Subprograms: Arguments

ICS312

Machine-Level and Systems Programming

Henri Casanova (henric@hawaii.edu)

Activation Records

- The stack is useful to store and retrieve return addresses, transparently managed via the CALL and RET instructions
- But it's much more useful than this
- In general, when calling a function, one puts all kinds of useful information on the stack
- When the function returns, this information is popped off the stack and the function's caller can safely resume execution
- The set of "useful information" is typically called an activation record (or a "stack frame")
- One very important component of an activation record is the parameters passed to the function
  - Another is the return address, as we've already seen

Subprogram Conventions

- When writing assembly, you could do whatever you want
- For instance, you could devise a clever scheme that reuses register values in creative ways instead of the stack
- Such solutions are typically error prone, making the code difficult to debug/extend/maintain, but can enhance performance
- Typically, one uses a consistent calling convention, so that there is a generic way to call a subprogram
- Of course compilers use calling conventions
  - The compiler, when generating assembly code, follows a standard method to generate assembly for all function calls
- Some languages specify which calling convention should be used
- What we describe in all that follows is (mostly) the convention used by the C language
  - i.e., C compilers must use this convention when generating assembly code from C code
  - We'll also use this convention when writing assembly by hand

A Simple Activation Record

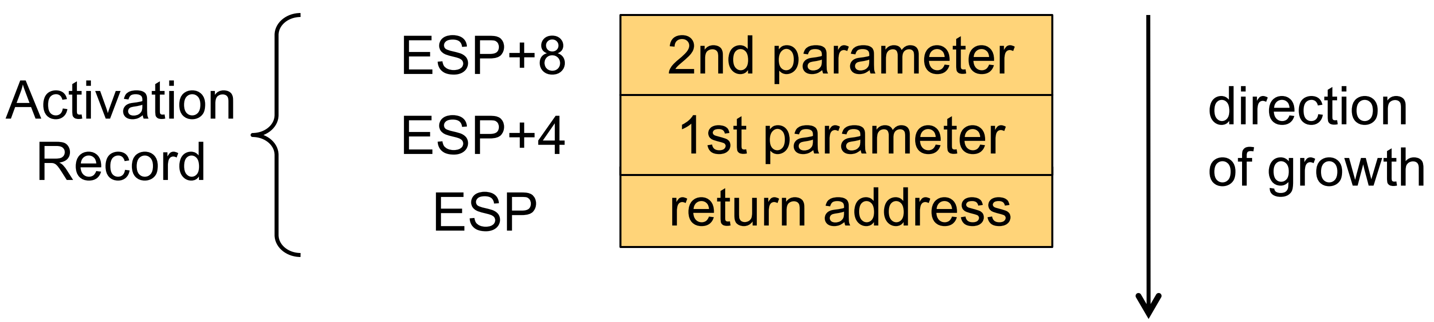
- To call a function you have to follow these steps:
  - **Push the parameters onto the stack**
  - Execute the CALL instruction, which pushes the return address onto the stack

- Warning: In the C calling convention parameters are pushed onto the stack in reverse order!
  - Say the function is f(a,b,c)
  - c is pushed onto the stack first
  - b is pushed onto the stack second
  - a is pushed onto the stack third

  - Makes sense-ish: the first parameter should be at a lower address than the second parameter

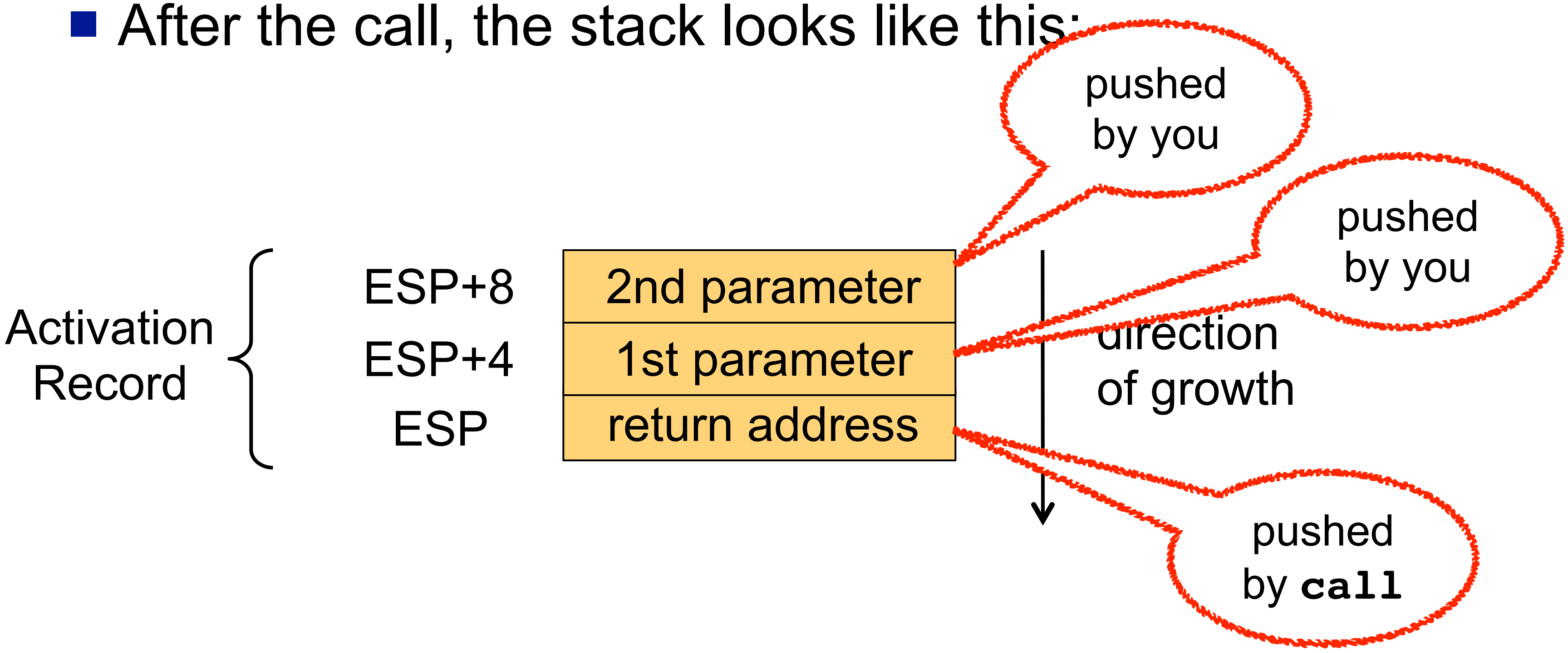
A Simple Activation Record

- Say you want to call a function with two 32-bit parameters
  - If parameters are < 32 bits, they need to be extended to 32-bit values (movzx or movsx), at least in this course
- After the call, the stack looks like this:



A Simple Activation Record

- Say you want to call a function with two 32-bit parameters
  - If parameters are < 32 bits, they need to be extended to 32-bit values (movzx or movsx), at least in this course
- After the call, the stack looks like this:



Using the Parameters

- Inside the code of the subprogram, parameters can be accessed via indirection from the stack pointer
- In our previous example:
  - **`mov eax, [ESP + 4]`** ; puts 1st parameter into eax
  - **`mov ebx, [ESP + 8]`** ; puts 2nd parameter into ebx
- Typically the subprogram does not pop the parameters off the stack before using them
  - It would be annoying to have to pop the return address first, and then push it back
  - It's convenient to have the parameters always stored in memory as opposed to being careful to constantly preserve them in registers
    - They may be copied into registers for performance reasons
    - But we can always get their original values from the stack

Accessing the stack in C

```
void main(int x) {
   x++;   // translated as: inc dword [esp + 4]
}
```

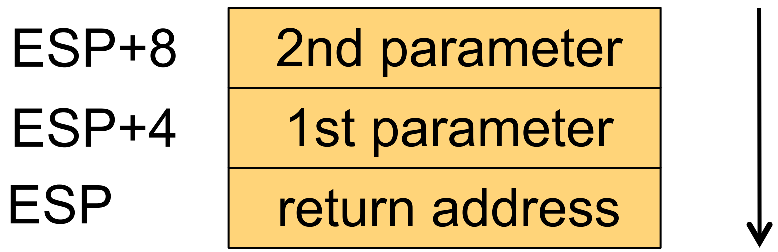
- The activation record on the stack is the subprogram’s little play pen
  - And yes, you can add one to a parameter as seen above, just as if it were a local variable
- The subprogram can modify its activation record in many ways, and eventually its activation record is wiped out anyway
- But, turns out, there is still a problem…

ESP and EBP

- There is one problem with referencing parameters using ESP, as in [ESP+4]
- If the subprogram uses the stack for something else, ESP will be modified!
  - So at some point in the program, the 1st parameter should be accessed as [ESP+4]
  - And at some other point, it may be accessed as [ESP+8], [ESP+12], etc., depending on how the stack grows
- So the convention is to use the **EBP** register as an anchor to save the value of ESP as soon as the subprogram starts
- Afterwards, the 1st parameter is **always** accessed as [EBP+4], the 2nd parameter is **always** accessed as [EBP+8], etc.

ESP and EBP

- Stack as it is when the subprogram begins



ESP and EBP

- Stack as it is when the subprogram begins

ESP+8	2nd parameter
ESP+4	1st parameter
ESP	return address

- EBP = ESP

EBP+8	2nd parameter
EBP+4	1st parameter
EBP = ESP	return address

ESP and EBP

- Stack as it is when the subprogram begins

ESP+8	2nd parameter
ESP+4	1st parameter
ESP	return address

- EBP = ESP

EBP+8	2nd parameter
EBP+4	1st parameter
EBP = ESP	return address

- Further use of the stack

ESP+16	EBP+8	2nd parameter
ESP+12	EBP+4	1st parameter
ESP+8	EBP	return address
	ESP+4	stuff
	ESP	stuff

Parameters still referred to as EBP+4 and EBP+8

ESP and EBP Mayhem

- **Big problem:** The **caller** may have been using EBP!
  - Typically to access its own parameters!!!
- So you can't just overwrite EBP (you = a subprogram being called)
- Because when you return, the caller will have a wrong EBP and will access its own parameters erroneously
- So you have to save EBP before overwriting it for your own purposes
- How do we deal with having to save stuff?
- We use the stack!!

Saving EBP on the Stack

- The convention is to first **push the value of EBP** onto the stack and then set **EBP = ESP**, as soon as the program starts
- So, the stack before the subprogram truly begins is:

ESP+12	2nd parameter
ESP+8	1st parameter
ESP+4	return address
EBP = ESP	**old value of EBP**

- Parameter accesses:
  - 1st parameter: [EBP+8]
  - 2nd parameter: [EBP+12]

- At the end of the subprogram, the value of EBP is popped and restored with a simple POP instruction

Subprogram Skeleton

```
func:
  push    ebp        ; save my caller's EBP
  mov     ebp, esp   ; set EBP = ESP

  . . .                   ; subprogram code

  pop     ebp   ; restore my caller's EBP
  ret           ; returns
```

Returning from a Subprogram

- After the subprogram finishes, one must "clean up" the stack
- The stack has on it:
  - The old EBP value, the return address, the parameters
- The old EBP value is popped in the subprogram (at the end)
- The return address is removed by the RET instruction
  - You don't see the POP, but it's there
- The parameters need to be removed from the stack
- The C convention specifies that the caller code must remove the parameters from the stack
  - Other languages specify that the callee must do it
  - In fact, it is well-known that it's a little bit more efficient to have the subprogram (i.e., the callee) do it!
- So one may wonder why C opts for the slower approach
- Turns out, it's all because of *varargs*
  - *Let's go into a bit of a detour…. if you're confused already, you can safely skip the next 2 slides when you study this content*

Variable Number of Arguments

- C allows or the declaration of functions with variable number of arguments
- A well-known example: printf()
  - `printf("%d", 2);`
  - `printf("%d %d", 2, 3);`
  - `printf("%s %d %c %f", "foo", 1, 'f', 3.14);`
- So sometimes there will be 1 argument to remove from the stack, sometimes 2, sometimes 3, etc.
- Having the subprogram (in this case printf) remove the arguments from the stack requires some complexity
  - e.g., pass an extra (shadow) parameter that specifies how many arguments should be removed
- Instead, the convention is that the caller removes the arguments, because it always knows how many there are
  - e.g., it's easy for a compiler to generate code that does this

Variable of Arguments in C

- Just in case you are curious, here is an example of a C program with a vararg function

```
#include <stdarg.h>
#include <stdio.h>

int func(int first, ...) {
  va_list args;
  va_start(args, first);
  printf("arg #1 = %d\n",first);
  printf("arg #2 = %d\n",va_arg(args, int));
  printf("arg #3 = %s\n",va_arg(args, char*));
  va_end(args);
```

```
int main() {
  func(2, (void*)3,
       (void*)"foo");
}
```

Vararg functions are a bit dangerous. If you call va_arg() more times than there are arguments on the stack, you'll just get bogus values!

