Debugging

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Docker image for demo

```
docker pull wentzell/debugging_demo
```

Outline

- What kind of bugs ?
- A selection of (open source) tools
- Examples. Tiny pieces of codes, show the tools in action
- Bug prevention.

- Here simple illustrations with (basic) C++
- Many tools usable in Fortran, similar tools in most languages.
- A few C++ specific issues.

Tests !

- How to detect bugs : have a good test suite.
- Test driven development
- It much better to kill bugs in a test than in a production code.

- Test coverage :
  - Are all functions tested ? For which parameters ?
  - If you do not RUN your function, it is harder to find bugs (but see static analysis, cf later).
  - There are tools to measure that (kcov, …). Not the topic here.

Different kind of bugs

- Out of bound read/write
  - e.g. array of size N, write/read in N+10.
- Memory leak
- Uninitialised variables
- Undefined behaviour
- Logic error
- Infinite loop
- …

Tools

- Static analysers
  - Static analyzers : detect errors in the code without running it.
  - Helps you to write better, cleaner code. Enforce subset of C++.
  - Compiler itself !, clang-tidy, cppcheck, …
- Dynamical analyzers
  - Automated checks of the code while running (check bounds, etc)
    - Valgrind: a "virtual" machine, checking each memory access, that each variable is initialized. No recompilation.*Fortran/C++*.
    - Clang/gcc sanitizers : compilation options that "instrument" your code automatically to do these checks. (clang/gcc only).
- Debugger
  - Execute program step by step : GDB, LLDB, …

Static/Dynamical checks

- Use them preventively, on your test suite/code
- Systematic use in "Continuous Integration" (Travis, Jenkins)
- Static analysis
  - Check all code.
  - Does not require tests
  - False positives possible
- Dynamic analysis
  - Require very good test coverage
  - Require to run the tests
  - Almost no false positive

Valgrind

- http://valgrind.org
- Best on Linux (does not work well on OS X).
- Various checkers : here we use “memory” (the default one).
- Contains other tools to analyse cache misses, profiling *CallGrind, CacheGrind*

Clang sanitizers

clang.llvm.org

- Dynamic analysis tools included with clang and gcc
  - Address Sanitizer `-fsanitize=address`
    detects buffer overflows, memory leaks, use-after-free,…
  - Memory Sanitizer (clang only) `-fsanitize=memory`
    detects reads of uninitialized memory
  - Undefined Behavior Sanitizer `-fsanitize=undefined`
    detects undefined behaviors
  - Thread Sanitizer `-fsanitize=thread`
    detects data races
- Used to systematically detect bugs by Google, Mozilla, …
- Much less memory/runtime overhead than Valgrind!

Availability

- Linux
  - Clang (>3.x), gcc (>4.9)
  - All sanitizers
- Os X
  - Not all sanitisers
  - Valgrind does not work well.
- Others : ?

- Recommendation : use Linux for debugging

Examples

1-Out of bounds !

- Typical error : read/write out of the memory reserved for an object.

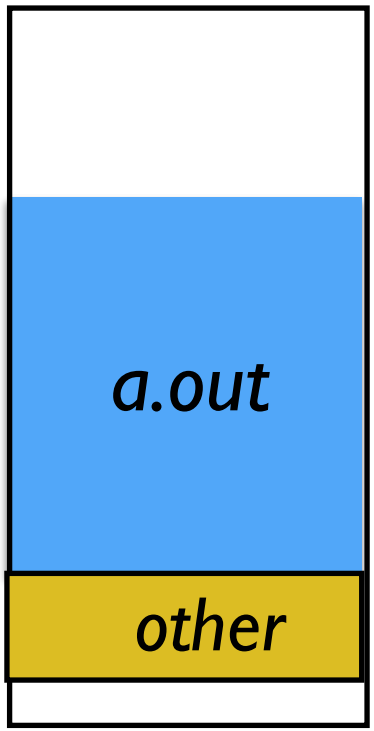
```
#include <vector>

int fun(int n) {
  std::vector<int> vec(100, 1);  // a 1d "array" of 100 int init to 1
  vec[n + 50] = 500;             // Invalid Write
  return vec[n + 50];            // Invalid Read
}
```

- Similar : use a “dangling” or null pointer, …
- How does it manifest itself ?

