Complex Lab "Systems Programming"
— Day 6 —
Debugging and Assembly

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Prologue: Evaluation

Please participate and help to improve the lab

https://befragung.zqa.tu-dresden.de/uz/de/sl/T7f6W2wfEFp7

Some Ethymology/History

Rear Admiral Grace Murray Hopper

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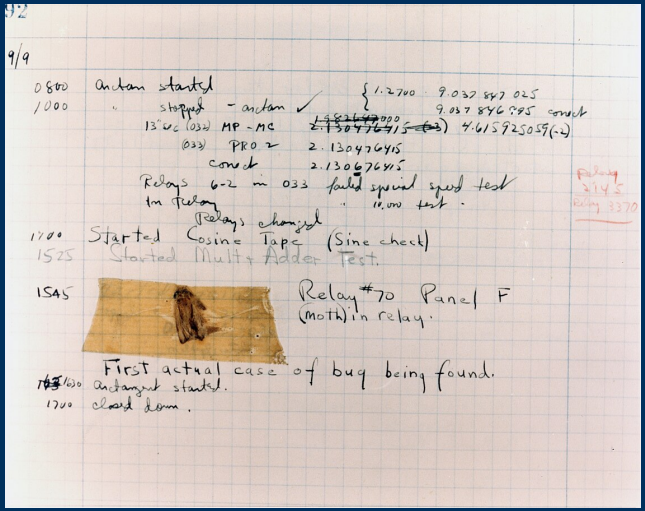

1947: "First actual case of bug being found"

Definitions

Bug ... flaw in a computer system that results in unexpected behavior

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

Variety

Debugging is not only finding living creatures in an electronic device:

- Programme crash
- Wrong result
- Slow execution

How to debug?

How to debug? Example: Digging

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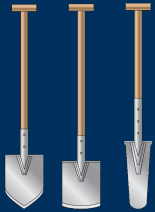

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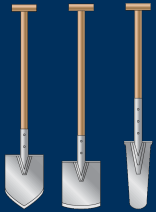

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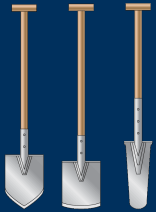

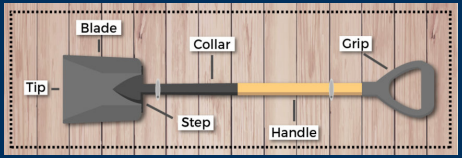

How to debug? Example: Digging

Debugging Tools

- strace
- ltrace
- gdb
- valgrind
- perf
- ptrace
- and even more...

