EECS 361
Computer Architecture
Lecture 4 – MIPS ISA

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Course slides developed in part by Profs. Hardavellas, Hoe, Falsafi, Martin, Roth, Lipasti, Goldstein, Mowry

Today's Lecture

- Quick Review of Last Lecture
- Basic ISA Decisions and Design
- Operations
- Instruction Sequencing
- Delayed Branch
- Procedure Calling

Quick Review of Last Lecture and Catch-up

Comparing Number of Instructions

Code sequence for (C = A + B) for four classes of instruction sets:

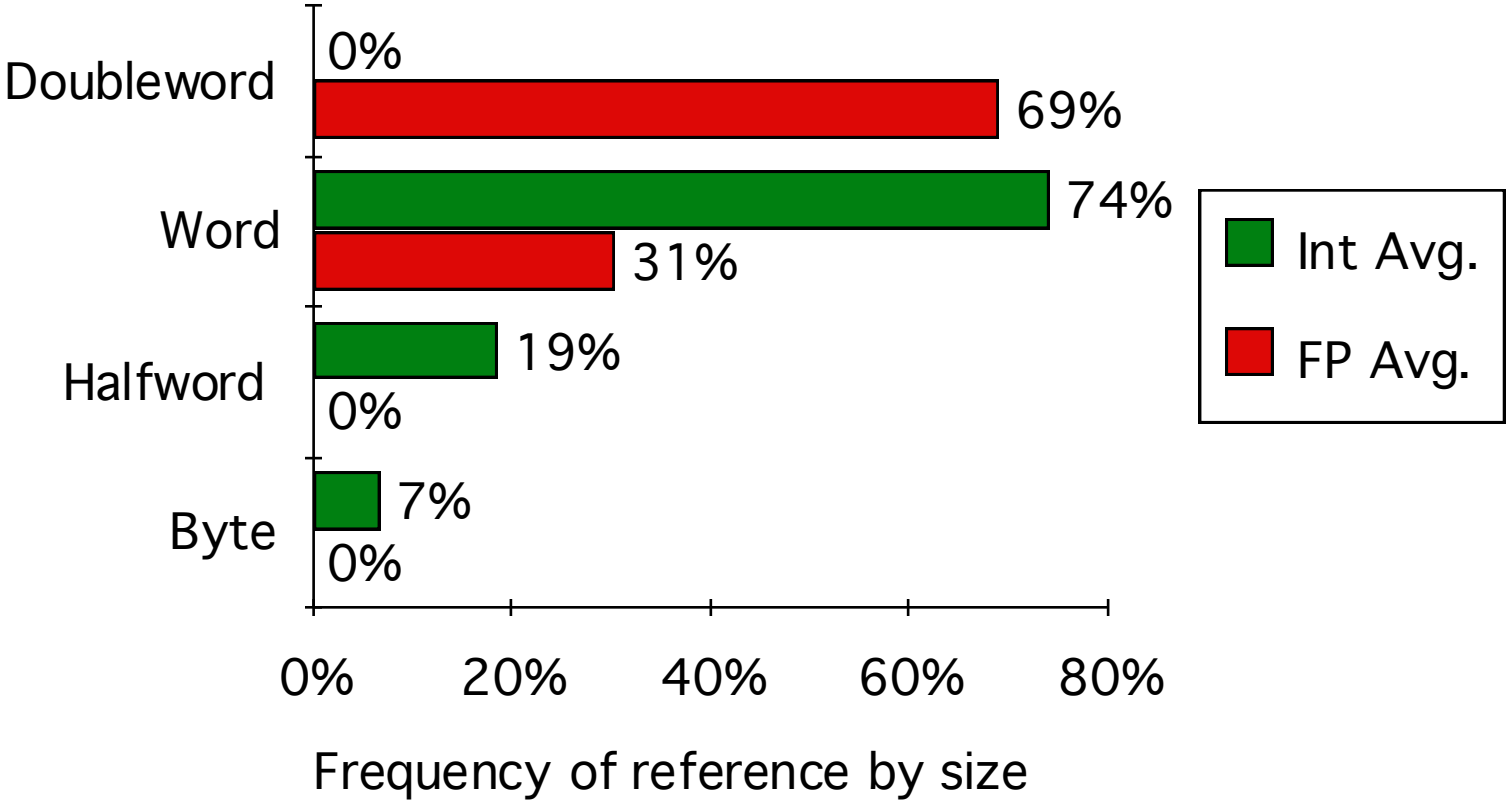
Stack	Accumulator	Register (register-memory)	Register (load-store)
Push A	Load A	Load R1,A	Load R1,A
Push B	Add B	Add R1,B	Load R2,B
Add	Store C	Store C, R1	Add R3,R1,R2
Pop C			Store C,R3

$$ExecutionTime = \frac{1}{Performance} = Instructions \times \frac{Cycles}{Instruction} \times \frac{Seconds}{Cycle}$$

General Purpose Registers Dominate

- 1975-present all machines use general purpose registers
- Advantages of registers
  - Registers are faster than memory
  - Registers compiler technology has evolved to efficiently generate code for register files
    - E.g., (A*B) – (C*D) – (E*F) can do multiplies in any order vs. stack
  - Registers can hold variables
    - Memory traffic is reduced, so program is sped up (since registers are faster than memory)
  - Code density improves (since registers are addressed with fewer bits than memory locations)
  - Registers imply operand locality

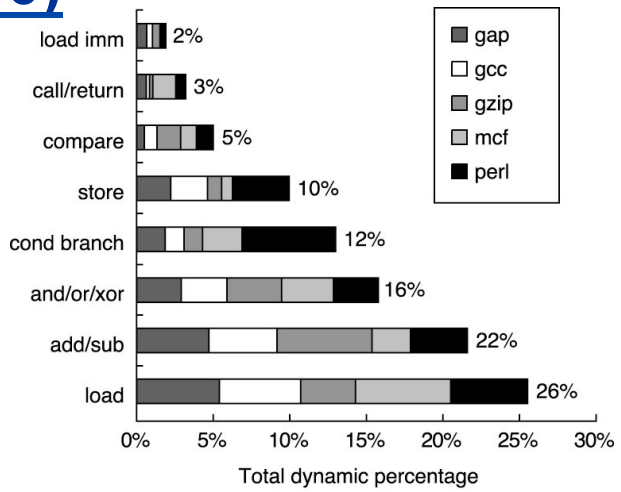
Operand Size Usage

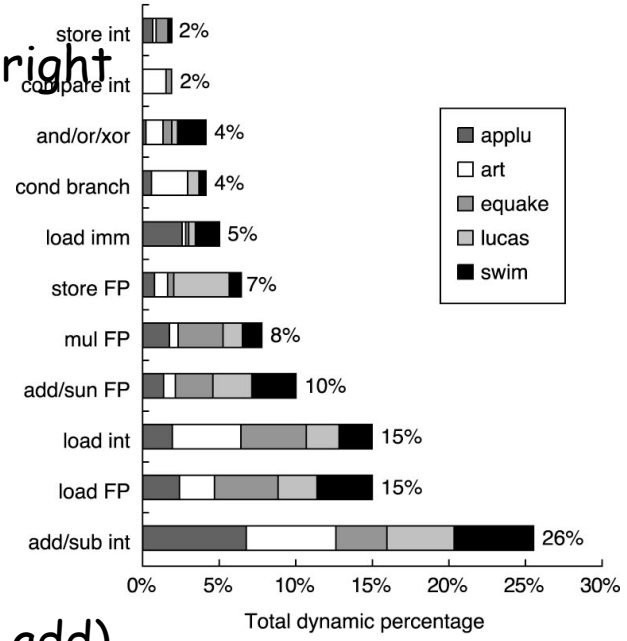


- Support for these data sizes and types:
  8-bit, 16-bit, 32-bit integers and
  32-bit and 64-bit IEEE 754 floating point numbers

