Subprograms: Local Variables

ICS312

Machine-Level and Systems Programming

Henri Casanova (henric@hawaii.edu)

Local Variables in Subprograms

- In all the examples we have seen so far, the subprograms were able to do their work using only registers
- But sometimes, a subprogram's needs are beyond the set of available registers and some data must be kept in memory
  - Just think of all subprograms you wrote that used more than 6 local variables (EAX, EBX, ECX, EDX, ESI, EDI)
- One possibility could be to declare a small .bss segment for each subprogram, to reserve memory space for all local variables
- Drawback #1: memory waste
  - This reserved memory consumes memory space for the entire duration of the execution even if the subprogram is only active for a tiny fraction of the execution time (or never!)
- Drawback #2: subprograms are not reentrant…

Re-entrant subprogram

- A subprogram is active if it has been called but the RET instruction hasn't been executed yet
- A subprogram is reentrant if it can be called from anywhere in the program
- This implies that the program can call itself, directly or indirectly, which enables recursion
  - e.g., f calls g, which calls h, which calls f
- At a given time, two or more instances of a subprogram can be active
  - Two or more activation records for this subprogram on the stack
- If we store the local variables of a subprogram in the .bss segment, then there can only be one activation!
  - Otherwise activation #2 could corrupt the local variables of activation #1
  - In other words, multiple activations would share the same play pen
- Therefore, programs would not be reentrant and one cannot have recursive calls when subprograms have local variables!
  - In the previous set of lecture notes, the recursive program had no local variables, so we were "lucky"
- Having reentrant programs is so useful that we **must** have it

Local variables on the stack

- Since activation records on the stack are used to store relevant information pertaining to a subprogram, why not use them for storing the subprogram local variables?
- The standard approach is to store local variables right after the saved EBP value on the stack
  - This is simply done by subtracting some amount to the ESP pointer
- The local variables are then accessed as [EBP-4], [EBP-8], etc.
- Let's see this on an example

Local Variables Example

- Say we have a subprogram that takes 2 parameters, uses 3 local variables, and doesn't return any value
- The code of the subprogram is as follows:

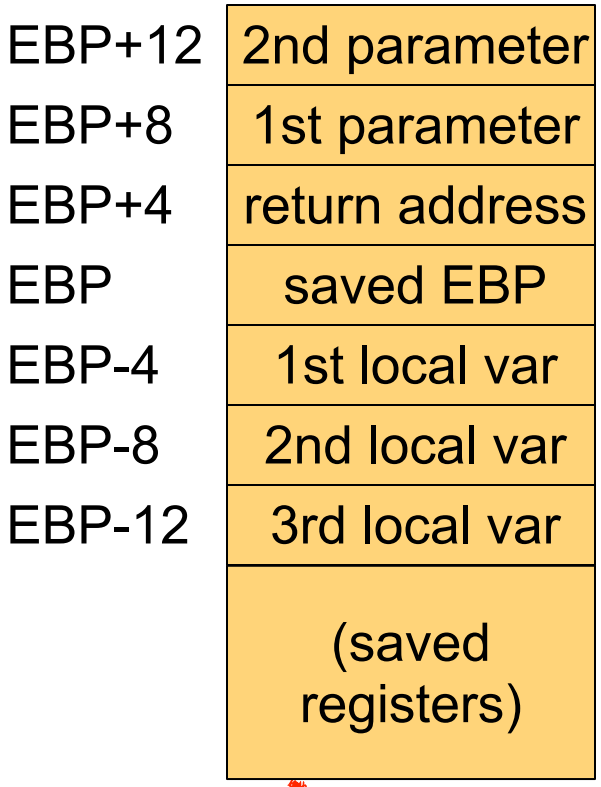
```
func:
    push   ebp              ; save old EBP value
    mov    ebp, esp         ; set EBP
    sub    esp, 12          ; add space for 3 locals

    ; subprogram body
    mov    esp, ebp         ; deallocate local variables
                            ; (could also be "add esp, 12")
    pop    ebp              ; restore old EBP value
    ret
```

- Let's look at the stack when the subprogram body begins

Local Variables Example

- Inside the body of the subprogram, parameters are referenced as:
  - [EBP+8]: 1st parameter
  - [EBP+12]: 2nd parameter
- and local variables are referenced as:
  - [EBP-4]: 1st local variable
  - [EBP-8]: 2nd local variable
  - [EBP-12]: 3rd local variable

