cs5460/6460 Operating Systems Lecture 4: Function invocations, and calling conventions

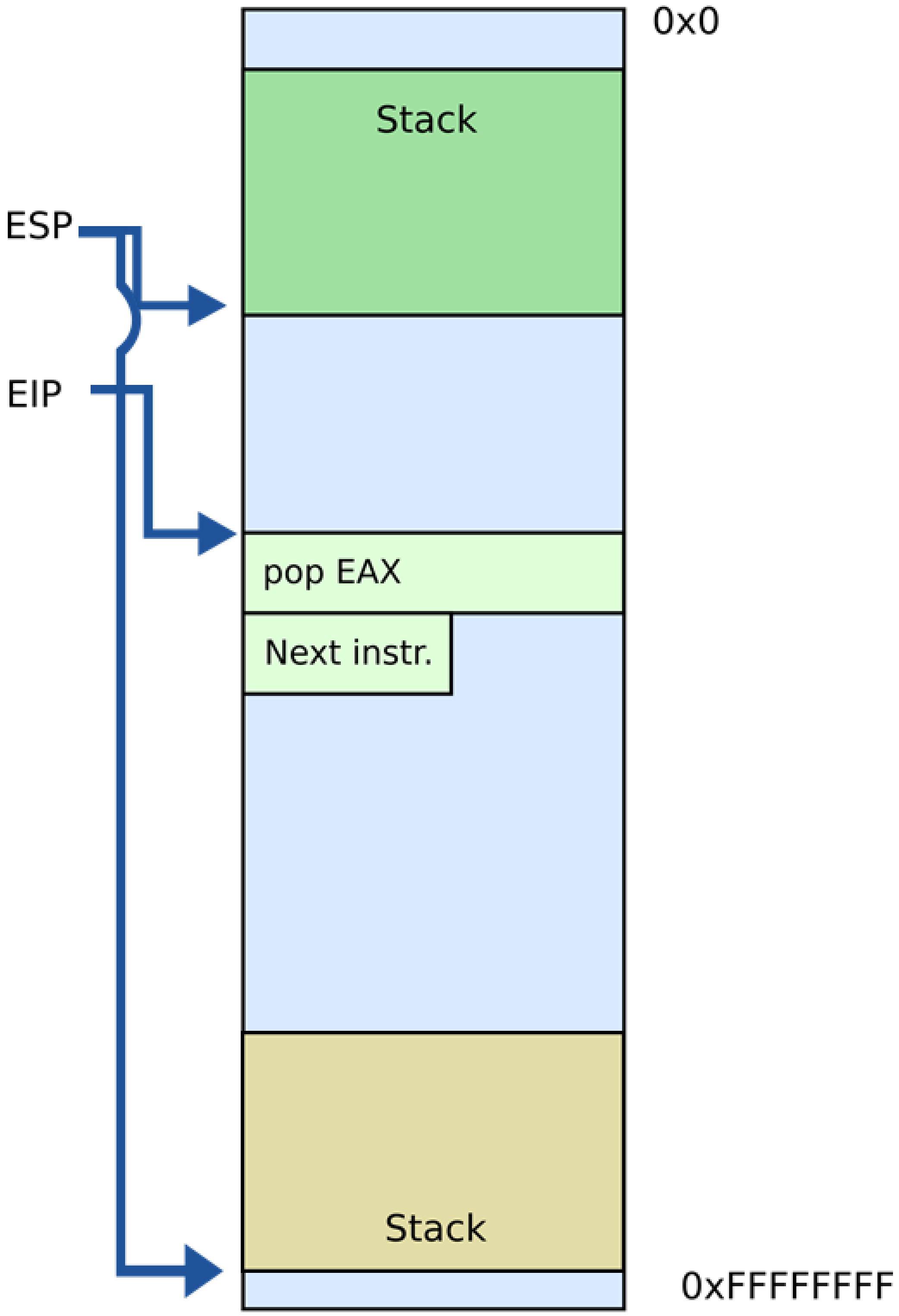
Anton Burtsev

Janurary, 2025

Recap: 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?

