

EEL-4713C
Computer Architecture
Instruction Set Architectures

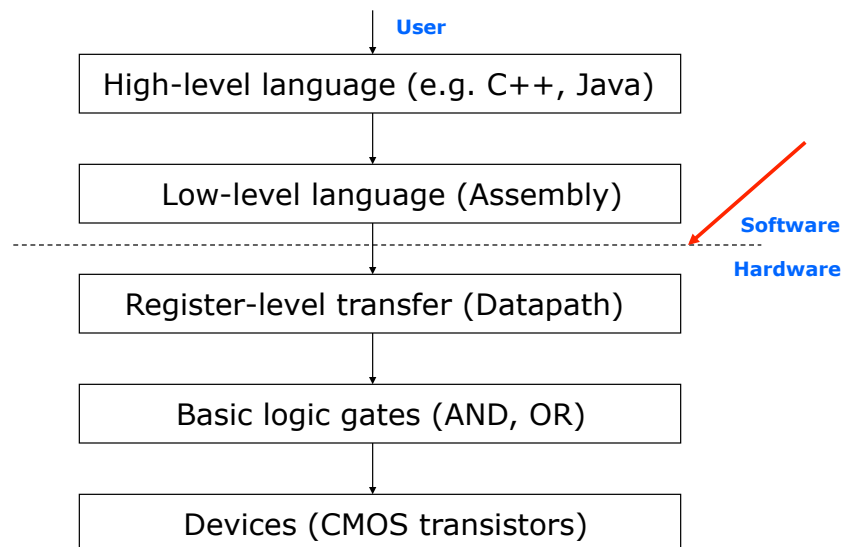
Outline

- **Instruction set architectures**
- **The MIPS instruction set**
 - Operands and operations
 - Control flow
 - Memory addressing
 - Procedures and register conventions
 - Pseudo-instructions
- **Reading:**
 - Textbook, Chapter 2
 - Sections 2.1-2.8, 2.10-2.13, 2.17-2.20

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Abstraction layers



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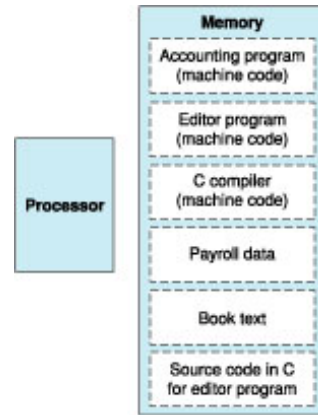
Introduction to Instruction Sets

- **Instructions: words of computer hardware's language**
 - Instruction sets: vocabulary
 - What is available for software to program a computer
- **Many sets exist; core functionality is similar**
 - Support for arithmetic/logic operations, data flow and control
- **We will focus on the MIPS set in class**
 - Simple to learn and to implement
 - Hardware perspective will be the topic of Chapter 5
 - Current focus will be on software, more specifically instructions that result from compiling programs written in the C language

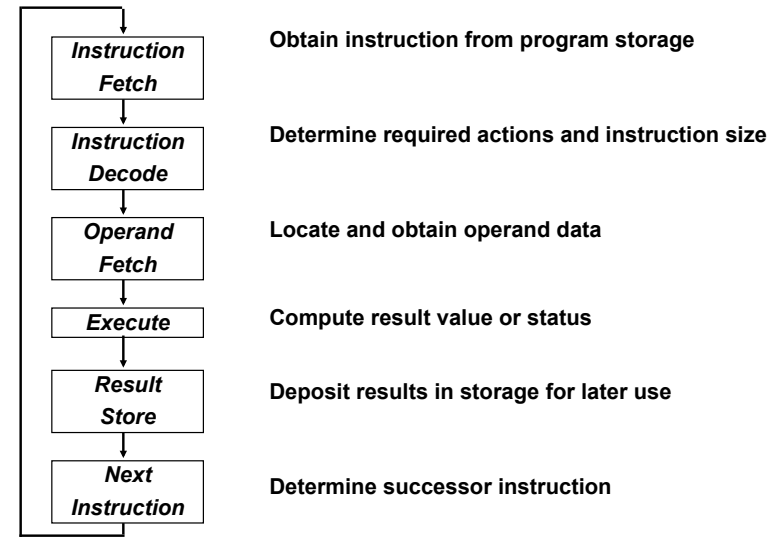
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Stored-program concept

- **Treat instructions as data**
 - Same technology used for both



Stored-program execution flow



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Basic issues and outline

- **What operations are supported?**
 - What operands do they use?
- **How are instructions represented in memory?**
- **How are data elements represented in memory?**
- **How is memory referenced?**
- **How to determine the next instruction in sequence?**

What operations are supported?

