

COMPLEX LAB “SYSTEMS PROGRAMMING”

— DAY 3 —

DEBUGGING AND ASSEMBLY

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2026-09-21

Some Ethymology/History



Rear Admiral Grace
Murray Hopper

Some Ethymology/History



Rear Admiral Grace Murray Hopper

9/2

9/9

0800 Antan started

1000 " stopped - antan ✓

13⁰⁰ MC (032) MP-MC ~~1.982649000~~ 2.130476415 ~~(-2)~~ 4.615925059 (-2)

(033) PRO 2 2.130476415

correct 2.130676415

Relays 6-2 in 033 failed special speed test
in Relay " 10,000 test.

Relays changed

1100 Started Cosine Tape (Sine check)

1525 Started Multi-Adder Test.

1545

Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.

1651/630 Antan started.

1700 closed down.

Relay 3145
Relay 3370

1947: "First actual case of bug being found"

Definitions

Bug ... flaw in a computer system that results in unintentional behaviour

Debugging ... process of searching and fixing deviations from the expected behaviour

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Debugging ... process of searching and fixing deviations from the expected behaviour

If debugging is the process of removing software bugs, then programming must be the process of putting them in.
— Edsger W. Dijkstra

Variety

Debugging is not only finding living creatures in an electronic device, but...

- Program crashes
- Slow execution
- Wrong results

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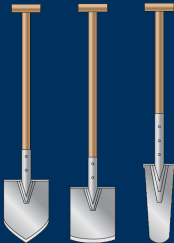
- Program crashes
- Slow execution
- Wrong results

Some (not too serious) jargon:

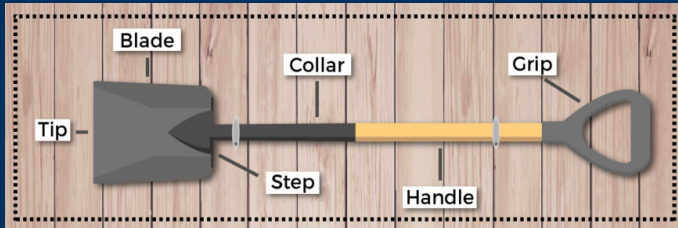
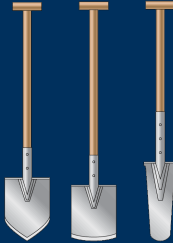
- Bohrbug & Heisenbug
- Mandelbug
- Schroedinbug
- Higgs-Bugson
- Hindenbug

How to debug?

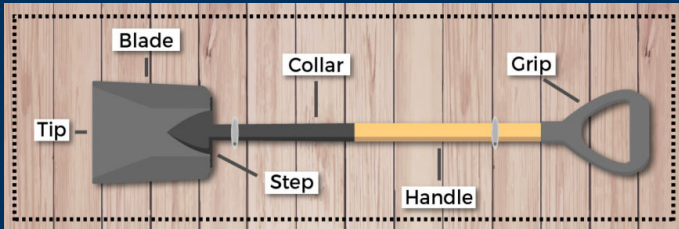
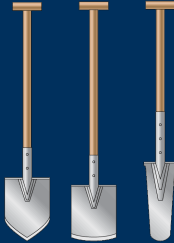
How to debug? Example: Digging



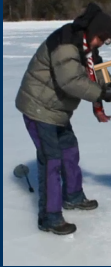
How to debug? Example: Digging



How to debug? Example: Digging



How to debug? Example: Digging



Debugging Tools

- `printf(...)` or rather `fprintf(stderr, ...)`
- `strace`
- `ltrace`
- `gdb`
- `valgrind`
- `perf`
- `ptrace`
- and even more...

Tracing System Calls — **strace**

Inspect system calls performed by a program

- Filtering: **strace -e**
- Timing: **strace -t[tt] / strace -T**
- Statistics: **strace -c**

Assignment №1

1. Which system calls are performed when you run `/bin/ls`?
2. How many calls are performed?
3. Why so many?

Tracing library calls — `ltrace`

Inspect all calls to *dynamically loaded* libraries

- Filtering: `ltrace -e`
- Timing: `ltrace -t[tt]` / `ltrace -T`
- Statistics: `ltrace -c`

Assignment №2

1. **wget** `https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/strace.tar.xz`
2. **tar -xJf** `strace.tar.xz`
3. **cd** `strace`

Make it print “SUCCESS”!

Hints: **file**, **strace** / **ltrace**

Problem: Memory Leaks

1. Allocate memory buffer

Problem: Memory Leaks

1. Allocate memory buffer
2. Use the buffer

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1. Allocate memory buffer
2. Use the buffer
3. Stop using the buffer

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4. (Optional) Loose pointer to the buffer

Problem: Memory Leaks

1. Allocate memory buffer
2. Use the buffer
3. Stop using the buffer
4. (Optional) Loose pointer to the buffer
5. Rinse and repeat

Dynamic Linker

- Recall static linking vs. dynamic linking

Details: `man ld.so`

Dynamic Linker

- Recall static linking vs. dynamic linking
- Resolves symbols by searching for libraries in **LD_LIBRARY_PATH**

Details: **man ld.so**

Dynamic Linker

- Recall static linking vs. dynamic linking
- Resolves symbols by searching for libraries in **LD_LIBRARY_PATH**
- **LD_PRELOAD**
 - Force loading of libraries
 - Loaded before any other *dynamic* library
 - Application has no choice

Details: **man ld.so**

Detecting Memory Leaks

- Use **LD_PRELOAD** to make the leaky program call custom implementations of **malloc** and **free**
- Track **malloc**/**free** information to report memory leaks at program termination
- Use the real **malloc**/**free** to perform the actual work

Interfacing with the Dynamic Linker

```
void* dlopen(const char* filename, int flag);  
char* dlerror(void);  
void* dlsym(void* handle, const char* symbol);  
int dlclose(void* handle);
```

And link with **libdl**, i.e. **gcc ... -ldl**

C/C++ Function Pointers

```
void* (*real_malloc) (size_t) = NULL;
```

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- Function return type

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- Function return type
- Variable name
- Function parameter types

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- Function return type
- Variable name
- Function parameter types
- Initial value

C/C++ Function Pointers

```
void* (*real_malloc) (size_t) = NULL;
```

- Function return type
- Variable name
- Function parameter types
- Initial value

or define a custom type for better readability

```
typedef void* (*malloc_ptr)(size_t);  
malloc_ptr real_malloc = NULL;
```

Finding the Real malloc

```
#define _GNU_SOURCE
#include <dlfcn.h>

// Inside the wrapper function
{
    static malloc_ptr real_malloc = NULL;
    real_malloc = (malloc_ptr) dlsym(RTLD_NEXT, "malloc");
}
```

Assignment №3

- Get <https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/wrap.tar.xz>
- In the **malloc/free** wrappers in **mallocWrap.c**:
 - Track memory management information: pointer (+ size)
 - Redirect work to the real **malloc** and **free**
- Upon exit, print all pointers (and allocation sizes) that were not freed
- You will need to be notified when the program ends $\Rightarrow$ **atexit()**
- **make** builds everything and runs a test against a “buggy” binary.

