CSC 411

Computer Organization (Spring 2024)
Lecture 16: Compiling/interpreting and running programs

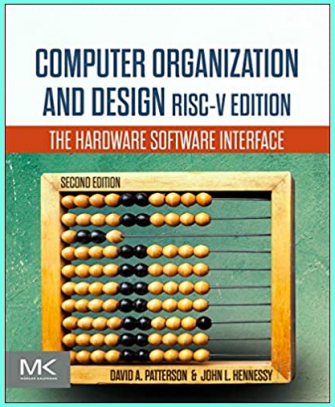
Prof. Marco Alvarez, University of Rhode Island

Disclaimer

Some figures and slides are adapted from:

Computer Organization and Design (Patterson and Hennessy)

The Hardware/Software Interface



Context

machine code

```
10110100 10110111 00101011
00011010 00010100 10111011
10001000 11110111 00101000
10101010 00101101 00010001
01010010 11101100 11010001
10010100 10010100 00100000
00000000 10100001 00110001
10101001 00010101 00101010
00100100 10010100 01110001
11110101 11101011 00101111
01010010 10000101 11111110
10101010 00101101 00010001
01010010 11101100 11010001
10010100 10010100 00100000
00000000 10100001 00110001
10101001 00010101 00101010
00100100 10010100 01110001
11110101 11101011 00101111
01010010 10000101 11111110
00101001 00000000 00000000
00000000 00000000 01010000
00001010 00001010 00101010
00101010 00100100 10011111
```

assembly

```
.equ STDOUT, 1
.equ SVC_WRITE, 64
.equ SVC_EXIT, 93

.text
.global _start
_start:
    stp x29, x30, [sp, -16]!
    mov x0, #STDOUT
    ldr x1, =msg
    mov x2, 13
    mov x8, #SVC_WRITE
    mov x29, sp
    svc #0
    ldp x29, x30, [sp], 16
    mov x0, #0
    mov x8, #SVC_EXIT
    svc #0

msg:  .ascii "Hello World!\n"
.align 4
```

C++

```
#include <iostream>

int main () {
  std::cout << "Hello World!"
      << std::endl;
}
```

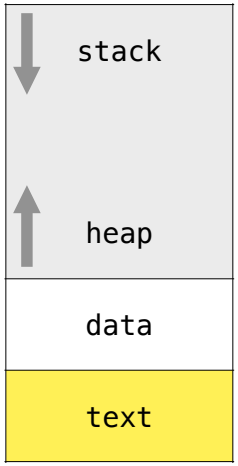
Python

```
print('Hello World')
```

increasing abstraction →

https://www.uvm.edu/~cbcafier/cs1210/book/02_programming_and_the_python_shell/programming.html

Context



High-level language program (in C)

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

Compiler

Assembly language program (for RISC-V)

```
swap:
      slli x6, x11, 3
      add  x6, x10, x6
      lw   x5, 0(x6)
      lw   x7, 4(x6)
      sw   x7, 0(x6)
      sw   x5, 4(x6)
      jalr x0, 0(x1)
```

Assembler

Binary machine language program (for RISC-V)

```
00000000001101011001100100010011
00000000011001010000001100110011
00000000000000011001100101000011
00000000100000011001100111000011
00000000011100110011000000100011
00000000101001100110100000100011
00000000000000001000000001100111
```

