Carnegie Mellon University

# Database Systems

# Query Execution II

15-445/645 SPRING 2025 » PROF. JIGNESH PATEL

# ADMINISTRIVIA

**Project #3** is due Sunday March 30th @ 11:59pm
→ Recitation on Fri, Mar 14 from 5:00 – 6:00 pm in GHC 5117.

Mid-term exam grades now posted.
→ Exam viewing for the next 3 OH, including today
→ The last OH for exam viewing is on March 24.
→ Special OH this Thu 9:00 am - 10:30 am, 9103 GHC.
→ Stats: Mean: 75.1, Std-dev: 10.4.
→ Notes: Used partial grading, and full points given on the join question.

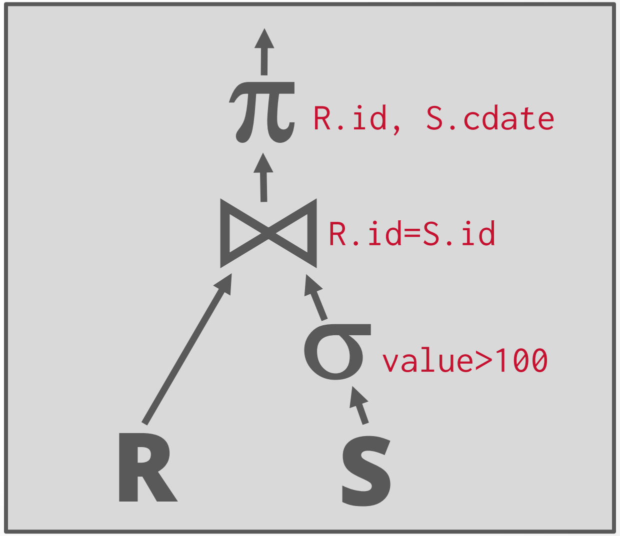
# LAST CLASS

We discussed composing operators into a plan to execute a query.

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

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

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



# PARALLEL QUERY EXECUTION

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

**DB Flash Talk: Confluent**

# 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 MODEL

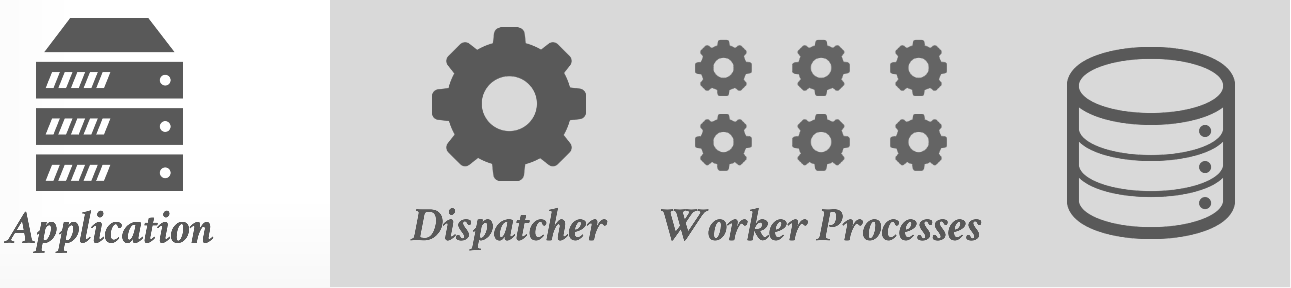
Approach #1: **Process** per DBMS Worker

Approach #2: **Thread** per DBMS Worker ⬅ *Most Common*

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



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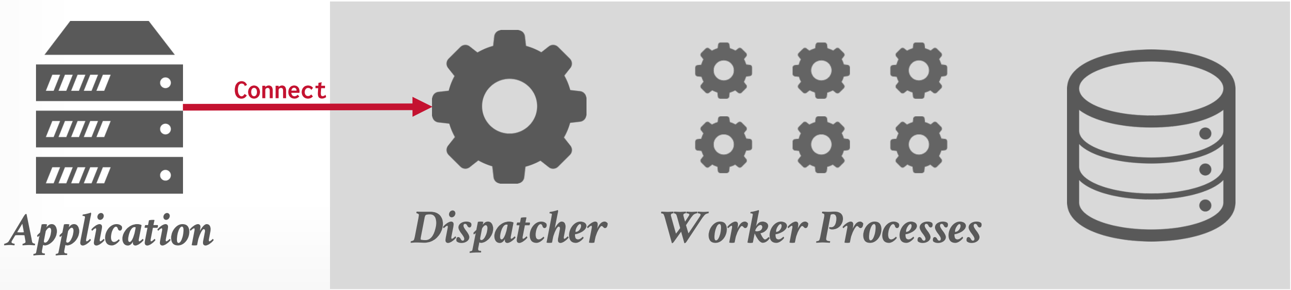

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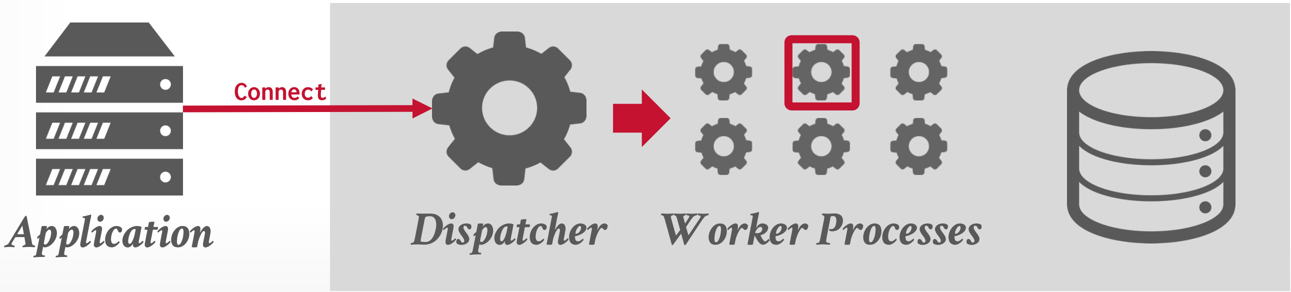

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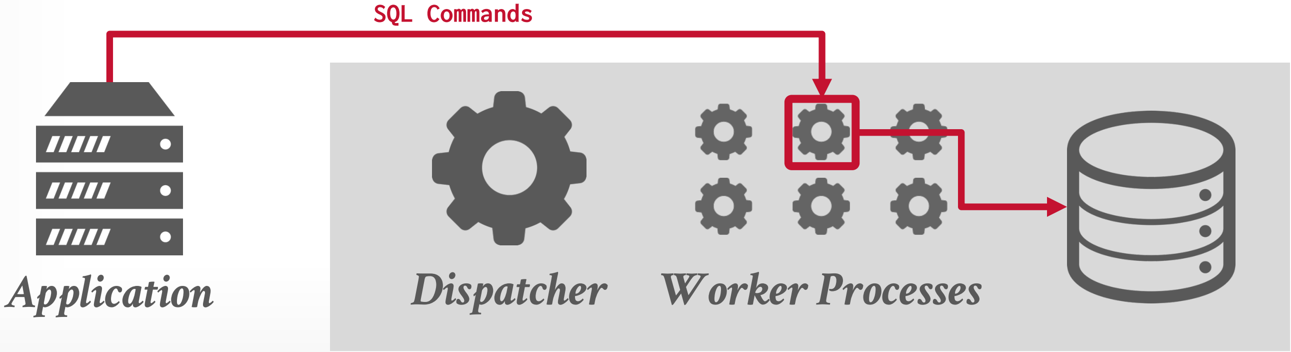


# THREAD PER WORKER

Single process with multiple worker threads.

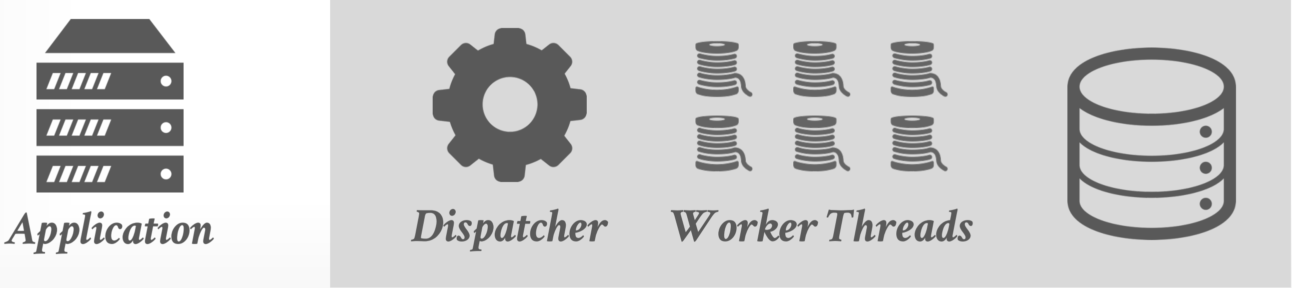
→ DBMS (mostly) manages its own scheduling.

→ 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!*



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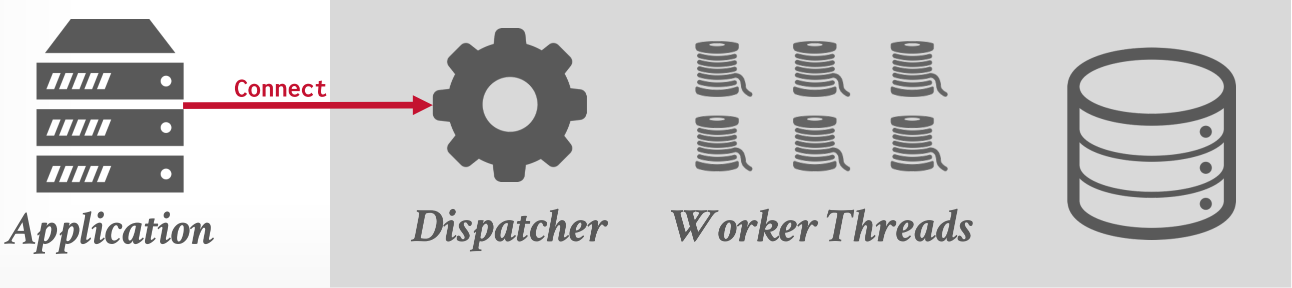

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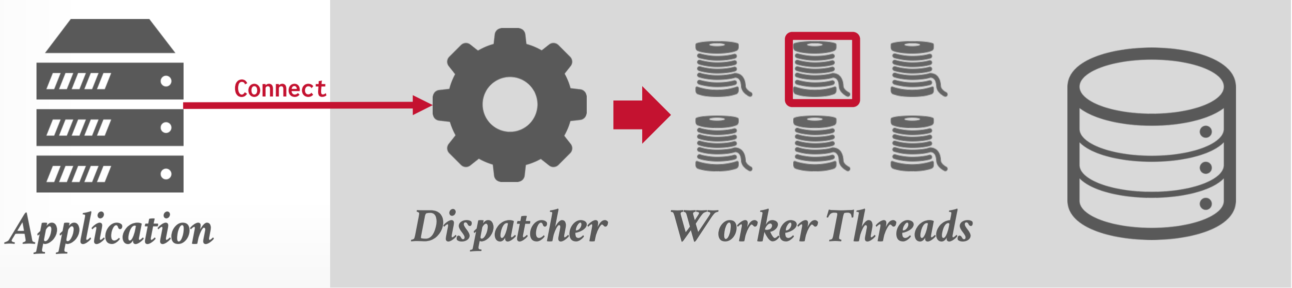

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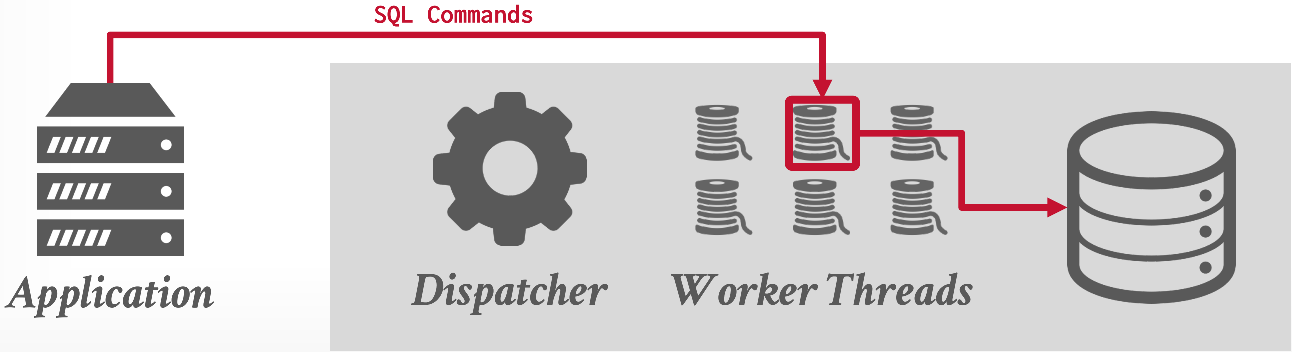

# EMBEDDED DBMS

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

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RocksDB
DuckDB
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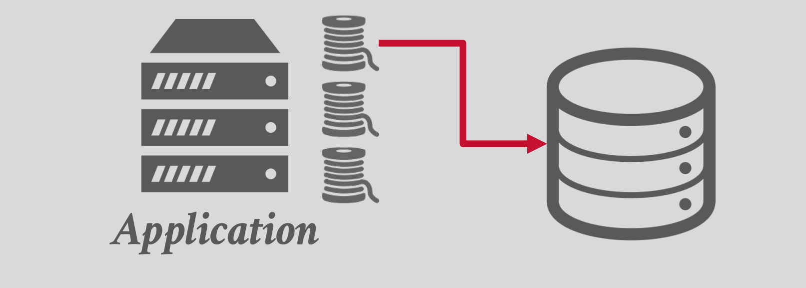

# SCHEDULING

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.