Hint: Keep it simple! Use a static array for tracking. Be careful about using **malloc/free** yourself (indirectly).

Example solution: <https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/mallocWrap.c>

An Anecdote

1. Bug report on strange sound on mp3 flash website

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2. Located in **libflashplayer.so**

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1. Bug report on strange sound on mp3 flash website
2. Located in **libflashplayer.so**
3. Reason: Use of **memcpy** for overlapping regions
4. Should use **memmove**, but plugin is closed source

Linus' Workaround

http://bugzilla.redhat.com/show_bug.cgi?id=638477#c38

1. Write your own **memcpy** similar to **memmove**
2. **gcc -O2 -c memcpy.c**
3. **ld -G memcpy.o -o memcpy.so**
4. **LD_PRELOAD=memcpy.so /opt/google/chrome/google-chrome &**

Valgrind

Binary recompilation framework (Valgrind core) with various tools:

MemCheck memory checks (default)

Cachegrind cache profiling

Callgrind call graph analysis

Helgrind race condition detection

Valgrind

Binary recompilation framework (Valgrind core) with various tools:

MemCheck memory checks (default)

Cachegrind cache profiling

Callgrind call graph analysis

Helgrind race condition detection

How do you pronounce “Valgrind”?

(from FAQ)

The “Val” as in the word “value”. The “grind” is pronounced with a short “i” — ie. “grinned” (rhymes with “tinned”) rather than “grined” (rhymes with “find”). Don’t feel bad: almost everyone gets it wrong at first.

Assignment №4

Analyse some programs with Valgrind:

- Get `https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/valgrind.tar.xz`
- Use **build.sh**

Static Checker

`https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/compiler.tar.xz`

scan-build

1. Install the Clang static analyser (e.g. **apt install clang-tools-<version>**)
2. Run **scan-build make** to analyse code
3. Run **scan-view** to see the report

Lists of static analysers

- <https://spinroot.com/static/>
- https://en.wikipedia.org/wiki/List_of_tools_for_static_code_analysis

Compiler Sanitisers

Additional libraries which are able to detect race conditions, memory bugs, undefined behavior, ...

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<https://os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/compiler.tar.xz>

Assignment №6: Address Sanitiser

1. Install **libasan** (e.g. **apt install libasan<version>**)
2. Run **make asan**: (re)builds all programs with **-fsanitize=address**
3. Run the programs

Details: **man gcc** and search for **-fsanitize**

The GNU Debugger

Interactive debugger (**gdb**):

- Breakpoints, Watchpoints
- Single-stepping, Reverse-stepping
- Inspect/modify registers & memory
- Scripting

Best with binaries containing debug info, e.g. compiled with **-g**
(or, ideally, **-ggdb3**)

Startup

- `gdb ... $BINARY` — launch binary

Startup

- `gdb ... $BINARY` — launch binary
- `gdb ... --args $BINARY ...` — launch binary with given arguments

Startup

- `gdb ... $BINARY` — launch binary
- `gdb ... --args $BINARY ...` — launch binary with given arguments
- `gdb ... $BINARY $CORE` — open core dump

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Startup

- `gdb ... $BINARY` — launch binary
- `gdb ... --args $BINARY ...` — launch binary with given arguments
- `gdb ... $BINARY $CORE` — open core dump
- `gdb ... [$BINARY] -p $PID` — attach to existing process
- `gdb -d $SRC_DIR ...` — add extra source directory

Basics

- `r[un] [args] [>...] [<...]`
- `start [args] [>...] [<...]`
- `starti [args] [>...] [<...]`
- `q[uit]`
- `h[elp] [command]`

Breakpoints & Watchpoints

- **b[reak]** {function | line | *address} [**if** condition]
- **wa[tch]** {variable | *address}
- **info** {**b[reak]** | **wa[tch]**}
- **commands** {id(s)}
- **c[ontinue]**

Inspecting the Program

- **l[ist] [+|-][N]** — show program code
- **disas[semble]** — disassemble current function
- **i[nfo] reg[isters]** — show register content
- **p[rint] [/FMT] {variable | expression}** — evaluate and print variable or expression
- **disp[lay] [/FMT] {variable | expression}** — evaluate and print every time the program stops
- **x/FMT {address}** — examine memory

Going Forward

- **s[tep]** — step to next source line
- **s[tep]i** — step to next assembler instruction
- **n[ext]** — step to next source line, proceeding through function calls
- **n[ext]i** — step to next assembler instruction, proceeding through function calls
- **u[ntil]** — run until past the current source line
- **fin[ish]** — run to return from current function

Going Backwards

- **record full** — start full execution recording
- **record stop** — stop execution recording
- **rs[tep]** — step to previous source line
- **rs[tep]i** — step to previous assembler instruction
- **rn[ext]** — step to previous line, proceeding through function calls
- **rn[ext]i** — step to previous assembler instruction, proceeding through function calls

See also: <https://rr-project.org/>

Walking the Call Stack

- **bt** — backtrace, show call stack
- **up [N]** — move “up” the call stack (towards caller)
- **do[wn] [N]** — move “down” the call stack (towards callee)

Remote Debugging

- GDB can connect to remote GDB servers
 - Via TCP or serial line
 - **set target remote** {address:port}
- Heavily used in OS/embedded development
- Qemu, Bochs/x86, Valgrind, etc. contain their own GDB servers

Alternate UI

- `[tui] layout {asm | src | regs}`
- <https://github.com/cyrus-and/gdb-dashboard>
- [https://sourceware.org/gdb/wiki/GDB Front Ends](https://sourceware.org/gdb/wiki/GDB_Front_Ends)

Scripting

- Conditional breakpoints and associated commands

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- Conditional breakpoints and associated commands
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- Run **`gdb -ex gdb_command`**
- Python API

Assignment №7

https:

`//os.inf.tu-dresden.de/Studium/SysProg/SS2026/debugging/gdb.tar.xz`

There are 4 versions of the Sieve of Eratosthenes

But only one works properly

What's wrong with the rest?

Under the Hood

System call `ptrace()`

- Child allows parent to intercept child interactions by `ptrace(PTRACE_TRACEME, 0, 0, 0);`
- Parent/Debugger inspects and modifies child state:
 - `PEEK/POKE`
 - `SETREGS/GETREGS`
 - `CONT/SYSCALL/SINGLESTEP`

But I Have no Source Code?!

There was this GDB command ...

