Assembly Language And Machine Code

C Statement:

```
int foo; foo = 15; foo = foo + 7;
```

MIPS Assembly Language:

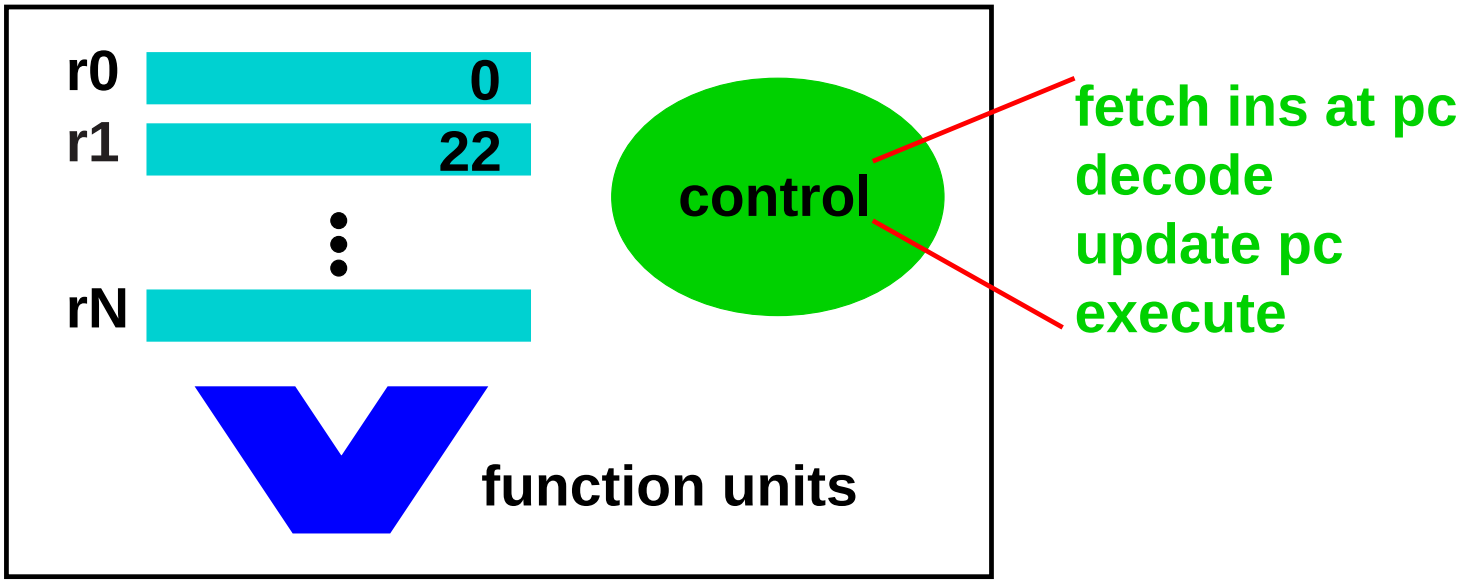
```
ori $1,$0,15            # set foo to 15
addiu $1,$1,7           # add 7 to foo
```

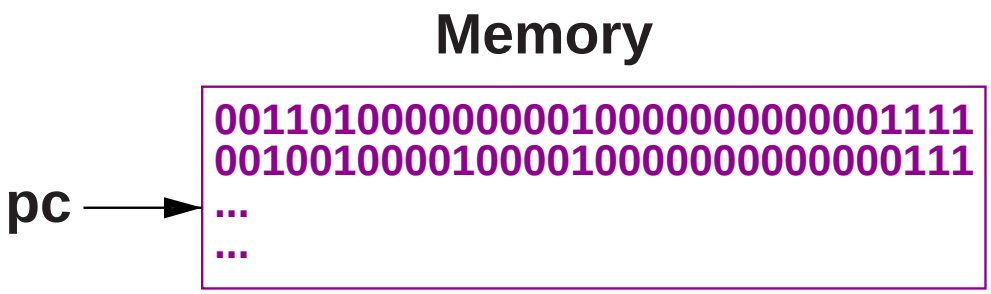
(register 1 holds the value of foo)

MIPS Machine Instructions:

```
00110100000000010000000000001111
00100100001000010000000000000111
```

