Parallel Programming Overview

- Task Parallelism
- OS support for task parallelism
- Parameter Studies
- Domain Decomposition
- Sequence Matching

Master/Slave paradigm

- Divide task into nearly parallel sub-tasks
- Start the master
- Start the slaves
- Master communicates sub-task specifications to slaves
- Slaves perform sub-tasks
- Slaves communicate results to master
- Master ensures that all results have been collected
- Shut down slaves
- Shut down master

Work Assignment

- Static scheduling
  - Divide work into n pieces which will take equal time where n is number of workers
- Dynamic scheduling
  - If tasks are of widely different sizes (times) there is a load balancing problem
  - Assign subset of sub-tasks to slaves
  - When slave finished assign another sub-task
  - Observations:
    - Still load balancing problem at end
    - Minimize by making sub-tasks small
    - If sub-tasks too small communication overhead will impact performance adversely

Unix OS Concepts for Parallel Programming

- Unix Process (task)
  - Executable code
  - Instruction pointer
  - Stack
  - Logical registers
  - Heap
  - Private address space
  - Task forking to create dependent processes – thousands of clock cycles
- Thread – “lightweight process”
  - Logical registers
  - Stack
  - Shared address space
    - Hundreds of clock cycles to create/destroy/synchronize threads

Local Process execution

- All processes children of init
- Processes spawned using fork-exec combination
- Fork creates a copy of the process
  - Differs from parent only in returned value from fork
    - 0 in child , pid of child in parent
- Exec substitute another program executable for the current program image
- If not familiar with this read 7.2.2 in book for details

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Remote Process Execution/File Access

- Rsh
- Ssh
  - Note that ssh slower due to encription
  - Ssh can do X forwarding – usually syntax to turn this off (-x)
  - Can be problems with NFS mounted file system due to all nodes trying to write .Xauthority file
- NFS
- Rcp
- Scp
- ftp/sftp
- Rdist – maintain identical copies of files across hosts
- Rsync – detect differences between files on different hosts and only transfer diffs

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Interprocess Communication with Sockets

- See section 7.2.5 in book
- Also http://www.cs.kent.edu/~farrell/sys2002/

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Parameter Studies

- Run same sequential program multiple times with different input data (parameters)
- Trivially parallel
- Common where one wants to see which set of parameters give the best approximation to known (experimental or theoretical results)
- Also where one wants to document the effects of parameters on results
  - See example in book (section 7.3) on testing compiler optimization flags

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Parallel Search

- Sequence matching in Computational Biology
  - databases of nucleotide (RNA or DNA) or amino acid sequences
  - Encoded as strings of characters
  - Information derived by matching given string exactly or approximately against large database
- Example program for matching: BLAST
  - Uses data in FASTA format
  - A program formatdb will build an indexed database from them
  - One can then use BLAST to search for similarities
    - Get list of matches and similarities

BLAST in Parallel

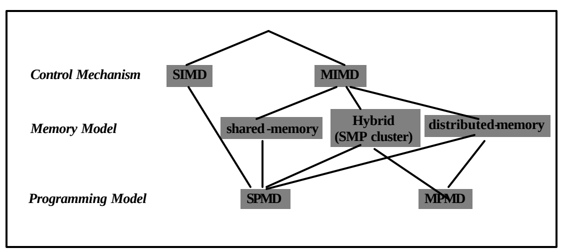
- Database can be large – 1.4 million sequences
- Use parallelism to compare all against all
- Use master/slave paradigm
  - Distribute entire db to each slave
  - Slaves run BLAST with input file of subset of db – chuck
    - Chunk sent to slave over socket
  - Slaves are persistent
  - Output of slaves copies to an output directory using scp
  - Master listens on a socket for added slaves so they can come and go
  - If slaves die they can be replaced with minimal impact
  - Master keeps track of chunk status and checkpoints so restart is possible.

