Storing Data in Memory

RV32 So Far…

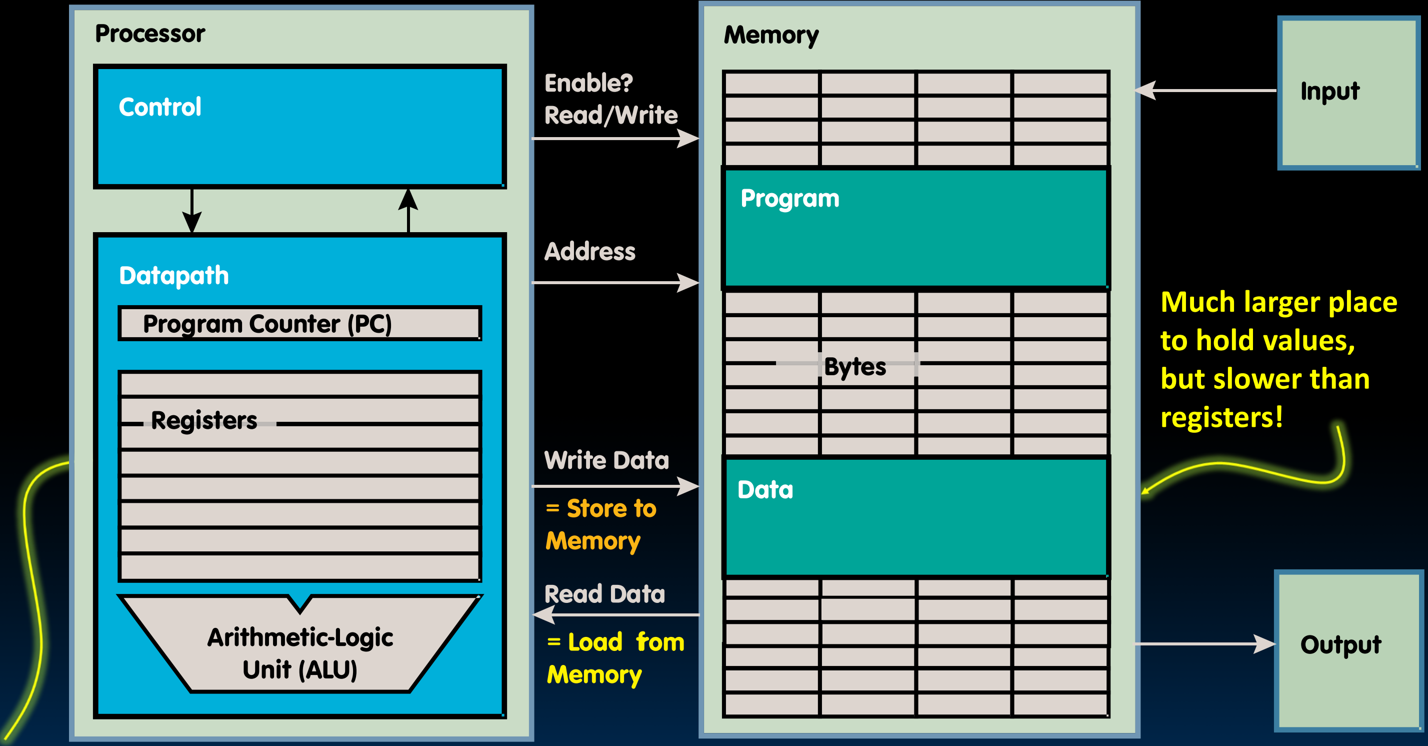
- Addition/subtraction

```
add rd, rs1, rs2
    R[rd] = R[rs1] + R[rs2]
sub rd, rs1, rs2
    R[rd] = R[rs1] - R[rs2]
```

