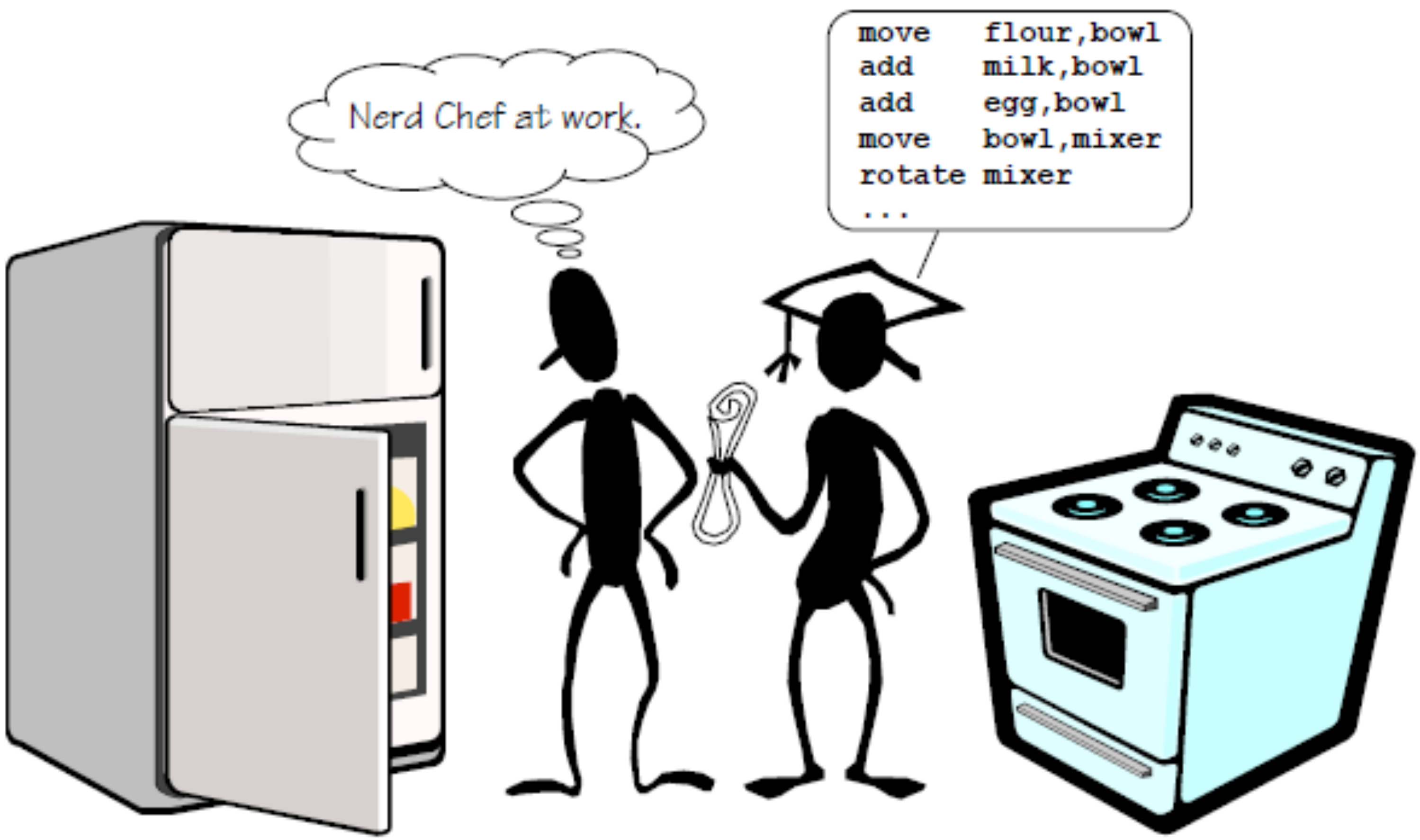
A Simple Computer

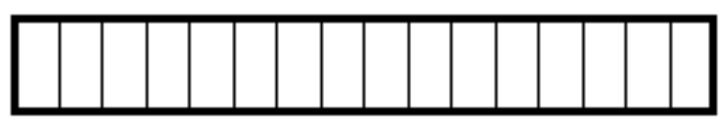


Computing Models

- A simple computer model with a unified notion of “data” and “instructions”
  - “Von Neumann” architecture model
  - The first key idea is a model of “memory”
- Others
  - Computing with a table, state-machines, Turing machines with many procedures, etc.

