Understanding CPU Microarchitecture and Platform Characteristics to Maximize Big Data Performance

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Intel Corporation

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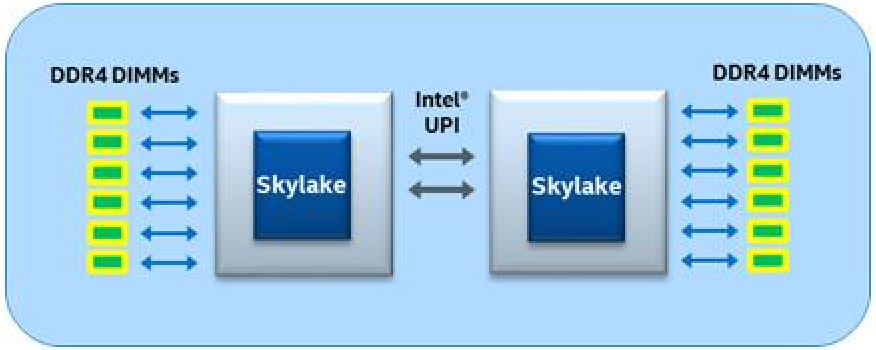
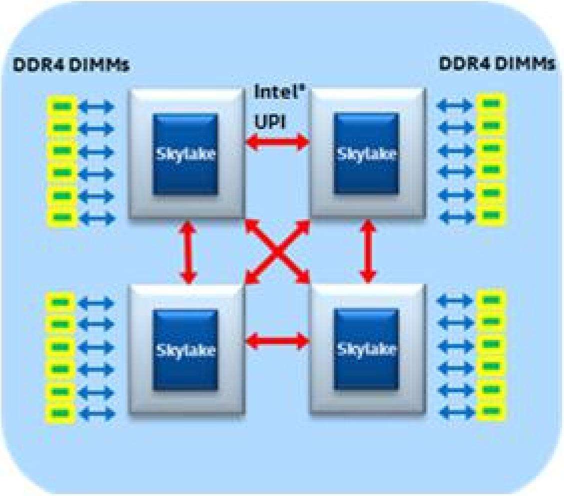
Agenda

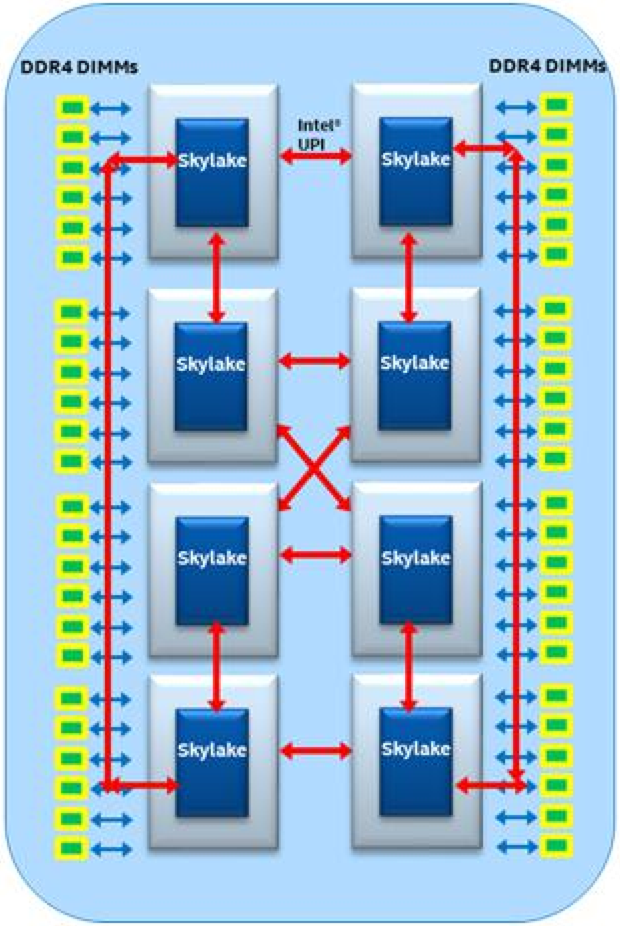
- Background
  - Intel Xeon Sever for Data Center
  - Apache Spark for Big Data
  - OLAP-DS Workload: based on a schema derived from TPC-DS
- Case Study
  - Case 1: Data Locality
  - Case 2: Cache Contention
  - Case 3: Resource Balancing
- Summary