- **“Classic” instruction sets:**
- **Typical “integer” arithmetic and logic functions:**
 - Addition, subtraction
 - Division, multiplication
 - AND, OR, NOT, ...
- **Floating-point operations**
 - Add, sub, mult, div, square root, exponential, ...
- **More recent add-ons:**
 - Multi-media, 3D operations

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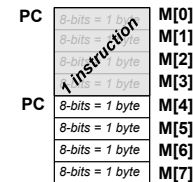
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MIPS operations

- See MIPS reference chart (green page of textbook) for full set of operations
- Most common: addition and subtraction
- MIPS assembly: add rd, rs, rt
 - register rd holds the sum of values currently in registers rs and rt

Memory Layout and Instruction Addressing

- In the MIPS architecture, memory is essentially an array of 8-bit bytes – thus the memory is byte addressable....



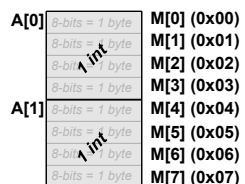
- ...but 1 instruction is 32-bits = 1 word
- PC is a special register that points to the current instruction being fetched
- Incrementing the PC (i.e., $PC++$) actually moves PC ahead 4 memory addresses $\rightarrow PC = PC + 4$

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Memory Layout and Data Addressing

- Data is typically 1 word (32 bits), but some data is smaller (i.e., ASCII characters are 8 bits), thus the memory must be byte addressable
- Assume we have an array of 2 words in high level code (i.e., int A[2])



- The base address of the array is 0x00
- A[0] is at 0x00; A[1] is at 0x04
- To access A[1] in assembly code, you have to know the base address of A (0x00) and the offset into the array, which is 1 word (in high level code), but 4 memory locations, thus the address of A[1] is:

$$base + 4(offset) = 0x00 + 4(1) = 0x04$$

Operands

- In MIPS, operands for arithmetic and logic operations always come from registers
 - Other sets (e.g. Intel IA-32/x86) support memory operands
- Registers: fast memory within the processor datapath
 - Goal is to be accessible within a clock cycle
 - How many?
 - » Smaller is faster – typically only a few registers are available
 - » MIPS: 32 registers
 - How wide?
 - » 32-bit and 64-bit now common
 - » Evolved from 4-bit, 8-bit, 16-bit
 - » MIPS: both 32-bit and 64-bit. We will only study 32-bit.

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Example

f = (g+h) – (i+j);

add \$t0,\$s1,\$s2 # \$t0 holds g+h

add \$t1,\$s3,\$s4 # \$t1 holds i+j

sub \$s0,\$t0,\$t1 # \$s0 holds f

(assume f=\$s0, g=\$s1, h=\$s2, i=\$s3, j=\$s4)

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Operands (cont)

- **Operands need to be transferred from registers to memory (and vice versa)**
- **Data transfer instructions:**
 - Load: transfer from memory to register
 - Store: transfer from register to memory
 - What to transfer?
 - » 32-bit integer? 8-bit ASCII character?
 - » MIPS: 32-bit, 16-bit and 8-bit
 - From where in memory?
 - » MIPS: 32-bit address needs to be provided
 - » addressing modes
 - Which register?
 - » MIPS: one out of 32 registers needs to be provided

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Example

A[12] = h + A[8];

lw \$t0,32(\$s3) # \$t0: A[8] (32=8*4bytes)

add \$t0,\$s2,\$t0 # \$t0 = h+A[8]

sw \$t0,48(\$s3) # A[12] holds final result

**(assume A is an array of 32-bit/4-Byte integer elements.
Base address of array A is \$s3. h=\$s2)**

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Immediate operands

- **Constants are commonly used in programming**
 - E.g. 0 (false), 1 (true)
- **Immediate operands:**
 - Which instructions need immediate operands?
 - » MIPS: some of arithmetic/logic (e.g. add)
 - » Loads and stores
 - » Jumps (will see later)
 - Width of immediate operand?
 - » In practice, most constants are small
 - » MIPS: pack 16-bit immediate in instruction code
- **Example: addi \$s3, \$s3, 4**