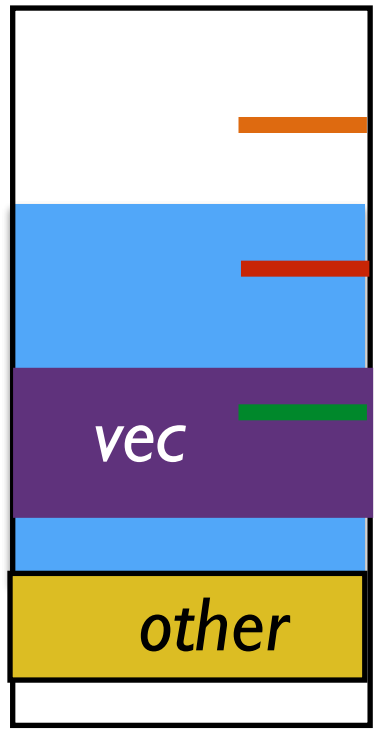
Demo

1-Out of bounds !

- Segfault : the program crashes …
- … or not !
- Hence it can be undetected for a while (or never ?).
- We need to find the first error



Computer memory



Computer memory

Segfault: crash

Even worse. No crash, but corrupt memory

OK

1-Out of bounds !

- Debugger is NOT the best tool in this case.
  - The code may not crash
  - We want a systematic check
  - We want the first error

- Valgrind

```
→ valgrind ./a.out 3
```

- Sanitizer Address (ASAN)

```
→ clang++ -fsanitize=address -fno-omit-frame-pointer -g 1-OutOfBounds.cpp
```

Demo

1-Out of bounds

- Summary :
  - Valgrind
    - Old tool (>15 years). Works with C++, Fortran, etc…
    - Find out of bounds for heap, but not for stack !
    - Can be slow (10x, 50x slower than original code).
  - Sanitizer Address (ASAN)
    - More recent tool. C++ specific.
    - Find more cases (stack and heap)
    - Much faster (2x, 3x slower than original code).

Demo

2-Invalid-iterator

- A Typical error in C++. Pointer or iterator invalidation.

```cpp
#include <iostream>
#include <vector>

int main() {
  std::vector<int> v(10, 3);      // 10 numbers init to 3
  auto p = v.begin();             // an iterator on the beginning of the vector
  std::cout << *p << std::endl;   // print the first value : should be 3
  v.push_back(7);                 // Add one more number to the vector,
  std::cout << *p << std::endl;   // print again the first value ???
}
```

2-Invalid-iterator

- A Typical error in C++. Pointer or iterator invalidation.

```cpp
#include <iostream>
#include <vector>

int main() {
  std::vector<int> v(10, 3);      // 10 numbers init to 3
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  std::cout << *p << std::endl;   // print the first value : should be 3
  v.push_back(7);                 // Add one more number to the vector,
  std::cout << *p << std::endl;   // print again the first value ???
}
```

- Next generation of compiler will detect this.
  Lifetime Proposal for std C++.

- Experimental branch of clang.

```
→ clang++ -Wlifetime 7-IteratorInvalid.cpp
```

https://godbolt.org/z/Z878Dp

3- Memory leak

- Allocate some memory, and … forget to release it

```
int main() {
  int *g = new int[100];  // allocate the array of 100 int on the heap
  g = nullptr;            // Lost the pointer.

  // ... whatever ...
}
```

- Effect : Often none, except if you call such a function a lot, you will run out of memory !
- Modern C++: no new/delete. Should not pass code review !
- Tools : Valgrind, ASAN (address sanitizer).

```
➜ valgrind --leak-check=full ./a.out
➜ clang++ -fsanitize=address -g Leak.cpp
```

