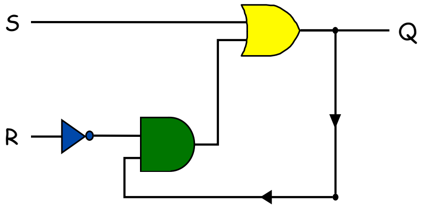
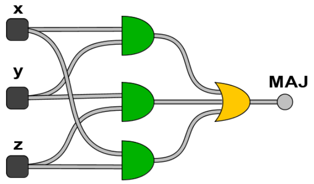
6.2: Sequential Circuits



Sequential vs. Combinational Circuits

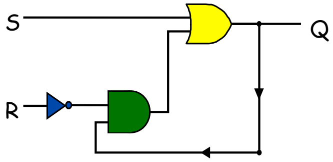
Combinational circuits.

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



Sequential circuits.

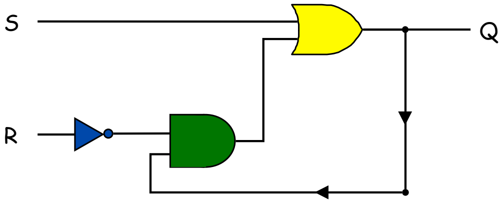
- Output determined by inputs AND previous outputs.
- Feedback loop.



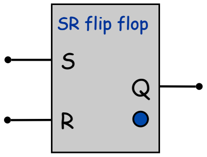
SR Flip-Flop

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

Memory Overview

Computers and TOY have many types of memory.

- Program counter.
- Registers.
- Main memory.

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

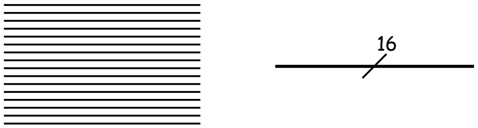
Need mechanism to organize and manipulate GROUPS of related bits.

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

Bus

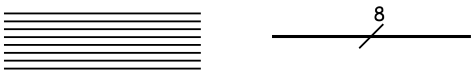
16-bit bus.

- Bundle of 16 wires.
- Memory transfer, register transfer.



8-bit bus.

- Bundle of 8 wires.
- TOY memory address.



4-bit bus.

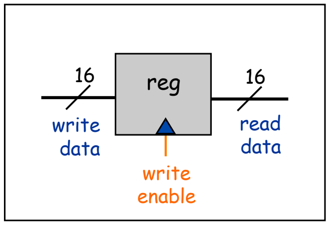
- Bundle of 4 wires.
- TOY register address.

Stand-Alone Register

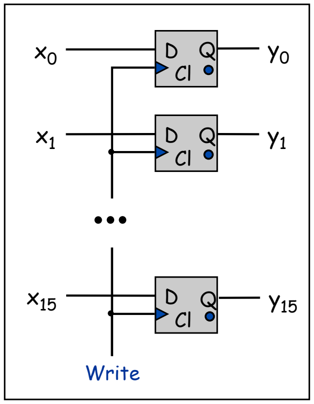
k-bit register.

- 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

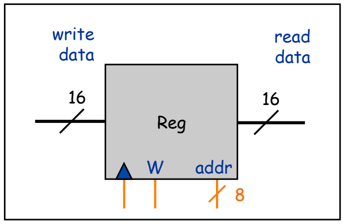
Register File Interface

n-by-k register file.

- Bank of n registers; each stores k bits.
- Read and write information to *one* of n registers.
  - log$_2$ n address inputs specifies which one
- Addressed bits always appear on output.
- If write enable and clock are asserted, k input bits are 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)

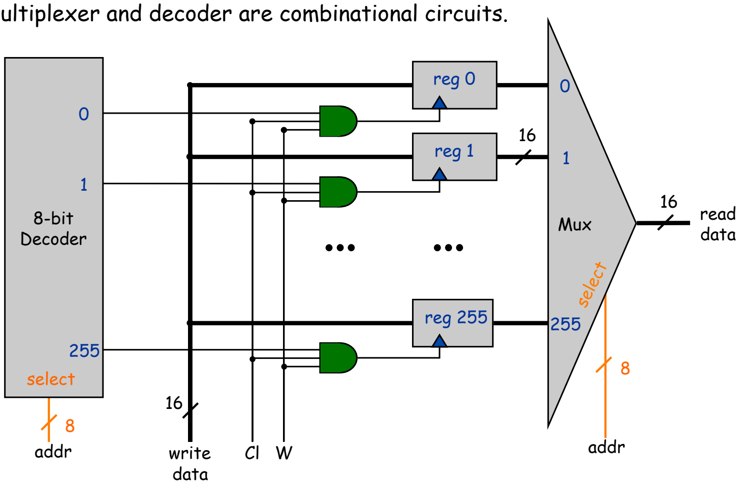


256 x 16 Register File Interface

Register File Implementation

Implementation example: TOY main memory.

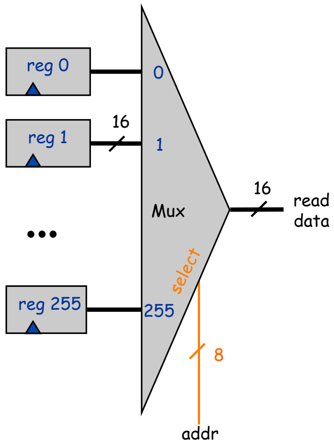
- Use 256 16-bit registers.
- Multiplexer and decoder are combinational circuits.



Register File Implementation: Reading

Implementation example: TOY main memory.

- Use 256 16-bit registers.
- Multiplexer is combinational circuit.

