Parallelism beyond MapReduce: Threads on Multicores

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MapReduce Pro and Con

- Pros:
  - Easy programming interface;
  - The underlying system can automatically support parallelism, data movement, load balancing, and fault-tolerance.
- Cons:
  - Programming interface is still restrictive for some applications;
  - Too much automation, too little direct control for performance optimization;
  - Not optimal for parallelism in single shared-memory multicore machine.

Threads

- Parallel programming model in a single shared-memory multi-core machine; without support for data move and management
- Programming model:
  - Create bunch of threads, each running something.
  - Multiple threads run in parallel on a multi-core.
  - All threads share the memory space (each thread can directly access any data in the memory space). [No direct data sharing in MapReduce]
  - Very flexible and fairly simple without synchronization.

Synchronization on Shared Data

- Two threads that operate on a shared counter:
  - One increases the counter by one;
  - The other decreases the counter by one.
- Counter increase may be implemented as:

```
register1 = counter;
register1 = register1 + 1;
counter   = register1;
```

- Counter decrease may be implemented as:

```
register2 = counter;
register2 = register2 - 1;
counter   = register2;
```

- Each counter operation must be protected from concurrent update by the other (synchronization by mutex locks).

Synchronization to Preserve Task Ordering (Dependencies)

- Task ordering needed in applications:
  - Word counting from individual documents need to complete before the aggregation of the counts;
  - In each iteration of K-means, the cluster assignment of all samples must happen before new cluster centers are computed and the next iteration commences.
- Dependencies can be preserved by synchronization (wait/signal).

When to Use Threads?

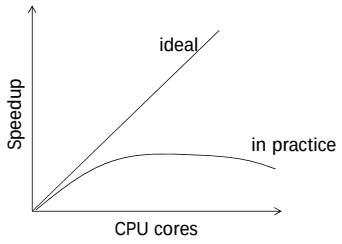
- When all data fit into memory, and
  - Threads is more flexible (than MapReduce) in allowing data sharing and controlling task ordering
  - Threads has less overhead (than MapReduce)
- When threads run in each multi-core machine of a large MapReduce cluster

Threads Programming Steps

- Decompose application into tasks
  - Like identify map tasks for MapReduce
  - Formalize the dependencies (more flexible than MapReduce)
  - How good is the decomposition?
    - Exposed parallelism, load balance, required synchronization
- Add synchronization
  - Preserve the task dependencies
  - Protect shared data structure for concurrent accesses
- Fine-grain vs. coarse-grained decomposition
  - Parallelism vs. challenges in control

Performance Objectives

- Fast speed
- Assume the sequential is already optimized, we want high speedup, ideally equaling the number of CPU cores



Application: Word Counting

- How to support word counting with threads?
  - Step 1: Each thread counts a subset of the document
  - Step 2: Counts are aggregated after all documents are counted
- Parallelism is step 1; dependency between steps 1 and 2
- Is it going to work well (good speedup)?
  - Good parallelism, reasonable load balancing, little dependency, but too small compute-to-data ratio

Application: K-means

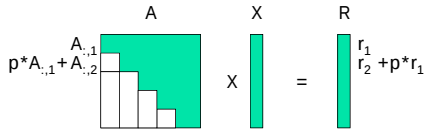
- How to support K-means with threads?
  - Within each iteration, parallelize the sample clustering
  - Synchronization between iterations
- Is it going to work well (good speedup)?
  - Some parallelism, good load balancing, more dependency (compared to word count), but better compute-to-data ratio (with a large number of iterations).

Application: PageRank Computation

- A linear system of equations (N variables, N linear equations)
- Solved iteratively with a matrix-vector multiplication at each step
- How to support PageRank with threads?
  - Within each iteration, parallelize the matrix-vector multiplication
  - Synchronization between iterations
- Is it going to work well (good speedup)?
  - Good parallelism, good load balancing, some dependency, good compute-to-data ratio (with a large number of iterations).
- But iterative method doesn't produce precise solution

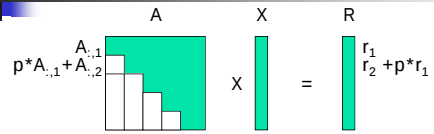
Application: Gaussian Elimination

- Simplification – ignore final solving step and pivoting
- Reduce an equation matrix into an equivalent upper-diagonal



for c=1 to N
  for r=c+1 to N
    zero out $A_{c,r}$ by adding $p*A_{:,c}$ to $A_{:,r}$

Application: Gaussian Elimination



for c=1 to N
  for r=c+1 to N
    zero out $A_{c,r}$ by adding $p*A_{:,c}$ to $A_{:,r}$

- How to parallelize? Dependencies:
  - Outer loop instances (e.g., c=2 depends on c=1)?
  - Inner loop instances (e.g., r=3 depends on r=2)?
  - Within one inner loop instance?
- Task decomposition:
  - Row, column, 2-dimensional

Irregular Parallelism

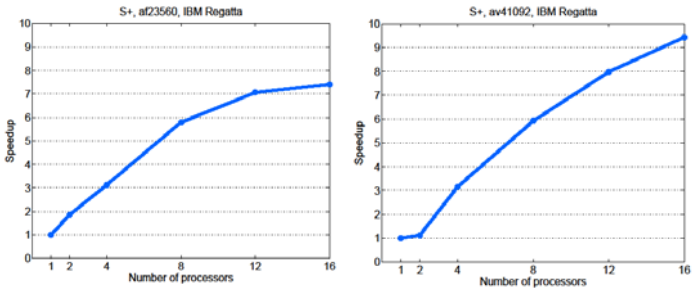
- Real problems contain large, sparse matrices
- Solve them as dense matrices waste time on zero-element operations
- Sparse matrix computation
  - Load imbalance
  - Managing nonzero fillins

Static vs. Dynamic Task Assignment

- Static task assignment
  - No. of tasks = No. of threads = No. of CPU cores
  - Each task gets a dedicated thread/CPU and runs to the end
- Dynamic task assignment
  - No. of tasks > No. of threads
  - Maintain a queue of ready tasks, protected by mutex lock
  - Each thread grabs a task and runs it; grabs another one when the current task completes
  - Advantage: good load balancing
  - Disadvantage: complex implementation, may hurt data locality

Example Speedup Results

- The speed ratio over the best sequential run



Performance Considerations

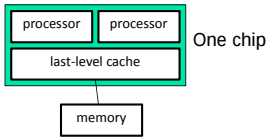
- Load balancing
- Synchronizations
  - your application synchronization and synchronization in the OS
- Memory bandwidth
  - is the performance bounded by reading from the memory?
- I/O
  - is the performance bounded by reading from the storage?
- Data locality
  - cache-efficient algorithms (block-based computation)
- Contention on shared resources

Multicore Architecture

- Last-level cache becomes a significant part of the chip

⇨ Multicore: add another processor core on the chip (sharing a single last-level cache)

- Low cost (manufacturing, power)



- Additional benefit: faster processor-to-processor sharing

Contention on Shared Resources

- Shared resources: cache space, memory bandwidth
- What am I not seeing the speedup I expect?
- Load balancing implication