# 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.

# PARALLEL EXECUTION

The DBMS executes multiple tasks simultaneously to improve hardware utilization.

→ Active tasks do not need to belong to the same query.

→ High-level approaches do not vary on whether the DBMS is multi-threaded, multi-process, or multi-node.

**Approach #1: Inter-Query Parallelism**

**Approach #2: Intra-Query Parallelism**

# INTER-QUERY PARALLELISM

Improve overall performance by allowing multiple queries to execute simultaneously.
→ Most DBMSs use a simple first-come, first-served policy.

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.

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

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*Lecture #16*

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# 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.

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

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

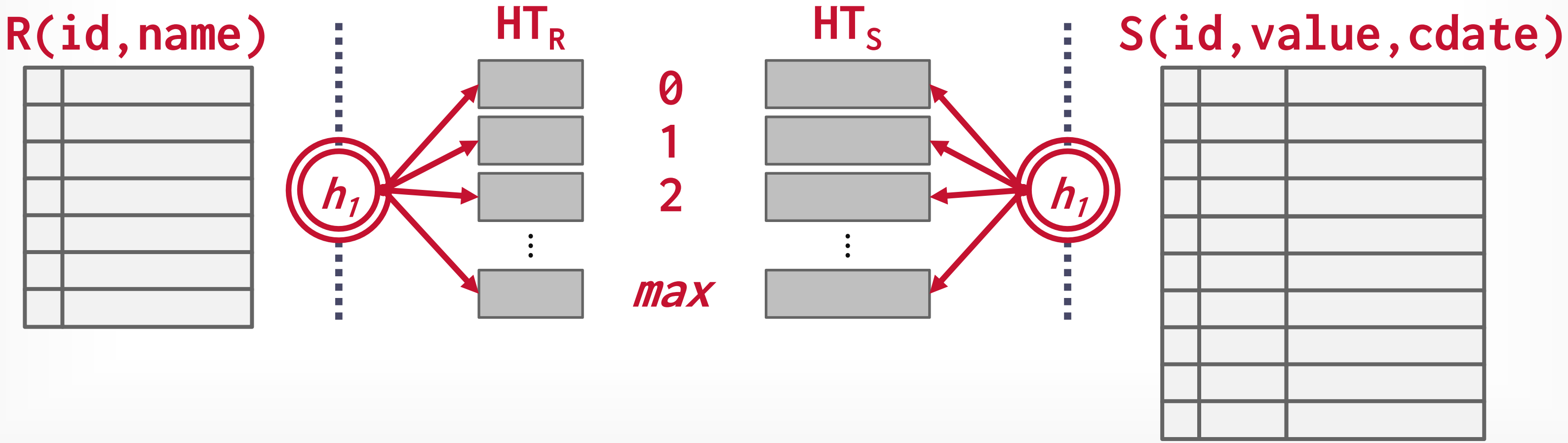
These techniques are not mutually exclusive.

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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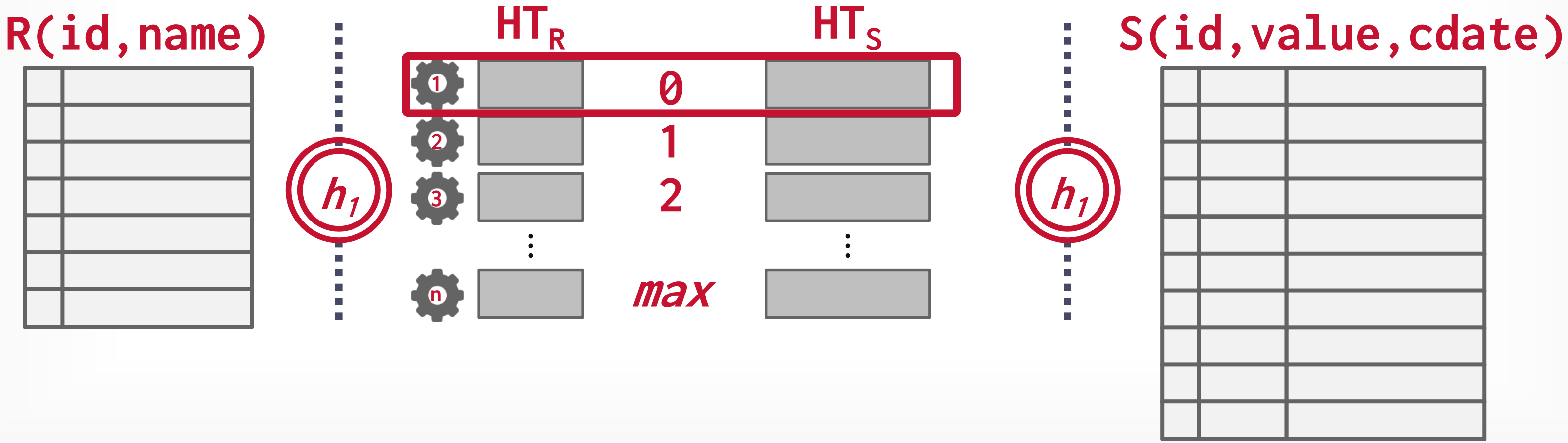

# INTRA-QUERY PARALLELISM

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

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

Approach #3: **Bushy**

# INTRA-QUERY PARALLELISM

Approach #1: **Intra-Operator** (Horizontal) ← ***Most Common***

Approach #2: **Inter-Operator** (Vertical) ← ***Less Common***

Approach #3: **Bushy** ← ***Higher-end Systems***

# INTRA-OPERATOR PARALLELISM

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

→ Operators are decomposed into independent instances 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

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SELECT A.id, B.value
  FROM A JOIN B
    ON A.id = B.id
 WHERE A.value < 99
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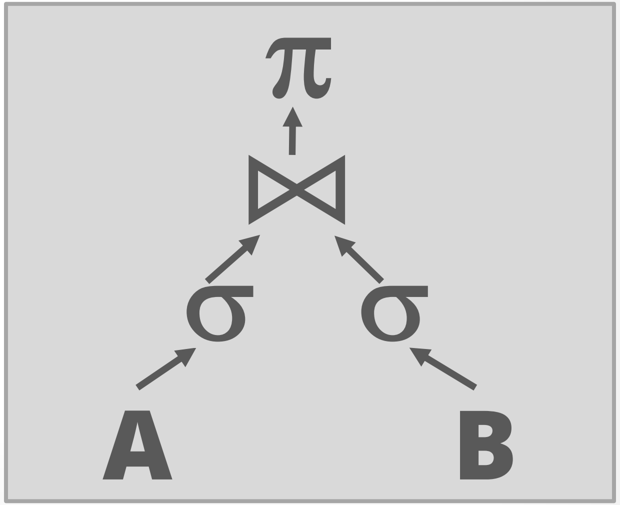

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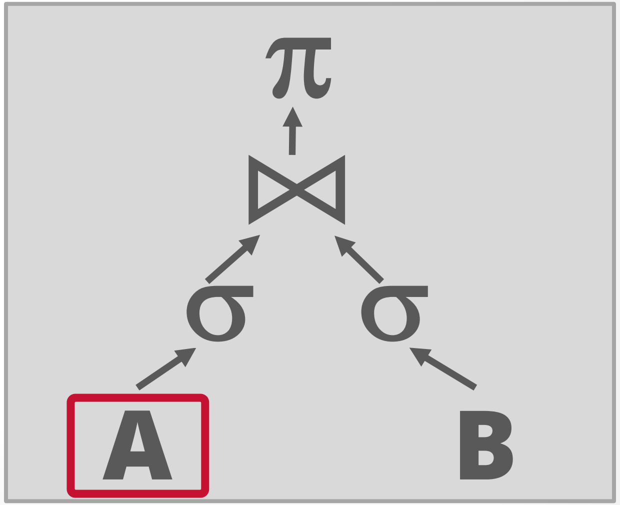

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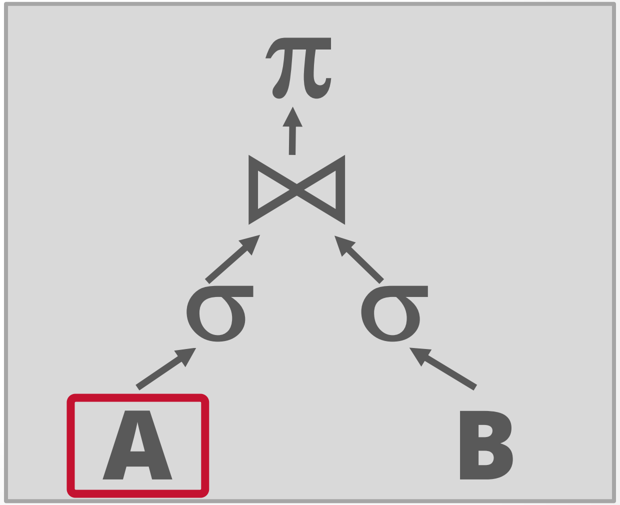

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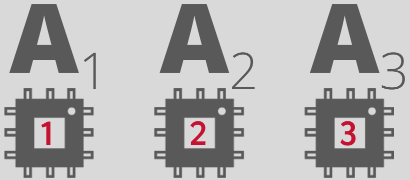

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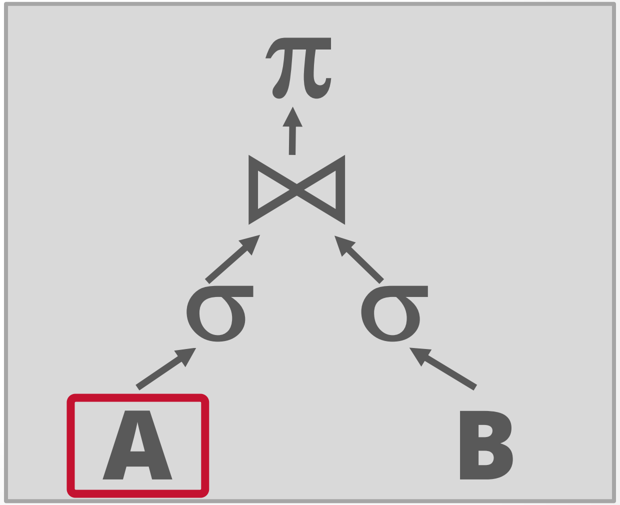