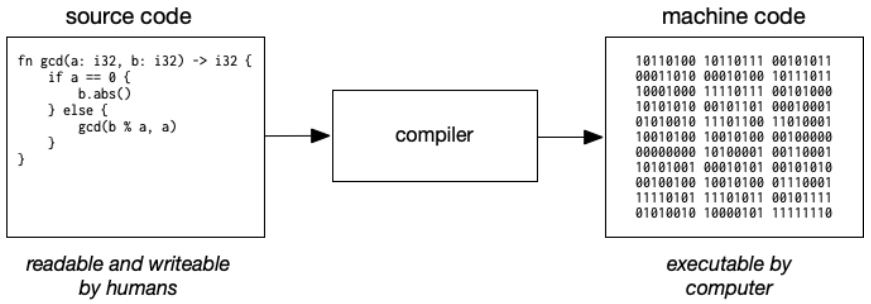
Compiling vs Interpreting

- Compiler
  - a program that acts as a **translator**, converting a program from a high-level language into another language
    - most of the time into a low-level language
  - because the entire program is translated at once, compilers can perform **optimizations** to make the code more efficient, resulting in faster execution (higher performance)
  - e.g. C/C++ compilers
- Interpreter
  - a program that reads and **translates code on the fly**
    - reads code line by line, translates it into machine code, and executes it
    - any language can be interpreted (including C or assembly)
  - preferred when performance is not critical
  - e.g. Javascript

Feature	Compiling	Interpreting
Translation Time	Entire program translated before execution	Code translated and executed line by line
Output	Machine code (executable file)	No direct output; relies on interpreter for execution
Execution Speed	Generally faster due to pre-optimization	Generally slower due to on-the-fly translation
Development Speed	Slower due to separate compilation step	Faster; code can be run and tested immediately
Portability	Limited portability (requires recompilation for different architectures)	Higher portability; interpreted code can often run on different systems
Optimizations	Extensive optimizations possible during compilation	Limited optimizations during interpretation
Error Checking	Can perform more comprehensive static analysis	Limited error checking during interpretation
Code Distribution	Compiled machine code (binary files)	Source code in original language

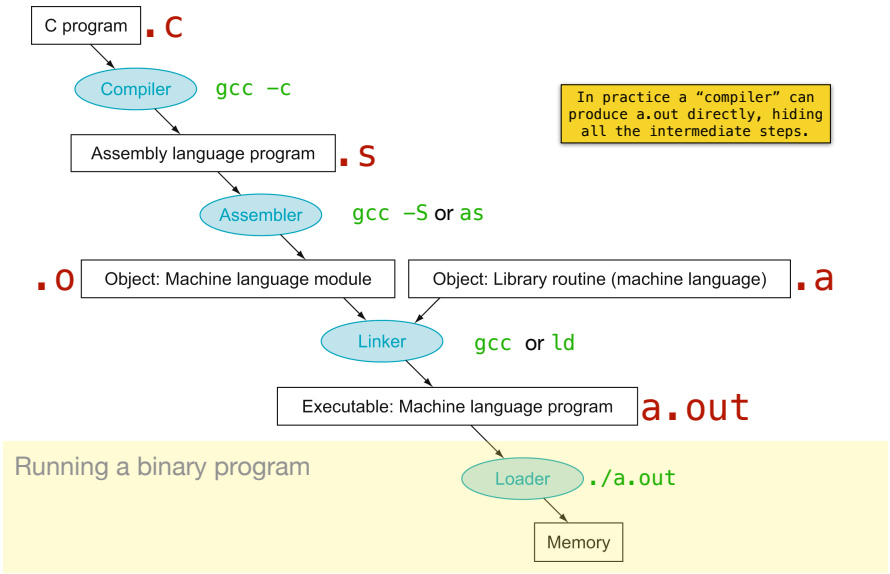
Compiling

Compiling programs (simplified)



https://www.uvm.edu/~cbcafier/cs1210/book/02_programming_and_the_python_shell/programming.html

Compiling/linking/running C programs



C Compiler

- Translates C language into assembly
  - symbolic form of machine language
  - in the 70s many operating systems were written in assembly language
- Optimizes generated code
  - optimization levels are specified using flags like –01, –02, and –03, which progressively increase the level of optimization performed by the compiler
    - other optimization flags include `–00`, `–0s`, `–0fast`, `–0g`, `–0z`