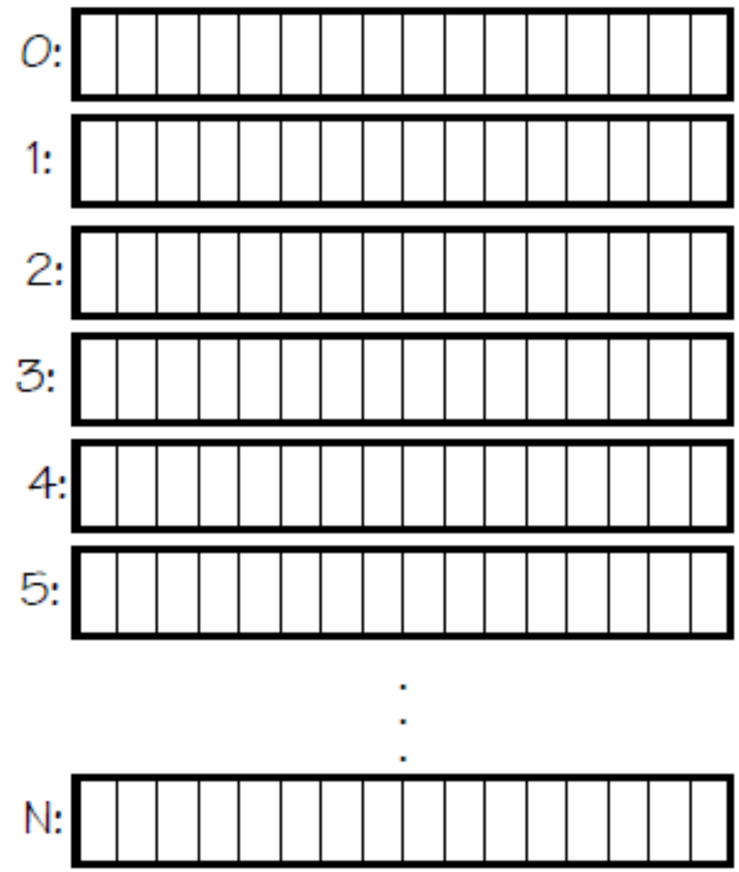
Memory

- Memory stores bits
- Bits are grouped into larger clusters called ***words***
- Each word has an **address and contents**
  - Address is a memory location's "Name"
  - Contents are a memory location's "Value"
- Memory stores "Data" and "Instructions"
- We often refer to addresses symbolically like variables in algebra

Address: 

