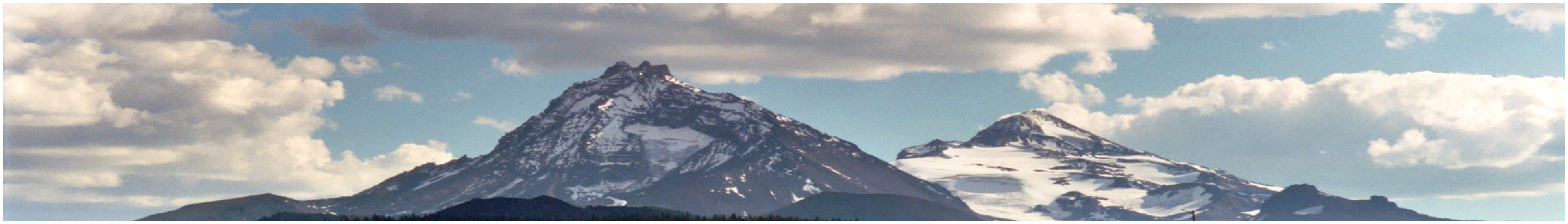


Parallel Performance Theory - 2

Parallel Computing

CIS 410/510

Department of Computer and Information Science

UNIVERSITY OF OREGON

Outline

- Scalable parallel execution
- Parallel execution models
- Isoefficiency
- Parallel machine models
- Parallel performance engineering

Scalable Parallel Computing

- Scalability in parallel architecture
  - Processor numbers
  - Memory architecture
  - Interconnection network
  - Avoid critical architecture bottlenecks
- Scalability in computational problem
  - Problem size
  - Computational algorithms
    - Computation to memory access ratio
    - Computation to communication ratio
- Parallel programming models and tools
- Performance scalability

Why Aren't Parallel Applications Scalable?

- Sequential performance
- Critical Paths
  - Dependencies between computations spread across processors
- Bottlenecks
  - One processor holds things up
- Algorithmic overhead
  - Some things just take more effort to do in parallel
- Communication overhead
  - Spending increasing proportion of time on communication
- Load Imbalance
  - Makes all processor wait for the "slowest" one
  - Dynamic behavior
- Speculative loss
  - Do A and B in parallel, but B is ultimately not needed

Critical Paths

- Long chain of dependence
  - Main limitation on performance
  - Resistance to performance improvement
- Diagnostic
  - Performance stagnates to a (relatively) fixed value
  - Critical path analysis
- Solution
  - Eliminate long chains if possible
  - Shorten chains by removing work from critical path

Bottlenecks

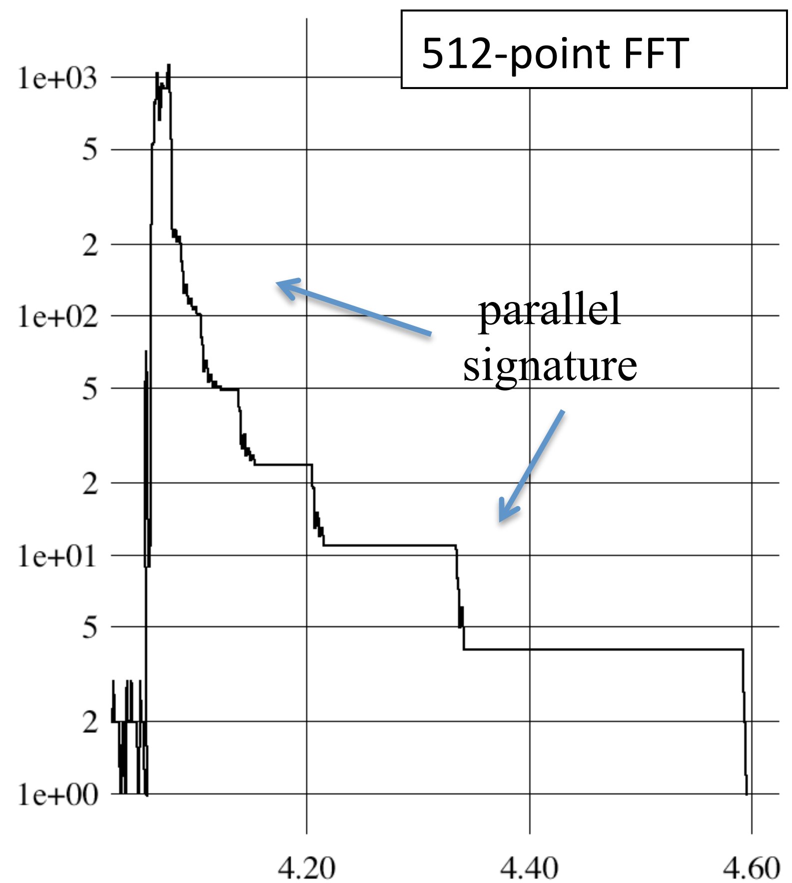
- How to detect?
  - One processor A is busy while others wait
  - Data dependency on the result produced by A
- Typical situations:
  - N-to-1 reduction / computation / 1-to-N broadcast
  - One processor assigning job in response to requests
- Solution techniques:
  - More efficient communication
  - Hierarchical schemes for master slave
- Program may not show ill effects for a long time
- Shows up when scaling

