CPS 104
Computer Organization and Programming

Lecture-5 : The MIPS-2000 Instruction Set Architecture

Sep. 10, 1999

Dietolf (Dee) Ramm

http://www.cs.duke.edu/~dr/cps104.html

 © GK&DR Fall 1999

Today's Lecture

Admin

- HW #1 due
- Outline
  - Review
  - MIPS-2000 ISA, we'll use it throughout semester
  - Instruction categories
  - Specific Instructions

Reading

Chapter 3, Appendix A

 © GK&DR Fall 1999

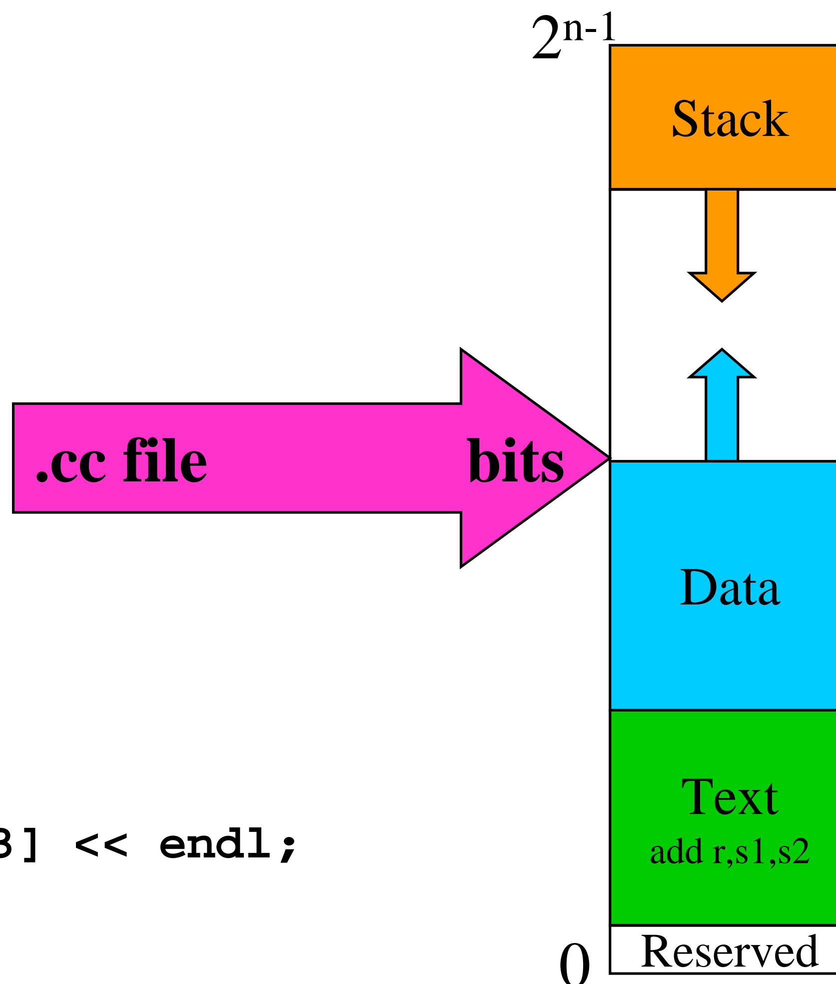
A Program

```
#include <iostream.h>

main()
{
  int *a = new int[100];
  int *p = a;
  int k;

  for (k = 0; k < 100; k++)
    {
      *p = k;
      p++;
    }

  cout << "entry 3 = " << a[3] << endl;
}
```