An Array of Words

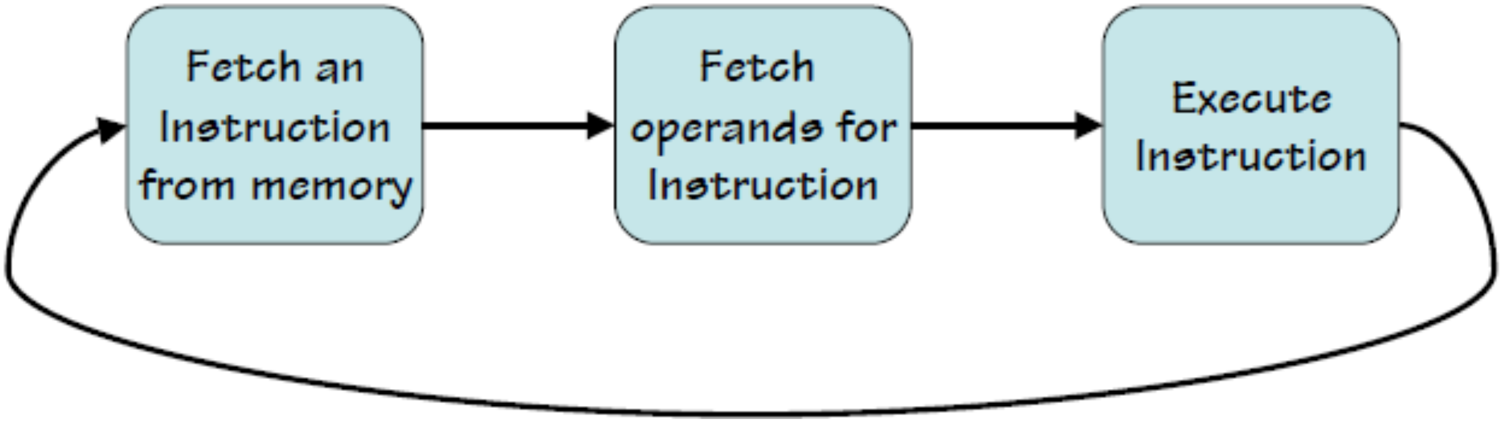
- Addresses are organized sequentially in an array
- Addresses are
  - Numerical
  - Symbolic (Label)
- The numerical address is fixed (governed by the hardware)
- Labels are user defined



Words = {Instructions, Data}

- Each word of memory can be interpreted as either binary data (number, character, a bit pattern, etc.) or as an **instructions**
- Not all bit patterns are valid instructions, however.
- Instructions cause the computer to perform a operation
- A program is a collection of instructions
- In general, instructions are executed sequentially

