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)
```

Segfaults are annoying

Programs randomly crashing is extremely irritating

- ...but a fact of life
- ... we are programmers
- ... it is our job to fix them

Lets discuss some tools for spotting errors

AddressSanitizer	Adds extra debugging checks
GDB	the GNU Debugger
Strace	Systemcall tracer
Ltrace	Library tracer
Valgrind	Memory error detector

AddressSanitizer

Tool from the LLVM project (`clang`) to give more information about crashes **at runtime**.
Other sanitizers exist:

UndefinedBehaviorSanitizer spots bad compilier practice

ThreadSanitizer spots bad multithreading practice

LeakSanitizer spots bad memory management

To use, compile with `clang` and add the `-fsanitize=address` flag

```
clang journal.c -fsanitize=address -o journal
```

Downsides

- Your program will use more memory and be slower
- Your program may be more easy to hack ;-)

Lets go!

Looks like its a NULL pointer dereference?

```
 $ ./journal <<<"hello"
AddressSanitizer:DEADLYSIGNAL
=================================================================
==302530==ERROR: AddressSanitizer: SEGV on unknown address 0x0000000000c0 (pc 0x7f99bd58e470 bp 0x7ffcea5c2120
==302530==The signal is caused by a READ memory access.
==302530==Hint: address points to the zero page.
    #0 0x7f99bd58e470 (/lib64/libc.so.6+0x66470) (BuildId: 37e4ac6a7fb96950b0e6bf72d73d94f3296c77eb)
    #1 0x453325 (/home/jh18636/journal+0x453325) (BuildId: becf911c680ef05574954cad1b054efee58f4fab)
    #2 0x5115f0 (/home/jh18636/journal+0x5115f0) (BuildId: becf911c680ef05574954cad1b054efee58f4fab)
    #3 0x7f99bd5627e4 (/lib64/libc.so.6+0x3a7e4) (BuildId: 37e4ac6a7fb96950b0e6bf72d73d94f3296c77eb)
    #4 0x42975d (/home/jh18636/journal+0x42975d) (BuildId: becf911c680ef05574954cad1b054efee58f4fab)

AddressSanitizer can not provide additional info.
SUMMARY: AddressSanitizer: SEGV (/lib64/libc.so.6+0x66470) (BuildId: 37e4ac6a7fb96950b0e6bf72d73d94f3296c77eb)
==302530==ABORTING
```

GDB: The GNU Debugger

Horrifically powerful

- Can step through a program at an assembly level
- Can watch registers and the stack change line by line
- Can program scripts and to react when certain things happen
- Can debug systems remotely
- Ported to every sort of computer you could wish for

Horrifically unintuitive

- It has a built in GUI but you'll wish it didn't (`layout regs`)
- Lots of unintuitive single letter commands
- Cryptic output
- But its the standard debugger!
  - Others (and GUIs) exist, but still worth having a basic knowledge of the CLI tool

Okay, lets try and debug

- `run` runs your program (with arguments if passed)
- `bt` gives you a backtrace by reading out the stack

```
$ 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_flags@entry
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/multiarc
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`...

Breakpoints let us stop when we reach a line of the program or an address.

- Create them with `b` address
- Delete them with `d`
- Run on to the next one with `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\000\f\00
(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 to you 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
`disas`	see the assembly code you're running
`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) = 0x7c74270
mmap(0x7c74271a8000, 348160, PROT_READ, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x17f000) = 0x7c74271a8000
mmap(0x7c74271fd000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_DENYWRITE, 3, 0x1d3000) = 0x7c74271
mmap(0x7c7427203000, 31600, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_FIXED|MAP_ANONYMOUS, -1, 0) = 0x7c7427203000
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(0x567699dd8000, 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) +++
```

Or if you prefer OpenBSD

```
ktrace ./journal2 <<<hello
kdump | grep -A 2 -B 2 open
```

```
--
 63085 journal2 CALL close(3)
 63085 journal2 RET close 0
 63085 journal2 CALL open(0x34d8c02f033,0x10000<O_RDONLY|O_CLOEXEC>)
 63085 journal2 NAMI "/usr/lib/libc.so.100.3"
 63085 journal2 RET open 3
 63085 journal2 CALL fstat(3,0x70bf220f2088)
 63085 journal2 STRU struct stat { dev=1077, ino=3784328, mode=-r--r--r-- , nlink=1, uid=0<"root">, gid=7<"bin">
--
 63085 journal2 CALL mprotect(0x34debfa5000,0x1000,0x1<PROT_READ>)
 63085 journal2 RET mprotect 0
 63085 journal2 CALL open(0,0x20a<O_RDWR|O_APPEND|O_CREAT>,0666<S_IRUSR|S_IWUSR|S_IRGRP|S_IWGRP|S_IROTH|S_IWOTH>
 63085 journal2 RET open -1 errno 14 Bad address
 63085 journal2 CALL kbind(0x70bf220f2268,24,0x5e8161d98e625637)
 63085 journal2 RET kbind 0
--
```

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 directory)
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...

```
#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…

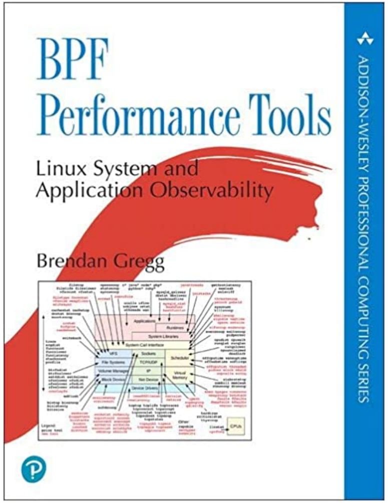
But there are other tools called linters that can get even more picky

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 : - (

This weeks lab

Is ~~evil~~ fun!

- I'm gonna give you 5 crackmes
- They'll ask you for the password
    - You have to work out what it is

Practice using the debugging tools to work out what the program is expecting.

Hmmm...

We're early...

- It's almost like I planned for this...

Well we could show you another use for debugging tools

- Sometimes being able to see what a program is doing is useful for **other** things ;-)