Cache Performance Analysis with Callgrind and KCachegrind

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Outline

- Background
- Callgrind and {Q,K}Cachegrind
  - Measurement
  - Visualization
- Demo
  - Example: Matrix Multiplication

This Talk is about Sequential Performance

Sequential vs. parallel performance

- conceptually orthogonal: performance improvement of sequential code parts always helps, but
- better optimized sequential code sometimes more difficult to parallelize
- parallel code: resources shared among threads/processes
  - on multicore: higher bandwidth requirement to main memory
  - use of shared caches:
    cores compete for space vs. cores prefetch for each other

Background

- sequential performance bottlenecks
  - logical errors (unneeded/redundant function calls)
  - bad algorithm (high complexity or huge “constant factor”)
  - bad exploitation of available resources

- how to improve sequential performance
  - use tuned libraries where available
  - check for above obstacles ➔ always by use of analysis tools

Sequential Performance Analysis Tools

- count occurrences of events
  - resource exploitation is related to events
  - SW-related: function call, OS scheduling, ...
  - HW-related: FLOP executed, memory access, cache miss, time spent for an activity (like running an instruction)

- relate events to source code
  - find code regions where most time is spent
  - check for improvement after changes
  - „Profile data“: histogram of events happening at given code positions
  - inclusive vs. exclusive cost

How to measure Events (1)

- target
  - real hardware
    - needs sensors for interesting events
    - for low overhead: hardware support for event counting
    - difficult to understand because of unknown micro-architecture, overlapping and asynchronous execution
  - machine model
    - events generated by a simulation of a (simplified) hardware model
    - no measurement overhead: allows for sophisticated online processing
    - simple models relatively easy to understand
- both methods (real vs. model) has advantages & disadvantages, but reality matters in the end

How to measure Events (2)

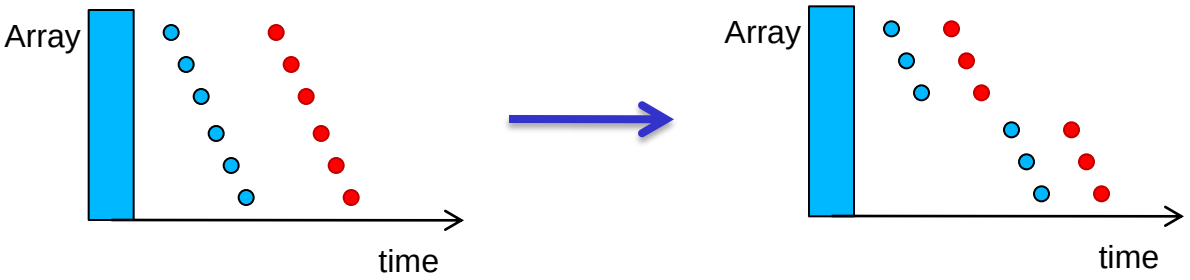
- SW-related
  - instrumentation (= insertion of measurement code)
    - into OS / application, manual/automatic, on source/binary level
    - on real HW: always incurs overhead which is difficult to estimate
- HW-related
  - read Hardware Performance Counters
    - gives exact event counts for code ranges
    - needs instrumentation
  - statistical: Sampling
    - event distribution over code approximated by checking every N-th event
    - hardware notifies only about every N-th event ➔ Influence tunable by N

Architectural Performance Problem Today: Main Memory

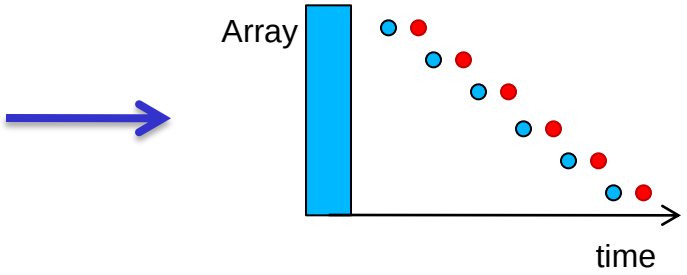
- access latency ~ 200 cycles
  - 400 FLOP wasted for one main memory access
  - Solution:
    - Memory controller on chip
    - Exploit fast caches (Locality of accesses!)
    - Prefetch data (automatically)
- bandwidth available for one chip ~ 3 – 30 GB/s
  - all cores have to share the bandwidth
  - can prevent effective prefetching
  - solution:
    - Share data in caches among cores
    - Keep working set in cache (temporal locality!)
    - use good data layout (spatial locality!)

