

Architecture and Parallel Computers

Chris Kauffman

*Last Updated:
Sun Sep 12 10:34:46 PM CDT 2021*

Logistics

Reading: Grama Ch 2

- ▶ **Focus on 2.3-5**, material pertaining to distributed memory
- ▶ We will return to shared memory arch later in the course
- ▶ Cache Coherence, PRAM models, False Sharing, Memory Bus are all shared memory topics
- ▶ Sections 2.1 and 2.2 optional, deeper architectures
- ▶ Sections 2.6 and 2.7 encouraged, deeper on networks

Assignment 1

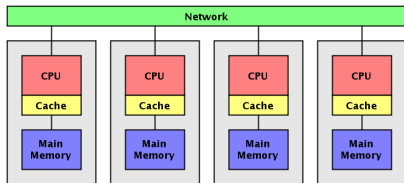
- ▶ Due Sat 9/18
- ▶ Today: Finish Parallel architecture (HW1: #1-2)
- ▶ Parallel Algorithm Decomposition (HW1: #3,4,6)
- ▶ Pair-work is allowed
- ▶ Questions?

SISD, SIMD, MIMD, SPAM, and other 4-letter words

- ▶ Traditional CPU, Single Instruction Single Data (SISD)
`ADD r1, r2 # add int in r2 to r1`
- ▶ Most computers now have cpu instructions to add multiple
`PHADD mm1, mm2 # add two ints in mm2 to ints in mm1`
- ▶ Smart compilers will select **vector instructions** when appropriate
- ▶ Explicit hardware parallelism is good for multimedia stuff (graphics, games, images, sound, videos)
- ▶ Flynn's taxonomy discusses several variants
 SISD SIMD SPMD
 MISD MIMD MPMD
- ▶ Some parallel programs exist as Multiple Program Multiple Data (MPMD) like client server models (`client.c` and `server.c` are separate programs)
- ▶ Our focus and the most common type of parallel program:
Single Program Multiple Data (SPMD): *Write one program which processes different hunks of data in parallel*

Recall: Distributed vs Shared Memory

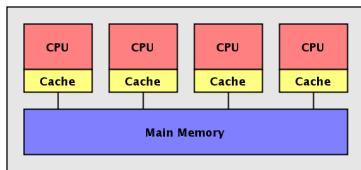
Distributed Memory



Source: Kaminsky/Parallel Java

- ▶ Far more scalable/cost effective
- ▶ Sharing information requires explicit send/receive commands between processors
- ▶ Communication requires more care/more expensive

Shared Memory



Source: Kaminsky/Parallel Java

- ▶ Convenience: no explicit send/receive, write shared memory address
- ▶ Requires coordination to prevent corrupting memory
- ▶ Communication cost is low but requires discipline

Modeling Distributed Memory Parallel Computers

- ▶ Will spend a some time discussing networks used in parallel computing
- ▶ These have consequences for algorithms, but unless you're building your own machine (for like \$1M) you're stuck with what you get
 - ▶ Example: We will use CSE Labs machines with MPI installed to do Distributed programming : lacks a high-powered, dense network interconnect
 - ▶ Example: If you have a chance to work on the [#2 Super Computer in the World, Summit](#), it is reported to have a [Fat Tree Network Architecture](#) can be exploited in its MPI communications

Static Networks for Distributed Machines

- ▶ String up a bunch of **Processing Elements (PEs)**
- ▶ Which PE is connected to which other?
- ▶ This can affect the cost of communication

Full Communication Costs

When sending a message of size m words of memory

- ▶ t_s : Startup time, incurred once
- ▶ t_h : Per-hop time, overhead incurred for each link between source and destination
- ▶ t_w : Per-word transfer time between two nodes, takes $t_w \times M$ time for each link between source and destination
- ▶ L : number of links to traverse
- ▶ M : number of words being sent
- ▶ Typical model for communication time w/ packet routing