- Add immediate

```
addi rd, rs1, imm
    R[rd] = R[rs1] + imm
```

Data Transfer: Load from and Store to memory

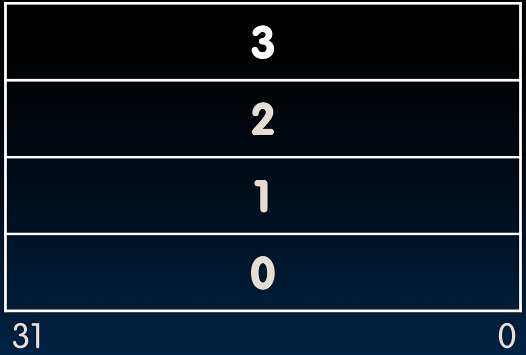


Much larger place to hold values, but slower than registers!

Very fast,
but limited space to hold values!

Memory Addresses are in Bytes

- Data typically smaller than 32 bits, but rarely smaller than 8 bits (e.g., char type)–works fine if everything is a multiple of 8 bits
- 8 bit chunk is called a *byte* (1 word = 4 bytes)
- Memory addresses are
  really in *bytes*, not words
- Word addresses are
  4 bytes apart
  - Word address is same
    as address of rightmost byte
    – least-significant byte
    (i.e. **Little-endian** convention)



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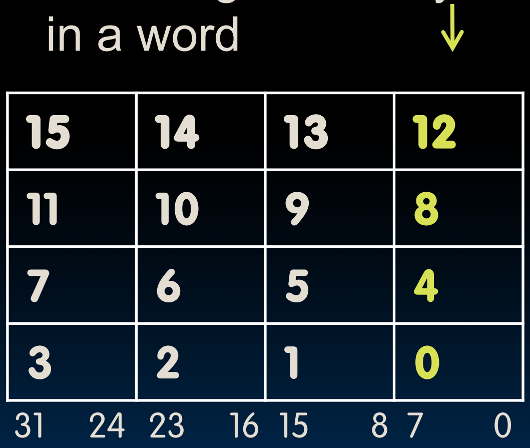
- Memory addresses are really in *bytes*, not words
- Word addresses are 4 bytes apart
  - Word address is same as address of rightmost byte – least-significant byte (i.e. **Little-endian** convention)

Least-significant byte in a word



Least-significant byte gets the smallest address

CS 61C

Big Endian vs. Little Endian

en.wikipedia.org/wiki/endianness

The adjective endian has its origin in the writings of 18th century writer Jonathan Swift. In the 1726 novel Gulliver's Travels, he portrays the conflict between sects of Lilliputians divided into those breaking the shell of a boiled egg from the big end or from the little end. He called them the "Big-Endians" and the "Little-Endians".

- **The order in which BYTES are stored in memory**
- **Bits always stored as usual (E.g., 0xC2=0b 1100 0010)**

Consider the number 1025 as we typically write it:

BYTE3	BYTE2	BYTE1	BYTE0
00000000	00000000	00000100	00000001

Big Endian

ADDR3	ADDR2	ADDR1	ADDR0
BYTE0	BYTE1	BYTE2	BYTE3
00000001	00000100	00000000	00000000

Examples

Names in China or Hungary (e.g., Nikolić Bora)

Java Packages: (e.g., org.mypackage.HelloWorld)

Dates in ISO 8601 YYYY-MM-DD (e.g., 2020-09-07)

Eating Pizza crust first

Little Endian

ADDR3	ADDR2	ADDR1	ADDR0
BYTE3	BYTE2	BYTE1	BYTE0
00000000	00000000	00000100	00000001

Examples

Names in the US (e.g., Bora Nikolić)

Internet names (e.g., cs.berkeley.edu)

Dates written in Europe DD/MM/YYYY (e.g., 07/09/2020)

