer, flip bits, then add 1



4-Bit Subtractor Interface



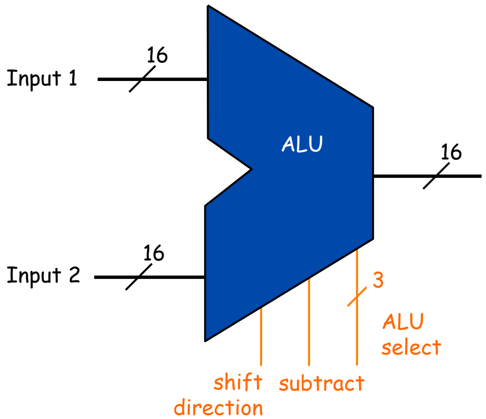
4-Bit Subtractor Implementation

Arithmetic Logic Unit: Interface

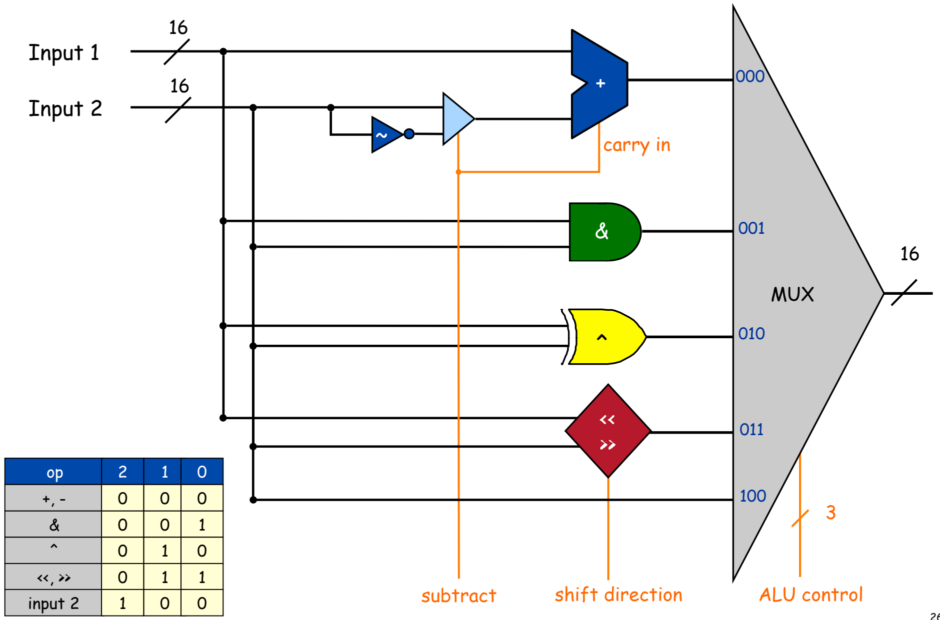
ALU Interface.

- Add, subtract, bitwise and, bitwise xor, shift left, shift right, copy.
- Associate 3-bit integer with 5 primary ALU operations.
  - ALU performs operations in parallel
  - control wires select which result ALU outputs

op	2	1	0
+, -	0	0	0
&	0	0	1
^	0	1	0
<<, >>	0	1	1
input 2	1	0	0



Arithmetic Logic Unit: Implementation



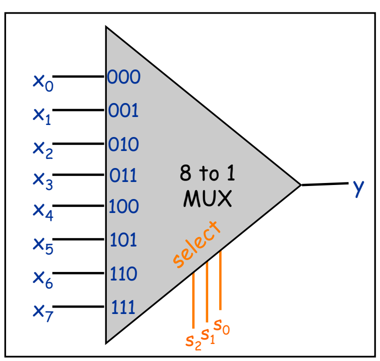
op	2	1	0
+, -	0	0	0
&	0	0	1
^	0	1	0
<<, >>	0	1	1
input 2	1	0	0

