Message Passing Computers

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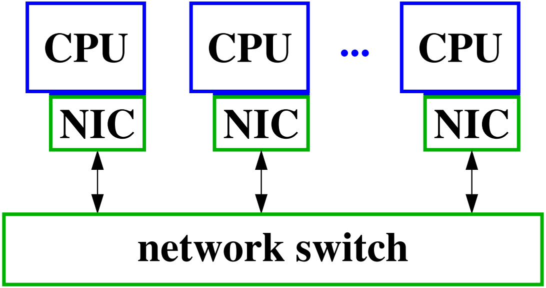
Outline:

- Network Topologies
- Performance Considerations
- Examples

Objectives

- Familiar with typical network topologies:
  rings, meshes, crossbars, tori, hypercubes, trees, fat-trees.
- Understand implications for programming
  - bandwidth bottlenecks
  - latency considerations
  - location matters
  - heterogeneous computers.

Message Passing Computers



- Multiple CPU's
- Communication through a network:
  - Commodity networks for small clusters.
  - Special high-performance networks for super-computers
- Programming model:
  - Explicit message passing between processes (like Erlang)
  - No shared memory or variables.

What programmers Want

- **Low latency**: messages take very little time from sender to receiver.
- **High bandwidth**:
  - We can send large amounts of data between processors.
  - Everyone can communicate at the same time.
- **Uniformity**:
  - All processors and connections are equivalent.
  - The programmer shouldn't need to worry about **where** each processor is.
- *"You can't always get what you want."*

Some simple message-passing clusters

- 25 linux workstations (e.g. lin01 . . . lin25.ugrad.cs.ubc.ca) and standard network routers.
  - A good platform for learning to use a message-passing cluster.
  - But, we'll figure out that network bandwidth and latency are key bottlenecks.
- A "blade" based cluster, for example:
  - 16 "blades" each with 4 6-core CPU chips, and 32G of DRAM.
  - An "infiniband" or similar router for about 10-100 times the bandwidth of typical ethernet.
  - The price tag is ∼$300K.
    - Great if you need the compute power.
    - But, we won't be using one in this class.

The Sunway TaihuLight

- The world's fastest (Linpack) super-computer (as of June 2016)
- 40,960 multicore CPUs
  - 256 cores per CPU chip.
  - 1.45GHz clock frequency, 8 flops/core/cycle.
- Total of 10,485,760 cores
- LINPACK performance: 93 PFlops
  - 1 Petaflop $= 10^3$ Teraflops $= 10^6$ Gigaflops = 10^{15} flops
  - 1 flop = one floating point operation per second
- Power consumption 15MW (computer) + cooling (unspecified)
- Tree-like
  - Five levels of hierarchy.
  - Each level has a high-bandwidth switch.
  - Some levels (all?) are fully-connected for that level.
- Programming model: A version linux with MPI tuned for this machine.
- For more information, see *Report on the Sunway TaihuLight System*, J. Dongarra, June 2016.

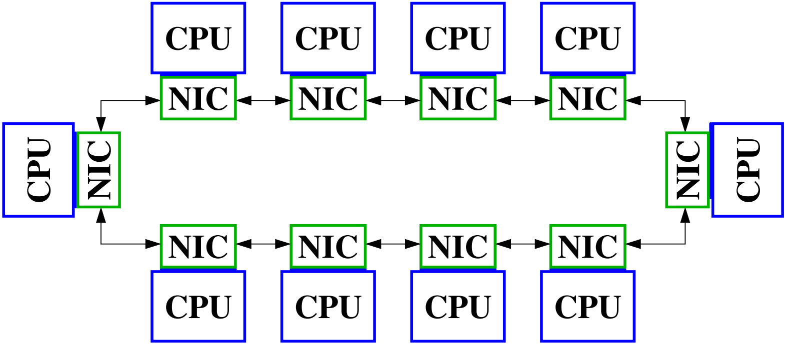
The Westgrid Clusters

- Clusters at various Western Canadian Universities (including UBC).
- Up to 27,000 cores.
- Available for research use.