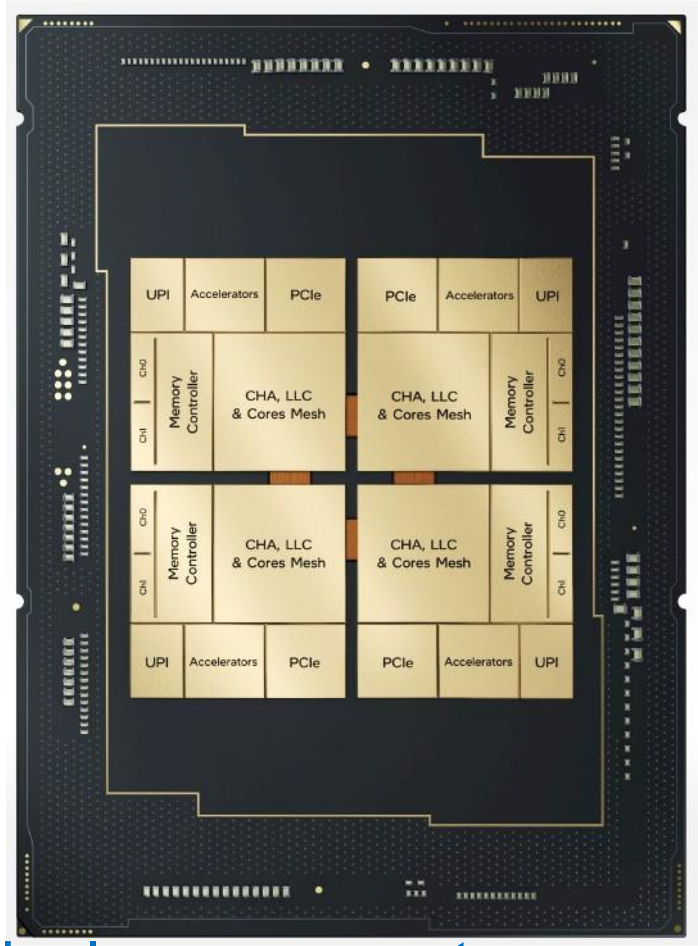
Intel Xeon Server

Intel Xeon Scalable Architecture







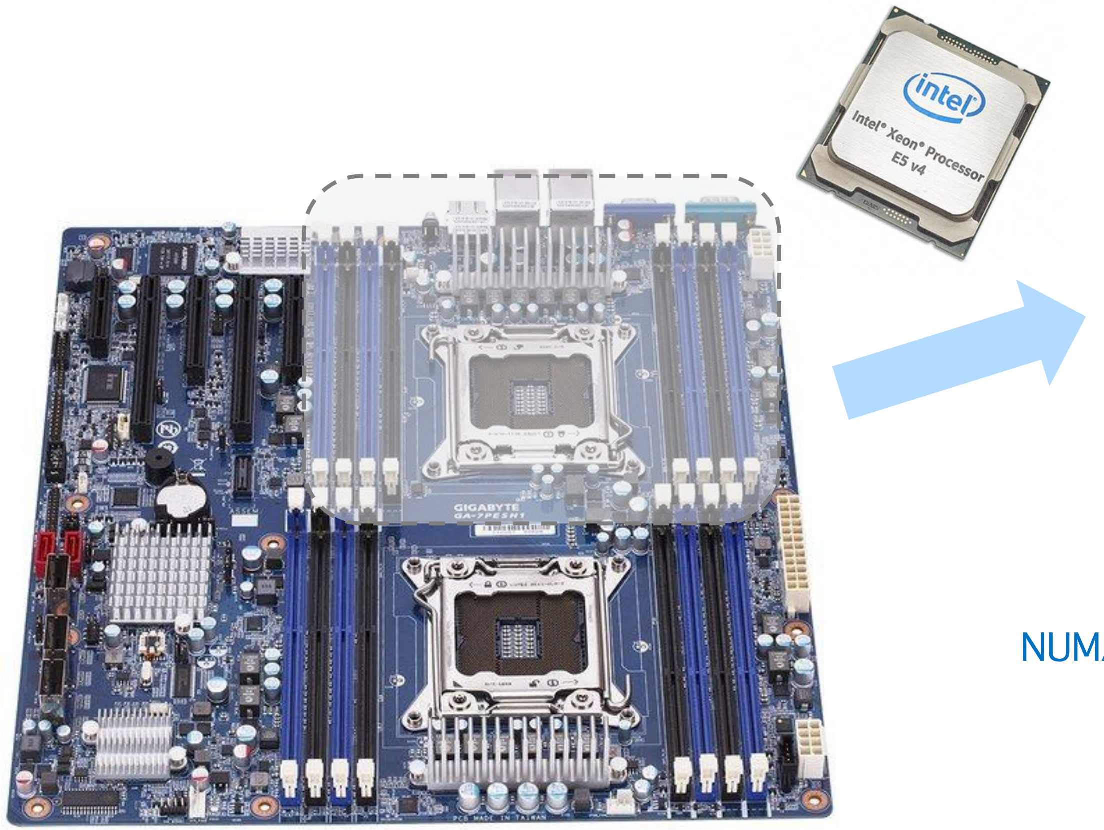


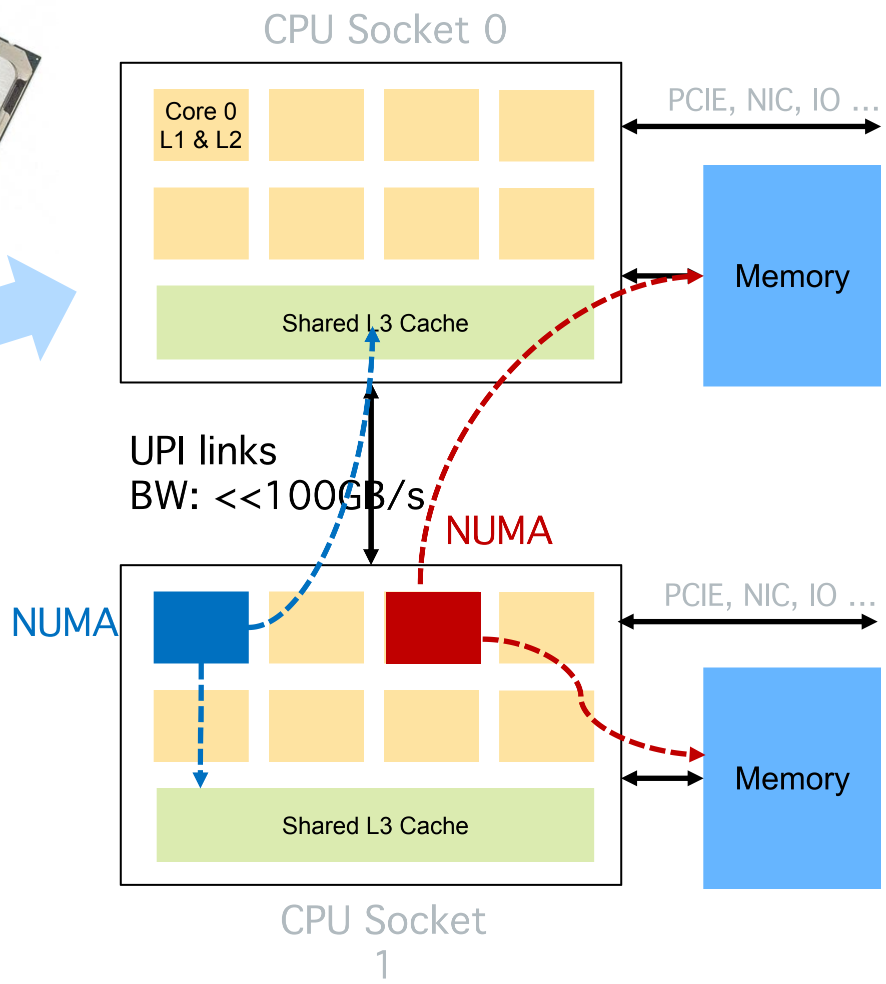
NUMA (Non-Uniform Memory Access): to scale from single processor to multiple processors

https://software.intel.com/content/www/us/en/develop/download/intel-64-and-ia-32-architectures-optimization-reference-manual.html

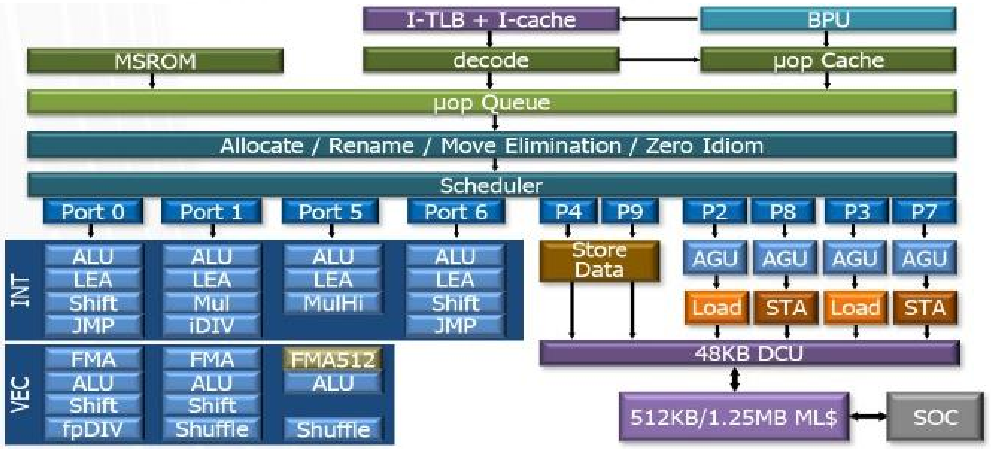
https://download.intel.com/newsroom/2021/client-computing/intel-architecture-day-2021-presentation.pdf

