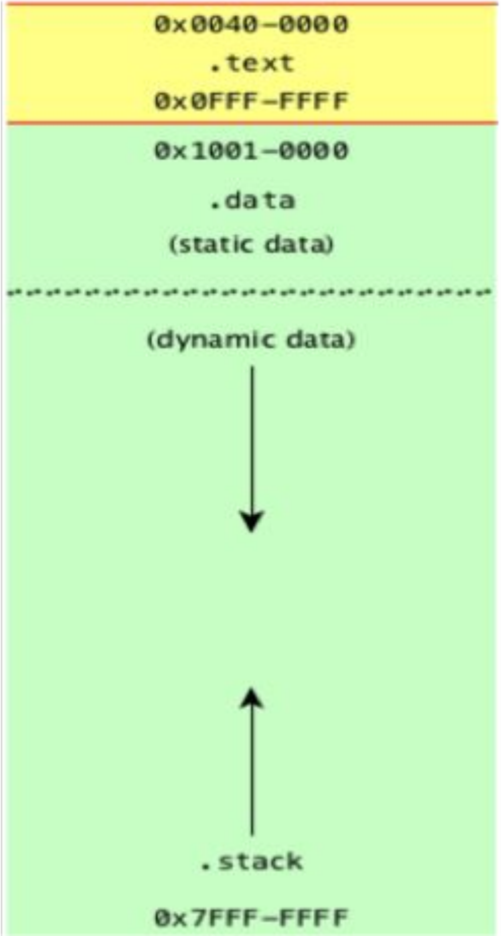
MIPS memory map

Static data is known at the time the program is loaded into memory.

Dynamic data is allocated at run time.



Fetch, Decode, Execute

Instruction cycle:

1. Fetch the next instruction from memory
2. Decode it
3. Execute it
4. Update the PC (program counter) += 4

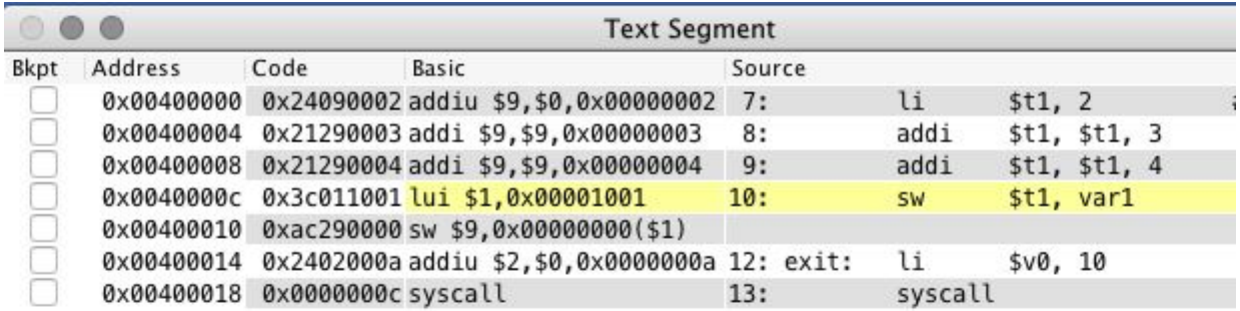
Register PC - Program Counter

Register PC is update by 4 after every instruction.

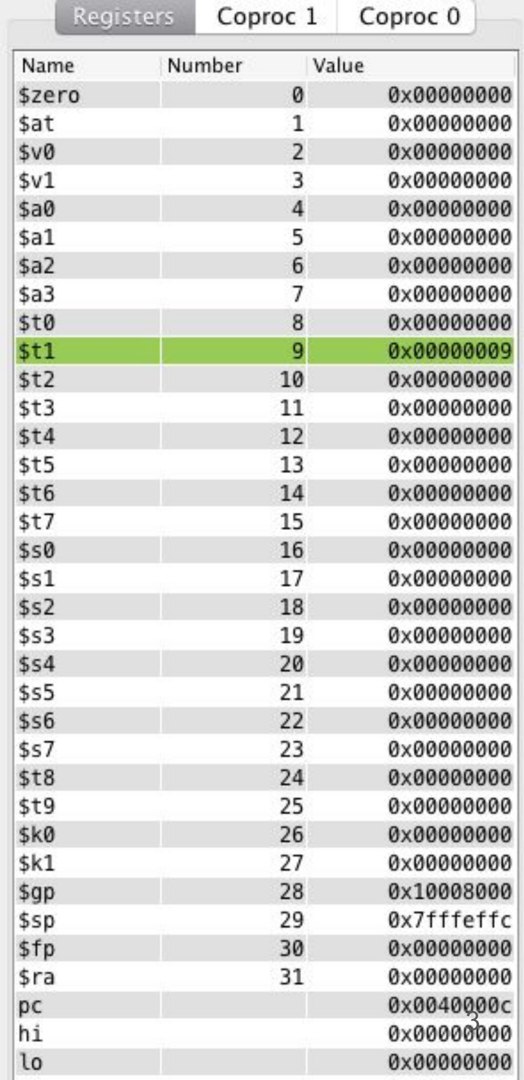
You can see this when you single-step through a program.

In the code below, we are about to execute 0x004000c

and we see that is the value in register PC



Bkpt	Address	Code	Basic	Source
☐	0x00400000	0x24090002	addiu $9,$0,0x00000002	7: li $t1, 2
☐	0x00400004	0x21290003	addi $9,$9,0x00000003	8: addi $t1, $t1, 3
☐	0x00400008	0x21290004	addi $9,$9,0x00000004	9: addi $t1, $t1, 4
☐	0x0040000c	0x3c011001	lui $1,0x00001001	10: sw $t1, var1
☐	0x00400010	0xac290000	sw $9,0x00000000($1)	
☐	0x00400014	0x2402000a	addiu $2,$0,0x0000000a	12: exit: li $v0, 10
☐	0x00400018	0x0000000c	syscall	13: syscall