Stack allows us to invoke functions

Calling functions

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

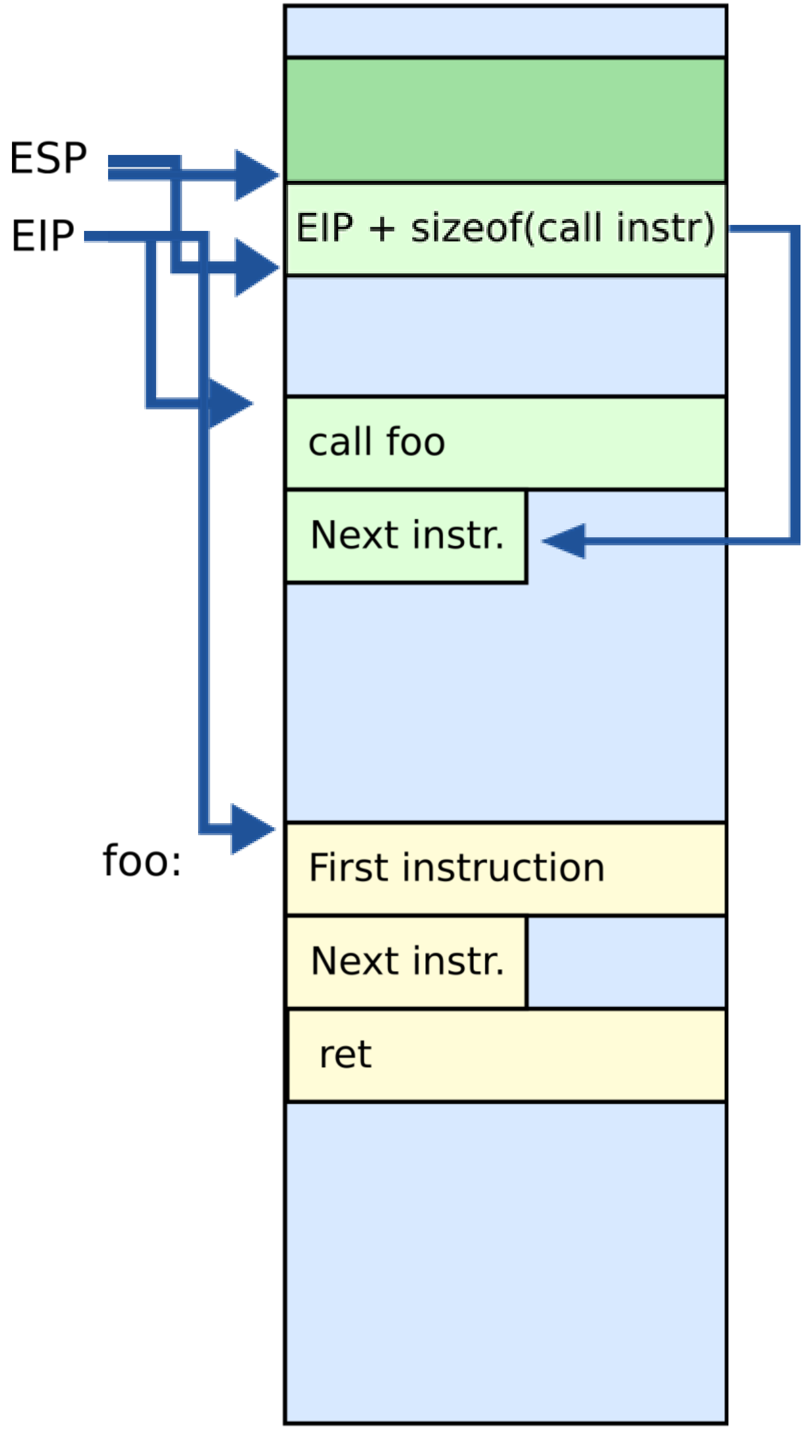
- Stack contains information for how to return from a subroutine
- i.e., from foo()

- Functions can be called from different places in the program

```
 if (a == 0) {
   foo();
   ...
} else {
   foo();
   ...
}
```