Intel Xeon System: NUMA Architecture





Intel Xeon Processor



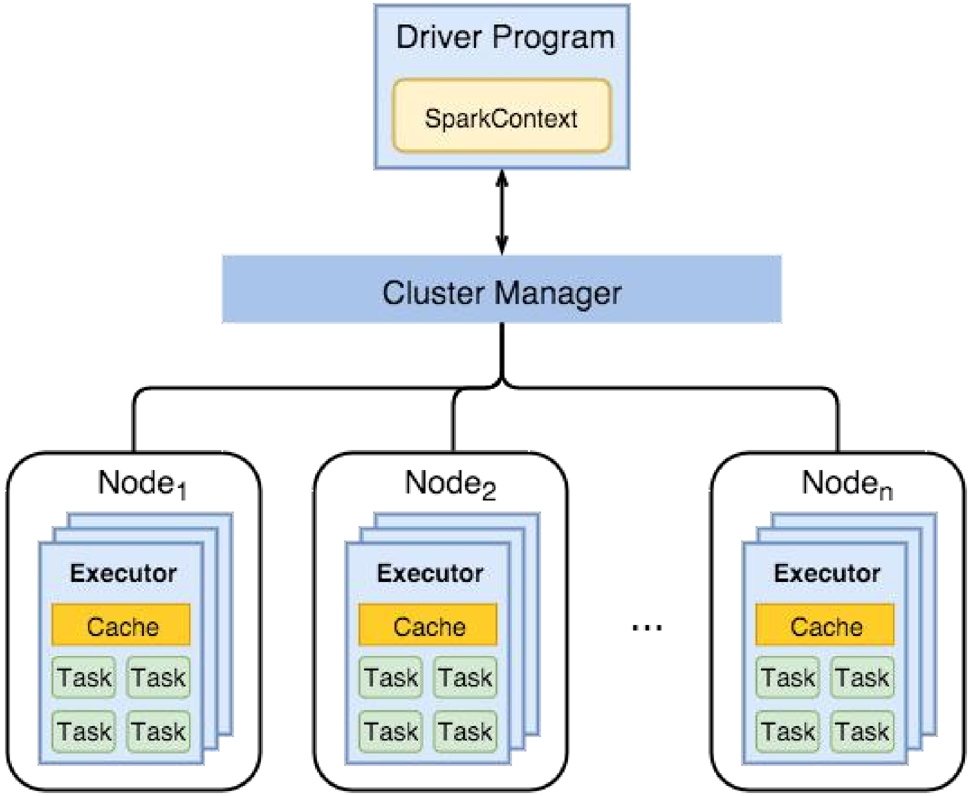
L3 shared among all cores. Some other resources (e.g. L1, L2, etc.) private to individual cores, which are shared/partitioned between two hardware threads.

https://software.intel.com/content/www/us/en/develop/download/intel-64-and-ia-32-architectures-optimization-reference-manual.html

Apache Spark for Big Data

Apache Spark Overview

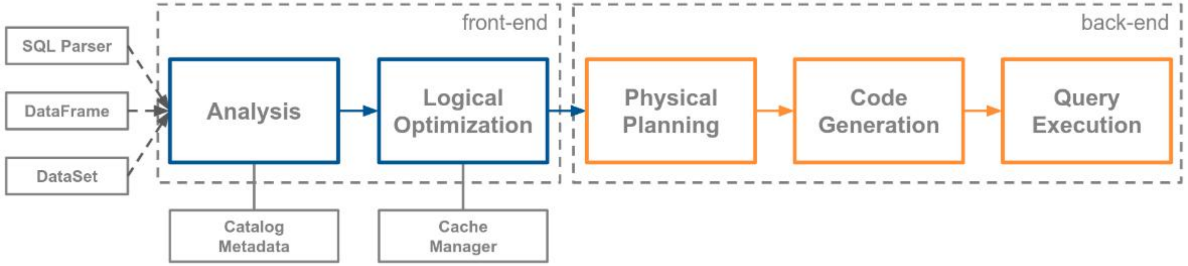
- Executor: The process responsible for executing a task.
- Manager: The machine on which the Driver program runs
- Worker: The machine on which the Executor program runs
- One task is executed on one partition of data on one executor (machine)
  - Job: A piece of code which reads some input from HDFS or local, performs some computation on the data and writes some output data.
  - Stages: Jobs are divided into stages, Map and Reduce
  - Each stage has some tasks, one task per partition.



- Each executor is a Java process, running with # of vcore, memory size, etc.
- Apache Spark only supports homogenous setting for executor
  - same configuration for executors

Inside an Executor

Lifecycle of a query



Example

```
SELECT count(*) FROM questions
   WHERE year == 2019
   GROUP BY user_id
INNER JOIN users ON questions.user_id = users.user_id
```

Physical Plan

```
*Project
+– * BroadcastHashJoin Inner BuildRight
    |– * HashAggregate
    |  +– Exchange
    |     +– * HashAggregate
    |        +– * Project
    |           +– * Filter
    |              +– * ColumnarToRow
    |                 +– Scan parquet
    +– BoradcastExchange
       +– * Project
          +– * Filter
             +– * ColumnarToRow
                +– Scan parquet
```

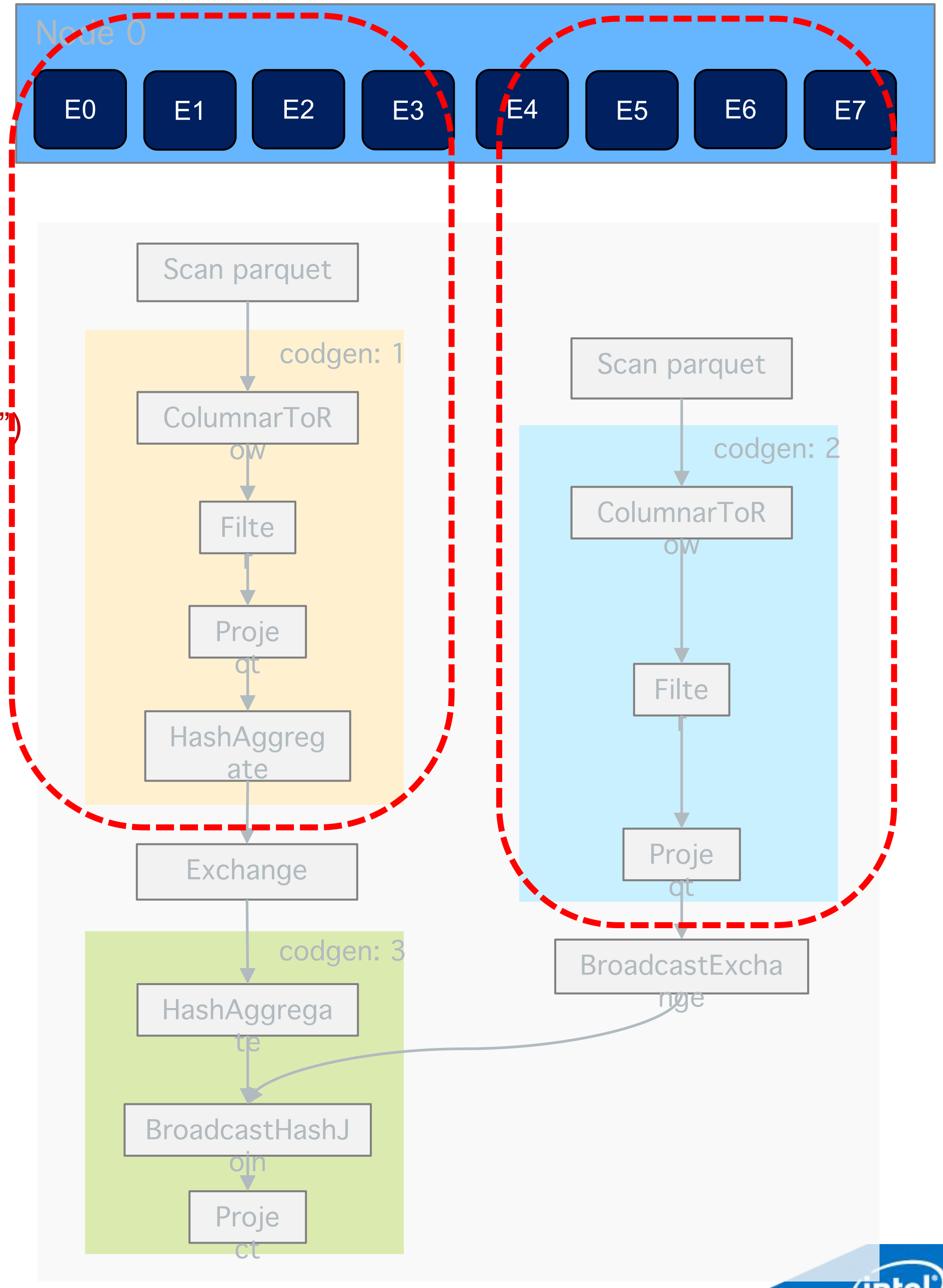
Execute A Physical Plan

```
*Project                                          codgen: 3
+– * BroadcastHashJoin Inner BuildRight
   |– * HashAggregate
   |  +– Exchange
   |     +– * HashAggregate                       codgen: 1
   |        +– * Project
   |           +– * Filter
   |              +– * ColumnarToRow
   |                 +– Scan parquet
   +– BroadcastExchange
      +– * Project                                codgen: 2
         +– * Filter
            +– * ColumnarToRow
               +– Scan parquet
```

exchange data among executors

→ partial aggregation ("GROUP BY")
→ select columns
→ filter w/ condition
→ columnar -> row execution
→ read input file ("user")