https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

C Compiler

Optimization name	Explanation	gcc level
High level	***At or near the source level; processor independent***	
Procedure integration	Replace procedure call by procedure body	03
Local	***Within straight-line code***	
Common subexpression elimination	Replace two instances of the same computation by single copy	01
Constant propagation	Replace all instances of a variable that is assigned a constant with the constant	01
Stack height reduction	Rearrange expression tree to minimize resources needed for expression evaluation	01
Global	***Across a branch***	
Global common subexpression elimination	Same as local, but this version crosses branches	02
Copy propagation	Replace all instances of a variable ***A*** that has been assigned ***X*** (i.e., ***A*** = ***X***) with ***X***	02
Code motion	Remove code from a loop that computes the same value each iteration of the loop	02
Induction variable elimination	Simplify/eliminate array addressing calculations within loops	02
Processor dependent	***Depends on processor knowledge***	
Strength reduction	Many examples; replace multiply by a constant with shifts	01
Pipeline scheduling	Reorder instructions to improve pipeline performance	01
Branch offset optimization	Choose the shortest branch displacement that reaches target	01

Assembler

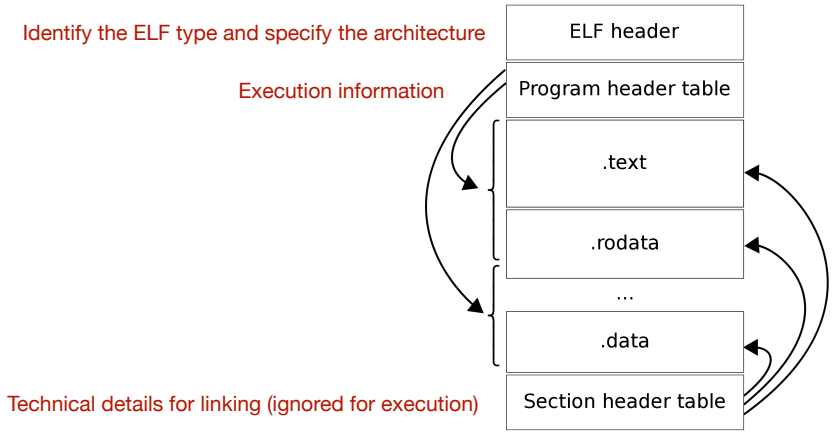
- Converts pseudo-instructions into actual instructions
- Converts actual assembly instructions into **machine code**
  - must determine memory addresses and offsets corresponding to all labels (requires two passes over program)
- Generates an **object file**
  - combination of machine instructions, data, and information needed to place instructions properly in memory

An object file

- Intermediate file produced by a compiler, typically consisting of the following:
  - object file header: describes contents (size/position) of other pieces of the object
  - text segment: translated instructions (machine code)
  - static data segment: data allocated for the life of the program
  - relocation information: for instructions/data that depend on absolute addresses (updated by the linker later)
  - symbol table: list of symbols (functions, labels, etc.) along with their respective addresses or values that can be used by other objects
  - debugging information: metadata for associating machine code with original source code

ELF files

- Executable and Linkable Format

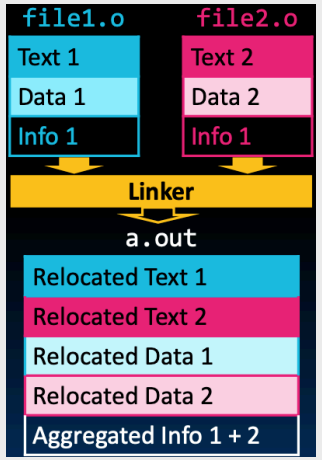


https://en.wikipedia.org/wiki/Executable_and_Linkable_Format

Linker

- Merges all object files, producing an executable
  - merge code and data segments from all objects
  - resolve all undefined labels (replace them with final addresses)
  - patch location-dependent and external references
- Could leave location dependencies to be fixed by a relocating loader
  - with virtual memory, no need to do this
  - program can be loaded into absolute location in virtual memory space

Linker



From Berkeley's CS61C lectures

```
Linker can resolve all
the TODO items from the
independent object
modules before generating
a final executable
```

Loader (OS task)

(1) reads header to determine text/data segment sizes

(2) creates address space large enough for text/data

(3) copies text/data from executable into memory

(4) copies the command line arguments (if any) onto the stack

(5) initializes registers (including sp, fp, gp)

(6) jump to startup routine

- copies arguments to x10 and x11 and calls main
- when main returns, terminate program with an `exit` system call