Name	Number	Value
$zero	0	0x00000000
$at	1	0x00000000
$v0	2	0x00000000
$v1	3	0x00000000
$a0	4	0x00000000
$a1	5	0x00000000
$a2	6	0x00000000
$a3	7	0x00000000
$t0	8	0x00000000
$t1	9	0x00000009
$t2	10	0x00000000
$t3	11	0x00000000
$t4	12	0x00000000
$t5	13	0x00000000
$t6	14	0x00000000
$t7	15	0x00000000
$s0	16	0x00000000
$s1	17	0x00000000
$s2	18	0x00000000
$s3	19	0x00000000
$s4	20	0x00000000
$s5	21	0x00000000
$s6	22	0x00000000
$s7	23	0x00000000
$t8	24	0x00000000
$t9	25	0x00000000
$k0	26	0x00000000
$k1	27	0x00000000
$gp	28	0x10008000
$sp	29	0x7fffeffc
$fp	30	0x00000000
$ra	31	0x00000000
pc		0x0040000c
hi		0x00000000
lo		0x00000000

Control structures

So far we have executed code sequentially.

We need:

Conditional execution, like an if statement

Repeated execution, like loops

Function calls

In assembly language we use branch and jump instructions to create these

Branch instructions

Branch instructions are conditional jumps

Branch to a labeled instruction if a condition is true; otherwise continue sequentially

There are two MIPS branch instructions: beq and bne

```
beq  rs, rt, label  # compare registers and branch if they are equal
bne rs, rt, label # compare registers and branch if they are not equal
```

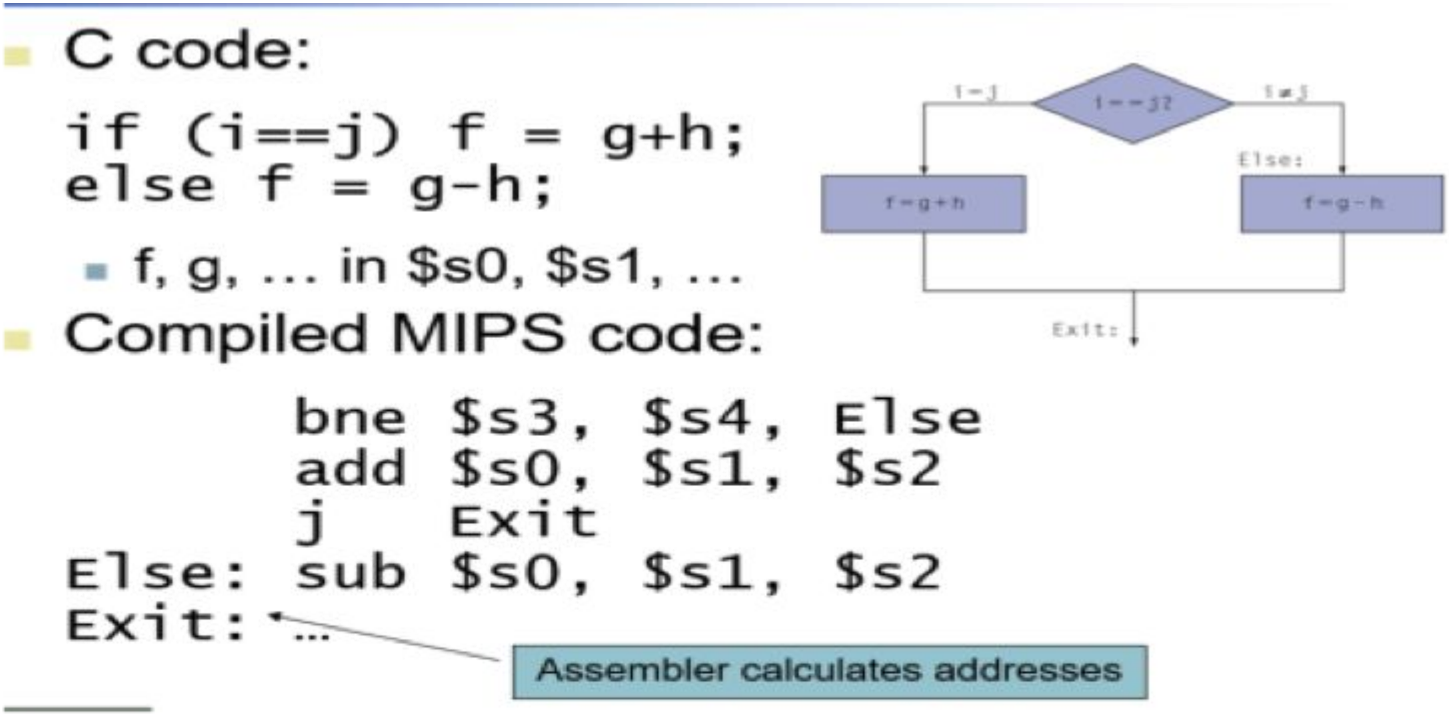
Jump

The jump instruction is unconditional.

```
j label		# start executing the code at label
```

This will cause the current value of the PC to be replaced by the address “label”

Implementing an if statement



- C code:

```
if (i==j) f = g+h;
else f = g-h;
```

  - f, g, … in $s0, $s1, …
- Compiled MIPS code:

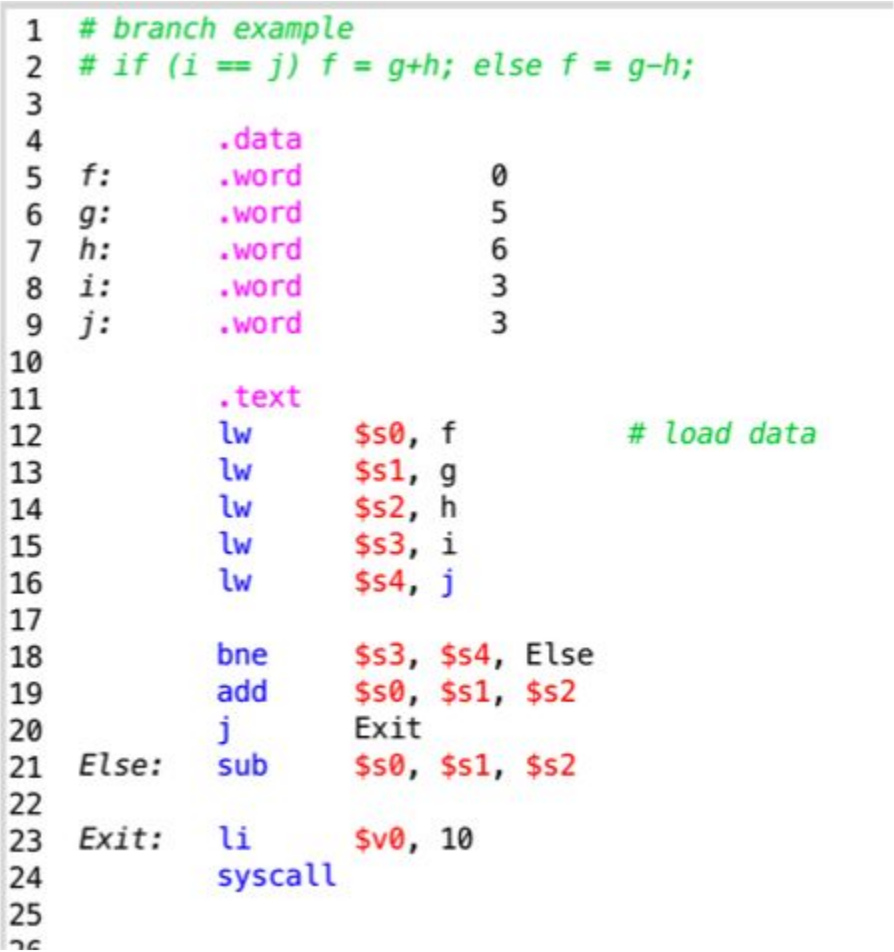
```
      bne $s3, $s4, Else
      add $s0, $s1, $s2
      j   Exit
Else: sub $s0, $s1, $s2
Exit: …
```

Assembler calculates addresses

IF-ELSE example

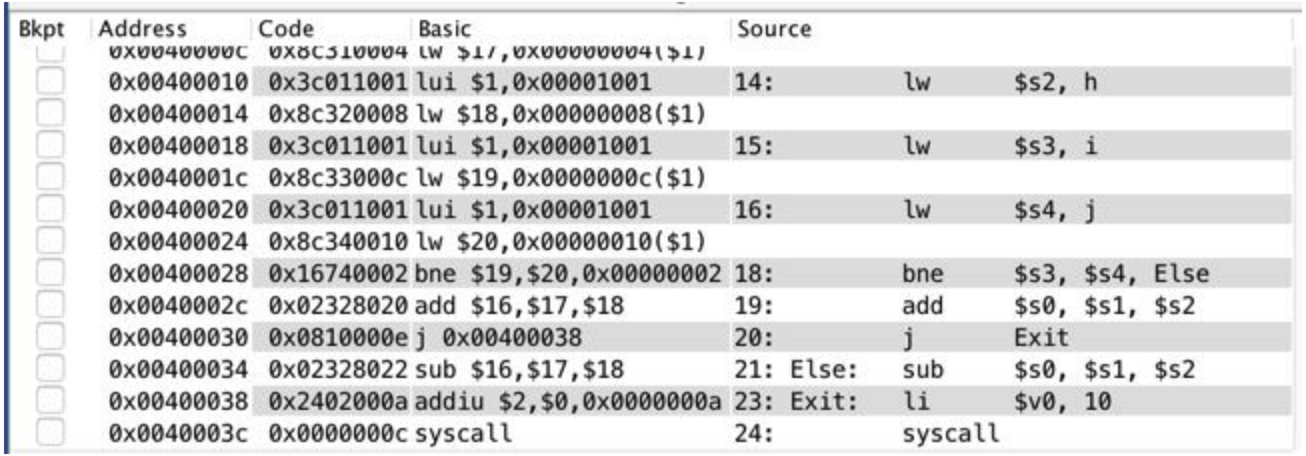
We jump over the add if the condition is false.

We have to jump over the sub if the condition is true.



```
# branch example
# if (i == j) f = g+h; else f = g-h;

        .data
f:      .word       0
g:      .word       5
h:      .word       6
i:      .word       3
j:      .word       3

        .text
        lw      $s0, f          # load data
        lw      $s1, g
        lw      $s2, h
        lw      $s3, i
        lw      $s4, j

        bne     $s3, $s4, Else
        add     $s0, $s1, $s2
        j       Exit
Else:   sub     $s0, $s1, $s2

Exit:   li      $v0, 10
        syscall
```

assembled

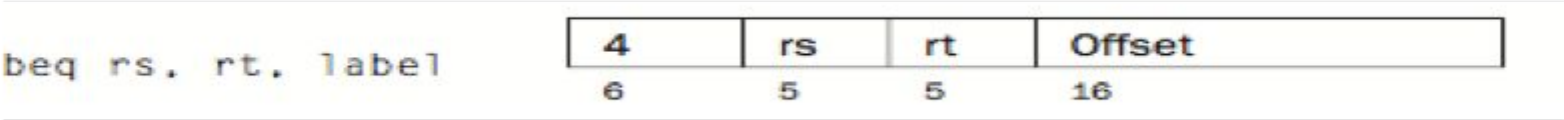


Bkpt	Address	Code	Basic	Source
☐	0x0040000c	0x8c310004	lw $17,0x00000004($1)	
☐	0x00400010	0x3c011001	lui $1,0x00001001	14: lw $s2, h
☐	0x00400014	0x8c320008	lw $18,0x00000008($1)	
☐	0x00400018	0x3c011001	lui $1,0x00001001	15: lw $s3, i
☐	0x0040001c	0x8c33000c	lw $19,0x0000000c($1)	
☐	0x00400020	0x3c011001	lui $1,0x00001001	16: lw $s4, j
☐	0x00400024	0x8c340010	lw $20,0x00000010($1)	
☐	0x00400028	0x16740002	bne $19,$20,0x00000002	18: bne $s3, $s4, Else
☐	0x0040002c	0x02328020	add $16,$17,$18	19: add $s0, $s1, $s2
☐	0x00400030	0x0810000e	j 0x00400038	20: j Exit
☐	0x00400034	0x02328022	sub $16,$17,$18	21: Else: sub $s0, $s1, $s2
☐	0x00400038	0x2402000a	addiu $2,$0,0x0000000a	23: Exit: li $v0, 10
☐	0x0040003c	0x0000000c	syscall	24: syscall

Branch statements use the I format

beq rs, rt, label

bne rs, rt, label



`beq rs, rt, label`

4	rs	rt	Offset
6	5	5	16

The offset is relative to the current PC value.

