CS 267 Applications of Parallel Computers

Lecture 3: Introduction to Parallel Architectures and Programming Models

Jim Demmel

http://www.cs.berkeley.edu/~demmel/cs267_Spr99

Recap of Last Lecture

- The actual performance of a simple program can be a complicated function of the architecture
- Slight changes in the architecture or program may change the performance significantly
- Since we want to write fast programs, we must take the architecture into account, even on uniprocessors
- Since the actual performance is so complicated, we need simple models to help us design efficient algorithms
- We illustrated with a common technique for improving cache performance, called blocking, applied to matrix multiplication
  - Blocking works for many architectures, but choosing the blocksize depends on the architecture

Outline

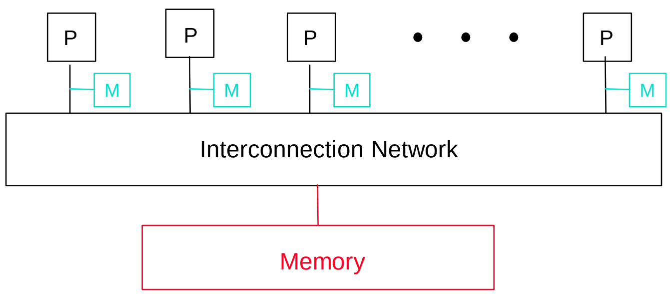
° Parallel machines and programming models

° Steps in writing a parallel program

° Cost modeling and performance trade-offs

Parallel Machines and Programming Models

A generic parallel architecture



° Where does the memory go?

Parallel Programming Models

° **Control**
- how is parallelism created
- what orderings exist between operations
- how do different threads of control synchronize

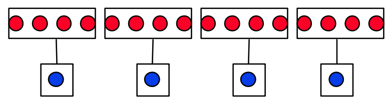
° **Naming**
- what data is private vs. shared
- how logically shared data is accessed or communicated

° **Set of operations**
- what are the basic operations
- what operations are considered to be atomic

° **Cost**
- how do we account for the cost of each of the above

Trivial Example

- $\sum_{i=0}^{n-1} f(A[i])$
- **Parallel Decomposition:**
  - Each evaluation and each partial sum is a task
- **Assign n/p numbers to each of p procs**
  - each computes independent "private" results and partial sum
  - one (or all) collects the p partial sums and computes the global sum

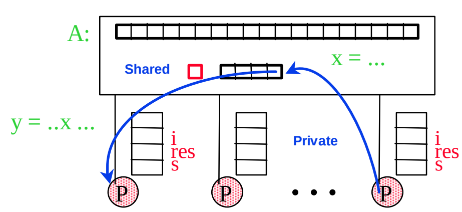


=> Classes of Data

- **Logically Shared**
  - the original n numbers, the global sum
- **Logically Private**
  - the individual function evaluations
  - what about the individual partial sums?

Programming Model 1

- **Shared Address Space**
  - program consists of a collection of threads of control,
  - each with a set of private variables
    - e.g., local variables on the stack
  - collectively with a set of shared variables
    - e.g., static variables, shared common blocks, global heap
  - threads communicate implicity by writing and reading shared variables
  - threads coordinate explicitly by synchronization operations on shared variables
    - writing and reading flags
    - locks, semaphores
- **Like concurrent programming on uniprocessor**



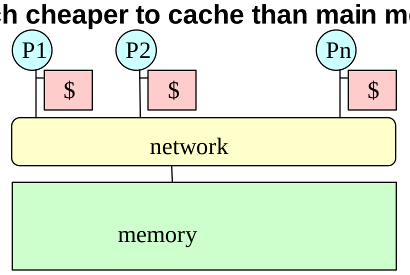
Machine Model 1

° A shared memory machine

° Processors all connected to a large shared memory

° "Local" memory is not (usually) part of the hardware
  • Sun, DEC, Intel "SMPs" (Symmetric multiprocessors) in Millennium; SGI Origin

° Cost: much cheaper to cache than main memory



° Machine model 1a: A Shared Address Space Machine
  • replace caches by local memories (in abstract machine model)
  • this affects the cost model -- repeatedly accessed data should be copied
  • Cray T3E

Shared Memory code for computing a sum

Thread 1

```
[s = 0 initially]
local_s1= 0
for i = 0, n/2-1
   local_s1 = local_s1 + f(A[i])
s = s + local_s1
```

Thread 2

```
[s = 0 initially]
local_s2 = 0
for i = n/2, n-1
   local_s2= local_s2 + f(A[i])
s = s +local_s2
```

What could go wrong?

