Carnegie Mellon University

Intro to Database Systems (15-445/645)

Lecture #14

Query Execution *Part 2*

SPRING 2024 ❯❯ Prof. Jignesh Patel

ADMINISTRIVIA

Project #2 is due ~~Wed Mar 12, 2024 @ 11:59pm~~

Fri Mar 15, 2024 @ 11:59pm

Special OH Thu Mar 14, 2024, 3-5pm GHC 5207

Project #3 is due Sun April 7, 2024 @ 11:59pm

Mid-Term

→ Grades have been posted to Canvas

→ See me during OH for exam viewing

→ You can post a regrade request on Gradescope

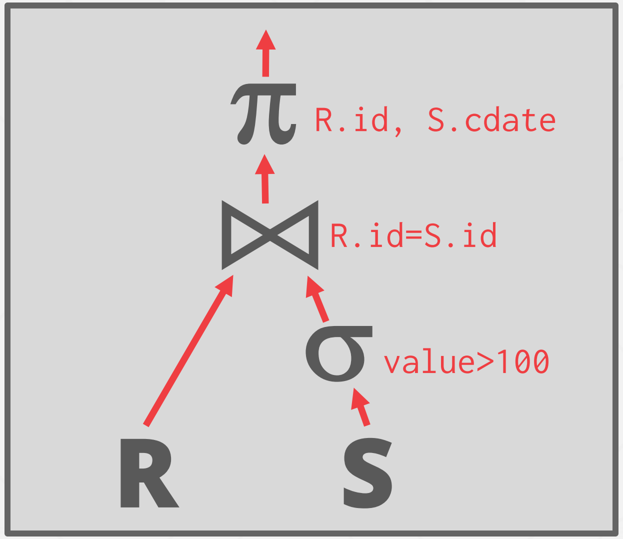
QUERY EXECUTION

In the last class, we discussed composing operators into a plan to execute an arbitrary query.

We assumed that queries execute with a single worker (e.g., a thread).

We will now discuss how to execute queries using multiple workers.

```
SELECT R.id, S.cdate
  FROM R JOIN S
    ON R.id = S.id
 WHERE S.value > 100
```



WHY CARE ABOUT PARALLEL EXECUTION?

Need to use the (parallel) hardware well
→ Higher Throughput
→ Lower Latency (especially important for human-in-the-loop scenarios)

Potentially lower ***total cost of ownership*** (TCO)
→ Fewer machines means less parts / physical footprint / energy consumption.

PARALLEL / DISTRIBUTED

The database is spread across multiple **resources** to

→ Deal with large data sets that don't fit on a single machine/node

→ Higher performance

→ Redundancy/Fault-tolerance

Appears as a single logical database instance to the application, regardless of physical organization.

→ SQL query for a single-resource DBMS should generate the same result on a parallel or distributed DBMS.

PARALLEL VS. DISTRIBUTED

Parallel DBMSs

→ Resources are physically close to each other.
→ Resources communicate over high-speed interconnect.
→ Communication is assumed to be cheap and reliable.

Distributed DBMSs

→ Resources can be far from each other.
→ Resources communicate using slow(er) interconnect.
→ Communication costs and problems cannot be ignored.

TODAY'S AGENDA

Process Models

Execution Parallelism

I/O Parallelism

PROCESS MODEL

A DBMS's **process model** defines how the system is architected to support concurrent requests / queries.

A **worker** is the DBMS component responsible for executing tasks on behalf of the client and returning the results.

PROCESS MODEL

Approach #1: **Process** per DBMS Worker

Approach #2: **Thread** per DBMS Worker

Approach #3: **Embedded** DBMS

PROCESS PER WORKER

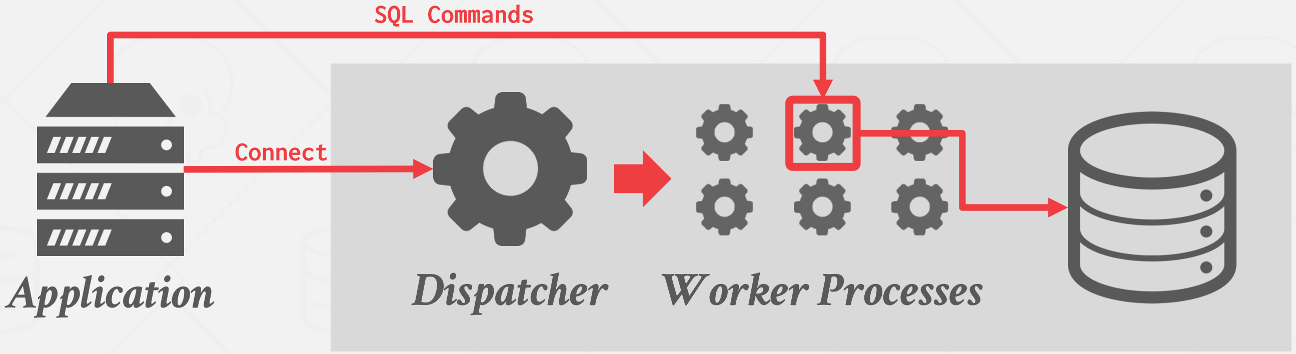
Each worker is a separate OS process.

→ Relies on the OS dispatcher.

→ Use shared-memory for global data structures.

→ A process crash does not take down the entire system.

→ Examples: IBM DB2, Postgres, Oracle



THREAD PER WORKER

Single process with multiple worker threads.

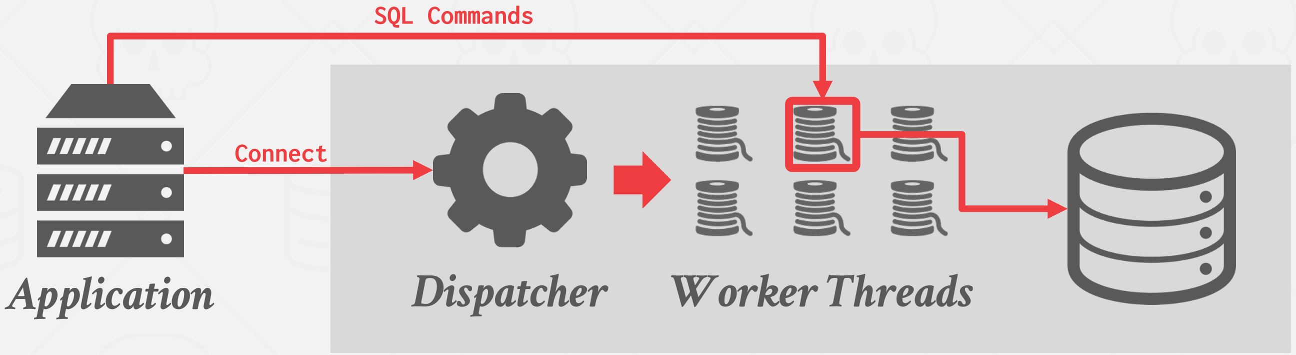
→ DBMS (mostly) manages its own scheduling.

→ May or may not use a dispatcher thread.

→ Thread crash (may) kill the entire system.

→ Examples: MSSQL, MySQL, DB2, Oracle (2014)

Almost every DBMS created in the last 20 years!



SCHEDULING

For each query plan, the DBMS decides where, when, and how to execute it.

→ How many tasks should it use?
→ How many CPU cores should it use?
→ What CPU core should the tasks execute on?
→ Where should a task store its output?

The DBMS nearly ***always*** knows more than the OS.

SQL SERVER – SQLOS

SQLOS is a user-level OS layer that runs inside the DBMS and manages provisioned hardware resources.

→ Determines which tasks are scheduled onto which threads.

→ It also manages I/O scheduling and higher-level concepts like logical database locks.

Non-preemptive thread scheduling through instrumented DBMS code.

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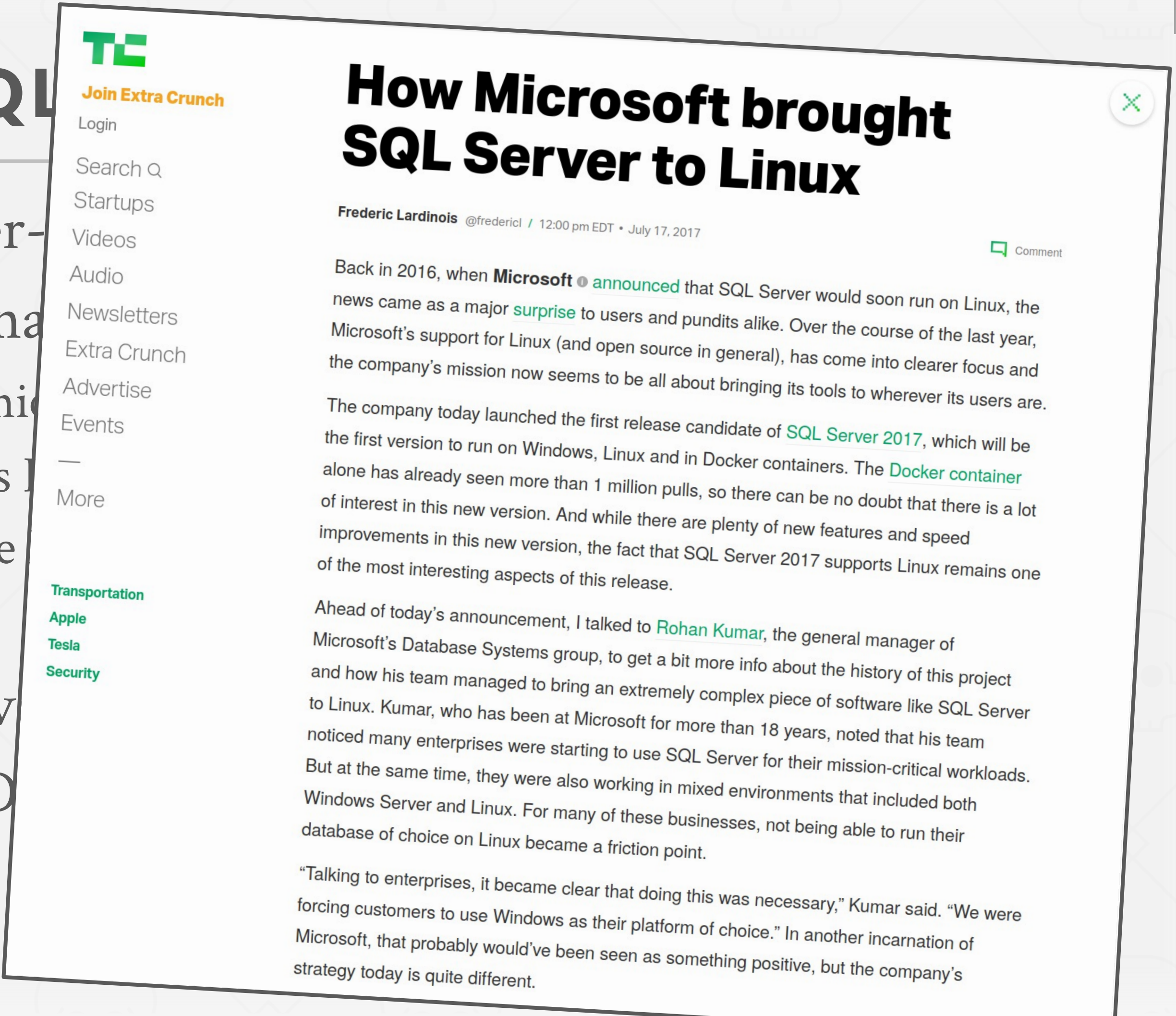

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How Microsoft brought SQL Server to Linux

Frederic Lardinois @fredericl / 12:00 pm EDT • July 17, 2017

Comment

Back in 2016, when **Microsoft** announced that SQL Server would soon run on Linux, the news came as a major surprise to users and pundits alike. Over the course of the last year, Microsoft's support for Linux (and open source in general), has come into clearer focus and the company's mission now seems to be all about bringing its tools to wherever its users are.

The company today launched the first release candidate of SQL Server 2017, which will be the first version to run on Windows, Linux and in Docker containers. The Docker container alone has already seen more than 1 million pulls, so there can be no doubt that there is a lot of interest in this new version. And while there are plenty of new features and speed improvements in this new version, the fact that SQL Server 2017 supports Linux remains one of the most interesting aspects of this release.

Ahead of today's announcement, I talked to Rohan Kumar, the general manager of Microsoft's Database Systems group, to get a bit more info about the history of this project and how his team managed to bring an extremely complex piece of software like SQL Server to Linux. Kumar, who has been at Microsoft for more than 18 years, noted that his team noticed many enterprises were starting to use SQL Server for their mission-critical workloads. But at the same time, they were also working in mixed environments that included both Windows Server and Linux. For many of these businesses, not being able to run their database of choice on Linux became a friction point.

"Talking to enterprises, it became clear that doing this was necessary," Kumar said. "We were forcing customers to use Windows as their platform of choice." In another incarnation of Microsoft, that probably would've been seen as something positive, but the company's strategy today is quite different.

SQL SERVER – SQLOS

SQLOS quantum is 4 ms, but the scheduler cannot enforce that.