Branch v. Jump

`j label`

The jump instruction is absolute, the PC is updated to point to label. We can jump anywhere in the code segment.

`beq $t1, $t2, label`

The branch instruction is relative to the current value of the PC. The 16-bit offset is added to the PC. If the offset is positive, it's a forward jump; if the offset is negative, it's a backward jump

branch addressing

Most branch targets are close, so a 16-bit offset is sufficient.

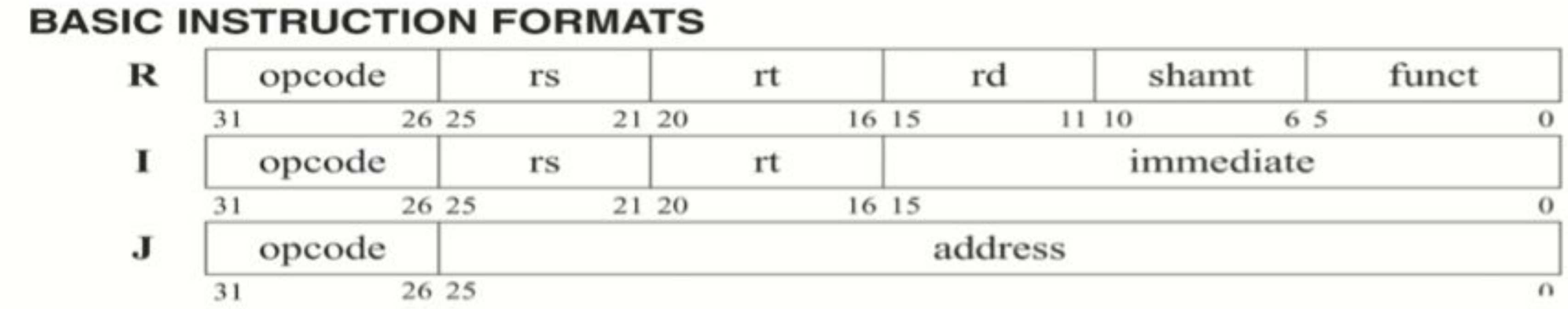
At a branch instruction, the PC is already pointing to the next instruction (PC+4)

target address = PC + offset*4

the offset is in words (4 bytes)

If the branch target is too far away, the assembler will rewrite it with jump.

MIPS has 3 instruction formats



BASIC INSTRUCTION FORMATS

R	opcode	rs	rt	rd	shamt	funct
	31 26	25 21	20 16	15 11	10 6	5 0
I	opcode	rs	rt	immediate		
	31 26	25 21	20 16	15 0		
J	opcode	address				
	31 26	25 0				

Jump Decoding

The J instruction format has 6 bits for the opcode, leaving 26 bits for the label.

ut addresses are 32 bits, so how does that work? At run time:

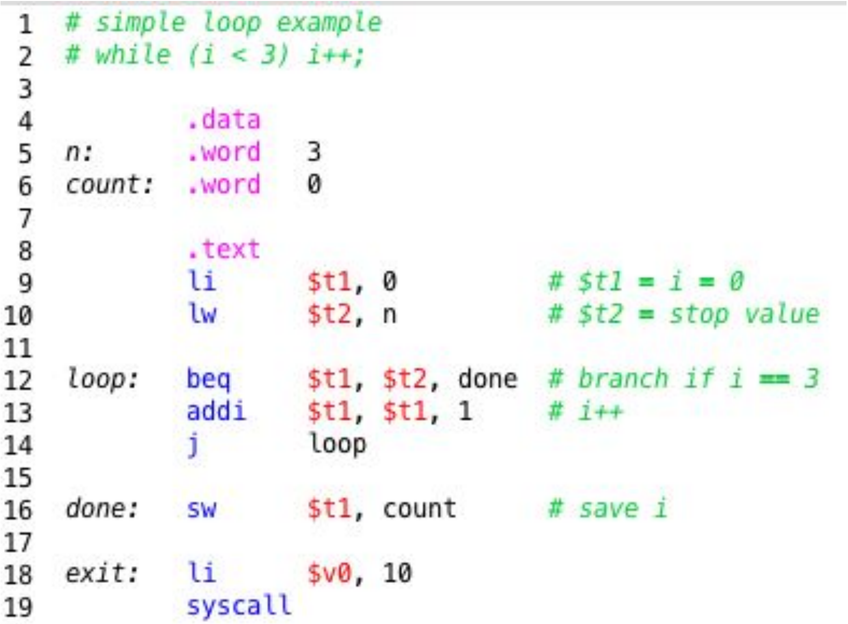
- First the 26 bit address is shifted left twice to become 28 bits
- Then the upper 4 bits of the PC are appended to the MSB of the address