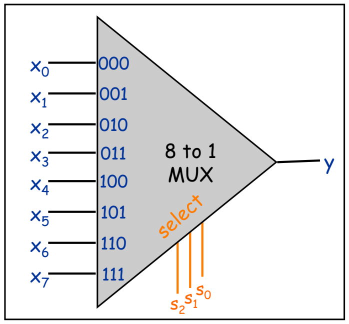


2^n-to-1 Multiplexer

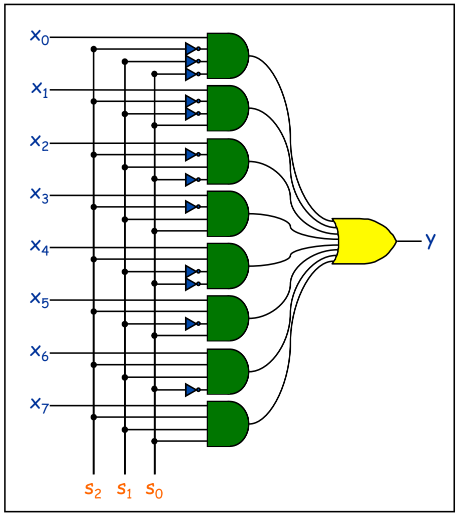
n = 8 for main memory

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



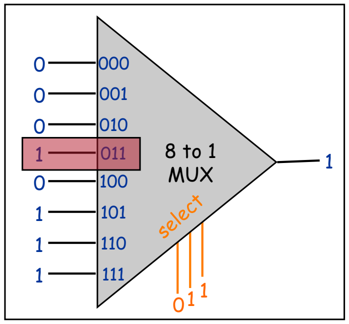
8-to-1 Mux Implementation

2^n-to-1 Multiplexer

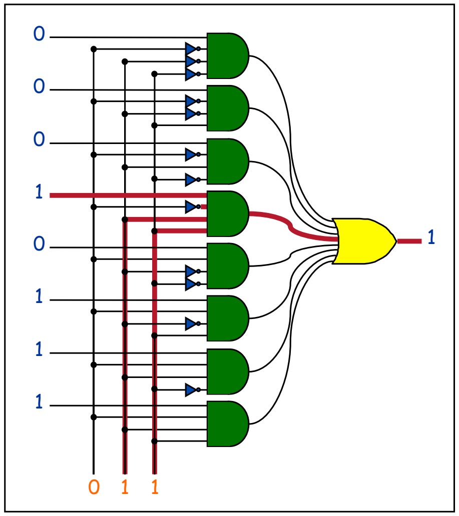
n = 8 for main memory

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



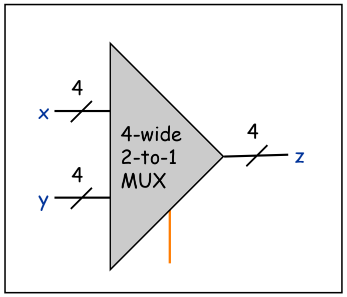
8-to-1 Mux Implementation

2^n-to-1 Multiplexer, Width = k

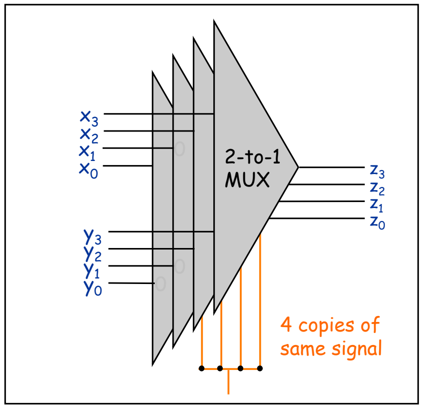
n = 8, k = 16 for main memory

2^n-to-1 multiplexer, width = k.

- Select from one of 2^n k-bit buses.
- Copies k "selected" data bits to output.
- Layering k 2^n-to-1 multiplexers.



Interface for 2-to-1 MUX, width = 4

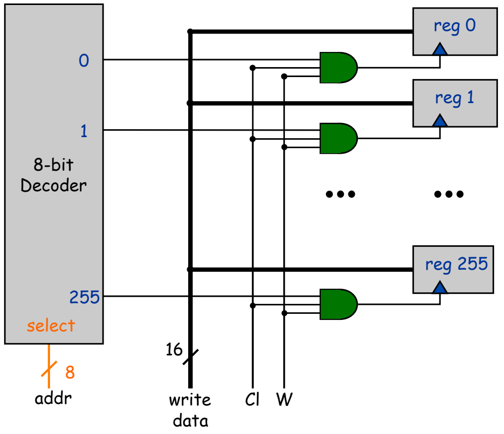


Implementation for 2-to-1 MUX, width = 4

Register File Implementation: Writing

Implementation example: TOY main memory.

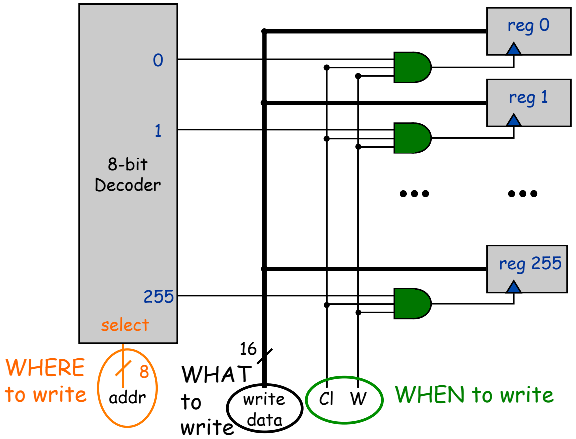
- Use 256 16-bit registers.
- Decoder is combinational circuit.



Register File Implementation: Writing

Implementation example: TOY main memory.

- Use 256 16-bit registers.
- Decoder is combinational circuit.

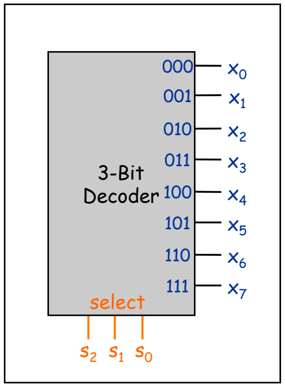


n-Bit Decoder

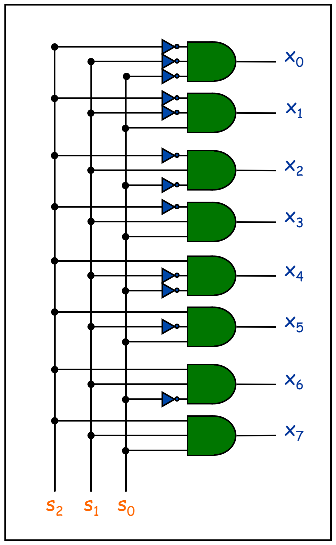
n = 8 for main memory

n-bit decoder.

- n address inputs, 2^n data outputs.
- Addressed output bit is 1; others are 0.



