CSE P 501 – Compilers

x86 Architecture

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Agenda

- Learn/review x86 architecture
  - Core 32-bit part only
    - Ignore crufty, backward-compatible things
  - Suggested target language for MiniJava
    - (But if you want to do something different – mips, PPC, ... – that should be fine – talk to us)
- After we've reviewed the x86 we'll look at how to map language constructs to code

x86 Selected History

Processor	Intro Year	Intro Clock	Transistors	Features
8086	1978	8 MHz	29 K	16-bit regs., segments
286	1982	12.5 MHz	134 K	Protected mode
386	1985	20 MHz	275 K	32-bit regs., paging
486	1989	25 MHz	1.2 M	On-board FPU
Pentium	1993	60 MHz	3.1 M	MMX on late models
Pentium Pro	1995	200 MHz	5.5 M	P6 core, bigger caches
Pentium II	1997	266 MHz	7 M	P6 w/MMX
Pentium III	1999	700 MHz	28 M	SSE (Streaming SIMD)
Pentium IV	2000	1.5 GHz	42 M	NetBurst core, SSE2
Xeon	2002	2.2 GHz	55 M	Hyper-Threading

And It's Backward-Compatible!

- Current Pentium/Xeon processors will run code written for the 8086(!)
- ∴ Much of the Intel descriptions of the architecture are loaded down with modes and flags that obscure the modern, fairly simple 32-bit processor model
  - Links to the Intel manuals on the course web
- These slides try to cover the core x86 instructions and assembly language

MASM – Microsoft Assembler

- MiniJava compiler project output will be assembler source program
  - Let the assembler handle the translation to binary
- Examples here use MASM – included in Visual Studio.NET
  - Used to write code for MMX, SSE, and other special applications
- Other x86 assemblers: nasm, gas (GNU)
  - OK to use if you wish; you'll need to use the appropriate syntax, but instructions are the same

MASM Statements

- Format is

  optLabel: opcode operands ; comment
  - optLabel is an optional label
  - opcode and operands make up the assembly language instruction
  - Anything following a ';' is a comment
- Language is very free-form
  - Comments and labels may appear on separate lines by themselves (we'll take advantage of this)

x86 Memory Model

- 8-bit bytes, byte addressable
- 16-, 32-, 64-bit words, doublewords, and quadwords
  - Usually data should be aligned on “natural” boundaries; huge performance penalty on modern processors if it isn’t
- Little-endian – address of a 4-byte integer is address of low-order byte

Processor Registers

- 8 32-bit, mostly general purpose registers
  - eax, ebx, ecx, edx, esi, edi, ebp (base pointer), esp (stack pointer)
- Other registers, not directly addressable
  - 32-bit eflags register
    - Holds condition codes, processor state, etc.
  - 32-bit “instruction pointer” eip
    - Holds address of first byte of next instruction to execute

Processor Fetch-Execute Cycle

- Basic cycle

```
while (running) {
  fetch instruction beginning at eip address
  eip <- eip + instruction length
  execute instruction
}
```

- Execution continues sequentially unless a jump is executed, which stores a new “next instruction” address in eip

Instruction Format

- Typical data manipulation instruction

  opcode dst,src
- Meaning is

  dst <- dst op src

Instruction Operands

- Normally, one operand is a register, the other is a register, memory location, or integer constant
  - In particular, can’t have both operands in memory – not enough bits to encode this
- Typical use is fairly “risc-like”
  - Modern processor cores optimized to execute this efficiently
  - Exotic instructions mostly for backward compatibility and normally not as efficient as equivalent code using simple instructions

x86 Memory Stack

- Register esp points to the top of stack
  - Dedicated for this use; don’t use otherwise
  - Points to the last 32-bit doubleword pushed onto the stack
  - Should always be doubleword aligned
    - It will start out this way, and will stay aligned unless your code does something bad
  - Stack grows down

Stack Instructions

push src
- esp <- esp – 4; memory[esp] <- src
  (e.g., push src onto the stack)

pop dst
- dst <- memory[esp]; esp <- esp + 4
  (e.g., pop top of stack into dst and logically remove it from the stack)

- These are highly optimized and heavily used
  - The x86 doesn't have enough registers, so the stack is frequently used for temporary space

Stack Frames

- When a method is called, a *stack frame* is traditionally allocated on the top of the stack to hold its local variables
- Frame is popped on method return
- By convention, ebp (base pointer) points to a known offset into the stack frame
  - Local variables referenced relative to ebp
  - (Aside: this can be optimized to use esp-relative addresses instead. Frees up ebp, but needs additional bookkeeping at compile time)

