# CS184b: Computer Architecture (Abstractions and Optimizations)

Day 20: May 23, 2003
Interconnect



## Previously

- CS184a
  - interconnect needs and requirements
  - basic topology
  - Mostly thought about static/offline routing
- This quarter
  - most systems require
  - interfacing issues
    - model, hardware, software

# Today

- Issues
- Topology/locality/scaling
  - (some review)
- Styles
  - from static
  - to online, packet, wormhole
- Online routing



# Issues

- Bandwidth
  - aggregate, per endpoint
  - local contention and hotspots
- Latency
- Cost (scaling)
  - locality
- Arbitration
  - conflict resolution
  - deadlock
- Routing
  - (quality vs. complexity)
- Ordering (of messages)

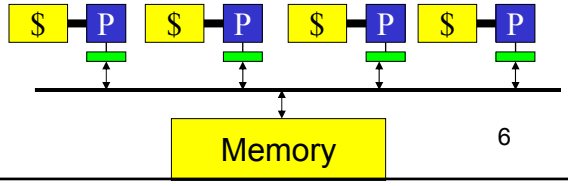
# Topology and Locality

(Partially) Review



# Simple Topologies: Bus

- Single Bus
  - simple, cheap
  - low bandwidth
    - not scale with PEs
  - typically online arbitration
    - can be offline scheduled



# Bus Routing

- Offline:
  - divide time into N slots
  - assign positions to various communications
  - run modulo N w/ each consumer/producer send/receiving on time slot
- *e.g.*
  1: A->B
  2: C->D
  3: A->C
  4: A->B
  5: C->B
  6: D->A
  7: D->B
  8: A->D



# Bus Routing

- Online:
  - request bus
  - wait for acknowledge
- Priority based:
  - give to highest priority which requests
  - consider ordering
  - $Got_i = Want_i \wedge Avail_i$
    $Avail_{i+1} = Avail_i \wedge /Want_i$
- Solve arbitration in log time using parallel prefix
- For fairness
  - start priority at different node
  - use cyclic parallel prefix
    - deal with variable starting point

# Token Ring

- On bus
  - delay of cycle goes as N
  - can't avoid, even if talking to nearest neighbor
- Token ring
  - pipeline bus data transit (ring)
    - high frequency
  - can exit early if local
  - use token to arbitrate use of bus

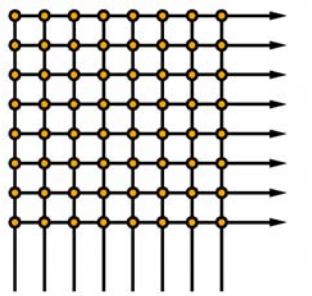


# Multiple Busses

- Simple way to increase bandwidth
  - use more than one bus
- Can be static or dynamic assignment to busses
  - static
    - A->B always uses bus 0
    - C-> always uses bus 1
  - dynamic
    - arbitrate for a bus, like instruction dispatch to k identical CPU resources

# Crossbar

- No bandwidth reduction
  - (except receiver at endoint)
- Easy routing (on or offline)
- Scales poorly
  - $N^2$ area and delay
- No locality

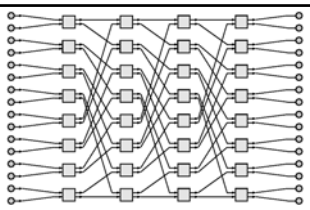




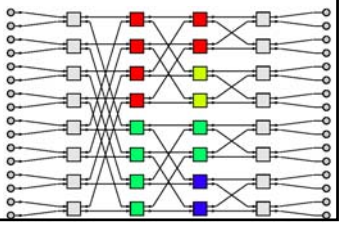
# Hypercube

- Arrange $2^n$ nodes in n-dimensional cube
- At most n hops from source to sink
  - log(number of nodes)
- High bisection bandwidth
  - good for traffic (but can you use it?)
  - bad for cost [$O(n^2)$]
- Exploit locality
- Node size grows
  - as log(N) [IO]
  - Maybe $\log^2(N)$ [xbar between dimensions]

# Multistage



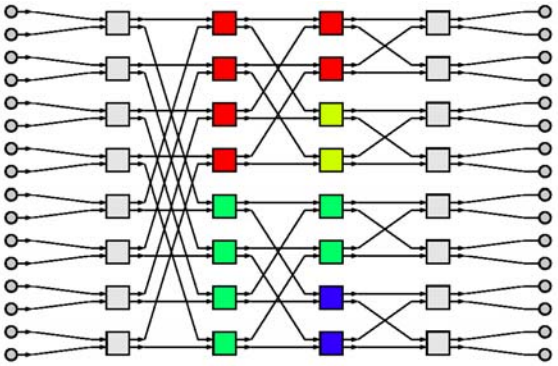
- Unroll hypercube vertices so log(N), constant size switches per hypercube node
  - solve node growth problem
  - lose locality
  - similar good/bad points for rest





