Complex Lab "Systems Programming" — Day 3 —

Debugging and Assembly

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Some Ethymology/History

Rear Admiral Grace Murray Hopper

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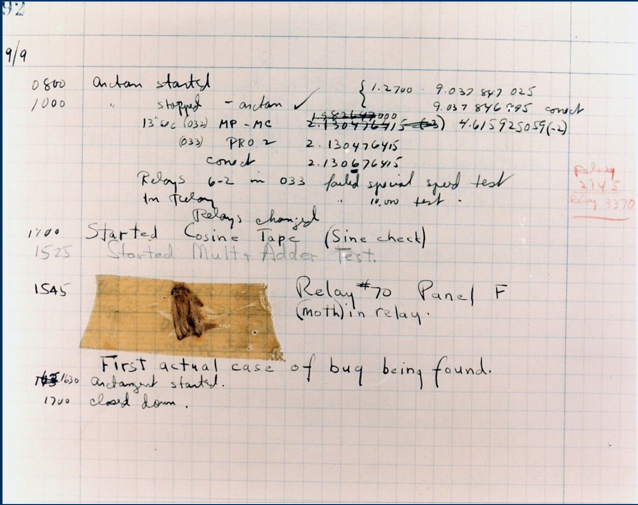

1947: “First actual case of bug being found”

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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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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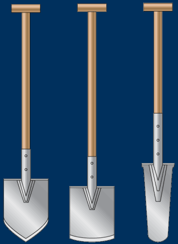
Jargon:

- Bohrbug & Heisenbug
- Mandelbug
- Schroedinbug

How to debug?

How to debug? Example: Digging



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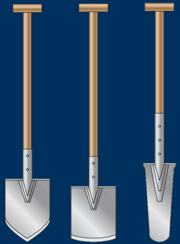

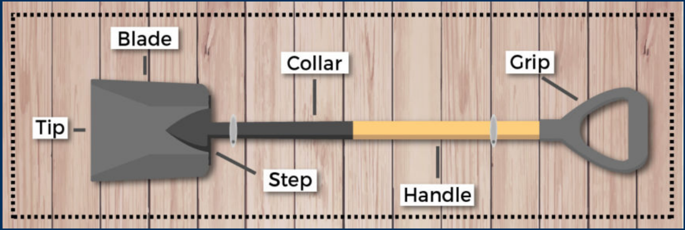

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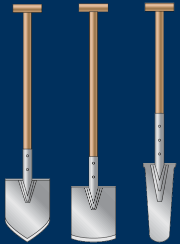

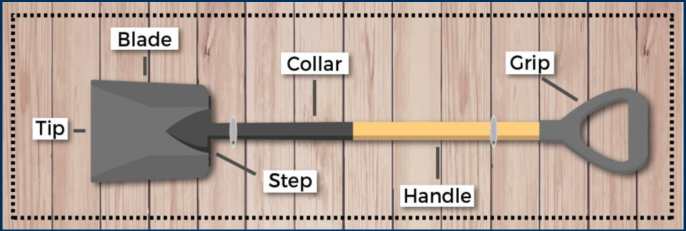

How to debug? Example: Digging

Debugging Tools

- 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

```
$ wget https://os.inf.tu-dresden.de/Studium/SysProg/SS2024/
    ↪ debugging/strace.tar.xz

$ tar -xJf strace.tar.xz

$ cd strace
```

Make it print “SUCCESS”!

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

Problem: Memory Leaks

1. Allocate memory buffer

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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`

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- Resolves symbols by searching for libraries in **`LD_LIBRARY_PATH`**

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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

```c
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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void* (*real_malloc) (size_t) = NULL;
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- Function return type
- Variable name
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- 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`

```c
#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/SS2024/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 sizes) that were not free'd;
- You will need to be notified when the program ends ⇒ **`atexit()`**

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

Sample solution: `https://os.inf.tu-dresden.de/Studium/SysProg/SS2024/debugging/mallocWrap.c`

An Anecdote

1. Bug report on strange sound on mp3 flash website

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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 mymemcpy.c`
3. `ld -G mymemcpy.o -o mymemcpy.so`
4. `LD_PRELOAD=mymemcpy.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

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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

Analyze some programs with Valgrind:

- Get `https://os.inf.tu-dresden.de/Studium/SysProg/SS2024/debugging/valgrind.tar.xz`
- Use **`build.sh`**

Static Checker

https://os.inf.tu-dresden.de/Studium/SysProg/SS2024/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, . . .

