IA-32 Architecture

CS 4440/7440 Malware Analysis and Defense

Intel x86 Architecture

- Security professionals constantly analyze assembly language code
- Many exploits are written in assembly
- Source code for applications and malware is not available in most cases
- We cover only the modern 32-bit view of the x86 architecture

x86 Primer

- CISC architecture
  - Lots of instructions and addressing modes
  - Operands can be taken from memory
  - Instructions are variable length
    - Depends on operation
    - Depends on addressing modes
- Architecture manuals at:

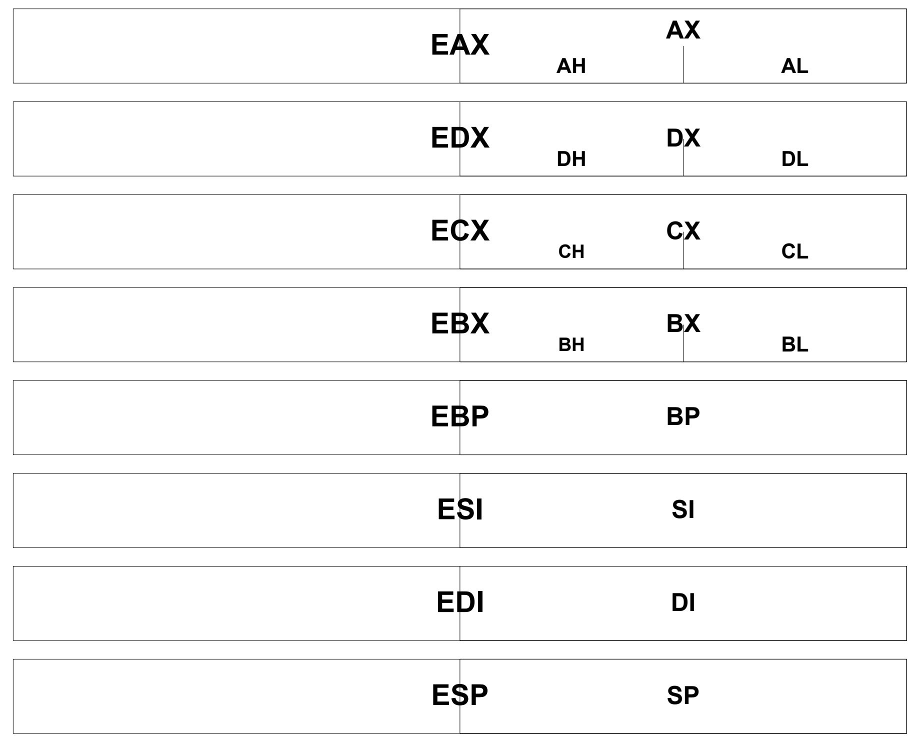
  http://www.intel.com/products/processor/manuals/index.htm

x86 Registers

- Eight 32-bit general registers:
  - EAX, EBX, ECX, EDX, ESI, EDI,
  - ESP (stack pointer),
  - EBP (base pointer, a.k.a. frame pointer)
- Names are not case-sensitive and are usually lower-case in assembly code (e.g. eax, ecx)

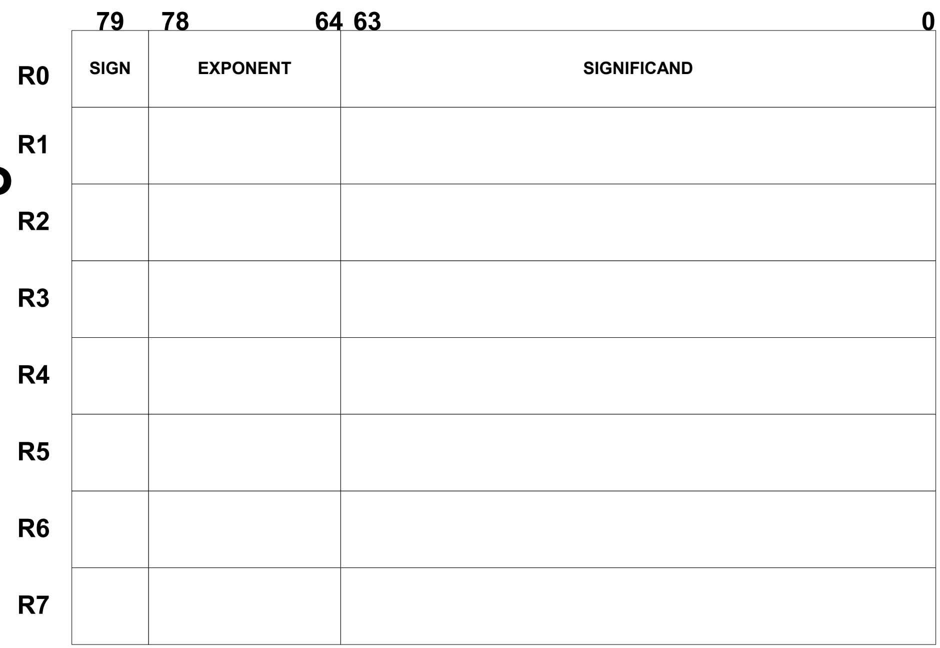
x86 Registers

- 8 general-purpose 32-bit registers
- ESP is the stack pointer; EBP is the frame pointer
- Not all registers can be used for all operations
  - Multiplication, division, shifting use specific registers



x86 Floating-point Registers

- Floating-point unit uses a stack
- Each register is 80-bits wide (doesn’t use IEEE FP standard)



x86 Instructions

- In MASM (Microsoft Assembler), the first operand is usually a destination, and the second operand is a source:

```
mov eax,ebx    ; eax := ebx
```

- Two-operand instructions are most common, in which first operand is both source and destination:

```
add eax,ecx     ; eax := eax + ecx
```

- Semicolon begins a comment

x86 Data Declarations

- Must be in a data section
- Give name, type, optional initialization:

```
.DATA
 count    DW   0   ; 16-bit, initialized to 0
 answer   DD   ?   ; 32-bit, uninitialized
```

