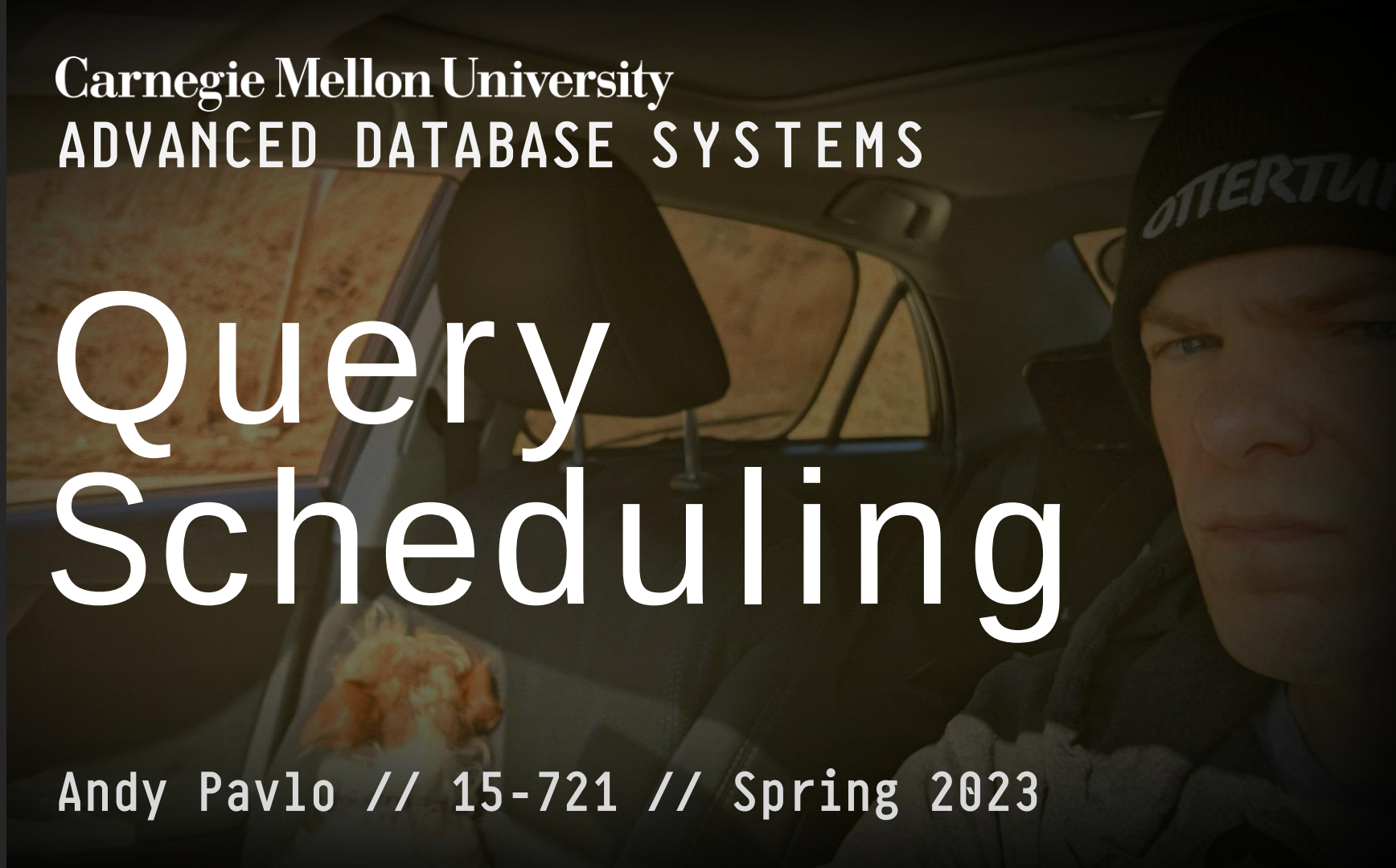
Lecture #07

Carnegie Mellon University

ADVANCED DATABASE SYSTEMS

Query Scheduling



Andy Pavlo // 15-721 // Spring 2023

LAST CLASS

We discussed query processing models.

→ Vectorized model is best for OLAP.

→ Top-to-bottom (pull) approach is probably better.

QUERY EXECUTION

A query plan is a DAG of **operators**.

An **operator instance** is an invocation of an operator on a unique segment of data.

A **task** is a sequence of one or more operator instances.

A **task set** is the collection of executable tasks for a logical pipeline.

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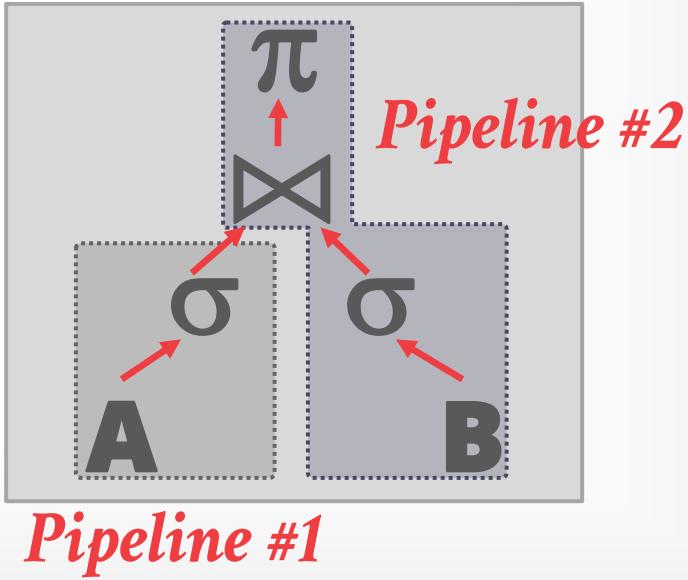

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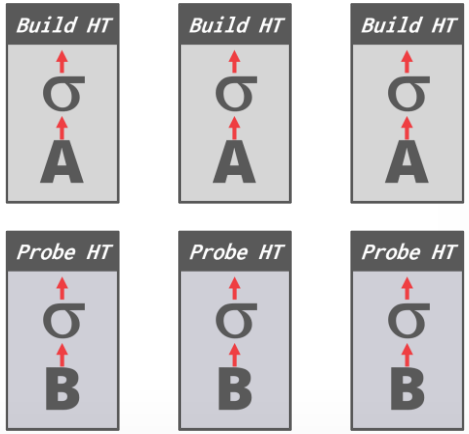


SCHEDULING

For each query plan, the DBMS must decide 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 ***always*** knows more than the OS.

SCHEDULING GOALS

Goal #1: Throughput

→ Maximize the # of completed queries.

Goal #2: Fairness

→ Ensure that no query is starved for resources

Goal #3: Query Responsiveness

→ Minimize tail latencies (especially for short queries)

Goal #4: Low Overhead

→ Workers should spend most of their time executing tasks not figuring out what task to run next.

TODAY'S AGENDA

Worker Allocation

Data Placement

Scheduler Implementations

PROCESS MODEL

A DBMS's **process model** defines how the system is architected to support concurrent requests from a multi-user application.

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

We will assume that the DBMS is multi-threaded.

ARCHITECTURE OF A DATABASE SYSTEM
FOUNDATIONS AND TRENDS IN DATABASES 2007

WORKER ALLOCATION

Approach #1: One Worker per Core

→ Each core is assigned one thread that is pinned to that core in the OS.
→ See `sched_setaffinity`

Approach #2: Multiple Workers per Core

→ Use a pool of workers per core (or per socket).
→ Allows CPU cores to be fully utilized in case one worker at a core blocks.

TASK ASSIGNMENT

Approach #1: Push

→ A centralized dispatcher assigns tasks to workers and monitors their progress.
→ When the worker notifies the dispatcher that it is finished, it is given a new task.

Approach #1: Pull

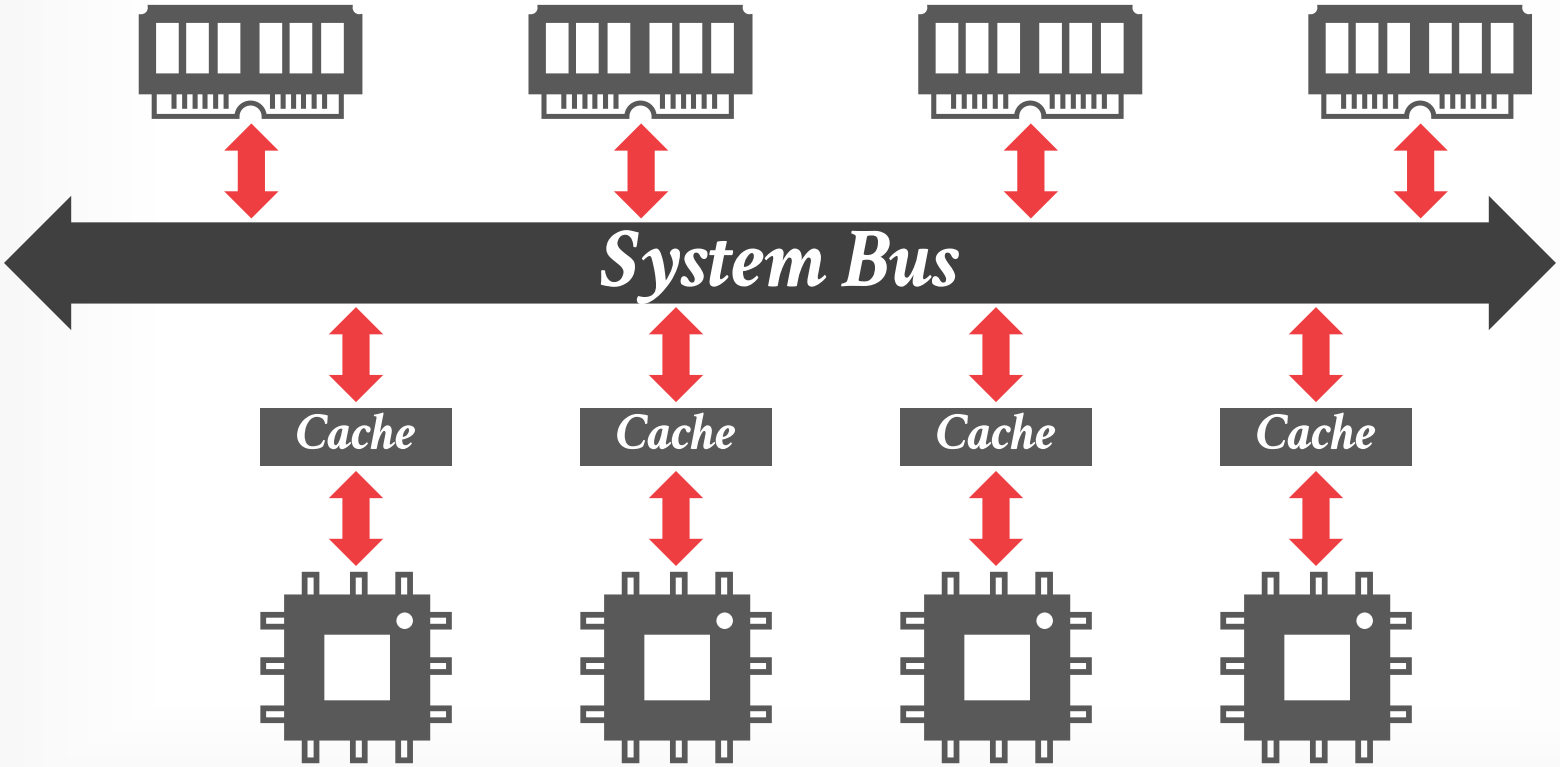
→ Workers pull the next task from a queue, process it, and then return to get the next task.

