ECE 485/585
Computer Organization and Design

Lecture 4: Instruction Set Architecture
Fall 2022

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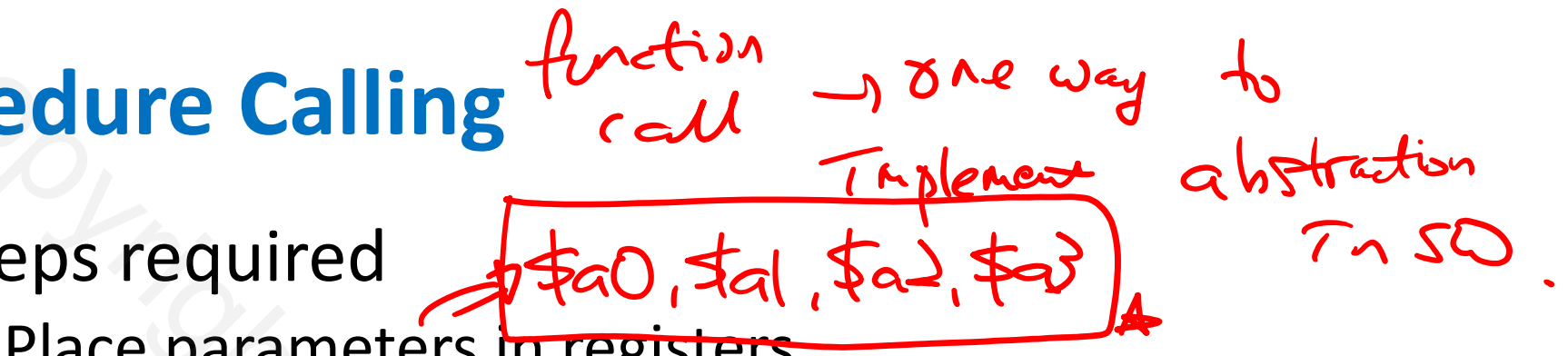
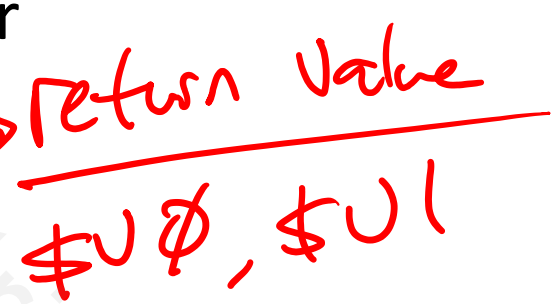
Procedure Calling

- Steps required
  1. Place parameters in registers
  2. Transfer control to procedure
  3. Acquire storage for procedure
  4. Perform procedure's operations
  5. Place result in register for caller
  6. Return to place of call

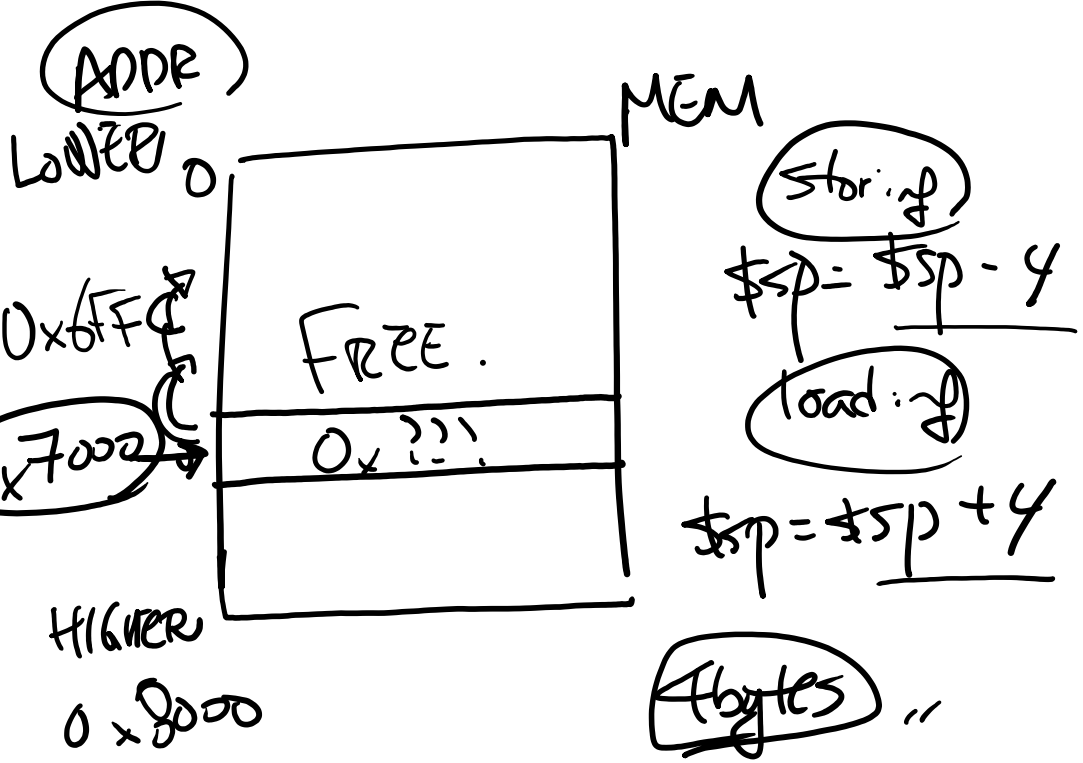




Register Usage

- $a0 – $a3: arguments (reg's 4 – 7)
- $v0, $v1: result values (reg's 2 and 3)
- $t0 – $t9: temporaries
  - Can be overwritten by callee
- $s0 – $s7: saved
  - Must be saved/restored by callee
- $gp: global pointer for static data (reg 28)
- $sp: stack pointer (reg 29)
- $fp: frame pointer (reg 30)
- $ra: return address (reg 31)

⇒ size of your current stack.



Name	Register number	Usage	Preserved on call?
$zero	0	The constant value 0	n.a.
$v0–$v1	2–3	Values for results and expression evaluation	no
$a0–$a3	4–7	Arguments	no
$t0–$t7	8–15	Temporaries	no
$s0–$s7	16–23	Saved	yes
$t8–$t9	24–25	More temporaries	no
$gp	28	Global pointer	yes
$sp	29	Stack pointer	yes
$fp	30	Frame pointer	yes
$ra	31	Return address	yes

Procedure Call Instructions

- Procedure call: jump and link

```
jal ProcedureLabel
```

  - Address of following instruction put in $ra
  - Jumps to target address

- Procedure return: jump register

```
jr $ra
```

  - Copies $ra to program counter
  - Can also be used for computed jumps
    - e.g., for case/switch statements

Leaf Procedure Example

- C code:

```
int leaf_example (int g, h, i, j)
{ int f;
  f = (g + h) - (i + j);
  return f;
}
```

  - Arguments g, …, j in $a0, …, $a3
  - f in $s0 (hence, need to save $s0 on stack)
  - Result in $v0

Leaf Procedure Example

- MIPS code:

```
leaf_example:
    addi $sp, $sp, -4
    sw   $s0, 0($sp)
    add  $t0, $a0, $a1
    add  $t1, $a2, $a3
    sub  $s0, $t0, $t1
    add  $v0, $s0, $zero
    lw   $s0, 0($sp)
    addi $sp, $sp, 4
    jr   $ra
```