- Can declare arrays:

```
array1  DD  100 DUP(0) ; 100 32-bit values,
                           ; initialized to zero
```

x86 Memory Operations

- “lea” instruction means “load effective address:

```
lea  eax,[count]  ; eax := address of count
```

- Can move through an address pointer

```
lea ebx,[count] ; ebx := address of count
mov [ebx],edx   ; count := edx
                ; ebx is a pointer
                ; [ebx] dereferences it
```

- We also will see the stack used as memory

x86 Stack Operations

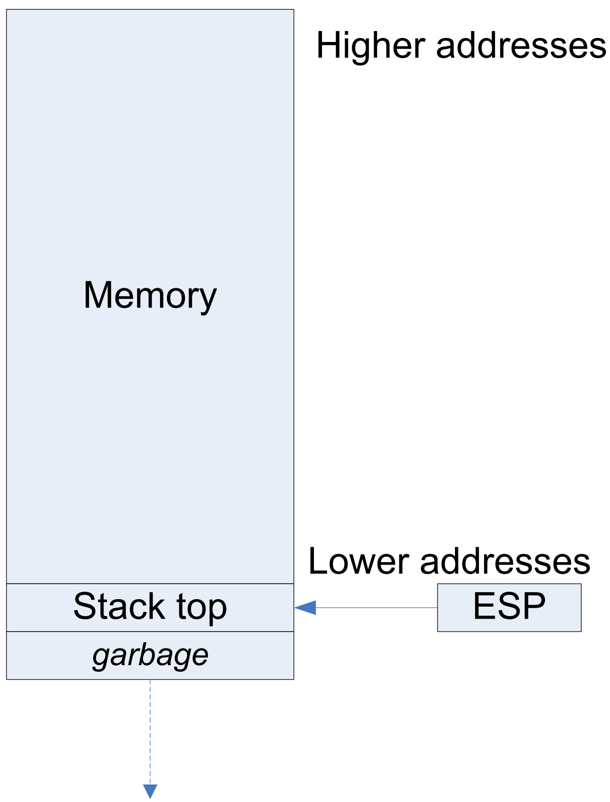
- The x86 stack is managed using the ESP (stack pointer) register, and specific stack instructions:

```
1.  push ecx   ; push ecx onto stack
2.  pop ebx    ; pop top of stack into register ebx
3.  call foo   ; push address of next instruction on
                ; stack, then jump to label foo
4.  ret        ; pop return address off stack, then
                ; jump to it
```

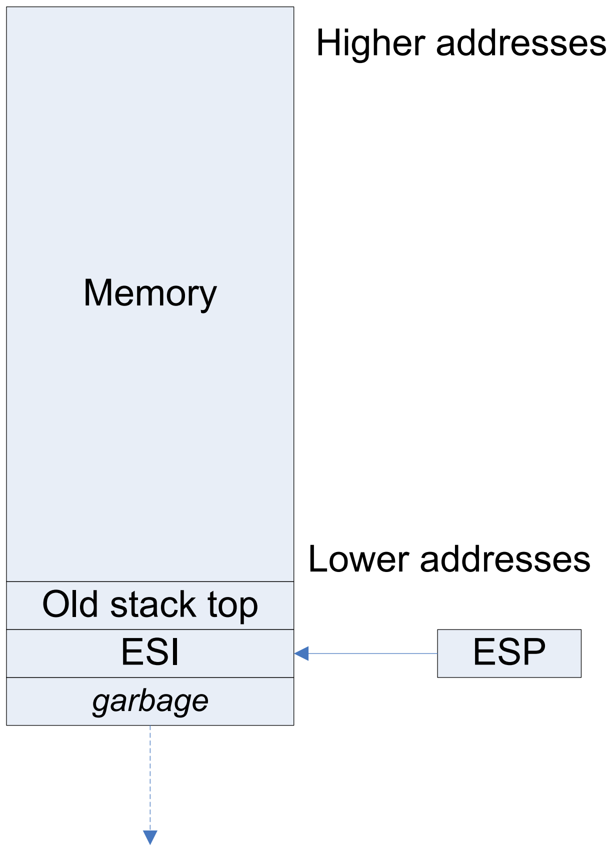
x86 Hardware Stack

- The x86 stack grows downward in memory addresses
- Decrementing ESP increases stack size;
  - incrementing ESP reduces it

