Software Routers

ECE/CS598HPN

Radhika Mittal

Logistics

- Warm-up assignment 1 due today.

Dataplane programmability is useful

- New ISP services
  - intrusion detection, application acceleration
- Flexible network monitoring
  - measure link latency, track down traffic
- New protocols
  - IP traceback, Rate Control Protocol (RCP)…

Enable flexible, extensible networks

But routers must be able to keep up with traffic rates!

Can we achieve both high speed and programmability for network routers?

- **Programmable hardware**
  - Limited flexibility
  - Higher performance per unit power or per unit $.
  - More on it in the next class!

- **Software routers**
  - RouteBrick's approach
    - *Can SW routers match the required performance?*
    - Possible through careful design that exploits parallelism within and across servers.
  - Higher power, more expensive.

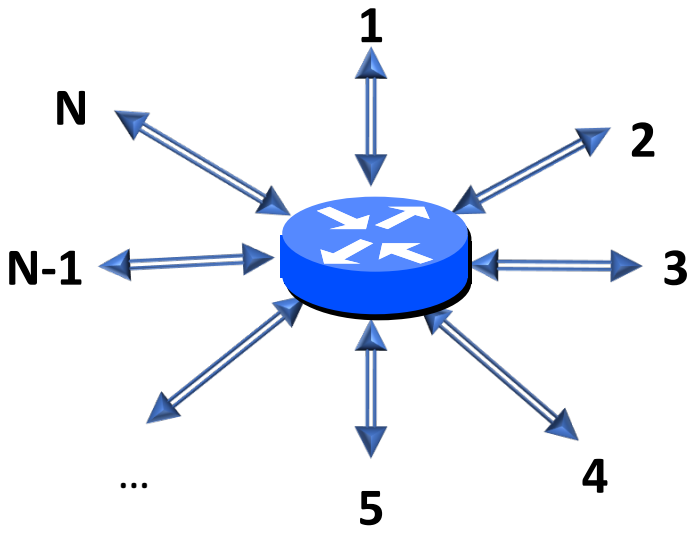
RouteBricks: Exploiting Parallelism to Scale Software Routers

SOSP'09

Mihai Dobrescu and Norbert Egi, Katerina Argyraki, Byung-Gon Chun, Kevin Fall Gianluca Iannaccone, Allan Knies, Maziar Manesh, Sylvia Ratnasamy