3-Bit Decoder Interface



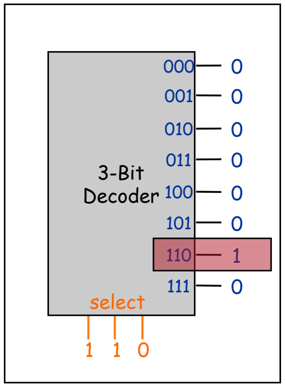
3-Bit Decoder Implementation

n-Bit Decoder

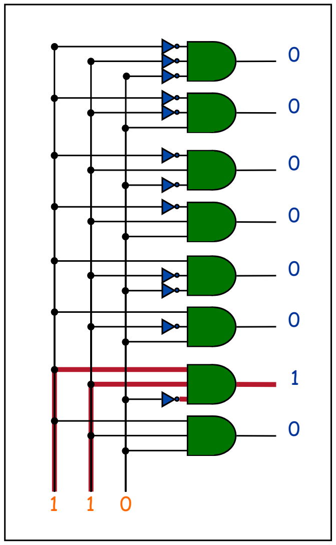
n = 8 for main memory

n-bit decoder.

- n address inputs, 2^n data outputs.
- Addressed output bit is 1; others are 0.



3-Bit Decoder Interface

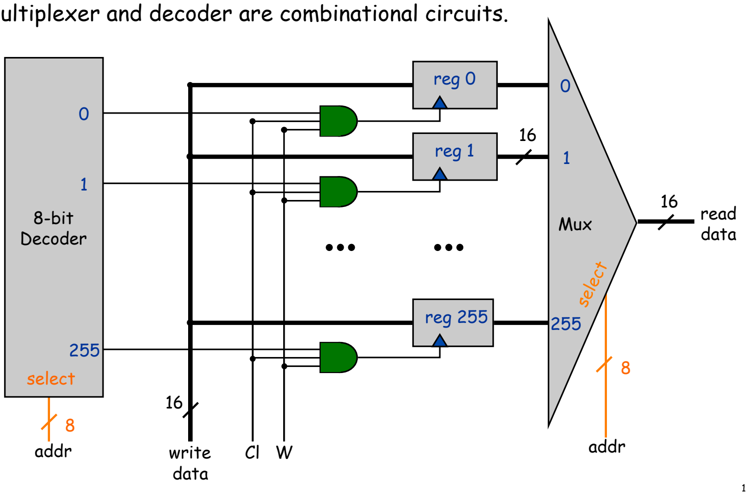


3-Bit Decoder Implementation

Register File Implementation: Reading and Writing

Implementation example: TOY main memory.

- Use 256 16-bit registers.
- Multiplexer and decoder are combinational circuits.



Register File Variations

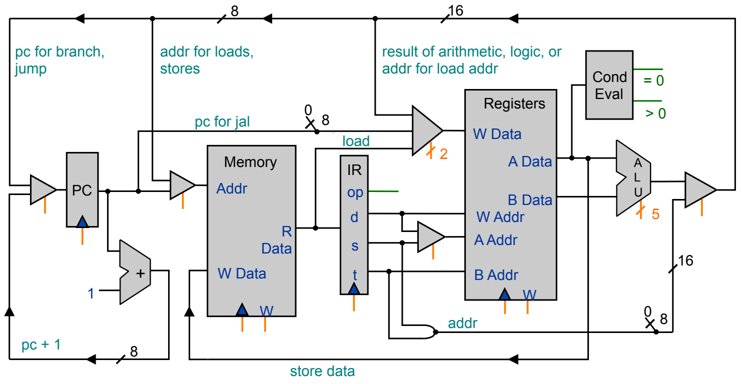
Read address can be different from Write address

- Not in Main Memory (one address from instruction or PC)
- But definitely in TOY registers (read from and write to different registers)

Can have multiple "ports"

- TOY registers supply TWO values per instruction
- How? Just get another set of 16-to-1, 16-wide multiplexors (and one more 4-bit address)

6.3: TOY Machine Architecture



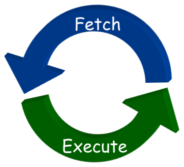
The TOY Machine

TOY machine.

- 256 16-bit words of memory.
- 16 16-bit registers.
- 1 8-bit program counter.
- 16 instructions types.

What we've done.

- Written programs for the TOY machine.
- Software implementation of fetch-execute cycle.
  - TOY simulator.



Our goal today.

- Hardware implementation of fetch-execute cycle.
  - TOY computer.

Designing a Processor

How to build a microprocessor?

- ➡ Develop instruction set architecture (ISA).
  - 16-bit words, 16 TOY machine instructions
- Determine major components.
  - ALU, memory, registers, program counter
- Determine datapath requirements.
  - "flow" of bits
- Establish clocking methodology.
  - 2-cycle design: fetch, execute
- Analyze how to implement each instruction.
  - determine settings of control signals

Instruction Set Architecture

Instruction set architecture (ISA).

- 16-bit words, 256 words of memory, 16 registers.
- Determine set of primitive instructions.
  - too narrow ⇒ cumbersome to program
  - too broad ⇒ cumbersome to build hardware
- TOY machine: 16 instructions.

Instructions	
0:	halt
1:	add
2:	subtract
3:	and
4:	xor
5:	shift left
6:	shift right
7:	load address

Instructions	
8:	load
9:	store
A:	load indirect
B:	store indirect
C:	branch zero
D:	branch positive
E:	jump register
F:	jump and link

Designing a Processor

How to build a microprocessor?

- Develop instruction set architecture (ISA).
  - 16-bit words, 16 TOY machine instructions
- ➡ Determine major components.
  - ALU, memory, registers, program counter
- Determine datapath requirements.
  - "flow" of bits
- Establish clocking methodology.
  - 2-cycle design: fetch, execute
- Analyze how to implement each instruction.
  - determine settings of control signals

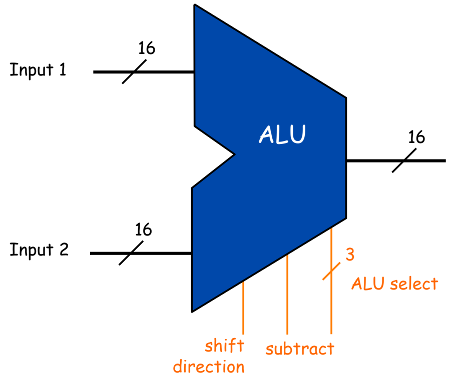
Arithmetic Logic Unit

TOY ALU.

