# Debugging

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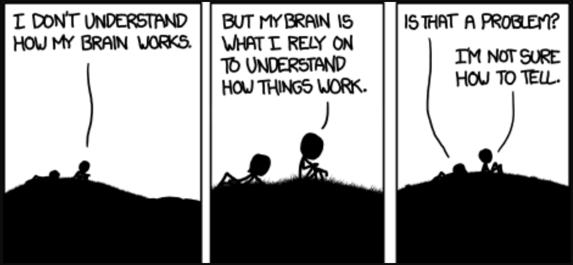
# What if your program or test isn't running correctly...

- Nonsense. All programs execute "correctly".
- We just told it to do the wrong thing.
- Debugging is the *art* of reconciling your mental model of what the code is doing with what you actually told it to do.




https://imgs.xkcd.com/comics/debugger.png

**Debugger: program to help detect errors in other programs.**

# Some common issues

| | |
|---|---|
| Arithmetic | Corner cases (`sqrt(-0.0)`), infinities |
| Memory access | Index out of range, uninitialized pointers |
| Logic | Infinite loop, corner cases |
| Misuse | Wrong input, ignored error, no initialization |
| Syntax | Wrong operators/arguments |
| Resource starvation | Memory leak, quota overflow |
| Parallel | Race conditions, deadlock |

# Debugging workflows

- As soon as you are convinced there is a real problem, create the simplest situation in which it repeatedly occurs.
- Take a scientific approach: model, hypothesis, experiment, conclusion.
- Try a smaller problem size, turning off different physical effects with options, etc, until you have a simple, fast, repeatable example.
- Try to narrow it down to a particular module/function/class.
- Integrated calculation: Write out intermediate results, inspect them.

# Ways to debug

To figure out what is going wrong, and where in the code, we can

1. Put strategic print/cerr statements in the code.
2. Use a debugger.

We don't like the first option.

# What's wrong with using print/cerr statements?

## Uses this strategy

- Constant cycle:
  - strategically add print statements
  - compile
  - run
  - analyze output
  - repeat
- Removing the extra code after the bug is fixed
- Repeat for each bug

## Problems with this approach

A bug is always unexpected, so you don't know where to put those strategic print statements.

As a result, this approach:

- is time consuming
- is error prone
- is confusing as print output might not appear when you think
- changes memory layout, output format, timing, etc.

**There's a better way!**

# Debuggers

are programs that can show what happens in a program at runtime.

## Features

1. Crash inspection
2. Function call stack
3. Step through code
4. Automated interruption
5. Variable checking and setting

## Should you use a graphical/IDE debugger?

- Local work station: graphical/IDE is convenient
- Remotely (SciNet): can be slow or hard to set up.
- In any case, graphical and text-based debuggers use the same concepts.

# Debuggers

## Preparing the executable for debugging

- Add required compilation flags, `-g`

  (both in compiling and linking!)
- Recommended: switch off optimization `-O0`
  (Recommended for production: `-O3 -march=native`)

## Command-line based symbolic debugger: gdb

- Free, GNU license, symbolic debugger.
- Available on many systems.
- Been around for a while, but still developed and up-to-date
- Command-line based, does not show code listing by default, unless you use the `-tui` option.

# Example

Consider this code:

```
// crash_example.cpp
#include <iostream>
void handle_command_line(int argc, char** argv) {
  if (argv[1][0] == '-' && argv[1][1] == 'h') {
    // print help
    std::cout << "Usage:   crash_example [-h]\n";
  } else {
    // ....
  }
}
int main(int argc, char** argv) {
  handle_command_line(argc,argv);
  // ...
}
```

which we compile on Linux with:

```
$ g++ -O0 -g crash_example.cpp -o crash_example
```

When run, it shows the following:

```
$ ./crash_example -h
Usage:   crash_example [-h]
```

```
$ ./crash_example
Segmentation fault (core dumped)
```

The first invocation works, but the second fails.

Why?

# Crash inspection

```
$ ./crash_example
Segmentation fault (core dumped)
```

We want to solve this segmentation fault.

- A segmentation fault means that your application is trying to access data at an invalid memory location.
- When the operating system detects the invalid memory location, it kills the application in that case and produces a core dump.
- The core contains the process's memory state, call stack, and failure mode at the moment of the crash, like a "black box".