© GK&DR Fall 1999

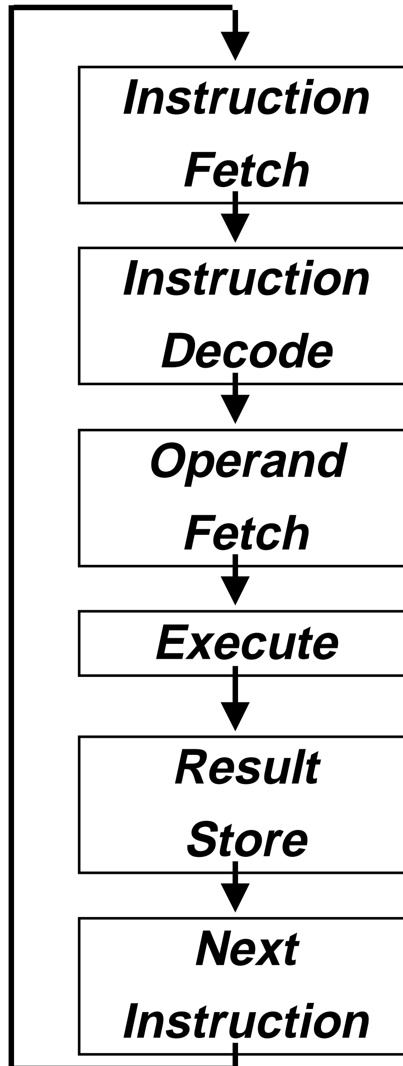
Stored Program Computer

- Instructions: a fixed set of built-in operations
- Instructions and data are stored in the (same) computer memory
- Fetch Execute Cycle

```
while (true){
     fetch instruction
     execute instruction
}
```


© GK&DR Fall 1999

What Must be Specified?



- Instruction Format
  - how do we tell what operation to perform?
- Location of operands and result
  - where other than memory?
  - how many explicit operands?
  - how are memory operands located?
  - which can or cannot be in memory?
- Data type and Size
- Operations
  - what are supported
- Successor instruction
  - jumps, conditions, branches
- *fetch-decode-execute is implicit!*

 © GK&DR Fall 1999

MIPS ISA Categories

- Arithmetic
  - add, sub, mul, etc
- Logical
  - and, or, shift
- Data Transfer
  - load, store
  - MIPS is LOAD/STORE architecture
- Conditional Branch
  - implement if, for, while… statements
- Unconditional Jump
  - support function call (procedure calls)

© GK&DR Fall 1999

MIPS Instruction Set Architecture

- 3-Address Load Store Architecture.
- Register and Immediate addressing modes for operations.
- Immediate and Displacement addressing for Loads and Stores.
- Examples:

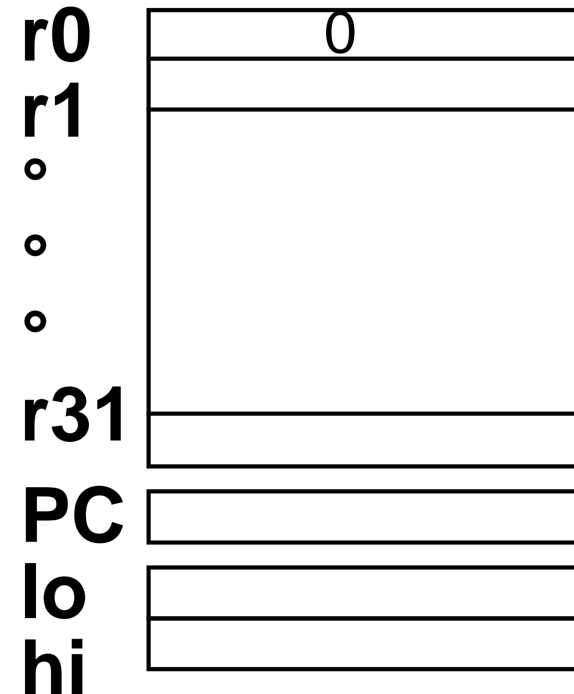
```
add     $1, $2, $3       #     $1 = $2 + $3
addi    $1, $1, 4        #     $1 = $1 + 4

lw      $1, 100 ($2)     #     $1 = Memory[$2 + 100]
sw      $1, 100 ($2)     #     Memory[$2 + 100] = $1

lui     $1, 100          #     $1 = 100 << 16
addi    $1, $3, 100      #     $1 =  $3 + 100
```

