COSC 462

Parallel Algorithms

The Design Basics

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Levels of Abstraction

Concepts	*Tools*
Algorithms: partitioning, communication, agglomeration, mapping	Domain, channel, task, locality, utilization
Messages, reductions	MPI_Reduce(), #omp reduce:+
Mutex, Semaphores, ...	lock()/unlock(), V()/P()
Atomics	compare_and_swap()
Memory coherency, transactions	vmovnrngoaps, clevict1

Example: Largest Value (sequential)

- for (**int** i=0; i<N; ++i) X[i] = rand()

  int largest = X[0]

  for (int i=1; i<N; ++i)

    if (largest < X[i])
      largest = X[i]

  printf("%d\n", largest);

- Complexity:
  - O(N) (memory accesses, comparisons)

Example: Largest Value (threaded)

- **for** (**int** i = 0; i < N; ++i) thread_create(thread_max, &X[i])

```
void thread_max(int *X) {
  lock()

  if (largest < X[0]) {
    largest = X[0]
  }
  unlock()
}
```

- Complexity
  - O(1)*num_threads (comparisons)
  - O(N) (memory accesses, locks)
- Amdahl fraction (sequential part)
  - 100%!!!
- Scaling (Gustafson)
  - Does not scale

Example: Largest Value (OpenMP)

- ```
  #pragma omp parallel for reduction(max:largest)
  for (int i=0; i<N; ++i)
    if (largest < X[i])
      largest = X[i]
  ```
- Complexity
  - O(N)/num_threads (comparisons)
  - O(N/num_threads)*num_threads (memory accesses)
- Amdahl fraction
  - s ⊖ 0% as N ⊖ ∞
  - Beware of hidden cost of reduction
- Scaling (Gustafson)
  - Good...
    - As long as reduction scales
  ```

Example: Largest Value (MPI)

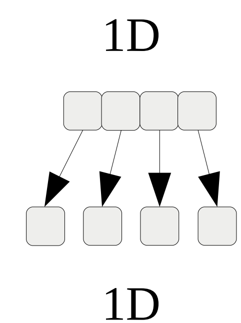
- MPI_Reduce(X, N / P, MPI_MAX)
- P = MPI::Comm::World.size
- Complexity
  - O(N) messages (no matter the implementation)
  - O(N) comparisons
  - O(N/P + log P) global time steps
- Amdahl fraction
  - s ϴ log P if P >> N
    - if P is small then N/P dominates
- Scaling (Gustafson)
  - Good
    - As long as MPI_Reduce() scales

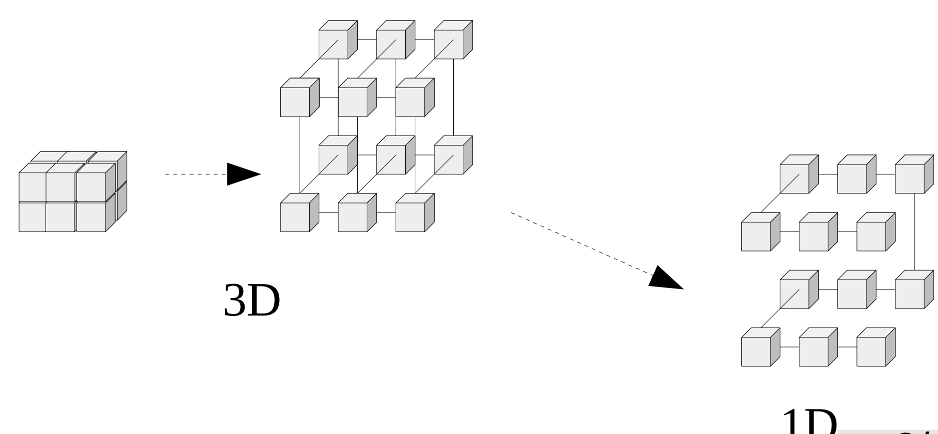
Design Methodology for Parallel Algorithms

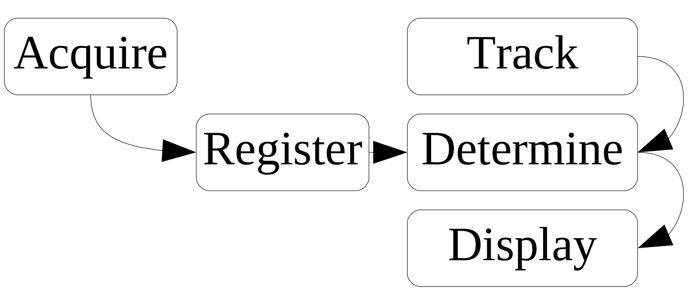
- Proposed by Ian Foster
  - In book: “Designing and Building Parallel Programs: Concepts and Tools for Parallel Software Engineering”
  - Publisher: Addison-Wesley, Reading, MA, 1995
  - Details repeated in course textbook by Micheal J. Quinn
- Principle:
  - Focus on the problem
    - Use the language of the problem, not the machine
  - Delay machine-dependent details and issues
- Design steps
  - Partitioning
  - Communication
  - Agglomeration
  - Mapping

Partitioning

- Divide computation into “small” pieces
- Approaches
  - Data-centric
  - Computation-centric
- Decompositions
  - Domain decomposition
  - Functional decomposition
- Result
  - (primitive) Tasks
  - Data items







Partitioning: Guidelines

- Have an *order of magnitude* more tasks than processors
  - Required to enough parallelism and further adjustments
- Redundant computation/storage is *minimized*
  - Important for scaling problem size
- Primitive tasks are roughly the *same size*
  - Important for load balancing
- Number of tasks is a function of problem size
  - Important for scaling the hardware with problem size
- Optimizations to keep in mind
  - Partitions (dimensionality, size) correspond (roughly) to hardware

Communication

- Communication is only necessary because of parallelism
  - It doesn't exist in sequential algorithms