Tracing System Calls — `strace`

Inspect system calls performed by a programme

- 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 *shared* libraries

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

Assignment №2

```
$ wget https://os.inf.tu-dresden.de/Studium/SysProg/SS2023/
    ↪ 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
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

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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 let the leaky programme call custom implementations of `malloc`/`free`
- Track `malloc`/`free` information to report memory leaks at programme 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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- Initial value

C/C++ Function Pointers

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

or using a custom type

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

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

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/SS2023/debugging/wrap.tar.xz`
- In the **`malloc`**/**`free`** wrappers in **`mallocWrap.c`**:
  - Track memory management information
  - 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 programme ends ⇒ **`atexit()`**

Hint: Be careful about using **`malloc`**/**`free`** yourself (indirectly).

Sample solution: `https://os.inf.tu-dresden.de/Studium/SysProg/SS2023/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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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

Analyze some programmes with Valgrind:

- Get `https://os.inf.tu-dresden.de/Studium/SysProg/SS2023/debugging/valgrind.tar.xz`
- Use `build.sh`

Static Checker

`https://os.inf.tu-dresden.de/Studium/SysProg/SS2023/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 programmes with `-fsanitize=address`)
3. Run the programmes

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 the `-g` (or, better, `-ggdb3`) option

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 Programme

- `l[ist] [+|-][N]` — show programme 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 programme 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/SS2023/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 inspect and modifies child state by `ptrace` requests:
  - `PEEK/POKE`
  - `SETREGS/GETREGS`
  - `CONT/SYSCALL/SINGLESTEP`

But I Have no Source Code?!

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

Also for:

- 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

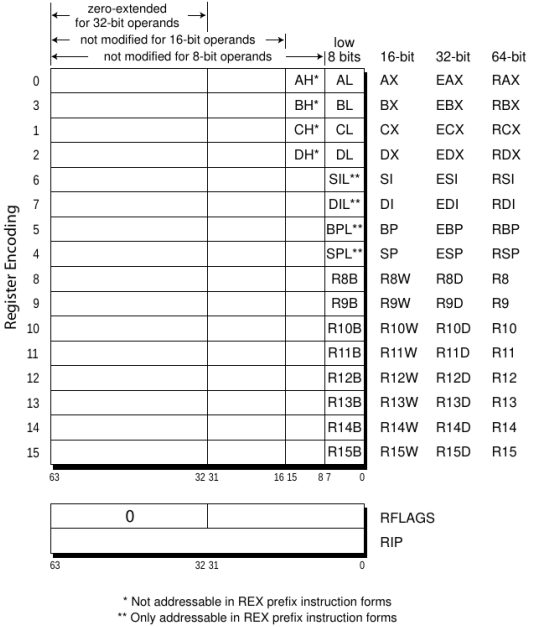

Figure 3-3. General Purpose Registers in 64-Bit Mode

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)SP — stack pointer