Example: Calling a Subprogram

Caller:

```
push    dword  2      ; second parameter
push    dword  1      ; first parameter
call    func          ; call the function
add     esp,  8       ; pop the two arguments
```

- Note that to pop the two arguments we merely add 8 to the stack pointer ESP
  - Since we do not care to get the values of the arguments at this point, it’s quicker than to call pop twice!
  - This is one case in which we do modify ESP directly
- This is because the stack is not really a stack, but just an array with a pointer: the parameter values will be overwritten next time a function is called or next time the stack is used
  - We don’t zero out “old” value, we just lazily overwrite them later

Return Values?

- Often, one wants a subprogram to return a value
  - e.g., a function that computes some number
- There are several ways to do this
- One way is to pass as a parameter the address of a zone of memory in which some result should be written
  - As in: void foo(int *x); foo(&a);
- This is not a *true* return value
  - As in: int foo();
- The C convention is that the return value is always stored in EAX when the function returns
  - It's the responsibility of the caller to save the EAX value before the call (if needed) and to restore it later

Recall the NASM Skeleton

```
    ; include directives

segment .data
    ; DX directives

segment .bss
    ; RESX directives

segment .text
        global asm_main
    asm_main:
        enter   0,0
         pusha
         ; Your program here
         popa
         mov    eax, 0
         leave
         ret
```

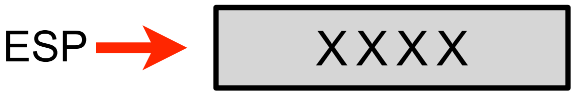
Returns value 0

Recall the NASM Skeleton

```
    ; include directives

segment .data
    ; DX directives

segment .bss
    ; RESX directives

segment .text
        global asm_main
    asm_main:
        enter   0,0
         pusha
         ; Your program here
         popa
         mov    eax, 0
         leave
         ret
```

The last two remaining things that we haven't explained yet (but soon)

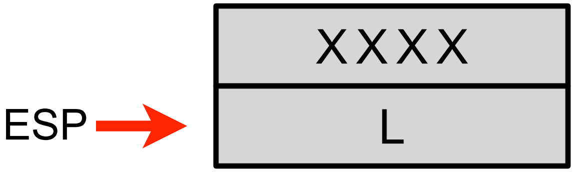
A Full Example




```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```

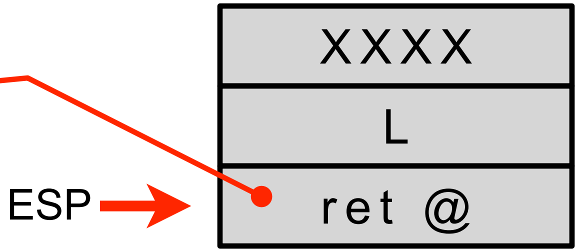
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push     ebp
        mov      ebp, esp
        push     dword [ebp+8]
        push     8
        call     reference
        add      esp, 8
        add      eax, 10
        pop      ebp
        ret
reference:
        push     ebp
        mov      ebp, esp
        mov      eax, [ebp+12]
        add      eax, [ebp+8]
        mov      eax, [eax]
        pop      ebp
        ret
```



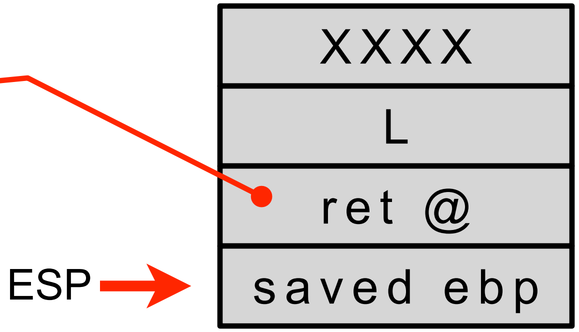
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



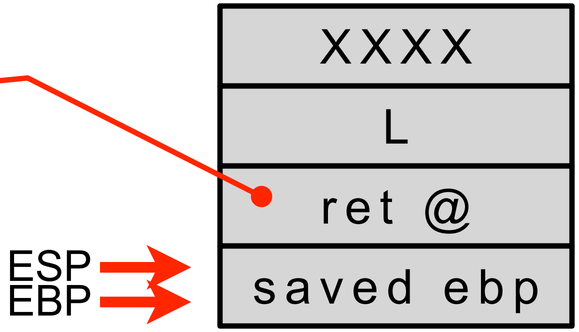
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push        ebp
        mov         ebp, esp
        push        dword [ebp+8]
        push        8
        call        reference
        add         esp, 8
        add         eax, 10
        pop         ebp
        ret
reference:
        push        ebp
        mov         ebp, esp
        mov         eax, [ebp+12]
        add         eax, [ebp+8]
        mov         eax, [eax]
        pop         ebp
        ret
```



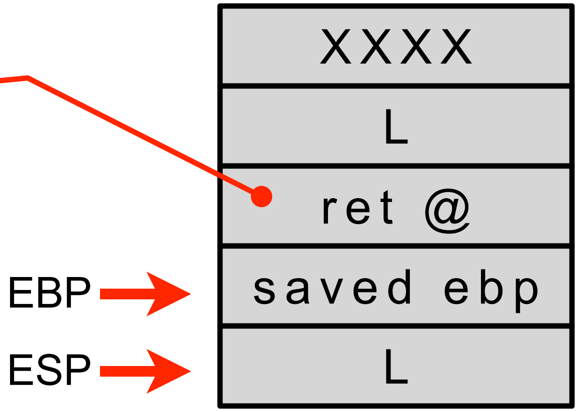
A Full Example