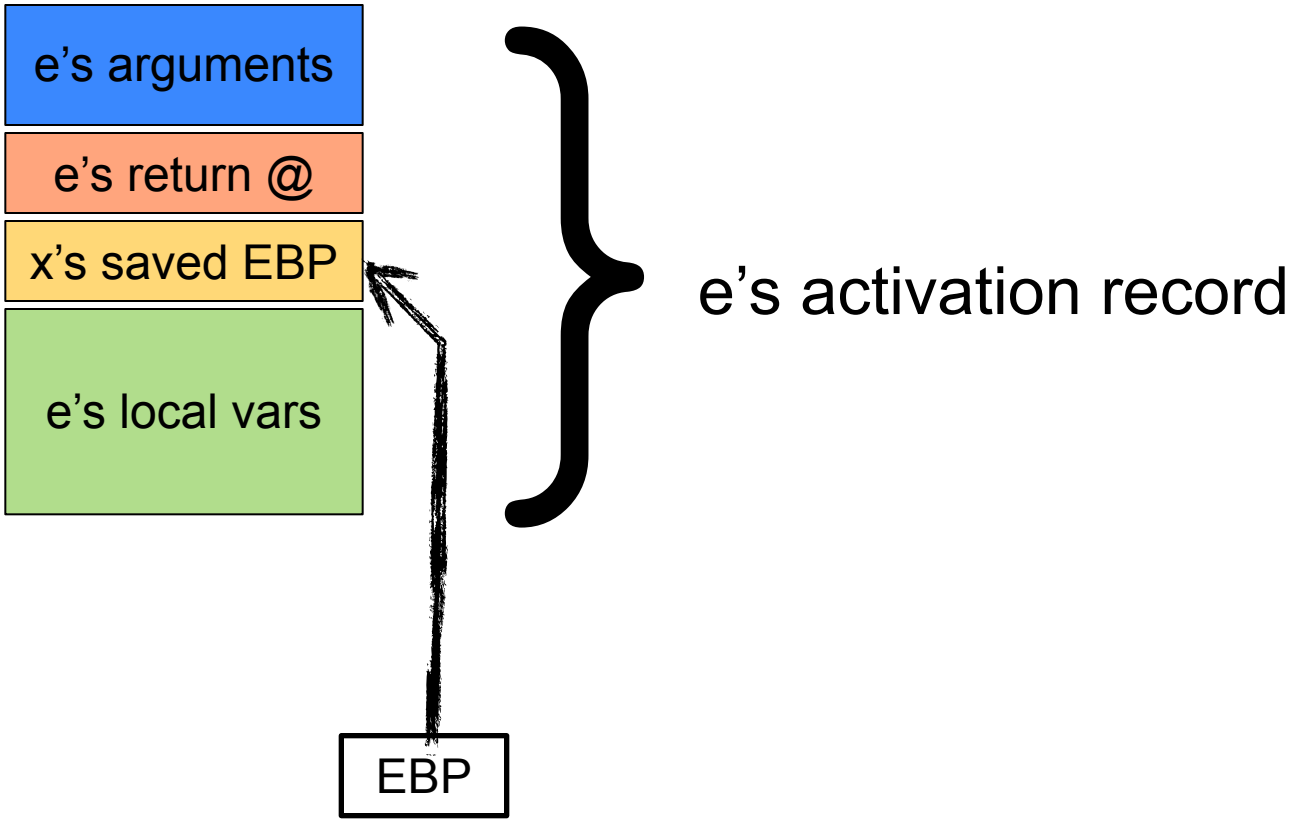


Very important you have this picture in mind; you should be able to redraw it

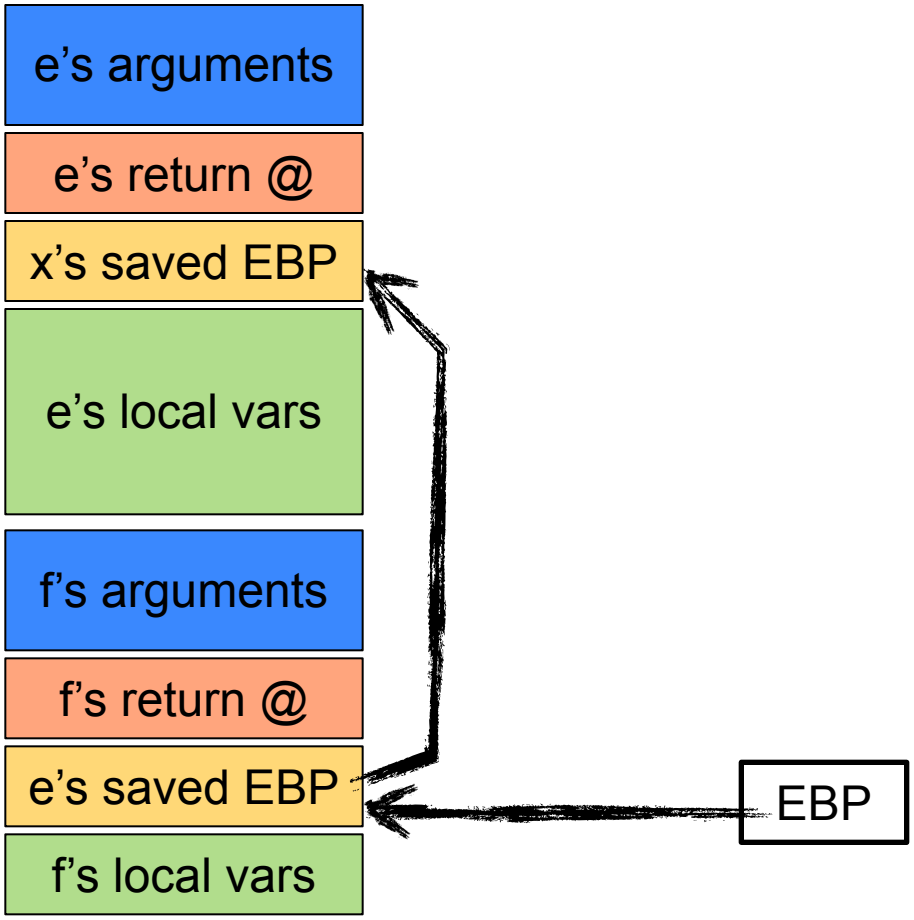
A “deep” stack

- Each call to a subprogram puts an activation record on the stack, saved EBP values and arguments
- Important: While a function is active, EBP always points to the saved EBP value saved for the function’s caller
  - EBP is the anchor point of the activation record (“B” stands for **Base** Pointer)
- We have seen this on a small example in the previous set of lecture notes
- Let’s look at a bigger example
  - But not with the corresponding assembly code
  - And not showing the “saved registers to avoid destruction of their values” on the stack