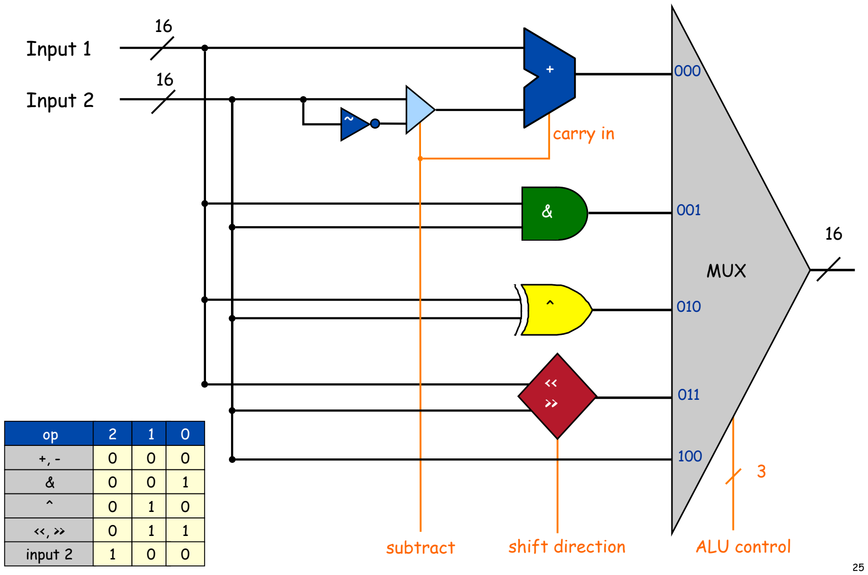
- Big combinational circuit.
- 16-bit bus.
- Add, subtract, and, xor, shift left, shift right, copy input 2.

technical hack

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



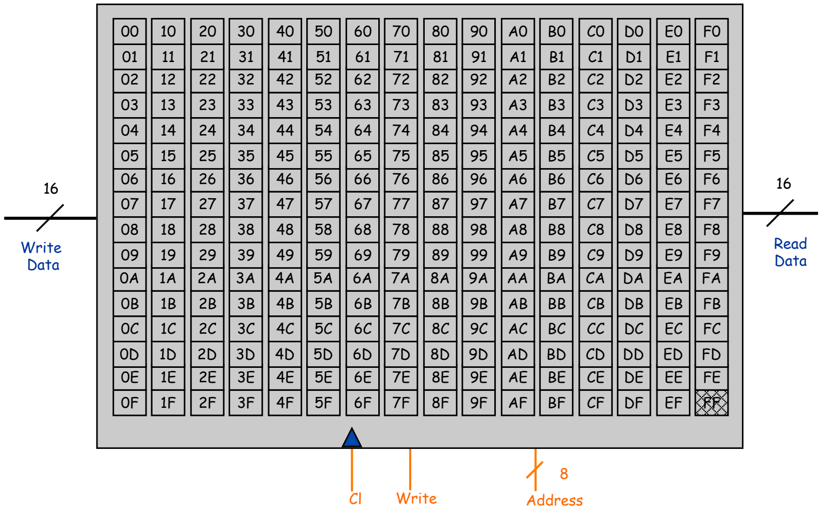
Arithmetic Logic Unit: Implementation



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

Main Memory

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

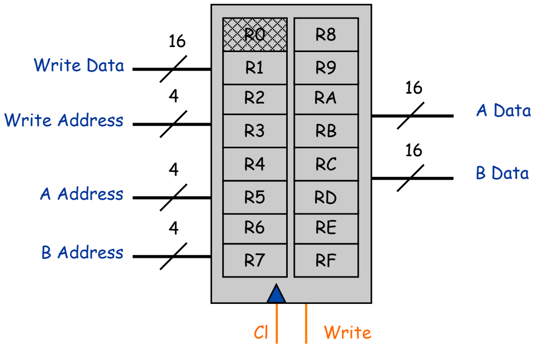


00	10	20	30	40	50	60	70	80	90	A0	B0	C0	D0	E0	F0
01	11	21	31	41	51	61	71	81	91	A1	B1	C1	D1	E1	F1
02	12	22	32	42	52	62	72	82	92	A2	B2	C2	D2	E2	F2
03	13	23	33	43	53	63	73	83	93	A3	B3	C3	D3	E3	F3
04	14	24	34	44	54	64	74	84	94	A4	B4	C4	D4	E4	F4
05	15	25	35	45	55	65	75	85	95	A5	B5	C5	D5	E5	F5
06	16	26	36	46	56	66	76	86	96	A6	B6	C6	D6	E6	F6
07	17	27	37	47	57	67	77	87	97	A7	B7	C7	D7	E7	F7
08	18	28	38	48	58	68	78	88	98	A8	B8	C8	D8	E8	F8
09	19	29	39	49	59	69	79	89	99	A9	B9	C9	D9	E9	F9
0A	1A	2A	3A	4A	5A	6A	7A	8A	9A	AA	BA	CA	DA	EA	FA
0B	1B	2B	3B	4B	5B	6B	7B	8B	9B	AB	BB	CB	DB	EB	FB
0C	1C	2C	3C	4C	5C	6C	7C	8C	9C	AC	BC	CC	DC	EC	FC
0D	1D	2D	3D	4D	5D	6D	7D	8D	9D	AD	BD	CD	DD	ED	FD
0E	1E	2E	3E	4E	5E	6E	7E	8E	9E	AE	BE	CE	DE	EE	FE
0F	1F	2F	3F	4F	5F	6F	7F	8F	9F	AF	BF	CF	DF	EF	FF

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.



R0	R8
R1	R9
R2	RA
R3	RB
R4	RC
R5	RD
R6	RE
R7	RF

Designing a Processor

How to build a microprocessor?

