

CSE P 501 – Compilers

x86 Lite for Compiler Writers

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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 – x86-64, MIPS, PPC, MMIX? ... – 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

- 30 Years of x86
 - 1978: 8086 – 16-bit processor, segmentation
 - 1982: 80286 – protected mode, floating point
 - 1985: 80386 – 32-bit architecture, “general-purpose” register set, VM
 - 1993: Pentium – mmx
 - 1999: Pentium III – SSE
 - 2000: Pentium IV – SSE2, SSE3, HT, virtualization
 - 2006: Core Duo, Core 2 – Multicore, SSE4+, x86-64
 - 2008: Atom, i7, ...
- Many internal implementation changes, pipelining, concurrency, &c



And It's Backward-Compatible!

- Current processors will run code written for the 8086(!)
 - (You can get VisiCalc 1.0 on the web!)
- ∴ Much of the Intel descriptions of the architecture are loaded down with modes and flags that obscure the modern, fairly simple 32-bit (and later 64-bit) processor model
- Modern processors have a RISC-like core
 - Simple, register-register & load/store architecture
 - Simple x86 instructions preferred; complex CICS instructions supported
 - We'll focus on the basic 32-bit core instructions



x86 Assembler

- MiniJava compiler project output will be an assembler source program
 - Let the assembler handle the translation to binary encodings, address resolutions, etc.
- Examples here use Intel/Microsoft syntax
 - Used by masm (included in Visual Studio)
- Other popular choice: GNU Assembler (in gcc)
 - Major differences: dst,src reversed; different instruction opcodes for different data formats (implied in Intel syntax); a few others
- You are free to use either



Intel ASM 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
 - Data should almost always 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 (same as every processor you've ever seen)
 - while (running) {
 - fetch instruction beginning at eip address
 - $eip \leftarrow eip + \text{instruction length}$
 - execute instruction
- Sequential execution unless a jump stores a new "next instruction" address in eip



Instruction Format

- Typical data manipulation instruction
 - opcode dst,src
- Meaning is
 - $dst \leftarrow dst \text{ op } src$
- 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



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 (not next “free” dblword)
 - 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

- $esp \leftarrow esp - 4$; $memory[esp] \leftarrow src$
(e.g., push src onto the stack)

pop dst

- $dst \leftarrow memory[esp]$; $esp \leftarrow esp + 4$
(e.g., pop top of stack into dst and logically remove it from the stack)
- These are highly optimized and heavily used
 - Function call protocol is stack-based
 - 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
 - (This is often optimized to use esp-relative addresses instead. Frees up ebp, needs additional bookkeeping at compile time)



Operand Address Modes (1)

- These should cover most of 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 field offset



Operand Address Modes (2)

- In full generality, a memory address can combine the contents of two registers (with one being scaled) plus a constant displacement:
 - [basereg + index*scale + constant]
 - Scale can be 2, 4, 8
- Main use is for array subscripting
- Example: suppose
 - Array of 4-byte ints
 - Address of the array A is in ecx
 - Subscript i is in eax
 - Code to store edx in A[i]
`mov [ecx+eax*4],edx`



dword ptr – Intel assembler

- 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
  - Not an issue in GNU as – different opcode mnemonics for different operand sizes

# Basic Data Movement and Arithmetic Instructions

mov dst,src

- $\text{dst} \leftarrow \text{src}$

add dst,src

- $\text{dst} \leftarrow \text{dst} + \text{src}$

sub dst,src

- $\text{dst} \leftarrow \text{dst} - \text{src}$

inc dst

- $\text{dst} \leftarrow \text{dst} + 1$

dec dst

- $\text{dst} \leftarrow \text{dst} - 1$

neg dst

- $\text{dst} \leftarrow -\text{dst}$   
(2's complement arithmetic negation)



# Integer Multiply and Divide

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`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 (but address modes can do simple scaling)

`idiv src`

- Divide `edx:eax` by `src` (`edx:eax` holds sign-extended 64-bit value; cannot use other registers for division)
- `eax <- quotient`
- `edx <- remainder`

`cdq`

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



# Bitwise Operations

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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

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- 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
  - But be careful – be sure semantics are OK
- There are additional instructions that shift and rotate double words, use a calculated shift amount instead of a constant, etc.



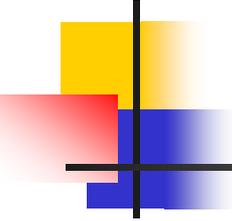
# Load Effective Address

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- 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.
- Also useful for computing arithmetic expressions that match address arithmetic



# Control Flow - GOTO

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- At this level, all we have is goto and conditional goto
- Loops and conditional statements are synthesized from these
- Optimization note: random 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 notes:
  - `dst` will be a label
  - Can have multiple labels on separate lines preceding an instruction
    - Convenient in compiler-generated asm lang.