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disas[semble] — disassemble current function

```
400d4e: 55                push    %rbp
400d4f: 48 89 e5          mov     %rsp,%rbp
400d52: bf 84 79 48 00    mov     $0x487984,%edi
400d57: e8 54 6b 00 00    callq   4078b0 <_IO_puts>
400d5c: 5d                pop     %rbp
400d5d: c3                retq
```

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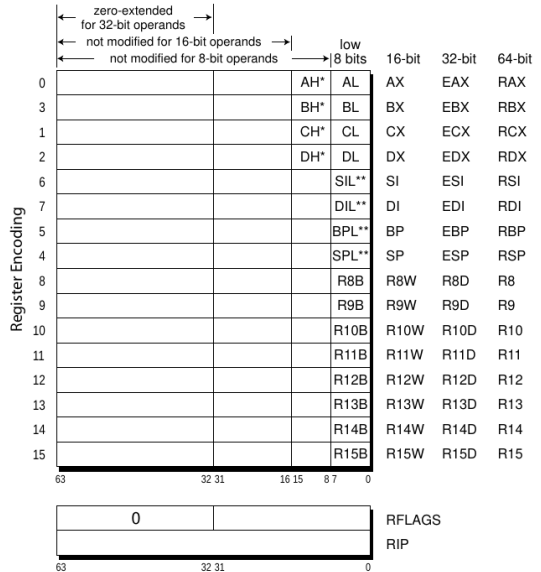
Uses for assembly language:

- Checking what your compiler actually produced
- System programming (e.g. kernel entry/exit)
- Direct hardware control (using specific instructions)

General Purpose Registers

- Data registers
- Flags register
- Instruction pointer

Details: Intel 64 and IA-32 Architectures Software Developer's Manuals



* Not addressable in REX prefix instruction forms

** Only addressable in REX prefix instruction forms

Figure 3-3. General Purpose Registers in 64-Bit Mode

Register Names

Did you know register names are there for a reason?

- (R/E)SP — stack pointer
- (R/E)BP — base pointer
- (R/E)IP — instruction pointer

Register Names

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- (R/E)SP — stack pointer
- (R/E)BP — base pointer
- (R/E)IP — instruction pointer
- (R/E)AX — accumulator
- (R/E)BX — base index
- (R/E)CX — counter
- (R/E)DX — data or extended accumulator
- (R/E)SI — source index
- (R/E)DI — destination index

Move Instructions

Move data between registers or to/from memory

```
movl    $1,%eax
```

```
movl    $0xff,%ebx
```

```
movl    (%ebx),%eax
```

```
movl    3(%ebx),%eax
```

Assembler Dialects

	AT&T	Intel
order	instr src, dest	instr dest, src
size	explicit (by instruction)	implicit (by register name)
Sigils	prefixes (\$, %)	automatic
mem. access	disp(base,index,scale) disp(base)	[base + index * scale + disp] [base + disp]
Examples	<pre>movl \$1,%eax movl \$0xff,%ebx movl (%ebx),%eax movl 3(%ebx),%eax</pre>	<pre>mov eax,1 mov ebx,0xffh mov eax,[ebx] mov eax,[ebx+3]</pre>

Arithmetic Operations

Addition / Subtraction

```
add    $1,%eax
```

```
add    %eax,%ebx
```

```
sub    $1,%eax
```

```
sub    %eax,%ebx
```

Arithmetic Operations

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```
sub     $1,%eax
```

```
sub     %eax,%ebx
```

Where to store the result?

Comparing Two Values

```
cmp $0, %eax  
cmp %eax, %ebx
```

Where to store the result?

Flags Register

Special purpose register that contains several bits to indicate the result of certain instructions, e.g. **cmp**

- 0 CF — Carry Flag
- 2 PF — Parity Flag
- 6 ZF — Zero Flag
- 7 SF — Sign Flag
- 8 TF — Trap Flag (single step)
- 9 IF — Interrupt Enable Flag

Details: https://en.wikipedia.org/wiki/FLAGS_register

Logical Operation

```
and  %eax,%ebx  
test %eax,%ebx  
or   %eax,%ebx  
xor  %eax,%ebx
```

(Conditionally) Jump to an Address

```
jmp 0xC0FFEE  
jmp %eax
```

Using the flags register...

```
ja 0xC0FFEE  
jae 0xC0FFEE  
jb[e] 0xC0FFEE  
jg[e] 0xC0FFEE  
jl[e] 0xC0FFEE  
jne 0xC0FFEE  
jz 0xC0FFEE
```

Details: <https://www.felixcloutier.com/x86/jcc>

Stack Operations

Push/pop register content to/from the stack

push %eax

pop %eax

(pusha)

(popa)

Function-related Operations

Call a function or return from one

```
call 0xC0FFEE
```

```
call 0xBADA55
```

```
ret
```

Calling Conventions

Describe the high-level function call interface

- How to pass parameters?
- Which registers must the called function preserve?
- Who does prepare/restore the stack?

Details: https://agner.org/optimize/calling_conventions.pdf

x86 aka x86_32 aka i386 aka IA-32 (Linux)

- Function arguments passed on the stack in right-to-left (RTL) order
- Integer values and memory addresses returned in **EAX**
- **EAX**, **ECX**, **EDX** caller-saved (volatile)
- Other registers callee-saved (non-volatile)

x86_64 aka AMD64 aka Intel 64 aka x64 (but *not* IA-64)

	Parameters in Registers	Param. Order on Stack	Cleanup
Microsoft	RCX, RDX, R8, R9	RTL(C)	Caller
System V	RDI, RSI, RDX, RCX, R8, R9	RTL(C)	Caller

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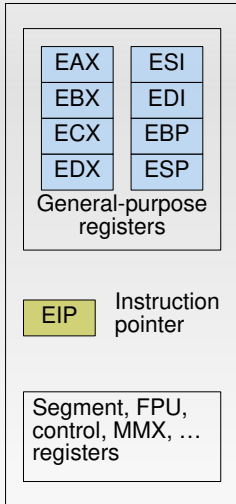
	Return	Callee Saved
Microsoft	RAX	RBX, RBP, RDI, RSI, R12 – R15
System V	RAX	RBX, RBP, R12 – R15

Interlude: Buffers on the Stack

Stolen from DOS...

The Battlefield: x86/32

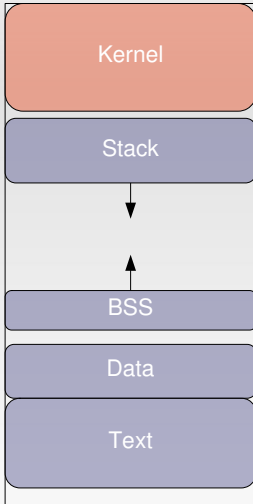
CPU



0xFFFFFFFF

Address Space

0xBFFFFFFF



0x00000000

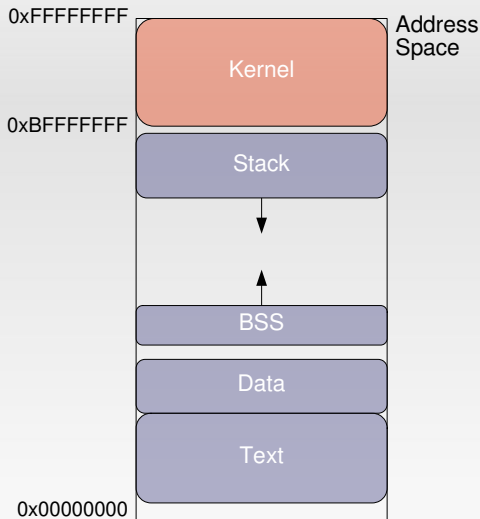
The Stack

- Stack frame per function

- Set up by compiler-generated code

- Used to store

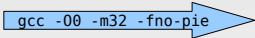
- Function parameters
 - If not in registers – GCC:
`__attribute__((regparm(<num>)))`
 - Local variables
 - Control information
 - Function return address



Calling a function