A codgen stage: an execution flow can be assigned to an executor




```
SELECT count(*) FROM questions
  WHERE year == 2019
  GROUP BY user_id
INNER JOIN users ON questions.user_id = users.user_id
```

OLAP-DS: based on a schema derived from TPC-DS

OLAP-DS Benchmark overview

- TPC-DS is a decision support benchmark that models several generally applicable aspects of a decision support system
- This study uses an OLAP workload (OLAP-DS) based on a schema derived from TPC-DS
  - Including 99 queries
  - examining large volumes of data, answering real-world business questions via ad-hoc reporting, online analytical processing and data-mining, and database maintenance functions
  - Performance Test is defined as Power Test and Throughput Tests

OLAP-DS Throughput Test

- The Throughput Test measures the ability of the system to process the most queries in the least amount of time with multiple users.
  - A query stream is defined as the sequential execution of a permutation of queries submitted by a single emulated user.
  - A session is defined as a uniquely identified process context capable of supporting the execution of user-initiated database activity.
  - A Throughput Test consists of S_q query sessions each running a single query stream.
  - The value of S_q is any even number larger than or equal to 4.

- Case Study
  - Case 1: Data Locality
  - Case 2: Cache Contention
  - Case 3: Resource Balancing

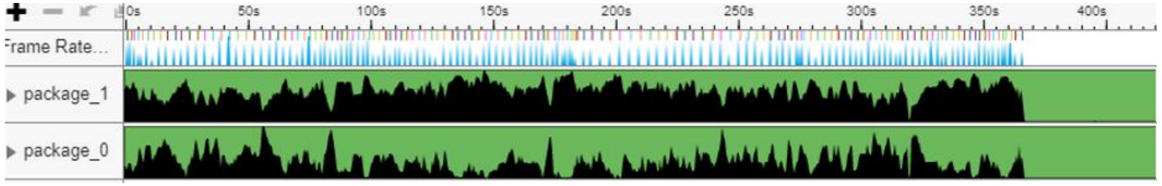
Case 1: Data Locality

- Excessive remote access may result in intensive inter-connect traffic and therefore poor performance

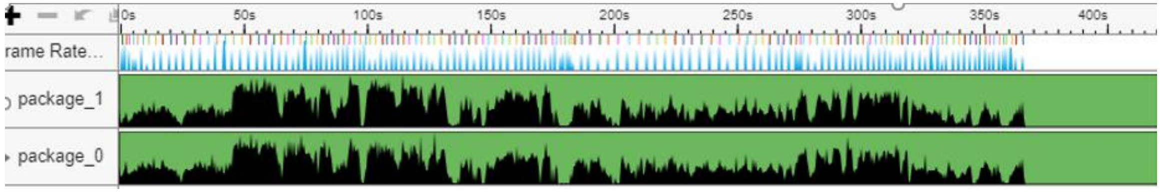
An example: Q88 on 2S Xeon, 28core/socket, totally 112 threads