Network Topologies

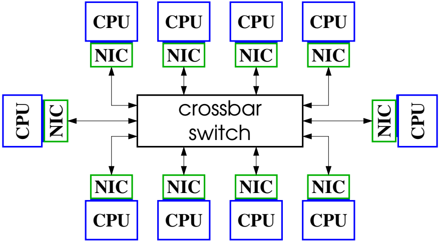
- Network topologies are to the message-passing community what cache-coherence protocols are to the shared-memory people:
  - **Lots** of papers have been published.
  - Machine designers are always looking for better networks.
  - Network topology has a strong impact on performance, the programming model, and the cost of building the machine.
- A message-passing machine may have multiple networks:
  - A general purpose network for sending messages between machines.
  - Dedicated networks for reduce, scan, and synchronization:
    - The reduce and scan networks can include ALUs (integer and/or floating point) to perform common operations such as sums, max, product, all, any, etc. in the networking hardware.
    - A synchronization network only needs to carry a few bits and can be designed to minimize latency.

Ring-Networks



- Advantages: simple.
- Disadvantages:
  - Worst-case latency grows as $O(P)$ where P is the number of processors.
  - Easily congested – limited bandwidth.

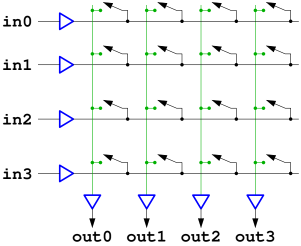
Star Networks



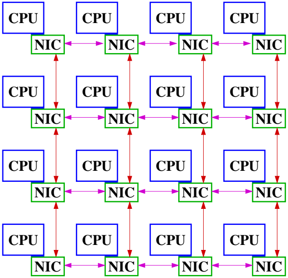
- Advantages:
  - Low-latency – single hop between any two nodes
  - High-bandwidth – no contention for connections with different sources and destinations.
- Disadvantages:
  - Amount of routing hardware grows as $O(P^2)$.
  - Requires lots of wires, to and from switch –

    Imagine trying to build a switch that connects to 1000 nodes!
- Summary
  - Surprisingly practical for 10-50 ports.
  - Hierarchies of cross-bars are often used for larger networks.

A crossbar switch

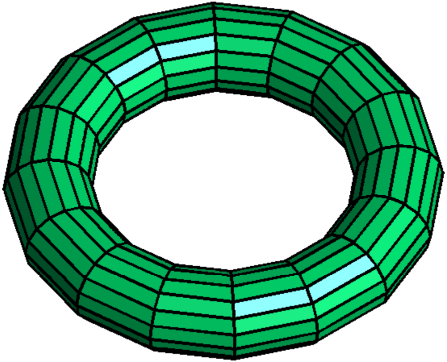


Meshes



- Advantages:
  - Easy to implement: chips and circuit boards are effectively two-dimensional.
  - Cross-section bandwidth grow with number of processors – more specifically, bandwidth grows as $\sqrt{P}$.
- Disadvantages:
  - Worst-case latency grows as $\sqrt{P}$.
  - Edges of mesh are "special cases."

Tori



- Advantages:
  - Has the good features of a mesh, and
  - No special cases at the edges.
- Disadvantages:
  - Worst-case latency grows as $\sqrt{P}$.

Mesh & Torus coordinates

- Consider an $N \times M$ grid of processors.
- Each processor can be identified by its coordinates, (i, j), with $0 \leq i < N$ and $0 \leq j < M$.
- For a **mesh**:
  - Processor (i, j) has a connection to $(i + 1, j)$ **if** $i < N - 1$.
  - Processor (i, j) has a connection to $(i - 1, j)$ **if** $i > 0$.
  - Processor (i, j) has a connection to $(i, j + 1)$ **if** $j < M - 1$.
  - Processor (i, j) has a connection to $(i, j - 1)$ **if** $j > 0$.
- For a **torus**:
  - Processor (i, j) has a bi-directional connection to $((i + 1) \bmod N, j)$.
  - Processor (i, j) has a bi-directional connection to $(i, (j + 1) \bmod M)$.
  - No special cases for the edges.
- Both definitions generalize to higher dimensions “in the obvious way”.

