Operating Systems

Steven Hand

12 lectures for CST Ia

Easter Term 2000

Part I: Computer Organisation

Recommended Reading

- Tannenbaum A S
  Structured Computer Organization (3rd Ed)
  Prentice-Hall 1990.

- Patterson D and Hennessy J
  Computer Organization & Design (2rd Ed)
  Morgan Kaufmann 1998.

- Bacon J M
  Concurrent Systems (2nd Ed)
  Addison Wesley 1997
  Especially Part I, and Chapters 23 & 25
  3 copies in book-locker.

- Silberschatz A, Peterson J and Galvin P
  Operating Systems Concepts (5th Ed.)
  Addison Wesley 1998.
  2 copies in book-locker.

- Leffler S J
  The Design and Implementation of the 4.3BSD
  UNIX Operating System.
  Addison Wesley 1989

- Solomon D
  Inside Windows NT (2nd Ed)
  Microsoft Press 1998.

Course Aims

- To provide you with a general understanding of how a computer works.
- To explain the structure and functions of an operating system.
- To illustrate key operating system aspects by example.
- To prepare you for future courses ...

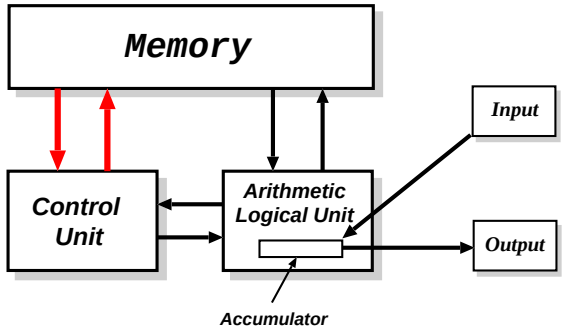
Course Outline

- Part I: Computer Organisation
  - Computer Foundations
  - Operation of a Simple Computer.
  - Input/Output.
- Part II: Operating System Functions.
  - Introduction to Operating Systems.
  - Processes & Scheduling.
  - Memory Management.
  - I/O & Device Management.
  - Filing Systems.
- Part III: Case Studies.
  - Unix.
  - Windows NT.

A Chronology of Early Computing

- (several BC): abacus used for counting
- 1614: logarithms disovered (John Napier)
- 1622: invention of the slide rule (Robert Bissaker)
- 1642: First mechanical digital calculator (Pascal)
- Charles Babbage (U. Cambridge) invents:
  - 1812: "Difference Engine"
  - 1833: "Analytical Engine"
- 1890: First electro-mechanical punched card data-processing machine (Hollerith, later IBM)
- 1905: Vacuum tube/triode invented (De Forest)
- 1935: the relay-based *IBM 601* reaches 1 MPS.
- 1939: *ABC* — first electronic digital computer (Atanasoff & Berry, Iowa State University)
- 1941: *Z3* — first programmable computer (Zuse)
- Jan 1943: the *Harvard Mark I* (Aiken)
- Dec 1943: *Colossus* built at 'Station X', Bletchley Park (Newman & Wynn-Williams, et al).

The Von Neumann Architecture



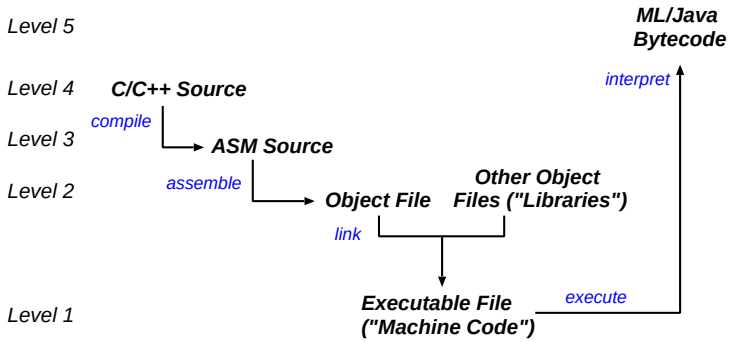
- 1945: *ENIAC* (Eckert & Mauchley, U. Penn):
  - 30 tons, 1000 square feet, 140 kW,
  - 18K vacuum tubes, 20×10-digit accumulators,
  - 100KHz, circa 300 MPS.
  - Used to calculate artillery firing tables.
  - (1946) blinking lights for the media ...
- But: "programming" is via plugboard ⇒ v. slow.
- 1945: von Neumann drafts "EDVAC" report:
  - design for a stored-program machine
  - Eckert & Mauchley mistakenly unattributed

Further Progress . . .

- 1947: "point contact" transistor invented (Shockley, Bardeen & Brattain, Bell Labs)
- 1949: *EDSAC*, the world's first stored-program computer (Wilkes & Wheeler, U. Cambridge)
  - 3K vacuum tubes, 300 square feet, 12 kW,
  - 500KHz, circa 650 IPS, 225 MPS.
  - 1024 17-bit words of memory in mercury ultrasonic delay lines.
  - 31 word "operating system" (!)
- 1954: *TRADIC*, first electronic computer without vacuum tubes (Bell Labs)
- 1954: first silicon (junction) transistor (TI)
- 1959: first integrated circuit (Kilby & Noyce, TI)
- 1964: IBM System/360, based on ICs.
- 1971: Intel 4004, first micro-processor (Ted Hoff):
  - 2300 transistors, 60 KIPS.
- 1978: Intel 8086/8088 (used in IBM PC).
- $\sim$ 1980: first VLSI chip ($>$ 100,000 transistors)

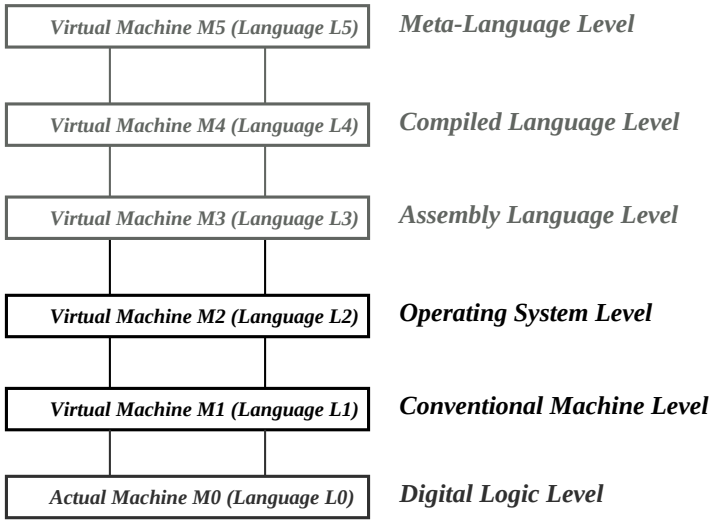
Today: $\sim$ 20 million transistors, $\sim 0.18\mu$, $\sim$ 1000 MHz.

Languages and Levels



- Modern machines all programmable with a huge variety of different languages.
- e.g. ML, java, C++, C, python, perl, FORTRAN, Pascal, Scheme, ...
- Can describe the operation of a computer at a number of different *levels*, but all levels are *functionally equivalent* (i.e. can perform the same set of tasks)
- Each level relates to the one below via either
  a) translation, or
  b) interpretation.

Layered Virtual Machines



- In one sense, there is a set of different machines M_0, M_1, M_2 ... M_n, each built on top of the other.
- Can consider each machine M_i to understand only machine language L_i.
- This course focuses on levels 1 and 2 ...

Bambi meets Digital Electronics

- Digital circuit = electrical circuit in which two logical values are present: `0` and `1`.
- We represent `0` by a low voltage level "Ground" e.g. +0 volts.
- We represent `1` by a high voltage level "V_{cc}", e.g. +5 volts.
- By using a power supply, a bunch of wires and some *transistors* we can build a digital circuit.
- When looking at digital logic, we use special logic symbols to represent a collection of underlying electronic components ⇒ don't need to know about the underlying stuff.