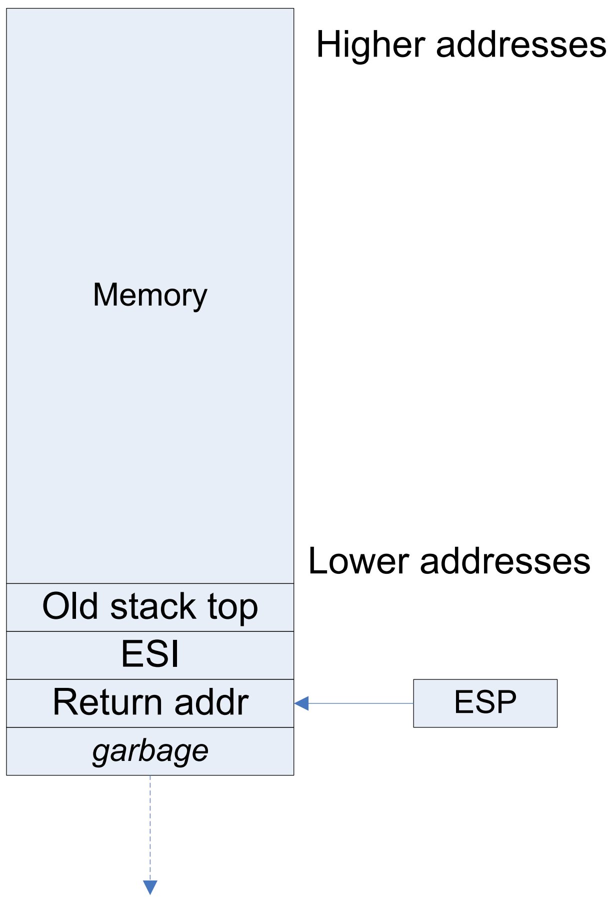
x86 Hardware Stack



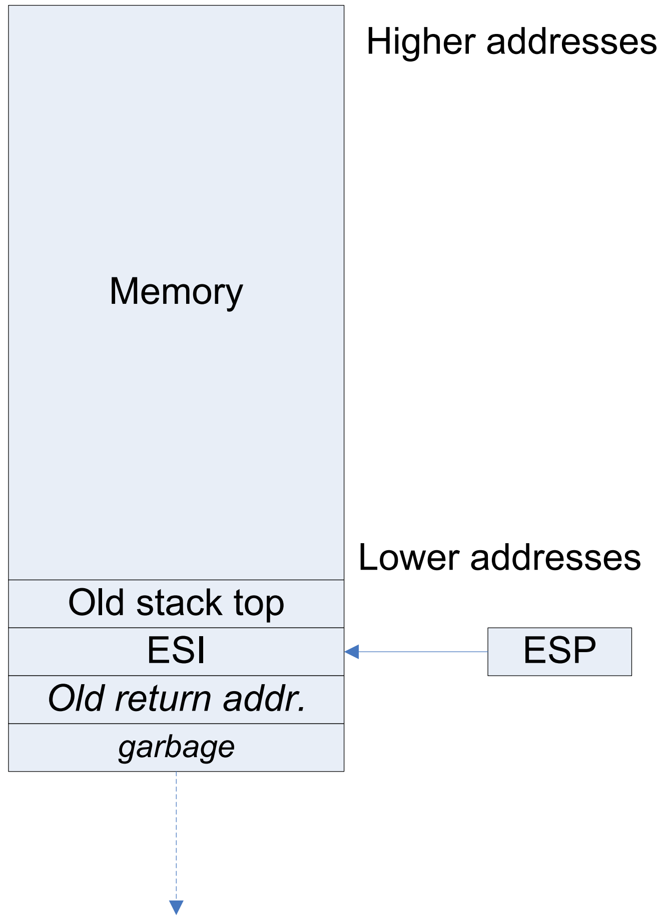
x86 Stack after "`push ESI`"



x86 Stack after `call`



x86 Stack after `ret`



x86 C Calling Convention

- A **calling convention** is an *agreement* among software designers
  - (e.g. of compilers, compiler libraries, assembly language programmers) on how to use registers and memory in subroutines
  - NOT enforced by hardware!
- Allows software pieces to interact compatibly,
  - e.g. a C function can call an ASM function, and vice versa

C Calling Convention cont.

- Questions answered by a calling convention:
  1. How are parameters passed?
  2. How are values returned?
  3. Where are local variables stored?
  4. Which registers must the caller save before a call, and which registers must the callee save if it uses them?

How Are Parameters Passed?

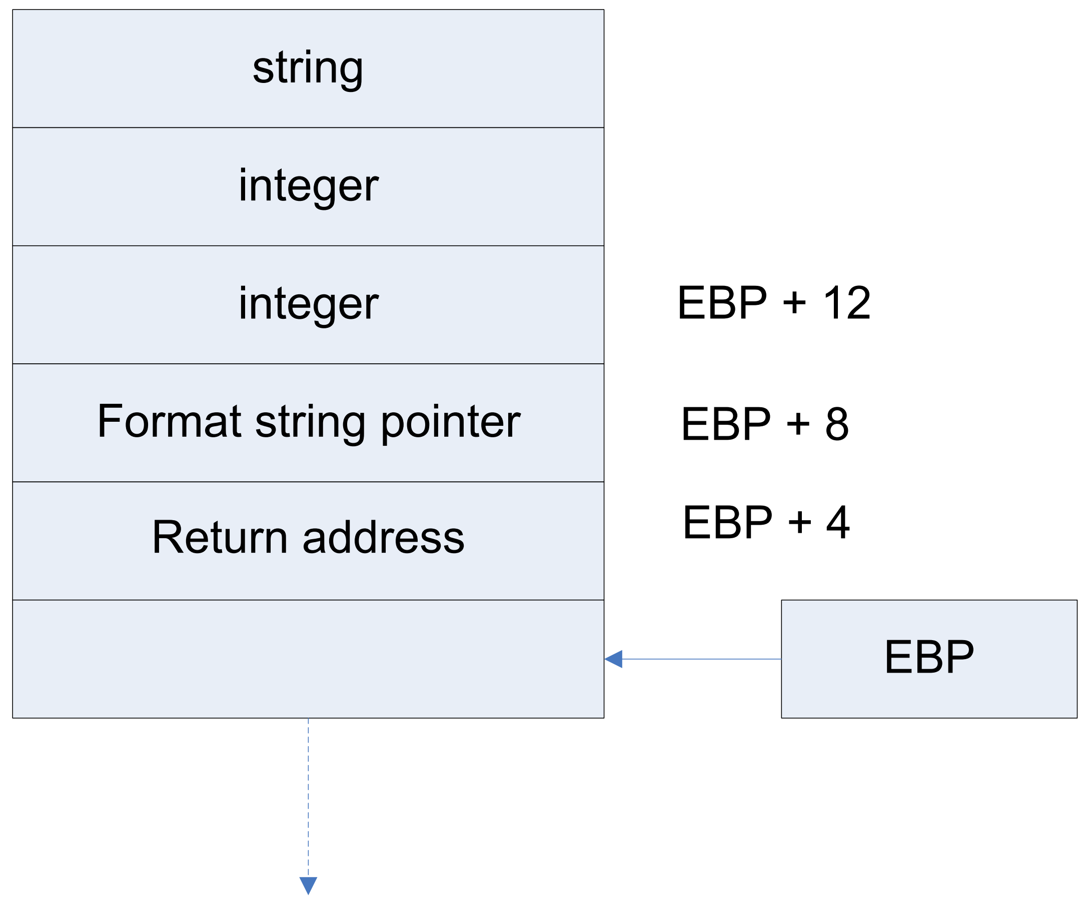
- Most machines use registers, because they are faster than memory
  - x86 has too few registers to do this
- Therefore, the stack must be used to pass parameters
- Parameters are pushed onto the stack in reverse order

Why Pass Parameters in Reverse Order?

