Packet Switch Architecture

3. Output Queueing Architectures
4. input Queueing Architectures
5. Switching Fabrics
6. Flow and Congestion Control in Sw. Fabrics

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5. Switching Fabrics

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- **5.3 What about Scalable Scheduling?**
  - self-routing fabrics, sorting networks: bad solution
  - fabrics with small internal buffers and flow control: good solution

5.1 Parallelism for High-Thruput: Inverse Multiplexing

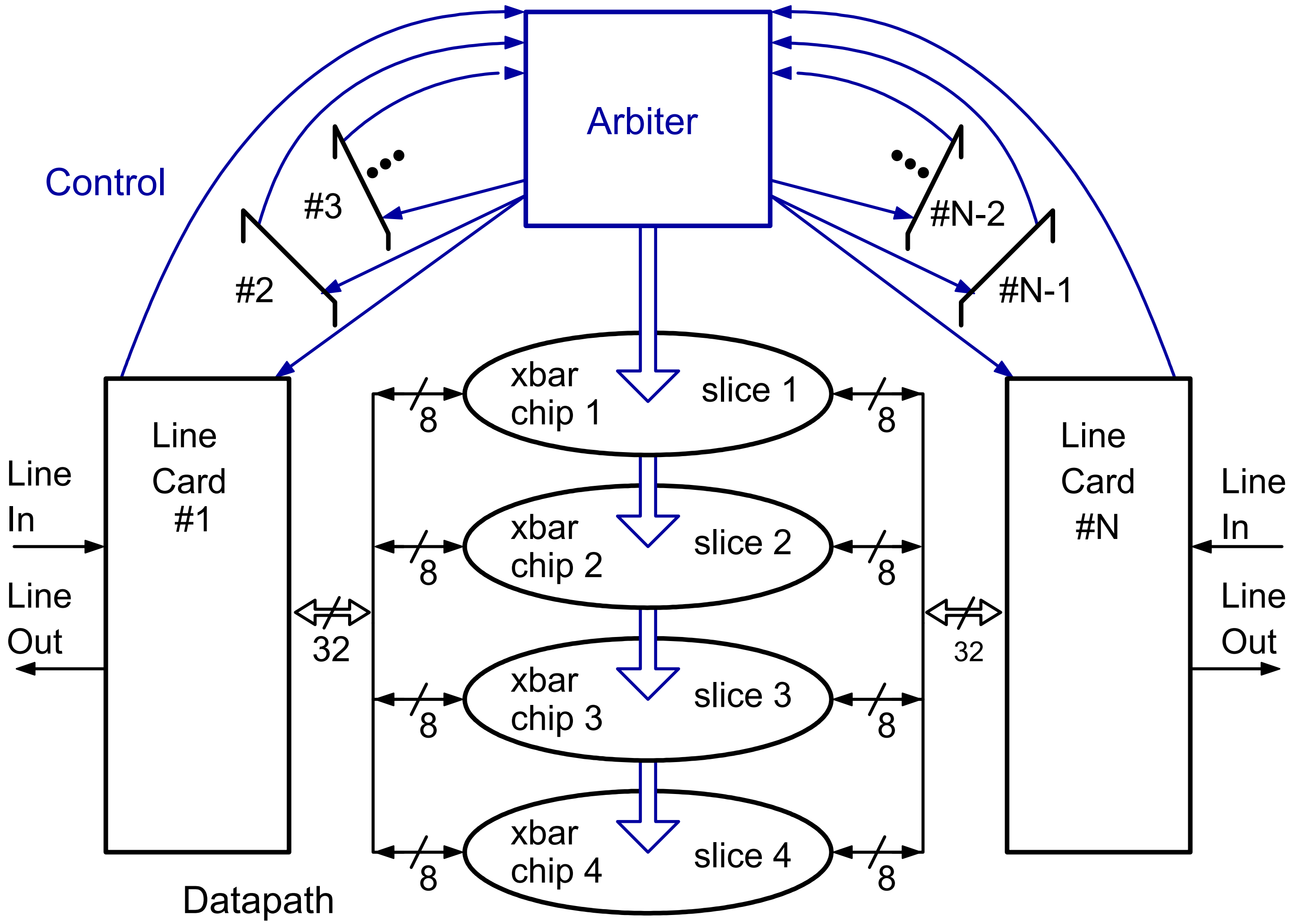
Bit	Byte-Slice	Packet	Flow
bit 1 of 8	By. 1-8	packet 1	flow 1
bit 2 of 8	By. 9-16	packet 2	flow 2
bit 3 of 8	By. 17-24	packet 3	flow 3
bit 4 of 8	By. 25-32	packet 4	flow 4
bit 5 of 8	By. 33-40	packet 5	flow 5
bit 6 of 8	By. 41-48	packet 6	flow 6
bit 7 of 8	By. 49-56	packet 7	flow 7
bit 8 of 8	By. 57-64	packet 8	flow 8
	of 64B cell	*Inverse Multiplexing*	

same handling for all wires
(same time, same destination)

different handling
(diff. times & destinations)

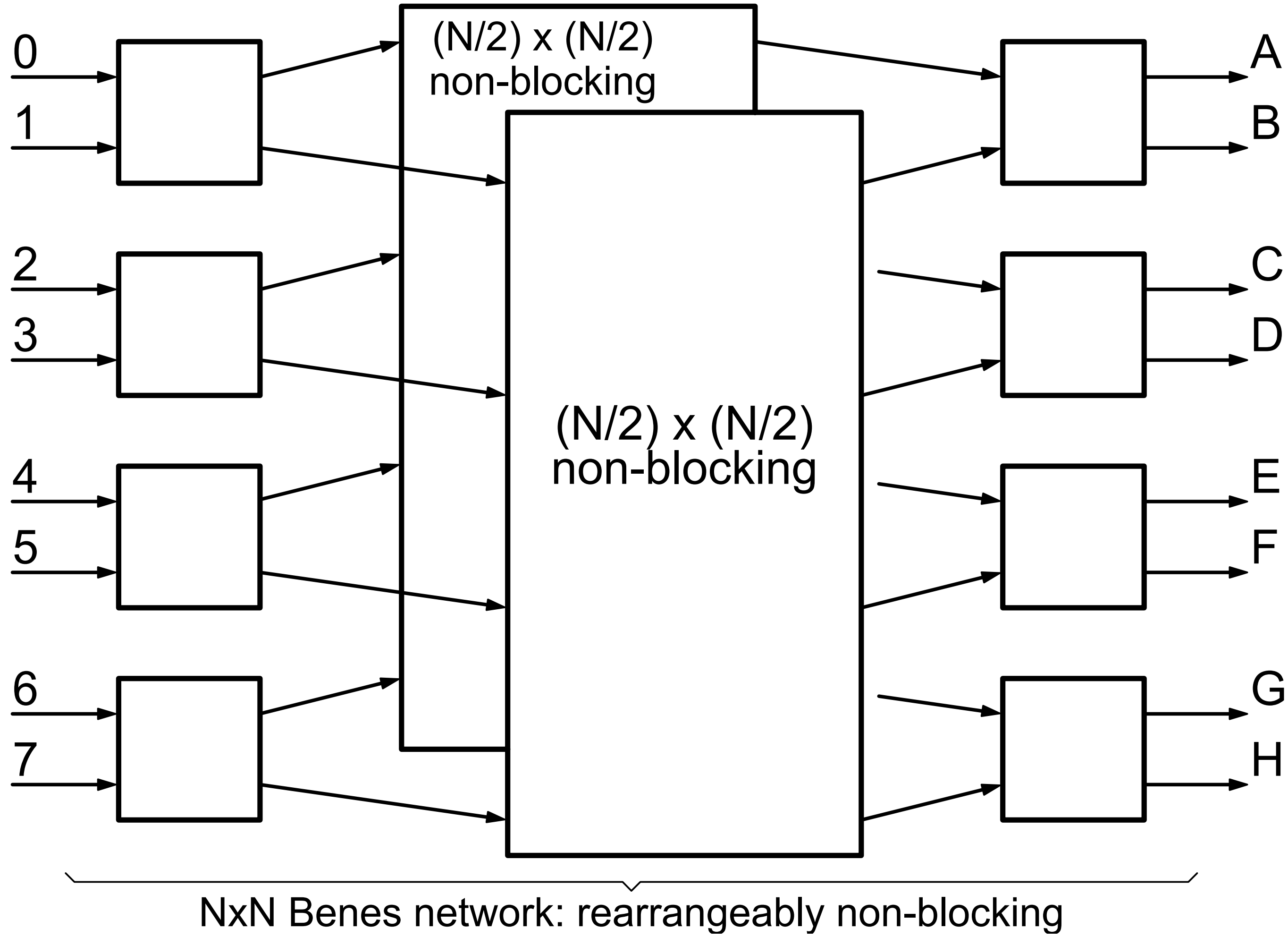
- Parallel wires or network routes for scaling (virtual) “link” throughput up
- Easy: central control, synchronized; Difficult: distributed control, asynch.