DBMS developers must add explicit yield calls in various locations in the source code.

```
SELECT * FROM R WHERE R.val = ?
```

```
last = now()
for tuple in R:
  if now() - last > 4ms:
     yield
     last = now()
  if eval(predicate, tuple, params):
    emit(tuple)
```

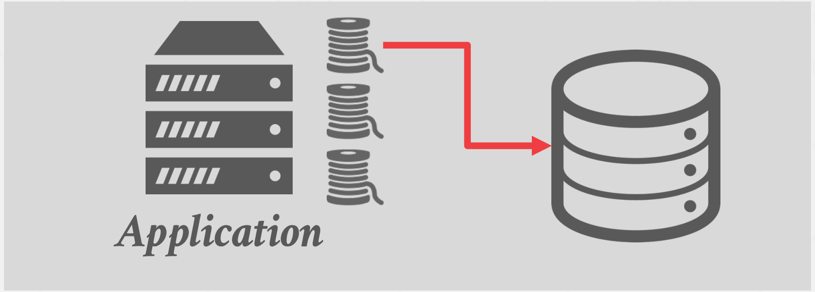
More on a different/modern way to do query/operator scheduling today (bonus material).

EMBEDDED DBMS

DBMS runs inside the same address space as the application. Application is (primarily) responsible for threads and scheduling.

The application may support outside connections.

→ Examples: BerkeleyDB, SQLite, RocksDB, LevelDB



SQLite
RocksDB
DuckDB
levelDB
YottaDB
WIREDTIGER
SPLINTERDB
bitcask

PROCESS MODELS

Advantages of a multi-threaded architecture:

→ Less overhead per context switch.

→ Do not have to manage shared memory.

The thread per worker model does **not** mean that the DBMS supports intra-query parallelism.

DBMS from the last 15 years use native OS threads unless they are Redis or Postgres forks.

INTER- VS. INTRA-QUERY PARALLELISM

Inter-Query: Execute multiple disparate queries simultaneously.

→ Increases throughput & reduces latency.

Intra-Query: Execute the operations of a single query in parallel.

→ Decreases latency for long-running queries, especially for OLAP queries.

INTER-QUERY PARALLELISM

Improve overall performance by allowing multiple queries to execute simultaneously.

If queries are read-only, then this requires almost no explicit coordination between the queries.

→ Buffer pool can handle most of the sharing if necessary.

Lecture #16

If multiple queries are updating the database at the same time, then this is hard to do correctly…

INTRA-QUERY PARALLELISM

Improve the performance of a single query by executing its operators in parallel.

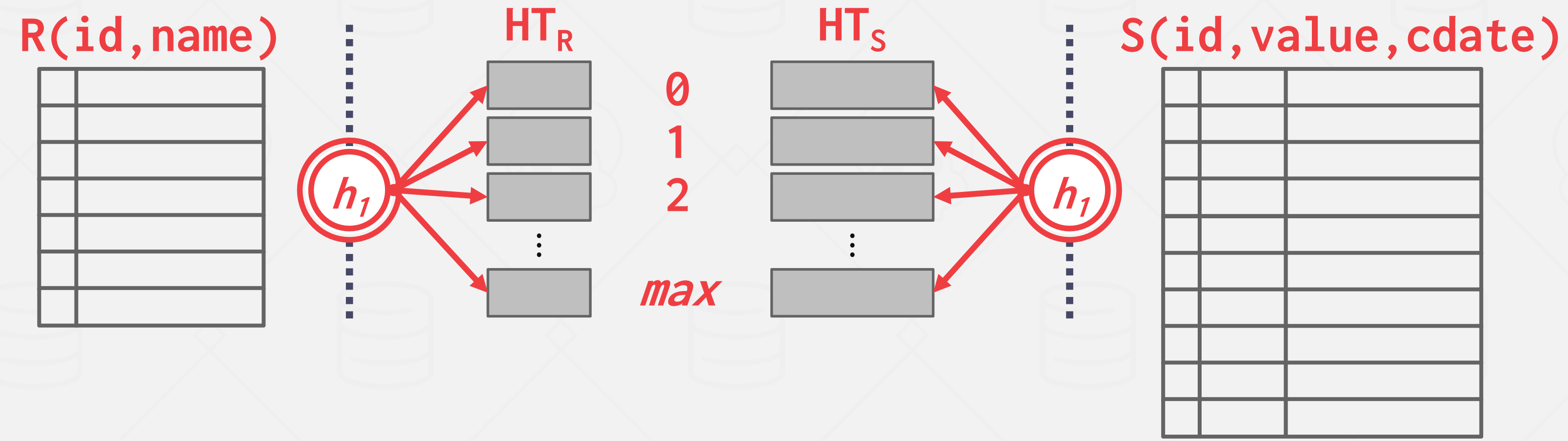
Think of the organization of operators in terms of a ***producer/consumer*** paradigm.

There are parallel versions of every operator.

→ Can either have multiple threads access centralized data structures or use partitioning to divide work up.

PARALLEL GRACE HASH JOIN

Use a separate worker to perform the join for each level of buckets for **R** and **S** after partitioning.



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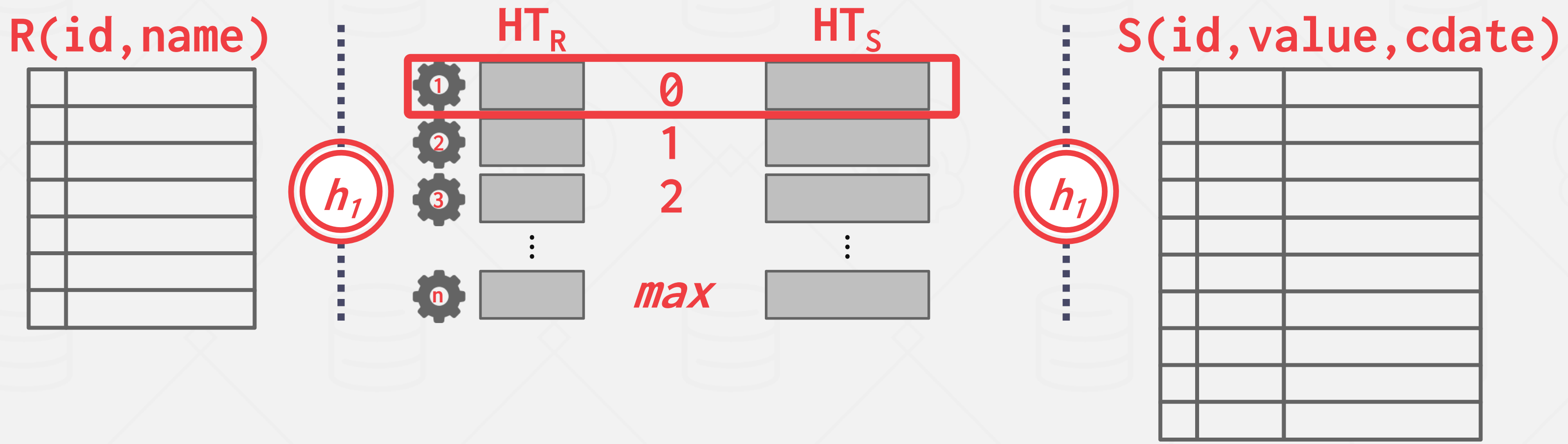


INTRA-QUERY PARALLELISM

Approach #1: **Intra-Operator** (Horizontal)

Approach #2: **Inter-Operator** (Vertical)

Approach #3: **Bushy**

INTRA-OPERATOR PARALLELISM

Approach #1: Intra-Operator (Horizontal)

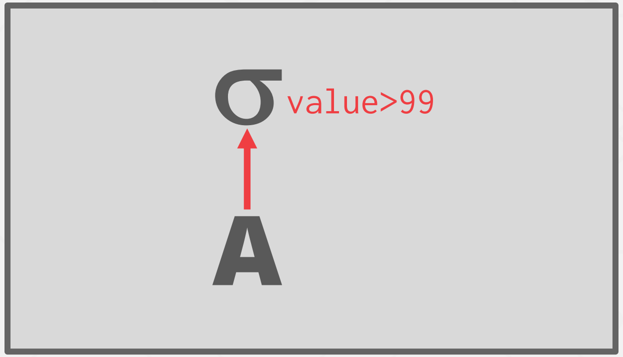
→ Decompose operators into independent **fragments** that perform the same function on different subsets of data.

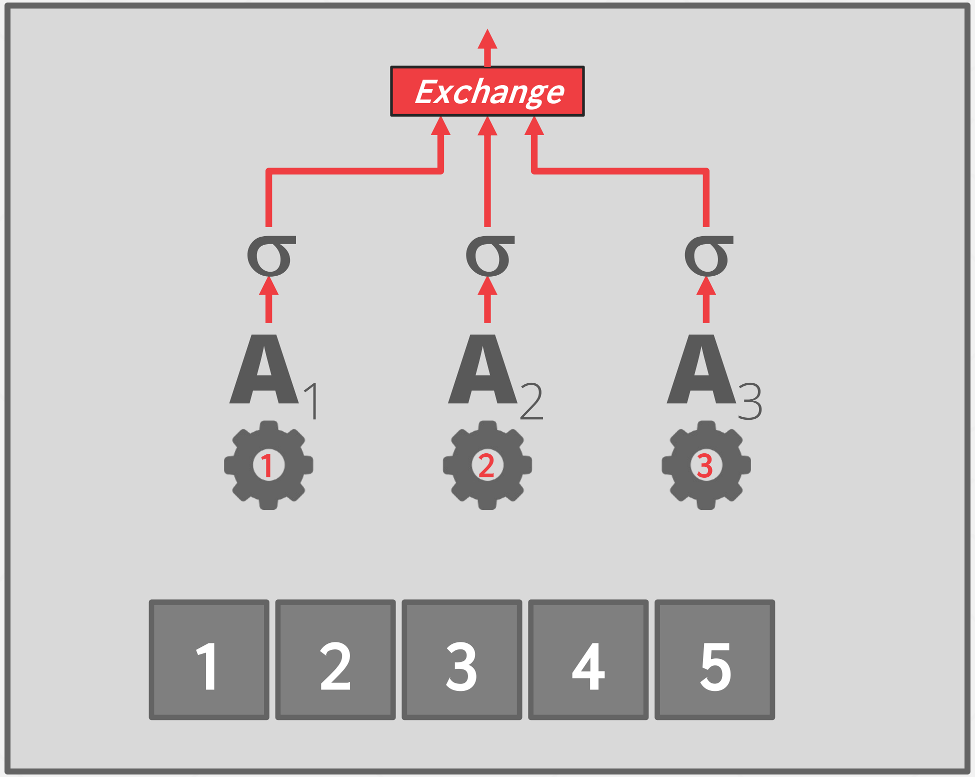
The DBMS inserts an **exchange** operator into the query plan to coalesce/split results from multiple children/parent operators.

→ Postgres calls this "gather"

INTRA-OPERATOR PARALLELISM

```
SELECT * FROM A
 WHERE A.val > 99
```





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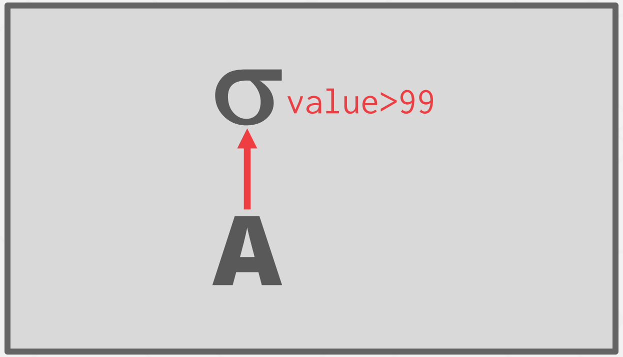

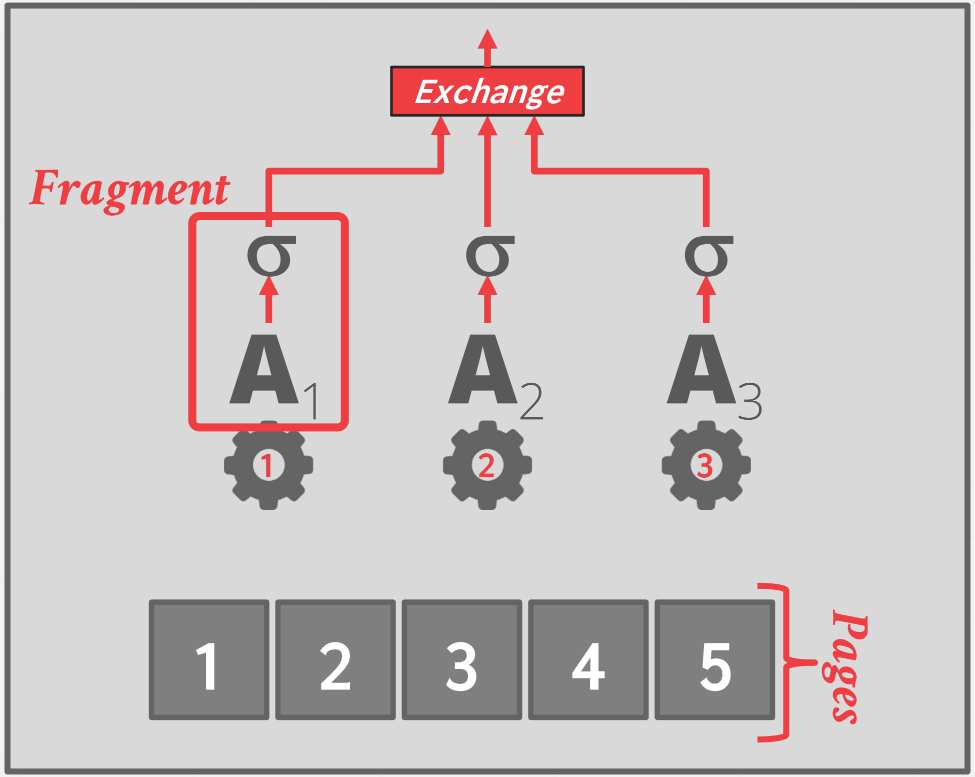

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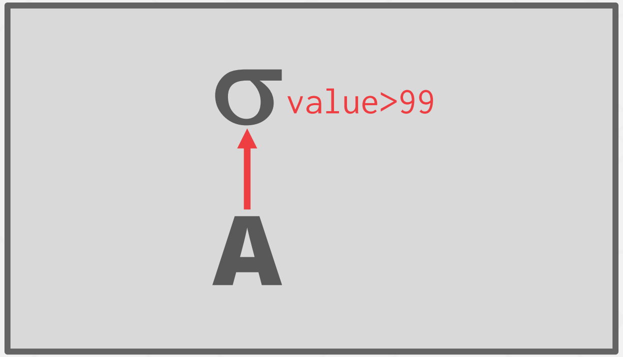

