Scheduling

Recap

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 running on the **server** that is responsible for executing tasks on behalf of the **client** and returning the results.
- Approaches
  - **Approach 1:** Process per DBMS Worker
  - **Approach 2:** Process Pool
  - **Approach 3:** Thread per DBMS Worker

Execution Parallelism

- **Inter-Query:** Different queries are executed concurrently.
  - Increases throughput & reduces latency.
- **Intra-Query:** Execute the operations of a single query in parallel.
  - Decreases latency for long-running queries.

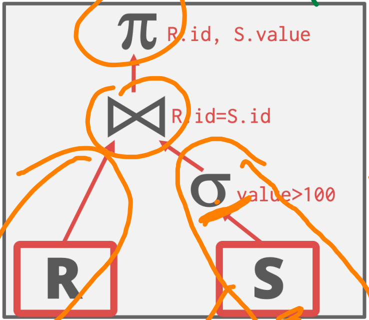
I/O Parallelism

- Split the DBMS installation across multiple storage devices.
  - Multiple Disks per Database
  - One Database per Disk
  - One Relation per Disk
  - Split Relation across Multiple Disks

Query Execution

- A query plan is comprised of **operators**.
- An **operator instance** is an invocation of an operator on some segment of data.
- A **task** is the execution of a sequence of one or more operator instances (*a.k.a.*, a **pipeline**).

```sql
SELECT R.id, S.cdate
  FROM R, S
  WHERE R.id = S.id AND S.value > 100
```



Scheduling

Easy

- 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.

Scheduler

Today's Agenda

- Data Placement
- Worker Allocation
- Scheduling
  - Hyper
  - HANA
  - SQL Server
- Flow Control

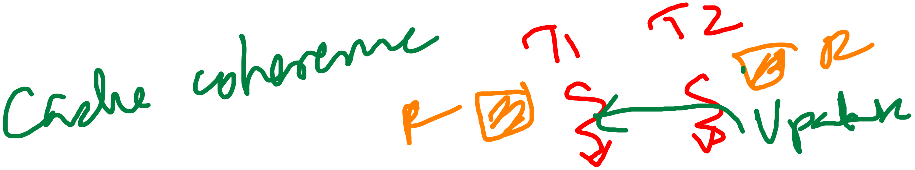
Data Placement

Observation

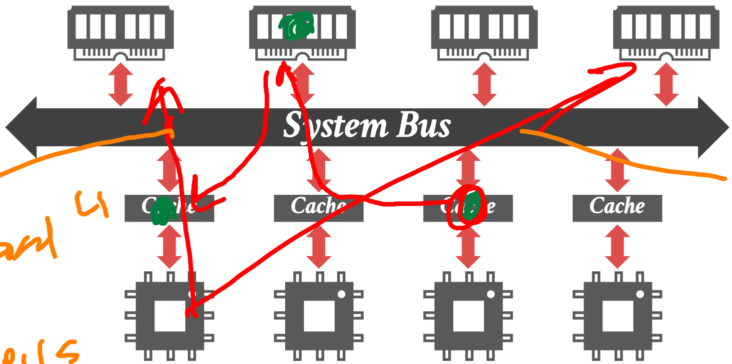
- Regardless of what worker allocation or task assignment policy the DBMS uses, it's important that workers operate on **local data**.
- The DBMS's scheduler must be aware of its hardware memory layout.
  - Uniform vs. Non-Uniform Memory Access
- Reference

Uniform Memory Access

- Cost of accessing data from a CPU core to any memory bank is roughly the same.
- Need to access data through the system bus.
- *a.k.a.*, Symmetric multi-processors (SMP).
- If two CPUs have a memory location in their caches and one of them does a write, then that CPU must send a **cache invalidation message** over the bus to the other CPU.



