Imperial College London

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GAPP: A Fast Profiler for Detecting Serialization Bottlenecks in Parallel Linux Applications

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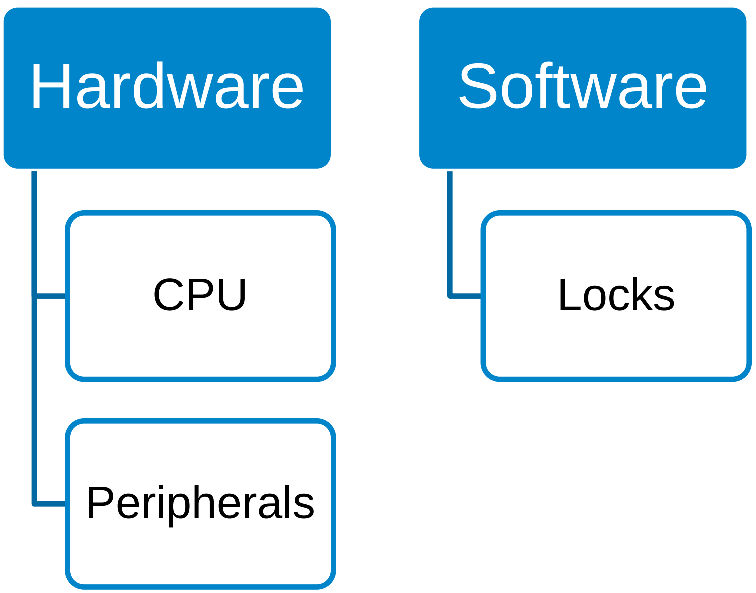
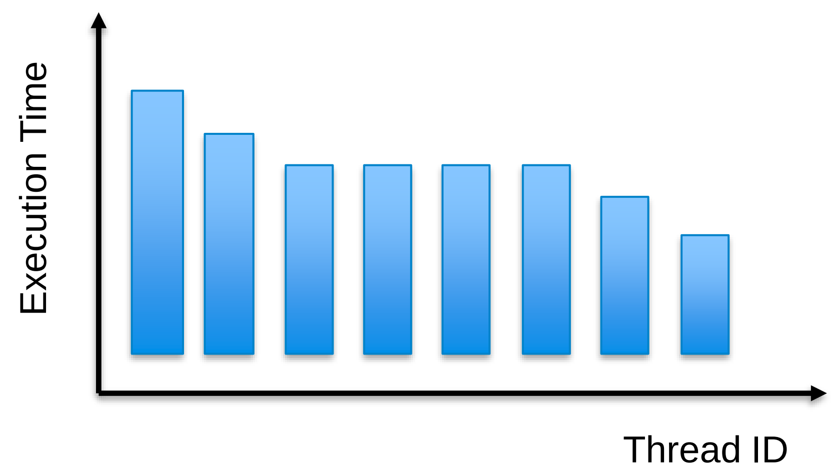
What causes serialization bottlenecks?