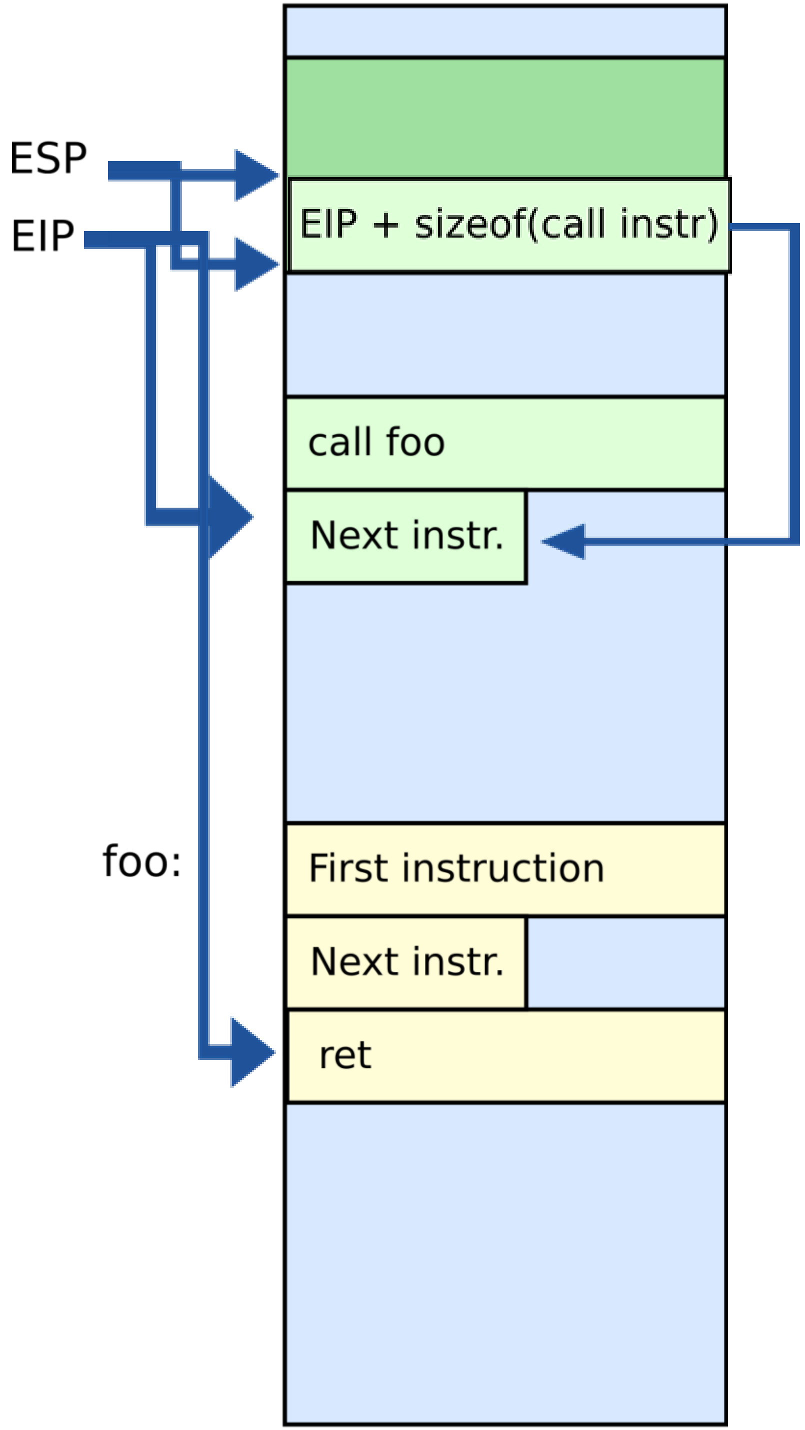
Stack

- Main purpose:
- Store the return address for the current procedure
- Caller pushes return address on the stack
- Callee pops it and jumps



Stack

- Main purpose:
- Store the return address for the current procedure
- Caller pushes return address on the stack
- Callee pops it and jumps



Calling functions

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

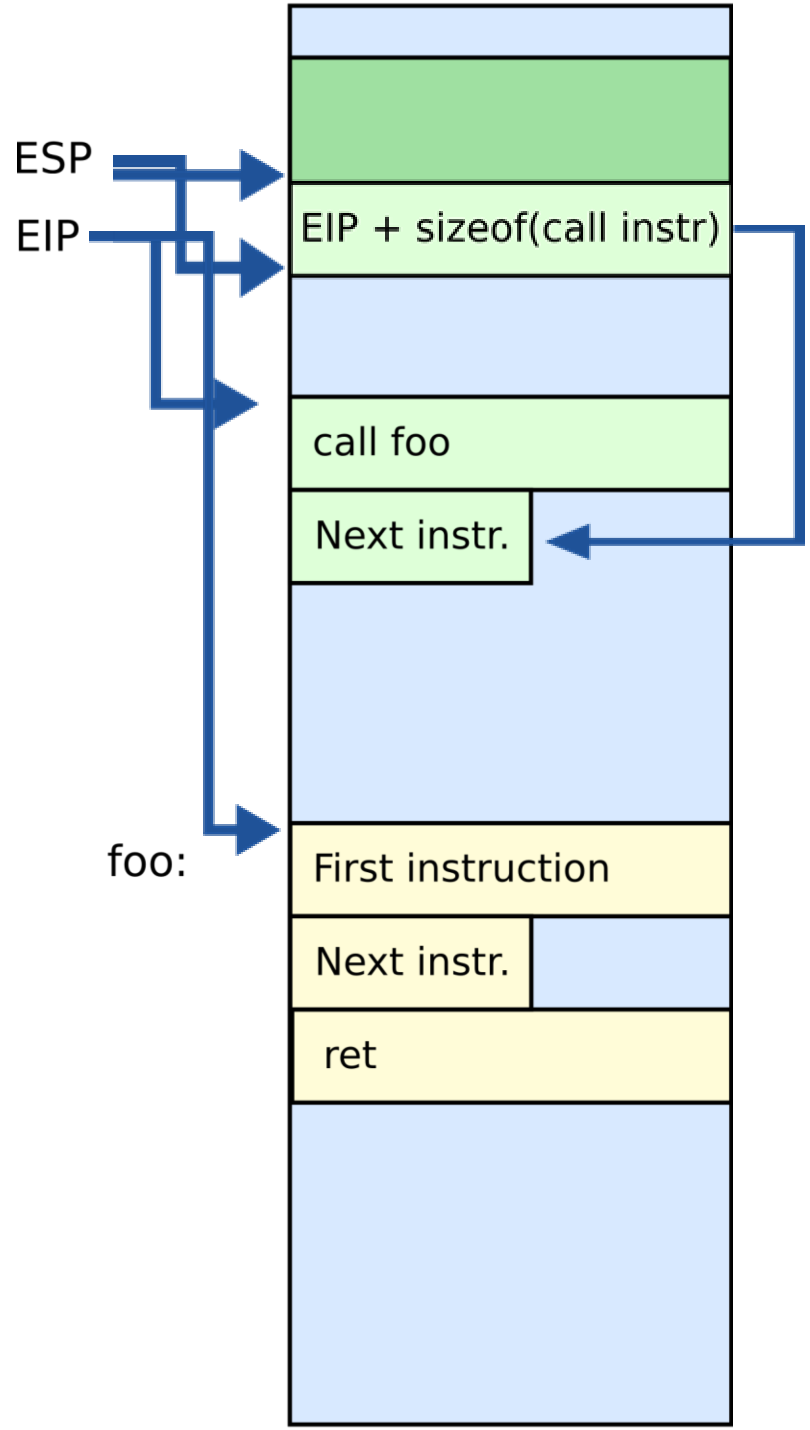
- Stack contains information for how to return from a subroutine
- i.e., from foo()