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- (R/E)AX — accumulator
- (R/E)BX — base register
- (R/E)CX — counter register
- (R/E)DX — 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

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

Arithmetic Operation

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 or pop register content to or 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 the called function must preserve
- Who does prepare/restoring the stack

Details: `https://en.wikipedia.org/wiki/X86_calling_conventions`

x86_32 aka i386 aka IA-32 (Linux)

- Function arguments are passed on the stack
- Integer values and memory addresses are returned in the EAX register
- Registers EAX, ECX, and EDX are caller-saved (volatile)
- Other registers are callee-saved (non-volatile)

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

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

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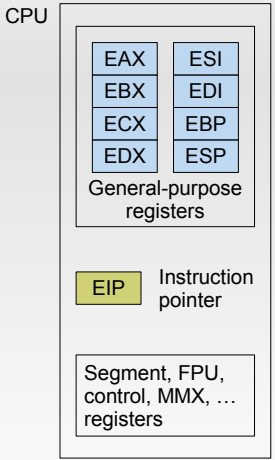
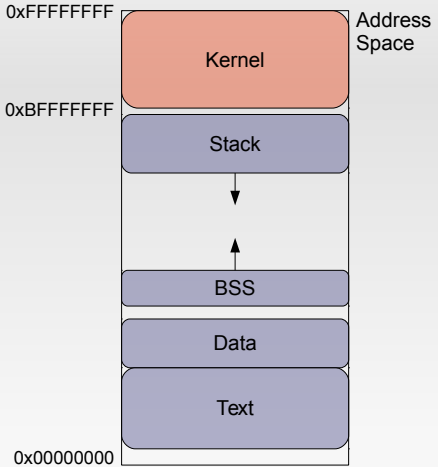
	Return	Callee Saved
Microsoft	RAX	RBX, RBP, RDI, RSI, R12 – R15
System V	RAX	RBX, RBP, R12 – R15

Interlude: Buffers on the Stack

Stolen from DOS...

The Battlefield: x86/32

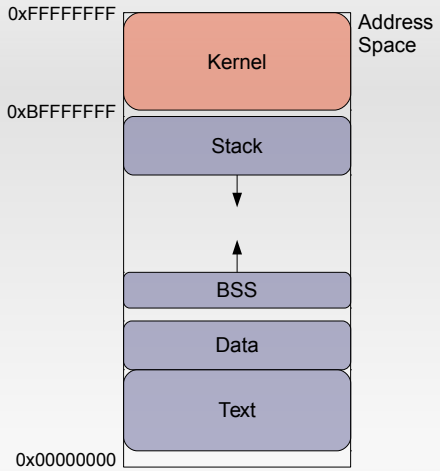




Exploitz

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
```

```
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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sum:
  pushl %ebp
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  popl %ebp
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```

Constants prefixed with $ sign

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

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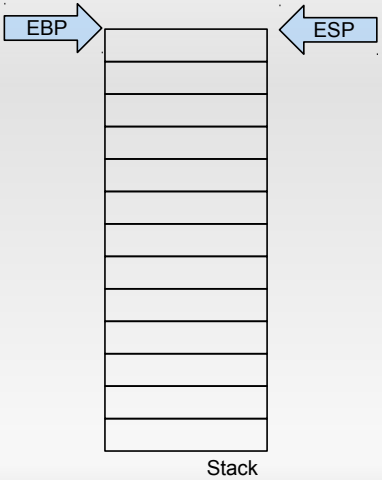


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  pushl %ebp
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EIP

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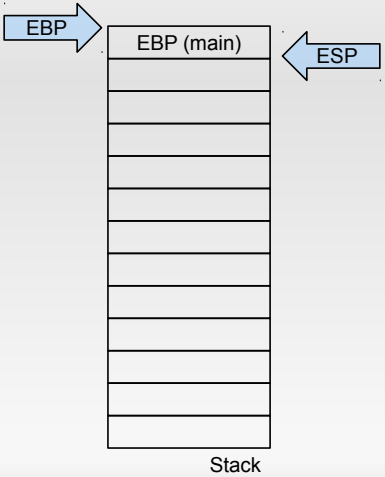


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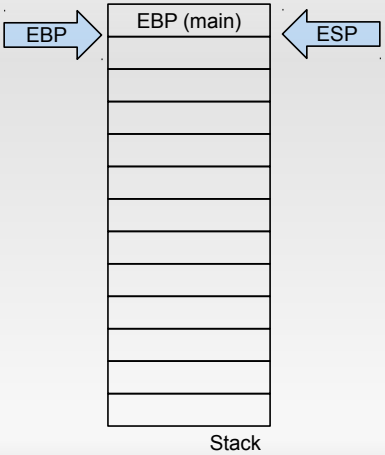


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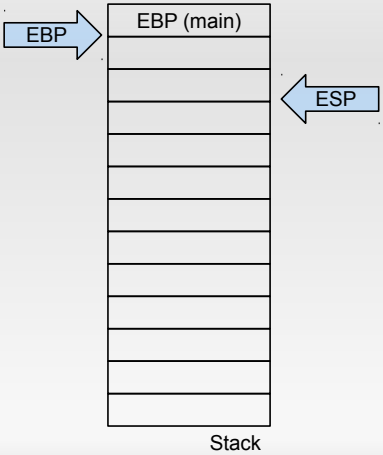


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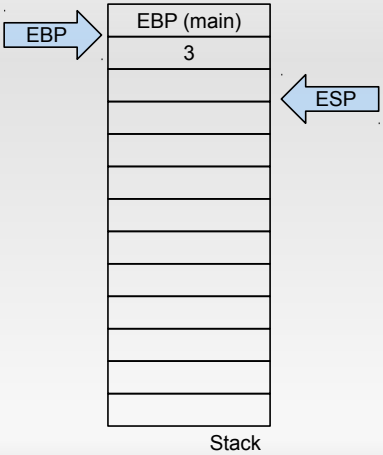


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Exploitz

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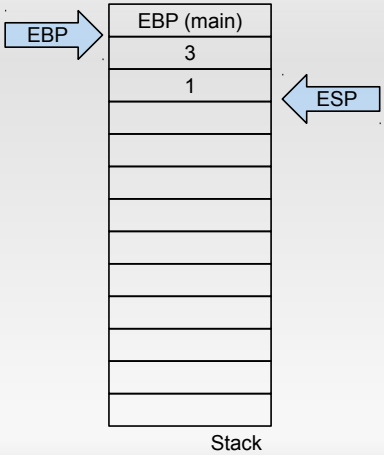


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sum:
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  leave
  ret

main:
  pushl %ebp
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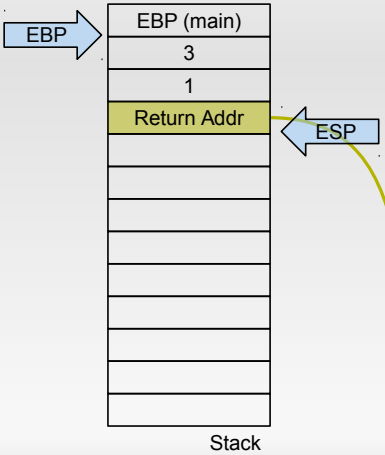
```

