Assembly code and the machine model

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Based on slides by Troels Henriksen

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Agenda

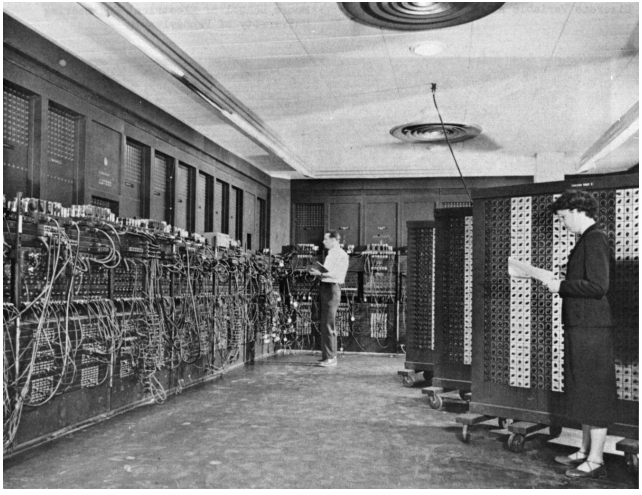
Machine execution
- Computer architectures
- Registers and instructions
- From C to RISC-V

Memory
- Byte-addressable memory
- In RISC-V

Control flow
- Conditionals
- Loops

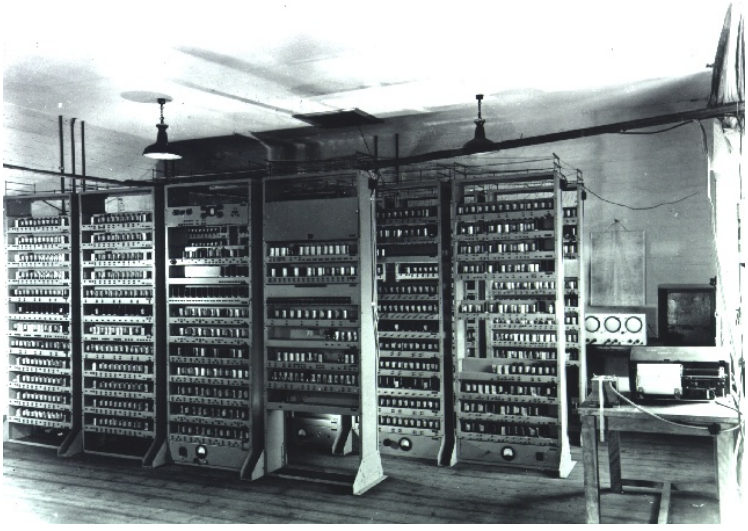
Programmable computers

Early computers were programmed by physically moving wires and switches.



ENIAC, 1947-1955, first programmable, electronic, general-purpose, digital computer.

Stored-program computers



EDSAC, 1949-1958, one of the first stored-program computers.

Machine code

Machine Code

A machine-readable sequence of *instructions* that cause the computer to change its state.

- A primitive programming language directly implemented by hardware.
- We use a textual surface syntax called *assembly code*.
- An *assembler* turns human-readable assembly code into actual machine code.

Types of machine code

- Early machine code languages were intended for human programming and had many conveniences and even high-level features.
- Each *architecture* has its own machine code; new machines often had new ones with more features.

PDP-7, 1965, a highly succesful and cheap minicomputer.

Types of machine code, continued

- Today the vast majority of programmers use *compilers* to generate machine code.
- Fairly few general-purpose architectures in use, most quite similar:

x86:	Intel and AMD processors, used in most PCs and servers.
ARM:	Previously mostly for low-power and mobile, now also used in Apple's newer laptops and encroaching on servers.
POWER:	IBMs architecture; still in use for some high-end servers.
RISC-V:	Open architecture, very new, currently mostly used for embedded purposes, but growing.
Long tail:	MIPS, SPARC, Alpha, z/Architecture, GPUs, DSPs, ...

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You will be taught RISC-V/32

- Concepts generalise to all other general-purpose architectures.
- ...but they might be uglier elsewhere.

Registers and instructions

The two main concepts are **registers** and **instructions**

```
add x1, x2, x3
```

- `add` is the instruction type.
- `x1`, `x2`, `x3` are names of registers.
- Add the values in the registers `x2` and `x3` and put the result in `x1`.
- **A register is basically a variable implemented in hardware.**
- **An instruction is basically a simple function implemented in hardware.**
- RISC-V/32 exposes a *fixed* number of registers with a *fixed* size (32 bits).
- ...and a fixed number of instructions.

Registers as variables

We can see the RISC-V machine as having 32 32-bit integer variables.

```
int32_t x0, x1, x2, x3, x4, x5, x6, x7 x8, x9, x10, x11,
x12, x13, x14, x15 x16, x17, x18, x19, x20, x21, x22, x23
      x23, x24, x25, x26, x27, x28, x29, x30, x31;
```

Each instruction then changes these variables.