Typical Cache Optimizations: Reordering Accesses

- Blocking



- Interweaving



- Also in multiple dimensions
- Data dependencies of algorithm have to be maintained

Callgrind

Cache Simulation with Call-Graph Relation

Callgrind: Basic Features

- based on Valgrind
  - runtime instrumentation infrastructure (no recompilation needed)
  - dynamic binary translation of user-level processes
  - Linux/AIX/OS X on x86, x86-64, PPC32/64, ARM (VG 3.6: ~10/2010)

  - correctness checking & profiling tools on top
    - “memcheck”: accessibility/validity of memory accesses
    - “helgrind” / ”drd”: race detection on multithreaded code
    - “cachegrind”/”callgrind”: cache & branch prediction simulation
    - “massif”: memory profiling

  - Open source (GPL)
  - www.valgrind.org

Callgrind: Basic Features

- part of Valgrind since 3.1
  - Open Source, GPL

- measurement
  - profiling via machine simulation (simple cache model)
  - instruments memory accesses to feed cache simulator
  - hook into call/return instructions, thread switches, signal handlers
  - instruments (conditional) jumps for CFG inside of functions

- presentation of results: `callgrind_annotate` / {Q,K}Cachegrind

Pro & Contra (i.e. Simulation vs. Real Measurement)

- usage of Valgrind
  - driven only by user-level instructions of one process
  - slowdown (call-graph tracing: 15-20x, + cache simulation: 40-60x)
    - “fast-forward mode”: 2-3x
  - ✓ allows detailed (mostly reproducable) observation
  - ✓ does not need root access / can not crash machine

- cache model
  - “not reality”: synchronous 2-level inclusive cache hierarchy (size/associativity taken from real machine, always including LLC)
  - ✓ easy to understand / reconstruct for user
  - ✓ reproducible results independent on real machine load
  - ✓ derived optimizations applicable for most architectures

Callgrind: Advanced Features

- interactive control (backtrace, dump command, …)
- “fast forward”-mode to get to quickly interesting code phases
- application control via “client requests” (start/stop, dump)

- avoidance of recursive function call cycles
  - cycles are bad for analysis (inclusive costs not applicable)
  - add dynamic context into function names (call chain/recursion depth)

- best-case simulation of simple stream prefetcher
- usage of cache lines before eviction
- optional branch prediction

Callgrind: Usage

- `valgrind –tool=callgrind [callgrind options] yourprogram args`
- cache simulator: `--simulate-cache=yes`
- branch prediction simulation (VG 3.6): `--simulate-cache=yes`
- enable for machine code annotation: `--dump-instr=yes`
- start in “fast-forward”: `--instr-atstart=yes`
  - switch on event collection: `callgrind_control –i on`
- spontaneous dump: `callgrind_control –d [dump identification]`
- current backtrace of threads (interactive): `callgrind_control –b`
- separate dumps per thread: `--separate-threads=yes`
- jump-tracing in functions (CFG): `--collect-jumps=yes`

{Q,K}Cachegrind

Graphical Browser for Profile Visualization

Features

- open source, GPL
- kcachegrind.sf.net (release of pure Qt version pending)
- included with KDE3 & KDE4

- visualization of
  - call relationship of functions (callers, callees, call graph)
  - exclusive/Inclusive cost metrics of functions
    - grouping according to ELF object / source file / C++ class
  - source/assembly annotation: costs + CFG
  - arbitrary events counts + specification of derived events