Operand Address Modes

- These should cover what we'll need

```
mov  eax,17          ; store 17 in eax
mov  eax,ecx         ; copy ecx to eax
mov  eax,[ebp-12]    ; copy memory to eax
mov  [ebp+8],eax     ; copy eax to memory
```

- References to object fields work similarly – put the object's memory address in a register and use that address plus an offset

dword ptr

- Obscure, but sometimes necessary…
- If the assembler can't figure out the size of the operands to move, you can explicitly tell it to move 32 bits with the qualifier "dword ptr"

```
mov   dword ptr  [eax+16],[ebp-8]
```

  - Use this if the assembler complains; otherwise ignore

Basic Data Movement and Arithmetic Instructions

mov dst,src
- dst <- src

add dst,src
- dst <- dst + src

sub dst,src
- dst <- dst – src

inc dst
- dst <- dst + 1

dec dst
- dst <- dst - 1

neg dst
- dst <- - dst
  (2's complement arithmetic negation)

Integer Multiply and Divide

imul dst,src
- dst <- dst * src
- 32-bit product
- dst *must* be a register

imul dst,src,imm8
- dst <- dst*src*imm8
- imm8 – 8 bit constant
- Obscure, but useful for optimizing array subscripts (if you have them)

idiv src
- Divide edx:eax by src (edx:eax holds sign-extended 64-bit value)
- eax <- quotient
- edx <- remainder

cdq
- edx:eax <- 64-bit sign extended copy of eax

Bitwise Operations

and dst,src
- dst <- dst & src

or dst,src
- dst <- dst | src

xor dst,src
- dst <- dst ^ src

not dst
- dst <- ~ dst (logical or 1's complement)

Shifts and Rotates

shl dst,count
- dst shifted left count bits

shr dst,count
- dst <- dst shifted right count bits (0 fill)

sar dst,count
- dst <- dst shifted right count bits (sign bit fill)

rol dst,count
- dst <- dst rotated left count bits

ror dst,count
- dst <- dst rotated right count bits

Uses for Shifts and Rotates

- Can often be used to optimize multiplication and division by small constants
  - If you're interested, look at "Hacker's Delight" by Henry Warren, A-W, 2003
    - Lots of very cool bit fiddling and other algorithms
- There are additional instructions that shift and rotate double words, use a calculated shift amount instead of a constant, etc.

Load Effective Address

- The unary & operator in C

```
lea  dst,src      ; dst <- address of src
```

  - dst must be a register
  - Address of src includes any address arithmetic or indexing
  - Useful to capture addresses for pointers, reference parameters, etc.

Control Flow - GOTO

- At this level, all we have is goto and conditional goto
- Loops and conditional statements are synthesized from these
- A jump (goto) stores the destination address in eip, the register that points to the next instruction to be fetched
- Optimization note: jumps play havoc with pipeline efficiency; much work is done in modern compilers and processors to minimize this impact

Unconditional Jumps

jmp dst
- eip <- address of dst
- Assembly language note: dst will be a label. Execution continues at first machine instruction in the code following that label
- Can have multiple labels on separate lines in front of an instruction

Conditional Jumps

- Most arithmetic instructions set bits in eflags to record information about the result (zero, non-zero, positive, etc.)
  - True of add, sub, and, or; but *not* imul or idiv
- Other instructions that set eflags

```
cmp dst,src     ; compare dst to src
test dst,src    ; calculate dst & src (logical
                ; and); doesn't change either
```


Conditional Jumps Following Arithmetic Operations

```
jz      label   ; jump if result == 0
jnz     label   ; jump if result != 0
jg      label   ; jump if result > 0
jng     label   ; jump if result <= 0
jge     label   ; jump if result >= 0
jnge    label   ; jump if result < 0
jl      label   ; jump if result < 0
jnl     label   ; jump if result >= 0
jle     label   ; jump if result <= 0
jnle    label   ; jump if result > 0
```

- Obviously, the assembler is providing multiple opcode mnemonics for individual instructions
- If you use these, it will probably be the result of an optimization

Compare and Jump Conditionally

- Very common pattern: compare two operands and jump if a relationship holds between them
- Would like to do this

  jmp_{cond} op1,op2,label

  but can't, because 3-address instructions aren't included in the architecture

cmp and jcc

- Instead, use a 2-instruction sequence

```
cmp     op1,op2
jcc     label
```

  where jcc is a conditional jump that is taken if the result of the comparison matches the condition cc

