Assembly Language: Overview

Goals of this Lecture

• Help you learn:
  • The basics of computer architecture
  • The relationship between C and assembly language
  • IA-32 assembly language, through an example
Context of this Lecture

Second half of the course

Starting Now

- C Language
- Assembly Language
- Machine Language

Afterward

- Application Program
- Operating System
- Hardware

Three Levels of Languages
High-Level Language

- Make programming easier by describing operations in a semi-natural language
- Increase the portability of the code
- One line may involve many low-level operations
- Examples: C, C++, Java, Pascal, …

```java
count = 0;
while (n > 1) {
    count++;
    if (n & 1)
        n = n*3 + 1;
    else
        n = n/2;
}
```

Assembly Language

- Tied to the specifics of the underlying machine
- Commands and names to make the code readable and writeable by humans
- Hand-coded assembly code may be more efficient
- E.g., IA-32 from Intel

```assembly
movl $0, %ecx
loop:  
cmpl $1, %edx
jle endloop
addl $1, %ecx
movl %edx, %eax
andl $1, %eax
je else
movl %edx, %eax
addl %eax, %edx
addl %eax, %edx
addl $1, %edx
jmp endif
else:
sarl $1, %edx
endif:
jmp loop
endloop:
```
Machine Language

- Also tied to the underlying machine
- What the computer sees and deals with
- Every instruction is a sequence of one or more numbers
- All stored in memory on the computer, and read and executed
- Unreadable by humans

Why Learn Assembly Language?

- Write faster code (even in high-level language)
  - By understanding which high-level constructs are better
  - … in terms of how efficient they are at the machine level
- Understand how things work underneath
  - Learn the basic organization of the underlying machine
  - Learn how the computer actually runs a program
  - Design better computers in the future
- Some software is still written in assembly language
  - Code that really needs to run quickly
  - Code for embedded systems, network processors, etc.
Why Learn Intel IA-32 Assembly?

- Program natively on our computing platform
  - Rather than using an emulator to mimic another machine
- Learn instruction set for the most popular platform
  - Most likely to work with Intel platforms in the future

- But, this comes at some cost in complexity
  - IA-32 has a large and varied set of instructions
  - More instructions than are really useful in practice
- Fortunately, you won’t need to use everything
A Typical Computer

[Diagram of a computer system with CPU, Memory, Chipset, I/O bus, Network, and ROM]

John Von Neumann (1903-1957)

- In computing
  - Stored program computers
  - Cellular automata
  - Self-replication
- Other interests
  - Mathematics (set theory, ergodic theory)
  - Nuclear physics (hydrogen bomb)
- Princeton connection
  - Princeton Univ & IAS, 1930-death
- Known for “Von Neumann architecture”
  - In contrast to less-successful “Harvard architecture”
Von Neumann Architecture

- **Central Processing Unit**
  - Control unit
  - Fetch, decode, and execute
  - Arithmetic and logic unit
  - Execution of low-level operations
  - General-purpose registers
  - High-speed temporary storage
  - Data bus
  - Provide access to memory

- **Memory**
  - Store executable machine-language instructions (text section)
  - Store data (rodata, data, bss, heap, and stack sections)
Control Unit: Instruction Pointer

- Stores the location of the next instruction
  - Address to use when reading machine-language instructions from memory (i.e., in the text section)
- Changing the instruction pointer (EIP)
  - Increment to go to the next instruction
  - Or, load a new value to “jump” to a new location

Control Unit: Instruction Decoder

- Determines what operations need to take place
  - Translate the machine-language instruction
- Control what operations are done on what data
  - E.g., control what data are fed to the ALU
  - E.g., enable the ALU to do multiplication or addition
  - E.g., read from a particular address in memory
Registers

- Small amount of storage on the CPU
  - Can be accessed more quickly than main memory

- Instructions move data in and out of registers
  - Loading registers from main memory
  - Storing registers to main memory

- Instructions manipulate the register contents
  - Registers essentially act as temporary variables
  - For efficient manipulation of the data

- Registers are the top of the memory hierarchy
  - Ahead of main memory, disk, tape, …

Keeping it Simple: All 32-bit Words

- Simplifying assumption: all data in four-byte units
  - Memory is 32 bits wide
  - Registers are 32 bits wide

- In practice, can manipulate different sizes of data
C Code vs. Assembly Code

Kinds of Instructions

- Reading and writing data
  - count = 0
  - n
- Arithmetic and logic operations
  - Increment: count++
  - Multiply: n * 3
  - Divide: n/2
  - Logical AND: n & 1
- Checking results of comparisons
  - Is (n > 1) true or false?
  - Is (n & 1) non-zero or zero?
- Changing the flow of control
  - To the end of the while loop (if “n > 1”)
  - Back to the beginning of the loop
  - To the else clause (if “n & 1” is 0)

```c
count = 0;
while (n > 1) {
    count++;
    if (n & 1)
        n = n*3 + 1;
    else
        n = n/2;
}
```
Variables in Registers

```c
int count = 0;
while (n > 1) {
    count++;
    if (n & 1)
        n = n*3 + 1;
    else
        n = n/2;
}
```