OBSERVATION

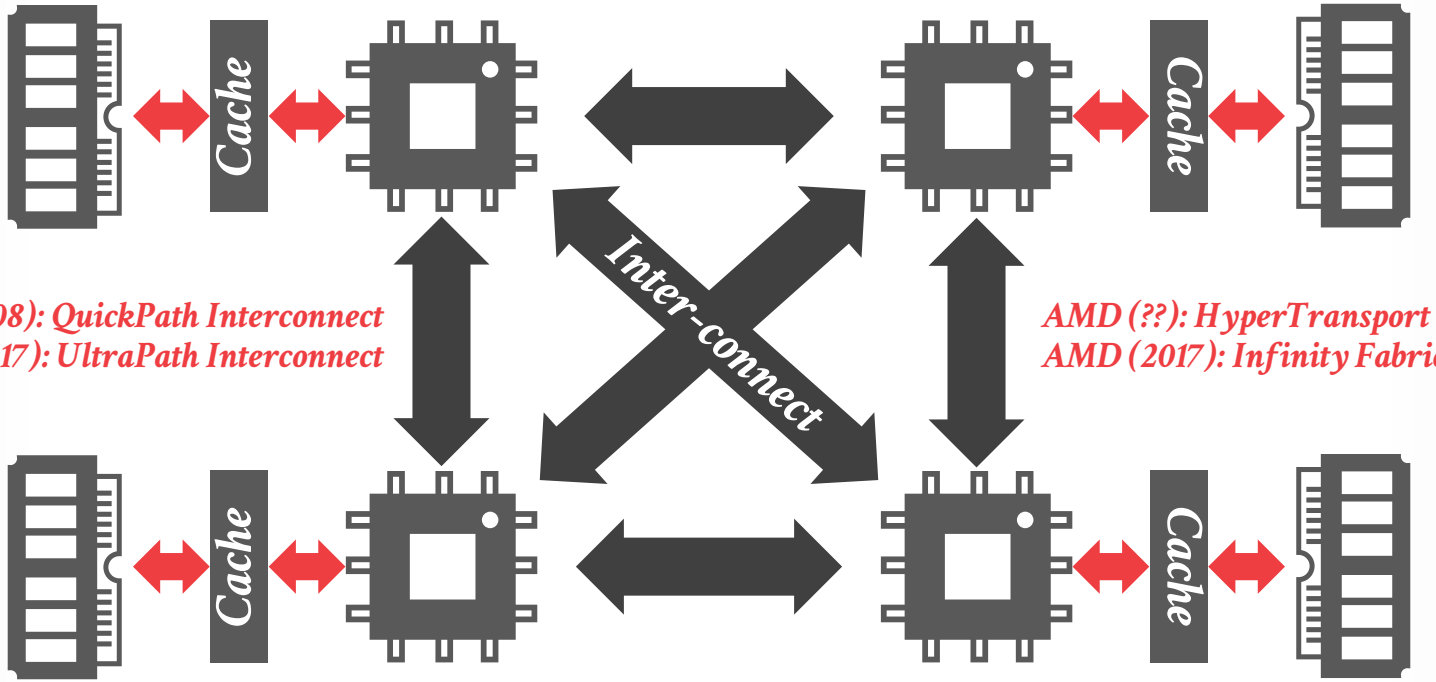
Regardless of what worker allocation or task assignment policy the DBMS uses, it's important that workers operate on local data.

The DBMS's scheduler must be aware of its hardware memory layout.
→ Uniform vs. Non-Uniform Memory Access

UNIFORM MEMORY ACCESS



NON-UNIFORM MEMORY ACCESS



Intel (2008): QuickPath Interconnect
Intel (2017): UltraPath Interconnect

AMD (??): HyperTransport
AMD (2017): Infinity Fabric

DATA PLACEMENT

The DBMS can partition memory for a database and assign each partition to a CPU.

By controlling and tracking the location of partitions, it can schedule operators to execute on workers at the closest CPU core.

See Linux's `move_pages` and `numactl`

MEMORY ALLOCATION

What happens when the DBMS calls **`malloc`**?

→ Assume that the allocator doesn't already have a chunk of memory that it can give out.

Almost nothing:

→ The allocator will extend the process' data segment.

→ But this new virtual memory is not immediately backed by physical memory.

→ The OS only allocates physical memory when there is a page fault on access.

Now after a page fault, where does the OS allocate physical memory in a NUMA system?

MEMORY ALLOCATION LOCATION

Approach #1: Interleaving

→ Distribute allocated memory uniformly across CPUs.

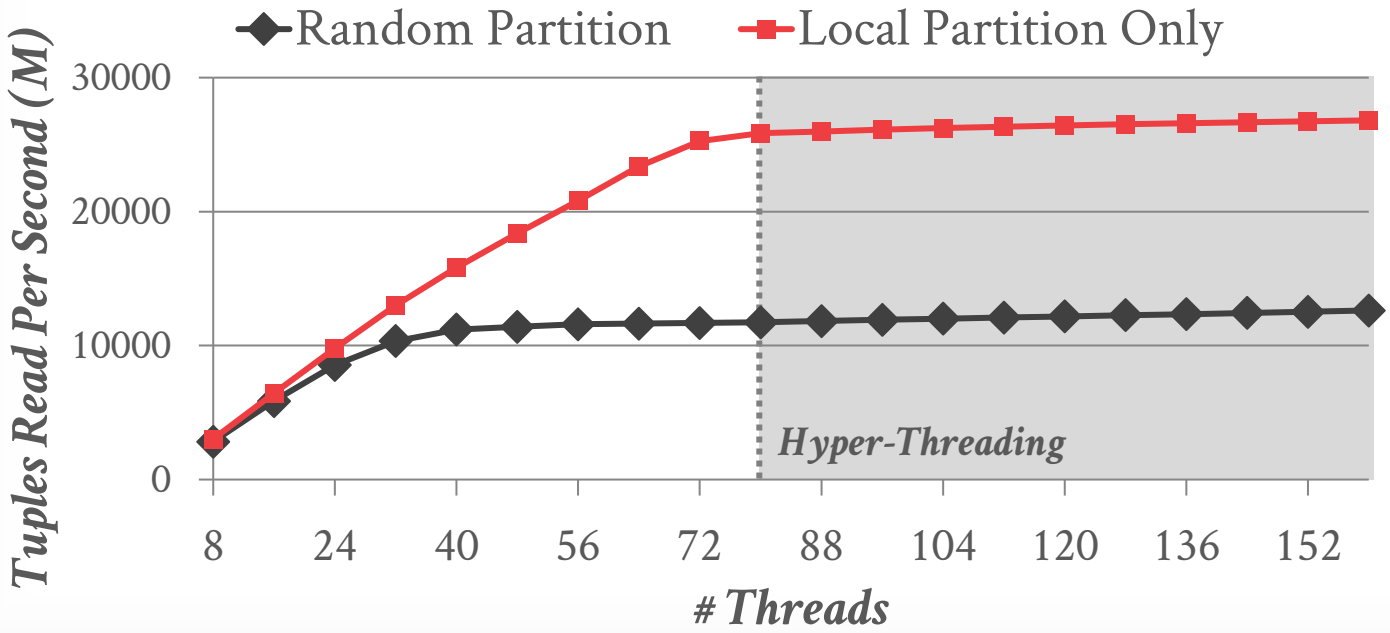
Approach #2: First-Touch

→ At the CPU of the thread that accessed the memory location that caused the page fault.

The OS can try to move memory to another NUMA region from observed access patterns.

DATA PLACEMENT – OLAP

Sequential Scan on 10m tuples
Processor: 8 sockets, 10 cores per node (2x HT)



Source: Haibin Lin

PARTITIONING VS. PLACEMENT

A **partitioning** scheme is used to split the database based on some policy.

→ Round-robin
→ Attribute Ranges
→ Hashing
→ Partial/Full Replication

A **placement** scheme then tells the DBMS where to put those partitions.

→ Round-robin
→ Interleave across cores

OBSERVATION

We have the following so far:

→ Task Assignment Model
→ Data Placement Policy

But how do we decide how to create a set of tasks from a logical query plan?

→ This is relatively easy for OLTP queries.
→ Much harder for OLAP queries…

STATIC SCHEDULING

The DBMS decides how many threads to use to execute the query when it generates the plan.
It does **not** change while the query executes.

→ The easiest approach is to just use the same # of tasks as the # of cores.

→ Can still assign tasks to threads based on data location to maximize local data processing.

MORSEL-DRIVEN SCHEDULING

Dynamic scheduling of tasks that operate over horizontal partitions called "morsels" distributed across cores.

→ One worker per core.
→ One morsel per task.
→ Pull-based task assignment.
→ Round-robin data placement.

Supports parallel, NUMA-aware operator implementations.

MORSEL-DRIVEN PARALLELISM: A NUMA-AWARE QUERY EVALUATION FRAMEWORK FOR THE MANY-CORE AGE
SIGMOD 2014

HYPER - ARCHITECTURE

No separate dispatcher thread.

The workers perform cooperative scheduling for each query plan using a single task queue.

→ Each worker tries to select tasks that will execute on morsels that are local to it.

→ If there are no local tasks, then the worker just pulls the next task from the global work queue.