Generic Parallel Programming Models

Single Program Multiple Data Stream (SPMD)
- Each CPU accesses same object code
- Same application run on different data
  - Data exchange may be handled explicitly/implicitly
- "Natural" model for SIMD machines
- Most commonly used generic parallel programming model
  - Message-passing
  - Shared-memory
- Usually uses process/task ID to differentiate
- Focus of remainder of this section

Multiple Program Multiple Data Stream (MPMD)
- Each CPU accesses different object code
- Each CPU has only data/instructions needed
- "Natural" model for MIMD machines

Parallel "Architectures" – Mapping Hardware Models to Programming Models



Methods of Problem Decomposition for Parallel Programming

Want to map (Problem + Algorithms + Data) to Architecture

Conceptualize mapping via e.g., pseudocode

Realize mapping via programming language

- Data Decomposition - data parallel program
  - Each processor performs the same task on different data
  - Example - grid problems
- Task (Functional) Decomposition - task parallel program
  - Each processor performs a different task
  - Example - signal processing – adding/subtracting frequencies from spectrum
- Other Decomposition methods

Categories of Parallel Problems

Generic Parallel Problem “Architectures” (after G Fox)

- Ideally Parallel (Embarrassingly Parallel, “Job-Level Parallel”)
  - Same application run on different data
  - Could be run on separate machines
  - Example: Parameter Studies
- Almost Ideally Parallel
  - Similar to Ideal case, but with “minimum” coordination required
  - Example: Linear Monte Carlo calculations, integrals
- Pipeline Parallelism
  - Problem divided into tasks that have to be completed sequentially
  - Can be transformed into partially sequential tasks
  - Example: DSP filtering
- Synchronous Parallelism
  - Each operation performed on all/most of data
  - Operations depend on results of prior operations
  - All processes must be synchronized at regular points
  - Example: Modeling Atmospheric Dynamics
- Loosely Synchronous Parallelism
  - similar to Synchronous case, but with “minimum” intermittent data sharing
  - Example: Modeling Diffusion of contaminants through groundwater

Designing and Building Parallel Applications

Attributes of Parallel Algorithms

- Concurrency - Many actions performed “simultaneously”
- Modularity - Decomposition of complex entities into simpler components
- Locality - Want high ratio of of local memory access to remote memory access
- Usually want to minimize communication/computation ratio
- Performance
  - Measures of algorithmic “efficiency”
    - Execution time
    - Complexity usually ~ Execution Time
    - Scalability

Designing and Building Parallel Applications

Partitioning - ***Break down main task into smaller ones – either identical or “disjoint”.***

Communication phase ***- Determine communication patterns for task coordination, communication algorithms.***

Agglomeration - ***Evaluate task and/or communication structures wrt performance and implementation costs. Tasks may be combined to improve performance or reduce communication costs.***

Mapping - ***Tasks assigned to processors; maximize processor utilization, minimize communication costs. Mapping may be either static or dynamic.***

May have to iterate whole process until satisfied with expected performance

- Consider writing application in parallel, using either SPMD message-passing or shared-memory
- Implementation (software & hardware) may require revisit, additonal refinement or re-design

Designing and Building Parallel Applications

Partitioning
- – Geometric or Physical decomposition (Domain Decomposition) - partition <u>data</u> associated with problem
- – Functional (task) decomposition – partition into disjoint <u>tasks</u> associated with problem
- – Divide and Conquer – partition problem into two simpler problems of approximately equivalent "size" – iterate to produce set of indivisible sub-problems

Generic Parallel Programming Software Systems

Message-Passing
- – Local tasks, each encapsulating local data
- – Explicit data exchange
- – Supports both SPMD and MPMD
- – Supports both task and data decomposition
- – Most commonly used
- – Process-based, but for performance, processes should be running on separate CPUs
- – Example API: MPI, PVM Message-Passing libraries
- – <u>MP systems, in particular, MPI, will be focus of remainder of workshop</u>

Data Parallel
- – Usually SPMD
- – Supports data decomposition
- – Data mapping to cpus may be either implicit/explicit
- – Example: HPF compiler

Shared-Memory
- – Tasks share common address space
- – No explicit transfer of data - supports both task and data decomposition
- – Can be SPMD, MPMD
- – Thread-based, but for performance, threads should be running on separate CPUs
- – Example API : OpenMP, Pthreads

Hybrid - **Combination of Message-Passing and Shared-Memory - supports both task and data decomposition**
- – Example: OpenMP + MPI

Programming Methodologies - Practical Aspects

Bulk of parallel programs written in Fortran, C, or C++
- **Generally, best compiler, tool support for parallel program development**