4-Uninitialized variables

- What happens if we forgot to initialise something ?

```
#include <iostream>

int main(int argc, char** argv) {
  int num = atoi(argv[1]);  // get the first arg and make it from string -> int
  int factorial;  // OOPS !
  for (int i = 1; i <= num; ++i) {
    factorial *= i;
  }
  std::cout << num << "! = " << factorial << "\n";
  return factorial;
}
```

- Static analyser
  - Compiler (clang -Wall detects it, but not gcc)
  - Cppcheck
- Dynamical analyzer: Valgrind, memory sanitiser (MSAN)
- Limitation : libraries must be compiled with *-fsanitize=memory*

Demo

```
➜ clang++ -g -fsanitize=memory  -fno-omit-frame-pointer -fsanitize-memory-track-origins factorial.cpp
```

5- Undefined behaviour

- Undefined behavior sanitizer finds many things :
  - Overflow
  - Division by zero
  - Wrong cast e.g. in calling C lib
  - … Undefined Behavior situation in C++…

5- Undefined behaviour

- Integer overflow.
- << is binary shift, we just shifted too much !

```cpp
#include <iostream>
int main(int argc, char** argv) {
  int num = atoi(argv[1]);  // get the first arg and make it from string -> int

  int t = num << 16;
  int r = t * t;
  std::cout << r << std::endl;

  double x = 1/0.0;
  std::cout << x << std::endl;
}
```

```
→ clang++ -Wall  int_overflow.cpp
→  ./a.out 5
0
→ clang++ -Wall -fsanitize=undefined  int_overflow.cpp
→ ./a.out 5
int_overflow.cpp:7:18:
runtime error: signed integer overflow: 327680 * 327680 cannot be represented in type 'int'
0
```

6-Logic error

- The logic of the code is flawed, but no automatic tool will find this !

```
#include <iostream>

int main(int argc, char** argv) {
  int num = atoi(argv[1]);  // get the first arg and make it from string -> int

  int factorial = 0;  // Oops !
  for (int i = 1; i <= num; ++i) {
    factorial *= i;
  }
  std::cout << num << "! = " << factorial << "\n";
  return factorial;
}
```

Demo

- Let's follow step by step and use the debugger.
- GDB : for many compiled languages: *C, C++, FORTRAN, Java, Pascal, Ada, D, Go*
- Gdbgui : a light interface to GDB (usable remotely). Or use an IDE

7-Infinite Loop

- Due to some logic flaw, your code is stuck in an infinite loop !

```c
int main() {

  int c = 0;

  while (1) {
    c += 1;
    // whatever
  }
}
```

- You can run, and attach gdb to your process on the fly

```
→ gdb ./a.out --pid=PID_OF_THE_PROCESS
```

Demo

GDB cheatsheet - page 1

Running

`# gdb <program> [core dump]`
Start GDB (with optional core dump).

`# gdb --args <program> <args…>`
Start GDB and pass arguments

`# gdb --pid <pid>`
Start GDB and attach to process.

`set args <args...>`
Set arguments to pass to program to be debugged.

`run`
Run the program to be debugged.

`kill`
Kill the running program.

Breakpoints

`break <where>`
Set a new breakpoint.

`delete <breakpoint#>`
Remove a breakpoint.

`clear`
Delete all breakpoints.

`enable <breakpoint#>`
Enable a disabled breakpoint.

`disable <breakpoint#>`
Disable a breakpoint.

Watchpoints

`watch <where>`
Set a new watchpoint.

`delete/enable/disable <watchpoint#>`
Like breakpoints.

<where>

function_name
Break/watch the named function.

line_number
Break/watch the line number in the current source file.

file:line_number
Break/watch the line number in the named source file.

Conditions

`break/watch <where> if <condition>`
Break/watch at the given location if the condition is met.
Conditions may be almost any C expression that evaluate to true or false.

`condition <breakpoint#> <condition>`
Set/change the condition of an existing break- or watchpoint.

Examining the stack

`backtrace`
`where`
Show call stack.

`backtrace full`
`where full`
Show call stack, also print the local variables in each frame.

`frame <frame#>`
Select the stack frame to operate on.

