Making things work as expected
System Programming Lab

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(based on slides of Björn Döbel)

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Introduction

Hands-on
  Tracing made easy
  Dynamic intervention
  Compiler-based helpers
  The GNU Debugger
  DIY debugging

The end
Names

Figure: Admiral Grace Hopper

Figure: 1940s: First actual case of bug being found

Definitions

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

Debugging
is a process of searching and fixing deviations from an expected behavior.
Debugging is not only finding living creatures in an electronic device:

- Program crash;
- Wrong result;
- Slow execution.
Outline

Introduction to debugging tools:

▶ strace
▶ ltrace
▶ gdb
▶ valgrind
▶ perf
▶ ptrace
▶ and even more...
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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 *shared* libraries

- Filtering: `ltrace -e`
- Timing: `ltrace -t[tt]` / `ltrace -T`
- Statistics: `ltrace -c`
Assignment №2

$ wget http://svn.inf.tu-dresden.de/repos/advsysprog/day6/01-strace/binary

Make it print “SUCCESS”!

Hints: file, strace, ltrace, objdump.
Dynamic linker

Dynamic linker resolves symbols according to LD_LIBRARY_PATH

Tell linker to load a library independent whether an application wants it or not by LD_PRELOAD

Details: man ld.so
Create a shared object containing empty implementations of:

```c
void *malloc(size_t size);
void free(void *ptr);
```
TARGET = mallocWrap.so
OBJ = wrap.o

CFLAGS = -Wall -g -fpic -D_GNU_SOURCE=1

$(TARGET) : $(OBJ) Makefile
    $(CC) -shared -o $(TARGET) $(OBJ) -ldl

.PHONY: clean

clean:
    $(RM) $(OBJ) $(TARGET)
Assignment №3, step 2

Create a C program with a memory leak:

```c
#include <stdlib.h>

int main(void)
{
    char *m = malloc(1024);
    (void)m;
    return 0;
}

Link with -rdynamic
```
Detecting Memory Leaks

- Use LD_PRELOAD to let the leaky program call your implementation of malloc/free
- Track malloc/free information to report memory leaks at program termination.
- Use the “real” malloc/free to perform the actual work.
void *dlopen(const char *filename, int flag);
char *dlerror(void);
void *dlsym(void *handle, const char *symbol);
int dlclose(void *handle);
Interfacing 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);
```
void * (*real_malloc) (size_t)
C/C++ Function pointers

```c
void * (*real_malloc) (size_t)
```

- Function return value
C/C++ Function pointers

```c
void * (*real_malloc) (size_t)
```

- Function return value
- Variable name
C/C++ Function pointers

```c
void * (*real_malloc) (size_t)
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- Function return value
- Variable name
- Function parameter types
C/C++ Function pointers

```c
void * (*real_malloc) (size_t)
```

- Function return value
- Variable name
- Function parameter types
Finding real malloc

```c
#include <dlfcn.h>

// ...

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

// ...

real_malloc = dlsym(RTLD_NEXT, "malloc")
```
Finding real malloc

#include <dlfcn.h>

// ...

void *(*real_malloc)(size_t) = NULL;
// ...

real_malloc = dlsym(RTLD_NEXT, "malloc")

And please link with -ldl!
In your malloc/free wrappers:
- Track memory management info;
- Redirect work to real malloc and free;
- Upon exit, print all pointers (and sizes) that were not free’d;
- You will need to be notified upon exit():
  - Wrap it;
  - Or use atexit();

Optional & tricky.
Check backtrace() to also store who malloc’d the leaked regions.
www.sourceware.org/bugzilla/show_bug.cgi?id=956
An anecdote

1. Bug report on Strange sound on mp3 flash website
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2. Located in libflashplayer.so

Linus' workaround: use LD_PRELOAD to replace memcpy with memmove
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Linus’ workaround

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

- Write your own memcpy
- gcc -O2 -c mymemcpy.c
- ld -G mymemcpy.o -o mymemcpy.so
- LD_PRELOAD mymemcpy.so \ /opt/google/chrome/google-chrome &
Valgrind

Binary recompilation framework (Valgrind core)

Tools to perform program analysis:
- MemCheck
- CacheGrind
- CallGrind
- Helgrind
Analyze some programs with Valgrind:

$> \text{svn co}

http://svn.inf.tu-dresden.de/repos/advsysprog/day6/03-valgrind/

$> \text{cd 03-valgrind}

$> ./build.sh
Static checker

http://svn.inf.tu-dresden.de/repos/advsysprog/day6/07-ccc/

scan-build

1. Install clang
2. Run scan-build make to analyze code
3. Run scan-view to see the report code

Link. List of static analyzers: http://spinroot.com/static/
Compiler sanitizers

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

Address sanitizer

1. Install libasan;
2. Run make asan;
   This compiles programs with -fsanitize=address;
3. Run program;

See man gcc/-fsanitize.
The GNU Debugger

Interactive debugger (gdb):
▶ breakpoints, watchpoints;
▶ single-stepping, reverse-stepping;
▶ inspect/modify registers & memory;
▶ scripting.

