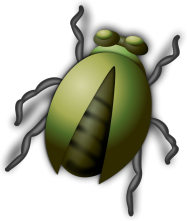
Detecting bugs and bottlenecks in C/C++ sources



Introducing *valgrind* and *gprof*

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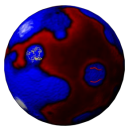

SFG-Meeting for Doctoral Researchers, St.-Afra-Klosterhof Meißen

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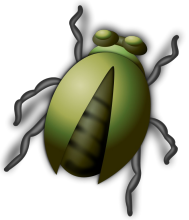
Motivation

"Certain input data crashes my program with a segmentation fault."

"My program is doing weird things."

"My program eats all the RAM. I need a machine with more."



"Did you check it with *valgrind*?"

- every code has bugs
- there is room for optimization

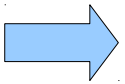
"Huh, what?"

General concepts

1. find/remove bugs 
2. find/reduce bottlenecks 
3. find/remove new bugs 
4. restart with 2. until:
   - no further speed improvement and 
   - no bugs are found 

Comparing different runs

- use identical parameter values
- use same input data (files)
- generate same random sequence:
  seed random number generator with identical initial value (e.g.: srand48(1))

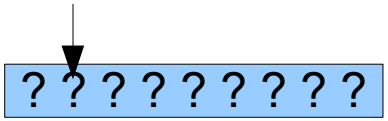


results and output data
of different runs should be identical

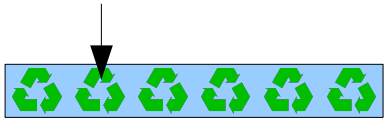
Memory problems

- buffer overruns:
  access outside boundaries, memory corruption

- uninitialized memory:
  unpredictable results

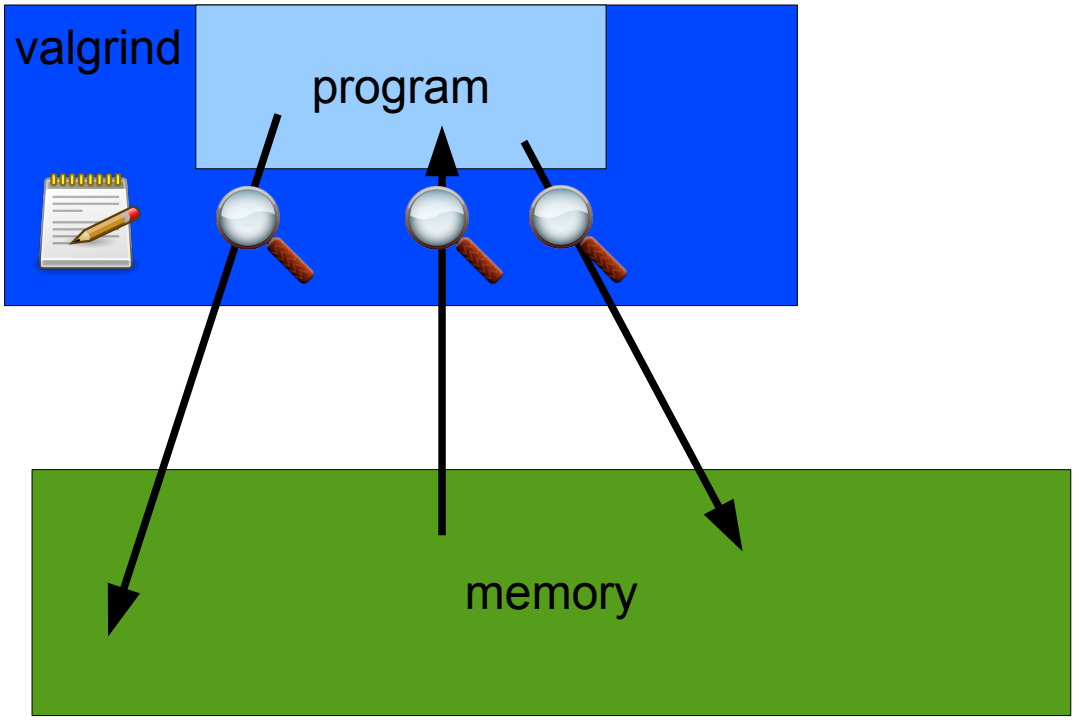


- incorrect memory management:
  access of unallocated/freed memory, delete vs. delete[]



- memory leaks:
  missing statements, out-of-memory errors, slowdown due to swapping

Mechanisms behind *valgrind*



- independent of source language
- even works without recompilation
- executes program in virtual machine
- logs every memory access
- monitors allocation and deallocation

