Distributed Memory Parallel Programming and MPI

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Parallel Programming Model

- Shared memory
  - Writes to a shared location are visible to all
- Distributed memory
  - No shared memory; data is partitioned and must be shared through explicit communication (message passing)
- Problems
  - Additional challenges to programmers: explicit communications, data partitioning
  - Slower inter-process communications
- Why distributed memory parallel programming?

Why Distributed Memory Parallel Programming?

- Less requirement on hardware support
  - cluster of machines connected by commodity network
  - more scalable (multiprocessor cache-coherence at large scale is expensive and difficult to build)
- No worry of multiprocessor memory consistency
  - no memory consistency-related errors
- More portable
  - can run on shared memory multiprocessors
  - can run on hybrid distributed/shared-memory platforms
- Better locality of parallel programs
  - programmer knows her/his program best

Parallel Programming Steps

Converting a sequential application to a parallel one

- Decompose into tasks
  - Also partition the data
- Assign tasks to processors
  - Also assign data to processors
- Orchestrate data access and synchronization
  - Also orchestrate message passing

Message Passing Interface

- De facto standard programming interface for message passing-based parallel programs
- You write a single program, multiple copies of which will run on multiple processors
  - Assumption: all processes do mostly similar things
  - Different parts distinguish through process ID
- Communications
  - Point-to-point: send/receive
  - Group communications: broadcast, gather, scatter, reduce, barrier
- It is a programming interface, not an implementation specification!

MPI Send/Receive

```
int MPI_Send(void *buf, int count, MPI_Datatype datatype, int dest, int tag, …);

int MPI_Recv(void *buf, int count, MPI_Datatype datatype, int source, int tag, …);
```

- Matching send/receive:
  - Process x sends a message to process y
  - Process y receives a message from process x

```
for (i = 0; i < nprocs; i++)
    if (i != me) {
        MPI_Send(&d, 1, MPI_INT, i, tag, MPI_COMM_WORLD);
    }

for (i = 1; i < nprocs; i++) {
    MPI_Recv(&d, 1, MPI_INT, MPI_ANY_SOURCE, tag, MPI_COMM_WORLD, &status);
}
```


MPI Send/Receive

Alternative send/receive modes:

- Nonblocking receive
- Nonblocking send
- Synchronous send
- … … … …

MPI Group Communications

- Barrier
  - All processes wait until all have arrived
- Broadcast
  - One process (root) sends a message to be received by others
- Reduce
  - A function (MAX, SUM, …) is applied to data supplied by all processes; result is returned at one process (root)
  - Function is evaluated following process rank order
  - Can be optimized if associative and/or commutative
- … … … …
- Can operate in a sub-set of processes
  - Customized MPI communicator

Performance Issues

- Load balance
  - dynamic task assignment difficult, why?
  - ⇨ careful data partition and task assignment

Performance Issues

- Synchronization/communication wait
  - ⇨ block as late as possible
  - ⇨ Receive as late as you can, use nonblocking Receive when you can

Performance Issues

- Long communication latency (vs. high bandwidth)
  - our Ethernet cluster: 250us latency, 80MB/sec bandwidth if 1KB per synchronization, effective bandwidth is 4MB/sec
  - ⇨ synchronize/wait as few times as possible

Performance Issues

- Group communication lead to group wait
  - ⇨ only when necessary, on smallest group necessary

Deadlocks

- Why does my MPI program get stuck?
- Possible reasons
  - Group communications are not called by all in the group
  - Receive without a matching send
  - Matching send for a receive cannot be reached
    - Receive before Send
    - Send before Receive; but Send blocked by insufficient buffer space
  - … … … …
- Debugging
  - First find out where each process is blocked at
  - How does it conflict with design? What's wrong with implementation?

Parallel Programming Example: Successive Over Relaxation

- SOR implements a mathematical model for many natural phenomena, e.g., heat dissipation, ocean currents
- Given a 2D grid of data, for some number of iterations:
  - For each internal grid point, compute average of its four neighbors

```
for (i=1; i<n; i++)
   for (j=1; j<n; j++)
      temp[i][j] = 0.25 * (grid[i-1][j]+grid[i+1][j]+grid[i][j-1]+grid[i][j+1]);
for( i=1; i<n; i++)
   for( j=1; j<n; j++)
      grid[i][j] = temp[i][j];
```


Parallel Programming Example: Successive Over Relaxation

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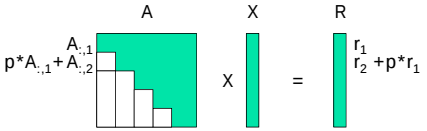
```

- Task decomposition and data partitioning:
  - 1D partitioning: each process manages some columns or rows
  - 2D partitioning: each process manages a 2D block of the grid
- Message passing:
  - Pass messages on boundary data
  - Send to all neighbors before receiving
- 1D or 2D partitioning?
- Nonblocking send/receive as much as possible

Gaussian Elimination

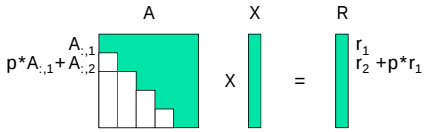
- Reduce an equation matrix into an equivalent upper-diagonal matrix
- Partial pivoting to maintain numerical stability



- Task decomposition and data partitioning:
- Communication/synchronization in row partitioning
  - Find the maximum pivot, distribute the major row
- Communication/synchronization in column partitioning
  - Distribute the major column

Gaussian Elimination

- Reduce an equation matrix into an equivalent upper-diagonal matrix
- Partial pivoting to maintain numerical stability



- Task decomposition and data partitioning:
  - Block vs. cyclic partitioning?

I/O for Parallel Programs

- Reading/writing large amount of data from/to storage
  - Parallel processes read a large matrix of data
  - Parallel processes write output statistics
- Using a dedicated I/O process
  - All I/O is issued at the dedicated I/O process; other processes communicate with the I/O process for I/O
  - Problem: scalability

MPI-I/O

- Often, each process reads/writes from/to a distinct file/data partition
- MPI-I/O
  - providing data structures to partition data, using standard interface to ease programming (file view, displacement, …)
  - http://www.mpi-forum.org/docs/mpi-3.0/mpi30-report.pdf (Sec 13.3)
  - limitation: not very helpful for accessing irregular data structures (sparse matrices)