EIP

Exploitz

So what happens on a call?

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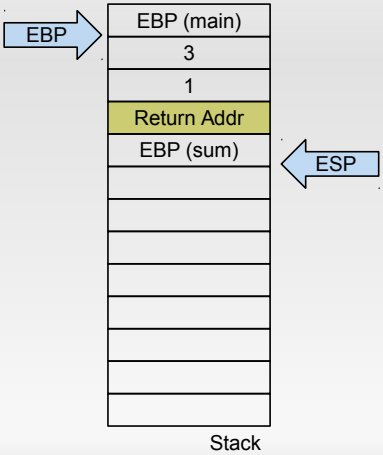

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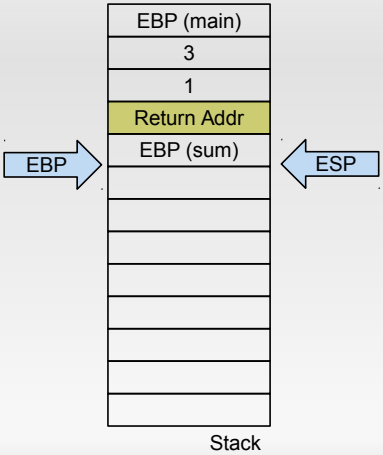


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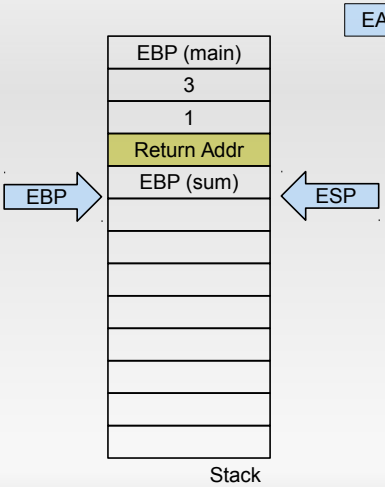


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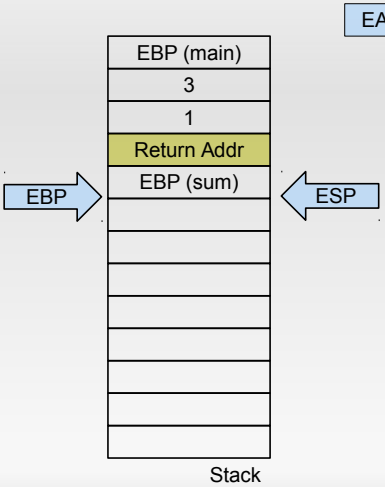


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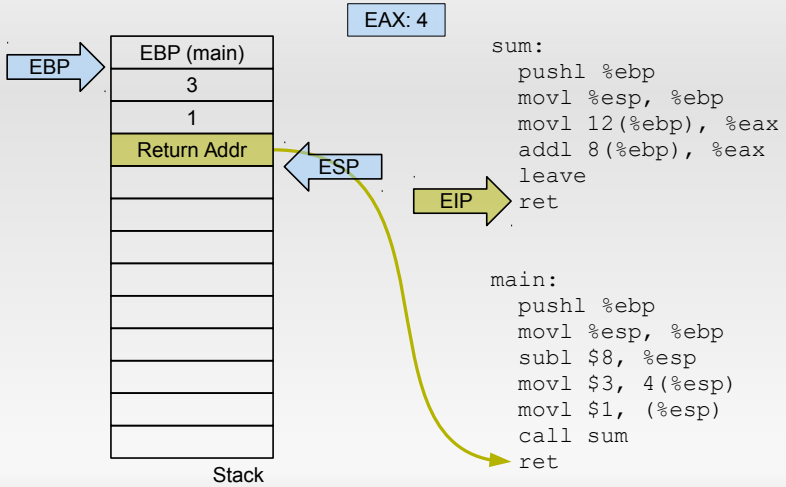

Exploitz

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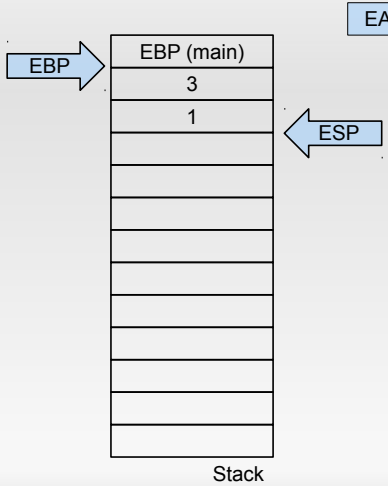