# Missing the core file?

## Core size limit

If the error message did not say `core dumped`, you need to set the limit

```
# ulimit -c unlimited
```

## Still no core file?

Core dump files used to always appear in the current directory with a name starting with `core` followed by the process ID.

Modern Linux distribution, handle core dumps in a variety of ways, but the original way is most convenient for debugging.

For Ubuntu and RedHat, the old default behaviour can be restored with the following command:

```
$ sudo sysctl -w kernel.core_pattern=core.%p
```

# Inspecting the crash with gdb

To inspect the crash, use the gdb command followed by the name of the application and the name of the core file, e.g.

```
$ gdb ./crash_example core.203739
```

```
GNU gdb (GDB) 13.2
<A header with general gdb information>
Reading symbols from ./crash_example...
[New LWP 203739]
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
Core was generated by `./crash_example`.
Program terminated with signal SIGSEGV, Segmentation fault.
#0  0x0000559697c9f1a7 in handle_command_line (argc=1, argv=0x7ffda30f8c98)
 at crash_example.cpp:4
4 if (argv[1][0] == '-' && argv[1][1] == 'h') {
(gdb)
```

This shows the error occured at line 4!

# Tip: start gdb with -tui -quiet options

```
┌─crash_example.cpp──────────────────────────────────────────────────────┐
│    4      if (argv[1][0] == '-' && argv[1][1] == 'h') {                  │
│    5        // print help                                               │
│    6        std::cout << "Usage:   crash_example [-h]\n";               │
│    7      } else {                                                      │
│    8        // ....                                                     │
│    9      }                                                             │
│   10    }                                                               │
│   11    int main(int argc, char** argv) {                               │
│   12      handle_command_line(argc,argv);                               │
│   13      // ...                                                        │
│   14    }                                                               │
│   15                                                                    │
│   16                                                                    │
│   17                                                                    │
│   18                                                                    │
│   19                                                                    │
│   20                                                                    │
│   21                                                                    │
└──────────────────────────────────────────────────────────────────────────┘
exec No process In:                                          L??   PC: ??
Reading symbols from crash_example...
[New LWP 352372]
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib64/libthread_db.so.1".
Core was generated by `./crash_example'.
Program terminated with signal SIGSEGV, Segmentation fault.
#0  0x0000000000401140 in handle_command_line (argc=1, argv=0x7fff843c03b8)
    at crash_example.cpp:4
(gdb) 
```

# Function Call Stack:

One of the commands availble at the gdb prompt is `backtrace`:

```
(gdb) backtrace
#0  0x0000559697c9f1a7 in handle_command_line (argc=1, argv=0x7ffda30f8c98)
    at crash_example.cpp:4
#1  0x0000559697c9f204 in main (argc=1, argv=0x7ffda30f8c98)
    at crash_example.cpp:12
```

This shows the line of the crash again, but also how the code got there, i.e., from line 12 in the `main` function in the file `crash_example.cpp`.

Note:

- Hexadecimal numbers at the beginning of the lines refer to positions in the executable.
- The backtrace also shows the values of the arguments, with pointers printed as hexadecimal memory addresses.

# Checking Variables:

The printed values of the arguments given by the backtrace do not help us.

But it would be helpful to known the values that occur in line 4 where the crash happens.

The gdb command for this is `print`, which makes print statements in the code unncessary for debugging.

Let's try it here:

```
(gdb) print argv[1][0]
Cannot access memory at address 0x0
```

This should be a surprise; where does an address 0x0 come from?

Let's try this:

```
(gdb) print argv[1]
0x0
```

This is a solid clue on what the bug is: we are dereferencing a null pointer.

The bug is that the code did not check if a first argument is actually present.

# Stepping Through Code

The debugger can also execute the code line-by-line, but the code has already crashed.

So we exit the debugger with the q command, and start it again without the core file:

```
$ gdb -tui -quiet ./crash_example
GNU gdb (GDB) 13.2
Reading symbols from ./crash_example...
(gdb)
```

It shows the code, but nothing has started running yet.

We can now type `run`, which would run the code, but it would just lead to the crash again.

Instead, we want to pause at the start of `main`, which the `start` command does:

```
(gdb) start
Temporary breakpoint 1 at 0x11f3: file crash_example.cpp, line 12.
Starting program: /home/rzon/Dropbox/SC-lectureNotes/crash_example
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
Temporary breakpoint 1, main (argc=1, argv=0x7fffffffc3c8)
 at crash_example.cpp:12
12 handle_command_line(argc,argv);
```

# Stepping Through Code (cont.)

The executation is now paused at line 12, which has not yet been executed.