Assignment №5: 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`)

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
- **`bt`** — backtrace

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
- **`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/`

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`

Scripting

- Run **`gdb -ex`** {gdb_command}
- Write GDB commands into a text file & run **`gdb -x`** {file}
- **`define mycommand`**
- Python API

Assignment №6

`https://os.inf.tu-dresden.de/Studium/SysProg/SS2024/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
```

But I Have no Source Code?!

There was this GDB command ...

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400d5c: 5d                pop    %rbp
400d5d: c3                retq
```

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

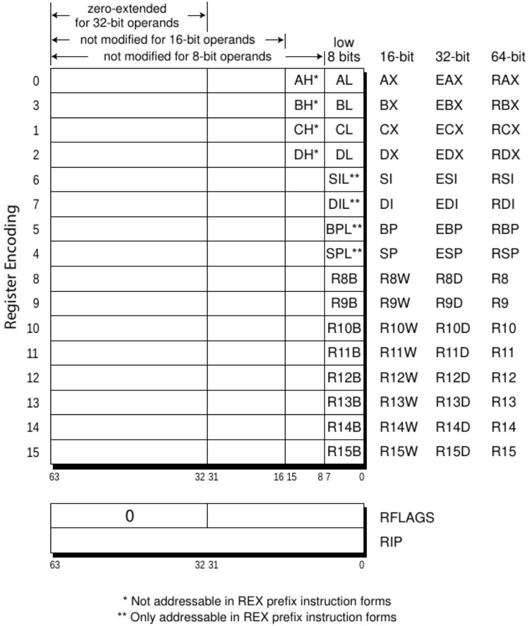

Figure 3-3. General Purpose Registers in 64-Bit Mode

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

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- (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)	[base + index * scale + disp]
	disp(base)	[base + disp]

Examples	`movl $1,%eax`
	`movl $0xff,%ebx`
	`movl (%ebx),%eax`
	`movl 3(%ebx),%eax`
		`mov eax,1`
		`mov ebx,0xffh`
		`mov eax,[ebx]`
		`mov eax,[ebx+3]`

Arithmetic Operations

Addition / Subtraction

```
add  $1,%eax
add  %eax,%ebx
sub  $1,%eax
sub  %eax,%ebx
```

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add   $1,%eax
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Where to store the result?

Comparing Two Values

```
cmp $0, %eax
cmp %eax, %ebx
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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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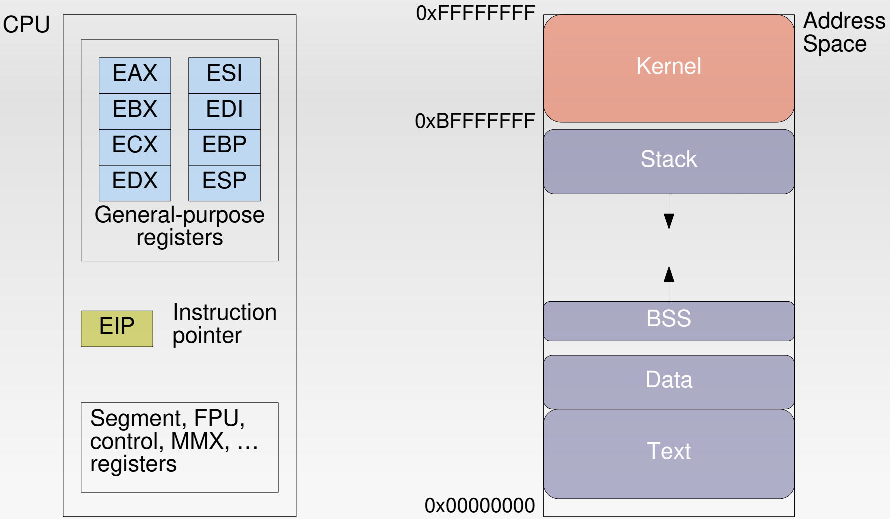
	Return	Callee Saved
Microsoft	**RAX**	**RBX**, **RBP**, **RDI**, **RSI**, **R12** – **R15**
System V	**RAX**	**RBX**, **RBP**, **R12** – **R15**

Interlude: Buffers on the Stack

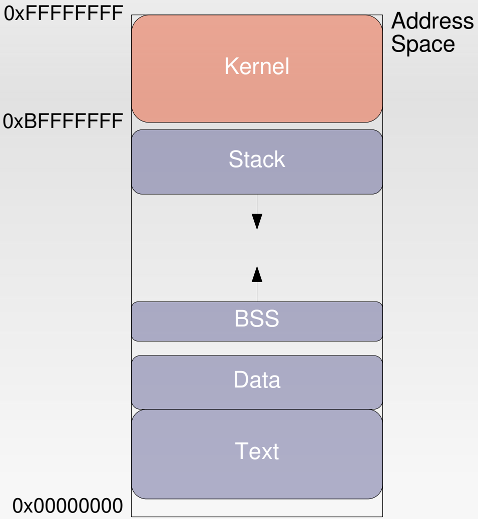
Stolen from DOS. . .

The Battlefield: x86/32



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