Typical Operations (little change since 1960)

Data Movement	Load (from memory) Store (to memory) memory-to-memory move register-to-register move input (from I/O device) output (to I/O device) push, pop (to/from stack)
Arithmetic	integer (binary + decimal) or FP Add, Subtract, Multiply, Divide
Shift	shift left/right, rotate left/right
Logical	not, and, or, set, clear
Control (Jump/Branch)	unconditional, conditional
Subroutine Linkage	call, return
Interrupt	trap, return
Synchronization	test & set (atomic r-m-w)
String	search, translate
Graphics (MMX)	parallel subword ops (4 16bit add)





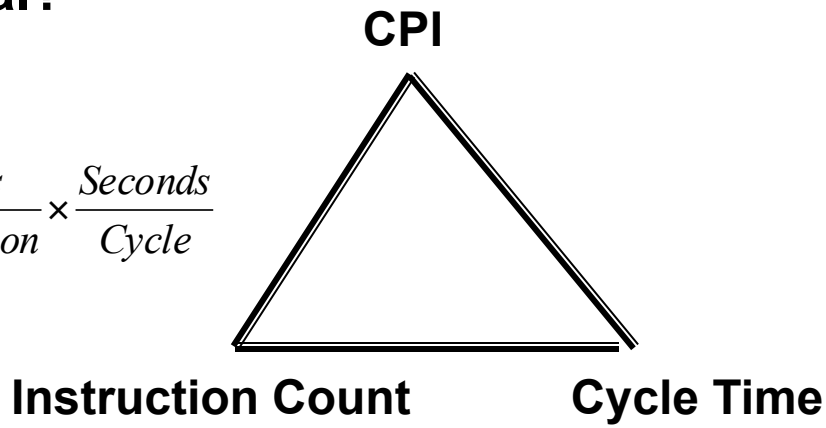
Addressing Modes

- Addressing modes specify a constant, a register, or a location in memory
  - **Register** `add r1, r2` `r1 <- r1+r2`
  - **Immediate** `add r1, #5` `r1 <- r1+5`
  - **Direct** `add r1, (0x200)` `r1 <- r1+M[0x200]`
  - **Register indirect** `add r1, (r2)` `r1 <- r1+M[r2]`
  - **Displacement** `add r1, 100(r2)` `r1 <- r1+M[r2+100]`
  - **Indexed** `add r1, (r2+r3)` `r1 <- r1+M[r2+r3]`
  - **Scaled** `add r1, (r2+r3*4)` `r1 <- r1+M[r2+r3*4]`
  - **Memory indirect** `add r1, @(r2)` `r1 <- r1+M[M[r2]]`
  - **Auto-increment** `add r1, (r2)+` `r1 <- r1+M[r2], r2++`
  - **Auto-decrement** `add r1, -(r2)` `r2--, r1 <- r1+M[r2]`
- Complicated modes reduce instruction count at the cost of complex implementations

Instruction Set Design Metrics

- Static Metrics
  - How many bytes does the program occupy in memory?
- Dynamic Metrics
  - How many instructions are executed?
  - How many bytes does the processor fetch to execute the program?
  - How many clocks are required per instruction?
  - How "lean" a clock is practical?

$$ExecutionTime = \frac{1}{Performance} = Instructions \times \frac{Cycles}{Instruction} \times \frac{Seconds}{Cycle}$$

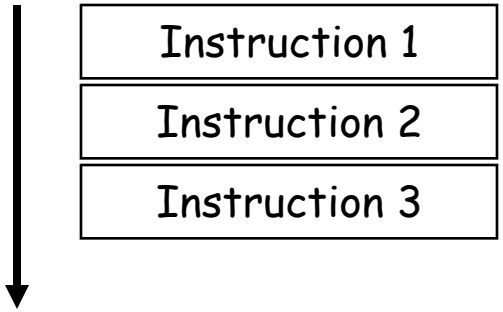


Instruction Sequencing

Instruction Sequencing

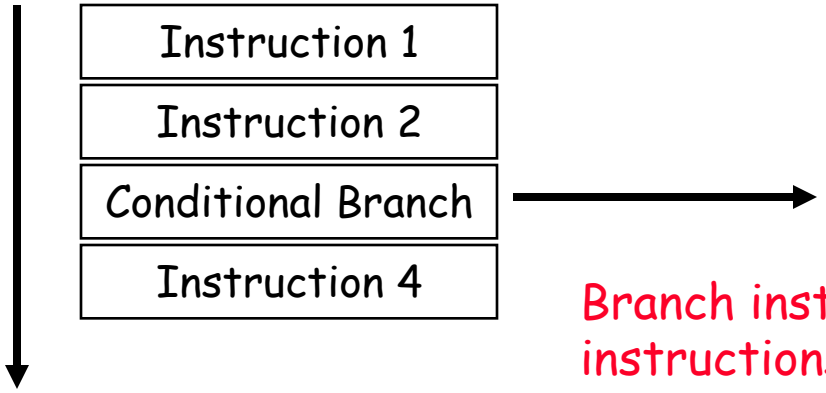
The next instruction to be executed is typically implied

- **Instructions execute sequentially**
- **Instruction sequencing increments a Program Counter**



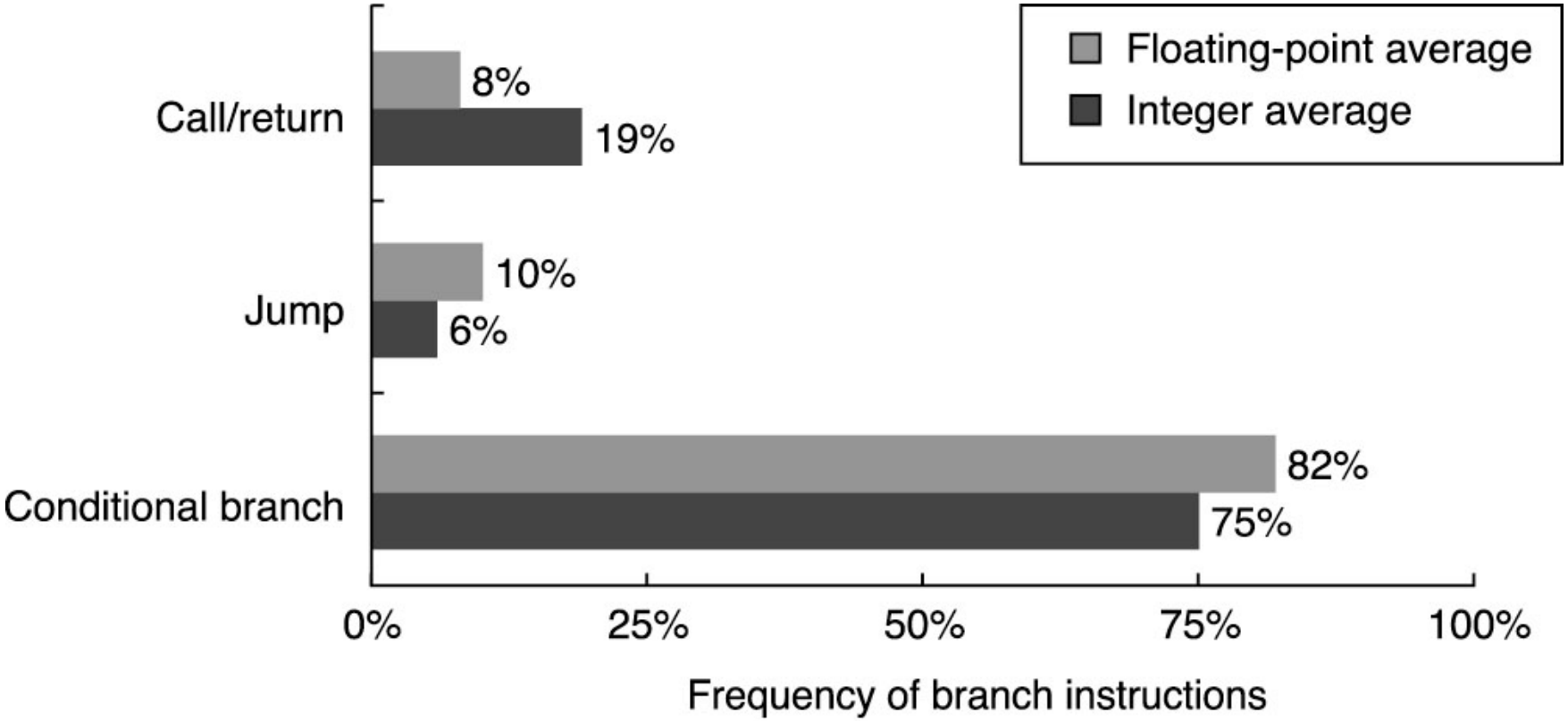
Sequencing flow is disrupted conditionally and unconditionally