Ex: 0x0810000c -> 000010 (opcode 2 hex) and: 0000000000000000001100

Shift left twice: 000000000000000000110000

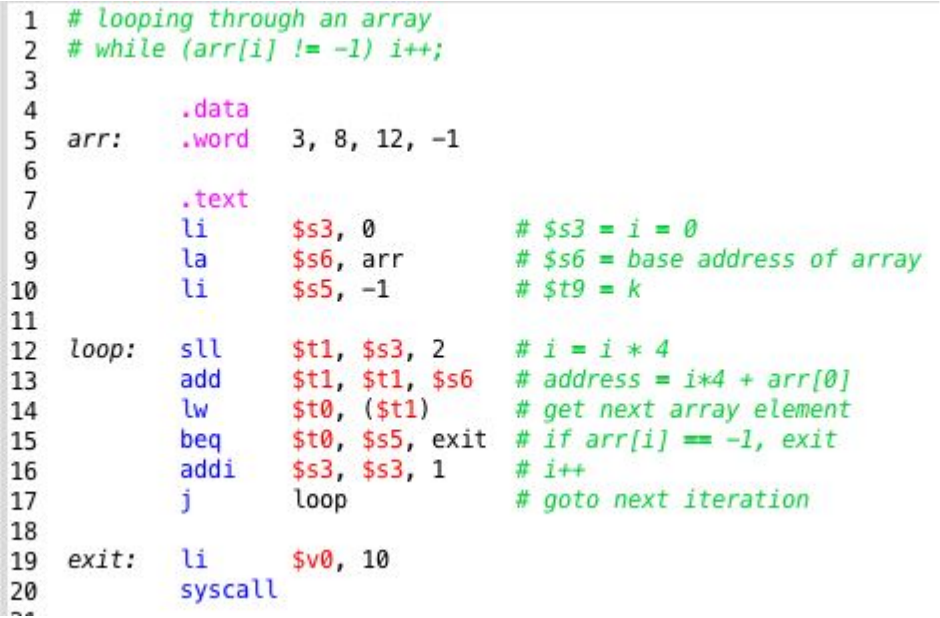
Append 4 MSB of PC: 0000000000000000000000110000B

Loops: counter loop



```
# simple loop example
# while (i < 3) i++;

        .data
n:      .word   3
count:  .word   0

        .text
        li      $t1, 0          # $t1 = i = 0
        lw      $t2, n          # $t2 = stop value

loop:   beq     $t1, $t2, done  # branch if i == 3
        addi    $t1, $t1, 1     # i++
        j       loop

done:   sw      $t1, count      # save i

exit:   li      $v0, 10
        syscall
```

Loops: looping through an array



```
# looping through an array
# while (arr[i] != -1) i++;

        .data
arr:    .word   3, 8, 12, -1

        .text
        li      $s3, 0          # $s3 = i = 0
        la      $s6, arr        # $s6 = base address of array
        li      $s5, -1         # $t9 = k

loop:   sll     $t1, $s3, 2     # i = i * 4
        add     $t1, $t1, $s6   # address = i*4 + arr[0]
        lw      $t0, ($t1)      # get next array element
        beq     $t0, $s5, exit  # if arr[i] == -1, exit
        addi    $s3, $s3, 1     # i++
        j       loop            # goto next iteration

exit:   li      $v0, 10
        syscall
```

Conditional statements

The beq and bne instructions can be used to create relational conditions like >, <=

First a condition is checked with slt (set less than) or slti instruction. Instruction slt or slti will set Rd to 1 if the condition is true, 0 otherwise.

Then a branch is taken, or not, based on if the condition is equal to $zero.

```
# slt example
slt $t0, $s3, $s4  # $t0 = $s3<$s4
beq $t0, $zero, label
# will branch if NOT $s3<$s4

# slti example
slti $t0, $s3, 10  # $t0 = $s3<10
bne $t0, $zero, label
# will branch if $s3<10
```

slt and slti

slt rd, rs, rt   # set rd=1 if rs<rt; otherwise rd=0

slti rd, rs, constant   # set rd=1 if rs<constant; otherwise rd=0

Used immediately before beq or bne.

Can be used to implement any conditional (<, <=, >, >=) by changing the order of the source operands

Why no blt, etc?

Two fast instructions are better than one slower one.

signed v. unsigned

signed comparison: slt and slti

unsigned comparison: sltu and sltiu

array bounds check

An unsigned comparison checks if x < y and also if x is negative

Case 1: $s1>$s2 indicates we have gone beyond the end of the array

Case 2: $s1 is negative

$s1 will be ">" $t2 with an unsigned check because it will have 1 in MSB

```
# jump to IndexOutOfBounds
#   if $s1>$t2 or $s1 is negative
sltu $t0, $s1, $t2
beq  $t0, $zero, IndexOutOfBounds
```

Pseudo-instructions for branches

These get converted into slt-beq or slt-bne instructions.

blt - branch less than

ble - branch less than or equal to

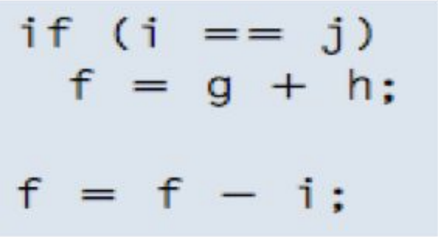
bgt - branch greater than

bge - branch greater than or equal to

```
blt $t1, $t2, exit
# will be assembled into:
slt $1, $9, $10
bne $1, $0, exit
```

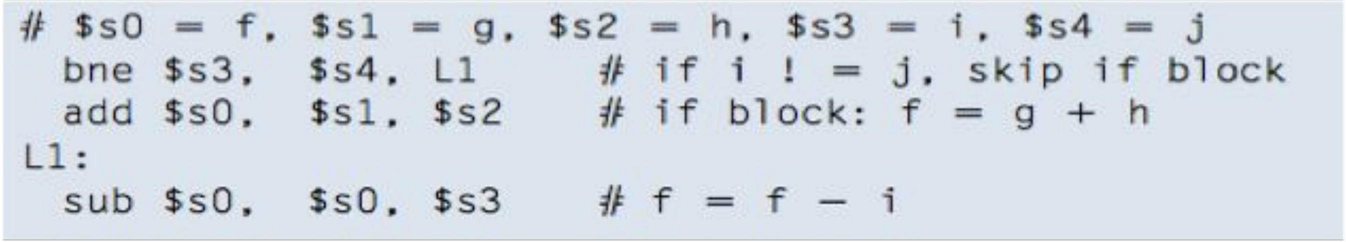
```
ble $t1, $t2, exit
# will be assembled int:
slt $1, $10, $9
beq $1, $0, exit
```

if example



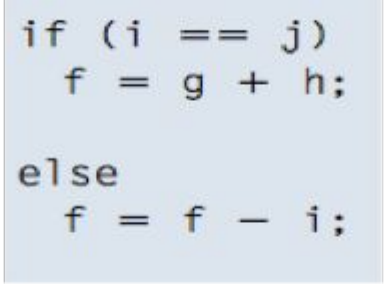
```
if (i == j)
  f = g + h;

f = f − i;
```