Acknowledgements: Slides from Sylvia Ratnasamy, UC Berkeley

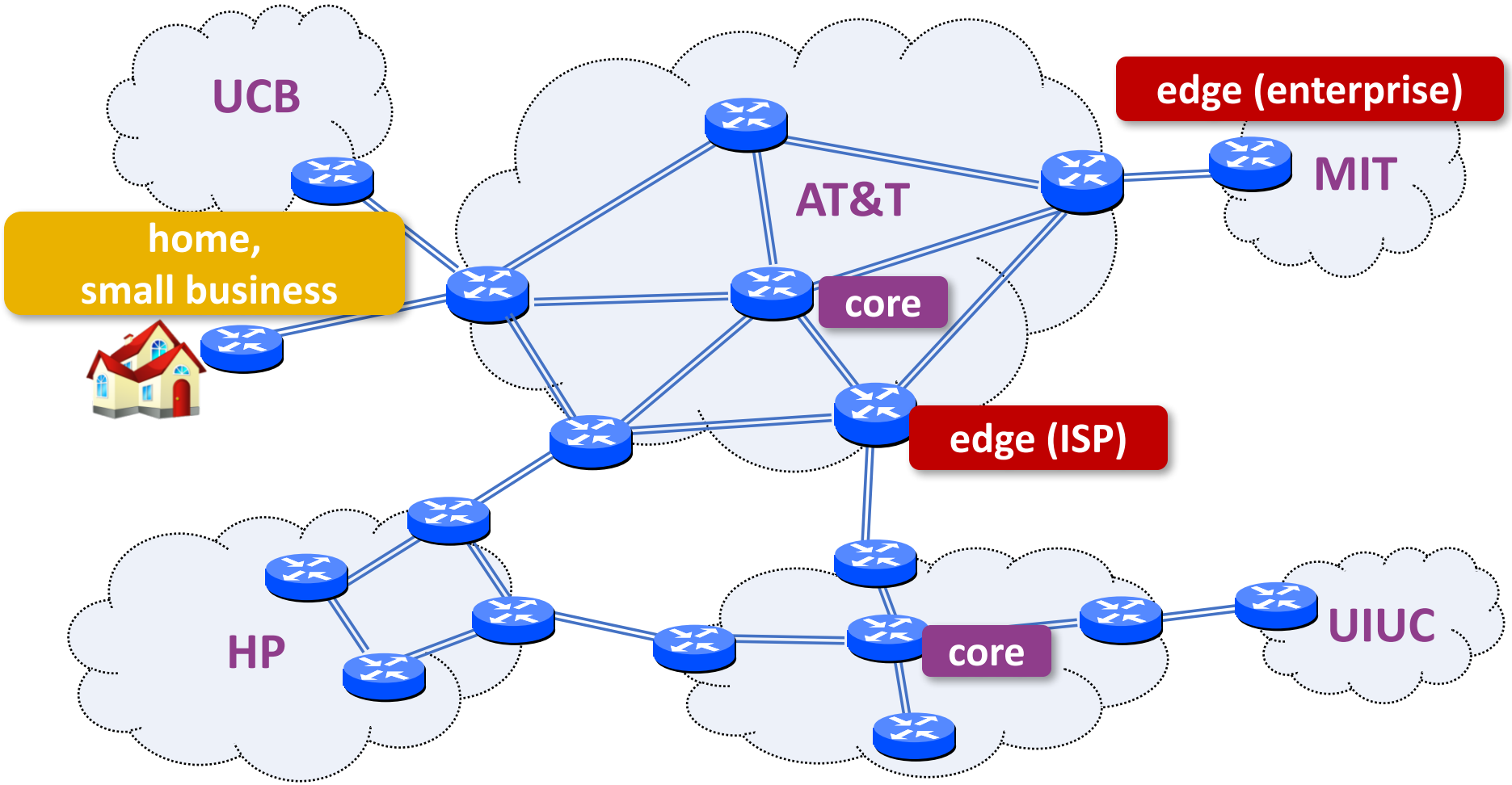
Router definitions



R ***bits per second (bps)***

- N = number of external router `ports'
- R = line rate of a port
- Router capacity = N x R

Networks and routers



Examples of routers (core)

Juniper T640

- R= 2.5/10 Gbps
- NR = 320 Gbps

Cisco CRS-1

- R=10/40 Gbps
- NR = 46 Tbps

72 racks, 1MW

Examples of routers (edge)

Cisco ASR 1006

- R=1/10 Gbps
- NR = 40 Gbps

Juniper M120

- R= 2.5/10 Gbps
- NR = 120 Gbps

Examples of routers (small business)

Cisco 3945E

- R = 10/100/1000 Mbps
- NR < 10 Gbps

Building routers

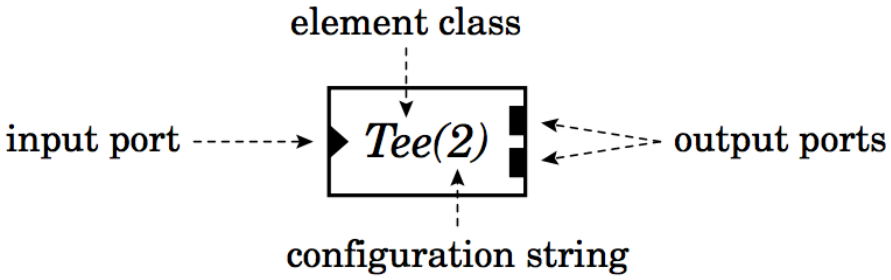
- edge, core
  - ASICs
  - network processors
  - commodity servers ← RouteBricks
- home, small business
  - ASICs
  - network, embedded processors
  - commodity PCs, servers
    - Click Modular Router: 1-2Gbps

