CERN School of Computing

Software Design in the Many-Cores era

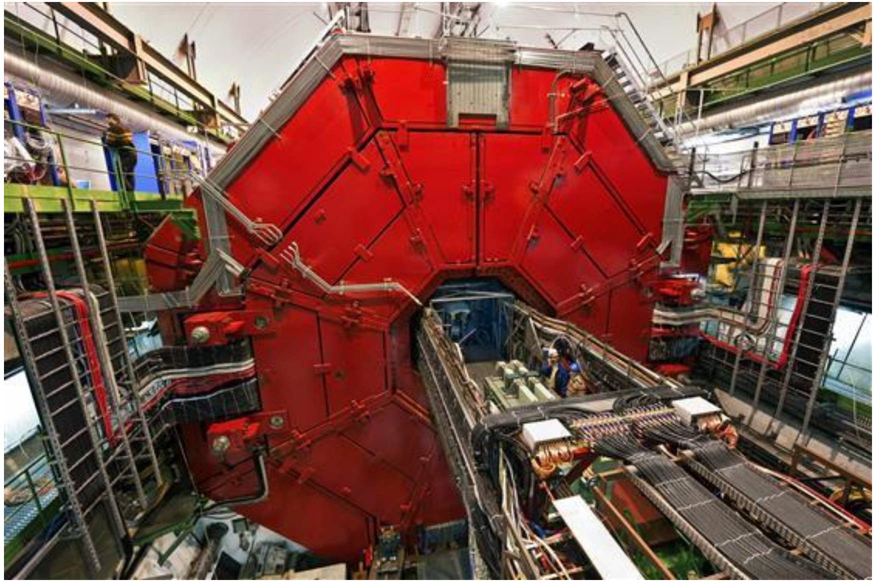
A. Gheata, S. Hageböck

CERN, EP-SFT

CERN School of Computing 2024

CPU Ninja

CERN School of Computing



Lecture III

Understanding, and Debugging a Complex Multithreaded Application

CERN School of Computing

Outline of This Lecture

The Goals:

- Understand the relation between performance and correctness
- Master the strategies to be able to **analyse**, **debug** ~~and **profile**~~*

a complex parallel application

Before running the application:

1) Elements of static code analysis: **Clang**

Three logical steps

If something goes wrong:

2) Understanding and debugging a multithreaded application with **GDB**

Now that it works, how fast is it?

3) Elements of high-level profiling: ~~**igprof**~~* basic principles

* covered by the **Benchmarking and Profiling** lecture

CERN School of Computing

Performance and Correctness

- **Correctness comes first**: if your program is buggy, unreliable, unpredictable, no performance consideration makes sense (at all)
- **Performance is then crucial***: algorithms translate to real machine code, running on real hardware with its own features (CPUs, memory hierarchy, accelerators)

A high-quality test suite must be part of every software tool

"Make it work, make it right, make it fast"

*For many areas of scientific computing at least

CERN School of Computing

Performance and Correctness

- **Correctness and performance: tightly correlated**
- Correctness checked quickly and extensively → runtime/memory improvements validated more easily
  - **Be in condition to label "changes"** in the final results as "acceptable", "expected" or "in the wrong direction"
  - Pandora's box**:** **what is the "right" result?** The one we had before? The new one? The "reference" one? **Not trivial at all!**
  - Use a grain of salt, **be in control of what happens!**

CERN School of Computing

Features of A Good Testsuite

- It's easy to run
  - One single command runs all tests
  - Tests can be selected, e.g. with regular expressions
- It's automatically ran
  - N times per day, or
  - Continuously check new code committed by developers
- Results are easy to interpret
  - E.g. Published on the web
  - Easy to track down problem, e.g. "test # 1206 failed with this output"

CERN School of Computing

Testing and parallel execution

- Test: minimal program aiming to stress a particular feature of the code
- Parallel code: no predictable order of operations possible
- The “same” test, execution pattern can be “different”
- Solution: properly designed tests
  - E.g. Maximising contention to “challenge” stability of the software

