143A: Principles of Operating Systems

Lecture 4: Calling conventions

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Recap from last time
Stack and procedure calls
What is stack?
Stack

- It's just a region of memory
  - Pointed by a special register ESP
- You can change ESP
  - Get a new stack
Why do we need stack?
Calling functions

// some code...
foo();
// more code..

• Stack contains information for how to return from a subroutine
  • i.e., foo()
• Main purpose:
  • Store the return address for the current procedure
  • Caller pushes return address on the stack
  • Callee pops it and jumps
Stack

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  - Store the return address for the current procedure
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  - Callee pops it and jumps
Stack

- Other uses:
  - Local data storage
  - Parameter passing
  - Evaluation stack
    - Register spill
Call/return

- **CALL instruction**
  - Makes an unconditional jump to a subprogram and pushes the address of the next instruction on the stack

```markdown
push eip + sizeof(CALL); save return
; address
```

```markdown
jmp _my_function
```

- **RET instruction**
  - Pops off an address and jumps to that address
Manipulating stack

- ESP register
  - Contains the memory address of the topmost element in the stack
- PUSH instruction

  ```
push 0xBAR
  ```

- Insert data on the stack
- Subtract 4 from ESP
Manipulating stack

- POP instruction
  
  `pop EAX`

  - Removes data from the stack
  - Saves in register or memory
  - Adds 4 to ESP

  \[
  \text{EAX} = 0\timesBAR
  \]
Example: PUSH

Stack Growth

Before Pushing Doubleword

<table>
<thead>
<tr>
<th>31</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td></td>
</tr>
<tr>
<td>n-4</td>
<td></td>
</tr>
<tr>
<td>n-8</td>
<td></td>
</tr>
</tbody>
</table>

ESP

After Pushing Doubleword

<table>
<thead>
<tr>
<th>31</th>
<th>0</th>
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<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Doubleword Value</td>
</tr>
</tbody>
</table>

ESP
Example: POP

Stack Growth

Before Popping Doubleword

After Popping Doubleword

Doubleword Value

ESP
Calling conventions
Calling conventions

• Goal: reentrant programs
  • How to pass arguments
    – On the stack?
    – In registers?
  • How to return values
    – On the stack?
    – In registers?
• Conventions differ from compiler, optimizations, etc.
Stack consists of frames

- Each function has a new frame

```c
void DrawSquare(...) {
    ...
    DrawLine(x, y, z);
}
```

- Use dedicated register **EBP** (frame pointer)
  - Points to the base of the frame
Stack consists of frames

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}
```

- Use dedicated register **EBP** (frame pointer)
  - Points to the base of the frame
Prologue/epilogue

- Each function maintains the frame
  - A dedicated register EBP is used to keep the frame pointer
  - Each function uses prologue code (blue), and epilogue (yellow) to maintain the frame

```assembly
my_function:
  push ebp ; save original EBP value on stack
  mov ebp, esp ; new EBP = ESP
  …. ; function body
  pop ebp ; restore original EBP value
  ret
```
How to allocate local variables?

```c
void my_function()
{
    int a, b, c;
    ...
}
```
Allocating local variables

On the stack!

- Each function has private instances of local variables
- Can call recursively

```c
foo(int x) {
    int a, b, c;
    a = x + 1;
    if ( a < 100 )
        foo(a);
    return;
}
```
Allocating local variables

- Stored right after the saved EBP value in the stack
- Allocated by subtracting the number of bytes required from ESP

```assembly
_my_function:
push ebp
mov ebp, esp
sub esp, LOCAL_BYTES ; = # bytes needed by locals
... 
mov esp, ebp
pop ebp
ret
```

; save original EBP value on stack
; new EBP = ESP
; function body
; deallocate locals
; restore original EBP value
Example

```c
void my_function() {
    int a, b, c;
    ...
}

_my_function:
    push ebp ; save the value of ebp
    mov ebp, esp ; ebp = esp, set ebp to be top of the stack (esp)
    sub esp, 12 ; move esp down to allocate space for the
                 ; local variables on the stack
```

- With frames local variables can be accessed by dereferencing EBP

```assembly
mov [ebp - 4], 10 ; location of variable a
mov [ebp - 8], 5 ; location of b
mov [ebp - 12], 2 ; location of c
```
Example

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void my_function() {
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```c
```
Example

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    mov [ebp -  4], 10   ; location of variable a
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    mov [ebp - 12], 2    ; location of c
```
How to pass arguments?

- Options
  - Registers
  - On the stack
How to pass arguments?

- x86 32 bit
  - Pass arguments on the stack
  - Return value is in EAX and EDX
- x86 64 bit – more registers!
  - Pass first 6 arguments in registers
    - RDI, RSI, RDX, RCX, R8, and R9
  - The rest on the stack
  - Return value is in RAX and RDX
x86_32: passing arguments on the stack

- Example function