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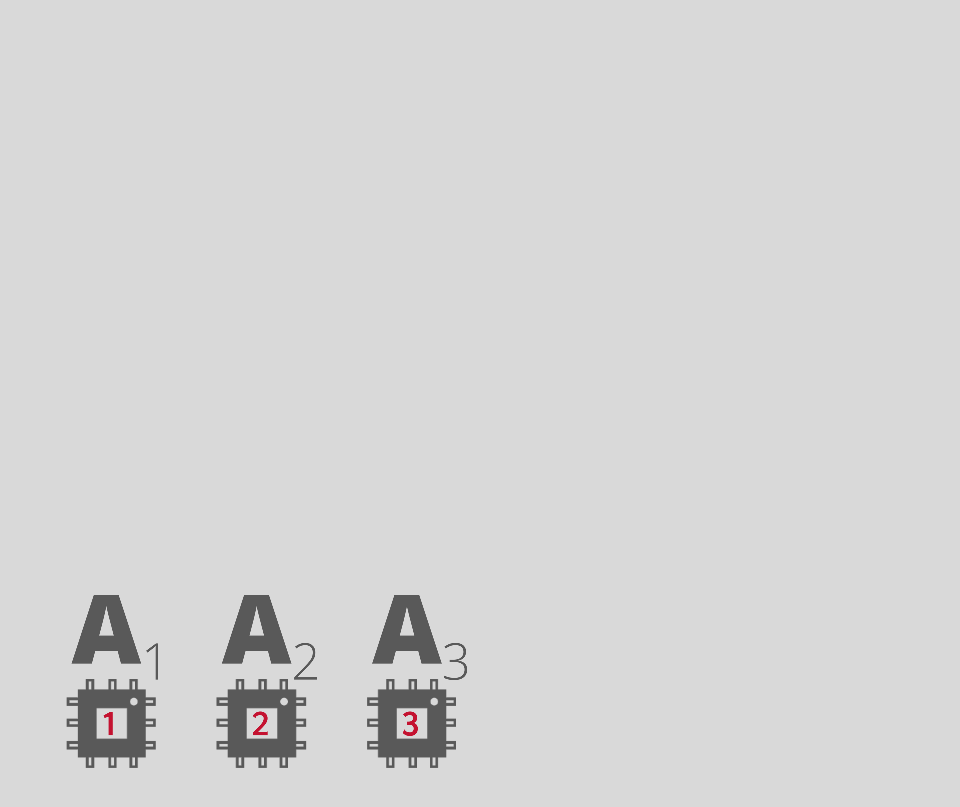

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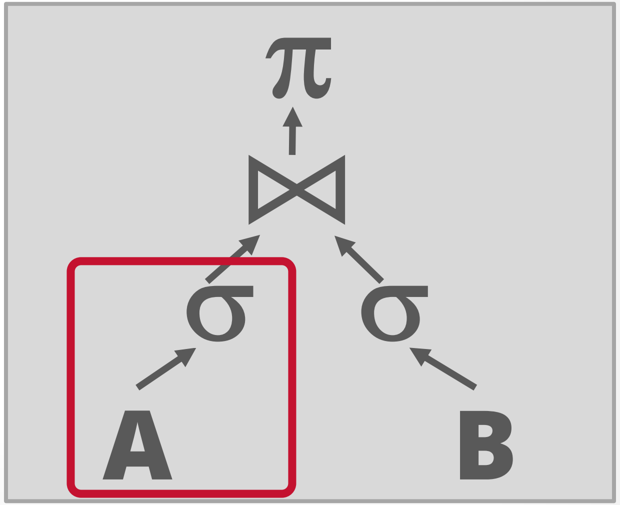

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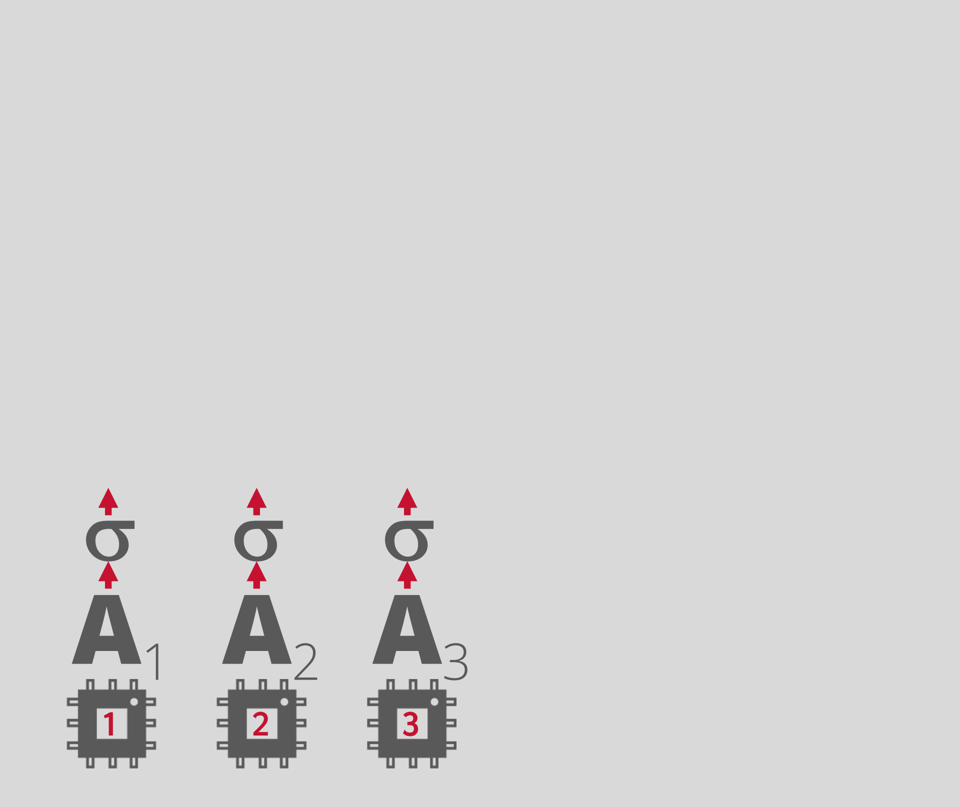

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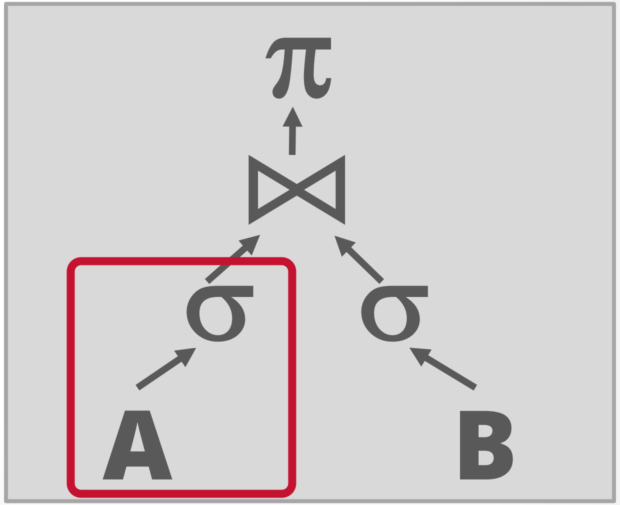

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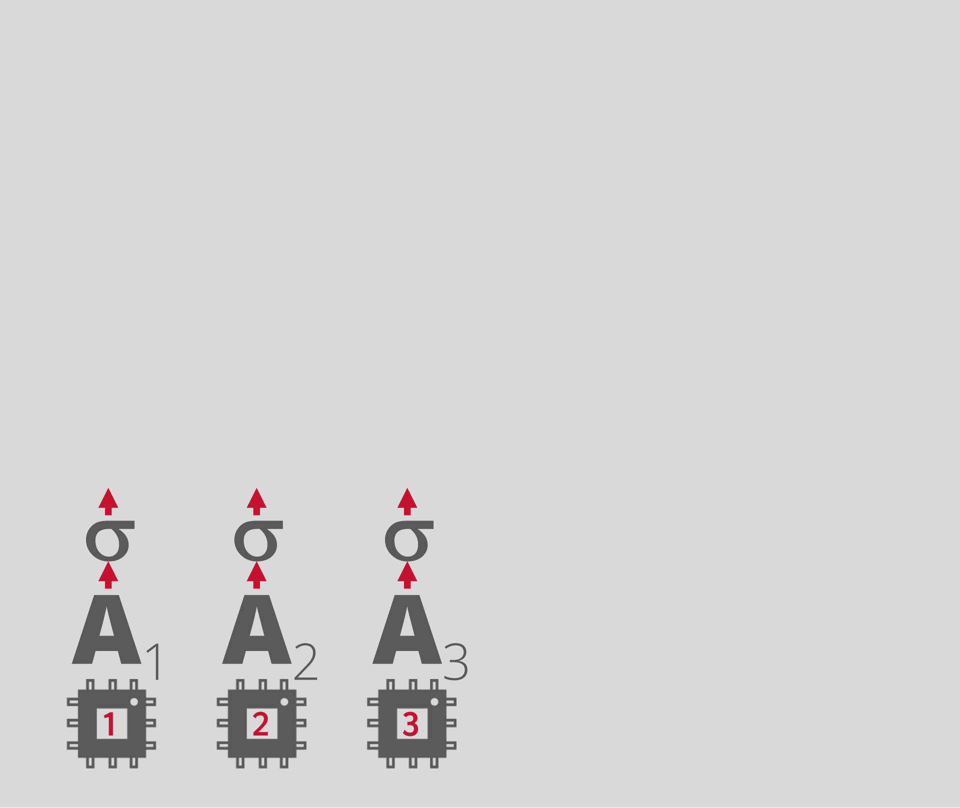

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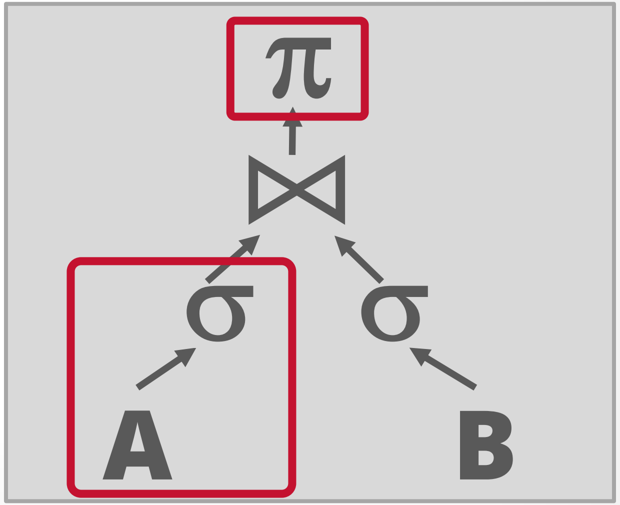

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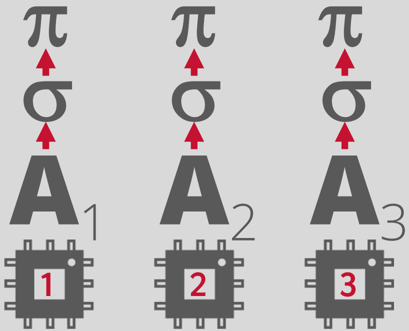

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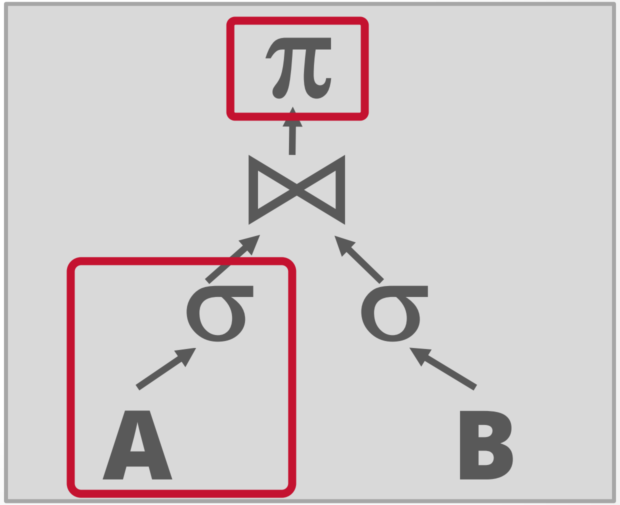