CERN School of Computing

Reproducibility

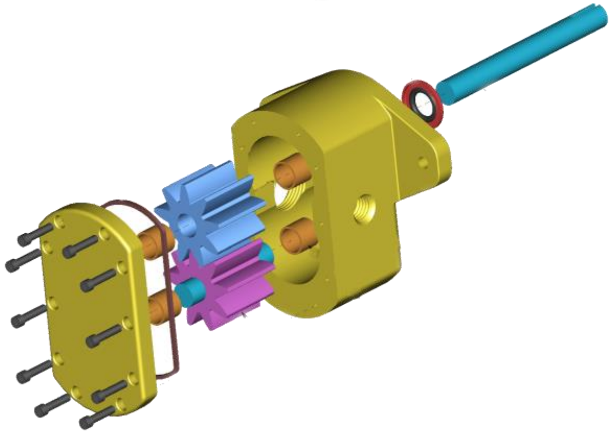
- E.g. two subsequent runs of the program produce the same histograms, identical bin by bin
- Simple for small setups
- Can be tricky with 5M lines, ~100 shared libraries
- Performance optimisations can lead to variations in final result (e.g. migration of entries to neighbouring bins)
    - Fundamental to remove all sorts of “noise”
- Non reproducibility in the sequential case: absence of control on the system
    - E.g. uninitialised variables, sloppy seeding of random generations, bogus memory access

Attitude Towards Testing

- Aim to test-driven development: write tests before code
  - Test features individually one by one
  - Use often asserts as watchdogs in complex code, to catch problems early
- For each bug reported/found: create a reproducing test, add it to the suite, fix it.
  - If it's not reproduced the bug does not exist!
- Don't live with broken windows: follow up each failure
  - Assume it always points to a serious problem
- Time invested in writing tests is strategic
  - It always rewards

If a software tool or one of its functionalities is not tested always assume it does not work

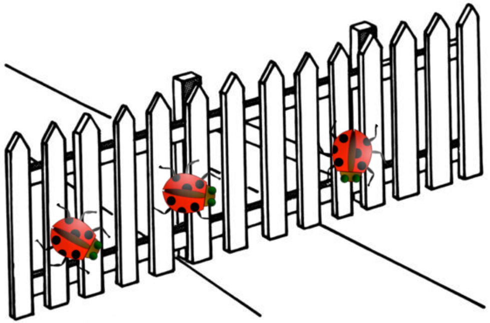
Elements of Static Code Analysis



CERN School of Computing

Static Code Analysis

- Idea: embed static analysis in testing suites
- The procedure of **analysing the source code *before* compiling and running to automatically find bugs**
  - Rise (yet other) fences to protect against mistakes and bugs
  - Easily pluggable in big projects' build infrastructures
  - E.g. code blocks never executed because of faulty logic in if statements, *thread unsafe constructs*, etc.
- Several tools available, commercial and open source
  - Reference on the market: Coverity
  - Open source: Clang Static Analyzer



LLVM and Clang

LLVM

- Free and open source
- A compiler infrastructure
- Frontend [C++,C,...] → Optimizer → Backend [x86, CUDA, ...]
- http://llvm.org

Clang

- LLVM frontend for C,C++ and Objective-C
- A possible alternative to GCC in some respects
- A lot of users - e.g. Apple, Intel (OpenCL)
- http://clang.llvm.org

Very powerful technology: e.g. C++ interpreter built on LLVM & Clang, **Cling**

http://root.cern.ch/drupal/content/cling

CERN School of Computing

Clang Static Analyser

The static analyser is part of the clang frontend

It offers the possibility to examine the program code on two levels:

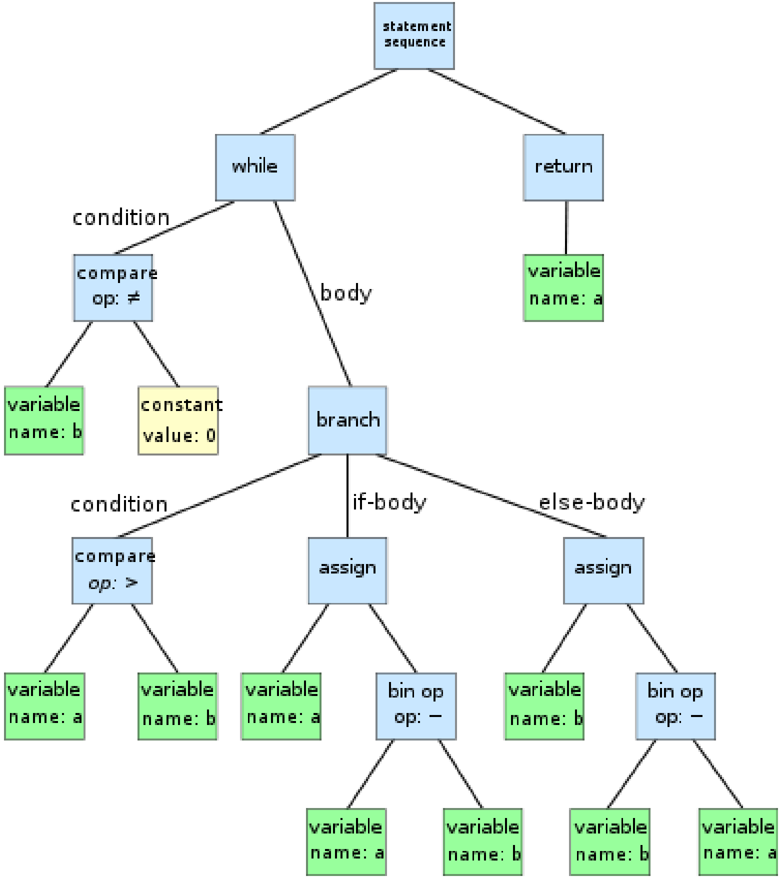
- Analysis of the Abstract Syntax Tree (AST)
- Symbolic Execution:
  - Every possible path through the program is explored and validated

http://clang-analyzer.llvm.org/

- **A battery of checks already included**: uninitialized access, dead stores, dereferencing null, invalid malloc calls, ...
  - User-defined can be added
- HTML report created automatically, detailed annotations of the source
- `scanbuild` tool: automatically replace the calls to the compiler in a makefile

To fire static analysis: `scan-build make`

An AST


statement sequence
while
return
condition
compare op: ≠
body
variable name: a
variable name: b
constant value: 0
branch
condition
if-body
else-body
compare op: >
assign
assign
variable name: a
variable name: b
variable name: a
bin op op: −
variable name: b
bin op op: −
variable name: a
variable name: b
variable name: b
variable name: a

CERN School of Computing

Analysis for Thread Unsafety

Clang Static Analyzer: Custom checks can be added in form of a plugin written in C++

Checks for thread unsafety were developed by the LHC experiments

- Used in production for Q/A of experiments software
- **Useful in general!**

Some examples:

- Non const global/local statics
- Use of mutable keyword
- Use of const_cast to remove constness
- Other removals of constness (e.g. explicit cast)
- …

Note the importance of const correctness

CERN School of Computing

Web Reports: an Example

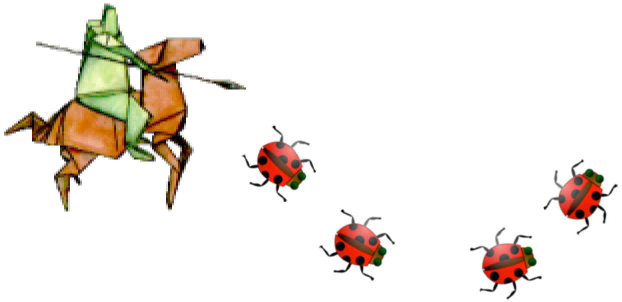
FastJet tool taken as guinea pig: used to cluster jets by several experiments' software - http://fastjet.fr/

```
void VoronoiDiagramGenerator::plotinit()
{
  double dx,dy,d;

  dy = ymax - ymin;
  dx = xmax - xmin;
  d = (double)(( dx > dy ? dx : dy) * 1.1);
  pxmin = (double)(xmin - (d-dx)/2.0);
  pxmax = (double)(xmax + (d-dx)/2.0);
  pymin = (double)(ymin - (d-dy)/2.0);
  pymax = (double)(ymax + (d-dy)/2.0);
  cradius = (double)((pxmax - pxmin)/350.0);
  //GS unused: openpl();
  //GS unused: range(pxmin, pymin, pxmax, pymax);
}


void VoronoiDiagramGenerator::clip_line(Edge *e)
{
  Site *s1, *s2;
  double x1=0,x2=0,y1=0,y2=0; //, temp = 0;

  x1 = e->reg[0]->coord.x;
  x2 = e->reg[1]->coord.x;

      Value stored to 'x2' is never read

  y1 = e->reg[0]->coord.y;
  y2 = e->reg[1]->coord.y;

  //if the distance between the two points this line
  //the square root of 2, then ignore it
  //TODO improve/remove
  //if(sqrt(((x2 - x1) * (x2 - x1)) + ((y2 - y1) * (
  //  {
  //    return;
  //  }
  pxmin = borderMinX;
  pxmax = borderMaxX;
```