```
L        dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



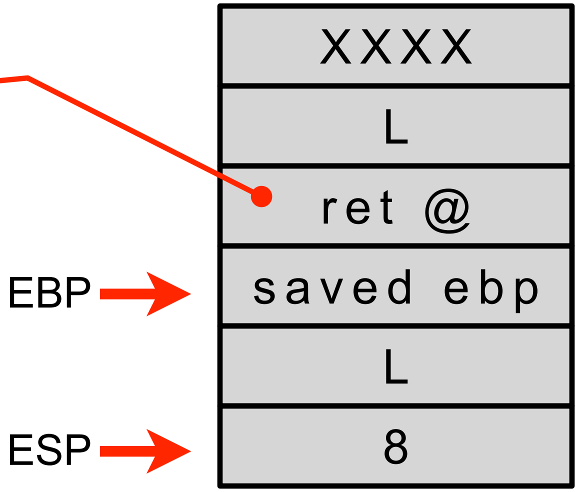
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push     ebp
        mov      ebp, esp
        push     dword [ebp+8]
        push     8
        call     reference
        add      esp, 8
        add      eax, 10
        pop      ebp
        ret
reference:
        push     ebp
        mov      ebp, esp
        mov      eax, [ebp+12]
        add      eax, [ebp+8]
        mov      eax, [eax]
        pop      ebp
        ret
```



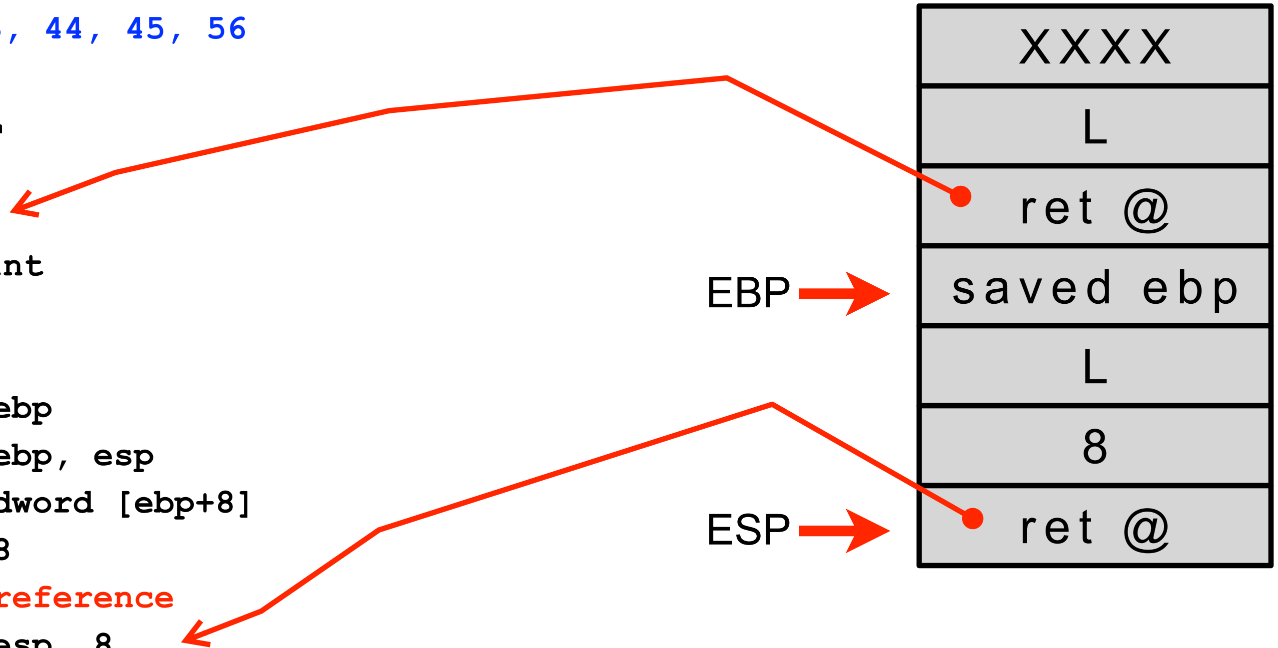
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push        ebp
        mov         ebp, esp
        push        dword [ebp+8]
        push        8
        call        reference
        add         esp, 8
        add         eax, 10
        pop         ebp
        ret
reference:
        push        ebp
        mov         ebp, esp
        mov         eax, [ebp+12]
        add         eax, [ebp+8]
        mov         eax, [eax]
        pop         ebp
        ret
```



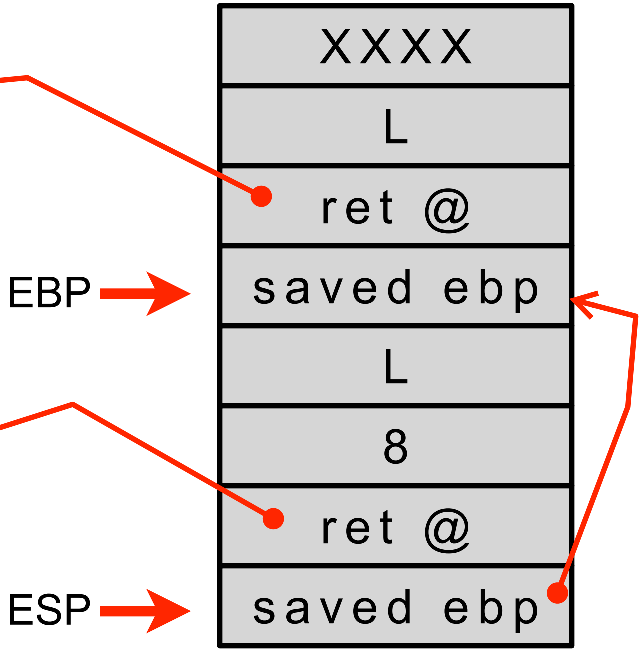
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push        ebp
        mov         ebp, esp
        push        dword [ebp+8]
        push        8
        call        reference
        add         esp, 8
        add         eax, 10
        pop         ebp
        ret
reference:
        push        ebp
        mov         ebp, esp
        mov         eax, [ebp+12]
        add         eax, [ebp+8]
        mov         eax, [eax]
        pop         ebp
        ret
```



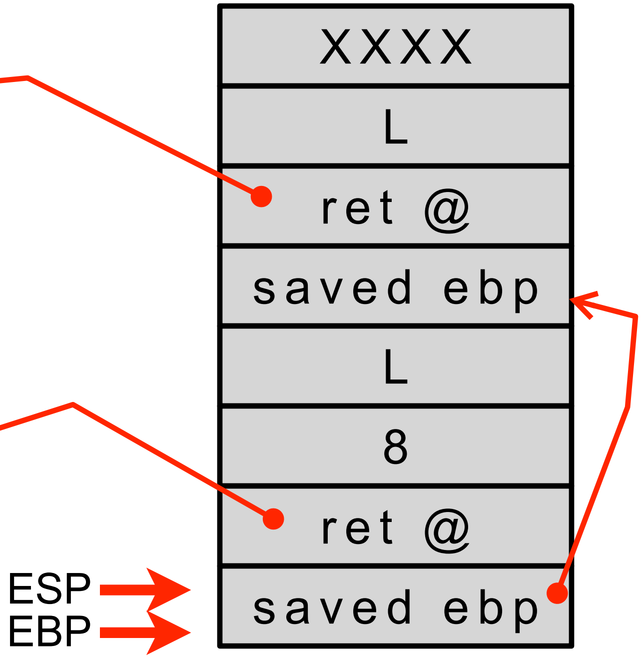
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



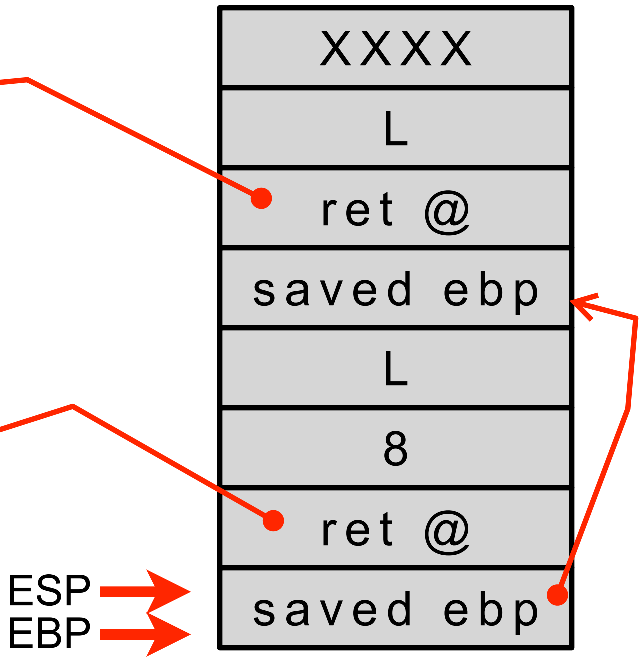
A Full Example