HYPER – DATA PARTITIONING

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  FROM A, B
 WHERE A.id = B.id
   AND A.value < 99
   AND B.value > 100
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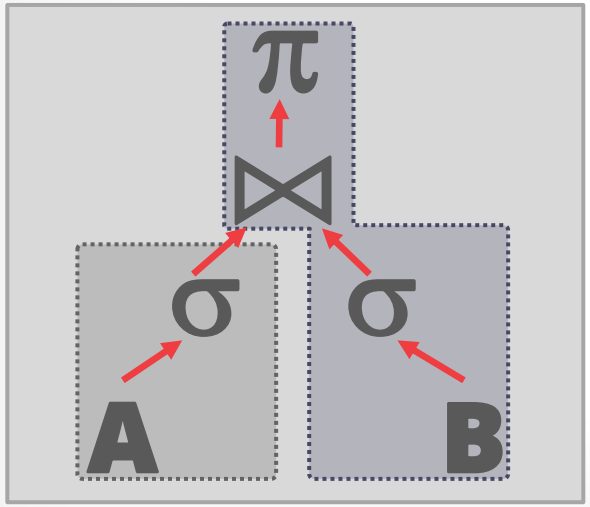
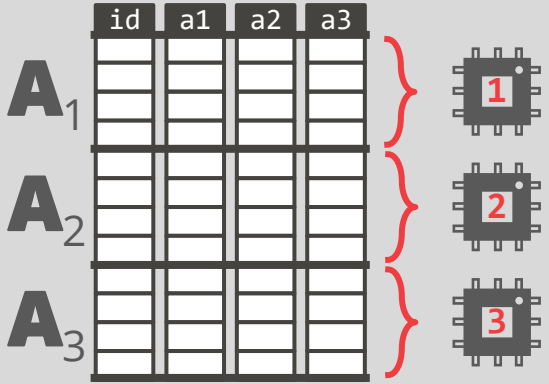


Data Table

Morsels



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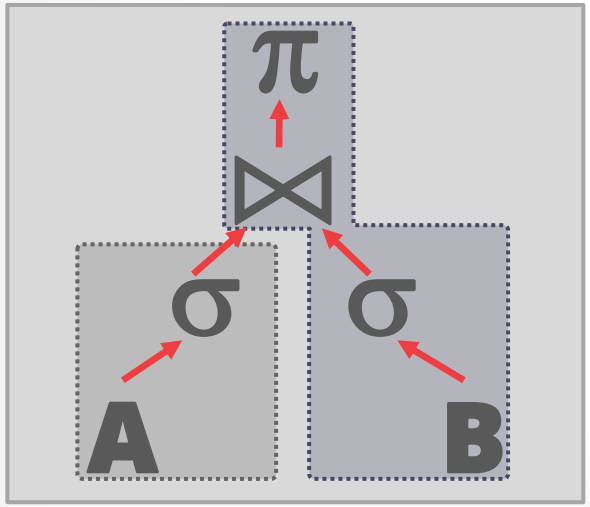

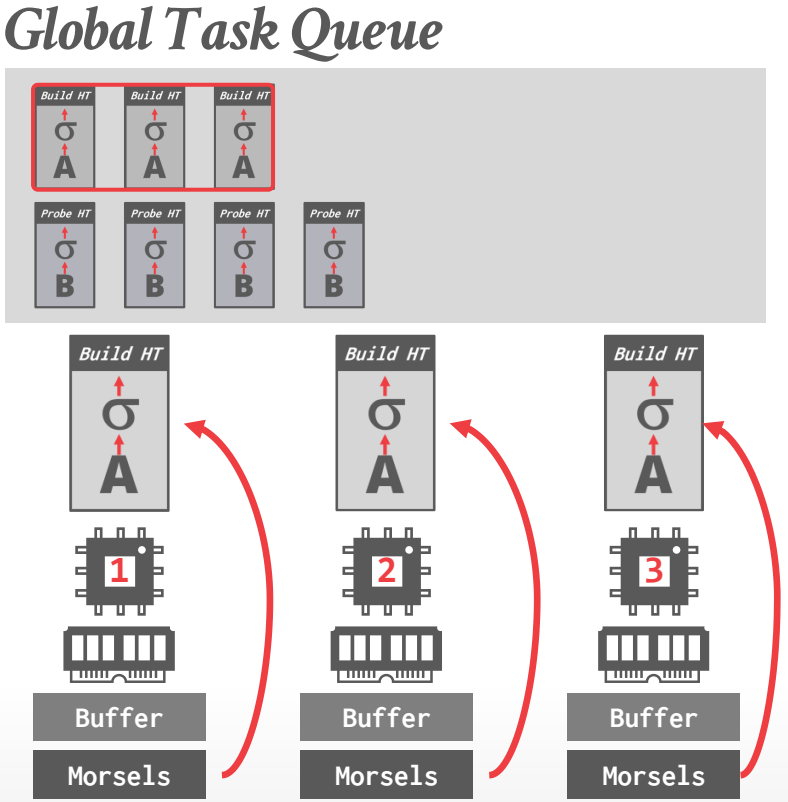

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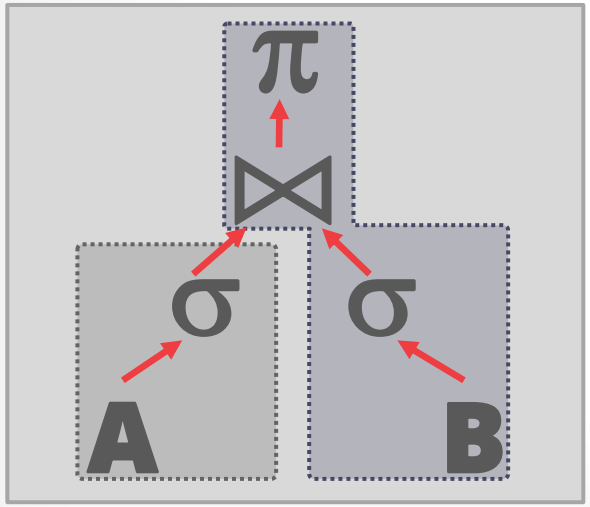

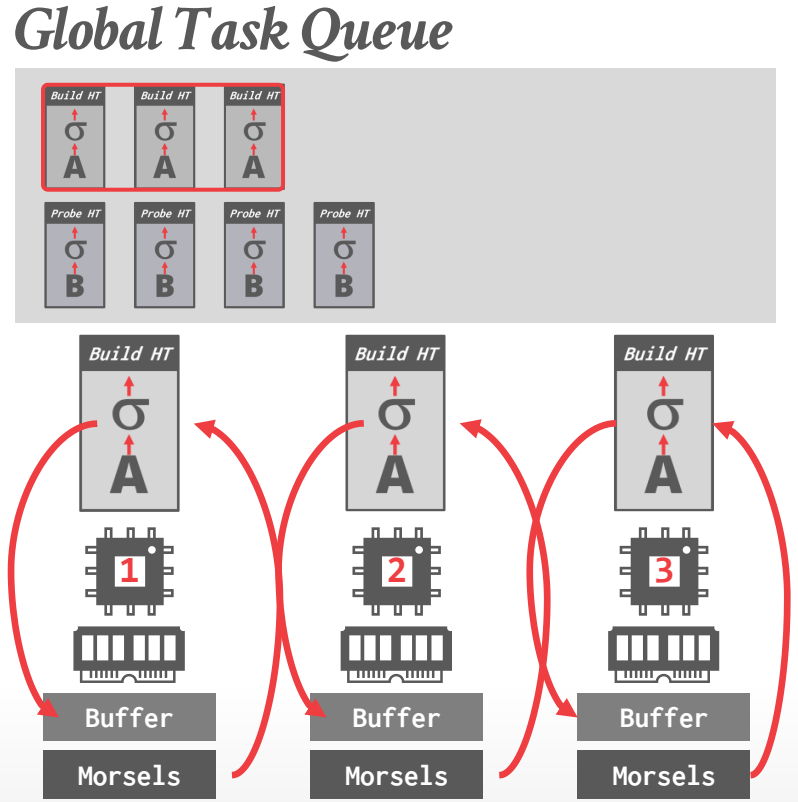

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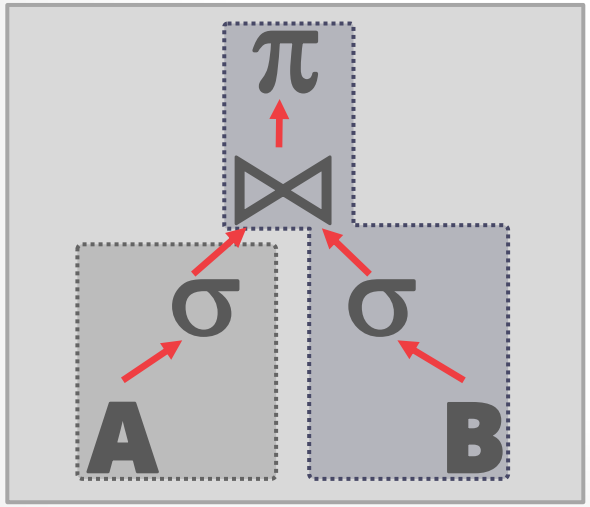

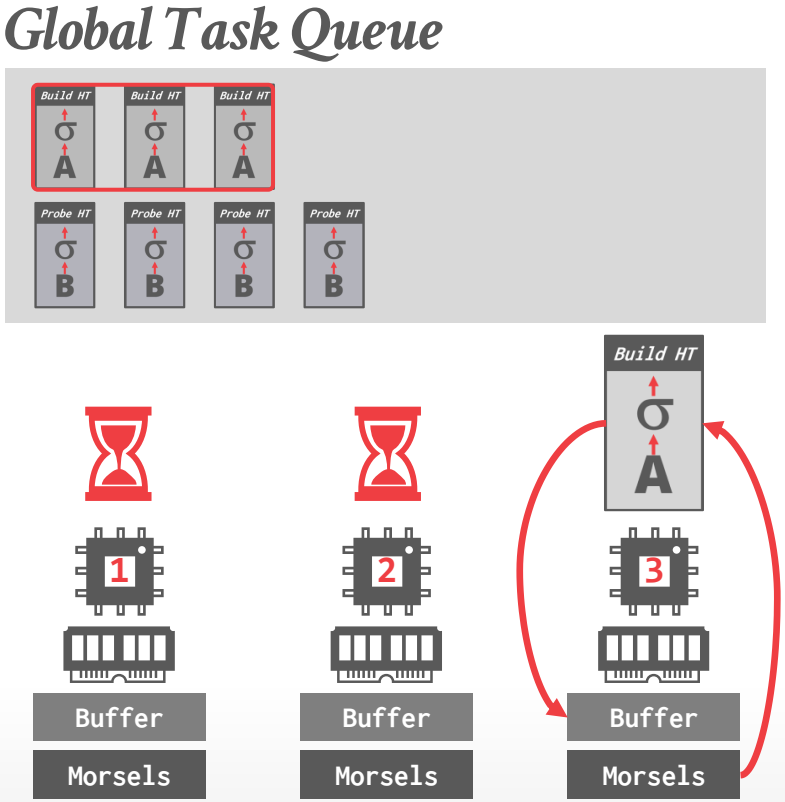

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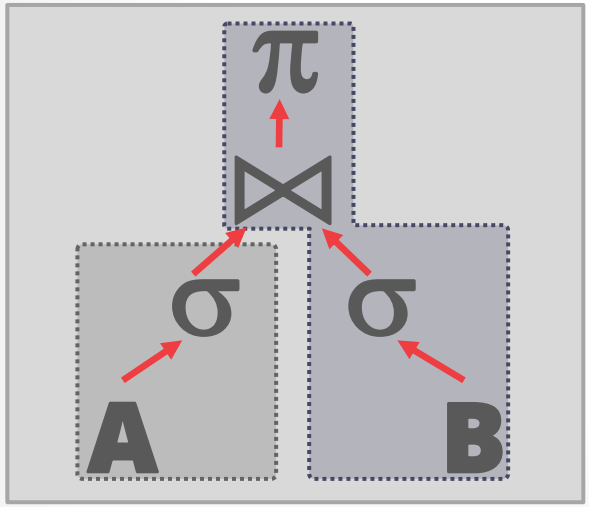
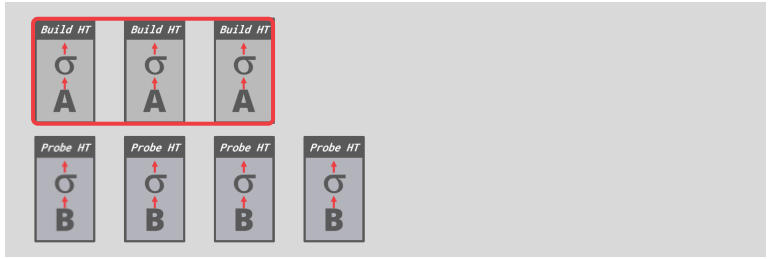
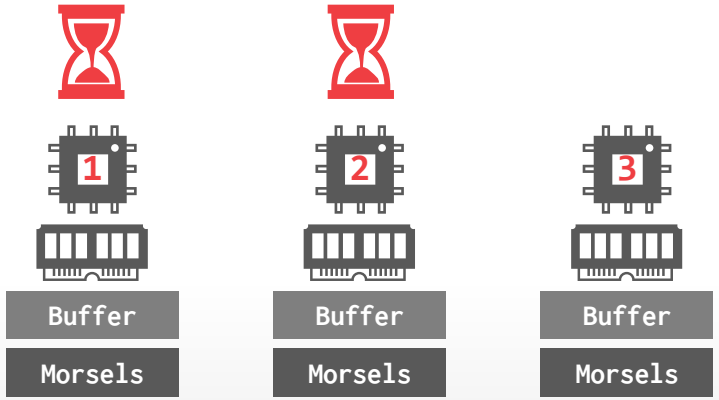