Algorithmic Overhead

- Different sequential algorithms to solve the same problem
- All parallel algorithms are sequential when run on 1 processor
- All parallel algorithms introduce addition operations (Why?)
  - *Parallel overhead*
- Where should be the starting point for a parallel algorithm?
  - Best sequential algorithm might not parallelize at all
  - Or, it doesn't parallelize well (e.g., not scalable)
- What to do?
  - Choose algorithmic variants that minimize overhead
  - Use two level algorithms
- Performance is the rub
  - Are you achieving better parallel performance?
  - Must compare with the best sequential algorithm

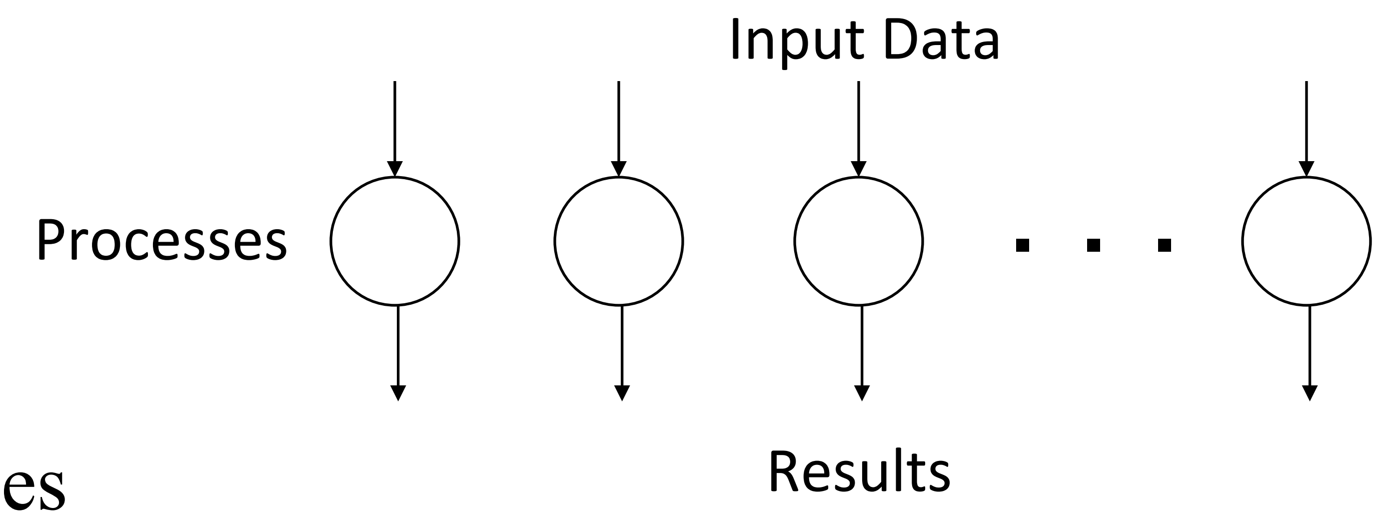
What is the maximum parallelism possible?

- Depends on application, algorithm, program
  - Data dependencies in execution
- Remember MaxPar
  - Analyzes the earliest possible "time" any data can be computed
  - Assumes a simple model for time it takes to execute instruction or go to memory
  - Result is the maximum parallelism available
- Parallelism varies!



Embarrassingly Parallel Computations

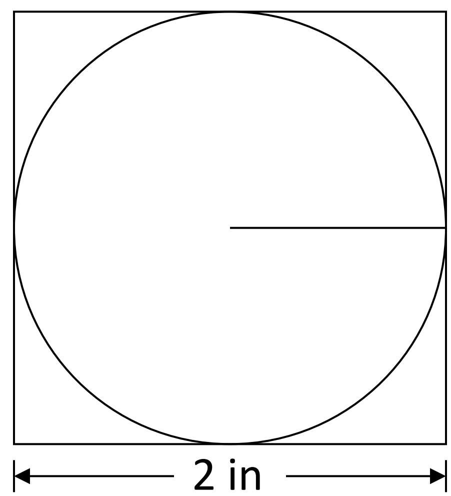
- No or very little communication between processes
- Each process can do its tasks without any interaction with other processes



- Examples
  - Numerical integration
  - Mandelbrot set
  - Monte Carlo methods

Calculating π with Monte Carlo

- Consider a circle of unit radius
- Place circle inside a square box with side of 2 in