<--num-executors 7 --executor-cores 16>

Poor Data locality / execution time 370sec



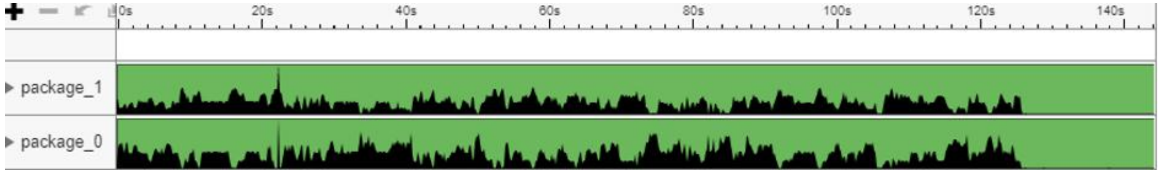
CPU cycle



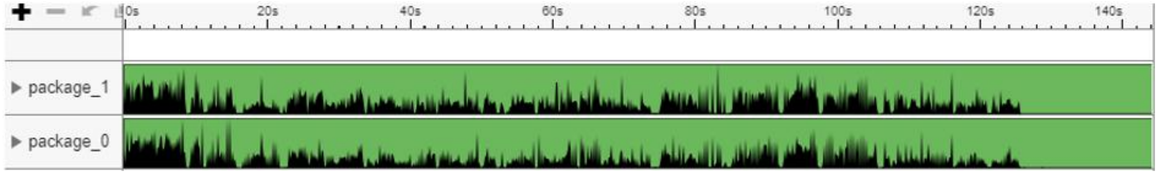
requests coming from a remote socket

<--num-executors 28 --executor-cores 4>

Improved Data locality / execution time 125sec



CPU cycle

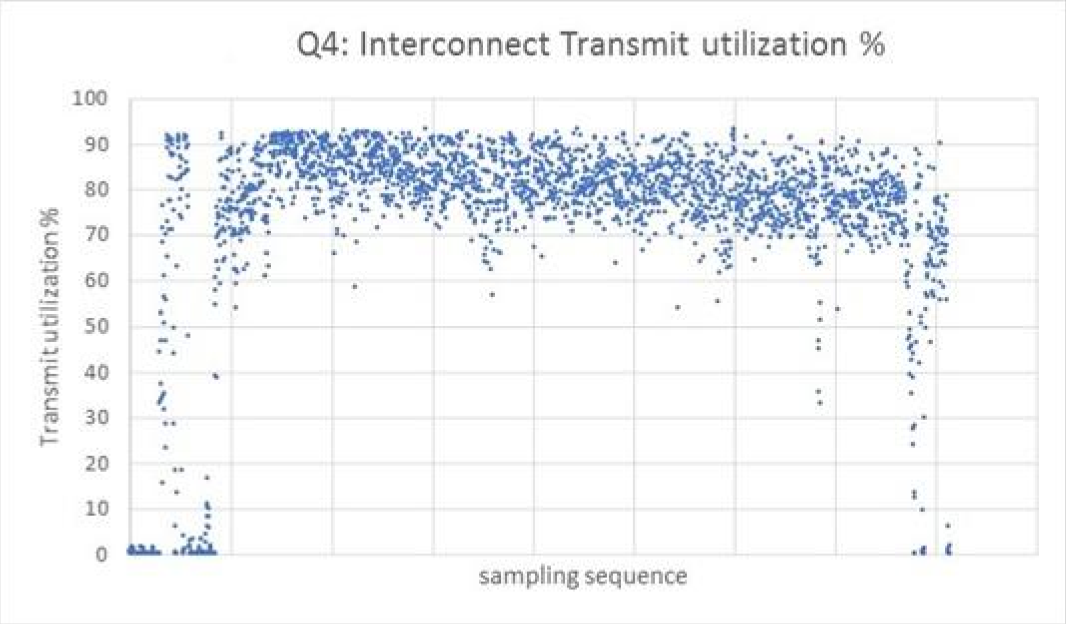


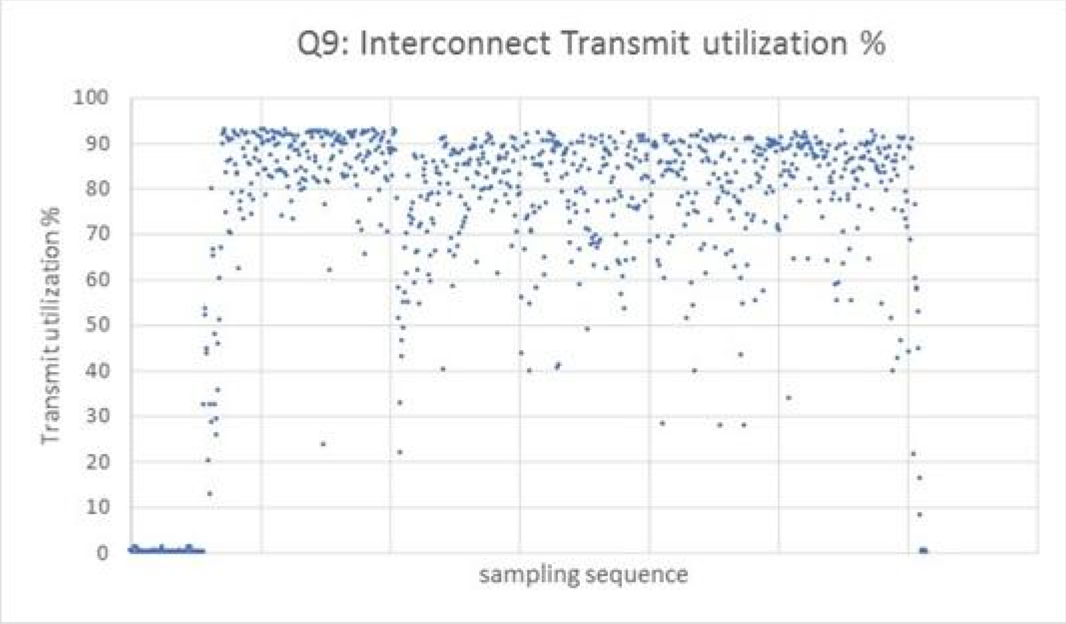
requests coming from a remote socket

Avoid artificial inter-socket communication that one executor always has cores on different sockets

Interconnect Traffic

- To develop or enable large applications with NUMA-aware is a challenge and demands significant investment on engineering resource
- Most enterprise and cloud applications demonstrate moderate to high (~50% or higher) remote memory access





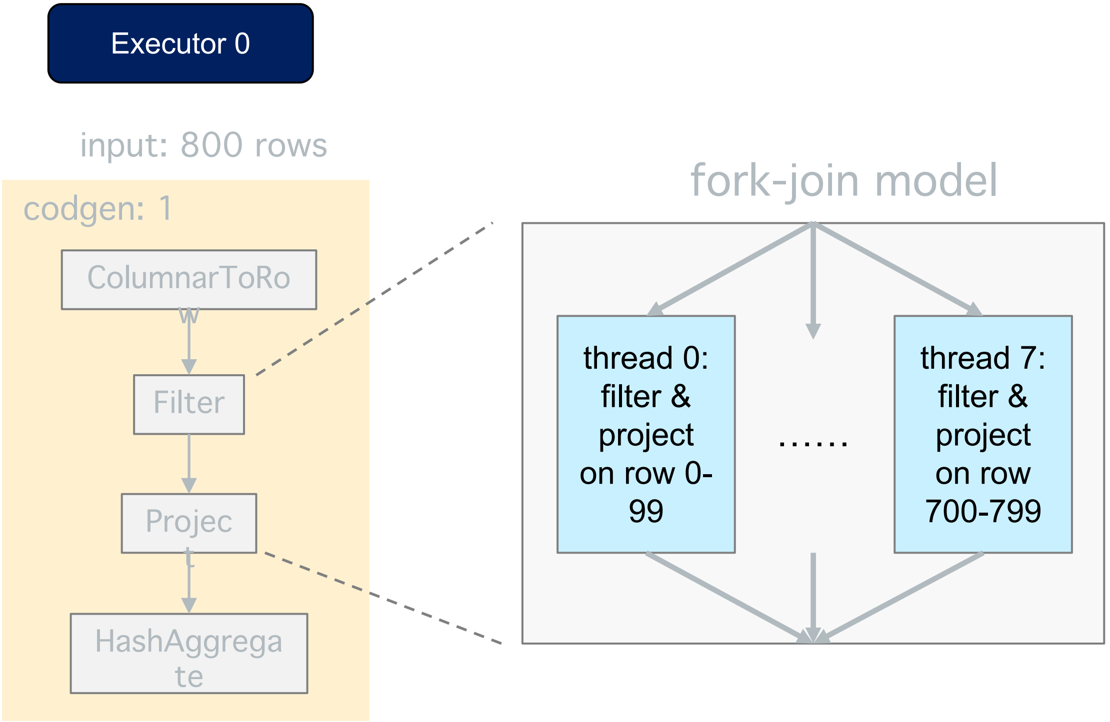
Even with good configuration, some software applications are inherently NUMA unfriendly

Why Spark Executor NUMA unfriendly

An executor is a multi-threaded process

Threading model: coarse-grain threading

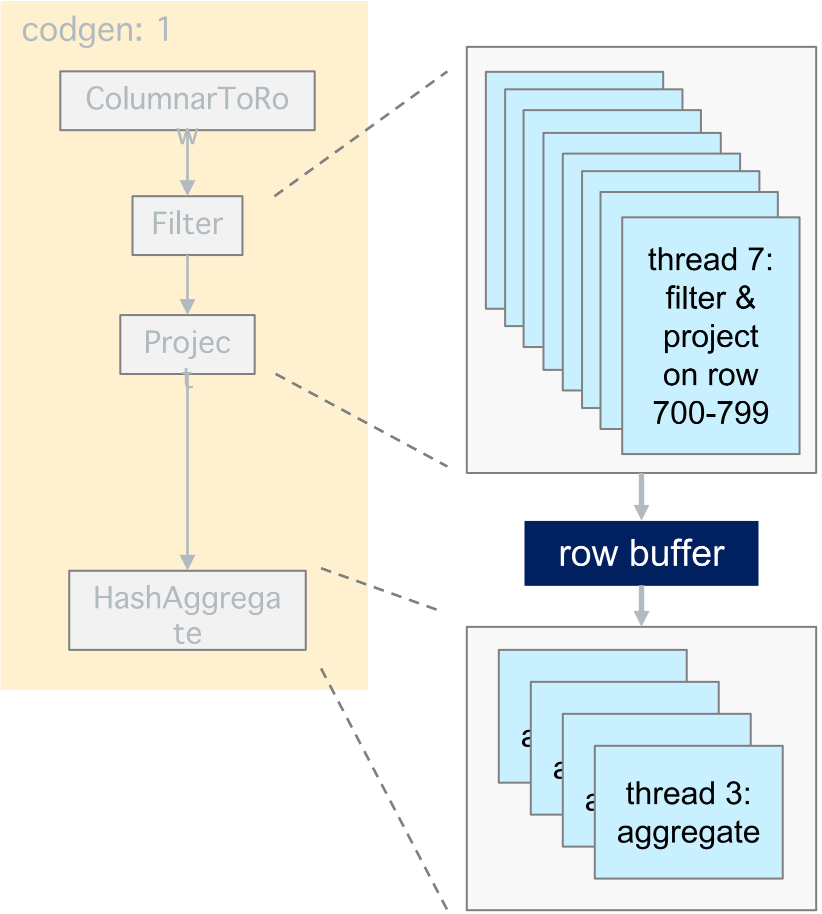
- spawn a new thread for a sub-task
  - Subquery, Filter, BroadcastExchange (local)
- # of active threads is dynamic at run time
  - difficult to pre-determine when and where a particular task thread will launch