A Simple Computer





Number Representation

Decimal: base 10, digits: '0', '1', ..., '9'

$$(683)_{10} = 6 \cdot 10^2 + 8 \cdot 10^1 + 3 \cdot 10^0$$

Binary: base 2, digits: '0', '1'

$$\begin{aligned}(1101)_2 &= 1 \cdot 2^3 + 1 \cdot 2^2 + 0 \cdot 2^1 + 1 \cdot 2^0 \\ &= 8 + 4 + 0 + 1 \\ &= (13)_{10}\end{aligned}$$

Hexadecimal: base 16, digits: '0' .. '9', 'a' .. 'f'

'a' = 10, 'b' = 11, 'c' = 12, 'd' = 13, 'e' = 14, 'f' = 15

$$(a6)_{16} = 10 \cdot 16^1 + 6 \cdot 16^0 = (166)_{10}$$

Often write `0xa6` instead of $(a6)_{16}$.

Number Representation

A Useful Trick: Converting between hexadecimal (hex) and binary.

$$
\begin{aligned}
\texttt{0xe3f8} &= 14 \cdot 16^3 + 3 \cdot 16^2 + 15 \cdot 16^1 + 8 \cdot 16^0 \\
&= 14 \cdot (2^4)^3 + 3 \cdot (2^4)^2 + 15 \cdot (2^4)^1 + 8 \cdot (2^4)^0 \\
&= (1110)_2 \cdot (2^4)^3 + (0011)_2 \cdot (2^4)^2 \\
&\quad + (1111)_2 \cdot (2^4)^1 + (1000)_2 \cdot (2^4)^0 \\
&= (\underbrace{1110}_{\texttt{0xe}}\ \underbrace{0011}_{\texttt{0x3}}\ \underbrace{1111}_{\texttt{0xf}}\ \underbrace{1000}_{\texttt{0x8}})_2
\end{aligned}
$$

1 hex digit = 4 bits

Negative Numbers

Various representations possible for signed binary arithmetic.

Sign-Magnitude: reserve left-most bit for the sign

+ Easy to negate a number
- Multiple zeros
- Arithmetic is more complicated

Example: 4-bit numbers

- $(+5)_{10}$ is given by 0 101
- $(-5)_{10}$ is given by 1 101

Negative Numbers

2's complement

- Flip all the bits and add 1
- \+ No wasted bits
- \+ Arithmetic works out
- \- Asymmetric range for positive and negative numbers

Example: 4-bit numbers

- $(+5)_{10}$ is given by 0101
- Flip bits: 1010
- Add 1: 1011

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Why 2's complement?

Let b be the integer we're trying to negate. (N-bits)

- Flip bits $\equiv$ subtract b from $\underbrace{111\cdots1}_{N\ 1s}$

$$\begin{array}{rcccc} & 1 & 1 & 1 & 1 \\ - & 0 & 1 & 0 & 1 \\ \hline & 1 & 0 & 1 & 0 \end{array}$$

$$\underbrace{111\cdots1}_{N\ 1s} = 2^N - 1$$

$$\begin{array}{rccccc} & 1 & 0 & 0 & 0 & 0 \\ - & & 0 & 0 & 0 & 1 \\ \hline & & 1 & 1 & 1 & 1 \end{array}$$

- Add 1

$$result = 2^N - b$$

Why 2's complement?

For 2's complement: $-b$ is represented by $2^N - b$.

... which is $-b$ modulo 2^N.

$\Rightarrow$ we can use the same computation structure to add positive and negative numbers if we use modulo 2^N arithmetic.

Sign Extension

How do I convert an 8-bit number into a 16-bit number?

- If the number is non-negative, left-most bit is 0

  $\Rightarrow$ add 0s to the left

- If the number is $-b$, then it corresponds to $2^8 - b$.