When execution is paused, we can print expressions, but we can now also step forward in the code.

For this, there are two commands:

- `next` executes this whole line, which in this case would again lead to the crash.
- `step` will step into any function calls on the line, i.e., it will pause at the first line of the first function call in the line.

Let's try `step` here:

```
(gdb) step
handle_command_line (argc=1, argv=0x7fffffffc3c8) at crash_example.cpp:4
4 if (argv[1][0] == '-' && argv[1][1] == 'h') {
```

which is indeed the first line of the function `handle_command_line` that was called from line 12.

Whenever the code is paused, we can print variables and expressions, but this time, before the crash has occured.

# Breakpoints

If you have a code where a crash or bug occurs only after the process has run for a while, having to step through the code from the start would be very inefficient.

Instead, you can setup an automated interruption called a break point at either a line or code or a function, and run the code until just before that point is executed.

The `break` command sets this up. E.g.

```
(gdb) break 4
Breakpoint 2 at 0x55555555519c: file crash_example.cpp, line 4.
```

```
(gdb) break handle_command_line
Note: breakpoint 2 also set at pc 0x55555555519c.
Breakpoint 3 at 0x55555555519c: file crash_example.cpp, line 4.
```

You can unset a breakpoint with the `delete` command, e.g. `delete 3`.

# Breakpoints (cont.)

With a breakpoint set, we can now run the code with `run`.

```
(gdb) run
The program being debugged has been started already.
Start it from the beginning? (y or n) y
Starting program: /home/rzon/Dropbox/SC-lectureNotes/crash_example
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".

Breakpoint 2, handle_command_line (argc=1, argv=0x7fffffffc3c8)
    at crash_example.cpp:4
4     if (argv[1][0] == '-' && argv[1][1] == 'h') {
```

As this example shows, the `run` command will ask you if you want to restart the application if it was already running.

If instead of starting from the start, you wanted to continue from where the code was, use the `continue` command instead.

# Setting Variables

When the program is paused in gdb, you can change the values of variables as well with `set`.

This will change the execution of the code and can be useful for experimentation, but keep in mind that this also makes the debugging process harder to reproduce.

For example, we could set the value of `argv[1]` to something valid:

```
(gdb) print argv[1]
$1 = 0x0
```

```
(gdb) set argv[1] = "-h"
```

```
(gdb) p argv[1]
$2 = 0x55555556aeb0 "-h"
```

```
(gdb) continue
Continuing.
Usage:   crash_example [-h]
[Inferior 1 (process 215420) exited normally]
```

Note: Here “Inferior” merely refers to the fact that the code was run under gdb.

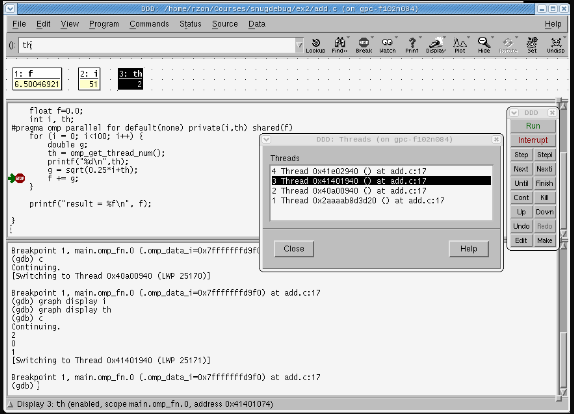
# GDB command summary

| | | |
|---|---|---|
| `help` | `h` | print description of command |
| `run` | `r` | run from beginning (+args) |
| `start` | `start` | run from main |
| `backtrace` | `ba` | function call stack |
| `break` | `b` | set breakpoint |
| `delete` | `d` | delete breakpoint |
| `continue` | `c` | continue |
| `list` | `l` | print part of the code |
| `step` | `s` | step into function |
| `next` | `n` | continue until next line |
| `print` | `p` | print variable |
| `display` | `disp` | print variable at every prompt |
| `finish` | `fin` | continue until function end |
| `set variable` | `set var` | change variable |
| `down` | `do` | go to called function |
| `until` | `unt` | continue until line/function |
| `up` | `up` | go to caller |
| `watch` | `wa` | stop if variable changes |
| `quit` | `q` | quit gdb |

