Debugging

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Whats all this about?

Writing programs is hard

- We should have strategies and *tools* for when things go wrong

Lets point you towards some!

An example program

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

int main(int argc, char *argv[]) {
  char message[128];
  size_t message_len = 256;
  char timestamp[128];
  time_t t;
  struct tm *tmp;
  FILE *file = fopen(argv[1], "a+");

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);

  t = time(NULL);
  tmp = localtime(&t);
  strftime(timestamp, 256, "%C", tmp);

  fprintf(file, "%s:␣%s\n", timestamp, message);
  return 0;
}
```

Lets compile!

```
make journal
```

```
cc    journal.c -o journal
```

And when we run...

```
./journal <<<"Hello World!"
```

```
Segmentation fault (core dumped)
```

Okay, lets try and debug

```
$ gdb ./journal
Reading symbols from ./journal...
(No debugging symbols found in ./journal)
(gdb) run <<<"hello"
Starting program: /home/joseph/Repos/Talks/COMS10012-Software-Tools/Debugging/journal <<<"hello"
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".

Program received signal SIGSEGV, Segmentation fault.
__vfprintf_internal (s=0x0, format=0x402026 "%s: %s\n", ap=ap@entry=0x7fffffffde50, mode_flags=mode_fl
722     ORIENT;
(gdb) bt
#0 __vfprintf_internal (s=0x0, format=0x402026 "%s: %s\n",
   ap=ap@entry=0x7fffffffde50, mode_flags=mode_flags@entry=0)
   at vfprintf-internal.c:722
#1 0x00007ffff7e2360a in __fprintf (stream=<optimized out>,
   format=<optimized out>) at fprintf.c:32
#2 0x000000000040125f in main ()
```

Lets make it a *little* easier

- -g adds debugging informations.
- -Og optimizes for debuggability

```
$ cc -Og -g journal.c -o journal
$ gdb ./journal
(gdb) run <<<"hello"
Starting program: /home/joseph/Repos/Talks/COMS10012-Software-Tools/Debugging/journal <<<"hello"
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".

Program received signal SIGSEGV, Segmentation fault.
__memcpy_avx_unaligned_erms () at ../sysdeps/x86_64/multiarch/memmove-vec-unaligned-erms.S:333
Downloading 0.01 MB source file /usr/src/debug/glibc-2.36.9000-19.fc38.x86_64/string/../sysdeps/x86_64
333         movl  %ecx, -4(%rdi, %rdx)
(gdb) bt
#0 __memcpy_avx_unaligned_erms ()
   at ../sysdeps/x86_64/multiarch/memmove-vec-unaligned-erms.S:333
#1 0x00007ffff7e496ac in __GI___getdelim (
   lineptr=lineptr@entry=0x7fffffffdff0, n=n@entry=0x7fffffffdfe8,
   delimiter=delimiter@entry=10, fp=0x7ffff7fa5aa0 <_IO_2_1_stdin_>)
   at iogetdelim.c:111
#2 0x00007ffff7e237d1 in __getline (lineptr=lineptr@entry=0x7fffffffdff0,
   n=n@entry=0x7fffffffdfe8, stream=<optimized out>) at getline.c:28
#3 0x00000000004011d6 in main (argc=<optimized out>, argv=<optimized out>)
   at journal.c:14
```

Looks like it all went wrong on line 14 of journal.c...

```
(gdb) b journal.c:14
Breakpoint 2 at 0x4011ba: file journal.c, line 14.
(gdb) run <<<"hello"
The program being debugged has been started already.
Start it from the beginning? (y or n) y
Starting program: /home/joseph/Repos/Talks/COMS10012-Software-Tools/Debugging/journal <<<"hello"
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".

Breakpoint 2, main (argc=<optimized out>, argv=<optimized out>) at journal.c:14
14  getline(&message, &message_len, stdin);
(gdb) inspect message
$3 = "@\000\000\000\000\000\000\000\000\200", '\000' <repeats 14 times>, "\006\000\000\000\216\000\000
(gdb) inspect message_len
$4 = 256
(gdb) d
Delete all breakpoints? (y or n) y
(gdb)
```

If in doubt... read the manual

In `man 3 getline`:

> *getline() reads an entire line from stream, storing the address of the buffer containing the text into *lineptr. The buffer is null-terminated and includes the newline character, if one was found.*
> *If *lineptr is set to NULL before the call, then getline() will allocate a buffer for storing the line. This buffer should be freed by the user program even if getline() failed.*
> *Alternatively, before calling getline(), *lineptr can contain a pointer to a malloc(3)-allocated buffer *n bytes in size. If the buffer is not large enough to hold the line, getline() resizes it with realloc(3), updating *lineptr and *n as necessary.*

Well we're passing a *statically* allocated buffer... lets fix that.

A new *example program

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

int main(int argc, char *argv[]) {
  char *message = NULL;
  size_t message_len;
  char timestamp[128];
  time_t t;
  struct tm *tmp;
  FILE *file = fopen(argv[1], "a+");

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);

  t = time(NULL);
  tmp = localtime(&t);
  strftime(timestamp, 256, "%C", tmp);

  fprintf(file, "%s:␣%s\n", timestamp, message);
  return 0;
}
```

```
cc -g -Og journal2.c -o journal2
```