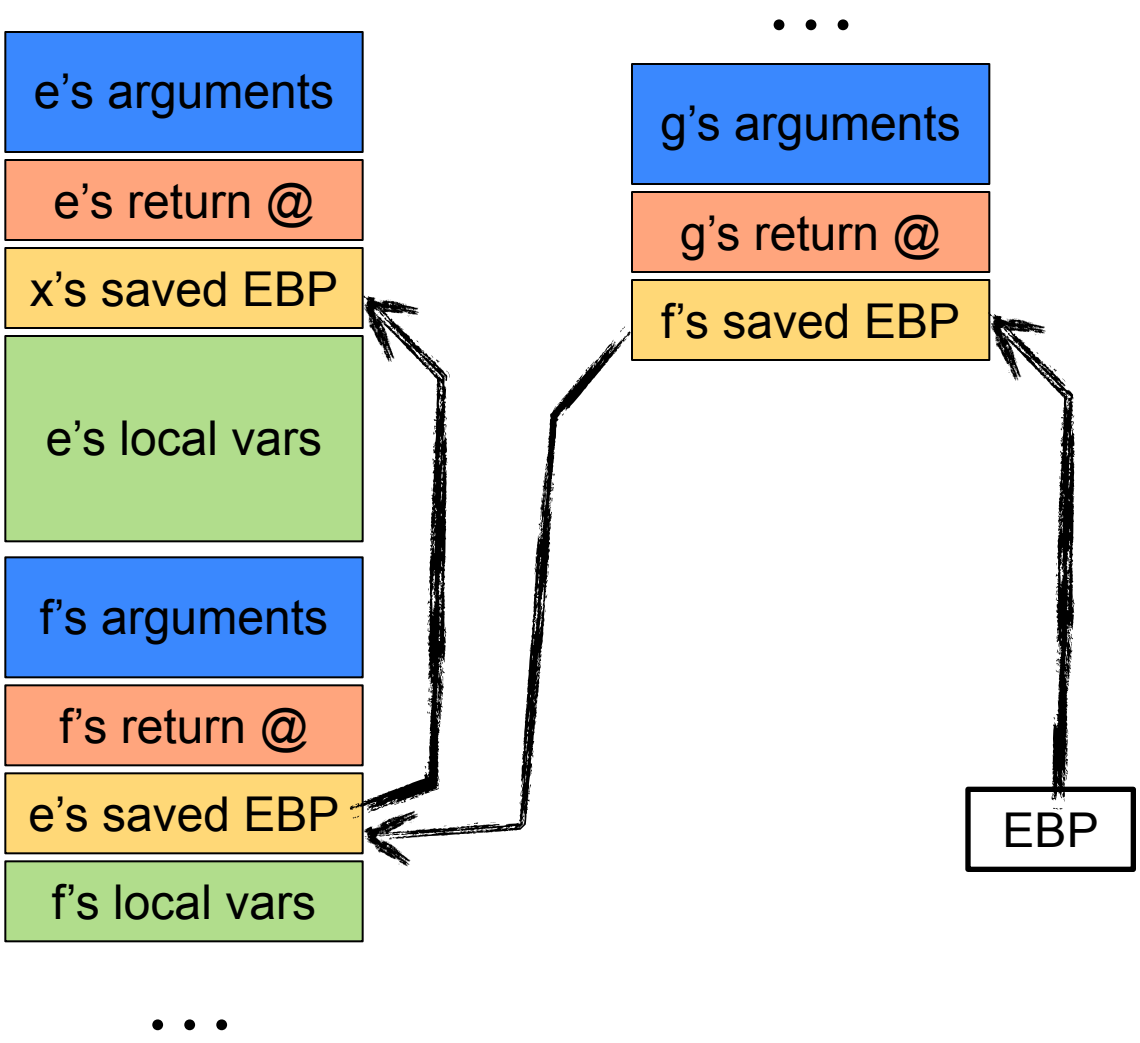
x() calls e() calls f() calls g() calls h()