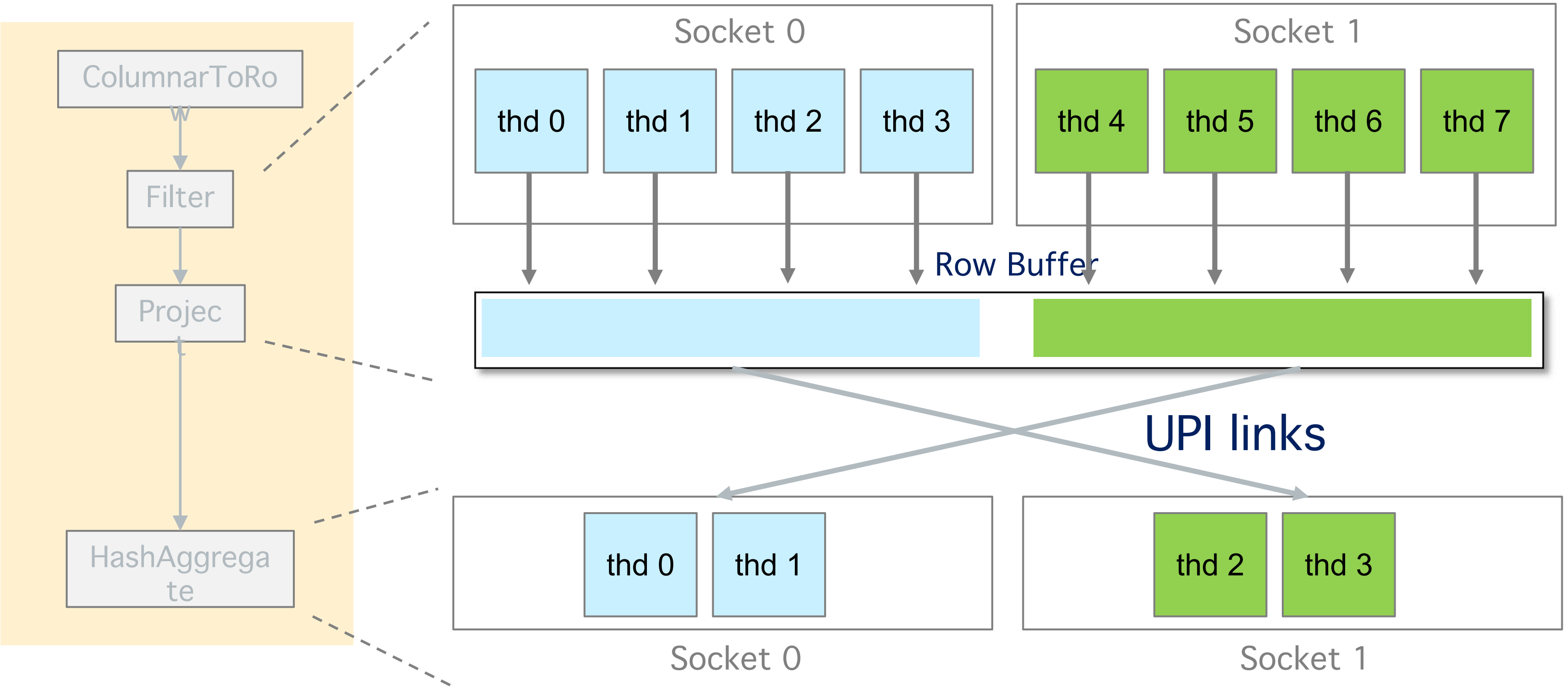
Why Executor NUMA unfriendly (2)

Inter-thread communication

- producer-consumer pattern
  - one sub-task's outputs → next sub-task's input
    - unmanaged row buffer (an array of key-value items)
- a thread may read a part of the buffer written by other threads in previous steps
  - esp. for aggregation ops (HashAggregate)
- and if threads are placed in different sockets, interconnect (UPI) traffic occurs



Why Executor NUMA unfriendly (3)



Rule of thumb (sensitivity to thread placement)

- a fatter DAG tree → more active threads
- more local exchange ops (HashAggregate, BroadcastExchange…) → more communication

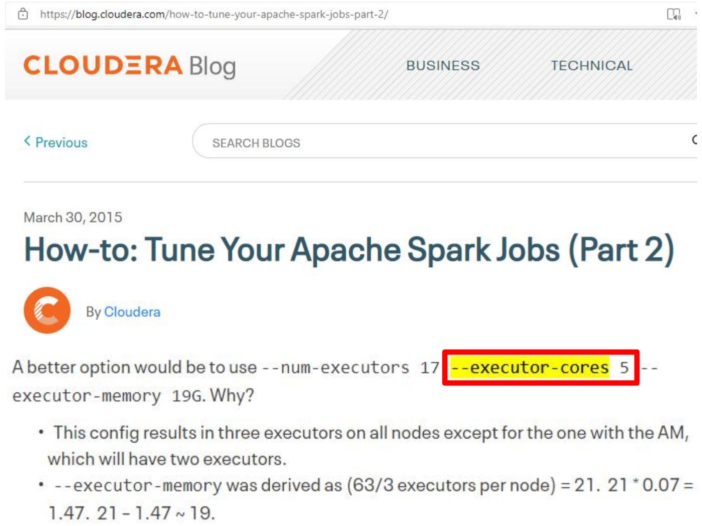
What can we do with Poor Data Locality?

- Software tuning and optimization
  - NUMA-binding
  - Configure executors (# of core) properly
  - NUMA-aware memory allocation
- Hardware enhancement and solution
  - Increase interconnect bandwidth
  - We have developed some novel technologies to improve interconnect efficiency

Case 2: Cache Contention

- The CPU architectural characteristic (e.g. shared L1/L2 cache) has been ignored or overlooked by the community
- The sub-optimal configuration leads to 7% performance regression in a state-of-art Xeon server

An example of cache contention:
https://blog.cloudera.com/how-to-tune-your-apache-spark-jobs-part-2/


https://blog.cloudera.com/how-to-tune-your-apache-spark-jobs-part-2/

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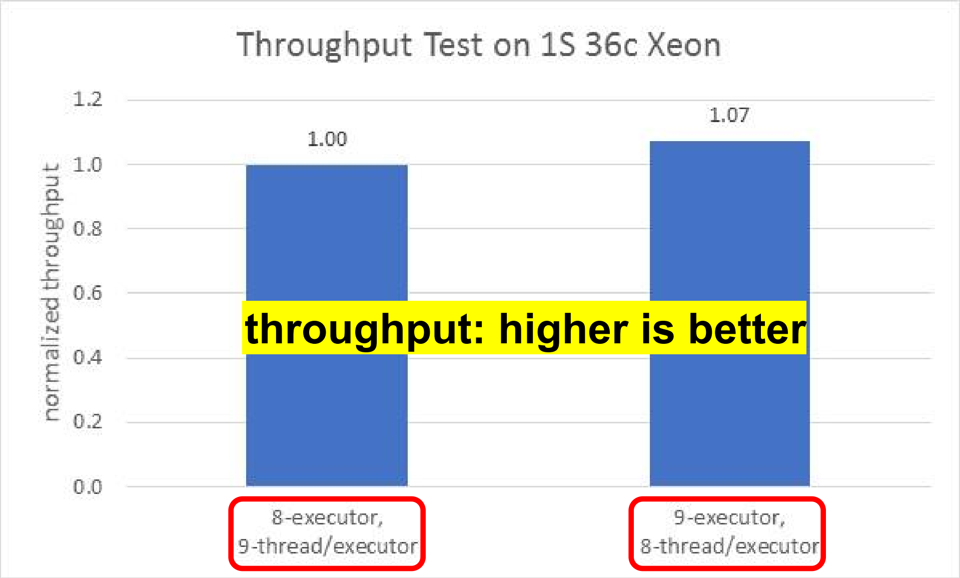
March 30, 2015

How-to: Tune Your Apache Spark Jobs (Part 2)

By Cloudera

A better option would be to use `--num-executors 17 --executor-cores 5 --executor-memory 19G`. Why?