5.1 Byte-Slicing: Tiny Tera & other commercial chips



Mckeown e.a.: “Tiny Tera: a Packet Switch Core”, IEEE Micro, Jan.-Feb.’97

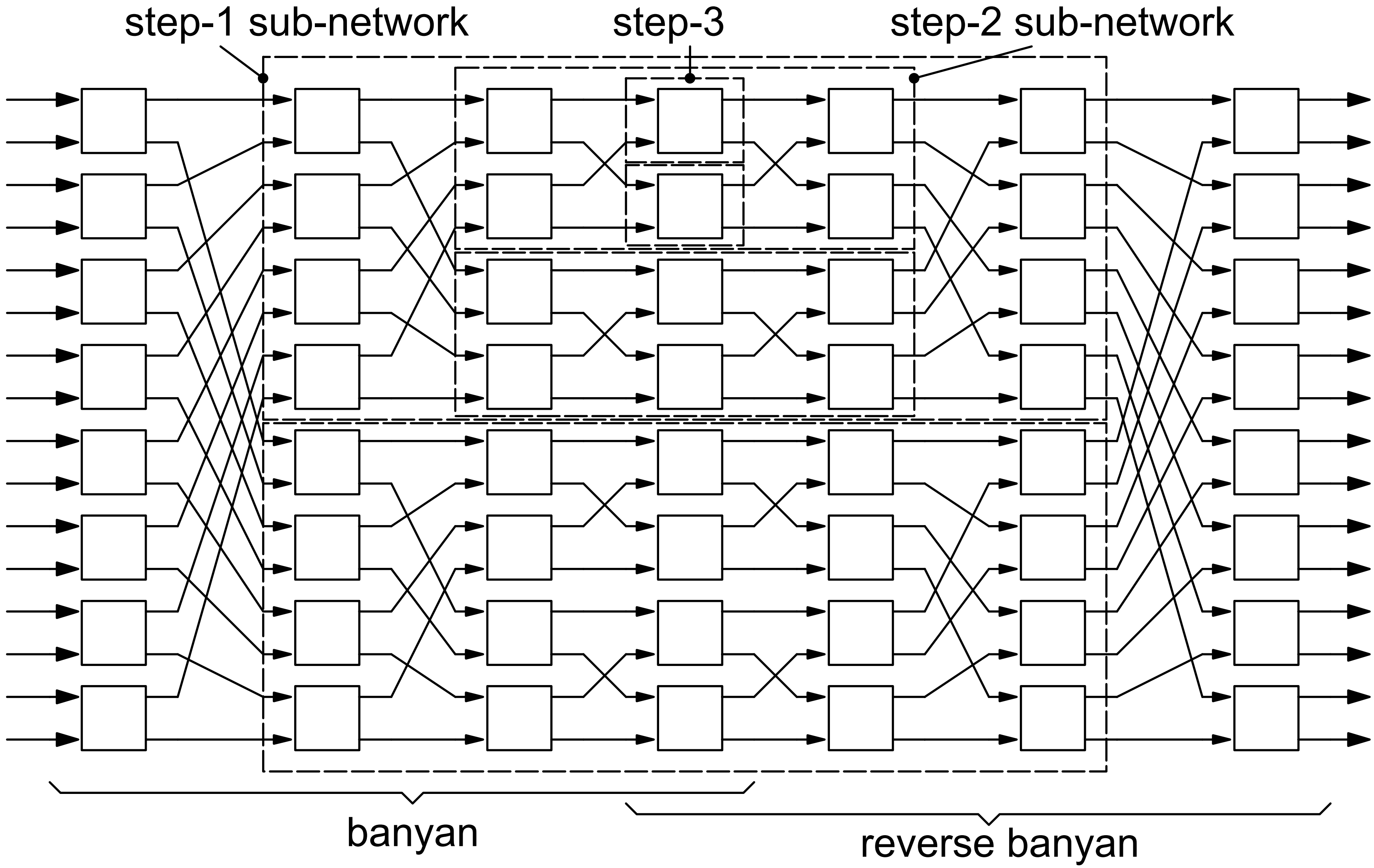
5.2.1 Benes Fabric: Recursive Definition



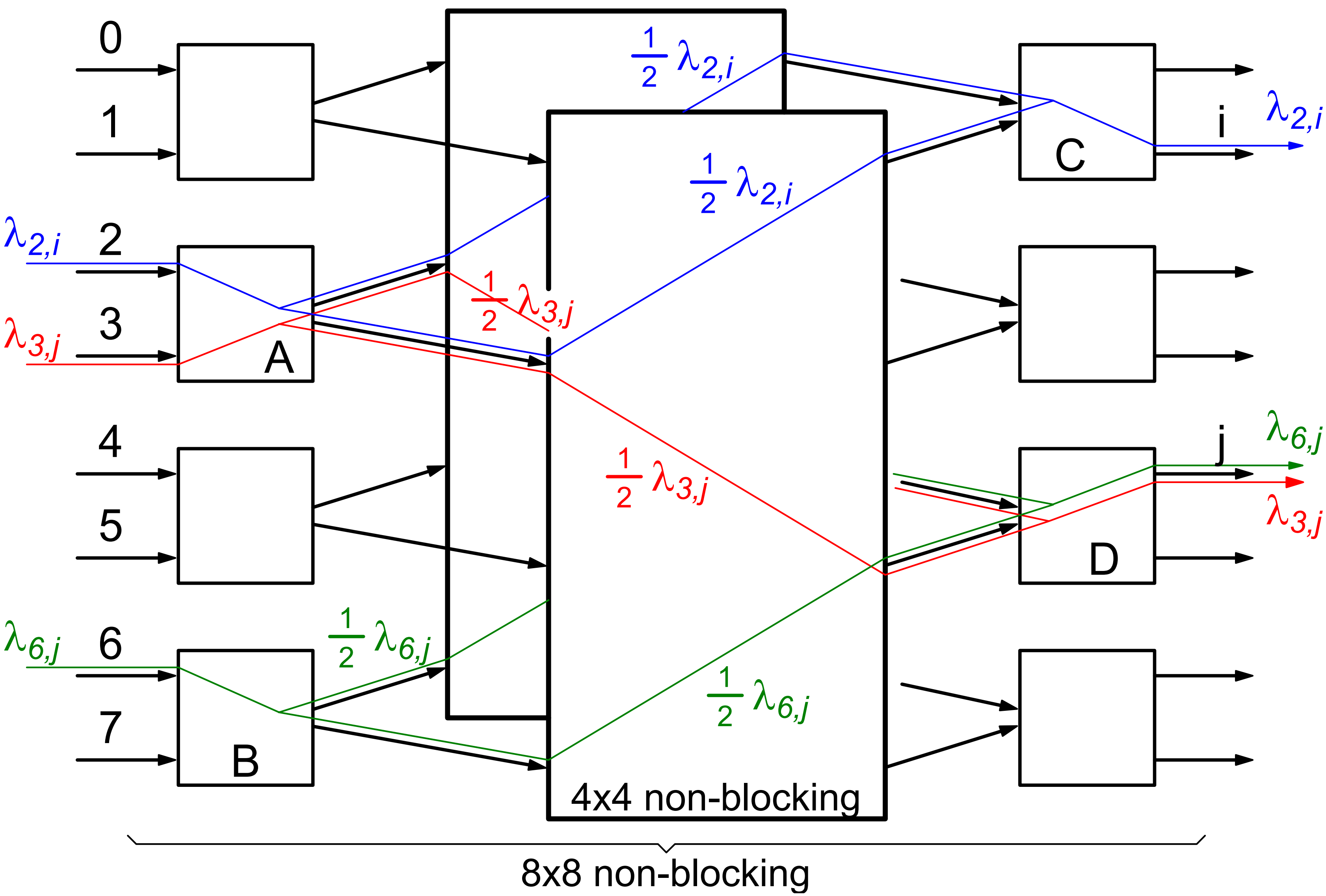
- Goal: reduce switch radix from *N×N* to *(N/2)×(N/2)*: combine ports in pairs
- Port-pairs require links of twice the throughput: use inverse multiplexing

⇒ Use two switches, of half the radix each, in parallel to provide req'd thruput

Full Construction of 16×16 Benes out of 2×2 Switches



Inverse Multiplexing for Non-Blocking Operation



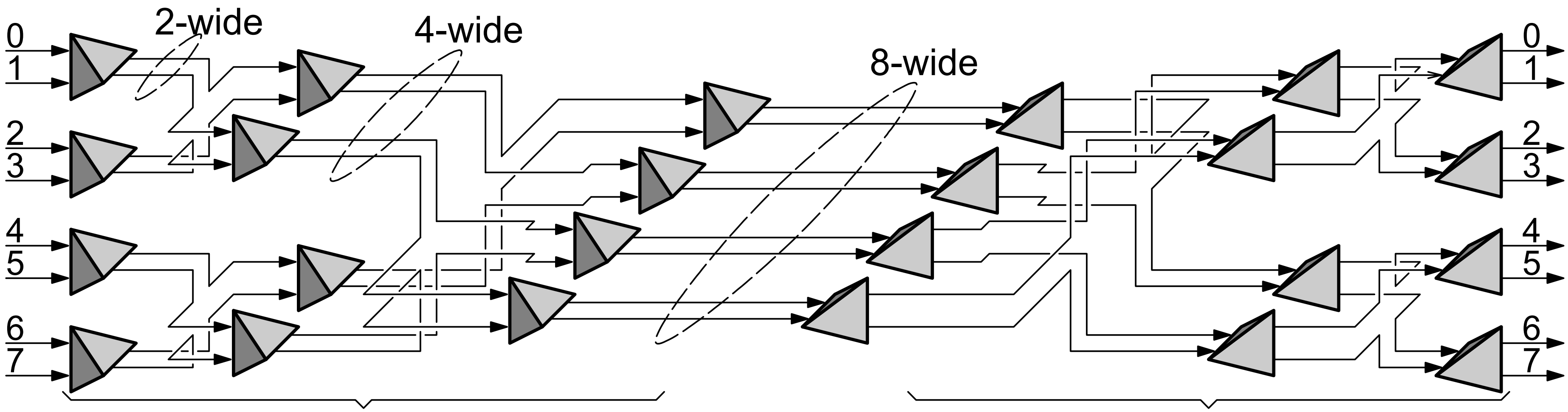
Per-Flow Inverse Mux'ing for Non-Blocking Operation

- Prove that overall $N \times N$ network is non-blocking, i.e. *any* feasible external traffic $\Rightarrow$ feasible rates on all internal links
- All traffic entering switch A is feasible, hence of aggregate rate $\leq 1+1 = 2$; it is split into two halves $\Rightarrow$ each of rate ≤ 1 $\Rightarrow$ traffic entering each *(N/2)×(N/2)* subnetwork is feasible
- It does *<u>not suffice</u>* to balance (equalize) the *aggregate* load out of switch A – must equally distribute *individual* (end-to-end) flows – *per-flow* inverse multiplexing

  $\Rightarrow$ each of $\lambda_{2,i}$; $\lambda_{3,j}$; $\lambda_{6,j}$ is individually split in two equal halves

  $\Rightarrow$ the sum of $\lambda_{3,j}+\lambda_{6,j}$ is also split in two equal halves
- All traffic exiting switch D is feasible, hence of aggregate rate $\leq 1+1 = 2$; it enters D in two equal halves $\Rightarrow$ each of rate ≤ 1 $\Rightarrow$ traffic exiting each *(N/2)×(N/2)* subnetwork is also feasible