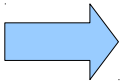
- advantages: no source code modification
- disadvantages: slowdown

Source code with memory bugs

```
 1  #include <iostream>
 2
 3  int main(void) {
 4      const int size = 100;
 5      int i = 0;
 6      double sum = 0.0;
 7
 8      double * vec = new double[size];
 9
10      for (i = size; i > 0; i--) {
11          vec[i] = static_cast<double>(i);
12      }
13
14      for (i = 0; i < size; i++) {
15          sum += vec[i];
16      }
17
18      std::cout << "sum=" << sum << std::endl;
19      return 1;
20  }
```



- compile:
  g++ -g -W -Wall -pedantic -o main main.cpp



run:
valgrind --tool=memcheck --leak-check=yes --track-origins=yes ./main

Output of memcheck: buffer overrun

```
==5027== Memcheck, a memory error detector
==5027== Copyright (C) 2002-2010, and GNU GPL'd, by Julian Seward et al.
==5027== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==5027== Command: ./main
==5027==
==5027== Invalid write of size 8
==5027==    at 0x804871C: main (main.cpp:11)
==5027==  Address 0x4318348 is 0 bytes after a block of size 800 alloc'd
==5027==    at 0x4026E3F: operator new[](unsigned int) (vg_replace_malloc.c:299)
==5027==    by 0x80486FE: main (main.cpp:8)
...
```

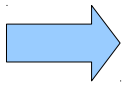
```
 8       double * vec = new double[size];
 9
10       for (i = size; i > 0; i--) {
11           vec[i] = static_cast<double>(i);
12       }
```

Where is the problem in line 11?
Debugging the code would be helpful!

Attach debugger to memcheck

valgrind --tool=memcheck --leak-check=yes --track-origins=yes --db-attach=yes ./main

```
==10849== Memcheck, a memory error detector
==10849== Copyright (C) 2002-2010, and GNU GPL'd, by Julian Seward et al.
==10849== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==10849== Command: ./main
==10849==
==10849== Invalid write of size 8
==10849==    at 0x804871C: main (main.cpp:11)
==10849==  Address 0x4318348 is 0 bytes after a block of size 800 alloc'd
==10849==    at 0x4026E3F: operator new[](unsigned int) (vg_replace_malloc.c:299)
==10849==    by 0x80486FE: main (main.cpp:8)
==10849==
==10849== ---- Attach to debugger ? --- [Return/N/n/Y/y/C/c] ---- Y
==10849== starting debugger with cmd: /usr/bin/gdb -nw /proc/10850/fd/1014 10850
GNU gdb (GDB) Red Hat Enterprise Linux (7.2-50.el6)
...
Reading symbols from /lib/ld-linux.so.2...(no debugging symbols found)...done.
Loaded symbols for /lib/ld-linux.so.2
0x0804871c in main () at main.cpp:11
11              vec[i] = static_cast<double>(i);
Missing separate debuginfos, use: debuginfo-install glibc-2.12-1.47.el6_2.12.i686
libgcc-4.4.6-3.el6.i686 libstdc++-4.4.6-3.el6.i686
(gdb) print i
$1 = 100
```



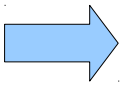
index error: vec[] only has elements 0 to 99

memcheck: uninitialised memory

```
...
==5027== Conditional jump or move depends on uninitialised value(s)
==5027==    at 0x41CA8A5: __printf_fp (in /lib/libc-2.12.so)
==5027==    by 0x41C6539: vfprintf (in /lib/libc-2.12.so)
==5027==    by 0x41ED82F: vsnprintf (in /lib/libc-2.12.so)
==5027==    by 0x40C0989: ??? (in /usr/lib/libstdc++.so.6.0.13)
==5027==    by 0x40C330D: std::ostreambuf_iterator<char, std::char_traits<char> > ...
==5027==    by 0x40C3665: std::num_put<char, std::ostreambuf_iterator<char,        ...
==5027==    by 0x40D5D4C: std::ostream& std::ostream::_M_insert<double>(double)    ...
==5027==    by 0x40D5F14: std::ostream::operator<<(double) (in /usr/lib/libstdc+   ...
==5027==    by 0x8048784: main (main.cpp:18)
==5027==  Uninitialised value was created by a heap allocation
==5027==    at 0x4026E3F: operator new[](unsigned int) (vg_replace_malloc.c:299)
==5027==    by 0x80486FE: main (main.cpp:8)
...
```

