Understanding Memory Access Bottlenecks On Multicore

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MUNICH-CORE INITIATIVE

Outline

- Introduction
  Relevance for Mini Symposium Topic
- Memory Access Bottlenecks and Metrics
  From Single- to Multicore
- Our Tool Suite
  Callgrind / KCachegrind
  Issues with Existing Visualizations & Experiences
- Conclusion and Future Work

Relevance for Mini Symposium Topic

- Usability
- Scalability

Cope with large amount of events (memory accesses !)

- In the measurement tool
- In the visualization tool

In measurement

- Use statistical methods / simulation
- Online processing to reduce amount of data
  - Filtering / Selection
  - Aggregation ($\rightarrow$ Profile)

Memory Access Bottlenecks

Main problem: “Memory wall”
Increasing performance gap main memory vs. processor

True for Multicore, too

Solution: Caches

True for Multicore, too

- Exploit locality of memory accesses (temporal / spatial)
- Lowers access latency by putting data copies into fast memory
  - Keep recently used copies (accounts for temporal locality)
  - Block oriented (accounts for spatial locality)
- „Bad memory access behavior“: Poor exploitation of caches

Optimization strategies

True for Multicore, too

- Improve temporal locality by reordering accesses
- Improve spatial locality by changing data layout
- Prefetch data needed in the future

Memory Access Bottlenecks

Multicore adds

- All the issues of parallel code
  - Load balancing, synchronization overhead, difficult to program …
- Cores share available resources for
  - Connection to main memory
  - Caches
- Software has to cope with new configurations
  - Caches shared vs. separate per core, increased memory hierarchy

Optimization strategies

- Best process placing for good exploitation of available caches?

Analysis of Memory Access Behavior

Good Tools™ give following answers

- Yes, we have a problem because of memory accesses
- And it happens there
  (code position + call path + data structure + thread/process)
- Yes, it makes sense to optimize (potential benefit)
- Just try to do this and that to avoid cache pollution / bad layout / …
  (good hints with expertise)

What are good metrics to see the problem and path to solution?

Metrics for Bad Memory Access Behavior

- Cache miss counts
  - Good: Pinpoints where time is lost (But: how much? Data structure?)
  - Difficult to derive optimization (e.g. what/how to block?)

- Temporal / spatial cache line usage:
  How much / often used before eviction
  - Easy to see bad memory layout (e.g. hash lookups)

- Model of idealized (unlimited) cache with LRU list of data accesses

- Simulation of bandwidth requirement

LRU List of Data Accesses

- Relates to behavior of fully associate cache
- Example: Address sequence 1 2 3 4 2 3 2 2 5

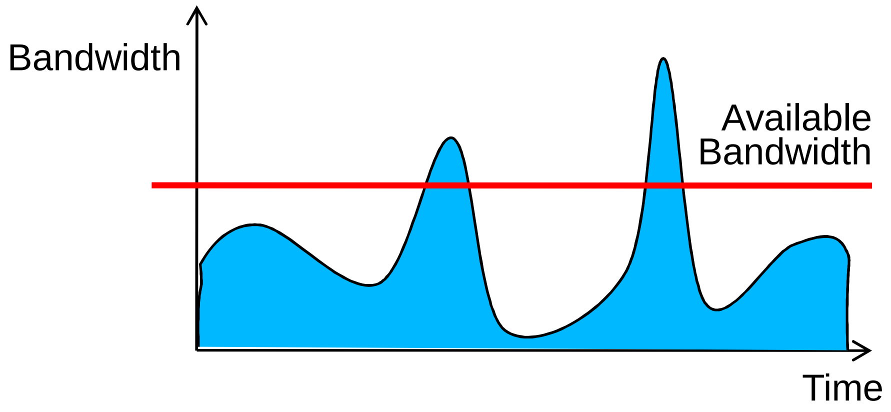
LRU offset	0	1	2	3	4
Address	5	2	3	4	1
Last access (time steps)	0	1	3	5	8

Distance	1	2	3
Accesses	1	1	2

- Provides size of working set (used in given time span)
- Stack reuse distance: histogram over move distances on access (See papers of K. Beyls)
  - Percentage of accesses covered by given cache size
  - Which data structures have bad locality with high influence

Simulation of Bandwidth Requirement

- What is the required amount of data with ideal memory? (Suppose only computation-boundness)
  - Has to be simulated
  - Simple CPU model (given latency for each opcode)



  - Which structures are better served from cache?
  - Gives hints for prefetching (can prefetching pollute cache?)