Conceptual View of 8x8 Benes: Virtual Parallel Links using Inverse Multiplexing



Methods to implement (per-flow) Inverse Multiplexing

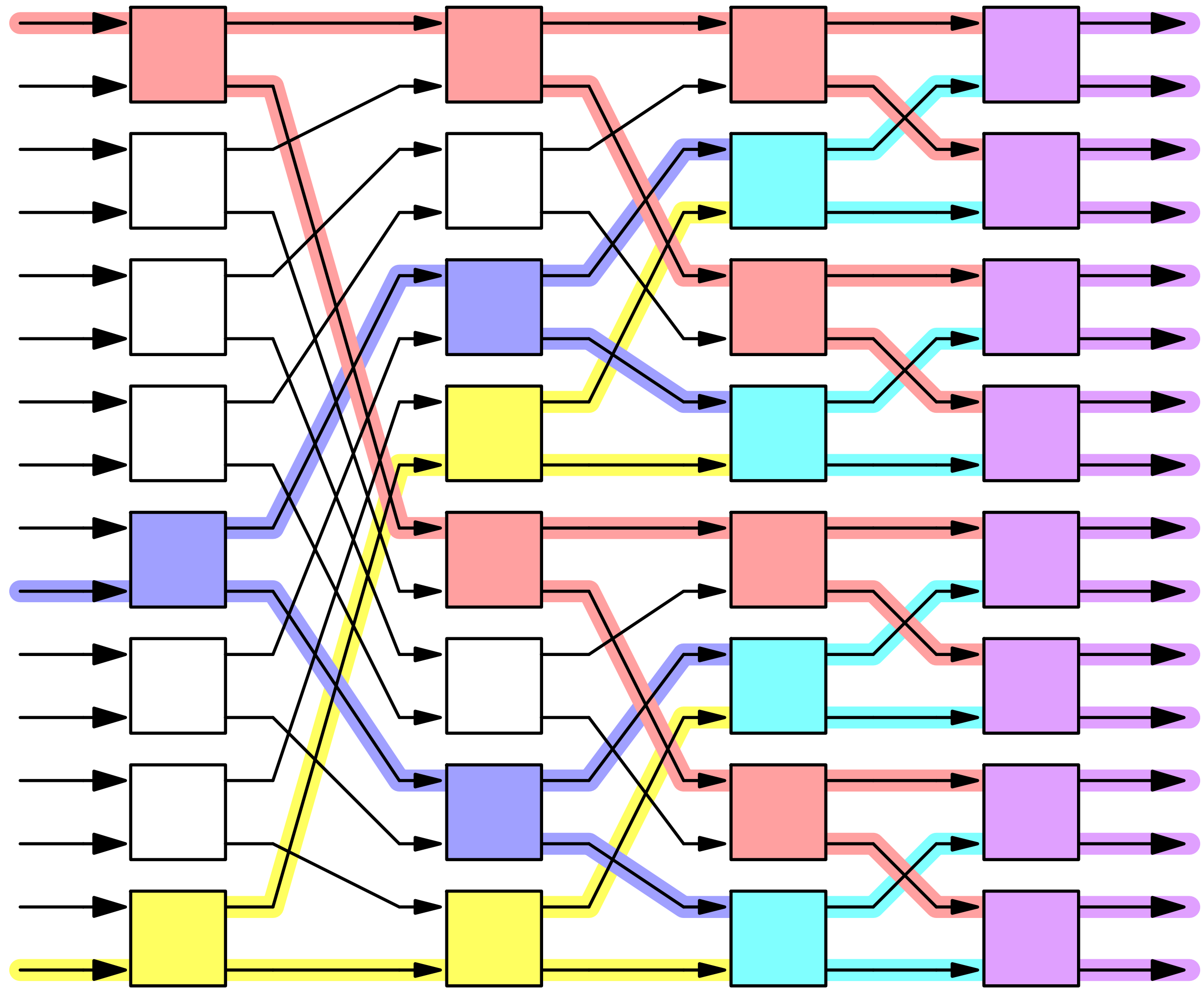
- *Per-Flow Round-Robin*, at packet granularity
  - for each flow, circularly and per-packet alternate among routes
  - requires maintaining per-flow state
  - danger of synchronized RR pointers: pck bursts to same route
  - alternative: arbitrary route selection, provided the (per-flow) imbalance counter has not exceeded upper bound value

Methods to implement (per-flow) inverse multiplexing (continued)

- *Adaptive Routing*, at packet granularity – usu. Indisciminate
  - – chose the route with least-occupied buffer (max. credits)
  - + does not maintain or use per-flow state
  - − per-flow load balancing only “after-the-fact”, when buffers fill up
- *Randomized* Route Selection, at packet granularity
  - + does not require maintaining per-flow state
  - − load balancing is approximate, and long-term
- **Packet Resequencing** (when needed): major cost of inv.mux’ng
  - – Chiussi, Khotimsky, Krishnan: IEEE GLOBECOM'98
- Hashed Route Selection *at entire Flow Granularity*
  - – route selection based on hash function of flow ID
  - + all packets of given flow through same route $\Rightarrow$ *in-order delivery*
  - − poor load balancing when small number of flows

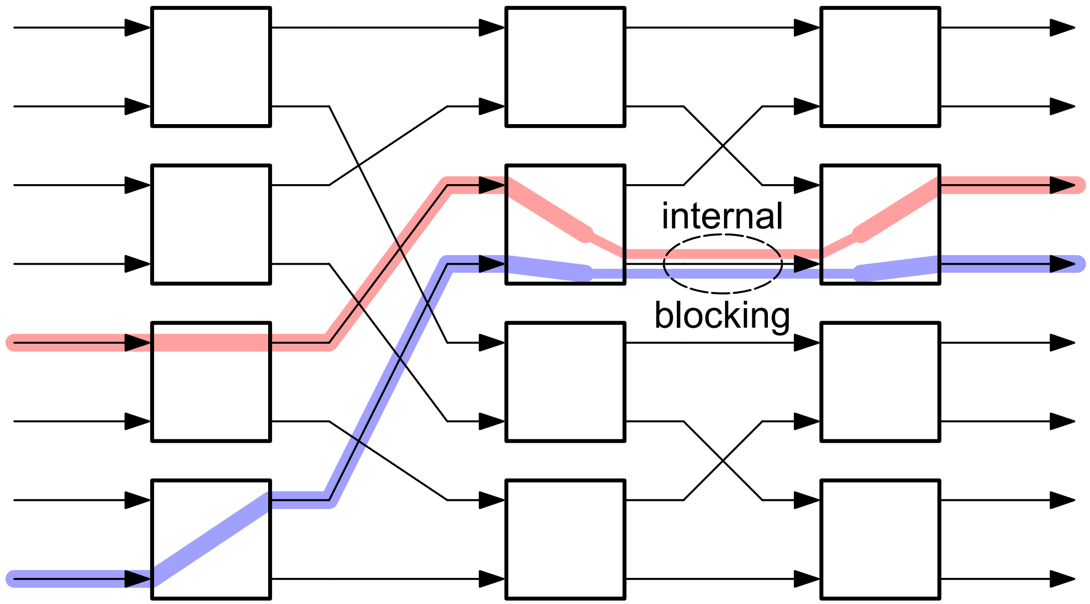
5.2.2 The Banyan (Butterfly) Network

- Single route from given input to given output
- Each input is the root of a tree leading to all outputs
- Trees share nodes
- (Similarly, outputs are roots of trees feeding each from all inputs)
- for $N \times N$ network made of 2×2 sw.:
- $\log_2 N$ stages, of
- $N/2$ sw. per stage



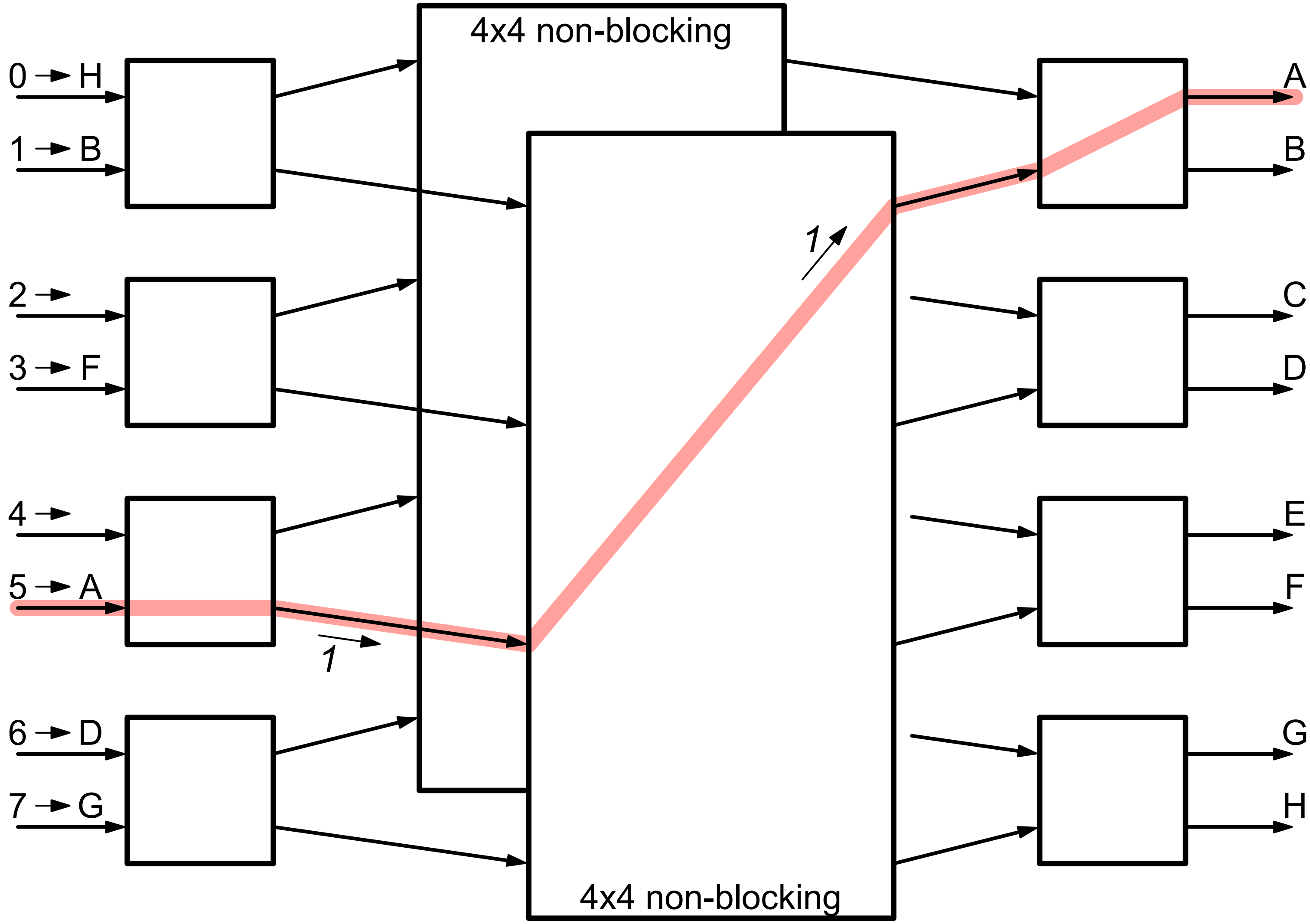
The banyan network is internally blocking