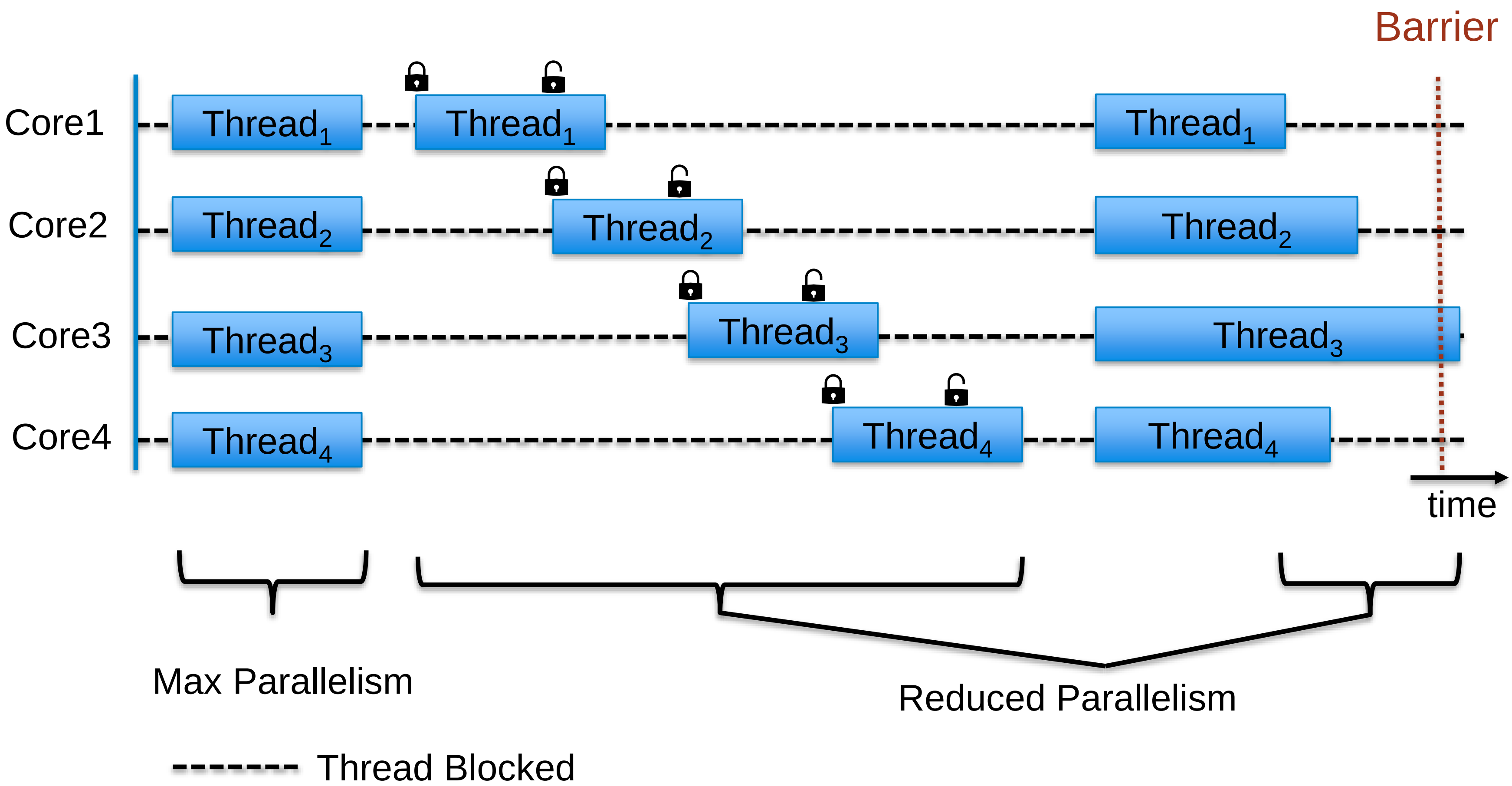
- Resource Contention



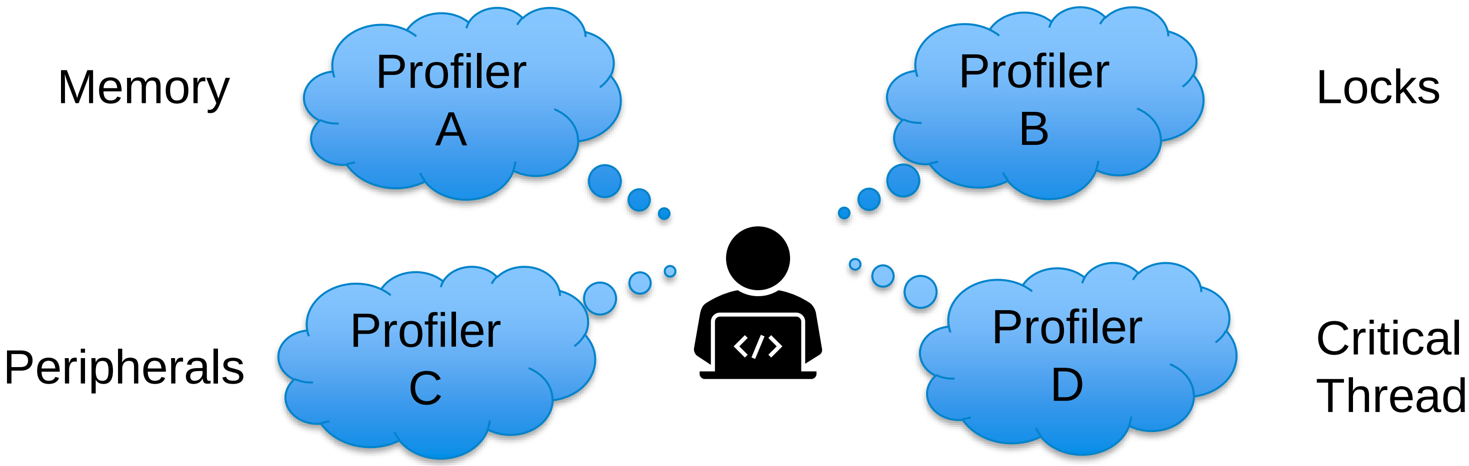
- Load Imbalance



Serialization Bottlenecks – Reduced Parallelism



Profilers for debugging performance issues



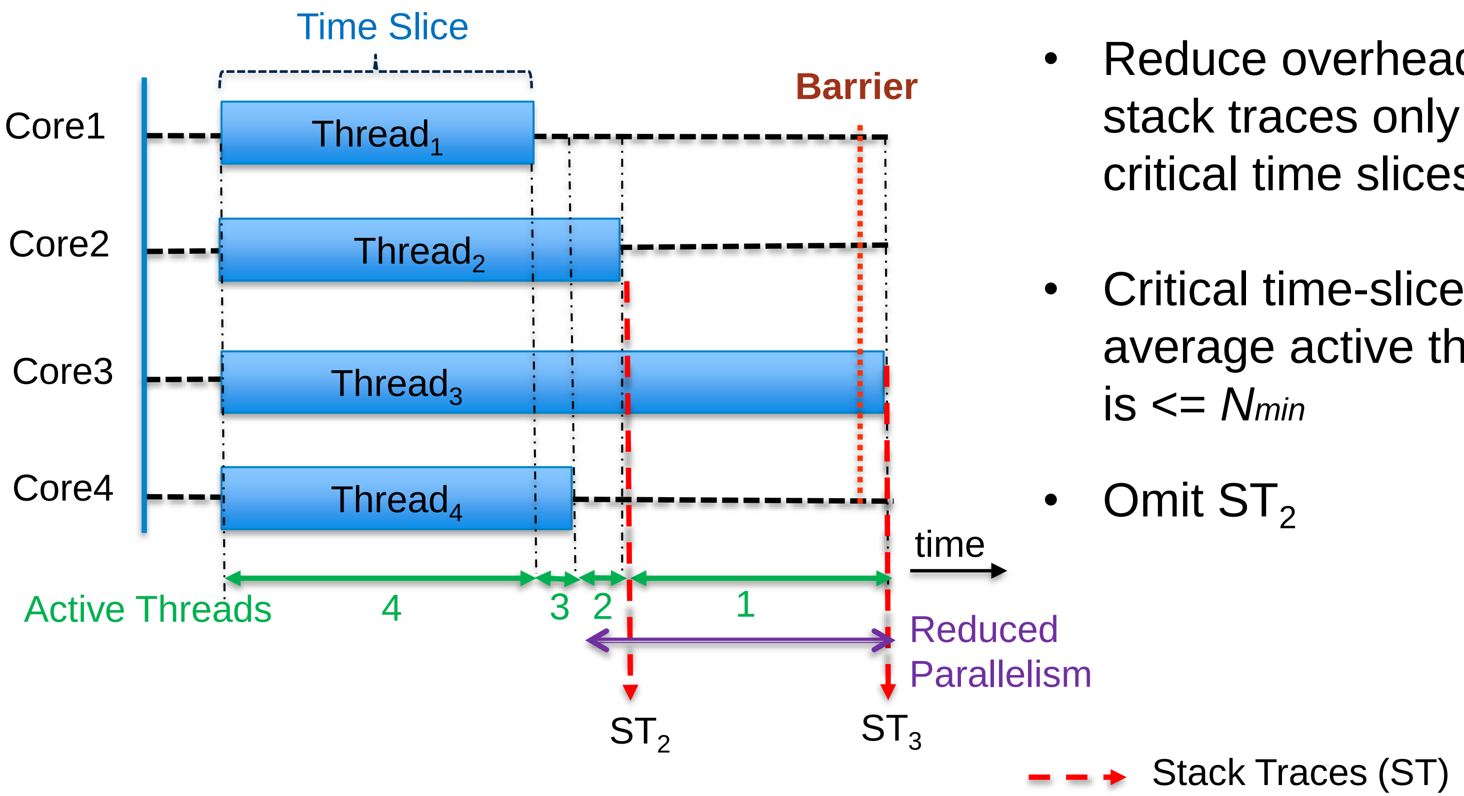
- There are many different sources of bottlenecks.

GAPP – Generic Automatic Parallel Profiler

- Can identify several different types of serialization bottlenecks.
- No need to instrument the application.
- Validated on multithreaded and multi-process parallel applications written in C/C++.