# Hypercube/Multistage Blocking

- Minimum length multistage
  - many patterns cause bottlenecks
  - *e.g.*

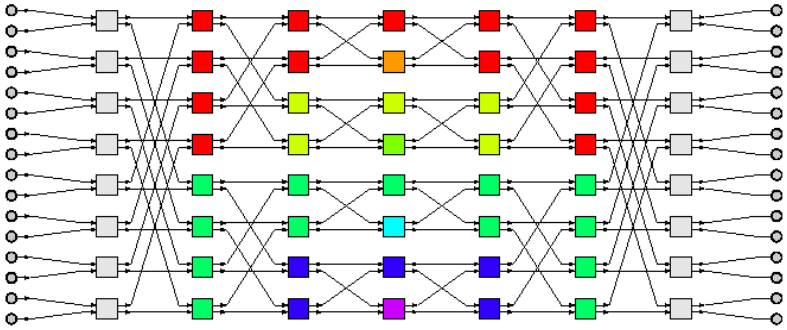


# Hypercube/Multistage Blocking

- Solvable with non-minimum length
  - *e.g.* Beneš
    - factor of 2 larger in nodes and latency
    - Routes all permutation (offline)
- Also solvable by routing multiple times through net
  - *i.e.* Beneš is two back-to-back MINs

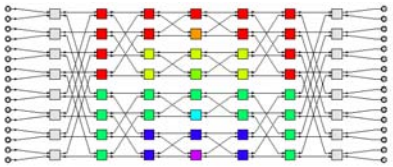


# Beneš Nework



# Beneš Routing

- Solve recursively by looping
- Start at a route
- Pick top or bottom half to route path
- Allocate at destination
- Look at other route must come in here
- Must take alternate path
- Continue until
  - cycle closes or ends



- If unrouted at this level,
  - pick new starting point and continue
- Once finish this level,
  - repeat/recurse on top and bottom subproblems remaining

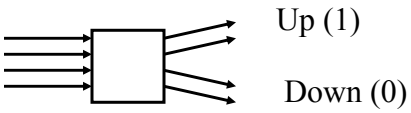


# Online Hypercube Blocking

- If routing offline, can calculate Benes-like route
- Online, don't have time, or global view
- **Observation**: only a few, canonically bad patterns
- **Solution**: Route to random intermediate
  - then route from there to destination
  - …turns worst-case into average case
    - at the expense of locality

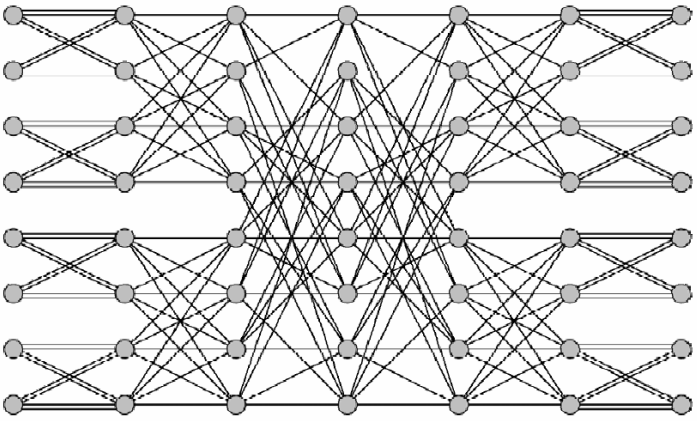
# Dilated Switches

- Have multiple outputs per logical direction
  - **Dilation:** number of outputs per direction
  - *E.g.* radix 2 switch w/ 4 outputs
    - 2 per direction
    - Dilation 2





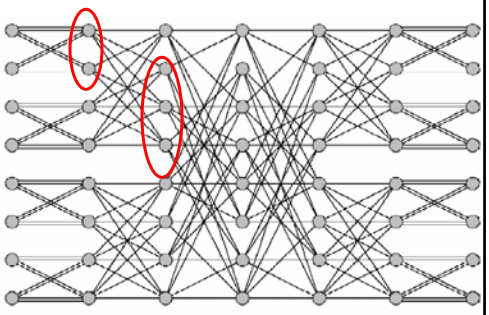

# Multi- Beneš



From: Maggs, Statistical Science, v8n1p70+, 1993

# Multi-Beneš

- Dilation > 1
- With expansion
  - Guarantee all subets of given size in one stage
  - Connect to a suitable factor more things in next stage
  - (only possible with dilation>2)
- **and** sufficiently light usage