Instruction	Meaning
`add` x_i, x_j, x_k	$x_i = x_j + x_k$
`sub` x_i, x_j, x_k	$x_i = x_j - x_k$
`addi` x_i, x_j, v	$x_i = x_j + v$
`and` x_i, x_j, x_k	$x_i = x_j \,\&\, x_k$
`andi` x_i, x_j, v	$x_i = x_j \,\&\, v$

Playing with a RISC-V interpreter

https://www.cs.cornell.edu/courses/cs3410/2019sp/riscv/interpreter/

From C to RISC-V

A compiler must decide in which registers to store variables.

```
int a, b, c, d, e;
```

C variable:	`a`	`b`	`c`	`d`	`e`
RISC-V register:	`x1`	`x2`	`x3`	`x4`	`x5`

(More variables than registers? We'll talk about that later.)

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Assembly instructions are very simple, so high-level languages must break up complex expressions, which often requires extra registers.

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e = (a + b) - (c + d);
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e = (a + b) - (c + d);
```

```
add x6, x1, x2      # a + b
add x7, x3, x4      # c + d
sub x5, x6, x7      # (a + b) - (c + d)
```

Register names

- The RISC-V registers have names and designated uses.

Register	Name	Intended use
x0	zero	The constant value 0 (writes ignored)
x1	ra	Return address
x2	ra	Stack pointer
x4	gp	Global pointer
x5–x7	t0–t2	Temporaries
x8–x9	s0–s1	Saved registers
x10–x11	a0–a1	Arguments/return values
x12–x17	a2–a7	Function arguments
x18–x27	s2–s11	Saved registers
x28–x31	t3–t6	Temporaries

- With a few exceptions, these uses are just **conventions**, not enforced by machine.
- We'll see why the conventions are useful in the next lecture.

Pseudo instructions

Pseudo instruction

An instruction allowed in the assembly syntax, but translated into one or more other instructions by the assembler.

- Think of them as shortcuts.
- Unfortunately, the browser RISC-V interpreter does not allow most pseudoinstructions.

`mv` x_i, x_j	Move

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`li` x_i, k	Load immediate	

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`nop`	No operation	`add zero, zero, zero`

Why are they not implemented directly in hardware?

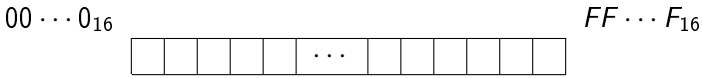
Compiler Explorer

https://godbolt.org/

Remember to set the compiler to “RISC-V rv32gc clang” (or some other RISC-V).

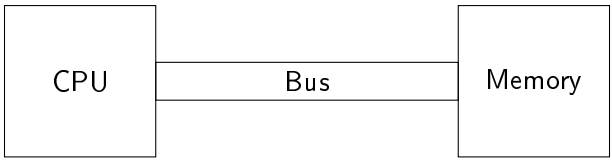
Byte-oriented memory organisation

- Registers are for scratch space; data is primarily stored in *memory*.



- **Programs refer to data by address**
  - Conceptually, envision as large array of bytes.
    - It's not really, but it works as a semantic model.
  - An address is like an index into that array.
    - A *pointer* stores an address.
    - **Addresses are ultimately just unsigned integers.**
- **System provides private address space to each *process*.**
  - You'll learn how in a few weeks; just trust me for now.

The Von Neumann Bottleneck



- **Reading:** CPU sends address to memory.
  - Memory responds with contents at address.
- **Writing:** CPU sends address and data to memory.
  - Memory overwrites location with new contents.
- **The bus is slow!**

The distance between computation and storage is the main performance obstacle in most programs.

Machine words

Any given computer has a "word size".

- "Native" size of integer-valued data.
  - But especially of memory addresses.
- 32-bit machines used to be the norm and are still found (e.g. **RISC-V/32**).
  - 2^{32} different addresses, meaning $4\mathit{GiB}$ can be addressed.
- 64-bit machines are most common.
  - 2^{64} different addresses, meaning $18\mathit{EiB}$ can be addressed.
  - $18.4 \cdot 10^{18}$ bytes.
  - Current machines only use lower 48 bits of address.
- Machines also support other data formats.
  - Fractions or multiples of word size.
  - Always integral number of types.
  - Smaller types (e.g. 16-bit integers) take less space in memory, but are (usually) not faster than the "native" words.
  - But bigger types (e.g. 128-bit integers) are slower.

Word-oriented memory organisation

- **Addresses specify byte locations**
  - Address of first byte in word.
  - Addresses of successive words differ by 4 (32 bit) or 8 (64 bit).
  - *Addresses always refer to a byte* even when addressing larger types.
- **We can take the address of any variable in a C program**
  - `&x` gives us the address of `x`.
  - If `x` has type `T`, then `&x` has type `T*`.

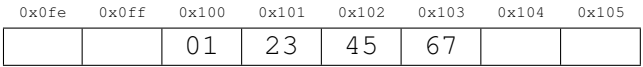
Byte ordering

- **So, how are the bytes within a multi-byte word ordered in memory?**
  - Most significant byte at lowest address, or least significant byte at lowest address?
- **Conventions**
  - Big endian: SPARC, POWER, Internet protocols.
    - Most significant byte has lowest address ("comes first").
  - Little endian: x86, ARM (mostly), RISC-V.
  - Most significant byte has highest address ("comes last").

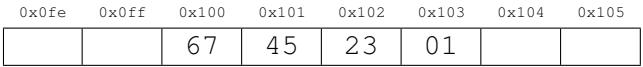
Byte ordering example

- **Example**
  - Variable has 4-byte value of `0x01234567`.
  - Address `&x` is `0x100`.
    - No matter what, the address of an object is always the address of the *first* byte in the object (counting from lowest addresses).

Big endian



Little endian



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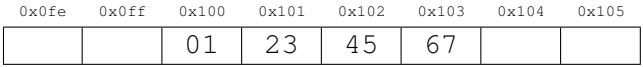

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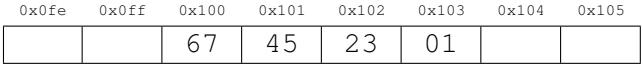

Important note

This difference is *not visible* unless you start decomposing integers as bytes with memory operations. Bit-shifting etc. always acts as expected.

An M-byte memory is conceptually an array