- This config results in three executors on all nodes except for the one with the AM, which will have two executors.
- `--executor-memory` was derived as (63/3 executors per node) = 21. 21 * 0.07 = 1.47. 21 - 1.47 ~ 19.

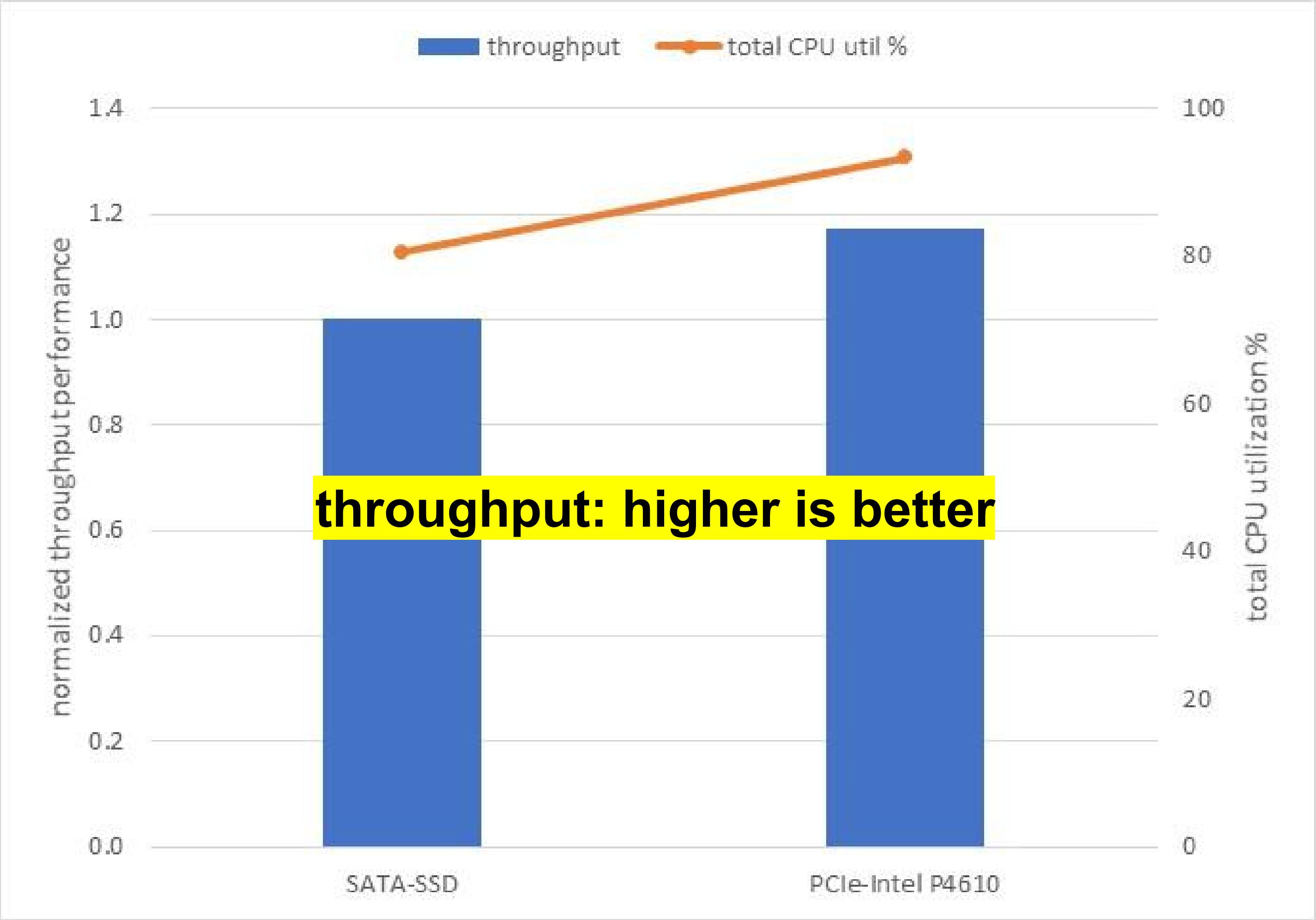


Avoid artificial L1/L2 contention: configure even # of vcore when HT is on

Case 3: System Resource Balancing

- Big Data system performance demands a balance of CPU, memory, storage, and networking resources
  - Compute: # of core, CPU frequency
  - Memory: bandwidth, capacity
  - Storage: Read/Write bandwidth
  - Network: bandwidth
- Fallacies and Pitfalls
  - Average usage
  - Theoretical peak capacity/bandwidth

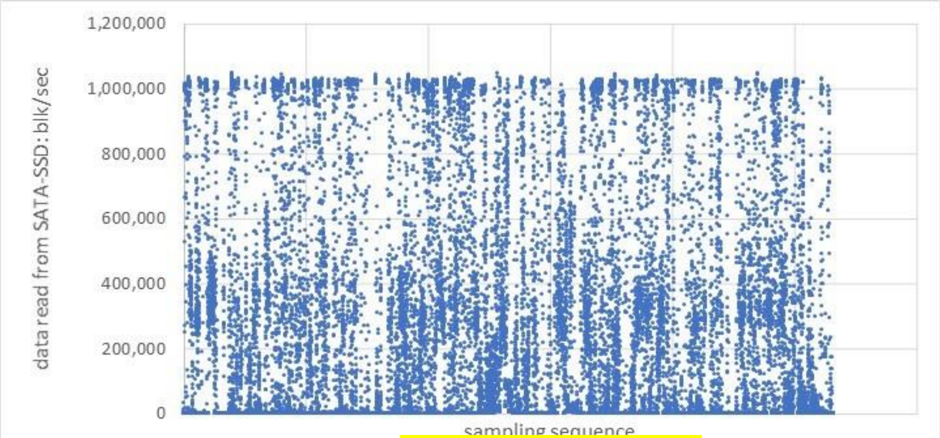
Fallacies and Pitfalls (1): Average Usage

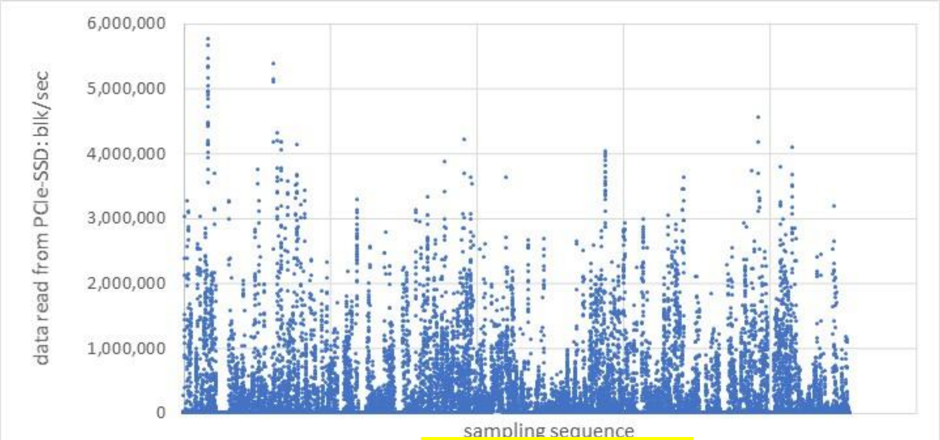


	SATA-SSD	P4618
bread/s	236,074	365,481
bwrtn/s	112,833	124,161

- SATA-SSD: SanDisk SDSSDA-1T00, Read/write speeds of up to 535MB/s / 450MB/s
- PCIe-SSD: Intel P4618 6.4TB, Read/write speeds of up to 6650MB/s / 5350MB/s
- Average usage is well below the SATA-SSD's spec.
- Why a faster SSD (i.e. PCIe-SSD) leads to 17% performance improvement?