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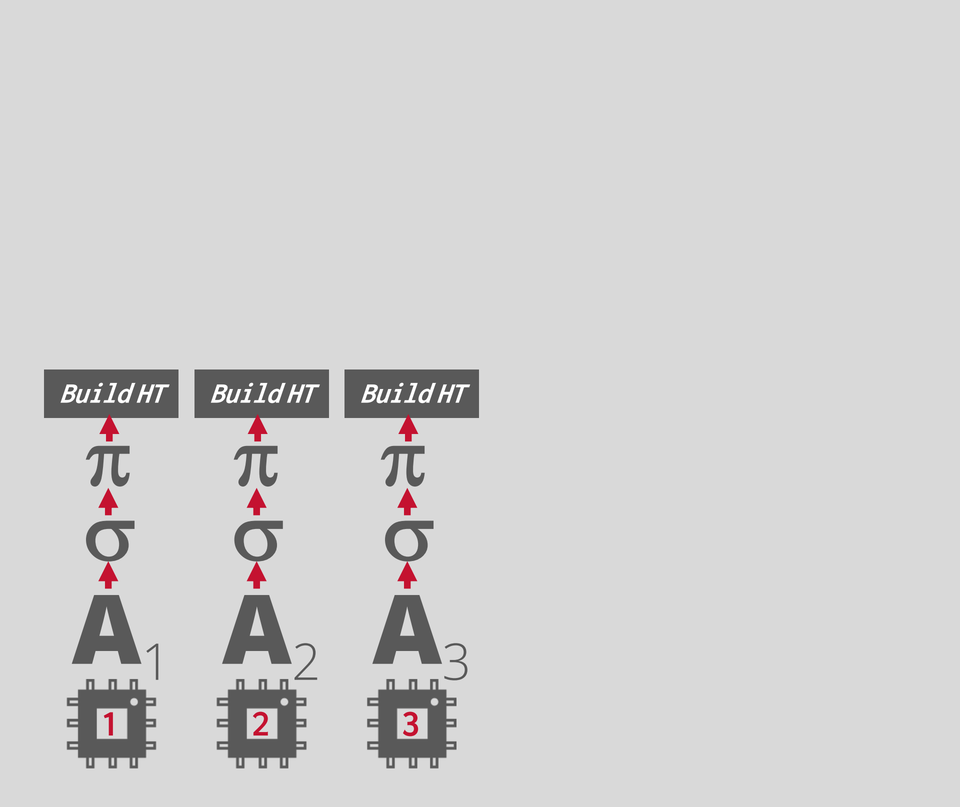

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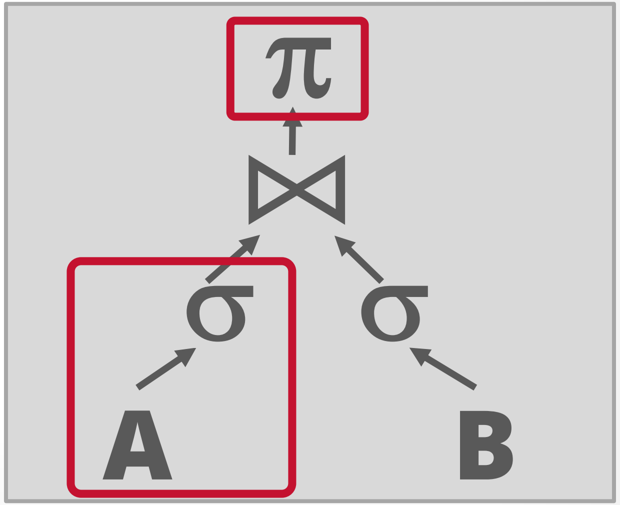

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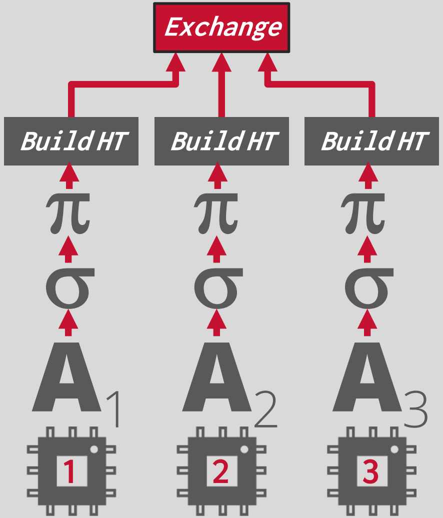

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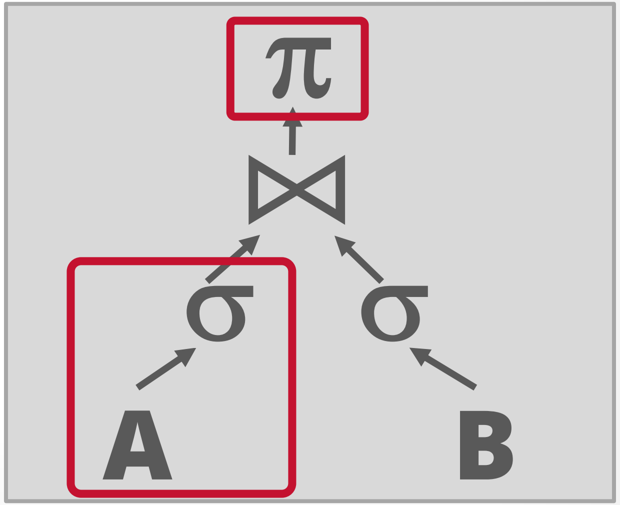

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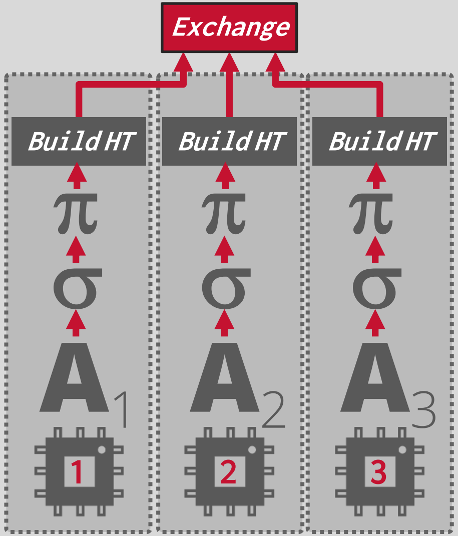

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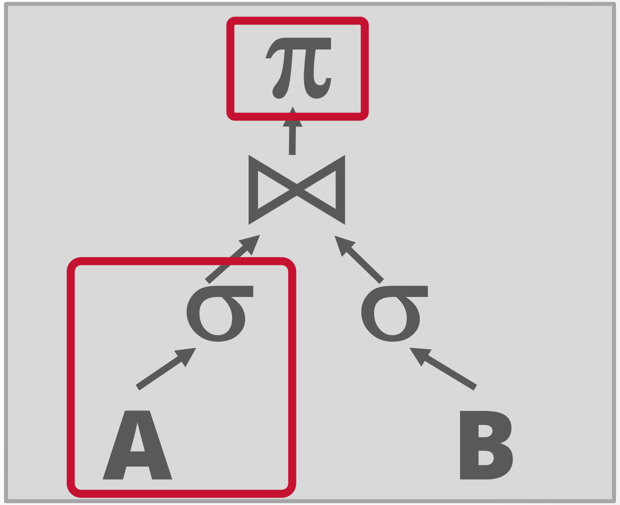

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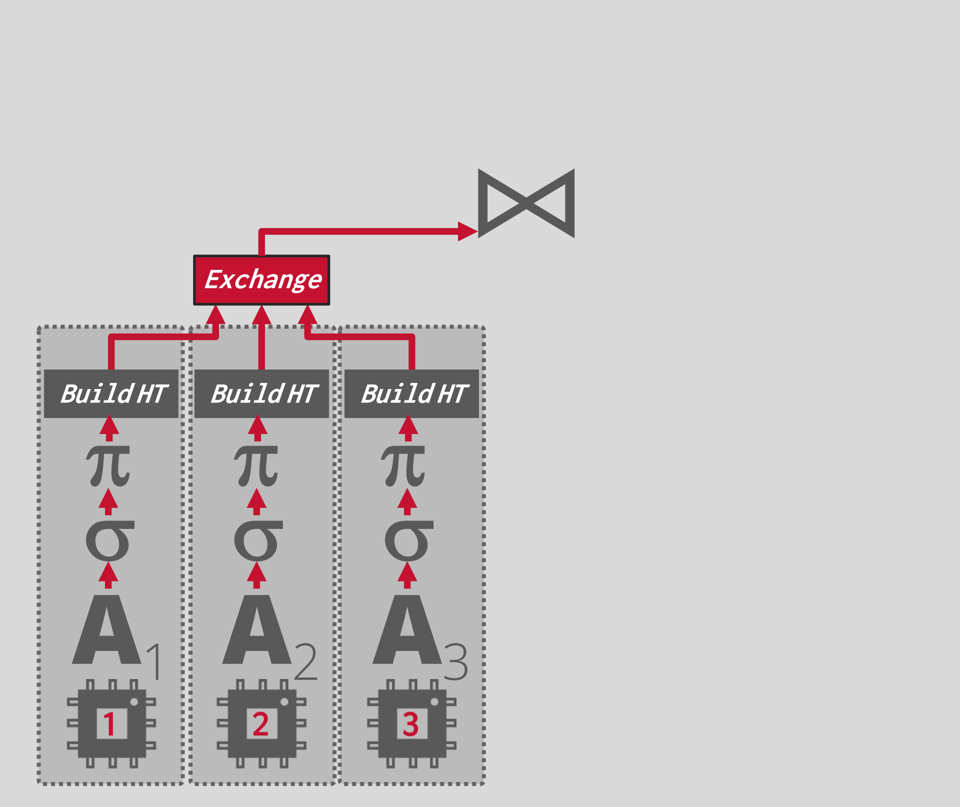

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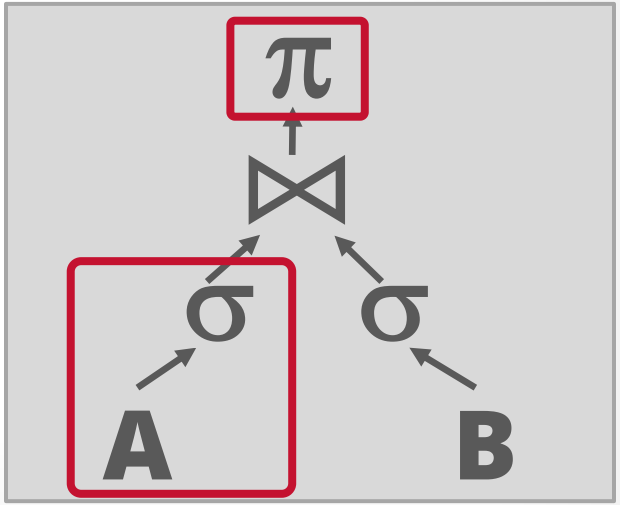

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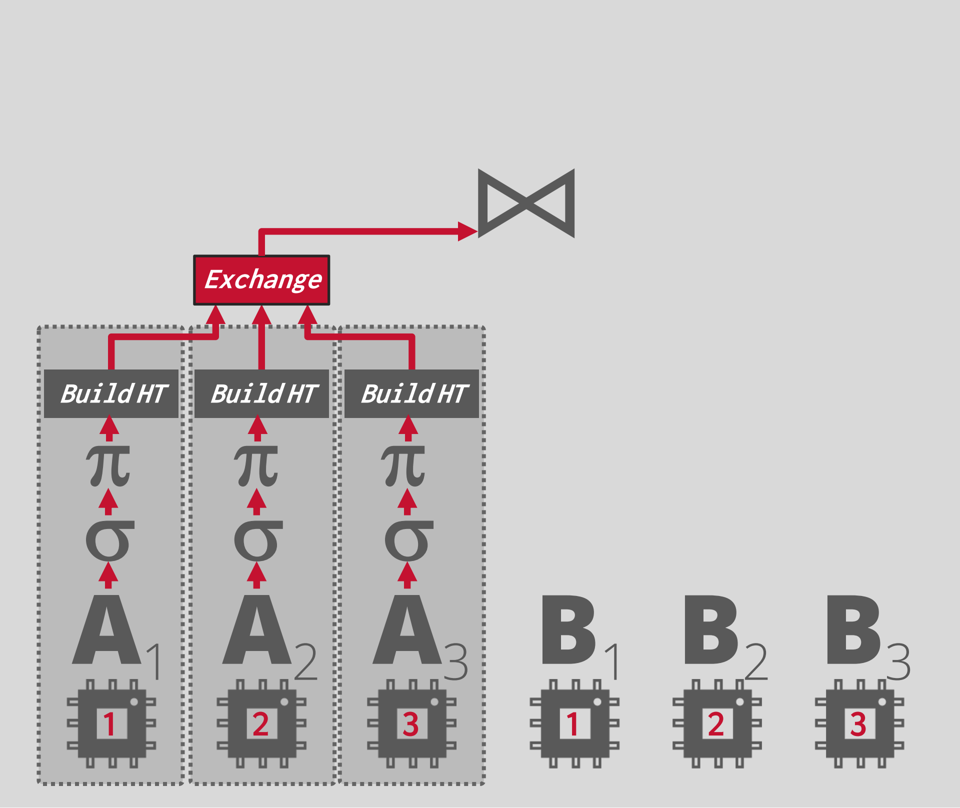