MIPS Integer Registers

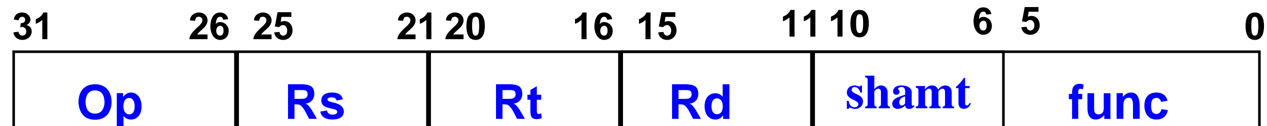
- Registers: fast memory, Integral part of the CPU.
- Programmable storage
  2^{32} bytes
- 31 x 32-bit GPRs (R0 = 0)
- 32 x 32-bit FP regs (paired DP)
- 32-bit HI, LO, PC



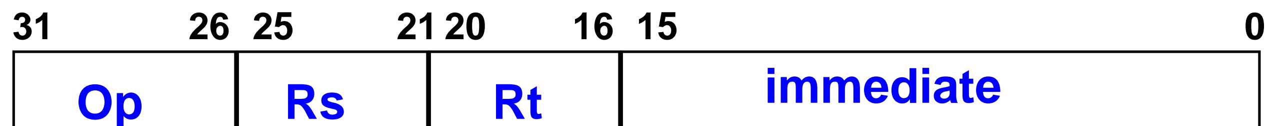
 © GK&DR Fall 1999

MIPS Instruction Formats

R-type: Register-Register



I-type: Register-Immediate



J-type: Jump / Call

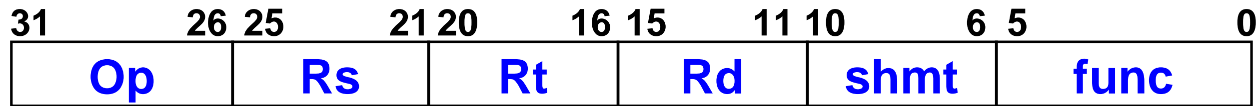
Terminology

Op = opcode

Rs, Rt, Rd = register specifier

© GK&DR Fall 1999

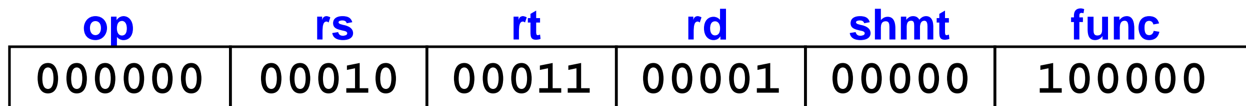
R Type: <OP> rd, rs, rt



op	a 6-bit operation code.
rs	a 5-bit source register.
rt	a 5-bit target (source) register.
rd	a 5-bit destination register.
shmt	a 5-bit shift amount.
func	a 6-bit function field.

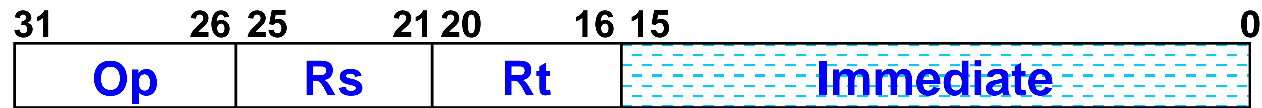
Operand Addressing: Register direct

Example: ADD $1, $2, $3 # $1 = $2 + $3



© GK&DR Fall 1999

I-Type <op> rt, rs, immediate



Immediate: 16 bit value

Operand Addressing:

Register Direct and Immediate

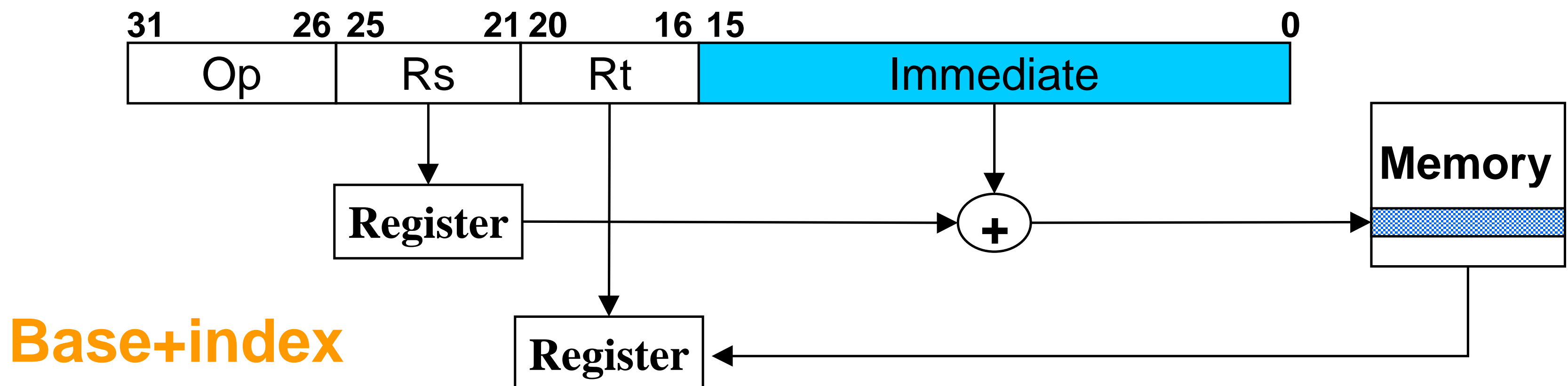
Add Immediate Example

addi $1, $2, -100 # $1 = $2 + (-100)

op	rs	rt	immediate
001000	00010	00001	1111 1111 1001 1100

© GK&DR Fall 1999

I-Type <op> rt, rs, immediate



Base+index

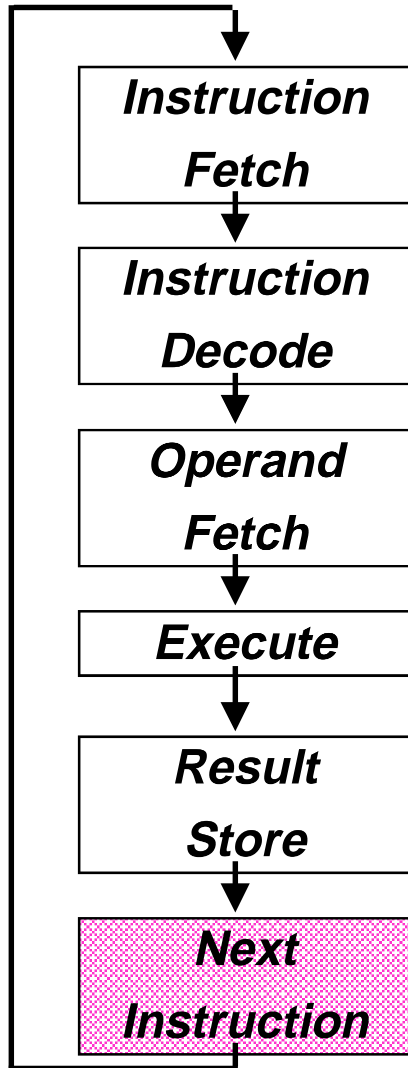
Load Word Example

lw $1, 100($2) # $1 = Mem[$2+100]

op	rs	rt	immediate
010011	00010	00001	0000 0000 0110 0100

© GK&DR Fall 1999

Successor Instruction




```
main()
{
   int x,y,same;          // $0 == 0 always
   x = 43;                // addi $1, $0, 43
   y = 2;                 // addi $2, $0, 2
   same = 0;              // addi $3, $0, 0
   if (x == y)
        same = 1;      // execute only if x == y
                       // addi $3, $0, 1
}
```

 © GK&DR Fall 1999

The Program Counter

- Special register (pc) that points to instructions
- Contains memory address (like a pointer)
- Instruction fetch is
  - inst = mem[pc]
- To fetch next sequential instruction pc = pc + ?
  - Size of instruction?