$$t_{comm} = t_s + Lt_h + t_w M$$

Grid and Torus

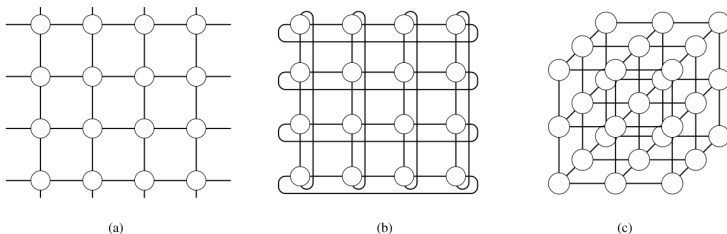


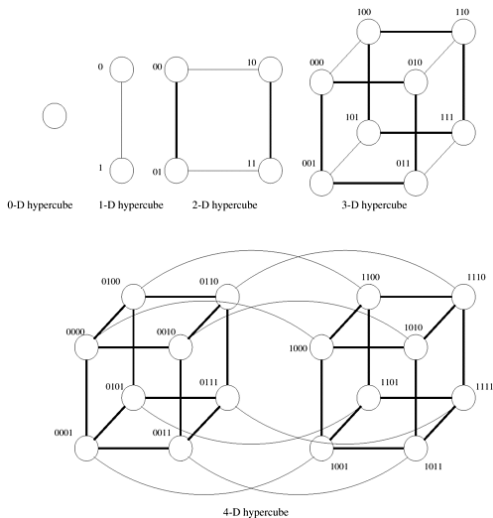
Figure 2.16 Two and three dimensional meshes: (a) 2-D mesh with no wraparound; (b) 2-D mesh with wraparound link (2-D torus); and (c) a 3-D mesh with no wraparound.

Source: Grama, Sec 2.4.3

- ▶ Common arrangement of links between PEs
- ▶ Each PE node connected to neighbors
- ▶ When wrapping around, grid becomes a torus
- ▶ For a 2D torus with p nodes, **how many links are required?**
- ▶ *Hint: surprisingly simple, think of each processor “owning” down and right links*
- ▶ **How many links in a 3D torus?**

Exercise: HyperCube

- ▶ N-dimension hypercube: connect two $(N - 1)$ dimension hypercubes, link corresponding nodes
- ▶ How many nodes and links in an N-dimension hypercube?
- ▶ *Hint: Nodes are easy, links are tricky, try Grama textbook...*



Answers: HyperCube

N-dimensional Hypercube has

- ▶ 2^N Processors
- ▶ $2^N * N/2$ links

Can show this via Proof by Induction but that's not our focus

That's a lot of Links

- ▶ Many communication patterns have excellent performance on a hypercube
- ▶ Building one requires wiring processors together in a highly complex manner
- ▶ Ex: 10-dimensional hypercube with 1024 Processors each with 10 links to a unique set of other processors
- ▶ Hypercubes are a favorite theoretical topology but
- ▶ Too expensive/complex for actual machines

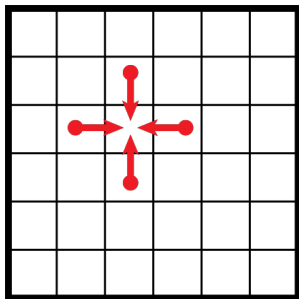
Exercise: Compare Networks: Parallel Stencil

- ▶ P processors
- ▶ Network 1: 2D-torus: $2P$ links
- ▶ Network 2: $\log_2(P)$ dim. Hypercube w/ $(P \log_2(P)/2)$ links
- ▶ **Discuss** advantages/disadvantages of torus vs hypercube arrangement for this application
- ▶ Outline an algorithm, estimate cost-effectiveness of code+hardware

Image “blurring”

- ▶ A large image is distributed across the P processors
- ▶ Each proc holds a 2D hunk of the image
- ▶ To blur the entire image, must assign RGB values which are average of “neighborhood”

Stencil



Answers Compare Networks: Parallel Stencil

- ▶ Divide image into 2D hunks
- ▶ PEs must communicate with other PEs that have neighboring hunks

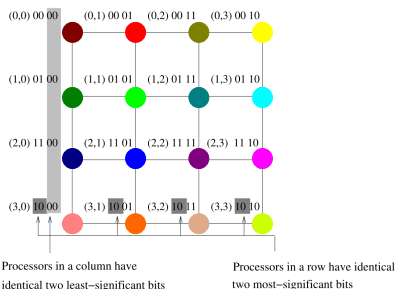
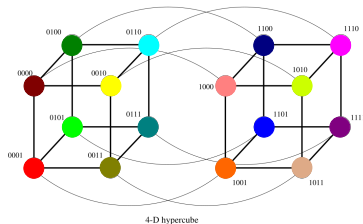
2D Torus

