Lecture 4:

Instructions: Language of the Computer (3/3)

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Introduction to Computer Architecture

UC Davis EEC 170, Winter 2021

From last time . . .

- What instructions look like
  - RISC-V: 32 bit instructions, different types (R, I, S, and more)
  - RISC-V: Instructions either compute something or move something to/from memory
  - Last lecture: logical, branch, jump instructions
- Calling procedures
  - Arguments and return values
  - Jump instructions and return addresses
  - Saving registers and RISC-V register conventions
  - The stack, and memory regions

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

Byte/Halfword/Word Operations

- **RISC-V byte/halfword/word load/store**
  - **Load byte/halfword/word: Sign extend to 64 bits in rd**
    - `lb rd, offset(rs1)`
    - `lh rd, offset(rs1)`
    - `lw rd, offset(rs1)`
  - **Load byte/halfword/word unsigned: Zero extend to 64 bits in rd**
    - `lbu rd, offset(rs1)`
    - `lhu rd, offset(rs1)`
    - `lwu rd, offset(rs1)`
  - **Store byte/halfword/word: Store rightmost 8/16/32 bits**
    - `sb rs2, offset(rs1)`
    - `sh rs2, offset(rs1)`
    - `sw rs2, offset(rs1)`

String Copy Example

- C code:
  - Null-terminated string

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

// C idiom: while (*x++ = *y++);
```

String Copy Example

x19: save, use as temporary
x6, x7: don't save, also temporaries
arguments: x10 = &y, x11 = &x
no return value

- **RISC-V code:**

```
strcpy:
 addi sp,sp,-8    // adjust stack for 1 doubleword
 sd   x19,0(sp)   // push x19
 add  x19,x0,x0   // i=0 (x19 contains i)
L1: add x5,x19,x10 // x10 = &y; x5 = addr of y[i]
 lbu  x6,0(x5)    // x6 = y[i]
 add  x7,x19,x11  // x11 = &x; x7 = addr of x[i]
 sb   x6,0(x7)    // x[i] = y[i]
 beq  x6,x0,L2    // if y[i] == 0 then exit
 addi x19,x19, 1  // i = i + 1
 jal  x0,L1       // next iteration of loop
L2: ld x19,0(sp) // restore saved x19
 addi sp,sp,8     // pop 1 doubleword from stack
 jalr x0,0(x1)    // and return
```

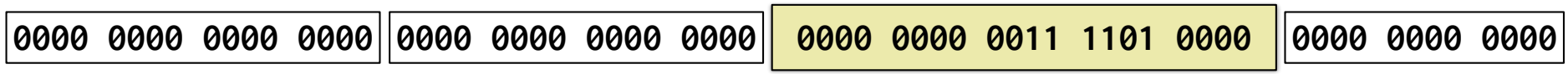
32-bit Constants

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

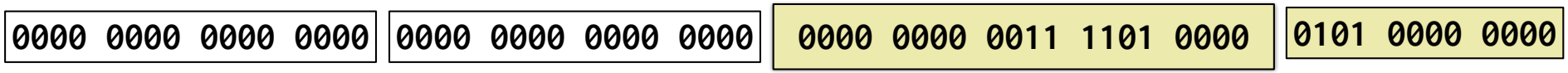
```
lui rd, constant
```


  - Copies 20-bit constant to bits [31:12] of rd
  - Extends bit 31 to bits [63:32]
  - Clears bits [11:0] of rd to 0