```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



A Full Example

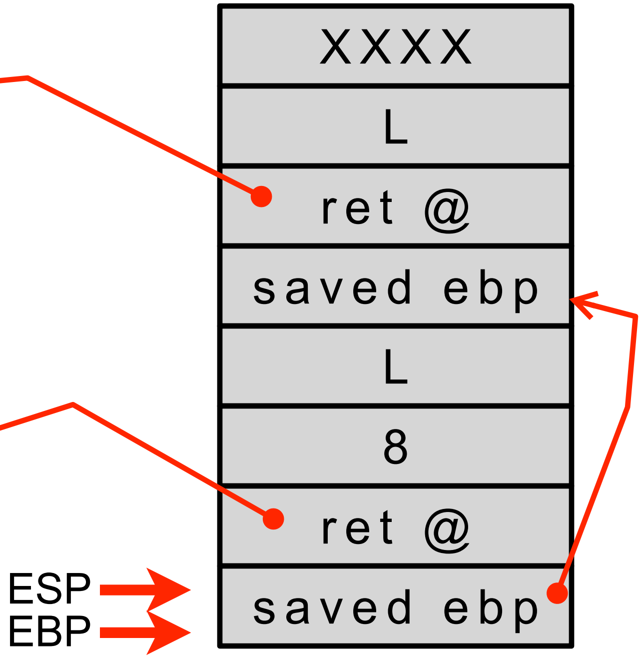
```
L        dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
         push      ebp
         mov       ebp, esp
         push      dword [ebp+8]
         push      8
         call      reference
         add       esp, 8
         add       eax, 10
         pop       ebp
         ret
reference:
         push      ebp
         mov       ebp, esp
         mov       eax, [ebp+12]
         add       eax, [ebp+8]
         mov       eax, [eax]
         pop       ebp
         ret
```