- **The ability of computers to test results and conditionally instructions is one of the reasons computers have become so useful**



Branch instructions are ~20% of all instructions executed

Dynamic Frequency



Methods of Testing Condition

- **Condition Codes**

  Processor status bits are set as a side-effect of arithmetic instructions (possibly on Moves) or explicitly by compare or test instructions.

  ex: add r1, r2, r3

  bz label

- **Condition Register**

  Ex: cmp r1, r2, r3

  bgt r1, label

- **Compare and Branch**

  Ex: bgt r1, r2, label

Condition Codes

Setting CC as side effect can reduce the # of instructions

```
X:    .
      .
      .
   SUB  r0, #1, r0
   CMP  r0, #0
   BRP  X
```

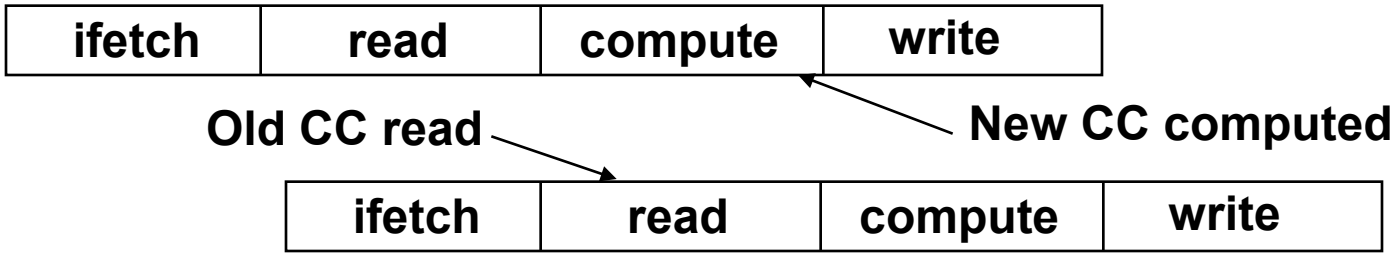
vs.

```
X:    .
      .
      .
   SUB  r0, #1, r0
   BRP  X
```

But also has disadvantages:

--- not all instructions set the condition codes;
which do and which do not often confusing!
e.g., shift instruction sets the carry bit

--- dependency between the instruction that sets the CC and the one that tests it: to overlap their execution, may need to separate them with an instruction that does not change the CC



Branches

--- Conditional control transfers

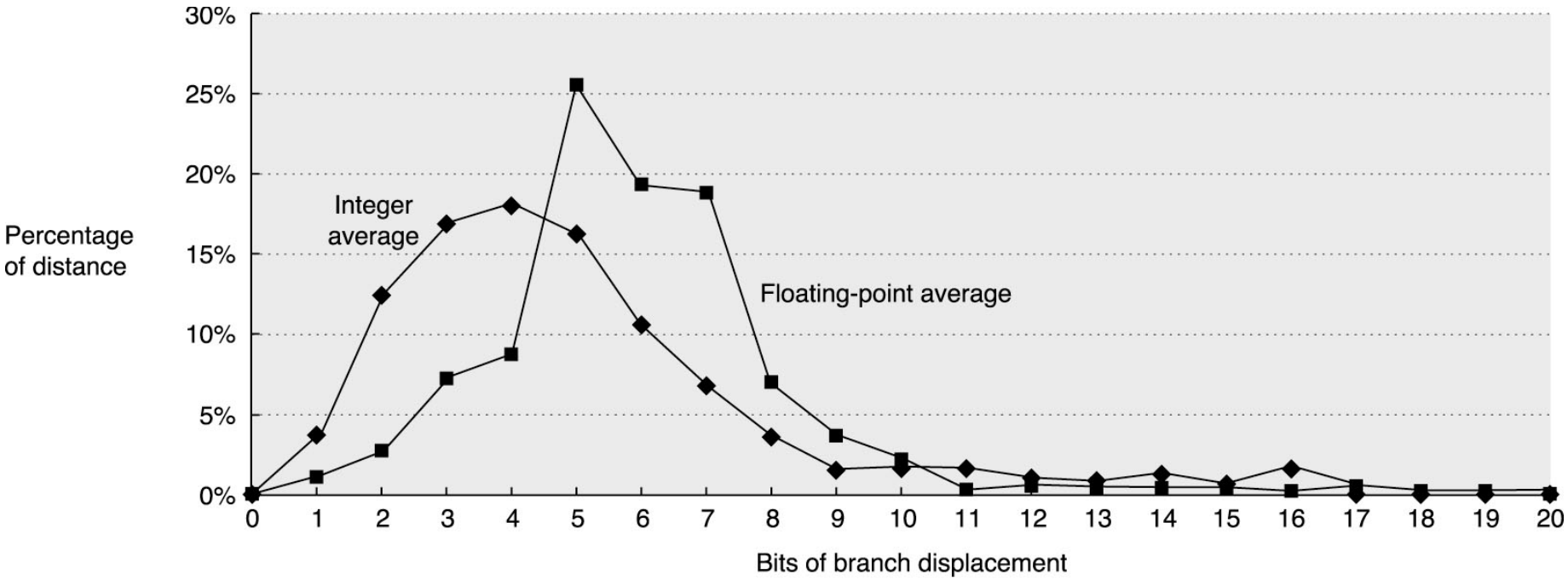
Four basic conditions:

N -- negative
Z -- zero
V -- overflow
C -- carry

Sixteen combinations of the basic four conditions:

Always	Unconditional
Never	NOP
Not Equal	~Z
Equal	Z
Greater	~[Z + (N ⊕ V)]
Less or Equal	Z + (N ⊕ V)
Greater or Equal	~(N ⊕ V)
Less	N ⊕ V
Greater Unsigned	~(C + Z)
Less or Equal Unsigned	C + Z
Carry Clear	~C
Carry Set	C
Positive	~N
Negative	N
Overflow Clear	~V
Overflow Set	V

Conditional Branch Distance



PC-relative (+-)

