Lecture 26: Performance Models for Distributed Memory Parallel Computing

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Overview

- Simple model of communication – s+rn
- LogP – adding overhead
- LogGP – adding long messages
- Hop Count – approximating contention (among other things)

Simple Model Of Communication – Two Parties

- T = s+rn model
  - T = latency + length / bandwidth
  - s = latency
  - r = 1/bandwidth
- On modern HPC systems, latency is 1-10usec and bandwidths are 0.1 to 10 GB/sec

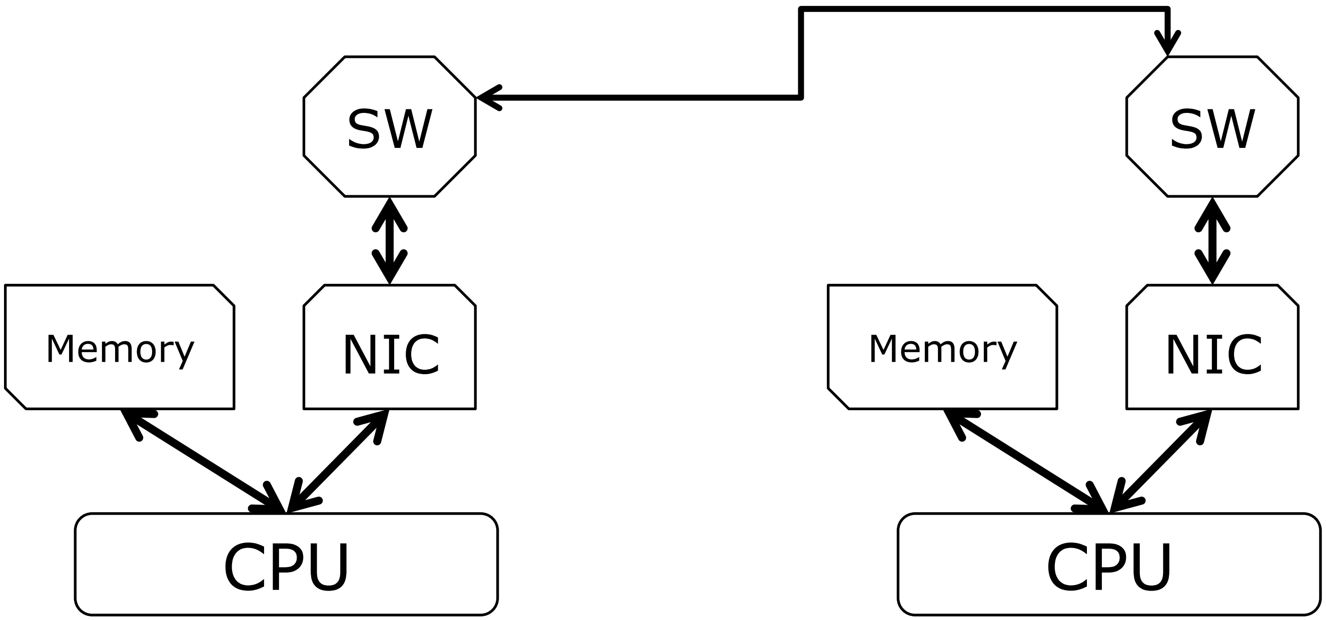
What Does s Contain?

- All costs for a short message to be sent from user program to user program
  - ♦ Including data that describes message
    - $s = s_0 + rn_e$, n_e = size of message "envelope"
- Can have separate parameter values for different cases:
  - ♦ Programming models (e.g., due to semantics of operations, such as required copies)
  - ♦ Implementations (quality of implementation)
  - ♦ Networks within a single machine
    - Intrachip, intranode, internode

What Does r Contain?

- r is 1/minimum of rate along path
  - That is, the achieved rate is limited by the slowest part of the path from one process to another
- r includes contributions from
  - Software to move data at each end, e.g., the rate at which software can feed the hardware
  - Hardware along each link, e.g., the rate that data moves along the wires or fibers