```
lui x19, 976    // 0x003D0
```

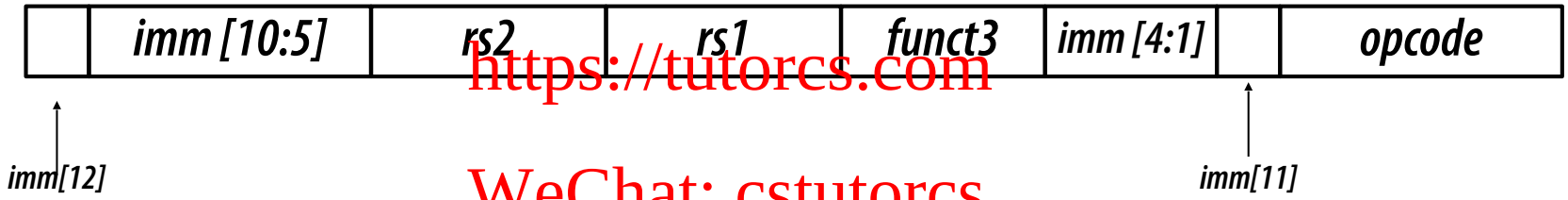



```
addi x19,x19,1280  // 0x500
```



Branch Addressing

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

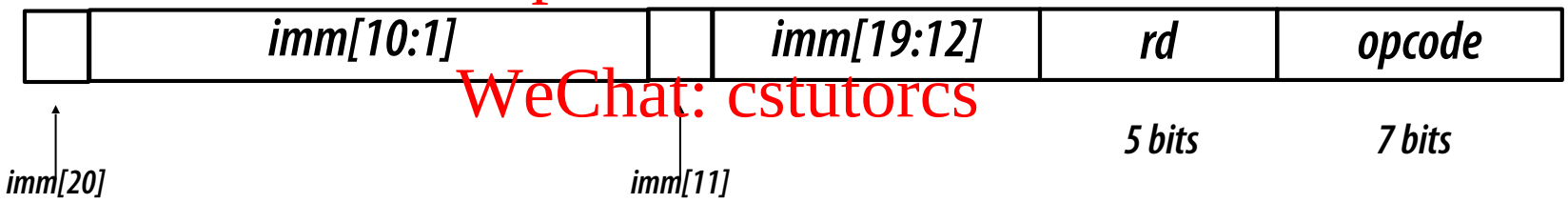


  - "The address uses an unusual encoding, which simplifies data path design but complicates assembly."
- PC-relative addressing
  - Target address = PC + immediate × 2
  - Why 2? "The RISC-V architects wanted to support the possibility of instructions that are 2 bytes long."

Jump Addressing

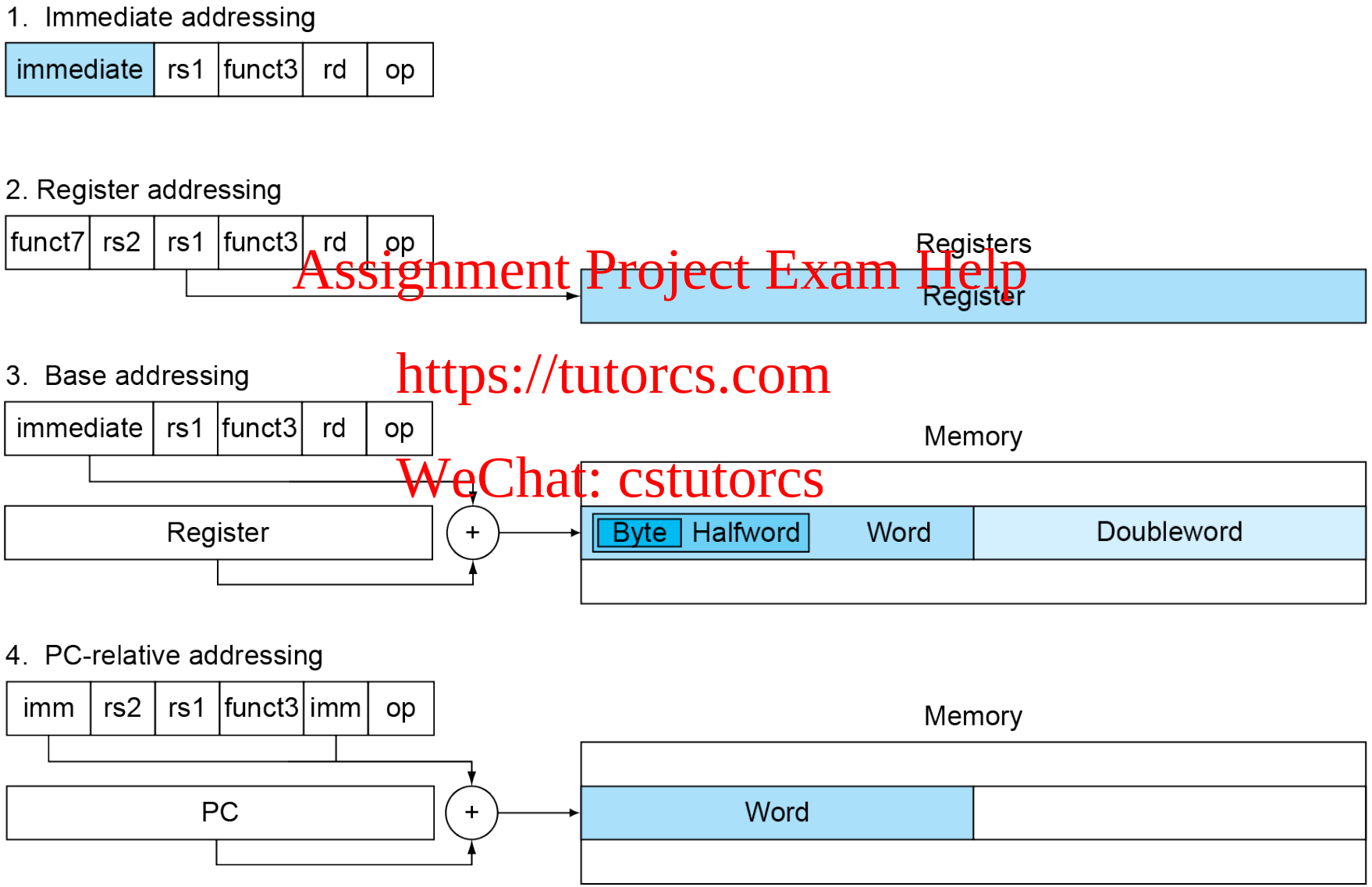
- Jump and link (jal) target uses 20-bit immediate for larger range
  - Also uses PC-relative addressing
  - Use `jal x0, Label` to jump (goto) to `Label` (unconditional jump)

- UJ format:



- For long jumps, eg, to 32-bit absolute address
  - lui: load address[31:12] to temp register
  - jalr: add address[11:0] and jump to target

RISC-V Addressing Summary



RISC-V Encoding Summary

Name (Field Size)	Field 7 bits	5 bits	5 bits	3 bits	5 bits	7 bits	Comments
R-type	funct7	rs2	rs1	funct3	rd	opcode	Arithmetic instruction format
I-type	immediate[11:0]		rs1	funct3	rd	opcode	Loads & immediate arithmetic
S-type	immed[11:5]	rs2	rs1	funct3	immed[4:0]	opcode	Stores
SB-type	immed[12,10:5]	rs2	rs1	funct3	immed[4:1,11]	opcode	Conditional branch format
UJ-type	immediate[20,10:1,11,19:12]				rd	opcode	Unconditional jump format
U-type	immediate[31:12]				rd	opcode	Upper immediate format

Synchronization

- Two processors sharing an area of memory
  - P1 writes, then P2 reads
  - Data race if P1 and P2 don't synchronize
    - Result depends of order of accesses
- Example (next slide):
  - load balance from memory to register
  - add $1 to register value
  - store balance from register to memory

Synchronization example

Suppose two cash machines, A and B, are both working on a deposit at the same time. Here's how the deposit() step typically breaks down into low-level processor instructions:

```
get balance (balance=0)
add 1
write back the result (balance=1)
```

When A and B are running concurrently, these low-level instructions interleave with each other (some might even be simultaneous in some sense, but let's just worry about interleaving for now):


```
A get balance (balance=0)
A add 1
A write back the result (balance=1)
                                    B get balance (balance=1)
                                    B add 1
                                    B write back the result (balance=2)
```

This interleaving is fine – we end up with balance 2, so both A and B successfully put in a dollar. But what if the interleaving looked like this:

```
A get balance (balance=0)
                                    B get balance (balance=0)
A add 1
                                    B add 1
A write back the result (balance=1)
                                    B write back the result (balance=1)
```

Synchronization

- Two processors sharing an area of memory
  - P1 writes, then P2 reads
  - Data race if P1 and P2 don't synchronize
    - Result depends of order of accesses
- Hardware support required
  - Atomic read/write memory operation
  - No other access to the location allowed between the read and write
- Could be a single instruction
  - E.g., atomic swap of register ↔ memory
  - Or an atomic pair of instructions

Synchronization in RISC-V

- Load reserved: `lr.d rd,(rs1)`
  - Load from address in rs1 to rd
  - Place reservation on memory address
- Store conditional: `sc.d rd,(rs1),rs2`
  - Store from rs2 (the value to be stored) to address in rs1
  - Succeeds if location not changed since the `lr.d`
    - Returns 0 in rd
  - Fails if location is changed
    - Returns non-zero value in rd

Synchronization in RISC-V

- **Example 1: atomic swap (to test/set lock variable)**

```
again:  lr.d x10,(x20)
        sc.d x11,(x20),x23 // X11 = status
        bne  x11,x0,again  // branch if store failed
        addi x23,x10,0     // X23 = loaded value
                           // X23 and Mem[x20] have swapped
```

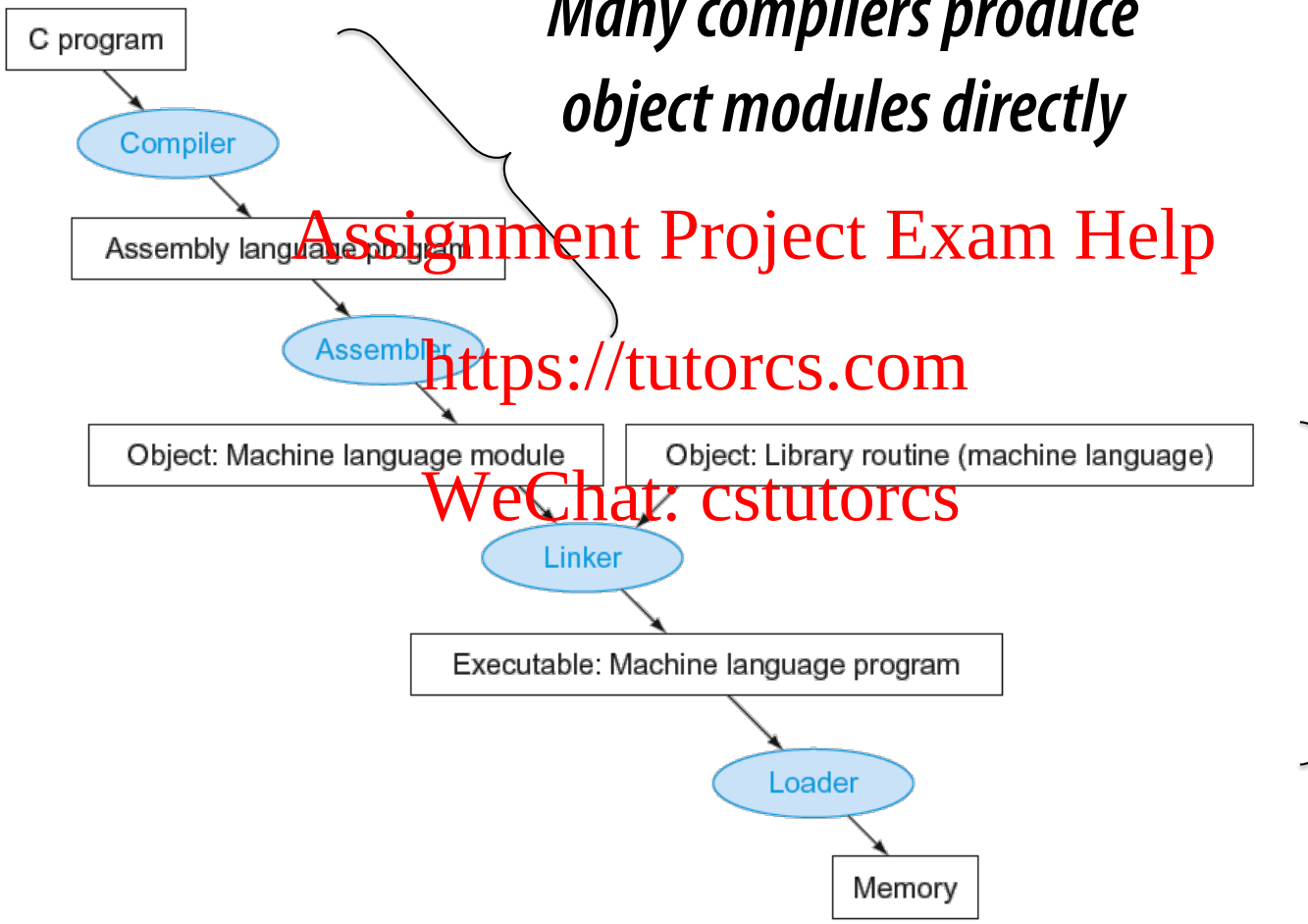

- **Example 2: lock**

```
        addi x12,x0,1      // "locked" == 1
again:  lr.d x10,(x20)     // read lock
        bne  x10,x0,again  // check if it is 0 yet
        sc.d x11,(x20),x12 // attempt to store "locked" == 1
        bne  x11,x0,again  // branch if fails
```

- **Unlock:**