```
int sum(int a, int b)
{
    return a+b;
}
```

```
sum:
    pushl %ebp
    movl %esp, %ebp
    movl 12(%ebp), %eax
    addl 8(%ebp), %eax
    popl %ebp
    ret
```



gcc -O0 -m32 -fno-pie

```
int main()
{
    return sum(1,3);
}
```

```
main:
    pushl %ebp
    movl %esp, %ebp
    subl $8, %esp
    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```

Assembly recap'd

%<reg> refers to register content

Offset notation: **X(%<reg>)** == memory location pointed to by <reg> + X

sum:

```
pushl %ebp
movl %esp, %ebp
movl 12(%ebp), %eax
addl 8(%ebp), %eax
popl %ebp
ret
```

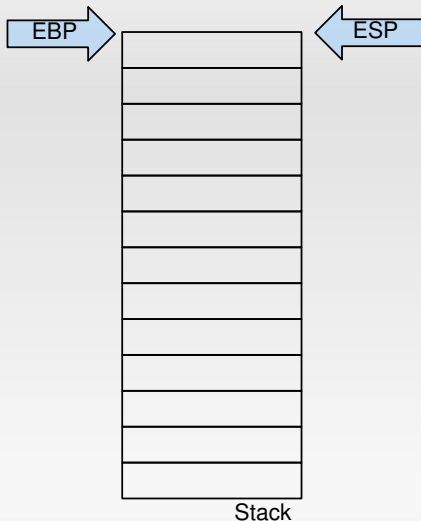
Constants prefixed with \$ sign

(%<reg>) refers to memory location pointed to by <reg>

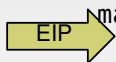
main:

```
pushl %ebp
movl %esp, %ebp
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movl $3, 4(%esp)
movl $1, (%esp)
call sum
ret
```

So what happens on a call?

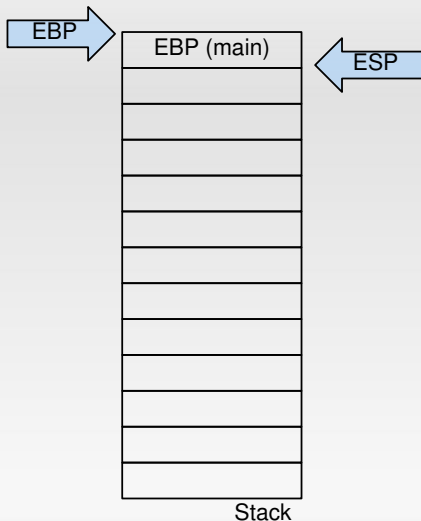


```
sum:
    pushl %ebp
    movl %esp, %ebp
    movl 12(%ebp), %eax
    addl 8(%ebp), %eax
    leave
    ret
```

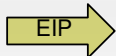


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    subl $8, %esp
    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```

So what happens on a call?

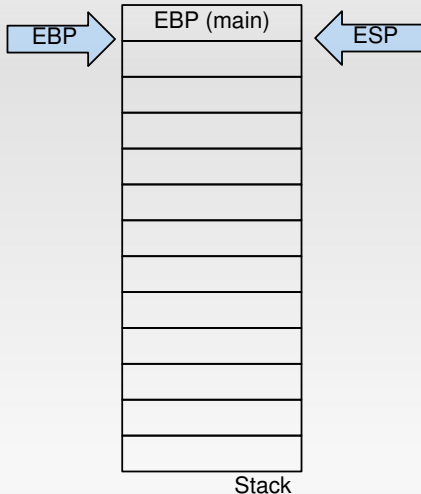


```
sum:
    pushl %ebp
    movl %esp, %ebp
    movl 12(%ebp), %eax
    addl 8(%ebp), %eax
    leave
    ret
```



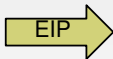
```
main:
    pushl %ebp
    movl %esp, %ebp
    subl $8, %esp
    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```

So what happens on a call?

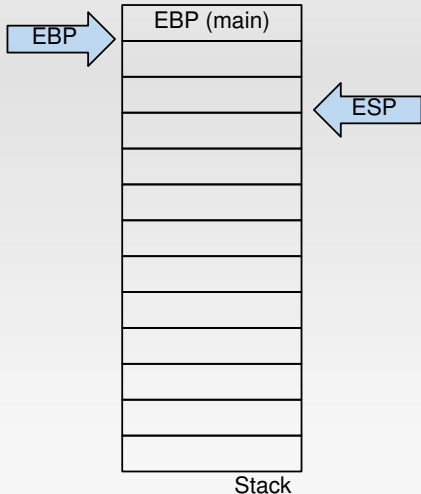


```
sum:
    pushl %ebp
    movl %esp, %ebp
    movl 12(%ebp), %eax
    addl 8(%ebp), %eax
    leave
    ret
```

```
main:
    pushl %ebp
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    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```

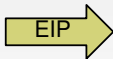


So what happens on a call?

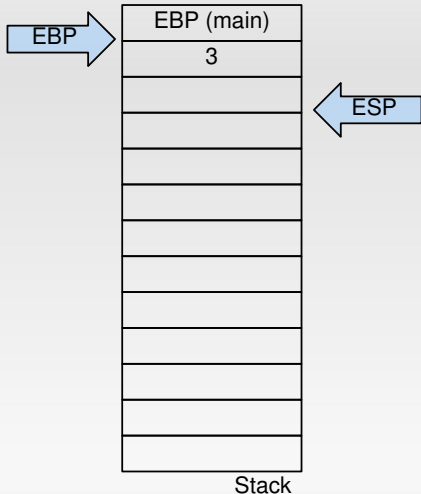


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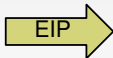


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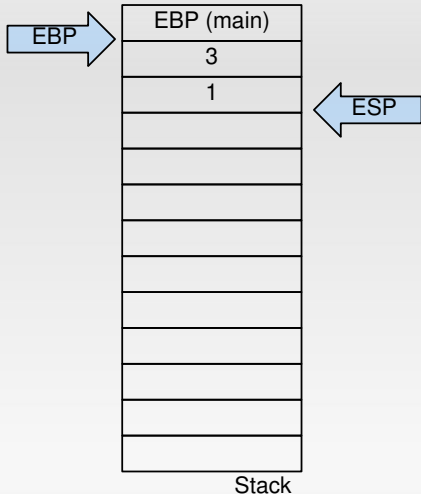


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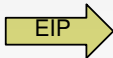