And now when we run...

```
$ ./journal2 <<<"hello"
Segmentation fault (core dumped)

$ gdb ./journal2
(gdb) run <<<"hello"
Starting program: /home/joseph/Repos/Talks/COMS10012-Software-Tools/Debugging/journal2 <<<"hello"

Program received signal SIGSEGV, Segmentation fault.
0x00007ffff7e2de82 in __vfprintf_internal () from /lib64/libc.so.6
Missing separate debuginfos, use: dnf debuginfo-install glibc-2.36.9000-19.fc38.x86_64
(gdb) bt
#0 0x00007ffff7e2de82 in __vfprintf_internal () from /lib64/libc.so.6
#1 0x00007ffff7e2360a in fprintf () from /lib64/libc.so.6
#2 0x0000000000401225 in main (argc=<optimized out>, argv=<optimized out>) at journal2.c:20
(gdb)
```

...well, we got further...

We could continue with gdb

GDB is an extremely powerful debugging tool

- Its also *really* hard to use
- See *Computer Systems B* next year, or *Systems and Software Security* at Masters level
- If you're on a Mac or BSD box check out `lldb`
- Or for a proper tutorial the documentation it refers you to *every time you open it*.

It is *well worth your time to learn…*

- But *this course* is about *Software Tools* and I want to show you *more* of them

`<<<input`	runs your program with input
`b`	set breakpoints
`c`	continue after hitting a breakpoint
`bt`	get a backtrace
`info`	get information about registers or variables or anything else
`x`	examine a variable/pointer
`help`	get help

Strace

The `strace` tool lets you trace what systemcalls a program uses

- On OpenBSD see `ktrace` and `kdump`
- On MacOS/FreeBSD see `dtruss` and `dtrace`

Lets run it!

```
make journal2
strace ./journal2 <<<'Hello' 2>&1
```

```
execve("./journal2", ["./journal2"], 0x7fffe3c9beb0 /* 23 vars */) = 0
brk(NULL)                               = 0x56769b94b000
access("/etc/ld.so.preload", R_OK) = -1 ENOENT (No such file or directory)
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=311295, ...}) = 0
mmap(NULL, 311295, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7c742720d000
close(3)                                = 0
openat(AT_FDCWD, "/usr/lib/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0\220^\2\0\0\0\0\0"..., 832) = 832
pread64(3, "\6\0\0\0\4\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0"..., 784, 64) = 784
fstat(3, {st_mode=S_IFREG|0755, st_size=1948952, ...}) = 0
mmap(NULL, 8192, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7c742720b000
pread64(3, "\6\0\0\0\4\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0@\0\0\0\0\0\0\0"..., 784, 64) = 784
mmap(NULL, 1973104, PROT_READ, MAP_PRIVATE|MAP_DENYWRITE, 3, 0) = 0x7c7427029000
mmap(0x7c742704d000, 1421312, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x24000) =
mmap(0x7c74271a8000, 348160, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x17f000) = 0x7c74271a
mmap(0x7c74271fd000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1d3000) =
mmap(0x7c7427203000, 31600, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7c74
close(3)                                = 0
mmap(NULL, 12288, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0x7c7427026000
arch_prctl(ARCH_SET_FS, 0x7c7427026740) = 0
set_tid_address(0x7c7427026a10) = 32033
set_robust_list(0x7c7427026a20, 24) = 0
rseq(0x7c7427027060, 0x20, 0, 0x53053053) = 0
mprotect(0x7c74271fd000, 16384, PROT_READ) = 0
mprotect(0x567699dd9000, 4096, PROT_READ) = 0
```

Too much output!