... and tons of similar errors more:
all referring to `main.cpp:18` and `main.cpp:8`

```
 8       double * vec = new double[size];
 |
14       for (i = 0; i < size; i++) {
15           sum += vec[i];
16       }
17
18       std::cout << "sum=" << sum << std::endl;
```



vec[0] was not initialized

memcheck: memory leak

```
...
==5027==
==5027== HEAP SUMMARY:
==5027==     in use at exit: 800 bytes in 1 blocks
==5027==   total heap usage: 1 allocs, 0 frees, 800 bytes allocated
==5027==
==5027== 800 bytes in 1 blocks are definitely lost in loss record 1 of 1
==5027==    at 0x4026E3F: operator new[](unsigned int) (vg_replace_malloc.c:299)
==5027==    by 0x80486FE: main (main.cpp:8)
==5027==
==5027== LEAK SUMMARY:
==5027==    definitely lost: 800 bytes in 1 blocks
==5027==    indirectly lost: 0 bytes in 0 blocks
==5027==      possibly lost: 0 bytes in 0 blocks
==5027==    still reachable: 0 bytes in 0 blocks
==5027==         suppressed: 0 bytes in 0 blocks
==5027==
...
```

not cleaned up properly

consumes all RAM if allocation is inside a loop

```
8       double * vec = new double[size];
```

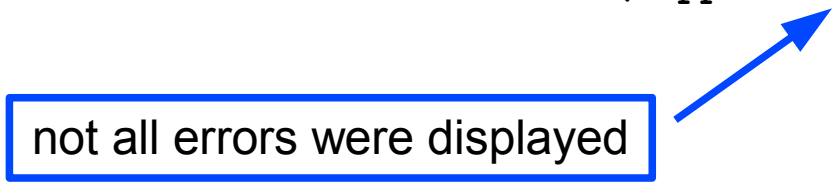
→ memory was allocated with **new** but never freed again

insert after line 16:

```
        delete[] vec;
```

Suppressed errors

```
...
==5027== For counts of detected and suppressed errors, rerun with: -v
==5027== ERROR SUMMARY: 146 errors from 80 contexts (suppressed: 21 from 10)
```



- every library may contain memory bugs
- some errors are “by design”
- *valgrind* suppresses known external errors
- own suppression rules can be defined

Program without bugs and leaks

```
==19177== Memcheck, a memory error detector
==19177== Copyright (C) 2002-2010, and GNU GPL'd, by Julian Seward et al.
==19177== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==19177== Command: ./main
==19177==
sum=4950
==19177==
==19177== HEAP SUMMARY:
==19177==     in use at exit: 0 bytes in 0 blocks
==19177==   total heap usage: 1 allocs, 1 frees, 800 bytes allocated
==19177==
==19177== All heap blocks were freed -- no leaks are possible
==19177==
==19177== For counts of detected and suppressed errors, rerun with: -v
==19177== ERROR SUMMARY: 0 errors from 0 contexts (suppressed: 20 from 9)
```

output of program

everything cleaned up

no errors

could be some work
until the output of *valgrind* for
your program looks like above