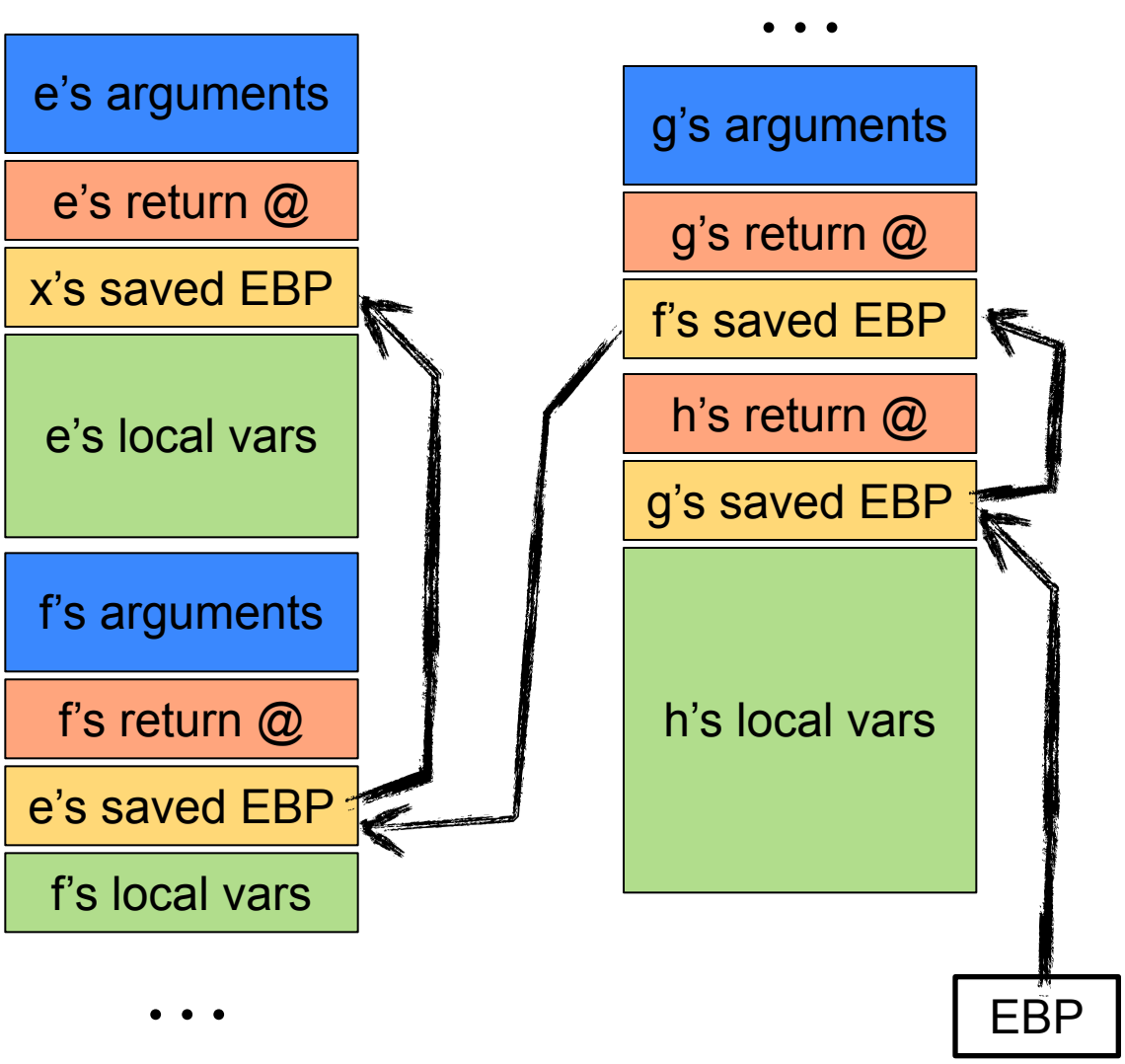
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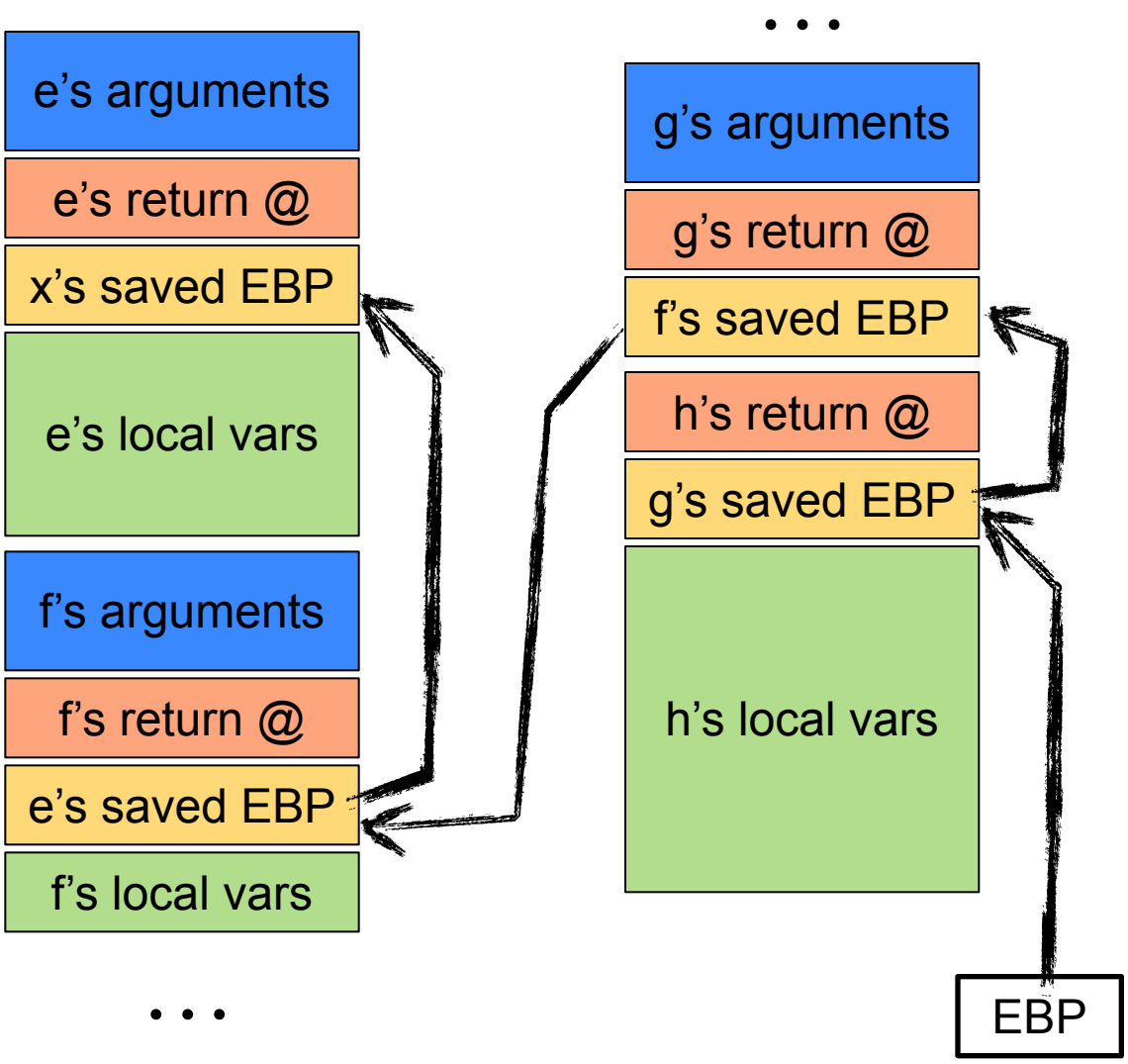
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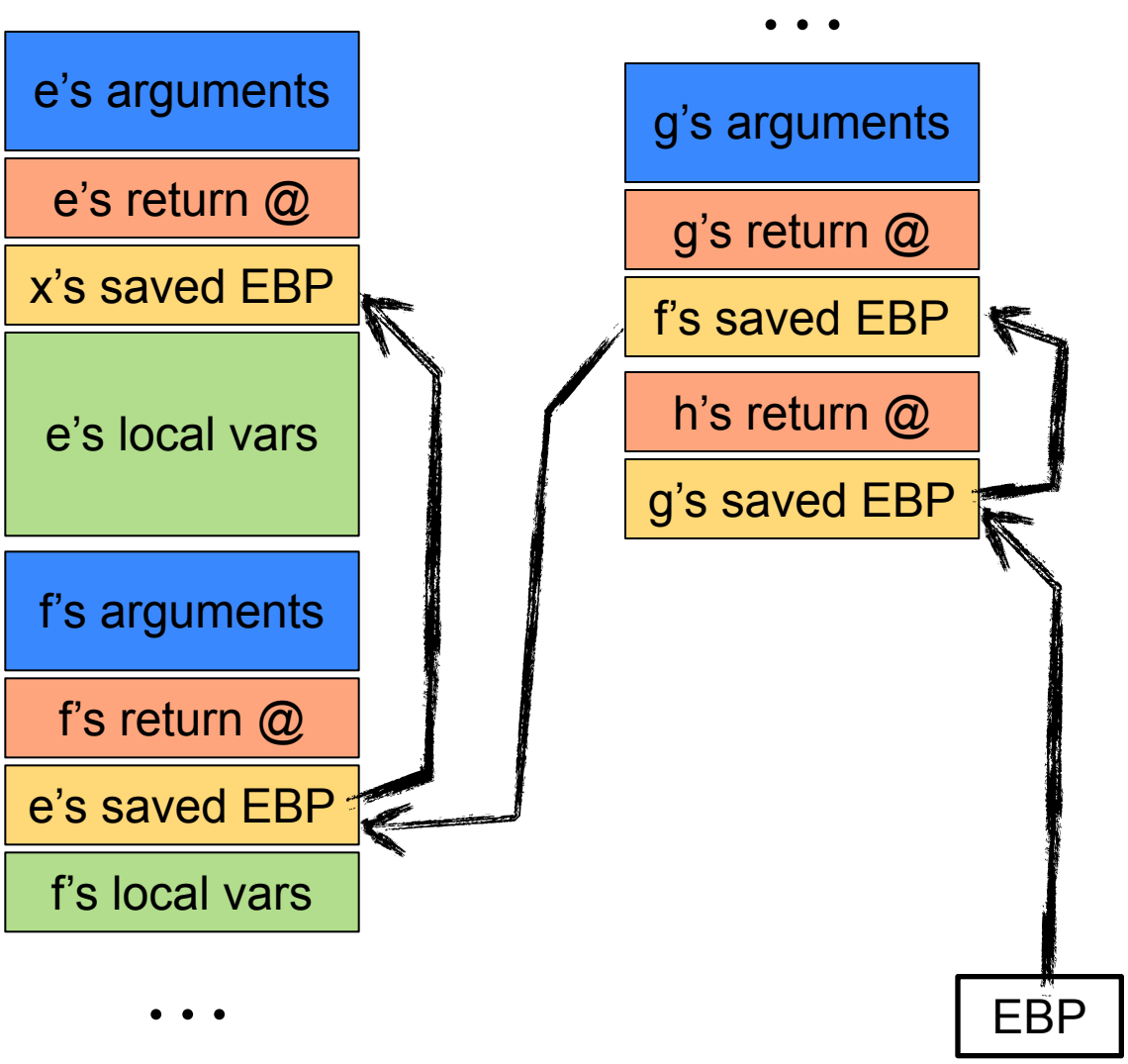


x() calls e() calls f() calls g() calls h()