# Graphical debuggers

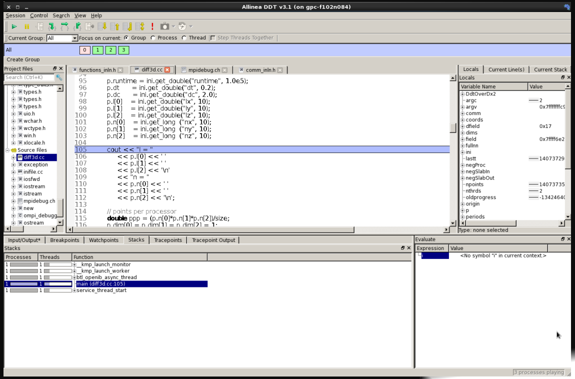
DDD: free, bit old, can do serial and threaded debugging.

```
module load ddd
```




DDT: commercial, on SciNet, part of “Linaro Forge” good for parallel debugging.

```
module load forge
```



# Tips to avoid debugging

- Write better code.
  - simple, clear, straightfoward code.
  - modularity (avoid global variables and 10,000 line functions).
  - avoid "cute tricks".
- Don't write code, use existing libraries.
- Write (simple) tests for each module.
- Use version control and small commits.
- Switch on the warnings, and understand them all, or better, fix them.
- Use defensive programming:

  Check arguments, use assert (which can be switched of with `-DNDEBUG` compilation flag)
  E.g.:

```
#include <cassert>
#include <cmath>
double mysqrt(double x) {
    assert(x>=0);
    return sqrt(x);
}
```

# Use the compiler's features

# Compilation and linking

Creating an executable takes two steps:

1. Compiling the code into machine language
2. Linking that to other compiled code

So far we have only seen single source file code, so you may think we only need step 1.

But the compiler needs to link the code corresponding to the libraries (`iostream`, `cmath` etc) that we are using.

We can (and will in the future) do both steps separately:

1. `g++ -c SOURCE.cpp -o SOURCE.o`

   will create an unlinked, compiled version of the code called an object file.

2. `g++ SOURCE.o -o SOURCE`

   will create the linked version that can be executed.

Both these command will need the -g to switch on debug symbols.

# Heed Compiler Warnings

The compiler has many options to help you find errors early on.

- `-Wall` switches on inspect all warnings.

  Any warning you see should be fixed or at least understood.
- `-Werror` turns warnings into an compilation failures.
- `-Wextra` for even more warnings
- `-std=c++17` chooses the C++ standard to follow.

  If this makes the compilation fail, your code was non-portable.

  (other standards are c++98, c++03, c++11, c++14, c++20 and c++23).
- `-Wfatal-errors` stops compilation at the first error.

  The first error due to e.g. a syntactical mistake, can trigger more errors.

  Usually the first error is the one to fix but it may have scrolled off screen.

# Optimization

Once everything is working, good.

But it won't be great until you let the compiler use its optimization capabilities.

These are activites with specific flags:

- `-O0`: no optimization (the default for g++)
- `-O1`: first level optimization
- `-O2`: second level optimization
- `-O3`: third level optimization

Combine these with

- `-march=native`: use all capabilities of the processor

For debugging, you should stick with `-g -O0` or `-g -Og`. Otherwise, use the highest level unless you have a reason not too.

# Assignment

Write a program that can take 2d data sampled at discrete time points and compute a moving average of the norm of the 2d points as a function of time.

- The data comes from a file with 3 columns, where the first column is time `t` and the second and third columns `x(t)` and `y(t)` are 2 coordinates.
- The program should compute the norm ($\sqrt{x^2 + y^2}$), and then its moving average over `n` points. I.e. for each array element, it should compute the average of it and the preveeding `n`-1 elements. `n` will be an input parameter.
- Perform this moving average also for the time values. Write the result in two-column form to a file.
- The program should take commmand line arguments that correspond to the input file name, the output file name and the width n of the running average.

Your code should be in a simple `.cpp` file and have three or more functions in addition to the main function, and should be commented.

Find the assignment and input file on the course website, where you can also upload your source file and the result file for the case `n`=5.

The assignment is due Thursday January 23rd 2025 at midnight.