Pitfall and solution via synchronization

° Pitfall in computing a global sum s = local_s1 + local_s2

Time ↓	Thread 1 (initially s=0)	Thread 2 (initially s=0)
	load s [from mem to reg]	
		load s [from mem to reg; initially 0]
	s = s+local_s1 [=local_s1, in reg]	s = s+local_s2 [=local_s2, in reg]
	store s [from reg to mem]	store s [from reg to mem]

° Instructions from different threads can be interleaved arbitrarily
° What can final result s stored in memory be?
° Race Condition
° Possible solution: Mutual Exclusion with Locks

Thread 1	Thread 2
lock	lock
load s	load s
s = s+local_s1	s = s+local_s2
store s	store s
unlock	unlock

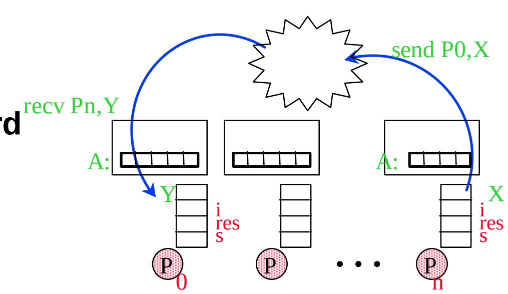
° Locks must be atomic (execute completely without interruption)

Programming Model 2

° Message Passing
- program consists of a collection of named processes
  - thread of control plus local address space
  - local variables, static variables, common blocks, heap
- processes communicate by explicit data transfers
  - matching pair of send & receive by source and dest. proc.
- coordination is implicit in every communication event
- logically shared data is partitioned over local processes

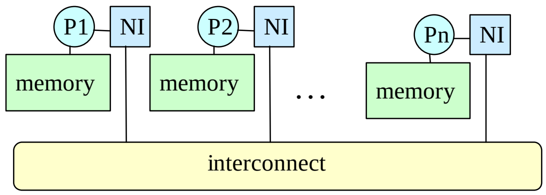
° Like distributed programming

° Program with standard libraries: MPI, PVM



Machine Model 2

- A distributed memory machine
  - Cray T3E (too!), IBM SP2, NOW, Millennium
- Processors all connected to own memory (and caches)
  - cannot directly access another processor's memory
- Each "node" has a network interface (NI)
  - all communication and synchronization done through this



Computing s = x(1)+x(2) on each processor

- First possible solution

Processor 1

```
send xlocal, proc2
    [xlocal = x(1)]
receive xremote, proc2
s = xlocal + xremote
```

Processor 2

```
receive xremote, proc1
send xlocal, proc1
    [xlocal = x(2)]
s = xlocal + xremote
```

- Second possible solution - what could go wrong?

Processor 1

```
send xlocal, proc2
    [xlocal = x(1)]
receive xremote, proc2
s = xlocal + xremote
```

Processor 2

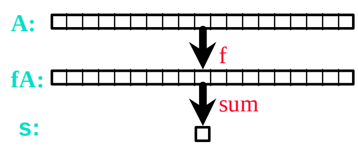
```
send xlocal, proc1
    [xlocal = x(2)]
receive xremote, proc1
s = xlocal + xremote
```

- What if send/receive act like the telephone system? The post office?

Programming Model 3

- **Data Parallel**
  - Single sequential thread of control consisting of parallel operations
  - Parallel operations applied to all (or defined subset) of a data structure
  - Communication is implicit in parallel operators and "shifted" data structures
  - Elegant and easy to understand and reason about
  - Not all problems fit this model
- **Like marching in a regiment**

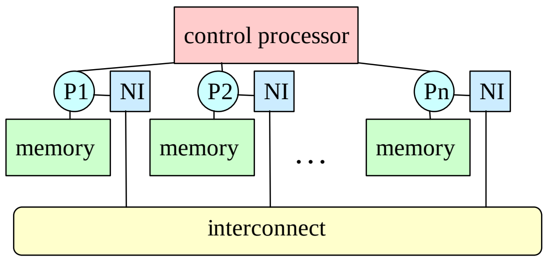
A = array of all data
fA = f(A)
s = sum(fA)



- **Think of Matlab**

Machine Model 3

- An SIMD (Single Instruction Multiple Data) machine
- A large number of small processors
- A single "control processor" issues each instruction
  - each processor executes the same instruction
  - some processors may be turned off on any instruction



- Machines not popular (CM2), but programming model is
  - implemented by mapping n-fold parallelism to p processors
  - mostly done in the compilers (HPF = High Performance Fortran)

Machine Model 4

° Since small shared memory machines (SMPs) are the fastest commodity machine, why not build a larger machine by connecting many of them with a network?