Eating Pizza skinny part first

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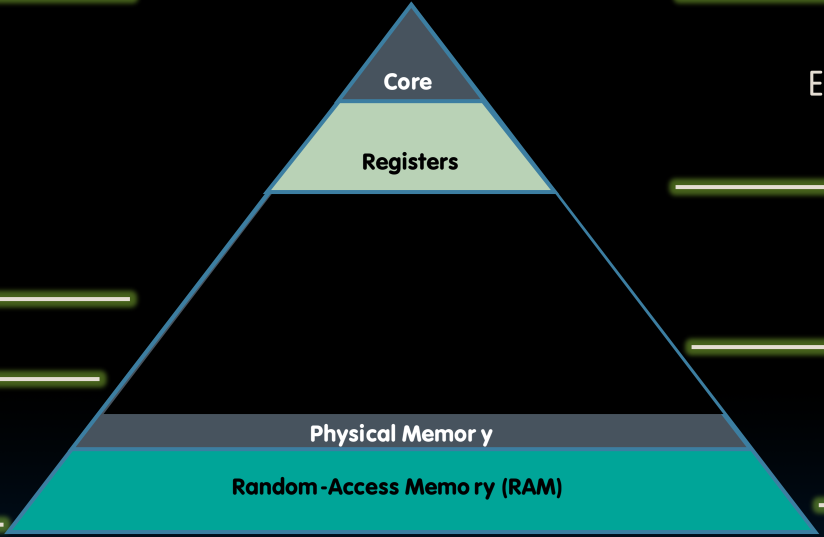
Data Transfer Instructions

Great Idea #3: Principle of Locality / Memory Hierarchy

Processor chip

DRAM chip
e.g. DDR3/4/5
HBM/HBM2/3



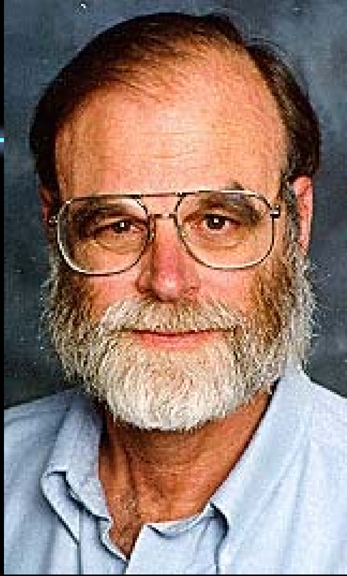
Extremely fast
Extremely expensive
Tiny capacity

Fast
Priced reasonably
Medium capacity

Speed of Registers vs. Memory

- Given that
  - Registers: 32 words (128 Bytes)
  - Memory (DRAM): Billions of bytes (2 GB to 64 GB on laptop)
- and physics dictates…
  - Smaller is faster
- How much faster are registers than DRAM??
  - About 50-500 times faster! (in terms of latency of one access - tens of ns)
    - But subsequent words come every few ns

Jim Gray's Storage Latency Analogy: How Far Away is the Data?



Jim Gray
Turing Award
B.S. Cal 1966
Ph.D. Cal 1969

100	Memory	Sacramento	1.5 hr
1 [ns]	Registers	My Head	1 min

Load from Memory to Register

- C code

```
int  A[100];
g = h + A[3];
```

- Using Load Word (`lw`) in RISC-V:

```
lw  x10,12(x15) # Reg x10 gets A[3]
add x11,x12,x10 # g = h + A[3]
```

Note: x15 – base register (pointer to A[0])

12 – offset in bytes

Offset must be a constant known at assembly time

Store from Register to Memory

- C code

```
int  A[100];
A[10] = h + A[3];
```

- Using Store Word (**sw**) in RISC-V:

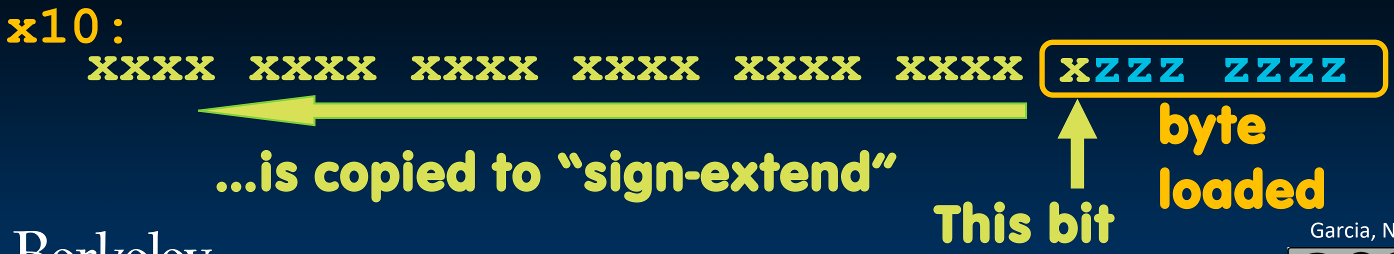
```
lw   x10,12(x15)   # Temp reg x10 gets A[3]
add  x10,x12,x10   # Temp reg x10 gets h + A[3]
sw     x10,40(x15) # A[10] = h + A[3]
```

Note: x15 – base register (pointer)
12,40 – offsets in bytes
x15+12 and x15+40 must be multiples of 4

Loading and Storing Bytes

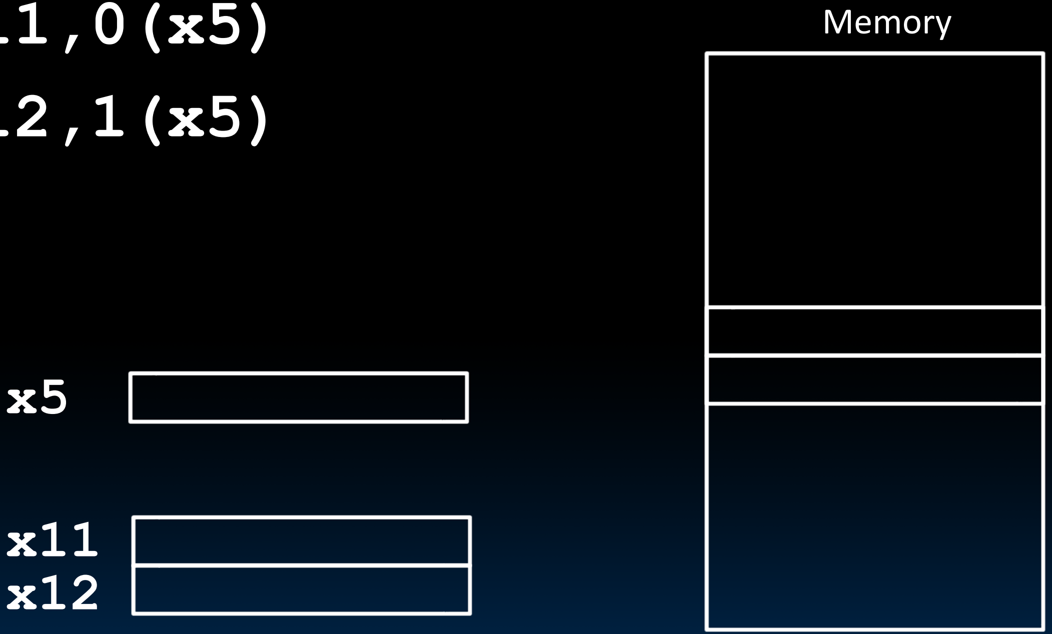
- In addition to word data transfers (**`lw`**, **`sw`**), RISC-V has byte data transfers:
  - load byte: **`lb`**
  - store byte: **`sb`**
- Same format as **`lw`**, **`sw`**
- E.g., **`lb x10,3(x11)`**
  - contents of memory location with address = sum of "3" + contents of register **`x11`** is copied to the low byte position of register **`x10`**.