Stepping

`step`
Go to next instruction (source line), diving into function.

`next`
Go to next instruction (source line) but don‘t dive into functions.

`finish`
Continue until the current function returns.

`continue`
Continue normal execution.

Variables and memory

`print/format <what>`
Print content of variable/memory location/register.

`display/format <what>`
Like „print“, but print the information after each stepping instruction.

`undisplay <display#>`
Remove the „display“ with the given number.

`enable display <display#>`
`disable display <display#>`
En- or disable the „display“ with the given number.

`x/nfu <address>`
Print memory.
n: How many units to print (default 1).
f: Format character (like „print“).
u: Unit.

Unit is one of:

b: Byte,
h: Half-word (two bytes)
w: Word (four bytes)
g: Giant word (eight bytes)).

GDB cheatsheet - page 2

Format

a	Pointer.
c	Read as integer, print as character.
d	Integer, signed decimal.
f	Floating point number.
o	Integer, print as octal.
s	Try to treat as C string.
t	Integer, print as binary (*t* = „two“).
u	Integer, unsigned decimal.
x	Integer, print as hexadecimal.

<what>

expression
: Almost any C expression, including function calls (must be prefixed with a cast to tell GDB the return value type).

file_name::*variable_name*
: Content of the variable defined in the named file (static variables).

function::*variable_name*
: Content of the variable defined in the named function (if on the stack).

{type}address
: Content at *address*, interpreted as being of the C type *type*.

$*register*
: Content of named register. Interesting registers are $esp (stack pointer), $ebp (frame pointer) and $eip (instruction pointer).

Threads

`thread <thread#>`
: Chose thread to operate on.

Manipulating the program

`set var <variable_name>=<value>`
: Change the content of a variable to the given value.

`return <expression>`
: Force the current function to return immediately, passing the given value.

Sources

`directory <directory>`
: Add *directory* to the list of directories that is searched for sources.

`list`
`list <filename>:<function>`
`list <filename>:<line_number>`
`list <first>,<last>`
: Shows the current or given source context. The *filename* may be omitted. If *last* is omitted the context starting at *start* is printed instead of centered around it.

`set listsize <count>`
: Set how many lines to show in „list“.

Signals

`handle <signal> <options>`
: Set how to handle signles. Options are:

(no)print: (Don‘t) print a message when signals occurs.

(no)stop: (Don‘t) stop the program when signals occurs.

(no)pass: (Don‘t) pass the signal to the program.

Informations

`disassemble`
`disassemble <where>`
: Disassemble the current function or given location.

`info args`
: Print the arguments to the function of the current stack frame.

`info breakpoints`
: Print informations about the break- and watchpoints.

`info display`
: Print informations about the „displays“.

`info locals`
: Print the local variables in the currently selected stack frame.

`info sharedlibrary`
: List loaded shared libraries.

`info signals`
: List all signals and how they are currently handled.

`info threads`
: List all threads.

`show directories`
: Print all directories in which GDB searches for source files.

`show listsize`
: Print how many are shown in the „list“ command.

`whatis variable_name`
: Print type of named variable.

8-Thread/OpenMP

- Race condition. Can you spot it/them ?

```cpp
#include <omp.h>
#include <iostream>
#include <vector>

int main(int argc, char* argv[]) {
  std::vector<double> data(100, 1.0);
  double sum;

  #pragma omp parallel shared(sum, data)
  {
    sum = 0.0;
    #pragma omp for
    for(int i = 0; i < data.size(); i++){
      sum += data[i];
    }
  }
  std::cout << sum << std::endl;
}
```

```
→ clang++ -fopenmp -g -fsanitize=thread 8-RaceCondition.cpp
```

- Experimental branch of clang.

Good practices

- Clear, expressive code (Modern C++)
- Code Review !
- Automated Tests (googletest, TDD)
- Version Control (git)
- Static analyzer (clang-tidy)
- Dynamic analyzer (Valgrind, clang sanitizer)
- Logic error. Debugger, step by step. GDB
- Print stuff ? Only in the last resort …

Thank you for your attention!