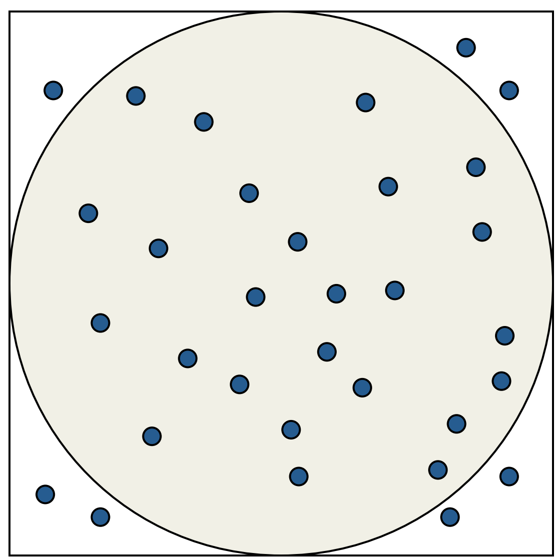


- The ratio of the circle area to the square area is:

$$\frac{\pi * 1 * 1}{2 * 2} = \frac{\pi}{4}$$

Monte Carlo Calculation of π

- Randomly choose a number of points in the square
- For each point *p*, determine if *p* is inside the circle
- The ratio of points in the circle to points in the square will give an approximation of π/4



Performance Metrics and Formulas

- T_1 is the execution time on a single processor
- T_p is the execution time on a p processor system
- $S(p)$ (S_p) is the *speedup*

$$S(p) = \frac{T_1}{T_p}$$

- $E(p)$ (E_p) is the *efficiency*

$$Efficiency = \frac{S_p}{p}$$

- $Cost(p)$ (C_p) is the *cost*

$$Cost = p \times T_p$$

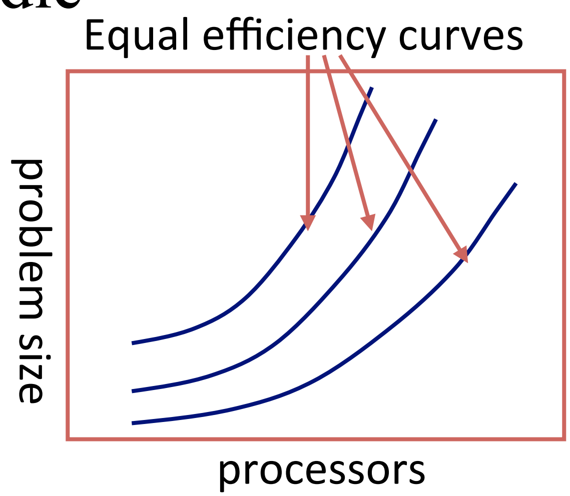
- Parallel algorithm is *cost-optimal*
  - *Parallel time = sequential time* ($C_p = T_1$, $E_p = 100\%$)

Analytical / Theoretical Techniques

- Involves simple algebraic formulas and ratios
  - Typical variables are:
    - data size (*N*), number of processors (*P*), machine constants
  - Want to model performance of individual operations, components, algorithms in terms of the above
    - be careful to characterize variations across processors
    - model them with max operators
  - Constants are important in practice
    - Use asymptotic analysis carefully
- Scalability analysis
  - Isoefficiency (Kumar)

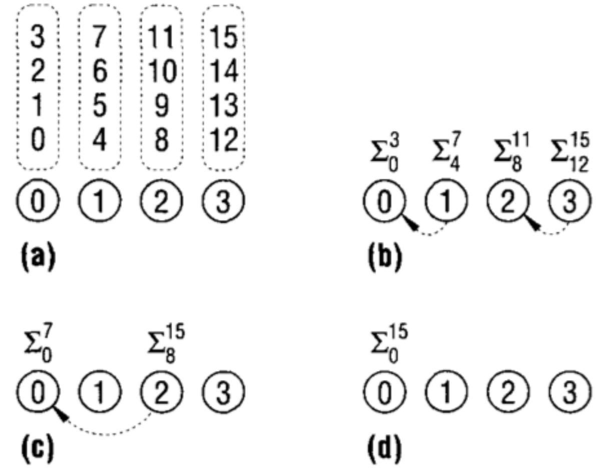
Isoefficiency

- Goal is to quantify scalability
- How much increase in problem size is needed to retain the same efficiency on a larger machine?
- Efficiency
  - $T_1 / (p * T_p)$
  - T_p = computation + communication + idle
- Isoefficiency
  - Equation for equal-efficiency curves
  - If no solution
    - problem is not scalable in the sense defined by isoefficiency
- See original paper by Kumar on webpage



Scalability of Adding n Numbers

- Scalability of a parallel system is a measure of its capacity to increase speedup with more processors
- Adding n numbers on p processors with strip partition:

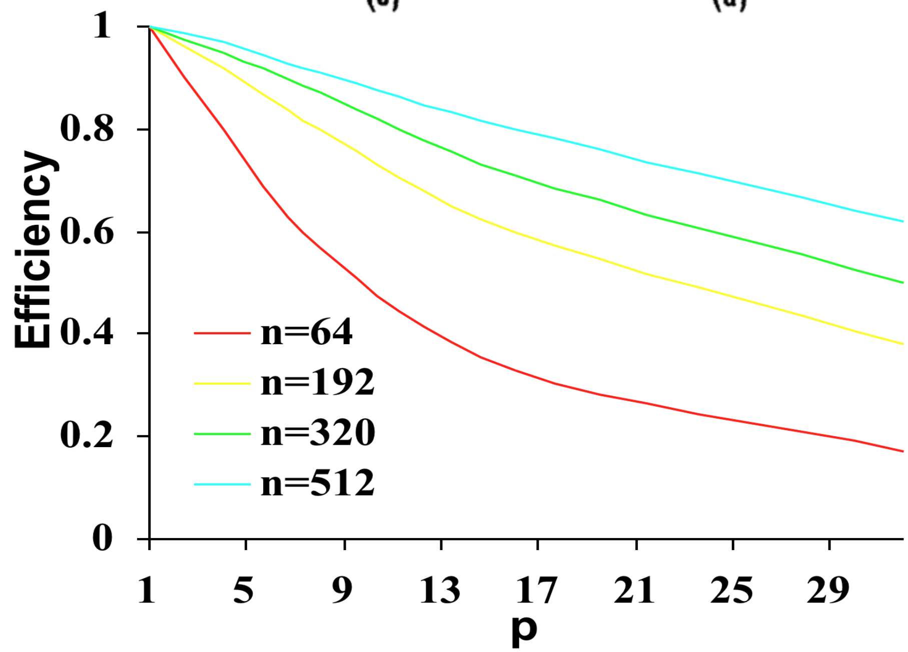


$$T_{par} = \frac{n}{p} - 1 + 2\log p$$

$$Speedup = \frac{n-1}{\frac{n}{p} - 1 + 2\log p}$$

$$\approx \frac{n}{\frac{n}{p} + 2\log p}$$

$$Efficiency = \frac{S}{p} = \frac{n}{n + 2p\log p}$$



Problem Size and Overhead

- Informally, problem size is expressed as a parameter of the input size
- A consistent definition of the size of the problem is the total number of basic operations (T_{seq})
  - Also refer to problem size as "work ($W = T_{seq}$)
- Overhead of a parallel system is defined as the part of the cost not in the best serial algorithm
- Denoted by T_O, it is a function of W and p

$$T_O(W,p) = pT_{par} - W \qquad (pT_{par} \textit{ includes overhead})$$

$$T_O(W,p) + W = pT_{par}$$

Isoefficiency Function

- With a fixed efficiency, W is as a function of p

$$T_{par} = \frac{W + T_O(W,p)}{p}$$

$W = T_{seq}$

$$Speedup = \frac{W}{T_{par}} = \frac{Wp}{W + T_O(W,p)}$$

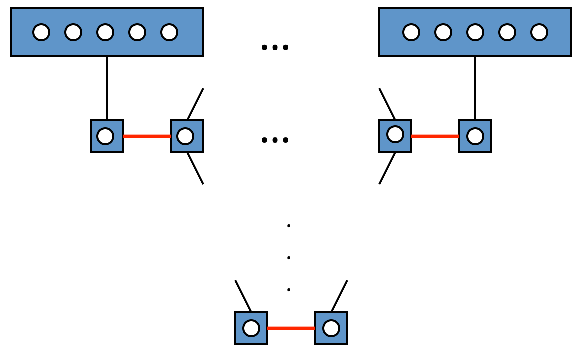
$$Efficiency = \frac{S}{p} = \frac{W}{W + T_O(W,p)} = \frac{1}{1 + \frac{T_O(W,p)}{W}}$$

$$E = \frac{1}{1 + \frac{T_O(W,p)}{W}} \rightarrow \frac{T_O(W,p)}{W} = \frac{1-E}{E}$$

$$W = \frac{E}{1-E} T_O(W,p) = KT_O(W,p)$$ Isoefficiency Function

Isoefficiency Function of Adding n Numbers

- Overhead function:
  - $T_O(W,p) = pT_{par} - W = 2p\log(p)$
- Isoefficiency function:
  - $W = K*2p\log(p)$



- If p doubles, W needs also to be doubled to roughly maintain the same efficiency
- Isoefficiency functions can be more difficult to express for more complex algorithms

More Complex Isoefficiency Functions

- A typical overhead function T_O can have several distinct terms of different orders of magnitude with respect to both p and W
- We can balance W against each term of T_O and compute the respective isoefficiency functions for individual terms
  - Keep only the term that requires the highest grow rate with respect to p
  - This is the asymptotic isoefficiency function