2^n-to-1 Multiplexer

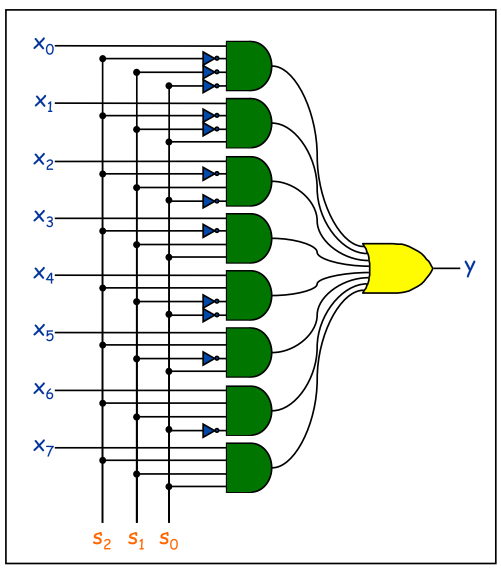
n = 8 for main memory

2^n-to-1 multiplexer.

- n select inputs, 2^n data inputs, 1 output.
- Copies "selected" data input bit to output.

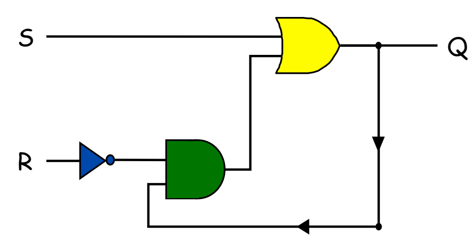


8-to-1 Mux Interface



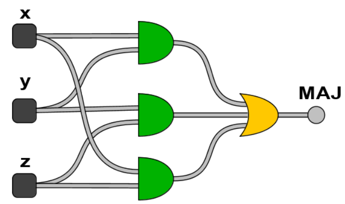
8-to-1 Mux Implementation

6.2: Sequential Circuits

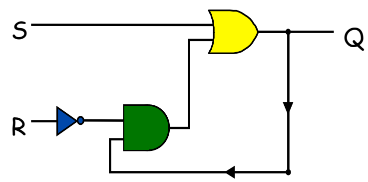


Sequential vs. Combinational Circuits

Combinational circuits.
- Output determined solely by inputs.
- Can draw solely with left-to-right signal paths.

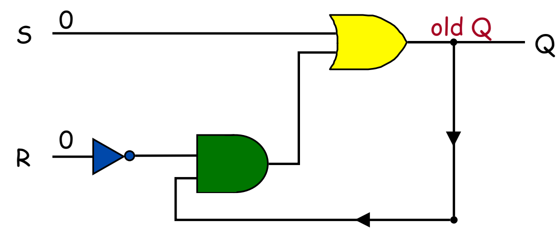


Sequential circuits.
- Output determined by inputs AND previous outputs.
- Feedback loop.



SR Flip-Flop

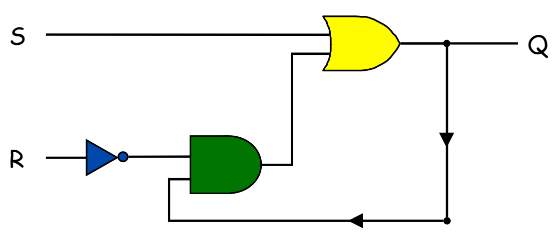
What is the value of Q if:
- S = 1 and R = 0 ? ⇒ Q is surely 1.
- S = 0 and R = 1 ? ⇒ Q is surely 0.
- S = 0 and R = 0 ? ⇒ Q is possibly 0 . . . or possibly 1.



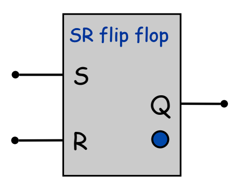
While S = R = 0 , Q *remembers* what it was the last time S or R was 1.