- Consider circuits: each $\lambda_{i,j}$ is either 1 or 0: single connection per port – "telephony" style
- There are *N!* such circuit connection patterns for a *N*×*N* network – each is a permutation of the numbers (1, 2, …, *N*)

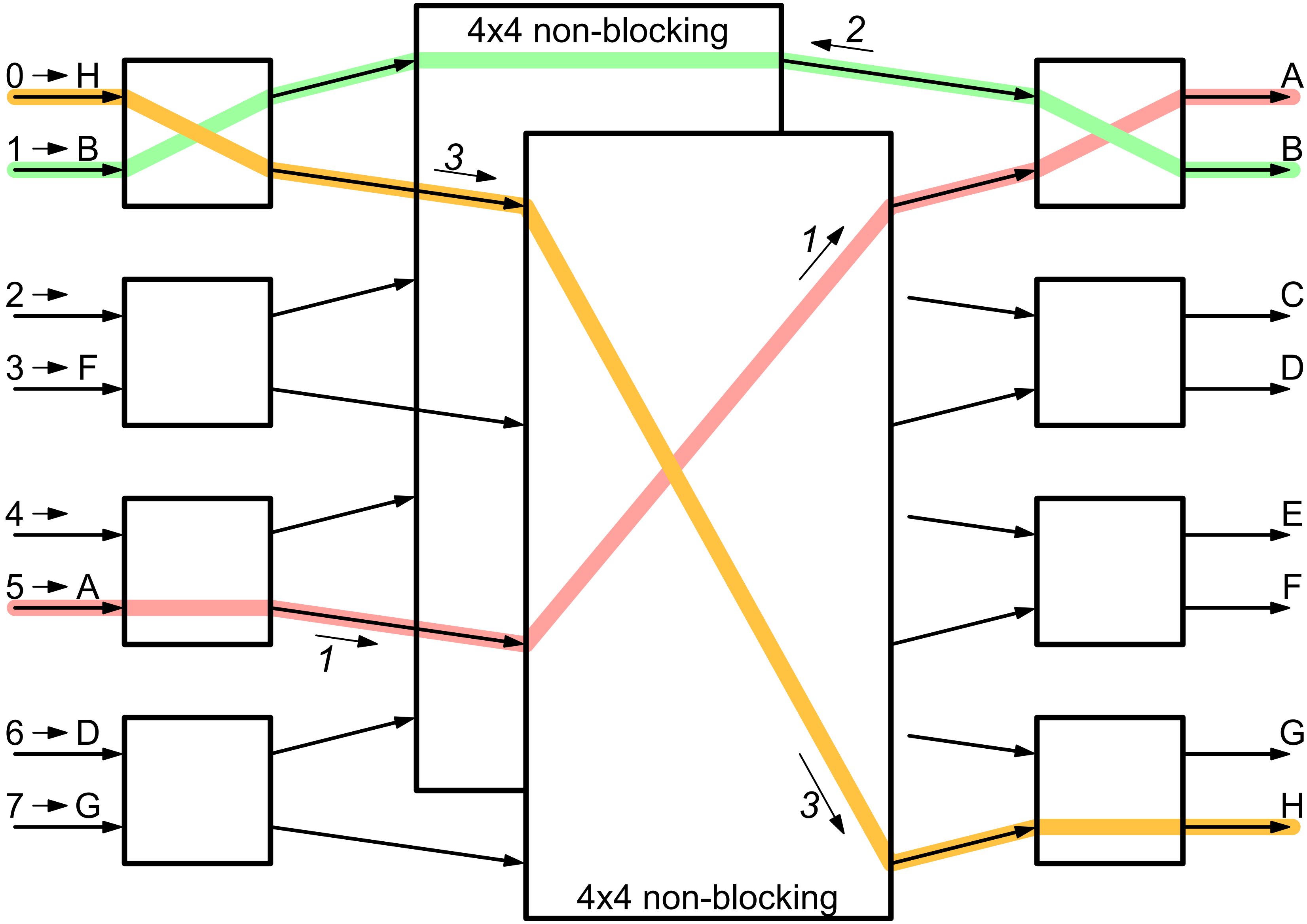


- Any network containing $(N/2)\cdot\log_2 N$ or less 2×2 switches (like the banyan does) has to be internally blocking, because it can only be placed into less than *N!* states, hence cannot route all *N!* existing sets of con. req's
- Each 2×2 switch can be placed in *2* different states; a network containing $(N/2)\cdot\log_2 N$ such switches can be placed into $2^{(N/2)\cdot\log N} = N^{(N/2)}$ different states; $N^{(N/2)} = N \cdot (N/2)^{(N/2)-1} \cdot 2^{(N/2)-1} < N \cdot [(N-1)\cdot \ldots \cdot(N/2+1)] \cdot [(N/2) \cdot \ldots \cdot 2] = N!$ ⇒ not enough states

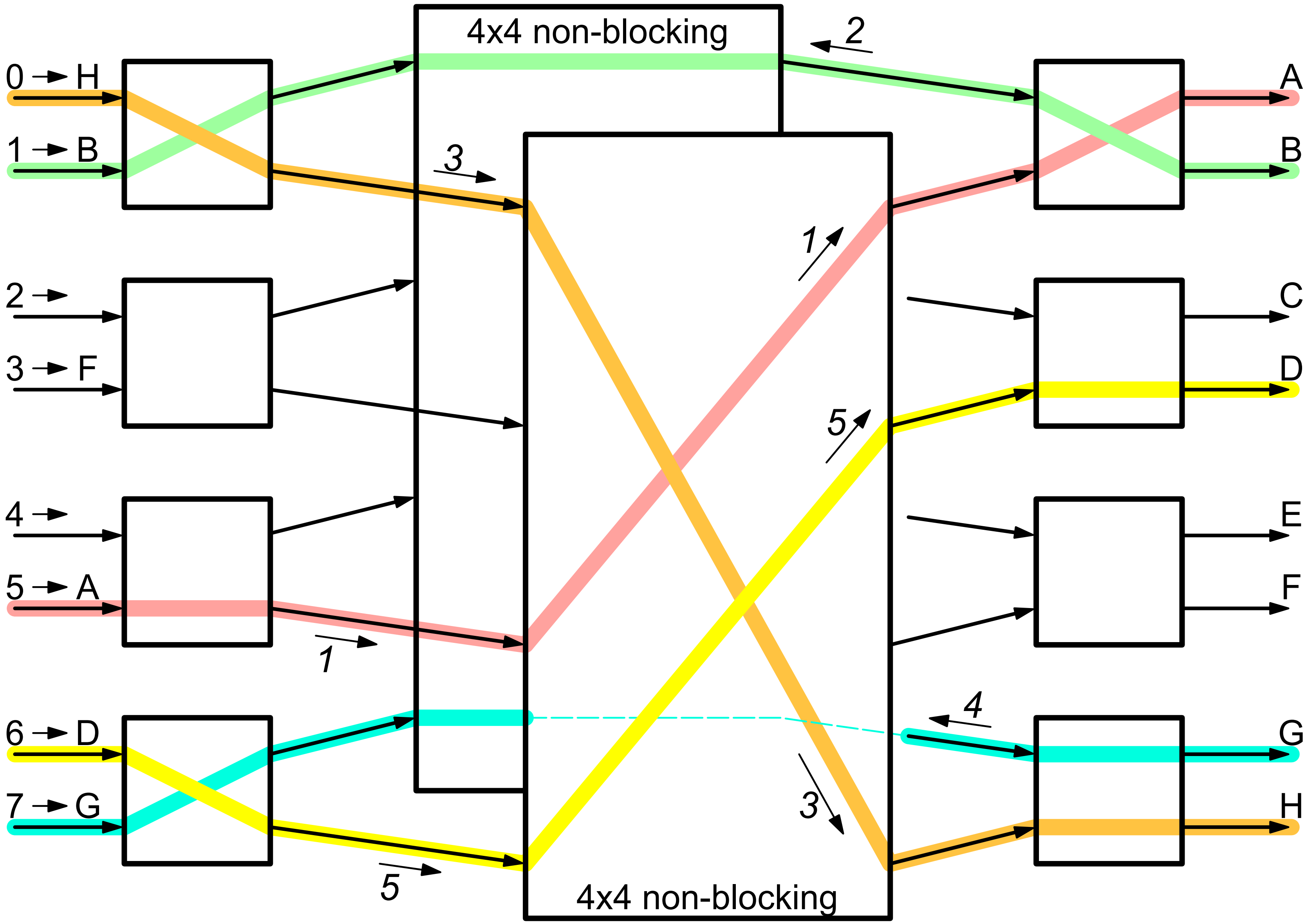
Benes Net under Telephony-Ckt Connection Requests



