Outline

• Overview
• Theoretical background
• Parallel computing systems
• Parallel programming models
• MPI/OpenMP examples
OVERVIEW
What is Parallel Computing?

- Parallel computing: use of multiple processors or computers working together on a common task.
  - Each processor works on part of the problem
  - Processors can exchange information
Paradigm #1: Data parallelism

- The program models a physical object, which gets partitioned and divided over the processors.
Paradigm #2: Task parallelism

- There is a list of tasks (for instance runs of a small program) and processors cycle through this list until it is exhausted.
- Tasks can be partially ordered: Directed Acyclic Graph
Why Do Parallel Computing?

• Limits of single CPU computing
  – performance
  – available memory

• Parallel computing allows one to:
  – solve problems that don’t fit on a single CPU
  – solve problems that can’t be solved in a reasonable time

• We can solve...
  – larger problems
  – faster
  – more cases
THEORETICAL BACKGROUND
Speedup & Parallel Efficiency

- **Speedup**: 
  
  \[ S_p = \frac{T_s}{T_p} \]

  - \( p \) = # of processors
  - \( T_s \) = execution time of the sequential algorithm
  - \( T_p \) = execution time of the parallel algorithm with \( p \) processors
  - \( S_p = p \) (linear speedup: ideal)

- **Parallel efficiency**

  \[ E_p = \frac{S_p}{p} = \frac{T_s}{pT_p} \]
Limits of Parallel Computing

• Theoretical Upper Limits
  – Amdahl’s Law

• Practical Limits
  – Load balancing
  – Non-computational sections

• Other Considerations
  – time to re-write code
Amdahl’s Law

- All parallel programs contain:
  - parallel sections (we hope!)
  - serial sections (unfortunately)
- Serial sections limit the parallel effectiveness
- Amdahl’s Law states this formally
  - Effect of multiple processors on speed up
    \[ S_P \leq \frac{T_S}{T_P} = \frac{1}{f_s + \frac{f_p}{P}} \rightarrow \frac{1}{f_s}, P \rightarrow \infty \]

where
- \( f_s = \) serial fraction of code
- \( f_p = \) parallel fraction of code
- \( P = \) number of processors
Amdahl’s Law
Practical Limits: Amdahl’s Law vs. Reality

• In reality, the situation is even worse than predicted by Amdahl’s Law due to:
  – Load balancing (waiting)
  – Scheduling (shared processors or memory)
  – Cost of Communications
  – I/O
Gustafson’s Law

- Effect of multiple processors on run time of a problem with a fixed amount of parallel work per processor.

\[ S_p \times P \times (P - 1) \]

- \( \alpha \) is the fraction of non-parallelized code where the parallel work per processor is fixed (not the same as \( f_p \) from Amdahl’s)
- \( P \) is the number of processors
Comparison of Amdahl and Gustafson

Amdahl: fixed work

\[ f_p = 0.5 \]

\[
S = \frac{1}{f_s + f_p / N}
\]

\[
S_2 = \frac{1}{0.5 + 0.5 / 2} = 1.3
\]

\[
S_4 = \frac{1}{0.5 + 0.5 / 4} = 1.6
\]

Gustafson: fixed work per processor

\[ = 0.5 \]

\[
S_p \times (P - 1)
\]

\[
S_2 \times 2 \times (2 - 1) = 1.5
\]

\[
S_4 \times 4 + 0.5 \times (4 - 1) = 2.5
\]
Scaling: Strong vs. Weak

- We want to know how quickly we can complete analysis on a particular data set by increasing the PE count
  - Amdahl’s Law
  - Known as “strong scaling”

- We want to know if we can analyze more data in approximately the same amount of time by increasing the PE count
  - Gustafson’s Law
  - Known as “weak scaling”
PARALLEL SYSTEMS
“Old school” hardware classification

<table>
<thead>
<tr>
<th></th>
<th>Single Instruction</th>
<th>Multiple Instruction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Data</td>
<td>SISD</td>
<td>MISD</td>
</tr>
<tr>
<td>Multiple Data</td>
<td>SIMD</td>
<td>MIMD</td>
</tr>
</tbody>
</table>

**SISD**  No parallelism in either instruction or data streams (mainframes)

**SIMD**  Exploit data parallelism (stream processors, GPUs)

**MISD**  doesn’t really exist

**MIMD**  Multiple instructions operating independently on multiple data streams (most modern general purpose computers)
Hardware in parallel computing

Memory access

• Shared memory
  – SGI Altix
  – Cluster nodes

• Distributed memory
  – Uniprocessor clusters

• Hybrid
  – Multi-processor clusters
  – Processor with co-processor (GPU)
  – Cluster with multiple co-processors (Stampede!)