- Some C functions have a variable number of parameters
  - First parameter determines the number of remaining parameters!
- Example: **`printf("%d %d %s\n", …);`**
- **`printf()`** library function
  - reads first parameter, then
  - determines that the number of remaining parameters is 3

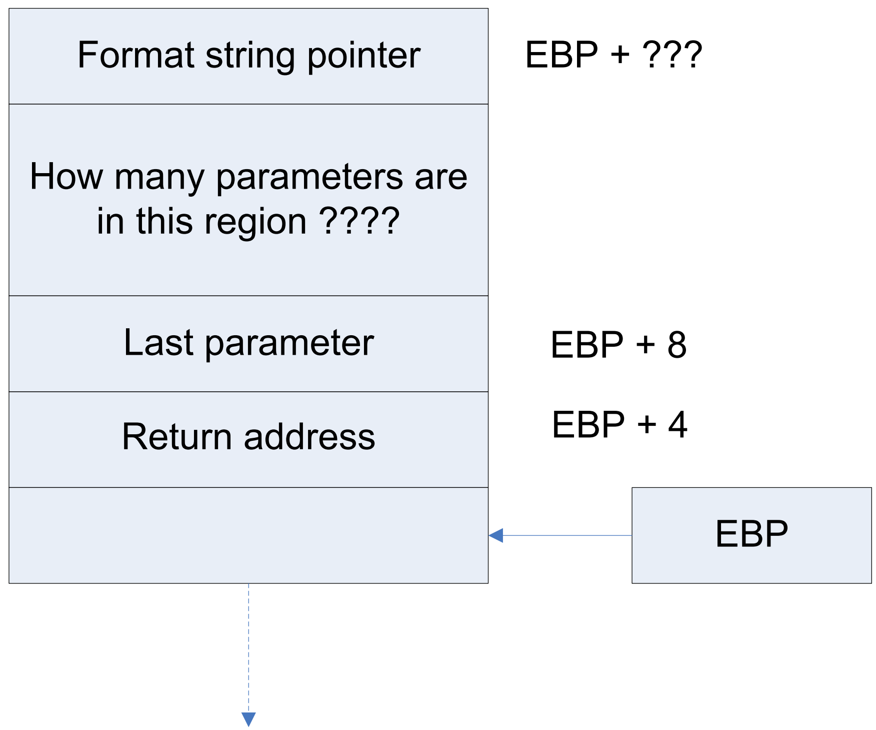
Reverse Order Parameters cont.

- **`printf()`** will always find the first parameter at [EBP + 8]



What if Parameter Order was NOT Reversed?

- **`printf()`** will always find the LAST parameter at **`[EBP + 8]`**; not helpful



C Calling Convention cont.

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How are Values Returned?

- Register eax contains the return value
- This means x86 can only return a 32-bit value from a function
- Smaller values are zero extended or sign extended to fill register eax
- If a programming language permits return of larger values (structures, objects, arrays, etc.),
  - a pointer to the object is returned in register eax

C Calling Convention cont.

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  1. How are parameters passed?
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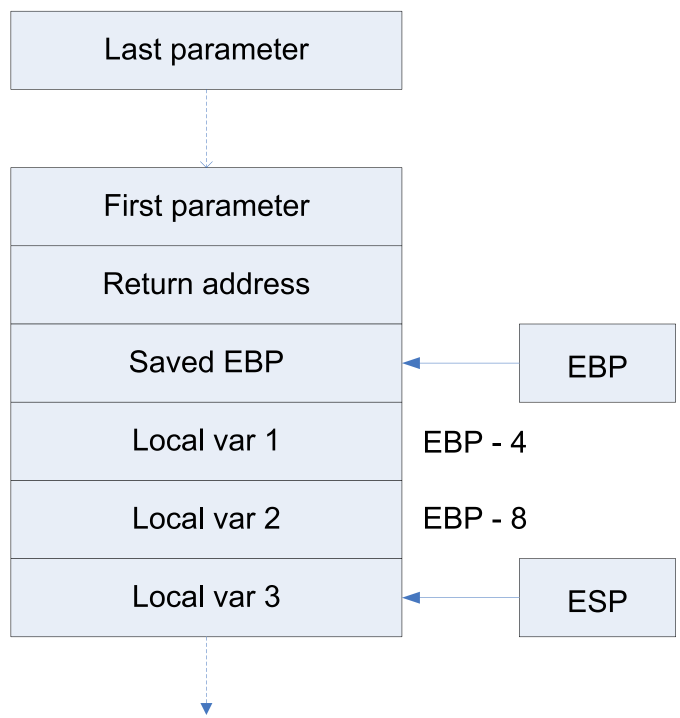
Where are Local Variables Stored?

- **Stack frame** for the currently executing function is between where EBP and ESP point in the stack



C Calling Convention cont.

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  1. How are parameters passed?
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  4. Which registers must the caller save before a call, and which registers must the callee save if it uses them?

Who Saves Which Registers?

- It is efficient to have the caller save some registers before the call, leaving others for the callee to save
- x86 only has 8 general registers; 2 are used for the stack frame (ESP and EBP)
- The other 6 are split between callee-saved (ESI, EDI) and caller-saved
- Remember: Just a *convention*, or agreement, among software designers

What Does the Caller Do?