Hypercubes

A 0–dimensional (1 node), radix–2 hypercube

A 0–dimensional (1 node), radix–2 hypercube

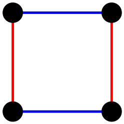
Hypercubes

A 1−dimensional (2 node), radix−2 hypercube

A 5−dimensional (32 node), radix−2 hypercube

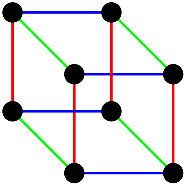
Hypercubes

A 2–dimensional (4 node), radix–2 hypercube



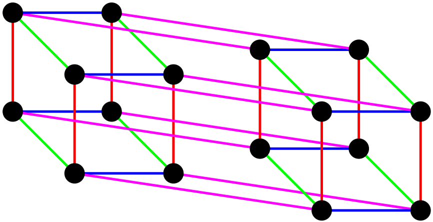
Hypercubes

A 3–dimensional (8 node), radix–2 hypercube



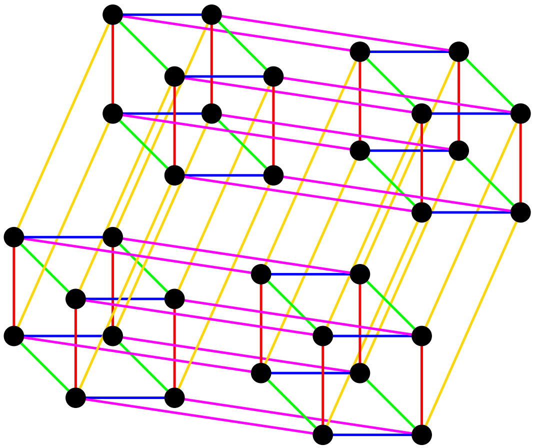
Hypercubes

A 4–dimensional (16 node), radix–2 hypercube



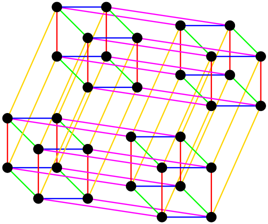
Hypercubes

A 5–dimensional (32 node), radix–2 hypercube



Hypercubes

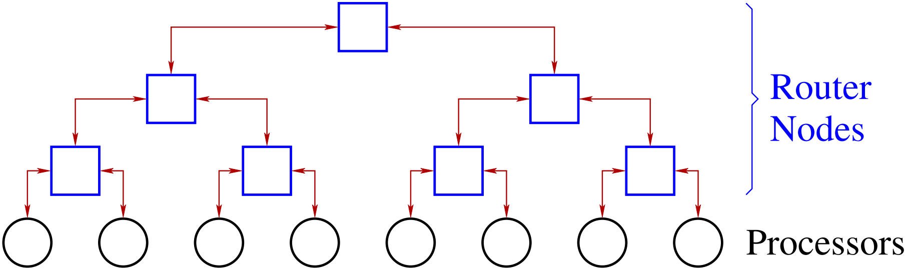
A 5−dimensional (32 node), radix−2 hypercube



Dimension Routing

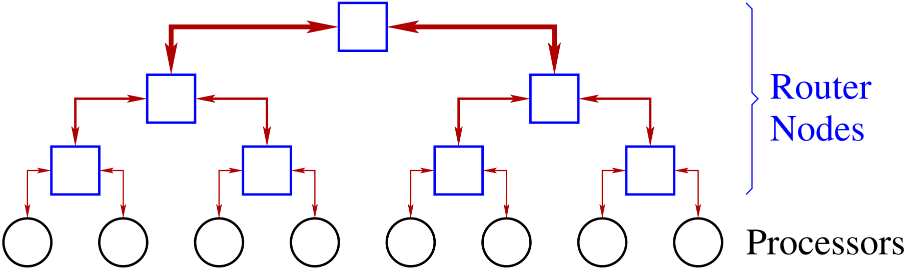
```
% Send a message, msg, from node src to node dst
for i = 1:d                          % d is dimension of the hypercube
  if(bit(i, src) != bit(i, dst))     % if different for dimension i
    send(msg, link[i]);              % then send msg to our i-neighbour
```

Trees



- Simple network: number of routing nodes $=$ number of processors $-$ 1.
- Wiring: $O(\log N)$ extra height ($O(N \log N)$) extra area.
  - Wiring: $O(\sqrt{N} \log N)$ extra area for H-tree.
- Low-latency: $O(\log N) + \text{wire delay}$.
- Low-bandwidth: bottleneck at root.

Fat-Trees



- Use M^α parallel links to connect subtrees with M leaves.
- $0 \leq \alpha \leq 1$
  - $\alpha = 0$: simple tree
  - $\alpha = 1$: strange crossbar
- Fat-trees are "universal"
  - For $\frac{2}{3} < \alpha < 1$ a fat-tree interconnect with volume V can simulate any interconnect that occupies the same volume with a time overhead that is poly-log factor of N.

It's all about wires

Consider a network with P processors and cross-section bandwidth of B.