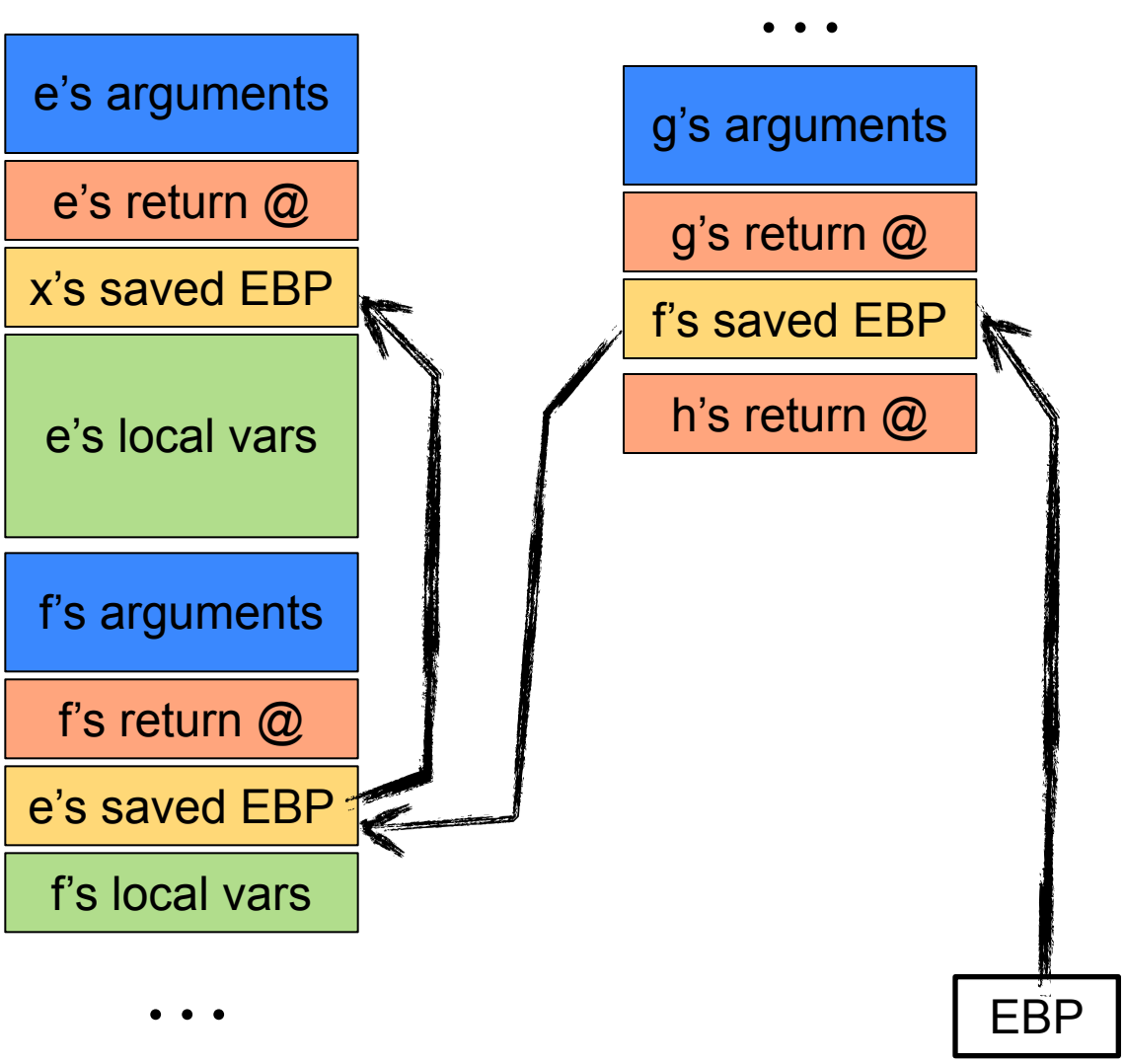
- The saved EBPs provide links between the activation records
- The current EBP is for the current function
- Let's see what happens when h returns

x() calls e() calls f() calls g() calls h()