- Functions can be called from different places in the program

```
 if (a == 0) {
  foo();
  ...
} else {
  foo();
  ...
}
```

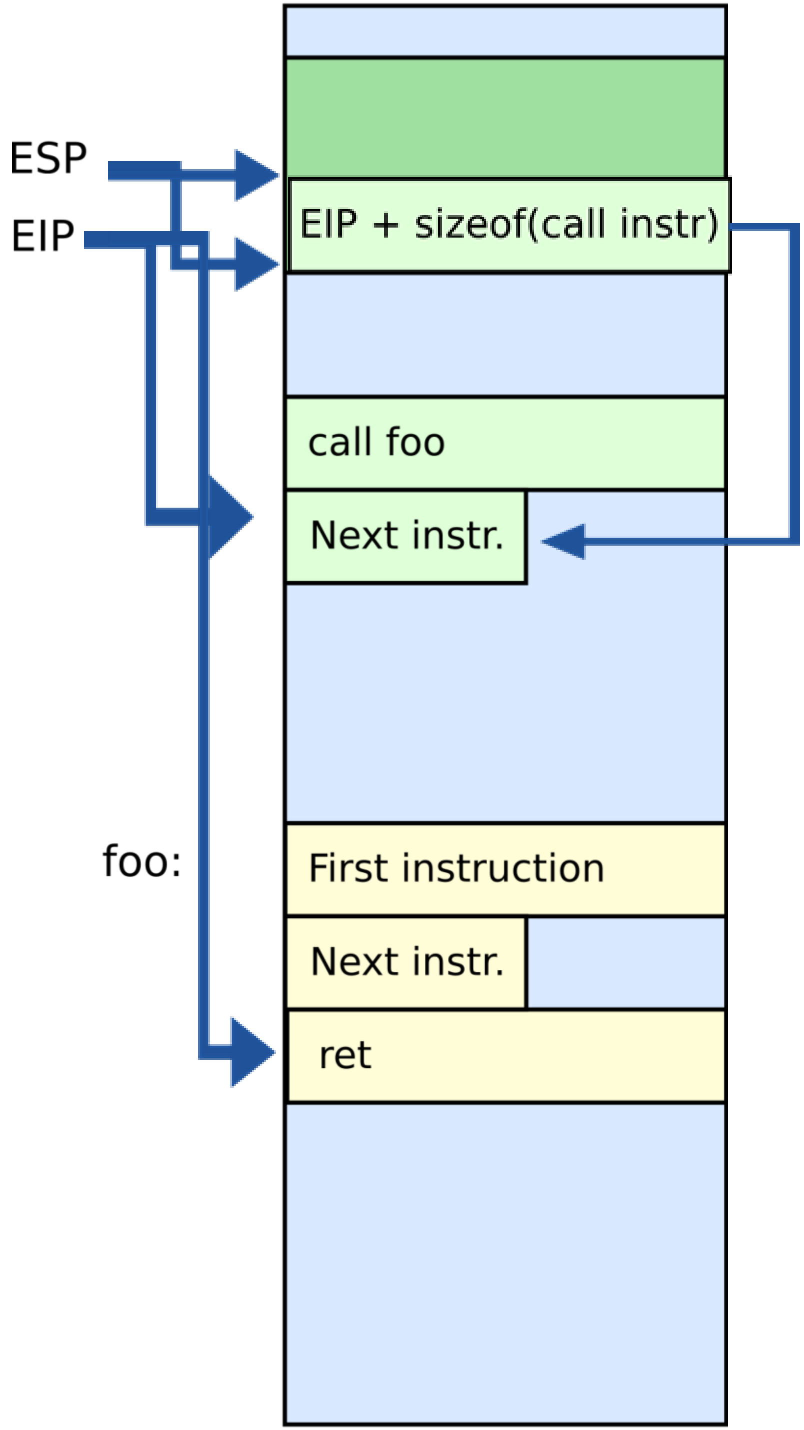
Stack

- Main purpose:
- Store the return address for the current procedure
- Caller pushes return address on the stack
- Callee pops it and jumps