- Implemented using extended Berkley Packet Filter (eBPF).
  - Provides fast and secure kernel tracing (~4% average runtime overhead).

Harness the symptom rather than the cause

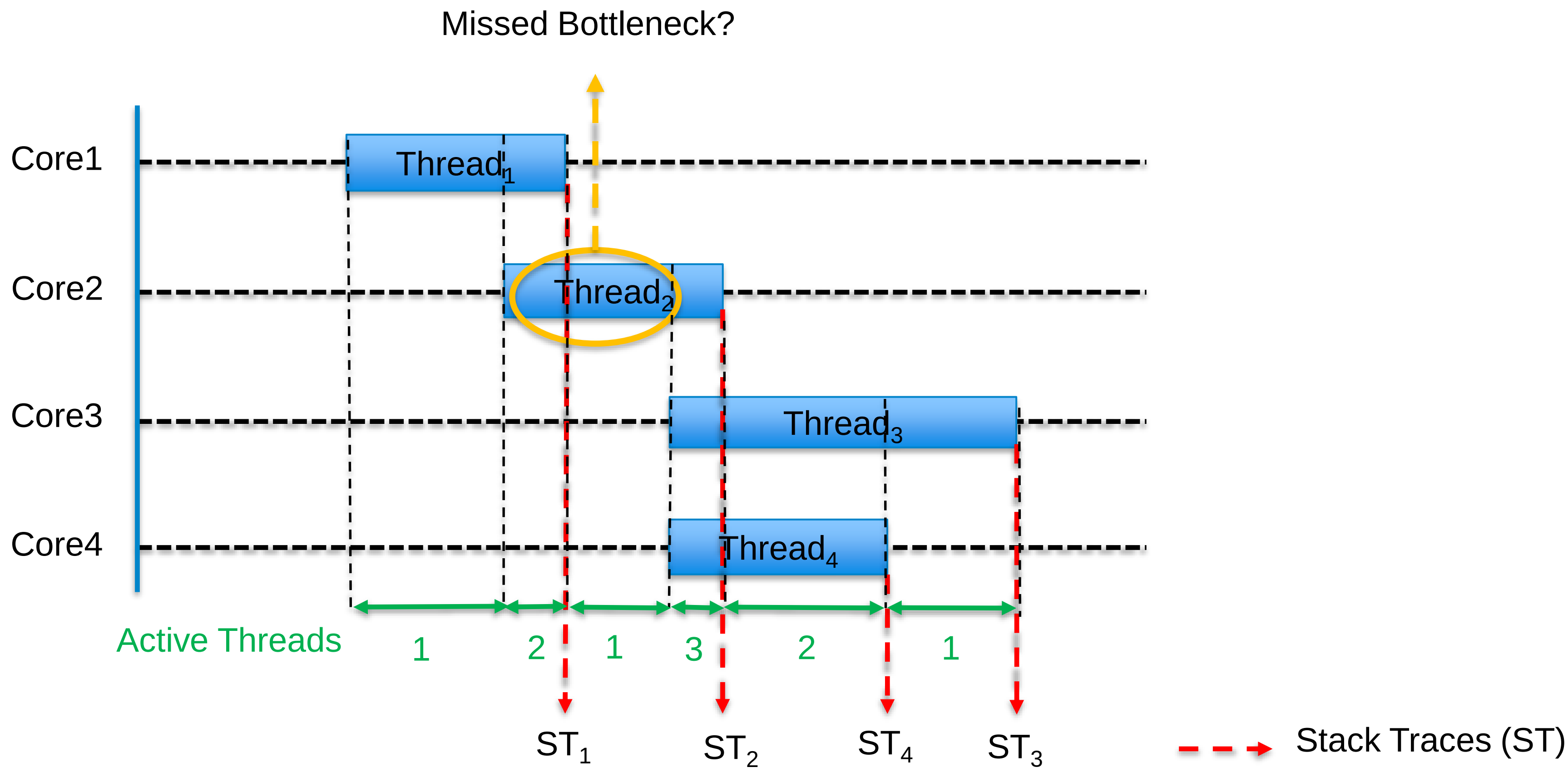
- Identify **when** and **where** reduced parallelism is exhibited
  - Number of active threads, N_{act} <= N_{min} , a tuneable threshold variable with a default value of N/2, where N is the total number of threads
    - Trace context switch events in the kernel.
  - Retrieve stack trace at the end of a time slice