Best used with binaries containing debug info (compiled with -g option)
Breakpoints

- `b[reak]` `{function | line | *address}`
- `w[atch]` `{variable | *address} {condition}`
- `c[ontinue]`
Inspecting your program

- `l[ist] [±][N]` – show program code
- `disasm` – disassemble current function
- `i[info] reg[isters]` – show register content
- `p[rint]/FMT {variable | expression}` – evaluate and print expression or variable
- `x/FMT {address}` – examine memory
- `bt` – backtrace
Going forwards

- `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;
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.
Scripting

- Write GDB commands into a text file
- Run `gdb -x {file}`

**Self-learning:** GDB/Python API

**Link:** UI for GDB
https://github.com/cyrus-and/gdb-dashboard
Assignment №5

$> svn co http://svn.inf.tu-dresden.de/repos/advsysprog/day6/04-gdb/

Example addFunc seems to add $10 + 20$, but prints $20$. Why?
Assignment №6

04-gdb/eratosthenes contains 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
  \texttt{ptrace(PTRACE\_TRACEME, 0, 0, 0)};
- Parent/Debugger inspect and modifies child state by ptrace
  requests:
  - \texttt{PEEK}/\texttt{POKE}
  - \texttt{SETREGS}/\texttt{GETREGS}
  - \texttt{CONT}/\texttt{SYSCALL}/\texttt{SINGLESTEP}
Tiny strace

Write a program that:

1. Gets another program on the command line;
2. Runs this program;
3. Uses `ptrace()` to inspect all system calls made by the traced program;
4. Printing system call numbers and return values is enough;
5. **optional***. You can print function names as well.
Syscall in a nutshell

```c
ssize_t write(int fd, const void *buf, size_t count);
```
Syscall in a nutshell

```c
ssize_t write(int fd, const void *buf, size_t count);
```

⇓

```c
ret = write(1, "Hello_World", 12);
```
Syscall in a nutshell

```c
ssize_t write(int fd, const void *buf, size_t count);

ret = write(1, "Hello World", 12);

movq $1, %rax ; use the write syscall
movq $1, %rdi ; write to stdout
movq $msg, %rsi ; use string "Hello World"
movq $12, %rdx ; write 12 characters
syscall ; make syscall
```
How to implement your own tracer

1. Fork a tracer
How to implement you own tracer

1. Fork a tracer
2. Child actions:
   2.1 Prepare child to be traced; `ptrace(PTRACE_TRACEME);`
   2.2 Wait until tracing starts; `raise(SIGSTOP);`
   2.3 Start a tracee. `execv(tracee, NULL);`
3. Parent actions:
   3.1 Configure distinguishable tracing; `ptrace(PTRACE_SETOPTIONS, child, 0, PTRACE_O_TRACESYSGOOD);`
   3.2 Trace until tracee exits (see next slide)
How to implement your own tracer

1. Fork a tracer
2. Child actions:
   2.1 Prepare child to be traced;
       \texttt{ptrace(PTRACE\_TRACEME);}
How to implement your own tracer

1. Fork a tracer
2. Child actions:
   2.1 Prepare child to be traced;
       `ptrace(PTRACE_TRACE_ME);`
   2.2 Wait until tracing starts;
       `raise(SIGSTOP);`
How to implement your own tracer

1. Fork a tracer

2. Child actions:
   2.1 Prepare child to be traced;
       \texttt{ptrace(PTRACE\_TRACEME);}
   2.2 Wait until tracing starts;
       \texttt{raise(SIGSTOP);}
   2.3 Start a tracee.
       \texttt{execv(tracee, NULL);}

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Setting up tracer

Tracer loop:

1. Wait for a syscall start
2. Fetch syscall number (in RAX or EAX)
   
   \[
   \text{syscall} = \text{ptrace}(\text{PTRACE_PEEKUSER}, \text{child}, \text{sizeof(long) \times ORIG_RAX});
   \]

3. Wait for a syscall end
4. Fetch return code
   
   \[
   \text{retval} = \text{ptrace}(\text{PTRACE_PEEKUSER}, \text{child}, \text{sizeof(long) \times RAX});
   \]
Catching a syscall

1. Continue tracee until next syscall:
   
   ```c
   ptrace(PTRACE_SYSCALL, child, 0, 0);
   ```

2. Wait until tracee is stopped:
   
   ```c
   waitpid(child, &status, 0);
   ```

3. Check if stopped because of syscall:
   
   ```c
   WIFSTOPPED(status) && WSTOPSIG(status) & 0x80
   ```

4. If not, check if tracee exited:
   
   ```c
   WIFEXITED(status)
   ```

5. If not go to step 1.
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   \text{waitpid}(\text{child}, &\text{status}, 0);
   \]

3. Check if stopped because of syscall:
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   \text{WIFSTOPPED}(\text{status}) \&\&
   \text{WSTOPSIG}(\text{status}) \& 0x80
   \]

4. If not, check if tracee exited:
   \[
   \text{WIFEXITED}(\text{status})
   \]

5. If not go to step 1.
Deciphering syscalls*

1. You need to decode syscall number to an actual function;
2. Find out which parameters it uses;
3. Fetch parameters;
4. Special treatment to strings;

More info:
https://github.com/nelhage/ministrace/tree/master
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Assignment №8 (optional)

$> \text{svn co http://svn.inf.tu-dresden.de/repos/advsysprog/day6/08-formula/}$

Debugging for fun & profit.
The program calculates:

\[ f = 333.75b^6 + a^2(11a^2b^2 - b^6 - 121b^4 - 2) + 5.5b^8 + \frac{a}{2b} \]

where, \( a = 77617, \ b = 33096 \)
Assignment №8 (optional)

```bash
$> svn co http://svn.inf.tu-dresden.de/repos/advsysprog/day6/08-formula/
```

Debugging for fun & profit.
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\]

where, \(a = 77617\), \(b = 33096\)
Prints: \(f = -1.1805916207174113e21\)
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where, \( a = 77617, \ b = 33096 \)
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The right answer: \( f = -0.8273960599468213681\ldots \)
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The right answer: \( f = -0.8273960599468213681 \ldots \)

Why? How to fix?
Conclusion

There are only two hard things in Computer Science: cache invalidation, naming things, and off-by-one errors.

— Phil Karlton