- Develop instruction set architecture (ISA).
  - 16-bit words, 16 TOY machine instructions
- Determine major components.
  - ALU, memory, registers, program counter
- ➡ Determine datapath requirements.
  - "flow" of bits
- Establish clocking methodology.
  - 2-cycle design: fetch, execute
- Analyze how to implement each instruction.
  - determine settings of control signals

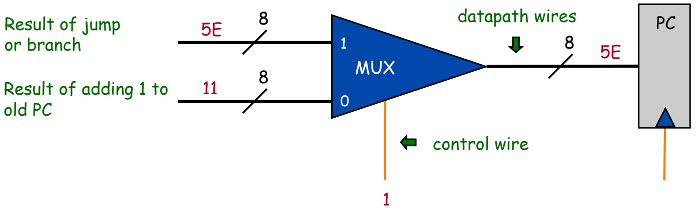
Datapath and Control

Datapath.

- Layout and interconnection of components.
- Must accommodate all instruction types.

Control.

- Choreographs the "flow" of information on the datapath.
- Depending on instruction, different control wires are turned on.



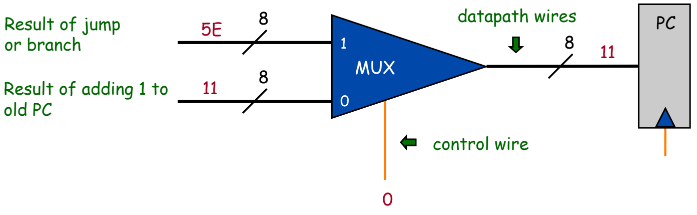
Datapath and Control

Datapath.

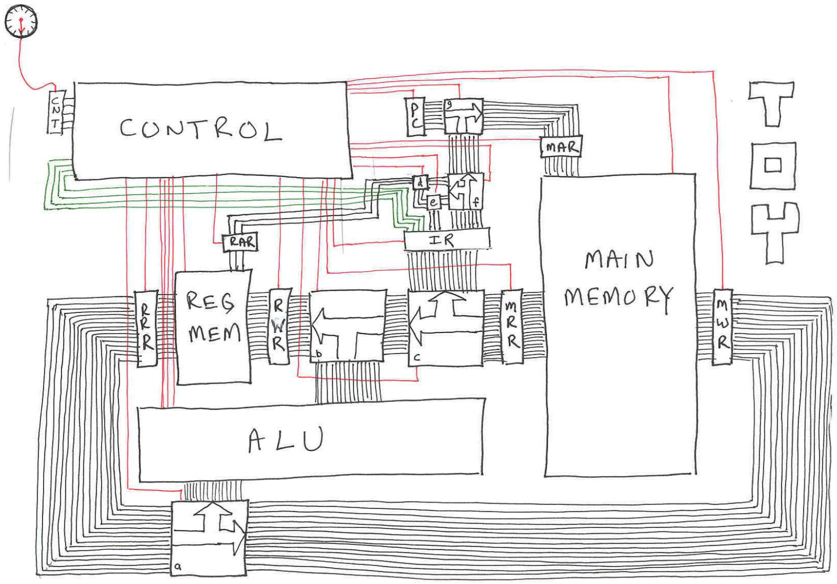
- Layout and interconnection of components.
- Must accommodate all instruction types.

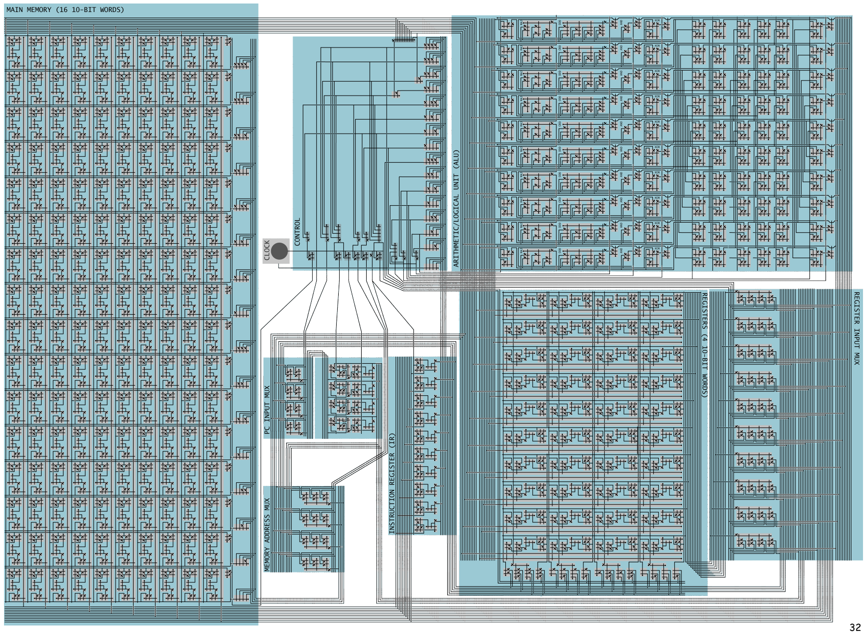
Control.

- Choreographs the "flow" of information on the datapath.
- Depending on instruction, different control wires are turned on.