```
        sd   x0,0(x20)     // free lock
```

Translation and Startup



Assembler tasks

- Translate assembly instructions into binary
- Do stuff that makes assembly writers' job easier
  - Translate labels to offsets (`beq a1, a2, Label`)
  - Pseudoinstructions:
    - `li` is "load immediate" (load a number into a register), not in instruction set
    - If it's small enough, assembler generates `addi`
    - If it's bigger, `lui` then `addi`
    - `mv` is a copy instruction (not in instruction set)

Producing an Object Module

- Assembler (or compiler) translates program into machine instructions
- Provides information for building a complete program from the pieces (following is Unix):
  - Header: describes contents of object module
  - Text segment: machine code
  - Static data segment: data allocated for the life of the program
  - Relocation info: which instructions/data words depend on absolute addresses in this program?
    - Address space layout randomization (e.g.) requires this
  - Symbol table: labels that are not defined (external references)
  - Debug info: for associating with source code

Linking Object Modules

- Much faster to link than recompile
- Produces an executable image
  1. Merges segments
  2. Resolve labels (determine their addresses)
  3. Patch location-dependent and external refs
- Could leave location dependencies for fixing by a relocating loader
  - But with virtual memory, no need to do this
  - Program can be loaded into absolute location in virtual memory space
- Nice example in the book (p. 128)

Loading a Program

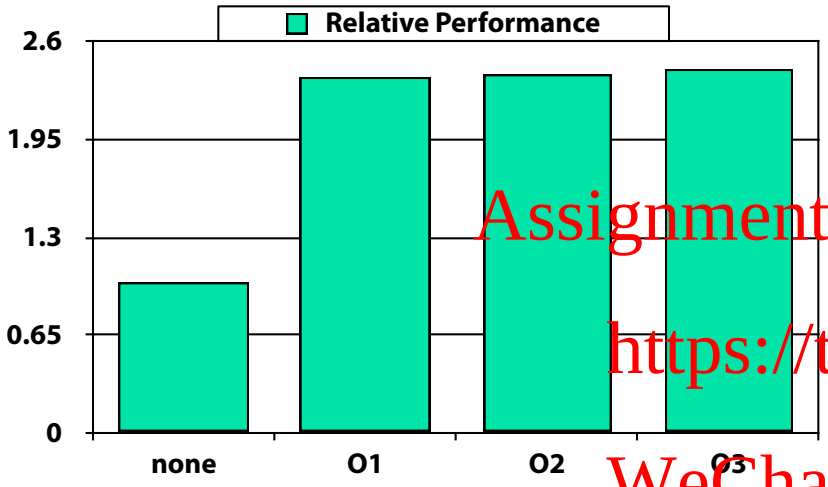
- Load from image file on disk into memory
  1. Read header to determine segment sizes
  2. Create virtual address space
  3. Copy text and initialized data into memory
     - Or set page table entries so they can be faulted in
  4. Set up arguments on stack
  5. Initialize registers (including sp, fp, gp)
  6. Jump to startup routine
     - Copies arguments to x10, … and calls main
     - When main returns, do exit syscall

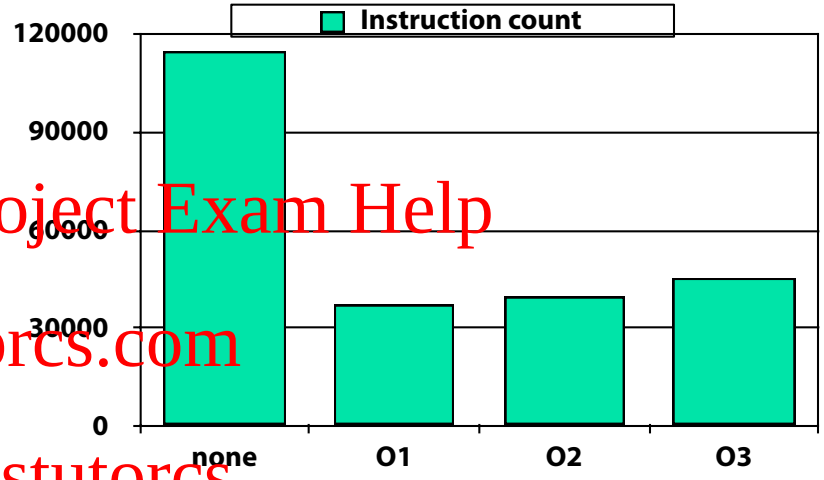
Dynamic Linking

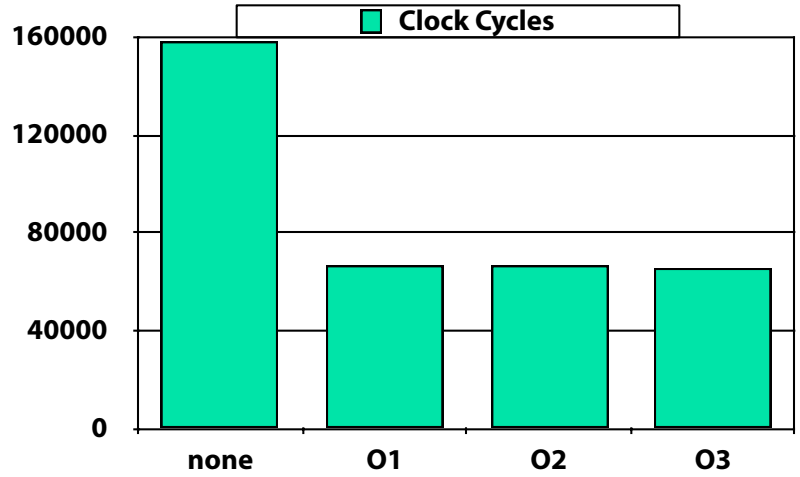
- Only link/load library procedure when it is called
  - Requires procedure code to be relocatable
  - Avoids image bloat caused by static linking of all (transitively) referenced libraries
  - Automatically picks up new library versions

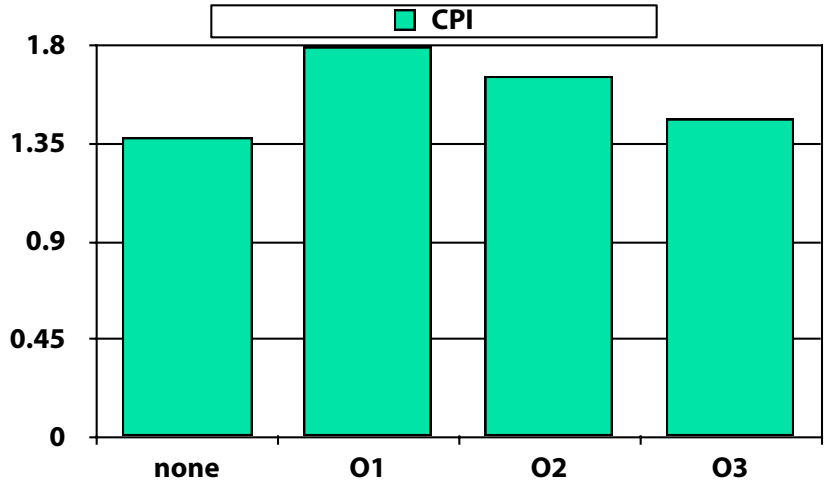
Effect of Compiler Optimization

- Compiled with gcc for Pentium 4 under Linux

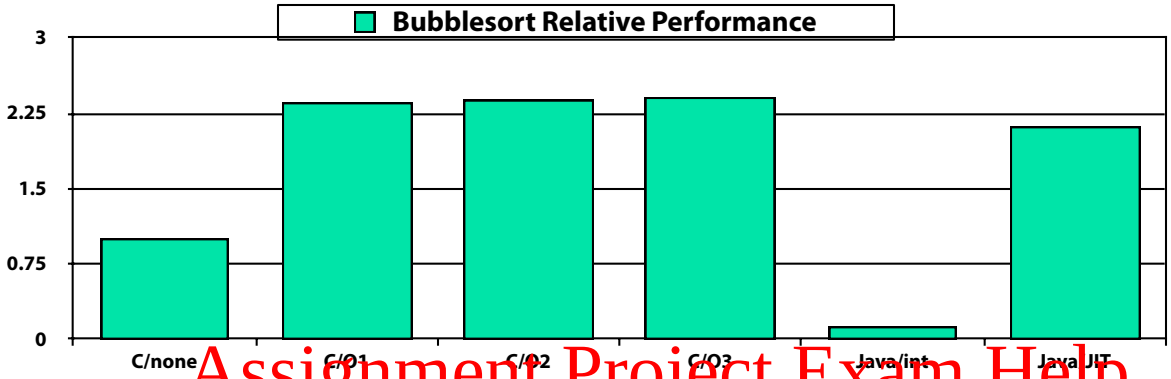


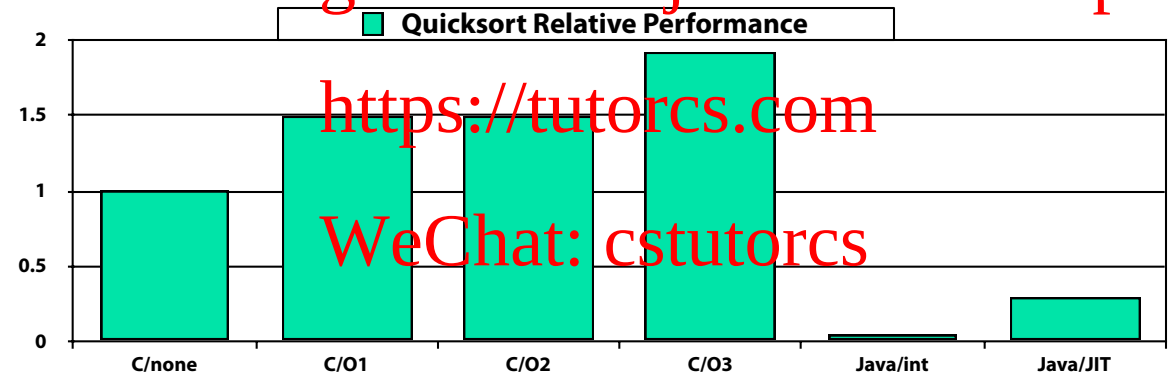


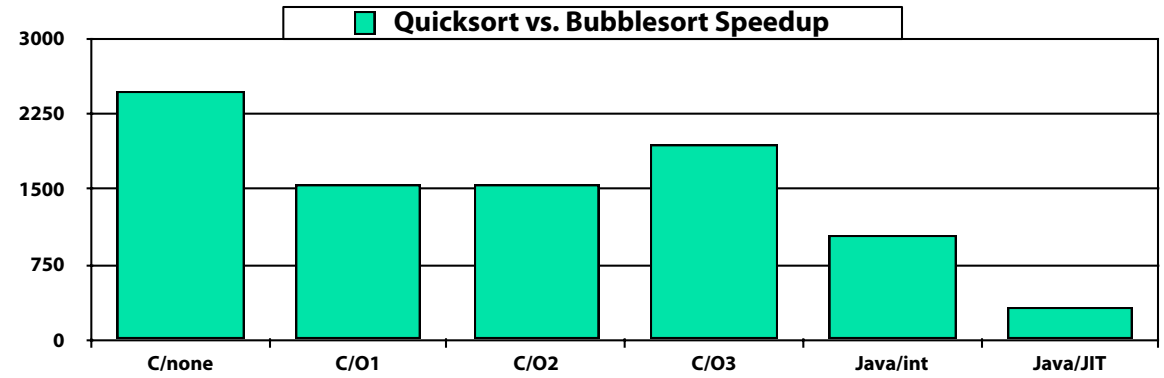




Effect of Language and Algorithm







Lessons Learnt

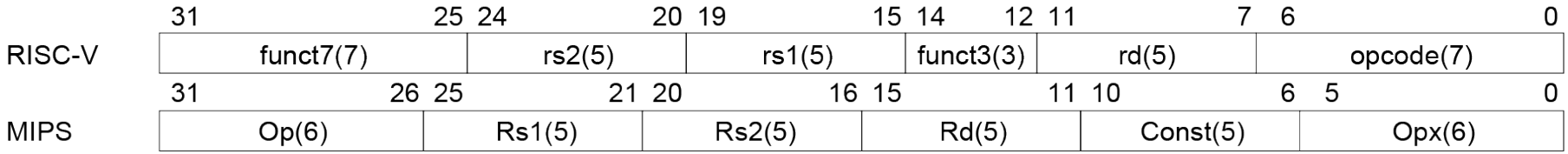
- Instruction count and CPI are not good performance indicators in isolation
- Compiler optimizations are sensitive to the algorithm
- Java/JIT compiled code is significantly faster than JVM interpreted
  - Comparable to optimized C in some cases