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  movl $3, 4(%esp)
  movl $1, (%esp)
  call sum
  ret
```

EIP

Exploitz

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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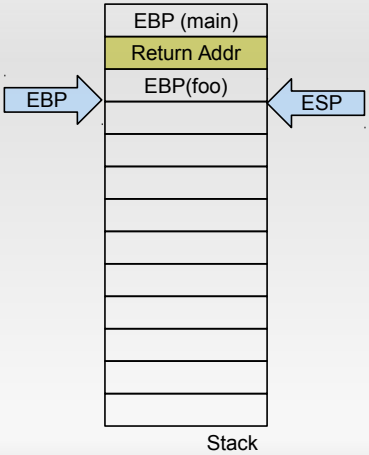


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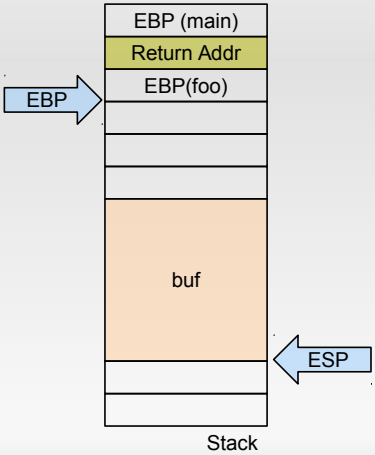


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EIP

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

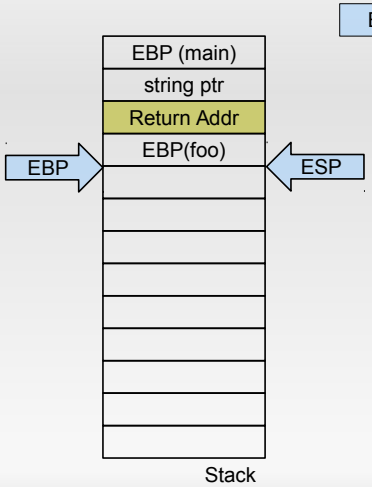
Calling a libC function

```
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

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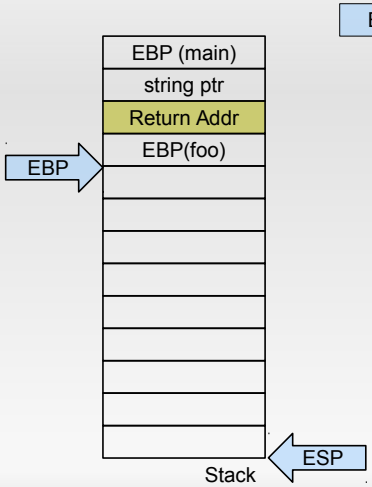


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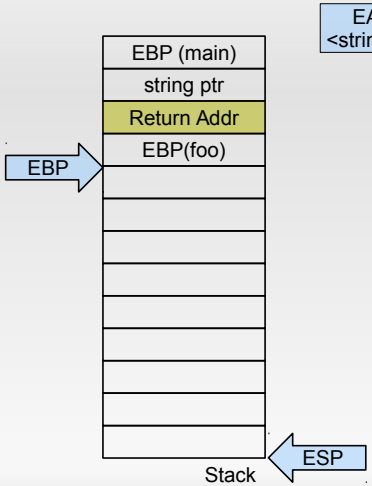


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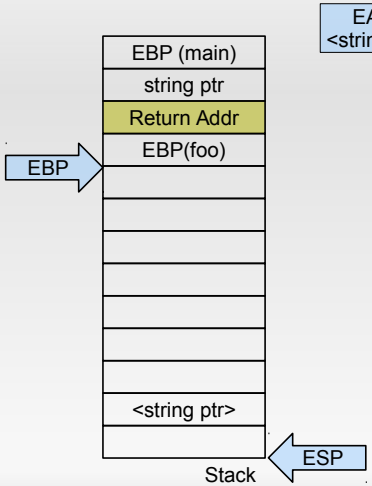