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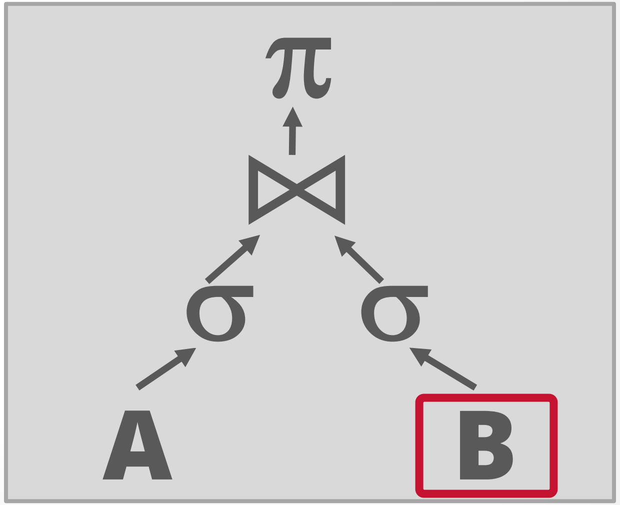

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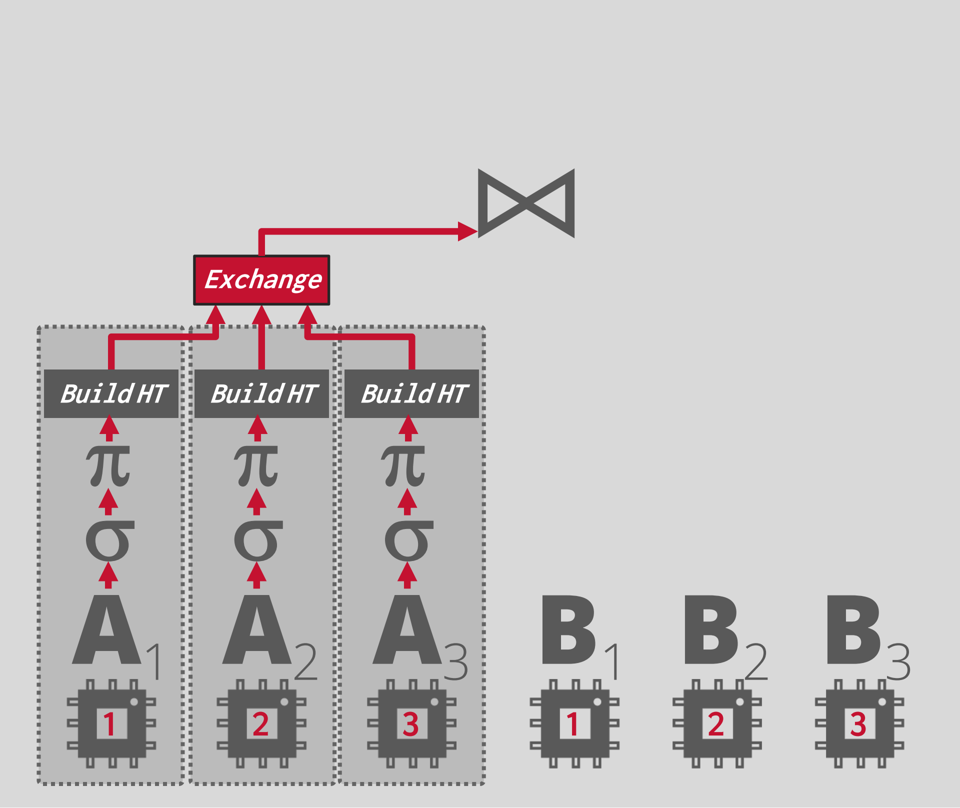

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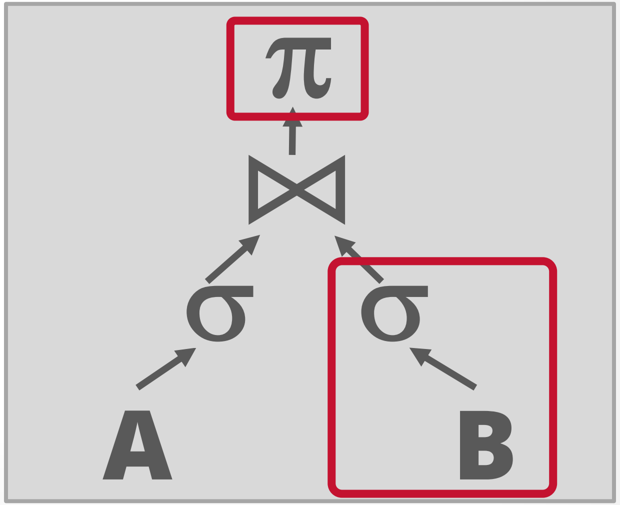

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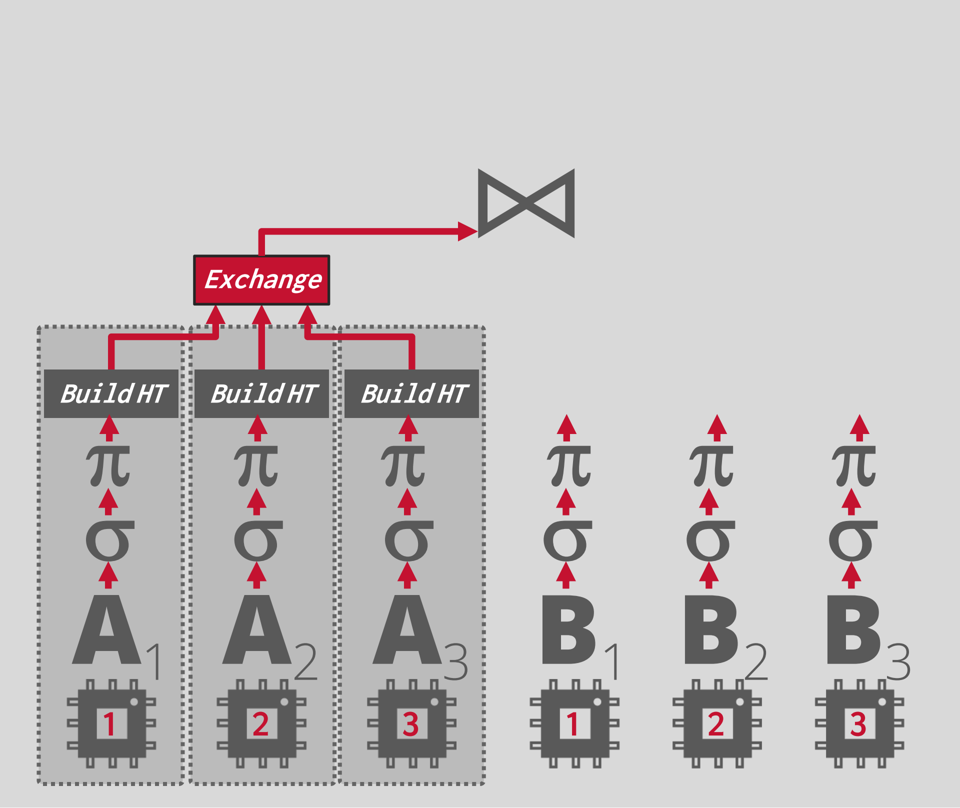

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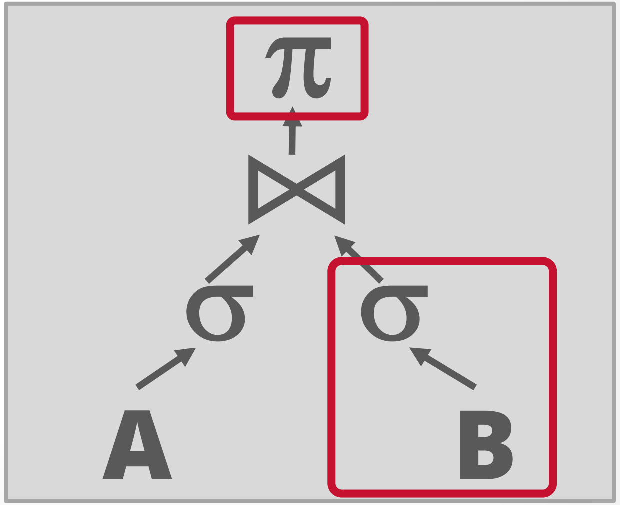

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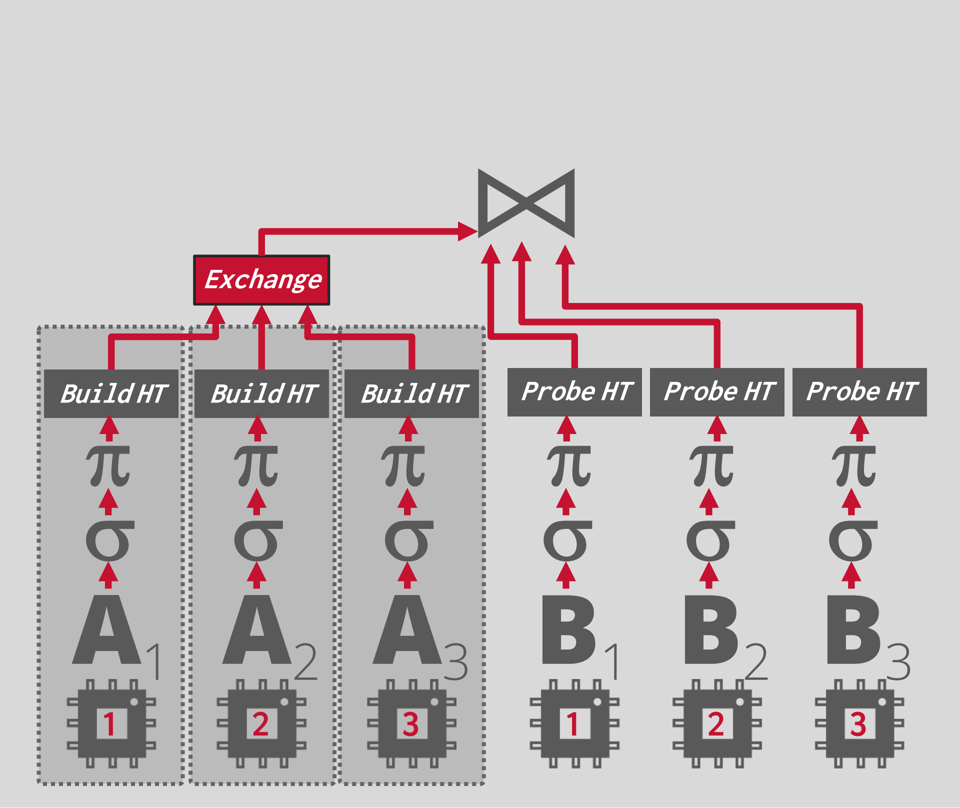

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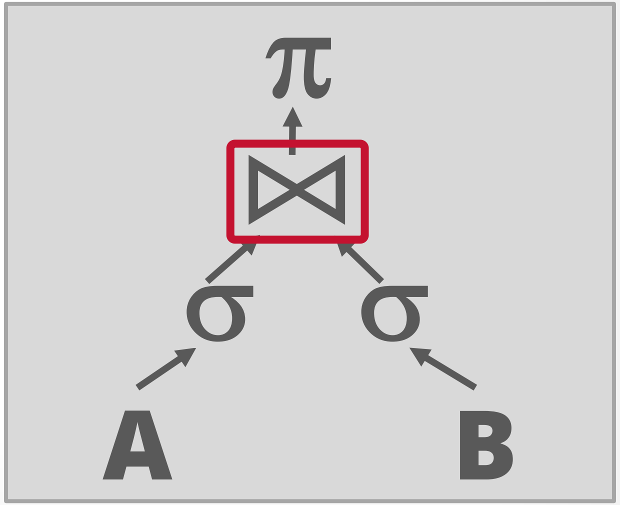