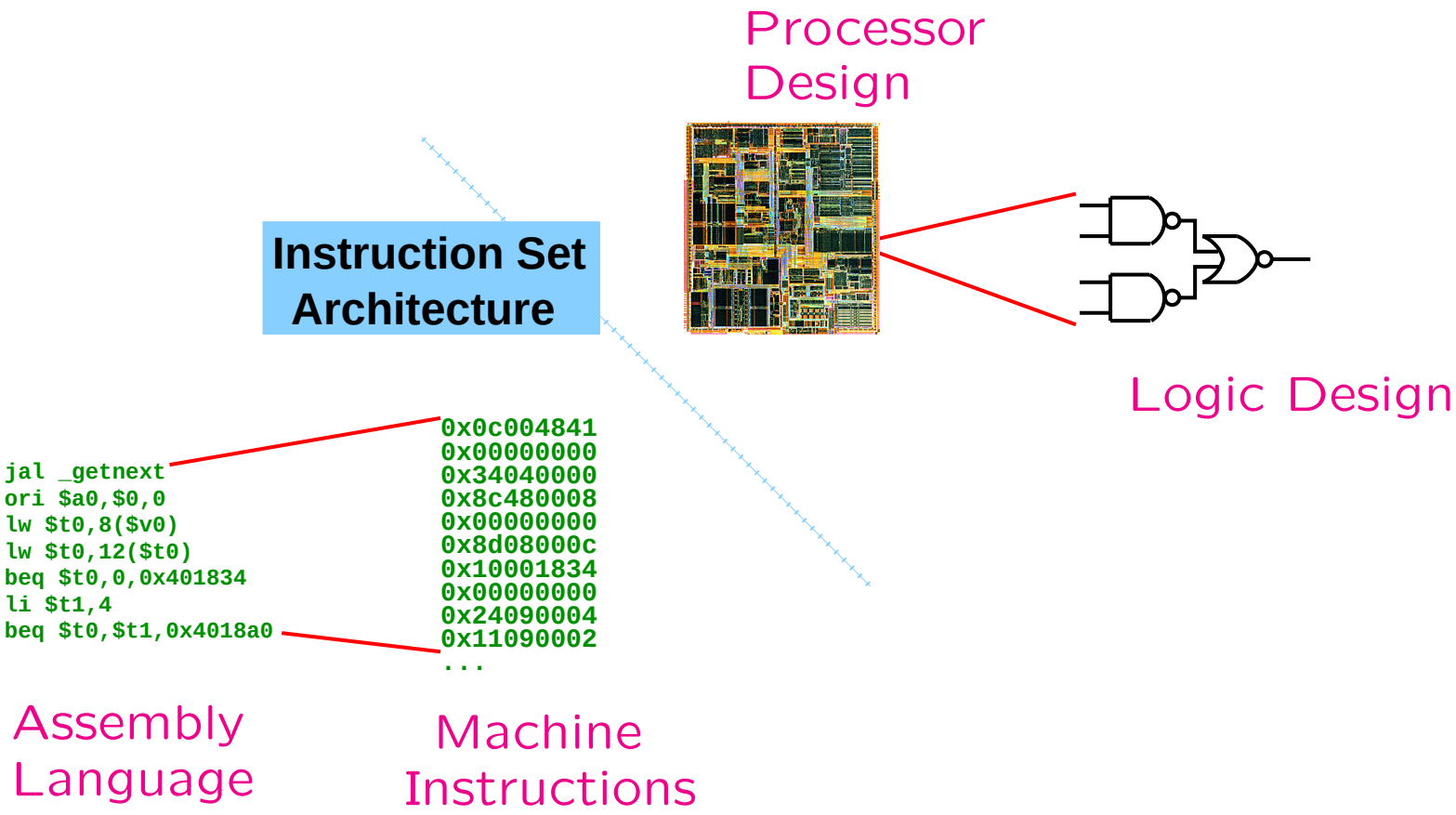
  $2^{16} - b = (2^8 - b) + (2^{16} - 2^8)$

  $\Rightarrow$ add 1s to the left

In both cases, replicate left-most bit

Known as "sign-extension"

Instruction Set Architecture



ISA: operands, data types, operations, encoding

MIPS Instruction Set Architecture

Basic features:

- Load/store architecture
  - Data must be in registers to be operated on
  - Keeps hardware simple
  - Memory operations only transfer data between registers and memory
- Emphasis on efficient implementation
- Very simple: basic operations rather than support for any specific language construct

MIPS Data Representation

Integer data types:

- Byte: 8 bits
- Half-words: 16 bits
- Words: 32 bits
- Double-words: 64 bits (not in basic MIPS I)

MIPS supports operations on signed and unsigned data types.