Adaption for Multicore

- Bandwidth requirement diagram (easy)
  - Additional curves for shared vs. separate caches
- Multiple LRU lists
  - for all cores
    - reuse distances with shared cache
    - provides information for workset overlapping
  - for each core pair: shared with other“, „invalidated by other“
    - Shows amount communication between cores (size + number)
- Should provide hints for
  - placement of processes (exploit same workset via shared cache)
  - prefetch helper thread for multiple cores

Our Tool Suite: Callgrind / KCachegrind

Measurement

- Based on Valgrind (runtime instrumentation, known for "memcheck")
- Instrument memory accesses feed cache simulator
- Profiling tool relating cache events to call-graph (path relation possible)

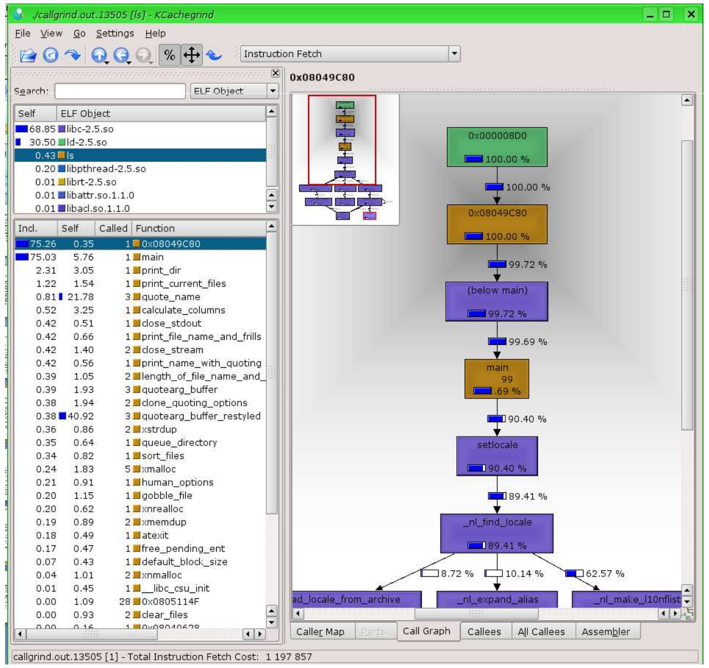
Pro and Contra

- Memory accesses only from user-level code, Slowdown (40-60x)
- Synchronous 2-level inclusive cache (optional hardware prefetcher)

✓ Does not need root access / can not crash machine
✓ Allows for sophisticated metrics (line usage, stack reuse distance)
✓ Easy to understand / reconstruct for user
✓ Reproducible results independent on real machine load
✓ Derived optimizations applicable for many architectures

Our Tool Suite: Callgrind / KCachegrind

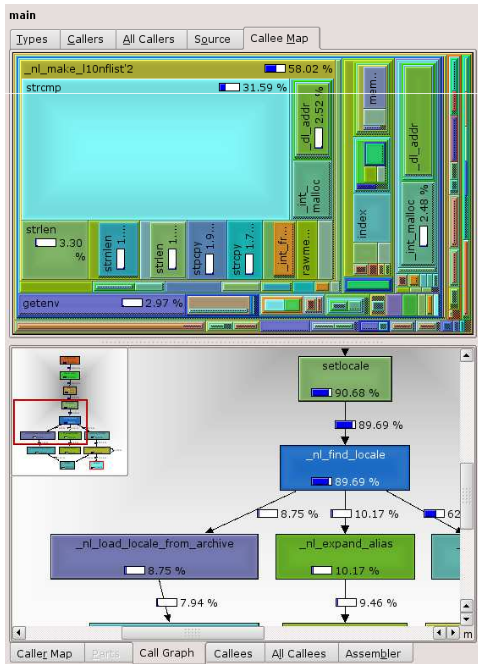
- Visualization
  - Call relationship of functions (callers, callees, call graph, tree map)
  - Source/Assembly annotation: event counts + control flow