Save $s0 on stack

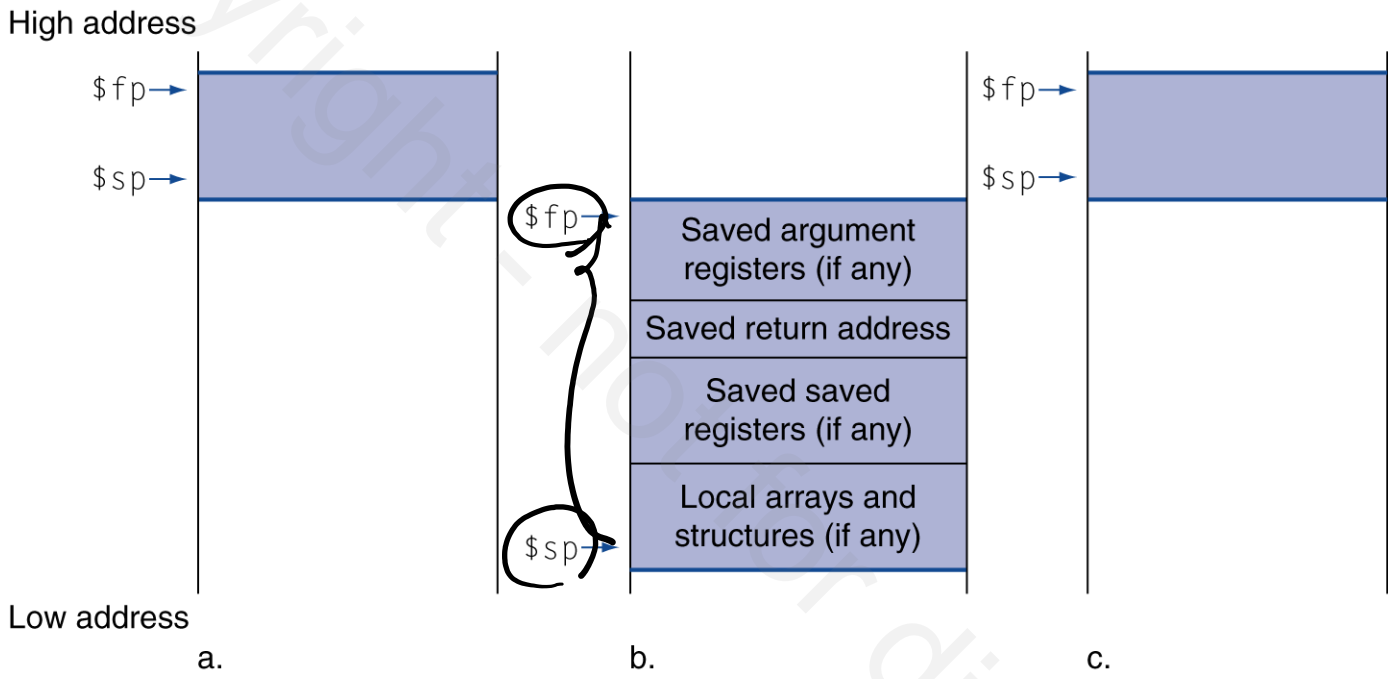
Procedure body

Result

Restore $s0

Return

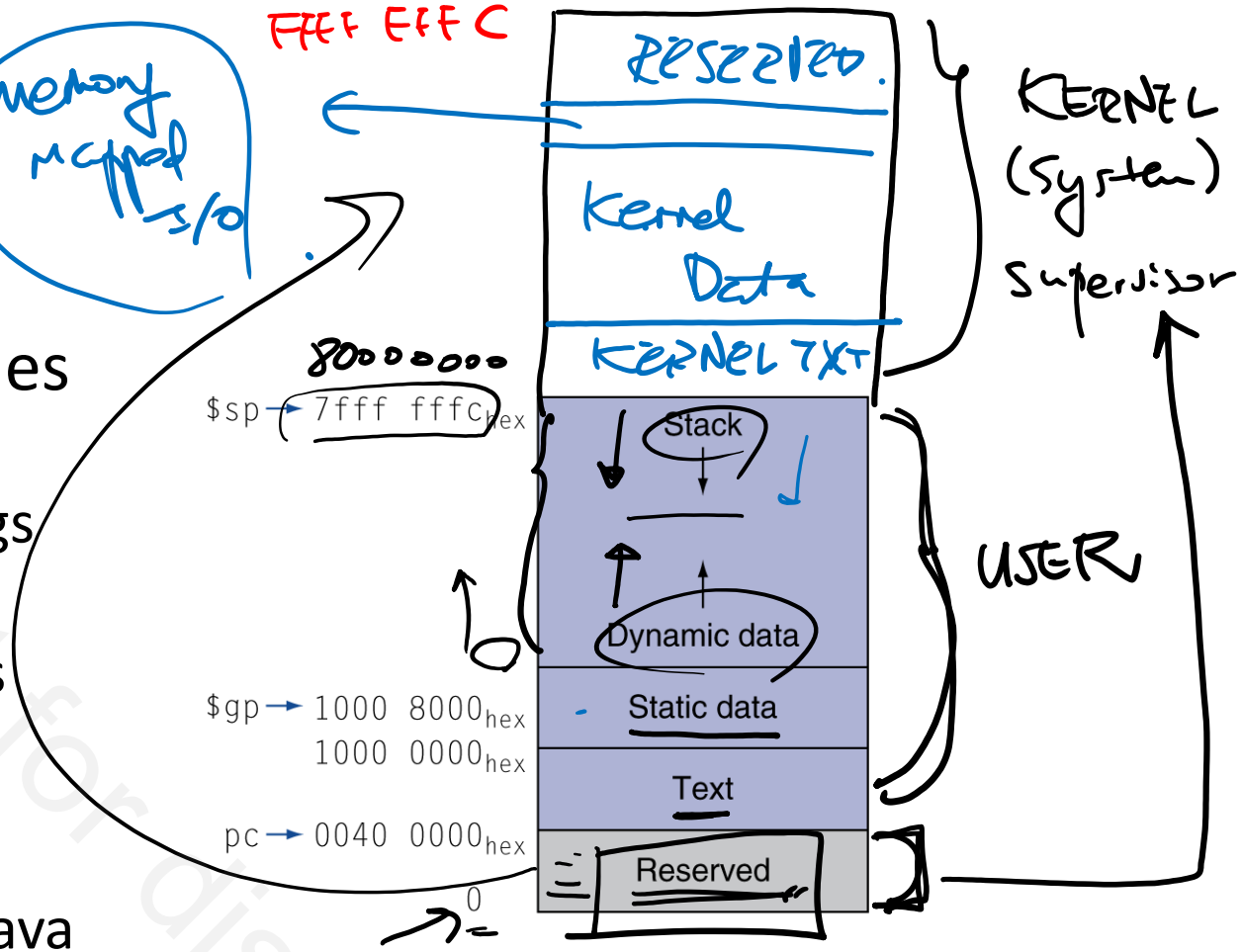
Local Data on the Stack



- Local data allocated by callee
  - e.g., C automatic variables
- Procedure frame (activation record)
  - Used by some compilers to manage stack storage

Memory Layout

- Text: program code
- Static data: global variables
  - e.g., static variables in C, constant arrays and strings
  - $gp initialized to address allowing ±offsets into this segment
- Dynamic data: heap
  - E.g., malloc in C, new in Java
- Stack: automatic storage



Character Data

- Byte-encoded character sets
  - ASCII: 128 characters
    - 95 graphic, 33 control
  - Latin-1: 256 characters
    - ASCII, +96 more graphic characters
- Unicode: 32-bit character set
  - Used in Java, C++ wide characters, …
  - Most of the world's alphabets, plus symbols
  - UTF-8, UTF-16: variable-length encodings