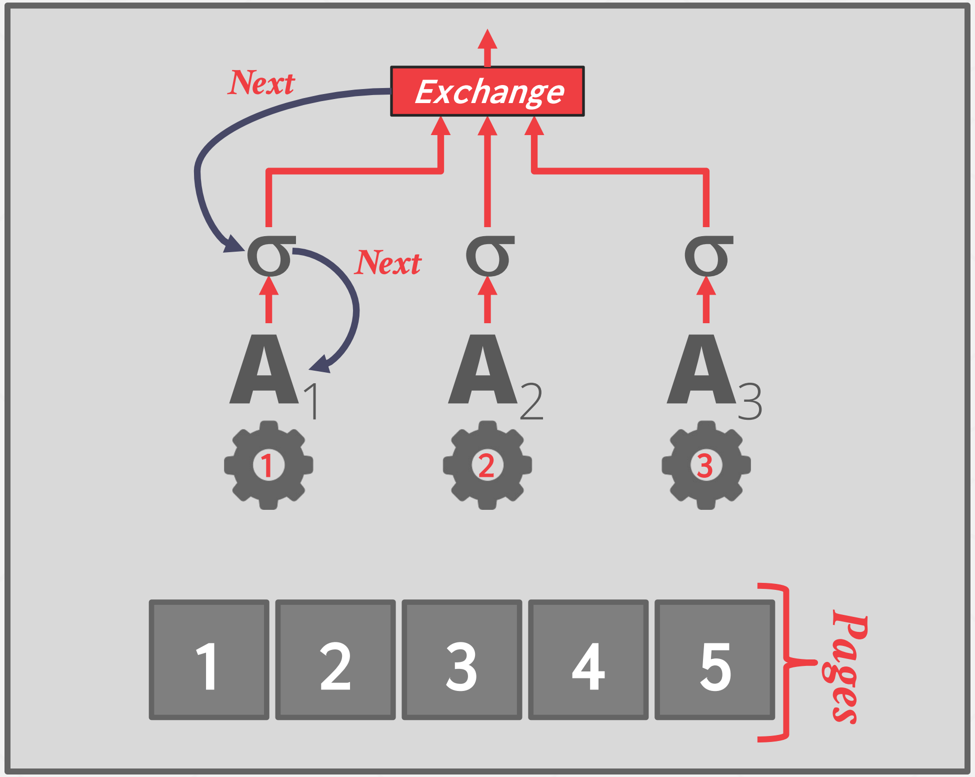

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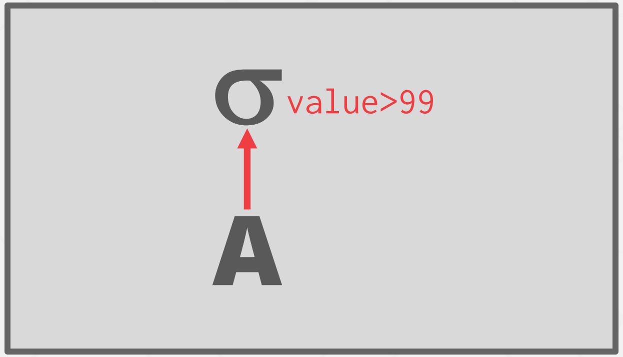

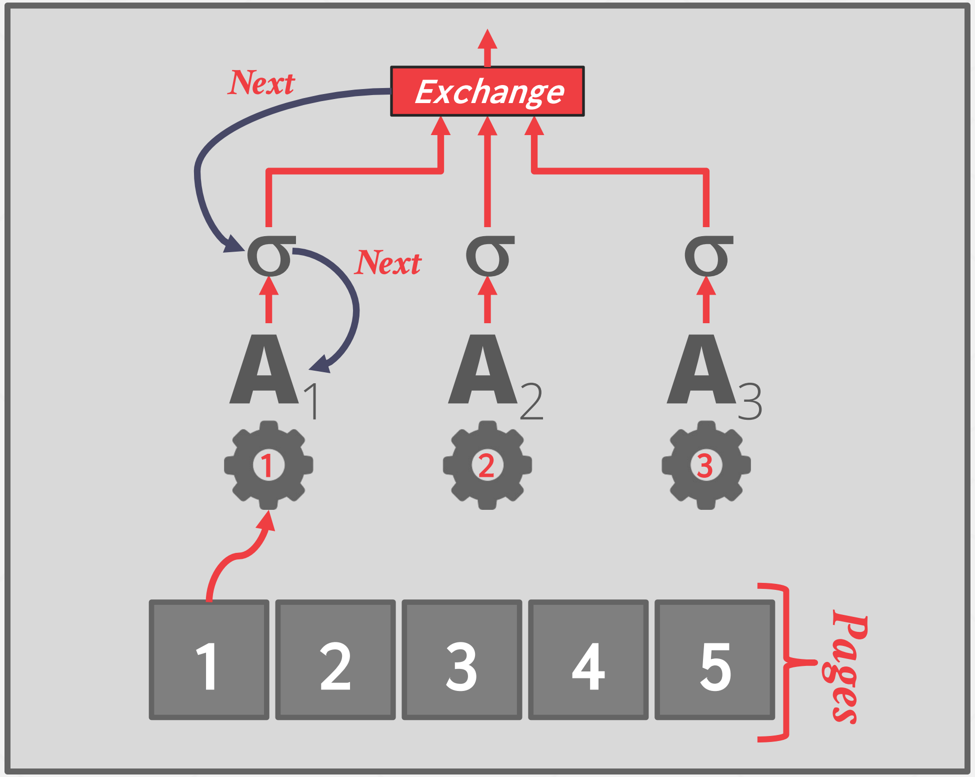

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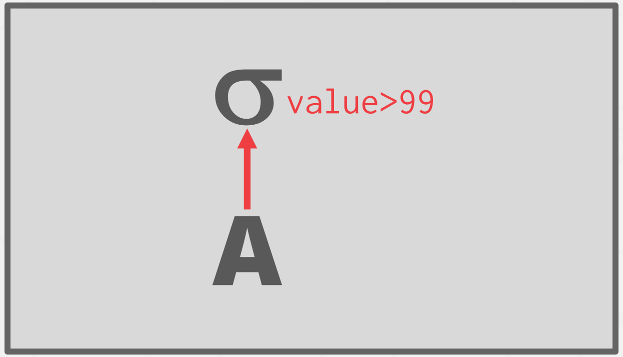

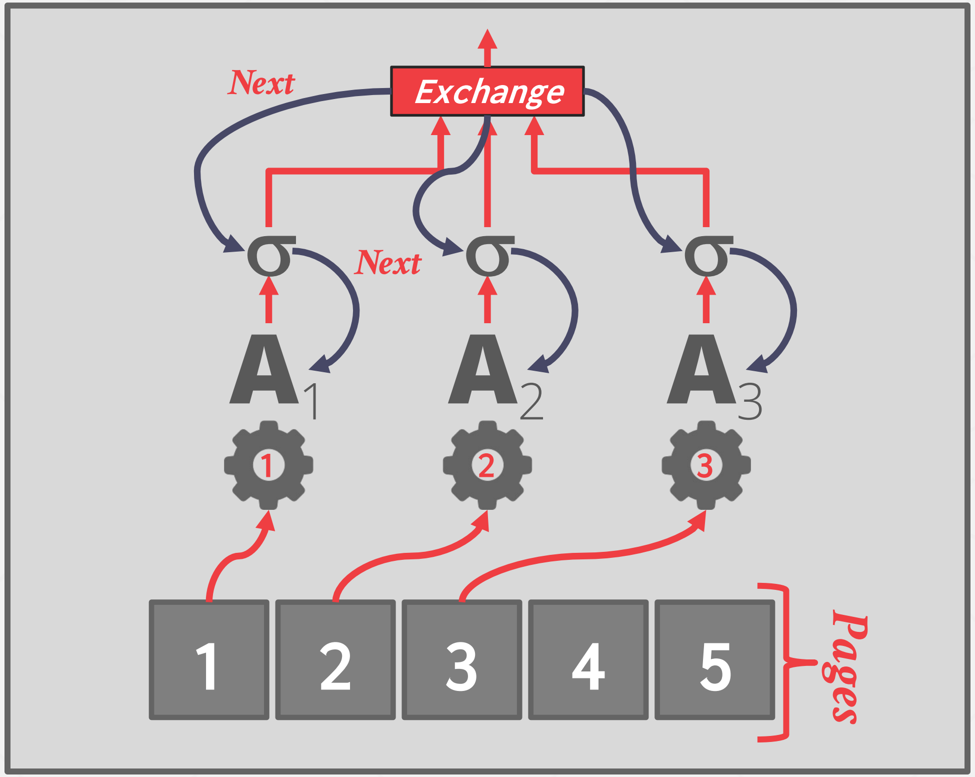

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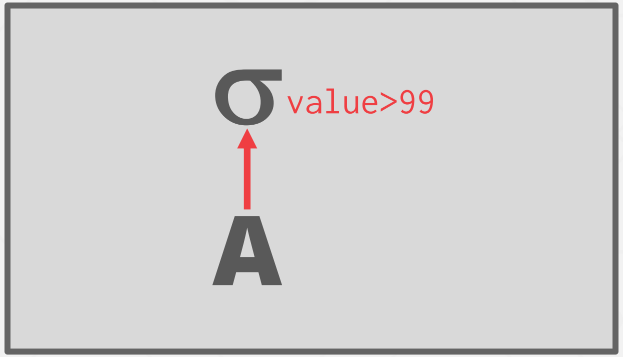
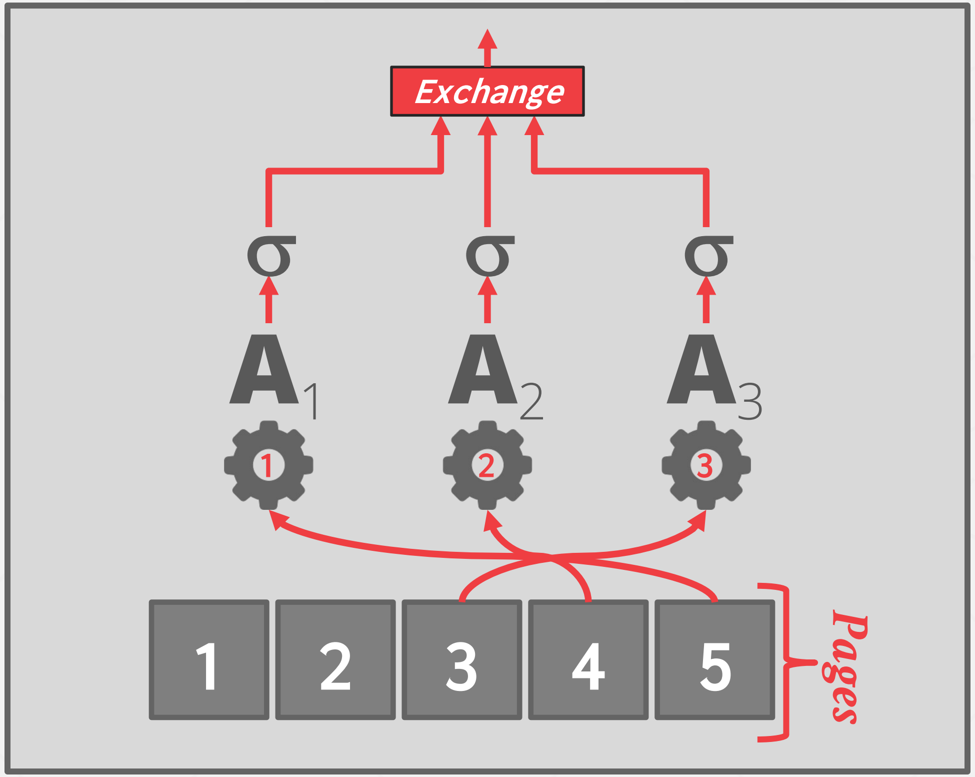
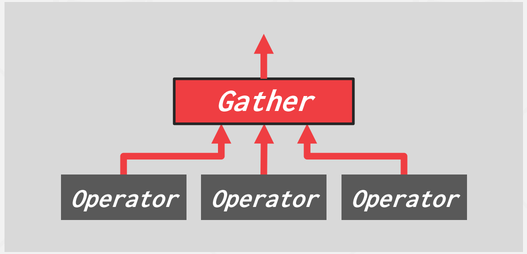




EXCHANGE OPERATOR

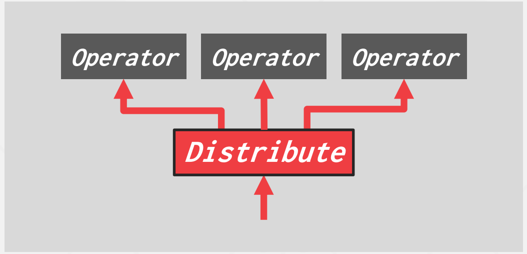
Exchange Type #1 – Gather

→ Combine the results from multiple workers into a single output stream.