° CLUMP = Cluster of SMPs

° Shared memory within one SMP, message passing outside

° Millennium, ASCI Red (Intel), ...

° Programming model?

- Treat machine as "flat", always use message passing, even within SMP (simple, but ignore important part of memory hierarchy)
- Expose two layers: shared memory and message passing (higher performance, but ugly to program)

Programming Model 5

° Bulk synchronous

° Used within the message passing or shared memory models as a programming convention

° *Phases* separated by global barriers

- Compute phases: all operate on local data (in distributed memory)
  - or read access to global data (in shared memory)
- Communication phases: all participate in rearrangement or reduction of global data

° Generally all doing the "same thing" in a phase

- all do f, but may all do different things within f

° Simplicity of data parallelism without restrictions

Summary so far

° Historically, each parallel machine was unique, along with its programming model and programming language

° You had to throw away your software and start over with each new kind of machine - ugh

° Now we distinguish the programming model from the underlying machine, so we can write portably correct code, that runs on many machines

- MPI now the most portable option, but can be tedious

° Writing portably fast code requires tuning for the architecture

- Algorithm design challenge is to make this process easy
- Example: picking a blocksize, not rewriting whole algorithm

Steps in Writing Parallel Programs

Creating a Parallel Program

° **Pieces of the job**
- **Identify work that can be done in parallel**
- **Partition work and perhaps data among processes=threads**
- **Manage the data access, communication, synchronization**

° **Goal: maximize Speedup due to parallelism**

Speedup_{prob}(P procs) = <u>Time to solve prob with "best" sequential solution</u>
Time to solve prob in parallel on P processors

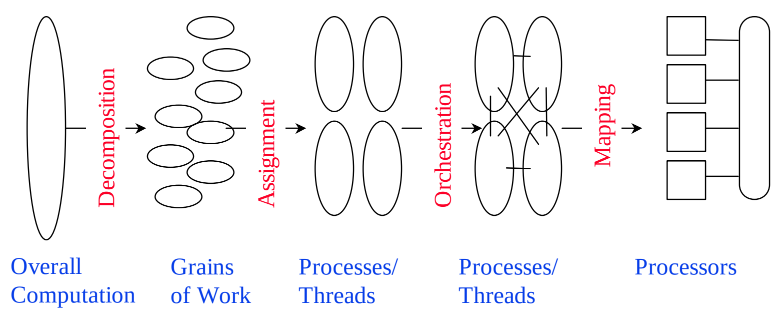
<= P (Brent's Theorem)

Efficiency(P) = Speedup(P) / P

<= 1

° Key question is when you can solve each piece
- statically, if information is known in advance
- dynamically, otherwise

Steps in the Process



° **Task:** arbitrarily defined piece of work that forms the basic unit of concurrency

° **Process/Thread:** abstract entity that performs tasks
- **tasks are assigned to threads via an assignment mechanism**
- **threads must coordinate to accomplish their collective tasks**

° **Processor:** physical entity that executes a thread

Decomposition

° **Break the overall computation into grains of work (tasks)**

- **identify concurrency and decide at what level to exploit it**
- **concurrency may be statically identifiable or may vary dynamically**
- **it may depend only on problem size, or it may depend on the particular input data**

° **Goal:** enough tasks to keep the target range of processors busy, but not too many

- **establishes upper limit on number of useful processors (i.e., scaling)**

Assignment

° **Determine mechanism to divide work among threads**

- **functional partitioning**
  - **assign logically distinct aspects of work to different threads**
    - eg pipelining
- **structural mechanisms**
  - **assign iterations of "parallel loop" according to simple rule**
    - eg proc j gets iterates j*n/p through (j+1)*n/p-1
  - **throw tasks in a bowl (task queue) and let threads feed**
- **data/domain decomposition**
  - **data describing the problem has a natural decomposition**
  - **break up the data and assign work associated with regions**
    - eg parts of physical system being simulated

° **Goal**

- **Balance the workload to keep everyone busy (all the time)**
- **Allow efficient orchestration**

Orchestration

° **Provide a means of**
- naming and accessing shared data,
- communication and coordination among threads of control