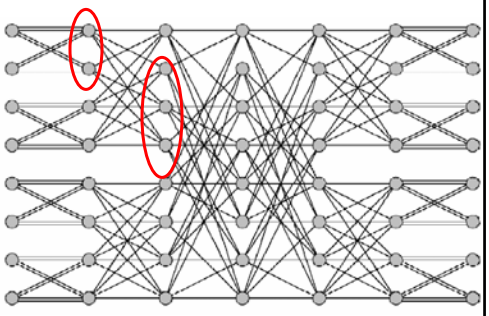


- Guarantee **non-blocking**
  - Always a path
- Can route greedily



# Multi- Beneš

- Guaranteeing expansion
  - All known deterministic wiring schemes are weak
- Randomly wiring up alternative paths
  - Gives strong expansion
  - With high probability



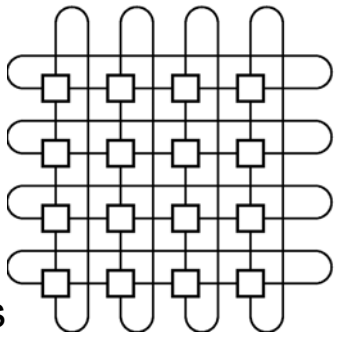
- Arora/Maggs/Leighton, SIAM Journal on Computing, v25n3p600, 1996.

# K-ary N-cube

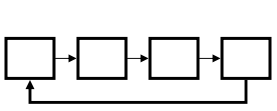
- Alternate reduction from hypercube
  - restrict to N<log(N) dimensional structure
  - allow more than 2 ordinates in each dimension
- *E.g.* mesh (2-cube), 3D-mesh (3-cube)
- Matches with physical world structure
- Bounds degree at node
- Has Locality
- Even more bottleneck potentials
  - make channels wider (CS184a)

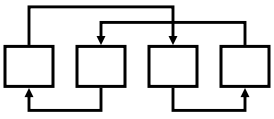


# Torus



- Wrap around n-cube ends
  - 2-cube → cylinder
  - 3-cube → donut
- Cuts worst-case distances
- Can be laid-out reasonable efficiently
  - maybe 2x cost in channel width?





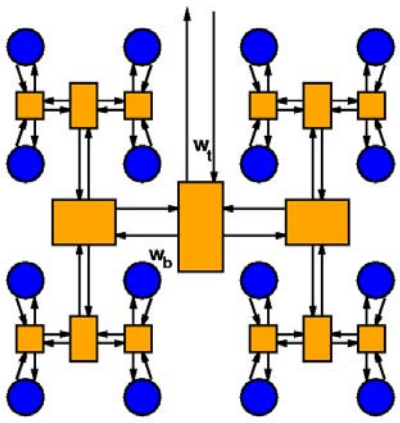
# Fat-Tree

- Saw that communications typically has locality (CS184a)
- Modeled recursive bisection/Rent's Rule
- Leiserson showed Fat-Tree was (area, volume) universal
  - w/in log(N) the area of **any** other structure
  - exploit physical space limitations wiring in {2,3}-dimensions



# Universal Fat-Tree

- P=0.5 for area universal
- P=2/3 for volume
- *I.e.* go as ratio
  - surface/perimeter
  - area/volume
- Directly related
  - results on depop.
    - CS184a



# MoT/Express Cube (Mesh with Bypass)

- Large machine in 2 or 3 D mesh
  - routes must go through square/cube root switches
  - vs. log(N) in fat-tree, hypercube, MIN
- Saw practically can go further than one hop on wire…
- Add long-wire bypass paths



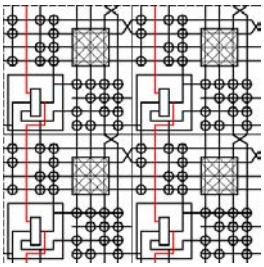
# Routing Styles

# Hardwired

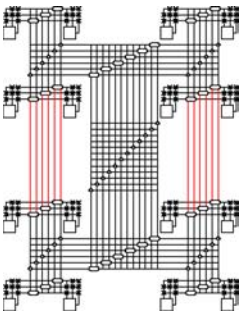
- Direct, fixed wire between two points
- *E.g.* Conventional gate-array, std. cell
- Efficient when:
  - know communication *a priori*
    - fixed or limited function systems
    - high load of fixed communication
      - often control in general-purpose systems
  - links carry high throughput traffic continually between fixed points