Contributions to r

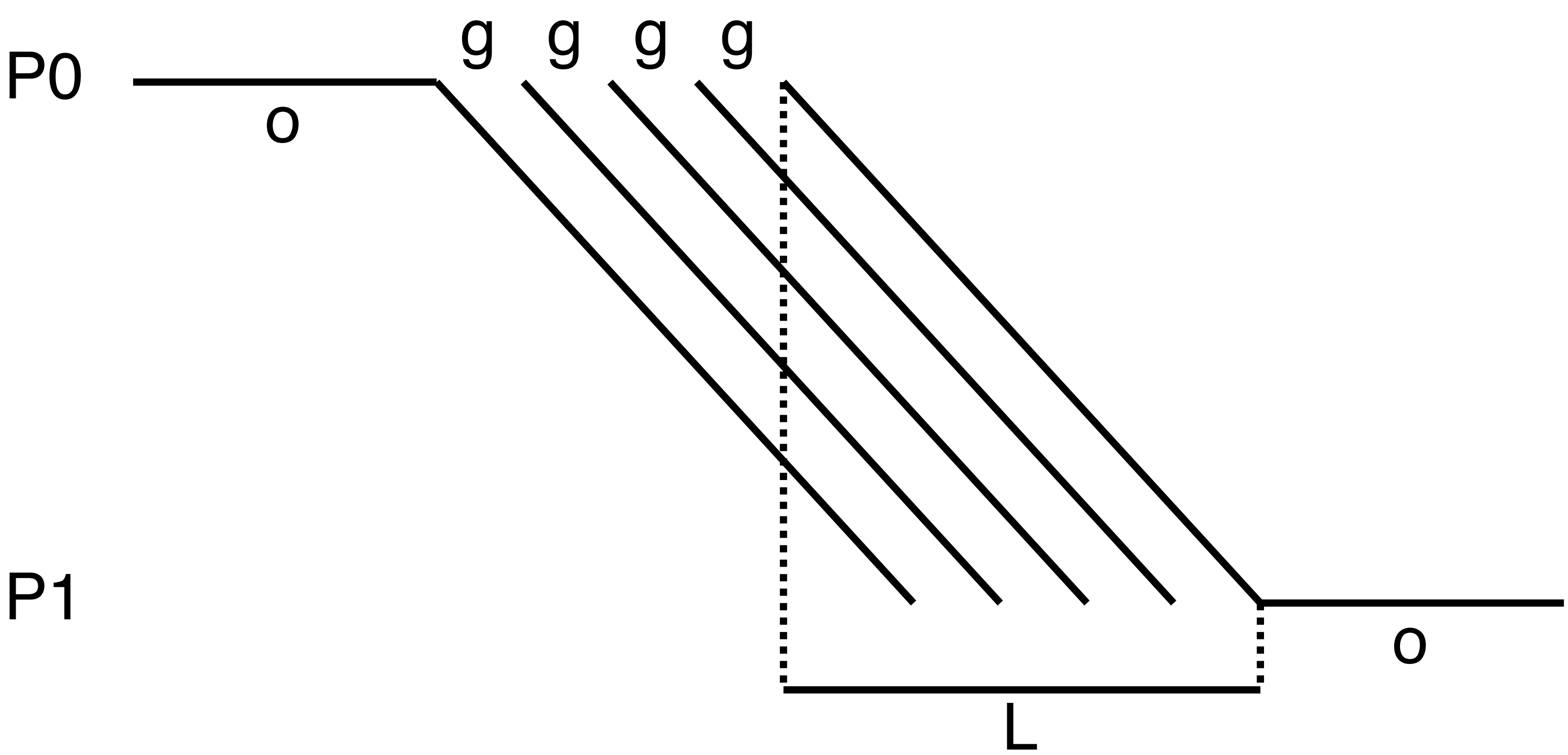


- Example path of data from one node to another

Improving the Model: LogP

- Represent time as separate components:
  - Latency (hardware)
  - overhead (software)
  - gap (inverse of bandwidth; seconds per message)
  - p (processors (nodes))
  - For analysis, measured in terms of processor cycles
- All maximum times
  - Used for *analysis* – like our performance expectation; *not* intended for *prediction*