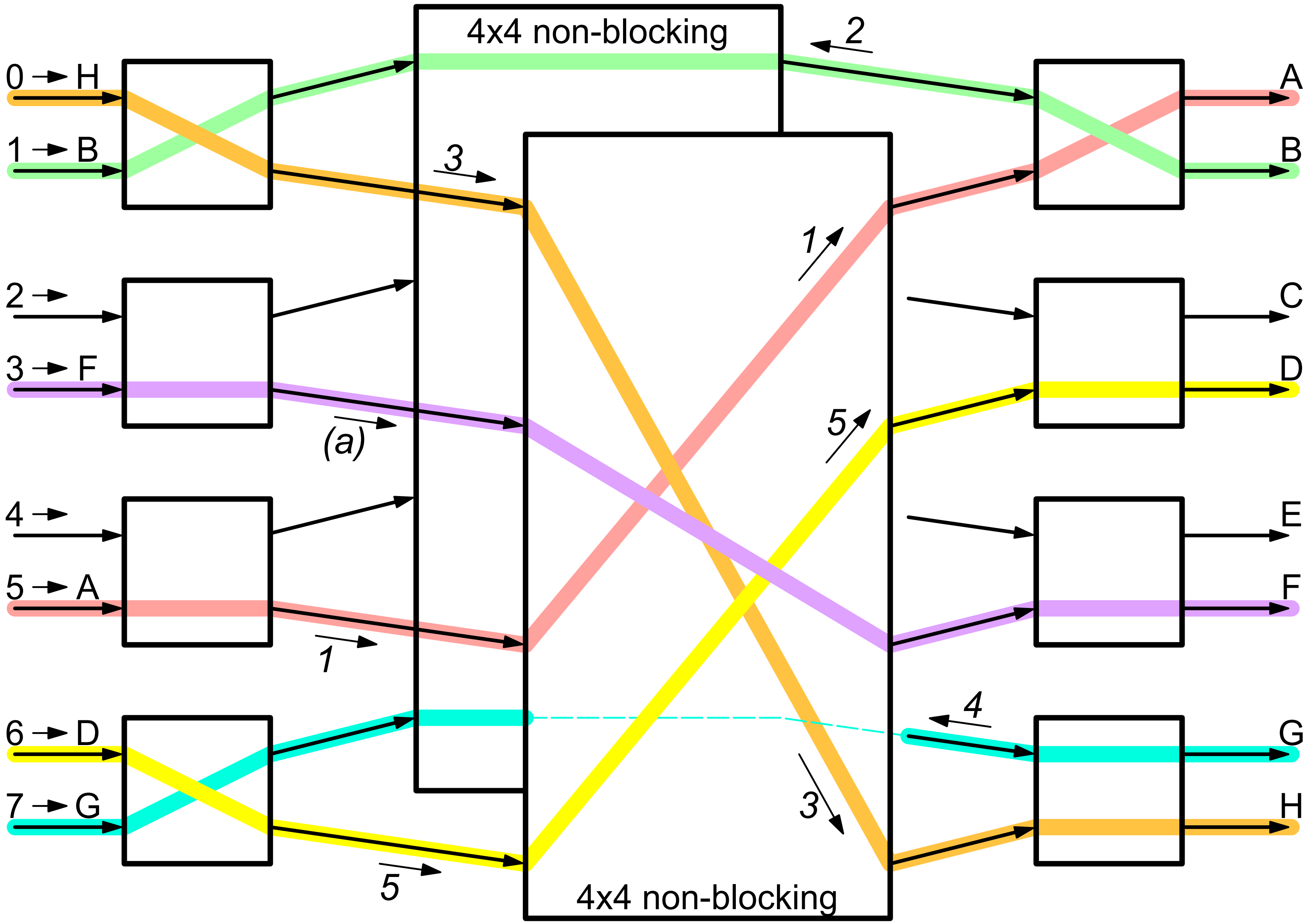
- Circuit Connections: Start from an input, use one of the subnets



- Continue from the brother port of the output, then the brother of the input

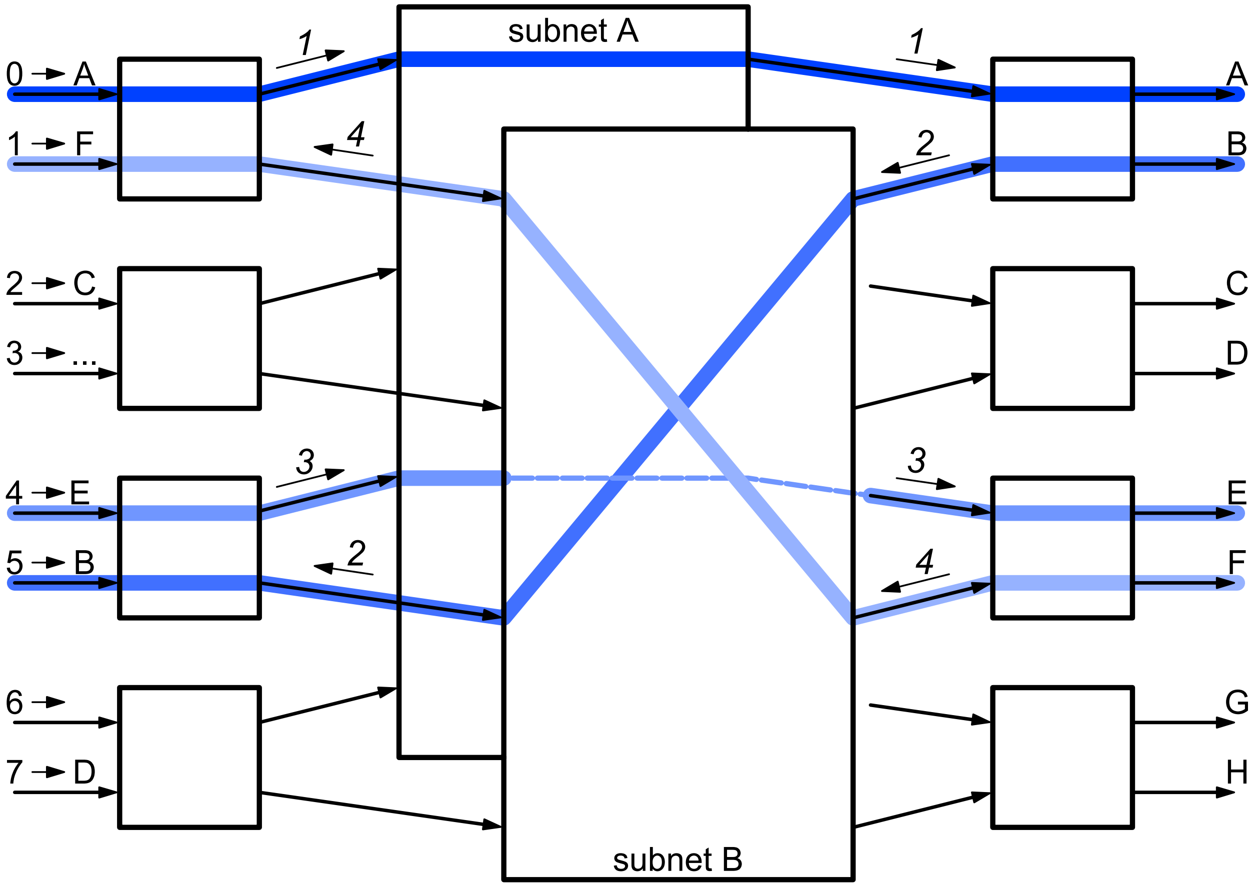


- Keep “threading” output and input switches, till closing or no-connection



- Start a new "thread" (a) from an unconnected input, till completing all conn.

(A) Thread termination on input side (1 of 2)

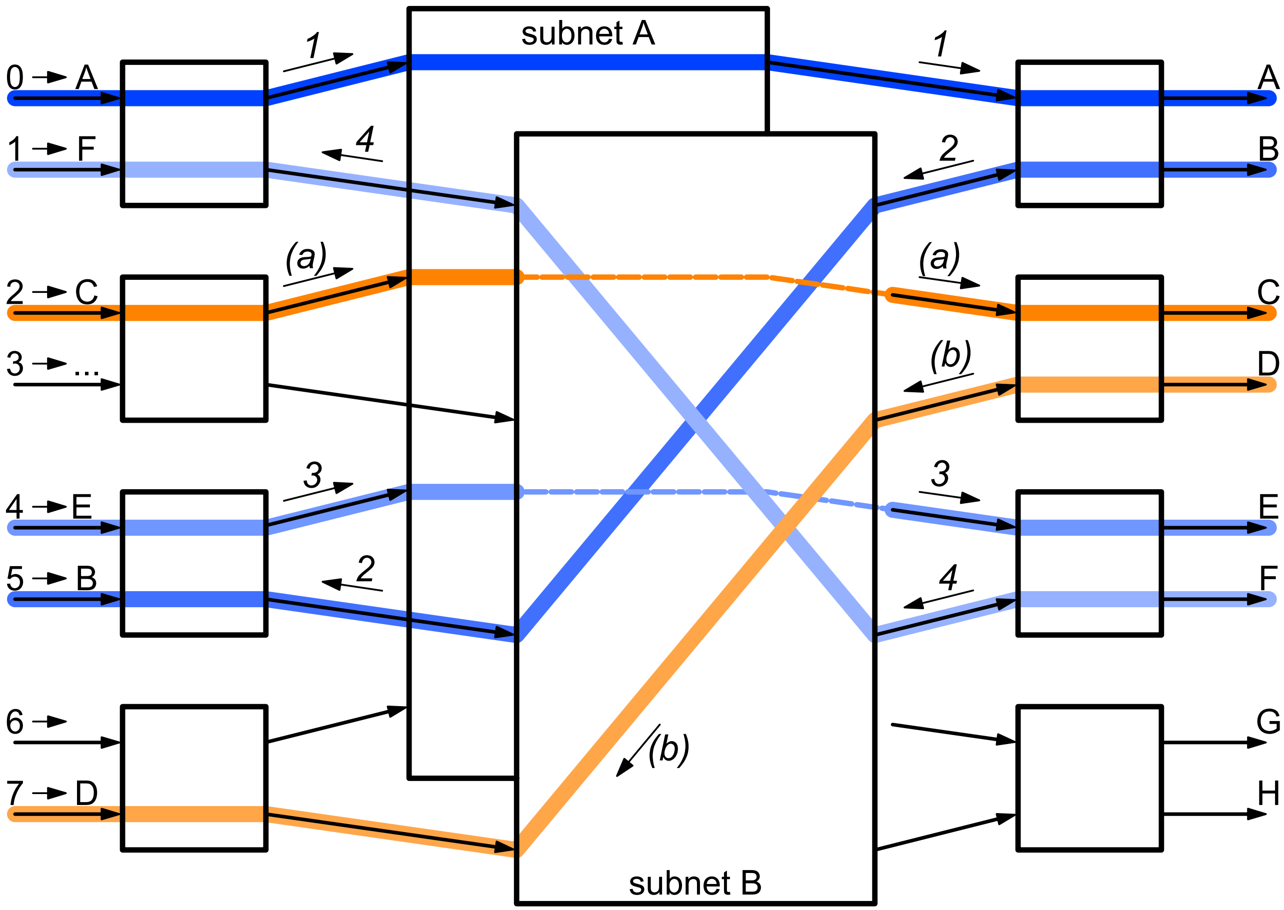


- Threads always start on the input side
- If a thread terminates on the input side:
  - all touched output switches are completely connected
  - concerning touched input switches:

    (1) if thread closes, all are complete,

    …

(A) Thread termination on input side (2 of 2)