- Nothing can fix a dumb algorithm!

MIPS Instructions

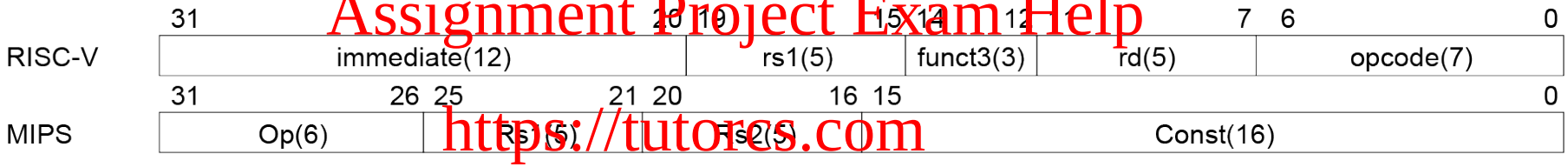
- MIPS: commercial predecessor to RISC-V
- Similar basic set of instructions
  - 32-bit instructions
  - 32 general purpose registers, register 0 is always 0
  - 32 floating-point registers
  - Memory accessed only by load/store instructions
    - Consistent use of addressing modes for all data sizes
- Different conditional branches
  - For <, <=, >, >=
  - RISC-V: blt, bge, bltu, bgeu
  - MIPS: slt, sltu (set less than, result is 0 or 1)
    - Then use beq, bne to complete the branch

Instruction Encoding: RISC-V vs. MIPS

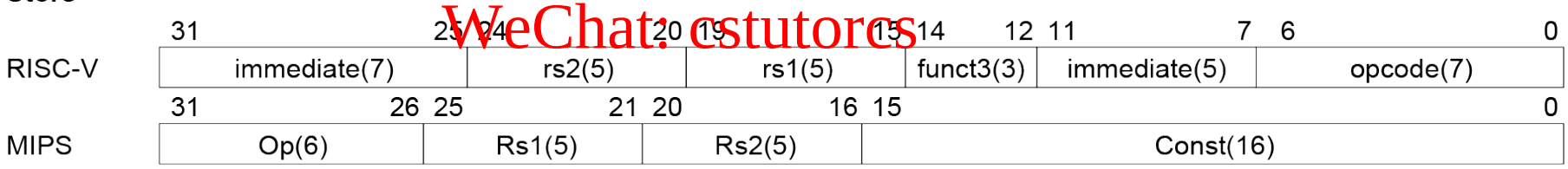
Register-register



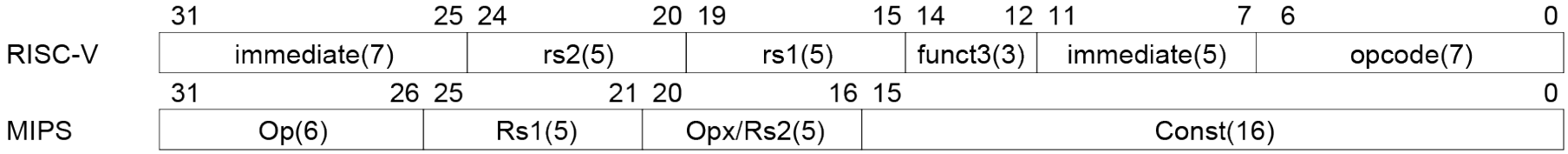
Load



Store



Branch



The 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

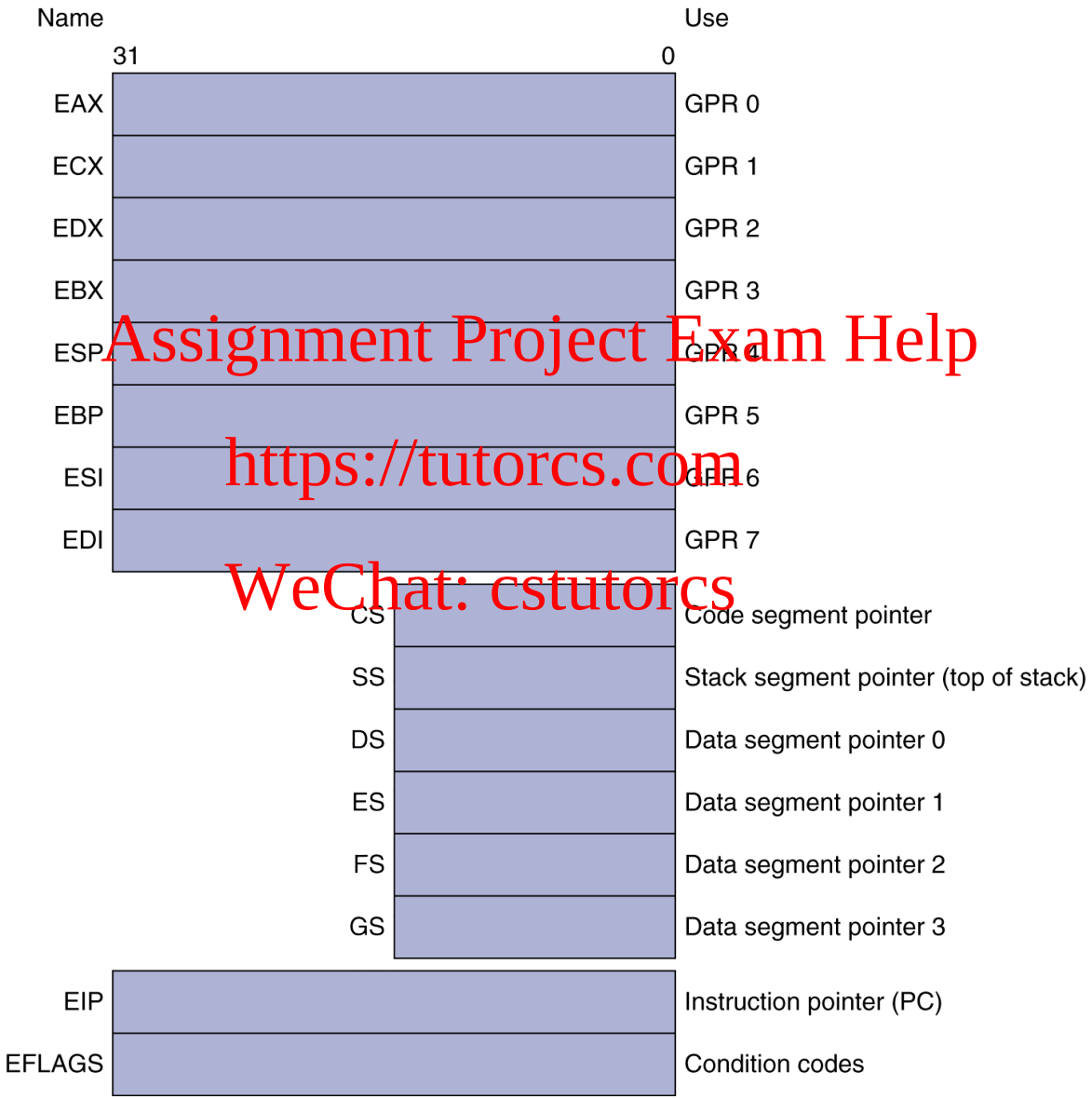
The Intel x86 ISA

- 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

The 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…
  - AVX: Advanced Vector Extension (announced 2008)
    - Longer SSE registers, more instructions
    - AVX-512 proposed 2013, implemented in Skylake (x86) 2017
- If Intel didn't extend with compatibility, its competitors would!
  - Technical elegance ≠ market success

Basic x86 Registers



Basic x86 Addressing Modes

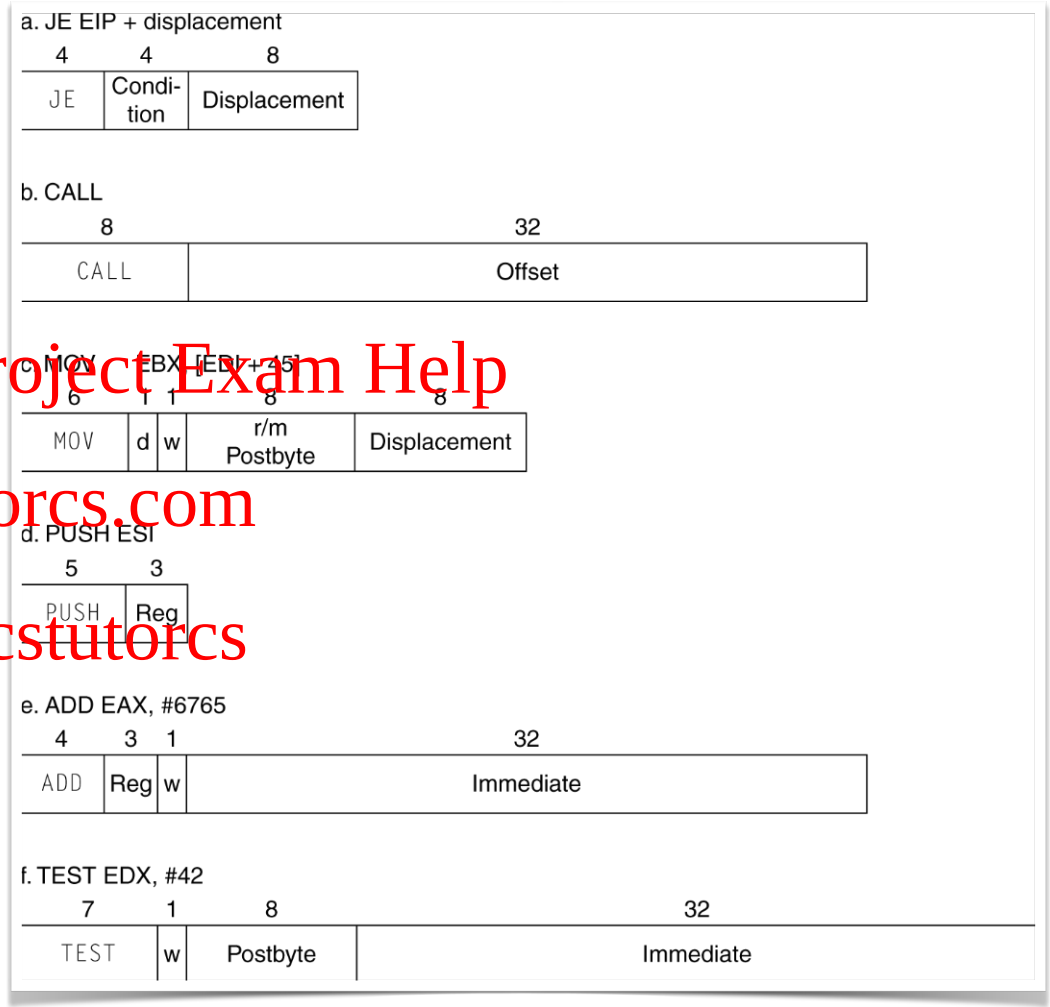
- Two operands per instruction

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

- 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