EAX = L

A Full Example

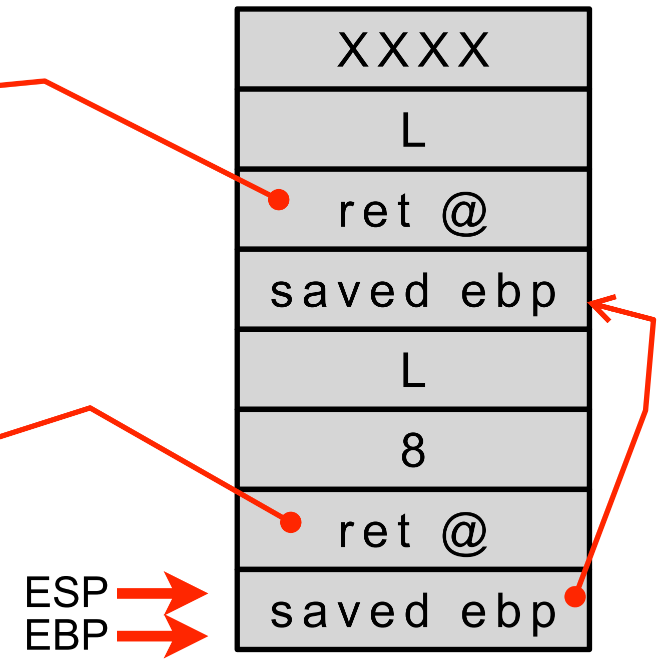
```
L         dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = L + 8

A Full Example

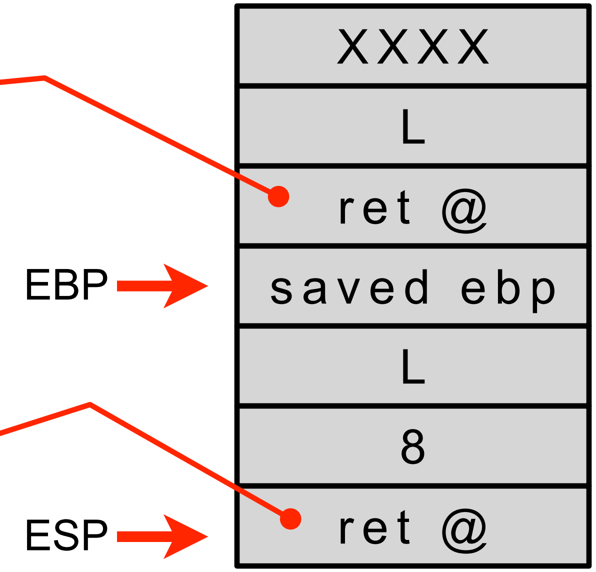
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = [L + 8] = 44

A Full Example

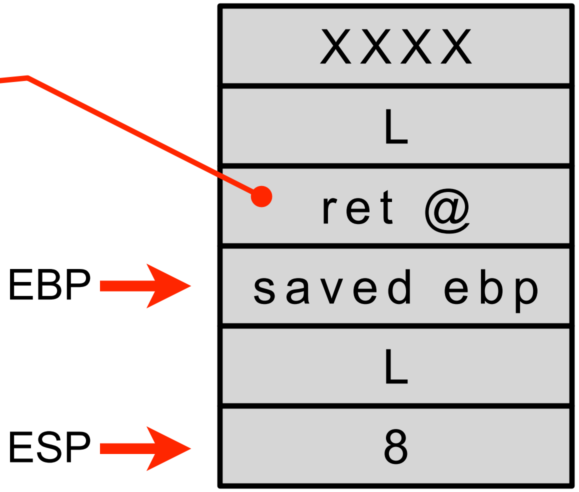
```
L        dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
         push       ebp
         mov        ebp, esp
         push       dword [ebp+8]
         push       8
         call       reference
         add        esp, 8
         add        eax, 10
         pop        ebp
         ret
reference:
         push       ebp
         mov        ebp, esp
         mov        eax, [ebp+12]
         add        eax, [ebp+8]
         mov        eax, [eax]
         pop        ebp
         ret
```



EAX = 44

A Full Example

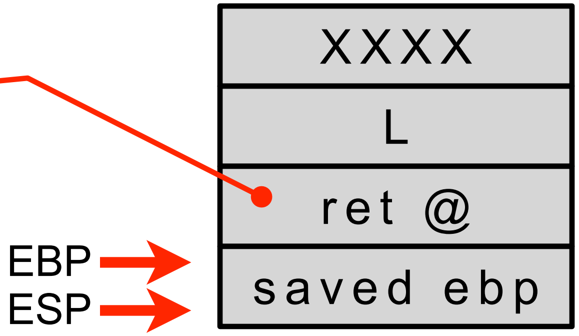
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = 44

A Full Example

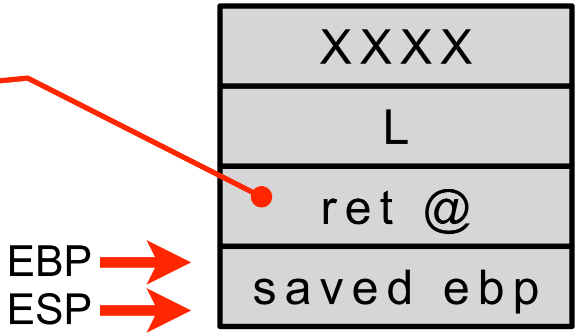
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push        ebp
        mov         ebp, esp
        push        dword [ebp+8]
        push        8
        call        reference
        add         esp, 8
        add         eax, 10
        pop         ebp
        ret
reference:
        push        ebp
        mov         ebp, esp
        mov         eax, [ebp+12]
        add         eax, [ebp+8]
        mov         eax, [eax]
        pop         ebp
        ret
```



EAX = 44

A Full Example

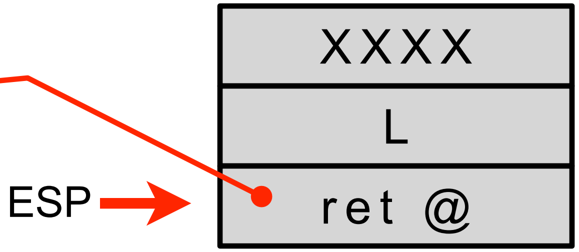
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = 44 + 10 = 54

A Full Example

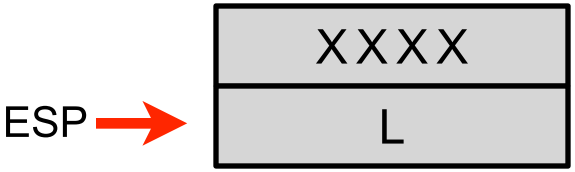
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = 54

A Full Example

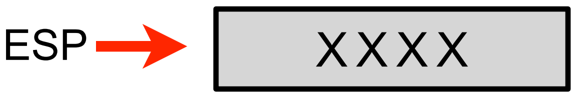
```
L       dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = 54

A Full Example

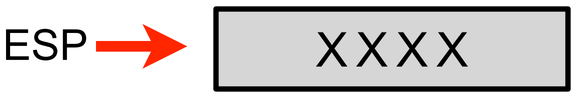
```
L        dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



EAX = 54

A Full Example

```
L        dd  42, 43, 44, 45, 56
...
push        dword L
call        func
add         esp, 4
call        print_int
...
func:
        push      ebp
        mov       ebp, esp
        push      dword [ebp+8]
        push      8
        call      reference
        add       esp, 8
        add       eax, 10
        pop       ebp
        ret
reference:
        push      ebp
        mov       ebp, esp
        mov       eax, [ebp+12]
        add       eax, [ebp+8]
        mov       eax, [eax]
        pop       ebp
        ret
```



prints "54"

C Translation of the previous program (reverse-engineering)

```
#include <stdio.h>
int     L[5] = {42, 43, 44, 45, 56};
int func(int *array);
int reference(int a, int *ptr);

int main(int argc, char **argv) {
 // ...
 printf("%d", func(L));
 // ...
}

int func(int *array) {
  return 10 + reference(8, array); // The 8 should be a 2 (2nd element of the array)
}

int reference(int a, int *ptr) {
    return *((int *)((char *)ptr + a));
    // return ptr[a / sizeof(int)];
}
```

In-class Exercise

- What 3 (perhaps 4) things are wrong with the following program?

```
      push   ebx
      push   dword 30
      call   func
      add    esp, 4
      call   print_int
      call   print_nl
      . . .

func: push   ebp
      mov    ebp, esp
      mov    eax, [ebp+8]
      add    eax, [ebp+4]
      ret
```

In-class Exercise

- What 4 things are wrong with the following program?

```
        push    ebx
        push    dword 30
        call    func
        add     esp, 8
        call    print_int
        call    print_nl
        . . .

func:   push    ebp
        mov     ebp, esp
        mov     eax, [ebp+12]
        add     eax, [ebp+8]
        pop     ebp
        ret
```