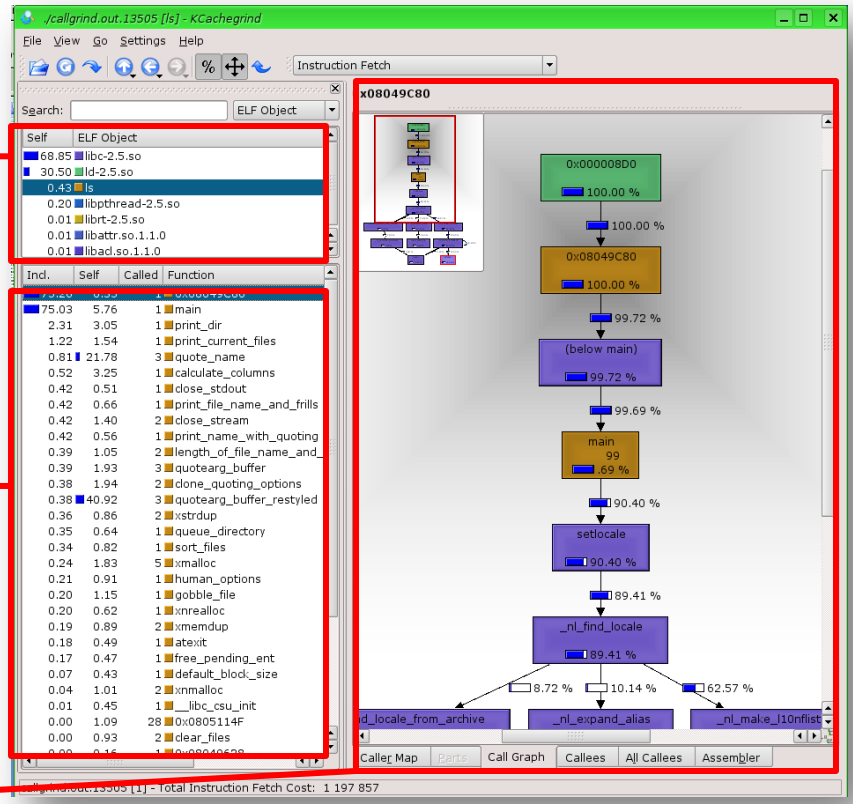
- callgrind support (file format, events of cache model)

Usage

- `kcachegrind callgrind.out.<pid>`

- left: “Dockables”
  - list of function groups groups according to
    - library (ELF object)
    - source
    - class (C++)
  - list of functions with
    - inclusive
    - exclusive costs

- right: visualization panes

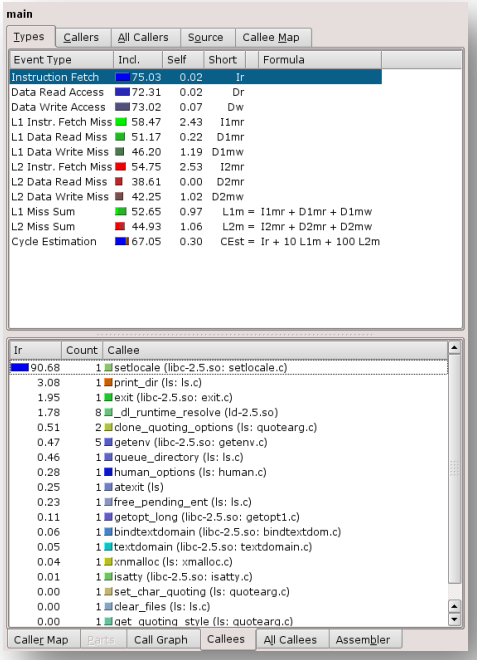


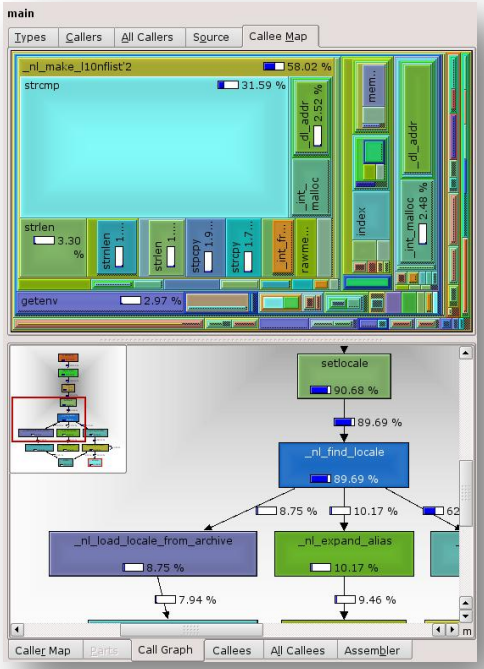
Visualization panes for selected function