# Conditional Jumps

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- 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

# Compare and Jump Conditionally

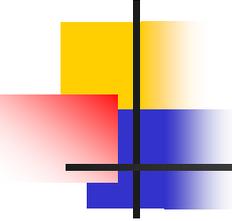


- Want: compare two operands and jump if a relationship holds between them

- Would like to do this

```
 jmpcond op1,op2,label
```

but can't, because 3-address instructions can't be encoded in x86



# cmp and jcc

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- Instead, use a 2-instruction sequence

```
 cmp op1,op2
```

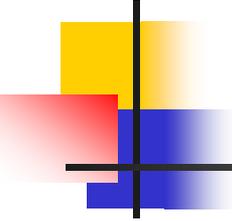
```
 jcc label
```

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  |

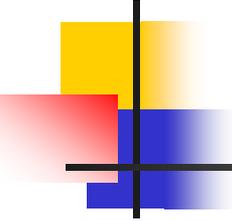
- Again, the assembler is mapping more than one mnemonic to some machine instructions



# Function Call and Return

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- 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

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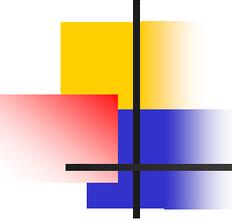
## call label

- Push address of next instruction and jump
- $esp \leftarrow esp - 4$ ;  $memory[esp] \leftarrow eip$   
 $eip \leftarrow \text{address of label}$

## ret

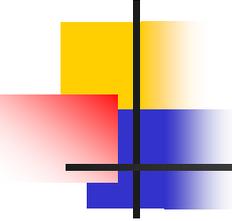
- Pop address from top of stack and jump
- $eip \leftarrow memory[esp]$ ;  $esp \leftarrow esp + 4$
- **WARNING!** The word on the top of the stack had better be an address, not some leftover data

# Win 32 C Function Call Conventions



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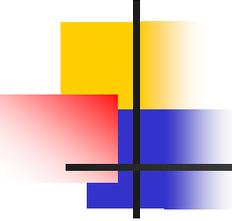
- Wintel code obeys the following conventions for C programs
  - Note: calling conventions normally designed very early in the instruction set/basic software design. Hard (e.g., basically impossible) to change later.
- C++ augments these conventions to include the “this” pointer
- We’ll use these conventions in our code



# Win32 C Register Conventions

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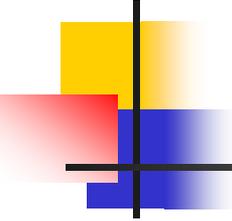
- These registers must be restored to their original values before a function returns, if they are altered during execution
  - esp, ebp, ebx, esi, edi
    - Traditional: push/pop from stack to save/restore
- A function may use the other registers (eax, ecx, edx) however it wants, without having to save/restore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



# Call Site

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- 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  $4 * (\# \text{ arguments})$  to esp after the return, since everything is either a 32-bit variable (int, bool), or a reference (pointer)

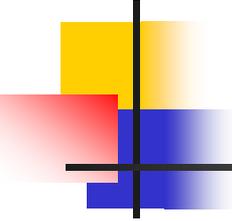


# Call Example

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n = sumOf(17,42)

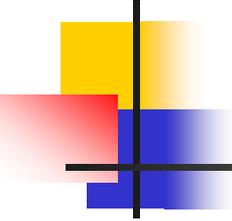
```
 push 42 ; push args
 push 17
 call sumOf ; jump &
 ; push addr
 add esp,8 ; pop args
 mov [ebp+offsetn],eax ; store result
```



# Callee

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- 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

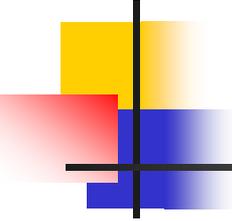


# Win32 Function Prologue

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- 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
```

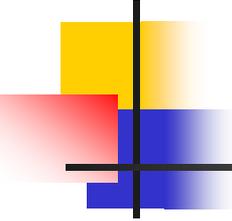


# Win32 Function Epilogue

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- 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
```

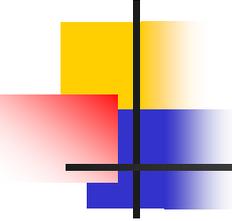


# Example Function

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- Source code

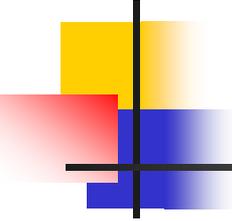
```
int sumOf(int x, int y) {
 int a, int b;
 a = x;
 b = a + y;
 return b;
}
```



# Stack Frame for sumOf

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



# Assembly Language Version

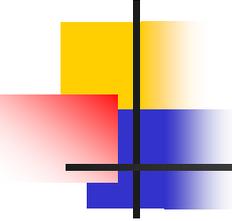
```
;; int sumOf(int x, int y) {
;; int a, int b;
sumOf:
 push ebp ; prologue
 mov ebp,esp
 sub esp, 8

;; 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

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- 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 execution
  - And later, optimizations