# Configurable

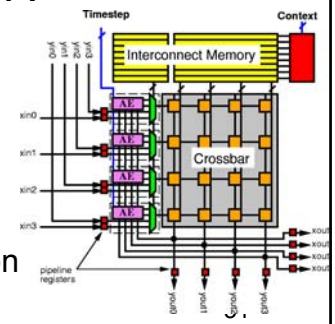


- Offline, lock down persistent route.
- *E.g.* FPGAs
- Efficient when:
  - link carries high throughput traffic
    - (loaded usefully near capacity)
  - traffic patterns change
    - on timescale >> data transmission



# Time-Switched

- Statically scheduled, wire/switch sharing
- *E.g.* TDMA, NuMesh, TSFPGA
- Efficient when:
  - thruput per channel < thruput capacity of wires and switches
  - traffic patterns change
    - on timescale >> data transmission






# Self-Route, Circuit-Switched

- Dynamic arbitration/allocation, lock down routes
- *E.g.* METRO/RN1
- Efficient when:
  - instantaneous communication bandwidth is high (consume channel)
  - lifetime of comm. > delay through network
  - communication pattern unpredictable
  - rapid connection setup important

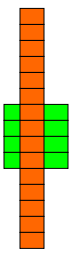
# Self-Route, Store-and-Forward, Packet Switched

- Dynamic arbitration, packetized data
- Get entire packet before sending to next node
- *E.g.* nCube, early Internet routers
- Efficient when:
  - lifetime of comm < delay through net
  - communication pattern unpredictable
  - can provide buffer/consumption guarantees
  - packets small



# Self-Route, Wormhole Packet-Switched

- Dynamic arbitration, packetized data
- *E.g.* Caltech MRC, Modern Internet Routers
- Efficient when:
  - lifetime of comm < delay through net
  - communication pattern unpredictable
  - can provide buffer/consumption guarantees
  - message > buffer length
    - allow variable (? Long) sized messages



# Online Routing



# Costs: Area

- Area
  - switch (1-1.5K / switch)
    - larger with pipeline (4K) and rebuffer
  - state (SRAM bit = 1.2K / bit)
    - multiple in time-switched cases
  - arbitrartion/decision making
    - usually dominates above
  - buffering (SRAM cell per buffer)
    - can dominate

# Costs: Latency

- Time local
  - make decisions
  - round-trip flow-control
- Time
  - blocking in buffers
  - quality of decision
    - pick wrong path
    - have stale data



# Intermediate

- For large # of predictable patterns
  - switching memory may dominate allocation area
  - area of routed case < time-switched
- Get offline, global planning advantage
  - by **source routing**
    - source specifies offline determined route path
    - offline plan avoids contention

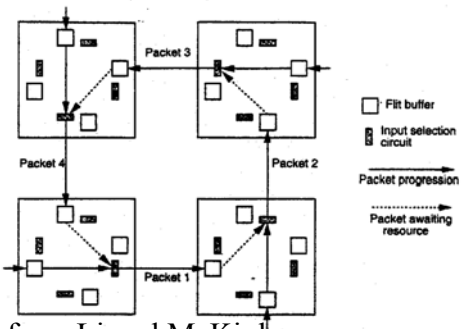
# Offline vs. Online

- If know patterns in advance
  - offline cheaper
    - no arbitration (area, time)
    - no buffering
    - use more global data
      - better results
- As becomes less predictable
  - benefit to online routing



# Deadlock

- Possible to introduce deadlock
- Consider wormhole routed mesh




[example from Li and McKinley, IEEE Computer v26n2, 1993]

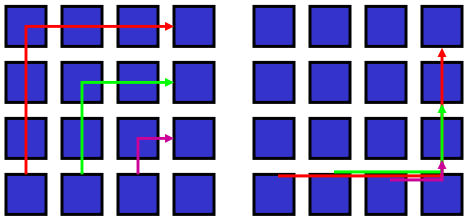
# Dimension Order Routing

- Simple (early Caltech) solution
  - order dimensions
  - force complete routing in lower dimensions before route in next higher dimension