In-class Exercise

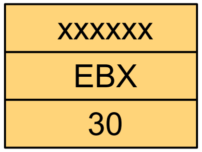
- What does the stack look like?

```
        push    ebx
        push    dword 30
        call    func
                <------------------------------- THERE?
        add     esp, 8
        call    print_int
        call    print_nl
        . . .

func:   push    ebp
        mov     ebp, esp
                <-------------------------------- HERE?
        mov     eax, [ebp+12]
        add     eax, [ebp+8]
        pop     ebp
        ret
```

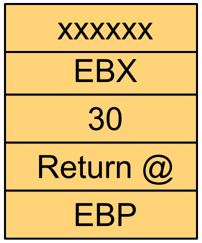
In-class Exercise

- What does the stack look like?

```
        push    ebx
        push    dword 30
        call    func

            <---------------------------
```




```
        add     esp, 8
        call    print_int
        call    print_nl
        . . .

func:   push    ebp
        mov     ebp, esp

          <-----------------------------
```




```
        mov     eax, [ebp+12]
        add     eax, [ebp+8]
        pop     ebp
        ret
```

A Full Example with Subprograms

- The book has a full example in Section 4.5.1
- Let’s do another example here
- Say we want to write a program that first reads in a sequence of 10 integers and then prints the number of odd integers
- We will use three functions:
  - get_integers(): get the 10 integers from the user
  - count_odds(): count the number of odd integers
  - is_odd(): determines whether an integer is odd
- We could do this without functions
  - The code would most likely be less readable
    - But faster! (usual tradeoff)
- For now, we’re writing the code in the most modular and “clean” fashion
- Let’s first look at the easy main program

Example: Main program

```
%include "asm_io.inc"

segment .data
      msg_odd db     "The number of odd numbers is: ",0

segment .bss
      integers resd   10  ; space for 10 integers

segment .text
      global  asm_main
asm_main:
      enter     0,0             ; set up
      pusha                     ; set up



      popa                      ; clean up
      mov       eax, 0          ; clean up
      leave                     ; clean up
      ret                       ; clean up
```

```
push    integers        ; we pass integers (address) to get_integers
push    dword 10        ; we pass the number of integers to get_integers
call    get_integers    ; call get_integers
add     esp, 8          ; clean up the stack
mov     eax, msg_odd    ; store the address of the message to print into eax
call    print_string    ; print the message
push    integers        ; we pass integers (address) to count_odds
push    dword 10        ; we pass the number of integers to count_odds
call    count_odds      ; call count_odds
add     esp, 8          ; clean up the stack
call    print_int       ; print the content of eax as an integer
                        ; (this is what count_odds returned)
call    print_nl        ; print a new line
```

Piecemeal segment declarations

- The NASM assembler allows for the declaration of multiple .data, .bss, and .text segments
- This makes it possible to declare subprograms in their own region of the .asm file, with parts of .data and .bss segments that are relevant for the subprograms
- Let's look at the get_integers() subprogram

Example: get_integers

```
;       FUNCTION: Get_Integers
;       Takes two parameters:  an address in memory in which to store integers, and a number of integers to store (>0)
;       Destroys values of eax, ebx, and ecx!!

segment .data
        msg_int         db      "Enter an integer: ",0

segment .text
get_integers:
        push    ebp                 ; save the value of EBP of the caller
        mov     ebp, esp            ; update the value of EBP for this subprogram

        mov     ecx, [ebp + 12]                 ; ECX = address at which to store the integers (parameter #2)
        mov     ebx, [ebp + 8]                  ; EBX = number of integers to read (parameter #1)
        shl     ebx, 2                          ; EBX = EBX * 4  (unsigned)
        add     ebx, ecx                        ; EBX = ECX + EBX = address beyond that of the last integer to be stored
loop1:
        mov     eax, msg_int                    ; EAX = address of the message to print
        call    print_string;                   ; print the message
        call    read_int                        ; read an integer from the keyboard (which will be stored in EAX)
        mov     [ecx], eax                      ; store the integer in memory at the correct address
        add     ecx, 4                          ; ECX = ECX + 4
        cmp     ecx, ebx                        ; compare ECX, EBX
        jb      loop1                           ; if ECX < EBX, jump to loop1   (unsigned)

        pop     ebp                 ; restore the value of EBP
        ret                         ; clean up
```

Example: count_odds

```
;    FUNCTION: count_odds
;    Takes two parameters:  an address in memory in which integers are stored, and the number of integers (>0)
;    Destroys values of eax, ebx, and edx!!  (eax = returned value)

segment .text
count_odds:
      push   ebp              ; save the value of EBP of the caller
      mov    ebp, esp         ; update the value of EBP for this subprogram

      mov    eax, [ebp + 12]              ; EAX = address at which integers are stored (parameter #2)
      mov    ebx, [ebp + 8]               ; EBX = number of integers (parameter #1)
      shl    ebx, 2           ; EBX = EBX * 4  (unsigned)
      add    ebx, eax         ; EBX = EAX + EBX = address beyond that of the last integer
      sub    ebx, 4           ; EBX = EBX - 4 = address of the last integer
      xor    edx, edx         ; EDX = 0 = number of odd integers
loop2:

      push   dword [ebx]      ; store the current integer on the stack
      call   is_odd                       ; call is_odd
      add    esp, 4                       ; clean up the stack
      add    edx, eax                     ; EDX += EAX  (EAX = 0 if even, EAX = 1 if odd)
      sub    ebx, 4                       ; EBX = EBX - 4
      cmp    ebx, [ebp+12]                ; compare EBX and the address of the first integer
      jnb    loop2                        ; if EBX >= [EBP+12]  jump to loop2   (unsigned test)

      mov    eax, edx                     ; EAX = EDX (= number of odd integers)

      pop    ebp              ; restore the value of EBP
      ret                     ; clean up
```

Example: is_odd

```
;       FUNCTION: is_odd
;       Takes one parameter:  an integers (>0)
;       Destroys values of eax and ecx (eax = returned value)

segment .text
is_odd:
        push    ebp             ; save the value of EBP of the caller
        mov     ebp, esp        ; update the value of EBP for this subprogram

        mov     eax, 0          ; EAX = 0
        mov     ecx, [ebp+8]    ; ECX = integer (parameter #1)
        shr     ecx, 1          ; Right logical shift
        adc     eax, 0          ; EAX = EAX + carry  (if even: EAX = 0, if odd: EAX = 1)

        pop     ebp             ; restore the value of EBP
        ret                     ; clean up
```

Destroyed Registers?