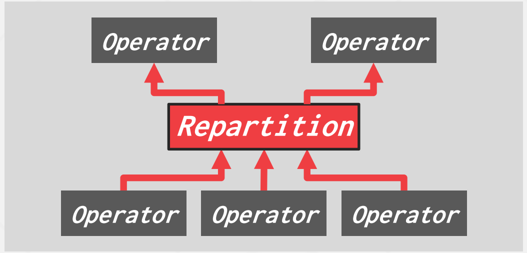
Exchange Type #2 – Distribute

→ Split a single input stream into multiple output streams.



Exchange Type #3 – Repartition

→ Shuffle multiple input streams across multiple output streams.



Source: Craig Freedman

INTRA-OPERATOR PARALLELISM

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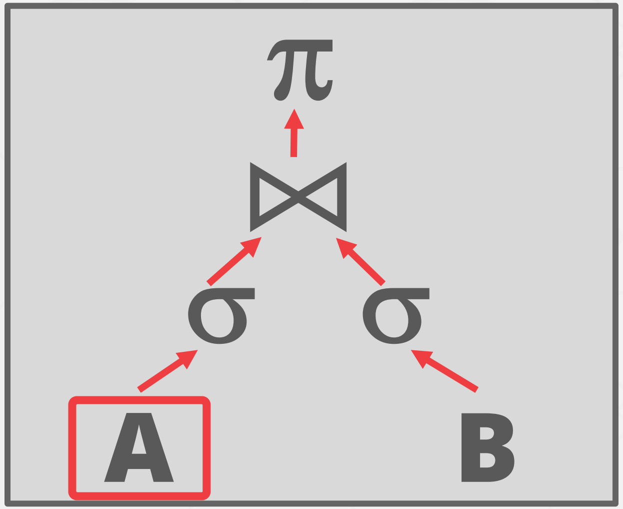

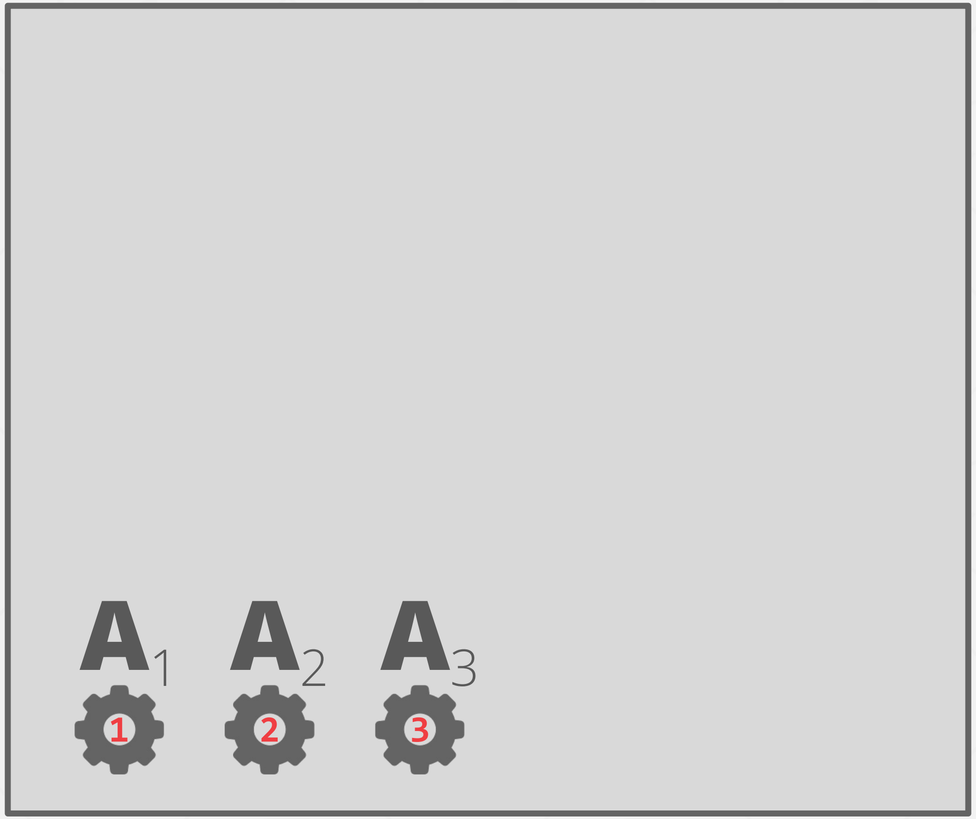

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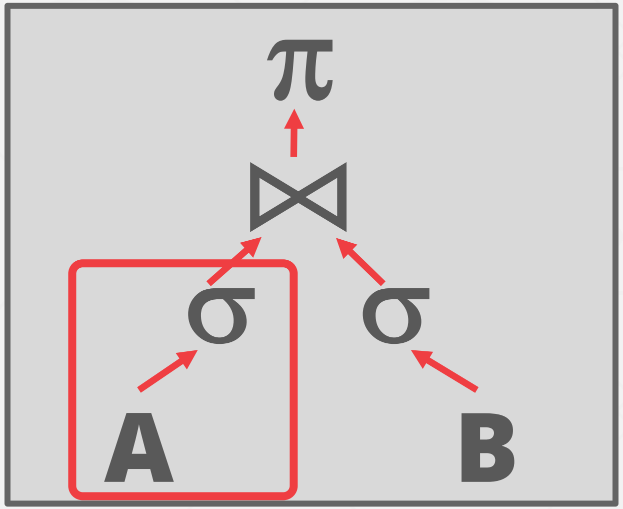

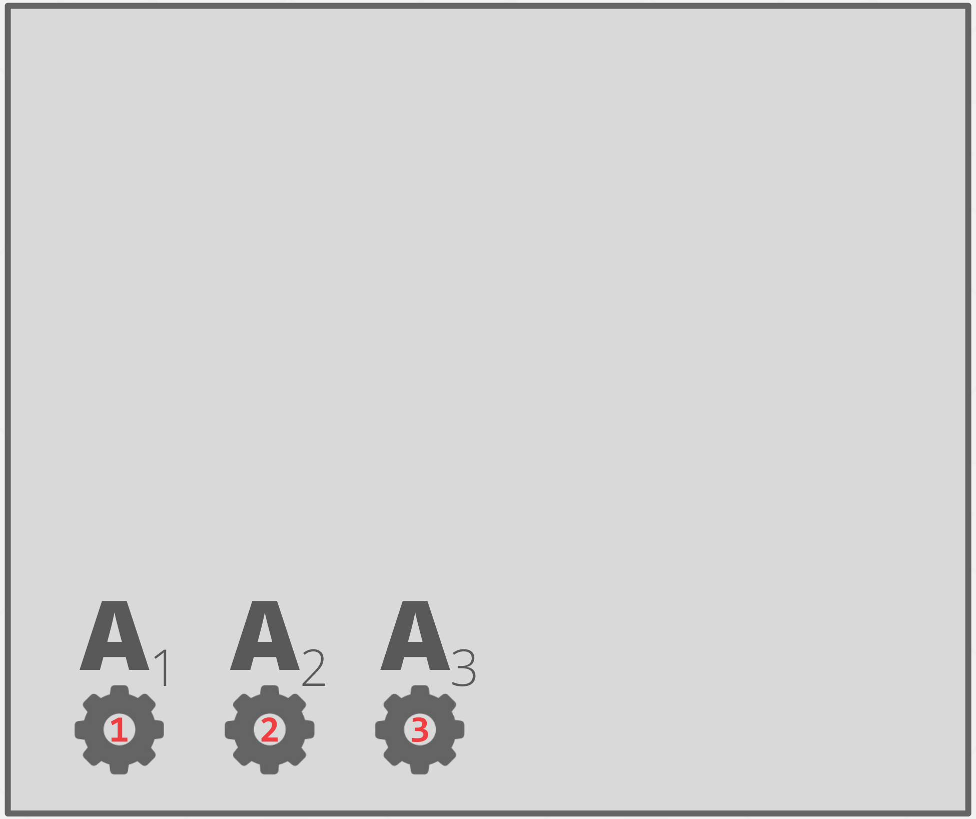

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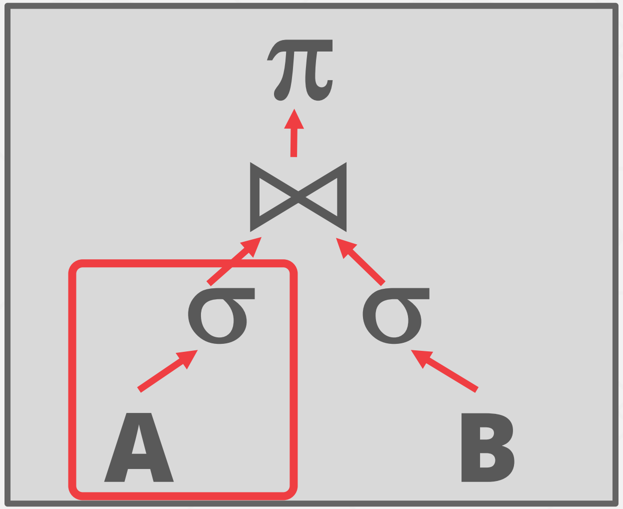

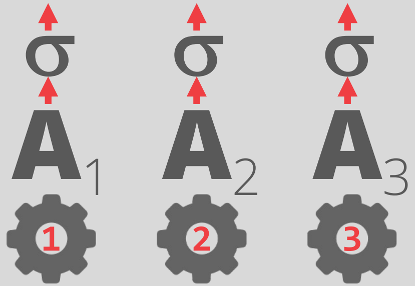

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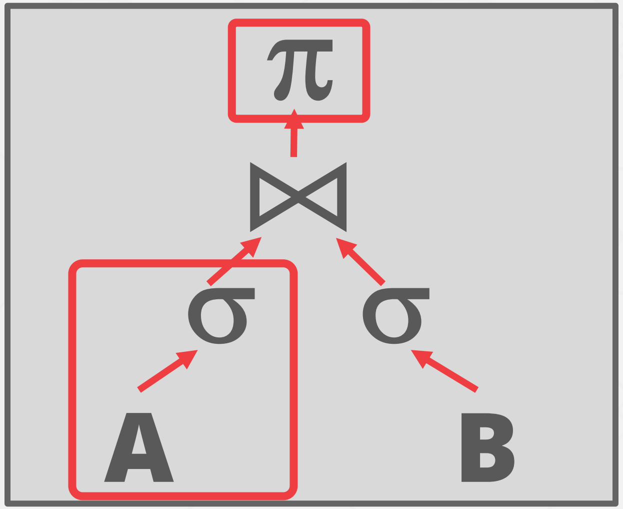

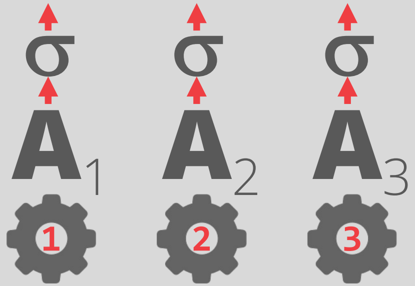

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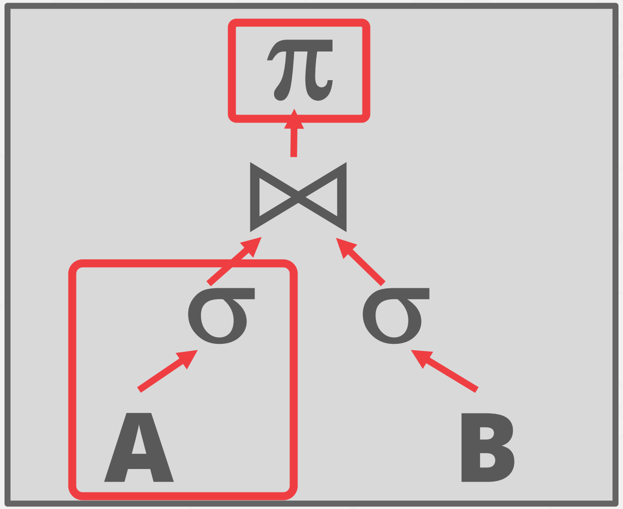

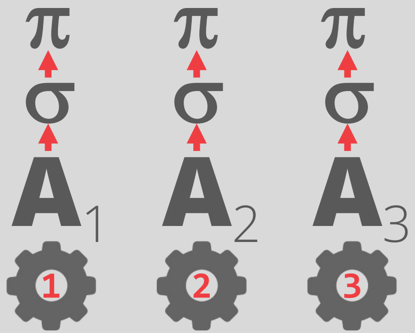

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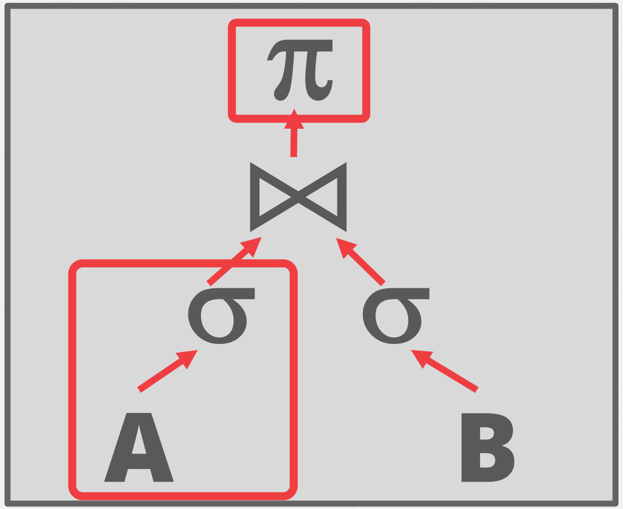