Converting a byte to a word? Sign-extend!

MIPS Instruction Types

- Arithmetic/Logical
  - three operands: result + two sources
  - operands: registers, 16-bit immediates
  - signed + unsigned operations
- Memory access
  - load/store between registers and memory
  - half-word and byte operations
- Control flow
  - conditional branches, fixed offsets and pc-relative

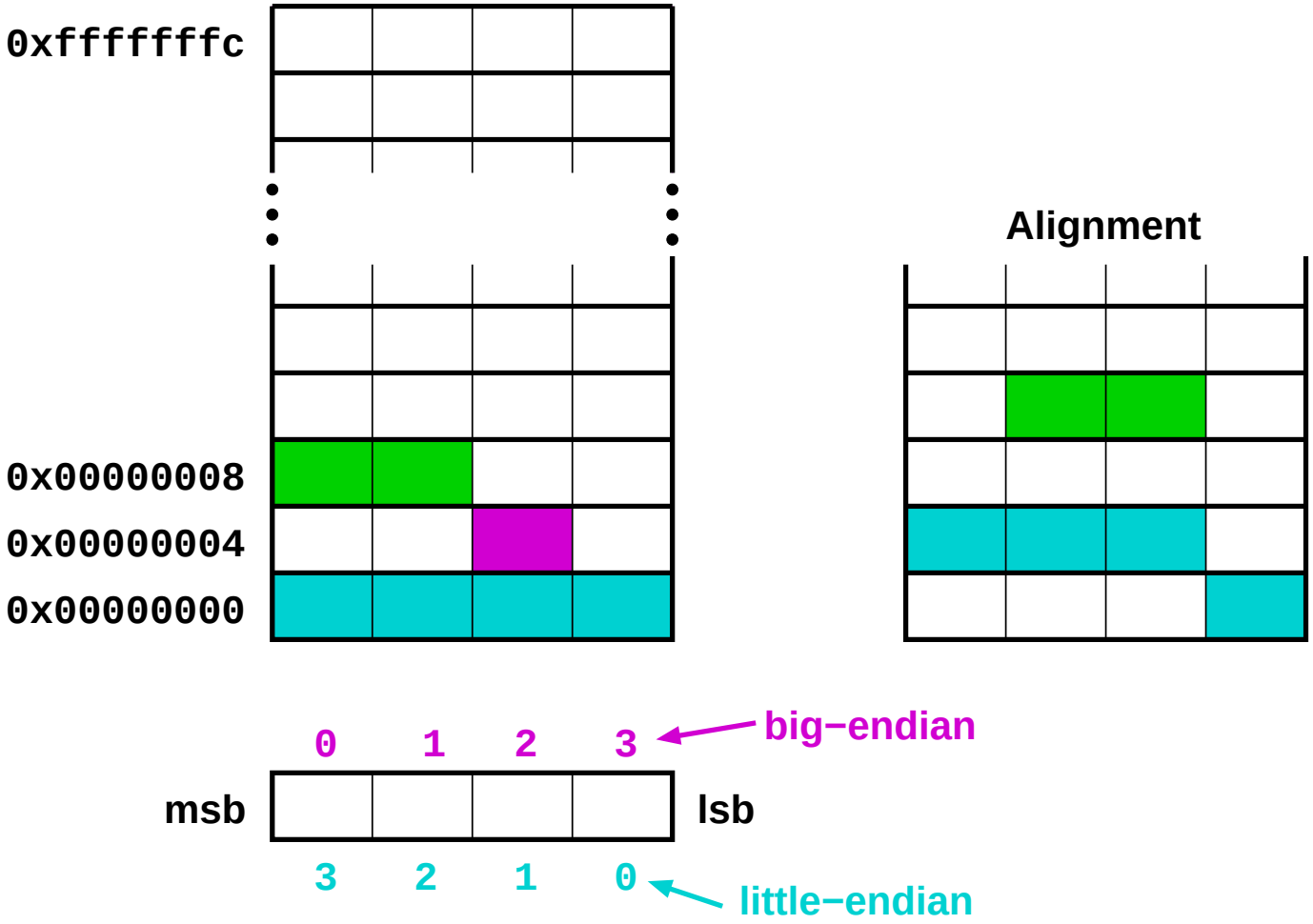
Data Storage

- 32 32-bit registers, register 0 is always zero.
- 2^{32} bytes of memory
- `hi`, `lo`: special 32-bit registers for multiply/divide
- `pc`, program counter
- 16 floating-point registers

Memory access:

- Byte addressing: can address individual bytes of memory
- How do bytes map into words?