Bottlenecks

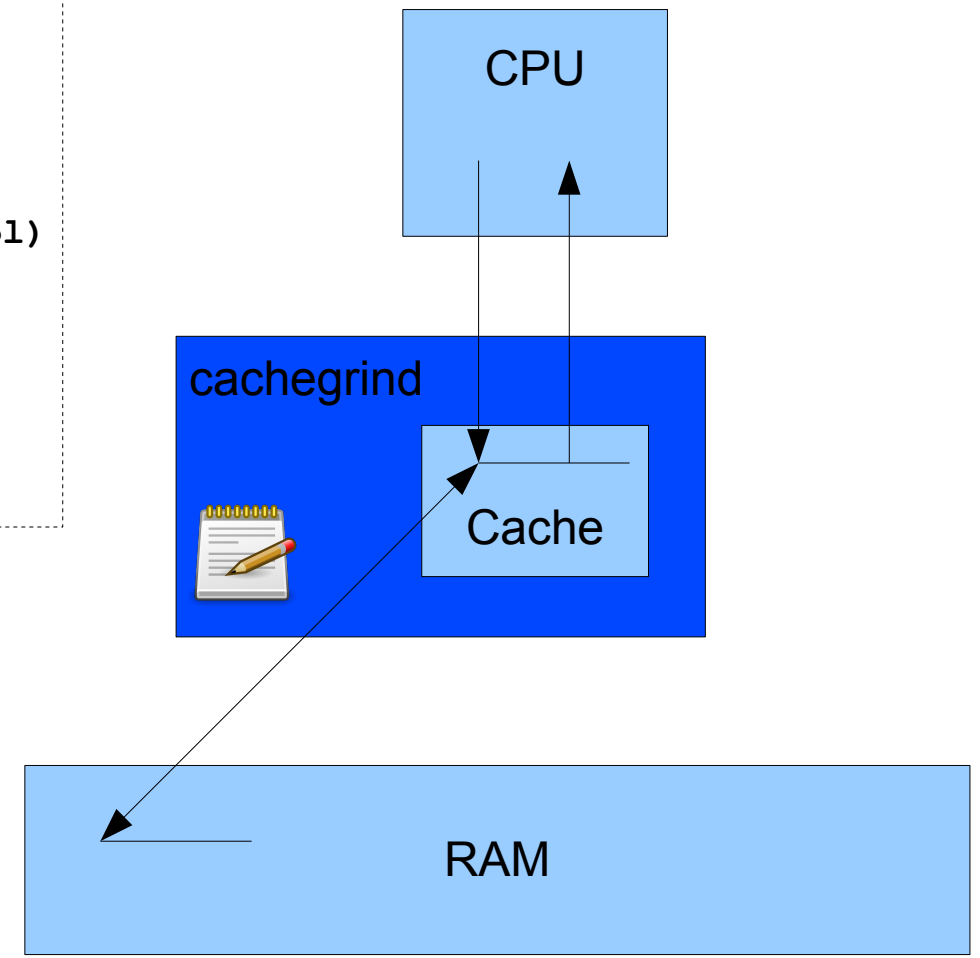
- cache access for large data structures
- slow/complex functions
- expensive algorithms inside loops

Optimizing cache access

```
const unsigned long _numRows = 100000;
const unsigned long _numCols = 100;

double ** _data;

...

unsigned long row, col;
     for (col = 0; col < _numCols; ++col)
     {
for (row = 0; row < _numRows; ++row)
{
          _data[row][col] = drand48();
     }
}
```

runtime:
0m10.370s

valgrind --tool=cachegrind ./main



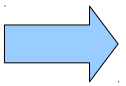
Profiling the bad code

```
==22619== Cachegrind, a cache and branch-prediction profiler
==22619== Copyright (C) 2002-2010, and GNU GPL'd, by Nicholas Nethercote et al.
==22619== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==22619== Command: ./main-unoptimized-for
==22619==
==22619==
==22619== I   refs:      14,227,732,318
==22619== I1  misses:             1,282
==22619== LLi misses:             1,234
==22619== I1  miss rate:           0.00%
==22619== LLi miss rate:           0.00%
==22619==
==22619== D   refs:       9,090,532,395  (5,690,976,115 rd   + 3,399,556,280 wr)
==22619== D1  misses:       108,562,631  (    7,489,387 rd   +   101,073,244 wr)
==22619== LLd misses:       108,386,395  (    7,321,226 rd   +   101,065,169 wr)
==22619== D1  miss rate:            1.1% (          0.1%     +           2.9%  )
==22619== LLd miss rate:            1.1% (          0.1%     +           2.9%  )
==22619==
==22619== LL refs:          108,563,913  (    7,490,669 rd   +   101,073,244 wr)
==22619== LL misses:        108,387,629  (    7,322,460 rd   +   101,065,169 wr)
==22619== LL miss rate:             0.4% (          0.0%     +           2.9%  )
```