Example coming from an old version of fastjet!

```
void VoronoiDiagramGenerator::clip_lin
{
  Site *s1, *s2;
  double x1=0,x2=0,y1=0,y2=0; //, temp

  x1 = e->reg[0]->coord.x;
  x2 = e->reg[1]->coord.x;

  Value stored to 'x2' is never read

  y1 = e->reg[0]->coord.y;
  y2 = e->reg[1]->coord.y;

  //if the distance between the two po
```

Understanding and Debugging - GDB



CERN School of Computing

Debugging

Suppose something is wrong with your application:

- It nicely terminates but yields wrong results (worst case scenario!)
- It crashes
- It runs forever occupying several CPUs
- It hangs forever with no CPU usage (e.g. a deadlock)

Effective debugging strategies and tools are the solution

The same techniques are also handy not only in case of problems

- Suppose that the overall behavior of a very complex application (~MLOC) is to be understood
  - E.g. CMS/Atlas/LHCb/Alice reconstruction

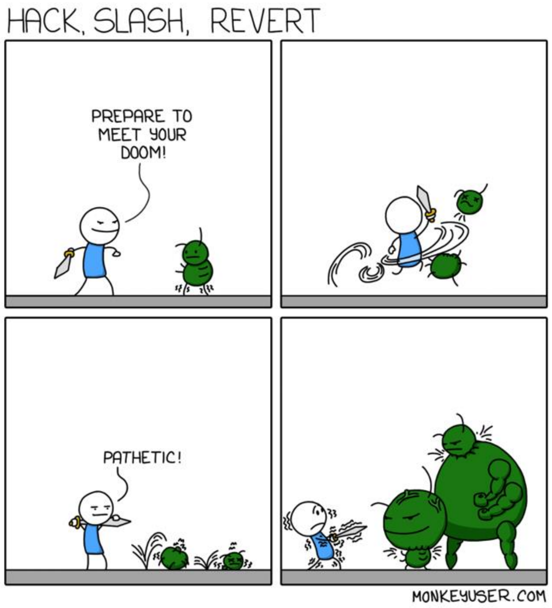
CERN School of Computing

Debugging Strategies

Write and use programs without bugs?

- There is *no such thing*, except in totally trivial cases
- All programs have and will have bugs

If possible, try not to introduce bugs in the first place!



Debug printouts as *'poor man's solution'*:

- (+) Immediate to everybody: sometimes it's enough!
- (−) Hard (impossible) to add printouts in 3rd party libraries
- (−) Distract the user from focussing on the debugging itself
- (−) Hard to use in a parallel program, encourage Heisenbugs influencing timing behaviour