 © GK&DR Fall 1999

The Program Counter

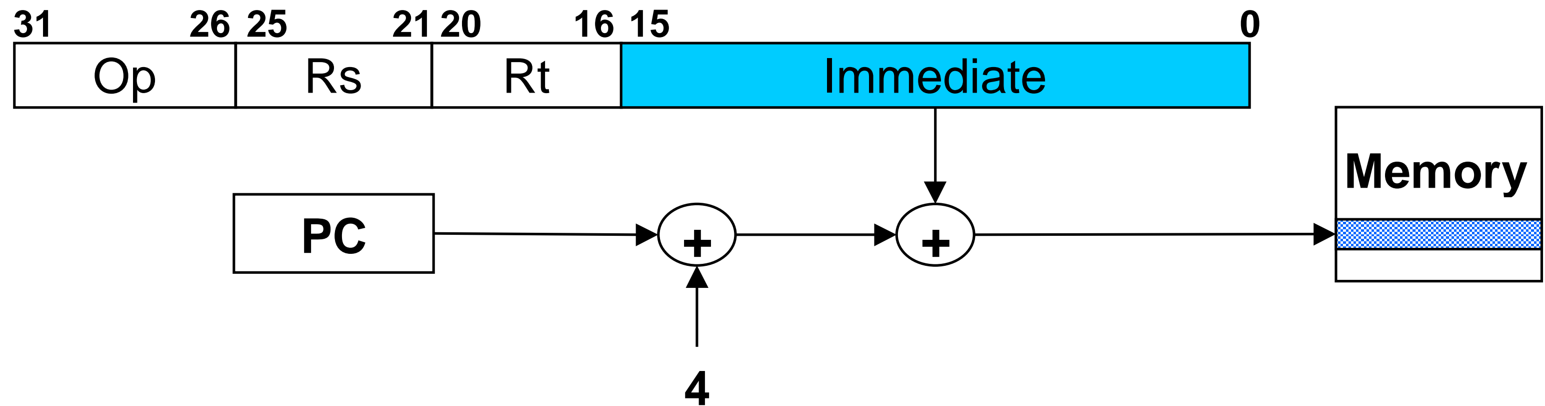
```
x = 43;         // addi $1, $0, 43
y = 2;          // addi $2, $0, 2
same = 0;       // addi $3, $0, 0
if (x == y)
   same = 1;   // addi $3, $0, 1 execute if x == y
```

PC
0x10000
0x10004
0x10008
0x1000c

Address	Instruction
0x10000	addi $1, $0, 43
0x10004	addi $2, $0, 2
0x10008	addi $3, $0, 0
0x1000c	addi $3, $0, 1

Clearly, this is not correct
We cannot always execute both 0x10008 and 0x1000c

I-Type <op> rt, rs, immediate



- **PC relative addressing**

<u>Branch Not Equal Example</u>

bne $1, $2, 100 **# If ($1!= $2) goto [PC+4+100]**

- **+4 because by default we increment for sequential**
  - more detailed discussion later in semester

op	rs	rt	immediate
000101	00001	00010	0000 0000 0110 0100

© GK&DR Fall 1999

The Program Counter

```
x = 43;         // addi $1, $0, 43
y = 2;          // addi $2, $0, 2
if (x == y)
   same = 1;    // addi $3, $0, $1 execute if x == y
```

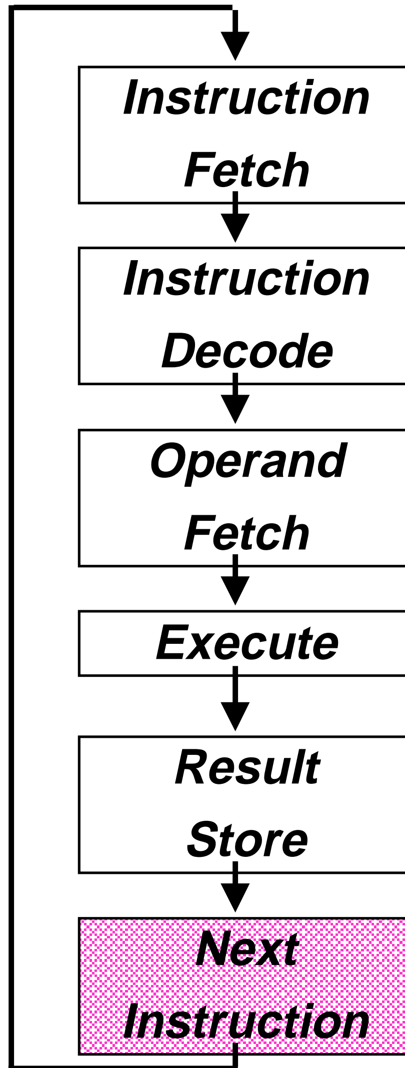
PC
0x10000
0x10004
0x10008
0x1000c
0x10010