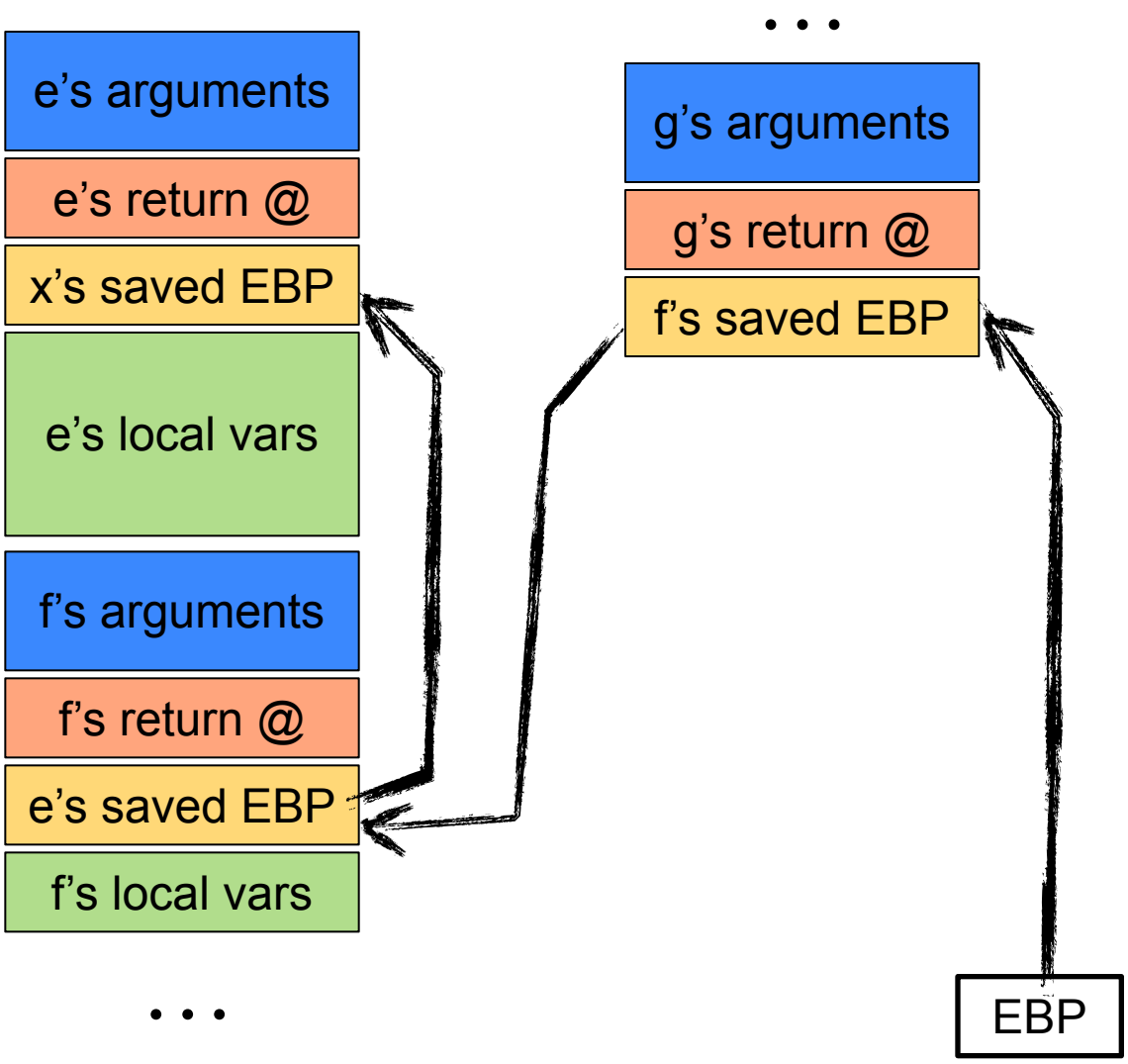
- When h returns
  - mov ESP, EBP

x() calls e() calls f() calls g() calls h()



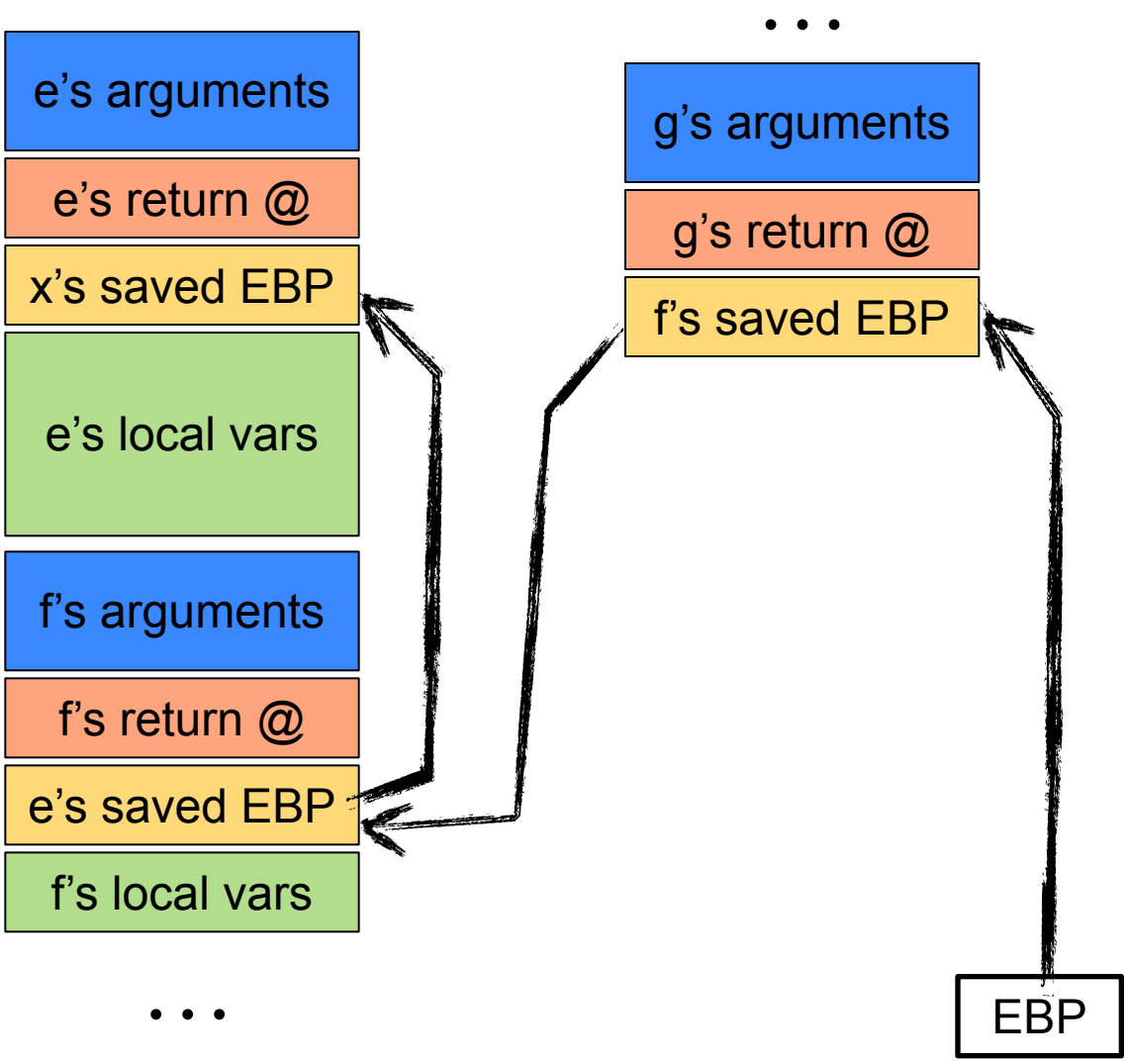
- When h returns
  - mov ESP, EBP
  - pop EBP

x() calls e() calls f() calls g() calls h()



- When h returns
  - mov ESP, EBP
  - pop EBP
  - pop return address

x() calls e() calls f() calls g() calls h()