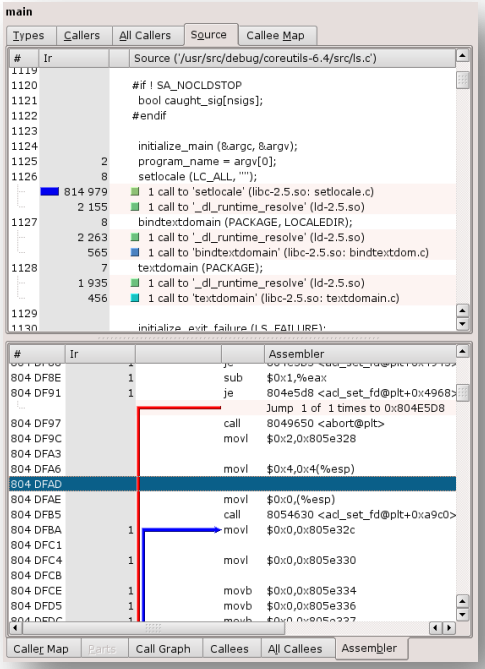
- List of event types
- List of callers/callees

- Treemap visualization
- Call Graph

- Source annotation
- Assemly annotation





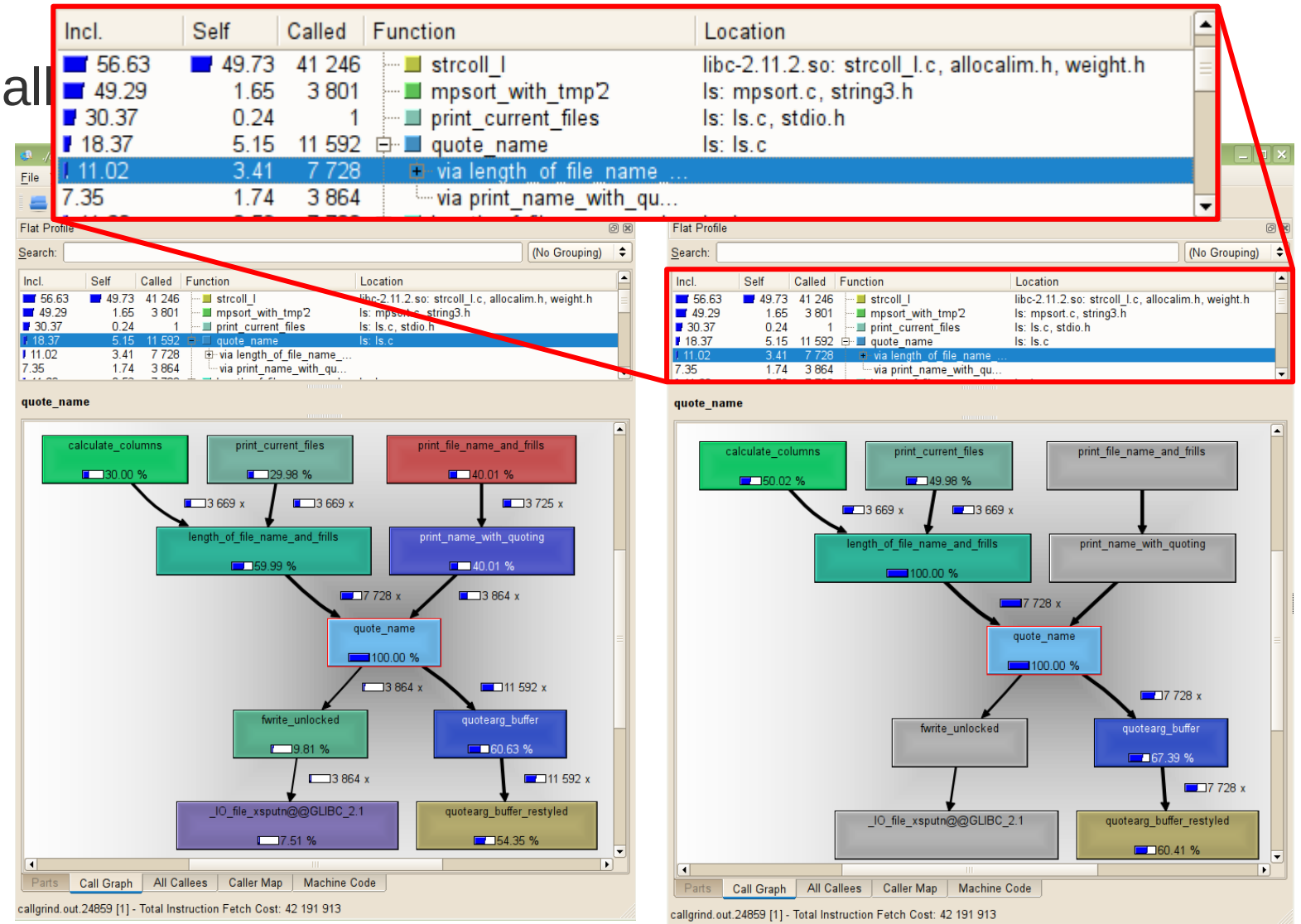


Upcoming …

- callgrind
  - event relation to data structures
  - command line tool for measurement merging & results
  - multicore cache simulation (detection of data sharing)