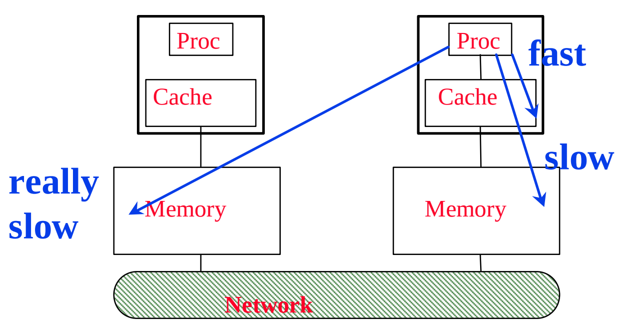
° **Goals:**
- correctness of parallel solution
  - respect the inherent dependencies within the algorithm
- avoid serialization
- reduce cost of communication, synchronization, and management
- preserve locality of data reference

Mapping

° **Binding processes to physical processors**

° **Time to reach processor across network does not depend on which processor (roughly)**
- lots of old literature on "network topology", no longer so important

° **Basic issue is how many remote accesses**



Example

- s = f(A[1]) + … + f(A[n])
- Decomposition
    - computing each f(A[j])
    - n-fold parallelism, where n may be >> p
    - computing sum s
- Assignment
    - thread k sums sk = f(A[k*n/p]) + … + f(A[(k+1)*n/p-1])
    - thread 1 sums s = s1+ … + sp (for simplicity of this example)
    - thread 1 communicates s to other threads
- Orchestration
    - starting up threads
    - communicating, synchronizing with thread 1
- Mapping
    - processor j runs thread j

Administrative Issues

- Assignment 2 will be on the home page later today
    - Matrix Multiply contest
    - Find a partner (outside of your own department)
    - Due in 2 weeks
- Lab/discussion section will be 5-6pm Tuesdays
- Reading assignment
    - www.cs.berkeley.edu/~demmel/cs267/lecture04.html
    - Optional:
        - Chapter 1 of Culler/Singh book
        - Chapters 1 and 2 of www.mcs.anl.gov/dbpp

Cost Modeling and Performance Tradeoffs

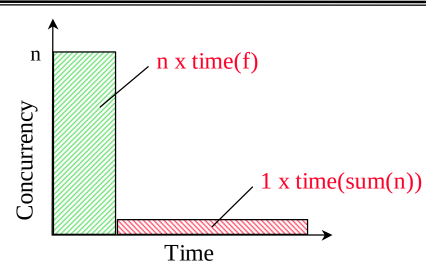
Identifying enough Concurrency

° **Parallelism profile**

- **area is total work done**

Simple Decomposition:
f (A[i]) is the parallel task

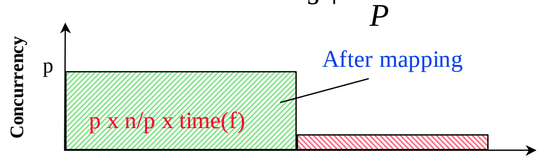
sum is sequential

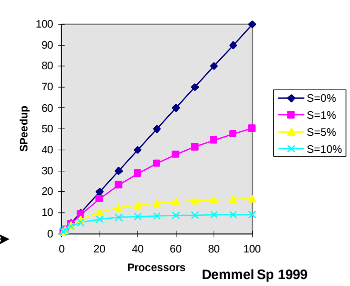


° **Amdahl's law**

- **let s be the fraction of total work done sequentially**

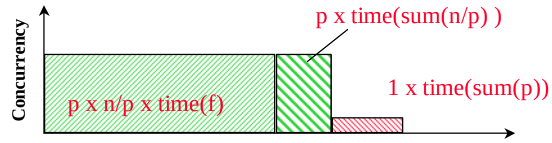
$$Speedup(P) \le \frac{1}{s + \frac{1-s}{P}} \le \frac{1}{s}$$



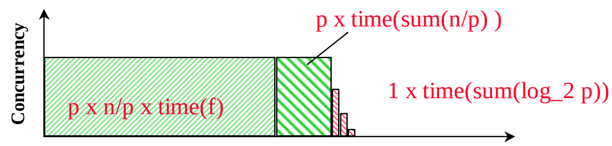


Algorithmic Trade-offs

- **Parallelize partial sum of the f's**
  - what fraction of the computation is "sequential"



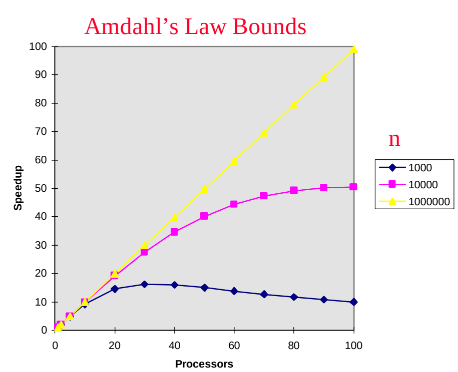
  - what does this do for communication? locality?
  - what if you sum what you "own"
- **Parallelize the final summation (tree sum)**