```
byte Memory[M];
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Main difference between registers and memory

Memory is *dynamically addressable*, while the registers we operate on are statically encoded in instructions.

- In a **stored program computer**, *instructions* are also just data stored in memory (4 bytes per instruction in RISC-V).
- In a **von Neumann** computer, instructions are stored in the *same memory* as all other data.
  - Allows for self-modifying code (don't do this).
- **Harvard architectures** store instructions in a separate (usually read-only) memory.

Memory transfer instructions

Note how the *dynamic contents* of a register influences *which* memory address we access.

Instruction	Meaning
`lb` x_i, v(x_j)	x_i = Memory[x_j + v]
`sb` x_i, v(x_j)	Memory[x_j + v] = x_i
`lw` x_i, v(x_j)	x_i = Memory[x_j + v]
`sw` x_i, v(x_j)	Memory[x_j + v] = x_i

Program Counter

The *program counter* (PC) is a special register that contains the address of the current instruction in memory.

Address	Contents (in assembly syntax)
0x100	`add x6, x1, x2`
0x104	`add x7, x3, x4`
0x108	`sub x5, x6, x7`

- Every *non-jump* instruction implicitly increments PC by 4.

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Control flow

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} else {
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}
```

```
blt x1, x2, L0
addi x3, x2, 0
jal x0, L1
L0:
addi x3, x1, 0
L1:
```

Instruction	Meaning
`blt` x_i, x_j, k	`if (`x_i `<` x_j`) PC +=` k
`jal` x_i, k	x_i `= PC + 4; PC +=` k

(Assembler automatically inserts right offset k when we use a label.)

Loops are implemented by jumping *backwards*

- Suppose we want to implement $c = a \times b$. Assume:
  - c is in register `a0`.
  - a is in register `a1`.
  - b is in register `a2`.
- We'll implement it by *repeated addition* of a (b times).

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```
addi a0, a1, 0      # initialise a0 = a1
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addi a0, a1, 0      # initialise a0 = a1
LOOP:               # loop label
beq a2, zero, END   # jump to end if no iterations left
```

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addi a2, a2, -1     # decrement b
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add a0, a0, a1      # add a to c
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jal zero, LOOP      # try again
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```

...is this correct for all a and b?

Fibonacci Numbers

```
int n = 10;
int a = 1;
int b = 1;
int i = 0;
while (n != 0) {
  out[i] = b;
  i = i + 1;
  int tmp = a + b;
  a = b;
  b = tmp;
  n = n - 1;
}
```

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  a = b;
  b = tmp;
  n = n - 1;
}
```

```
addi a0, zero, 10
addi t0, zero, 1
addi t1, zero, 1
addi t2, zero, 0
LOOP:
beq a0, zero, DONE
addi a0, a0, -1
sw t1, 0(t2)
addi t2, t2, 4
add t3, t0, t1
add t0, zero, t1
add t1, zero, t3
jal zero, LOOP
DONE:
```

Takeaways

- Instructions operate on data stored in **registers**.
- Load/store instructions ferry data between registers and byte-addressed **memory**.
- Branch/jump instructions move the **instruction pointer**.
- Assembly is somewhat tedious but fundamentally **simple**.
- **Hint:** when you have to write an assembly program, consider first writing it in C(-ish) syntax with a single "instruction" per statement, and translate from there.