Global Task Queue





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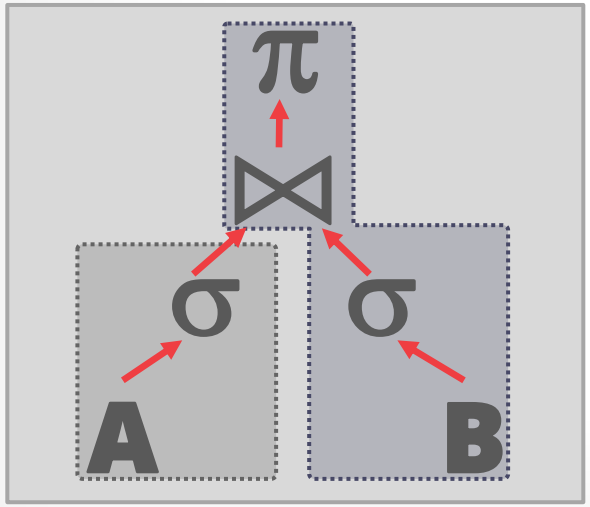

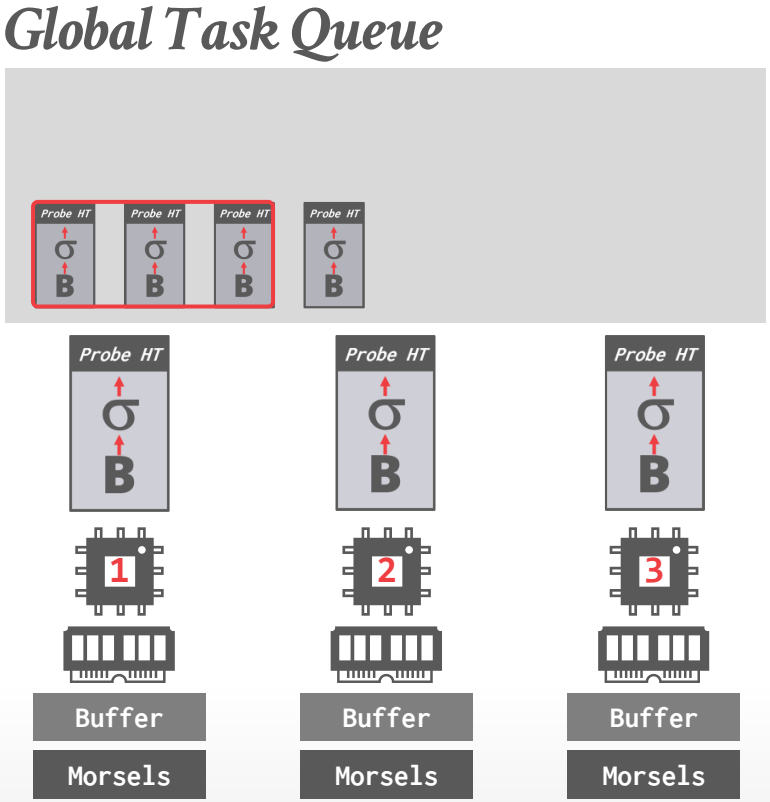

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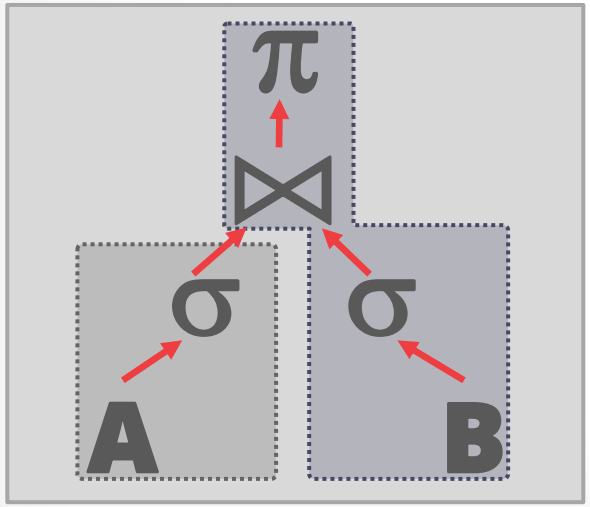

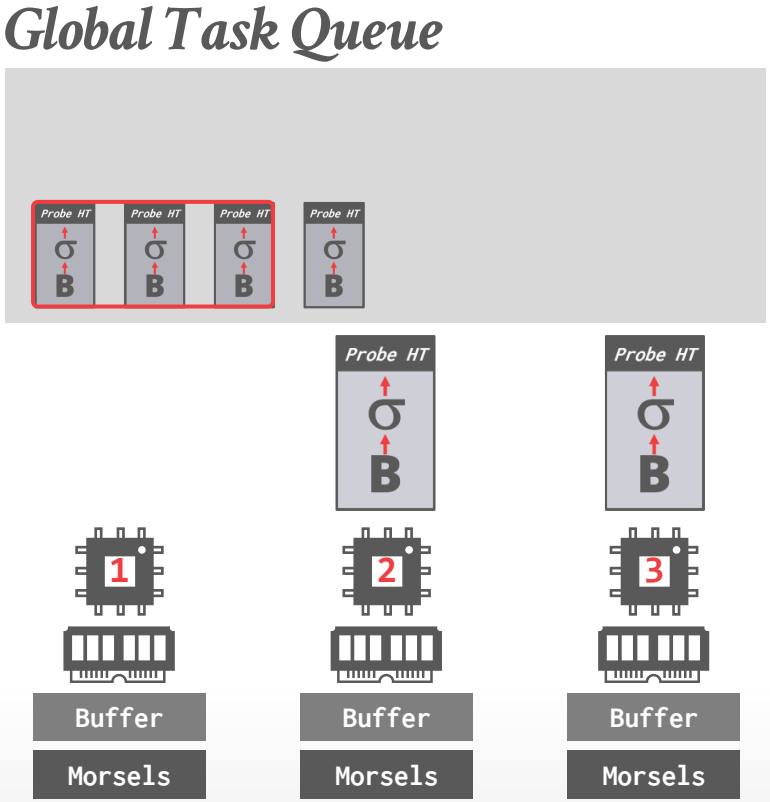

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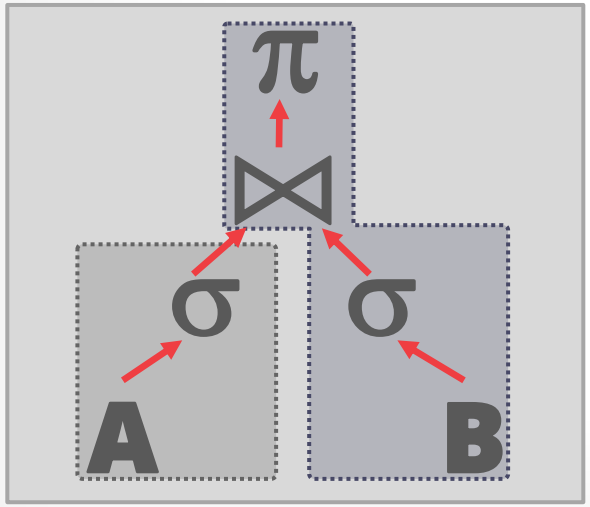
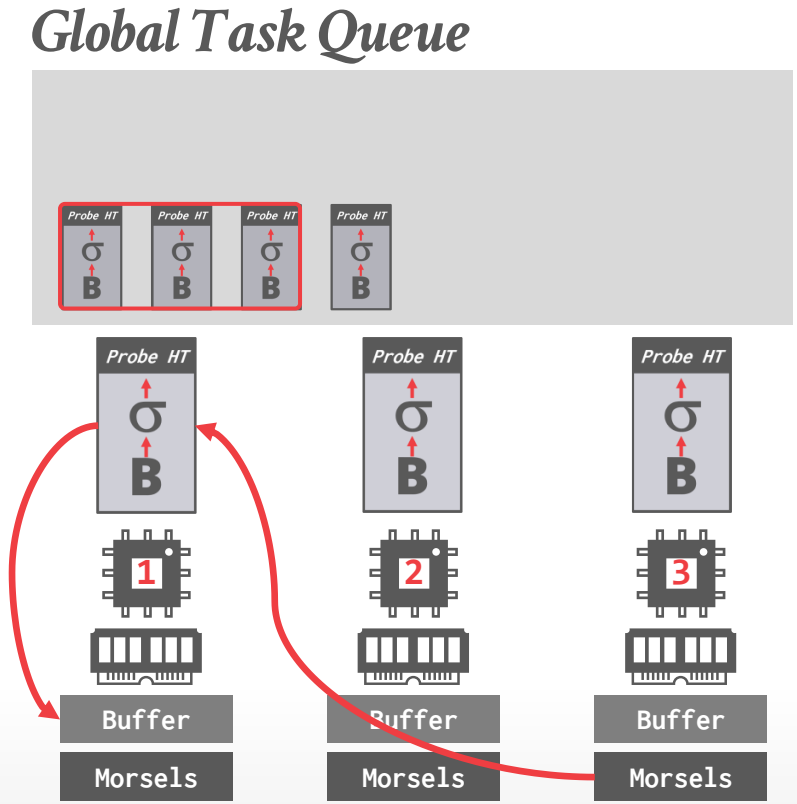




MORSEL-DRIVEN SCHEDULING

Because there is only one worker per core and one morsel per task, HyPer must use work stealing because otherwise threads could sit idle waiting for stragglers.

The DBMS uses a lock-free hash table to maintain the global work queues.

OBSERVATION

Tasks can have different execution costs per tuple.

→ Example: Simple Selection vs. String Matching

HyPer also has no notion of execution priorities.

→ All query tasks are executed with the same

→ Short-running queries get blocked behind long-running queries.

UMBRA – MORSEL SCHEDULING 2.0

Tasks are not created statically at runtime.

Each task may contain multiple morsels.

Modern implementation of stride scheduling.

Priority decay.