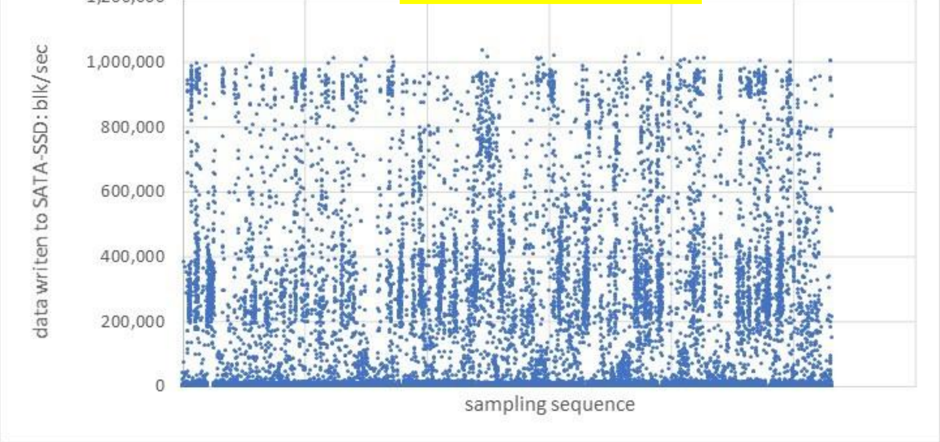
I/O Bandwidth Bounded with SATA-SSD

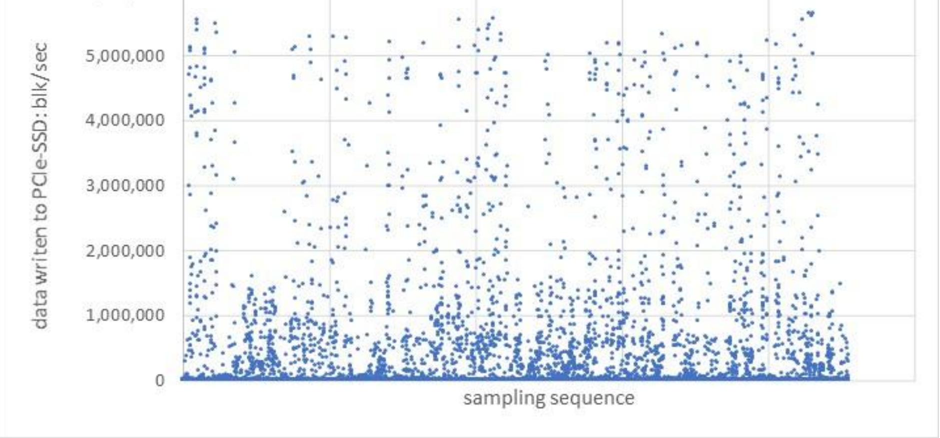




SATA-SSD

PCIe-SSD





- SATA-SSD: frequently reach Read / Write bandwidth limits

- PCIe-SSD: enough capability to meet Read / Write demand

Transient behavior is important for non-steady state workloads

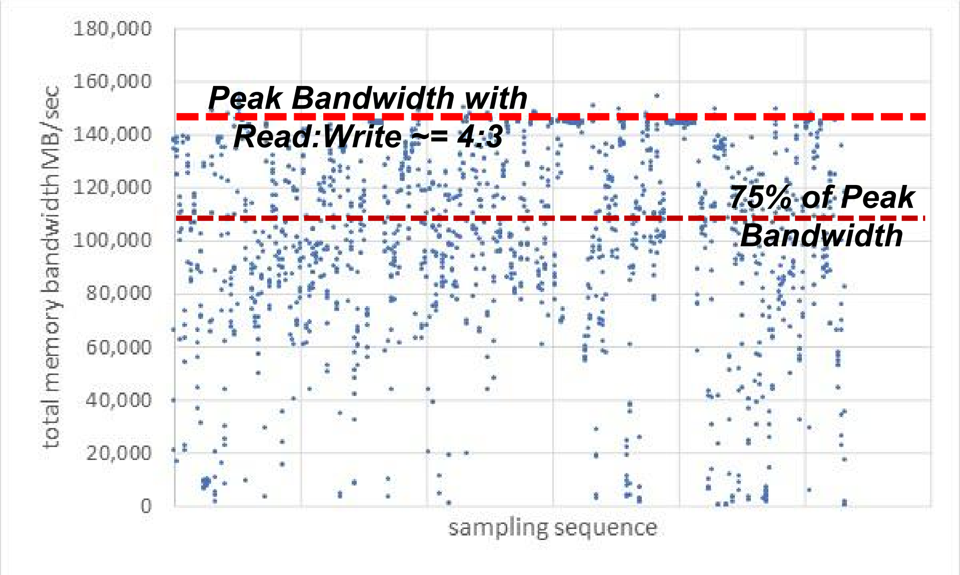
Fallacies and Pitfalls (2): Theoretical Peak

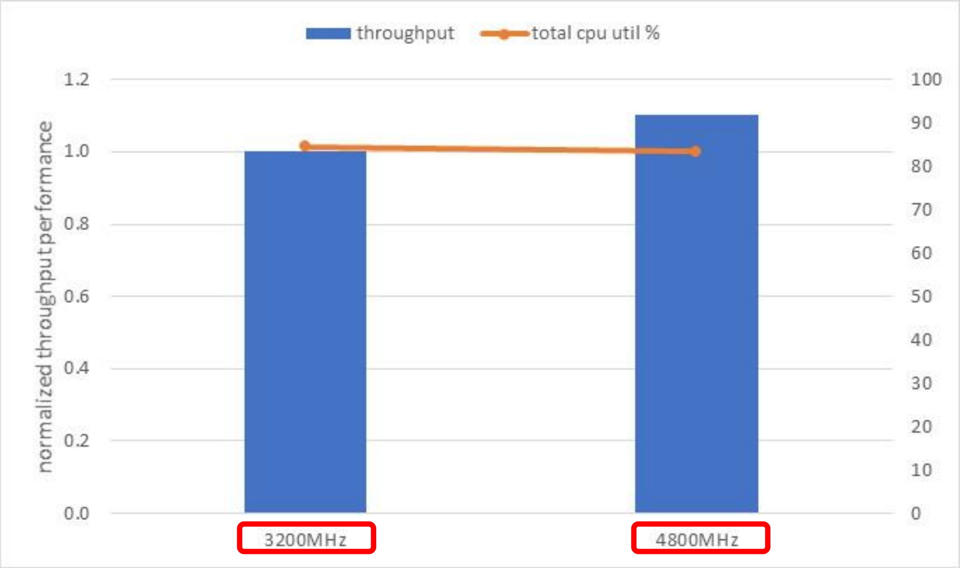
- Theoretical peak bandwidth is greater than actual bandwidth

  <memory-speed (3.2GT/s)* data-bus-width (8 bytes per channel) x # of channel (8) x # of socket (1)>
  = 205 GB/sec

- The actual peak bandwidth depends on data access pattern, and is usually much less than the theoretical peak

  <actual peak bandwidth with Read:Write ~= 4:3> ~= 145 MB/sec, measured via a microbenchmark





A good grasp of queuing theory (e.g. 75% rule) helps your performance analysis

Summary

- Develop your knowledge on CPU microarchitecture
    - NUMA is almost everywhere
- Understand your application and workload
    - Balance system resources
- Use your experience and intuition
    - Knowledge of Probability and Queuing theory speeds up your analysis

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