Boolean Algebra

- Named after guy called Boole (1850s)
- Simply algebra on values in the set $B = \{0, 1\}$.
- Four possible functions with 1 input and 1 output; we only care about two:
  - Identity function, **I**, maps 0 to 0, and 1 to 1.
  - Inversion function, **NOT**, maps 0 to 1, and 1 to 0.
- Sixteen possible functions with 2 inputs and 1 output; we only care about five:
  - **AND** : Output is 1 iff both inputs are 1.
  - **OR** : Output is 0 iff both inputs are 0.
  - **NAND** : Output is 0 iff both inputs are 1.
  - **NOR** : Output is 1 iff both inputs are 0.
  - **XOR** : Output is 1 if both inputs are different, or 0 if they are the same.
- Using these we can build more complex functions.

Truth Tables

- Just a way to visualise what various boolean functions do, e.g. for the AND and OR functions:

A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

A	B	A OR B
0	0	0
0	1	1
1	0	1
1	1	1

- You may like to fill out the below using the descriptions on the previous page:

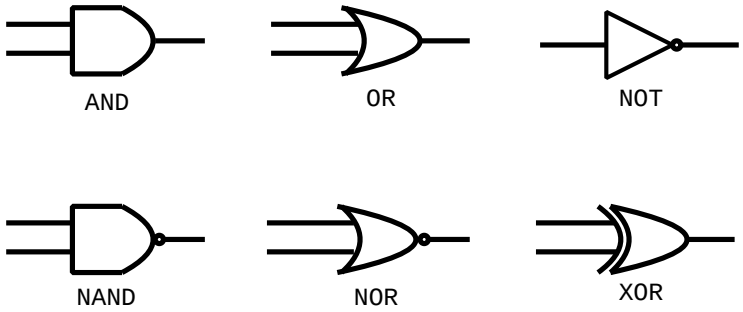
A	B	A NAND B
0	0	
0	1	
1	0	
1	1	

A	B	A NOR B
0	0	
0	1	
1	0	
1	1	

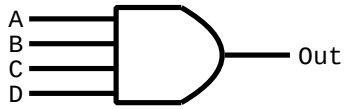
A	B	A XOR B
0	0	
0	1	
1	0	
1	1	

- Can extend to > 2 inputs (and to > 1 output).

Logic Gates



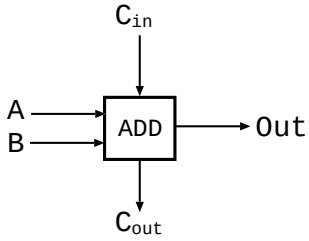
- Digital logical versions of the boolean functions.
- Notice the "bubbles" at the end of NOT, NAND and NOR: these represent the inversion function.
- e.g. A NAND B is just NOT (A AND B).
- Sometimes see versions of gates with > 2 inputs; semantics are the "obvious" ones, e.g.



`Out` is `1` iff *all* inputs are 1; otherwise `Out` is `0`.

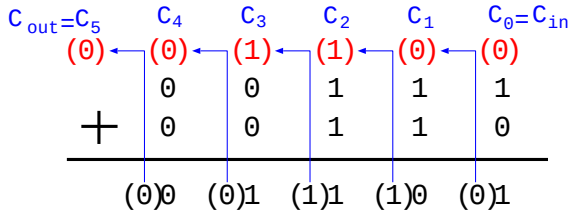
More Complex Circuits

- In digital electronics course see how to make more complicated circuits from the six basic ones.
- (You don't need to know for this course.)
- One is called a (full) adder; just adds together two bits and produces an output, e.g.



A	B	C_{in}	Out	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

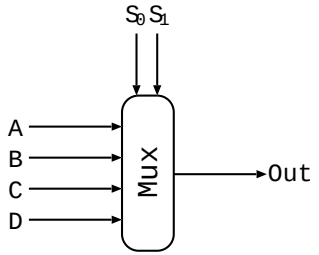
- Notice has a carrry in (which comes from the bit on its "right") and a carry out (which goes to the bit on its "left"), e.g.



Multiplexors

- A multiplexor ("mux") has $n + \log_2 n$ inputs.
- First n inputs are *data*.
- The rest ($\log_2 n$) are *control* inputs.

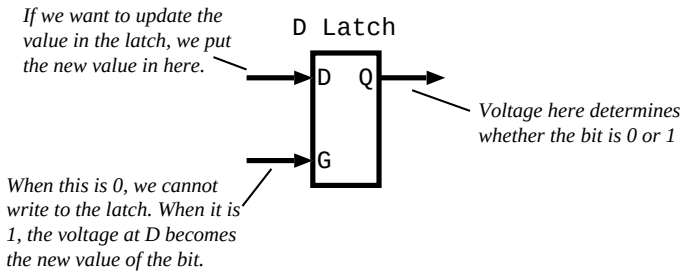
$\Rightarrow$ the values of these *select* which data input should be output, e.g.



S_0	S_1	Out
0	0	A
0	1	B
1	0	C
1	1	D

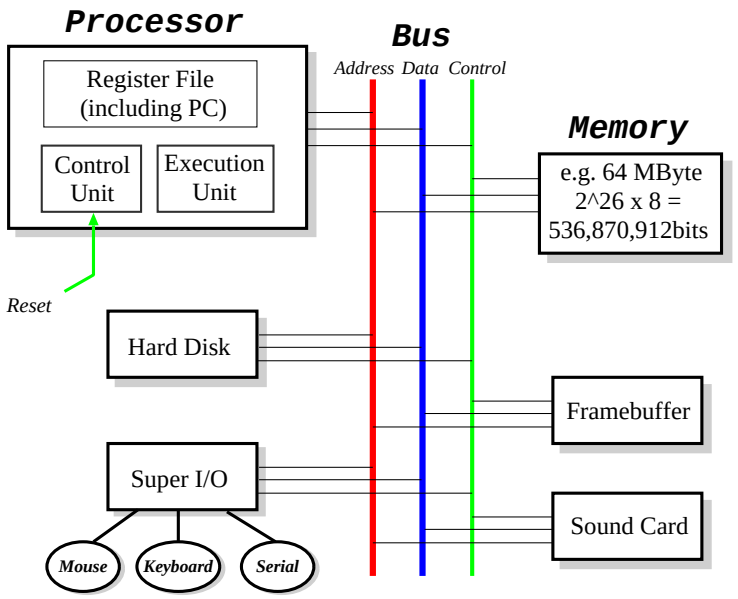
- Just treat the selection inputs as a binary number which determines the input that should be passed through to the output.

Latches



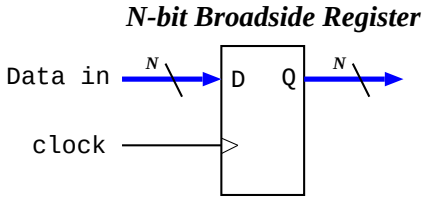
- Finally consider a *latch*: this is a special circuit which can "remember" a bit (viz. a `0` or a `1`).
- Internally work by *feedback* (but don't need to know how it works for this course).
- Has a *data* input called `D`, and a data output called `Q`.
- The voltage at `Q` represents the value stored inside the latch (i.e. if a high voltage, then latch is storing a `1`, otherwise latch is storing a `0`).
- To control *writing* a value into the latch have a *gate* input called `G`.
- Can only update the value in the latch if `G` is `1`.

A (Simple) Modern Computer



- Processor (CPU): executes programs.
- Memory: stores both programs & data.
- Devices: for input and output.
- Bus: transfers information.