Visualizing LogP

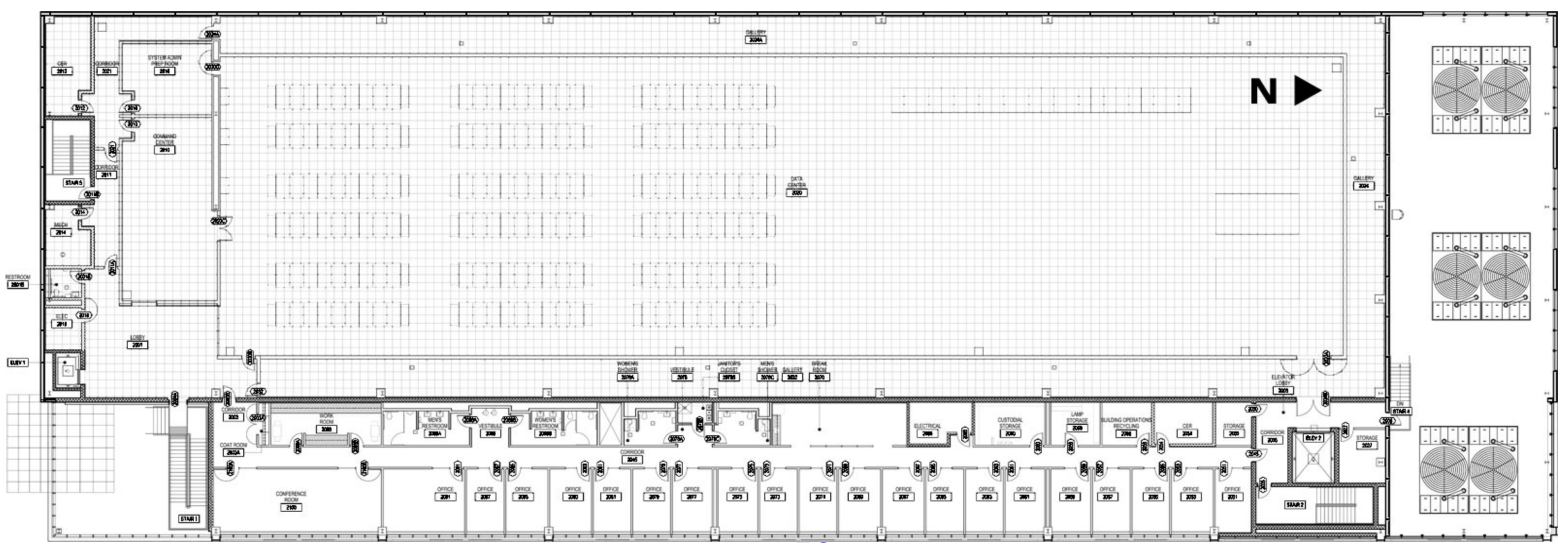


Working with LogP

- Short messages (single message packet):
  - 2o+L
- Finite capacity of network
  - Ceil(L/g) messages in transit between any pair of nodes
- Long messages
  - Pipeline of depth L with rate g and overhead o (at each end)
    - Depth L because it takes L units of time for message to travel through network and one message every g units of time. You'd like g = 1, but it might not.

Why Separate Latency and Overhead?

- Latency is Hardware – including time for data to traverse network
  - ♦ Question: What is the difference in distance (measured in clock cycles) between close and far nodes in large machine like BW?
  - ♦ Some facts:
    - Speed of light is about 30cm/nanosecond
    - Large systems are O(10,000) sq ft



One Answer

- Nearby nodes are less than 15cm apart
  - For 2GHz clock, that is 1 clock cycle
- Far away nodes may be $2*sqrt(10,000ft^2) = 2*100ft = 2 *100*30cm = 6000cm$
- 6000cm/15cm/clock = 400 clock cycles
  - Only 0.2 usec
- Note speed of signal in wire < speed of light; distance is minimum possible rather than typical

Why Separate Latency and Overhead?

- Overhead is involvement of CPU
- Significant difference between message passing (matching) and put/get (e.g., PGAS)
  - ♦ Message passing: receiver must find matching receive in a queue of posted but unmatched receives or save information on the message in a queue of unexpected messages
  - ♦ Overhead typically scales linearly with the number of messages in the queue
    - Linear algorithms fastest when queues nearly empty