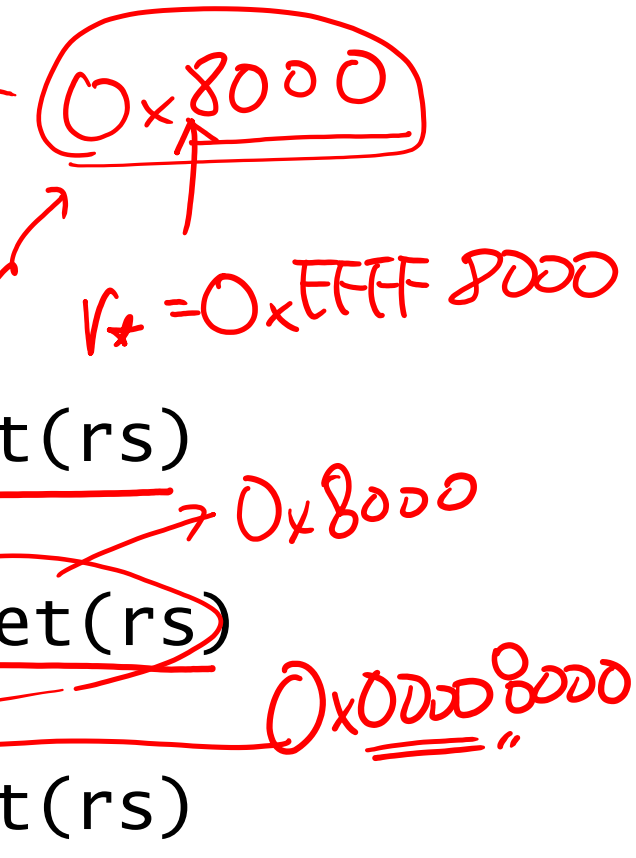
ASCII Representation

ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter	ASCII value	Char-acter
32	space	48	0	64	@	80	P	96	`	112	p
33	!	49	1	65	A	81	Q	97	a	113	q
34	"	50	2	66	B	82	R	98	b	114	r
35	#	51	3	67	C	83	S	99	c	115	s
36	$	52	4	68	D	84	T	100	d	116	t
37	%	53	5	69	E	85	U	101	e	117	u
38	&	54	6	70	F	86	V	102	f	118	v
39	'	55	7	71	G	87	W	103	g	119	w
40	(	56	8	72	H	88	X	104	h	120	x
41	)	57	9	73	I	89	Y	105	i	121	y
42	*	58	:	74	J	90	Z	106	j	122	z
43	+	59	;	75	K	91	[	107	k	123	{
44	,	60	<	76	L	92	\	108	l	124	|
45	-	61	=	77	M	93	]	109	m	125	}
46	.	62	>	78	N	94	^	110	n	126	~
47	/	63	?	79	O	95	_	111	o	127	DEL

Byte/Halfword Operations

- Could use bitwise operations
- MIPS byte/halfword load/store
  - String processing is a common case

`lb rt, offset(rs)`	`lh rt, offset(rs)`
• Sign extend to 32 bits in rt	
`lbu rt, offset(rs)`	`lhu rt, offset(rs)`
• Zero extend to 32 bits in rt	
`sb rt, offset(rs)`	`sh rt, offset(rs)`
• Store just rightmost byte/halfword	



Endian { BIG : most significant byte of the data will be stored in the least significant byte address

LITTLE : most significant byte of the data will be stored in the most significant byte address.

Ex) lb $t0, 0($t1)

↳ 0x10010000 ⟹ Value 0x55667788

0101 0101

0x00000055

Signed ext.

i) BIG ENDIAN $t0 = ?

ii) LITTLE ENDIAN $t0 = > 0xFFFFFF88

10001000

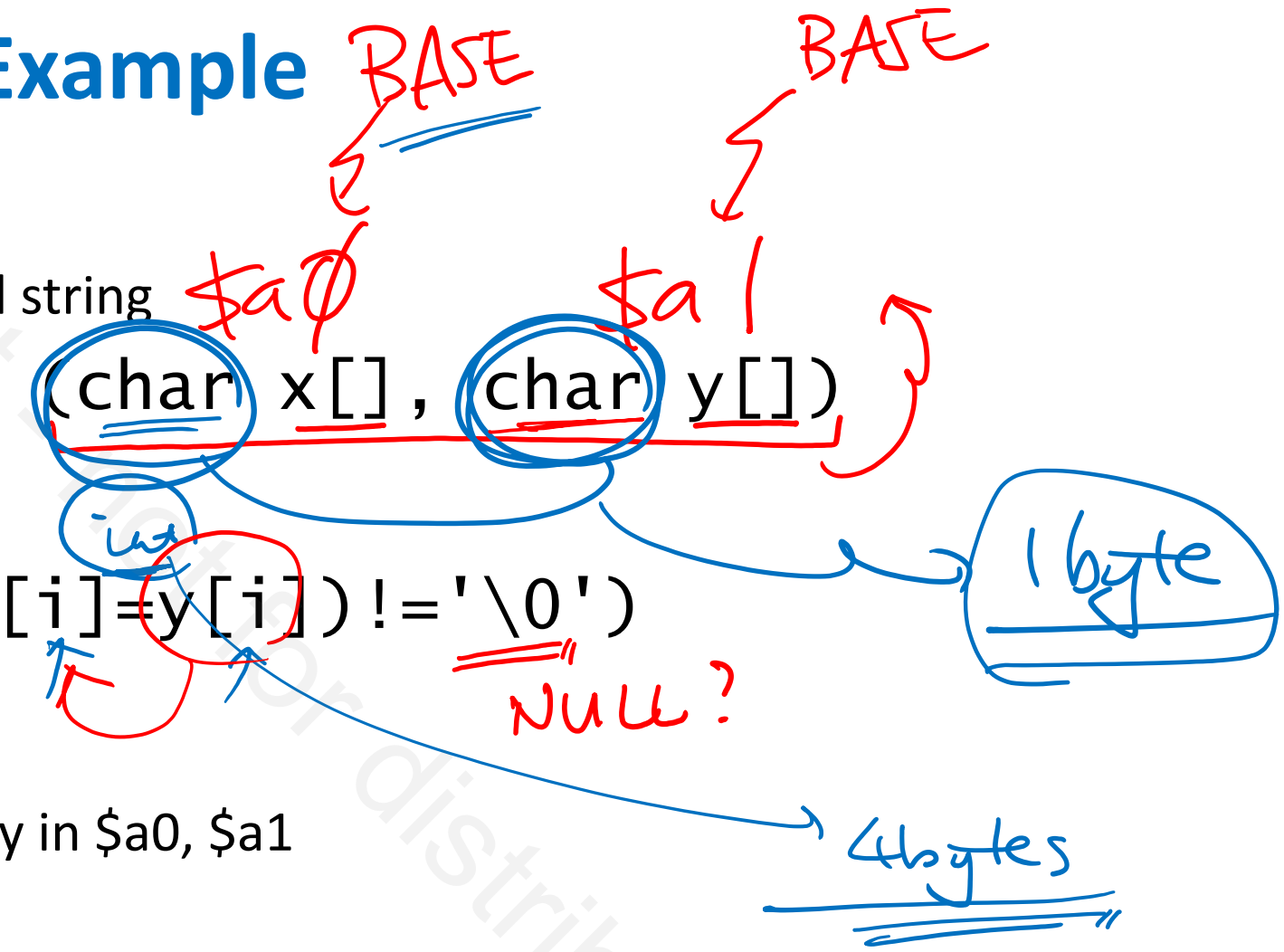
lbu

String Copy Example

- C code (naïve):
  - Null-terminated string

```
void strcpy (char x[], char y[])
{ int i;
  i = 0;
  while ((x[i]=y[i])!='\0')
    i += 1;
}
```

  - Addresses of x, y in $a0, $a1
  - i in $s0

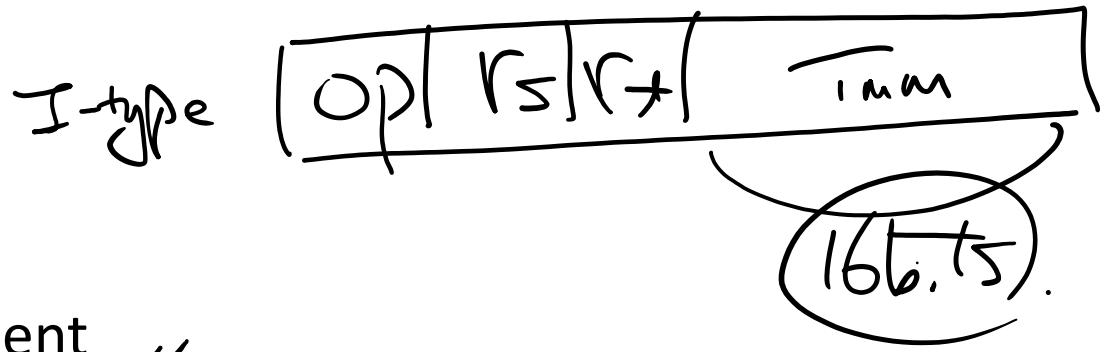


String Copy Example

- MIPS code:

```
strcpy:
    addi $sp, $sp, -4       # adjust stack for 1 item
    sw   $s0, 0($sp)        # save $s0
    add  $s0, $zero, $zero  # i = 0
L1: add  $t1, $s0, $a1      # addr of y[i] in $t1
    lbu  $t2, 0($t1)        # $t2 = y[i]
    add  $t3, $s0, $a0      # addr of x[i] in $t3
    sb   $t2, 0($t3)        # x[i] = y[i]
    beq  $t2, $zero, L2     # exit loop if y[i] == 0
    addi $s0, $s0, 1        # i = i + 1
    j    L1                 # next iteration of loop
L2: lw   $s0, 0($sp)        # restore saved $s0
    addi $sp, $sp, 4        # pop 1 item from stack
    jr   $ra                # and return
```

32-bit Constants



- Most constants are small
  - 16-bit immediate is sufficient
- For the occasional 32-bit constant

```
lui rt, constant
```

  - Copies 16-bit constant to left 16 bits of rt
  - Clears right 16 bits of rt to 0
- Example: load the following 32-bit constant to $s0
  - 0000 0000 0011 1101 0000 1001 0000 0000

li $s0,

MACRO FUNC.