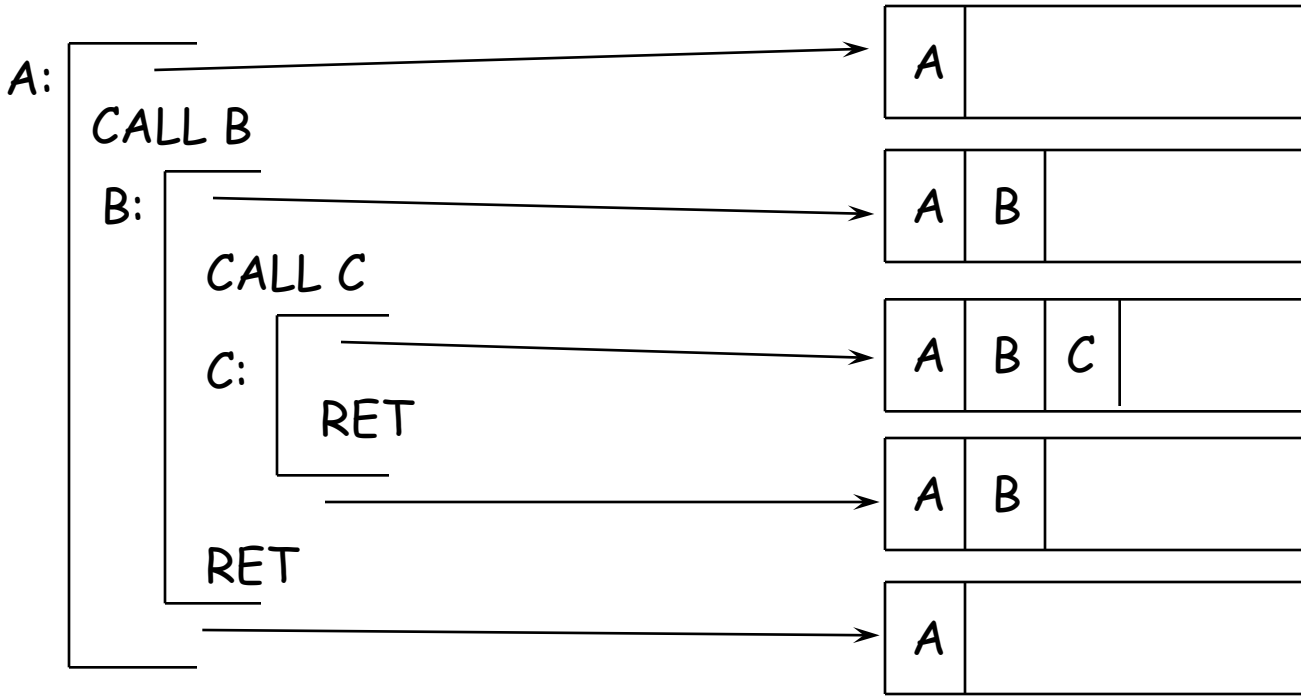
25% of integer branches are 2 to 4 instructions

At least 8 bits suggested (± 128 instructions)

Language and Compiler Driven Facilities

Calls: Why Are Stacks So Great?

Stacking of Subroutine Calls & Returns and Environments:



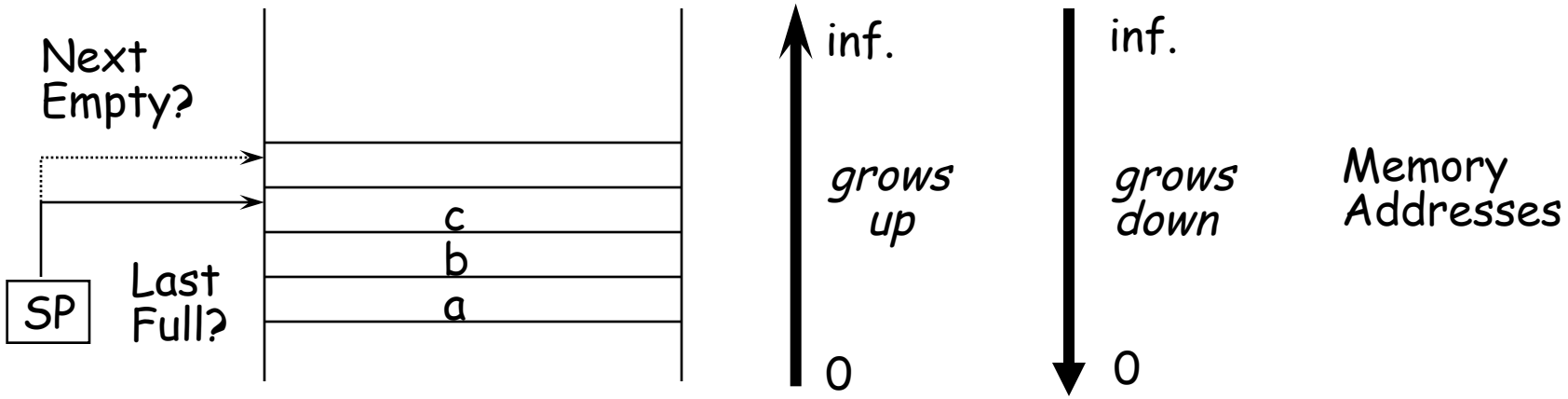
Some machines provide a memory stack as part of the architecture
(e.g., VAX)

Sometimes stacks are implemented via software convention
(e.g., MIPS)

Memory Stacks

Useful for stacked environments/subroutine call & return even if operand stack not part of architecture

Stacks that Grow Up vs. Stacks that Grow Down:



How is empty stack represented?

Grows-Up / Last Full

POP: Read from Mem(SP)
Decrement SP

PUSH: Increment SP
Write to Mem(SP)

Grows-Up / Next Empty

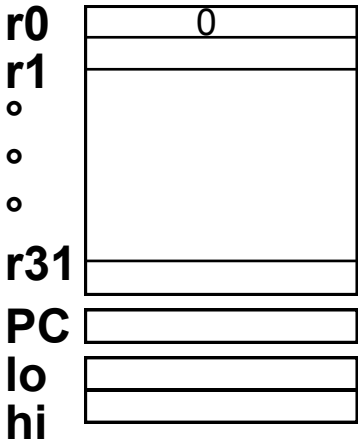
POP: Decrement SP
Read from Mem(SP)