MIPS:



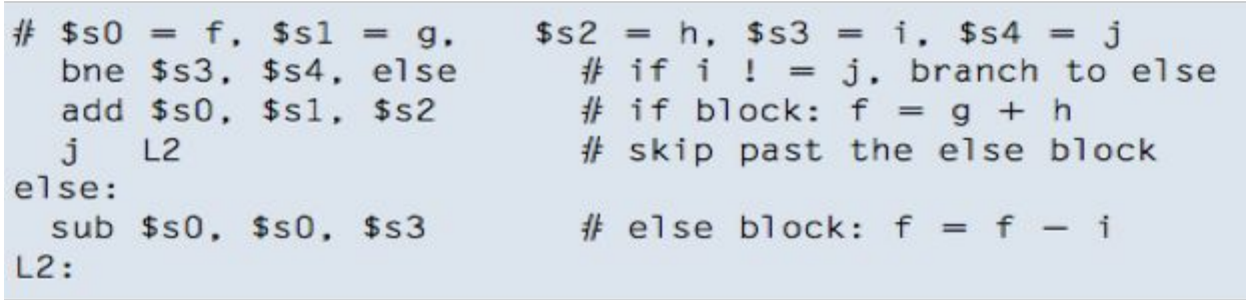
```
# $s0 = f, $s1 = g, $s2 = h, $s3 = i, $s4 = j
  bne $s3, $s4, L1      # if i ! = j, skip if block
  add $s0, $s1, $s2     # if block: f = g + h
L1:
  sub $s0, $s0, $s3     # f = f − i
```

if-else example



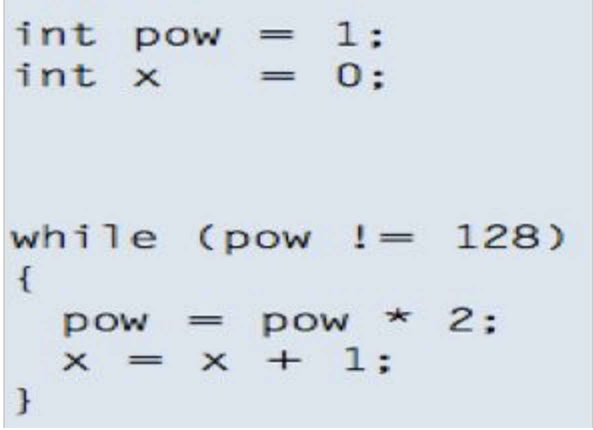
```
if (i == j)
  f = g + h;

else
  f = f − i;
```

MIPS code:

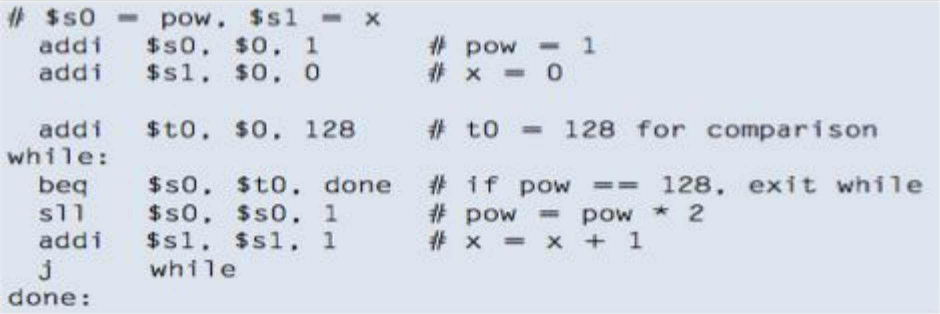


```
# $s0 = f, $s1 = g,   $s2 = h, $s3 = i, $s4 = j
  bne $s3, $s4, else      # if i ! = j, branch to else
  add $s0, $s1, $s2       # if block: f = g + h
  j   L2                  # skip past the else block
else:
 sub $s0, $s0, $s3        # else block: f = f − i
L2:
```

while loop



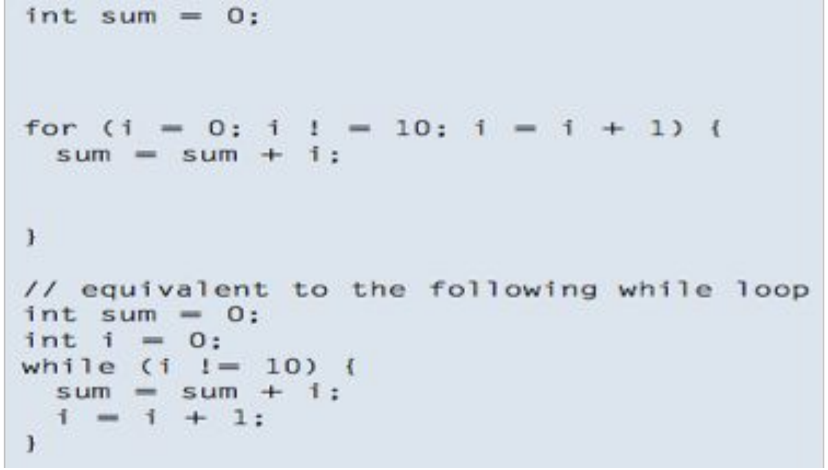
```c
int pow = 1;
int x   = 0;



while (pow != 128)
{
  pow = pow * 2;
  x = x + 1;
}
```