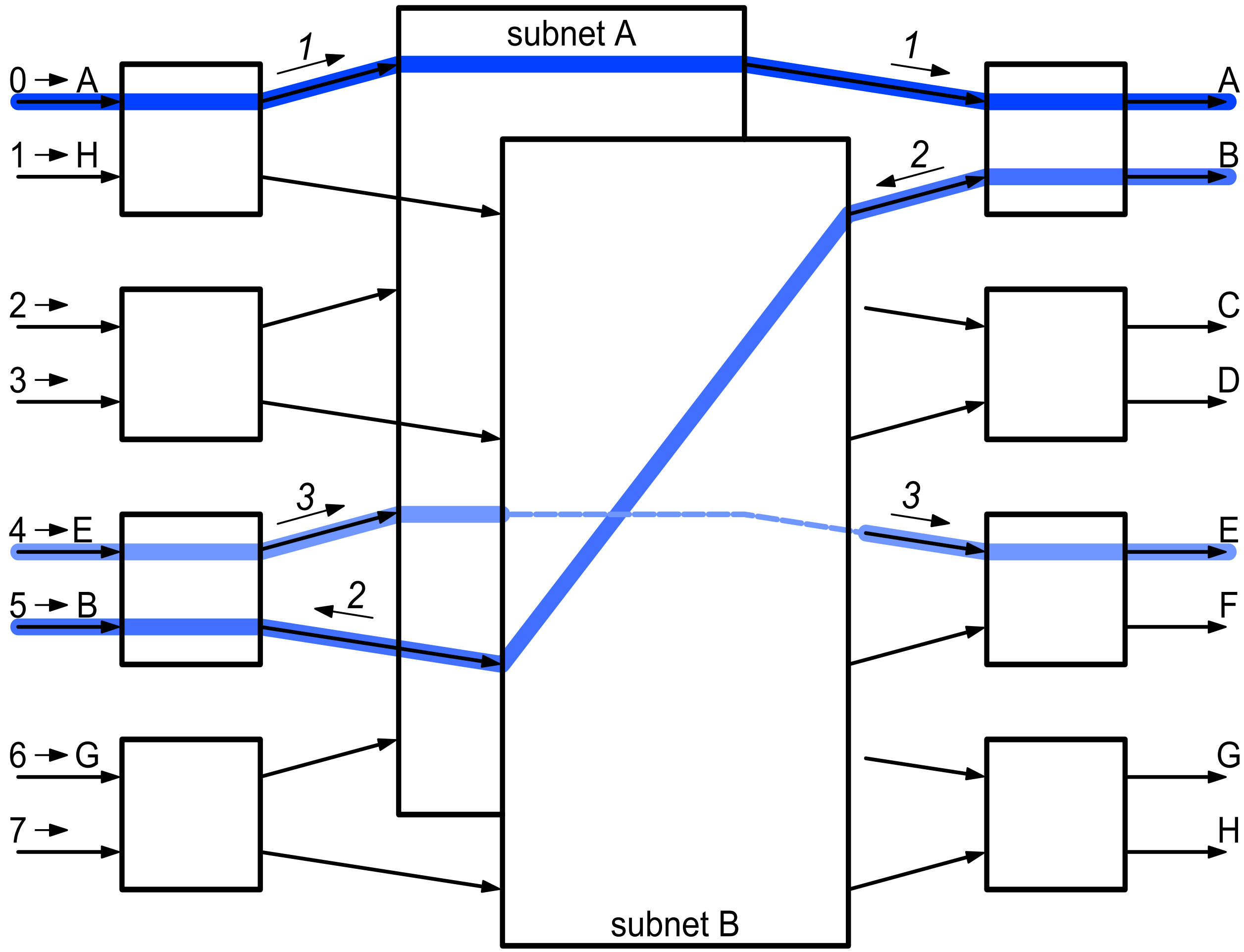


- Threads always start on the input side
- If a thread terminates on the input side:
  - –all touched output switches are completely connected
  - –concerning touched input switches:

    (1) if thread closes (4), all are complete,

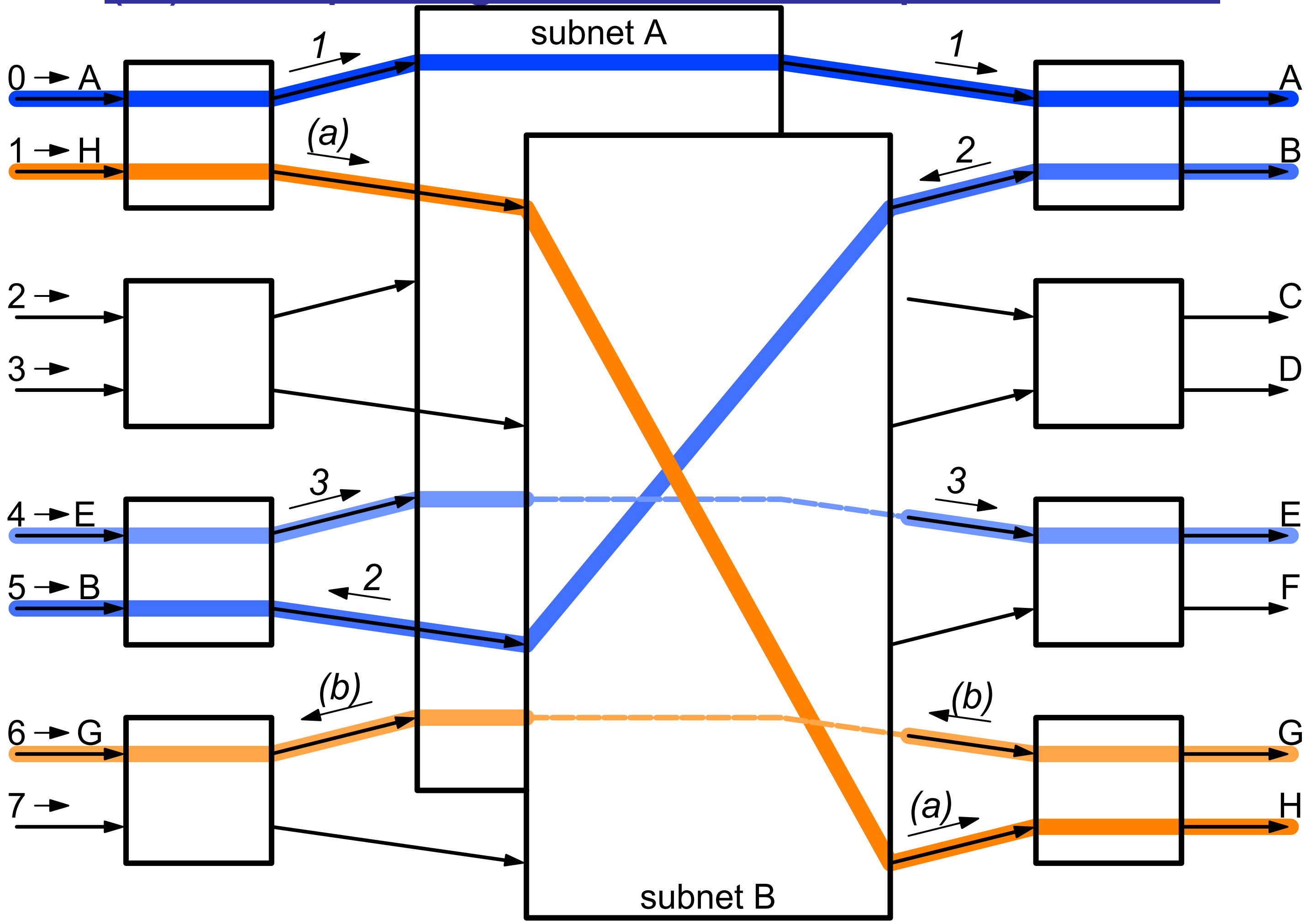
    (2) if thread terminates on half-used input (b): all touched input switches are complete, except the first one, which is half-covered by this thread

(B) Thread termination on output side



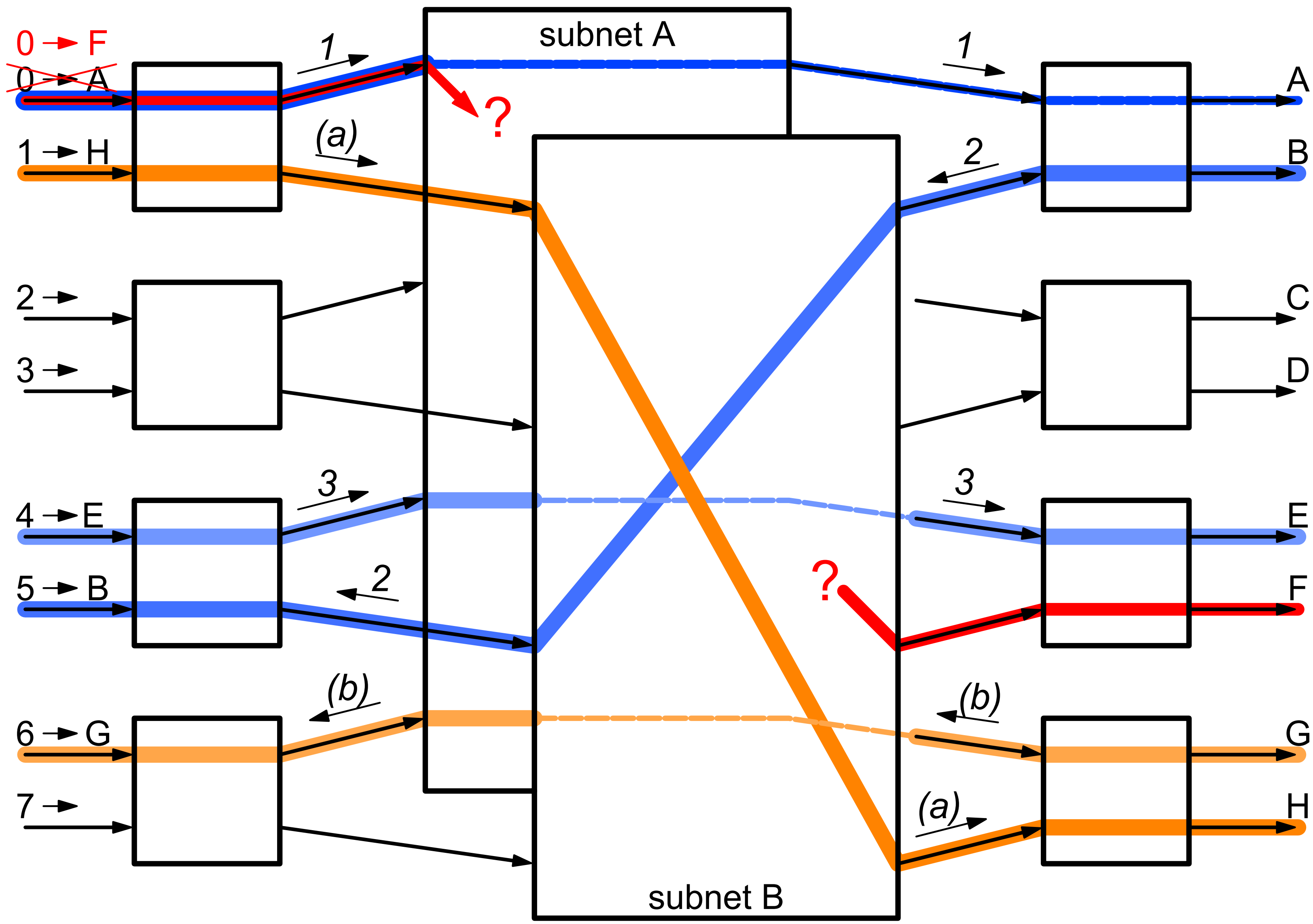
- Threads always start on the input side
- If a thread terminates on the output side:
  - all touched output switches are completely connected
  - the first touched input switch is half-covered