PUSH: Write to Mem(SP)
Increment SP

MIPS ISA

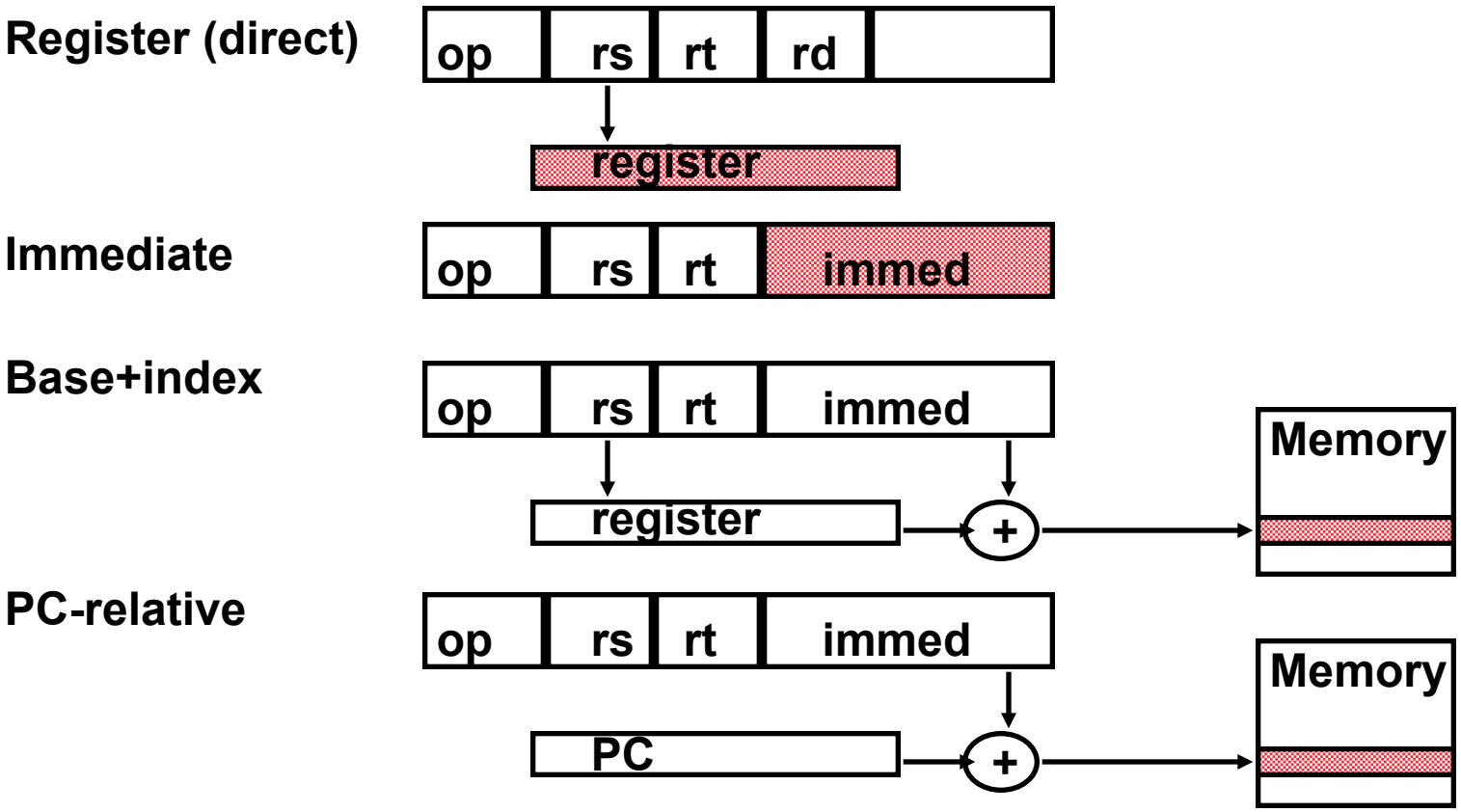
MIPS R2000 / R3000 Registers

- Programmable storage



MIPS Addressing Modes/Instruction Formats

- All instructions 32 bits wide



MIPS R2000 / R3000 Operation Overview

Arithmetic logical

Add, AddU, Sub, SubU, And, Or, Xor, Nor, SLT, SLTU

AddI, AddIU, SLTI, SLTIU, AndI, OrI, XorI, LUI

SLL, SRL, SRA, SLLV, SRLV, SRAV

Memory Access

LB, LBU, LH, LHU, LW, LWL,LWR

SB, SH, SW, SWL, SWR

Multiply / Divide

Start multiply, divide

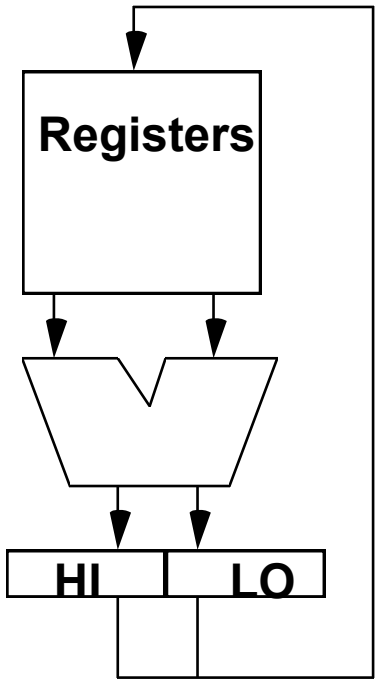
- MULT rs, rt
- MULTU rs, rt
- DIV rs, rt
- DIVU rs, rt

Move result from multiply, divide

- MFHI rd
- MFLO rd

Move to HI or LO

- MTHI rd
- MTLO rd

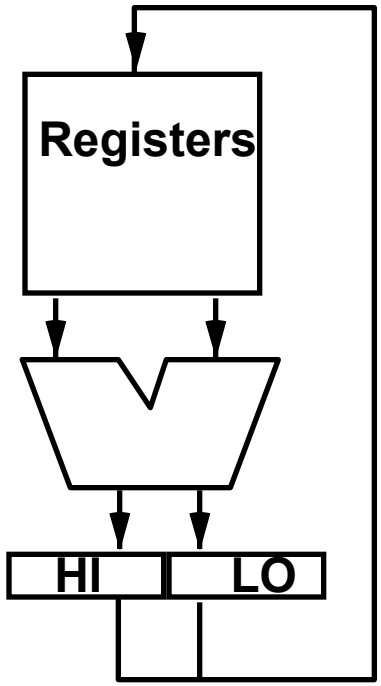


Multiply / Divide

Start multiply, divide

- **MULT rs, rt**
  - **Move to HI or LO**
- **MTHI rd**
- **MTLO rd**

Why not Third field for destination?
(Hint: how many clock cycles for multiply or divide vs. add?)



MIPS arithmetic instructions

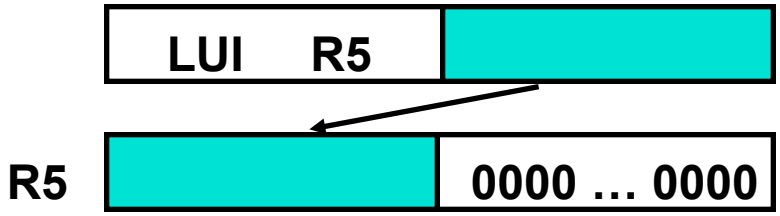
Instruction	*Example*	*Meaning*	*Comments*
add	add $1,$2,$3	$1 = $2 + $3	3 operands; exception possible
subtract	sub $1,$2,$3	$1 = $2 – $3	3 operands; exception possible
add immediate	addi $1,$2,100	$1 = $2 + 100	+ constant; exception possible
add unsigned	addu $1,$2,$3	$1 = $2 + $3	3 operands; no exceptions
subtract unsigned	subu $1,$2,$3	$1 = $2 – $3	3 operands; no exceptions
add imm. unsign.	addiu $1,$2,100	$1 = $2 + 100	+ constant; no exceptions
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, Hi = $2 mod $3	Lo = quotient, Hi = remainder
divide unsigned	divu $2,$3	Lo = $2 ÷ $3, Hi = $2 mod $3	Unsigned quotient & 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

MIPS logical instructions

Instruction	*Example*	*Meaning*	*Comment*
and	and $1,$2,$3	$1 = $2 & $3	3 reg. operands; Logical AND
or	or $1,$2,$3	$1 = $2 | $3	3 reg. operands; Logical OR
xor	xor $1,$2,$3	$1 = $2 ⊕ $3	3 reg. operands; Logical XOR
nor	nor $1,$2,$3	$1 = ~($2 |$3)	3 reg. operands; Logical NOR
and immediate	andi $1,$2,10	$1 = $2 & 10	Logical AND reg, constant
or immediate	ori $1,$2,10	$1 = $2 | 10	Logical OR reg, constant
xor immediate	xori $1, $2,10	$1 = ~$2 &~10	Logical XOR reg, constant
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 variable
shift right logical	srlv $1,$2, $3	$1 = $2 >> $3	Shift right by variable
shift right arithm.	srav $1,$2, $3	$1 = $2 >> $3	Shift right arith. by variable

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 halfword
LHU R1, 40(R3)	Load halfword 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)



Remember - Methods of Testing Condition

° Condition Codes

Processor status bits are set as a side-effect of arithmetic instructions (possibly on Moves) or explicitly by compare or test instructions.

ex: add r1, r2, r3

bz label

° Condition Register

Ex: cmp r1, r2, r3

bgt r1, label

° Compare and Branch

Ex: bgt r1, r2, label

Compare and Branch

- Compare and Branch
  - BEQ rs, rt, offset if R[rs] == R[rt] then PC-relative branch
  - BNE rs, rt, offset <>0
- Compare to zero and Branch
  - BLEZ rs, offset if R[rs] <= 0 then PC-relative branch
  - BGTZ rs, offset >0
  - BLTZ <0
  - BGEZ >=0
  - BLTZAL rs, offset if R[rs] < 0 then branch and link (into R 31)
  - BGEZAL >=0
- 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	

Signed vs. Unsigned Comparison

Value?
2's comp Unsigned?