Byte Ordering And Alignment



"On Holy Wars and a Plea for Peace", Cohen (1980)

Data Movement

Load/store architecture

- Read data from memory: "load"
- Write data to memory: "store"

Load:

- Normally overwrites entire register
- Loading bytes/half-words
  - unsigned: zero-extend
  - signed: sign-extend

Store: writes bottom byte/bottom half-word/word of register to memory.

Addressing Modes For Data Movement

How do we specify an address in memory?

- Instructions compute effective address (EA)

MIPS: One addressing mode for loads/stores

- register indirect with immediate offset
- EA = register + signed immediate

Example:

```
lh $5, 8($29)
lw $7, -12($29)
lbu $7, 1($30)
```

Requires aligned addresses!

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Addressing Modes

Other architectures have more than one way to specify EA.

- EA = signed immediate
- EA = register
- EA = register + k $\times$ register (k=1,2,4,8)
- EA = register + k $\times$ register + signed immediate

MIPS favors simplicity $\Rightarrow$ fast hardware

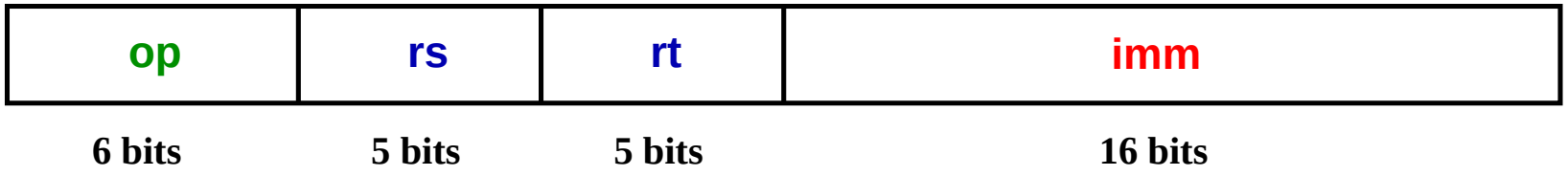
MIPS Load/Store Instructions

```
lb   rt, imm(rs)  # load byte (signed)
lbu  rt, imm(rs)  # load byte (unsigned)

lh   rt, imm(rs)  # load half-word (signed)
lhu  rt, imm(rs)  # load half-word (unsigned)

lw   rt, imm(rs)  # load word

sb   rt, imm(rs)  # store byte
sh   rt, imm(rs)  # store half-word
sw   rt, imm(rs)  # store word
```



MIPS Load/Store Instructions

C Code

```
foo = x[3]; x[4] = foo + 1;
```

Assembly

```
lw     $16, 12($17)  # reg 16 contains foo, reg 17
                     # contains the address of x
addiu  $8, $16, 1    # add 1 to foo
sw     $8, 16($17)   # store into x[4]
```

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Integer Arithmetic Operations

- Constants
  - register zero is always zero
  - immediates are 16-bits wide
- Signed + unsigned operations
- Logical operations
  - bitwise operations on operands
  - always unsigned

Integer Arithmetic Operations

```
add    rd, rs, rt    # rd = rs + rt
addi   rt, rs, imm   # rt = rs + s_ext(imm)
addiu  rt, rs, imm   # rt = rs + s_ext(imm)
addu   rd, rs, rt    # rd = rs + rt
slt    rd, rs, rt    # rd = (rs <s rt)
slti   rt, rs, imm   # rt = (rs <s s_ext(imm))
sltiu  rt, rs, imm   # rt = (rs < s_ext(imm))
sltu   rd, rs, rt    # rd = (rs < rt)
sub    rd, rs, rt    # rd = rs - rt
subu   rd, rs, rt    # rd = rs - rt
```