only few instruction misses

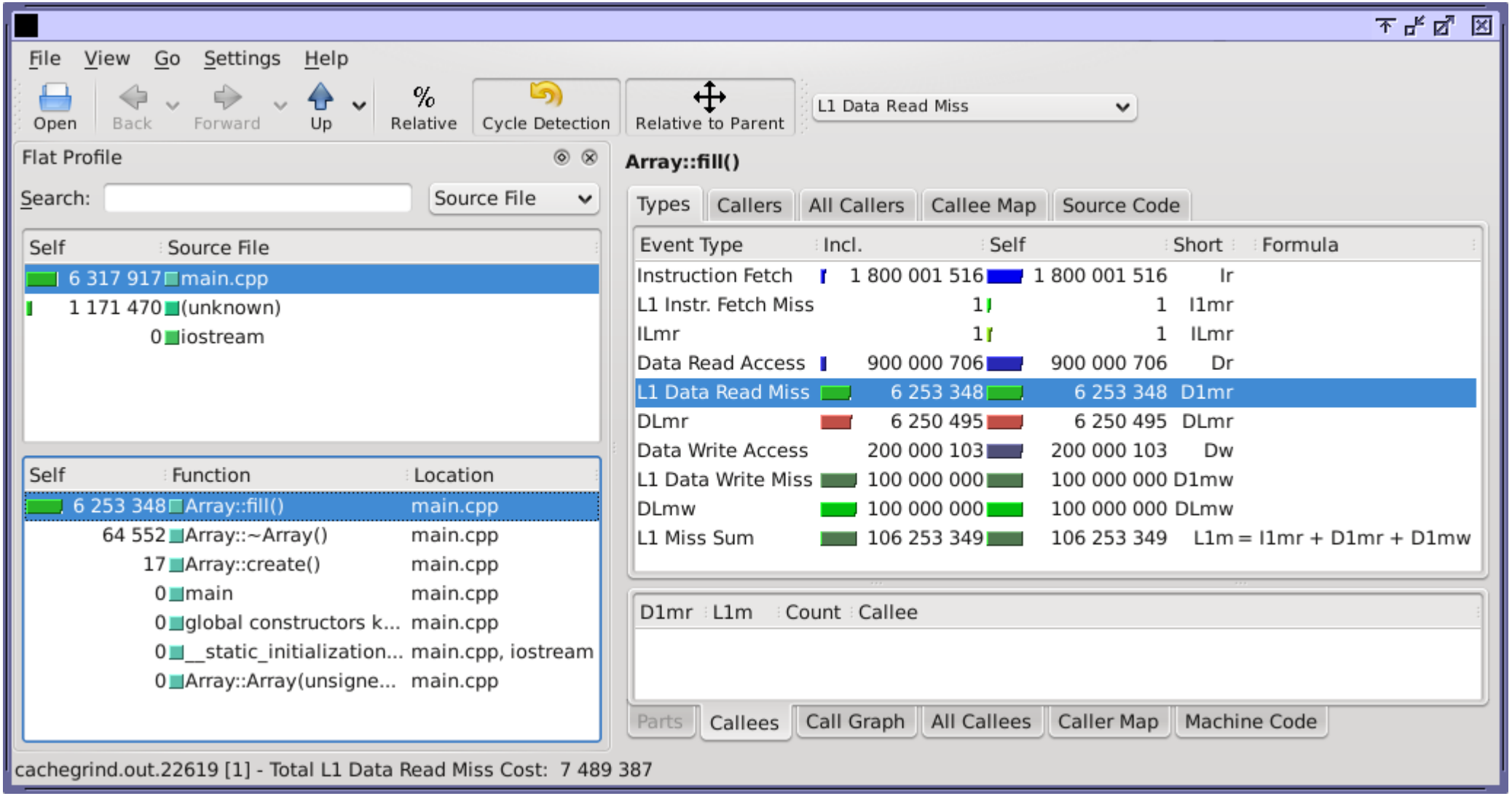
some data misses

runtime in valgrind:
5m54.599s
slowdown: 35x



analyze in detail:
kcachegrind cachegrind.out.22619

Analyze output with KCachegrind



Optimized cache access

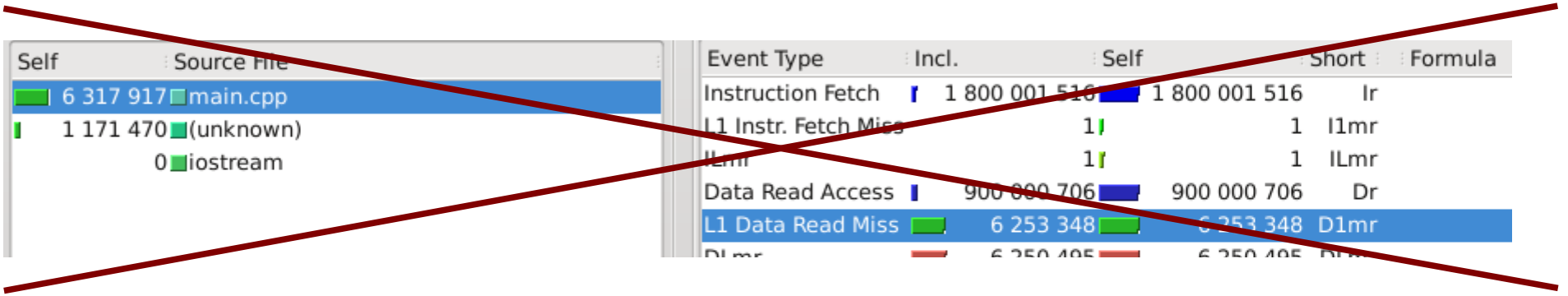
```
==22281== Cachegrind, a cache and branch-prediction profiler
==22281== Copyright (C) 2002-2010, and GNU GPL'd, by Nicholas Nethercote et al.
==22281== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==22281== Command: ./main-optimized-for
==22281==
==22281==
==22281== I   refs:      14,242,730,818
==22281== I1  misses:             1,282
==22281== LLi misses:             1,234
==22281== I1  miss rate:           0.00%
==22281== LLi miss rate:           0.00%
==22281==
==22281== D   refs:       9,098,531,595  (5,697,975,415 rd   + 3,400,555,180 wr)
==22281== D1  misses:        15,002,398  (    1,301,904 rd   +    13,700,494 wr)
==22281== LLd misses:        14,821,711  (    1,131,926 rd   +    13,689,785 wr)
==22281== D1  miss rate:            0.1% (          0.0%     +           0.4%  )
==22281== LLd miss rate:            0.1% (          0.0%     +           0.4%  )
==22281==
==22281== LL refs:           15,003,680  (    1,303,186 rd   +    13,700,494 wr)
==22281== LL misses:         14,822,945  (    1,133,160 rd   +    13,689,785 wr)
==22281== LL miss rate:             0.0% (          0.0%     +           0.4%  )
```