Execution Loop

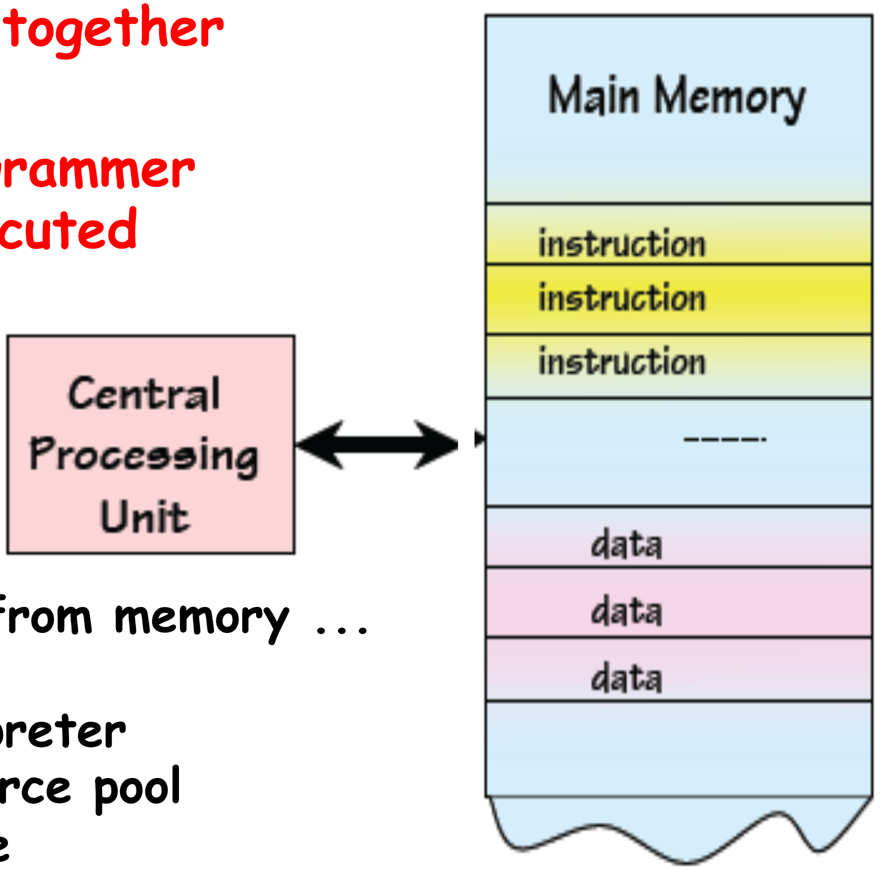


- The execution of a program is governed by a simple repetitive loop
- Typically, instructions are fetched from sequential addresses
- A special register, call the program counter (PC), is used to point to the current instruction in memory

The Stored-Program Computer

- Instructions and Data are stored together in a common memory
- Sequential semantics: To the programmer all instructions appear to be executed sequentially

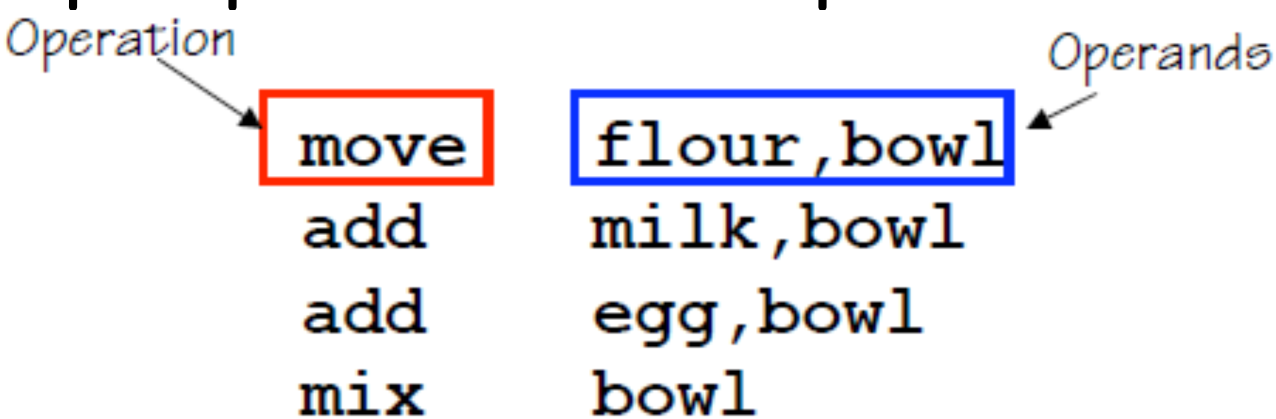
Key idea: Memory holds not only data, but *coded instructions* that make up a *program*.



CPU fetches and executes instructions from memory ...
- The CPU is a H/W interpreter
- Program IS simply data for this interpreter
- Main memory: Single expandable resource pool
- constrains both data and program size
- don't need to make separate decisions of how large of a program or data memory to buy

Anatomy of an Instruction

- Instruction sets have a simple structure
- Broken into fields
  - Operation (Opcode) - Verb
  - Operands - Noun
- Recipes provide a near perfect analogy



Instruction Operands

- Operands come from three sources
  - Memory
  - As an immediate constant
  (part of the instruction)
  - From one of several a special “scratch-pad” locations called “registers”
- Registers hold temporary results
- Most operations are performed using the contents of registers
- Registers can be the “source” or “destination” or instructions

UNC-101

- The UNC-101 is a simple 16-bit computer
- It has
  - 65536 or 2^{16} memory locations
  - Each location has 16-bits
  - 15 registers, that are referred to as ($1-$15)
  - A special operand, $0, that can be used anywhere that a register is allowed. It provides a value of 0, and cannot write to it
  - A simple instruction set