- We are now in a "clean" state, where g is the active subprogram
- The EBP register and its saved values provide the crucial link between activation records
- If EBP values get corrupted, then all is lost

ENTER and LEAVE

- We always have the same *prologue* and the same *epilogue*

```
push  ebp           ; save old EBP value
mov   ebp, esp      ; set EBP
sub   esp, X        ; reserve X=4*N bytes for N locals
```

```
mov   esp, ebp      ; remove space for local vars
pop   ebp           ; restore old EBP value
ret                 ; return
```

ENTER and LEAVE

- There are two convenient functions: ENTER and LEAVE

```
push  ebp           ; save old EBP value
mov   ebp, esp      ; set EBP
sub   esp, X        ; reserve X=4*N bytes for N locals
```




```
enter X, 0
```

```
mov   esp, ebp      ; remove space for local vars
pop   ebp           ; restore old EBP value
ret                 ; return
```




```
leave
ret
```

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
```



We Finally Understand the Skeleton

```
    ; include directives

segment .data
    ; DX directives

segment .bss
    ; RESX directives

segment .text
        global asm_main
    asm_main:
        enter   0,0       ; Save EBP, reserve 0 bytes for local variables
        pusha             ; Save ALL registers
        ; Your program here
        popa              ; Restore ALL registers
        mov     eax, 0    ; Set the return value to 0
        leave             ; Restore EBP, remove space for local variables
        ret               ; Pop the return address and jump to it
```

Knowing your stack

- At this point it should be clear that it is very important to understand how the stack works and how to use it
- When programming in assembly you should always have a mental picture of the stack
  - Something you don't do when using a high-level programming language typically
  - As always, abstractions are great, but having no idea how they are implemented can be problematic when hunting bugs
    - Basic example: "running out of stack space"
- It's typically a good idea to be consistent
  - Compilers are consistent by design

A Full Example

- Let's write the assembly code equivalent to the following C/Java function

```
int f(int num) {    // computes Fibonacci numbers
      int x, sum;
      if (num == 0) return 0;
      if (num == 1) return 1;
      x = f(num-1);
      sum = x + f(num-2);
      return sum;
}
```

- Let's do it live… (even though the next slides have one version of the code)
  - That version has several "optimizations"

A Full Example (main program)

```
%include "asm_io.inc"

segment .data
        msg1            db      "Enter n: ", 0
        msg2            db      "The result is: ", 0

        . . . ; 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        f               ; call f
        pop         ebx             ; remove the parameter from the stack
        mov         ebx, eax        ; save the value returned by f
        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

        . . . ; clean up
```

A Full Example (function f)

```
;       FUNCTION: f
;       Takes one parameter:  an integer
;       eax = return value
segment .text
f:
  enter  8,0   ; num in [ebp+8]
               ; local var x in[ebp-4]
               ; local var sum in [ebp-8]
  push    ebx     ; save ebx
  push    ecx     ; save ecx
  push    edx     ; save edx

  mov     eax, [ebp+8]   ; eax = num
  sub     eax, 2         ; eax -= 2
  jns     next     ; if not <0, goto next
  add     eax, 2   ; eax += 2
  jmp     end
next:
  mov     eax, [ebp+8]    ; eax = num
  add     eax, -1         ; eax -= 1
  push    eax      ; put (num -1) on stack
  call    f        ; call f (recursively)
  add     esp, 4   ; remove (num-1) from stack
  mov     [ebp-4], eax    ; put the returned
                          ; value in x
  mov     eax, [ebp+8]    ; eax = num
  add     eax, -2         ; eax -= 2
  push    eax            ; put (num -2) on
                         ; the stack
  call     f             ; recursive call
           ; the return value is in eax
  add     esp, 4   ; remove (num-2) from stack
  add     eax, [ebp-4]     ; eax += x

end:
  pop     edx           ; restore edx
  pop     ecx           ; restore ecx
  pop     ebx           ; restore ebx
  leave                 ; clean up the stack
  ret                   ; return
```

Not actually used!

"Optimizing" both base cases as one!

High-level code

- Even though we do assembly in this course, we can now draw stacks for high-level code
- Example:

```
main() {
   int a = 10;
   f(a, 2*a);
}

f(int x, int y) {
  int z = x*3;
  int t;
  // what is the stack here?
}
```

High-level code Example

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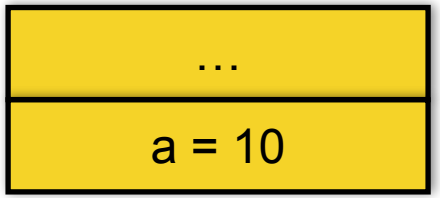
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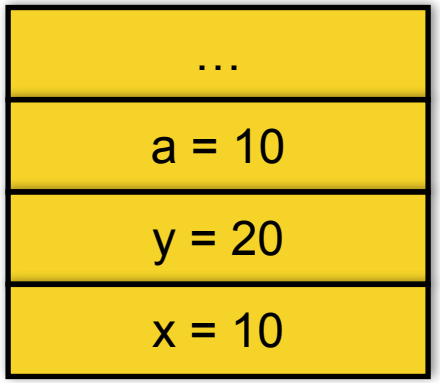
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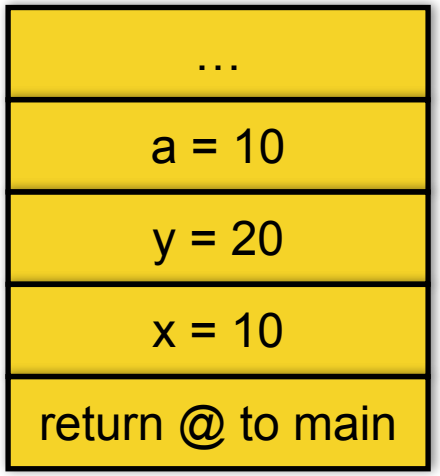
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High-level code Example

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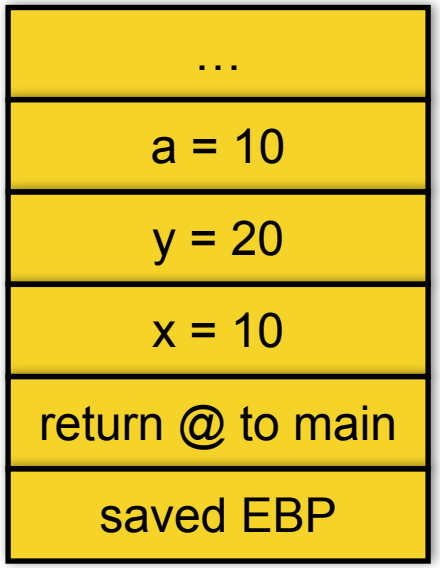
f(int x, int y) {
  int z = x*3;
  int t;
  // what is the stack here?
}
```