Address	Instruction
0x10000	addi $1, $0, 43
0x10004	addi $2, $0, 2
0x10008	addi $3, $0, 0
0x1000c	bne $1, $2, 4
0x10010	addi $3, $0, 1

Understand branches

 © GK&DR Fall 1999

Successor Instruction




```
int equal(int a1, int a2) {
   int tsame;
   tsame = 0;
   if (a1 == a2)
         tsame = 1;    // only if a1 == a2
   return(tsame);
}
main()
{
   int x,y,same;          // r0 == 0 always
   x = 43;                // addi $1, $0, 43
   y = 2;                 // addi $2, $0, 2
   same = equal(x,y); // need to call function
   // other computation
}
```


© GK&DR Fall 1999

The Program Counter

- **Branches are limited to 16 bit immediate**
- **Big programs?**

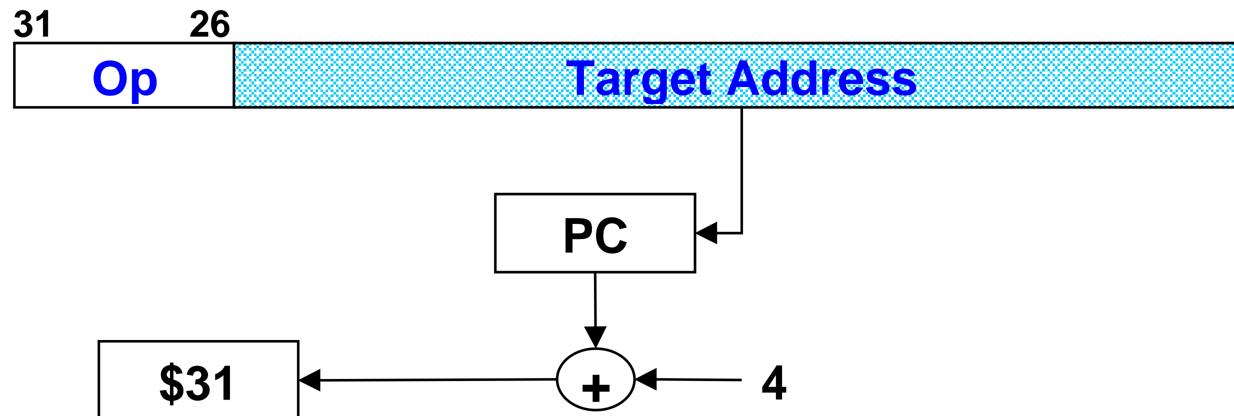
```
x = 43; // addi $1, $0, 43
y = 2;  // addi $2, $0, 2
same = equal(x,y);
```

Address	Instruction
0x10000	addi $1, $0, 43
0x10004	addi $2, $0, 2
0x10008	"go execute equal"

Address	Instruction
0x30408	addi $3, $0, 0
0x3040c	beq $1, $2, 8
0x30410	addi $3, $0, 1
	"return $3"

© GK&DR Fall 1999

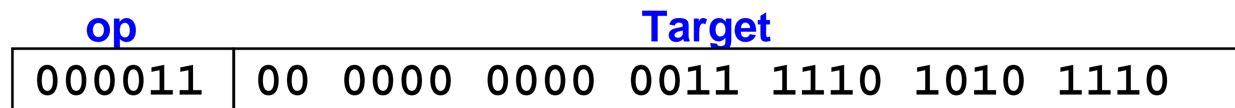
J-Type: <op> target



Jump and Link Example

jal 0x0fab8 # PC<- 0x0fab8, $31<-PC+4

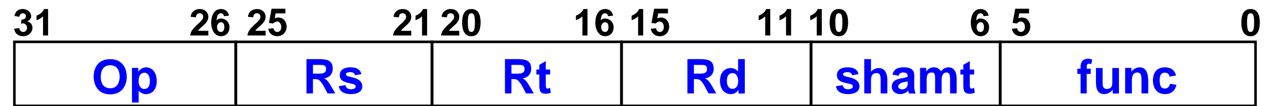
$31 set as side effect, used for returning, implicit operand



Please note, The two least-significant bits are not used!