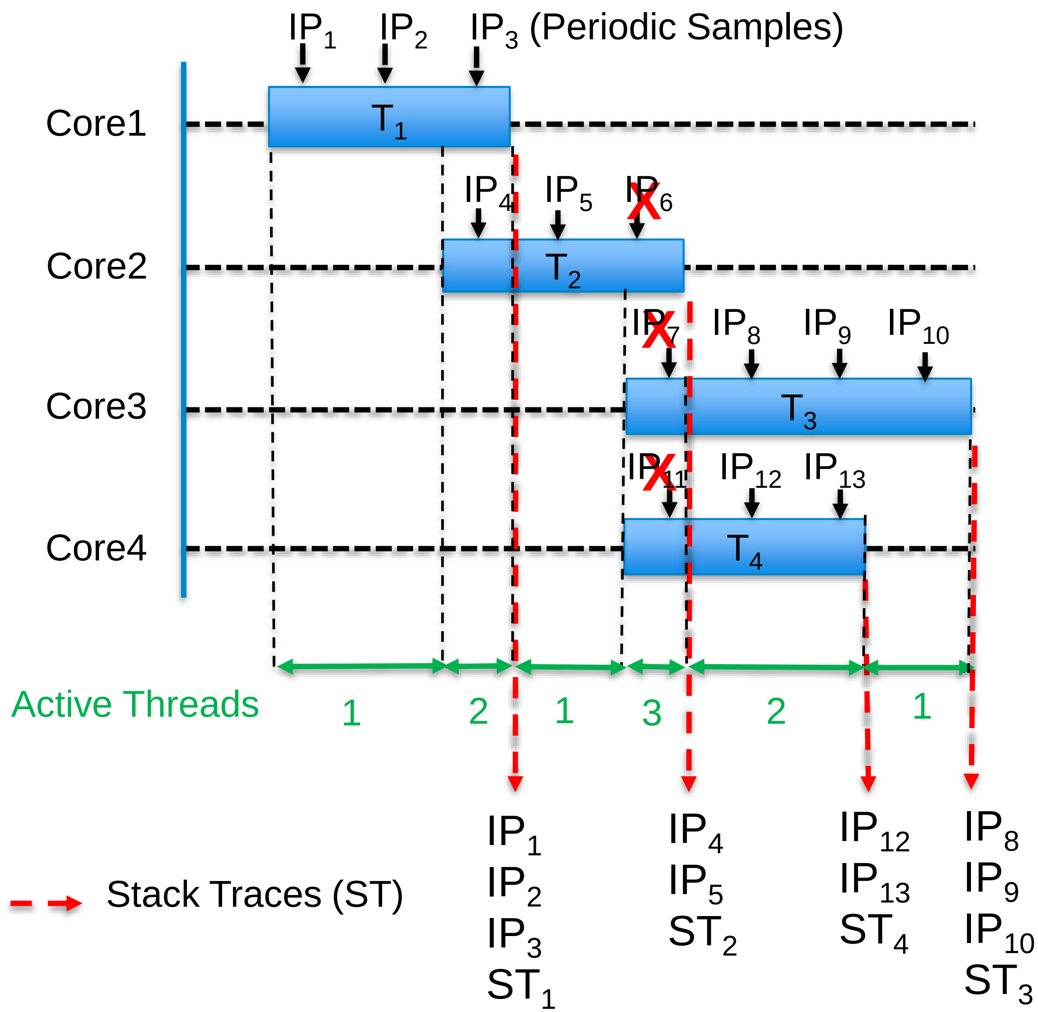
- Reduce overhead - retrieve stack traces only from critical time slices
- Critical time-slice – whose average active thread count is <= N_{min}
- Omit ST_2

Are stack traces enough to identify bottleneck?