- ▶ Maps VERY easily onto a 2D Torus / Grid
- ▶ PEs locally blur
- ▶ Exchange pixels with 4 neighbors except for boundary Procs

Answers Compare Networks: Parallel Stencil

Hypercube

- ▶ Intuition: have many more links than in the 2D Torus, should be possible to place neighboring pixel hunks on neighboring procs
- ▶ Find a map from 2D to Hypercube discussed in Grama 2.7.1 - uses Gray Codes for Proc Numbering and is beyond assignment / exam question
- ▶ Can then apply same principle of local blur + exchange with neighbor



Exercise: Compare Networks: Parallel Sum

- ▶ P processors
- ▶ Network 1: 2D-torus: $2P$ links
- ▶ Network 2: $\log_2(P)$ dim. Hypercube w/ $(P \log_2(P)/2)$ links
- ▶ **Discuss** advantages/disadvantages of torus vs hypercube arrangement for this application
- ▶ Outline an algorithm, estimate cost-effectiveness of code+hardware

Sum Array of Numbers

- ▶ Each proc holds a hunk of the data array
- ▶ Want a single processor to eventually contain sum o
- ▶ **State your algorithm:** Try to minimize communication at each step, exploit as much parallelism as possible

Networks

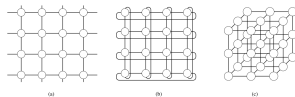
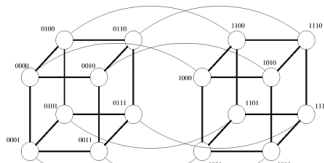


Figure 2.16 Two and three dimensional meshes: (a) 2-D mesh with no wraparound; (b) 2-D mesh with wraparound link (2-D torus); and (c) a 3-D mesh with no wraparound.



Answers: Compare Networks: Parallel Sum

Goal: Get sum on Proc 0

First, each Proc sums its own chunk of numbers then...

2D Torus: N by N Square

- ▶ Send values UP rows then LEFT across columns
 - ▶ $2*N$ Communication steps, always neighbors
 - ▶ Many Procs **Idle** during communication
- ▶ Other Communication steps will result in multi-hop communication with non-neighbor procs - will revisit this later

N-dimensional HyperCube

- ▶ Each Proc has a binary address: ex: 100110
- ▶ Starting with bit $i = (N - 1)$ while $i > 0$
 - ▶ Each Proc with bit $i == 1$ sends to $i == 0$
 - ▶ Decrement i , repeat
- ▶ Takes N communication steps

Some details on Parallel Sum

- ▶ We will talk more about parallel sum later
- ▶ Parallel sum is an example of a **reduction**
- ▶ For those curious, have a look at [Lecture notes by Susan Hayes](#)

Characteristics of Various Networks

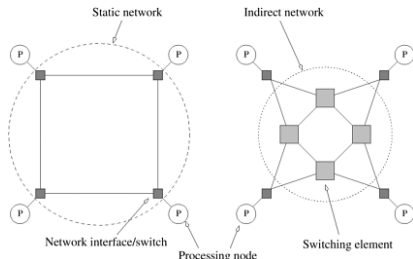
Table 2.1. A summary of the characteristics of various static network topologies connecting p nodes.

Network	Diameter	Bisection Width	Arc Connectivity	Cost (No. of links)
Completely-connected	1	$p^2/4$	$p - 1$	$p(p - 1)/2$
Star	2	1	1	$p - 1$
Complete binary tree	$2 \log((p + 1)/2)$	1	1	$p - 1$
Linear array	$p - 1$	1	1	$p - 1$
2-D mesh, no wraparound	$2(\sqrt{p} - 1)$	\sqrt{p}	2	$2(p - \sqrt{p})$
2-D wraparound mesh	$2\lfloor\sqrt{p}/2\rfloor$	$2\sqrt{p}$	4	$2p$
Hypercube	$\log p$	$p/2$	$\log p$	$(p \log p)/2$
Wraparound k -ary d -cube	$d\lfloor k/2\rfloor$	$2k^{d-1}$	$2d$	dp