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Instruction representations

- Stored program: instructions are in memory
- Must be represented with some binary encoding
- Assembly language
 - mnemonics used to facilitate people to “read the code”
 - E.g. MIPS add \$t0,\$s1,\$s2
- Machine language
 - Binary representation of instructions
 - E.g. MIPS 00000010001100100100000000100000
- Instruction format
 - Form of representation of an instruction
 - E.g. MIPS 00000010001100100100000000100000
 - » Red: “add” code; brown: “\$s2”

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MIPS instruction encoding fields

op	rs	rt	rd	shamt	funct
----	----	----	----	-------	-------

- op (6 bits): basic operation; “opcode”
- rs (5 bits): first register source operand
- rt (5 bits): second register source operand
- rd (5 bits): register destination
- shamt (5 bits): shift amount for binary shift instructions
- funct (6 bits): function code; select which variant of the “op” field is used. “function code”
- “R-type”
 - Two other types: I-type, J-type; will see later

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Logical operations

- Bit-wise operations; packing and unpacking of bits into words
- MIPS:
 - Shift left/right
 - » E.g. sll \$s1,\$s2,10
 - Bit-wise AND, OR, NOT, NOR
 - » E.g. and \$s1,\$s2,\$s3
 - Immediate AND, OR
 - » E.g. andi \$s1,\$s2,100
- What does andi \$s1,\$s1,0 do?

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Decision-making: control flow

- A microprocessor fetches an instruction from memory address pointed by a register (PC)
- The PC is *implicitly incremented* to point to the next memory address in sequence after an instruction is fetched
- Software requires more than this:
 - Comparisons; if-then-else
 - Loops; while, for
- Instructions are required to change the value of PC from the implicit next-instruction
 - Conditional branches
 - Unconditional branches

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MIPS control flow

- **Conditional branches:**
 - beq \$s0,\$s1,L1
 - » Go to statement labeled L1 if \$s0 equal to \$s1
 - bne \$s0,\$s1,L1
 - » Go to statement labeled L1 if \$s0 not equal to \$s1
- **Unconditional branches:**
 - J L2
 - » Go to statement labeled L2

Example: if/then/else

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

```
bne $s3,$s4,Else # go to else if i!=j
add $s0,$s1,$s2 # f=g+h
j Exit
```

Else: sub \$s0,\$s1,\$s2

Exit:

(\$s3=i, \$s4=j, \$s1=g, \$s2=h, \$s0=f)

Example: while loop

While (save[i]==k) i=i+1;

```
Loop: sll $t1,$s3,2 # $t1 holds 4*i
      add $t1,$t1,$s6 # $t1: addr of save[i]
      lw  $t0,0($t1) # $t0: save[i]
      bne $t0,$s5,Exit # not equal? end
      addi $s3,$s3,1 # increment i
      j Loop          # loop back
Exit:
```

(\$s3=i, \$s5=k, \$s6 base address of save[])

MIPS control flow

- **Important note:**
 - MIPS register \$zero is not an ordinary register
 - » It has a fixed value of zero
 - A special case to facilitate dealing with the zero value, which is commonly used in practice
- **E.g. MIPS does not have a branch-if-less-than**
 - Can construct it using set-less-than (slt) and register \$zero:
 - E.g.: branch if \$s3 less than \$s2
 - » slt \$t0,\$s3,\$s2 # \$t0=1 if \$s3<\$s2
 - » bne \$t0,\$zero,target # branch if \$t0 not equal to zero

MIPS control flow: supporting procedures

- Instruction “jump-and-link” (jal JumpAddr)
 - Jump to 26-bit immediate address JumpAddr
 - » Used when calling a subroutine
 - Set R31 (\$ra) to PC+4
 - » Save return address (next instruction after procedure call) in a specific register
- Instruction “jump register” (jr \$rx)
 - Jump to address stored in address \$rx
 - jr \$ra: return from subroutine