Uniform Memory Access

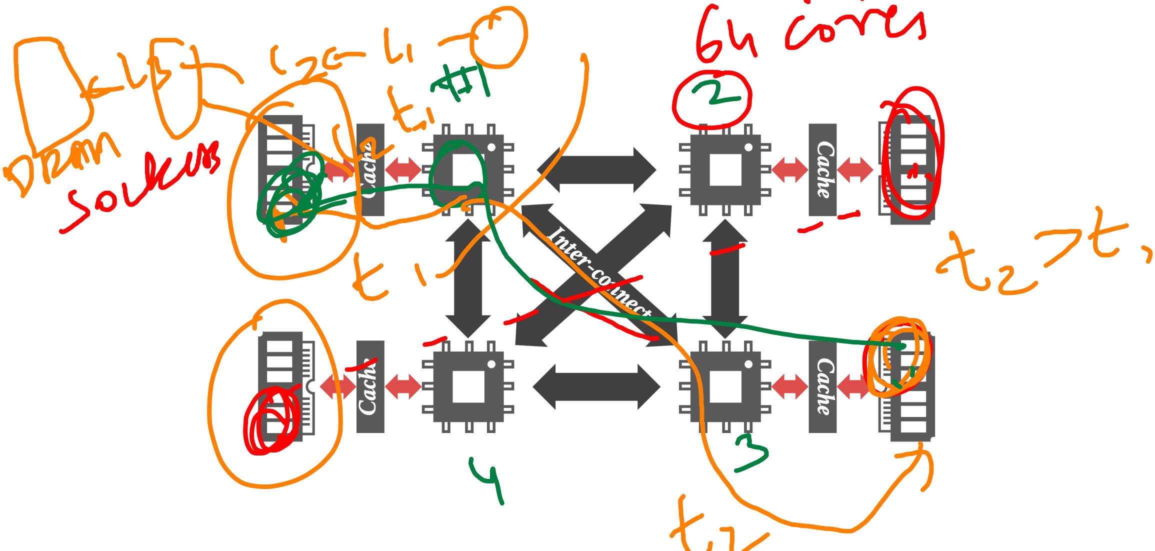


Non-Uniform Memory Access

- Every core has its own L1/L2 cache.
- All cores on the same **socket** share an L3 cache.
- Cost of accessing data from a CPU core to any memory bank is **not uniform**.
  - Intel (2008): QuickPath Interconnect
  - Intel (2017): UltraPath Interconnect
  - AMD (2017): Infinity Fabric

AMD Ryzen Thread Ripper

Non-Uniform Memory Access



Data Placement

- The DBMS can partition memory for a database and assign each partition to a CPU.
- Same problem arises in **distributed DBMSs**.
- By controlling and tracking the location of partitions, it can schedule operators to execute on workers at the closest CPU core.
- Linux Support
  - `move_pages`: moves the specified pages to the given memory nodes
  - `numactl`: runs processes with a specific NUMA scheduling or memory placement policy.
  - `cpunodebind`: Only execute command on the CPUs of given nodes.
  - `membind`: Only allocate memory from nodes.

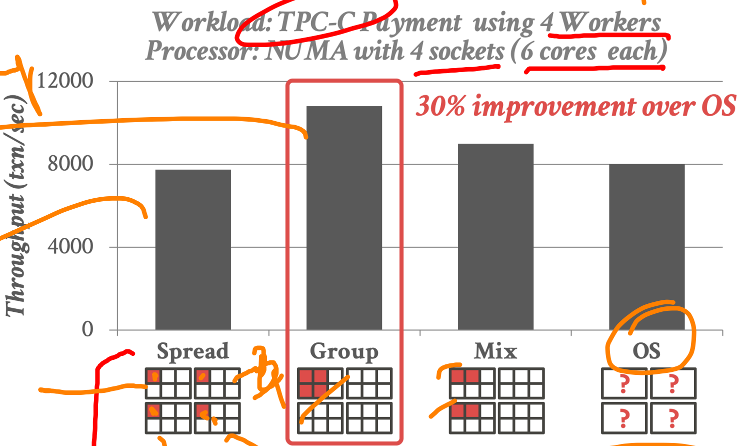
Memory Allocation

- 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.
  - Default policy that works well for most applications.
- **Approach 2: First-Touch**
  - At the CPU of the thread that accessed the memory location that caused the page fault.
  - Better policy for DBMSs.
- The OS can try to move memory to another NUMA region from observed access patterns.