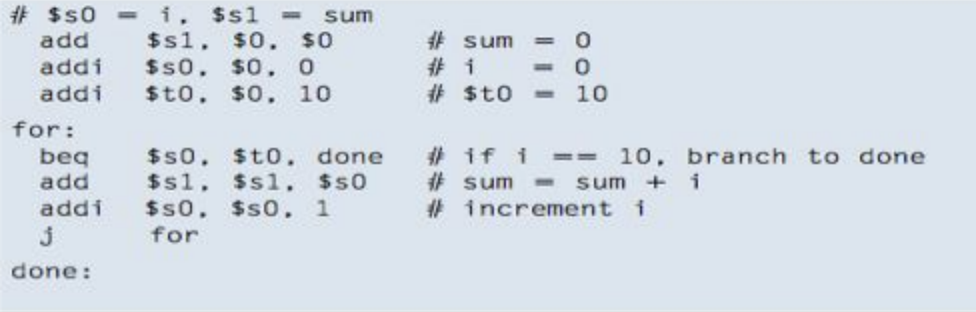
```
# $s0 = pow, $s1 = x
  addi  $s0, $0, 1      # pow = 1
  addi  $s1, $0, 0      # x = 0

  addi  $t0, $0, 128    # t0 = 128 for comparison
while:
  beq   $s0, $t0, done  # if pow == 128, exit while
  sll   $s0, $s0, 1     # pow = pow * 2
  addi  $s1, $s1, 1     # x = x + 1
  j     while
done:
```

for loop

MIPS code:



```
int sum = 0;


for (i = 0; i ! = 10; i = i + 1) {
  sum = sum + i;


}

// equivalent to the following while loop
int sum = 0;
int i = 0;
while (i != 10) {
  sum = sum + i;
  i = i + 1;
}
```



```
# $s0 = i, $s1 = sum
  add    $s1, $0, $0      # sum = 0
  addi   $s0, $0, 0       # i   = 0
  addi   $t0, $0, 10      # $t0 = 10
for:
  beq    $s0, $t0, done   # if i == 10, branch to done
  add    $s1, $s1, $s0    # sum = sum + i
  addi   $s0, $s0, 1      # increment i
  j      for
done:
```

functions aka procedures aka subroutines

Steps to calling a function:

In calling code:

1. place arguments in registers
2. transfer control to procedure
3. process any return values

In the called procedure:

1. acquire storage (stack) for procedure if needed
2. perform procedure's operations
3. place results in register for caller
4. return to place of call

MIPS registers for functions

$a0 - $a3 - arguments for the function

$v0, $v1 - return values from the function

$t0 - $t9 - temporaries (may be overwritten by the function)

$s0 - $s7 - saved (function must save/restore them on the stack)

$sp - stack pointer, points to the top of the stack

Not important in MARS: $fp frame pointer, $gp global pointer

How to call functions in MIPS

Call a function:

jal ProcedureLabel

jal "jump and link:

- first saves $pc to $ra so we can get back
- then jumps to ProcedureLabel

As we execute jal, $pc will already be pointing to the instruction immediately after jal; we need to save this return address in $ra

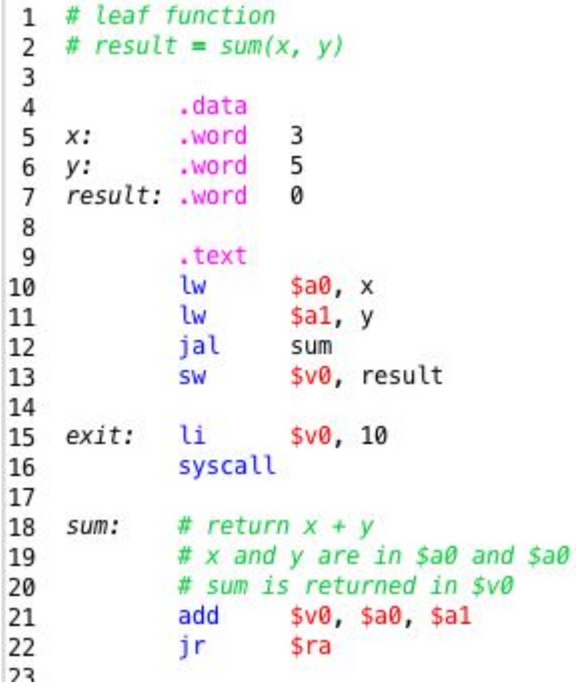
Return from a function:

jr $ra

jr "jump register" will jump to the value in $ra

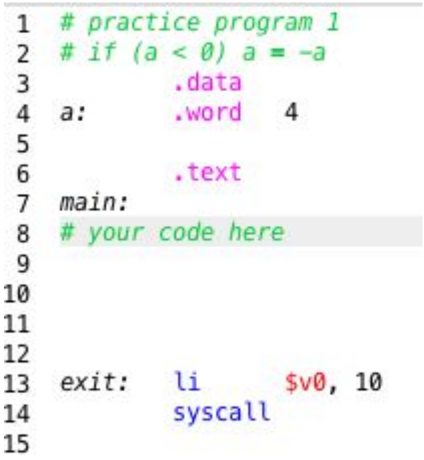
it copies the $ra to the $pc so that the next instruction to be executed is after the jal

leaf function



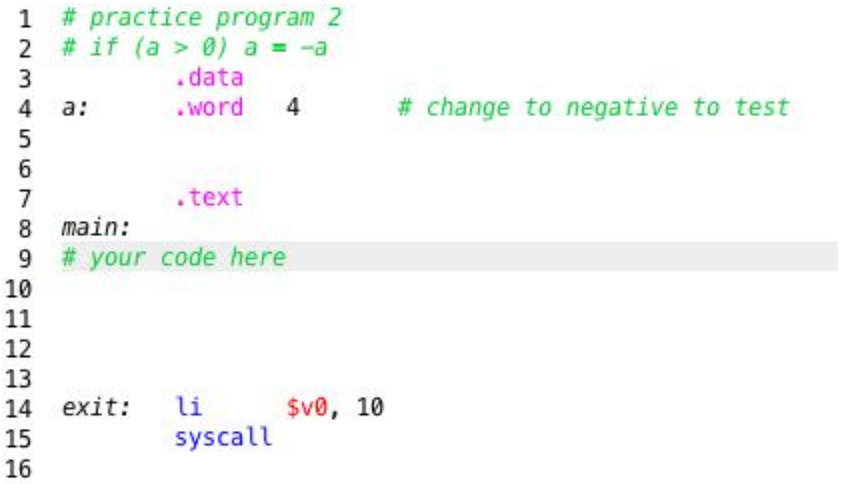
```
# leaf function
# result = sum(x, y)

        .data
x:      .word   3
y:      .word   5
result: .word   0

        .text
        lw      $a0, x
        lw      $a1, y
        jal     sum
        sw      $v0, result

exit:   li      $v0, 10
        syscall

sum:    # return x + y
        # x and y are in $a0 and $a0
        # sum is returned in $v0
        add     $v0, $a0, $a1
        jr      $ra
```