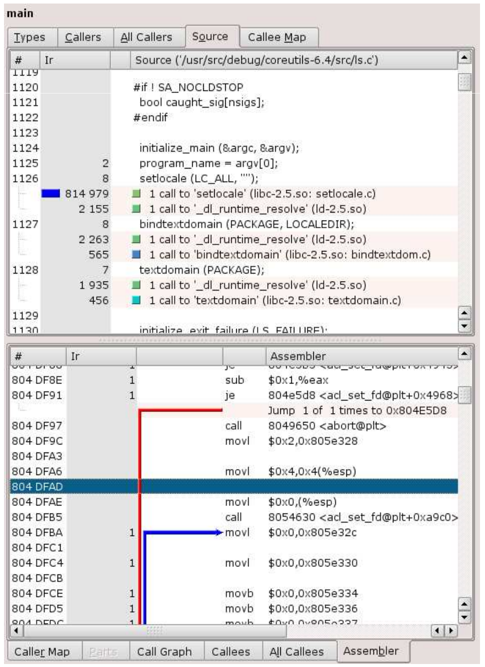


Self	ELF Object
68.85	libc-2.5.so
30.50	ld-2.5.so
0.43	ls
0.20	libpthread-2.5.so
0.01	librt-2.5.so
0.01	libattr.so.1.1.0
0.01	libacl.so.1.1.0

Incl.	Self	Called	Function
75.26	0.35	1	0x08049C80
75.03	5.76	1	main
2.31	3.05	1	print_dir
1.22	1.54	1	print_current_files
0.81	21.78	3	quote_name
0.52	3.25	1	calculate_columns
0.42	0.51	1	close_stdout
0.42	0.66	1	print_file_name_and_frills
0.42	1.40	2	close_stream
0.42	0.56	1	print_name_with_quoting
0.39	1.05	2	length_of_file_name_and_
0.39	1.93	3	quotearg_buffer
0.38	1.94	2	clone_quoting_options
0.38	40.92	3	quotearg_buffer_restyled
0.36	0.86	2	xstrdup
0.35	0.64	1	queue_directory
0.34	0.82	1	sort_files
0.24	1.83	5	xmalloc
0.21	0.91	1	human_options
0.20	1.15	1	gobble_file
0.20	0.62	1	xnrealloc
0.19	0.89	2	xmemdup
0.18	0.49	1	atexit
0.17	0.47	1	free_pending_ent
0.07	0.43	1	default_block_size
0.04	1.01	2	xnmalloc
0.01	0.45	1	__libc_csu_init
0.00	1.09	28	0x0805114F
0.00	0.93	2	clear_files