Or better: Use a debugger like GDB

CERN School of Computing

★ GDB: The GNU Project Debugger

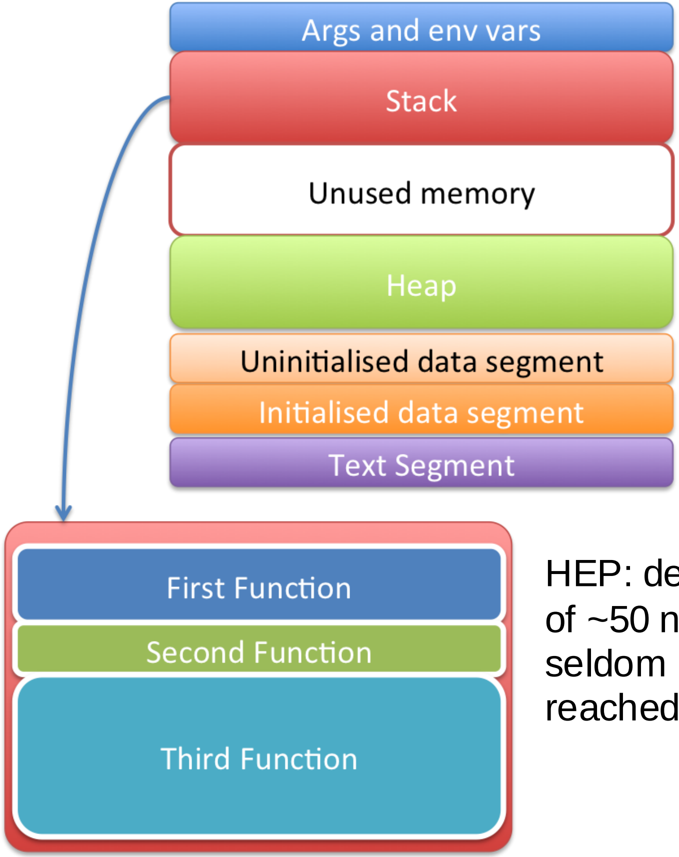
- **Free and open source**, available on every Linux box
- GDB is an interactive command line tool which can "see":
  - Within a program during its execution
  - A posteriori, what a program was doing when it crashed
- Works with applications written in C and C++ (among other languages)
- No recompilation needed (although debugging symbols can be handy)
- Stop the execution at some specified point
  - Execute line by line, stepping into functions if needed
- Examine what is happening: e.g. print variable content
- Thread aware: e.g. Stop threads, switch among them …

http://www.gnu.org/software/gdb/

CERN School of Computing

Reminder: A Program in Memory

- **Text Segment**: code to be executed.
- **Initialized Data Segment**: global variables initialized by the programmer.
- **Uninitialized Data Segment**: This segment contains uninitialized global variables.
- **The stack**: The stack is a collection of stack frames. It grows whenever a new function is called. "Thread private".
- **The heap**: Dynamic memory (e.g. requested with "`new`").



HEP: depth of ~50 not seldom reached

CERN School of Computing

An Example

```
#include <iostream>

void display(int x, int *xp) {
  std::cout << "In display():\n"
            << " o value of x is " << x
            << ", address of x is " << &x <<std::endl
            << " o xp points to " << xp
            << " which holds " << *xp <<std::endl; }

int main() {
  int a = 42;
  int *ap = &a;
  std::cout << "In main():\n"
            << " o value of a is "<< a
            << ", address of a is " << &a << std::endl
            << " o ap points to " << ap
            << " which holds " << *ap << std::endl;
  display(a, ap);
  return 0; }
```

g++ –o myExample myExample.cpp –g

To fire gdb: `gdb myexecutable`

CERN School of Computing

An Example

```
$ gdb myExample
[ … Some output … ]
(gdb) run
Starting program: /Users/<whoever>/gdb/myExample
Reading symbols for shared libraries
+++.............................. done
In main():
 o value of a is 5, address of a is 0x7fff5fbff744
 o ap points to 0x7fff5fbff744 which holds 5
In display():
 o value of x is 5, address of x is 0x7fff5fbff71c
 o xp points to 0x7fff5fbff744 which holds 5

Program exited normally.
```

```
#i
vo
in
          << " o ap points to " << ap
          << " which holds " << *ap << std::endl;
  display(a, ap);
  return 0; }
```

To fire gdb: `gdb myexecutable`

Break Points

- So far so good – you could have done this already without GDB!
- **But,** GDB allows you to stop the execution of the application at a certain line or function with break points:

```
(gdb) break 12
Breakpoint 1 at 0x100000c60: file myExample.cpp, line 12.
(gdb) run
Starting program: /Users/<whoever>/gdb/myExample

Breakpoint 1, main () at myExample: 12
12 int *ap = &a;
(gdb)
```

The break could have been introduced when a certain function is invoked:

→***break <function name>***

(“*break display*” in our case)

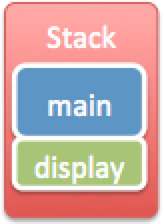
Impossible to do with printouts ☺

CERN School of Computing

And Now?