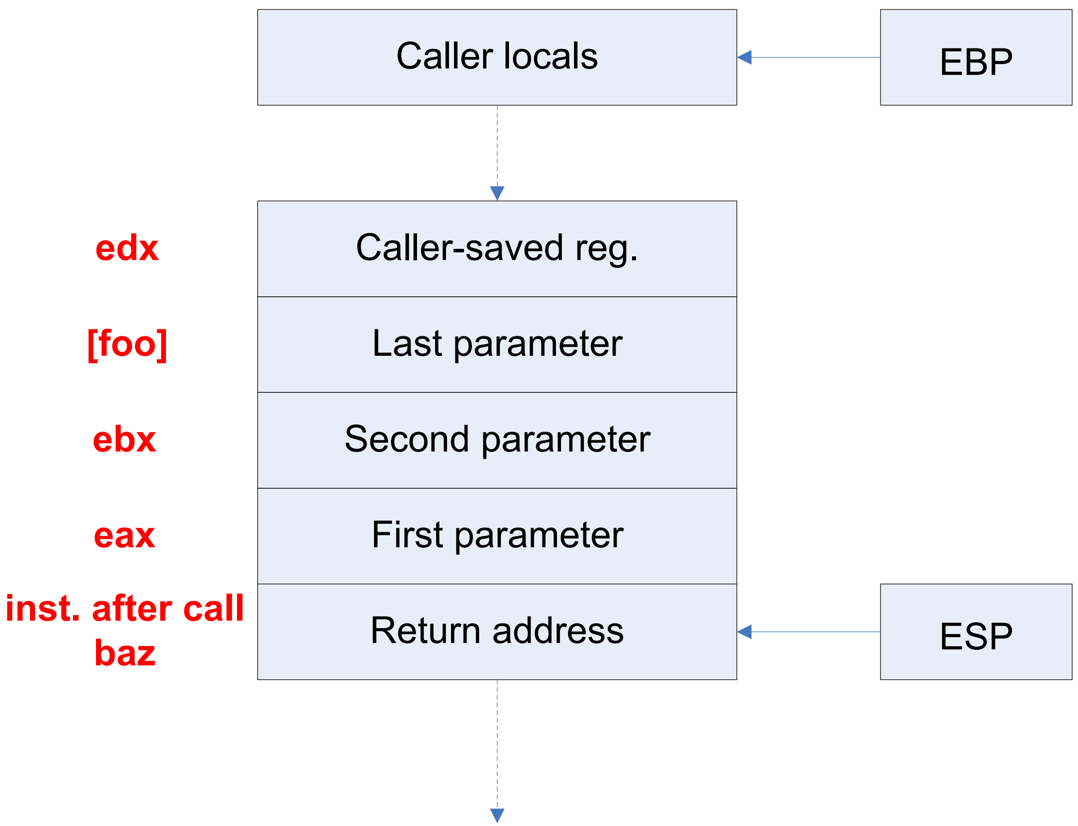
- Example: Call a function and pass 3 integer parameters to it

```
push edx      ; caller-saved register
push [foo]    ; Var foo is last parameter
push ebx      ; ebx is second parameter
push eax      ; eax is first parameter
call baz      ; push return address, jump
add esp,12    ; toss old parameters
pop edx       ; restore caller-saved edx
              ; eax holds return value
```

- eax, ebx did not need to be saved here

Stack after Call

- x86 stack immediately after `call baz`



Callee Stack Frame Setup

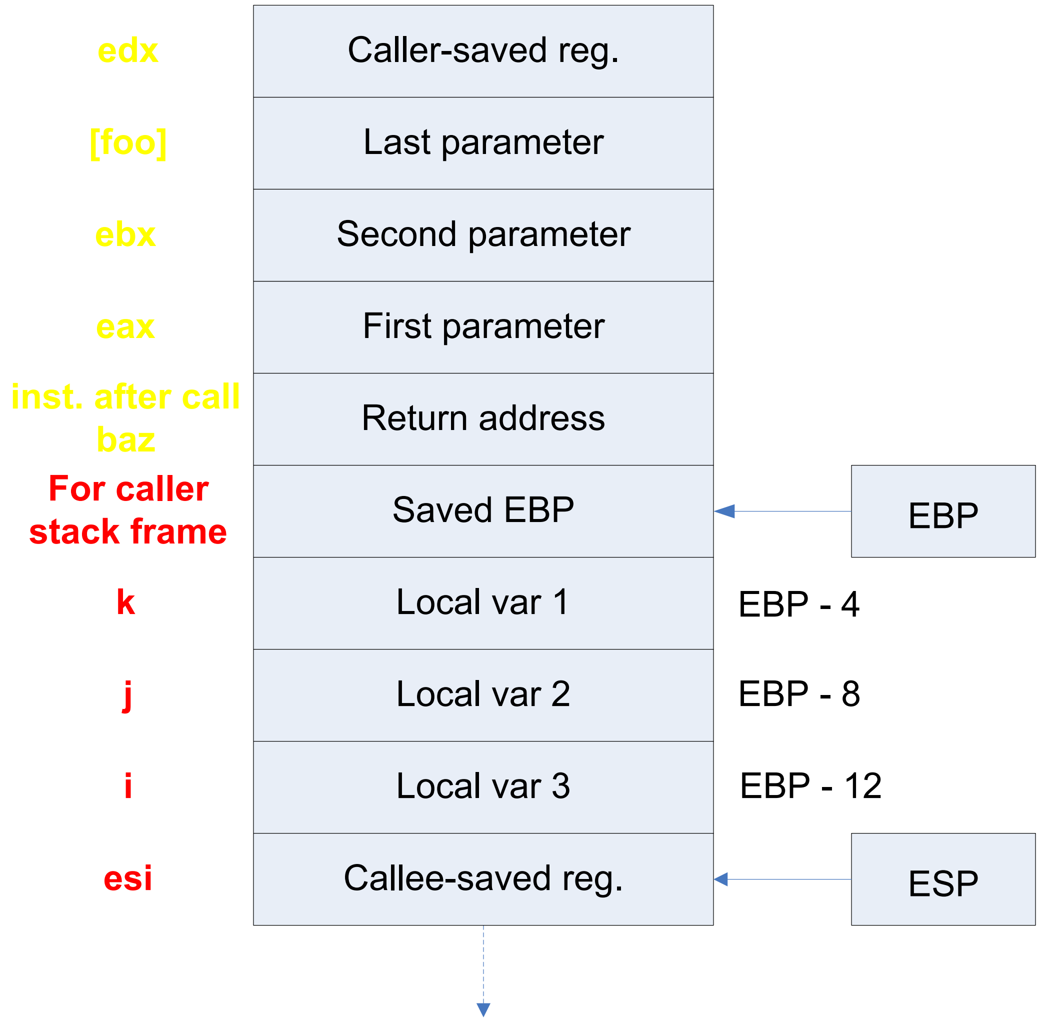
- The standard subroutine prologue code sets up the new stack frame:

```
; Prologue code at top of function
push ebp          ; save old base pointer
move ebp,esp      ; Set new base pointer
sub esp,12        ; Make room for locals
push esi          ; Func uses ESI, so save
:
:
```