Processor type

• Single core CPU
  – Intel Xeon (Prestonia, Wallatin)
  – AMD Opteron (Sledgehammer, Venus)
  – IBM POWER (3, 4)

• Multi-core CPU (since 2005)
  – Intel Xeon (Paxville, Woodcrest, Harpertown...)
  – AMD Opteron (Barcelona, Shanghai, Istanbul,...)
  – IBM POWER (5, 6...)

• GPU based
  – Tesla systems
Shared and distributed memory

- All processors have access to a pool of shared memory
- Access times vary from CPU to CPU in NUMA systems
- Example: SGI Altix, IBM P5 nodes
- Memory is local to each processor
- Data exchange by message passing over a network
- Example: Clusters with single-socket blades
Hybrid systems

- A limited number, N, of processors have access to a common pool of shared memory

- To use more than N processors requires data exchange over a network

- Example: Cluster with multi-socket blades
Multi-core systems

- Extension of hybrid model

- Communication details increasingly complex
  - Cache access
  - Main memory access
  - Quick Path / Hyper Transport socket connections
  - Node to node connection via network
Co-processor Systems

- Calculations made in both CPUs and co-processors (GPU, MIC)
- No longer limited to single precision calculations
- Load balancing critical for performance
- Requires specific libraries and compilers (GPU: CUDA, OpenCL, MIC: OpenMP)
PROGRAMMING MODELS
Parallel programming models

• Data Parallelism
  – Each processor performs the same task on different data

• Task Parallelism
  – Each processor performs a different task on different data

• Most applications fall between these two
Single Program Multiple Data

• SPMD: dominant programming model for shared and distributed memory machines.
  – One source code is written
  – Code can have conditional execution based on which processor is executing the copy
  – All copies of code start simultaneously and communicate and sync with each other periodically

• MPMD: more general, and possible in hardware, but no system/programming software enables it
SPMD Model

```
source.c
```

- processor 0
- processor 1
- processor 2
- processor 3

Network
Data Parallel Programming Example

- One code will run on 2 CPUs
- Program has array of data to be operated on by 2 CPUs so array is split into two parts.

```plaintext
program:
...  
if CPU=a then 
    low_limit=1
    upper_limit=50
elseif CPU=b then 
    low_limit=51
    upper_limit=100
end if
do I = low_limit, upper_limit
    work on A(I)
end do
... 
end program
```

```plaintext
program:
... 
low_limit=1
upper_limit=50
do I= low_limit, upper_limit
    work on A(I)
end do
... 
end program
```

```plaintext
program:
... 
low_limit=51
upper_limit=100
do I= low_limit, upper_limit
    work on A(I)
end do
... 
end program
```
Distributed Data Parallel Programming

- Since each CPU has local address space: local indexing only

```
program:
  ...
  low_limit=1
  upper_limit=50
  do I= low_limit, upper_limit
     work on A(I-low_limit)
  end do
  ...
end program
```

```
program:
  ...
  low_limit=51
  upper_limit=100
  do I= low_limit, upper_limit
     work on A(I-low_limit)
  end do
  ...
end program
```
Task Parallel Programming Example

- One code will run on 2 CPUs
- Program has 2 tasks (a and b) to be done by 2 CPUs

```
program.f:
  ...
  initialize
  ...
  if CPU=a then
    do task a
  elseif CPU=b then
    do task b
  end if
  ...
  end program
```

```
CPU A
program.f:
  ...
  initialize
  ...
  do task a
  ...
  end program
```

```
CPU B
program.f:
  ...
  initialize
  ...
  do task b
  ...
  end program
```
Shared Memory Programming: OpenMP

- Shared memory systems (SMPs, cc-NUMAs) have a single address space:
  - applications can be developed in which loop iterations (with no dependencies) are executed by different processors
  - shared memory codes are mostly data parallel, ‘SPMD’ kinds of codes
  - OpenMP is the standard for shared memory programming (compiler directives)
  - Vendors offer native compiler directives
Accessing Shared Variables

• If multiple processors want to write to a shared variable at the same time, there could be conflicts:
  – Process 1 and 2
  – read X
  – compute X+1
  – write X

• Programmer, language, and/or architecture must provide ways of resolving conflicts
OpenMP Example #1: Parallel Loop

```c
!$OMP PARALLEL DO
    do i=1,128
        b(i) = a(i) + c(i)
    end do
!$OMP END PARALLEL DO
```

- The first directive specifies that the loop immediately following should be executed in parallel.