Detour: Click Modular Router

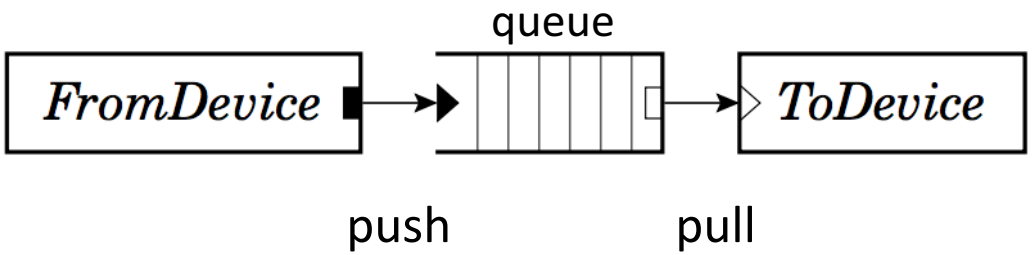
- Monolithic routing module in Linux
  - Difficult to reason about or extend.
- Click: modular software router

Detour: Click Modular Router

- Element:



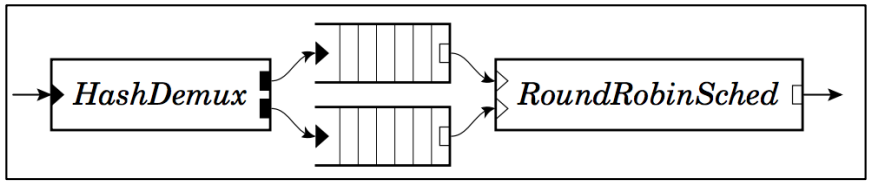
- Connection between elements:

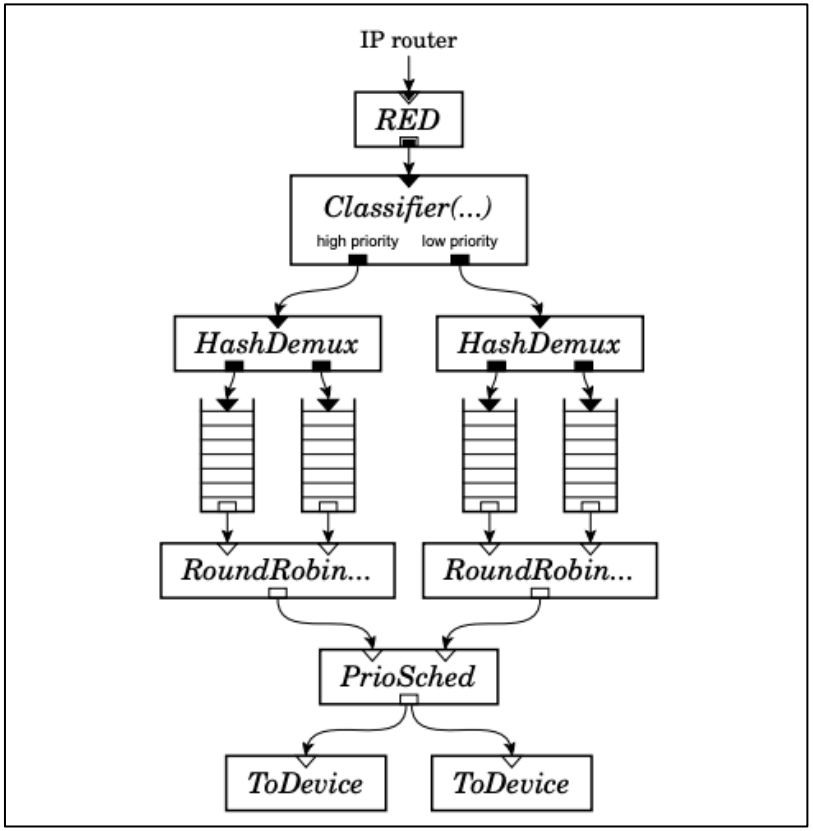


- Rules about permitted connections.