- KCachegrind
  - pure Qt version (Windows/OS X)
  - call graph context visualization

Call


Incl. Self Called Function Location
56.63 49.73 41 246 strcoll_l libc-2.11.2.so: strcoll_l.c, allocalim.h, weight.h
49.29 1.65 3 801 mpsort_with_tmp'2 ls: mpsort.c, string3.h
30.37 0.24 1 print_current_files ls: ls.c, stdio.h
18.37 5.15 11 592 quote_name ls: ls.c
11.02 3.41 7 728 via length_of_file_name_...
7.35 1.74 3 864 via print_name_with_qu...
Flat Profile
Search:
(No Grouping)
quote_name
calculate_columns 30.00 %
print_current_files 29.98 %
print_file_name_and_frills 40.01 %
3 669 x
3 669 x
3 725 x
length_of_file_name_and_frills 59.99 %
print_name_with_quoting 40.01 %
7 728 x
3 864 x
quote_name 100.00 %
3 864 x
11 592 x
fwrite_unlocked 9.81 %
quotearg_buffer 60.63 %
3 864 x
11 592 x
_IO_file_xsputn@@GLIBC_2.1 7.51 %
quotearg_buffer_restyled 54.35 %
Parts
Call Graph
All Callees
Caller Map
Machine Code
callgrind.out.24859 [1] - Total Instruction Fetch Cost: 42 191 913
calculate_columns 50.02 %
print_current_files 49.98 %
print_file_name_and_frills
3 669 x
3 669 x
length_of_file_name_and_frills 100.00 %
print_name_with_quoting
7 728 x
quote_name 100.00 %
7 728 x
fwrite_unlocked
quotearg_buffer 67.39 %
7 728 x
_IO_file_xsputn@@GLIBC_2.1
quotearg_buffer_restyled 60.41 %

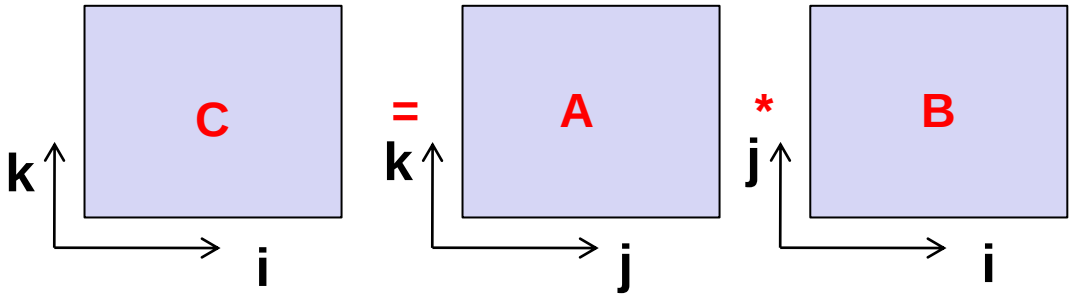
Demo

Getting started

- Try it out yourself on Live-DVD
  - see /usr/local/packages/kcachegrind/README
- Test: What happens in „/bin/ls“ ?
  - **`valgrind --tool=callgrind ls /usr/bin`**
  - **`qcachegrind`**
  - What function takes most instruction executions? Purpose?
  - Where is the main function?

Detailed analysis of matrix multiplication

- Kernel for C = A * B
  - Side length N ➔ N^3 multiplications + N^3 additions




```
c[k][i] = a[k][j] * b[j][i]
```

  - 3 nested loops (i,j,k): Best index order?
  - Optimization for large matrixes: Blocking

Detailed analysis of matrix multiplication

- To try out...
  - cp -r /usr/local/packages/kcachegrind/example-mm .
  - **`make CFLAGS='-O2 -g'`**
  - Timing of orderings (e.g. size 800): **`./mm 800`**
  - Cache behavior for small matrix (fitting into cache):
    `valgrind --tool=callgrind --simulate-cache=yes ./mm 300`
  - How good is L1/L2 exploitation of the MM versions?
  - Large matrix (mm800/callgrind.out). How does blocking help?

?

Q&A

?