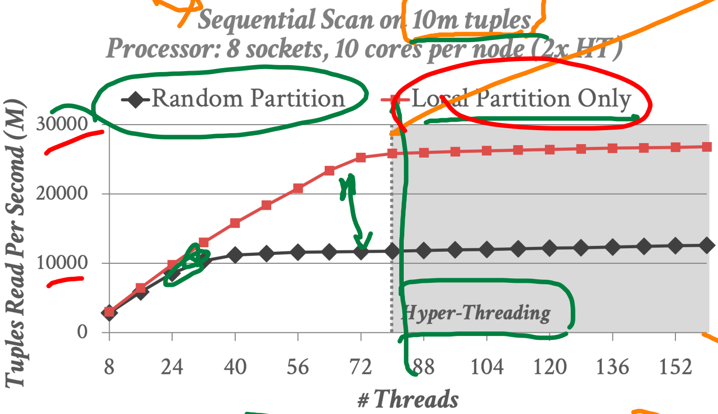
Data Placement - OLTP



Data Placement - OLTP

- Spread: assigns each thread to a core in a different socket.
- Group: assigns all threads to the same socket.
- Mix: assigns two cores per socket.
- OS: let the operating system dothe scheduling.

Data Placement - OLAP



Data Placement - OLAP

10m tuples / 16 thread > 10m tuples / 64 thread

- We are always processing the same number of tuples.
- Performance gap is smaller with fewer threads since more tuples are local to the core.
- With hyper-threading, no significant performance improvement since we are bottlenecked by memory bandwidth.
- So adding more logical cores doesn't help (already waiting for cacheline fills).

CPU-bound

Mem-bound

IO-bound

Network-bound

Partitioning vs. Placement Schemes

- 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.
  - Place the partition on a single socket
  - Distribute the partition across all sockets

Worker Allocation

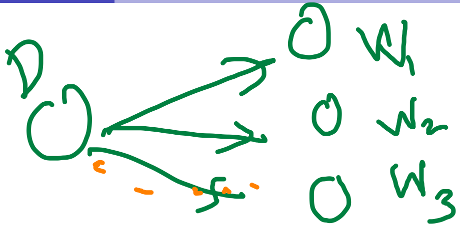
Observation

- Determining the right **number of workers** to use for a query plan depends on:
  - the number of CPU cores.
  - the size of the data.
  - the functionality of the operators.

Worker Allocation

- **Approach 1: One Worker per Core**
  - ▶ Each core is assigned one thread that is pinned to that core in the OS.
  - ▶ 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 2: Pull**
  - Workers pull the next task from a queue, process it, and then return to get the next task.

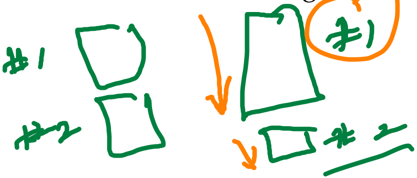
Scheduling – Hyper

Observation

- We have the following so far:
  - Process Model
  - 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 number of tasks as the number of cores.
  - Can still assign tasks to threads based on data location to maximize local data processing.
- Limitation: our assumption about the distribution of data can be wrong.
- This leads to **stragglers**.



Dynamic Scheduling

- Dynamic scheduling of tasks that operate over horizontal partitions called **morsels** that are distributed across cores.
  - One worker per core
  - Pull-based task assignment
  - Round-robin data placement
- Supports parallel, NUMA-aware operator implementations.
- Duplicate or steal tasks to avoid stragglers.
- Reference

Architecture

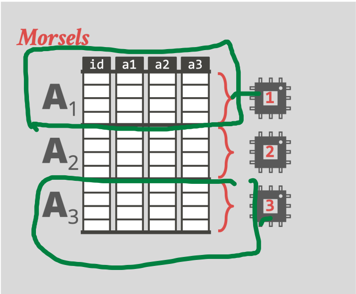
- No centralized dispatcher thread (*i.e.*, pull model)
- The workers perform **cooperative scheduling** for each query plan using a single task queue.
  - Each worker tries to select tasks that will execute on morsels that are local to it.
  - If there are no local tasks, then the worker just pulls the next task from the global work queue.