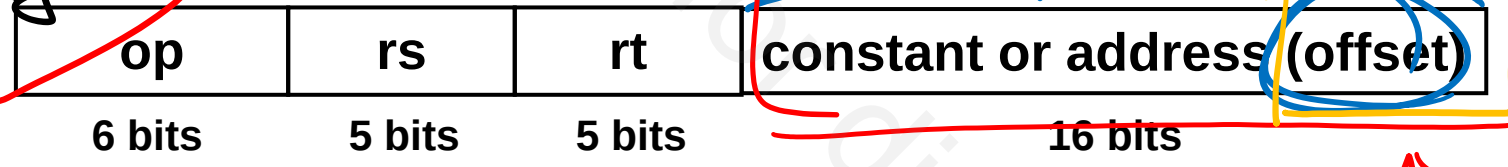
$s0

```
lui $s0, 61
ori $s0, $s0, 2304
```

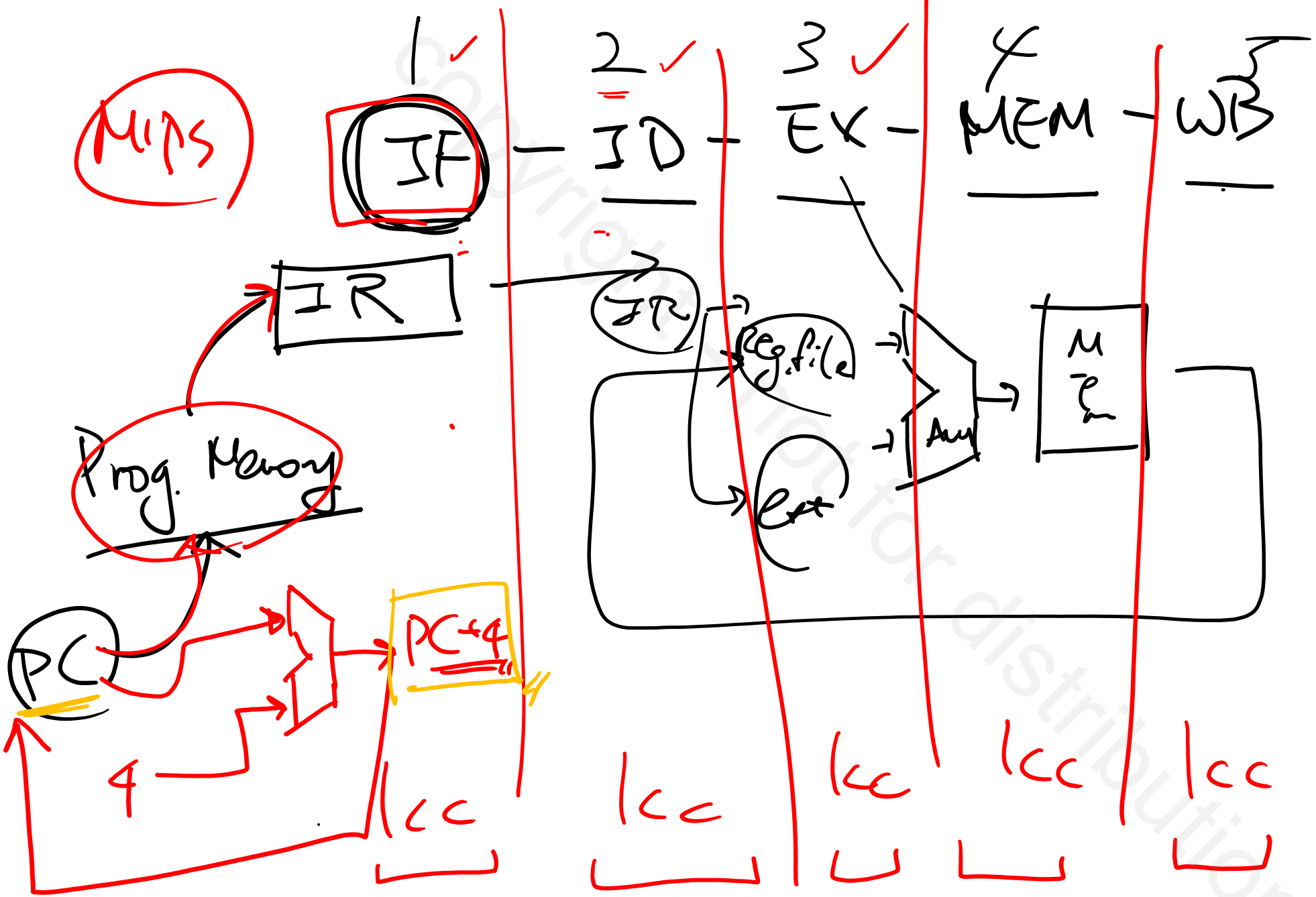
0000 0000 0011 1101	0000 0000 0000 0000
0000 0000 0011 1101	0000 1001 0000 0000

Branch Addressing

- Branch instructions specify
  - Opcode, two registers, target address
- Most branch targets are near branch
  - Forward or backward

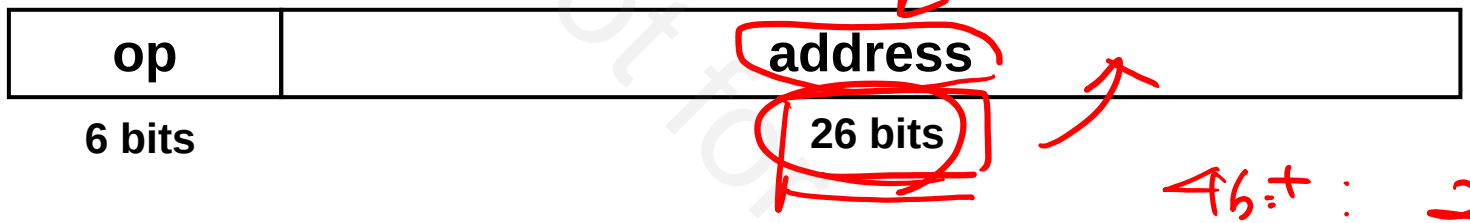


- **PC-relative addressing**
  - **Target address = PC + offset × 4**
  - **PC already incremented by 4 by this time**



Jump Addressing

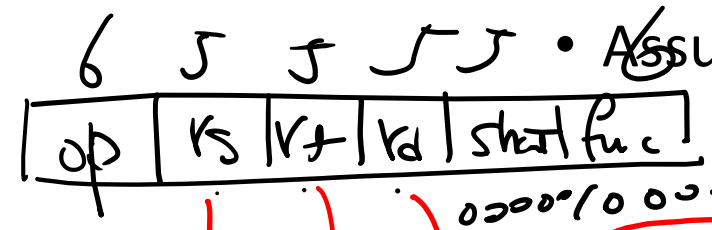
- Jump (`j` and `jal`) targets could be anywhere in text segment
  - Encode full address in instruction



- **(Pseudo)Direct jump addressing**
  - **Target address = $PC_{31...28}$: (address × 4)**

Target Addressing Example

- Loop code from earlier example
- Assume Loop at location 80000




```
Loop: sll  $t1, $s3, 2
      add  $t1, $t1, $s6
      lw   $t0, 0($t1)
      bne  $t0, $s5, Exit
      addi $s3, $s3, 1
      j    Loop
Exit: …
```