Stack

- Main purpose:
- Store the return address for the current procedure
- Caller pushes return address on the stack
- Callee pops it and jumps



Example

```
foo(int a) {
    if (a == 0)
        return;
    a--;
    foo(a);
    return;
}

foo(4);
```

Calling conventions

Calling conventions

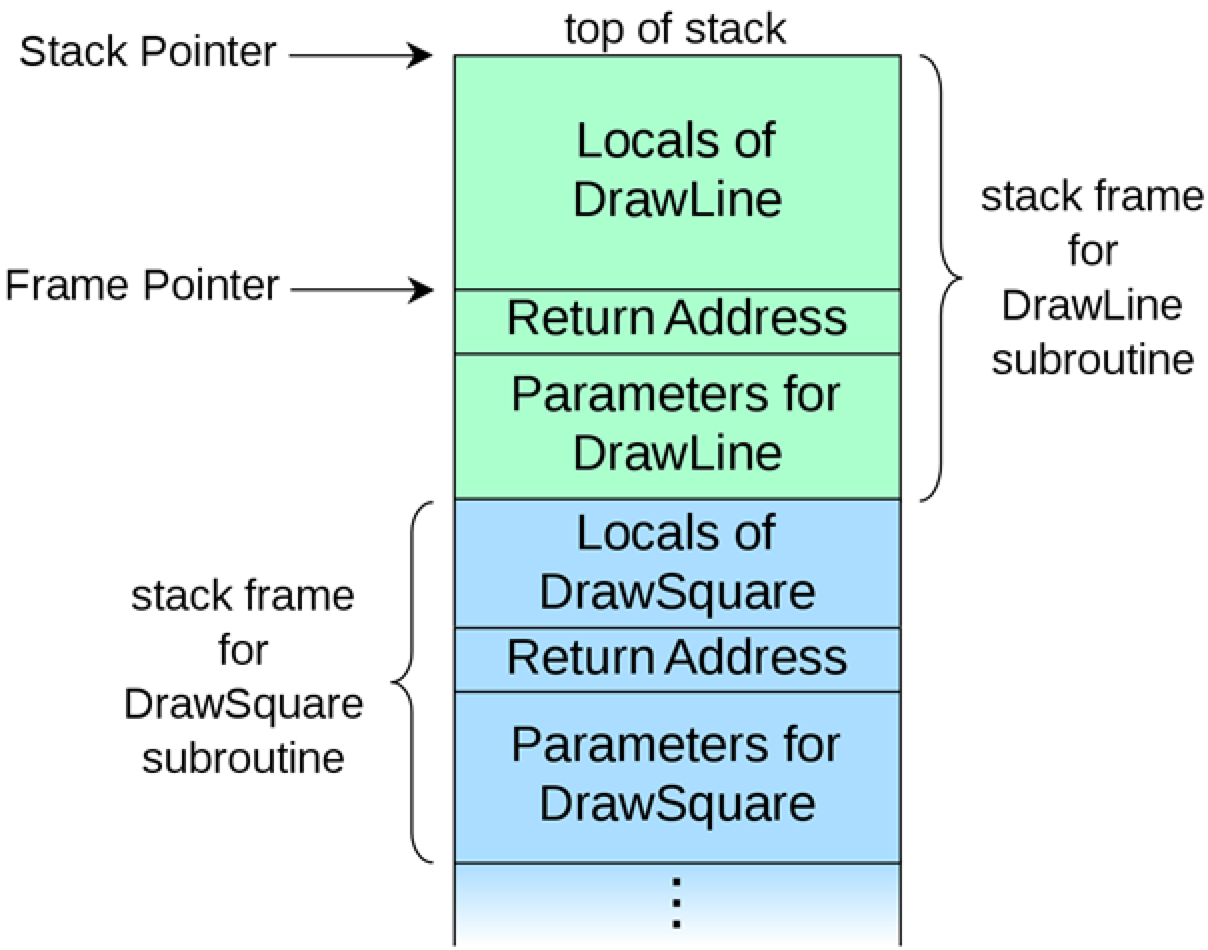
- Goal: re-entrant programs
- How to pass arguments
  - On the stack?
  - In registers?
- How to return values
  - On the stack?
  - In registers?
- Conventions vary between compilers, optimizations, etc.