Support for procedures

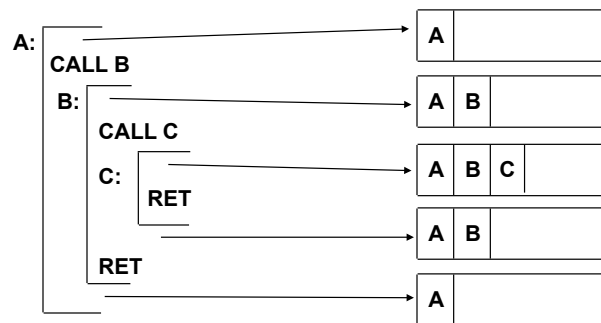
- Handling arguments and return values
 - \$a0-\$a3: registers used to pass parameters to subroutine
 - \$v0-\$v1: registers used to return values
 - Software convention – these are general-purpose registers
- How to deal with registers that procedure body needs to use, but caller does not expect to be modified?
 - E.g. in nested/recursive subroutines
- Memory “stacks”
 - Placeholder for register values that need to be preserved during procedure call

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Procedure calls and stacks

Stacking of Subroutine Calls & Returns and Environments:



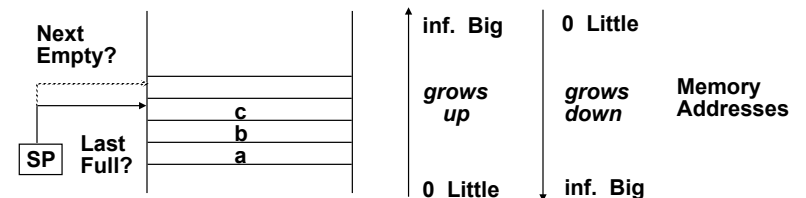
Some machines provide a memory stack as part of the architecture (e.g., VAX)

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:



Little --> Big/Last Full

POP: Read from Mem(SP)
Decrement SP

PUSH: Increment SP
Write to Mem(SP)

Little --> Big/Next Empty

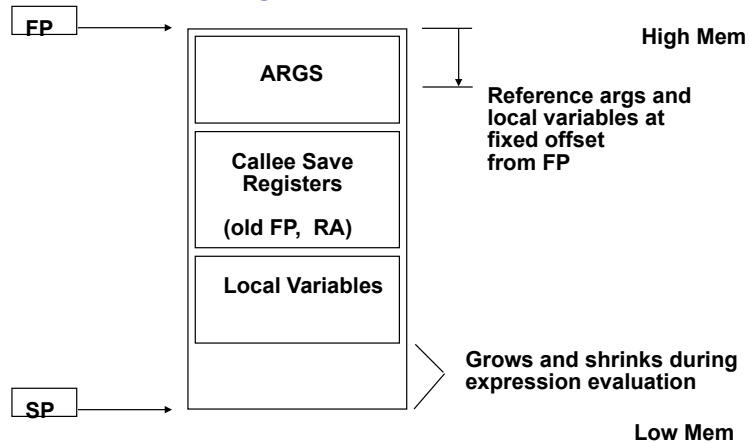
POP: Decrement SP
Read from Mem(SP)

PUSH: Write to Mem(SP)
Increment SP

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Call-Return Linkage: Stack Frames



SP may change during the procedure; FP provides a stable reference to local variables, arguments

MIPS: Software conventions for Registers

0	zero	constant 0	16	s0	callee saves
1	at	reserved for assembler	(caller can clobber)
2	v0	expression evaluation &	23	s7	
3	v1	function results	24	t8	temporary (cont'd)
4	a0	arguments	25	t9	
5	a1		26	k0	reserved for OS kernel
6	a2		27	k1	
7	a3		28	gp	Pointer to global area
8	t0	temporary: caller saves	29	sp	Stack pointer
...	...	(callee can clobber)	30	fp	frame pointer
15	t7		31	ra	Return Address (HW)

See Figure 2.18.