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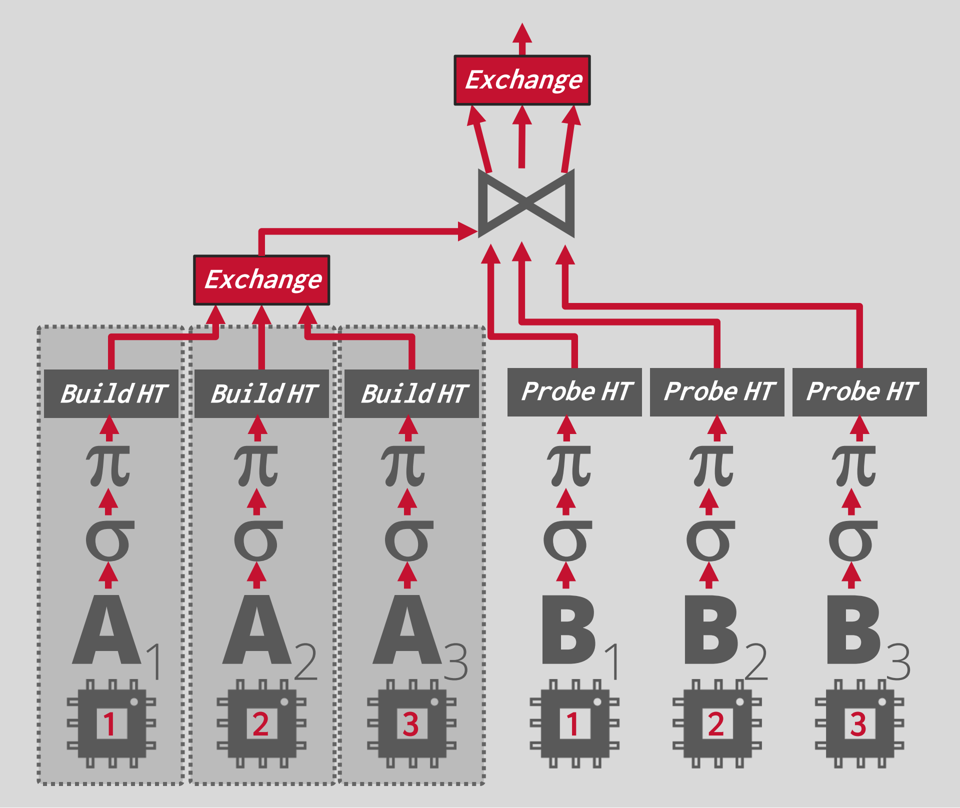

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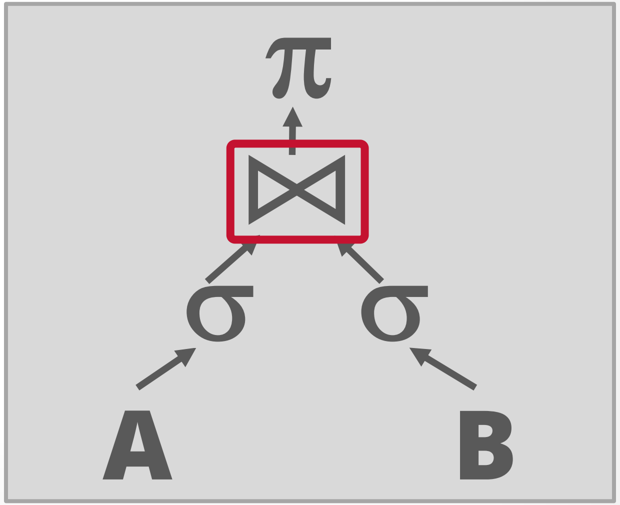
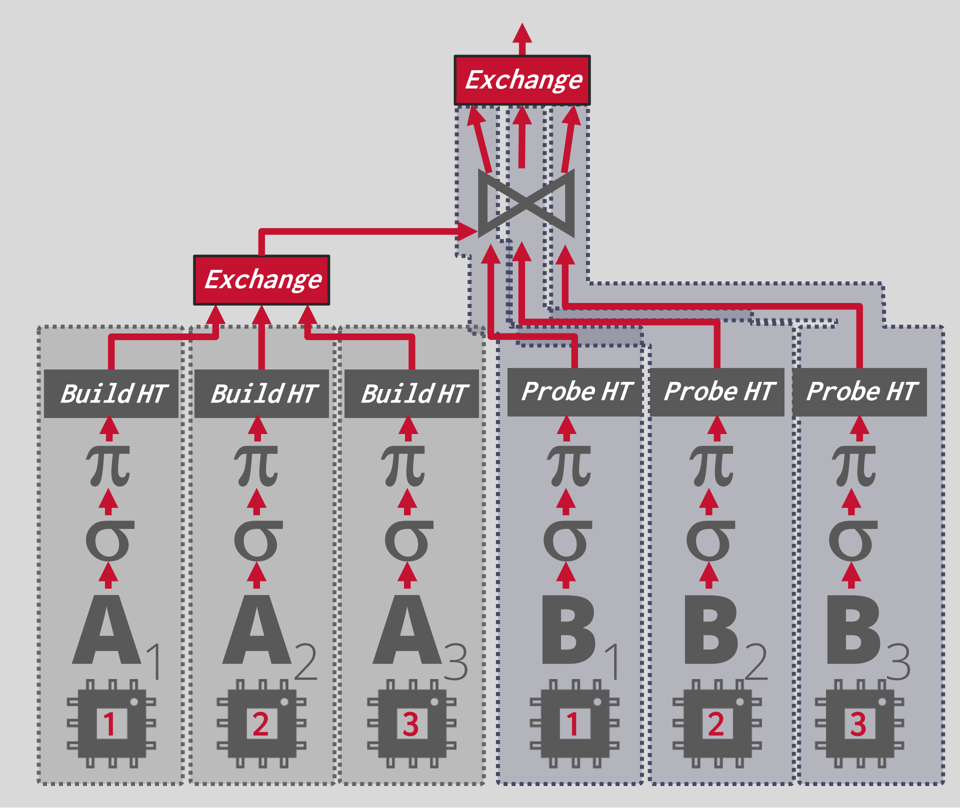
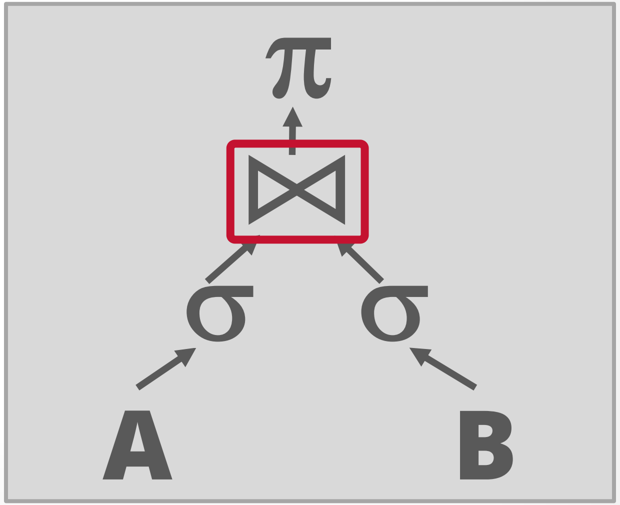


# INTRA-OPERATOR PARALLELISM



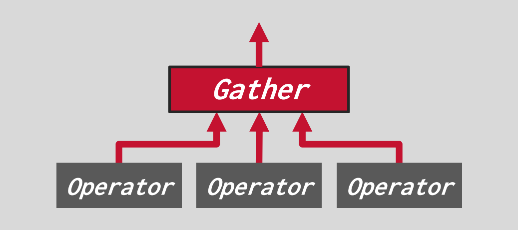
```
SELECT A.id, B.value
  FROM A JOIN B
    ON A.id = B.id
 WHERE A.value < 99
   AND B.value > 100
```



# EXCHANGE OPERATOR

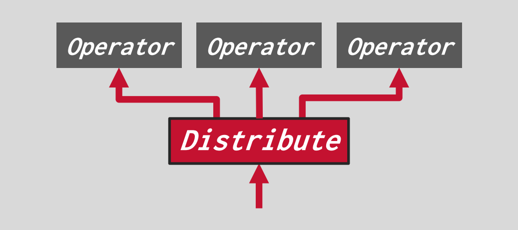
## Exchange Type #1 – Gather

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



## Exchange Type #2 – Distribute

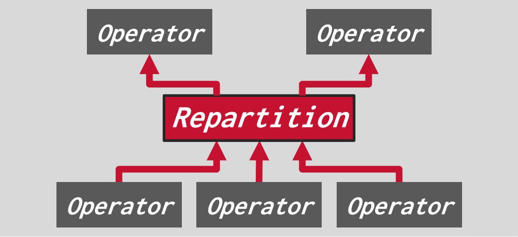
→ Split a single input stream into multiple output streams.



## Exchange Type #3 – Repartition

→ Shuffle multiple input streams across multiple output streams.

→ Some DBMSs always perform this step after every pipeline (e.g., Dremel/BigQuery).



Source: Craig Freedman

# INTER-OPERATOR PARALLELISM

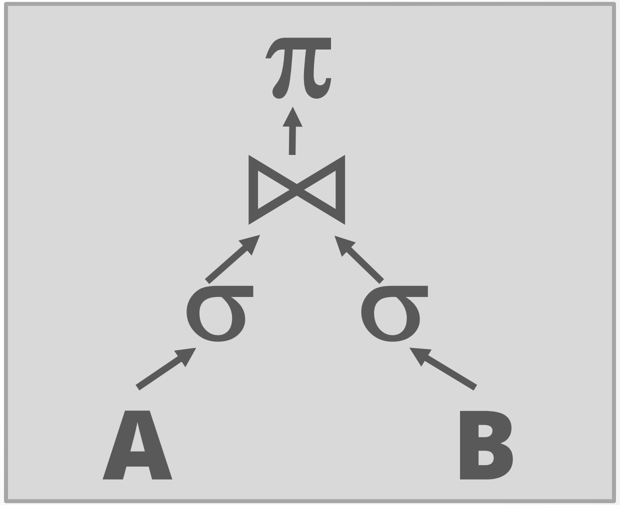
**Approach #2: Inter-Operator (Vertical)**

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

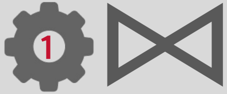
Also called **pipelined parallelism**.