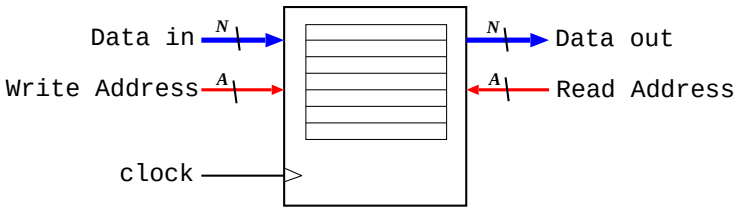
Registers



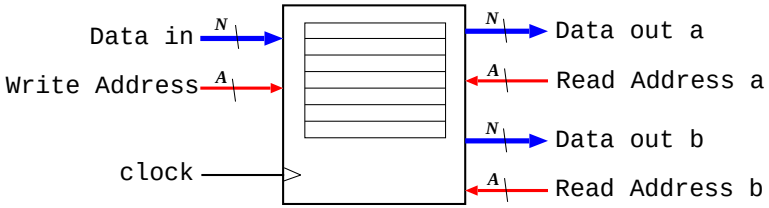
- Fastest type of "memory" there is ($\sim 2ns$).
- Lives on chip.
- Register of N bits: take N D flip-flops and common their `clock` inputs.
- Today N typically 32, but 64 becoming more common.

Register Files

M x N Register File



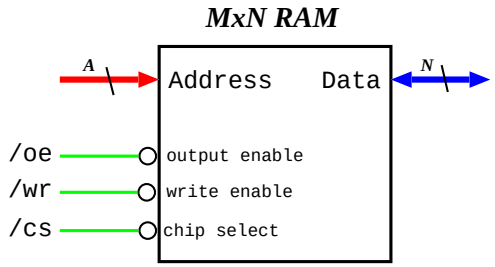
Dual Read-Ported Register File



- Usually want > 1 register i.e. a *register file*.
- Holds M registers of N bits each $\Rightarrow$ require $A = \log_2 M$ address lines.
- Number of *ports* determines how many simultaneous reads or writes can be supported.

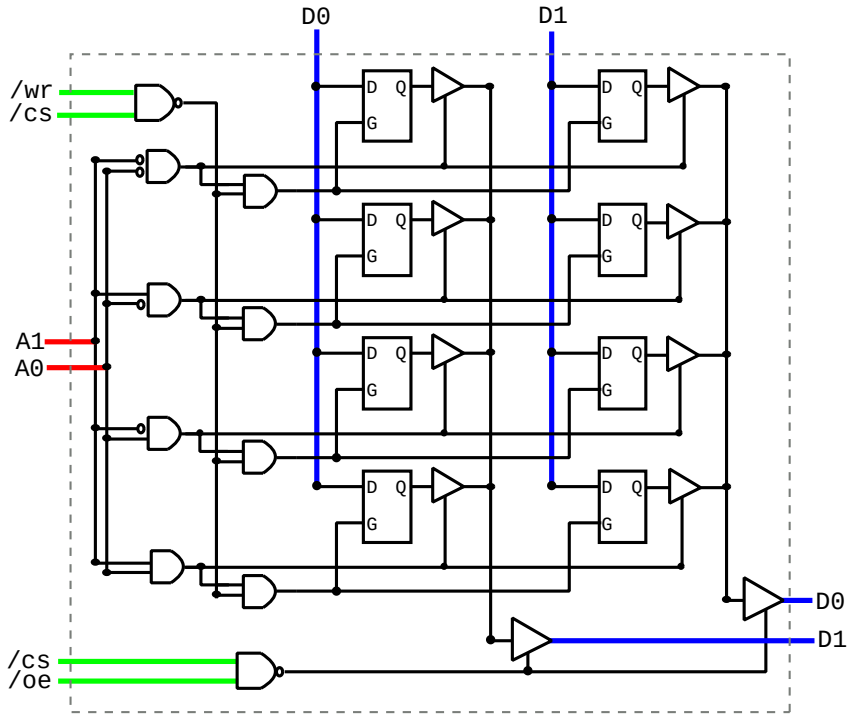
Random Access Memory

MxN RAM



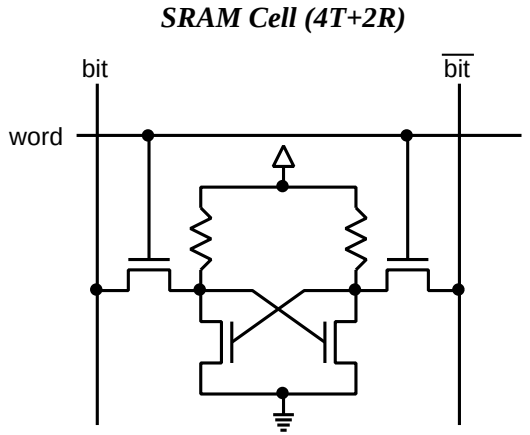
- Much larger than register file ... but also much slower.
- Only one access port; control lines from bus say if read (`/oe`) or write (`/wr`).
- Also have chip select (`/cs`); master "on/off" switch for the device.
- Two main technologies: SRAM & DRAM.

Static RAM (SRAM)



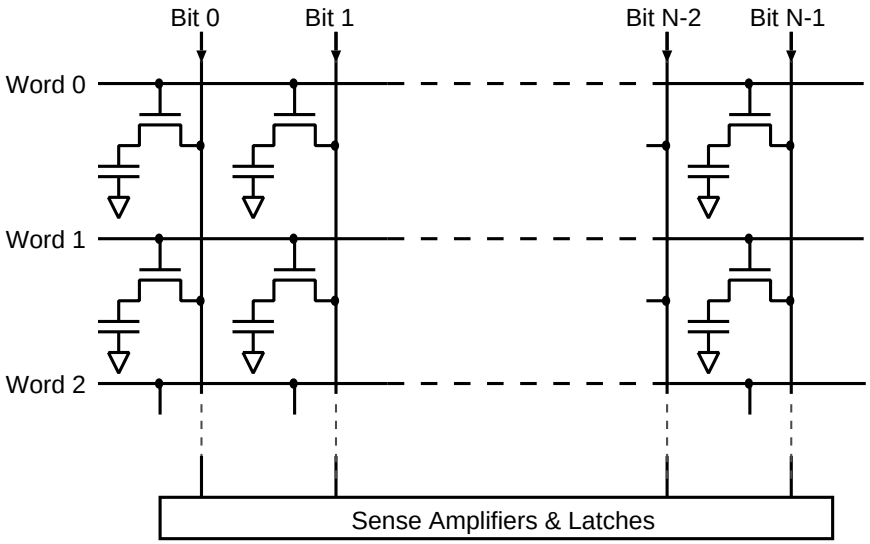
- Relatively fast (currently $5 - 20ns$).
- Logically an array of (transparent) D-latches
- In reality, only cost ~ 6 transistors per bit.