callgrind.out.13505 [1] - Total Instruction Fetch Cost: 1 197 857





```
#     Ir        Source ('/usr/src/debug/coreutils-6.4/src/ls.c')
1120            #if ! SA_NOCLDSTOP
1121              bool caught_sig[nsigs];
1122            #endif
1123
1124              initialize_main (&argc, &argv);
1125         2    program_name = argv[0];
1126         8    setlocale (LC_ALL, "");
       814 979    1 call to 'setlocale' (libc-2.5.so: setlocale.c)
         2 155    1 call to '_dl_runtime_resolve' (ld-2.5.so)
1127         8    bindtextdomain (PACKAGE, LOCALEDIR);
         2 263    1 call to '_dl_runtime_resolve' (ld-2.5.so)
           565    1 call to 'bindtextdomain' (libc-2.5.so: bindtextdom.c)
1128         7    textdomain (PACKAGE);
         1 935    1 call to '_dl_runtime_resolve' (ld-2.5.so)
           456    1 call to 'textdomain' (libc-2.5.so: textdomain.c)
1129
```

```
#          Ir        Assembler
804 DF8E    1   sub    $0x1,%eax
804 DF91    1   je     804e5d8 <acl_set_fd@plt+0x4968>
                       Jump  1 of  1 times to 0x804E5D8
804 DF97        call   8049650 <abort@plt>
804 DF9C        movl   $0x2,0x805e328
804 DFA3
804 DFA6        movl   $0x4,0x4(%esp)
804 DFAD
804 DFAE        movl   $0x0,(%esp)
804 DFB5        call   8054630 <acl_set_fd@plt+0xa9c0>
804 DFBA    1   movl   $0x0,0x805e32c
804 DFC1
804 DFC4    1   movl   $0x0,0x805e330
804 DFCB
804 DFCE    1   movb   $0x0,0x805e334
804 DFD5    1   movb   $0x0,0x805e336
```

Experiences with existing Visualizations

Provide not only graphical results, but

- export to ASCII lists (HTML / XML), or better
- equivalent command line tool for scriptability: merging, querying, …

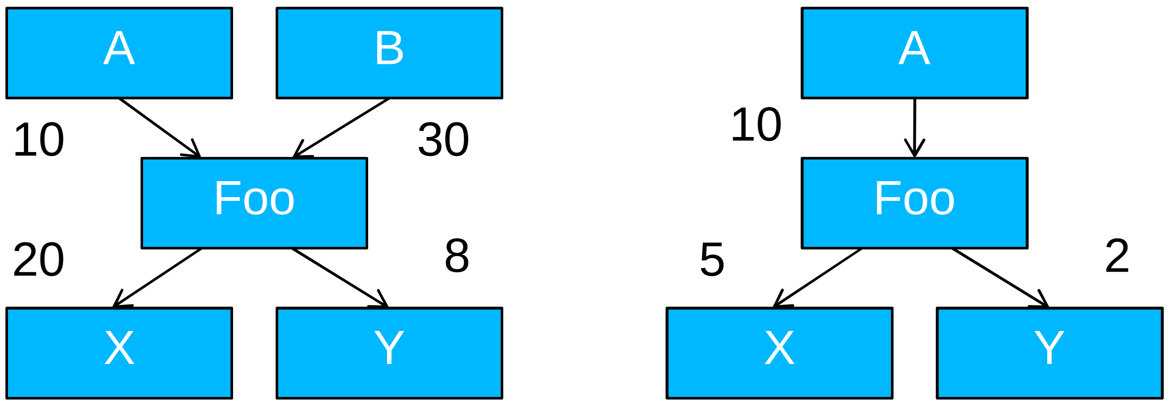
Graphical interface

- Very clean user interface, small number of views / areas
- Only a few different view types into data, familiar to users
  - ✓ lists, call graphs, bar charts, heat maps, diagrams
  - – tree maps, fully crowded 3-D views
- Highly interactive views
  - responsive
  - zoomable (one visualization with multiple detail levels)
  - intuitive narrowing / filtering of data
  - non-disruptive browsing (incremental or animation)
- Careful, consistent use of color coding