# 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
```

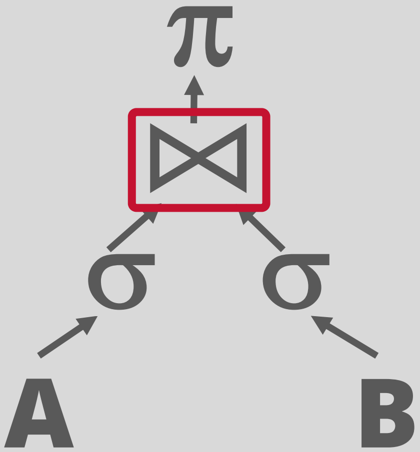


# INTER-OPERATOR PARALLELISM

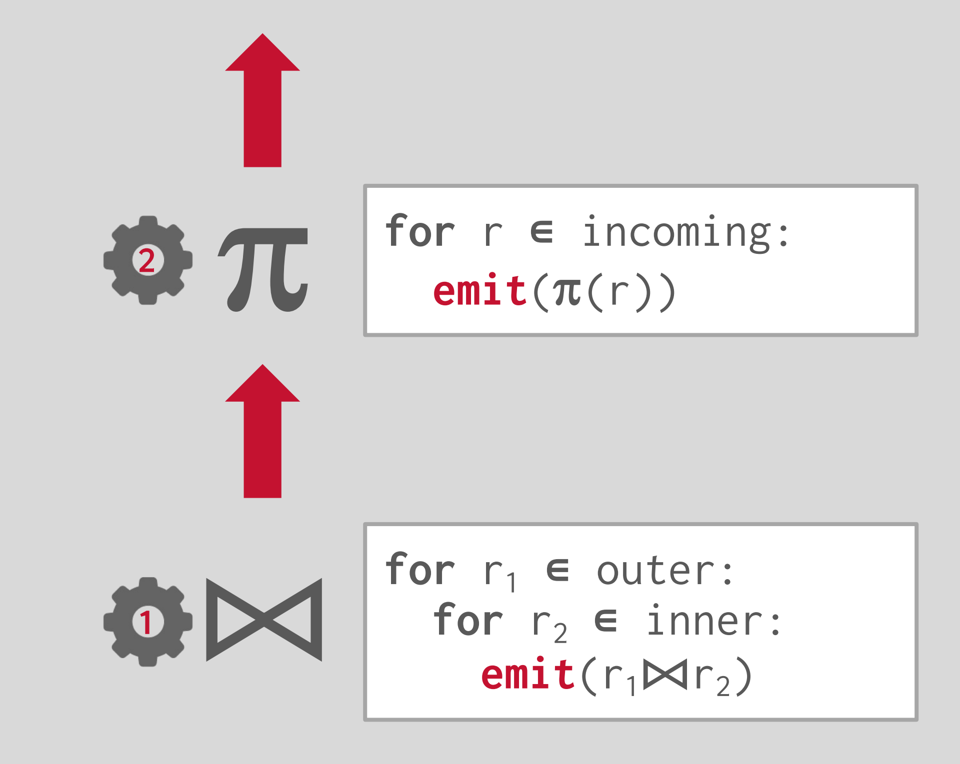


```
for $r_1$ ∈ outer:
  for $r_2$ ∈ inner:
    emit($r_1$⋈$r_2$)
```

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



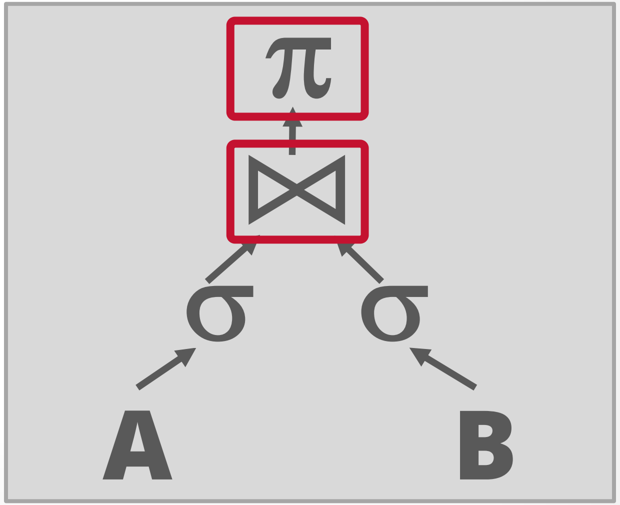
# INTER-OPERATOR PARALLELISM



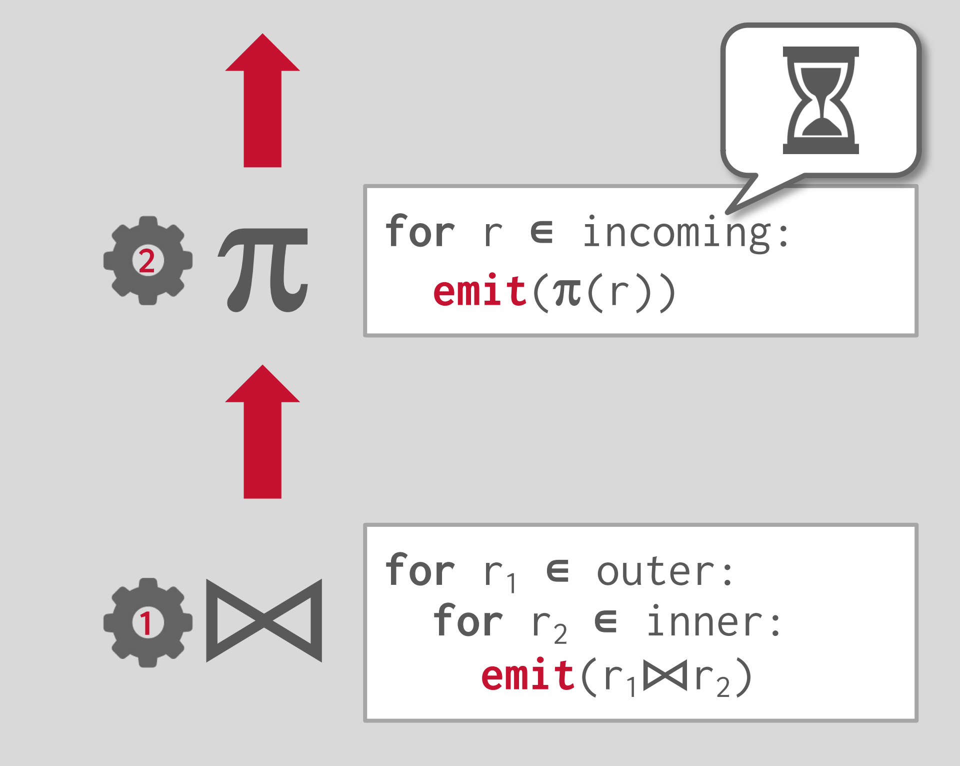
```
for r ∈ incoming:
  emit(π(r))
```

```
for $r_1$ ∈ outer:
  for $r_2$ ∈ inner:
    emit($r_1 \bowtie r_2$)
```

```
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



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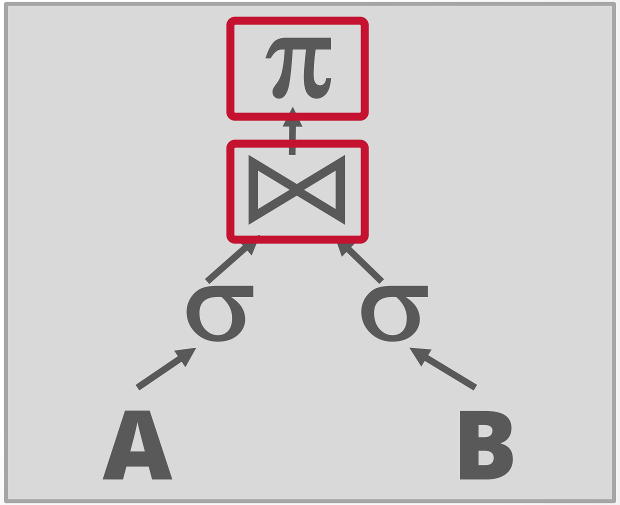


# BUSHY PARALLELISM

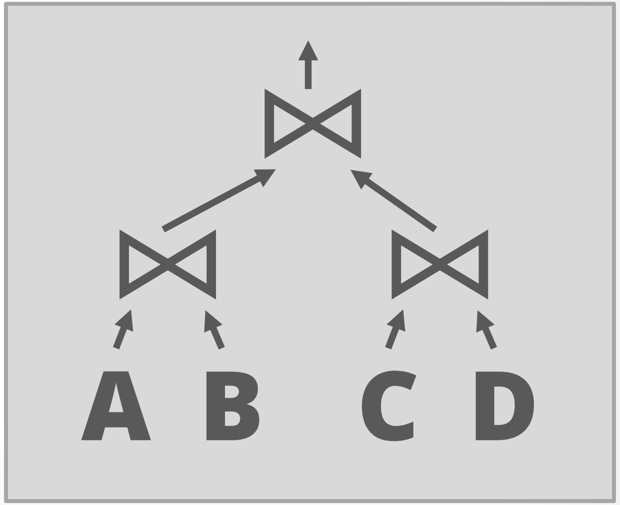
## Approach #3: Bushy Parallelism

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

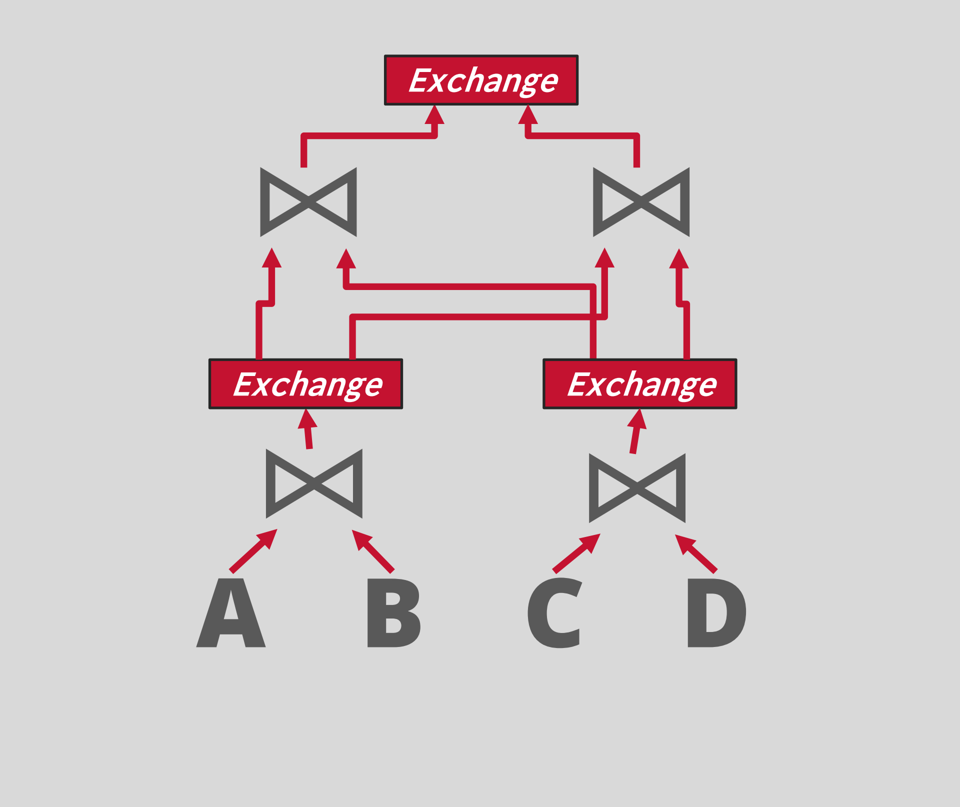
→ Still need exchange operators to combine intermediate results from segments.

# BUSHY PARALLELISM

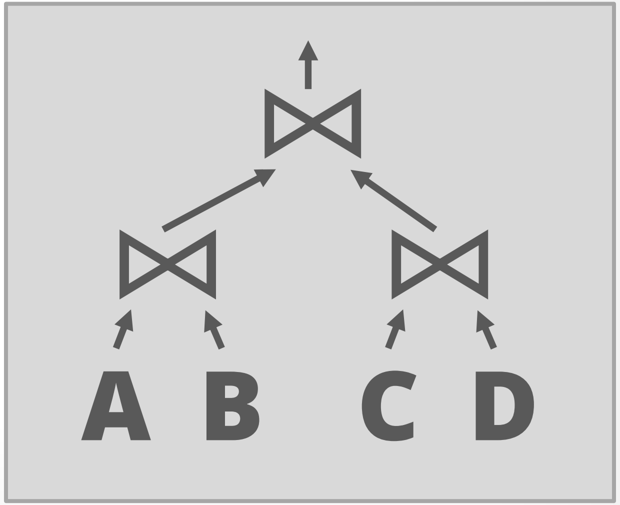
```
SELECT *
  FROM A
  JOIN B
  JOIN C
  JOIN D
```