Work Stealing

Data Partioning

- Morsel is a Hyper term.
- Number of tuples to provide the right amount of parallelism (*e.g.*, 100 K tuples)
- Slightly bigger than a block, smaller than a partition.

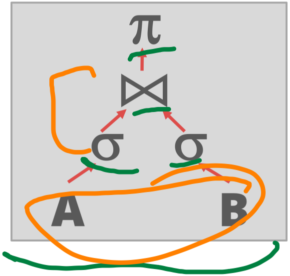
Data Table



Morsel-Driven Dynamic Scheduling

- Because there is only one worker per core, 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.

Example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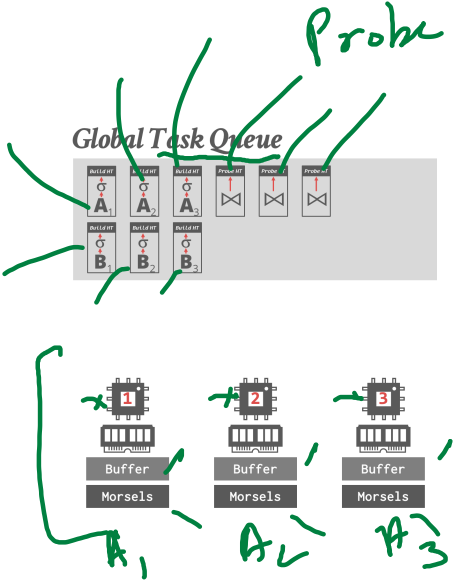
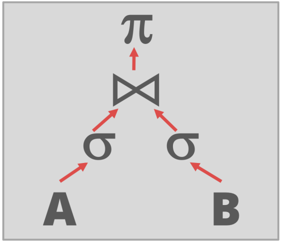
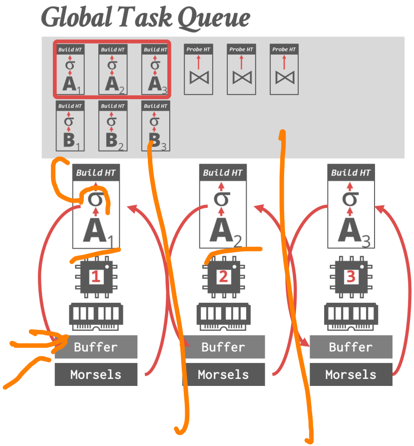

Global Task Queue
Build HT
Probe HT
1
2
3
Buffer
Morsels

Morsel-Driven Dynamic Scheduling

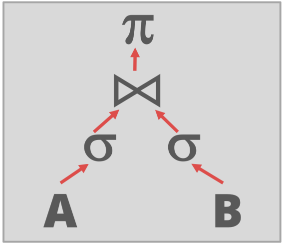
- Each worker will have the morsels stored locally.
- As the workers execute tasks, they will store the output in their local buffers (rather than a shared global buffer).
- When they select the next task, they try to pick ones that will maximize the reuse of morsels in their local buffers.
- This scheduling policy minimizes cross-communication between workers.

Example





Example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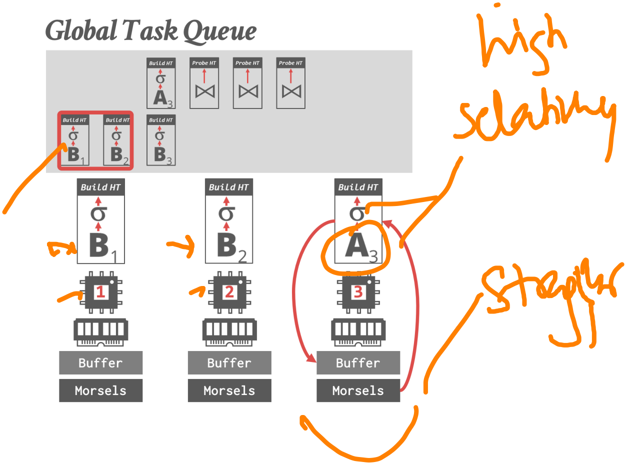
Global Task Queue
Build HT
Probe HT
Probe HT
Probe HT
Build HT
Build HT
Build HT
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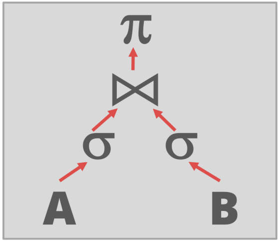
Build HT
Build HT
1
2
3
Buffer
Buffer
Buffer
Morsels
Morsels
Morsels