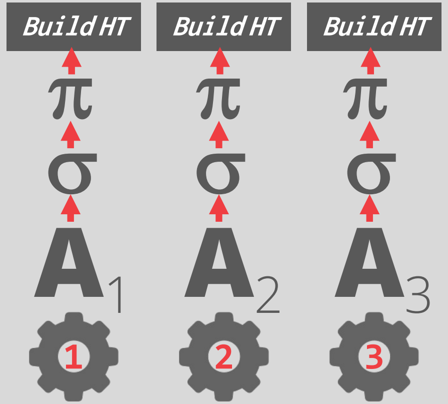

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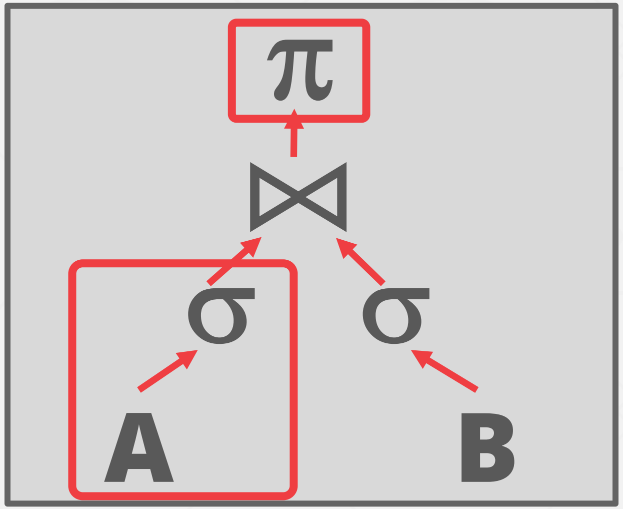

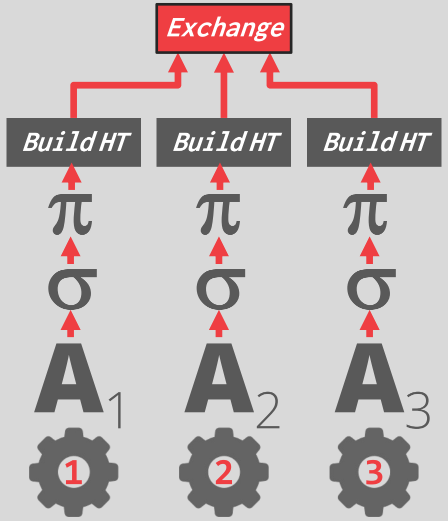

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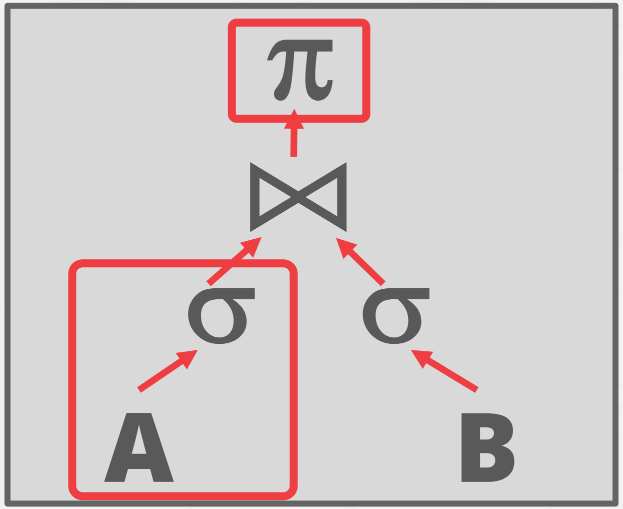

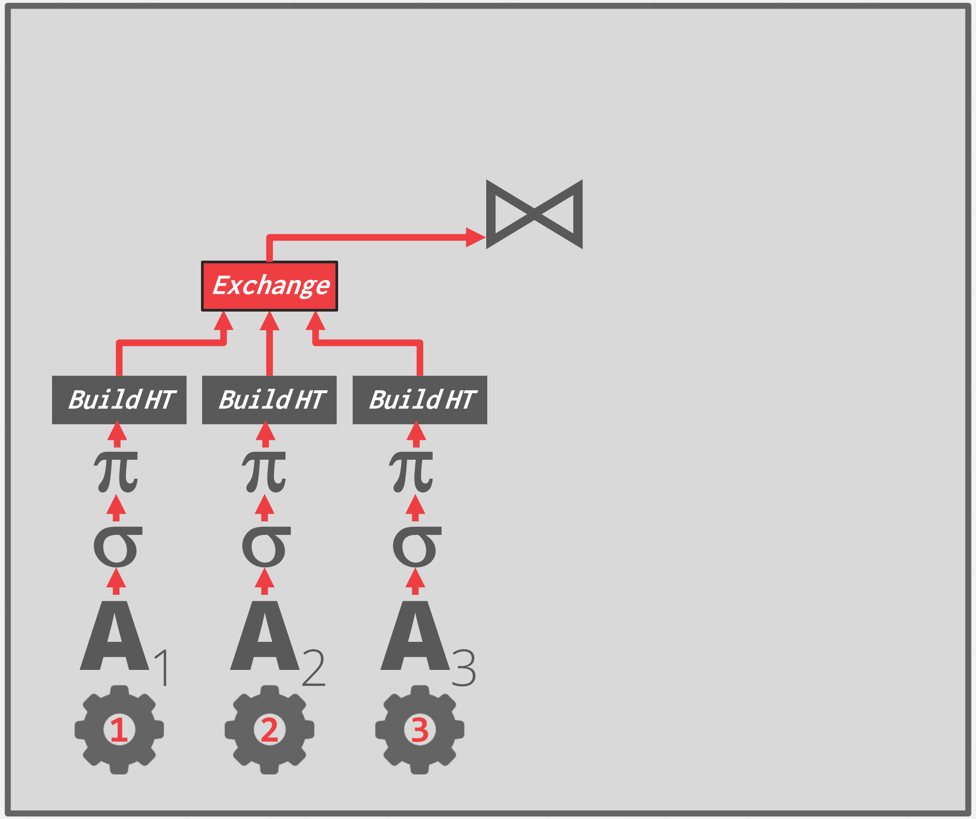

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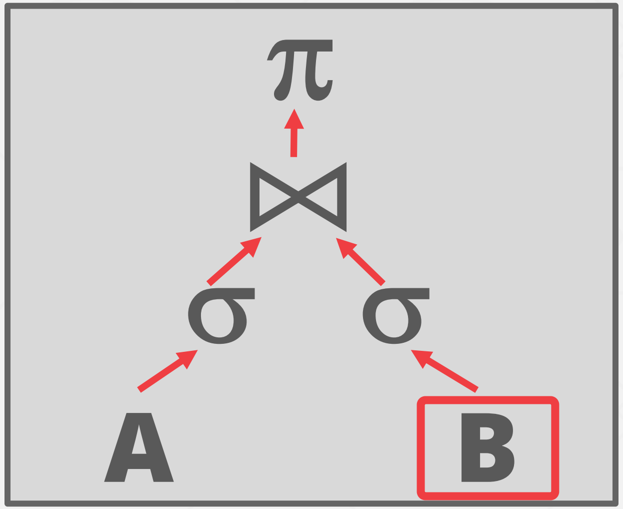

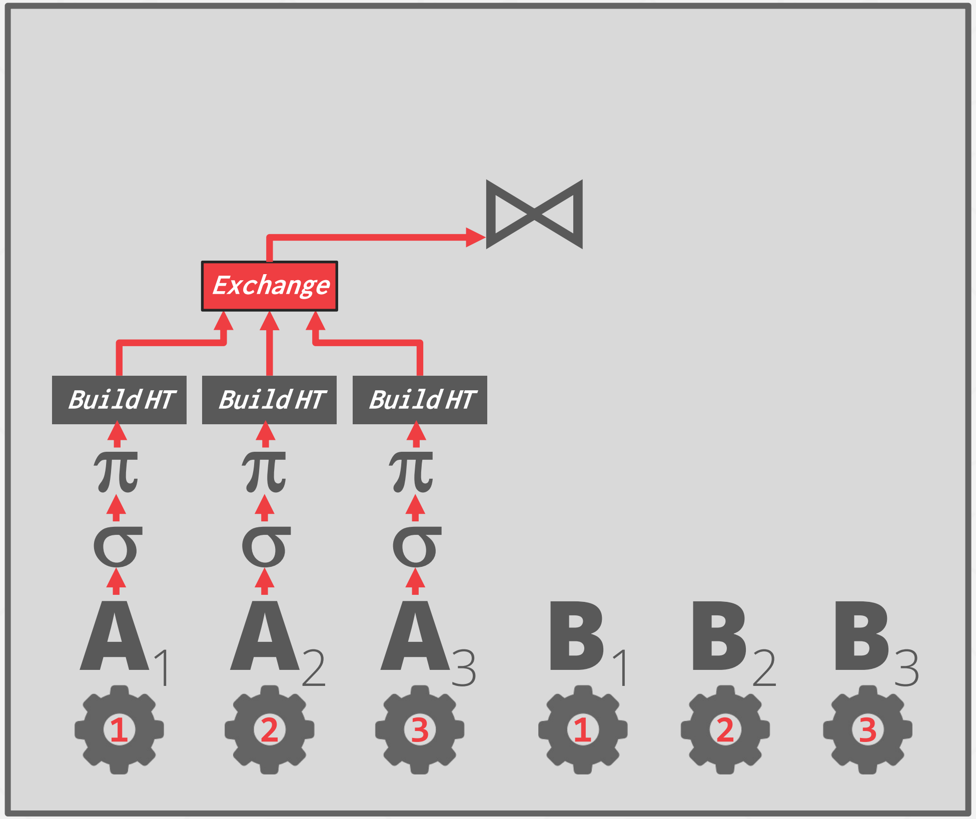

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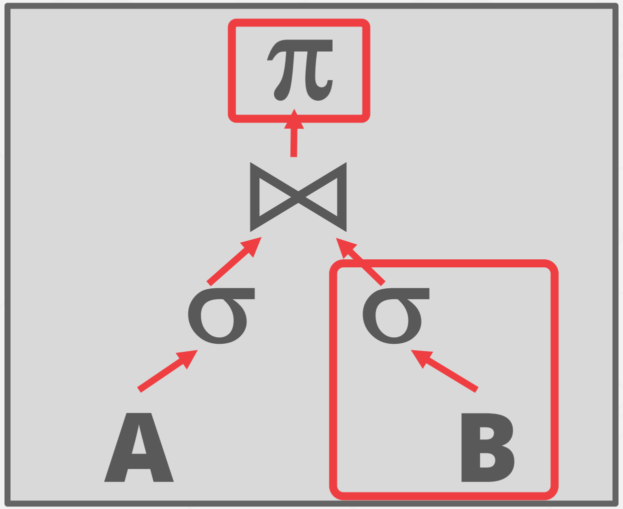

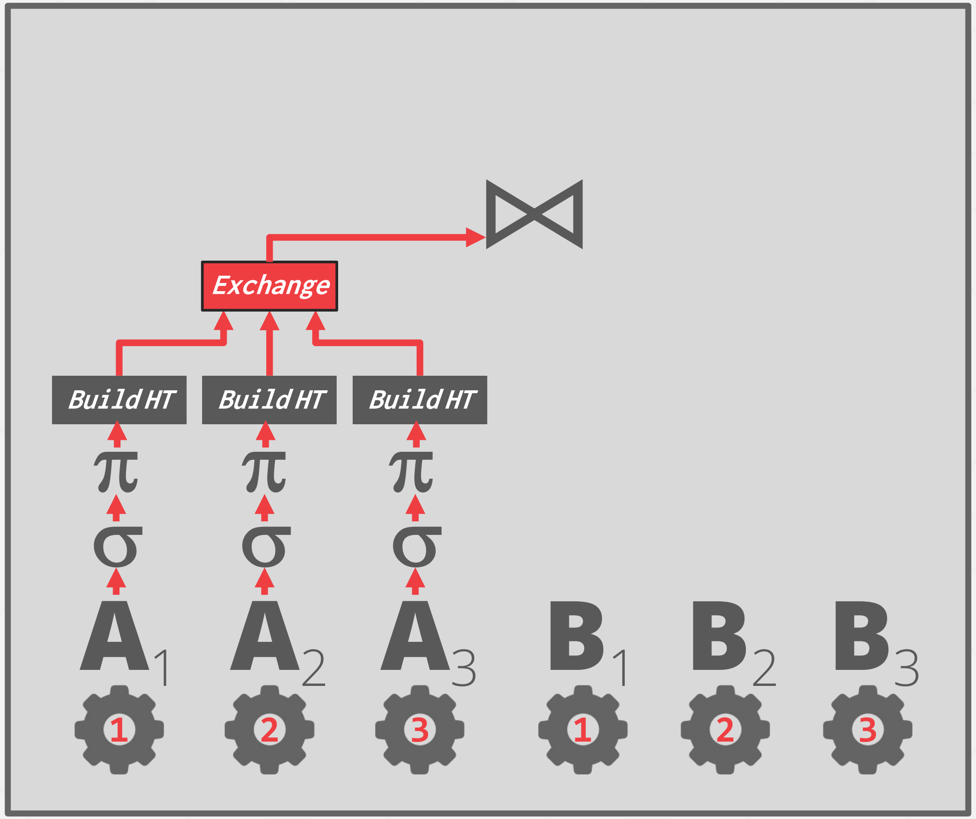

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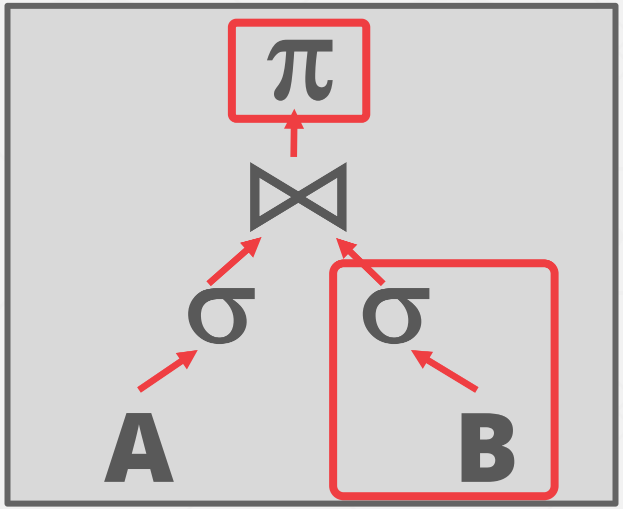