```c
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

```c
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

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```

Constants prefixed with **$** sign

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

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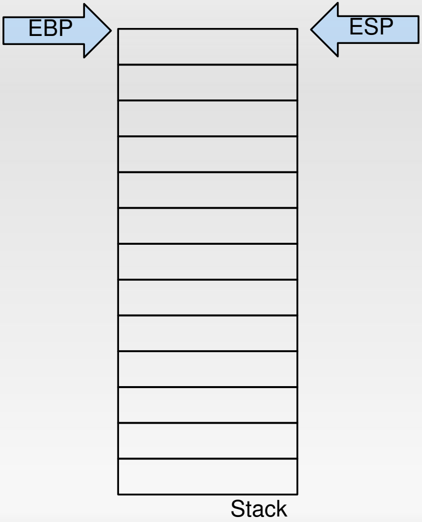
So what happens on a call?

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sum:
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    leave
    ret

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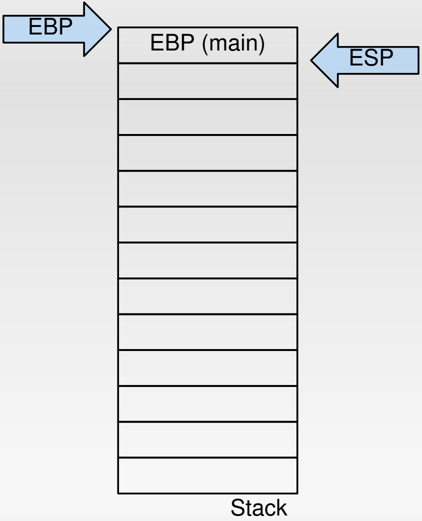


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EIP → movl %esp, %ebp

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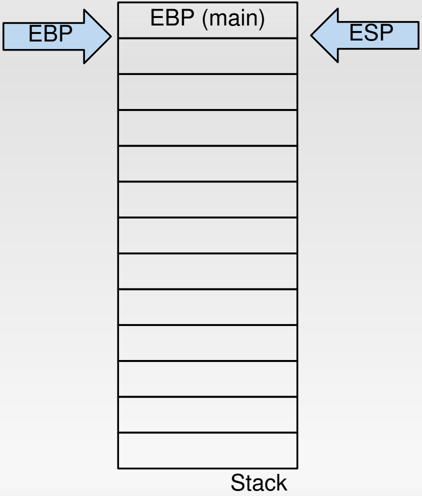


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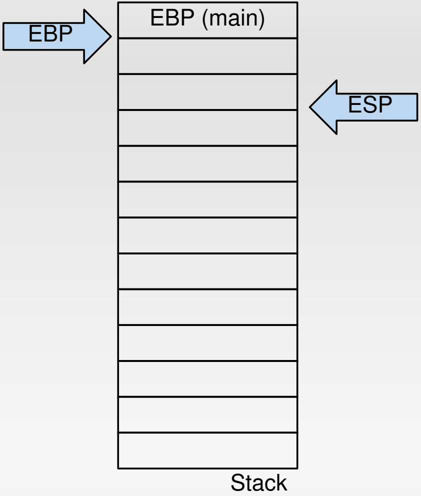


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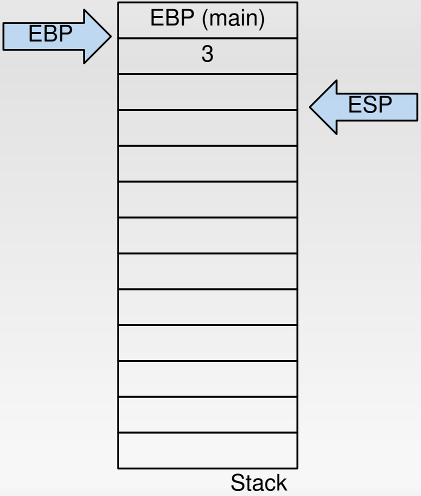


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  subl $8, %esp
  movl $3, 4(%esp)
  movl $1, (%esp)
  call sum
  ret
```
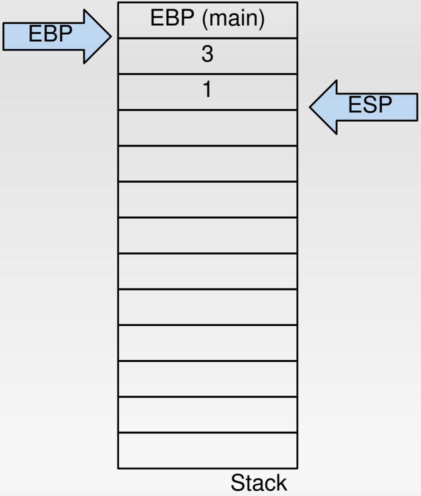