Isoefficiency

- Consider a parallel system with an overhead function

$$T_O = p^{3/2} + p^{3/4} W^{3/4}$$

- Using only the first term

$$W = K p^{3/2}$$

- Using only the second term

$$W = K p^{3/4} W^{3/4}$$
$$W^{1/4} = K p^{3/4}$$
$$W = K^4 p^3$$

- $K^4 p^3$ is the overall asymptotic isoefficiency function

Parallel Computation (Machine) Models

- PRAM (parallel RAM)
  - Basic parallel machine
- BSP (Bulk Synchronous Parallel)
  - Isolates regions of computation from communication
- LogP
  - Used for studying distribute memory systems
  - Focuses on the interconnection network
- Roofline
  - Based in analyzing "feeds" and "speeds"

PRAM

- Parallel Random Access Machine (PRAM)
- Shared-memory multiprocessor model
- Unlimited number of processors
  - Unlimited local memory
  - Each processor knows its ID
- Unlimited shared memory
- Inputs/outputs are placed in shared memory
- Memory cells can store an arbitrarily large integer
- Each instruction takes unit time
- Instructions are sychronized across processors (SIMD)

PRAM Complexity Measures

- For each individual processor
  - *Time*: number of instructions executed
  - *Space*: number of memory cells accessed
- PRAM machine
  - *Time*: time taken by the longest running processor
  - *Hardware*: maximum number of active processors
- Technical issues
  - How processors are activated
  - How shared memory is accessed

Processor Activation

- P_0 places the number of processors (p) in the designated shared-memory cell
  - Each active P_i, where $i < p$, starts executing
  - *O(1)* time to activate
  - All processors halt when P_0 halts

- Active processors explicitly activate additional processors via FORK instructions
  - Tree-like activation
  - *O(log p)* time to activate

PRAM is a Theoretical (Unfeasible) Model

- Interconnection network between processors and memory would require a very large amount of area
- The message-routing on the interconnection network would require time proportional to network size
- Algorithm's designers can forget the communication problems and focus their attention on the parallel computation only
- There exist algorithms simulating any PRAM algorithm on bounded degree networks
- Design general algorithms for the PRAM model and simulate them on a feasible network

Classification of PRAM Models

- *EREW* (Exclusive Read Exclusive Write)
  - No concurrent read/writes to the same memory location
- *CREW* (Concurrent Read Exclusive Write)
  - Multiple processors may read from the same global memory location in the same instruction step
- *ERCW* (Exclusive Read Concurrent Write)
  - Concurrent writes allowed
- *CRCW* (Concurrent Read Concurrent Write)
  - Concurrent reads and writes allowed
- CRCW > (ERCW,CREW) > EREW

CRCW PRAM Models

- COMMON: all processors concurrently writing into the same address must be writing the same value
- ARBITRARY: if multiple processors concurrently write to the address, one of the competing processors is randomly chosen and its value is written into the register
- PRIORITY: if multiple processors concurrently write to the address, the processor with the highest priority succeeds in writing its value to the memory location
- COMBINING: the value stored is some combination of the values written, e.g., sum, min, or max
- COMMON-CRCW model most often used

Complexity of PRAM Algorithms

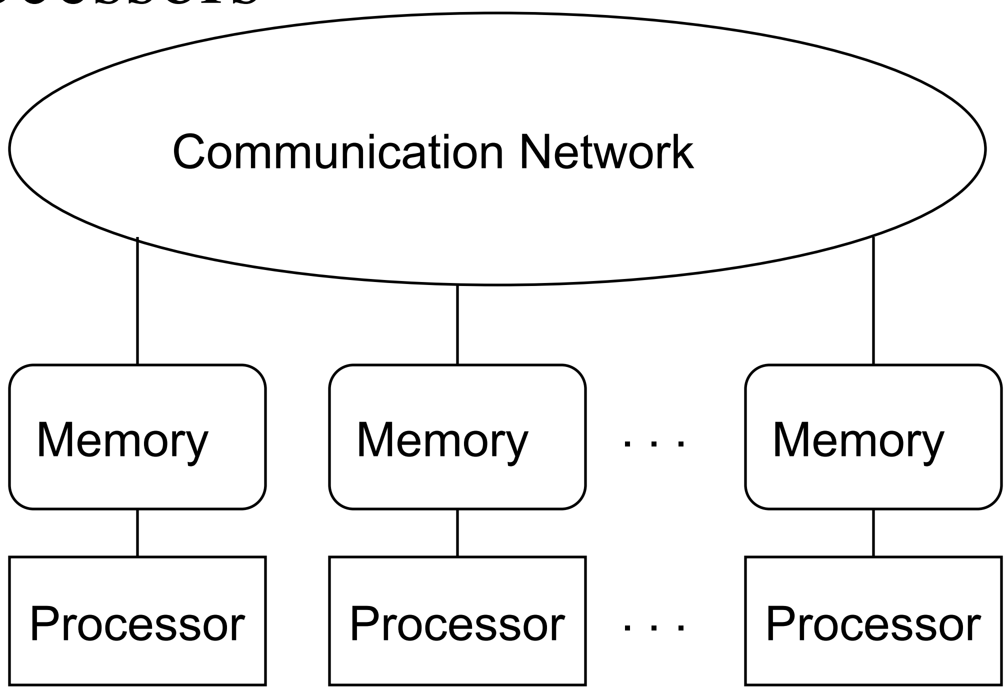
Problem / Model	EREW	CRCW
Search	O(log n)	O(1)
List Ranking	O(log n)	O(log n)
Prefix	O(log n)	O(log n)
Tree Ranking	O(log n)	O(log n)
Finding Minimum	O(log n)	O(1)