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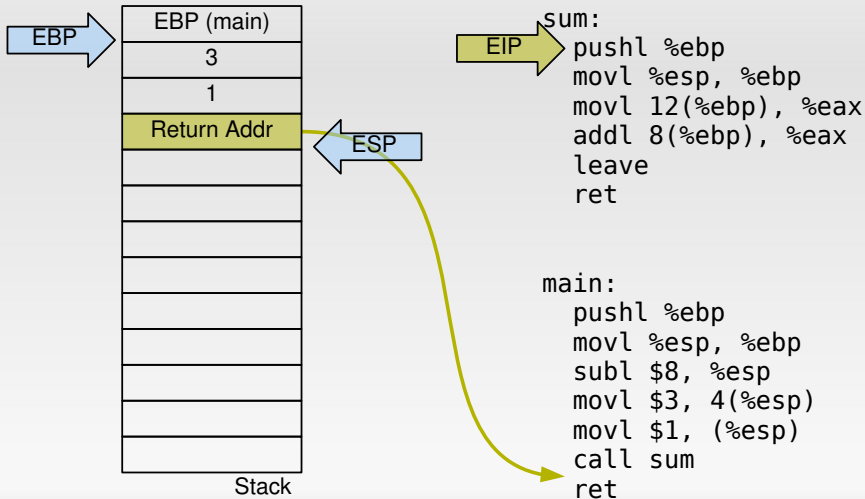


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```

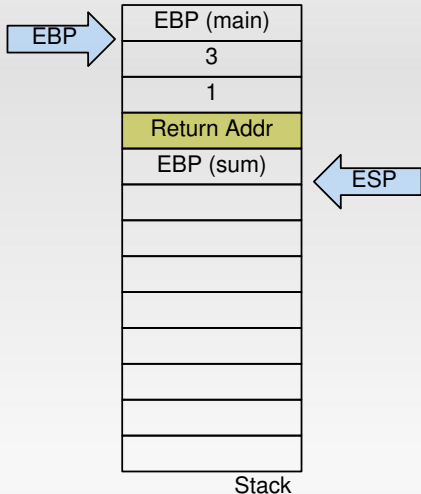
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    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```



So what happens on a call?



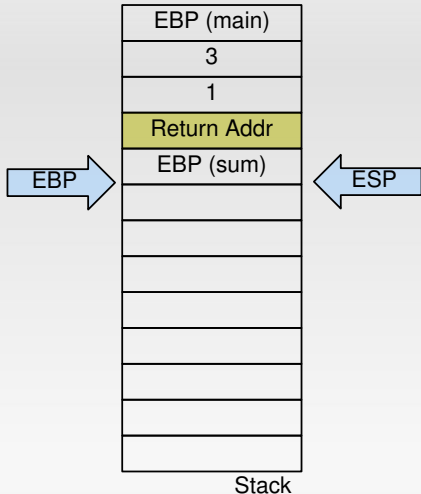
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ret

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movl %esp, %ebp
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movl \$1, (%esp)
call sum
ret

So what happens on a call?



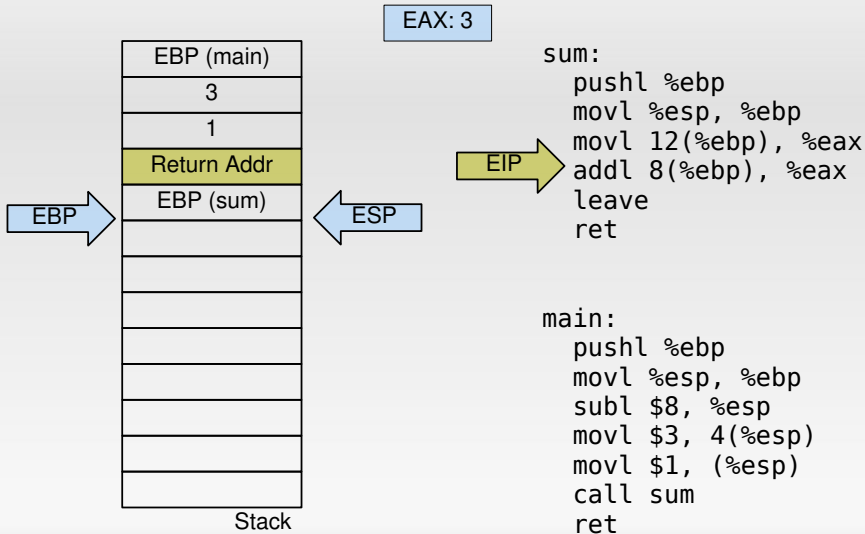
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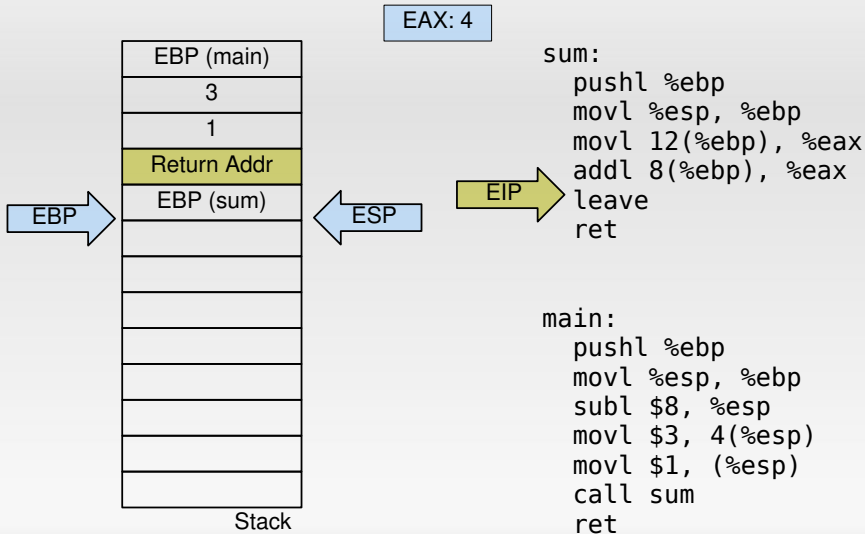
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movl $3, 4(%esp)
movl $1, (%esp)
call sum
ret
```

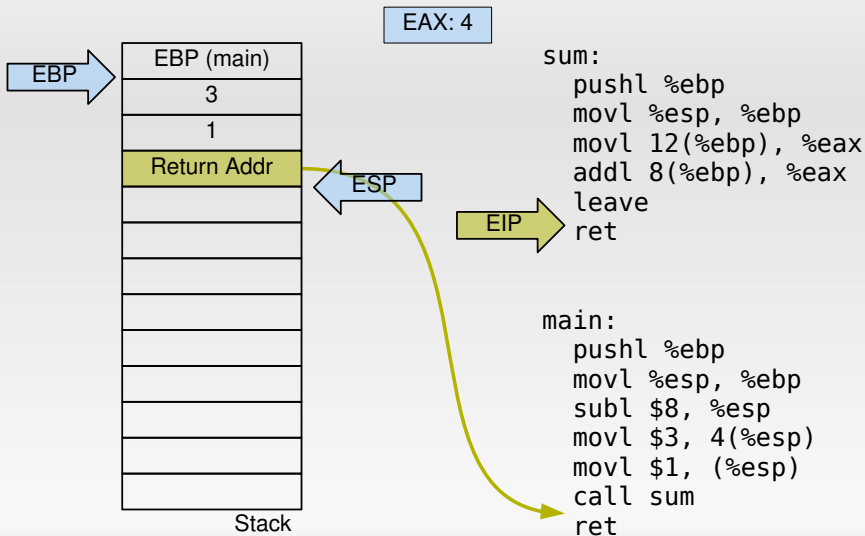
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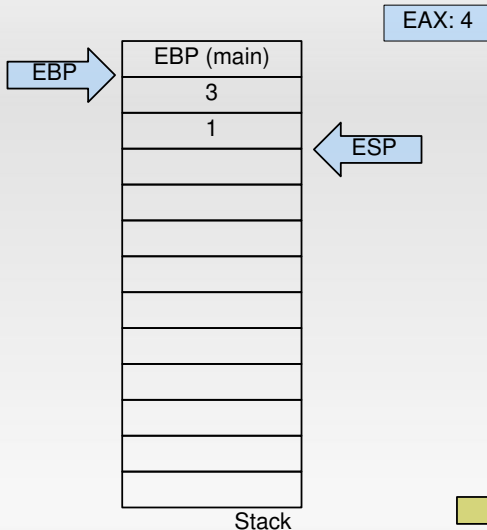
So what happens on a call?



So what happens on a call?



So what happens on a call?



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sum:
    pushl %ebp
    movl %esp, %ebp
    movl 12(%ebp), %eax
    addl 8(%ebp), %eax
    leave
    ret
```

```
main:
    pushl %ebp
    movl %esp, %ebp
    subl $8, %esp
    movl $3, 4(%esp)
    movl $1, (%esp)
    call sum
    ret
```