You can dump the stack with ***where***:

```
(gdb) where
#0  display (x=42, xp=0x7fff5fbff7c4) at myExample:6
#1  0x0000000100000d2c in main () at myExample.cpp:14
```



See some of the surrounding code with ***list***:

```
(gdb) list
#include <iostream>

1 void display(int x, int *xp) {
2   std::cout << "In display():\n"
              << " o value of x is " << x
              << ", address of x is " << &x <<std::endl
              << " o xp points to " << xp
              << " which holds " << *xp <<std::endl; }

3 int main() {
4 int a = 42;
5 int *ap = &a;
```

CERN School of Computing

Interlude: Debugging Symbols

The compiler does not automatically bring the names of the symbols in the executables and libraries, the machine does not need them!

Humans do: include *debugging symbols* in the compiled binaries.

- Names of variables, functions, classes, namespaces, …

Debugging symbols, 3 facts to remember:

- Do not slow down the program!
- Do not increase its memory footprint!
- Do make binaries bigger (more disk space needed)!

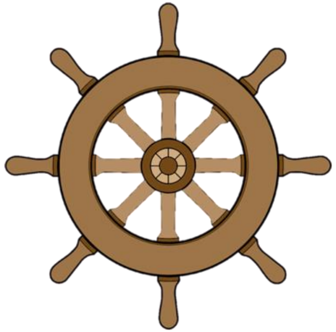
With GCC:

g++ […] –g

Navigating Program Execution

To “navigate” the program execution you can use:

- **step:** continue running until control reaches new line. “Step into” functions
- **next:** like step but functions are executed without stopping
- **finish:** continue until end of current stack frame
- **return <*expression*>:** prematurely exit the stack returning expression.
- **break:** show break points list
  - **disable** <*n*>: disable break point n
  - **enable** <*n*>: enable break point n
  - **delete** <*n*>: delete break point n
- **info threads:** show threads
- **thread <n>:** step into thread n



CERN School of Computing

The Print Statement

```
1 #include "time.h"
2 #include <iostream>
3 int main() {
4   int t = clock();
5   std::cout << t << std::endl;
6   return 0;
7 }
```

print allows you to inspect the value of a variable.

```
(gdb) break 5
Breakpoint 1 at 0x100000d50: file ex12_2.cpp, line 5.
(gdb) run
Starting program: /Users/danilopiparo/gdb/ex12_2
Reading symbols for shared libraries
++............................. done

Breakpoint 1, main () at ex12_2.cpp:5
5             std::cout << t << std::endl;
(gdb) print t
$1 = 6637
(gdb) next
6637
6             return 0;
```

CERN School of Computing

Interlude 3: Machine Code with GDB

Food For Thought

```
double myFloor(double x) {
  const int xi = int(x);
  return x < 0 ? xi -1 : xi;
}
int main() {
  myFloor(-3.14);
}
```

- Looking at the assembly is the only way to understand what the compiler actually did
- GDB allows to do that easily with `disass`
- More targeted than Unix `objdump`

CERN School of Computing

Interlude 3: Machine Code with GDB

Food For Thought

```
(gdb) disass /m myFloor
Dump of assembler code for function myFloor(double):
1       double myFloor(double x){
2         const int xi = int(x);
  0x00000000004004e0 <+0>:     cvttsd2si %xmm0,%eax
3         return x<0?xi-1:xi;
  0x00000000004004e4 <+4>:     cmpltsd 0x113(%rip),%xmm0        # 0x400600
  0x00000000004004ed <+13>:    lea    -0x1(%rax),%edx
  0x00000000004004f0 <+16>:    cvtsi2sd %eax,%xmm2
  0x00000000004004f4 <+20>:    cvtsi2sd %edx,%xmm1
  0x00000000004004f8 <+24>:    andpd  %xmm0,%xmm1
  0x00000000004004fc <+28>:    andnpd %xmm2,%xmm0
  0x0000000000400500 <+32>:    orpd   %xmm1,%xmm0

4       }
  0x0000000000400504 <+36>:    retq
End of assembler dump.
```

