Sequential Performance Analysis with Callgrind and KCachegrind

4th Parallel Tools Workshop, HLRS, Stuttgart, September 7/8, 2010

Josef Weidendorfer

Lehrstuhl für Rechnertechnik und Rechnerorganisation
Institut für Informatik, Technische Universität München

Outline

- Background
- Callgrind and {Q,K}Cachegrind
  - Measurement
  - Visualization
- Demo & Hands-on
  - Getting started
  - 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
- with parallel code, exploitation of available resources changes
  - on multicore: higher bandwidth requirement to main memory
  - use of shared caches:
    cores compete for space vs. prefetching effects among cores

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
  - software-related: function call, OS scheduling, ...
  - hardware-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
  - 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
  - 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

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!)

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)

  - 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

Callgrind: Pro and Contra

- 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`
- start in “fast-forward”: `--instr-atstart=yes`
  - switch on event collection: `callgrind_control –i on`
- jump-tracing in functions (CFG): `--collect-jumps=yes`
- separate dumps per thread: `--separate-threads=yes`
- current backtrace of threads (interactive): `callgrind_control –b`
- spontaneous dump: `callgrind_control –d [dump identification]`

{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

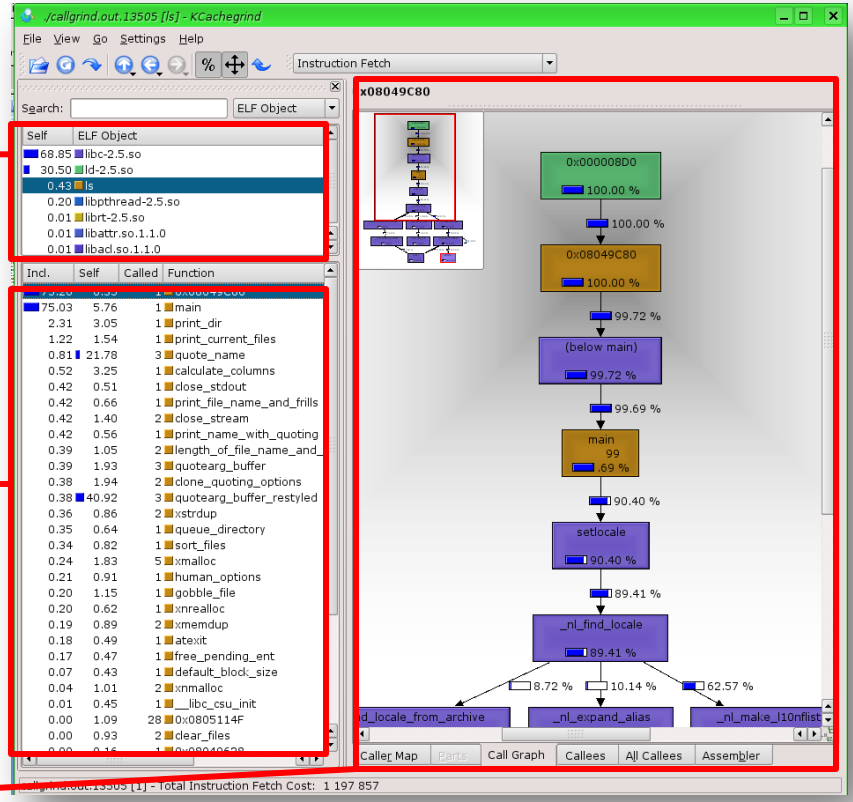
- callgrind support (file format, events of cache model)