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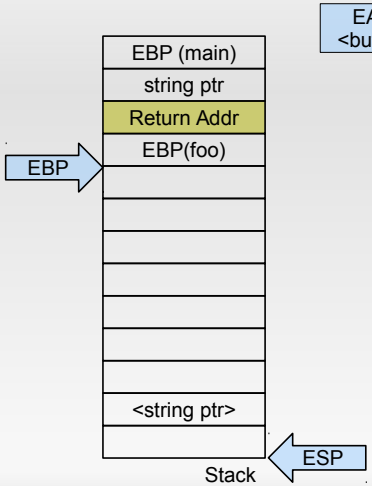
Exploitz

Calling a libC function

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EIP

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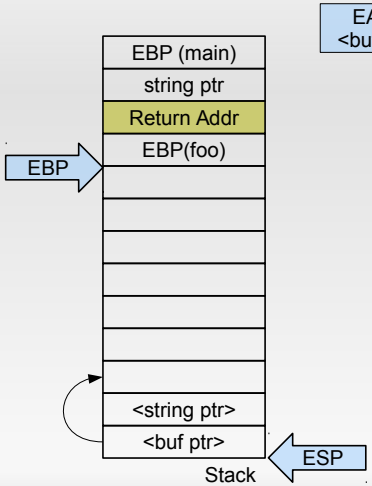


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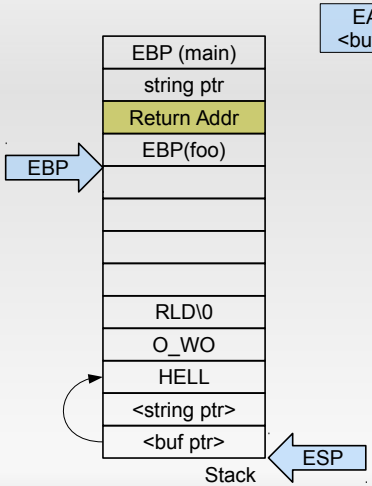
Exploitz

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
```

EIP

string = ”Hello world”

Exploitz

Inline Assembly

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

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

```
asm volatile ("add␣%0,␣%0;" : "+r"(i) );
```

	Constraints		Modifiers
r	any general purpose register	=	write only operand
a	al, ax, eax, rax	+	read / write
c	cl, cx, ecx, rcx		
D	edi, rdi		
m	memory operand		

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, anyone?

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Spot the problem, anyone?
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;

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               "mov␣%edx,␣%0\n\t"
               "mov␣%eax,␣%1\n\t"
               : "=r" (hi), "=r" (lo)
              );

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

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Clobbering is important!

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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

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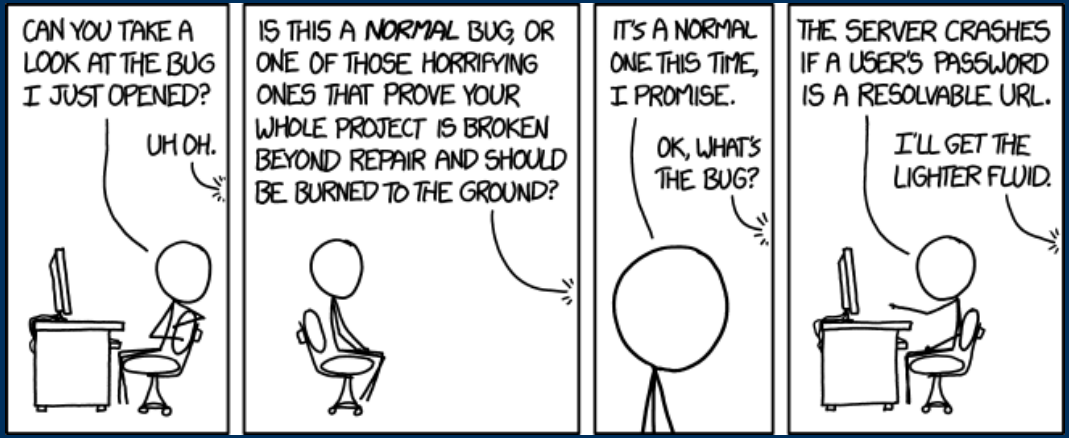
- RTSC is not for free
- Interruption by other programmes, migration
  - Own OS: measure in kernel and disable IRQs
  - Linux user space: difficult
    - Set CPU affinity
    - Collect 1000s of samples and ignore outliers



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

Image Sources

Slide 3

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

Slide 37

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

Image Sources

Slide 6

- Nenad Stojkovic, flikr: nenadstojkovic, CC-BY 2.0
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