Dynamically linked libraries

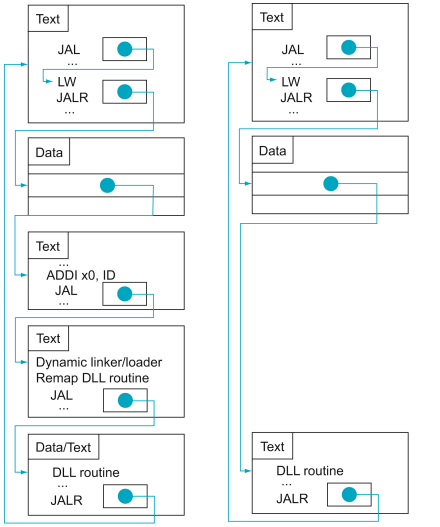
- Statically linked libraries
  - library procedures become part of the executable code
    - if new versions are released code must be recompiled otherwise executable keeps using the old versions
    - loads procedures in the library even if those calls are not executed
- Dynamically linked libraries (DLLs)
  - only link/load library procedure when it is called
  - automatically picks up new library versions
  - requires procedure code to be relocatable

Lazy linkage

Dynamically linked library via lazy procedure linkage:

(a) Steps for the first time a call is made to the DLL routine.

(b) The steps to find the routine, remap it, and link it are skipped on subsequent calls.



Example

sum_int.h

```
#ifndef __SUM__
#define __SUM__

int sum(int a, int b);
#endif
```

sum_int.c

```
extern int baseline;

int sum(int a, int b) {
    if (a < b)
        return (a + b) - baseline;
    else
        return a + b;
}
```

prog.c

```
#include "sum_int.h"

int baseline = 10;

int main() {
    int a = 10;
    int b = 20;

    int c = sum(a, b);

    return 0;
}
```

sum_int.o

```
7f454c46 01010100 00000000 00000000 0100f300 01000000 00000000 00000000
44020000 00000000 34000000 00002800 0a000900 130101fe 232e8100 13040102
2326a4fe 2324b4fe 0327c4fe 832784fe 6350f702 0327c4fe 832784fe 3307f700
b7070000 83a70700 b307f740 6f000001 0327c4fe 832784fe b307f700 13850700
0324c101 13010102 67800000 00474343 3a202867 63383931 64386463 32336529
2031332e 322e3000 411b0000 00726973 63760001 11000000 04100572 76333269
32703100 00000000 00000000 00000000 00000000 01000000 00000000 00000000
0400f1ff 00000000 00000000 00000000 03000100 00000000 00000000 00000000
03000300 00000000 00000000 00000000 03000400 0b000000 00000000 00000000
00000100 16000000 3c000000 00000000 00000100 1a000000 48000000 00000000
00000100 00000000 00000000 00000000 03000500 00000000 00000000 00000000
03000600 1e000000 00000000 58000000 12000100 22000000 00000000 00000000
10000000 0073756d 5f696e74 2e630024 78727633 32693270 31002e4c 32002e4c
33007375 6d006261 73656c69 6e650000 1c000000 10060000 00000000 2c000000
1a0b0000 00000000 2c000000 33000000 00000000 30000000 1b0b0000 00000000
30000000 33000000 00000000 38000000 11070000 00000000 002e7379 6d746162
002e7374 72746162 002e7368 73747274 6162002e 72656c61 2e746578 74002e64
61746100 2e627373 002e636f 6d6d656e 74002e72 69736376 2e617474 72696275
74657300 00000000 00000000 00000000 00000000 00000000 00000000 00000000
00000000 00000000 00000000 20000000 01000000 05000000 00000000 34000000
50000000 00000000 00000000 04000000 00000000 1b000000 04000000 40000000
00000000 b0010000 48000000 07000000 01000000 04000000 0c000000 26000000
01000000 03000000 00000000 8c000000 00000000 00000000 00000000 01000000
00000000 2c000000 08000000 03000000 00000000 8c000000 00000000 00000000
00000000 01000000 00000000 31000000 01000000 30000000 00000000 8c000000
1c000000 00000000 00000000 01000000 01000000 3a000000 03000070 00000000
00000000 a8000000 1c000000 00000000 00000000 01000000 00000000 01000000
02000000 00000000 00000000 c4000000 c0000000 08000000 0a000000 04000000
10000000 09000000 03000000 00000000 00000000 84010000 2b000000 00000000
00000000 01000000 00000000 11000000 03000000 00000000 00000000 f8010000
4c000000 00000000 00000000 01000000 00000000
```

```
xxd -g4 -c 32 sum_int.o
```

```
objdump -d sum_int.o
```