Conditional Jumps Following Arithmetic Operations

```
je      label   ; jump if op1 == op2
jne     label   ; jump if op1 != op2
jg      label   ; jump if op1 > op2
jng     label   ; jump if op1 <= op2
jge     label   ; jump if op1 >= op2
jnge    label   ; jump if op1 < op2
jl      label   ; jump if op1 < op2
jnl     label   ; jump if op1 >= op2
jle     label   ; jump if op1 <= op2
jnle    label   ; jump if op1 > op2
```

- Again, the assembler is mapping more than one mnemonic to some of the actual machine instructions

Function Call and Return

- The x86 instruction set itself only provides for transfer of control (jump) and return
- Stack is used to capture return address and recover it
- Everything else – parameter passing, stack frame organization, register usage – is a matter of convention and not defined by the hardware

call and ret Instructions

call label
- Push address of next instruction and jump
- esp <- esp – 4; memory[esp] <- eip
  eip <- address of label

ret
- Pop address from top of stack and jump
- eip <- memory[esp]; esp <- esp + 4
- **WARNING!** The word on the top of the stack had better be an address, not some leftover data

Win 32 C Function Call Conventions

- Wintel compilers obey the following conventions for C programs
  - Note: calling conventions normally designed very early in the instruction set/ basic software design. Hard to change later.
- C++ augments these conventions to handle the "this" pointer
- We'll use these conventions in our code

Win32 C Register Conventions

- These registers must be restored to their original values before a function returns, if they are altered during execution
  esp, ebp, ebx, esi, edi
  - Traditional: push/pop from stack to save/restore
- A function may use the other registers (eax, ecx, edx) however it wants, without having to save/restore them
- A 32-bit function result is expected to be in eax when the function returns

Call Site

- Caller is responsible for
  - Pushing arguments on the stack from right to left (allows implementation of varargs)
  - Execute call instruction
  - Pop arguments from stack after return
    - For us, this means add 4*(# arguments) to esp after the return, since everything is either a 32-bit variable (int, bool), or a reference (pointer)

Call Example

n = sumOf(17,42)

```
    push 42                 ; push args
    push 17
    call   sumOf            ; jump &
                            ;   push addr
    add    esp,8            ; pop args
    mov    [ebp+offset_n],eax   ; store result
```


Callee

- Called function must do the following
  - Save registers if necessary
  - Allocate stack frame for local variables
  - Execute function body
  - Ensure result of non-void function is in eax
  - Restore any required registers if necessary
  - Pop the stack frame
  - Return to caller

Win32 Function Prologue

- The code that needs to be executed before the statements in the body of the function are executed is referred to as the *prologue*
- For a Win32 function f, it looks like this:

```
f:  push   ebp              ; save old frame pointer
    mov    ebp,esp          ; new frame ptr is top of
                            ;  stack after arguments and
                            ;  return address are pushed
    sub    esp,"# bytes needed"
                            ; allocate stack frame
```


Win32 Function Epilogue

- The *epilogue* is the code that is executed to obey a return statement (or if execution "falls off" the bottom of a void function)
- For a Win32 function, it looks like this:

```
    mov    eax,"function result"
                            ; put result in eax if not already
                            ;    there (if non-void function)
    mov    esp,ebp          ; restore esp to old value
                            ;    before stack frame allocated
    pop    ebp              ; restore ebp to caller's value
    ret                     ; return to caller
```


Example Function

- Source code

```
int sumOf(int x, int y) {
  int a, int b;
  a = x;
  b = a + y;
  return b;
}
```


Stack Frame for sumOf

Assembly Language Version

```
;; int sumOf(int x, int y) {
;;  int a, int b;
sumOf:
   push  ebp      ; prologue
   mov   ebp,esp
   sub   esp, 8

;;  a = x;
   mov  eax,[ebp+8]
   mov  [ebp-4],eax

;;  b = a + y;
   mov  eax,[ebp-4]
   add  eax,[ebp+12]
   mov  [ebp-8],eax

;;  return b;
   mov  eax,[ebp-8]
   mov  esp,ebp
   pop  ebp
   ret
;; }
```


Coming Attractions

- Now that we've got a basic idea of the x86 instruction set, we need to map language constructs to x86
  - Code Shape
- Then on to basic code generation
  - And later, an optimization sampler