R1= 0...00 0000 0000 0000 0001 **two**

R2= 0...00 0000 0000 0000 0010 **two**

R3= 1...11 1111 1111 1111 1111 **two**

After executing these instructions:

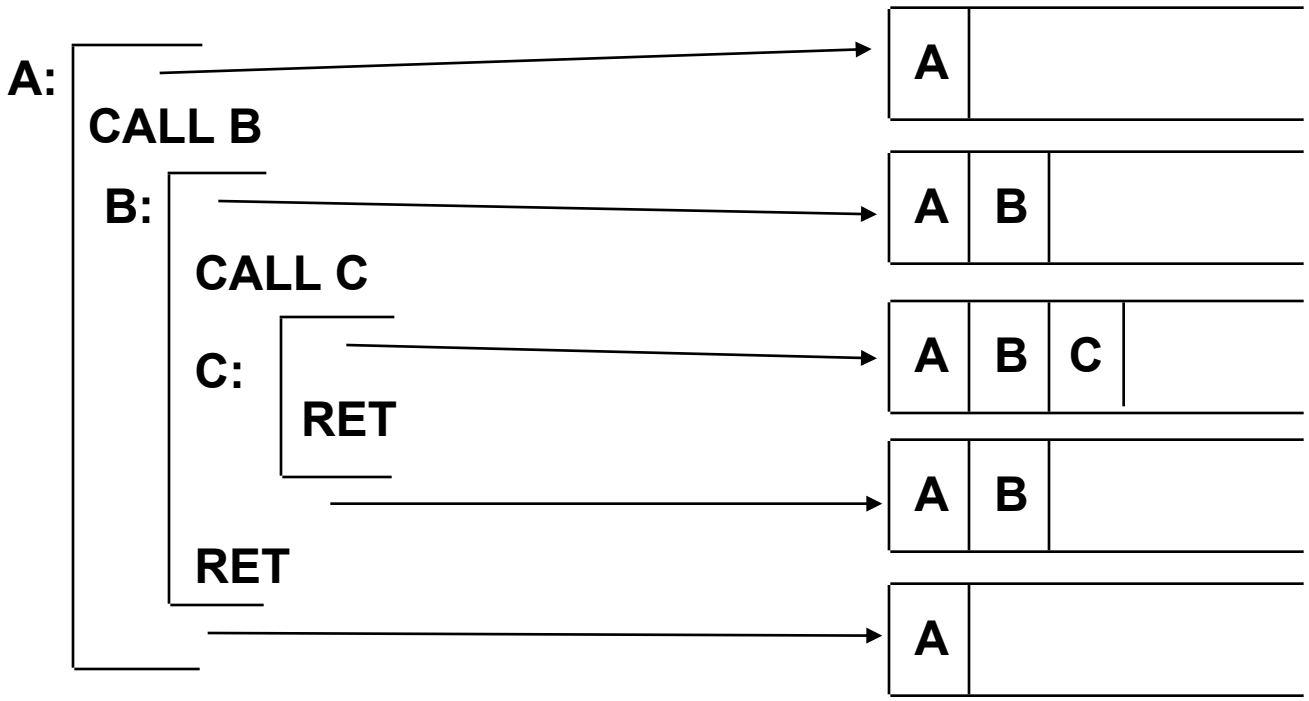
```
slt  r4,r2,r1 ;  if (r2 < r1) r4=1; else r4=0
slt  r5,r3,r1 ;  if (r3 < r1) r5=1; else r5=0
sltu r6,r2,r1 ;  if (r2 < r1) r6=1; else r6=0
sltu r7,r3,r1 ;  if (r3 < r1) r7=1; else r7=0
```

What are values of registers r4 - r7? Why?

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

Calls: Why Are Stacks So Great?

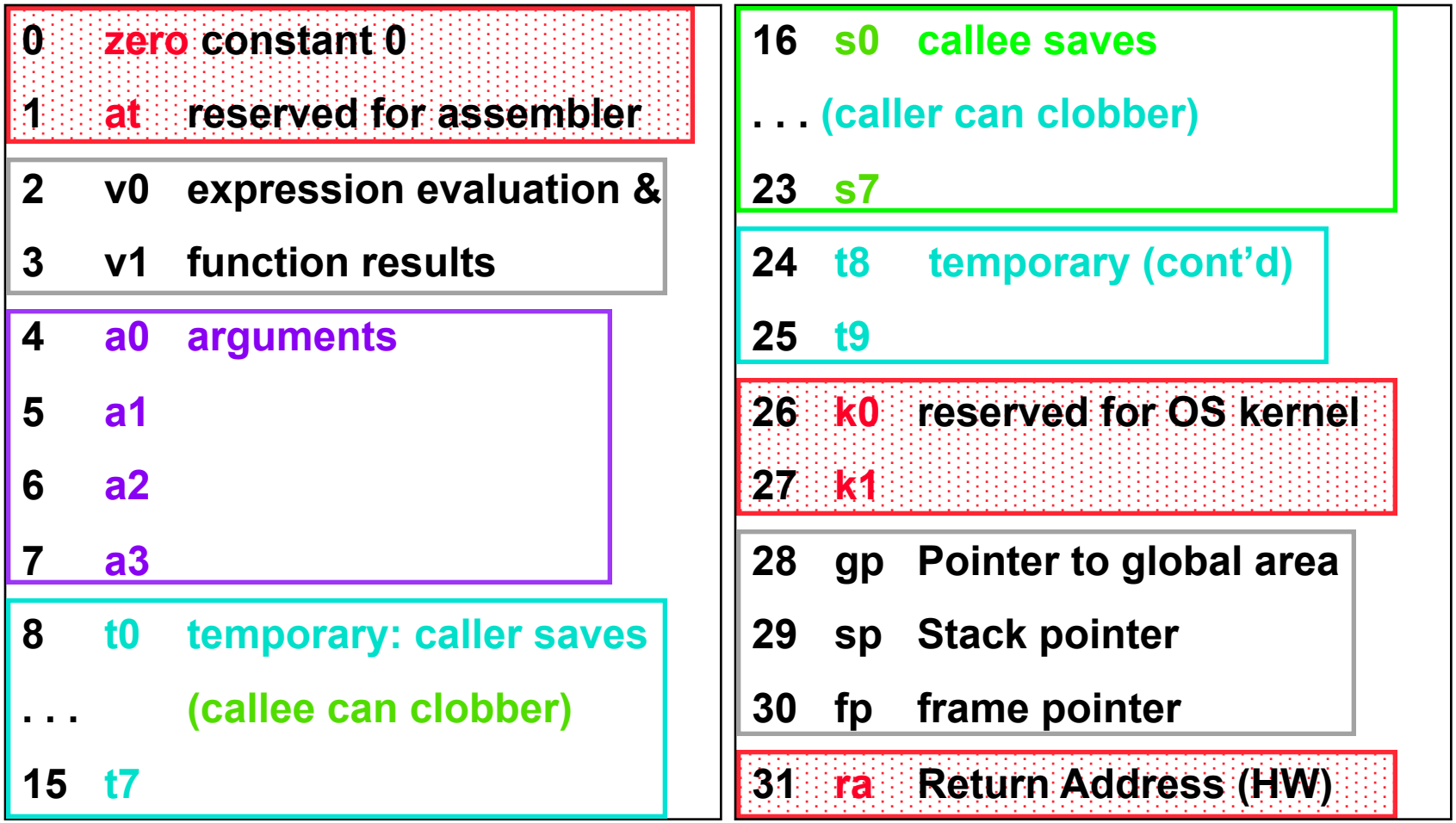
Stacking of Subroutine Calls & Returns and Environments:



Some machines provide a memory stack as part of the architecture (e.g., VAX)

Sometimes stacks are implemented via software convention (e.g., MIPS)

MIPS: Software conventions for Registers



Example in C: swap

```
swap(int v[ ], int k)
{
   int temp;
   temp = v[k];
   v[k] = v[k+1];
   v[k+1] = temp;
}
```