Bulk of parallel programs use Message-Passing with MPI
- **Performance, portability, mature compilers, libraries for parallel program development**

Data and/or tasks are split up onto different processors by:
- **Distributing the data/tasks onto different CPUs, each with local memory (MPPs,MPI)**
- **Distribute work of each loop to different CPUs (SMPs,OpenMP, Pthreads)**
- **Hybrid - distribute data onto SMPs and then within each SMP distribute work of each loop (or task) to different CPUs within the box (SMP-Cluster, MPI&OpenMP, LAM)**

Typical Data Decomposition for Parallelism

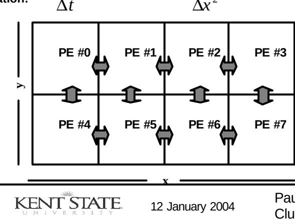
Example: Solve 2-D Wave Equation:

Original partial differential equation:

$$\frac{\partial \Psi}{\partial t} = D \cdot \frac{\partial^2 \Psi}{\partial x^2} + B \cdot \frac{\partial^2 \Psi}{\partial y^2}$$

Finite Difference Approximation:

$$\frac{f_i^{n+1} - f_i^n}{\Delta t} = D \cdot \frac{f_{i+1,j}^n - 2 f_{i,j}^n - f_{i-1,j}^n}{\Delta x^2} + B \cdot \frac{f_{i,j+1}^n - 2 f_{i,j}^n - f_{i,j-1}^n}{\Delta y^2}$$



Sending Data Between CPUs

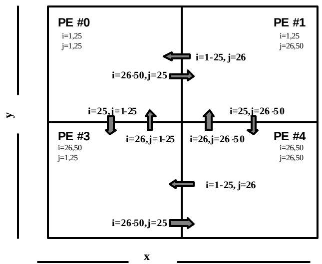
Finite Difference Approximation:

$$\frac{f_i^{n+1} - f_i^{n}}{\Delta t} = D \cdot \frac{f_{i+1,j}^{n} - 2f_{i,j}^{n} - f_{i-1,j}^{n}}{\Delta x^2} + B \cdot \frac{f_{i,j+1}^{n} - 2f_{i,j}^{n} - f_{i,j-1}^{n}}{\Delta y^2}$$

Sample Pseudo Code

```
if (taskid =0) then
 li = 1
 ui = 25
 lj = 1
 uj = 25
 send(1:25)=f(25,1:25)
elseif (taskid =1)then
....
elseif (taskid =2) then
...
elseif(taskid=3) then
...
end if

do j = lj,uj
  do i = li,ui
    work on f(i,j)
  end do
end do
```



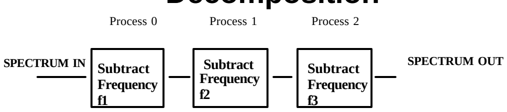
Basics of Task Parallel Decomposition - SPMD

Same program will run on 2 different CPUs
Task decomposition analysis has defined 2 tasks (a and b) to be done by 2 CPUs

```
program.f
…
initialize
…
if TaskID=A then
   do task a
elseifTaskID=B then
   do task b
end if
….
end program
```

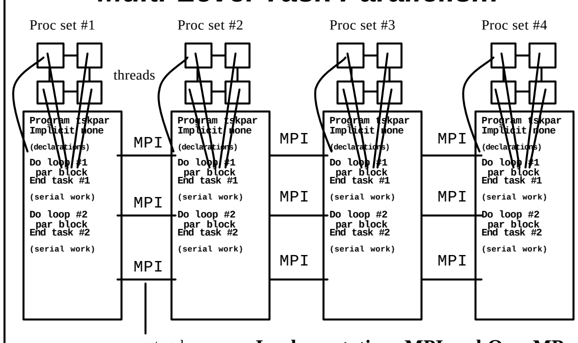
Task A Execution Stream	Task B Execution Stream
program.f … Initialize … do **task a** … end program	program.f … Initialize … do **task b** … end program

Typical Task Parallel Decomposition



- **Signal processing**
  - Use one processor for each independent task
  - Can use more processors if one is overloaded

Multi-Level Task Parallelism



Implementation: MPI and OpenMP

Parallel Application Performance Concepts

- Parallel Speedup
- Parallel Efficiency
- Parallel Overhead
- Limits on Parallel Performance