- Stack traces retrieved at the end of a time-slice would point to bottleneck code only if it happened to execute at the end of a time-slice.



Combining bottleneck code and call paths



- Periodically sample instruction pointers.
- Reject samples if $N_{act} > N_{min}$
- Combine instruction pointers and stack traces of each critical time-slice
- Each critical time-slice is assigned a metric, Criticality Metric[1] (*Cmetric*), which takes into account the duration and degree of parallelism of a time-slice.

[1]Du Bois, Kristof, et al. "Criticality stacks: Identifying critical threads in parallel programs using synchronization behavior.“, ISCA ‘13

Ranking Bottlenecks

- Similar call paths, their samples and CMetric are combined and sorted to display potential critical call paths, functions and lines of codes and Cmetric of individual threads.

Critical Path 1:

deflate_slow()
<---deflate()
<---compress()
<---Compress()

Functions and lines + Frequency

deflate_slow – 1465

deflate.c:1650 (StackTop) -- 575
deflate.c:1580 -- 354

Optimization Opportunities

ThreadID	CMetric
25778	256130902
25779	417320962
⋮	
25783	5003332502
25784	5003756997

Load Imbalance, if any

GAPP - Evaluation

- Evaluated using applications from the Parsec-3.0 benchmark suite and two large open source projects, MySQL and Nektar++.

- All applications except Nektar++ were multithreaded
  - Each was executed with 64 threads.

- Nektar++, a spectral/hp element framework which uses message passing, was executed with 16 MPI processes.

Load imbalance from thread CMetric

Multithreaded Task Parallel Application - Ferret

- Six pipeline stages - first and last stages perform I/O with single threads.

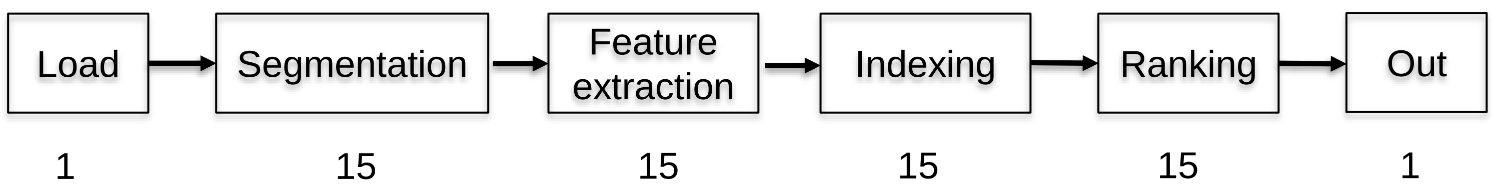


Fig: Ferret pipeline stages with initial thread allocation

<u>Critical Path 1:</u>

emd ()
<---sdist_emd ()
<---raw_query ()
<---cass_table_query ()
<---t_rank ()
<---start_thread ()

<u>Functions and lines + Frequency</u>

isOptimal -- 41314
emd.c:422 -- 20813
emd.c:423 -- 10760
emd.c:420 -- 6657
findBasicVariables -- 41301
emd.c:350 -- 7366
emd.c:353 -- 6713
emd.c:383 -- 5827

Fig: GAPP Profile for Ferret

Optimizing Ferret by thread reallocation

- Ranking phase exhibited higher CMetric when compared to other stages.
- Optimized by re-allocating threads to ranking phase.