Other RISC-V Instructions

- Base integer instructions (RV64I)
  - Those previously described, plus
  - auipc rd, immed // rd = (imm<<12) + pc
    - followed by jalr (adds 12-bit immed) for long jump
  - slt, sltu, slti, sltui: set less than (like MIPS)
  - addw, subw, addiw: 32-bit add/sub
  - sllw, srlw, srlw, slliw, srliw, sraiw: 32-bit shift
- 32-bit variant: RV32I
  - registers are 32-bits wide, 32-bit operations

Instruction Set Extensions

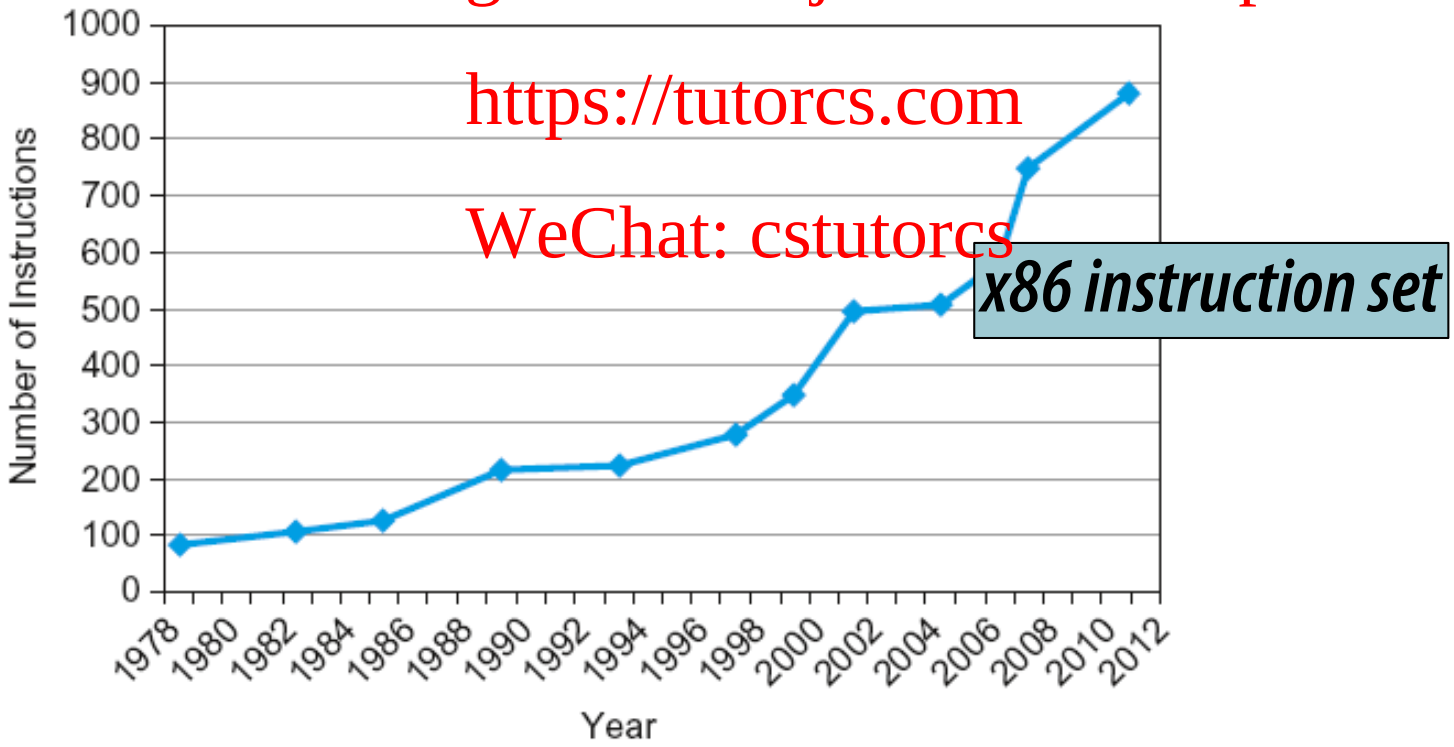
- M: integer multiply, divide, remainder
- A: atomic memory operations
- F: single-precision floating point
- D: double-precision floating point
- C: compressed instructions
  - 16-bit encoding for frequently used instructions

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 accrue more instructions



Pitfalls

- Sequential words are not at sequential addresses
  - MIPS-V addresses are byte addresses
  - Increment by 4 or 8, not by 1!
- Keeping a pointer to an automatic variable after procedure returns
  - e.g., passing pointer back via an argument
  - Pointer becomes invalid when stack popped

Concluding Remarks

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

We likely don't have time for the next few slides

- Great example though!

C Sort Example

- Illustrates use of assembly instructions for a C bubble sort function
- Swap procedure (leaf)

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

  - v in x10, k in x11, temp in x5

The Procedure Swap