BSP Overview

- Bulk Synchronous Parallelism
- A parallel programming model
- Invented by Leslie Valiant at Harvard
- Enables performance prediction
- SPMD (Single Program Multiple Data) style
- Supports both direct memory access and message passing semantics
- BSPlib is a BSP library implemented at Oxford

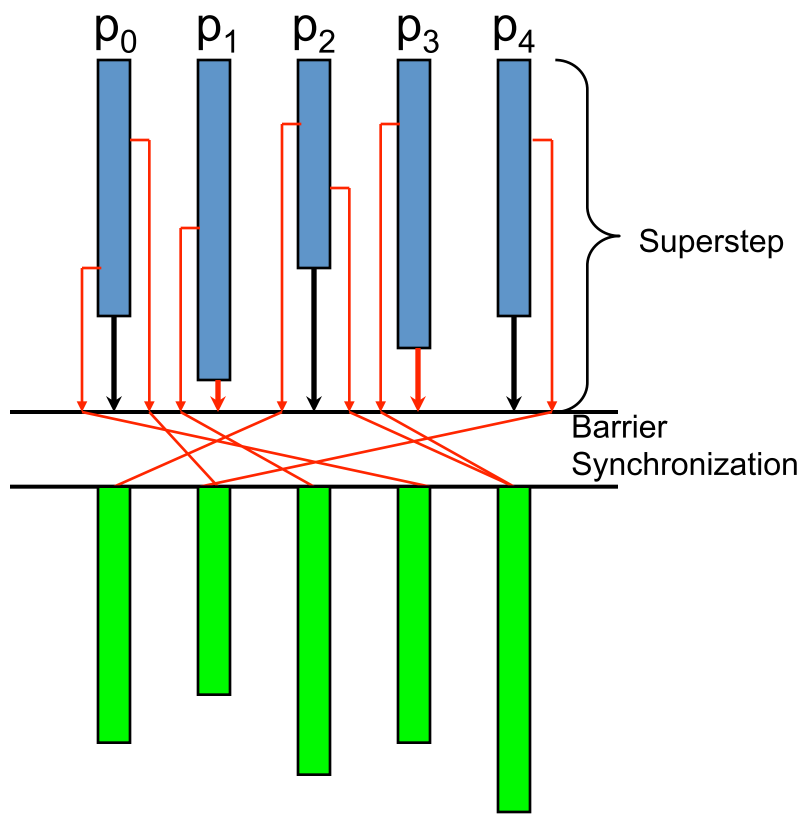
Components of BSP Computer

- A set of processor-memory pairs
- A communication point-to-point network
- A mechanism for efficient barrier synchronization of all processors



BSP Supersteps

- A BSP computation consists of a sequence of *supersteps*
- In each superstep, processes execute computations using locally available data, and issue communication requests
- Processes synchronized at the end of the superstep, at which all communications issued have been completed