Addr	op	rs	rt	rd	shamt	func
0x80000	0	0	19	9	4	0
0x80004	0	9	22	9	0	32
0x80008	35	9	8	0		
0x8000C	5	8	21	2		
0x80010	8	19	19	1		
0x80014	2	20000				
0x80018						

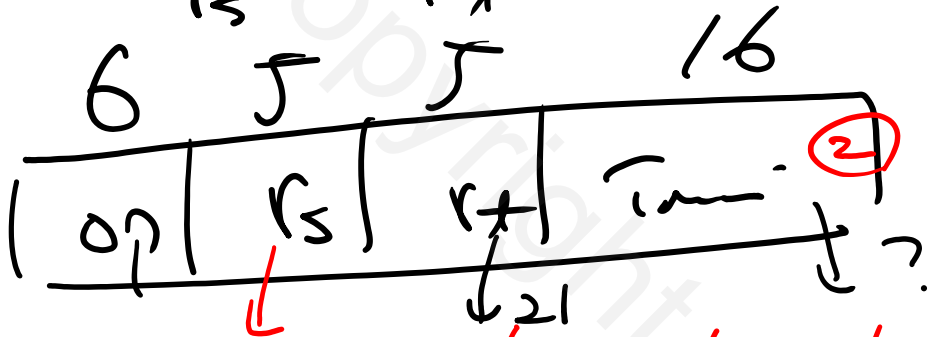
000000 01001 10110 01001 00000 100000 = 0x01364820

① bne $t0, $s5, Exit

Imm.

Exit Label

0x80018



I-type

target = PC + (offset × 4)

0x80018 = PC current + 4 + (Imm × 4)

0x80018 = 0x8000C + (Imm × 4)

2 = 0x80010 + (Imm × 4)

0x0 = Imm × 4

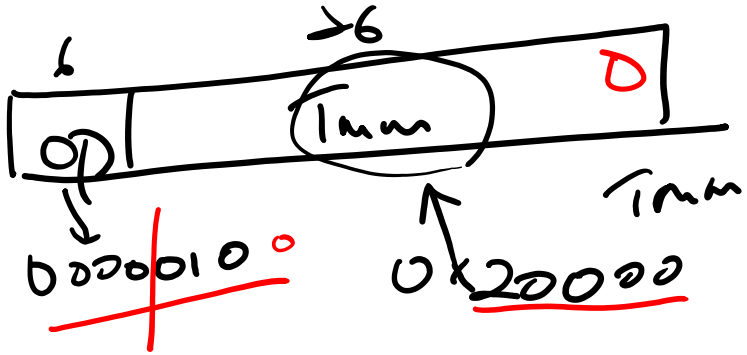
∴ Imm = 2

000101 01000 10101 0000 0000 0000 0010

∴ 0x150002

② J Loop → 0x80000

0x04020000



Imm × 4 = 0x80000

2

1000

0010

Branching Far Away

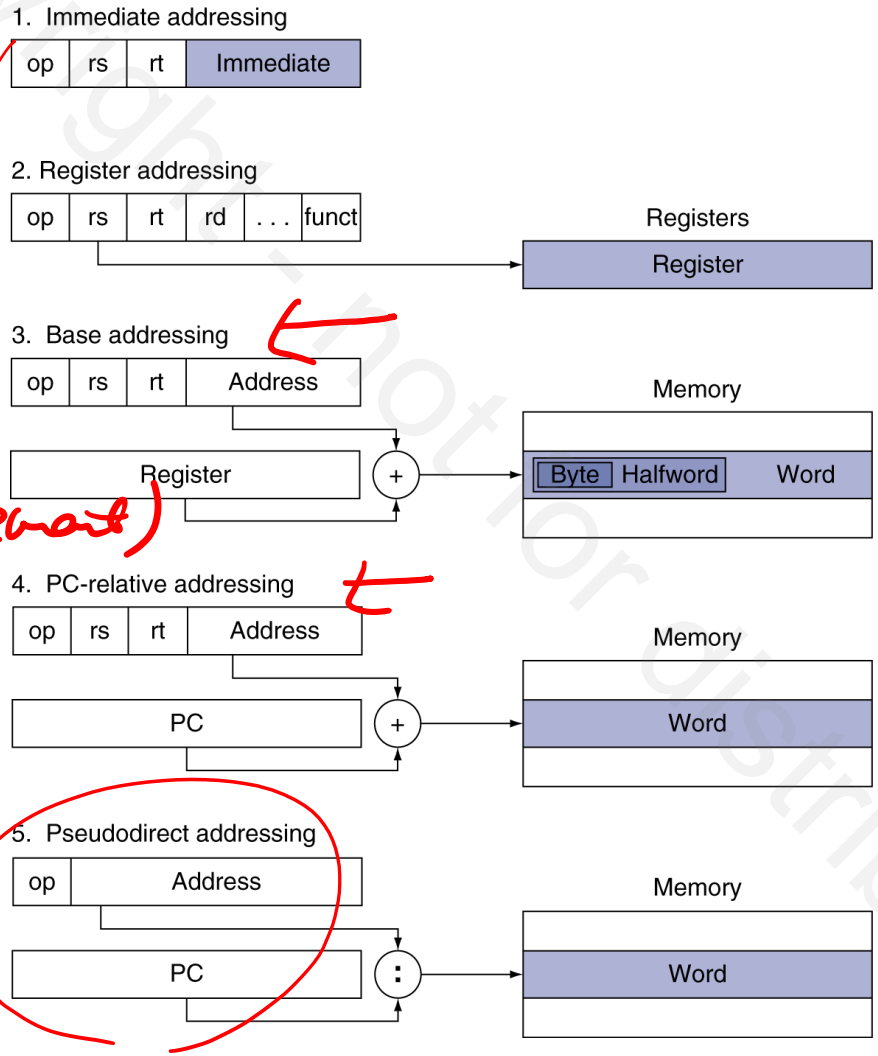
- If branch target is too far to encode with 16-bit offset, assembler rewrites the code
- Example

```
        beq $s0,$s1, L1
              ↓
        bne $s0,$s1, L2
        j L1
L2:     …
```

Addressing Mode Summary

3 modes

1. Register operand
2. Immediate operand
3. Register + offset (displacement)



Concluding Remarks

- Design principles
  1. Simplicity favors regularity
  2. Smaller is faster
  3. Make the common case fast
  4. Good design demands good compromises
- Layers of software/hardware
  - Compiler, assembler, hardware
- MIPS: typical of RISC ISAs
  - c.f. x86

Concluding Remarks

- Measure MIPS instruction executions in benchmark programs
  - Consider making the common case fast
  - Consider compromises

Instruction class	MIPS examples	SPEC2006 Int	SPEC2006 FP
Arithmetic	`add, sub, addi`	16%	48%
Data transfer	`lw, sw, lb, lbu, lh, lhu, sb, lui`	35%	36%
Logical	`and, or, nor, andi, ori, sll, srl`	12%	4%
Cond. Branch	`beq, bne, slt, slti, sltiu`	34%	8%
Jump	`j, jr, jal`	2%	0%

MIPS operands

Name	Example	Comments
32 registers	`$s0-$s7, $t0-$t9, $zero, $a0-$a3, $v0-$v1, $gp, $fp, $sp, $ra, $at`	Fast locations for data. In MIPS, data must be in registers to perform arithmetic, register `$zero` always equals 0, and register `$at` is reserved by the assembler to handle large constants.
2^{30} memory words	Memory[0], Memory[4], ..., Memory[4294967292]	Accessed only by data transfer instructions. MIPS uses byte addresses, so sequential word addresses differ by 4. Memory holds data structures, arrays, and spilled registers.