```
swap:
  slli x6,x11,3    // reg x6 = k * 8
  add  x6,x10,x6   // reg x6 = v + (k * 8)
  ld   x5,0(x6)    // reg x5 (temp) = v[k]
  ld   x7,8(x6)    // reg x7 = v[k + 1]
  sd   x7,0(x6)    // v[k] = reg x7
  sd   x5,8(x6)    // v[k+1] = reg x5 (temp)
  jalr x0,0(x1)    // return to calling routine
```

The Sort Procedure in C

- Non-leaf (calls swap)

```
void sort (long long int v[], size_t n)
{
  size_t i, j;
  for (i = 0; i < n; i += 1) {
    for (j = i - 1;
         j >= 0 && v[j] > v[j + 1];
         j -= 1) {
      swap(v,j);
    }
  }
}
```

  - v in x10, n in x11, i in x19, j in x20

The Outer Loop

- **Skeleton of outer loop:**
  - **for (i = 0; i <n; i += 1) {**

```
   li   x19,0              // i = 0
for1tst:
   bge  x19,x11,exit1      // go to exit1 if x19 ≥ x11 (i≥n)

   (body of outer for-loop)

   addi x19,x19,1          // i += 1
   j    for1tst            // branch to test of outer loop
exit1:
```

The Inner Loop

- **Skeleton of inner loop:**
  - **for (j = i – 1; j >= 0 && v[j] > v[j + 1]; j – – = 1) {**

```
    addi x20,x19,-1    // j = i -1
for2tst:
    blt  x20,x0,exit2  // go to exit2 if X20 < 0 (j < 0)
    slli x5,x20,3      // reg x5 = j * 8
    add  x5,x10,x5     // reg x5 = v + (j * 8)
    ld   x6,0(x5)      // reg x6 = v[j]
    ld   x7,8(x5)      // reg x7 = v[j + 1]
    ble  x6,x7,exit2   // go to exit2 if x6 ≤ x7
    mv   x21, x10      // copy parameter x10 into x21
    mv   x22, x11      // copy parameter x11 into x22
    mv   x10, x21      // first swap parameter is v
    mv   x11, x20      // second swap parameter is j
    jal  x1,swap     // call swap
    addi x20,x20,-1  // j -= 1
    j    for2tst     // branch to test of inner loop
  exit2:
```

Preserving Registers

- **Preserve saved registers:**

```
addi sp,sp,-40  // make room on stack for 5 regs
sd   x1,32(sp)  // save x1 on stack
sd   x22,24(sp) // save x22 on stack
sd   x21,16(sp) // save x21 on stack
sd   x20,8(sp)  // save x20 on stack
sd   x19,0(sp)  // save x19 on stack
```


- **Restore saved registers:**

```
exit1:
  sd   x19,0(sp)  // restore x19 from stack
  sd   x20,8(sp)  // restore x20 from stack
  sd   x21,16(sp) // restore x21 from stack
  sd   x22,24(sp) // restore x22 from stack
  sd   x1,32(sp)  // restore x1 from stack
  addi sp,sp, 40  // restore stack pointer
  jalr x0,0(x1)
```