Parallel Application Performance Concepts

- Parallel Speedup - ratio of best sequential time to parallel execution time
  - $S(n) = ts/tp$
- Parallel Efficiency - fraction of time processors in use
  - $E(n) = ts/(tp*n) = S(n)/n$
- Parallel Overhead
  - Communication time (Message-Passing)
  - Process creation/synchronization (MP)
  - Extra code to support parallelism, such as Load Balancing
  - Thread creation/coordination time (SMP)
- Limits on Parallel Performance

Limits of Parallel Computing

- Theoretical upper limits
  - Amdahl's Law
  - Gustafson's Law
- Practical limits
  - Communication overhead
  - Synchronization overhead
  - Extra operations necessary for parallel version
- Other Considerations
  - Time used to re-write (existing) code

Parallel Computing - Theoretical Performance Upper Limits

- All parallel programs contain:
  - Parallel sections
  - Serial sections

Serial sections limit the parallel performance

Amdahl's Law provides a theoretical upper limit on parallel performance for <u>size-constant</u> problems

Amdahl's Law

- **Amdahl's Law places a strict limit on the speedup that can be realized by using multiple processors**
  - Effect of multiple processors on run time for <u>size -constant problems</u>
  - Effect of multiple processors on parallel speedup, S:

$$t_n = \left(f_p / N + f_s\right) t_1$$

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

  - Where
    - fs = serial fraction of code
    - fp = parallel fraction of code
    - N = number of processors
    - t1 = sequential execution time

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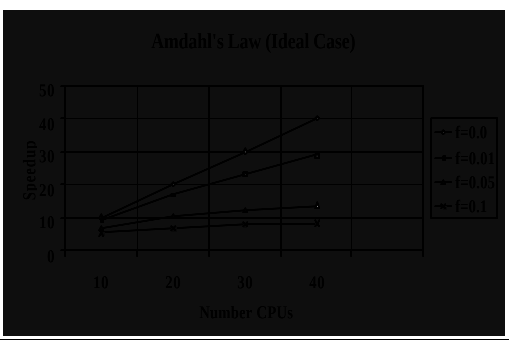
Amdahl's Law



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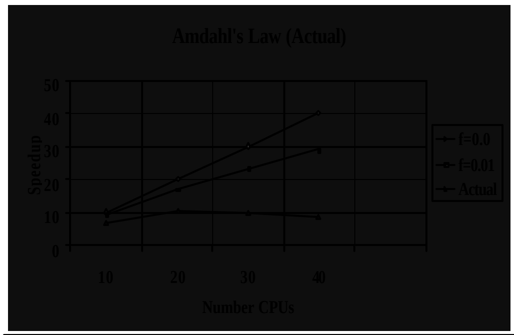
Amdahl's Law (Continued)



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Gustafson's Law

Consider scaling problem size as processor count increased

Ts = serial execution time

Tp(N,W) = parallel execution time for same problem, size <u>W</u>, on <u>N</u> CPUs

S(N,W) = Speedup on problem size W, N CPUs

S(N,W) = (Ts + Tp(1,W))/(Ts + Tp(N,W))

Consider case where Tp(N,W) ~ W*W/N

S(N,W) -> (N*Ts + N*W*W)/(N*Ts + W*W) -> N

Gustafson's Law provides some hope for parallel applications to deliver on the promise.

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Parallel Programming Analysis - Example

Consider solving 2-D Poisson's equation by iterative method on a regular grid with M points –

$$u_{i,j}^{k+1} = c_1 \cdot u_{i,j}^{k} - c_2 (u_{i,j-1}^{k} + u_{i-1,j}^{k} + u_{i,j+1}^{k} + u_{i+1,j}^{k})$$

$t_C =$ time to perform a floating-point computation - addition, multiply

$T_{serial} =$ time to do serial iteration update $= 8 \cdot M \cdot t_C$

$$T_{parallel} = 6 \cdot \frac{M}{N} \cdot t_C + (t_L + \frac{\sqrt{M}}{\sqrt{N}} t_D) + 2 \cdot \frac{M}{N} t_C + \mathit{ln}[N(t_C + t_L + t_D)]$$