SRAM Reality



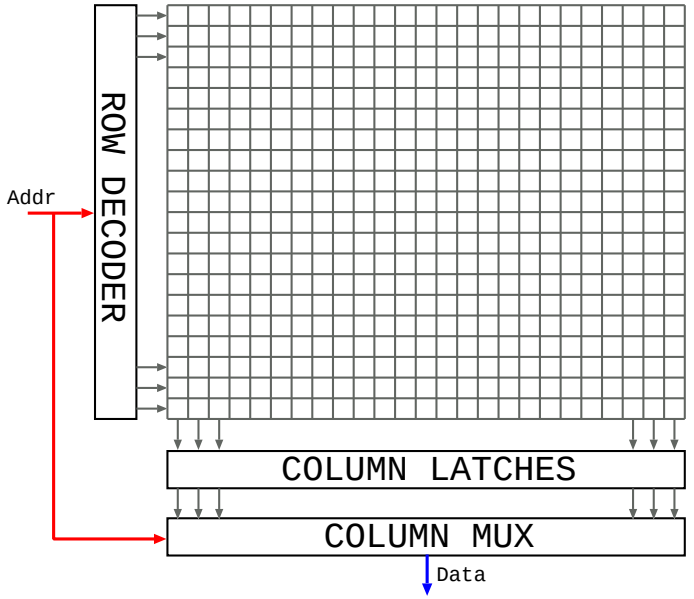
- State held in cross-coupled inverters.
- More common is $6T$ cell; use depletion mode transistors as load resistors.
- Read: precharge `bit` and $\overline{\texttt{bit}}$, strobe `word`, detect difference (sense amp).
- Write: precharge either `bit` (for "1") or $\overline{\texttt{bit}}$, (for "0"), strobe `word`.
- Just FYI (not examinable).

Dynamic RAM (DRAM)



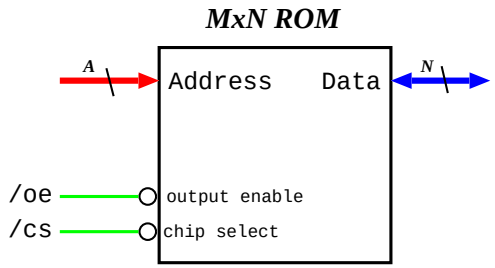
- Use a single transistor to store a bit.
- Write: put value on bit lines, strobe word line.
- Read: pre-charge, strobe word line, amplify, latch.
- "Dynamic": refresh periodically to restore charge.
- Slower than SRAM: typically $50ns - 100ns$.

DRAM Decoding



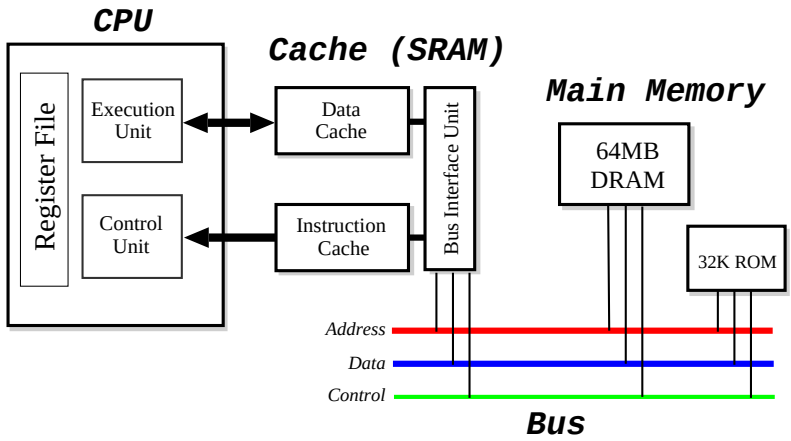
- Two stage: row, then column.
- Usually share address pins: RAS & CAS select decoder or mux.
- FPM, EDO, SDRAM faster for same row reads.

Read-Only Memory



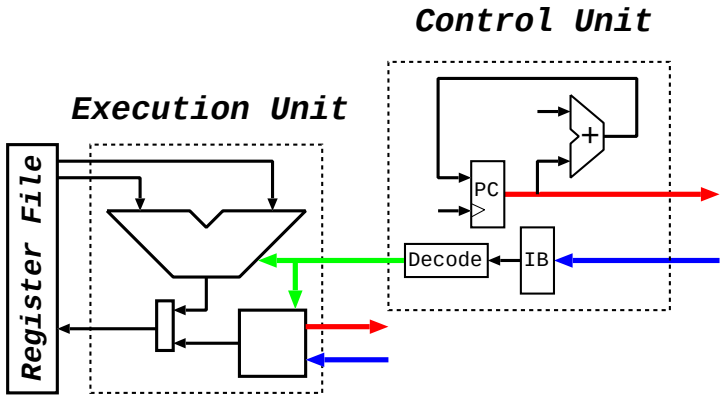
- Same symbol as RAM except no `/wr`.
- Combinatorial, not sequential logic.
- Major advantage: *non-volatile*, i.e. information remains even if no power.
- Disadvantages: immutable, expensive (at least for first one).
- More flexible variants, e.g. PROM, EPROM, EEPROM.
- Don't confuse with NVRAM ...

Memory Hierarchy



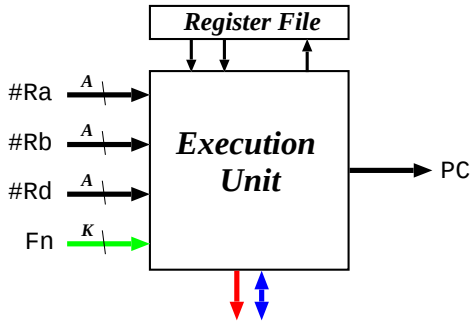
- Use *cache* between main memory and register: try to hide delay in accessing slow DRAM.
- Split of instruction and data at cache level ⇒ "Harvard" architecture.
- Cache ↔ CPU interface uses a custom bus.
- Today have ∼ 512KB cache, ∼ 64MB RAM.

The Fetch-Execute Cycle



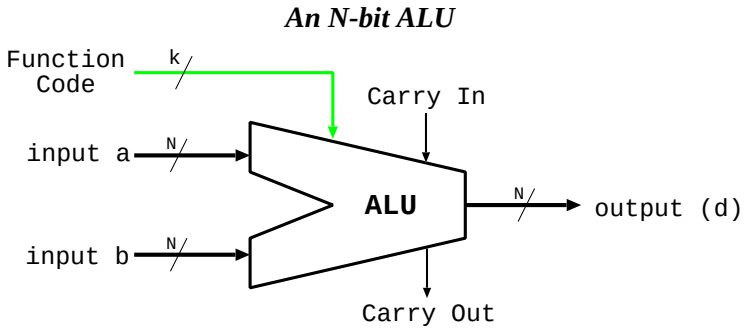
- A special register called PC holds a memory address; on reset, initialised to 0.
- Then:
  1. Instruction *fetched* from memory address held in PC into instruction buffer (IB).
  2. Control Unit determines what to do: *decodes* instruction.
  3. Execution Unit *executes* instruction.
  4. PC updated, and back to Step 1.
- Continues pretty much forever ...

Execution Unit



- The "calculator" part of the processor.
- Broken into parts (*functional units*), e.g.
  - Arithmetic Logic Unit (ALU).
  - Shifter/Rotator.
  - Multiplier.
  - Divider.
  - Memory Access Unit (MAU).
  - Branch Unit.
- Choice of functional unit determined by signals from control unit.

Arithmetic Logic Unit



- Inputs from register file; output to register file.
- Performs simple two-operand functions:
  - a + b
  - a - b
  - a AND b
  - a OR b
  - etc.
- Typically perform *all* possible functions; use function code to select (mux) output.