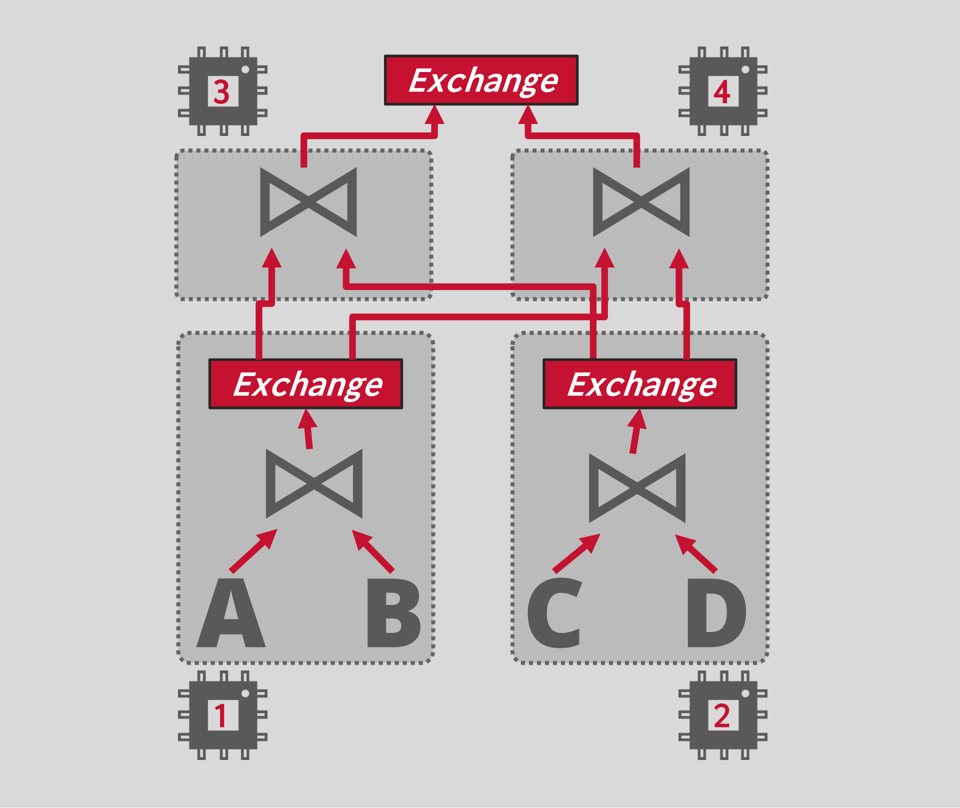
# BUSHY PARALLELISM



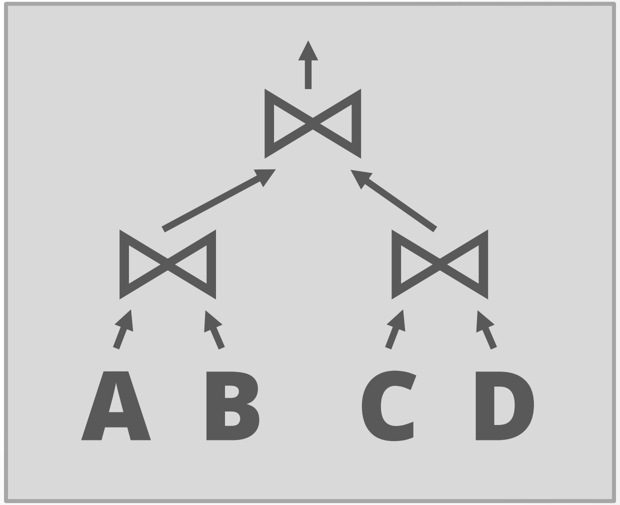
```
SELECT *
  FROM A
  JOIN B
  JOIN C
  JOIN D
```



# BUSHY PARALLELISM



```
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.

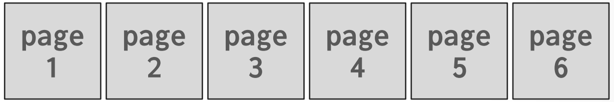
# MULTI-DISK PARALLELISM

Store data across multiple disks to improve performance + durability.

# MULTI-DISK PARALLELISM

Store data across multiple disks to improve performance + durability.

*File of 6 pages (logical view):*

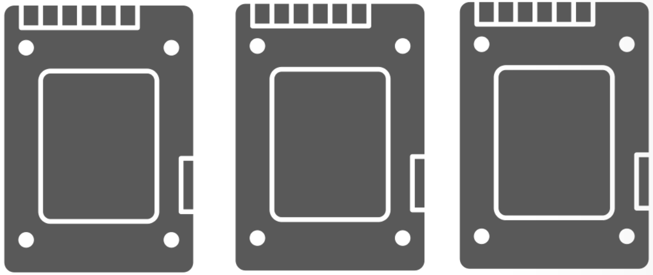


# MULTI-DISK PARALLELISM

Store data across multiple disks to improve performance + durability.

***File of 6 pages (logical view):***

| page 1 | page 2 | page 3 | page 4 | page 5 | page 6 |
|---|---|---|---|---|---|



***Physical layout of pages across disks***

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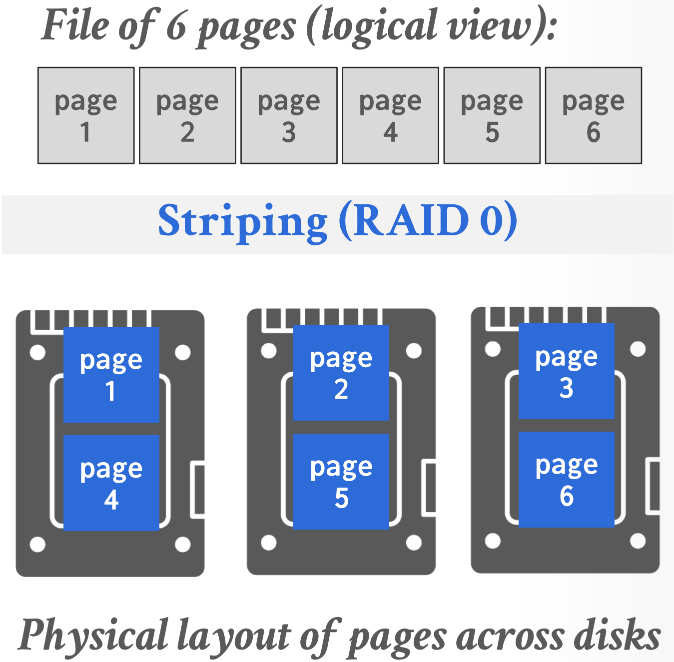


*File of 6 pages (logical view):*

| page 1 | page 2 | page 3 | page 4 | page 5 | page 6 |
|---|---|---|---|---|---|

**Striping (RAID 0)**

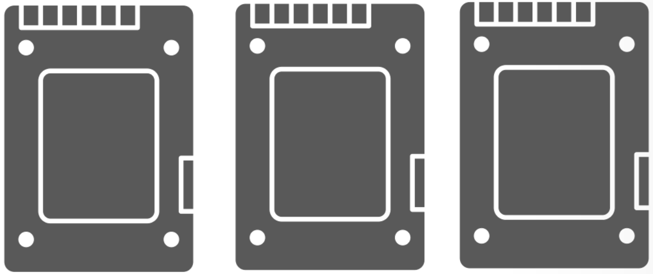
*Physical layout of pages across disks*

# MULTI-DISK PARALLELISM

Store data across multiple disks to improve performance + durability.

*File of 6 pages (logical view):*

| page 1 | page 2 | page 3 | page 4 | page 5 | page 6 |
|---|---|---|---|---|---|



*Physical layout of pages across disks*

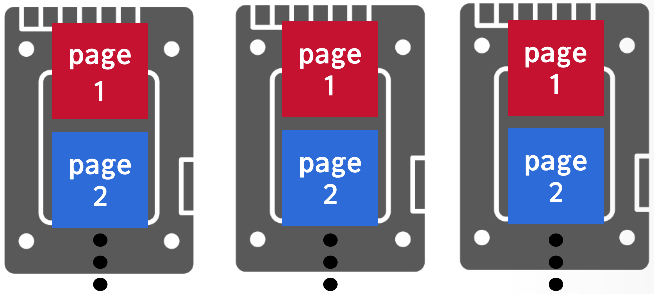
# MULTI-DISK PARALLELISM

Store data across multiple disks to improve performance + durability.

*File of 6 pages (logical view):*

| page 1 | page 2 | page 3 | page 4 | page 5 | page 6 |
|---|---|---|---|---|---|

**Mirroring (RAID 1)**



*Physical layout of pages across disks*

# MULTI-DISK PARALLELISM

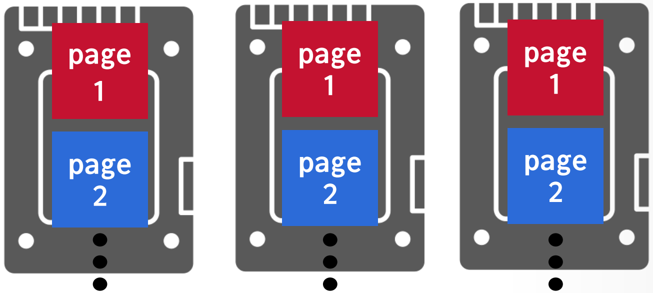
Store data across multiple disks to improve performance + durability.

**Hardware-based:** I/O controller makes multiple physical devices appear as single logical device.
→ Transparent to DBMS (e.g., RAID).

*File of 6 pages (logical view):*

| page 1 | page 2 | page 3 | page 4 | page 5 | page 6 |
|---|---|---|---|---|---|

**Mirroring (RAID 1)**



*Physical layout of pages across disks*

# MULTI-DISK PARALLELISM

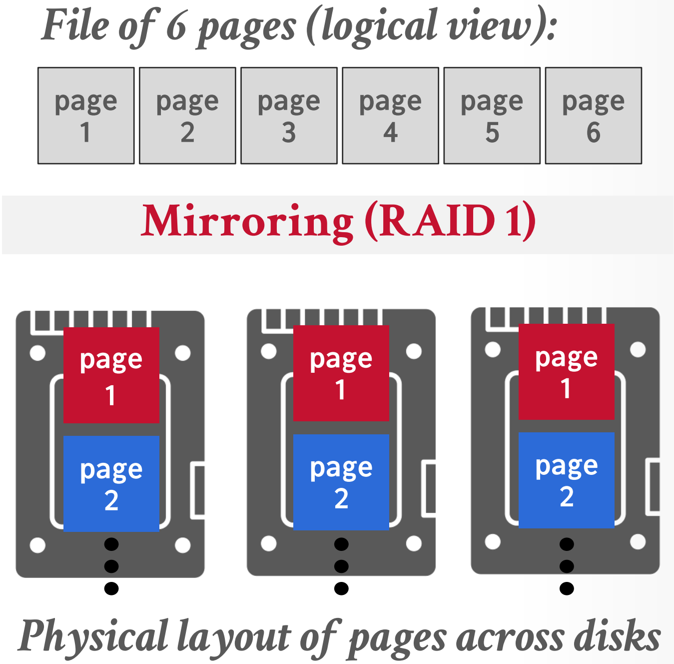
Store data across multiple disks to improve performance + durability.

**Hardware-based:** I/O controller makes multiple physical devices appear as single logical device.

→ Transparent to DBMS (e.g., RAID).

**Software-based:** DBMS manages erasure codes at the file/object level.

→ Faster and more flexible.



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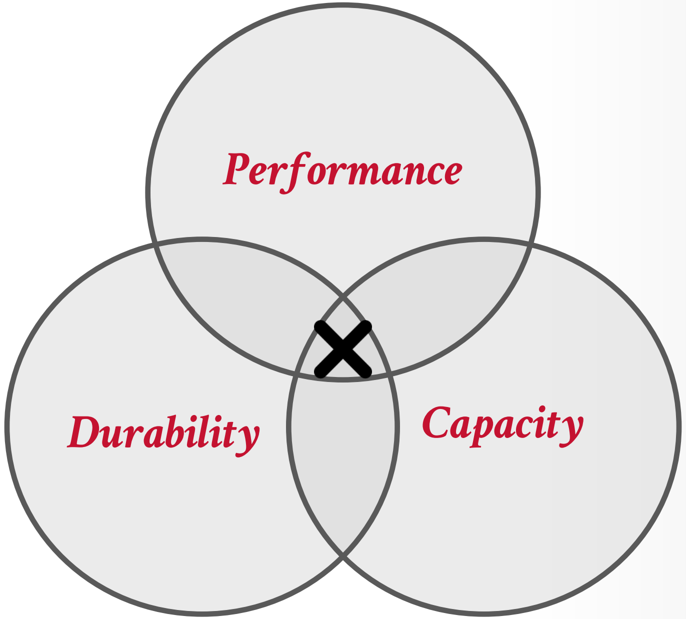

# DATABASE PARTITIONING

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