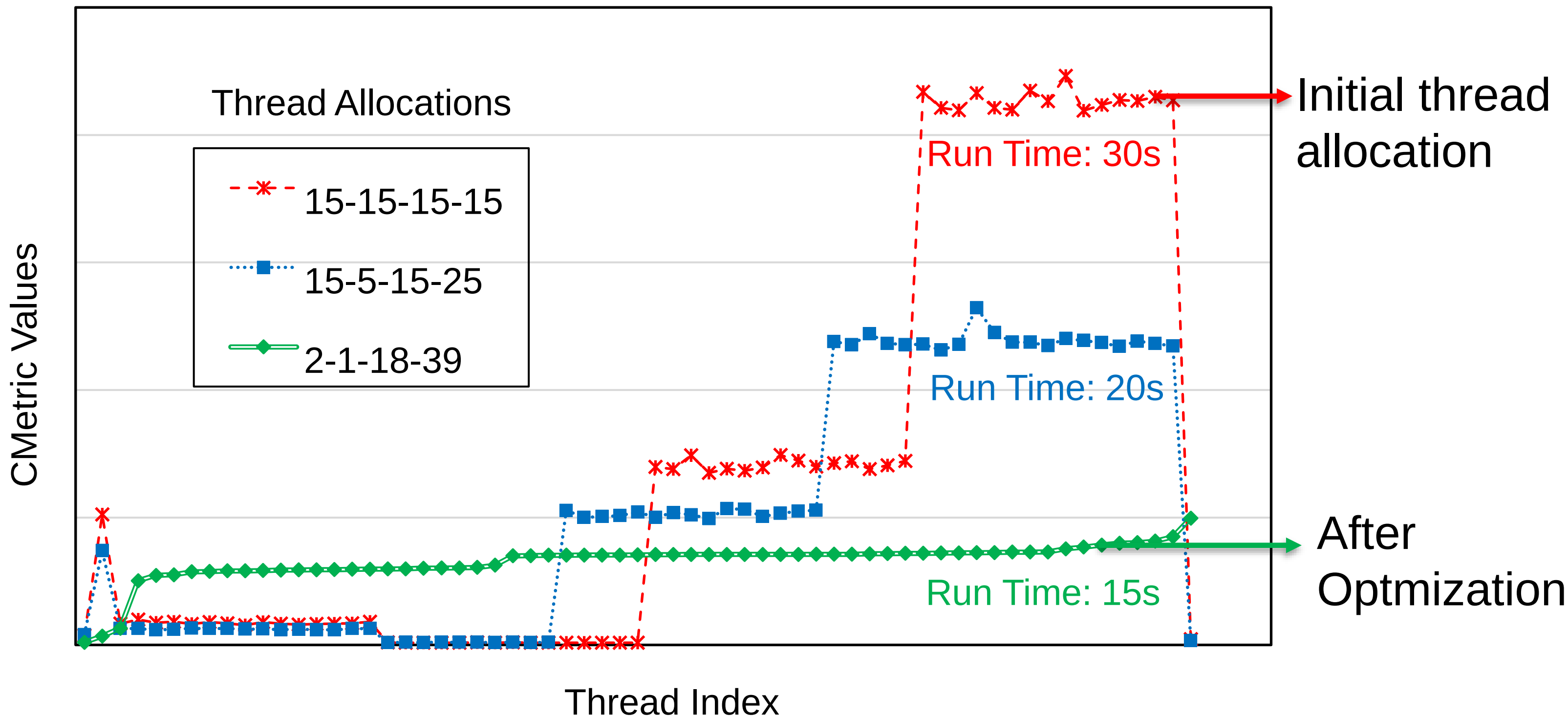


Fig: Cmetric for different thread allocations - Ferret

Resource Contention – MySQL

Sysbench OLTP_read_write workload

Critical Path1

fil_flush()[mysqld]
<---log_write_up_to()
<--trx_commit_complete_for_mysql()
<---innobase_commit()
<---ha_commit_low()
<---TC_LOG_DUMMY::commit()
<---ha_commit_trans()
<---trans_commit()
<---mysql_execute_command()
<---Prepared_statement::execute()

Functions and lines + frequency

pfs_os_file_flush_func -- 1462
os0file.ic:507 (StackTop) -- 1462

Disk I/O

Critical Path 2

sync_array_reserve_cell()
<---rw_lock_s_lock_spin()
<---pfs_rw_lock_s_lock_func()
<---row_search_mvcc()
<---ha_innobase::index_read()
<---handler::ha_index_read_idx_map()
<---join_read_const_table()
<---JOIN::extract_func_dependent_tables()
<---JOIN::make_join_plan()
<---JOIN::optimize()

Functions and lines + frequency

sync_array_reserve_cell() -- 469
sync0arr.cc:389 (StackTop) -- 469

Spin-wait Loop

Optimizing MySQL

Critical Function1
(Hardware Resource Contention)

- **pfs_os_file_flush_func()**
  - Invoked by InnoDB, flushes write buffers to disk
  - Increasing buffer size improved transaction rate by 19% and reduced latency by 16%