# Dimension Order Routing

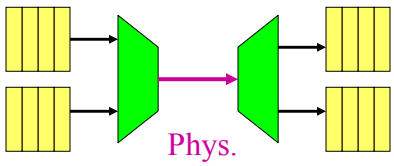
- Avoids cycles in channel graph
- Limits routing freedom
- Can cause artificial congestion
  - consider
    - (0,0) to (3,3)
    - (1,0) to (3,2)
    - (2,0) to (3,1)



- [There is a rich literature on how to do better]

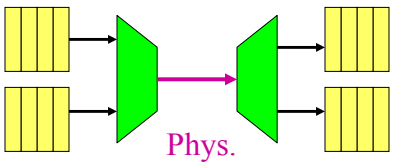
# Virtual Channel

- **Variation**: each physical channel represents multiple logical channels
  - each logical channel has own buffers
  - blocking in one VC allows other VCs to use the physical link






# Virtual Channels




- Benefits
  - can be used to remove cycles
    - *e.g.* separate increasing and decreasing channels
    - route increasing first, then decreasing
    - more freedom than dimension ordered
  - prioritize traffic
    - *e.g.* prevent control/OS traffic from being blocked by user traffic
  - better utilization of physical routing channels

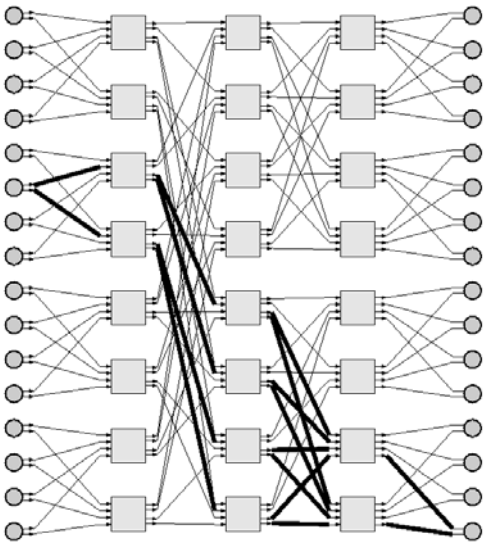
# Lost Freedom?

- Online routes often make (must make) decisions based on local information
- Can make wrong decision
  - *i.e.* two paths look equally good at one point in net
    - but one leads to congestion/blocking further ahead



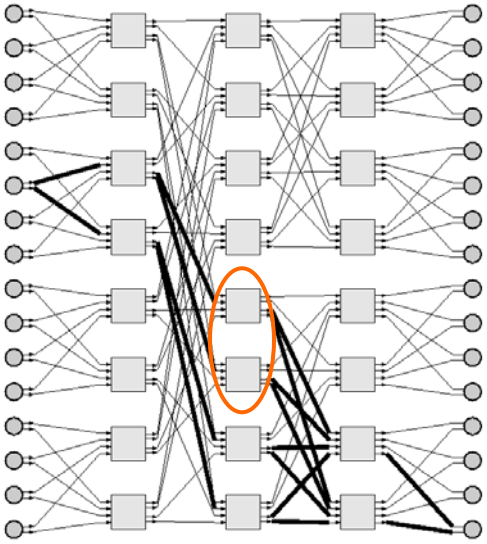
# Multibutterfly Network

- Dilated routers
  - have multiple outputs in each logical direction
  - Means multiple paths between any src,sink pair
- Use to avoid congestion
  - also faults



# Multibutterfly Network

- Can get into local blocking when there is a path
- Costs of not having global information





# Transit/Metro

- Self-routing circuit switched network
- When have choice
  - select randomly
    - avoid bad structural cases
- When blocked
  - drop connection
  - allow to route again from source
  - stochastic search explores all paths
    - finds any available

# Chaos Router

- For mesh/packet
  - when blocked, allow route in **any** direction
  - allows to take non-minimizing path to get around congestion
  - avoids deadlock since blocking causes misroute
- Refs:
  - [Konstantinidou and Snyder, SPAA90]
  - http://www.cs.washington.edu/research/projects/lis/chaos/www/chaos.html



# Admin

- No class Monday or Wednesday
  - Monday = Memorial Day Holiday
  - Wednesday … André out…
- Final class next Friday

# Big Ideas

- Must work with constraints of physical world
  - only have 3 dimensions (2 on current VLSI) in which to build interconnect
  - Interconnect can be dominate area, time
  - gives rise to universal networks
    - *e.g.* fat-tree



# Big Ideas

- Structure
  - exploit physical locality where possible
- Structure
  - the more predictable behavior
    - cheaper the solution
  - exploit earlier binding time
    - cheaper configured solutions
    - allow higher quality offline solutions