EIP → `movl $3, 4(%esp)`

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)      <- EIP
  call sum
  ret
```

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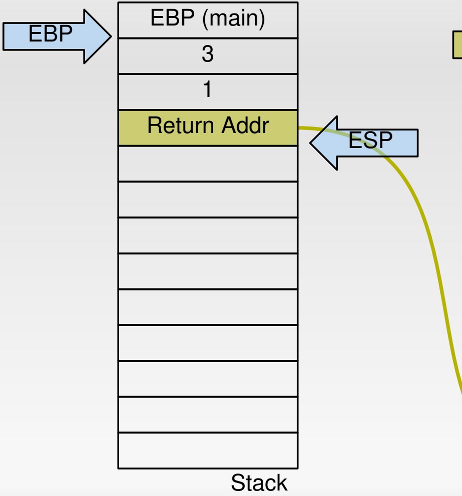

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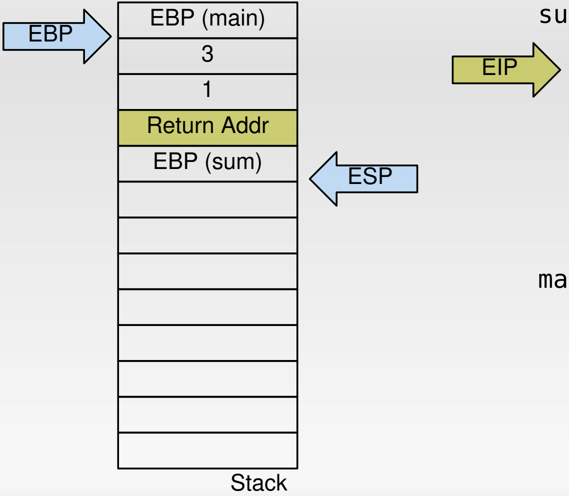


```
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  pushl %ebp
  movl %esp, %ebp
  movl 12(%ebp), %eax
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  leave
  ret

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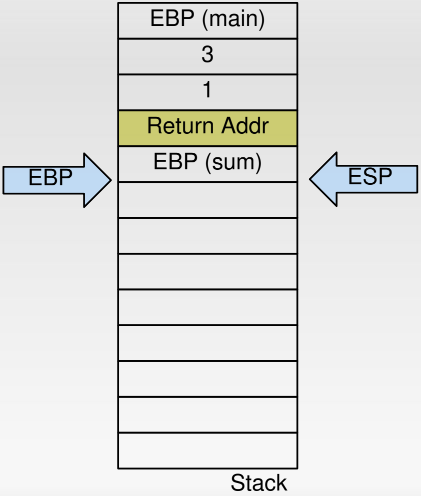