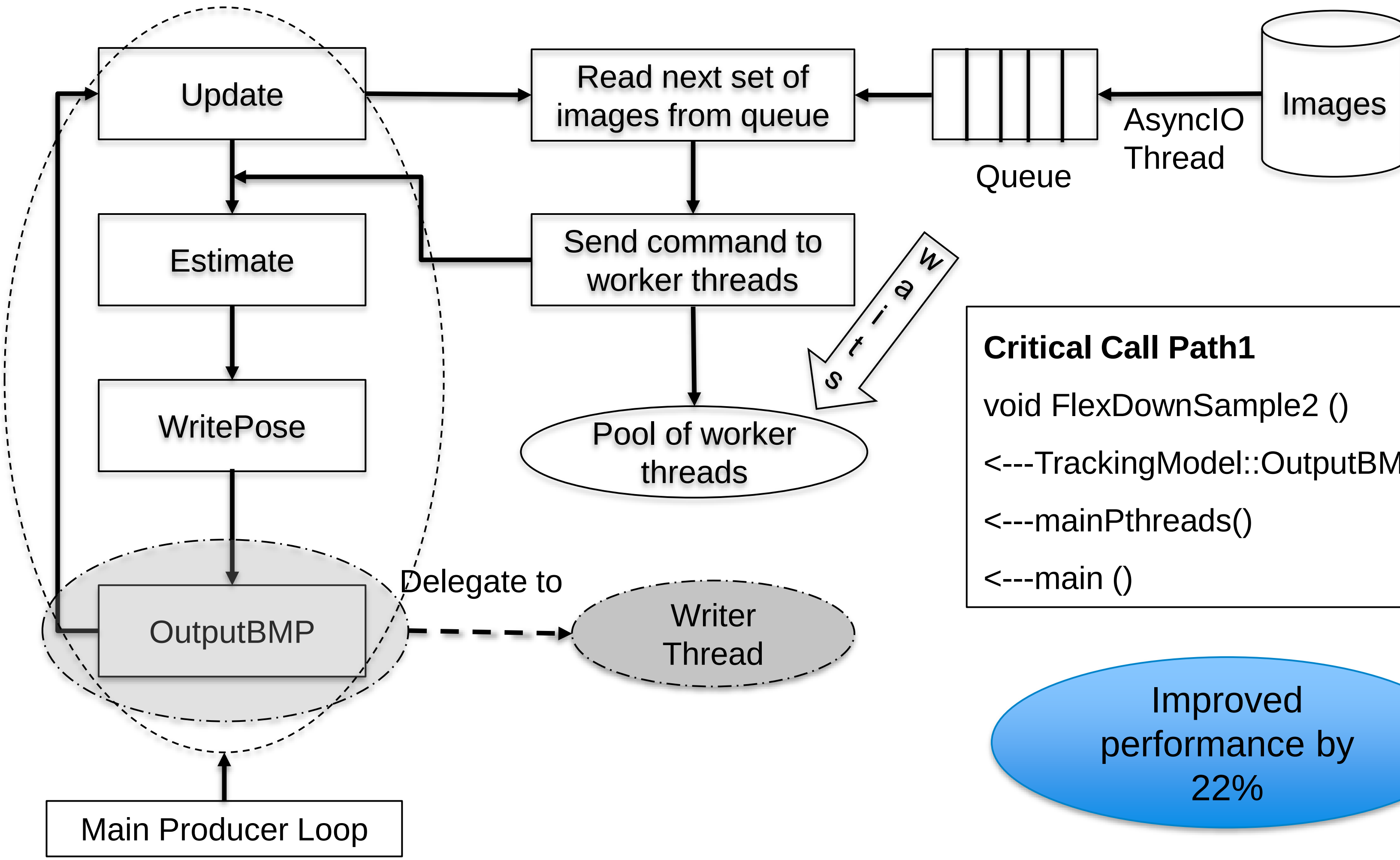
Critical Function2
(Software Resource Contention)

- **sync_array_reserve_cell()**
  - Invoked from a custom built spin lock, that blocks after spinning for a predefined time.
  - Increasing spin wait time reduced cache misses by 10.6%

These 2 modifications cumulatively improved query transaction rate by 34% and reduced average latency by 25%.

Bodytrack – Parsec3.0

Multithreaded application that follows producer-consumer paradigm



Critical Call Path1

void FlexDownSample2 ()

<---TrackingModel::OutputBMP()

<---mainPthreads()

<---main ()

Improved performance by 22%

GAPP on MPI Applications

- Nektar++ - a spectral/hp element framework that implements several PDE solvers.
- Evaluated using the Incompressible Navier-Stokes Solver with 16 MPI processes.

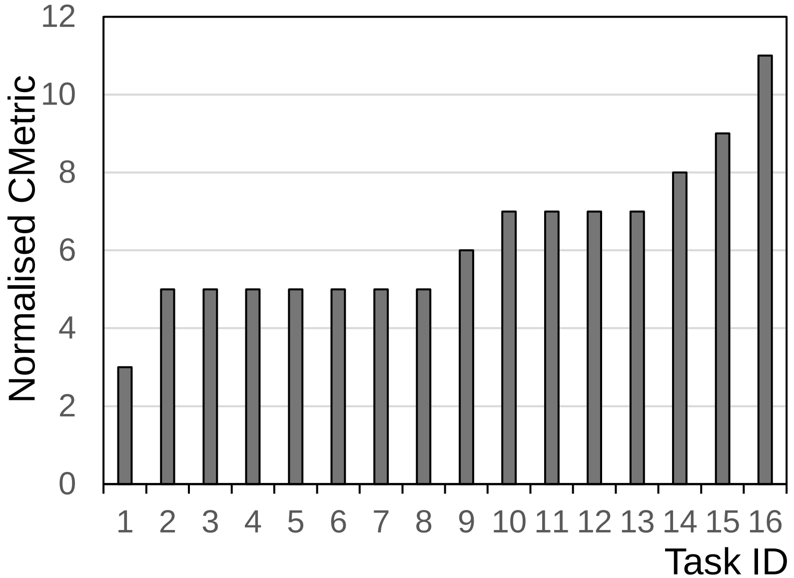


Fig:Cmetric of Individual Processes

- Load imbalance was found to be due to non-uniform partitioning of the mesh.