Example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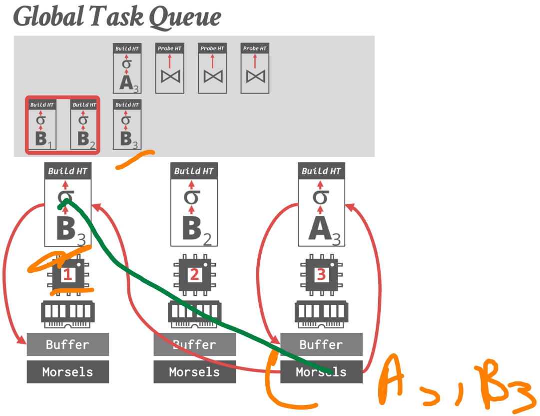

Global Task Queue
Build HT
Probe HT
Build HT
Build HT
Build HT
Buffer
Morsels
A3, B3

Scheduling – HANA

NUMA-Aware Scheduler

- Pull-based scheduling with multiple worker threads that are organized into **groups**.
  - Each CPU can have multiple groups.
  - The scheduler can scale up/down the number of threads in a group
- Uses a separate **watchdog thread** to check whether groups are saturated and can reassign tasks dynamically.
- Reference

Thread Groups

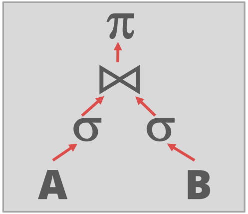
- Each thread group has a soft and hard priority queue.
  - **Soft queue:** Threads **can** steal tasks from other groups' soft queues.
  - **Hard queue:** Threads **cannot** steal tasks from other groups' hard queues (*e.g.*, garbage collection, networking).
- Four different pools of threads per group:
  - **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:** Like free but doesn't wake up on its own.

NUMA-Aware Scheduler

- Dynamically adjust **thread pinning** based on whether a task is CPU or memory bound.
- Found that work stealing was not as beneficial for systems with a larger number of sockets (*e.g.*, 64 sockets).
- If you have too many sockets, then put all tasks in the hard queue to prevent stealing.
- Using thread groups allows cores to execute other tasks instead of just only queries.

Scale-up >$1m

Example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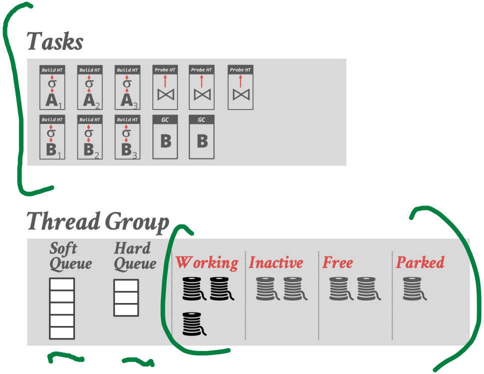
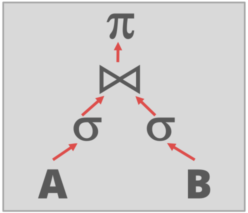

Tasks
Build HT
A1
A2
A3
B1
B2
B3
Probe HT
GC
B
Thread Group
Soft Queue
Hard Queue
Working
Inactive
Free
Parked