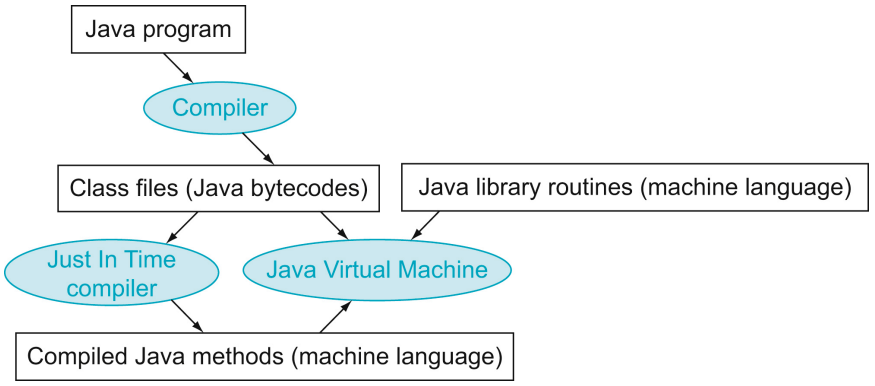
```
00000000 <sum>:
   0:   fe010113            addi    sp,sp,-32
   4:   00812e23            sw      s0,28(sp)
   8:   02010413            addi    s0,sp,32
   c:   fea42623            sw      a0,-20(s0)
  10:   feb42423            sw      a1,-24(s0)
  14:   fec42703            lw      a4,-20(s0)
  18:   fe842783            lw      a5,-24(s0)
  1c:   02f75063            bge     a4,a5,3c <.L2>
  20:   fec42703            lw      a4,-20(s0)
  24:   fe842783            lw      a5,-24(s0)
  28:   00f70733            add     a4,a4,a5
  2c:   000007b7            lui     a5,0x0
  30:   0007a783            lw      a5,0(a5) # 0 <sum>
  34:   40f707b3            sub     a5,a4,a5
  38:   0100006f            j       48 <.L3>

0000003c <.L2>:
  3c:   fec42703            lw      a4,-20(s0)
  40:   fe842783            lw      a5,-24(s0)
  44:   00f707b3            add     a5,a4,a5

00000048 <.L3>:
  48:   00078513            mv      a0,a5
  4c:   01c12403            lw      s0,28(sp)
  50:   02010113            addi    sp,sp,32
  54:   00008067            ret
```

```
objdump -d a.out
```