High-level code Example

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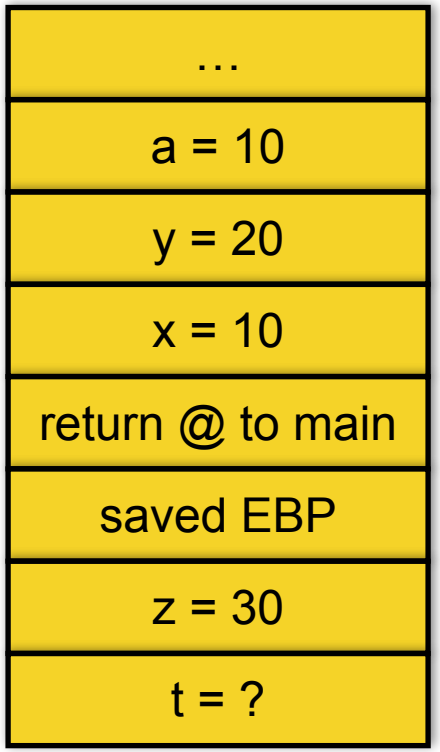
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  // what is the stack here?
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```



High-level code Example

```
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   int a = 10;
   f(a, 2*a);
}

f(int x, int y) {
  int z = x*3;
  int t;
  // what is the stack here?
}
```



In-class Exercise

- Draw the stack for:

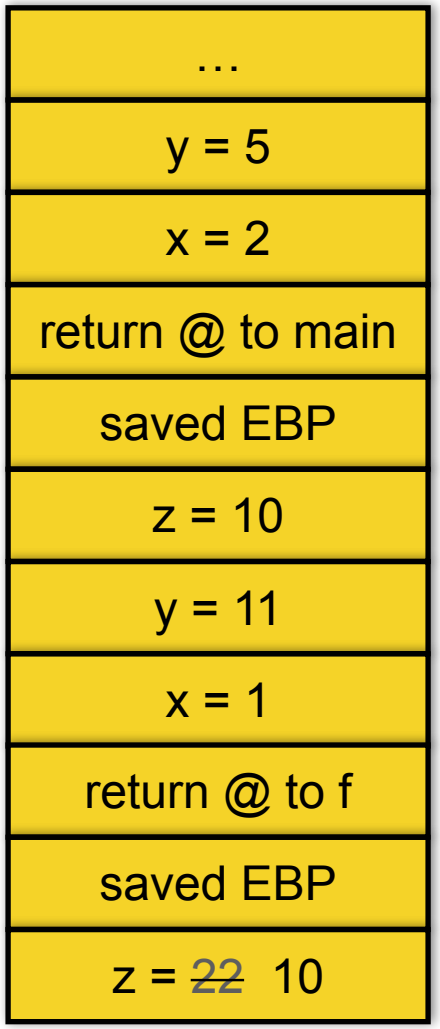
```
main() {
   f(2, 5);
}

f(int x, int y) {
  int z = y * 2;
  if (x == 1) {
    z = 10;
    // what is the stack here?
  } else {
    f(x-1, z+1);
  }
}
```

Solution

```
main() {
   f(2, 5);
}

f(int x, int y) {
  int z = y * 2;
  if (x == 1) {
    z = 10;
    // what is the stack here?
  } else {
    f(x-1, z+1);
  }
}
```



We are done! (with the stack)

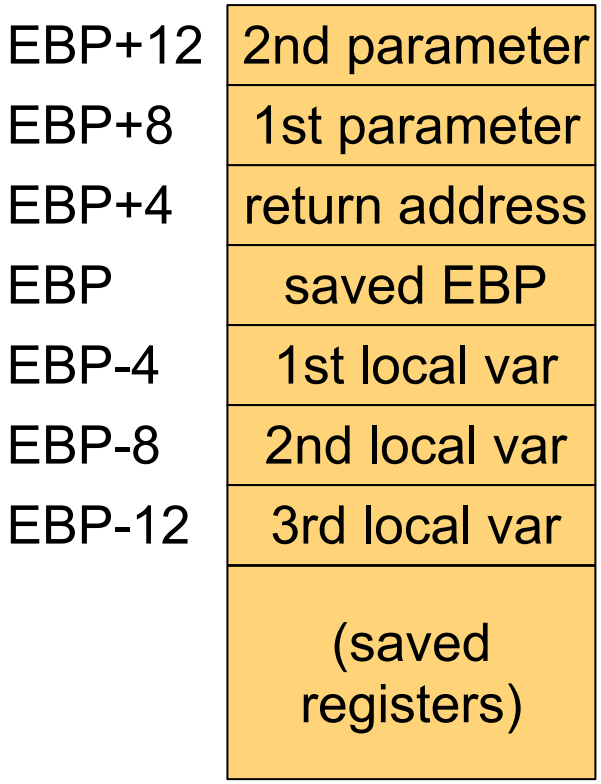
- At this point you know everything that's can be on the stack, and why it's there
- Details vary depending on compilers
  - So if you disassemble compiled code, you may find out that things are weirdly out-of-order, and extra things are on the stack, etc.
- But the principles remain
- To demonstrate that it's all real, let's write a piece of C code that "spies" on the stack to discover local variable values of its callers……

Spying on the stack is useful

- This is what your debugger does!
- When you debug a compiled program (using your IDE debugger, using low-tech gdb, etc.) you can always go “up” and “down” the stack to check all local variables
- This is basically jumping back and forth between activation records
  - And we can do that because activation records are linked by saved EBP pointers (see a few slides back)
- The small program we just wrote is a horrible version of what a debugger does
  - And because we didn’t compile with -g, we lost so-called “debugging information”
  - e.g., we no don’t know variable names in the source code

Important Takeaways

- Local variables are stored on the stack
  - Otherwise we couldn't have recursive subprograms have local variables!
- Now we can draw the stack for high-level code
- Full stack picture:



Conclusion

- At this point we know everything we need to know about the stack
  - At least in this course
- Let's look at some of the posted practice questions
- We'll have an in-class quiz next week on this module
- We have a Sample Homework Assignment #7
- We have an Optional Homework Assignment #8
- Onward to "Buffer Overflow"…
- And then the "practice" Software Reverse Engineering module