MIPS assembly language

Category	Instruction	Example	Meaning	Comments
Arithmetic	add	`add $s1,$s2,$s3`	$s1 = $s2 + $s3	Three register operands
	subtract	`sub $s1,$s2,$s3`	$s1 = $s2 – $s3	Three register operands
	add immediate	`addi $s1,$s2,20`	$s1 = $s2 + 20	Used to add constants
Data transfer	load word	`lw $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Word from memory to register
	store word	`sw $s1,20($s2)`	Memory[$s2 + 20] = $s1	Word from register to memory
	load half	`lh $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Halfword memory to register
	load half unsigned	`lhu $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Halfword memory to register
	store half	`sh $s1,20($s2)`	Memory[$s2 + 20] = $s1	Halfword register to memory
	load byte	`lb $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Byte from memory to register
	load byte unsigned	`lbu $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Byte from memory to register
	store byte	`sb $s1,20($s2)`	Memory[$s2 + 20] = $s1	Byte from register to memory
	load linked word	`ll $s1,20($s2)`	$s1 = Memory[$s2 + 20]	Load word as 1st half of atomic swap
	store condition. word	`sc $s1,20($s2)`	Memory[$s2+20]=$s1;$s1=0 or 1	Store word as 2nd half of atomic swap
	load upper immed.	`lui $s1,20`	$s1 = 20 * 2^{16}	Loads constant in upper 16 bits
Logical	and	`and $s1,$s2,$s3`	$s1 = $s2 & $s3	Three reg. operands; bit-by-bit AND
	or	`or $s1,$s2,$s3`	$s1 = $s2 | $s3	Three reg. operands; bit-by-bit OR
	nor	`nor $s1,$s2,$s3`	$s1 = ~ ($s2 | $s3)	Three reg. operands; bit-by-bit NOR
	and immediate	`andi $s1,$s2,20`	$s1 = $s2 & 20	Bit-by-bit AND reg with constant
	or immediate	`ori $s1,$s2,20`	$s1 = $s2 | 20	Bit-by-bit OR reg with constant
	shift left logical	`sll $s1,$s2,10`	$s1 = $s2 << 10	Shift left by constant
	shift right logical	`srl $s1,$s2,10`	$s1 = $s2 >> 10	Shift right by constant
Conditional branch	branch on equal	`beq $s1,$s2,25`	if ($s1 == $s2) go to PC + 4 + 100	Equal test; PC-relative branch
	branch on not equal	`bne $s1,$s2,25`	if ($s1!= $s2) go to PC + 4 + 100	Not equal test; PC-relative
	set on less than	`slt $s1,$s2,$s3`	if ($s2 < $s3) $s1 = 1; else $s1 = 0	Compare less than; for `beq`, `bne`
	set on less than unsigned	`sltu $s1,$s2,$s3`	if ($s2 < $s3) $s1 = 1; else $s1 = 0	Compare less than unsigned
	set less than immediate	`slti $s1,$s2,20`	if ($s2 < 20) $s1 = 1; else $s1 = 0	Compare less than constant
	set less than immediate unsigned	`sltiu $s1,$s2,20`	if ($s2 < 20) $s1 = 1; else $s1 = 0	Compare less than constant unsigned
Unconditional jump	jump	`j 2500`	go to 10000	Jump to target address
	jump register	`jr $ra`	go to $ra	For switch, procedure return
	jump and link	`jal 2500`	$ra = PC + 4; go to 10000	For procedure call

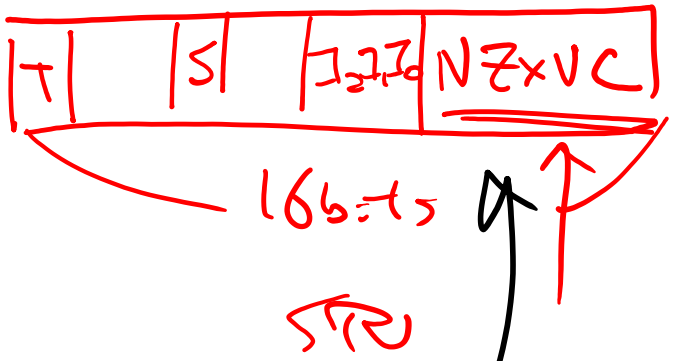
FIGURE 2.1 MIPS assembly language revealed in this chapter. This information is also found in Column 1 of the MIPS Reference Data Card at the front of this book.

ARM & MIPS Similarities

- ARM: the most popular embedded core
- Similar basic set of instructions to MIPS

	ARM	MIPS
Date announced	1985	1985
Instruction size	32 bits	32 bits
Address space	32-bit flat	32-bit flat
Data alignment	Aligned	Aligned
Data addressing modes	9	3
Registers	15 × 32-bit	31 × 32-bit
Input/output	Memory mapped	Memory mapped

Compare and Branch in ARM



- Uses condition codes for result of an arithmetic/logical instruction
  - Negative, zero, carry, overflow
  - Compare instructions to set condition codes without keeping the result
- Each instruction can be conditional
  - Top 4 bits of instruction word: condition value
  - Can avoid branches over single instructions

beq $t0, $t2, label

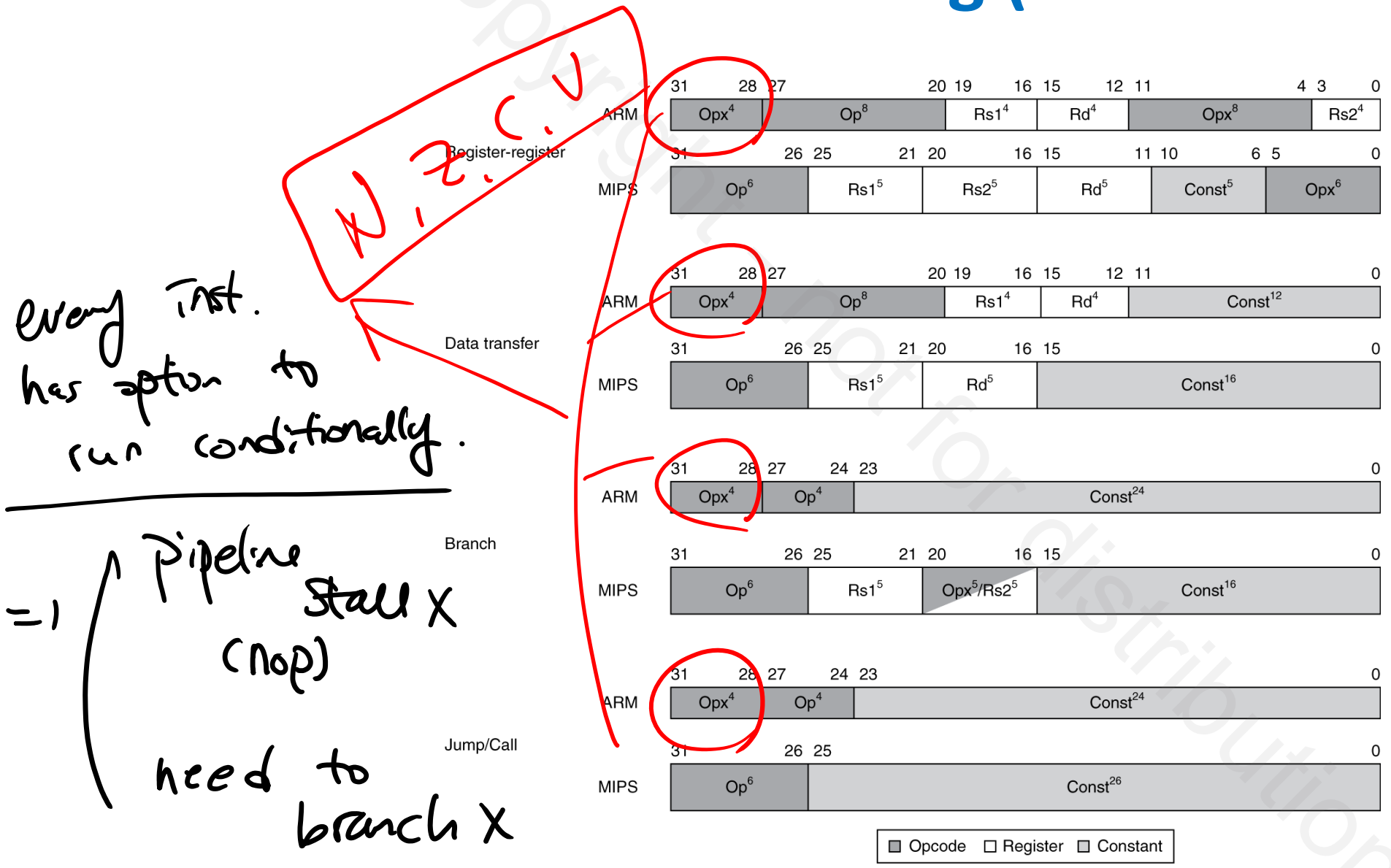
MIPS

SUB D3, D1

BEQ LABEL

MC68K

Instruction Encoding (ARM vs MIPS)