Assume swap is called as a procedure

Assume temp is register $15; arguments in $a1, $a2; $16 is scratch reg:

Write MIPS code

swap: MIPS

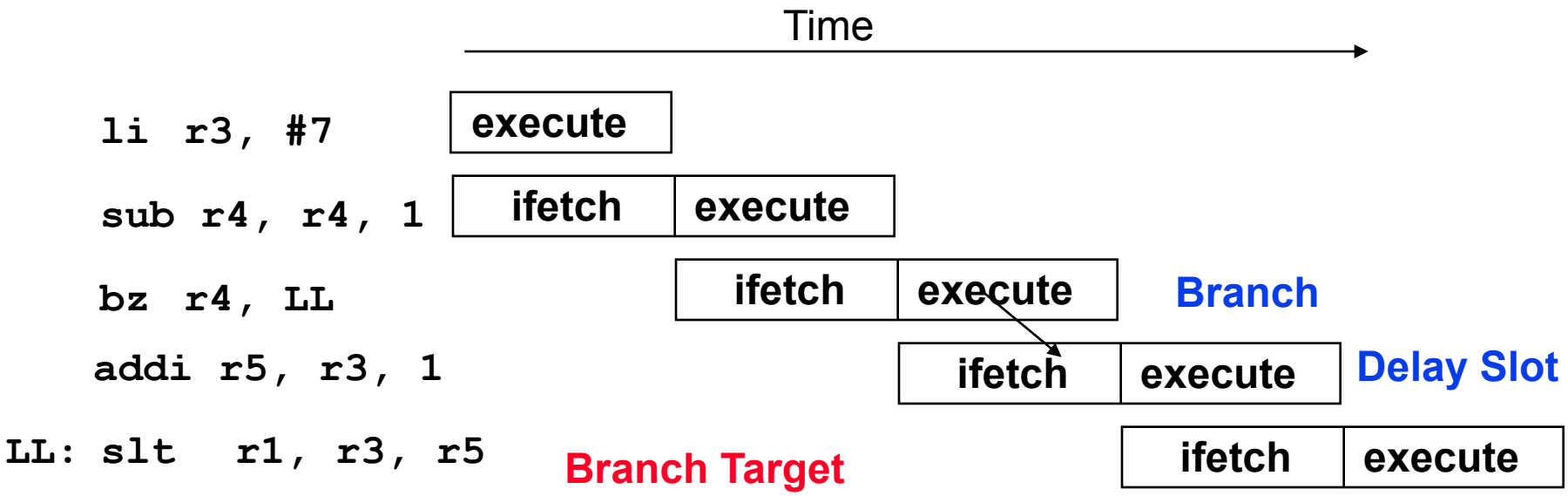
```
swap:
   addi   $sp,$sp, –4       ; create space on stack
   sw     $16, 4($sp)       ; callee saved register put onto stack
   sll    $t2, $a2,2        ; multiply k by 4
   addu   $t2, $a1,$t2      ; address of v[k]
   lw     $15, 0($t2)       ; load v[k]
   lw     $16, 4($t2)       ; load v[k+1]
   sw     $16, 0($t2)       ; store v[k+1] into v[k]
   sw     $15, 4($t2)       ; store old value of v[k] into v[k+1]
   lw     $16, 4($sp)        ; callee saved register restored from stack
   addiu  $sp,$sp, 4         ; restore top of stack
   jr     $31                ; return to place that called swap
```

Delayed Branches

```
        li   r3, #7
        addi r5, r3, 1
        sub  r4, r4, 1
        bz   r4, LL
        subi r6, r6, 2
LL:     slt  r1, r3, r5
```

- In the "Raw" MIPS the instruction after the branch is executed even when the branch is taken?
  - This is hidden by the assembler for the MIPS "virtual machine"
  - allows the compiler to better utilize the instruction pipeline (???)

Branch & Pipelines

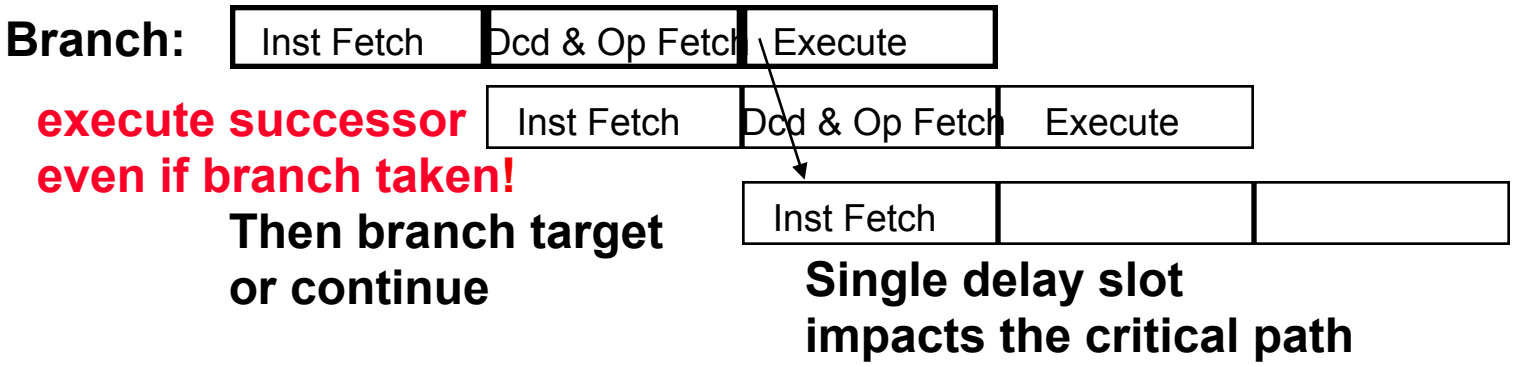


By the end of Branch instruction, the CPU knows whether or not the branch will take place.

However, it will have fetched the next instruction by then, regardless of whether or not a branch will be taken.

Why not execute it?

Filling Delayed Branches



Compiler fills about 60% of branch delay slots

About 80% of instructions executed in branch delay slots useful in computation

About 50% (60% x 80%) of slots usefully filled

How?

- try to move down from above jump
- move up from target, if safe

```
        add r3, r1, r2
        sub r4, r4, 1
        bz  r4, LL
        NOP
        ...
LL:     add rd, ...
```

Is this violating the ISA abstraction?

Standard and Delayed Interpretation

PC

```
        add   rd, rs, rt      R[rd] <- R[rs] + R[rt];
                              PC <- PC + 4;
        beq   rs, rt, offset  if  R[rs] == R[rt] then PC <- PC + SX(offset)
                                                 else PC <- PC + 4;
        sub   rd, rs, rt      . . .
        . . .
L1:     target
```