Improvements for existing Visualization: Call Graph

Issue: Tools seems to claim to always have full path profiling data

Example: Foo selected A selected

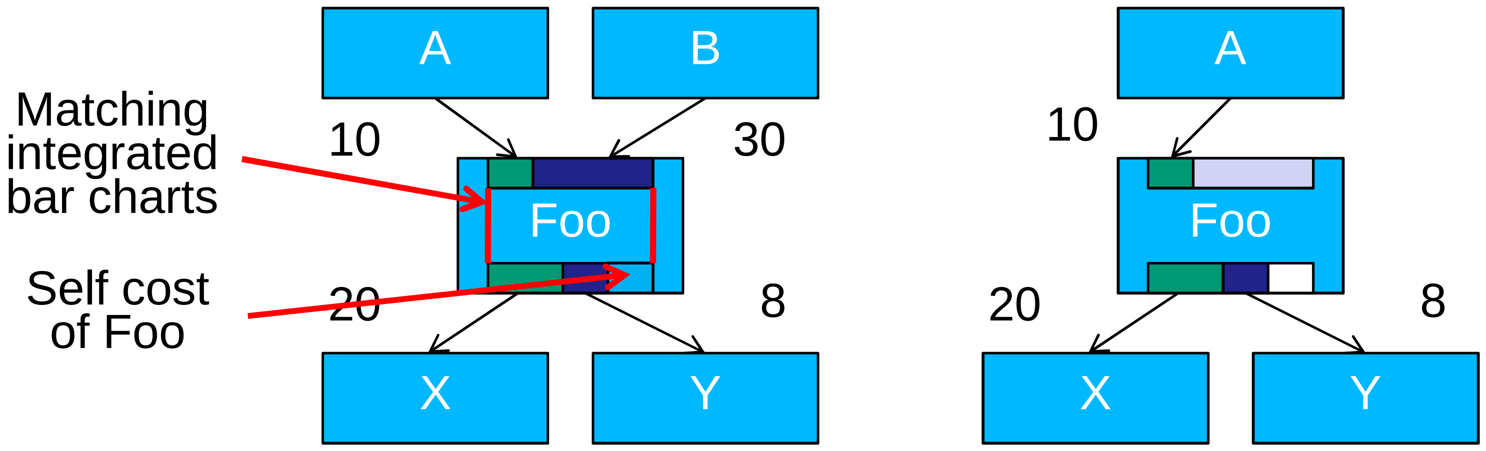


Reality could have been: Foo → X only when called from B !

Improvements for existing Visualization: Call Graph

Issue: Tools seems to claim to always have full path profiling data

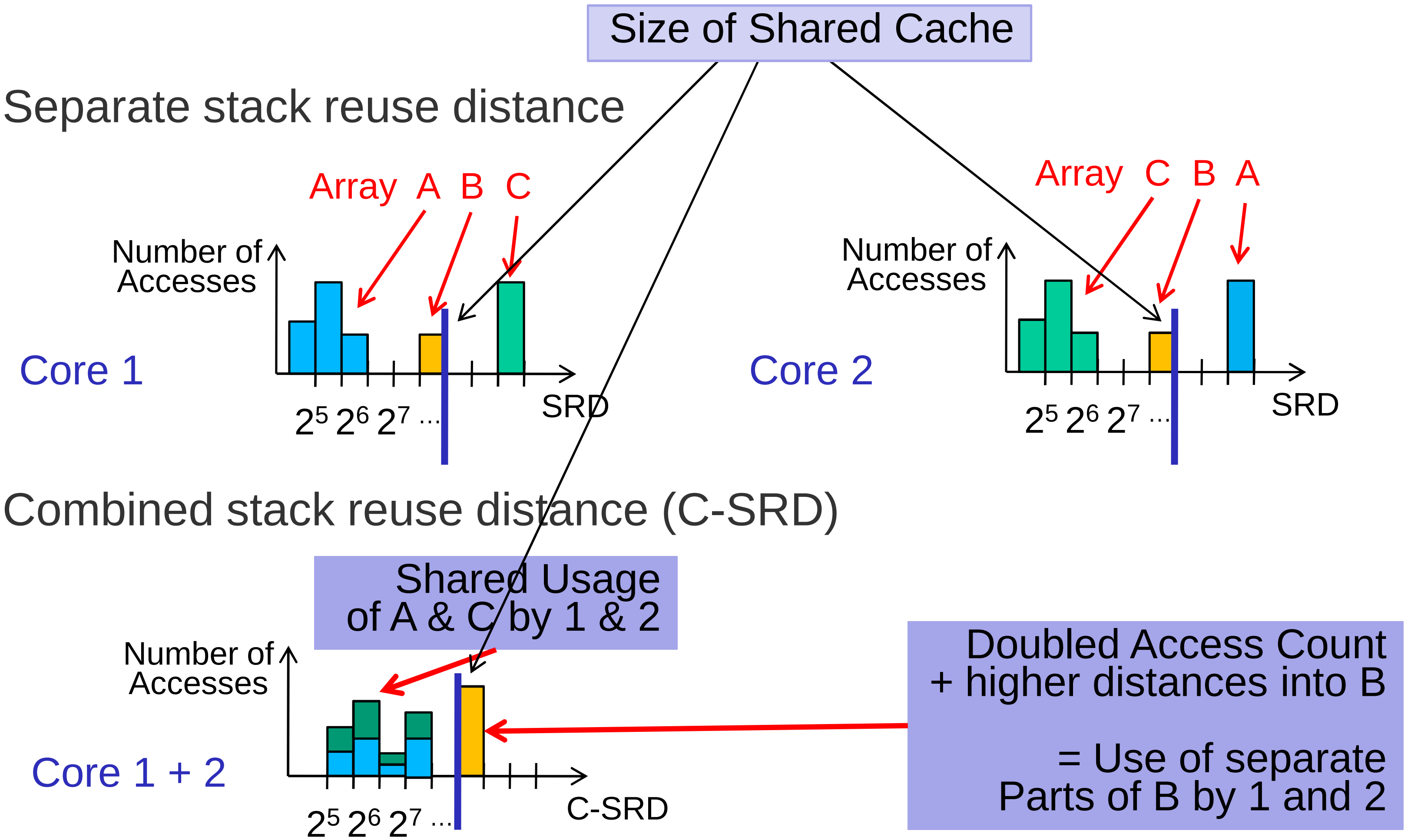
Example: Foo selected A selected (improved)