- Determine communication patterns
  - Local (Small group of processes communicate)
  - Global (Most of the the processes communicate)
- Tasks communicate through channels
  - Visualize your channels to see how many you need
  - Estimate the amount of communication in the channels
- Ideally:
  - Communication is balanced
  - Communication occurs between small number of tasks
  - Communication is performed in parallel
  - Computation is performed in parallel
    - Good: {compute() ; send()} || {compute();receive()}
    - Bad: {compute(); send()} || {receive(); compute()}

Agglomeration

- Primitive tasks are grouped (agglomerated) to achieve:
  - Better performance
    - Lower communication overhead (bandwidth)
    - Smaller number of messages (latency due to message startup)
  - Simpler code
- Guiding principle: maintain (or increase) locality
  - Locality minimizes or eliminates communication
- Example agglomeration targets
  - Data dimensions
    - Merge dimension(s) for example use 1D instead of 2D
  - Channels with excessive communication

Agglomeration Guidelines

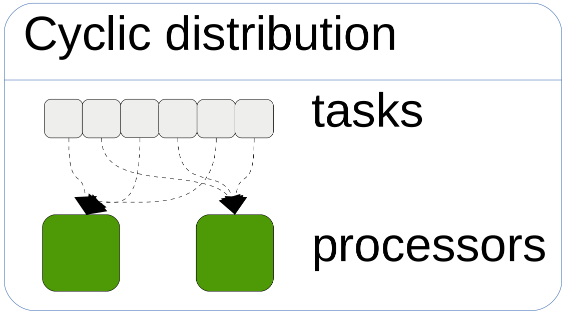
- Increase *locality* as much as possible
- *Replicated computation* must be shorter than communication it replaced
- The partitioning must still scales
  - Tasks and their data are still small enough
- Agglomerated tasks are similar (for load balancing) in terms of:
  - Computation
  - Communication
- Number of agglomerated tasks is a function of the global problem size:
  - Tasks = f(size)
- Number of agglomerated tasks is small but as large as number of processors:
  - Tasks > Processors
- The existing sequential code can be used for agglomerated tasks (with minimal modifications)

Mapping

- Mapping assigns tasks to processors
  - This should optimize for the the hardware
- Increase processor utilization
  - Processors should run in parallel
  - Processors should compute for (roughly) the same amount of time between communication exchanges
- Decrease communication
  - If a channel is mapped to the same processor, the communication through that channel may be removed
  - Make communication local
    - Channels should connect close groups of processors
- Often, finding optimal mapping is NP-hard
  - Many mapping problems can be reduced to graph coloring

Mapping: Decision Tree

- The number of tasks is **static**
  - The communication pattern **structured**
    - Roughly *constant* computation time per task
      - Agglomerate to minimize communication
      - One task per processor
    - Computation time per task *varies* by region
      - Cyclically map tasks to processors to balance communication load



  - The communication pattern is **unstructured**
    - Use static load balancing
- The number of tasks is **dynamic**
  - *Frequent* communication between tasks
    - Use dynamic load balancing
  - Many *short-lived* tasks and no intertask communication
    - Use a runtime task-scheduling

Mapping: Checklist

- Consider both designs:
  - One task per processor
  - Multiple tasks per processor
- Consider both task-processor allocations:
  - Static
  - Dynamic
- For dynamic task-processor allocation:
  - Ensure task allocation/management is not a bottleneck
- For static task-processor allocation:
  - Have an order of magnitude more tasks than processors

Back to "Largest Value" Example