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EIP → `movl 12(%ebp), %eax`

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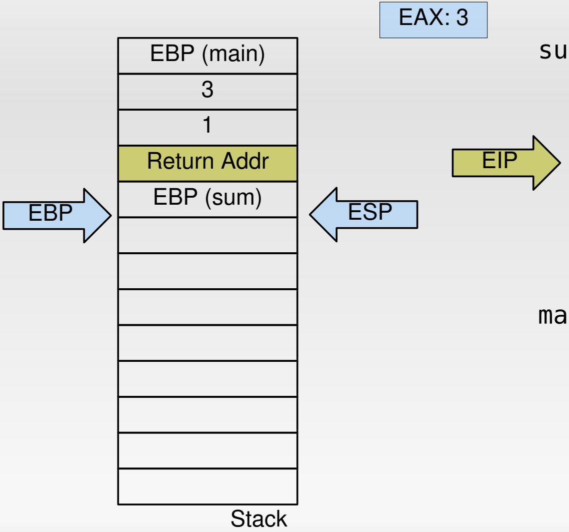


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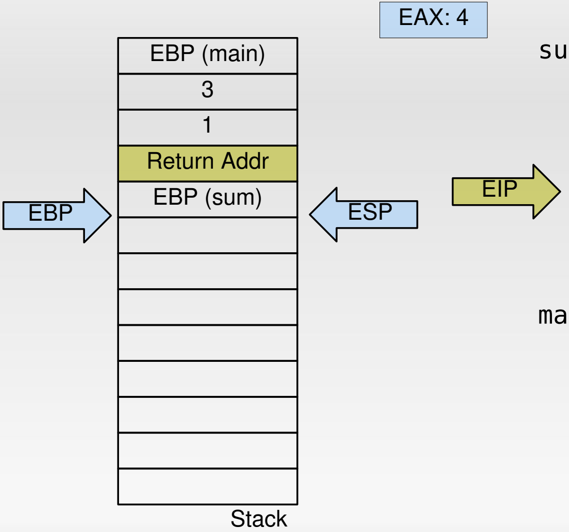


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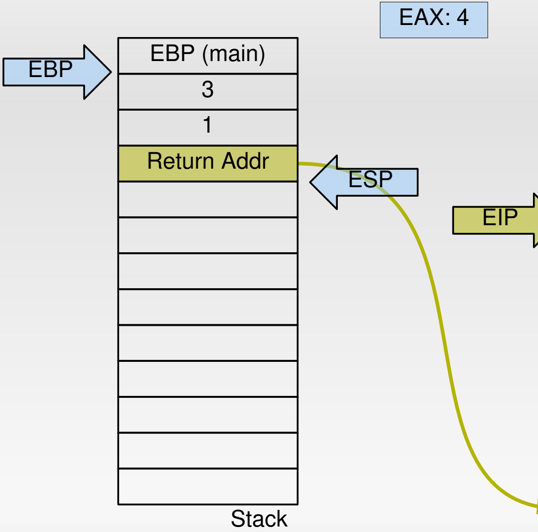


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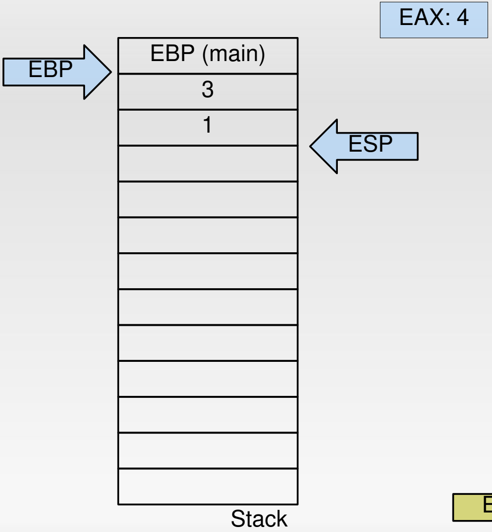