(C) Completing half-covered input switches



- New threads always start from a half-covered input switch, if there is one
  ⇒ all threads cover all out-sw's they touch, in-sw's are covered in sequence

Benes Fabric: *Rearrangeably* Non-Blocking

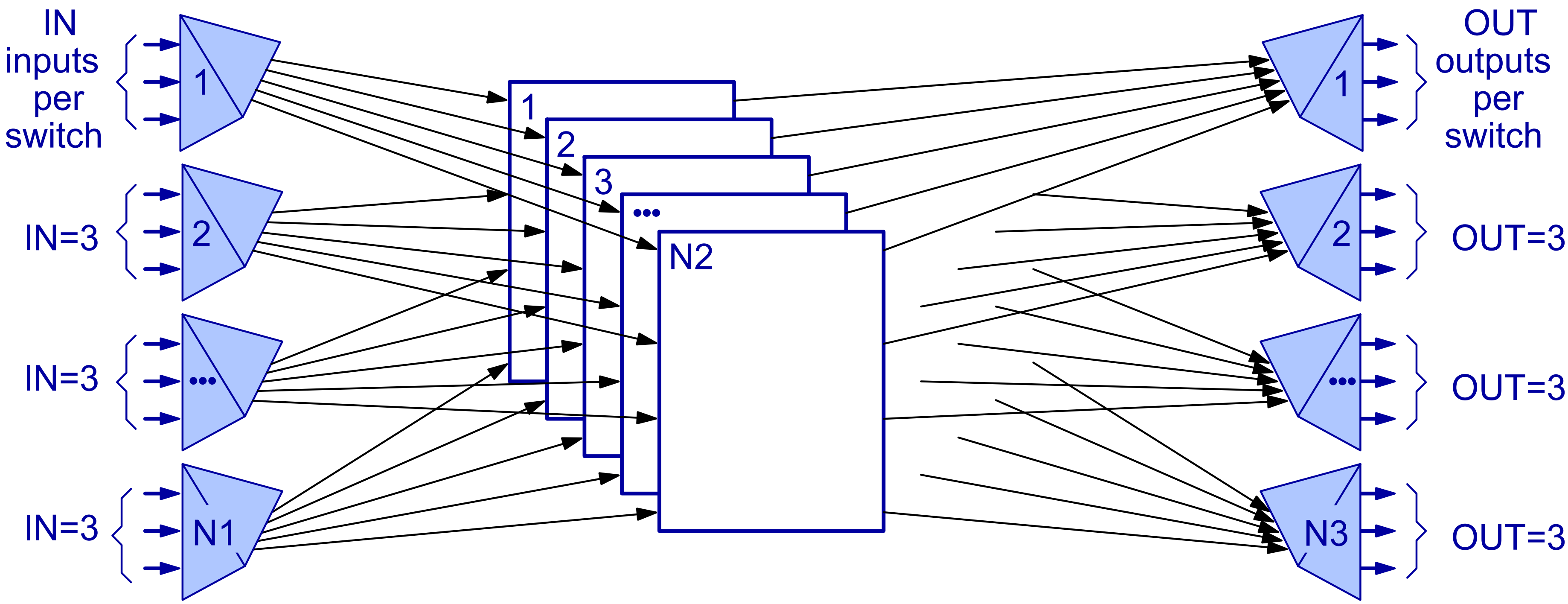


Which is the lowest-cost non-blocking fabric?

- $N \times N$ Benes network, made of 2×2 switches:
  - $2 \cdot (\log_2 N) - 1$ stages (2 banyans back-to-back, 1 shared stage)
  - $N/2$ switches per stage $\Rightarrow$ total switches = $N \cdot (\log_2 N) - N/2$
  - number of states that the Benes network can be in = $2^{\#\text{switches}}$ = $2^{N \cdot (\log N) - N/2} = (2^{\log N})^N / 2^{N/2} = N^N / 2^{N/2} = [N \cdot \ldots \cdot N] \cdot [(N/2) \cdot \ldots \cdot (N/2)] > N \cdot (N-1) \cdot \ldots \cdot 2 \cdot 1 = N!$ $\Rightarrow$ Benes has more states than the minimum required for a net to be non-blocking
  - Benes was seen to be non-blocking: *(i)* circuits and the "threading" algorithm, *(ii)* packets and inverse multiplexing
  - *"rearrangeably"* non-blocking: in a partially connected network, making a new connection may require re-routing existing ones
- Impossible for any network with about half the switches of the Benes (e.g. banyan) to be non-blocking (# of states)

$\Rightarrow$Benes is probably the lowest-cost *practical* non-blocking fabric

5.2.3 Clos Networks (generalization of Benes nets)

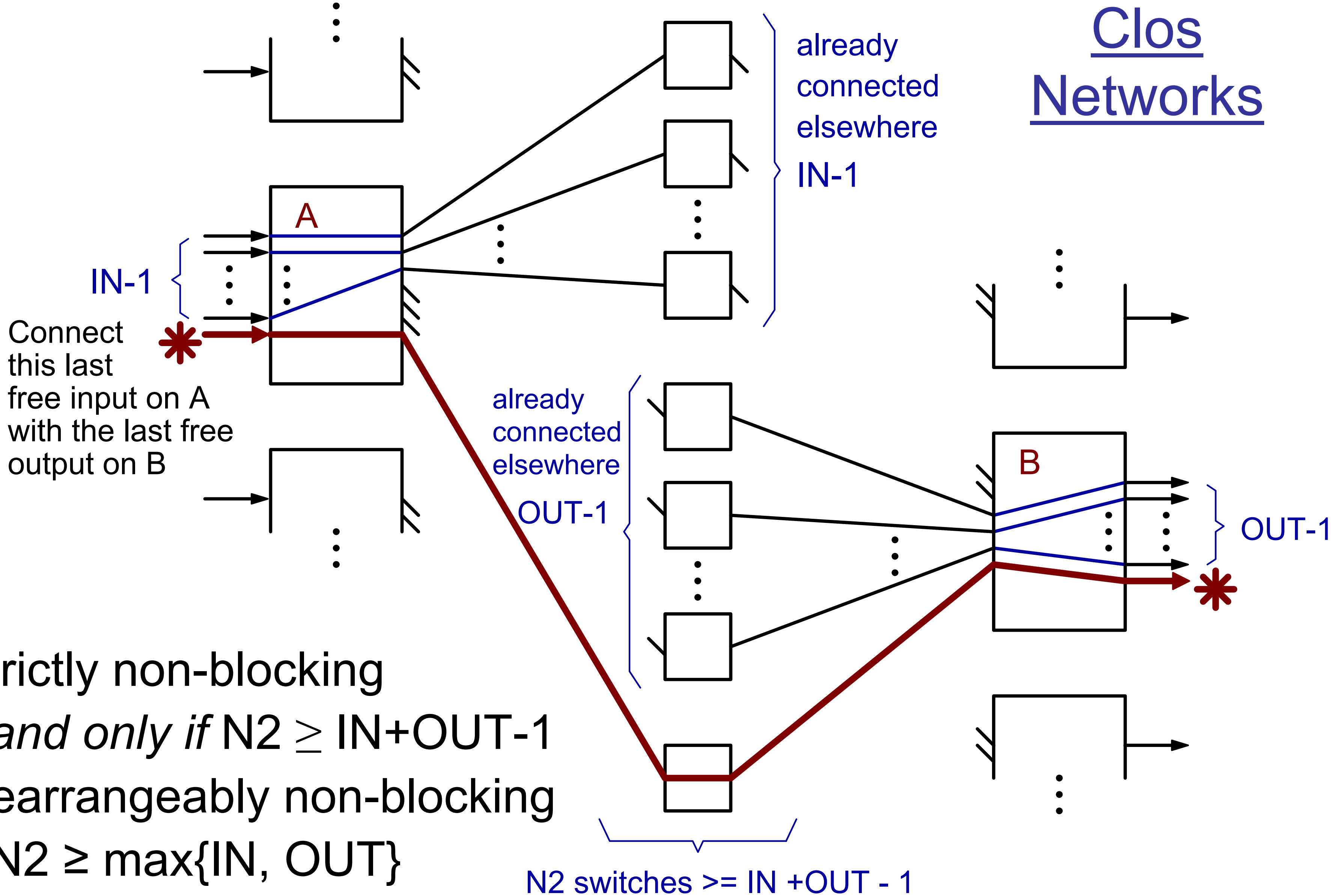


5-parameter Network: (IN, N1, N2, N3, OUT)