SR Flip-Flop

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



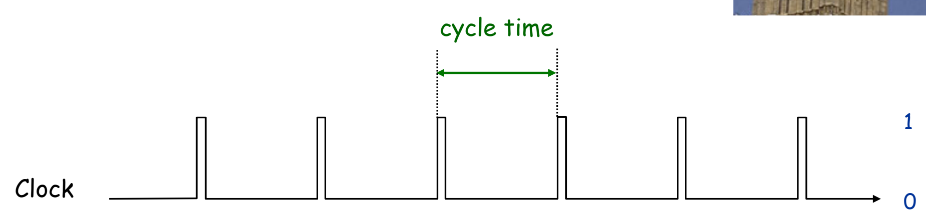
Implementation



Interface

Clock

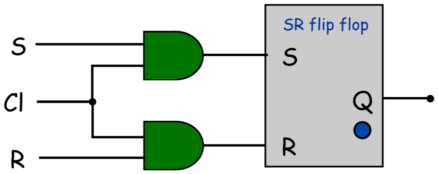
Clock.
- Fundamental abstraction.
  - regular on-off pulse
- External analog device.
- Synchronizes operations of different circuit elements.
- 1 GHz clock means 1 billion pulses per second.



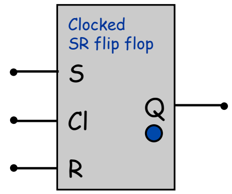
Clocked SR Flip-Flop

Clocked SR Flip-Flop.

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



Implementation

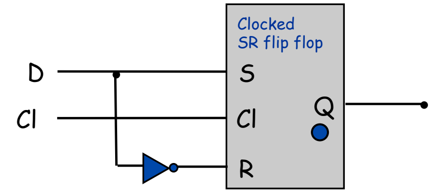


Interface

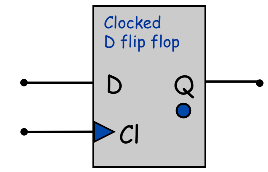
Clocked D Flip-Flop

Clocked D Flip-Flop.

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



Implementation



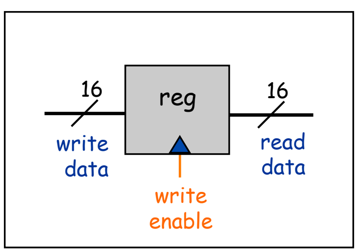
Interface

Stand-Alone Register

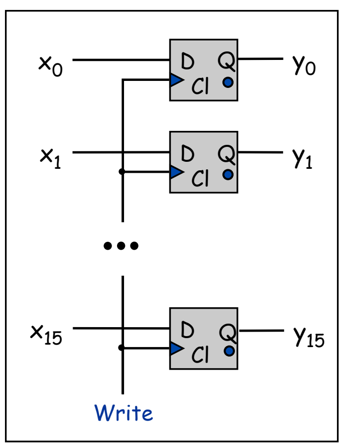
k-bit register.