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  movl $3, 4(%esp)
  movl $1, (%esp)
  call sum
  ret
```

Now let's add a buffer

```c
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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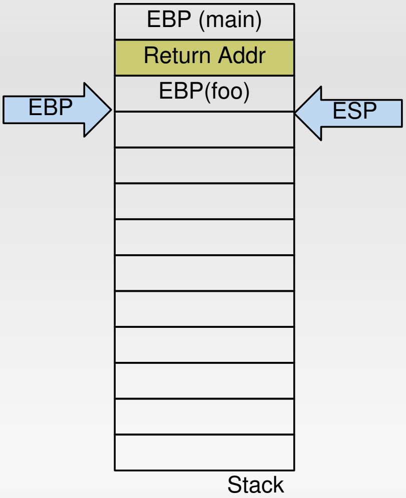


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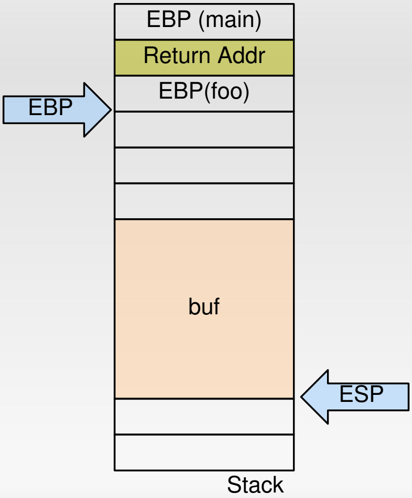


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    pushl %ebp
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    movl $0, %eax
    leave
    ret