This code sets up the stack frame of the callee

Stack After Prologue Code

- After the prologue code sets up the new stack frame:



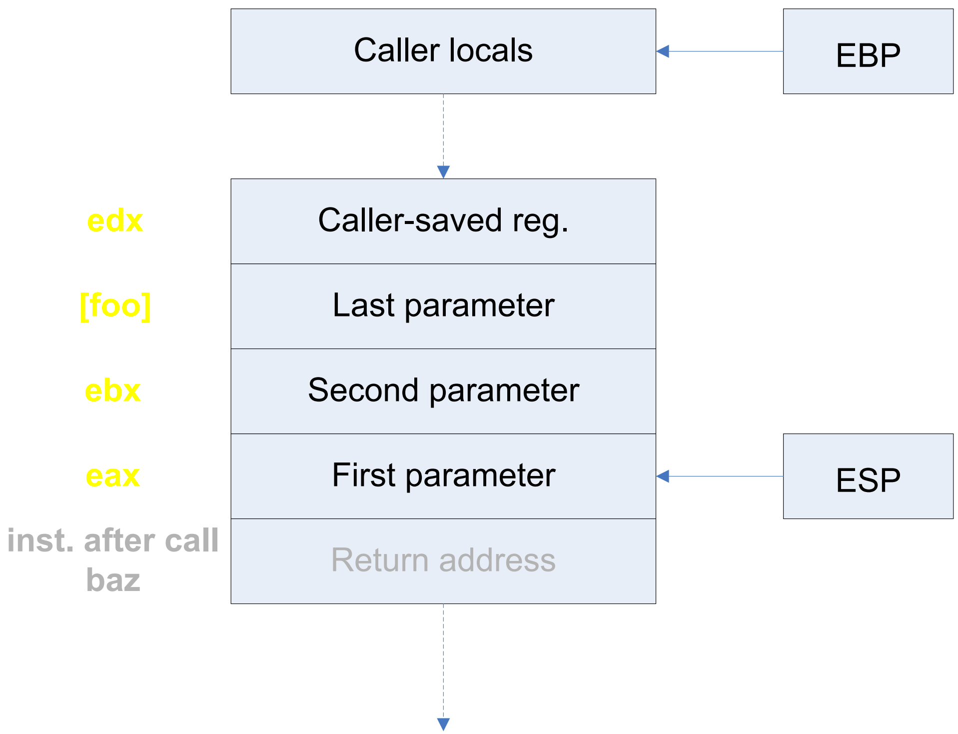
Callee Stack Frame Cleanup

- Epilogue code at end cleans up frame (mirror image of prologue):

```
; Epilogue code at bottom of function
pop esi              ; Restore callee-saved ESI
move esp,ebp         ; Deallocate stack frame
pop ebp              ; Restore caller's EBP
ret                  ; return
```

Stack After Return

- After epilogue code and return:



Caller Stack Cleanup

- After the return, caller has a little cleanup code:

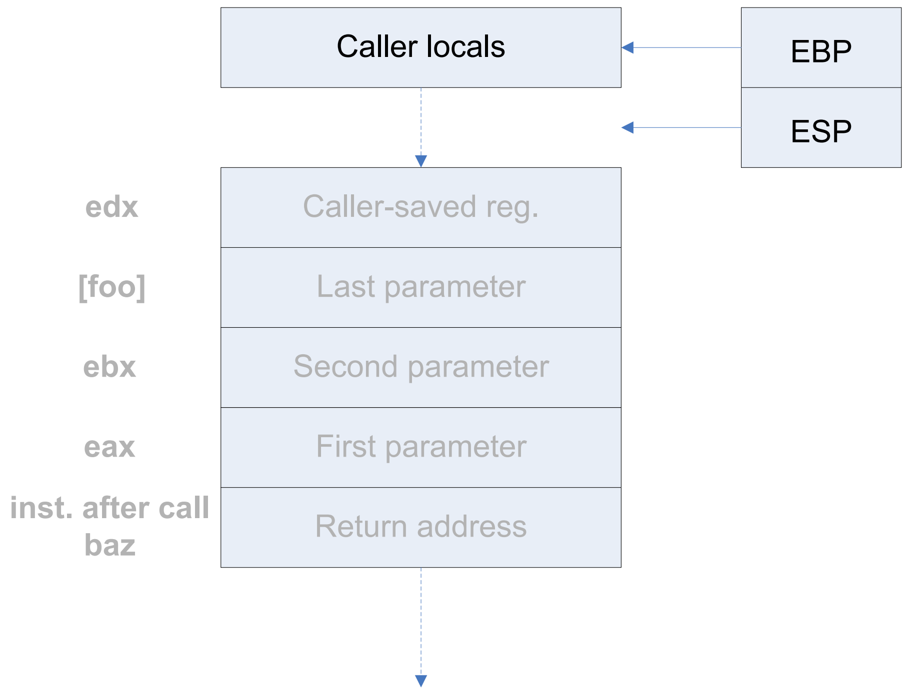
```
add esp,12    ; deallocate parameter space
pop edx       ; restore caller-saved register
```

Today

- Finish covering x86 background
- Reading Assignment
  - Szor, Chapter 2 (if you haven't already)
  - "Smashing the Stack for Fun and Profit"
- We will cover some details of the PE file format
  - Szor, pp. 160-172, section 4.3.2.1, describes PE format
  - Pay special attention to pp. 163-165, where the fields of interest to virus creators are discussed

Caller Stack After Cleanup

- After the caller's cleanup code:



Register Save Question

- Why would it be less efficient to have all registers be callee-saved, rather than splitting the registers into caller-saved and callee-saved? (Just think of one example of inefficiency.)