SELF-TUNING QUERY SCHEDULING FOR ANALYTICAL WORKLOADS
SIGMOD 2021

UMBRA – MORSEL SCHEDULING 2.0

Tasks are r

Each task r

Modern in

Priority de

SELF-TUNING QUERY SCHEDULING FOR ANALYTICAL WORKLOADS
SIGMOD 2021

UMBRA – STRIDE SCHEDULING

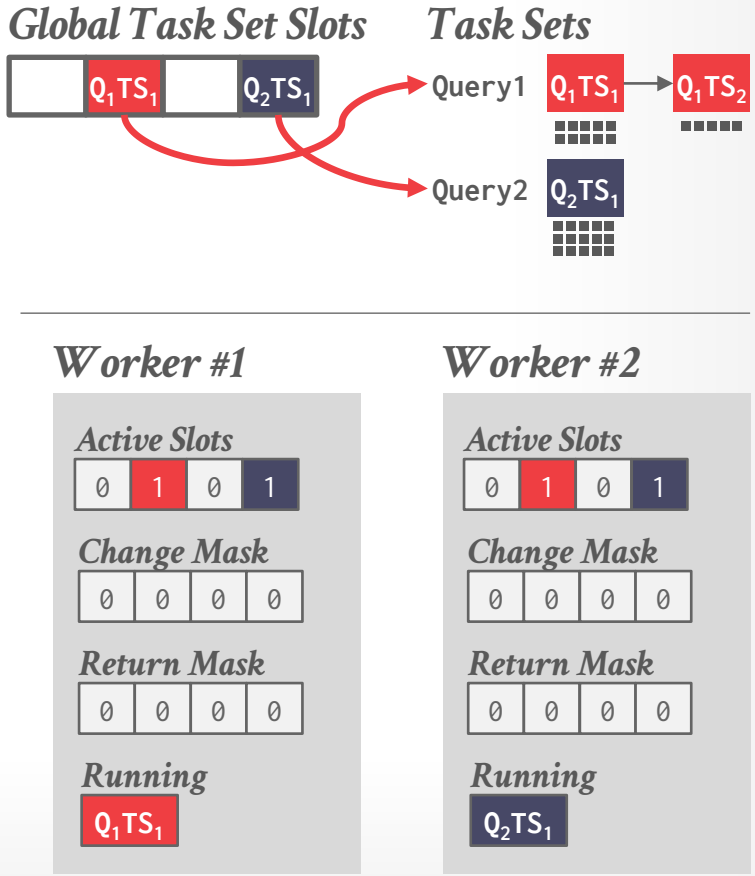
Each worker maintains its own thread-local meta-data about the available tasks to execute.

→ **Active Slots:** Which entries in the global slot array have active task sets available.

→ **Change Mask:** Indicates when a new task set is added to the global slot array.

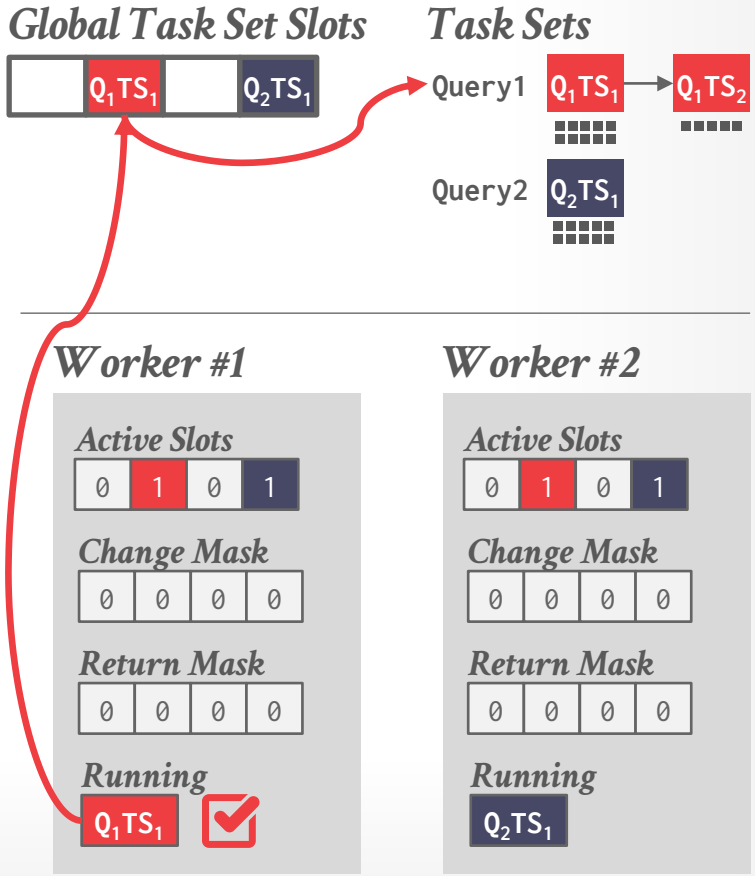
→ **Return Mask:** Indicates when a worker completes a task set.

Workers perform CaS updates to TLS meta-data to broadcast changes.



UMBRA – STRIDE SCHEDULING

When a worker completes the last morsel for a query's active task set, it inserts the next task set into the global slot array and updates the return mask for all workers.



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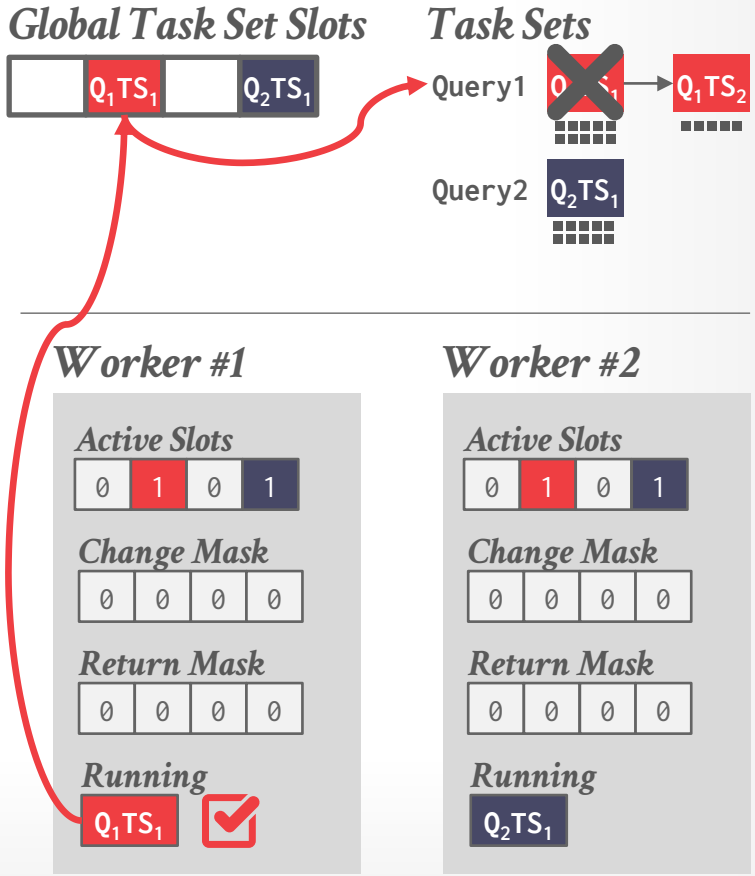

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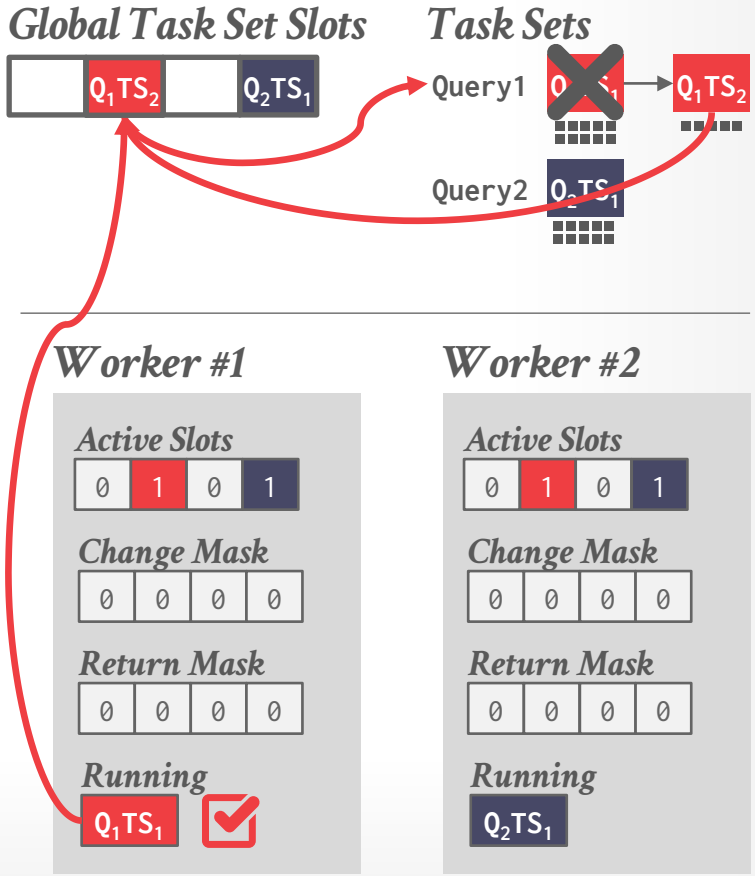

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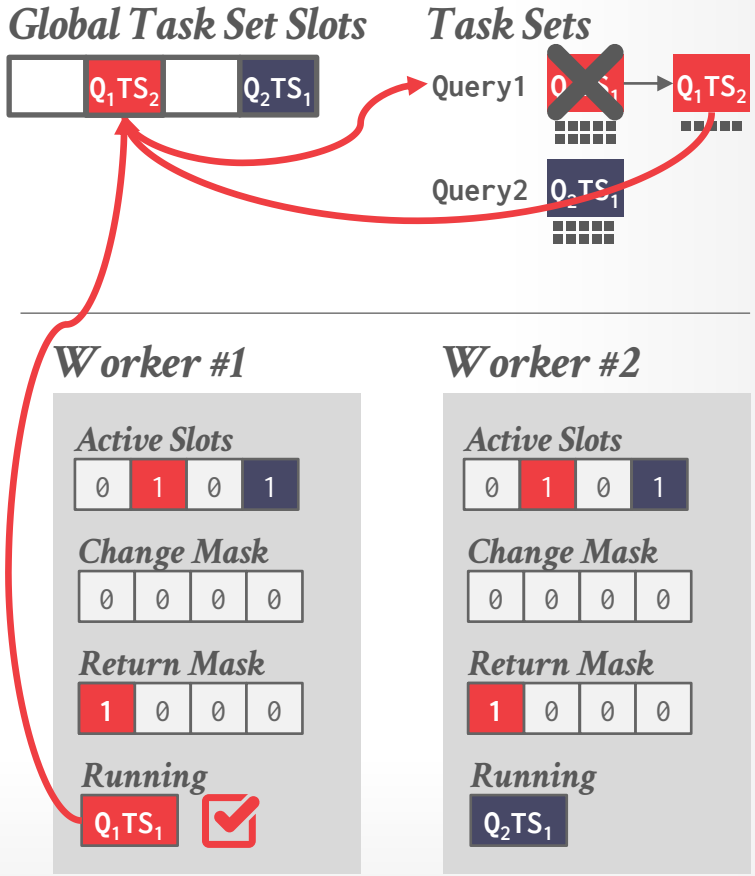

SAP HANA – NUMA-AWARE SCHEDULER

Pull-based scheduling with multiple worker threads that are organized into groups (pools).