this example: the (3, 4, 5, 4, 3) Clos Network

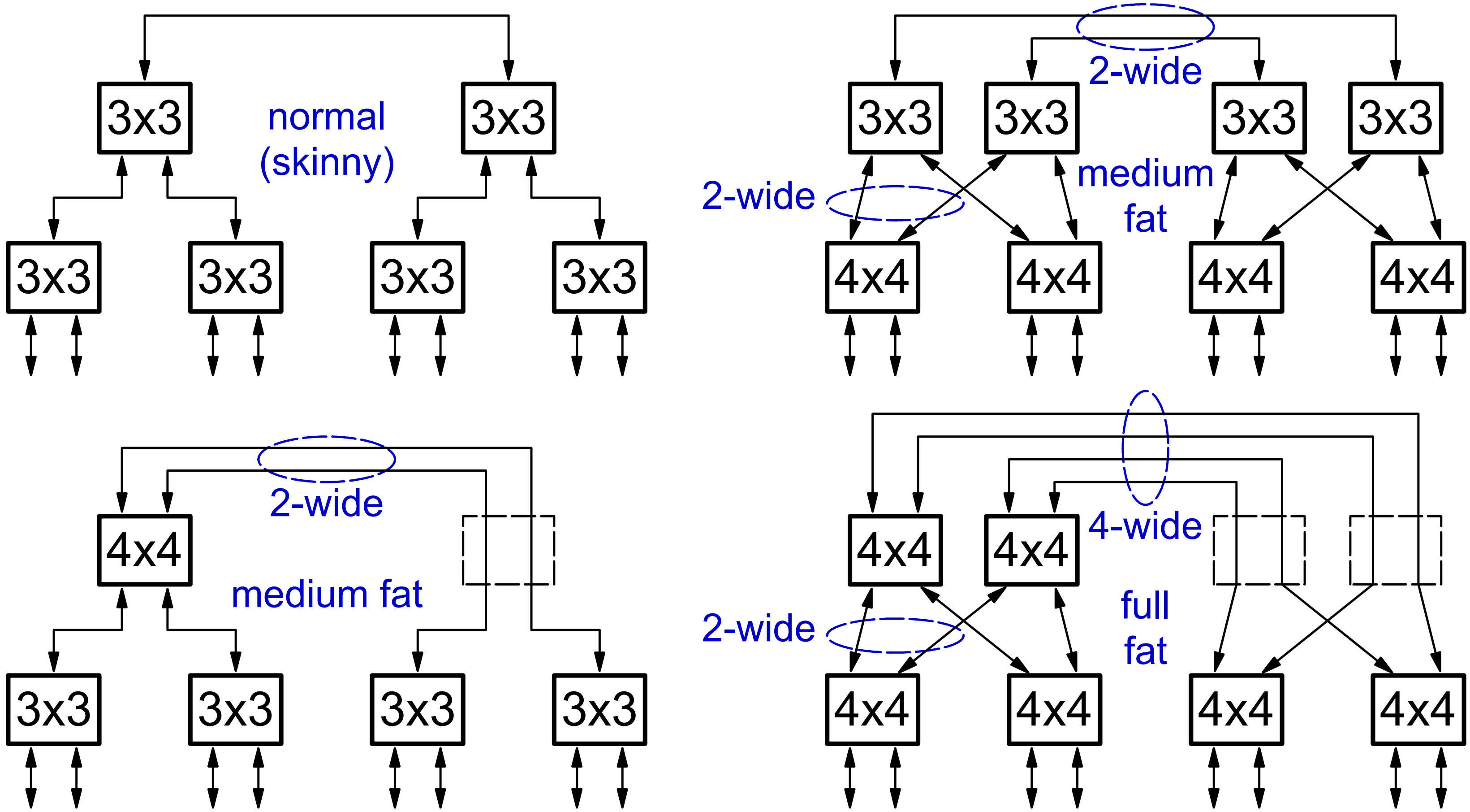
usually: IN = OUT, and N1 = N3

Clos Networks



- Strictly non-blocking *if and only if* N2 $\geq$ IN+OUT-1
- Rearrangeably non-blocking *if* N2 $\geq$ max{IN, OUT}

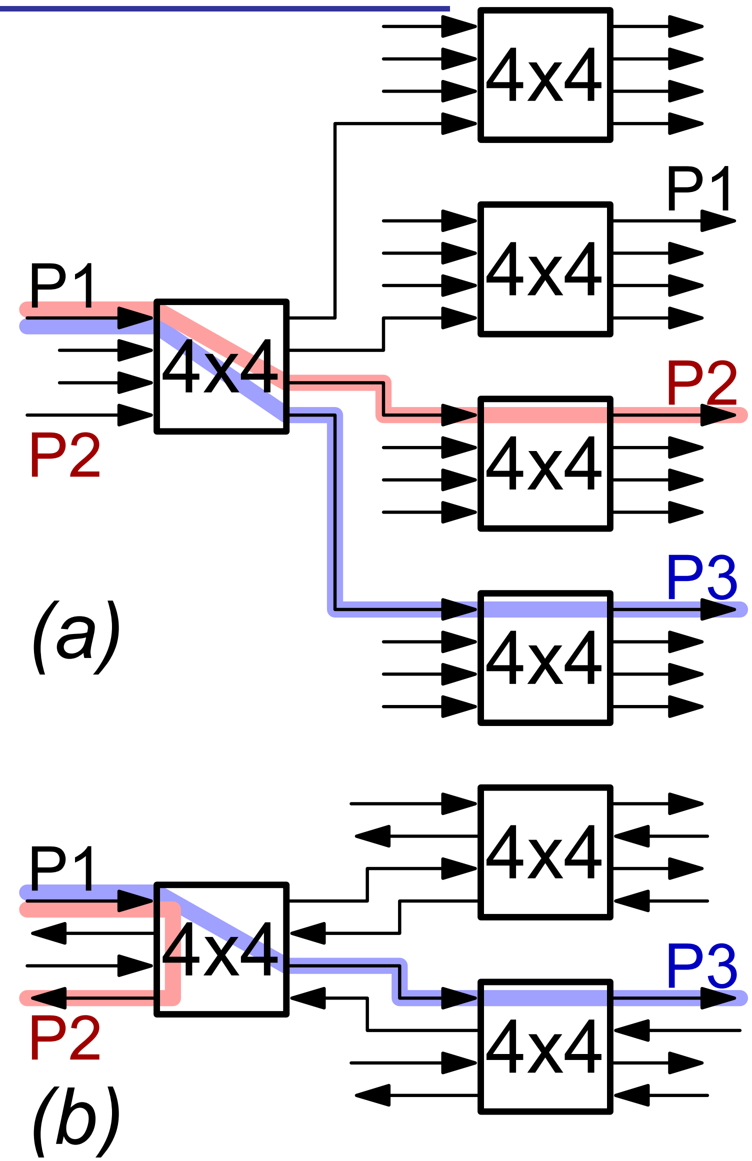
5.2.4 Fat Trees: customizable local versus global traffic



- Customizable percent fat – configurable amounts of internal blocking
- Bidirectional links, like most practical interconnects
- Skinny trees support local traffic – Full-fat tree is like folded Benes

Switch Radix, Hop Count, Network Diameter

- Most of our examples used unidirectional links – fig. *(a)*
  - "indirect" nets have ports at edges.
- Most practical interconnects use bidirectional links – fig. *(b)*
  - "direct" nets provide external ports on all switches.
- If some destinations are reachable at reduced hop count (P2 in *(b)*), that is at the expense of the total number of destinations reachable at a given hop count – or larger network diameter.
- Energy consumption to cross the net critically depends on the number of chip-to-chip hops, because chip power is dominated by I/O pin driver consum.



5.3 Towards Scalable Switches

- Buffer throughput limitation ⇒ use input queueing or CIOQ
- Input queued crossbar scalability limited primarily by:
  - quadratic cost growth rate, $O(N^2)$, of crossbar
  - scheduler complexity & efficiency, i.e. solving the output contention (congestion management) problem
- To solve the crossbar cost ⇒ use switching fabrics
- To solve the scheduler / contention / congestion problem:
  - (sorting / self-routing networks – bad solution)
  - Switching Fabrics with Small Internal Buffers, large input VOQ's, and Internal Backpressure (Flow Control)

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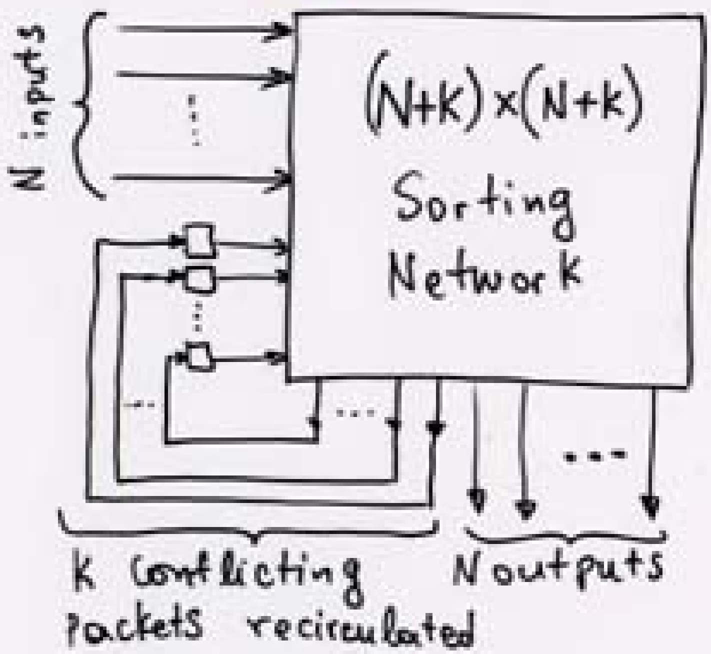
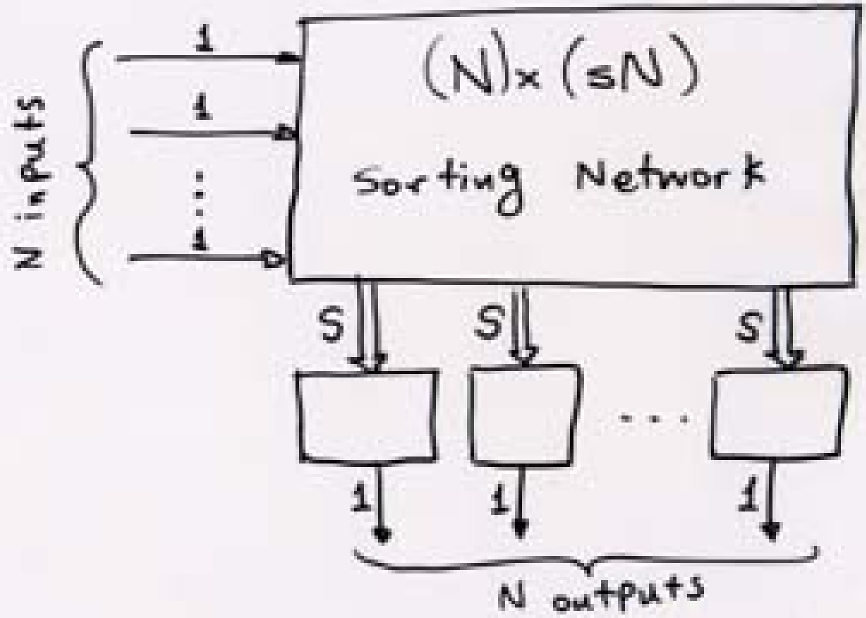
Central Scheduler is Impractical for large N

Solution 1: Sorting Networks w. Distributed Control (see ch.5 for details)

- all incoming packets allowed in — no central scheduling
- conflicting packets appropriately steered — distributed control





- uses communication paths as buffer memory
  ... too expensive
- Knock-Out Style
  but different Sw. Fabric
- Sorting Networks are quite large ... not too practical

Central Scheduler is Impractical for large N

Solution 2: Switching Fabrics with Internal Buffering & Backpressure