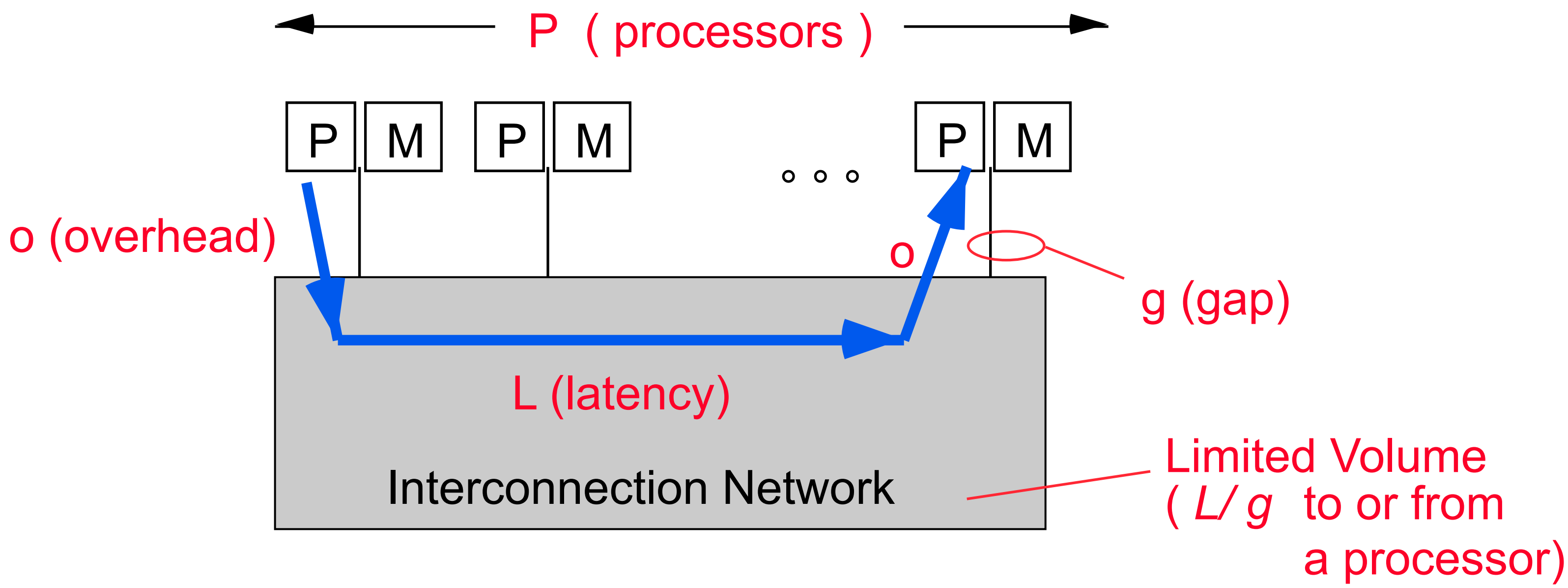
BSP Performance Model Parameters

- p = number of processors
- l = barrier latency, cost of achieving barrier synchronization
- g = communication cost per word
- s = processor speed
- l, g, and s are measured in FLOPS
- Any processor sends and receives at most h messages in a single superstep (called h-relation communication)
- Time for a superstep = max number of local operations performed by any one processor + $g*h + l$

The LogP Model (Culler, Berkeley)

- Processing
  - Powerful microprocessor, large DRAM, cache => P
- Communication
  - Significant latency (100's of cycles) => L
  - Limited bandwidth (1 – 5% of memory) => g
  - Significant overhead (10's – 100's of cycles) => o
    - on both ends
    - no consensus on topology
    - should not exploit structure
  - Limited capacity
- No consensus on programming model
  - Should not enforce one

LogP



- Latency in sending a (small) mesage between modules
- overhead felt by the processor on sending or receiving message
- gap between successive sends or receives (1/BW)
- Processors

LogP "Philosophy"

- Think about:
  - Mapping of N words onto P processors
  - Computation within a processor
    - its cost and balance
  - Communication between processors
    - its cost and balance
- Characterize processor and network performance
- Do not think about what happens in the network
- This should be enough

Typical Values for g and l

	p	g	l
Multiprocessor Sun	2-4	3	50-100
SGI Origin 2000	2-8	10-15	1000-4000
IBM-SP2	2-8	10	2000-5000
NOW (Network of Workstations)	2-8	40	5000-20000

Parallel Programming

- To use a scalable parallel computer, you must be able to write parallel programs
- You must understand the programming model and the programming languages, libraries, and systems software used to implement it
- Unfortunately, parallel programming is not easy

Parallel Programming: Are we having fun yet?

Source: Bernd Mohr

Parallel Programming Models

- Two general models of parallel program
  - Task parallel
    - problem is broken down into tasks to be performed
    - individual tasks are created and communicate to coordinate operations
  - Data parallel
    - problem is viewed as operations of parallel data
    - data distributed across processes and computed locally
- Characteristics of scalable parallel programs
  - Data domain decomposition to improve data locality
  - Communication and latency do not grow significantly

Shared Memory Parallel Programming

- Shared memory address space
- (Typically) easier to program
  - Implicit communication via (shared) data
  - Explicit synchronization to access data
- Programming methodology
  - Manual
    - multi-threading using standard thread libraries
  - Automatic
    - parallelizing compilers
    - OpenMP parallelism directives
  - Explicit threading (e.g. POSIX threads)

Distributed Memory Parallel Programming

- Distributed memory address space
- (Relatively) harder to program
  - Explicit data distribution
  - Explicit communication via messages
  - Explicit synchronization via messages
- Programming methodology
  - Message passing
    - plenty of libraries to chose from (MPI dominates)
    - send-receive, one-sided, active messages
  - Data parallelism

Parallel Programming: Still a Problem?