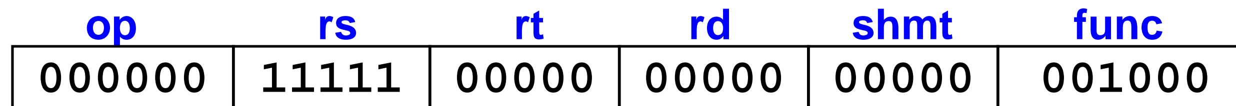
© GK&DR Fall 1999

R Type: <OP> rd, rs, rt



Jump Register Example

jr $31 # PC <- $31



© GK&DR Fall 1999

Instructions for Procedure Call and Return

```
int equal(int a1, int a2) {
   int tsame;
   tsame = 0;
   if (a1 == a2)
        tsame = 1;
   return(tsame);
}
main()
{
   int x,y,same;
   x = 43;
   y = 2;
   same = equal(x,y);
   // other computation
}
```

Address	Instruction
0x10000	addi $1, $0, 43
0x10004	addi $2, $0, 2
0x10008	jal 0x30408
0x1000c	??

Address	Instruction
0x30408	addi $3, $0, 0
0x3040c	bne $1, $2, 4
0x30410	addi $3, $0, 1
0x30414	jr $31

PC	$31
0x10000	??
0x10004	??
0x10008	??
0x30408	0x1000c
0x3040c	0x1000c
0x30410	0x1000c
0x30414	0x1000c
0x1000c	0x1000c

© GK&DR Fall 1999

MIPS Arithmetic Instructions

Instruction	Example	Meaning	Comments
add	add $1,$2,$3	$1 = $2 + $3	3 operands
subtract	sub $1,$2,$3	$1 = $2 – $3	3 operands
add immediate	addi $1,$2,100	$1 = $2 + 100	+ constant
add unsigned	addu $1,$2,$3	$1 = $2 + $3	3 operands
subtract unsigned	subu $1,$2,$3	$1 = $2 – $3	3 operands
add imm. unsign.	addiu $1,$2,100	$1 = $2 + 100	+ constant
multiply	mult $2,$3	Hi, Lo = $2 x $3	64-bit signed product
multiply unsigned	multu $2,$3	Hi, Lo = $2 x $3	64-bit unsigned product
divide	div $2,$3	Lo = $2 ÷ $3,	Lo = quotient,
		Hi = $2 mod $3	Hi = remainder
divide unsigned	divu $2,$3	Lo = $2 ÷ $3,	Unsigned quotient
		Hi = $2 mod $3	Unsigned remainder
Move from Hi	mfhi $1	$1 = Hi	Used to get copy of Hi
Move from Lo	mflo $1	$1 = Lo	Used to get copy of Lo

Which add for address arithmetic? Which for integers?