Instructions: Concrete Examples

addi $4, $5, 1

Register[4] ← Register[5] + 1

- All instructions are broken to parts
  - Operation codes (Opcodes), usually mnemonic
  - Operands usually stylized (e.g. "$" implies the contents of the register, whose number follows)

Arithmetic Instructions

add $D, $A, $B   Reg[D] ← Reg[A] + Reg[B]
sub $D, $A, $B   Reg[D] ← Reg[A] - Reg[B]
sgt $D, $A, $B   Reg[D] ← 1 if (Reg[A] > Reg[B])
                                    0, otherwise

- Where D, A, B are one of {1,2, … 15}
- All operands come from registers

Immediate Arithmetic Instructions

addi \$D, \$A, imm $Reg[D] \leftarrow Reg[A] + imm$
subi \$D, \$A, imm $Reg[D] \leftarrow Reg[A] - imm$
sgti \$D, \$A, imm $Reg[D] \leftarrow$ 1 if $(Reg[A] > imm)$
0, otherwise

- Where D, A are one of {1,2, … 15}
- 2 operands come from registers
- Third, "Immediate" operand is a constant, which is encoded as part of the instructions

Multiply? Divide?

- You may have noticed that some math function are missing, such as multiply and divide
- Often, more complicated operations are implemented using a series of instructions called a routine
- Simple operations lead to faster computers, because it is often the case the speed of a computer is limited by the most complex task it has to perform. Thus, simple instructions permit fast computer (KISS principle)

KISS == RISC?

- In the later 20 years of the 1900's computer architectures focused on developing simple computers that were able to execute as fast as possible
- Led to minimalist, and simple, instruction sets
  - Do a few things fast
  - Compose more complicated operations from a series of simple ones
- Collectively, these computers were called Reduced Instruction Set Computers (RISC)

Load/Store

- Certain instructions are reserved for accessing the contents of memory
- The *only* instructions that access memory
- Move data to registers, operate on it, save it

st \$D,\$A	memory[Reg[A]] ← Reg[D]
ld \$D,\$A	Reg[D] ← memory[Reg[A]]
stx \$D,\$A,imm	memory[Reg[A]+imm] ← Reg[D]
ldx \$D,\$A,imm	Reg[D] ← memory[Reg[A]+imm]

Bitwise Logic Instructions

and $D, $A, $B   Reg[D] ← Reg[A] & Reg[B]
or $D, $A, $B   Reg[D] ← Reg[A] | Reg[B]
xor $D, $A, $B   Reg[D] ← Reg[A] ^ Reg[B]

- Where D, A, B are one of {1,2, … 15}
- All operands come from registers
- Performs a bitwise 2-input Boolean operation on the bits of the A and B operands and saves the result in D
- Assuming Reg[1] = 12 (0x000c) and Reg[2] = 10 (0x000a)
  and $3,$1,$2 # gives Reg[3] = 8 (0x0008)
  or $3,$1,$2 # gives Reg[3] = 14 (0x000e)
  xor $3,$1,$2 # gives Reg[3] = 6 (0x0006)

Closing the Gap

- A computer language closer to one we'd speak
  - High-Level construct:

    total = item1 + item2
  - Assembly language:

```
ldx $1,$0,item1
ldx $2,$0,item2
add $1,$1,$2
stx $1,$0,total
```

  - Binary (machine language):

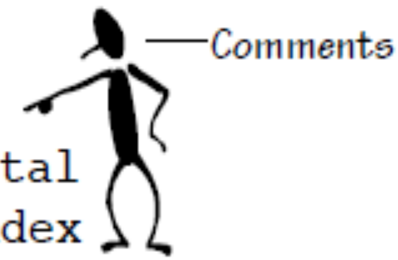
    0xf10f, 0x0008, 0xf20f, 0x0009, 0x0112, 0xf10e, 0x0007

An Assembler

- A symbolic machine language
- One-to-one correspondence between computer instruction = line of assembly
- Translates symbolic code to binary machine code
- Manages tedious details
  - Locating the program in memory
  - Figures out addresses