Source: Bernd Mohr

Parallel Computing and Scalability

- Scalability in parallel architecture
  - Processor numbers
  - Memory architecture
  - Interconnection network
  - Avoid critical architecture bottlenecks
- Scalability in computational problem
  - Problem size
  - Computational algorithms
    - computation to memory access ratio
    - computation to communication ratio
- Parallel programming models and tools
- Performance scalability

Parallel Performance and Complexity

- To use a scalable parallel computer well, you must write high-performance parallel programs
- To get high-performance parallel programs, you must understand and optimize performance for the combination of programming model, algorithm, language, platform, …
- Unfortunately, parallel performance measurement, analysis and optimization can be an easy process
- Parallel performance is complex

Parallel Performance Evaluation

- Study of performance in parallel systems
  - Models and behaviors
  - Evaluative techniques
- Evaluation methodologies
  - Analytical modeling and statistical modeling
  - Simulation-based modeling
  - Empirical measurement, analysis, and modeling
- Purposes
  - Planning
  - Diagnosis
  - Tuning

Parallel Performance Engineering and Productivity

- Scalable, optimized applications deliver HPC promise
- Optimization through *performance engineering* process
  - Understand performance complexity and inefficiencies
  - Tune application to run optimally on high-end machines
- How to make the process more effective and productive?
- What performance technology should be used?
  - Performance technology part of larger environment
  - Programmability, reusability, portability, robustness
  - Application development and optimization productivity
- Process, performance technology, and its use will change as parallel systems evolve
- Goal is to deliver effective performance with high productivity value now and in the future

Motivation

- Parallel / distributed systems are complex
  - Four layers
    - application
      - algorithm, data structures
    - parallel programming interface / middleware
      - compiler, parallel libraries, communication, synchronization
    - operating system
      - process and memory management, IO
    - hardware
      - CPU, memory, network
- Mapping/interaction between different layers

Performance Factors

- Factors which determine a program's performance are complex, interrelated, and sometimes hidden
- Application related factors
  - Algorithms dataset sizes, task granularity, memory usage patterns, load balancing. I/O communication patterns
- Hardware related factors
  - Processor architecture, memory hierarchy, I/O network
- Software related factors
  - Operating system, compiler/preprocessor, communication protocols, libraries

Utilization of Computational Resources

- Resources can be under-utilized or used inefficiently
  - Identifying these circumstances can give clues to where performance problems exist
- Resources may be "virtual"
  - Not actually a physical resource (e.g., thread, process)
- Performance analysis tools are essential to optimizing an application's performance
  - Can assist you in understanding what your program is "really doing"
  - May provide suggestions how program performance should be improved

Performance Analysis and Tuning: The Basics

- Most important goal of performance tuning is to reduce a program's wall clock execution time
  - Iterative process to optimize efficiency
  - Efficiency is a relationship of execution time
- So, where does the time go?
- Find your program's hot spots and eliminate the bottlenecks in them
  - ***Hot spot***: an area of code within the program that uses a disproportionately high amount of processor time
  - ***Bottleneck*** : an area of code within the program that uses processor resources inefficiently and therefore causes unnecessary delays
- Understand *what*, *where*, and *how* time is being spent

Sequential Performance

- Sequential performance is all about:
  - How time is distributed
  - What resources are used where and when
- "Sequential" factors
  - Computation
    - choosing the right algorithm is important
    - compilers can help
  - Memory systems and cache and memory
    - more difficult to assess and determine effects
    - modeling can help
  - Input / output

Parallel Performance

- Parallel performance is about sequential performance AND parallel interactions
  - Sequential performance is the performance within each thread of execution
  - "Parallel" factors lead to overheads
    - concurrency (threading, processes)
    - interprocess communication (message passing)
    - synchronization (both explicit and implicit)
  - Parallel interactions also lead to parallelism inefficiency
    - load imbalances

Sequential Performance Tuning

- Sequential performance tuning is a *time-driven* process
- Find the thing that takes the most time and make it take less time (i.e., make it more efficient)
- May lead to program restructuring
  - Changes in data storage and structure
  - Rearrangement of tasks and operations
- May look for opportunities for better resource utilization
  - Cache management is a big one
  - Locality, locality, locality!
  - Virtual memory management may also pay off
- May look for opportunities for better processor usage

Parallel Performance Tuning

- In contrast to sequential performance tuning, parallel performance tuning might be described as *conflict-driven* or *interaction-driven*
- Find the points of parallel interactions and determine the overheads associated with them
- Overheads can be the cost of performing the interactions
  - Transfer of data
  - Extra operations to implement coordination
- Overheads also include time spent waiting
  - Lack of work
  - Waiting for dependency to be satisfied

Interesting Performance Phenomena

- Superlinear speedup
  - Speedup in parallel execution is greater than linear
  - $S_p > p$
  - How can this happen?
- Need to keep in mind the relationship of performance and resource usage
- Computation time (i.e., real work) is not simply a linear distribution to parallel threads of execution
- Resource utilization thresholds can lead to performance inflections

Parallel Performance Engineering Process