- Tells reality
- With real path profiles: Allows for interactive filtering of data
- Also for filtering in other dimensions (partitioning against threads)

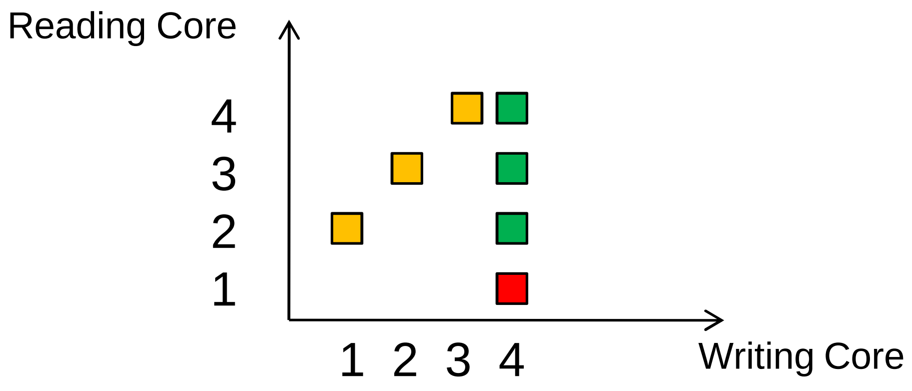
Visualization for Multicore

- Separate stack reuse distance
- Combined stack reuse distance (C-SRD)



Visualization for Multicore (2)

- Similar to get communication behavior among cores
  - Only count invalidations (with separate caches)
    - Heat map (color: number of invalidations)



- Histograms similar to last slide…

Conclusion

- Memory Access analysis on Single/Multicore benefits from better metrics than cache misses
- Simulation with runtime instrumentation proved useful for this
- We propose metrics and visualization for workset overlapping/communication on Multicore

Future work

Work in progress

- Measurement
  - Should stay usable (resource consumption of simulation)
  - Enhancement for multicore simulation in industry cooperation
  - Keep amount of data small
    - E.g. online aggregation also for bandwidth requirement
    - Statistical reconstruction of approximative time scale visualization ?
- Visualization
  - Prototype some visualizations for multicore memory access
  - Conduct usability studies