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

EIP → movl $0, %eax

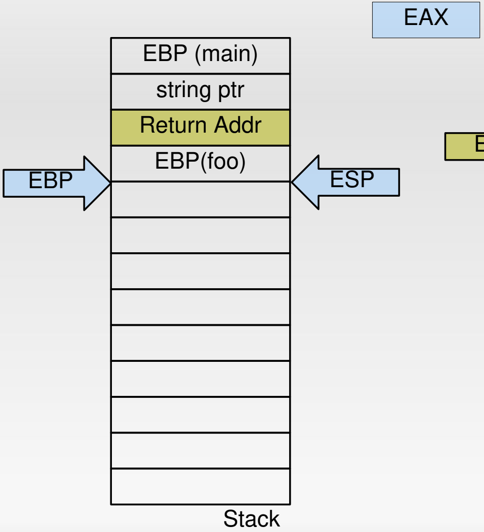
Calling a libC function

```c
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

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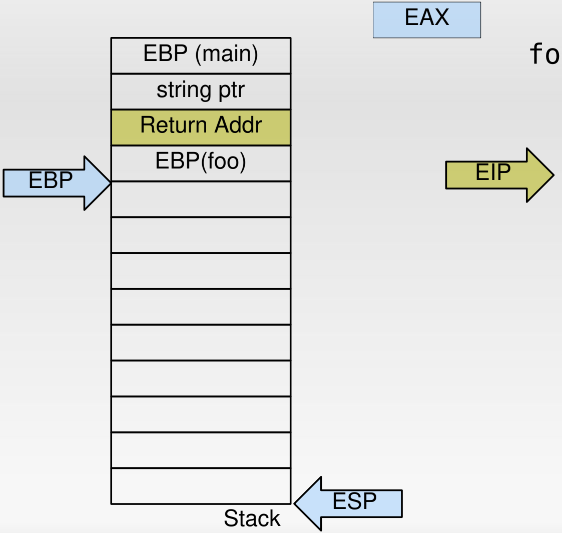


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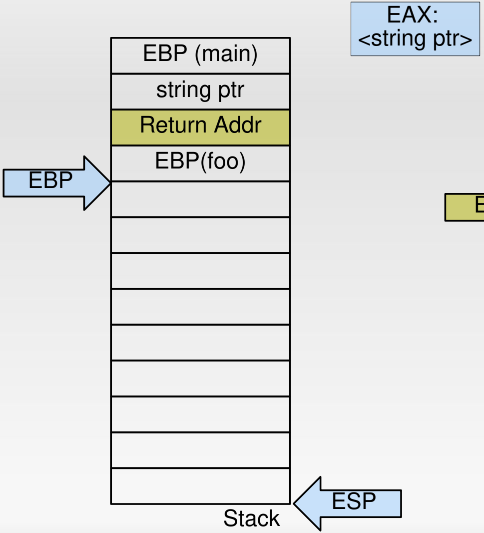


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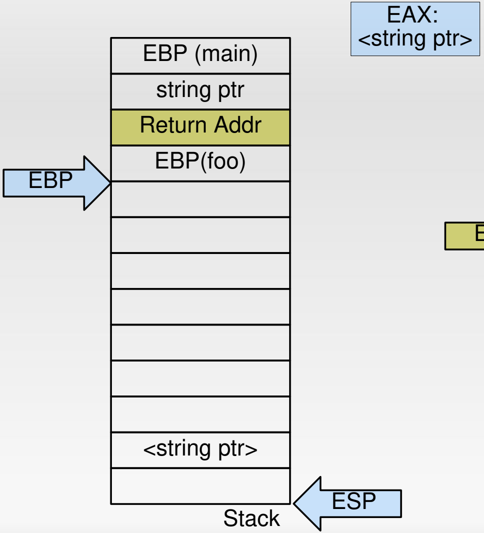


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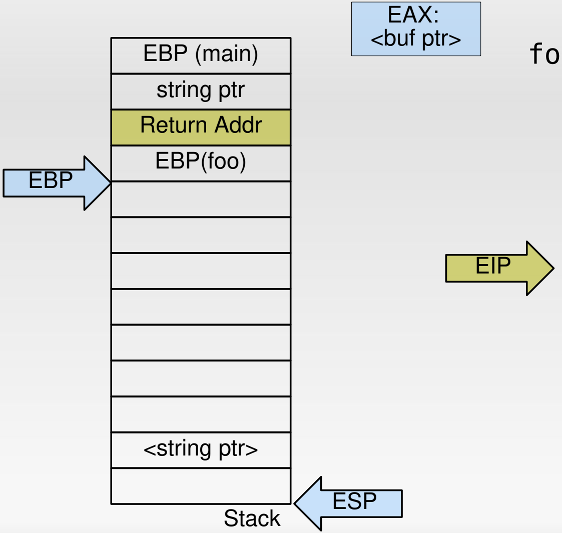


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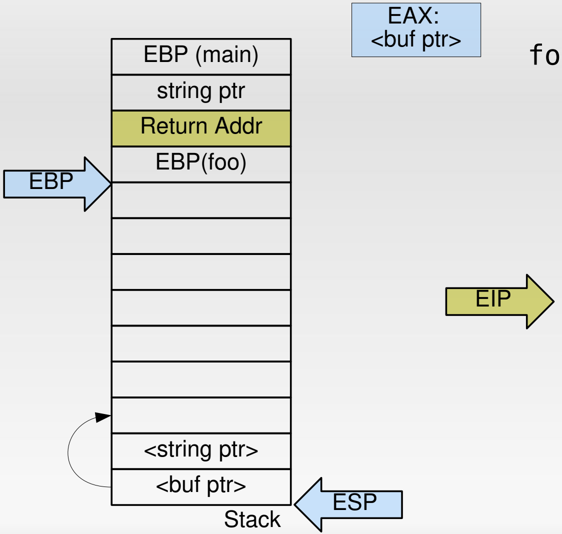


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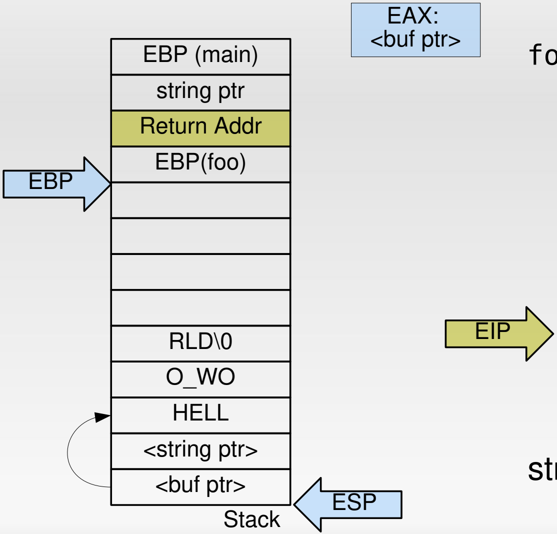


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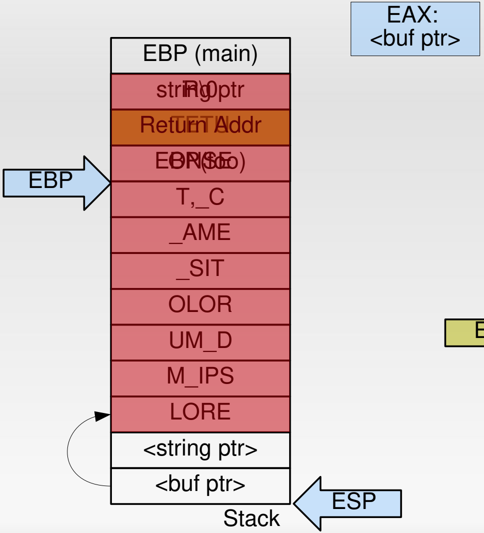
  call strcpy
  xorl %eax, %eax
  leave
  ret
```