Detour: Click Modular Router

- Examples:

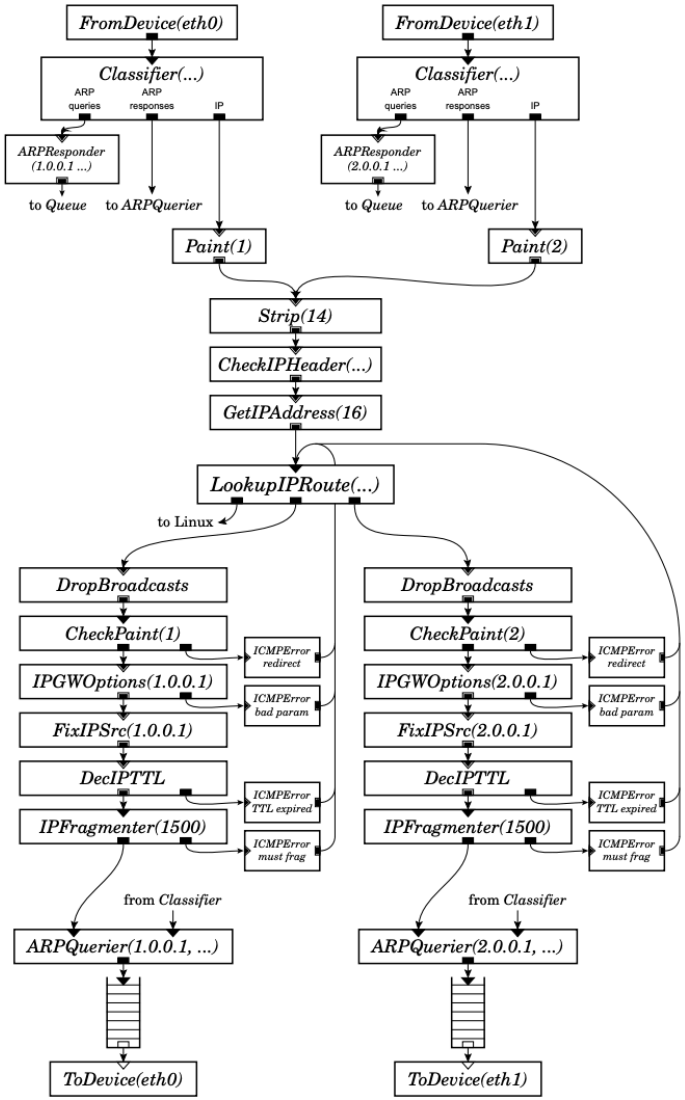




Detour: Click Modular Router

Example: IP Router

(stare at it on your own)