Example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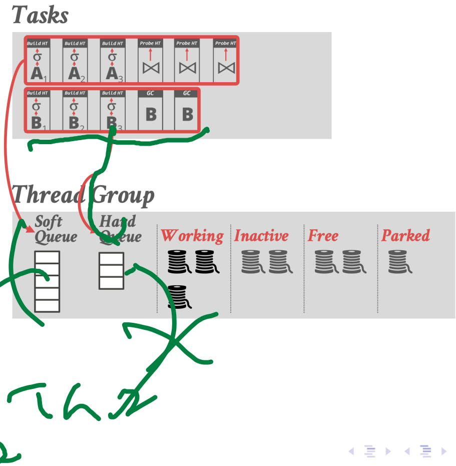
Tasks
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Probe HT
GC
Thread Group
Soft Queue
Hard Queue
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Inactive
Free
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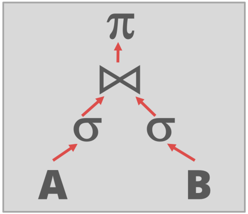
Example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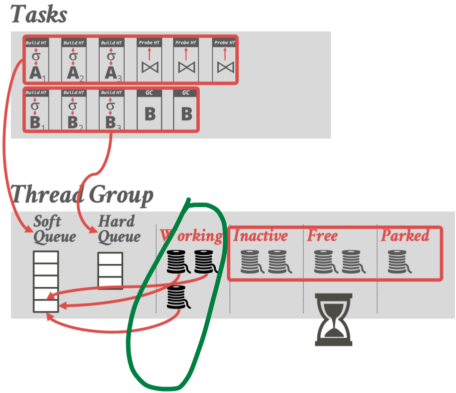
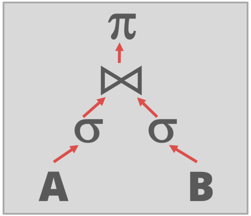

Tasks
Build HT
Build HT
Build HT
Probe HT
Probe HT
Probe HT
A1
A2
A3
Build HT
Build HT
Build HT
GC
GC
B1
B2
B3
B
B
Thread Group
Soft Queue
Hard Queue
Working
Inactive
Free
Parked

Example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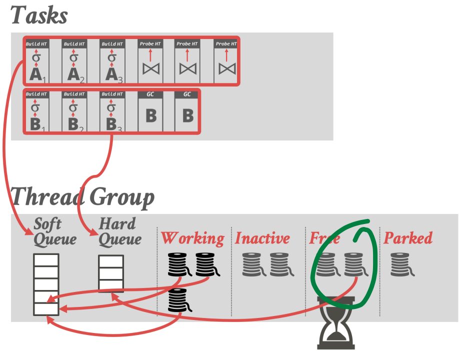
Tasks
Build HT
Build HT
Build HT
Probe HT
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GC
GC
Thread Group
Soft Queue
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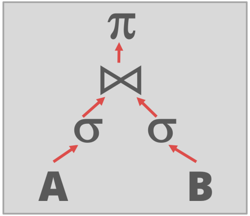
Parked

Example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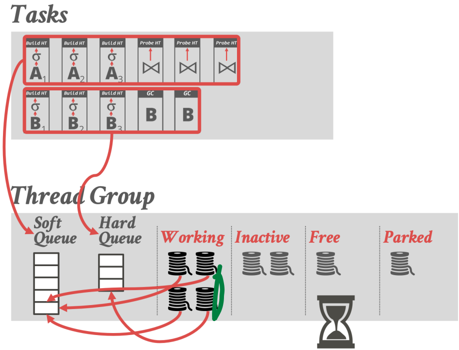
Tasks
Build HT
Probe HT
GC
Thread Group
Soft Queue
Hard Queue
Working
Inactive
Free
Parked

Scheduling – 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.
- Reference

SQLOS

- **Quantum** is the amount of time that the scheduler allows a thread to run before making a new decision.
- SQLOS quantum is 4 ms but the scheduler **cannot** enforce that.
- Linux: Quantum length is not fixed, 100 ms for special-purpose real-time processes.
- DBMS developers must add explicit **yield** calls in various locations in the source code.

SQLOS

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

last = now()
for t in range(table.num_tuples):
  tuple = get_tuple(table, t)
  if eval(predicate, tuple, params):
    emit(tuple)
  if now() - last > 4ms:
    yield
    last = now()
```

Flow Control

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: Out-of-memory error
- 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.

Conclusion

Conclusion

- A DBMS is a beautiful, strong-willed independent piece of 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
- Don't let the OS ruin your life.
- Next Class
  - Parallel Join Algorithms

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