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

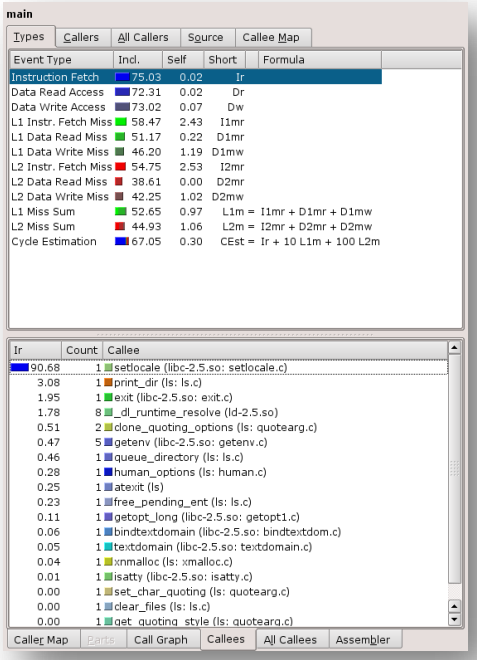


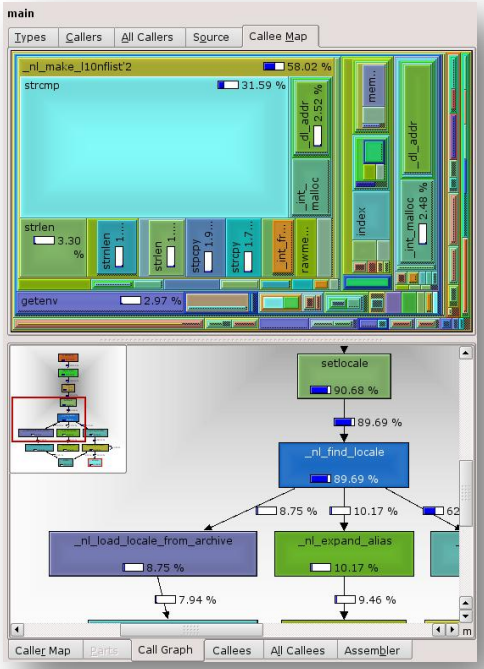
Visualization panes for selected function

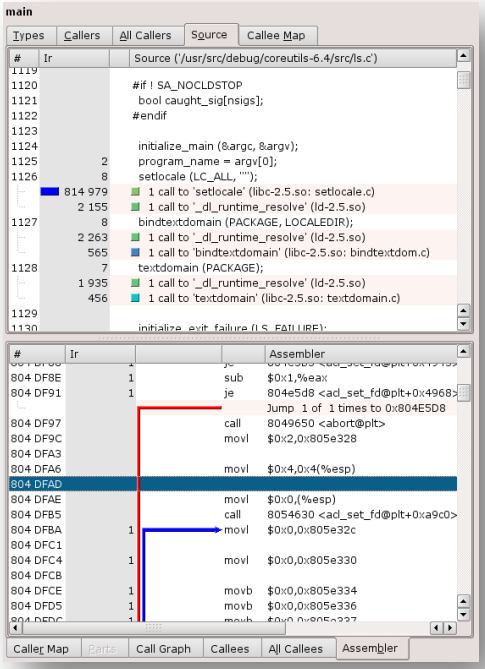
- List of event types
- List of callers/callees

- Treemap visualization
- Call Graph

- Source annotation
- Assemly annotation







Upcoming …

- callgrind
  - multicore cache simulation
    (detection of data sharing, not load balancing)
  - command line tool for measurement merging & results
  - event relation to data structures

- KCachegrind
  - pure Qt version (Windows/OS X)

Demo & Hands-on

Getting started

- Login to cluster (or use Knoppix locally):
  - `ssh rzvmpi13@frbw.dgrid.hlrs.de` (PW: tws_us4er)
  - `svn co --username tws_user https://svn.gforge.hlrs.de/svn/tws-examples/kcachegrind`

- Setup your environment:
  - **`module load valgrind`**
  - **`tws-examples/kcachegrind/README`**

- Test: What happens in „/bin/ls“ ?
  - **`valgrind --tool=callgrind ls /usr/bin`**
  - **`kcachegrind`**
  - 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
  - 3 nested loops (i,j,k): Best index order?
  - Optimization for large matrixes: Blocking

- Code: mm/mm.c
  - **`make CFLAGS='-O2 -g'`**
  - Timing of orderings (size 300 – 800): **`./mm 300 800`**
  - 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

?