Example in C: swap

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

swap: MIPS

Using saved registers (\$a0=v[], \$a1=k):

```
swap:
    addi    $sp,$sp,-12 ; room for 3 words
    sw      $s0,8($sp)
    sw      $s1,4($sp)
    sw      $s2,0($sp)
    sll     $s1,$a1,2    ; multiply k by 4
    addu    $s1,$a0,$s1  ; address of v[k]
    lw      $s0,0($s1)   ; load v[k]
    lw      $s2,4($s1)   ; load v[k+1]
    sw      $s2,0($s1)   ; store v[k+1] into v[k]
    sw      $s0,4($s1)   ; store old v[k] into v[k+1]
    lw      $s0,8($sp)
    lw      $s1,4($sp)
    lw      $s2,0($sp)
    addi    $sp,$sp,12 ; restore stack pointer
    jr      $ra          ; return to caller
```

swap(int v[], int k)

```
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```


swap: MIPS

Using temporaries (\$a0=v[], \$a1=k)

swap:

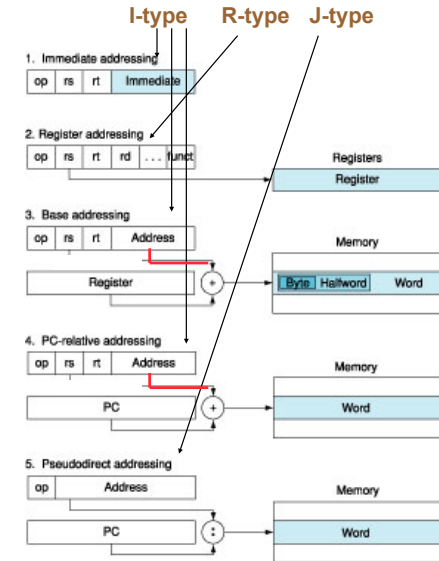
```
sll    $t1, $a1, 2    ; multiply k by 4
addu   $t1, $a0, $t1  ; address of v[k]
lw     $t0, 0($t1)    ; load v[k]
lw     $t2, 4($t1)    ; load v[k+1]
sw     $t2, 0($t1)    ; store v[k+1] into v[k]
sw     $t0, 4($t1)    ; store old v[k] into v[k+1]
jr     $ra            ; return to caller
```

swap(int v[], int k)

```
{
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

MIPS Addressing modes

- Common modes that compilers generate are supported:
 - Immediate
 - 16 bits, in inst
 - Register
 - 32-bit register contents
 - Base
 - Register + constant offset; 8-, 16- or 32-bit data in memory
 - PC-relative
 - PC+constant offset
 - Pseudo-direct
 - 26-bit immediate, shifted left 2x and concatenated to the 4 MSB bits of the PC



MIPS Addressing: 32-bit constants

- All MIPS instructions are 32-bit long
 - Reason: simpler, faster hardware design: instruction fetch, decode, cache
- However, often 32-bit immediates are needed
 - For constants and addresses
- Loading a 32-bit constant to register takes 2 operations
 - Load upper (a.k.a. most-significant, MSB) 16 bits (“lui” instruction)
 - Also fills lower 16 bits with zeroes
 - lui \$s0, 0x40 results in \$s0=0x4000
 - Load lower 16 bits (“ori” instruction, or immediate)
 - e.g. ori \$s0, \$s0, 0x80 following lui above results in \$s0=0x4080

MIPS Addressing: targets of jumps/branches

- Conditional branches:
 - 16-bit displacement relative to current PC
 - I-type instruction, see reference chart
 - “Back” and “forth” jumps supported
 - Signed displacement; positive and negative
 - “Short” conditional branches suffice most of the time
 - E.g. small loops (back); if/then/else (forward)
- Jumps:
 - For “far” locations
 - 26-bit immediate, J-type instruction
 - Shifted left by two (word-aligned) -> 28 bits
 - Concatenate 4 MSB from PC -> 32 bits

Instructions for synchronization

- Multiple cores, multiple threads
- Synchronization is necessary to impose ordering
 - E.g.: a group working on a shared document
 - Two concurrent computations where there is a dependence
 - » $A = (B + C) * (D + E)$
 - » The additions can occur concurrently, but the multiplication waits for both
- Proper instruction set design can help support efficient synchronization primitives

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MIPS synchronization primitives