Now let's add a buffer

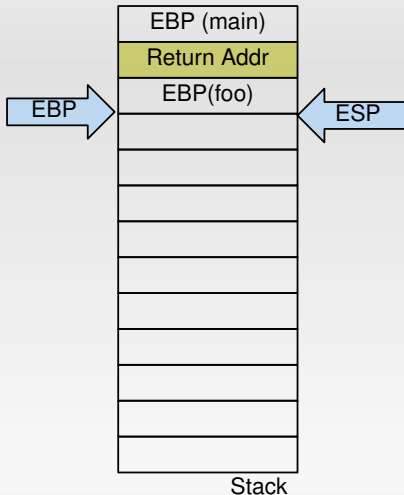
```
int foo()  
{  
    char buf[20];  
    return 0;  
}
```

```
int main()  
{  
    return foo();  
}
```

```
foo:  
    pushl %ebp  
    movl %esp, %ebp  
    subl $32, %esp  
    movl $0, %eax  
    leave  
    ret
```

```
main:  
    pushl %ebp  
    movl %esp, %ebp  
    call foo  
    popl %ebp  
    ret
```

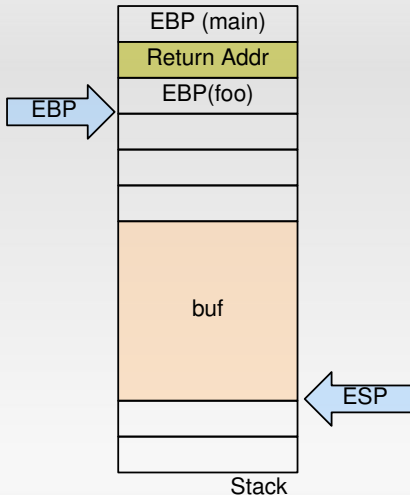
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    leave
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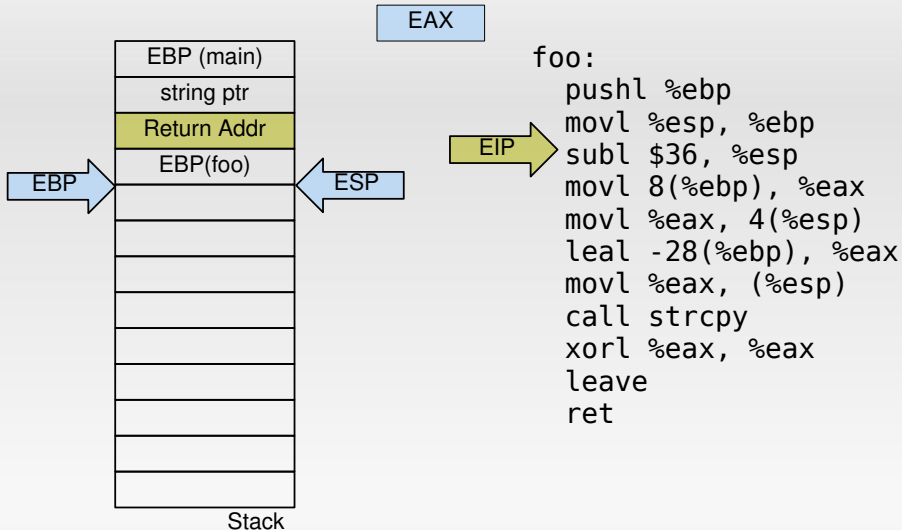
Calling a libC function

```
int foo(char *str)
{
    char buf[20];
    strcpy(buf, str);
    return 0;
}
```

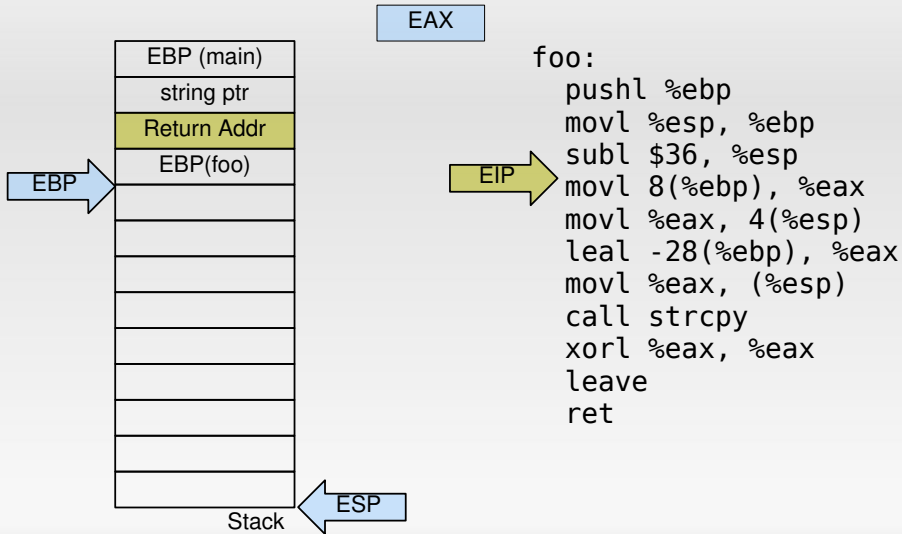
```
int main(int argc,
          char *argv[])
{
    return foo(argv[1]);
}
```

```
foo:
    pushl %ebp
    movl %esp, %ebp
    subl $36, %esp
    movl 8(%ebp), %eax
    movl %eax, 4(%esp)
    leal -28(%ebp), %eax
    movl %eax, (%esp)
    call strcpy
    xorl %eax, %eax
    leave
    ret
```