- C -

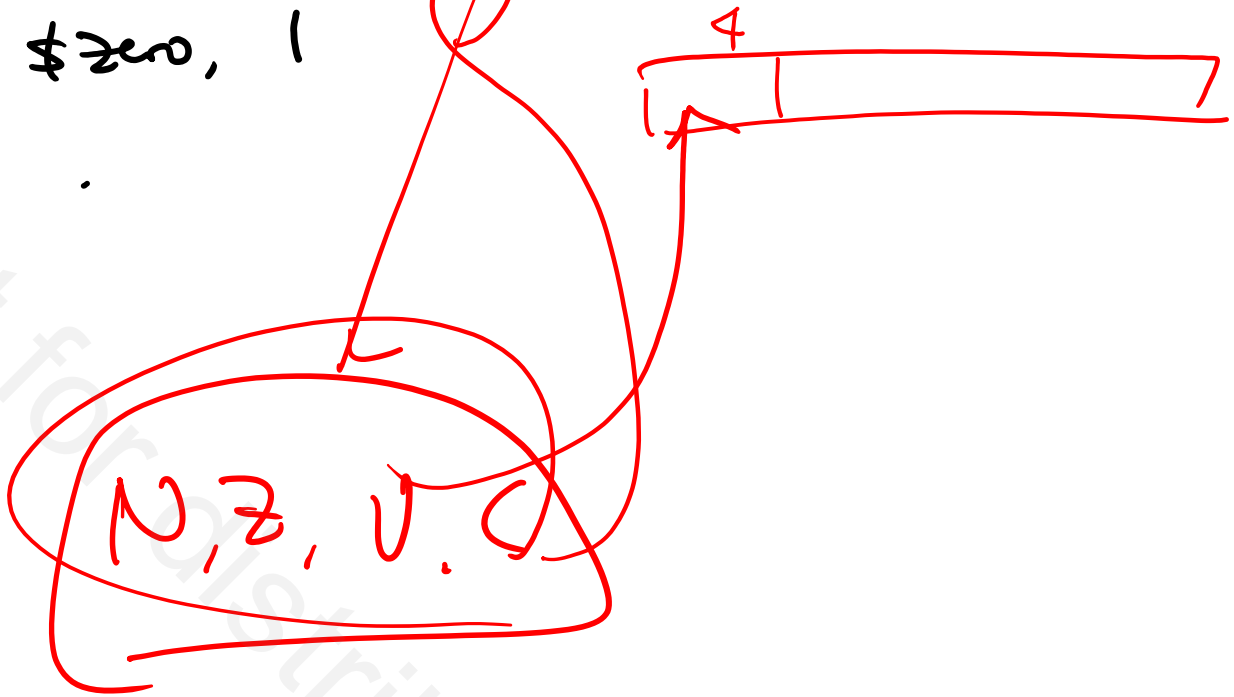
```
if (x <= 0)
    x = 0;
else
    x = 1;
```

- MIPS -

```
    bgt  $t0, $zero, LABEL1
    add  $t0, $zero, $zero
    j    Exit
LABEL1: add $t0, $zero, 1
Exit:   ~~~~~~~~~~~~~~~~~~
```

- ARM -

```
CMP   r0, #0
MOVLE r0, #0
MOVGT r0, #1
```



Addressing Modes

Addressing mode	ARM	MIPS
Register operand	X	X
Immediate operand	X	X
Register + offset (displacement or based)	X	X
Register + register (indexed)	X	—
Register + scaled register (scaled)	X	—
Register + offset and update register	X	—
Register + register and update register	X	—
Autoincrement, autodecrement	X	—
PC-relative data	X	—

FIGURE 2.33 Summary of data addressing modes. ARM has separate register indirect and register 1 offset addressing modes, rather than just putting 0 in the offset of the latter mode. To get greater addressing range, ARM shifts the offset left 1 or 2 bits if the data size is halfword or word.

Addressing Modes

	Instruction name	ARM	MIPS
Register-register	Add	add	addu, addiu
	Add (trap if overflow)	adds; swivs	add
	Subtract	sub	subu
	Subtract (trap if overflow)	subs; swivs	sub
	Multiply	mul	mult, multu
	Divide	—	div, divu
	And	and	and
	Or	orr	or
	Xor	eor	xor
	Load high part register	—	lui
	Shift left logical	lsl[1]	sllv, sll
	Shift right logical	lsr[1]	srlv, srl
	Shift right arithmetic	asr[1]	srav, sra
	Compare	cmp, cmn, tst, teq	slt/i,slt/iu
Data transfer	Load byte signed	ldrsb	lb
	Load byte unsigned	ldrb	lbu
	Load halfword signed	ldrsh	lh
	Load halfword unsigned	ldrh	lhu
	Load word	ldr	lw
	Store byte	strb	sb
	Store halfword	strh	sh
	Store word	str	sw
	Read, write special registers	mrs, msr	move
	Atomic Exchange	swp, swpb	ll;sc

Unique Features of ARM

- ARM does not have $zero
  - Separate opcodes to perform some operations that MIPS can do with $zero
- ARM supports multiword arithmetic
  - Novel interpretation of 12-bit immediate field
    - 8 LSBs are zero-extended to 32-bit value
    - Then, rotated right by the number of bits specified in the first 4 bits of the field multiplied by 2
    - Capable of representing all powers of two in a 32-bit word
- Operand shifting not limited to immediate values
  - 2nd reg. of all arithmetic/logical operations has option to be shifted before the operation
- Has instructions to save groups of registers
  - Any of the 16 registers can be loaded/stored into a memory in a single instruction

Intel x86 ISA

- Evolution with backward compatibility
  - 8080 (1974): 8-bit microprocessor
    - Accumulator, plus 3 index-register pairs
  - 8086 (1978): 16-bit extension to 8080
    - Complex instruction set (CISC)
  - 8087 (1980): floating-point coprocessor
    - Adds FP instructions and register stack
  - 80286 (1982): 24-bit addresses, MMU
    - Segmented memory mapping and protection
  - 80386 (1985): 32-bit extension (now IA-32)
    - Additional addressing modes and operations
    - Paged memory mapping as well as segments