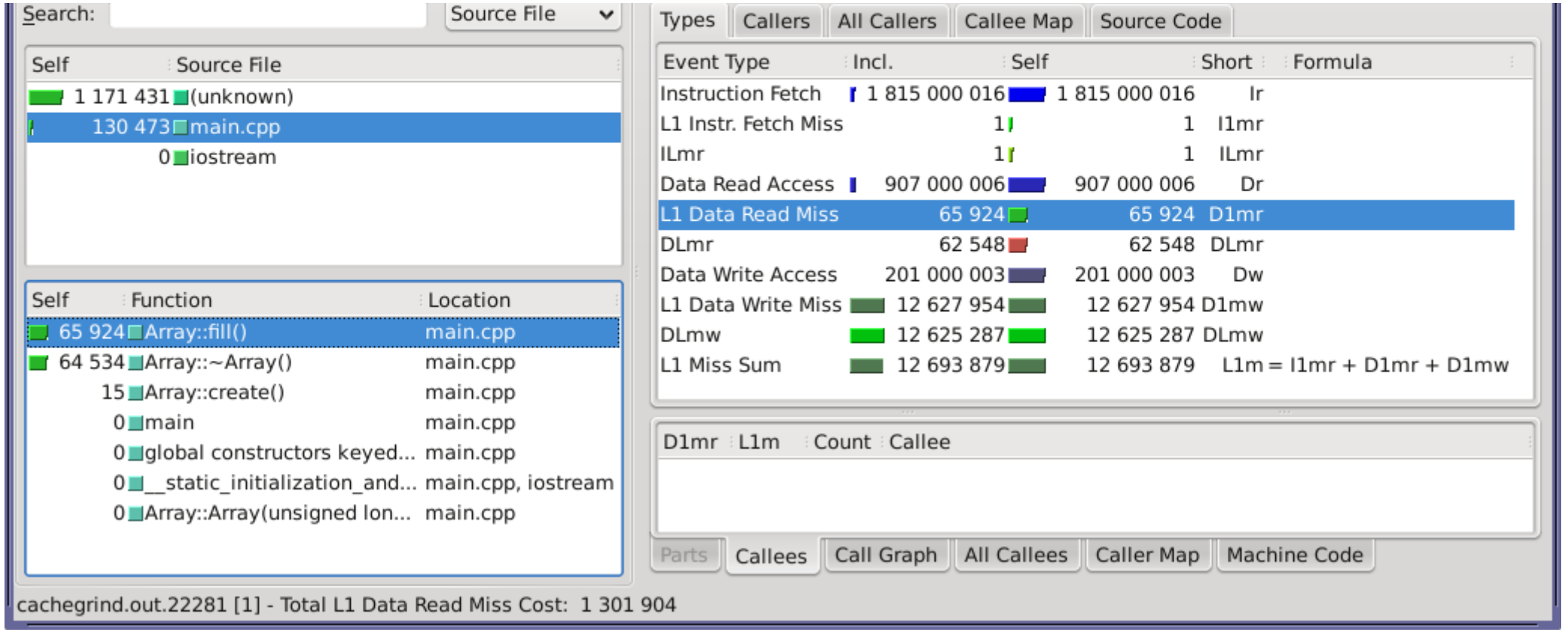
data misses were reduced

runtime in valgrind:
5m29.112s
slowdown: 60x

runtime after optimization:
0m4.796s
speedup: 2x

Success measured by cachegrind





Analyzing function calls

- determine which function calls what other function
- detecting dependencies, loops and recursive calls

```
class CoinTossing
{
public:
    CoinTossing();

    void run();

    void tossIt();
    void setHeads();
    void setTails();

    void calculation(long);
};
```

runtime:
0m10.415s

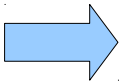
g++ -g -W -Wall -pedantic -o main main.cpp