Idea 1: Maintain stack as frames

- Each function has a new frame

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

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

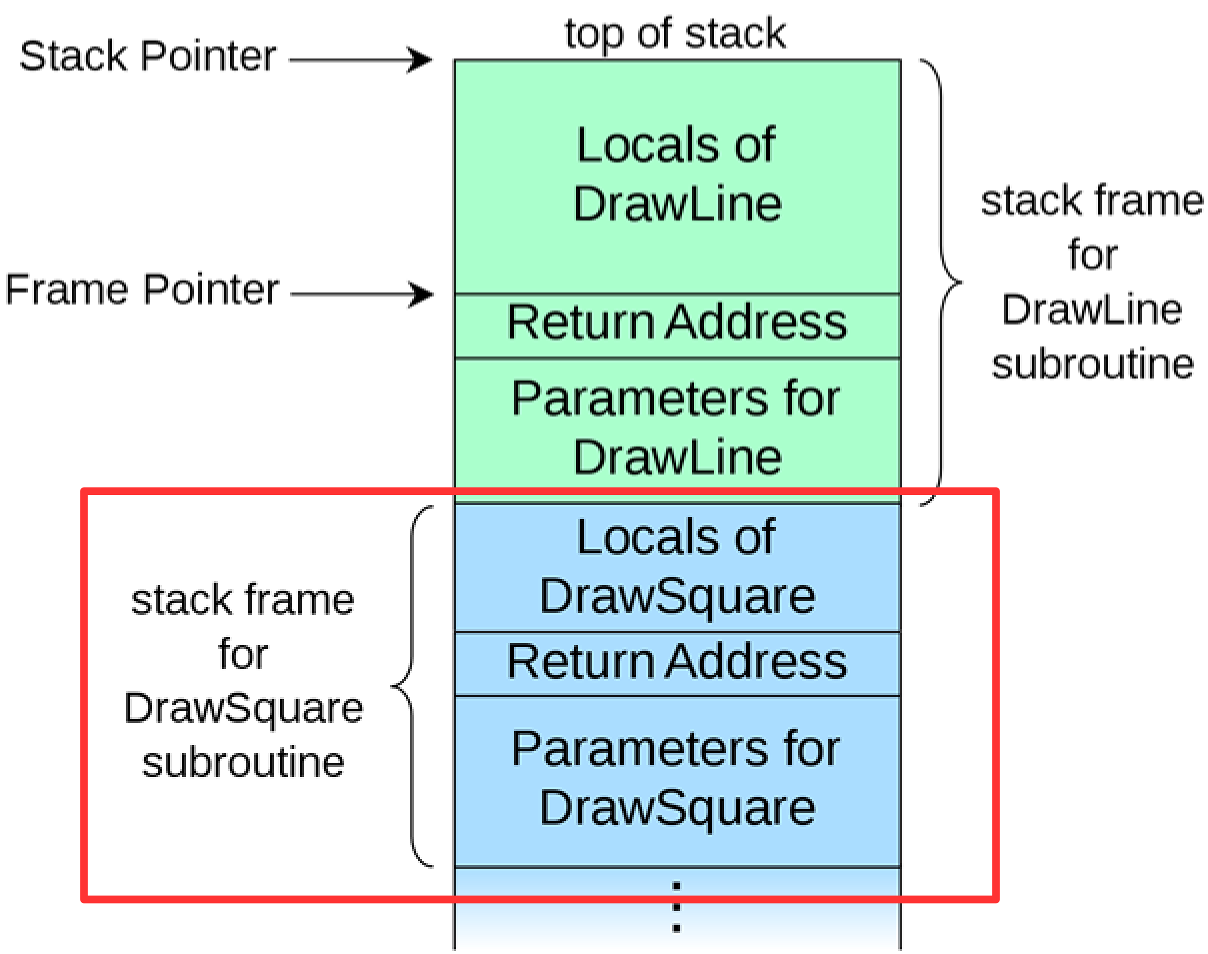


Maintain stack as frames

- Each function has a new frame

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

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

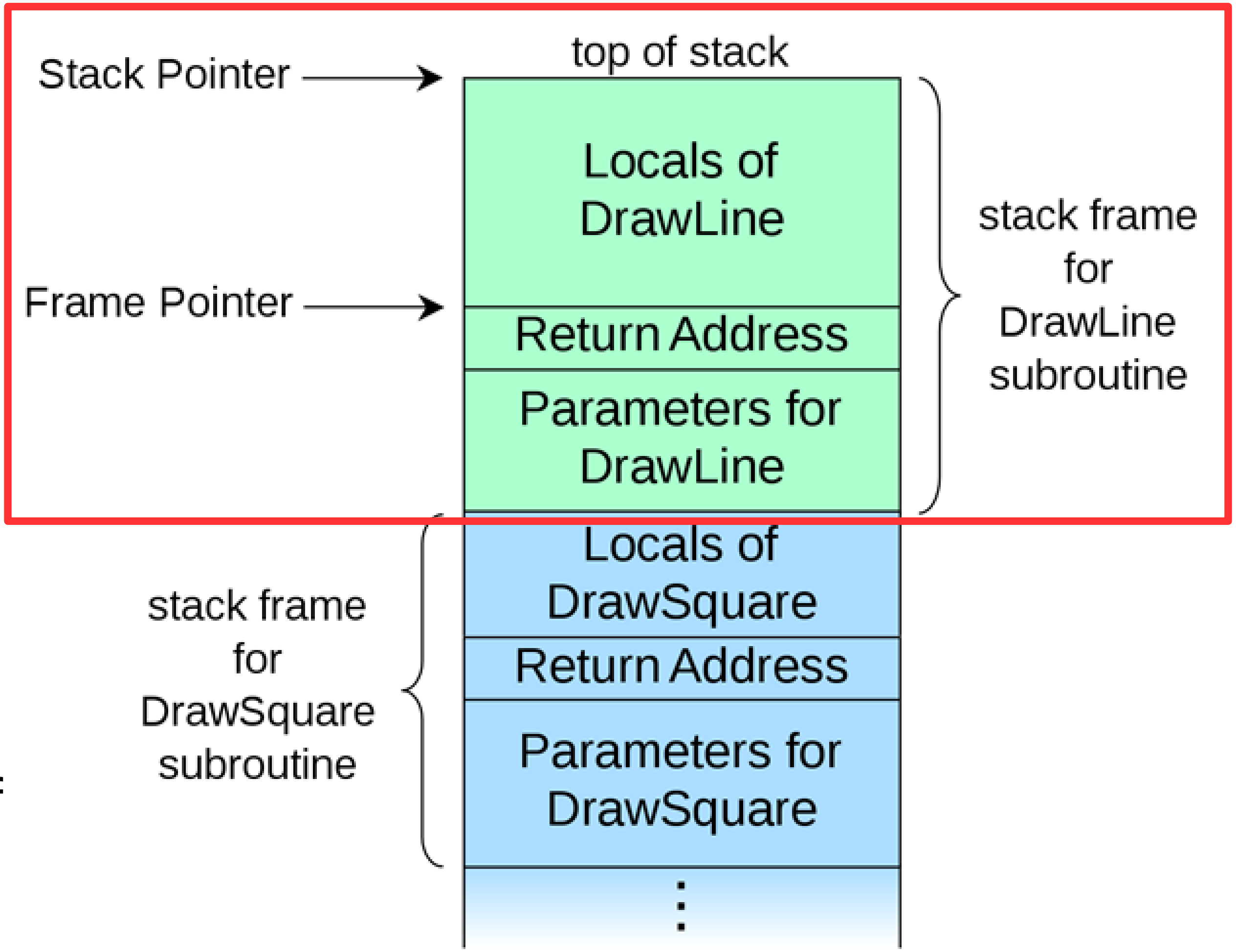


Maintain stack as frames

- Each function has a new frame

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

- 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

```
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
```

Local variables

What types of variables do you know?

- Or where these variables are allocated in memory?

What types of variables do you know?

- Global variables
  - Initialized → data section
  - Uninitalized → BSS
- Dynamic variables
  - Heap
- Local variables
  - Stack

Global variables

```c
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    static char world[] = "world!";
    printf("%s %s\n", hello, world);
    return 0;
}
```

Global variables

```
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    static char world[] = "world!";
    printf("%s %s\n", hello, world);
    return 0;
}
```

- Allocated in the data section
- It is split in initialized (non-zero), and non-initialized (zero)
- As well as read/write, and read only data section

Global variables

Dynamic variables (heap)

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
     char world[] = "world!";
     char *str = malloc(64);
     memcpy(str, "beautiful", 64);
      printf("%s %s %s\n", hello, str, world);
      return 0;
}
```

Dynamic variables (heap)

```c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    char world[] = "world!";
    char *str = malloc(64);
    memcpy(str, "beautiful", 64);
    printf("%s %s %s\n", hello, str, world);
    return 0;
}
```

- Allocated on the heap
- Special area of memory provided by the OS from where malloc() can allocate memory

Dynamic variables (heap)

Local variables

- Local variables

```
#include <stdio.h>

char hello[] = "Hello";