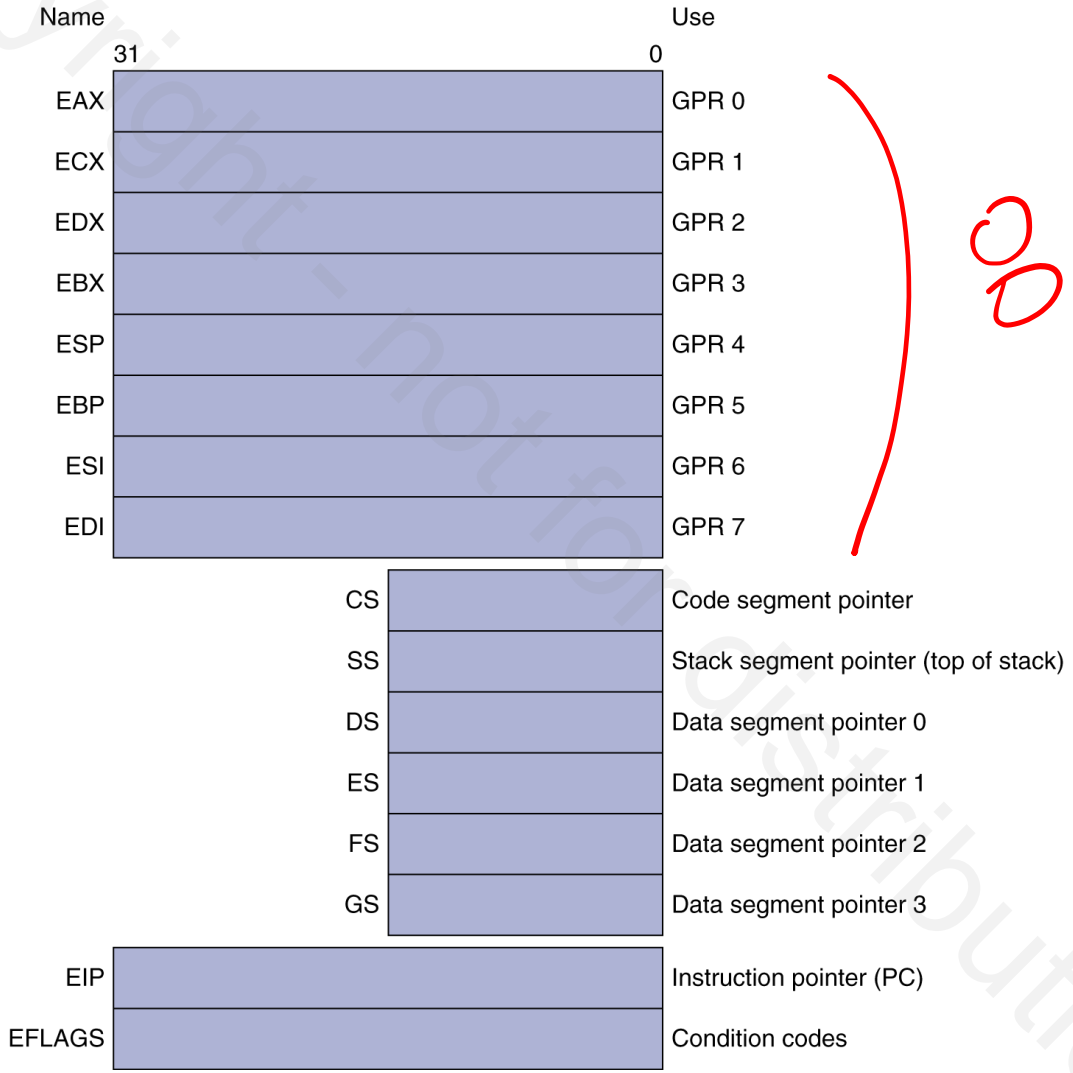
Intel x86 ISA

- Further evolution…
  - i486 (1989): pipelined, on-chip caches and FPU
    - Compatible competitors: AMD, Cyrix, …
  - Pentium (1993): superscalar, 64-bit datapath
    - Later versions added MMX (Multi-Media eXtension) instructions
    - The infamous FDIV bug
  - Pentium Pro (1995), Pentium II (1997)
    - New microarchitecture (see Colwell, *The Pentium Chronicles*)
  - Pentium III (1999)
    - Added SSE (Streaming SIMD Extensions) and associated registers
  - Pentium 4 (2001)
    - New microarchitecture
    - Added SSE2 instructions

Intel x86 ISA

- And further…
  - AMD64 (2003): extended architecture to 64 bits
  - EM64T – Extended Memory 64 Technology (2004)
    - AMD64 adopted by Intel (with refinements)
    - Added SSE3 instructions
  - Intel Core (2006)
    - Added SSE4 instructions, virtual machine support
  - AMD64 (announced 2007): SSE5 instructions
    - Intel declined to follow, instead…
  - Advanced Vector Extension (announced 2008)
    - Longer SSE registers, more instructions
- If Intel didn't extend with compatibility, its competitors would!
  - Technical elegance ≠ market success

Basic x86 Registers



Basic x86 Addressing Modes

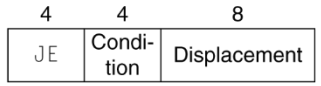
- Two operands per instruction

Source/dest operand	Second source operand
Register	Register
Register	Immediate
Register	Memory
Memory	Register
Memory	Immediate

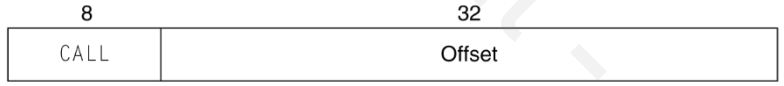
- Memory addressing modes
  - Address in register
  - Address = R_{base} + displacement
  - Address = $R_{base} + 2^{scale} \times R_{index}$ (scale = 0, 1, 2, or 3)
  - Address = $R_{base} + 2^{scale} \times R_{index}$ + displacement

x86 Instruction Encoding

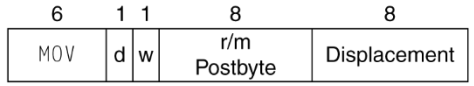
a. JE EIP + displacement



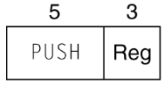
b. CALL



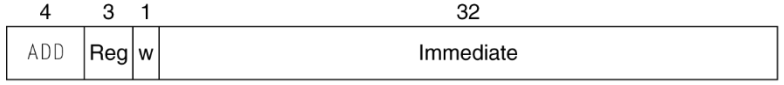
c. MOV EBX, [EDI + 45]



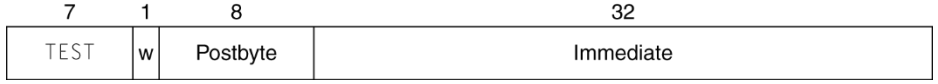
d. PUSH ESI



e. ADD EAX, #6765



f. TEST EDX, #42



- Variable length encoding
  - Postfix bytes specify addressing mode
  - Prefix bytes modify operation
    - Operand length, repetition, locking, …

Implementing IA-32

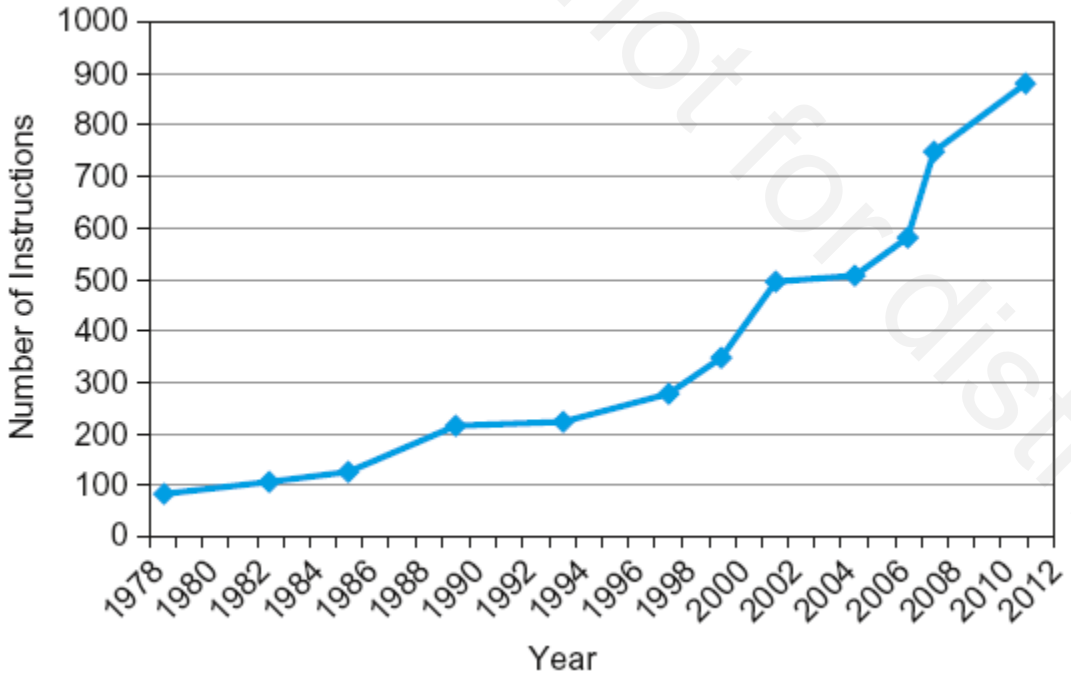
- Complex instruction set makes implementation difficult
  - Hardware translates instructions to simpler microoperations
    - Simple instructions: 1–1
    - Complex instructions: 1–many
  - Microengine similar to RISC
  - Market share makes this economically viable
- Comparable performance to RISC
  - Compilers avoid complex instructions

Fallacies

- Powerful instruction ⇒ higher performance
  - Fewer instructions required
  - But complex instructions are hard to implement
    - May slow down all instructions, including simple ones
  - Compilers are good at making fast code from simple instructions
- Use assembly code for high performance
  - But modern compilers are better at dealing with modern processors
  - More lines of code ⇒ more errors and less productivity

Fallacies

- Backward compatibility ⇒ instruction set doesn't change
  - But they do accrete more instructions



x86 instruction set