Number Representation

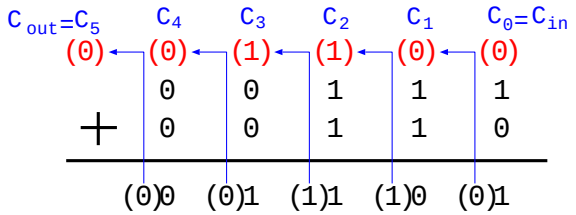
0000_2	0_{16}	0110_2	6_{16}	1100_2	C_{16}
0001_2	1_{16}	0111_2	7_{16}	1101_2	D_{16}
0010_2	2_{16}	1000_2	8_{16}	1110_2	E_{16}
0011_2	3_{16}	1001_2	9_{16}	1111_2	F_{16}
0100_2	4_{16}	1010_2	A_{16}	10000_2	10_{16}
0101_2	5_{16}	1011_2	B_{16}	10001_2	11_{16}

- a n-bit register $b_{n-1}b_{n-2}\ldots b_1b_0$ can represent 2^n different values.
- Call b_{n-1} the *most significant bit* (msb), b_0 the *least significant bit* (lsb).
- Unsigned numbers: treat the obvious way, i.e. val $= b_{n-1}2^{n-1} + b_{n-2}2^{n-2} + \cdots + b_1 2^1 + b_0 2^0$, e.g. $1101_2 = 2^3 + 2^2 + 2^0 = 8 + 4 + 1 = 13$.
- Represents values from 0 to $2^n - 1$ inclusive.
- For large numbers, binary is unwieldy: use hexadecimal (base 16).
- To convert, group bits into groups of 4, e.g. $1111101010_2 = 0011|1110|1010_2 = 3EA_{16}$.
- Often use "$0x$" prefix to denote hex, e.g. $0x107$.
- Can use dot to separate large numbers into 16-bit chunks, e.g. $0x3FF.FFFF$.

Number Representation (2)

- What about *signed* numbers? Two main options:
- Sign & magnitude:
  - top (leftmost) bit flags if negative; remaining bits make value.
  - e.g. byte $10011011_2 \rightarrow -0011011_2 = -27$.
  - represents range $-(2^{n-1}-1)$ to $+(2^{n-1}-1)$, and the bonus value -0 (!).
- 2's complement:
  - to get $-x$ from x, invert every bit and add 1.
  - e.g. $+27 = 00011011_2 \Rightarrow$ $-27 = (11100100_2 + 1) = 11100101_2$.
  - treat $1000\ldots000_2$ as -2^{n-1}.
  - represents range -2^{n-1} to $+(2^{n-1}-1)$
- Note:
  - in both cases, top-bit means "negative".
  - both representations depend on n;
- In practice, all modern computers use 2's complement ...

Unsigned Arithmetic



- (we use 5-bit registers for simplicity)
- Unsigned addition: C_n means "carry":

```
   00101    5          11110   30
 + 00111    7        +  00111    7
------------        --------------
0  01100   12        1  00101    5
------------        --------------
```

- Unsigned subtraction: $\overline{C_n}$ means "borrow":

```
   11110   30          00111    7
 + 00101  -27        +  10110  -10
------------        --------------
1  00011    3        0  11101   29
------------        --------------
```

Signed Arithmetic

- In signed arithmetic, carry no good on its own. Use the *overflow* flag, $V = (C_n \oplus C_{n-1})$.
- Also have *negative* flag, $N = b_{n-1}$ (i.e. the msb).
- Signed addition:

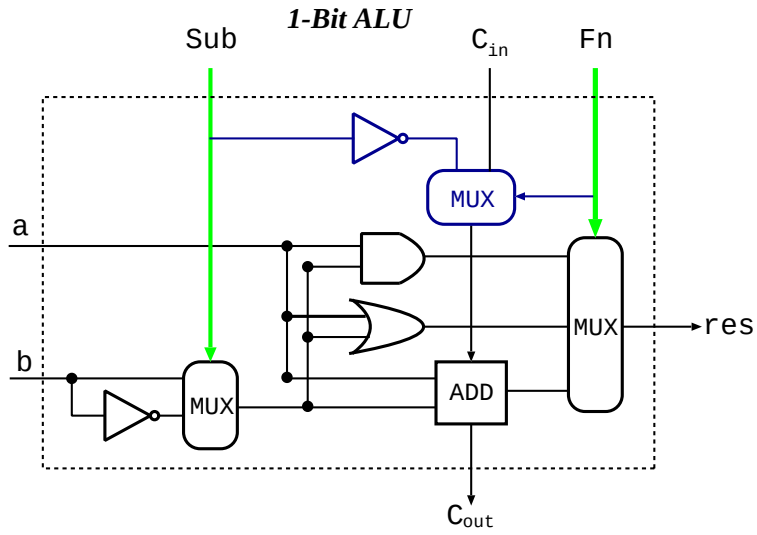
```
   00101    5          01010   10
 + 00111    7        + 00111    7
-------------        --------------
0  01100   12        0  10001  -15
-------------        --------------
   0                    1
```

- Signed subtraction:

```
   01010   10          10110  -10
 + 11001   -7        + 10110  -10
-------------        --------------
1  00011    3        1  01100   12
-------------        --------------
   1                    0
```

- Note that in overflow cases the sign of the result is always wrong (i.e. the N bit is inverted).

ALU Implementation



- Eight possible functions (4 types):
  1. a AND b, a AND $\overline{b}$.
  2. a OR b, a OR $\overline{b}$.
  3. $a + b$, $a + b$ with carry.
  4. $a - b$, $a - b$ with borrow.
- To make n-bit ALU bit, connect together (use carry-lookahead on adders).

Arithmetic & Logical Instructions

- Some common instructions are:

Mnemonic		C/Java Equivalent
`and`	$d \leftarrow a, b$	`d = a & b;`
`xor`	$d \leftarrow a, b$	`d = a ^ b;`
`bis`	$d \leftarrow a, b$	`d = a | b;`
`bic`	$d \leftarrow a, b$	`d = a & (~b);`
`add`	$d \leftarrow a, b$	`d = a + b;`
`sub`	$d \leftarrow a, b$	`d = a - b;`
`rsb`	$d \leftarrow a, b$	`d = b - a;`
`shl`	$d \leftarrow a, b$	`d = a << b;`
`shr`	$d \leftarrow a, b$	`d = a >> b;`

  Both d and a *must* be registers; b can be a register or a (small) constant.

- Typically also have `addc` and `subc`, which handle carry or borrow. Useful for multi-precision (unsigned) arithmetic, e.g.

```
add  d0, a0, b0    // compute "low" part.
addc d1, a1, b1    // compute "high" part.
```

- May also get:
  - Arithmetic shifts: `asr` and `asl`(?)
  - Rotates: `ror` and `rol`.

Conditional Execution

- Seen C, N, V; add Z (zero), logical NOR of all bits in output.

- Can predicate execution based on (some combination) of flags, e.g.

```
sub d, a, b    // compute d = a - b
beq proc1      // if equal, goto proc1
br  proc2      // otherwise goto proc2
```

  Java equiv $\sim$ `if (a==b) proc1() else proc2();`

- On most computers, mainly limited to branches.

- On ARM (and IA64), everything conditional, e.g.

```
sub   d, a, b    # compute d = a - b
moveq d, #5      # if equal, d = 5;
movne d, #7      # otherwise d = 7;
```

  Java equiv: `d = (a==b) ?  5 :  7;`

- "Silent" versions useful when don't really want result, e.g. `tst`, `teq`, `cmp`.

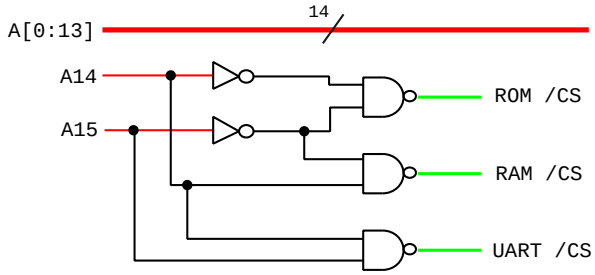
Condition Codes

Suffix	Meaning	Flags
`EQ`, `Z`	Equal, zero	Z == 1
`NE`, `NZ`	Not equal, non-zero	Z == 0
`MI`	Negative	N == 1
`PL`	Positive (incl. zero)	N == 0
`CS`, `HS`	Carry, higher or same	C == 1
`CC`, `LO`	No carry, lower	C == 0
`VS`	Overflow	V == 1
`VC`	No overflow	V == 0
`HI`	Higher	C == 1 && Z == 0
`LS`	Lower or same	C == 0 || Z == 1
`GE`	Greater than or equal	N == V
`GT`	Greater than	N == V && Z == 0
`LT`	Less than	C != V
`LE`	Less than or equal	C != V || Z == 1

- `HS`, `LO`, etc. used for unsigned comparisons (recall that $\overline{C}$ means "borrow").
- `GE`, `LT`, etc. used for signed comparisons: check both N and V so always works.