→ Each CPU can have multiple groups.

→ Each group has a soft and hard priority queue.

Uses a separate "watchdog" thread to check whether groups are saturated and can reassign tasks dynamically.

SCALING UP CONCURRENT MAIN-MEMORY COLUMN-STORE SCANS: TOWARDS ADAPTIVE NUMA-AWARE DATA AND TASK PLACEMENT
VLDB 2015

SAP HANA – THREAD GROUPS

DBMS maintains **soft** and **hard** priority task queues for each thread group.

→ Threads can steal tasks from other groups' soft queues.

Four different pools of thread per group:

→ **Working**: Actively executing a task.
→ **Inactive**: Blocked inside of the kernel due to a latch.
→ **Free**: Sleeps for a little, wake up to see whether there is a new task to execute.
→ **Parked**: Waiting for a task (like a free thread) but blocked in the kernel until the watchdog thread wakes it up.

SAP HANA – NUMA-AWARE SCHEDULER

Dynamically adjust thread pinning based on whether a task is CPU or memory bound.
→ Allow more cross-region stealing if DBMS is CPU-bound.

SAP found that work stealing was not as beneficial for systems with a larger number of sockets.
→ HyPer (2-4 sockets) vs. HANA (64 sockets)

Using thread groups allows cores to execute other tasks instead of just only queries.

SAP HANA – NUMA-AWARE SCHEDULER

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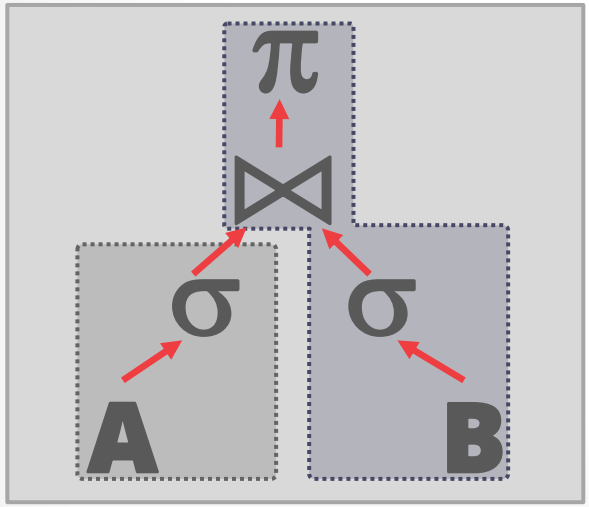

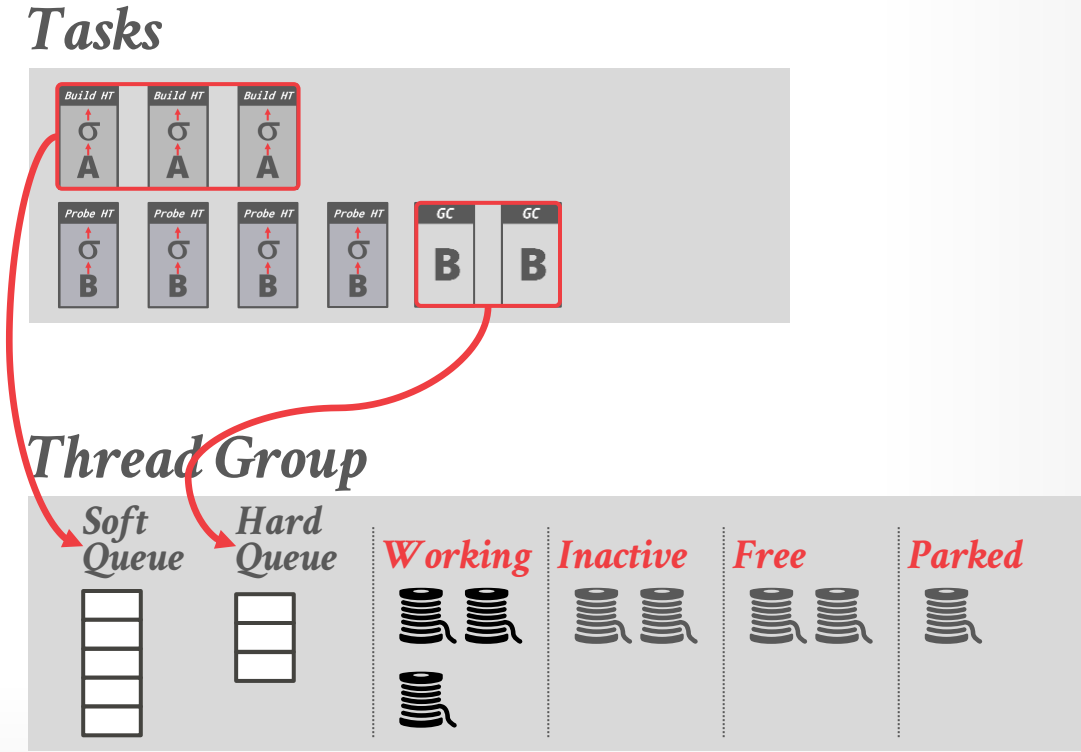

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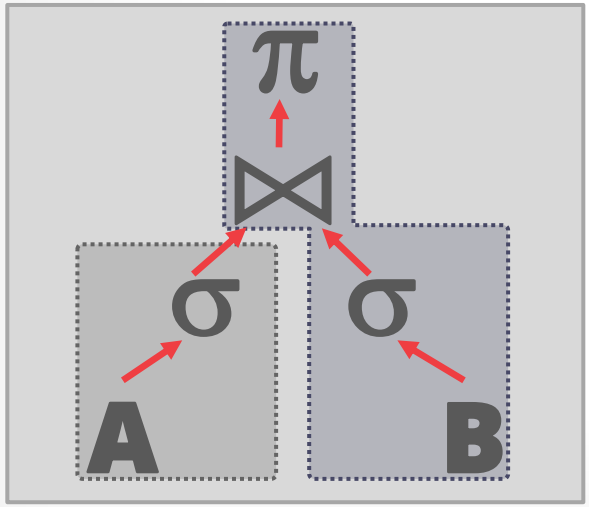

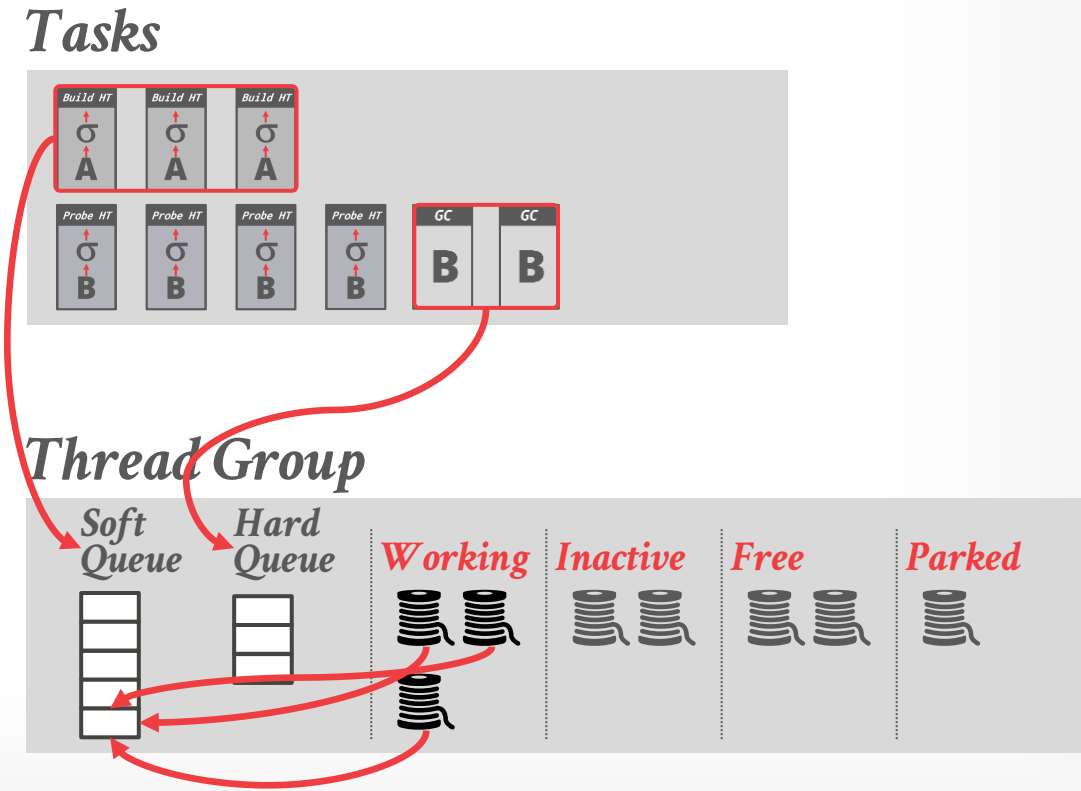

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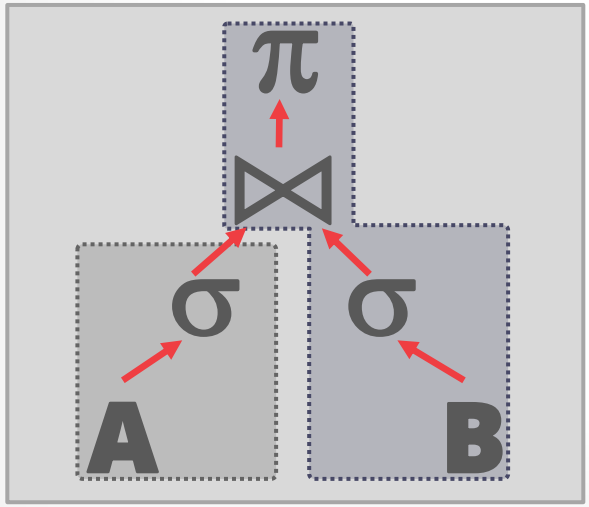