int main(int ac, char **av)
{
    //static char world[] = "world!";
    char world[] = "world!";
    printf("%s %s\n", hello, world);
    return 0;
}
```

Local variables...

- Each function has private instances of local variables

```
 foo(int x) {
    int a, b, c;
    ...
    return;
}
```

- Function can be called recursively

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

How to allocate local variables?

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

How to allocate local variables?

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

- On the stack!

Poll Q1: Where do we allocate global variables

Poll Q2: Where do we allocate dynamic variables

Allocating local variables

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

```
_my_function:
    push ebp            ; save original EBP value on stack
    mov ebp, esp        ; new EBP = ESP
    sub esp, LOCAL_BYTES ; = # bytes needed by locals
    …                   ; function body
    mov esp, ebp        ; deallocate locals
    pop ebp             ; restore original EBP value
    ret
```

Example

```
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 de-referencing EBP

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

Example

```
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 de-referencing EBP

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

How to pass arguments?

- Possible options:
- In 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

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

- Example invocation

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

- Generated code

```
push 10
push 5
push 2
call _my_function
```

Example stack

```
:    :
| 10 | [ebp + 16] (3rd function argument)
|  5 | [ebp + 12] (2nd argument)
|  2 | [ebp + 8]  (1st argument)
| RA | [ebp + 4]  (return address)
| FP | [ebp]      (old ebp value)← EBP points here
|    | [ebp - 4]  (1st local variable)
:    :
:    :
|    | [ebp - X]  (esp - the current stack pointer)
```

Example: caller side code

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```
caller:
 ; manage own stack 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
```