`strace` lets you use regexp to filter what syscalls you look at

- ...or you could just use `grep`...

```
make journal2
strace -e '/open.*' ./journal2 <<<hello 2>&1
```

```
cc    journal2.c -o journal2
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/usr/lib/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, NULL, O_RDWR|O_CREAT|O_APPEND, 0666) = -1 EFAULT (Bad address)
openat(AT_FDCWD, "/etc/localtime", O_RDONLY|O_CLOEXEC) = 3
--- SIGSEGV {si_signo=SIGSEGV, si_code=SEGV_MAPERR, si_addr=0xc0} ---
+++ killed by SIGSEGV (core dumped) +++
```

Oh yeah... we forgot an arg

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

int main(int argc, char *argv[]) {
  char *message = NULL;
  size_t message_len;
  char timestamp[128];
  time_t t;
  struct tm *tmp;
  FILE *file = fopen(argv[1], "a+");

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);

  t = time(NULL);
  tmp = localtime(&t);
  strftime(timestamp, 256, "%C", tmp);

  fprintf(file, "%s:␣%s\n", timestamp, message);
  return 0;
}
```

Lets fix that...

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

int main(int argc, char *argv[]) {
  char *message = NULL;
  size_t message_len;
  char timestamp[128];
  time_t t;
  struct tm *tmp;

  if (argc < 2) { printf("Usage␣%s␣path/to/log\n", argv[0]); exit(1); };
  FILE *file = fopen(argv[1], "a+");

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);

  t = time(NULL);
  tmp = localtime(&t);
  strftime(timestamp, 256, "%C", tmp);

  fprintf(file, "%s:␣%s\n", timestamp, message);
  return 0;
}
```

And if you cant spot the difference

```
diff -u journal{2,3}.c
```

```
--- journal2.c 2024-02-07 11:14:29.060025998 +0000
+++ journal3.c 2024-02-07 12:16:09.220079001 +0000
@@ -8,6 +8,8 @@
  char timestamp[128];
  time_t t;
  struct tm *tmp;
+
+ if (argc < 2) { printf("Usage␣%s␣path/to/log\n", argv[0]); exit(1); };
  FILE *file = fopen(argv[1], "a+");

  printf("Type␣your␣log:␣");
```

Now when we run!

```
$ ./journal3 documents/log.txt <<<hello
Segmentation fault (core dumped)
```

Lets try `ltrace` this time (no equivalent on other platforms)...

- It traces *library* calls

ltrace and a bit more strace

```
make journal3
ltrace ./journal3 documents/log.txt <<<hello 2>&1
```

```
fopen("documents/log.txt", "a+")     = 0
printf("Type␣your␣log:␣")            = 15
getline(0x7ffd196b0018, 0x7ffd196b0020, 0x76a22f8538e0, 0x7ffd196b0020) = 6
time(0)                              = 1707308599
localtime(0x7ffd196b0028)            = 0x76a22f85a320
strftime("20", 256, "%C", 0x76a22f85a320) = 2
fprintf(0, "%s:␣%s\n", "20", "hello\n" <no return ...>
--- SIGSEGV (Segmentation fault) ---
+++ killed by SIGSEGV +++
```

```
strace -e openat ./journal3 documents/log.txt <<<hello 2>&1
```

```
openat(AT_FDCWD, "/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "/usr/lib/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
openat(AT_FDCWD, "documents/log.txt", O_RDWR|O_CREAT|O_APPEND, 0666) = -1 ENOENT (No such file or dire
openat(AT_FDCWD, "/etc/localtime", O_RDONLY|O_CLOEXEC) = 3
--- SIGSEGV {si_signo=SIGSEGV, si_code=SEGV_MAPERR, si_addr=0xc0} ---
+++ killed by SIGSEGV (core dumped) ++
```

Lets fix that...

```c
#include <stdio.h>
#include <stdlib.h>
#include <time.h>
#include <errno.h>

int main(int argc, char *argv[]) {
  char *message = NULL;
  size_t message_len;
  char timestamp[128];
  time_t t;
  struct tm *tmp;

  if (argc < 2) { printf("Usage␣%s␣path/to/log\n", argv[0]); exit(1); };
  FILE *file = fopen(argv[1], "a+");
  if (file == NULL) {
    perror("Failed␣to␣open␣log");
    exit(2);
  }

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);

  t = time(NULL);
  tmp = localtime(&t);
  strftime(timestamp, 256, "%C", tmp);

  fprintf(file, "%s:␣%s\n", timestamp, message);
  return 0;
}
```

What has changed again?

```
diff -u journal{3,4}.c
```

```
--- journal3.c 2024-02-07 12:31:13.196788801 +0000
+++ journal4.c 2024-02-07 12:31:13.293455473 +0000
@@ -1,6 +1,7 @@
 #include <stdio.h>
 #include <stdlib.h>
 #include <time.h>
+#include <errno.h>

 int main(int argc, char *argv[]) {
  char *message = NULL;
@@ -11,6 +12,10 @@

  if (argc < 2) { printf("Usage␣%s␣path/to/log\n", argv[0]); exit(1); };
  FILE *file = fopen(argv[1], "a+");
+ if (file == NULL) {
+   perror("Failed␣to␣open␣log");
+   exit(2);
+ }

  printf("Type␣your␣log:␣");
  getline(&message, &message_len, stdin);
```