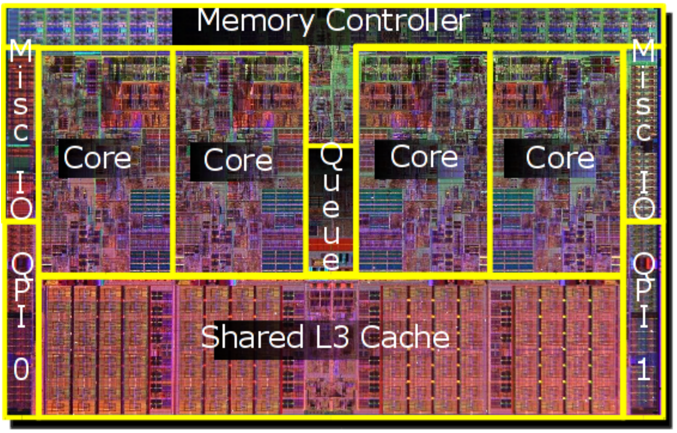


TOY "Classic", Back Of Envelope Design

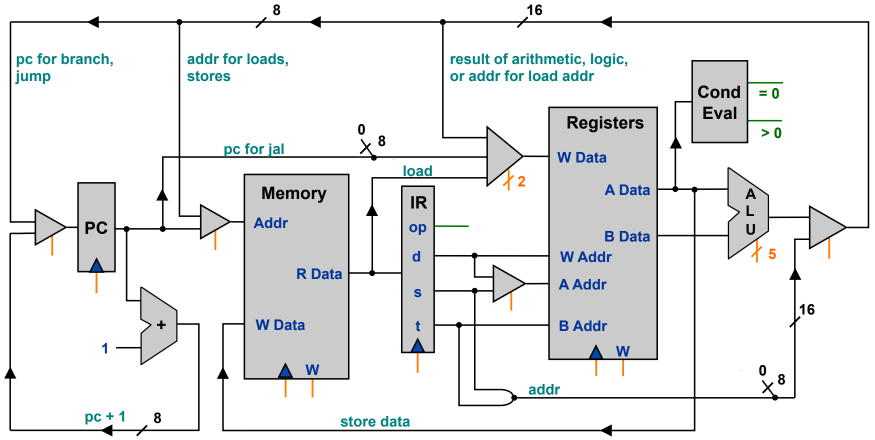



MAIN MEMORY (16 10-BIT WORDS)
CLOCK
CONTROL
ARITHMETIC/LOGICAL UNIT (ALU)
REGISTERS (4 10-BIT WORDS)
REGISTER INPUT MUX
PC INPUT MUX
MEMORY ADDRESS MUX
INSTRUCTION REGISTER (IR)

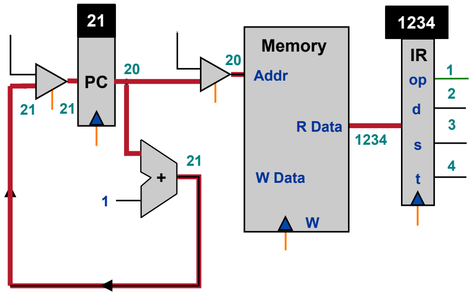
Real Microprocessor Chip (Intel Nehalem)



The TOY Datapath



The TOY Datapath: Add



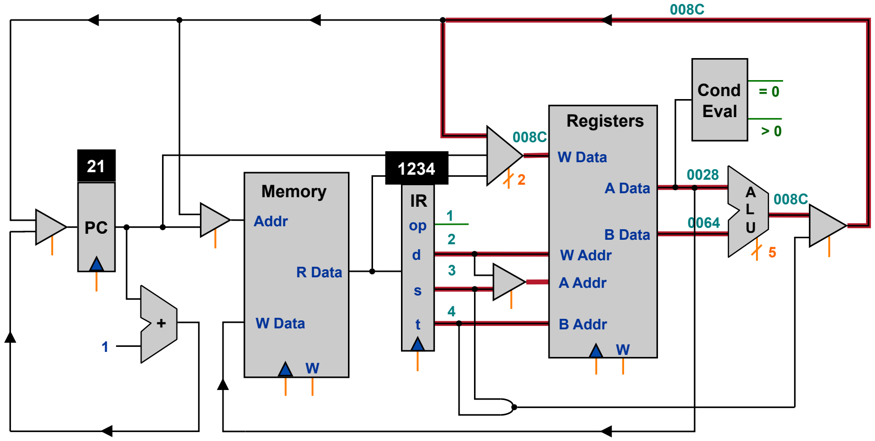
Before fetch:

```
pc = 20, mem[20] = 1234
```

After fetch:

```
pc = 21
IR = 1234: R[2] ← R[3] + R[4]
```

The TOY Datapath: Add



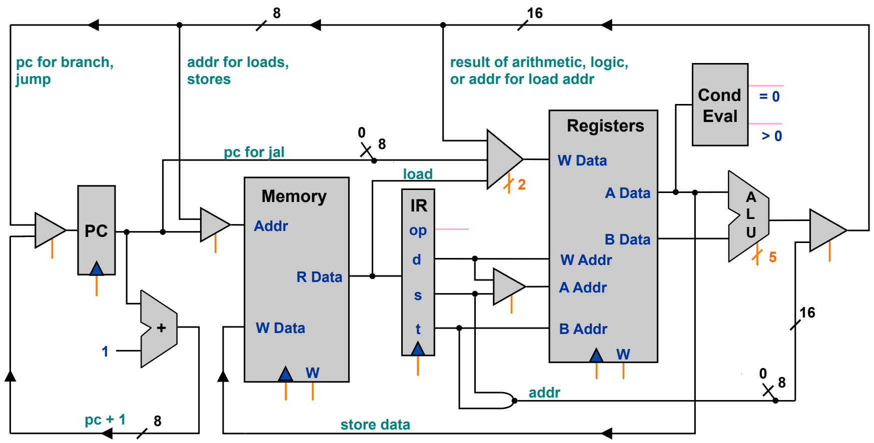
Before execute:

```
pc = 21
IR = 1234: R[2] ← R[3] + R[4]
R[3] = 0028, R[4] = 0064
```

After execute:

```
pc = 21
R[2] = 008C
```

Do Try This At Home



Trace the flow of some other instructions through the datapath picture.

Designing a Processor

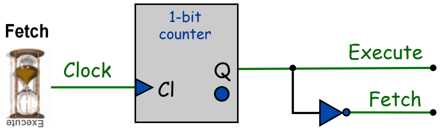
How to build a microprocessor?

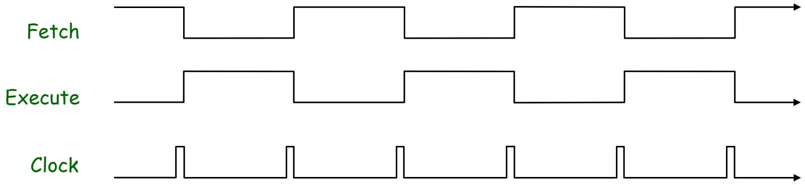
- Develop instruction set architecture (ISA).
  - 16-bit words, 16 TOY machine instructions
- Determine major components.
  - ALU, memory, registers, program counter
- Determine datapath requirements.
  - "flow" of bits
- ➡ Establish clocking methodology.
  - 2-cycle design: fetch, execute
- Analyze how to implement each instruction.
  - determine settings of control signals

Clocking Methodology

Two cycle design (fetch and execute).

- Use 1-bit counter to distinguish between 2 cycles.
- Use two cycles since fetch and execute phases each access memory and alter program counter.