  - Generalize Amdahl's law for arbitrary "ideal" parallelism profile

Problem Size is Critical

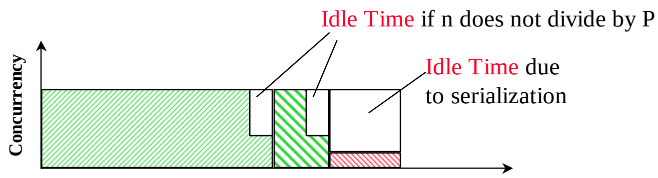
- Suppose Total work= n + P
- Serial work: P
- Parallel work: n
- s = serial fraction
  = P/ (n+P)



In general seek to exploit a fraction of the peak parallelism in the problem.

Load Balance

- Insufficient Concurrency will appear as load imbalance

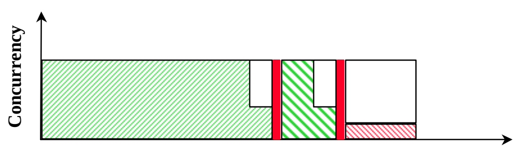


- Use of coarser grain tends to increase load imbalance.
- Poor assignment of tasks can cause load imbalance.
- Synchronization waits are instantaneous load imbalance

$$Speedup(P) \le \frac{Work(1)}{\max_p(Work(p) + idle)}$$

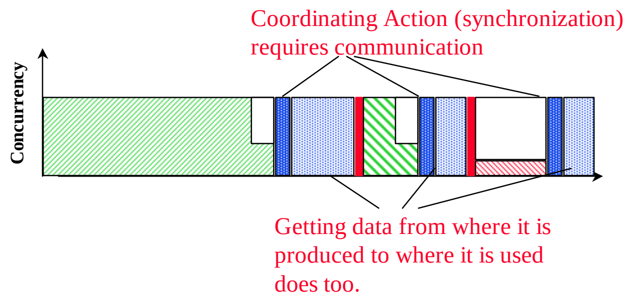
Extra Work

- There is always some amount of extra work to manage parallelism
  - e.g., to decide who is to do what



$$Speedup(P) \le \frac{Work(1)}{\mathrm{Max}_p(Work(p) + idle + extra)}$$

Communication and Synchronization

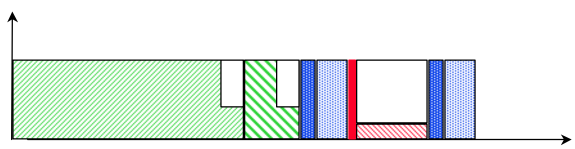


$$Speedup(P) \le \frac{Work(1)}{\max(Work(P) + idle + extra + comm)}$$

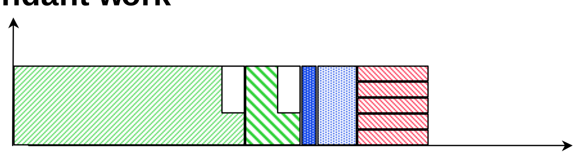
- There are many ways to reduce communication costs.

Reducing Communication Costs

- Coordinating placement of work and data to eliminate unnecessary communication



- Replicating data
- Redundant work



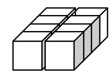
- Performing required communication efficiently
  - e.g., transfer size, contention, machine specific optimizations

The Tension

$$Speedup(P) \le \frac{Work(1)}{\max(Work(P) + idle + comm + extraWork)}$$

Minimizing one tends to increase the others

- Fine grain decomposition and flexible assignment tends to minimize load imbalance at the cost of increased communication
  - In many problems communication goes like the surface-to-volume ratio
  - Larger grain => larger transfers, fewer synchronization events
- Simple static assignment reduces extra work, but may yield load imbalance



CS267 L3 Programming Models.37 Demmel Sp 1999

The Good News

- The basic work component in the parallel program may be more efficient that in the sequential case
  - Only a small fraction of the problem fits in cache
  - Need to chop problem up into pieces and concentrate on them to get good cache performance.
  - Similar to the parallel case
  - Indeed, the best sequential program may emulate the parallel one.
- Communication can be hidden behind computation
  - May lead to better algorithms for memory hierarchies
- Parallel algorithms may lead to better serial ones
  - parallel search may explore space more effectively

CS267 L3 Programming Models.38 Demmel Sp 1999