PC

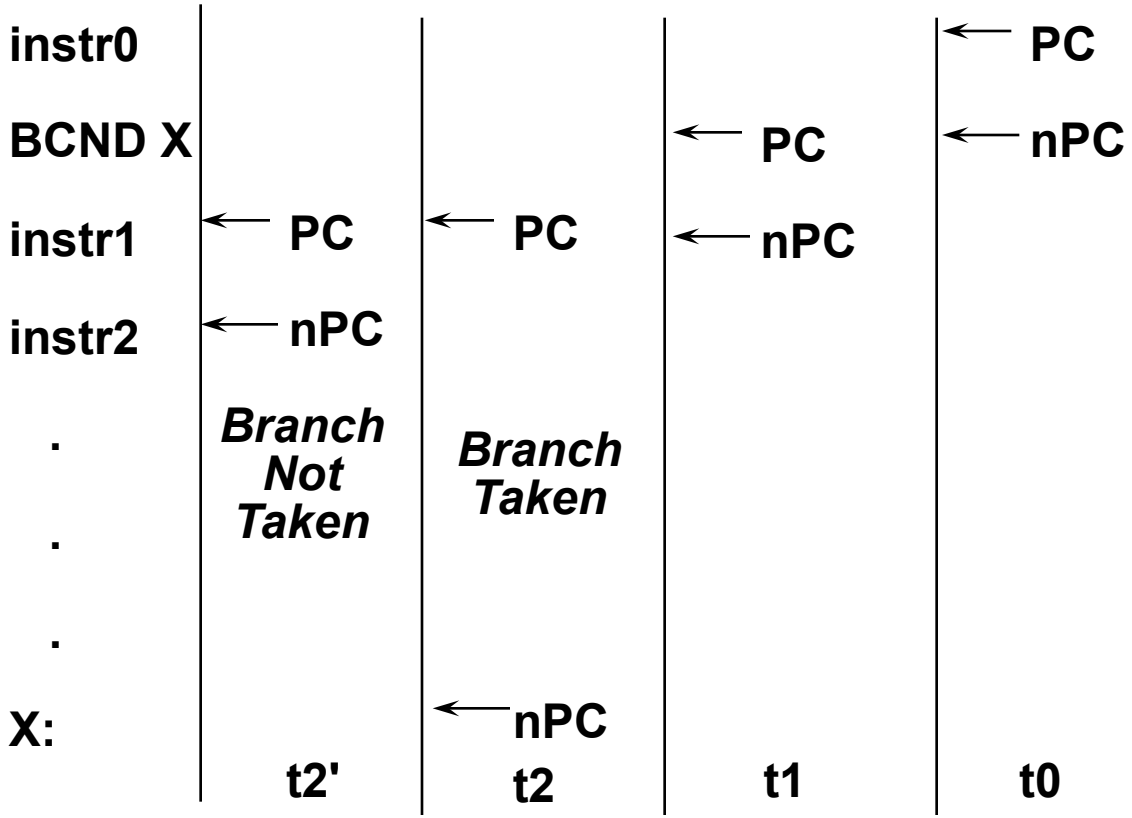
nPC

```
        add   rd, rs, rt      R[rd] <- R[rs] + R[rt];
                              PC <- nPC;   nPC <- nPC + 4;
        beq   rs, rt, offset  PC <- nPC;
                              if  R[rd] == R[rt] then nPC <- nPC + 4;
                                                 else nPC <- nPC + 4;
        sub   rd, rs, rt      PC <- nPC;
        . . .                 …
L1:     target
```

Delayed Loads?

Delayed Branches (cont.)

Execution History



Branches are the bane (or pain!) of pipelined machines
Delayed branches complicate the compiler slightly, but make pipelining easier to implement and more effective
Good strategy to move some complexity to compile time

Miscellaneous MIPS instructions

° break	A breakpoint trap occurs, transfers control to exception handler
° syscall	A system trap occurs, transfers control to exception handler
° coprocessor instrs.	Support for floating point: discussed later
° TLB instructions	Support for virtual memory: discussed later
° restore from exception	Restores previous interrupt mask & kernel/user mode bits into status register
° load word left/right	Supports misaligned word loads
° store word left/right	Supports misaligned word stores

Details of the MIPS instruction set

- Register zero always has the value zero (even if you try to write it)
- Branch and jump instructions put the return address PC+4 into the link register
- All instructions change all 32 bits of the destination register (including lui, lb, lh) and all read all 32 bits of sources (add, sub, and, or, …)
- Immediate arithmetic and logical instructions are extended as follows:
  - logical immediates are zero extended to 32 bits
  - arithmetic immediates are sign extended to 32 bits
- The data loaded by the instructions lb and lh are extended as follows:
  - lbu, lhu are zero extended
  - lb, lh are sign extended
- Overflow can occur in these arithmetic and logical instructions:
  - add, sub, addi
  - it cannot occur in addu, subu, addiu, and, or, xor, nor, shifts, mult, multu, div, divu

Other ISAs

- Intel 8086/88 => 80286 => 80386 => 80486 => Pentium => P6 => Core iX
  - 8086 few transistors to implement 16-bit microprocessor
  - tried to be somewhat compatible with 8-bit microprocessor 8080
  - successors added features which were missing from 8086 over next ~30 years
  - product several different Intel engineers over 10 to 15 years
  - Announced 1978
- VAX simple compilers & small code size =>
  - efficient instruction encoding
  - powerful addressing modes
  - powerful instructions
  - few registers
  - product of a single talented architect
  - Announced 1977

Machine Examples: Address & Registers

Intel 8086	2^{20} x 8 bit bytes AX, BX, CX, DX SP, BP, SI, DI CS, SS, DS IP, Flags	acc, index, count, quot stack, string code,stack,data segment
VAX 11	2^{32} x 8 bit bytes 16 x 32 bit GPRs	r15-- program counter r14-- stack pointer r13-- frame pointer r12-- argument ptr
MC 68000	2^{24} x 8 bit bytes 8 x 32 bit GPRs 7 x 32 bit addr reg 1 x 32 bit SP 1 x 32 bit PC	
MIPS	2^{32} x 8 bit bytes 32 x 32 bit GPRs 32 x 32 bit FPRs HI, LO, PC	

VAX Operations

- General Format:

  (operation) (datatype) (2, 3)

  2 or 3 explicit operands

- For example

  add (b, w, l, f, d) (2, 3)

  Yields

  addb2 addw2 addl2 addf2 addd2

  addb3 addw3 addl3 addf3 addd3

swap: MIPS vs. VAX

```
swap:
   addiu  $sp,$sp, –4
   sw     $16, 4($sp)
   sll    $t2, $a2,2
   addu   $t2, $a1,$t2
   lw     $15, 0($t2)
   lw     $16, 4($t2)
   sw     $16, 0($t2)
   sw     $15, 4($t2)
   lw     $16, 4($sp)
   addiu  $sp,$sp, 4
   jr     $31
```

```
.word ^m<r0,r1,r2,r3> ; saves r0 to r3

movl    r2, 4(ap)       ; move arg v[] to reg
movl    r1, 8(ap)       ; move arg k to reg
movl    r3, (r2)[r1]    ; get v[k]
addl3   r0, #1,8(ap) ;  reg gets k+1
movl    (r2)[r1],(r2)[r0] ; v[k] = v[k+1]
movl    (r2)[r0],r3     ; v[k+1] gets old v[k]

ret     ; return to caller, restore r0 -  r3
```

Summary

- Use general purpose registers with a load-store architecture: YES
- Provide at least 16 general purpose registers plus separate floating-point registers: 31 GPR & 32 FPR
- Support these addressing modes: displacement (with an address offset size of 12 to 16 bits), immediate (size 8 to 16 bits), and register deferred; : YES: 16 bits for immediate, displacement (disp=0 => register deferred)
- All addressing modes apply to all data transfer instructions : YES
- Use fixed instruction encoding if interested in performance and use variable instruction encoding if interested in code size : Fixed
- Support these data sizes and types: 8-bit, 16-bit, 32-bit integers and 32-bit and 64-bit IEEE 754 floating point numbers: YES
- Support these simple instructions, since they will dominate the number of instructions executed: load, store, add, subtract, move register-register, and, shift, compare equal, compare not equal, branch (with a PC-relative address at least 8-bits long), jump, call, and return: YES, 16b
- Aim for a minimalist instruction set: YES

Summary: Salient features of MIPS R3000

- **32-bit fixed format inst** (3 formats)
- **32 32-bit GPR** (R0 contains zero) and 32 FP registers (and HI LO)
  - partitioned by software convention
- **3-address, reg-reg arithmetic instr.**
- **Single address mode for load/store:** base+displacement
  - no indirection
- **16-bit immediate plus LUI**
- **Simple branch conditions**
  - compare against zero or two registers for =
  - no condition codes
- **Delayed branch**
  - execute instruction after the branch (or jump) even if the branch is taken (Compiler can fill a delayed branch with useful work about 50% of the time)