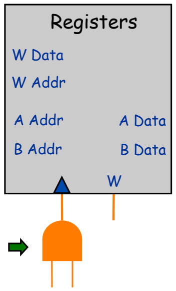
Clocking Methodology

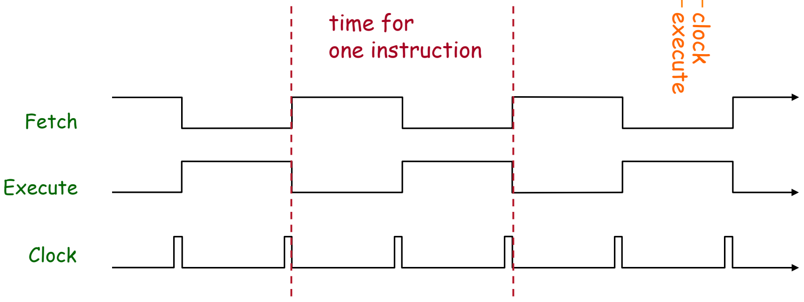
4 distinguishable epochs.

- During fetch phase.
- At very end of execute phase.
- During execute phase.
- At very end of fetch phase.

Ex: can only write at very end of execute phase.

- `R1 ← R1 + R1`





Designing a Processor

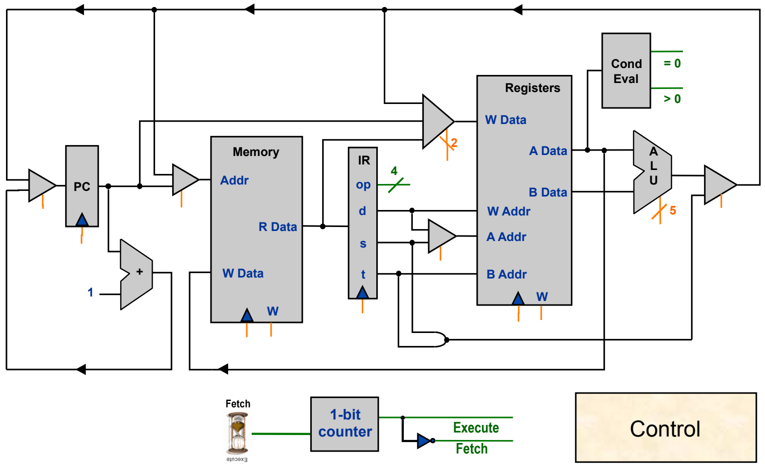
How to build a microprocessor?

- Develop instruction set architecture (ISA).
  - 16-bit words, 16 TOY machine instructions
- Determine major components.
  - ALU, memory, registers, program counter
- Determine datapath requirements.
  - "flow" of bits
- Establish clocking methodology.
  - 2-cycle design: fetch, execute
- ➡ Analyze how to implement each instruction.
  - determine settings of control signals

Control

Control: controls components, enables connections.

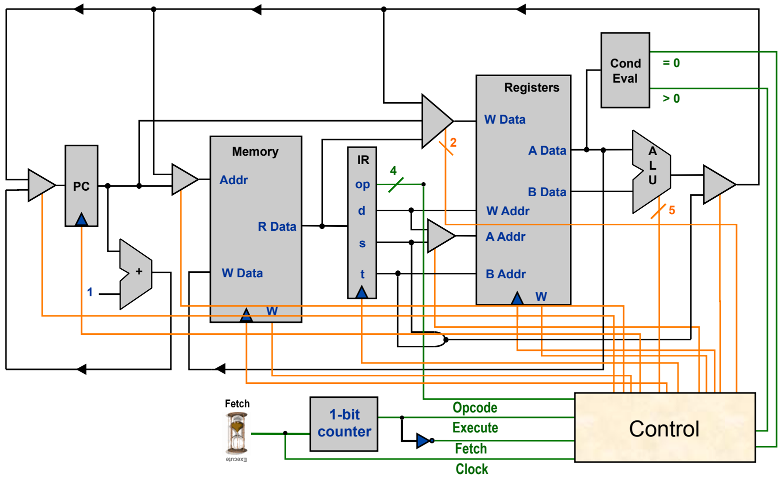
- Input: opcode, clock, conditional evaluation. (green)
- Output: control wires. (orange)



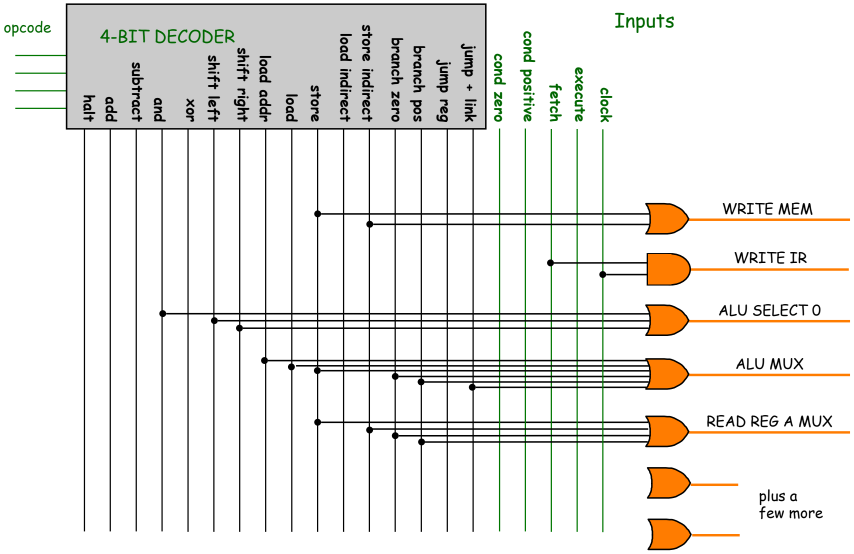
Control

Control: controls components, enables connections.