string = "Hello world"

Our first buffer overflow™

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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      <- EIP
  xorl %eax, %eax
  leave
  ret
```
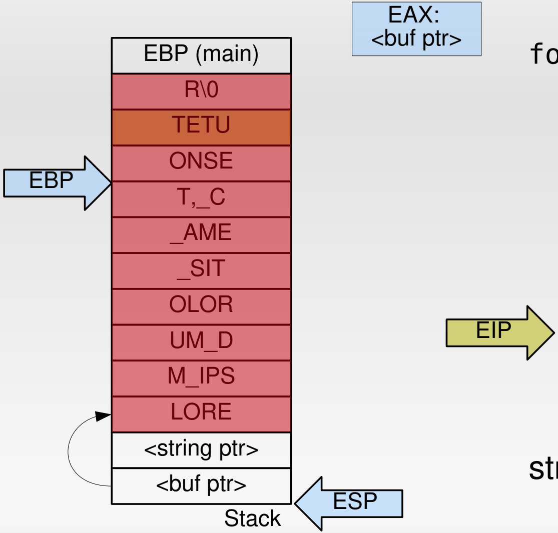

string = ”Lorem ipsum dolor sit amet, consetetur”

Our first buffer overflow™

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  movl %eax, (%esp)
  call strcpy
  xorl %eax, %eax
  leave
  ret
```

string = ”Lorem ipsum dolor
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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

Modifiers

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

```
asm volatile ("add␣%%eax,␣%%eax;" : "+a"(i) );
```

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- D … **EDI**, **RDI**
- m … memory operand

Modifiers

- = … 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 ("add␣%1,␣%0;"
                : "+r"(a)
                : "r"(b)
               );
  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/Other-Builtins.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

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?
Check CPU flags (**`lscpu`**) for **`constant_tsc`**

Reading the TSC

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

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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;
}
```

Reading the TSC

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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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               : "=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

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

Benchmarking Considerations

- RTSC 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

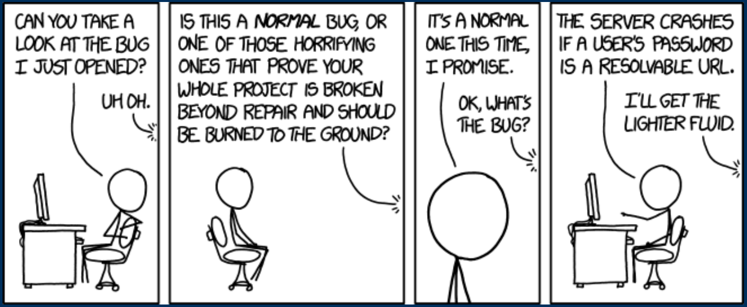

Image Sources I

Slide 2

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

Slide 36

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

Image Sources II

Slide 5

- Nenad Stojkovic, flikr: nenadstojkovic, CC-BY 2.0
- Wannapik Studio, https://www.wannapik.com/vectors/87599
- https://www.pikrepo.com/fgrza/people-digging-soil-using-shovels
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