- For simplicity, assume a two-dimensional implementation (chip or circuit board)
- Wires (or optical fibers, etc.) have $\Omega(1)$ diameter.
- This gives a lower bound for the **diameter** of the machine of $\Omega(B)$.
- The bound for the area of the machine is $\Omega(B^2)$.
- P processors take $\Theta(P)$ area not counting the network.
- If B is asymptotically bigger than $\sqrt{P}$, then the machine becomes "all wire" as $P \rightarrow \infty$.
- Similar reasoning applies for a three-dimensional machine:
  - Cross section area must be $\Omega(B)$.
  - Diameter must be $\Omega(\sqrt{B})$.
  - Volume must be $\Omega(B^{3/2})$.
  - If $B > O(P^{2/3})$, then the machine is asymptottically all wiere.

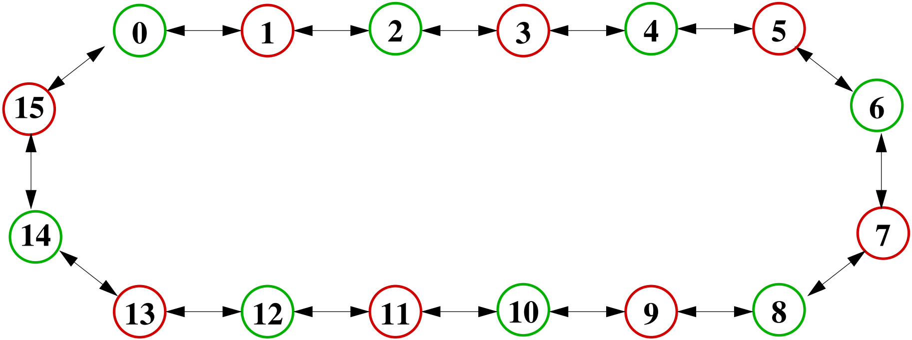
Performance Considerations

- Bandwidth
  - How many bytes per-second can we send between two processors?
    - May depend on which two processors: neighbours may have faster links than spanning the whole machine.
  - Bisection bandwidth: find the worst way to divide the processors into to sets of $P/2$ processors each.
    - How many bytes per-second can we send between the two partitions?
    - If we divide this by the number of processors, we typically get a much smaller value that the peak between two processors.
- Latency
  - How long does it take to send a message from one processor to another?
    - Typically matters the most for short messages.
    - Round-trip time is often a good way to measure latency.
- Cost
  - How expensive is the interconnect – it may dominate the total machine cost.
    - Cost of the network interface hardware.
    - Cost of the cables.

Real-life networks

- InfiniBand is becoming increasingly prevalent
- Peak bandwidths $\geq$ 6GBytes/sec.
  - achieved bandwidths of 2–3GB/s.
- Support for RDMA and "one-sided" communication
  - CPU A can read or write a block of memory residing with CPU B.
- Often, networks include trees for synchronization (e.g. barriers), and common reduce and scan operations.
- The MPI (message-passing interface) evolves to track the capabilities of the hardware.

Bandwidth Matters



- Assume each link has a bandwidth in each direction of 1Gbyte/sec.
- Each node, i, sends an 8Kbyte message to node $(i + 1) \bmod P$, where P is the number of processors?
- How long does this take?
- What if each node, i, sends an 8Kbyte message to node $(i + P/2) \bmod P$?

What this means for programmers

- Location matters.
  - The meaning of location depends on the machine.
  - Challenges of heterogeneous machines.
    - Communication on chip is much higher bandwidth and lower latency than communication across a circuit board or backplane (e.g. between blades).
    - Communication between processors on the same circuit board or backplane is much faster than communication between such clusters.
- Message passing makes it possible to account for heterogeneity.
  - We can adapt simple algorithms to work on a heterogeneous architecture.
  - But we need to have the right models.

Summary

- Message passing machines have an architecture that corresponds to the message-passing programming paradigm.
- Message passing machines can range from
  - Clusters of PC's with a commodity switch.
  - Clouds: lots of computers with a general purpose network.
  - Super-computers: lots of compute nodes tightly connected with high-performance interconnect.
- Many network topologies have been proposed:
  - Performance and cost are often dominated by network bandwidth and latency.
  - The network can be more expensive than the CPUs.
  - Peta-flops or other instruction counting measures are an indirect measure of performance.
- Implications for programmers
  - Location matters
  - Communication costs of algorithms is very important
  - Heterogeneous computing is likely in your future.