Callgrind

valgrind --tool=callgrind ./main

```
==14756== Callgrind, a call-graph generating cache profiler
==14756== Copyright (C) 2002-2010, and GNU GPL'd, by Josef Weidendorfer et al.
==14756== Using Valgrind-3.6.0 and LibVEX; rerun with -h for copyright info
==14756== Command: ./main
==14756==
==14756== For interactive control, run 'callgrind_control -h'.
Please enter the probability for heads: 0.1
sum: -796
==14756==
==14756== Events    : Ir
==14756== Collected : 22897841697
==14756==
==14756== I   refs:      22,897,841,697
```

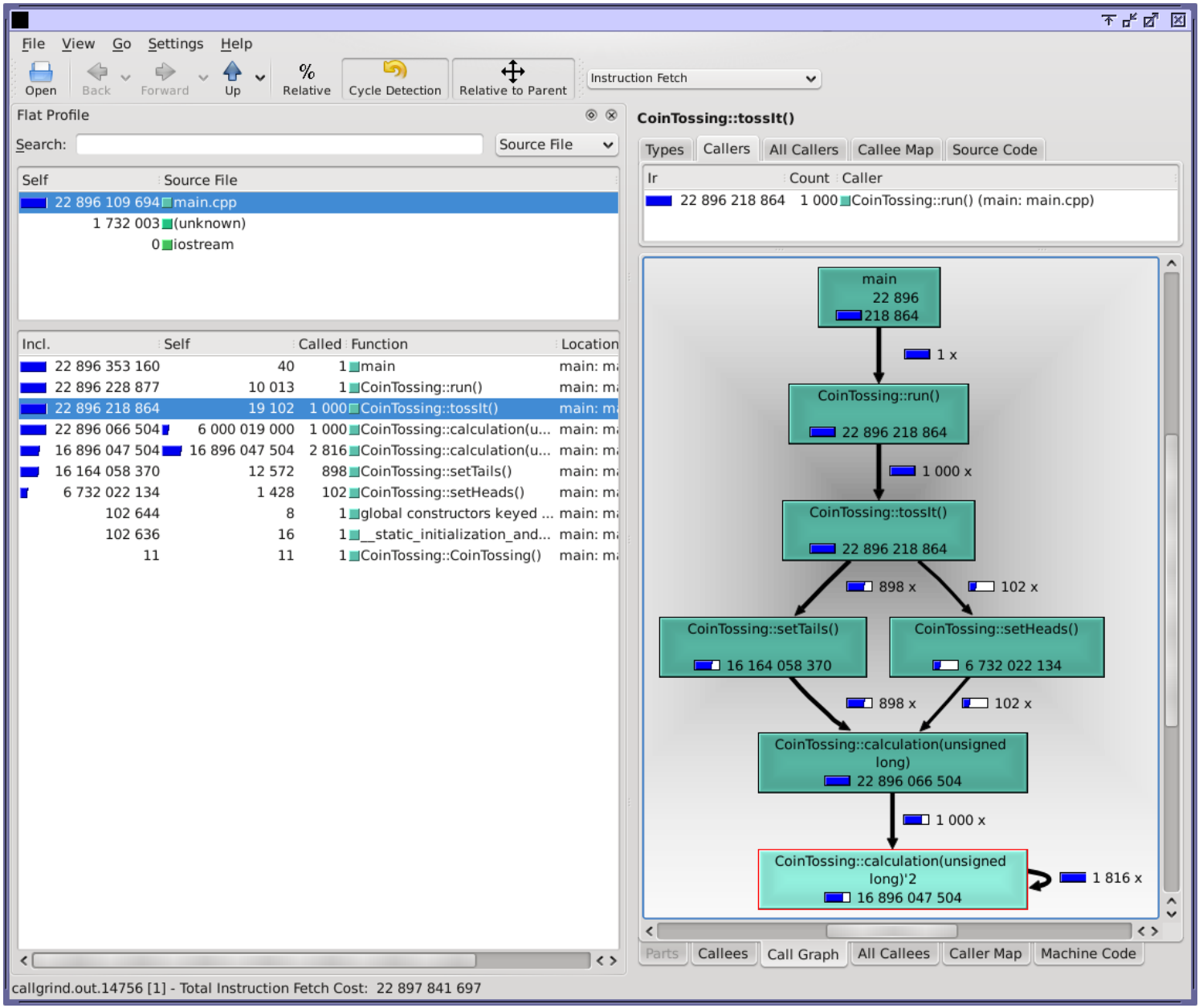
runtime in valgrind:
6m14.553s
slowdown: 36x