RISC-V also has "unsigned byte" loads (**`lbu`**) which zero extends to fill register. Why no unsigned store byte '**`sbu`**'?


x10:
xxxx xxxx xxxx xxxx xxxx xxxx xzzz zzzz
…is copied to "sign-extend"
This bit
byte loaded

Example: What is in `x12` ?

```
addi x11,x0,0x3F5
sw x11,0(x5)
lb x12,1(x5)
```



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Substituting `addi`

The following two instructions:

```
lw  x10,12(x15)   # Temp reg x10 gets A[3]
add x12,x12,x10   # reg x12 = reg x12 + A[3]
```

Replace `addi`:

```
addi x12, value # value in A[3]
```

But involve a load from memory!

Add immediate is so common that it deserves its own instruction!

Decision Making

RV32 So Far…

- Addition/subtraction

```
add rd, rs1, rs2
sub rd, rs1, rs2
```

- Add immediate

```
addi rd, rs1, imm
```

- Load/store

```
lw  rd,  rs1, imm
lb  rd,  rs1, imm
lbu rd,  rs1, imm
sw  rs1, rs2, imm
sb  rs1, rs2, imm
```

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Computer Decision Making

- Based on computation, do something different
- In programming languages: *if*-statement

- RISC-V: *if*-statement instruction is

  `beq reg1,reg2,L1`

  means: go to statement labeled L1
  if (value in reg1) == (value in reg2)

  ….otherwise, go to next statement
- **`beq`** stands for *branch if equal*
- Other instruction: **`bne`** for *branch if not equal*

Types of Branches

- Branch – change of control flow
- Conditional Branch – change control flow depending on outcome of comparison
  - branch *if* equal (`beq`) or branch *if not* equal (`bne`)
  - Also branch if less than (`blt`) and branch if greater than or equal (`bge`)
  - And unsigned versions (`bltu`, `bgeu`)
- Unconditional Branch – always branch
  - a RISC-V instruction for this: *jump* (`j`), as in `j label`

Example *if* Statement

- Assuming translations below, compile *if* block

  f → **x10**   g → **x11**   h → **x12**

  i → **x13**   j → **x14**

```
if (i == j)              bne x13,x14,Exit
   f = g + h;            add x10,x11,x12
                    Exit:
```

- May need to negate branch condition

Example *if-else* Statement

- Assuming translations below, compile

f → `x10`   g → `x11`   h → `x12`

i → `x13`   j → `x14`

```
if (i == j)              bne x13,x14,Else
   f = g + h;            add x10,x11,x12
else                     j Exit
   f = g - h;       Else:sub x10,x11,x12
                    Exit:
```

Magnitude Compares in RISC-V

- General programs need to test < and > as well.
- RISC-V magnitude-compare branches:

  "Branch on Less Than"

  Syntax: **`blt reg1,reg2, Label`**

  Meaning: **`if (reg1 < reg2) goto Label;`**

  "Branch on Less Than Unsigned"

  Syntax: **`bltu reg1,reg2, Label`**

  Meaning: **`if (reg1 < reg2)// treat registers as unsigned integers`**
  `goto label;`

  Also "Branch on Greater or Equal" **`bge`** **and** **`bgeu`**

  Note: No '**`bgt`**' or '**`ble`**' instructions

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Loops in C/Assembly

- There are three types of loops in C:
  - while
  - do … while
  - for
- Each can be rewritten as either of the other two, so the same branching method can be applied to these loops as well.
- Key concept: Though there are multiple ways of writing a loop in RISC-V, the key to decision-making is conditional branch

C Loop Mapped to RISC-V Assembly

```
int A[20];
int sum = 0;
for (int i=0; i < 20; i++)
    sum +=  A[i];
```

```
  add x9, x8, x0 # x9=&A[0]
  add x10, x0, x0 # sum
  add x11, x0, x0 # i
  addi x13,x0, 20 # x13
Loop:
  bge x11,x13,Done
  lw x12, 0(x9)    # x12 A[i]
  add x10,x10,x12 # sum+=
  addi x9, x9,4    # &A[i+1]
  addi x11,x11,1   # i++
  j Loop
Done:
```