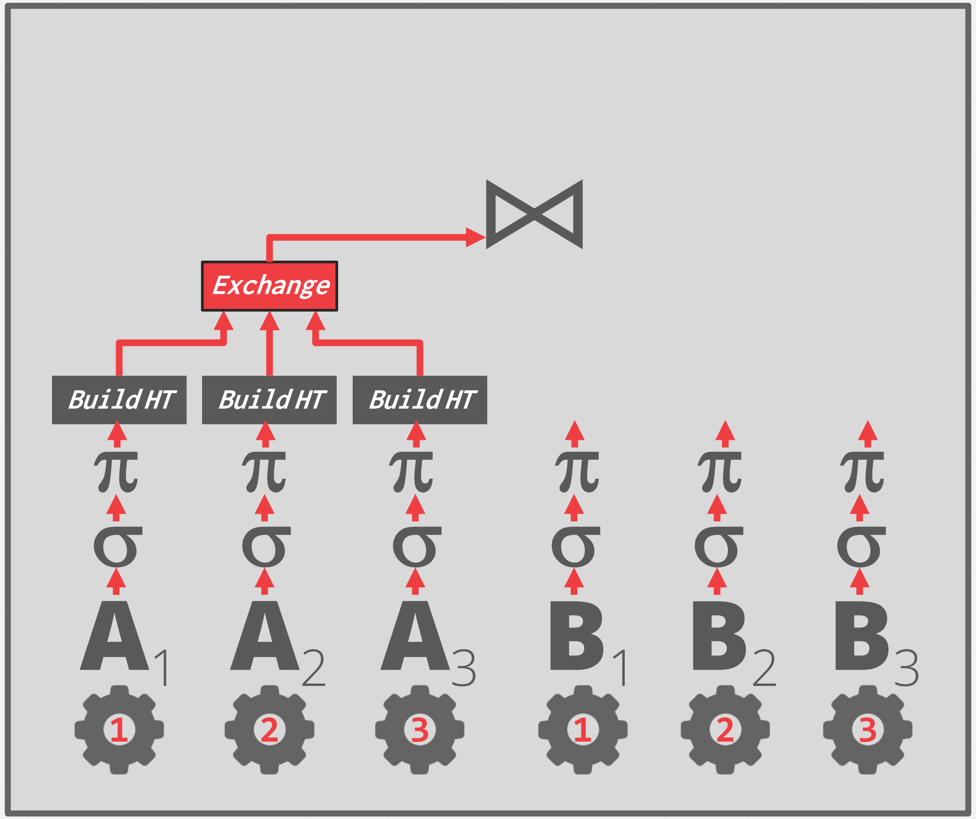

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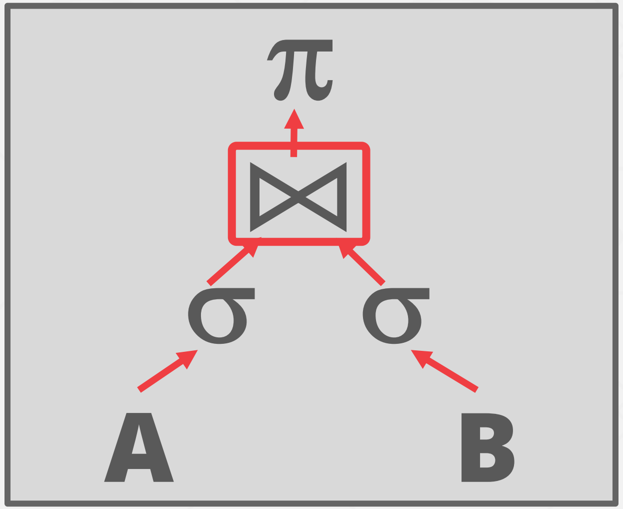
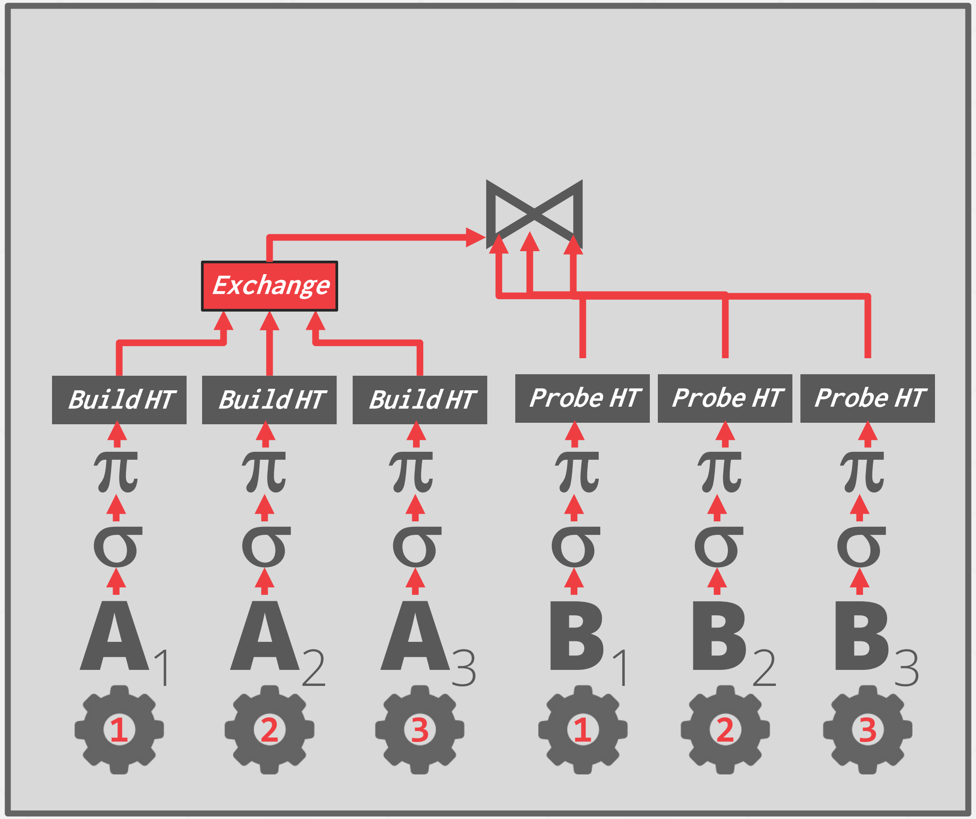
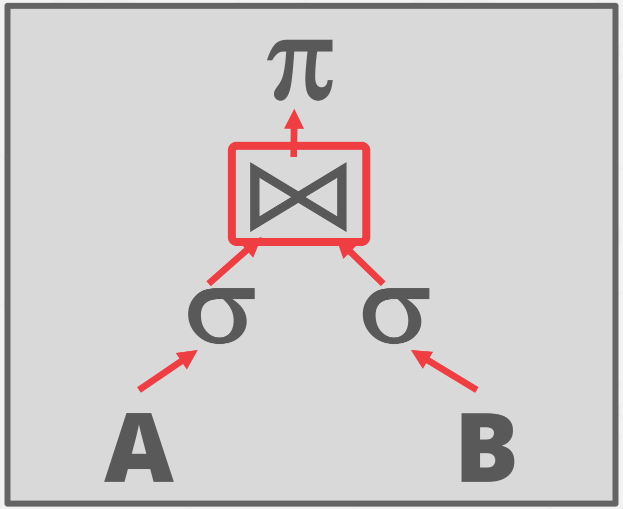
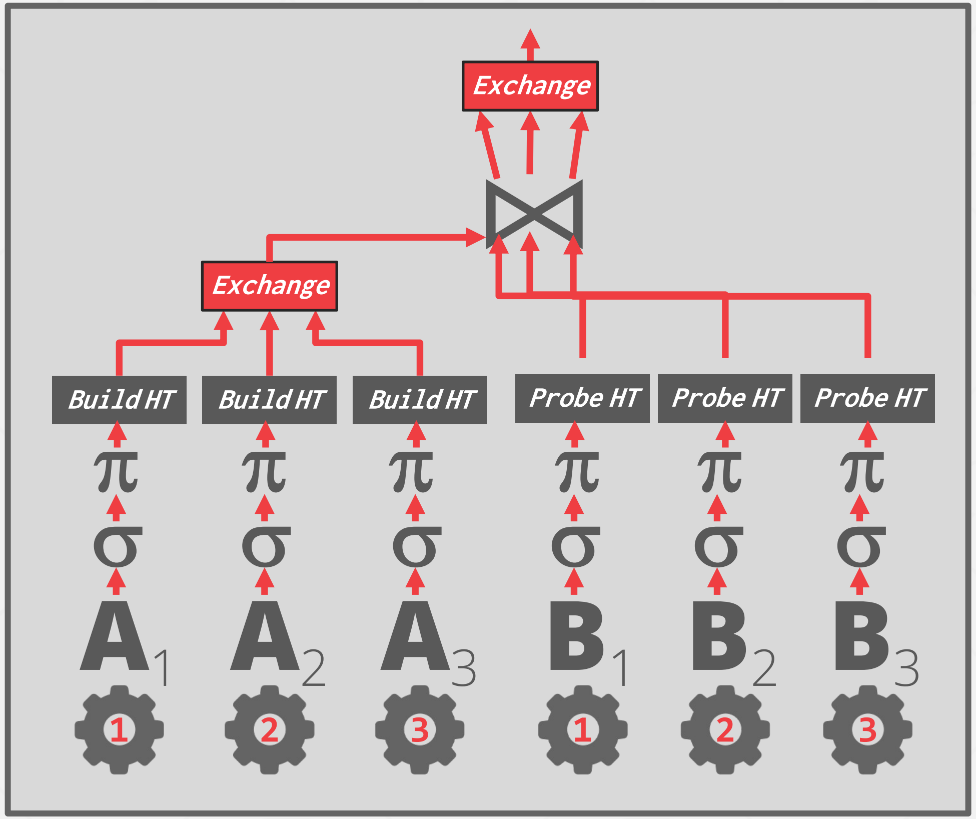




INTRA-OPERATOR PARALLELISM

```
SELECT A.id, B.value
  FROM A JOIN B
    ON A.id = B.id
 WHERE A.value < 99
   AND B.value > 100
```





INTER-OPERATOR PARALLELISM

Approach #2: Inter-Operator (Vertical)

→ Operations are overlapped in order to pipeline data from one stage to the next without materialization.

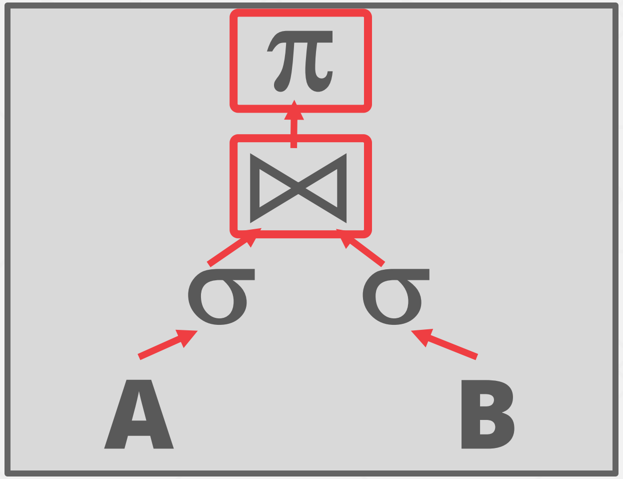
→ Workers execute operators from different segments of a query plan at the same time.