 © GK&DR Fall 1999

MIPS Logical Instructions

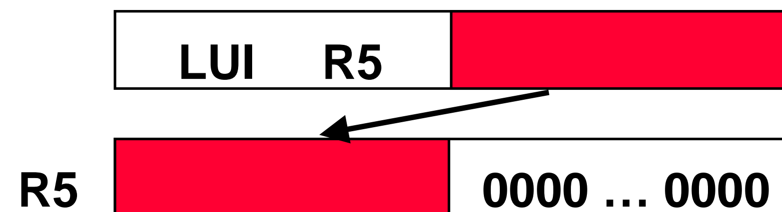
Instruction	Example	Meaning	Comment
and	and $1,$2,$3	$1 = $2 & $3	Bitwise AND
or	or $1,$2,$3	$1 = $2 | $3	Bitwise OR
xor	xor $1,$2,$3	$1 = $2 ⊕ $3	Bitwise XOR
nor	nor $1,$2,$3	$1 = ~($2 | $3)	Bitwise NOR
and immediate	andi $1,$2,10	$1 = $2 & 10	Bitwise AND reg, const
or immediate	ori $1,$2,10	$1 = $2 | 10	Bitwise OR reg, const
xor immediate	xori $1, $2,10	$1 = ~$2 &~10	Bitwise XOR reg, const
shift left logical	sll $1,$2,10	$1 = $2 << 10	Shift left by constant
shift right logical	srl $1,$2,10	$1 = $2 >> 10	Shift right by constant
shift right arithm.	sra $1,$2,10	$1 = $2 >> 10	Shift right (sign extend)
shift left logical	sllv $1,$2,$3	$1 = $2 << $3	Shift left by var
shift right logical	srlv $1,$2, $3	$1 = $2 >> $3	Shift right by var
shift right arithm.	srav $1,$2, $3	$1 = $2 >> $3	Shift right arith. by var

© GK&DR Fall 1999

MIPS Data Transfer Instructions

Instruction	Comment
SW R3, 500(R4)	Store word
SH R3, 502(R2)	Store half
SB R2, 41(R3)	Store byte
LW R1, 30(R2)	Load word
LH R1, 40(R3)	Load half word
LHU R1, 40(R3)	Load half word unsigned
LB R1, 40(R3)	Load byte
LBU R1, 40(R3)	Load byte unsigned
LUI R1, 40	Load Upper Immediate (16 bits shifted left by 16)

Why do we need LUI?



 © GK&DR Fall 1999

MIPS Compare and Branch

Compare and Branch

beq	rs, rt, offset	if R[rs] == R[rt] then PC-relative branch
bne	rs, rt, offset	<>

Compare to zero and Branch

blez	rs, offset	if R[rs] <= 0 then PC-relative branch
bgtz	rs, offset	>
bltz	rs, offset	<
bgez	rs, offset	>=
bltzal	rs, offset	if R[rs] < 0 then branch and link (into R 31)
bgeal	rs, offset	>=

- Remaining set of compare and branch take two instructions
- Almost all comparisons are against zero!

MIPS jump, branch, compare instructions

Instruction	Example	Meaning
branch on equal	beq $1,$2,100	if ($1 == $2) go to PC+4+100
	Equal test; PC relative branch	
branch on not eq.	bne $1,$2,100	if ($1!= $2) go to PC+4+100
	Not equal test; PC relative	
set on less than	slt $1,$2,$3	if ($2 < $3) $1=1; else $1=0
	Compare less than; 2's comp.	
set less than imm.	slti $1,$2,100	if ($2 < 100) $1=1; else $1=0
	Compare < constant; 2's comp.	
set less than uns.	sltu $1,$2,$3	if ($2 < $3) $1=1; else $1=0
	Compare less than; natural numbers	
set l. t. imm. uns.	sltiu $1,$2,100	if ($2 < 100) $1=1; else $1=0
	Compare < constant; natural numbers	
jump	j 10000	go to 10000
	Jump to target address	
jump register	jr $31	go to $31
	For switch, procedure return	
jump and link	jal 10000	$31 = PC + 4; go to 10000
	For procedure call	

© GK&DR Fall 1999

Signed v.s Unsigned Comparison

R1= `0…00 0000 0000 0000 0001`

R2= `0…00 0000 0000 0000 0010`

R3= `1…11 1111 1111 1111 1111`

- **After executing these instructions:**

```
slt  r4,r2,r1
slt  r5,r3,r1
sltu r6,r2,r1
sltu r7,r3,r1
```

- **What are values of registers r4 - r7? Why?**

r4 = ; r5 = ; r6 = ; r7 = ;

Summary

- **MIPS has 5 categories of instructions**
  - Arithmetic, Logical, Data Transfer, Conditional Branch, Unconditional Jump
- **3 Instruction Formats**

Next Time

- **Assembly Programming**

Reading

- **Ch. 3, Appendix A**

- **Only Wednesday discussion**

© GK&DR Fall 1999