- 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

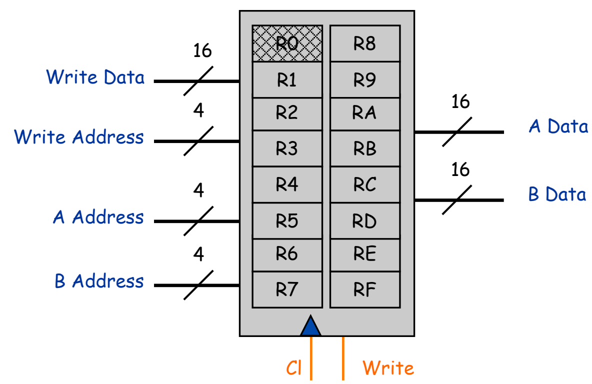


16-bit Register Implementation

Registers

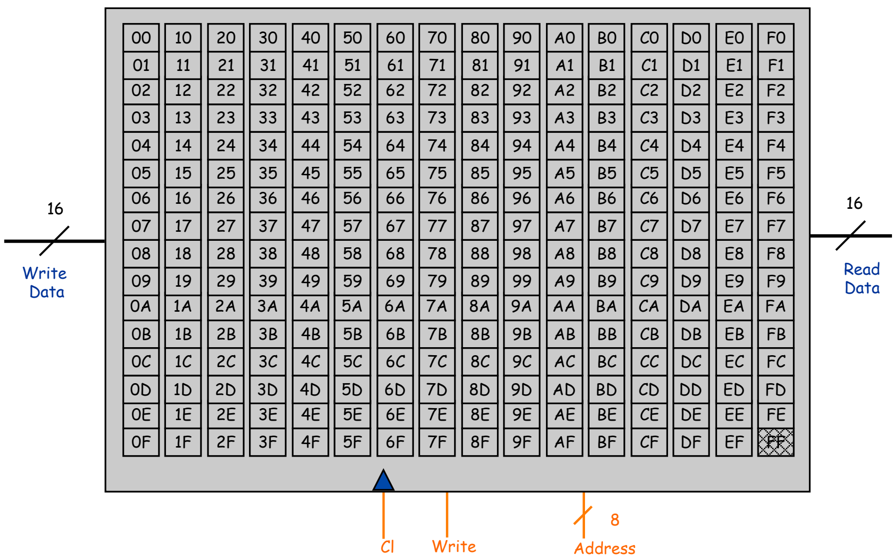
TOY registers: fancy 16 x 16-bit register file.

- Want to be able to read two registers, and write to a third in the same instructions: `R1 ← R2 + R3.`
- 3 address inputs, 1 data input, 2 data outputs.
- Add decoders and muxes for additional ports.

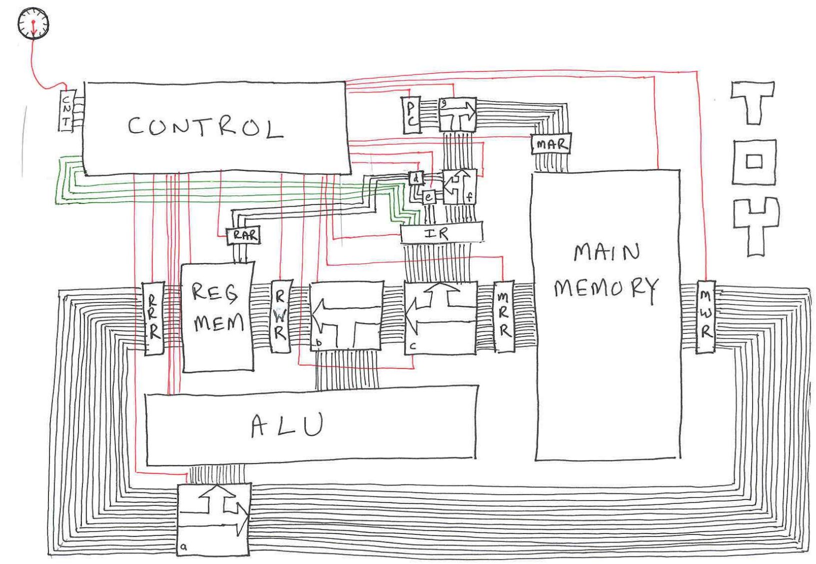


Main Memory

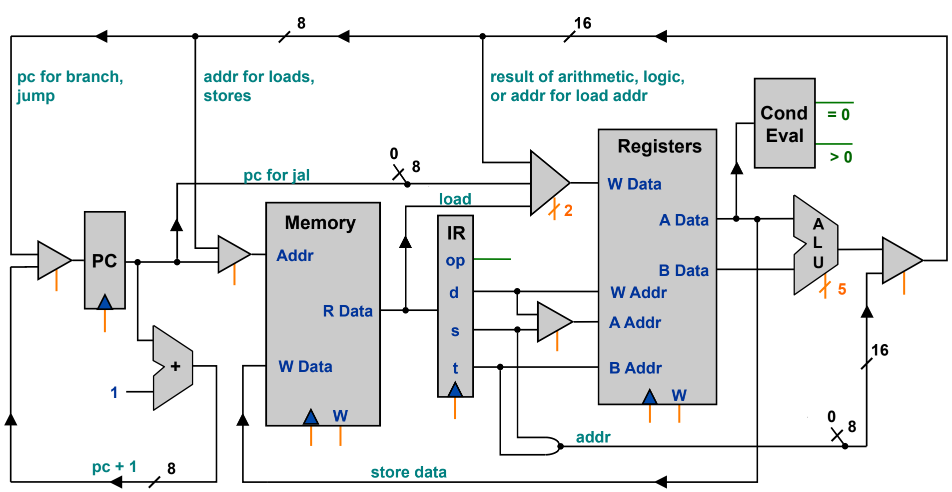
TOY main memory: 256 x 16-bit register file.