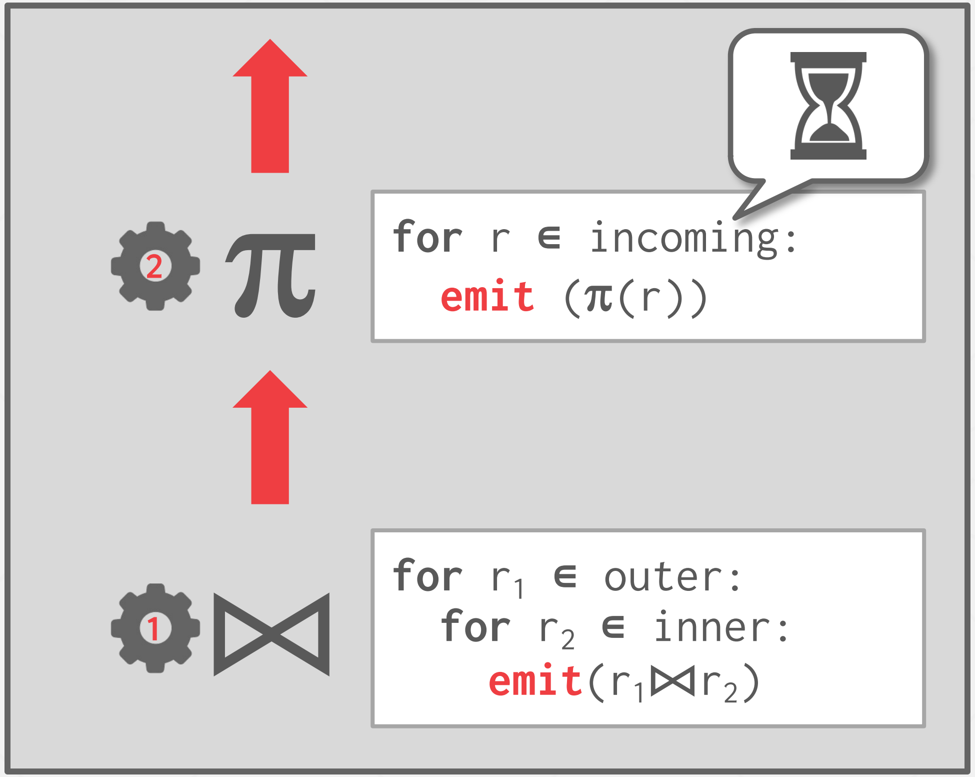
→ More common in streaming systems (continuous queries)

Also called **pipeline parallelism**.

INTER-OPERATOR PARALLELISM

```
SELECT A.id, B.value
  FROM A JOIN B
    ON A.id = B.id
 WHERE A.value < 99
   AND B.value > 100
```





```
for r ∈ incoming:
  emit (π(r))
```

```
for r₁ ∈ outer:
  for r₂ ∈ inner:
    emit(r₁⋈r₂)
```

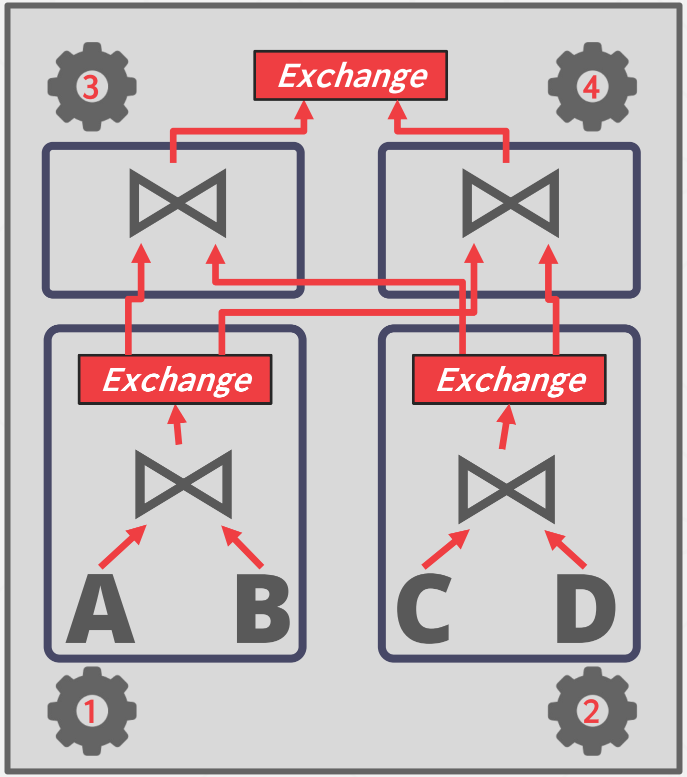
BUSHY PARALLELISM

Approach #3: Bushy Parallelism

→ Hybrid of intra- and inter-operator parallelism where workers execute multiple operators from different segments of a query plan at the same time.

→ Still need exchange operators to combine intermediate results from segments.

```
SELECT *
  FROM A JOIN B JOIN C JOIN D
```



OBSERVATION

Using additional processes/threads to execute queries in parallel won't help if the disk is always the main bottleneck.

It can sometimes make the DBMS's performance worse if a worker is accessing different segments of the disk at the same time.

I/O PARALLELISM

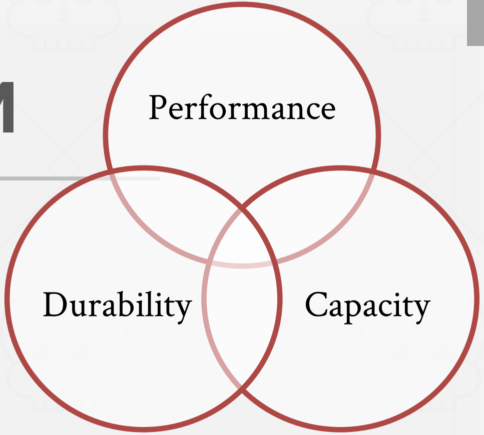
Split the DBMS across multiple storage devices to improve disk bandwidth latency.

Many different options that have trade-offs:
→ Multiple Disks per Database
→ One Database per Disk
→ One Relation per Disk
→ Split Relation across Multiple Disks

Some DBMSs support this natively. Others require admin to configure outside of DBMS.

MULTI-DISK PARALLELISM

MULTI-DISK PARALLELISM



Data on the disk can get corrupted (bit rot), or an entire disk can fail.

Get higher performance from a disk array.

Hardware-based: A hardware controller manages multiple devices, e.g. RAID.

MULTI-DISK PARALLELISM

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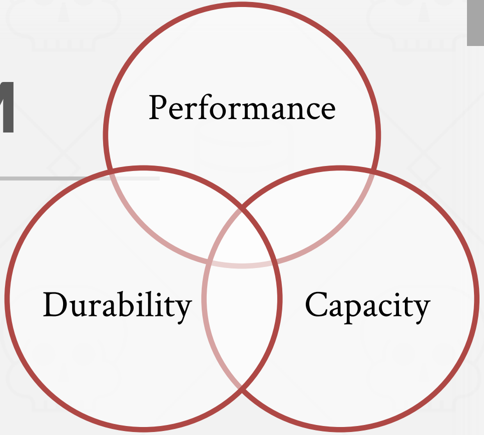

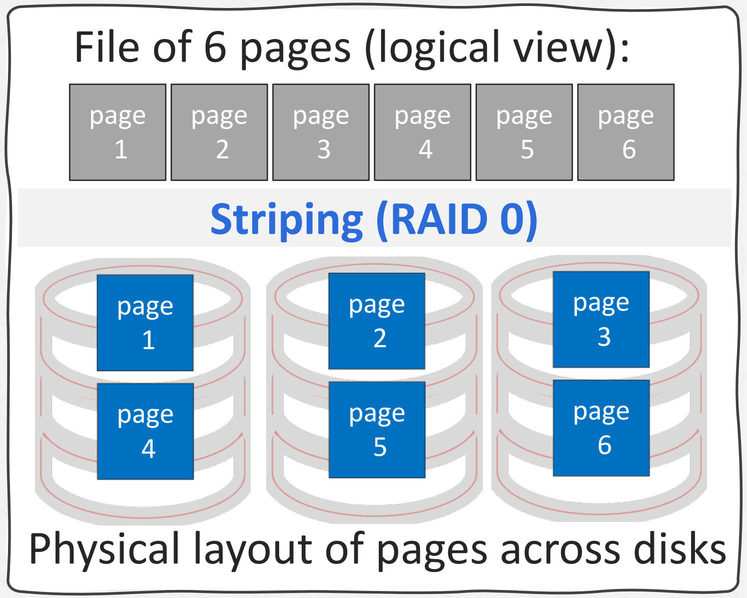

MULTI-DISK PARALLELISM

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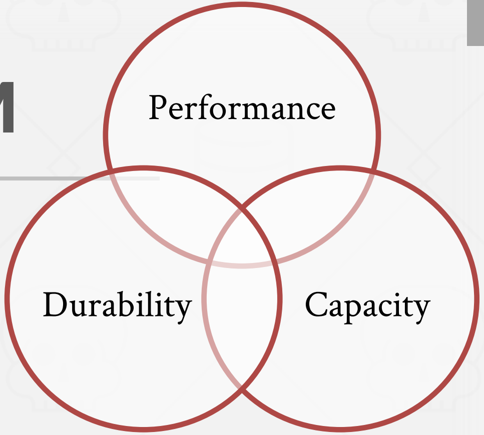
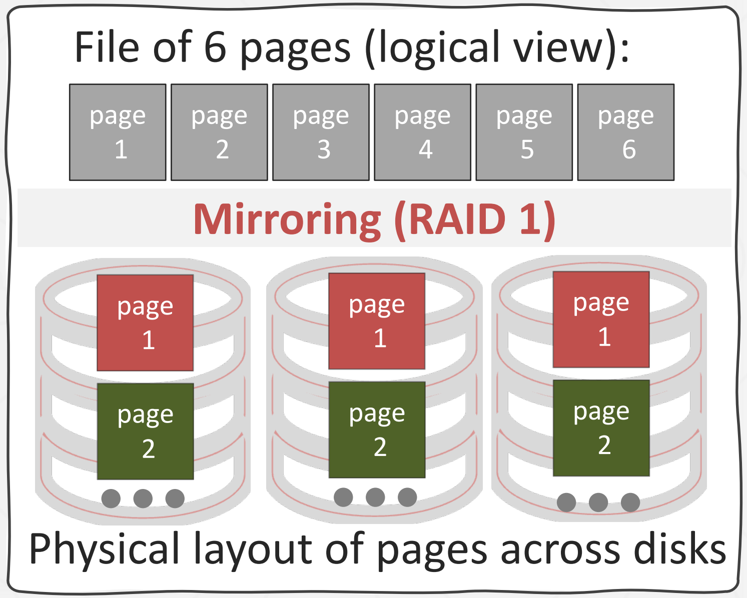
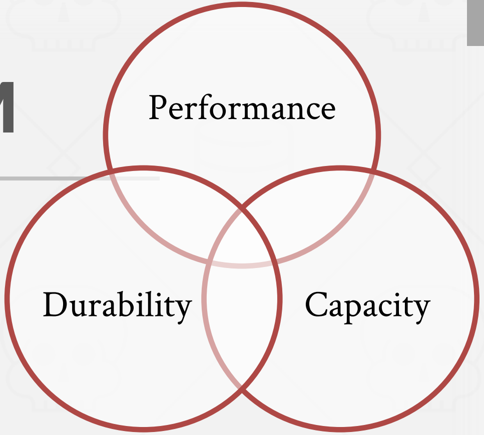




MULTI-DISK PARALLELISM



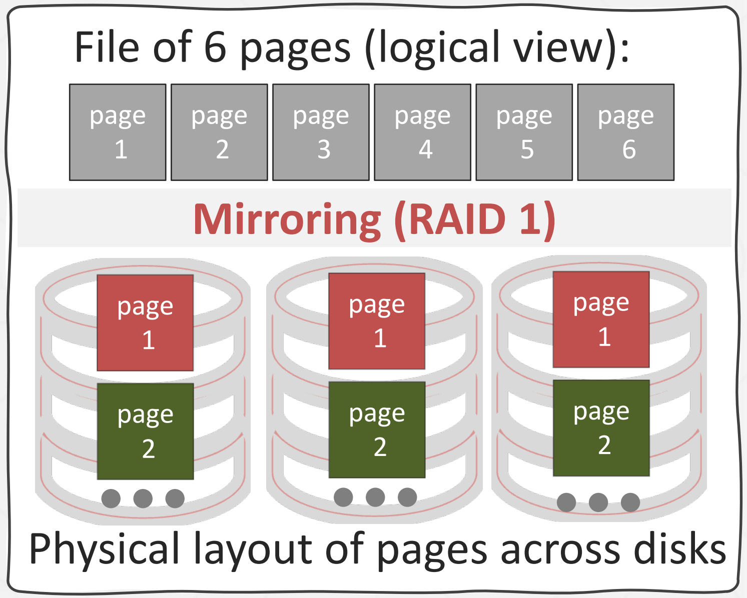
Data on the disk can get corrupted (bit rot), or an entire disk can fail.

Get higher performance from a disk array.

Hardware-based: A hardware controller manages multiple devices, e.g. RAID.

Software-based: Use erasure codes at the file/object level. Faster and more flexible.

This is **transparent** to the DBMS.



DATABASE PARTITIONING

Some DBMSs allow you to specify the disk location of each individual database.

→ The buffer pool manager maps a page to a disk location.

This is also easy to do at the filesystem level if the DBMS stores each database in a separate directory.

→ The DBMS recovery log file might still be shared if transactions can update multiple databases.

PARTITIONING

Split a single logical table into disjoint physical segments that are stored/managed separately.

Partitioning should (ideally) be transparent to the application.

→ The application should only access logical tables and not have to worry about how things are physically stored.

We will cover this further when we talk about distributed databases.

CONCLUSION

Parallel execution is important, which is why (almost) every major DBMS supports it.

However, it is hard to get right.

→ Coordination Overhead
→ Scheduling
→ Concurrency Issues
→ Resource Contention

NEXT CLASS

Query Optimization
→ Logical vs Physical Plans
→ Search Space of Plans
→ Cost Estimation of Plans

Scheduler

So far, we have largely taken a **data flow** perspective of the query processing model.