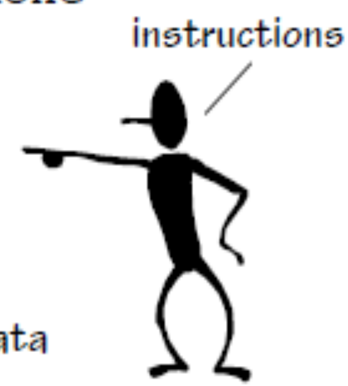
  (e.g. item1 rather than 0x0008)
- Generates a list of numbers

Assembly Code




```
main:  add    $1,$0,$0              # $1 = total
       add    $2,$0,$0              # $2 = index
loop:  ldx    $3,$2,item            # $3 = item[index]
       add    $1,$1,$3              # total = total + $3
       sgei   $4,$2,10              # if (index >= 10)
       bne    $0,$4,$0,done         #     we're done
       addi   $2,$2,1               # next index
       beq    $0,$0,$0,loop         # loop back
done:  stx    $1,$0,total           # save total
end:   beq    $0,$0,$0,end          # the end

total: .data  0
item:  .data  1,3,5,7,9,11,13,15,17,19
```



Assembly Errors

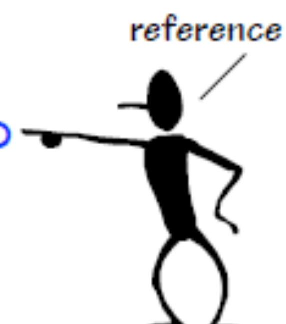
- Generally, the assembler will generate a useful error message to help correcting your program

```
add $1,$1,1
beq $0,$0,loop
mul $1,$2,$3
ldx array,$0,$1
```

Labels

- Declaration
  - At the beginning of a line
  - Ends with a colon
- Reference
  - Anywhere that an immediate operand is allowed


```
loop:     addi $1,$1,1
          beq  $0,$0,$0,loop
```



Closing the Gap…

- Understand how to program computers at a "high-level", much closer to a spoken language
- Computers require precise, unambiguous, instructions
- Computers have no context… like people do
- However, we can imagine "higher-level" instructions and "systematic" methods for converting them into "low-level" assembly instructions

Accessing Array Variables

- What we want:
  - The vector of related variables referenced via numeric subscripts rather than distinct names
- Examples:

"High-Level Language"

```
int a[5];

main() {
    int i = 3;
    a[i] = 2;
}
```

"MIPS Assembly"

```
main:    ldx   $2,$0,i
         addi $3,$0,2
         stx   $3,$2,a
halt:    beq  $0,$0,$0,halt



a:       .space 5
i:       .data 3
```

Allocates space for a 5 uninitialized integers

Accessing a "Data Structure"

- What we want:
  - Data structures are another aggregate variable type, where elements have "names" rather than indices
- Examples:

"High-Level Language"

```
struct point {
    int x, y;
} p;

main() {
    p.x = 3;
    p.y = 2;
}
```

"Assembly"

```
main:   addi    $1,$0,p
        addi    $2,$0,3
        stx     $2,$1,0
        addi    $2,$0,2
        stx     $2,$1,1
halt:   beq   $0,$0,$0,halt

p:      .space    2
```

Allocates space for 2 uninitialized integers (8-bytes)

Conditionals

High-Level

```
if (expr) {
    STUFF
}
```

Assembly:

```
    (compute expr in $rx)
    beq $0,$rx,$0,Lendif
    (compile STUFF)
Lendif:
```

High-Level

```
if (expr) {
    STUFF1
} else {
    STUFF2
}
```

Assembly:

```
    (compute expr in $rx)
    beq $0,$rx,$0,Lelse
    (compile STUFF1)
    beq $0,$0,$0,Lendif
Lelse:
    (compile STUFF2)
Lendif:
```