analyze in detail:
callgrind-annotate --auto=yes

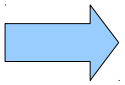
kcachegrind callgrind.out.14756

Analyze output of callgrind



Profiling with GCC

- profiling tools embedded in GNU Compiler Collection (GCC)
- compilation adds profiling instrumentation via option (-pg)
- sampling-based approach



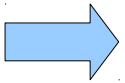
runtime of relevant parts must be much larger than sampling interval to avoid measurement errors

Compile and profile

- compile: g++ -pg -g -W -Wall -pedantic -o main main.cpp
- run: ./main
- produces binary output gmon.out, which contains profiling data

runtime:
0m10.633s

- no slowdown in our example
- slowdown in real-world projects: around 5x



much faster than *callgrind* (30x)

gprof: flat profile

gprof --flat-profile main

```
Flat profile:

Each sample counts as 0.01 seconds.
  %   cumulative   self              self     total
 time   seconds   seconds    calls   s/call   s/call  name
100.00     10.56    10.56     1000     0.01     0.01  CoinTossing::calculation(long)
  0.00     10.56     0.00     1000     0.00     0.01  CoinTossing::tossIt()
  0.00     10.56     0.00      898     0.00     0.01  CoinTossing::setTails()
  0.00     10.56     0.00      102     0.00     0.01  CoinTossing::setHeads()
  0.00     10.56     0.00        1     0.00     0.00  global constructors keyed to main
  0.00     10.56     0.00        1     0.00     0.00  __static_initialization_a...
  0.00     10.56     0.00        1     0.00    10.56  CoinTossing::run()
  0.00     10.56     0.00        1     0.00     0.00  CoinTossing::CoinTossing()
```

- gather data from several runs:
  move gmon.out to gmon.out.{id}

  gprof --sum main gmon.out.*
  gprof --flat-profile main gmon.sum

gprof: call graph

gprof --graph main

```
                     Call graph (explanation follows)
granularity: each sample hit covers 4 byte(s) for 0.09% of 10.56 seconds

index % time    self  children    called     name
                                                 <spontaneous>
[1]    100.0    0.00   10.56                 main [1]
                0.00   10.56       1/1           CoinTossing::run() [4]
                0.00    0.00       1/1           CoinTossing::CoinTossing() [12]
-----------------------------------------------
                                2816              CoinTossing::calculation(long) [2]
                1.08    0.00     102/1000        CoinTossing::setHeads() [6]
                9.48    0.00     898/1000        CoinTossing::setTails() [5]
[2]    100.0   10.56    0.00    1000+2816     CoinTossing::calculation(long) [2]
                                2816              CoinTossing::calculation(long) [2]
-----------------------------------------------
                0.00   10.56    1000/1000        CoinTossing::run() [4]
[3]    100.0    0.00   10.56    1000          CoinTossing::tossIt() [3]
                0.00    9.48     898/898         CoinTossing::setTails() [5]
                0.00    1.08     102/102         CoinTossing::setHeads() [6]
-----------------------------------------------
                0.00   10.56       1/1           main [1]
[4]    100.0    0.00   10.56       1          CoinTossing::run() [4]
                0.00   10.56    1000/1000        CoinTossing::tossIt() [3]
-----------------------------------------------
```

Summary

- check for bugs
  valgrind --tool=memcheck
- look for cache misses
  valgrind --tool=cachegrind
- look for functions with bottlenecks
  valgrind --tool=callgrind

- analyze output with KCachegrind
- significant slowdown of execution
- *gprof* provides information similar to *callgrind* but much faster

Alternative tools

- memory debuggers:

  Purify, Insure++
- profiling tools:

  Quantify

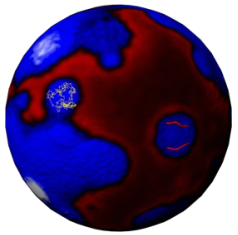
- thread checking:

  valgrind --tool=helgrind

References

- valgrind.org
  sourceware.org/binutils/docs/gprof/
- T. Grötker, U. Holtmann, H. Keding and M. Wloka: The Developer's Guide to Debugging, Springer (2008).
- W. von Hagen: The Definitive Guide to GCC, Apress (2006).

Acknowledgements



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