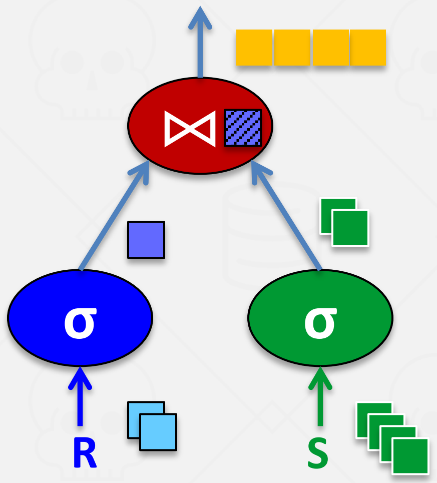
The **control flow** was implicit in the processing model. We can make the control flow more explicit with a scheduler.

Query schedulers are often not discussed in database papers. We'll look at what was done in the Quickstep (academic) project. Based on allowing frequent switches between data flow and control flow.

Bonus

Clean Separation of Data Flow and Control Flow

The "traditional" way

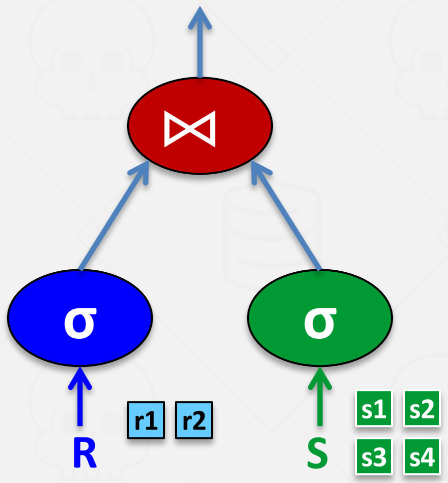


```
SELECT * FROM R, S
WHERE R.b > 10
    AND S.c >100
    AND R.a= S.a
```

The Quickstep way

The Quickstep Scheduler

Clean Separation of Data Flow and Control Flow



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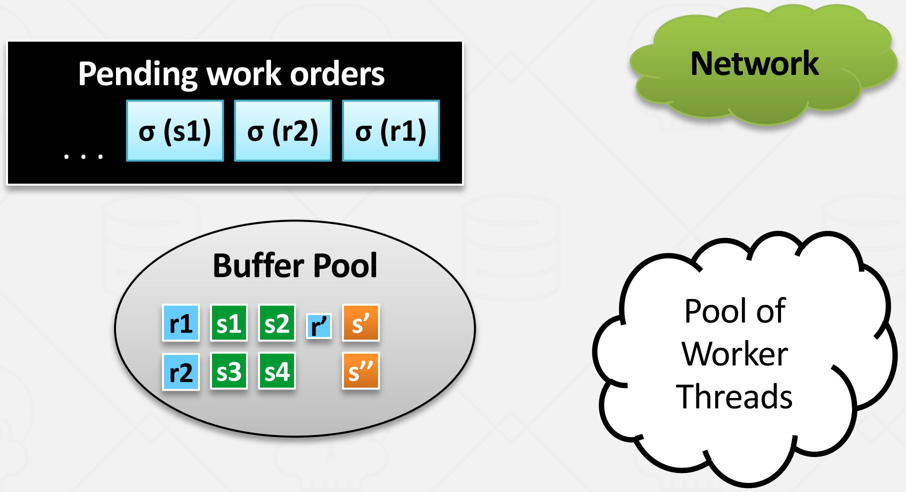


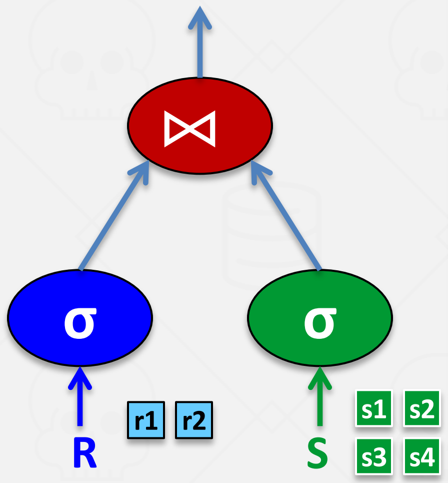
Buffer pool: Abstraction to manage "data blocks"/pages using LRU-2.

Data blocks = base data, intermediate results, QP data structures (Hash tables)
Variable length, but multiples of a base block size. Thus, hash tables can grow (via doubling in size)

Bonus

The Quickstep Scheduler

Clean Separation of Data Flow and Control Flow



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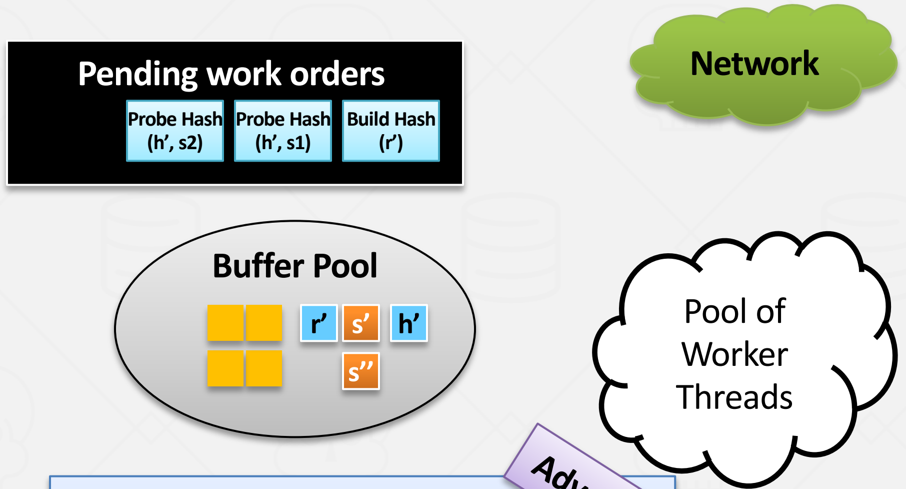
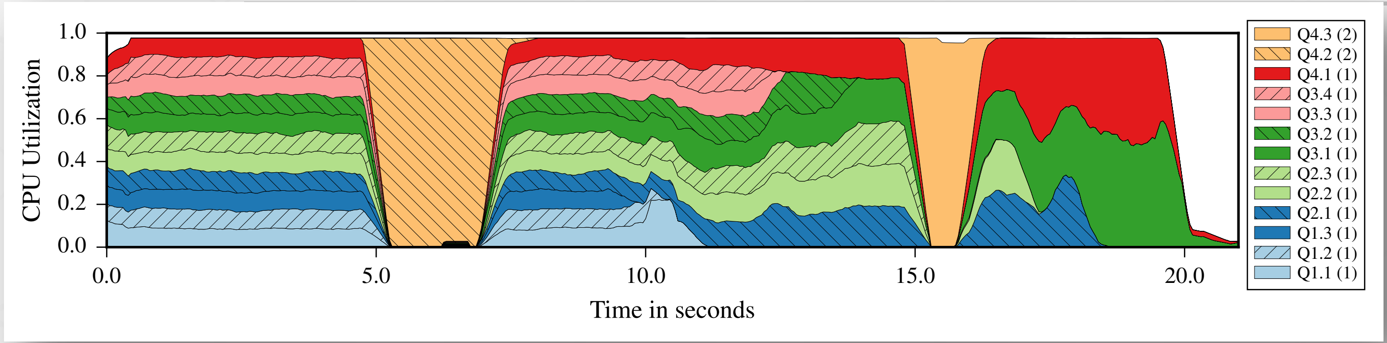
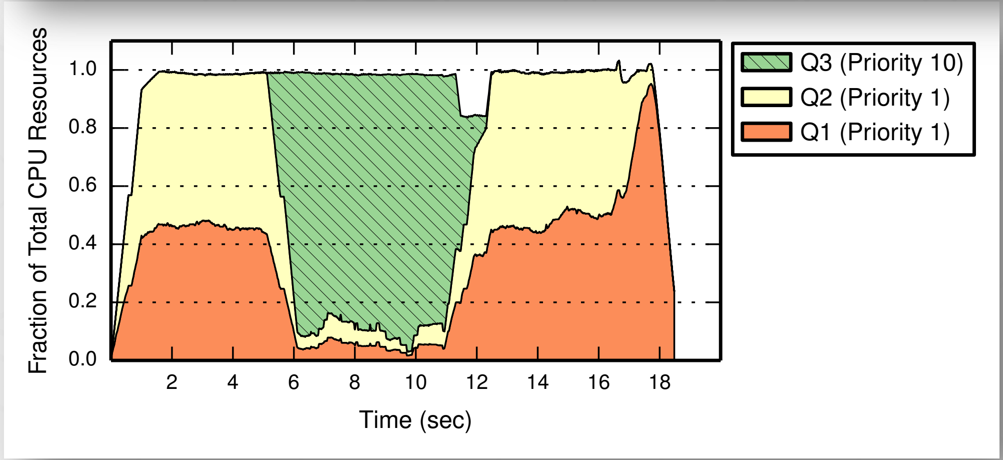


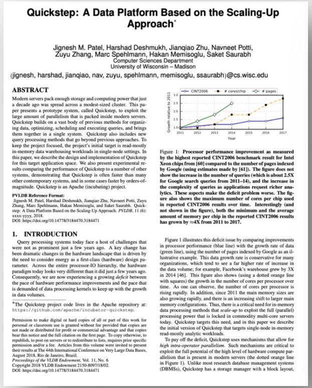
Advantages

+ Cleaner Abstraction
+ Dynamic Optimization
+ In-built query suspension
+ Better p9X
+ Manageability and Debug-ability

Priority scheduling = Elastic behavior







Quickstep: A Data Platform Based on the Scaling-Up Approach*

Jignesh M. Patel, Harshad Deshmukh, Jianqiao Zhu, Navneet Potti, Zuyu Zhang, Marc Spehlmann, Hakan Memisoglu, Saket Saurabh
Computer Sciences Department
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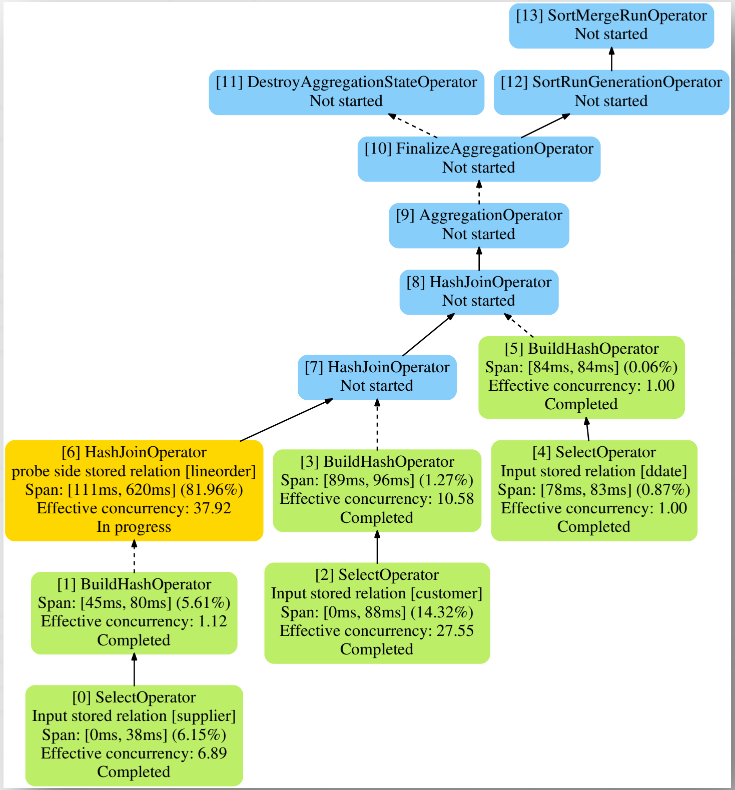
Morsel-Driven Parallelism: A NUMA-Aware Query Evaluation Framework for the Many-Core Age

Viktor Leis* Peter Boncz† Alfons Kemper* Thomas Neumann*
* Technische Universität München † CWI
* {leis,kemper,neumann}@in.tum.de † p.boncz@cwi.nl

Bonus

In-built Query Progress Monitoring


[13] SortMergeRunOperator
Not started
[11] DestroyAggregationStateOperator
Not started
[12] SortRunGenerationOperator
Not started
[10] FinalizeAggregationOperator
Not started
[9] AggregationOperator
Not started
[8] HashJoinOperator
Not started
[7] HashJoinOperator
Not started
[5] BuildHashOperator
Span: [84ms, 84ms] (0.06%)
Effective concurrency: 1.00
Completed
[6] HashJoinOperator
probe side stored relation [lineorder]
Span: [111ms, 620ms] (81.96%)
Effective concurrency: 37.92
In progress
[3] BuildHashOperator
Span: [89ms, 96ms] (1.27%)
Effective concurrency: 10.58
Completed
[4] SelectOperator
Input stored relation [ddate]
Span: [78ms, 83ms] (0.87%)
Effective concurrency: 1.00
Completed
[1] BuildHashOperator
Span: [45ms, 80ms] (5.61%)
Effective concurrency: 1.12
Completed
[2] SelectOperator
Input stored relation [customer]
Span: [0ms, 88ms] (14.32%)
Effective concurrency: 27.55
Completed
[0] SelectOperator
Input stored relation [supplier]
Span: [0ms, 38ms] (6.15%)
Effective concurrency: 6.89
Completed