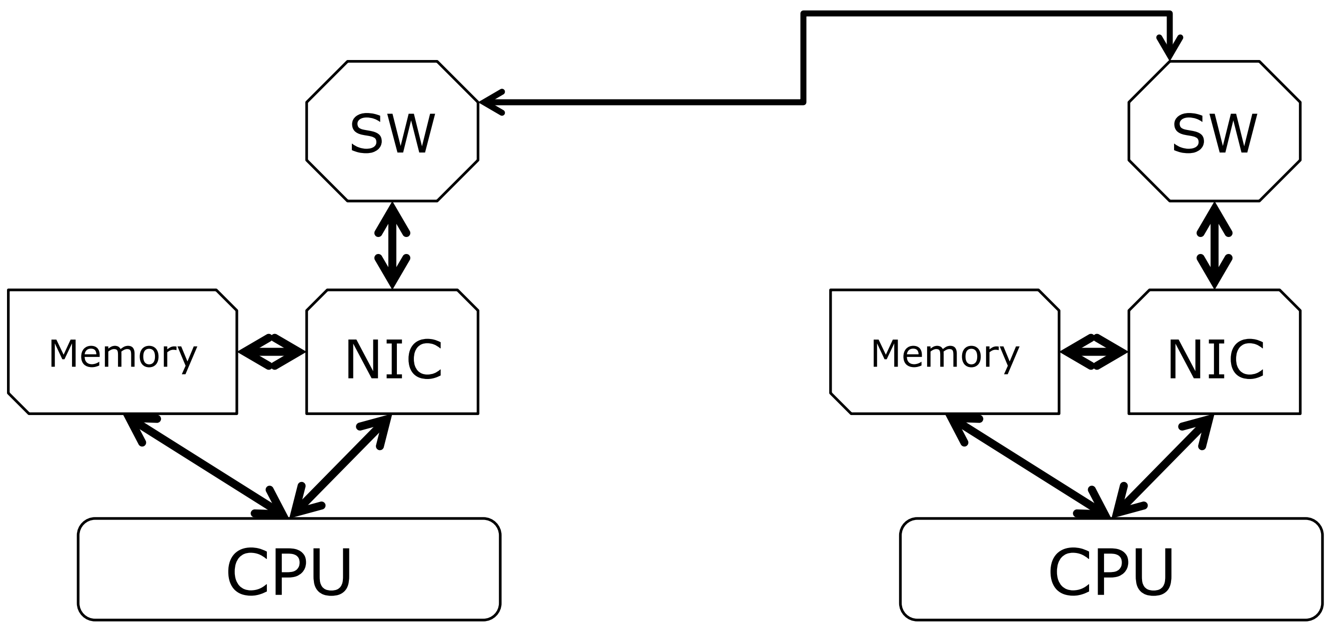
Why no Topology in LogP?

- Question for class:
  - Average distance in graph for 3D mesh and a hypercube
    - P = 1024 (time LogP paper written)
    - P = 32,768 (slightly larger than Blue Waters)
    - P = 98304 (LLNL Sequoia)
- The authors of logp contend that contention should be fixed in the network hardware (see Section 5.6 in the paper)

Average Number of Hops

Network	Average Distance	P=1024	P=32,768	P=98,304
Hypercube	½ log p	5	7.5	8.29
Butterfly	log p	10	15	16.6
4th degree Fat Tree	$2\log_4 p - 2/3$	9.33	14.3	15.9
3D Torus	$\frac{3}{4} p^{1/3}$	7.5	24	34.6
3D Mesh	$p^{1/3}$	10	32	46.2
2D Torus	$\frac{1}{2} p^{1/2}$	16	90.5	157
2D Mesh	$2/3\ p^{1/2}$	21	121	209

Contributions to r Revisited



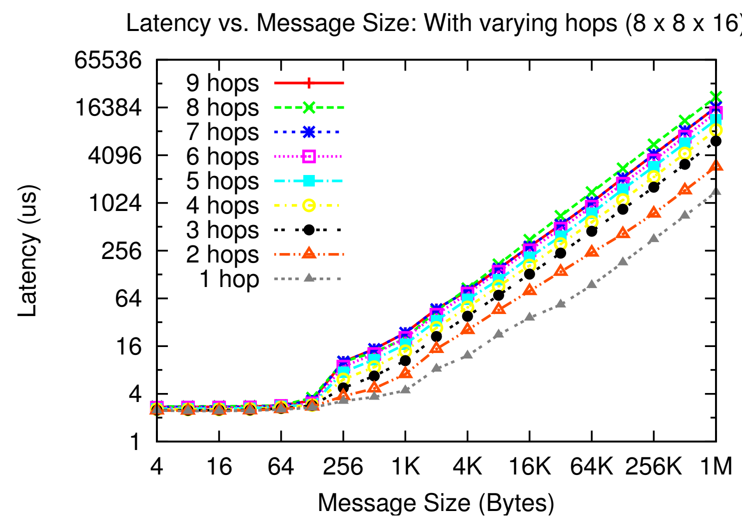
- Example path of data from one node to another: Using remote direct memory access

More on Long Messages: LogGP

- The LogP model targets short messages, or messages made up of a sequence of short messages (the "g" term)
- Features such as RDMA mean that long messages may have a different rate.
- The LogGP model introduces an additional parameter G used for long messages