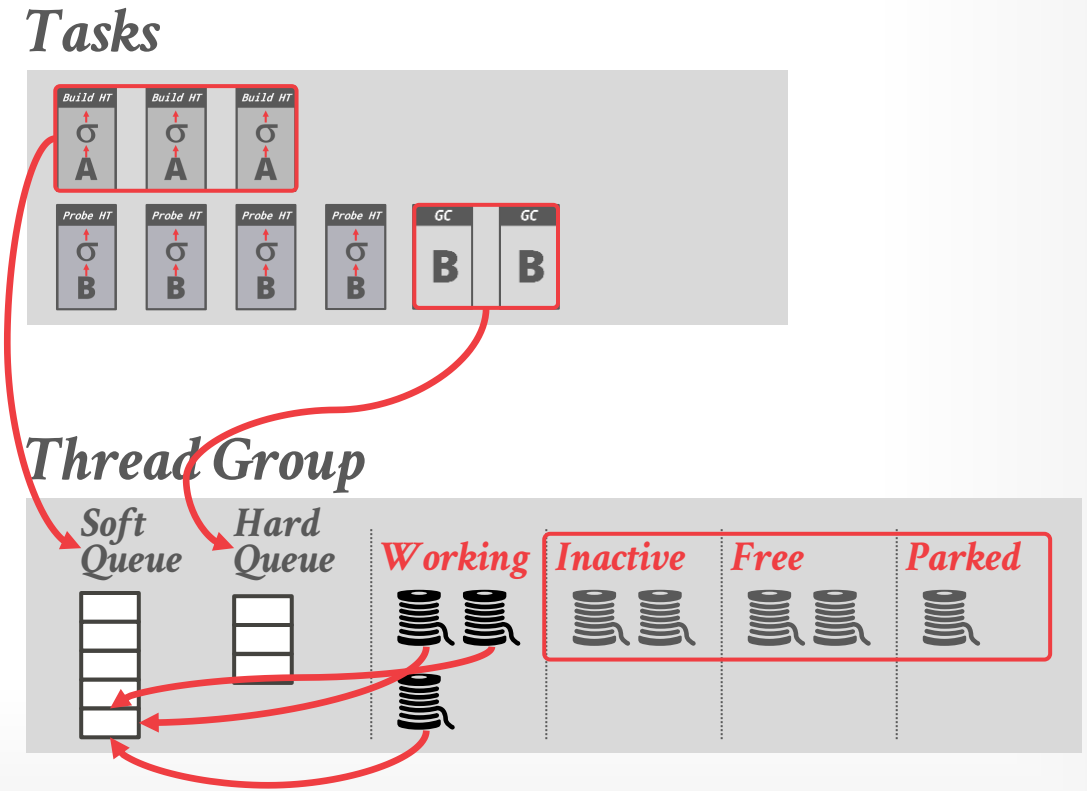

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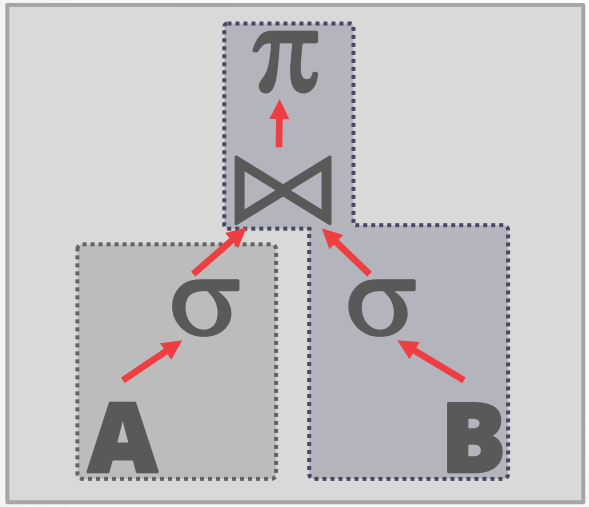