Referring to a register: percent sign ("%")

Registers

- \( n \) %edx
- \( \text{count} \) %ecx

Immediate and Register Addressing

```c
int count=0;
while (n>1) {
    count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}
```

Referring to a immediate operand: dollar sign ("$")
Immediate and Register Addressing

count=0;
while (n>1) {
count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}

Computing intermediate value in register EAX

Immediate and Register Addressing

count=0;
while (n>1) {
count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}

Shifting right by 1 bit is cheaper than division!
Changing Program Flow

- Cannot simply run next instruction
  - Check result of a previous operation
  - Jump to appropriate next instruction
- Flags register (EFLAGS)
  - Stores the status of operations, such as comparisons, as a side effect
  - E.g., last result was positive, negative, zero, etc.
- Jump instructions
  - Load new address in instruction pointer
- Example jump instructions
  - Jump unconditionally (e.g., `{ }")
  - Jump if zero (e.g., "n&1")
  - Jump if greater/less (e.g., "n>1")

```c
count=0;
while (n>1) {
  count++;
  if (n&1)
    n = n*3+1;
  else
    n = n/2;
}
```

Conditional and Unconditional Jumps

- Comparison `cmp1` compares two integers
  - Done by subtracting the first number from the second
    - Discarding the results, but setting flags as a side effect
  - Example:
    - `cmp1 $1, %edx` (computes %edx – 1)
    - `jle endloop` (checks whether result was 0 or negative)
- Logical operation `andl` compares two integers
  - Example:
    - `andl $1, %eax` (bit-wise AND of %eax with 1)
    - `je else` (checks whether result was 0)
- Also, can do an unconditional branch `jmp`
  - Example:
    - `jmp endif and jmp loop`
Jump and Labels: While Loop

```
while (n>1) {
    count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}
```

Jump and Labels: While Loop

```
count=0;
while (n>1) {
    movl $0, %ecx
    loop: cmpl $1, %edx
           jle endloop
           ...
    jmp loop

    cmpl $1, %edx
    jle endloop
    addl $1, %ecx
    movl %edx, %eax
    addl %eax, %edx
    addl $1, %edx
    addl $1, %ecx
    jmp endif

    movl %edx, %eax
    addl %eax, %edx
    addl %eax, %edx
    addl $1, %edx
    jmp endif

    sarl $1, %edx
    endif:
    jmp loop

    movl $0, %ecx
    endloop:
```
Jump and Labels: If-Then-Else

if (n&1)  
...  
else  
...

"then" block

else:
jmp endif

"else" block

endif:

Jump and Labels: If-Then-Else

count=0;
while(n>1) {
  count++;
  if (n&1)
    n = n*3+1;
  else
    n = n/2;
}

loop:
  movl $0, %ecx
  cmpl $1, %edx
  jle endloop
  addl $1, %ecx
  movl %edx, %eax
  andl $1, %eax
  je else
  endif:
  movl %edx, %eax
  addl %eax, %edx
  addl %eax, %edx
  addl %eax, %edx
  addl $1, %edx
  jmp endif
  ”then" block
else:
  sarl $1, %edx
  jmp loop
  ”else” block
endif:
  jmp loop
  endloop:
Making the Code More Efficient...

count=0;
while(n>1) {
    count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}

Replace with “jmp loop”

Complete Example

count=0;
while (n>1) {
    count++;
    if (n&1)
        n = n*3+1;
    else
        n = n/2;
}
Reading IA-32 Assembly Language

• Referring to a register: percent sign (“%”)
  E.g., “%ecx” or “%eip”

• Referring to immediate operand: dollar sign (“$”)
  E.g., “$1” for the number 1

• Storing result: typically in the second argument
  E.g. “addl $1, %ecx” increments register ECX
  E.g., “movl %edx, %eax” moves EDX to EAX

• Assembler directives: starting with a period (“.”)
  E.g., “.section .text” to start the text section of memory

• Comment: pound sign (“#”)
  E.g., “# Purpose: Convert lower to upper case”

Conclusions

• Assembly language
  • In between high-level language and machine code
  • Programming the “bare metal” of the hardware
  • Loading and storing data, arithmetic and logic operations, checking results, and changing control flow

• To get more familiar with IA-32 assembly
  • Read more assembly-language examples
    • Chapter 3 of Bryant and O’Hallaron book
  • Generate your own assembly-language code
    • gcc217 –S –O2 code.c