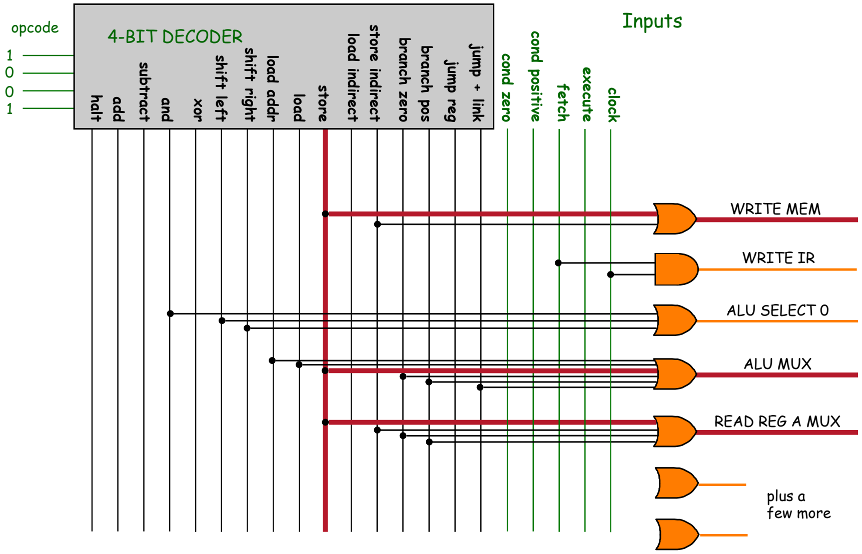
- Input: opcode, clock, conditional evaluation. (green)
- Output: control wires. (orange)



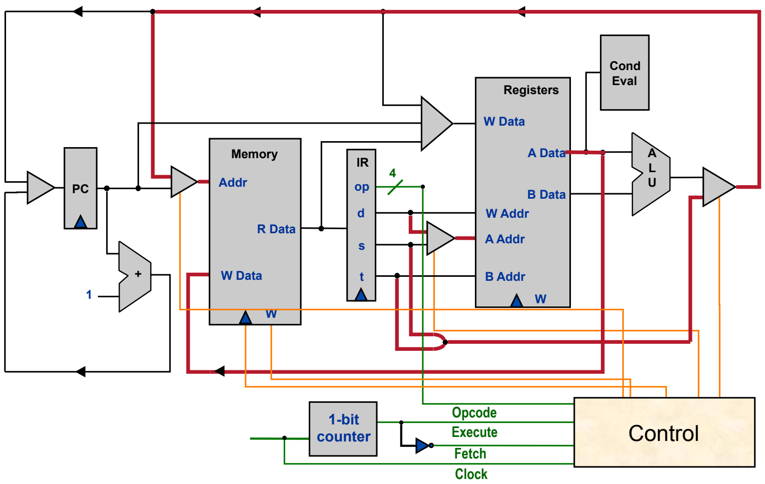
Implementation of Control



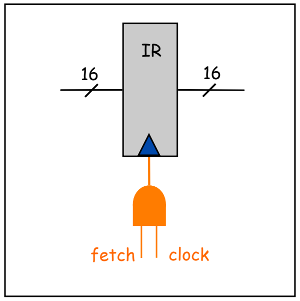
Implementation of Control: Store



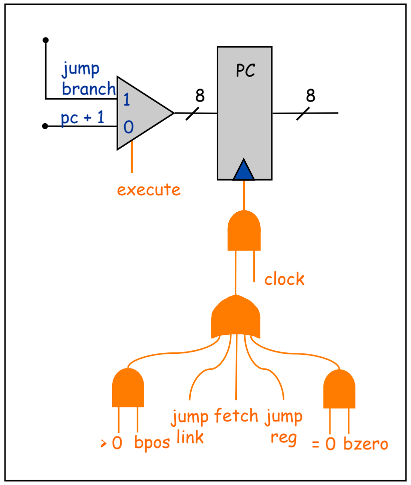
Control: Execute Phase of Store



Stand-Alone Registers



Instruction Register



Program Counter

Pipelining

Pipelining.

- At any instant, processor is either fetching instructions or executing them (and so half of circuitry is idle).
- Why not fetch next instruction while current instruction is executing?
  - Analogy: washer / dryer.

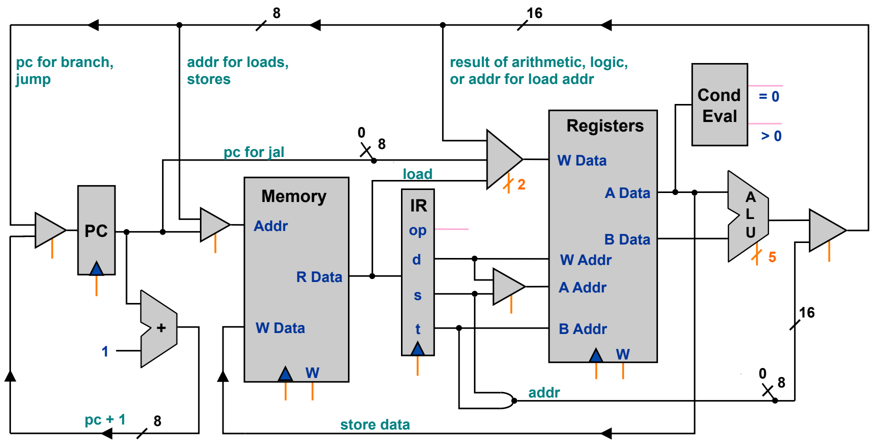
Issues.

- Jump and branch instructions change PC.
  - "Prefetch" next instruction.
- Fetch and execute cycles may need to access same memory.
  - Solution: use two memory “caches”.

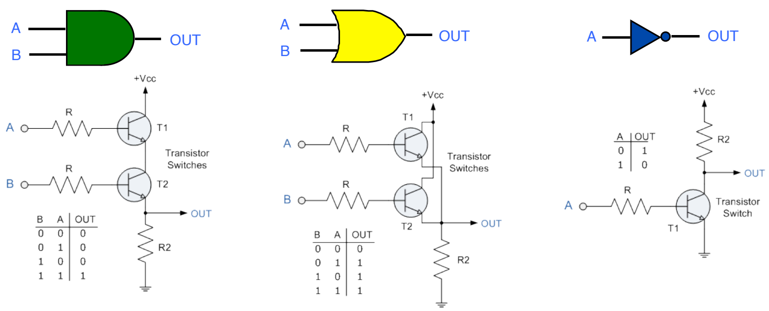
Result.

- Better utilization of hardware.
- Can double speed of processor.

Goodbye, TOY



The final secret



B	A	OUT
0	0	0
0	1	0
1	0	0
1	1	1

B	A	OUT
0	0	0
0	1	1
1	0	1
1	1	1

A	OUT
0	1
1	0

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

*not counting the passive resistors