Accessing Memory

- To load/store values need the *address* in memory.
- Most modern machines are *byte addressed*: consider memory a big array of 2^A bytes, where A is the number of address lines in the bus.
- Lots of things considered "memory" via address decoder, e.g.



- Typically each device decodes only a subset of low address lines, e.g.

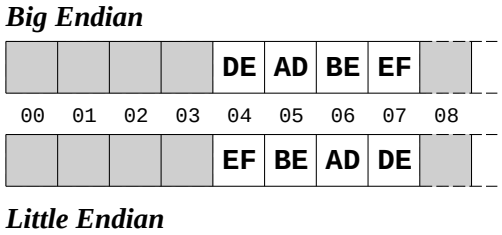
Device	Size	Data	Decodes
ROM	1024 bytes	32-bit	`A[2:9]`
RAM	16384 bytes	32-bit	`A[2:13]`
UART	256 bytes	8-bit	`A[0:7]`

Loads & Stores

- Have variable sized values, e.g. bytes (8-bits), words (16-bits), longwords (32-bits) and quadwords (64-bits).

- Load or store instructions usually have a suffix to determine the size, e.g. '`b`' for byte, '`w`' for word, '`l`' for longword.

- When storing > 1 byte, have two main options: big endian and little endian; e.g. storing longword `0xDEADBEEF` into memory at address `0x4`.



  If read back a *byte* from address `0x4`, get `0xDE` if big-endian, or `0xEF` if little-endian.

- Today have x86 & Alpha little endian; Sparc & 68K, big endian; Mips & ARM either.

Addressing Modes

- An *addressing mode* tells the computer where the data for an instruction is to come from.

- Get a wide variety, e.g.

Register:	`add r1, r2, r3`
Immediate:	`add r1, r2, #25`
PC Relative:	`beq 0x20`
Register Indirect:	`ldr r1, [r2]`
" + Displacement:	`str r1, [r2, #8]`
Indexed:	`movl r1, (r2, r3)`
Absolute/Direct:	`movl r1, $0xF1EA0130`
Memory Indirect:	`addl r1, ($0xF1EA0130)`

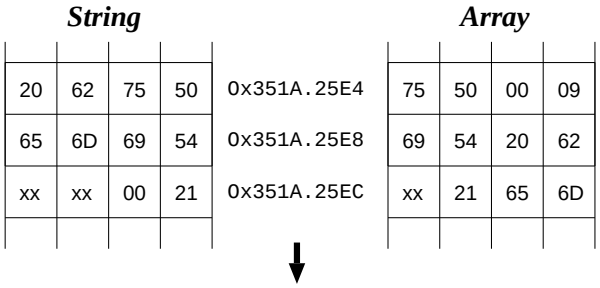
- Most modern machines are *load/store* $\Rightarrow$ concentrate on first five ...

Data Representation

- Seen signed and unsigned integers already.
- Memory can also hold:
  - Natural Language,
  - Real numbers (floating point),
  - Compound Data Structures,
  - Instructions
- Always just some number of bits ⇒ up to programmer to interpret what is where ...

Representing Text

- Two main standards:
  1. ASCII: 7-bit code holding (English) letters, numbers, punctuation and a few other characters.
  2. Unicode: 16-bit code supporting practically all international alphabets and symbols.
- ASCII default on many operating systems, and on the early Internet (e.g. e-mail).
- Unicode becoming more popular (esp UTF-8!).
- In both cases, represent in memory as either *strings* or *arrays*: e.g. "Pub Time!"



ASCII Character Set

- For reference only:

	2	3	4	5	6	7
0	spc	0	@	P	‘	p
1	!	1	A	Q	a	q
2	"	2	B	R	b	r
3	#	3	C	S	c	s
4	$	4	D	T	d	t
5	%	5	E	U	e	u
6	&	6	F	V	f	v
7	’	7	G	W	g	w
8	(	8	H	X	h	x
9	)	9	I	Y	i	y
A	*	:	J	Z	j	z
B	+	;	K	[	k	{
C	,	<	L	\	l	|
D	-	=	M	]	m	}
E	.	>	N	^	n	~
F	/	?	O	_	o	del

- To determine code for a character, use column as first hex digit, row as second.
- e.g. space is 0x20, W is 0x57, 4 is 0x34.
- Low characters ($<$ 0x20) are non-printing control characters, e.g. warning bell, backspace, carriage return.

Floating Point (1)

- In many cases want to deal with very large or very small numbers.
- Use idea of “scientific notation”, e.g. $n = m \times 10^e$
  - m is called the *mantissa*
  - e is called the *exponent*.

  e.g. $C = 3.01 \times 10^8$ m/s.
- For computers, use binary i.e. $n = m \times 2^e$, where m includes a “binary point”.
- Both m and e can be positive or negative; typically
  - sign of mantissa given by an additional *sign* bit.
  - exponent is stored in a *biased* (*excess*) format.

$\Rightarrow$ use $n = (-1)^s m \times 2^{e-b}$, where $0 \leq m < 2$ and b is the bias.

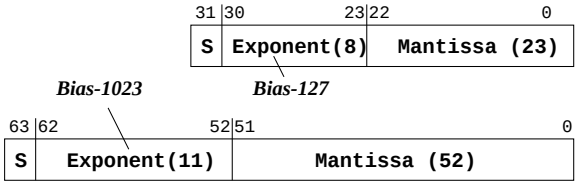
- e.g. 4-bit mantissa & 3-bit bias-3 exponent allows positive range $[0.001_2 \times 2^{-3}, 1.111_2 \times 2^4]$

$=$ [$(\frac{1}{8})(\frac{1}{8})$, $(\frac{15}{8})16$], or [$\frac{1}{64}$, 30]

Floating Point (2)

- In practice use IEEE floating point with *normalised* mantissa $m = 1.xx\ldots x_2$
  $\Rightarrow$ use $n = (-1)^s((1+m) \times 2^{e-b})$,

- Both single (`float`) and double (`double`) precision:



- IEEE fp reserves $e = 0$ and $e =$ max:
  - ± 0 (!): both e and m zero.
  - $\pm\infty$: $e =$ max, m zero.
  - NaNs : $e =$ max, m non-zero.
  - *denorms* : $e = 0$, m non-zero

- Normal positive range $[2^{-126}, \sim 2^{128}]$ for single, or $[2^{-1022}, \sim 2^{1024}]$ for double.

- NB: still only $2^{32}/2^{64}$ values — just spread out.

Data Structures

- Records / structures: each field stored as an offset from a *base address*.

- Variable size structures: explicitly store addresses (*pointers*) inside structure, e.g.

```
datatype rec = node of int * int * rec
             |     leaf of int;

val example = node(4, 5, node(6, 7, leaf(8)));
```

Imagine `example` is stored at address `0x1000`:

Address	Value	Comment
0x0F30	0xFFFF	Constructor tag for a leaf
0x0F34	8	Integer 8
⋮		
0x0F3C	0xFFFE	Constructor tag for a node
0x0F40	6	Integer 6
0x0F44	7	Integer 7
0x0F48	0x0F30	Address of inner node
⋮		
0x1000	0xFFFE	Constructor tag for a node
0x1004	4	Integer 4
0x1008	5	Integer 5
0x100C	0x0F3C	Address of inner node

Instruction Encoding

- An instruction comprises:

  a) an *opcode*: specify what to do.

  b) zero or more *operands*: where to get values.

  e.g. `add r1, r2, r3` ≡

1010111	001	010	011

- Old machines (and x86) use *variable length* encoding motivated by low code density.