```c
void my_function(int x, int y, int z)
{
    ...
}
```

- Example invocation

```c
my_function(2, 5, 10);
```

- Generated code

```c
push 10
push 5
push 2
call _my_function
```
Example stack

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>[ebp + 16] (3rd function argument)</td>
</tr>
<tr>
<td>5</td>
<td>[ebp + 12] (2nd argument)</td>
</tr>
<tr>
<td>2</td>
<td>[ebp + 8] (1st argument)</td>
</tr>
<tr>
<td>RA</td>
<td>[ebp + 4] (return address)</td>
</tr>
<tr>
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<td>[ebp] (old ebp value) ← EBP points here</td>
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<tr>
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Example stack

| FP | [ebp] (old ebp value) \( \leftarrow \) EBP points here

| [ebp - 4] (1st local variable)

| [ebp - X] (esp - the current stack pointer)
Example stack

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Example: callee side code

```c
void my_function(int x, int y, int z) {
    int a, b, c;
    ...
    return;
}
```

```assembly
_my_function:
push ebp
mov ebp, esp
sub esp, 12 ; allocate local varaibles
            ; sizeof(a) + sizeof(b) + sizeof(c)
            ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
            ; a=[ebp-4]=[esp+8],
            ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
mov esp, ebp ; deallocate local variables
pop ebp
ret
```
Example: callee side code

```c
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}
```

```assembly
_my_function:
push ebp
mov ebp, esp
sub esp, 12 ; allocate local variables
            ; sizeof(a) + sizeof(b) + sizeof(c)
            ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
            ; a=[ebp-4]=[esp+8],
            ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
mov esp, ebp ; deallocate local variables
pop ebp
ret
```
Example: callee
side code

```c
void my_function(int x, int y, int z)
{
    int a, b, c;
    ...
    return;
}

_my_function:
    push ebp
    mov ebp, esp ; ebp = esp
    sub esp, 12 ; allocate local variables
        ; sizeof(a) + sizeof(b) + sizeof(c)
    ; x = [ebp + 8], y = [ebp + 12], z = [ebp + 16]
    ; a=[ebp-4]=[esp+8],
    ; b=[ebp-8]=[esp+4], c=[ebp-12] = [esp]
    mov esp, ebp ;deallocate local variables (esp = ebp)
    pop ebp
    ret
```
Example: caller side code

```c
int callee(int, int, int);

int caller(void)
{
    int ret;
    ret = callee(1, 2, 3);
    ret += 5;
    return ret;
}
```

caller:

; make new call frame
push    ebp
mov     ebp, esp

; push call arguments
push    3
push    2
push    1

call    callee

; remove arguments from frame
add     esp, 12

; use subroutine result
add     eax, 5

; restore old call frame
pop     ebp

; return
ret
Example: caller side code

```c
int callee(int, int, int);

int caller(void)
{
    int ret;
    ret = callee(1, 2, 3);
    ret += 5;
    return ret;
}
```

caller:
```assembly
    ; make new call frame
    push    ebp
    mov     ebp, esp
    ; push call arguments
    push    3
    push    2
    push    1
    ; call subroutine 'callee'
call callee
    ; remove arguments from frame
    add     esp, 12
    ; use subroutine result
    add     eax, 5
    ; restore old call frame
    pop     ebp
    ; return
    ret
```
Back to stack frames, so why do we need them?

- ... They are not strictly required
- GCC compiler option -fomit-frame-pointer can disable them

Don't keep the frame pointer in a register for functions that don't need one. This avoids the instructions to save, set up and restore frame pointers; it also makes an extra register available in many functions. It also makes debugging impossible on some machines.
Referencing args without frames

Initially parameter is
- [ESP + 4]

Later as the function pushes things on the stack it changes, e.g.
- [ESP + 8]
• Debugging becomes hard
  • As ESP changes one has to manually keep track where local variables are relative to ESP (ESP + 4 or +8)
    – Compiler can do this!
    – But it's hard for a human
• It's hard to unwind the stack in case of a crash
  – To print out a backtrace
And you only save...

- A couple instructions required to maintain the stack frame
- And 1 register (EBP)
  - x32 has 8 registers (and one is ESP)
    - So taking another one is 12.5% of register space
    - Sometimes its worse it!
  - x64 has 16 registers, so it doesn't really matter
- That said, GCC sets `-fomit-frame-pointer` to “on”
  - At -O, -O1, -O2 ...
  - Don't get surprised
Saving and restoring registers
Saving register state across invocations

- Processor doesn't save registers
  - General purpose, segment, flags
- Again, a calling convention is needed
  - Agreement on what gets saved by a callee and caller
Saving register state across invocations

- Registers EAX, ECX, and EDX are caller-saved
  - The function is free to use them
- ... the rest are callee-saved
  - If the function uses them it has to restore them to the original values
• In general there are multiple calling conventions
  • We described cdecl
  • Make sure you know what you're doing
  • https://en.wikipedia.org/wiki/X86_calling_convention
    s#List_of_x86_calling_conventions
  • It's easy as long as you know how to read the table
Questions?
References

- https://en.wikibooks.org/wiki/X86_Disassembly/Functions_and_Stack_Frames
- https://en.wikipedia.org/wiki/Calling_convention