GDB And Threads

- GDB allows to inspect the behaviour of the threads of a process
  - info threads: display running threads
  - thread <n>: step into a thread

```
#include <thread>
#include <vector>
#include <chrono>
void sleep() {
std::this_thread::sleep_for(std::chrono::seconds(100)); };
int main() {
std::vector<std::thread> myThreads;
for (int i=0; i<2; i++) myThreads.emplace_back(std::thread(sleep));
// Line 11
for (auto& t : myThreads) t.join();
}
```

CERN School of Computing

```
$ gdb ./threadsSleep
[ … some output … ]
Reading symbols from /home/dpiparo/CSC/Examples/threadsSleep...done.
(gdb) break 11
```

Set a break point at line 11

CERN School of Computing

```
$ gdb ./threadsSleep
[ … some output … ]
Reading symbols from /home/dpiparo/CSC/Examples/threadsSleep...done.
(gdb) break 11
Breakpoint 1 at 0x400a8f: file threadsSleep.cpp, line 11.
(gdb) run
Starting program: /home/dpiparo/CSC/Examples/threadsSleep
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
[New Thread 0x7ffff6fe7700 (LWP 4440)]
[New Thread 0x7ffff67e6700 (LWP 4441)]

Breakpoint 1, main () at threadsSleep.cpp:12
12          for (auto& t : myThreads)
```

- GDB informs us it found the line at which it will break
- Run the application
- GDB informs us that 2 threads were spawned
- The breakpoint is reached

CERN School of Computing

```
$ gdb ./threadsSleep
[ … some output … ]
Reading symbols from /home/dpiparo/CSC/Examples/threadsSleep...done.
```

- Get info about threads
- GDB prints the threads ids and which function is being executed
- The * identifies the thread where the break point was successful
- By default GDB freezes all threads simultaneously at a breakpoint
  - “Take a snapshot of the execution status”

```
14          for (auto& t : myThreads)
(gdb) info threads
  Id   Target Id         Frame
  3    Thread 0x7ffff67e6700 (LWP 4441) "threadsSleep" 0x00007ffff76b252d in nanosleep () at ../sysdeps/unix/syscall-template.S:82
  2    Thread 0x7ffff6fe7700 (LWP 4440) "threadsSleep" 0x00007ffff76b252d in nanosleep () at ../sysdeps/unix/syscall-template.S:82
* 1    Thread 0x7ffff7fd4740 (LWP 4437) "threadsSleep" main () at threadsSleep.cpp:14
```

CERN School of Computing

```
$ gdb ./threadsSleep
[ … some output … ]
Reading symbols from /home/dpiparo/CSC/Examples/threadsSleep...done.
(gdb) b 11
Breakpoint 1 at 0x400a8f: file threadsSleep.cpp, line 11.
(gdb) run
Starting program: /home/dpiparo/CSC/Examples/threadsSleep
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
[New Thread 0x7ffff6fe7700 (LWP 4440)]
[New Thread 0x7ffff67e6700 (LWP 4441)]
```

- Suppose we are interested in thread 2, let's switch to it
- GDB informs us we are now in thread 2
- The cryptic messages are due to the fact that we compiled our exe with debugging symbols, not all the components it depends on!

```
•1    Thread 0x7ffff7fd4740 (LWP 4437) "threadsSleep" main () at threadsSleep.cpp:12
(gdb) thread 2
[Switching to thread 2 (Thread 0x7ffff6fe7700 (LWP 4440))]
#0  0x00007ffff76b252d in nanosleep () at ../sysdeps/unix/syscall-template.S:82
82      ../sysdeps/unix/syscall-template.S: No such file or directory.
```

```
$ gdb ./threadsSleep
[ … some output … ]
Reading symbols from /home/dpiparo/CSC/Examples/threadsSleep...done.
(gdb) b 11
Breakpoint 1 at 0x400a8f: file threadsSleep.cpp, line 11.
(gdb) run
Starting program: /home/dpiparo/CSC/Examples/threadsSleep
[Thread debugging using libthread_db enabled]
Using host libthread_db library "/lib/x86_64-linux-gnu/libthread_db.so.1".
[New Thread 0x7ffff6fe7700 (LWP 4440)]
[New Thread 0x7ffff67e6700 (LWP 4441)]

Breakpoint 1, main () at threadsSleep.cpp:12
14          for (auto& t : myThreads)
(gdb) info threads
 Id   Target Id         Frame
 3    Thread 0x7ffff67e6700 (LWP 4441) "threadsSleep" 0x00007ffff76b252d in nanosleep () at
../sysdeps/unix/syscall-template.S:82
 2    Thread 0x7ffff6fe7700 (LWP 4440) "threadsSleep" 0x00007ffff76b252d in nanosleep () at
../sys
•1
(gdb)
[Switc
#0  0x
82        ../sysdeps/unix/syscall-template.S: No such file or directory.
(gdb) where
#0  0x00007ffff76b252d in nanosleep () at ../sysdeps/unix/syscall-template.S:82
#1  0x0000000000400caf in sleep() () at /usr/include/c++/4.8/thread:279
#2  0x00007ffff7b87a10 in ?? () from /usr/lib/x86_64-linux-gnu/libstdc++.so.6
#3  0x00007ffff76aae9a in start_thread (arg=0x7ffff6fe7700) at pthread_create.c:308
#4  0x00007ffff73d7ccd in clone () at ../sysdeps/unix/sysv/linux/x86_64/clone.S:112
#5  0x0000000000000000 in ?? ()
(gdb)
```