Now when we run...

```
$ ./journal4 <<<hello
Usage ./journal4 path/to/log

$ ./journal4 documents/log.txt <<<hello
Failed to open log: No such file or directory

$ ./journal4 /etc/passwd <<<hello
Failed to open log: Permission denied

$ ./journal4 /dev/stdout
Type your log: hello
20: hello
```

20?!

From `man 3 strftime`:

```
%c    The preferred date and time representation for the current locale. (The specific format
      used in the current locale can be obtained by calling nl_langinfo(3) with D_T_FMT as
      an argument for the %c conversion specification, and with ERA_D_T_FMT for the %Ec
      conversion specification.) (In the POSIX locale this is equivalent to %a %b %e %H:%M:%S
      %Y.)

%C    The century number (year/100) as a 2-digit integer. (SU) (The %EC conversion
      specification corresponds to the name of the era.) (Calculated from tm_year.)
```

Debugging tools can’t catch poorly written code!

But other tools can catch things...

Thinking back to when we fixed up `getline`... it said it would allocate the memory for the line

- ...did we ever free it?

```
valgrind ./journal4 /dev/stdout <<<hello
```

```
==36111== Memcheck, a memory error detector
==36111== Copyright (C) 2002-2022, and GNU GPL'd, by Julian Seward et al.
==36111== Using Valgrind-3.20.0 and LibVEX; rerun with -h for copyright info
==36111== Command: ./journal4 /dev/stdout
==36111==
20: hello

Type your log: ==36111==
==36111== HEAP SUMMARY:
==36111==  in use at exit: 592 bytes in 2 blocks
==36111== total heap usage: 13 allocs, 11 frees, 13,684 bytes allocated
==36111==
==36111== LEAK SUMMARY:
==36111== definitely lost: 120 bytes in 1 blocks
==36111== indirectly lost: 0 bytes in 0 blocks
==36111==  possibly lost: 0 bytes in 0 blocks
==36111== still reachable: 472 bytes in 1 blocks
==36111==     suppressed: 0 bytes in 0 blocks
==36111== Rerun with --leak-check=full to see details of leaked memory
==36111==
==36111== For lists of detected and suppressed errors, rerun with: -s
==36111== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 0 from 0)
```

Wrap up

In this lecture we've cone over the ***very basics*** of several debugging tools

- `strace`, `ltrace`, `valgrind` and `gdb` will help deal with most of the bugs you encounter

But so will good defensive programming strategies

- *Always* check the return code of functions
- *Always* check assumptions
- *Always* fix your compiler warnings

…actually get more warnings!

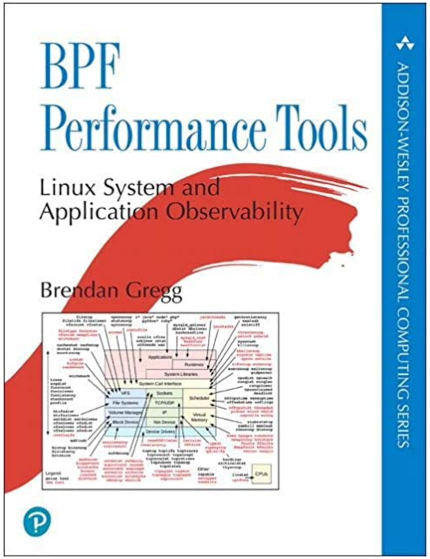
Compiling with the `-Wall -Wextra --std=c11 -pedantic` will make the compiler really picky about your C code…
But there are *other tools* called *linters* that can get even more picky

C/C++	Clang Static Analyser, Rats
Java	FindBugs
Haskell	hlint
Python	pylint, mypy
Shellscript	shellcheck

Other tools for C/C++ can add extra runtime checks

ASan	Address Sanitizer; checks for pointer shenangians
UBSan	Undefined Behaviour Sanitizer; checks for C gotchas

BPF tools



BPF Performance Tools

Linux System and Application Observability

Brendan Gregg

ADDISON-WESLEY PROFESSIONAL COMPUTING SERIES

Linux has a (reasonably) new instrumentation framework called *eBPF*

- It lets you get *loads* of detail about what programs are doing
- Highly Linux specific
- I need to learn it : - (