- Load linked (ll)
 - Load a value from memory to a register, like a regular load
 - But, in addition, hardware keeps track of the address from which it was loaded
- Store conditional (sc)
 - Store a value from register to memory succeeds *only if* no updates to load linked address
 - Register value also change: 0 if store failed, 1 if succeeded

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Synchronization primitives

- Typically multiple cores share a single logical main memory, but each has its own register set
 - Or multiple processes in a single core
- “Locks” are basic synchronization primitives
 - Only one process “gets” a lock at a time
- Key insight: “atomic” read/write on memory location can be used to create locks
 - Goal: nothing can interpose between read/write to memory location
 - Cannot be achieved simply using regular loads and stores – why?
- Different possible approaches to supporting primitives in the ISA
 - Involving moving data between registers and memory

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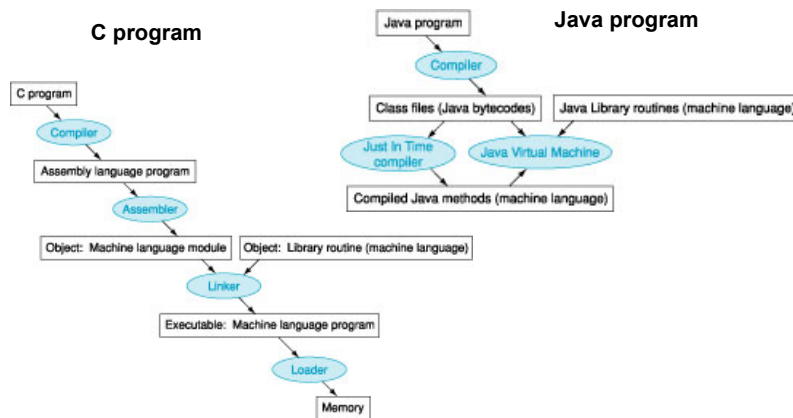
Example

- Goal: build simple “lock”
 - Value “0” indicates it is free
 - Value “1” indicates it is not available
 - E.g. if a group is collaborating on the same document, an individual may only make changes if it successfully gets lock=0
- Primitive: atomic exchange \$s4 and 0(\$s1)
 - Attempt to acquire a lock: exchange “1” (\$s4) with mem location 0 (\$s1)
- Try: add \$t0, \$zero, \$s4 - \$t0 gets \$s4
- ll \$t1, 0(\$s1) - load-linked lock addr
- sc \$t0, 0(\$s1) - conditional store “1”
- beq \$t0,\$zero,try - if failed, \$t0=0; retry
- add \$s4, \$zero, \$s1 - success: copy to \$s4

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Compiler, assembler, linker

- From high-level languages to machine executable program



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Assembler

- Translates assembly-level program into machine-level code
 - “Object” files (.o)
- Supports instructions of the processor’s ISA, as well as “pseudo-instructions” that facilitate programming and code generation
 - Example: `move $t0,$t1` a pseudo-instruction for `add $t0,$zero,$t1`
 - » Makes it more readable
 - Other examples: branch on less than (`blt`), load 32-bit immediate
 - » “unfold” pseudo-instruction into more than 1 real instruction
 - Cost: one register (`$at`) reserved to assembler, by convention

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Compiler

- Translates high-level language program (source code) into assembly-level
 - E.g. MIPS assembly; Java bytecodes
- Functionality: check syntax, produce correct code, perform optimizations (speed, code size)
 - See 2.11 for more details

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Linker

- Large programs can generate large object files
- Multiple developers may be working on various modules of a program concurrently
 - Sensible to partition source code across multiple files
- In addition, many commonly used functions are available in libraries
 - E.g. disk I/O, `printf`, network sockets, ...
- Linker: takes multiple independent object files and composes an “executable file”

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Loader

- **Brings executable file from disk to memory for execution**
 - Allocates memory for text and data
 - Copies instructions and input parameters to memory
 - Initializes registers & stack
 - Jumps to start routine (C's "main()")
- **Dynamically-linked libraries**
 - Link libraries to executables, "on-demand", after being loaded
 - Often the choice for functions common to many applications
 - Why?
 - » Reduce size of executable files – disk & memory space saved
 - » Many executables can share these libraries
 - .DLL in Windows, .so (shared-objects) in Linux

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Details of the MIPS instruction set