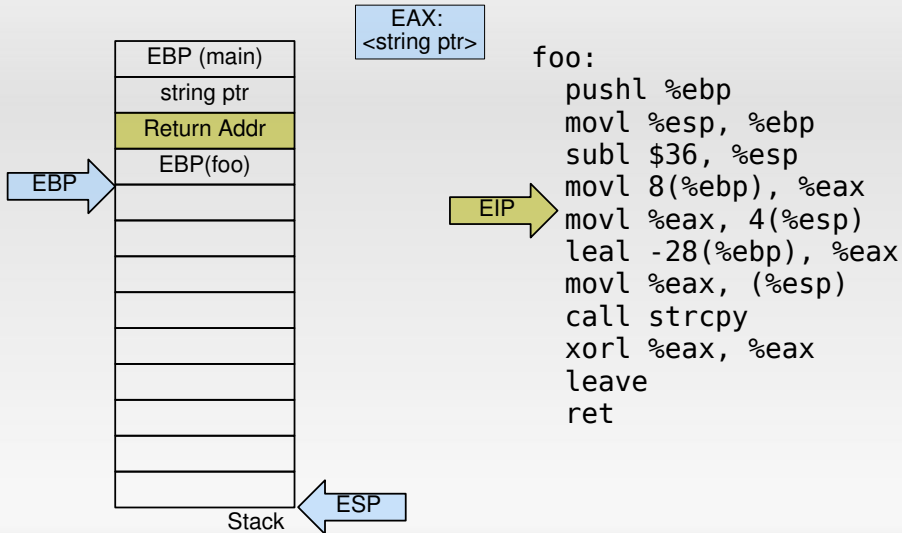
Calling a libC function



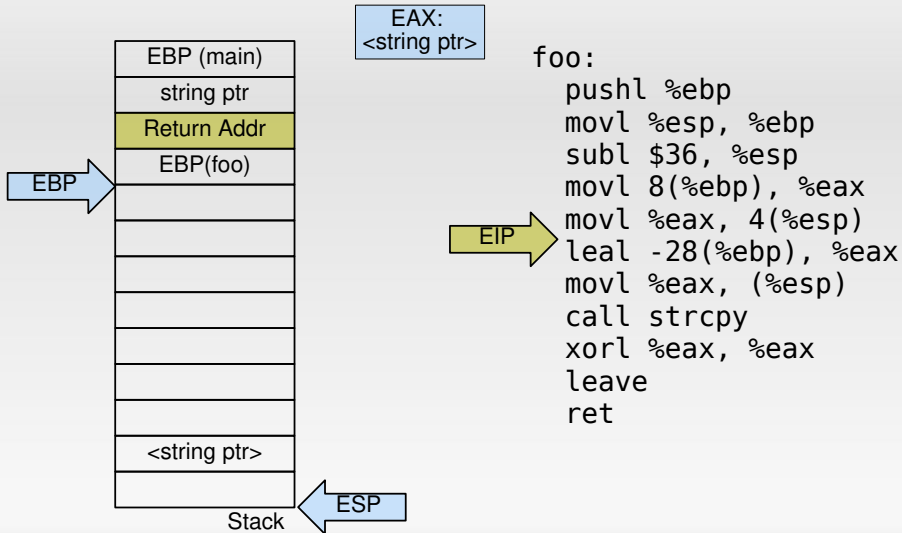
Calling a libC function



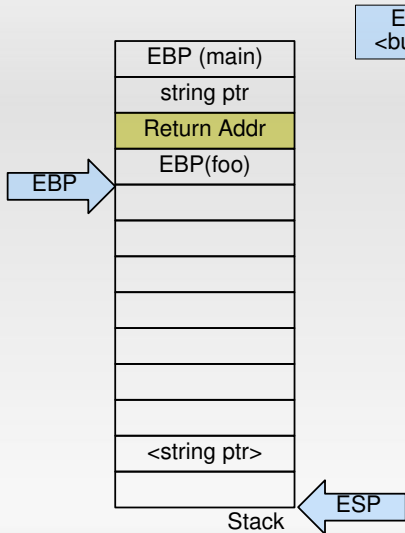
Calling a libC function



Calling a libC function



Calling a libc function



EAX:
<buf ptr>

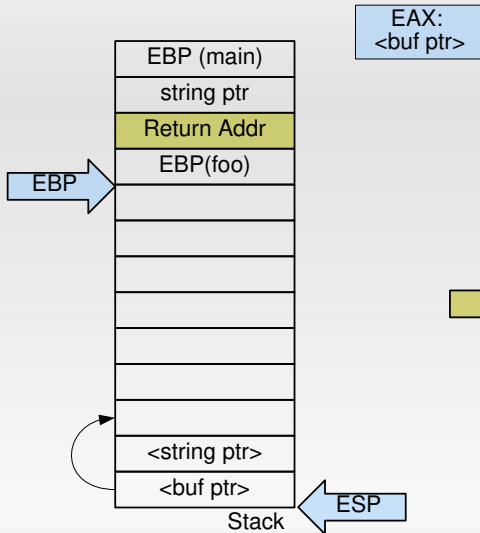
```
foo:
```

```

pushl %ebp
movl %esp, %ebp
subl $36, %esp
movl 8(%ebp), %eax
movl %eax, 4(%esp)
leal -28(%ebp), %eax
movl %eax, (%esp)
call strcpy
xorl %eax, %eax
leave
ret

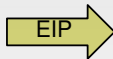
```

Calling a libC function

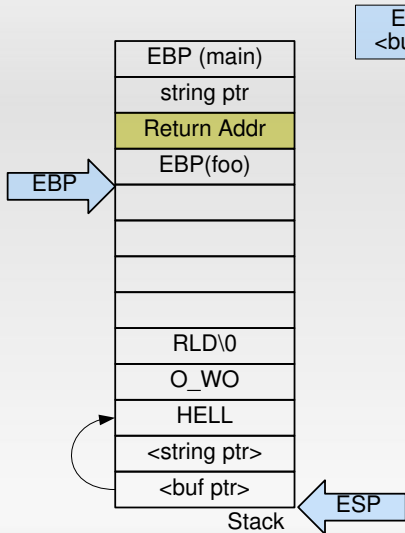


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leal -28(%ebp), %eax
movl %eax, (%esp)
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ret
```



Calling a libC function

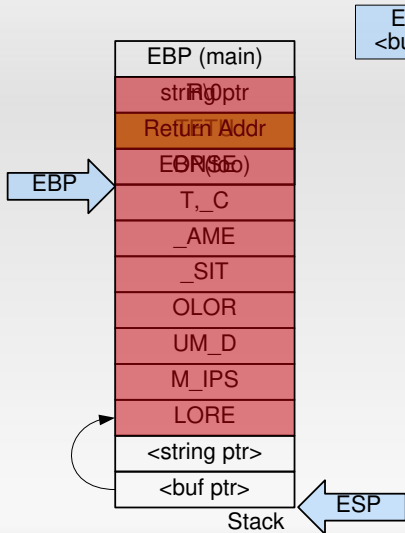


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movl %eax, 4(%esp)
leal -28(%ebp), %eax
movl %eax, (%esp)
call strcpy
xorl %eax, %eax
leave
ret
```

string = "Hello world"