- Now let’s print the stack of thread number 2!

GDB And Threads

- **By default GDB stops all threads simultaneously if a breakpoint is reached** (so called "stop mode")
- It allows also to stop the thread where the breakpoint was reached and let the others proceed ("non-stop mode")
  - De facto the user can bend the runtime behaviour of the application to her needs!

```
# Enable the async interface.
set target-async 1

# Pagination breaks non-stop.
set pagination off

# Finally, turn it on [off]!
set non-stop on [off]
```

Commands to switch between stop and non-stop modes within the gdb prompt

CERN School of Computing

More GDB (Black) Magic

Suppose your program behaves in a weird way now.

- You can “attach” gdb to a running process (e.g. 300% CPU since minutes…)
- ***gdb <PID>***

Impossible to do with printouts ☺

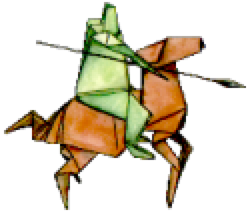
To get your pid:
ps aux | grep <Program name>

Suppose your program crashed after hours of running, leaving you with no plots, but a core dump.

- You can resume it as it was at the moment of the crash
- **gdb *program core-file***

Helgrind and DRD

- Another pair of tools useful for debugging parallel programs
- Part of the Valgrind suite
- Allow to catch thread errors at runtime
  - `valgrind --tool=helgrind ./myProgram`



- Detection of potential thread unsafe operations, lock ordering problems, …
  - Difference between DRD and Helgrind: detection algorithms
- Downside: false positives ☹
- Complementary tools: address and thread sanitiser offered by CLANG and GCC compiler suites.

High Level Profiling

A Simple Question

Q: Why should we strive for software performance, correctness, efficiency, ultimately throughput?

For Money!

From “The Wolf of Wall Street”

Code Optimisation

- When dealing with large software projects, **performance measurement is daily business**
  - Especially for multithreaded applications: *parallel Vs serial case, performance of different configurations of the parallel applications …*
- **The identification of the hotspots** (and their removal) is worth an enormous amount of resources
  - But don't optimise before you know "what"!
- A plethora of tools available, covering all quantities related to performance
  - open source: **perf, valgrind, igprof** … or not: **Intel VTune, Apple Instruments**, …
  - Using several methods: stack sampling, HW performance counters, …
- Profilers can extract precious data allowing to do optimisations:
  - What are the symbols that have the longest runtime?
  - What are the symbols that allocate the most memory?

The Golden Rule of Optimisation

Don't develop theories,
measure your program!

It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts. **Sherlock Holmes**

CERN School of Computing

Take Away Messages

Dealing with a parallel application is complex:

Use procedures to **rise fences to protect against mistakes**, like static analysis to find bugs in an automatic way

- **Embed such tools in the build infrastructure of your SW**

Use tools to **inspect, manipulate their behaviour at runtime, like GDB**

- Become familiar with them, multithreaded programs are tough to debug

Use tools to measure performance, do not speculate

- Start from simple yet powerful tools like **perf, igprof**
- Choose more complex ones to dive into the details