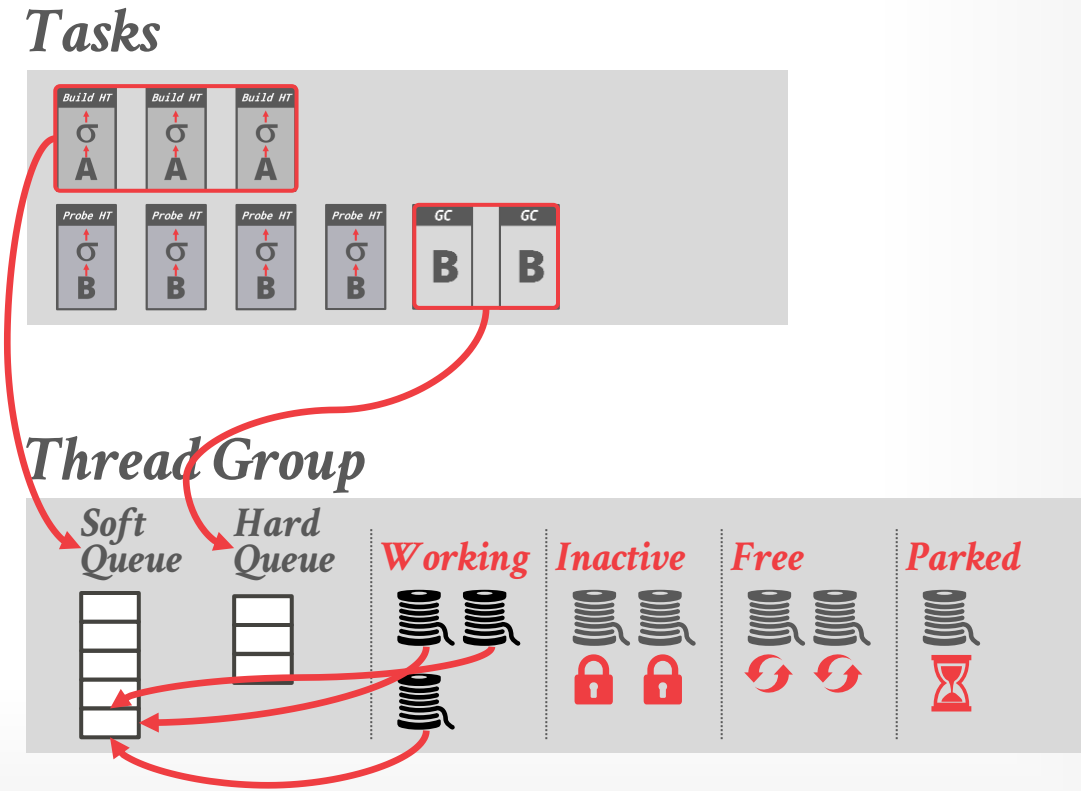

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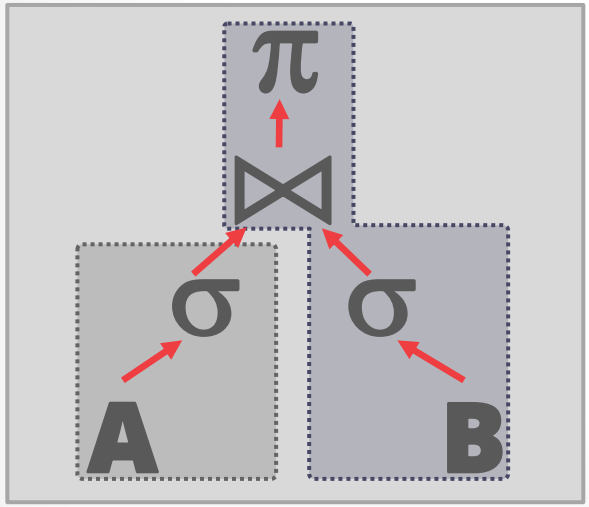
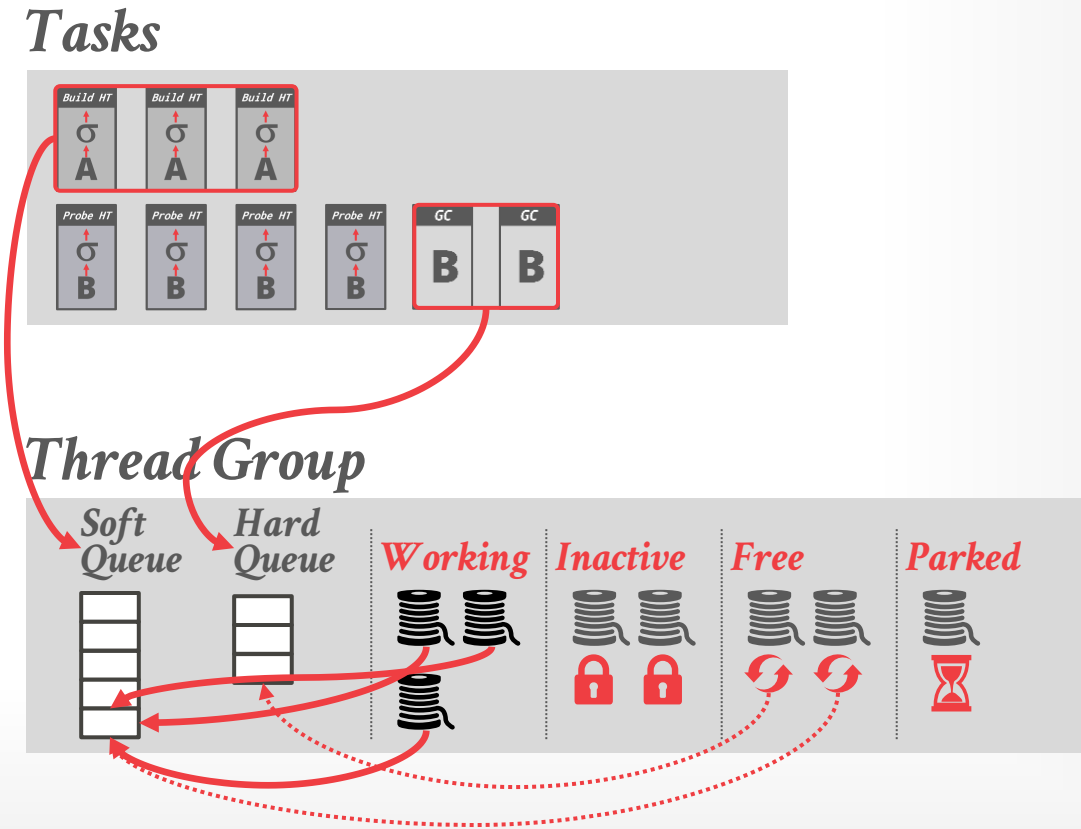
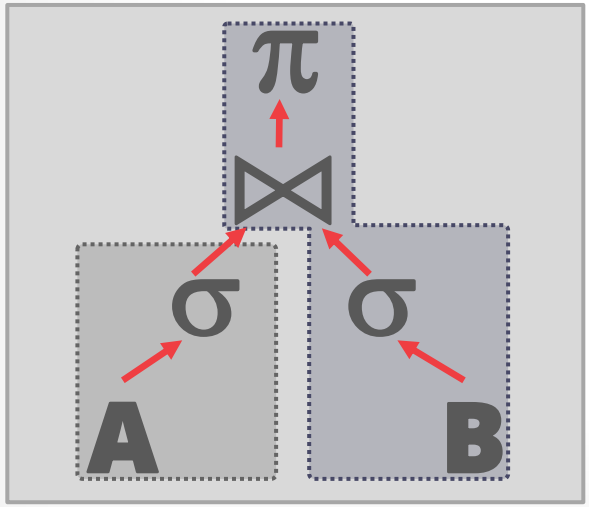
   AND B.value > 100
```

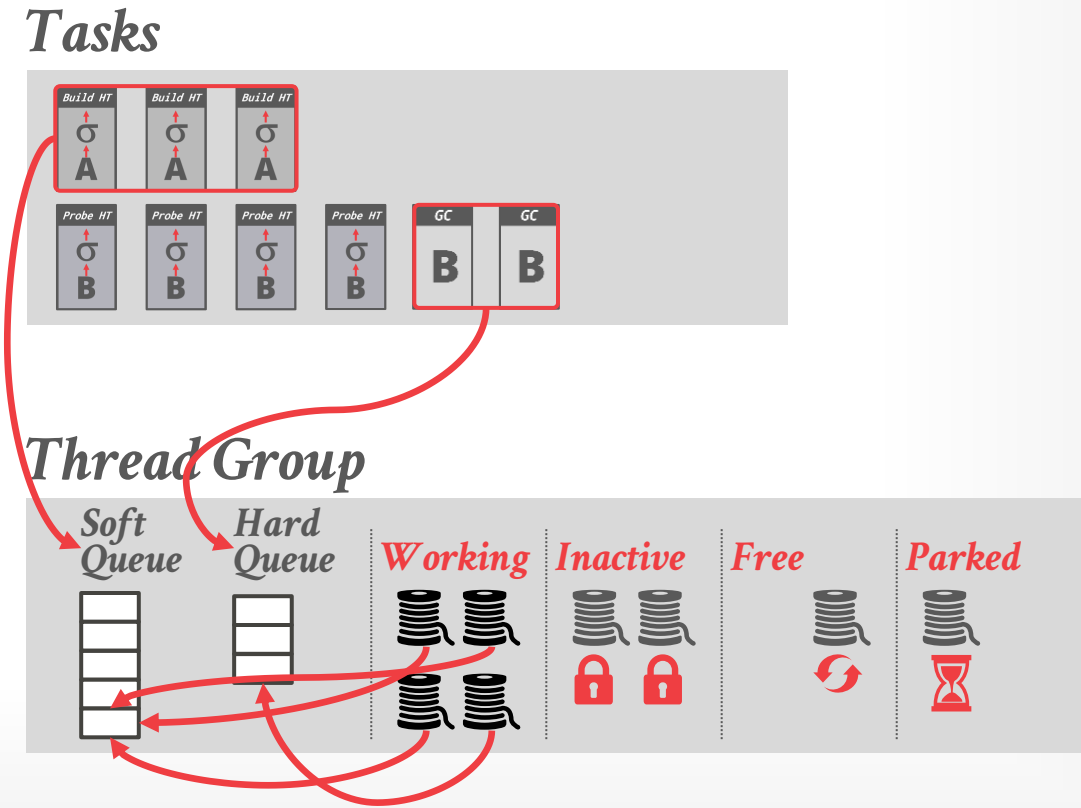




SAP HANA – NUMA-AWARE SCHEDULER

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





SQL SERVER – SQLOS

SQLOS is a user-mode NUMA-aware OS layer that runs inside of the DBMS and manages provisioned hardware resources.

→ Determines which tasks are scheduled onto which threads.
→ Also manages I/O scheduling and higher-level concepts like logical database locks.

Non-preemptive thread scheduling through instrumented DBMS code.

MICROSOFT SQL SERVER 2012 INTERNALS
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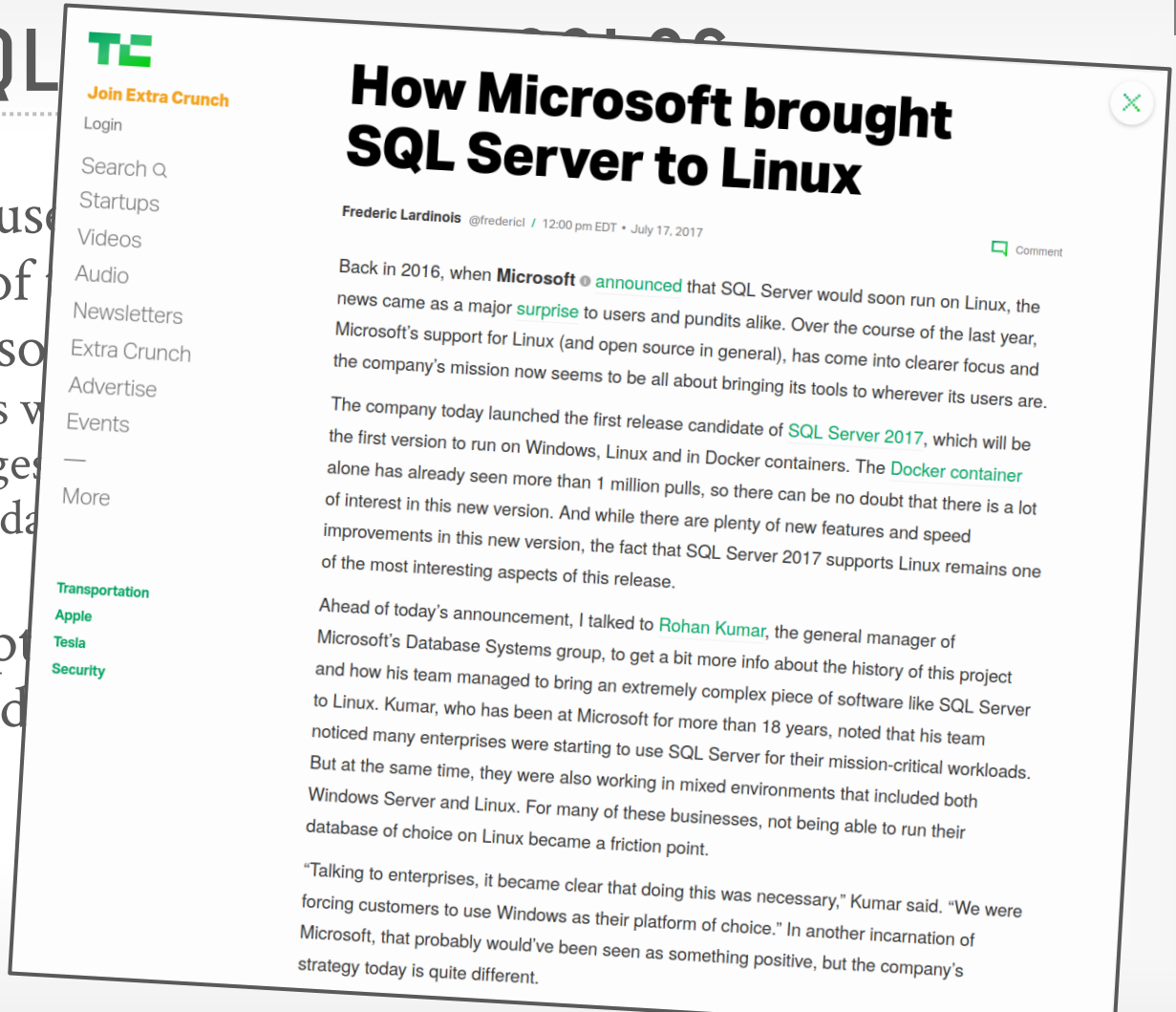
SQL

SQLOS is a use
runs inside of
hardware reso
→ Determines w
→ Also manages
like logical da

Non-preempt
instrumented



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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.

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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.

Other Examples:
→ ScyllaDB
→ FaunaDB
→ CoroBase

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

Approximate Plan

```
for t in R:
  if eval(predicate, tuple, params):
    emit(tuple)
```

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.

Other Examples:
→ ScyllaDB
→ FaunaDB
→ CoroBase

```
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)
```

SQL SERVER – SQLOS

SQLOS quantum i
scheduler cannot e

DBMS developers
explicit yield calls
locations in the so

Other Examples:
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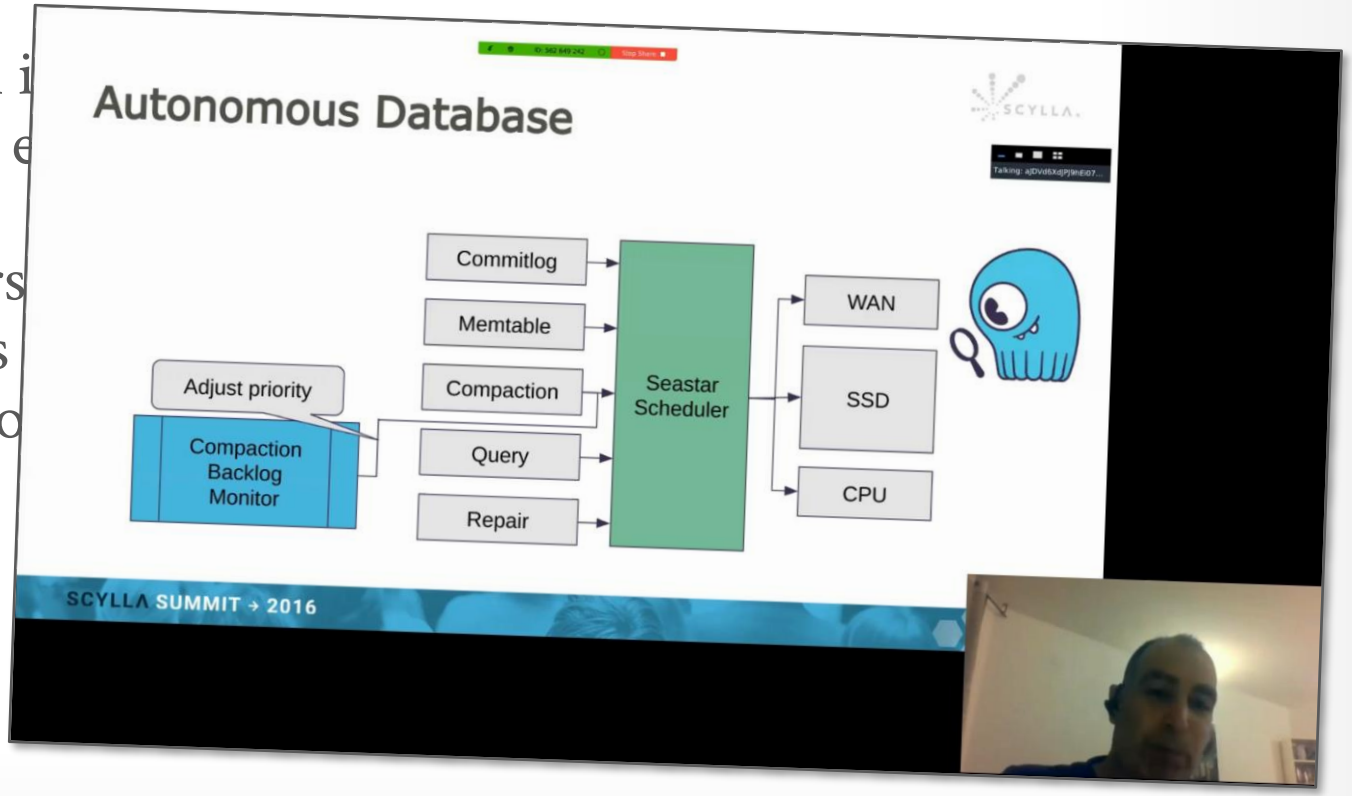

OBSERVATION

If requests arrive at the DBMS faster than it can execute them, then the system becomes overloaded.

The OS cannot help us here because it does not know what threads are doing:
→ CPU Bound: Do nothing
→ Memory Bound: OOM

Easiest DBMS Solution: Crash

FLOW CONTROL

Approach #1: Admission Control

→ Abort new requests when the system believes that it will not have enough resources to execute that request.

Approach #2: Throttling

→ Delay the responses to clients to increase the amount of time between requests.

→ This assumes a synchronous submission scheme.

PARTING THOUGHTS

We ignored disk I/O scheduling.

A DBMS is a beautiful, strong-willed independent software. But it must use hardware correctly.

→ Data location is an important aspect of this.
→ Tracking memory location in a single-node DBMS is the same as tracking shards in a distributed DBMS

Do not let the OS ruin your life.

NEXT CLASS

Vectorized Query Execution