- The second directive specifies the end of the parallel section (optional).

- For codes that spend the majority of their time executing the content of simple loops, the PARALLEL DO directive can result in significant parallel performance.
OpenMP Example #2: Private Variables

```c
!$OMP PARALLEL DO SHARED(A,B,C,N) PRIVATE(I,TEMP)
do I=1,N
   TEMP = A(I)/B(I)
   C(I) = TEMP + SQRT(TEMP)
end do
!$OMP END PARALLEL DO
```

- In this loop, each processor needs its own private copy of the variable TEMP.
- If TEMP were shared, the result would be unpredictable since multiple processors would be writing to the same memory location.
Distributed Memory Programming: MPI

• Distributed memory systems have separate address spaces for each processor
  – Local memory accessed faster than remote memory
  – Data must be manually decomposed
  – MPI is the standard for distributed memory programming (library of subprogram calls)
  – Older message passing libraries include PVM and P4; some vendors have native libraries such as SHMEM (T3E) and LAPI (IBM)
Data Decomposition

- For distributed memory systems, the ‘whole’ grid or sum of particles is decomposed to the individual nodes
  - Each node works on its section of the problem
  - Nodes can exchange information

![Diagram of Data Decomposition](image-url)
Typical Data Decomposition

- Example: integrate 2-D propagation problem:

Starting partial differential equation:

\[
\frac{2}{t} = D \times \frac{2}{x^2} + B \times \frac{2}{y^2}
\]

Finite Difference Approximation:

\[
\frac{f_{i,j}^{n+1} - f_{i,j}^n}{t} = D \cdot \frac{f_{i+1,j}^n - f_{i,j}^n}{x^2} + B \cdot \frac{f_{i,j+1}^n - f_{i,j}^n}{y^2}
\]
MPI Example #1

• Every MPI program needs these:

```c
#include "mpi.h"
int main(int argc, char *argv[])
{
    int nPEs, iam;
    /* Initialize MPI */
    ierr = MPI_Init(&argc, &argv);
    /* How many total PEs are there */
    ierr = MPI_Comm_size(MPI_COMM_WORLD, &nPEs);
    /* What node am I (what is my rank?) */
    ierr = MPI_Comm_rank(MPI_COMM_WORLD, &iam);
    ...
    ierr = MPI_Finalize();
}
```
#include "mpi.h"

int main(int argc, char *argv[])
{
    int numprocs, myid;
    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    /* print out my rank and this run's PE size */
    printf("Hello from %d of %d\n", myid, numprocs);
    MPI_Finalize();
}

MPI Example #2
MPI: Sends and Receives

- MPI programs must send and receive data between the processors (communication)

- The most basic calls in MPI (besides the three initialization and one finalization calls) are:
  - MPI_Send
  - MPI_Recv

- These calls are blocking: the source processor issuing the send/receive cannot move to the next statement until the target processor issues the matching receive/send.
Message Passing Communication

- Processes in message passing programs communicate by passing messages
- Basic message passing primitives
  - Send (parameters list)
  - Receive (parameter list)
- Parameters depend on the library used
MPI Example #3: Send/Receive

```c
#include "mpi.h"

int main(int argc,char *argv[])
{
    int numprocs,myid,tag,source,destination,count,buffer;
    MPI_Status status;

    MPI_Init(&argc,&argv);
    MPI_Comm_size(MPI_COMM_WORLD,&numprocs);
    MPI_Comm_rank(MPI_COMM_WORLD,&myid);
    tag=1234;
    source=0;
    destination=1;
    count=1;

    if(myid == source){
        buffer=5678;
        MPI_Send(&buffer,count,MPI_INT,destination,tag,MPI_COMM_WORLD);
        printf("processor %d sent %d\n",myid,buffer);
    }
    if(myid == destination){
        MPI_Recv(&buffer,count,MPI_INT,source,tag,MPI_COMM_WORLD,&status);
        printf("processor %d got %d\n",myid,buffer);
    }
    MPI_Finalize();
}
```
Final Thoughts

• Systems with multiple shared memory nodes are becoming common for reasons of economics and engineering.

• Going forward, this means that the most practical programming paradigms to learn are
  – Pure MPI, and
  – OpenMP + MPI
Further reading

• General page: http://www.tacc.utexas.edu/~eijkhout/istc/istc.html

• Direct download: http://tinyurl.com/EijkhoutHPC