Example: caller side code

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```
caller:
  ; manage own stack 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
```

Example: caller side code

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```
caller:
  ; manage own stack 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
```

Example: caller side code

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```asm
caller:
  ; manage own stack 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
```

Example: caller side code

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

int caller(void)
{
    int ret;

    ret = callee(1, 2, 3);
    ret += 5;
    return ret;
}
```

```asm
caller:
  ; manage own stack 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
```

Example: caller side code

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```asm
caller:
  ; manage own stack 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
```

Wait! Where is return ret;?

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

int caller(void)
{
   int ret;

   ret = callee(1, 2, 3);
   ret += 5;
   return ret;
}
```

```
caller:
  ; manage own stack 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
```

Example: callee side code

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

```asm
_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
```

leave instruction

```
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 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
  pop ebp
  ret
```

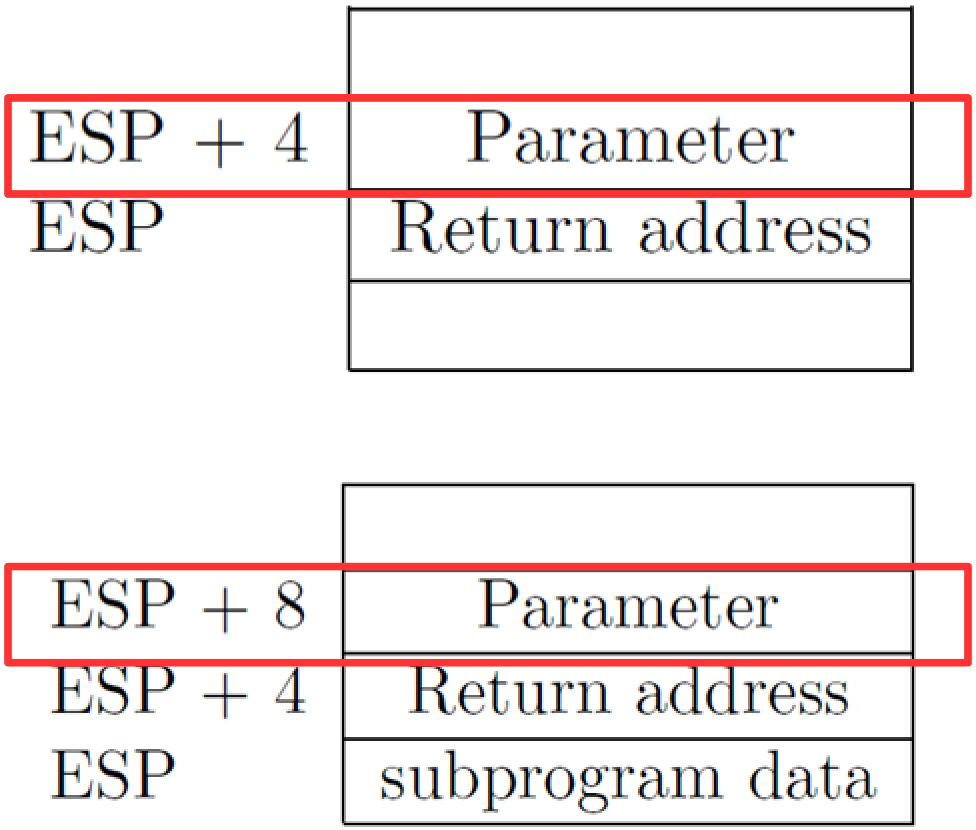
- x86 has a special instruction for this
- leave

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 easily do this and generate correct code!**
- **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: one register (EBP)
  - x32 has 8 registers (and one is ESP, so 7 are left)
  - So taking another one is 1/7 or 14.28% of register space
  - Sometimes it makes sense!
- 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

Relevant part of the GCC manual

3.10 Options That Control Optimization
https://gcc.gnu.org/onlinedocs/gcc/Optimize-Options.html

Poll

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 the callee and the 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 multiple calling conventions
- We described **cdecl**
- **Make sure you know what you're doing**

https://en.wikipedia.org/wiki/X86_calling_conventions#cdecl

- It's easy as long as you know how to read the table

Intel vs GNU ASM

Intel

- Copy ebx into eax

mov eax, ebx

- Move the 4 bytes in memory at the address contained in EBX into EAX

mov eax, [ebx]

- Move 4 bytes at memory address ESI + (-4) into EAX

mov eax, [esi-4]

GNU

mov %ebx, %eax

mov (%ebx), %eax

mov -4(%esi), %eax

Questions?

References

- https://en.wikibooks.org/wiki/X86_Disassembly/Functions_and_Stack_Frames
- https://en.wikipedia.org/wiki/Calling_convention
- https://en.wikipedia.org/wiki/X86_calling_conventions
- http://stackoverflow.com/questions/14666665/trying-to-understand-gcc-option-fomit-frame-pointer