More on Topology and Contention

- Vendors often insist that topology no longer matters
- Evidence (and logic) say otherwise
- See Bhatele (Ph.D. thesis and numerous papers); introduced *hop count* metric



This example from IBM BG/P using messages between equidistant pairs; from "Quantifying Network Contention on Large Parallel Machines", Bhatele and Kale

Hop Count

- L becomes L(h) and roughly h*L(1)
- Use of hop count and hop bytes
  - ♦ Communication time increases with increasing hop count, thus
  - ♦ Performance decreases as average hop count increases
  - ♦ Thus arrange
    - Algorithm to have low hop count
    - Mapping of processes to core/chip/node to (approximately) minimize hop count

Hop Count and LogP

- LogP rejected topology – why consider hop count?
  - ♦ Machines larger, gap and overhead smaller. Thus variation in latency is significant (more than an order of magnitude)
    - Just a constant term ➔ can be ignored in theoretical analysis
    - A big constant term ➔ cannot be ignored in performance expectations
  - ♦ LogP assumes networks/programming systems will have low contention on network links
    - Not true, even for fast, high-radix switched networks
      - Avoiding Hot-Spots on two-level direct networks, Bhatele, Jain, Gropp, Kale, SC2011
  - ♦ Recall ring example (lecture 20, slide 35)
    - Effective bandwidth = (1/k)*peak bandwidth
    - K = hop count

Including Contention in the Performance Model

- Hard. Made harder by innovation in the network hardware that tries to reduce the impact of contention
  - ♦ Adaptive routing
    - Rather than a fixed route, each switch picks route to avoid very busy links while still moving toward destination
    - Local decisions can still lead to contention
  - ♦ Timing critical
    - Finite resources at each switch may be exceeded in bursts but ok if paced properly (though that's almost impossible to accomplish)

Simulation

- Use the computer to simulate the network, using simplified rules for message transit through the network
  - Injection
  - Switching
- Many tools, both open source and proprietary
- A few examples:
  - Bigsim http://charm.cs.uiuc.edu/research/bigsim
  - ORCS http://htor.inf.ethz.ch/research/orcs/
  - LogGOPSim http://htor.inf.ethz.ch/research/LogGOPSim/

Emulation

- Like simulation, but much more detailed and accurate modeling of network
  - Needs many details (some trade secrets) of the hardware
  - Very likely to be much slower than simulation
- Because more accurate, can expose foibles of the specific design, such as buffer exhaustion and problems with adaptive routing method

Worst Case Analysis

- Pick a routing strategy and network, then essentially do what simulation would do, but use worst case at each time/location to simplify the analysis
  - Pro: parameterized; one analysis applies to many cases
  - Con: big simplification, can significantly overestimate communication time

Capacity

- Assume that adaptive routing is perfect. Then one limit to network performance is the total capacity of the network – the number of bytes (or message packets) in transit at any time
  - 1-D mesh: p-1 links
  - 2-D mesh: $2(p - p^{1/2})$ links
  - 3-D mesh: $3(p - p^{2/3})$ links
- Another limit is the ability of the nodes to *fill* the network
  - This is the *injection rate* limit
  - Determined by the rate at which nodes can inject data into the network

Relationship Between Capacity and Hop Count

- Higher average hop count increases the amount of data *in* the network at any one time, assuming either long messages or large numbers of small messages

Nonblocking and Asynchronous

- Nonblocking in MPI only describes whether a routine blocks the process during an operation.
  - Not whether the communication and computation can take place concurrently
    - Sometimes called asynchronous communication
- Performance models must distinguish these cases
  - MPI implementations may offer different modes, each of which has different tradeoffs
  - E.g., MPICH_ASYNC_PROGRESS
    - Establishes separate communication thread
    - Now requires thread safe implementation, which increases overhead o (and may increase the gap g)

Readings

- LogP – A practical model of parallel computation, CACM 39(11): 78-85 (1996)
  - http://dl.acm.org/citation.cfm?doid=240455.240477
- LogGP: Incorporating Long Messages into the LogP Model for Parallel Computation. J. Parallel Distrib. Comput. 44(1): 71-79 (1997)
  - http://www.sciencedirect.com/science/article/pii/S0743731597913460

Questions for Discussion

- Express s + rn using the parameters of
  - Logp
  - logGp

Some Solutions

- For LogP:
  - s = 2o + L
    - Could add a term for the message envelope
  - r = 1/(gw), where w is the length of the message sent
- For LogGP
  - s = 2o + L
  - r = 1/G
    - Since s + rn typically uses r for the asymptotically large message time