There are little tricks that come into play when compiling conditional code blocks. For instance, the statement:

```
if (y < 32) {
    x = x + 1;
}
```

becomes:

```
  ldx  $2,$0,y
  sgei $1,$2,32
  bne  $0,$1,$0,Lendif
  ldx  $2,$0,x
  addi $2,$2,1
  stx  $2,$0,x
Lendif:
```

Loops

High-Level:

```
while (expr) {
    STUFF
}
```

Assembly:

```
Lwhile:
    (compute expr in $rx)
    beq $0,$rX,$0,Lendw
    (compile STUFF)
    beq $0,$0,$0,Lwhile
Lendw:
```

Alternate Assembly:

```
    beq $0,$0,$0,Ltest
Lwhile:
    (compile STUFF)
Ltest:
    (compute expr in $rx)
    bne $0,$rX,$0,Lwhile
Lendw:
```

Computers spend a lot of time executing loops. Generally loops come in 3 flavors:

- do something “while” a statement is true
- do something “until” a statement becomes true
- repeat something a prescribed number of times

FOR Loops

- Most high-level languages provide loop constructs that establish and update an iteration variable that controls the loop's behavior

High-Level code:

```
int sum = 0;

int a[10] =
    {1,2,3,4,5,6,7,8,9,10};


int i;

for (i=0; i<10; i=i+1) {
    sum = sum + a[i];
}
```

Assembly:

```
        add   $3,$0,$0       # i=0
Lfor:   ldx   $2,$0,sum
        ldx   $1,$3,a
        add   $2,$2,$1
        stx   $2,$0,sum
        add   $3,$3,1        # i=i+1
        sgei  $2,$3,10
        beq   $0,$2,$0,Lfor
Lendfor:

sum:    .data 0x0
a:      .data 1,2,3,4,5
        .data 6,7,8,9,10
```

Procedures

- Procedures or "subroutines" are reusable code fragments, that are "called", executed, and then return back from where they were called from.

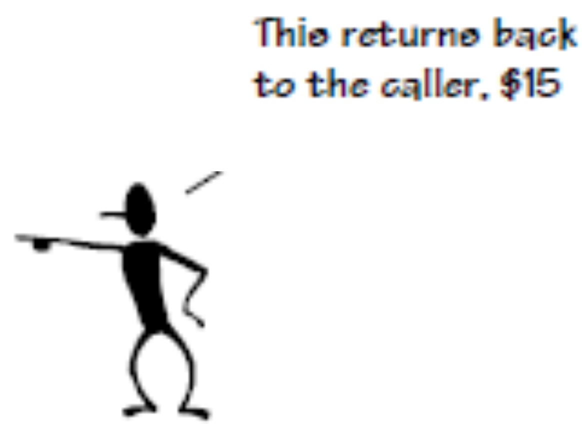
```
beq    $15,$0,$0,routine
add    $1,$1,$3
```

Before branching to the instruction at "routine" the address of the following instruction is stored in the destination argument, $15

Procedure Body

- The "Callee" executes its instructions and then "returns" back to the "Caller"
- Uses the jump register (jr) instruction

```
routine:    add     $2,$0,$0
            addi    $3,$0,1
loop:       sge     $4,$1,$3
            beq     $0,$4,$0,return
            sub     $1,$1,$3
            addi    $2,$2,1
            addi    $3,$3,2
            beq     $0,$0,$0,loop
return:     jr      $0,$15
```



Parameters

- Most interesting functions have parameters that are "passed" to them by the caller
- Examples Mult(x, y), Sqrt(x)
- Caller and Callee must agree on a way to pass parameters and return results. Usually this is done by a convention
- For example, we could pass parameters in sequential registers ($1,$2, $3, etc.) and a single returned value in the next available register.

```
ldx     $1,$0,a
beq     $15,$0,$0,routine
ldx     $1,$0,x
addi    $1,$1,$2
```