- Most modern machines use fixed length encoding for simplicity. e.g. ARM ALU operations.

31–28	27–26	25	24–21	20	19–16	15–12	11–0
Cond	**00**	*I*	*Opcode*	*S*	*Ra*	*Rd*	*Operand 2*

`and r13, r13, #31` = `0xe20dd01f` =

1110	00	1	0000	0	1101	1101	000000011111

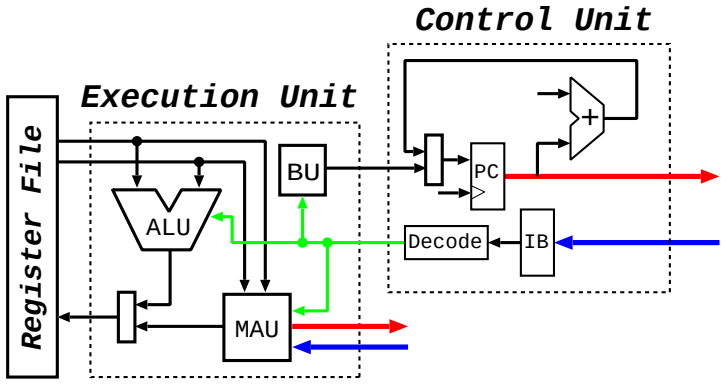
`bic r3, r3, r2` = `0xe1c33002` =

1110	00	0	1110	0	0011	0011	000000000010

`cmp r1, r2` = `0xe1510002` =

1110	00	0	1010	1	0001	0000	000000000010

Fetch-Execute Cycle Revisited



1. CU fetches & decodes instruction and generates (a) control signals and (b) operand information.

2. Inside EU, control signals select functional unit ("instruction class") and operation.

3. If ALU, then read one or two registers, perform operation, and (probably) write back result.

4. If BU, test condition and (maybe) add value to `PC`.

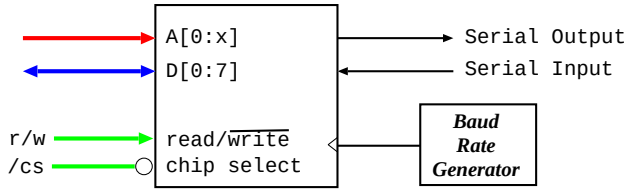
5. If MAU, generate address ("addressing mode") and use bus to read/write value.

6. Repeat *ad infinitum*.

I/O Devices

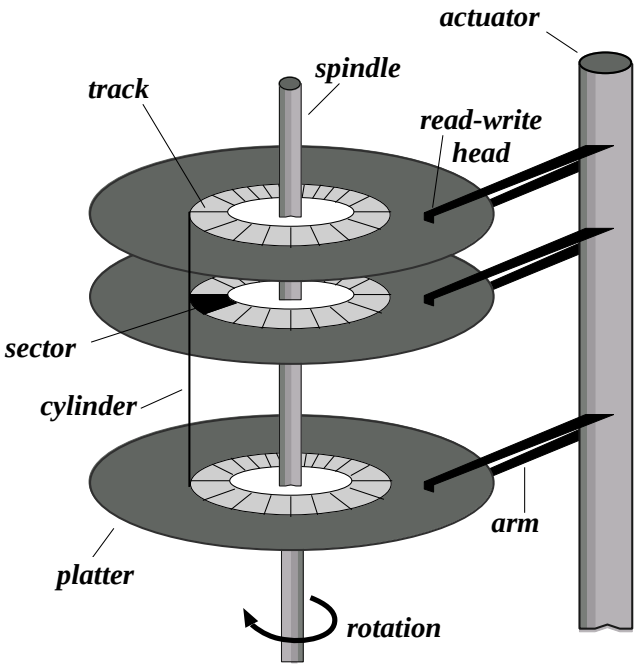
- Devices connected to processor via a *bus* (e.g. ISA, PCI).
- Includes a wide range:
  - Mouse,
  - Keyboard,
  - Graphics Card,
  - Sound card,
  - Floppy drive,
  - Hard-Disk,
  - CD-Rom,
  - Network card,
  - Printer,
  - Modem
  - etc.
- Often two or more stages involved (e.g. IDE, SCSI, RS-232, Centronics, etc.)

UARTs



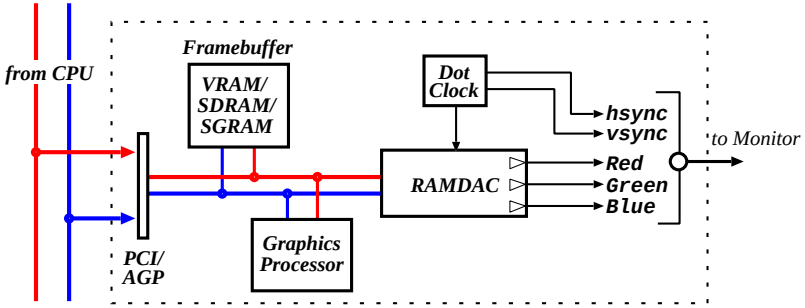
- Universal Asynchronous Receiver/Transmitter:
  - stores 1 or more bytes internally.
  - converts parallel to serial.
  - outputs according to RS-232.
- Various baud rates (e.g. 1,200 – 115,200)
- Slow and simple ... and very useful.
- Make up "serial ports" on PC.
- Max throughput $\sim$ 14.4KBytes; variants up to 56K (for modems).

Hard Disks



- Whirling bits of (magnetized) metal ...
- Rotate 3,600 – 7,200 times a minute.
- Capacity $\sim$ 10 GBytes ($\approx 10 \times 2^{30} bytes$).

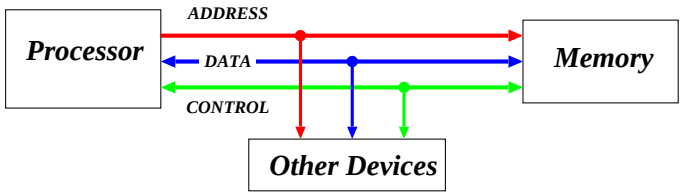
Graphics Cards



- Essentially some RAM (framebuffer) and some digital-to-analogue circuitry (RAMDAC).
- RAM holds array of *pixels*: picture elements.
- Resolutions e.g. 640x480, 800x600, 1024x768, 1280x1024, 1600x1200.
- Depths: 8-bit (LUT), 16-bit (RGB=555, 24-bit (RGB=888), 32-bit (RGBA=888).
- Memory requirement = $x \times y \times$ depth, e.g. 1024x768 @ 16bpp needs 1536KB.