Several metrics described in textbook

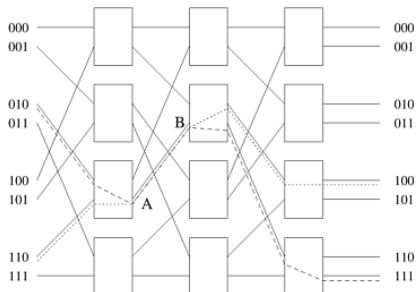
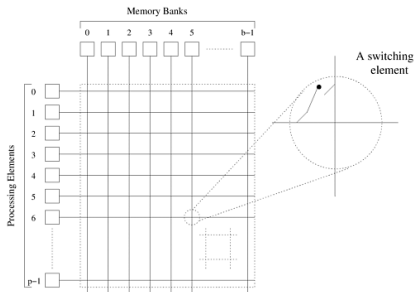
- ▶ *Diameter*: how many hops away any two procs can be
- ▶ *Bisection width*: number of links to break to partition network
- ▶ *Arc Connectivity*: number of paths between two nodes
- ▶ *Cost*: can correspond to number of links

Dynamic Networks



- ▶ In a static network, connections are fixed
- ▶ Dynamic networks use switches: send data into network with destination, may alter a connection to point in a different direction
- ▶ Akin to the internet: packet switching network
- ▶ Textbook mixes concepts somewhat: Network for
 - ▶ Distributed PEs to communicate
 - ▶ PEs to share memory

CrossBar and Omega Network



Fat Trees

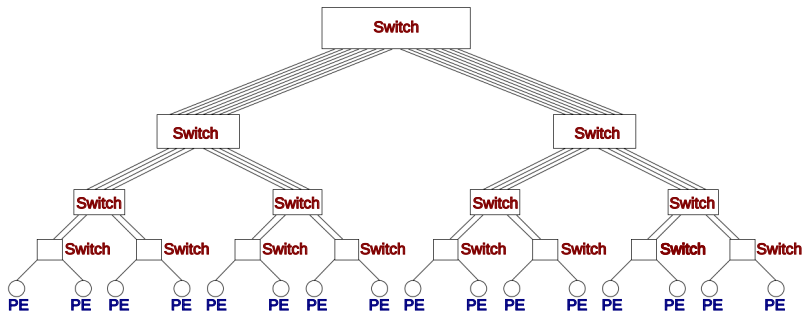


Figure 2.19 A fat tree network of 16 processing nodes.

Often used as network switches are commodities while still providing good speeds

Routing: Store/Forward Packet, Switching, Cut-Through

When sending messages, intermediate nodes must decide what to do with a message: **Routing protocol/scheme**

Store and Forward

- ▶ Accumulate the whole message (all M words), store it until it can be forwarded to next hop
- ▶ Easy to build but requires large-ish internal buffers and generally has bad performance

Standard Packet Switching

- ▶ Break message into chunks (packets)
- ▶ Use packet header to carry error-correction info, routing info
- ▶ Optimized for the unreliable internet (go around overloaded/dead nodes)
- ▶ Better but incurs overhead to solve problems that aren't present in most parallel machines

Routing: Cut-through Routing

- ▶ A standard in HPC applications
- ▶ Similar to packet switching: break message into chunks
- ▶ Send a *tracer* from source to destination to determine route - all packets then follow that route
- ▶ Send message in *flits* (packets) along tracer route - reduces latency
- ▶ Include minimal overhead in packet for error correction, re-routing, etc.
- ▶ Cost to communicate message size M between two PEs L hops away

$$t_{comm} = t_s + Lt_h + t_w M$$

The Simplified Model Communication Model

When analyzing performance of programs, consider the following

- ▶ t_s : Startup time, incurred once
- ▶ t_h : Per-hop time, overhead incurred for each link between source and destination
- ▶ t_w : Per-word transfer time between two nodes, takes $t_w \times M$ time for each link between source and destination
- ▶ L : number of links to traverse
- ▶ M : number of words being sent

Simplified model advocated by Grama et. al

$$t_{comm} = t_s + t_w M$$

- ▶ Easy to understand/use
- ▶ Relatively easy to apply to programs
- ▶ Ignores a pretty big component: why?
- ▶ Why would the text adopt this podunk model?

Our Approach

Analyzing Communication Patterns

Will incorporate number of hops L between PEs in the network

$$t_{comm} = t_s + Lt_h + t_wM$$

Try to derive good source/destination pairs and message routes

Analyzing Programs

Will ignore network topology, congestion, number of hops

$$t_{comm} = t_s + t_wM$$

Somewhat unrealistic but makes analysis much simpler