Preview

January 24: Speed-up		
	Reading:	McCool *et al.*, Chapter 2, Section 2.5.
January 26: Energy, Power, and Time		
January 29: Performance Loss		
	Reading:	McCool *et al.*, Chapter 2, Section 2.6.
	Homework:	HW 2 earlybird (11:59pm), HW 3 goes out.
January 31: Parallel Performance: Models		
	Homework:	HW 2 due (11:59pm).
February 2-9: Sorting		
February 13: Tuesday – Mark's office hours		
	Homework:	HW 3 earlybird (11:59pm).
		HW 4 goes out – midterm review, maybe some simple CUDA
February 14: Intro. to GPUs & CUDA		
	Homework:	HW 3 due (11:59pm).
February 16: A CUDA example		
February 19-23: break week		
February 28: midterm		

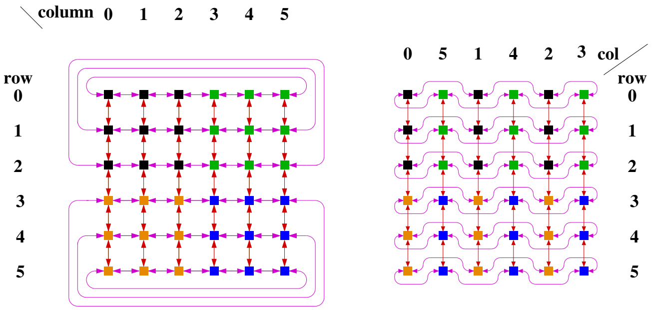
Review

- Consider a machine with 4096 processors.
- What is the maximum latency for sending a message between two processors (measured in network hops) if the network is
  - A ring?
  - A crossbar?
  - A 2-D mesh?
  - A 3-D mesh?
  - A hypercube?
  - A binary tree?
  - A radix-4 tree?

Supplementary Material

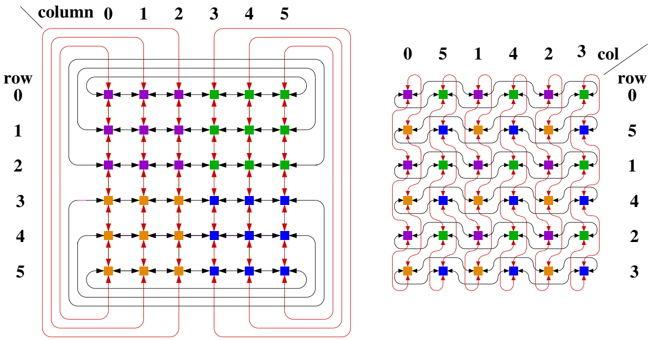
- Message-passing origami: how to fold a mesh into a torus.
- How big is a hypercube: it's all about the wires.

From a mesh to a torus (1/2)



- Fold left-to-right, and make connections where the left and right edges meet.
- Now, we've got a cylinder.
- Note that there are no "long" horizontal wires: the longest wires jump across one processor.

From a mesh to a torus (2/2)



- Fold top-to-bottom, and make connections where the top and bottom edges meet.
- Now, we've got a torus.
- Again there are no "long" wires.

How big is a hypercube?

- Consider a hypercube with $N = 2^d$ nodes.
- Assume each link can transfer one message in each direction in one time unit. The analysis here easily generalizes for links of higher or lower bandwidths.
- Let each node send a message to each of the other nodes.
- Using dimension routing,
  - Each node will send $N/2$ messages for each of the d dimensions.
  - This takes time $N/2$.
  - As soon as one batch of messages finishes the dimension-0 route, that batch can continue with the dimension-1 route, and the next batch can start the dimension 0 route.
  - So, we can route with a throughput of $\binom{N}{2}$ messages per $N/2$ time.

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- Consider any plane such that $N/2$ nodes are on each side of the plane.
  - $\frac{1}{2}\binom{N}{2}$ messages must cross this plane in $N/2$ time.
  - This means that at least $N-1$ links must cross the plane.
  - The plane has area $O(N)$.

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- Consider any plane such that $N/2$ nodes are on each side of the plane.
  - The plane has area $O(N)$.
- Because the argument applies for *any* plane, we conclude that the hypercube has diameter $O(\sqrt{N})$ and thus volume $O(N^{\frac{3}{2}})$.
- Asymptotically, the hypercube is all wire.