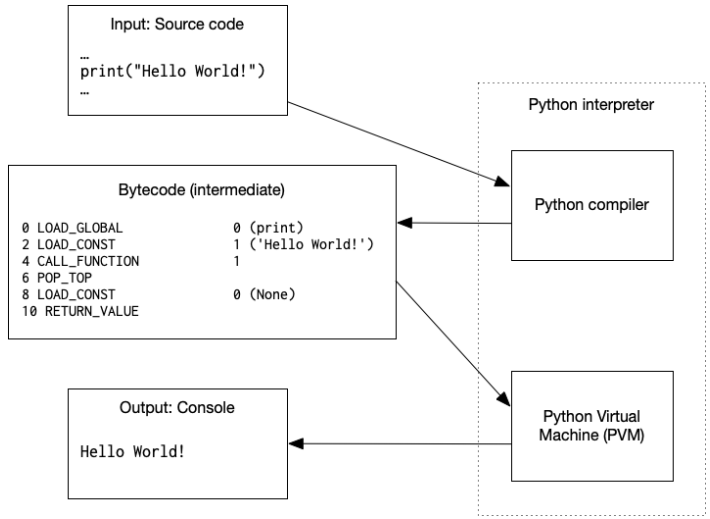
```
000101d0 <sum>:
   101d0:   fe010113            addi    sp,sp,-32
   101d4:   00812e23            sw      s0,28(sp)
   101d8:   02010413            addi    s0,sp,32
   101dc:   fea42623            sw      a0,-20(s0)
   101e0:   feb42423            sw      a1,-24(s0)
   101e4:   fec42703            lw      a4,-20(s0)
   101e8:   fe842783            lw      a5,-24(s0)
   101ec:   00f75e63            bge     a4,a5,10208 <sum+0x38>
   101f0:   fec42703            lw      a4,-20(s0)
   101f4:   fe842783            lw      a5,-24(s0)
   101f8:   00f70733            add     a4,a4,a5
   101fc:   d3c1a783            lw      a5,-708(gp) # 13564 <baseline>
   10200:   40f707b3            sub     a5,a4,a5
   10204:   0100006f            j       10214 <sum+0x44>
   10208:   fec42703            lw      a4,-20(s0)
   1020c:   fe842783            lw      a5,-24(s0)
   10210:   00f707b3            add     a5,a4,a5
   10214:   00078513            mv      a0,a5
   10218:   01c12403            lw      s0,28(sp)
   1021c:   02010113            addi    sp,sp,32
   10220:   00008067            ret
```

Modern interpreters

Java applications



Python interpreter



https://www.uvm.edu/~cbcafier/cs1210/book/02_programming_and_the_python_shell/programming.html

Python interpreter

python -m dis <file>

```
mylist = [1, 2, 3, 'hello', 'world']

myslice = mylist[3:]

print(myslice)
```

```
1   0 BUILD_LIST      0
    2 LOAD_CONST      0 ((1, 2, 3, 'hello', 'world'))
    4 LIST_EXTEND     1
    6 STORE_NAME      0 (mylist)

2   8 LOAD_NAME       0 (mylist)
   10 LOAD_CONST      1 (3)
   12 LOAD_CONST      2 (None)
   14 BUILD_SLICE     2
   16 BINARY_SUBSCR
   18 STORE_NAME      1 (myslice)

3   20 LOAD_NAME      2 (print)
   22 LOAD_NAME       1 (myslice)
   24 CALL_FUNCTION   1
   26 POP_TOP
   28 LOAD_CONST      2 (None)
   30 RETURN_VALUE
```

Impacts on performance

Sort example in C

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

```
swap:
  slli x6, x11, 2  # reg x6 = k * 4
  add  x6, x10, x6 # reg x6 = v + (k * 4)
  lw   x5, 0(x6)   # reg x5 (temp) = v[k]
  lw   x7, 4(x6)   # reg x7 = v[k + 1]
  sw   x7, 0(x6)   # v[k] = reg x7
  sw   x5, 4(x6)   # v[k+1] = reg x5 (temp)
  jalr x0, 0(x1)   # return to caller
```

```
void sort (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);
        }
    }
}
```

Saving registers

```
sort:   addi sp, sp, -20        # make room on stack for 5 registers
        sw x1, 16(sp)           # save return address on stack
        sw x22, 12(sp)          # save x22 on stack
        sw x21, 8(sp)           # save x21 on stack
        sw x20, 4(sp)           # save x20 on stack
        sw x19, 0(sp)           # save x19 on stack
```

Procedure body

Move parameters	`addi x21, x10, 0` # copy parameter x10 into x21 `addi x22, x11, 0` # copy parameter x11 into x22
Outer loop	`addi x19,x0, 0` # i = 0 `for1tst:bge x19, x22, exit1` # go to exit1 if i >= n
Inner loop	`addi x20, x19, -1` # j = i - 1 `for2tst:blt x20, x0, exit2` # go to exit2 if j < 0 `slli x5, x20, 2` # x5 = j * 4 `add x5, x21, x5` # x5 = v + (j * 4 `lw x6, 0(x5)` # x6 = v[j] `lw x7, 4(x5)` # x7 = v[j + 1] `ble x6, x7, exit2` # go to exit2 if x6 < x7
Pass parameters and call	`addi x10, x21, 0` # first swap parameter is v `addi x11, x20, 0` # second swap parameter is j `jal x1, swap` # call swap
Inner loop	`addi x20, x20, -1` j for2tst `jal, x0 for2tst` # go to for2tst
Outer loop	`exit2: addi x19, x19, 1` # i += 1 `jal, x0 for1tst` # go to for1tst