GAPP Profile - Nektar ++

For each critical path

Critical Path 1:

__GI___poll ()[libc-2.27.so]
<---MPIDI_CH3I_Progress ()[libmpi.so.12.1.1]
<---MPIC_Wait ()[libmpi.so.12.1.1]
<---MPIC_Recv ()[libmpi.so.12.1.1]
<---MPIR_Bcast_binomial ()[libmpi.so.12.1.1]
<---MPIR_Bcast_intra ()[libmpi.so.12.1.1]
<---MPIR_Bcast ()[libmpi.so.12.1.1]
<---MPIR_Bcast_impl ()[libmpi.so.12.1.1]
<---MPIR_Allreduce_intra ()[libmpi.so.12.1.1]
<---MPIR_Allreduce_impl ()[libmpi.so.12.1.1]

Functions and lines + Frequency

dgemv_ () [libblas.so.3.8.0] -- 594

double Vmath::Dot2<double>()
[libLibUtilities-g.so.5.0.0b] -- 116

gather_double_add ()
[libMultiRegions-g.so.5.0.0b] -- 58

Combining functions and lines from critical paths

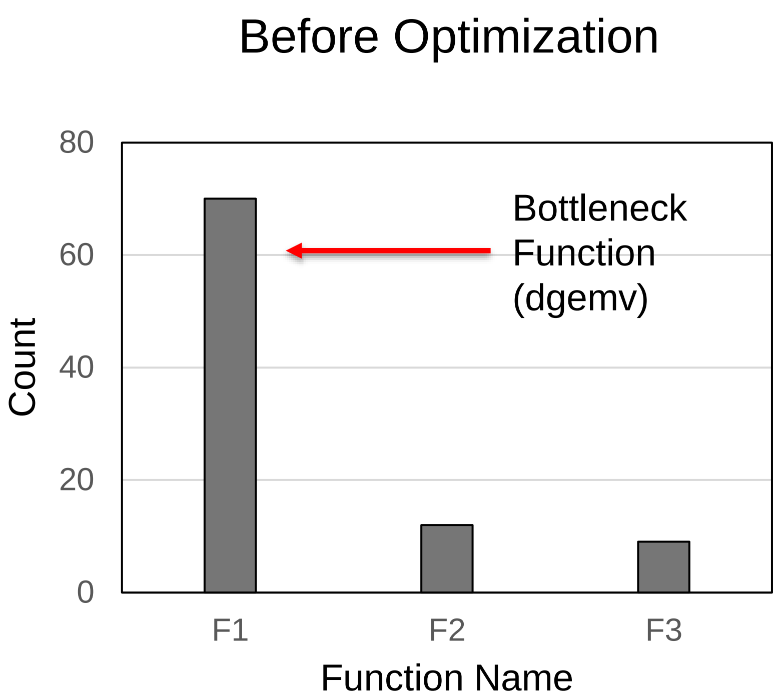
Top Critical Functions and lines + Frequency

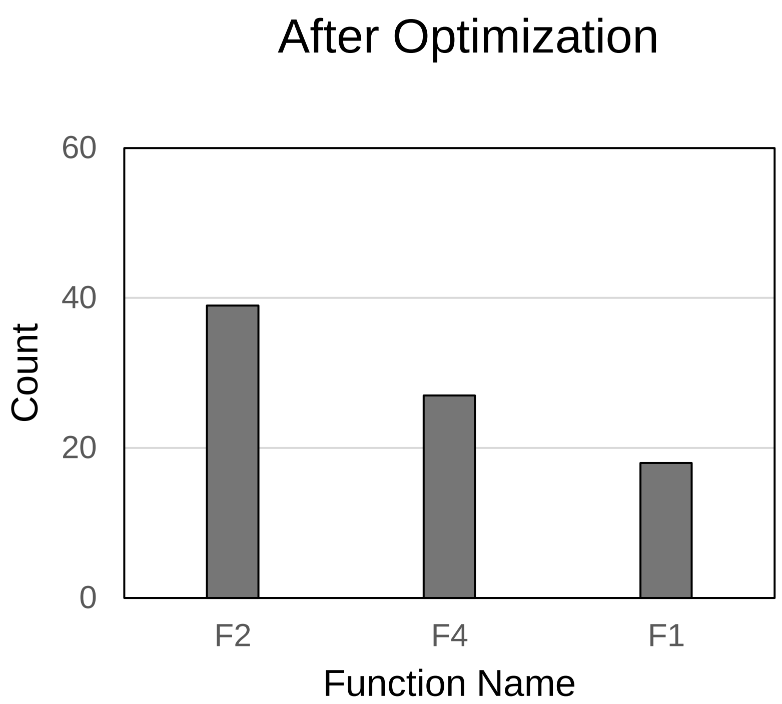
dgemv_ () [libblas.so.3.8.0] -- 781

double Vmath::Dot2<double>()
[libLibUtilities-g.so.5.0.0b] -- 170

gather_double_add ()
[libMultiRegions-g.so.5.0.0b] -- 100

Optimizing critical functions – Nektar++





- Bottleneck Function – matrix multiplication routine exported by the BLAS library.
- **Replacing the default BLAS libraries with OpenBLAS improved run time by 27%.**

Conclusion

- GAPP was able to identify different types of serialization bottlenecks in different class of applications.
- Robust
  - Consistent results across multiple runs under the same test condition.
- Customizable
  - Tuneable parameters: N_{min}, sampling frequency, stack depth, option to include results from dynamic libraries
- Limitation
  - Will not work with spin-wait loops which doesn't block.
- Available at
  - https://github.com/RN-dev-repo/GAPP

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