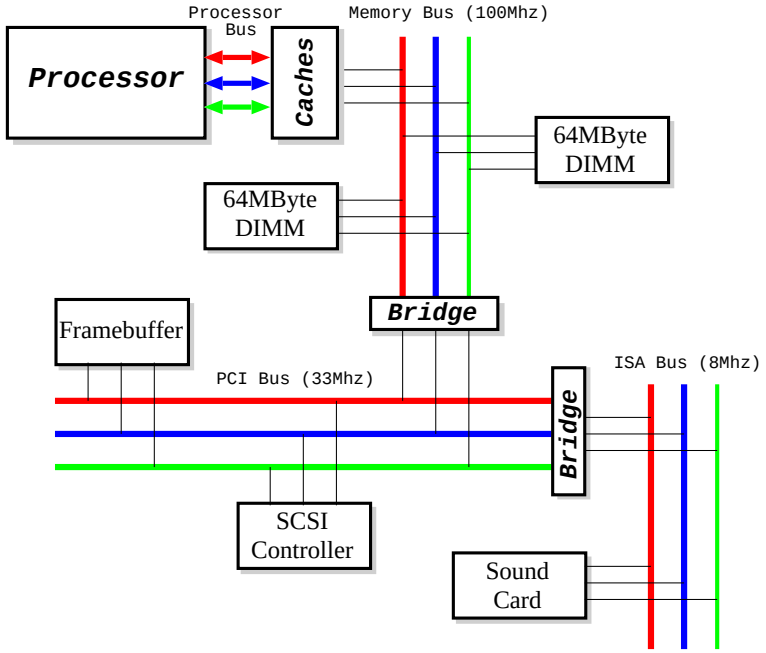
$\Rightarrow$ full-screen 50Hz video requires 7.5MBytes/s (or 60Mbits/s).

Buses



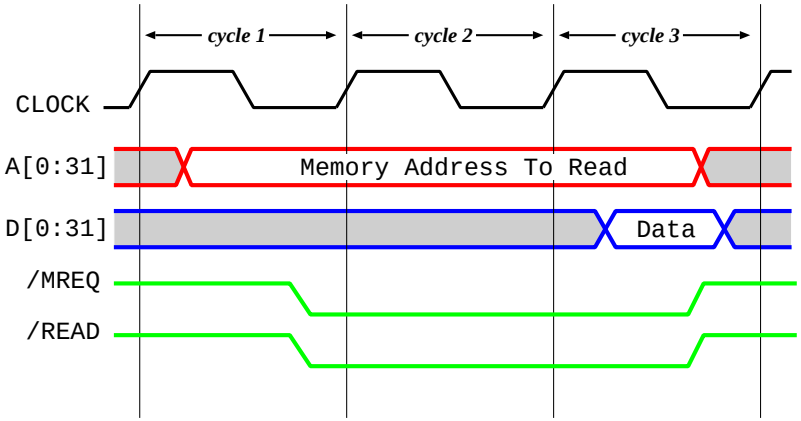
- Bus = collection of *shared* communication wires:
  - ✔ low cost.
  - ✔ versatile / extensible.
  - ✘ potential bottle-neck.
- Typically comprises address lines, data lines and control lines (+ power/ground).
- Operates in a *master-slave* manner, e.g.
  1. master decides to e.g. read some data.
  2. master puts addr onto bus and asserts 'read'
  3. slave reads addr from bus and retrieves data.
  4. slave puts data onto bus.
  5. master reads data from bus.

Bus Hierarchy



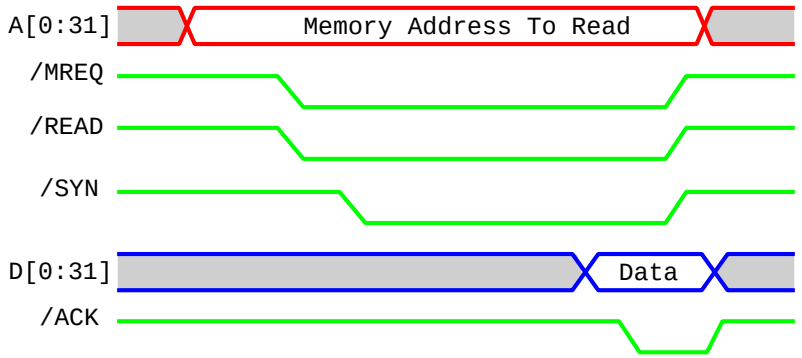
- In practice, have lots of different buses with different characteristics e.g. data width, max #devices, max length.
- Most buses are *synchronous* (share clock signal).

Synchronous Buses



- Figure shows a read transaction which requires three bus cycles.
  1. CPU puts address onto address lines and, after settle, asserts control lines.
  2. Memory fetches data from address.
  3. Memory puts data on data lines, CPU latches value and then deasserts control lines.
- If device not fast enough, can insert *wait states*.
- Faster clock/longer bus can give *bus skew*.

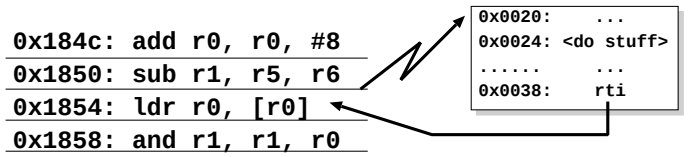
Asynchronous Buses



- Asynchronous buses have no shared clock; instead work by *handshaking*, e.g.
  - CPU puts address onto address lines and, after settle, asserts control lines.
  - Next, CPU asserts `/SYN` to say everything ready.
  - As soon as memory notices `/SYN`, it fetches data from address and puts it onto bus.
  - Memory then asserts `/ACK` to say data is ready.
  - CPU latches data, then deasserts `/SYN`.
  - Finally, Memory deasserts `/ACK`.
- More handshaking if mux address & data ...

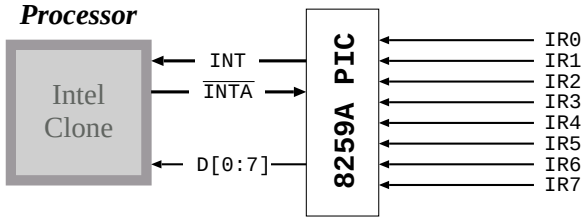
Interrupts

- Bus reads and writes are *transaction* based: CPU requests something and waits until it happens.
- But e.g. reading a block of data from a hard-disk takes $\sim 2ms$, which is $\sim 1,000,000$ clock cycles!
- *Interrupts* provide a way to decouple CPU requests from device responses.
  1. CPU uses bus to make a request (e.g. *writes* some special values to a device).
  2. Device goes off to get info.
  3. Meanwhile CPU continues doing other stuff.
  4. When device finally has information, raises an *interrupt*.
  5. CPU uses bus to read info from device.
- When interrupt occurs, CPU *vectors* to handler, then *resumes* using special instruction, e.g.



Interrupts (2)

- Interrupt lines ($\sim 4 - 8$) are part of the bus.
- Often only 1 or 2 pins on chip $\Rightarrow$ need to encode.
- e.g. ISA & x86:



1. Device asserts `IRx`.
2. PIC asserts `INT`.
3. When CPU can interrupt, strobes `INTA`.
4. PIC sends interrupt number on `D[0:7]`.
5. CPU uses number to index into a table in memory which holds the addresses of handlers for each interrupt.
6. CPU saves registers and jumps to handler.

Direct Memory Access (DMA)

- Interrupts good, but even better is a device which can read and write processor memory *directly*.
- a generic DMA "command" might include
  - source address
  - source increment / decrement / do nothing
  - sink address
  - sink increment / decrement / do nothing
  - transfer size
- get one interrupt at end of data transfer
- DMA channels may be provided by devices themselves:
  - e.g. a disk controller
  - pass disk address, memory address and size
  - give instruction to read or write
- Also get "stand-alone" programmable DMA controllers.

Summary

- Computers made up of four main parts:
  1. Processor (including register file, control unit and execution unit),
  2. Memory (caches, RAM, ROM),
  3. Devices (disks, graphics cards, etc.), and
  4. Buses (synch/async, interrupts, DMA).
- Information represented in all sorts of formats (signed & unsigned integers, strings, floating point, data structures, instructions).
- Can (hopefully) understand all of these at some level, but gets pretty complex.

$\Rightarrow$ to be able to actually *use* a computer, need an operating system.