6.3: Machine Architecture



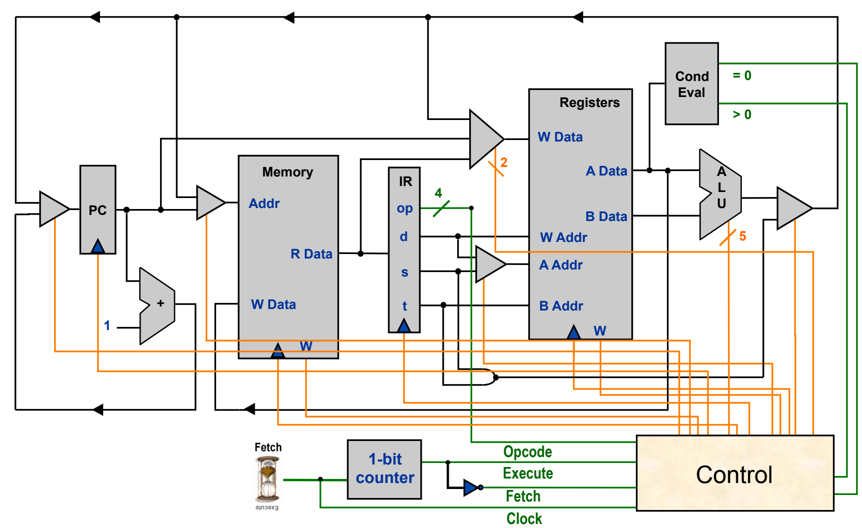
The TOY Datapath



Control

Control: controls components, enables connections.

- Input: opcode, clock, conditional evaluation. (green)
- Output: control wires. (orange)



Summary

Combinational circuits: how to compute things

- And, Or, Not primitives sufficient for any Boolean function
- Systematic method: truth tables and sum-of-products
- Examples
  - Majority
  - Binary adder
  - Multiplexor

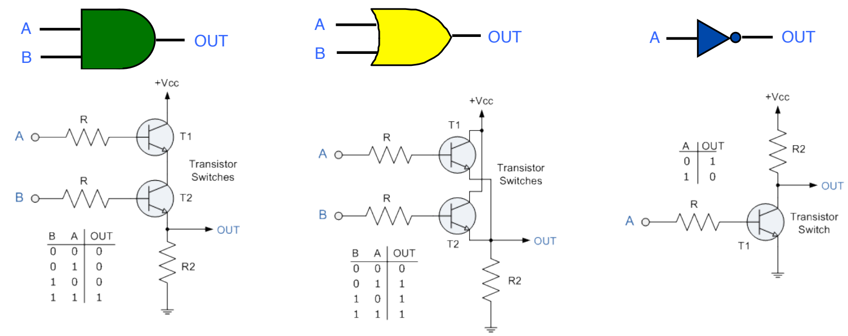
Sequential circuits: where to put things

- Flip flop primitive holds one bit
- Many flip flops make a *register* (16 for TOY)
- Many registers make a *register file*
- Lots and lot of registers make a *memory* (256 for TOY)

A whole computer

- Uses *combinational circuits* to perform computations
- Uses *sequential circuits* to store results
- Uses a little of each for control

The final secret



All three of our logic primitives can be made using a *single** type of electronic primitive: the *transistor*!

*not counting the passive resistors