Problem 1



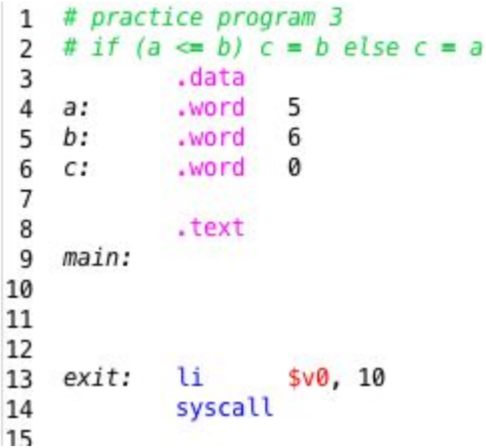
```
# practice program 1
# if (a < 0) a = -a
        .data
a:      .word   4

        .text
main:
# your code here




exit:   li      $v0, 10
        syscall

```

Problem 2



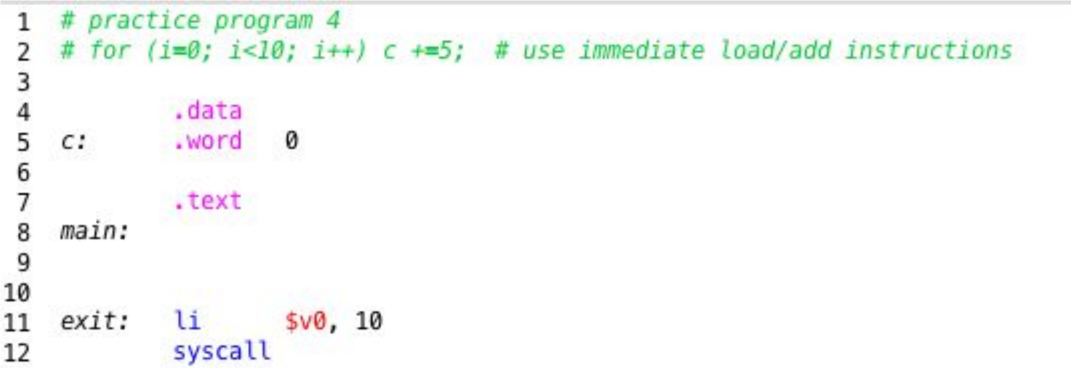
```
# practice program 2
# if (a > 0) a = -a
        .data
a:      .word   4       # change to negative to test


        .text
main:
# your code here




exit:   li      $v0, 10
        syscall

```

Problem 3



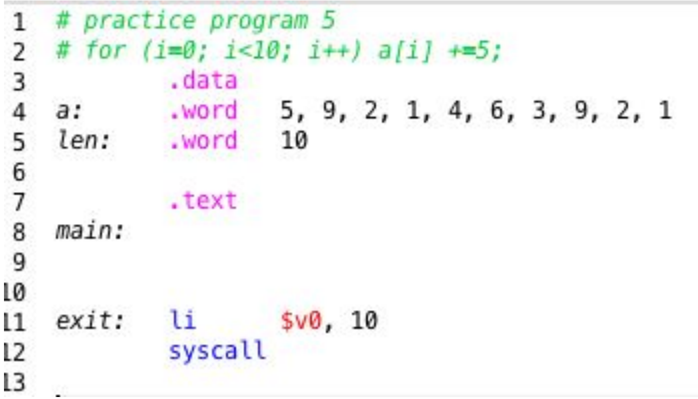
```
# practice program 3
# if (a <= b) c = b else c = a
        .data
a:      .word   5
b:      .word   6
c:      .word   0

        .text
main:



exit:   li      $v0, 10
        syscall

```

Problem 4



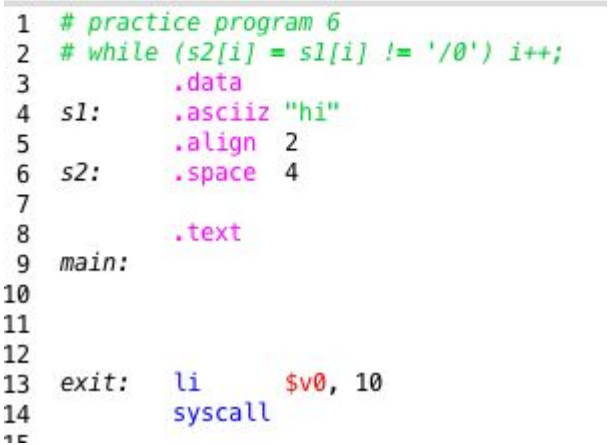
```
# practice program 4
# for (i=0; i<10; i++) c +=5;  # use immediate load/add instructions

        .data
c:      .word   0

        .text
main:


exit:   li      $v0, 10
        syscall
```

Problem 5



```
# practice program 5
# for (i=0; i<10; i++) a[i] +=5;
        .data
a:      .word   5, 9, 2, 1, 4, 6, 3, 9, 2, 1
len:    .word   10

        .text
main:


exit:   li      $v0, 10
        syscall

```

Problem 6



```
# practice program 6
# while (s2[i] = s1[i] != '/0') i++;
        .data
s1:     .asciiz "hi"
        .align  2
s2:     .space  4

        .text
main:



exit:   li      $v0, 10
        syscall
```

Problem 7

move the loop in Problem 7 to a subroutine that you call from the main program