Call Stack: Virus Implications

- The return address is a primary target of malware
- If the malware can change the return address on the stack, it can cause control to pass to malware code
- We saw an example with buffer overflows
- E.g., "Tricky Jump" document on web page for another virus technique

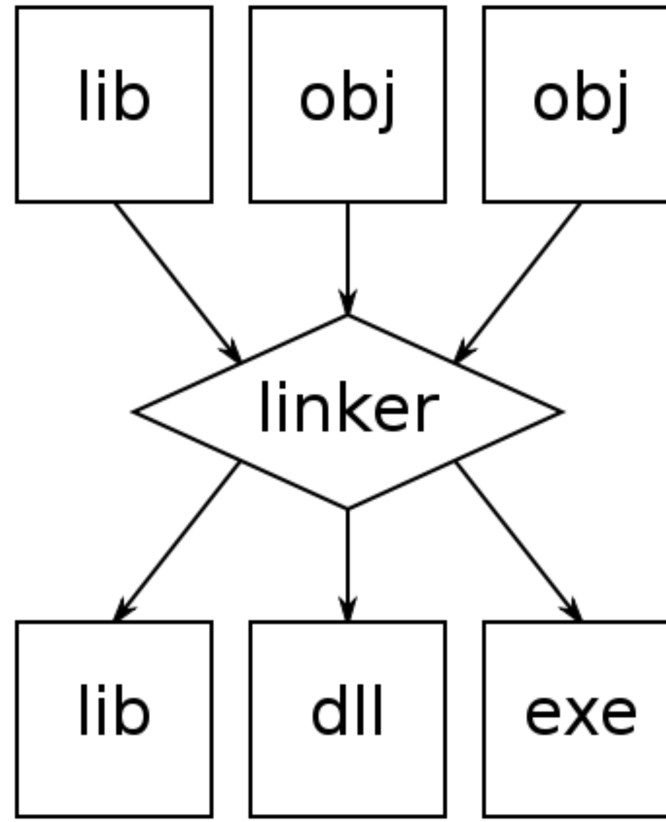
x86 Executable Files

- The standard format of a *.exe file, produced by compiling and linking, is the PE (Portable Executable) file
- Also called PE32 (because it is 32-bit code); newer format is PE64, and PE32+ is a transitional format
- Older formats exist for 16-bit DOS and Windows 3.1
- We will stick to the PE32 format, calling it PE for brevity

Linker

A **linker** is a program that

- takes one or more object files generated by a compiler and
- combines them into a single executable file, library file, or another object file.

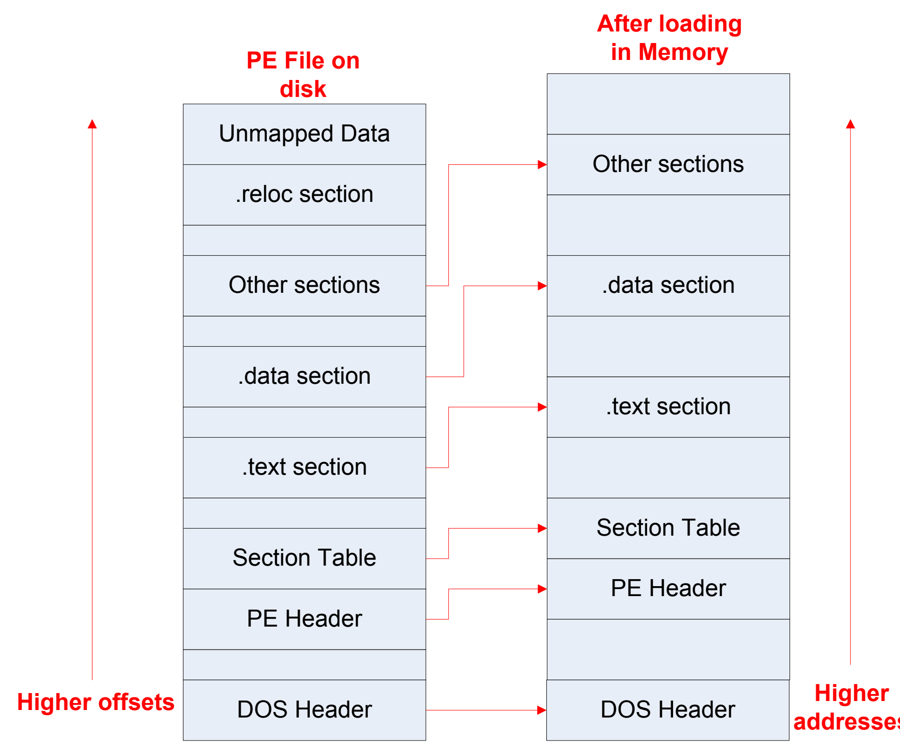


Loader

- **Loader**: the part of an OS responsible for loading programs and libraries into memory.
- **Loading**: an essential stage in the process of starting a program, as it places programs into memory and prepares them for execution.
- **Loading a program** involves
  - reading the contents of the executable file containing the program instructions into memory, and then
  - carrying out other required tasks to initialize the executable for running.
- Once loading complete, OS passes control to the loaded program code.

PE File Format

- Important to know how to analyze PE files when analyzing malware
- Overview:

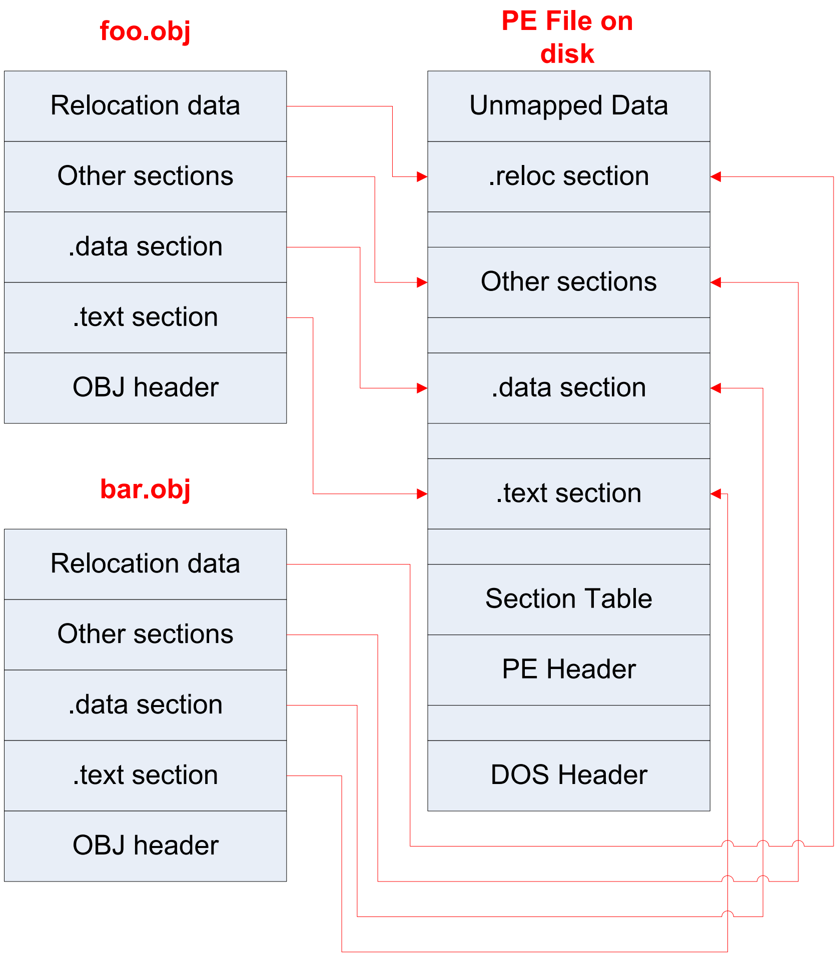


PE File Format

- Why the dead spaces?
  - Alignment restrictions
  - Loader increases dead spaces to use page boundaries (4KB), while alignment is to a lesser size (e.g. 128B) in the PE file on disk
- Some linkers make PE file align to page boundaries
  - Simplifies the loader's job
  - Make PE file bigger on disk

Producing a PE File

- Compiler produces multiple *.obj files
  - i.e., in case of separate compilation
- Linker groups like sections together and creates headers and section tables:



Detour: Motivation for Learning File Formats

- Question: Why do we care about the details of the PE file format?
- Answer: Because a virus writer will try to infect the PE file in such a way as to make the virus code execute, while making the PE file look as it would normally look. The job of anti-virus software is to find well-disguised viruses.

Next time

- Finish x86 slides
- Learn about "Obfuscated Tricky Jumps"

Virtual Addresses

- Addresses within *.obj and PE files are RVA (Relative Virtual Addresses)
- They are offsets relative to the eventual base address that the loader chooses at load time
- VA (virtual address) = base address (load point for section) + RVA
- Physical address is wherever the VA is mapped by the OS to actual RAM
- Linker cannot know final VA, as loading has not happened yet; must deal with RVA

Loading the PE File

- OS provides kernel32.dll, which is linked with almost every PE file
  - Application might also make use of other DLLs, such as compiler libraries, etc.
  - Loader must ensure that all dependent DLLs are loaded and ready to use
  - Linker cannot know where in memory the library functions, etc., will be loaded
- **Therefore**, PE file code calls external API functions through function pointers

PE Function Pointers

- For each DLL from which the PE file imports (uses) API functions, the linker creates an IAT (Import Address Table) in the PE
  - The Import Address Table is a table of function pointers into another DLL
  - Function calls from your application to the DLL your application depends on are made through these function pointers
- Linker initializes the IAT to RVAs
- Loader fills in the virtual addresses at load time

PE Function Pointers Example

- Your C code: `call printf(…)`
- Compiler records in the OBJ header the need to import `printf()` from the DLL that contains `stdio`
- Compiler produces initial IAT for `stdio` in the OBJ header
- Linker merges IATs from all *.obj files
  - Offset (RVA) of `printf()` within `stdio` DLL is fixed and can be determined by the linker simply by looking at the `stdio` library object code

PE Function Pointers Example cont'd.

- Linker patches new IAT RVA for **`printf()`** into your object code:
  - **`call dword ptr 0x41003768`**
  - This is an indirect call through a pointer
- Address **`0x41003768`** is an IAT entry that will be filled in by the loader
- Loader replaces IAT entry with VA at load time; it knows where **`stdio`** DLL is loaded

Import Address Table

.idata name

25000 virtual address (00425000 to 00425B72)

C0000040 flags

    Initialized Data

    Read Write

Section contains the following imports:

KERNEL32.dll

4251EC Import Address Table

110 GetCommandLineA

216 HeapFree

1E9 GetVersionExA

210 HeapAlloc

1A3 GetProcessHeap

Using the IAT

In the .text segment:

```
_GetCommandLineA@0:
  00415C7E: FF 25 EC 51 42 00  jmp dword ptr
            [__imp__GetCommandLineA@0]
_HeapFree@12:
  00415C84: FF 25 F0 51 42 00  jmp  dword ptr
                                    [__imp__HeapFree@12]
_GetVersionExA@4:
  00415C8A: FF 25 F4 51 42 00  jmp  dword ptr
                                    [__imp__GetVersionExA@4]
_HeapAlloc@12:
  00415C90: FF 25 F8 51 42 00  jmp  dword ptr
                                    [__imp__HeapAlloc@12]
_GetProcessHeap@0:
  00415C96: FF 25 FC 51 42 00  jmp  dword ptr
                                    [__imp__GetProcessHeap@0]
```

DOS Header

- If a program is invoked within a DOS command prompt window, it starts executing here
- For most PE32 executables, the DOS header contains a tiny executable that prints: "This application must be run from Windows", then exits

PE Header

- DOS Header points to PE header
- PE header points to IATs and the section table, which points to all code and data sections
- Viruses use the PE Header to navigate around the PE file, find where to insert virus code, etc.

PE Sections

- Common sections are `.text` (for code), `.data` (read/write data), `.rdata` (read-only data, `.reloc` (relocation data used to build IATs)
- The attribute bits determine whether a section can be read, written, executed, etc., NOT the section name; viruses might modify the attribute bits so that a `.text` section becomes writable!
- Class web page links to more details on PE files

Analyzing PE Files

- DUMPBIN tool produces readable printout of a PE file
- **`DUMPBIN /ALL /RAWDATA:NONE`** is most common usage
- **`/DISASM`** switch also useful: disassembles the code sections
- Class web page links to more details on DUMPBIN tool

See you later