- Note that in the previous program we have added comments specifying which registers are destroyed
- The caller is then responsible for making sure that its registers are not corrupted
- However, in a program that has many functions it becomes really annoying to constantly have to pay attention to what needs to be saved and what doesn't
- The typical approach is to have the subprogram save what it knows it will overwrite onto the stack!
  - And comment that the caller doesn't need to worry about anything
- Let's look at examples…

Saving Registers in Subprograms

- Just saving EBP

```
func:
   push      ebp           ; save original EBP
   mov       ebp, esp      ; set EBP = ESP

   . . .                   ; subprogram code

   mov       eax, ...      ; set return value

   pop       ebp           ; restore original EBP
   ret                     ; returns
```

Saving Registers in Subprograms

- Saving, for instance, EBX and ECX, in addition to EBP

```
func:
   push      ebp          ; save original EBP
   mov       ebp, esp     ; set EBP = ESP
   push      ebx          ; save EBX
   push      ecx          ; save ECX

   . . .                  ; subprogram code

   mov       eax, ...     ; set return value

   pop       ecx          ; restore ECX
   pop       ebx          ; restore EBX
   pop       ebp          ; restore ebp
   ret                    ; returns
```

Saving Registers in Subprograms

- Saving "all" registers using PUSHA and POPA

```
func:
   push      ebp            ; save original EBP
   mov       ebp, esp       ; set EBP = ESP
   pusha                    ; save all (including new EBP)

   . . .                    ; subprogram code

   mov       eax, ...       ; set return value

   popa                     ; restore all (including new EBP)
   pop       ebp            ; restore original ebp
   ret                      ; returns
```

Saving Registers in Subprograms

- Saving "all" registers using PUSHA and POPA

```
func:
    push        ebp             ; save original EBP
    mov         ebp, esp        ; set EBP = ESP
    pusha                       ; save all (including new EBP)

    . . .                       ; subprogram code

    mov         eax, ...        ; set return value

    popa                        ; restore all (including new EBP)
    pop         ebp             ; restore original ebp
    ret                         ; returns
```

Overwrites the return value
that's stored in eax!

Dealing with Return Value

- Saving “all” registers using PUSHA and POPA + return value handling

```
.bss:
   returnvalue  resd    1        ; place in memory for the return value
func:
   push         ebp              ; save original EBP
   mov          ebp, esp         ; set EBP = ESP
   pusha                         ; save all (including new EBP)

   . . .                         ; subprogram code

   mov          [returnvalue], eax      ; save return value in memory

   popa                          ; restore all (including new EBP)
   mov          eax, [returnvalue]      ; retrieve the saved return
   value
                                 ; (as done in our skeleton)
   pop          ebp              ; restore original ebp
   ret                           ; returns
```

Dealing with Return Value

- Saving "all" registers using PUSHA and POPA + return value handling

```
.bss:
   returnvalue  resd    1       ; place in memory for the return value
func:
   push         ebp
   mov          ebp
   pusha                                                            P)

   . . .

   mov          [ret                                        in memory

   popa                         ; restore all (including new EBP)
   mov          eax, [returnvalue]      ; retrieve the saved return
   value
                                ; (as done in our skeleton)
   pop          ebp             ; restore original ebp
   ret                          ; returns
```

A much better option is to put the return value in a local variable, which we'll see in the next set of lecture notes

Recursion

- The subprogram calling conventions we have just described enable recursion out of the box!

- Let's live-code a example program that computes the sum of the first n integers
  - Yes, it's n(n+1)/2, and even if we didn't know this, an iterative program would be more efficient; but for the sake of this example let's just write a recursive program to compute it

Example: Recursive Program

```
   . . .
segment .data
   msg1        db       'Enter n: ', 0
   msg2        db       'The sum is: ', 0
segment .text
   . . .                         ; declaration of asm_main and setup

   mov         eax, msg1         ; eax = address of msg1
   call        print_string      ; print msg1
   call        read_int          ; get an integer from the keyboard (in EAX)
   push        eax               ; put the integer on the stack (parameter
   #1)
   call        recursive_sum     ; call recursive_sum
   add         esp, 4            ; remove the parameter from the stack
   mov         ebx, eax          ; save the value returned by recursive_sum
   mov         eax, msg2         ; eax = address of msg2
   call        print_string      ; print msg2
   mov         eax, ebx          ; eax = sum
   call        print_int         ; print the sum
   call        print_nl          ; print a new line

   . . .                         ; cleanup
```

Example: recursive_sum()

```
segment .bss
    value           resd, 1             ; to store the return value temporarily
segment .text
recursive_sum
    push            ebp                 ; save ebp
    mov             ebp, esp            ; set EBP = ESP
    pusha                               ; save all registers (probably overkill)
    mov             ebx, [ebp+8]        ; ebx = integer (parameter #1)
    cmp             ebx, 0              ; ebx = 0 ?
    jnz             next                ; if (ebx != 0) go to next
    xor             ecx, ecx            ; ECX = 0
    jmp             end                 ; Jump to end
next:
    mov             ecx, ebx            ; ECX = EBX
    dec             ecx                 ; ECX = ECX - 1
    push            ecx                 ; put ECX on the stack
    call            recursive_sum               ; recursive call to recursive_sum!
    add             esp, 4              ; pop the parameter from the stack
    add             ebx, eax            ; EBX = EBX + recursive_sum(EBX -1)
    mov             ecx, ebx            ; ECX = EBX
end:                                    ; at this point, ECX contains the result
    mov             [value], ecx        ; save ECX, the return value, in memory
    popa                                ; restore registers
    mov             eax, [value]        ; put the saved returned value into eax
    pop             ebp                 ; restore EBP
    ret                                 ; return
```

Important Takeaways

- A subprogram’s data is on the stack and called an activation record or a stack frame
  - So far we have seen this content in the activation records: return address, saved EBP value, other saved register values as needed, arguments
- Arguments are
  - Pushed by the caller (in “reverse order” from a high-level perspective)
  - Popped by the caller
- The EBP register is used as an “anchor” so that the code of the subprogram always knows where its activation record is
  - Needed, because the value of ESP keeps changing
- The EBP value of a subprogram’s caller should be saved on the stack by that subprogram before it overwrites that value
- Values of other registers used by the caller may also need to be pushed onto the stack
- A subprogram’s return value is store in the EAX register
- And just like that, we have recursion “for free”

Conclusion

- You must absolutely make sure you fully understand all code examples in this set of slides
  - Not that this is not true for all code examples in this course!
- In the next set of lecture notes we'll talk about local variables in subprograms