Our first buffer overflow™



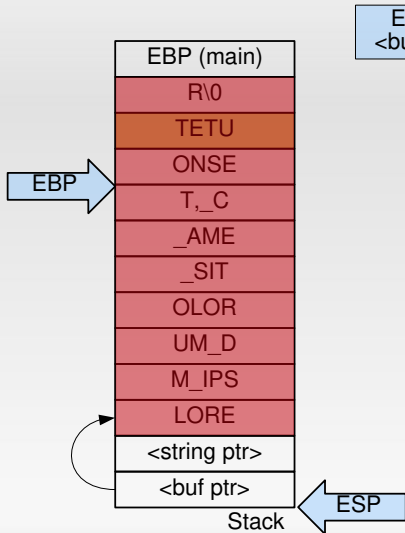
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xorl %eax, %eax
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```

string = "Lorem ipsum dolor
sit amet, consetetur"

Our first buffer overflow™



EAX:
<buf ptr>

foo:

```
    pushl %ebp
    movl %esp, %ebp
    subl $36, %esp
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    movl %eax, 4(%esp)
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    movl %eax, (%esp)
    call strcpy
    xorl %eax, %eax
    leave
    ret
```

string = "Lorem ipsum dolor
sit amet, consetetur"

Inline Assembly

```
asm [volatile] ( AssemblerTemplate  
                  [ : [OutputOperands]  
                  [ : [InputOperands]  
                  [ : [Clobbers] ]]);
```

Example: `int i = 42;`
`asm volatile ("add,%%eax,%%eax"
 : "+a"(i)
 : // no other input, just i
 : // no clobber
);`

Details: <https://gcc.gnu.org/onlinedocs/gcc/Extended-Asm.html>

Register Constraints and Modifiers

Constraints

r ... any general purpose register
a ... **AL, AX, EAX, RAX**
d ... **DL, DX, EDX, RDX**
D ... **EDI, RDI**
m ... memory operand
X ... any operand whatsoever

Modifiers (for output operands)

= ... write-only
+ ... read & write

```
asm volatile ("add_%%eax, _%%eax;" : "+a"(i) );
```

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Modifiers (for output operands)

= ... write-only
+ ... read & write

```
asm volatile ("add_%%eax, _%%eax;" : "+a"(i) );
```



```
asm volatile ("add_%0, _%0;" : "+r"(i) );
```

Example: Adding two Numbers

```
int add(int a, int b) {  
    asm volatile ("addl%1,%0;"  
                  : "+r"(a)      // out (+in)  
                  : "r"(b)       // in  
                  );  
    return a;  
}
```

Compiler Builtins

GCC (and others) come with special *intrinsics* that map to optimised code

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Examples:

- Common libC functions like `__builtin_memcpy`
- `__builtin_expect`
- `__builtin_popcount`
- `__builtin_prefetch`
- `__builtin_unreachable`
- `__builtin_return_address`

Details:

<https://gcc.gnu.org/onlinedocs/gcc/Built-in-Functions.html>

<https://gcc.gnu.org/onlinedocs/gcc/x86-Built-in-Functions.html>

CPU Time Stamp Counter

64 bit register counting the clocks since system startup

- Pentium*, early Xeon CPUs: increment with every CPU cycle
- Newer Xeons and Core*: increment at a constant rate
- AMD up to K8: per CPU, increment with every CPU cycle

Spot the problem?

CPU Time Stamp Counter

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- Pentium*, early Xeon CPUs: increment with every CPU cycle
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Spot the problem?

Check CPU flags (**1scpu**) for **constant_tsc**

Reading the TSC

Instruction: **rdtsc** stores TSC in **EAX** (lower 32 bits) and **EDX** (higher 32 bits)

Reading the TSC

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```
unsigned long long rdtsc() {  
    unsigned long long hi, lo;  
  
    asm volatile("rdtsc;"  
                 "mov_%%edx, _%0\n\t"  
                 "mov_%%eax, _%1\n\t"  
                 : "=r" (hi), "=r" (lo)  
                 );  
  
    return (hi << 32) | lo;  
}
```

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```

Spot the problem?

Clobbering is important!

Instruction: **rdtsc** stores TSC in **EAX** (lower 32 bits) and **EDX** (higher 32 bits)

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unsigned long long rdtsc() {  
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                 : "=r" (hi), "=r" (lo)  
                 :  
                 : "eax", "edx"  
                );  
  
    return (hi << 32) | lo;  
}
```

Catching Out-of-Order Execution

Before measurement

```
unsigned long long rdtsc_pre() {
    unsigned long long hi, lo;

    asm volatile("cpuid\n\t"
                 "rdtsc\n\t"
                 "mov_%%edx,_%0\n\t"
                 "mov_%%eax,_%1\n\t"
                 : "=r" (hi), "=r" (lo)
                 :
                 : "rax", "rbx", "rcx", "rdx");

    return (hi << 32) | lo;
}
```

After measurement

```
unsigned long long rdtsc_post() {
    unsigned long long hi, lo;

    asm volatile("rdtscp\n\t"
                 "mov_%%edx,_%0\n\t"
                 "mov_%%eax,_%1\n\t"
                 "cpuid\n\t"
                 : "=r" (hi), "=r" (lo)
                 :
                 : "rax", "rbx", "rcx", "rdx");

    return (hi << 32) | lo;
}
```

Details: "How to Benchmark Code Execution Times on Intel IA-32 and IA-64 Instruction Set Architectures", Gabriele Paoloni

Benchmarking Considerations

- **rdtsc** is not for free
- Interruption by other programs, migration to other CPU core, ...

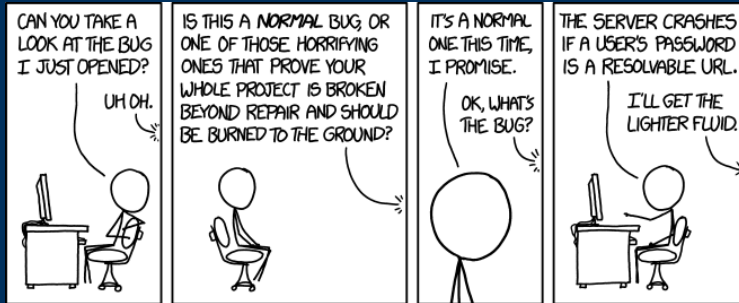
Benchmarking Considerations

- **rdtsc** is not for free
- Interruption by other programs, migration to other CPU core, ...
 - Kernel: disable IRQs
 - User space: difficult
 - Set CPU affinity
 - Collect 1000s of samples and ignore outliers

Conclusion

“Everyone knows that debugging is twice as hard as writing a program in the first place. So if you’re as clever as you can be when you write it, how will you ever debug it?”

— Brian Kernighan



<https://xkcd.com/1700/>, CC-BY-NC 2.5, Randall Munroe

Image Sources I

Slide 2

- United States Navy
- Naval Surface Warfare Center, U.S. Naval History and Heritage Command Photograph.

Slide 38

Intel 64 and IA-32 Architectures Software Developer's Manuals

Image Sources II

Slide 5

- Nenad Stojkovic, flickr: nenadstojkovic, CC-BY 2.0
- Wannapik Studio, <https://www.wannapik.com/vectors/87599>
- <https://www.pikrepo.com/fgrza/people-digging-soil-using-shovels>
- <https://www.flickr.com/photos/wwworks/3377221745>, CC-BY 2.0
- Wikipedia, <https://commons.wikimedia.org/wiki/File:Shovels.png>
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