- Register zero always has the value zero (even if you try to write it)
- Jump and link instruction puts 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

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Miscellaneous MIPS instructions

- **Break**
 - A breakpoint trap occurs, transfers control to exception handler
- **Syscall**
 - A system trap occurs, transfers control to exception handler
- **coprocessor instructions**
 - 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

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Reduced and Complex Instruction Sets

- **MIPS is one example of a RISC-style architecture**
 - Reduced Instruction Set Computer
 - Designed from scratch in the 80's
- **Intel's "IA-32" architecture (x86) is one example of a CISC architecture**
 - Complex Instruction Set
 - Has been evolving over almost 30 years

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x86

- **Example of a CISC ISA**
 - P6 microarchitecture and subsequent implementations use RISC micro-operations
- **Descended from 8086**
- **Most widely used general purpose processor family**
 - Steadily gaining ground in high-end systems; 64-bit extensions now from AMD and Intel

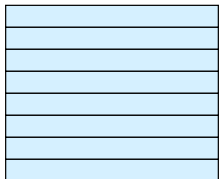
Some history

- 1978: 8086 launched; 16-bit wide registers; assembly-compatible with 8-bit 8080
- 1982: 80286 extends address space to 24 bits (16MB)
- 1985: 80386 extends address space and registers to 32 bits (4GB); paging and protection for O/Ss
- 1989-95: 80486, Pentium, Pentium Pro; only 4 instructions added; RISC-like pipeline
- 1997-2001: MMX extensions (57 instructions), SSE extensions (70 instructions), SSE-2 extensions; 4 32-bit floating-point operations in a cycle
- 2003: AMD extends ISA to support 64-bit addressing, widens registers to 64-bit.
- 2004: Intel supports 64-bit, relabeled EM64T
- Ongoing: Intel, AMD extend ISA to support virtual machines (Intel VT, AMD Pacifica). Dual-core microprocessors.

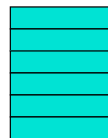
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x86 Registers



32-bit General purpose registers
EAX, EBX, ECX, EDX,
EBP, ESI, EDI, ESP
Special uses for certain instructions
(e.g. EAX functions as accumulator,
ECX as counter for loops)



16-bit segment registers
CS, DS, SS, ES, FS, GS



80-bit floating point stack
ST(0)-ST(7)

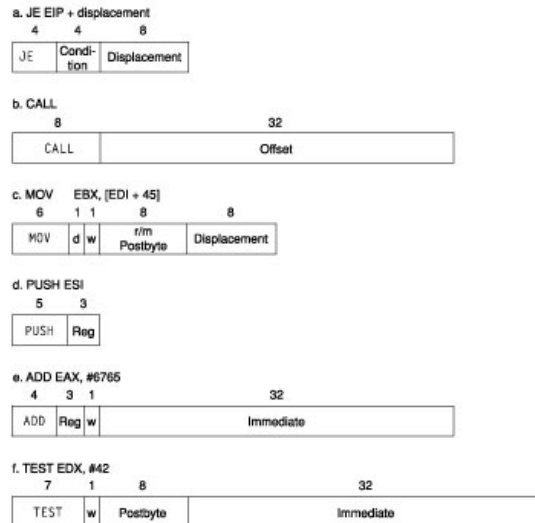
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X86 operations

- Destination for operations can be register or memory
- Source can be register, memory or immediate
- Data movement: move, push, pop
- ALU operations
- Control flow: conditional branches, unconditional jumps, calls, returns
- String instructions: move, compare
 - MOVS: copies from string source to destination, incrementing ESI and EDI; may be repeated
 - Often slower than equivalent software loop

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X86 encoding



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RISC vs. CISC

- Long ago, assembly programming was very common
 - And memories were much smaller
 - CISC gives more programming power and can reduce code size
- Nowadays, most programming is done with high-level languages and compilers
 - Compilers do not use all CISC instructions
 - Simpler is better from an implementation standpoint – more on this during class
- Support for legacy codes and volume
 - Push for continued support of CISC ISAs like x86
- Compromise approach
 - Present CISC ISA to the ‘outside world’
 - Convert CISC instructions to RISC internally

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Next lecture

- Introduction to the logic design process
 - Refer to slides and Appendix C, sections C.5-C.6

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