Restoring registers

```
exit1:  lw x19, 0(sp)           # restore x19 from stack
        lw x20, 4(sp)           # restore x20 from stack
        lw x21, 8(sp)           # restore x21 from stack
        lw x22, 12(sp)          # restore x22 from stack
        lw x1, 16(sp)           # restore return address from stack
        addi sp, sp, 20         # restore stack pointer
```

Procedure return

```
        jalr x0, 0(x1)          # return to calling routine
```

Applying compiler optimizations

gcc optimization	Relative performance	Clock cycles (millions)	Instruction count (millions)	CPI
None	1.00	158,615	114,938	1.38
O1 (medium)	2.37	66,990	37,470	1.79
O2 (full)	2.38	66,521	39,993	1.66
O3 (procedure integration)	2.41	65,747	44,993	1.46

The programs sorted 100,000 32-bit words with the array initialized to random values. These programs were run on a Pentium 4 with a clock rate of 3.06 GHz and a 533 MHz system bus with 2 GB of PC2100 DDR SDRAM. It used Linux version 2.4.20.

Comparing sorting algorithms

- Compiler optimizations are sensitive to the algorithm
- Java/JIT significantly faster than JVM interpreted

Language	Execution method	Optimization	Bubble Sort relative performance	Quicksort relative performance	Speedup Quicksort vs. Bubble Sort
C	Compiler	None	1.00	1.00	2468
	Compiler	O1	2.37	1.50	1562
	Compiler	O2	2.38	1.50	1555
	Compiler	O3	2.41	1.91	1955
Java	Interpreter	–	0.12	0.05	1050
	JIT compiler	–	2.13	0.29	338

Nothing can fix slow algorithms

Optimization example

Arrays vs pointers

- Array indexing typically involves
  - multiplying index by element size
  - adding to array base address
- Pointers correspond directly to memory addresses
  - can avoid indexing complexity

Example: clearing an array

```
void clear1(int array[], int size) {
    int i;
    for (i = 0 ; i < size ; i += 1)
        array[i] = 0;
}
```

```
void clear2(int *array, int size) {
    int *p = array;
    int *end = p + size;
    for ( ; p < end ; p++)
        *p = 0;
}
```

```
    li   x5, 0       # i = 0
l1:
    slli x6, x5, 2   # x6 = i * 4
    add  x7, x10, x6 # x7 = &array[i]
    sw   x0, 0(x7)   # array[i] = 0
    addi x5, x5, 1   # i = i + 1
    blt  x5, x11, l1 # if (i<size) go to l1
```

```
    add x5, x0, x10 # p = addr of array[0]
    slli x6, x11, 2 # x6 = size * 4
    add x7, x10, x6 # x7 = addr of array[size]
l2:
    sw x0, 0(x5)    # *p = 0
    addi x5, x5, 4  # p = p + 4
    bltu x5, x7, l2 # if (p<end) go to l2
```

(*) assembly code above does not consider the case of `size = 0`

compilers can do this by applying optimizations: strength reduction (shift instead of multiply) and induction variable elimination (eliminate address calculation inside the loop)

Fallacies

- Powerful instructions (x86) ⇒ higher performance
  - complex instructions are hard to implement
    - may slow down all instructions, including simple ones
  - compilers are good at making fast code from simple instructions
- Write assembly code for higher performance
  - modern compilers are better (than most humans) at dealing with modern processors
  - more lines of code ⇒ more errors and less productivity

Fallacies

- Backward compatibility ⇒ instruction set "doesn't change"
  - x86 keeps adding more instructions (difficult to build compatible processors)

Growth of the x86 instruction set over time