Building routers

- edge, core
  - ASICs
  - network processors
  - commodity servers ← RouteBricks
- home, small business
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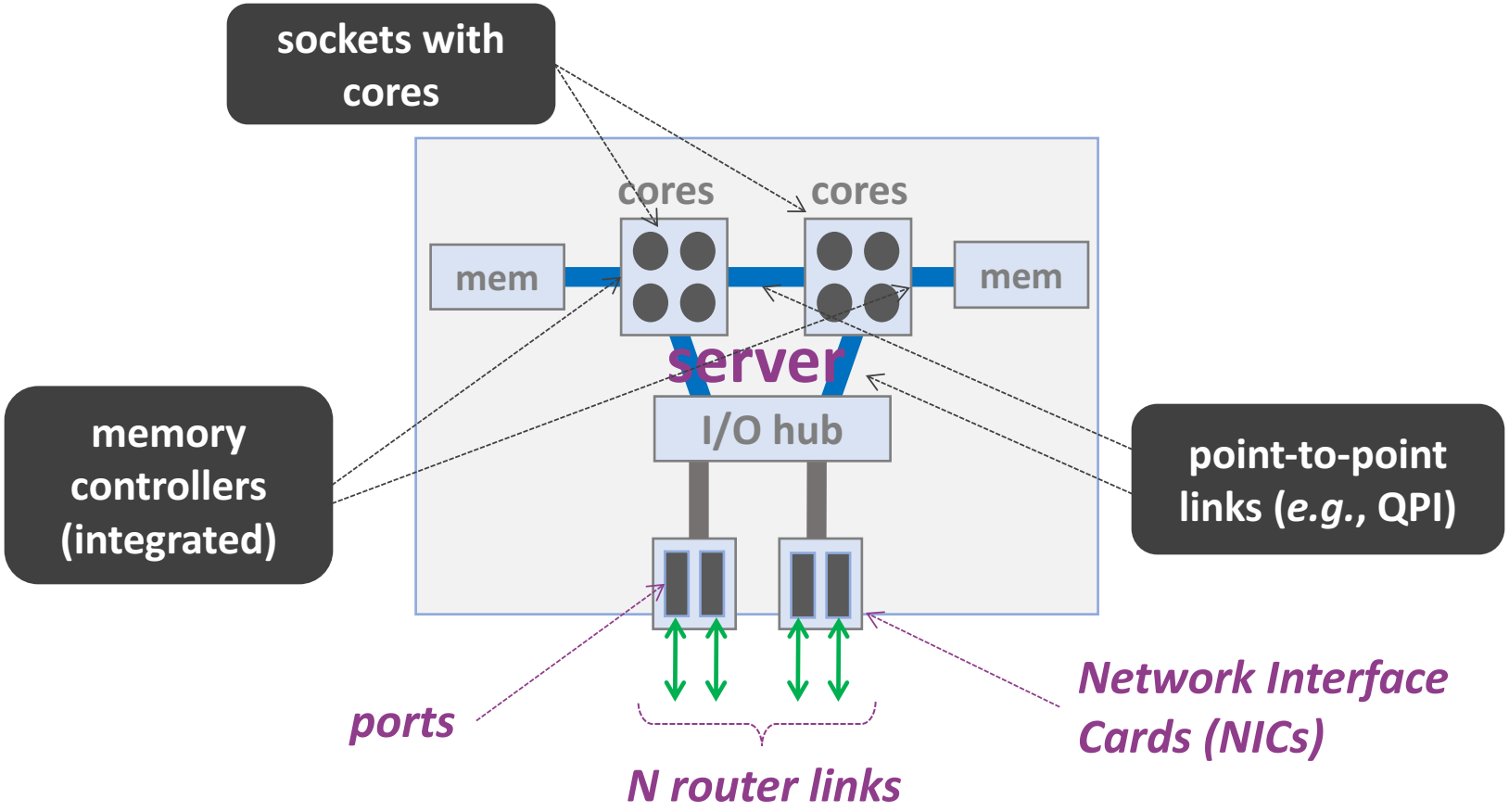
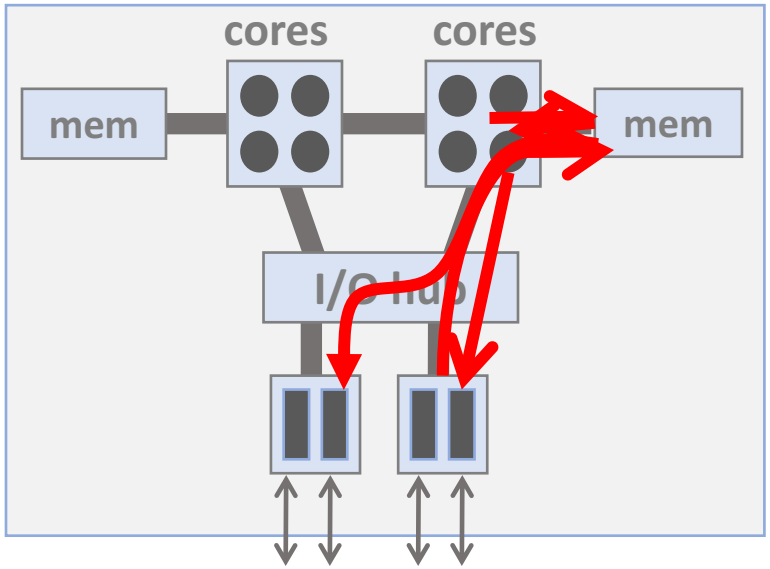
  - network, embedded processors
  - commodity PCs, servers
    - Click Modular Router: 1-2Gbps

A single-server router



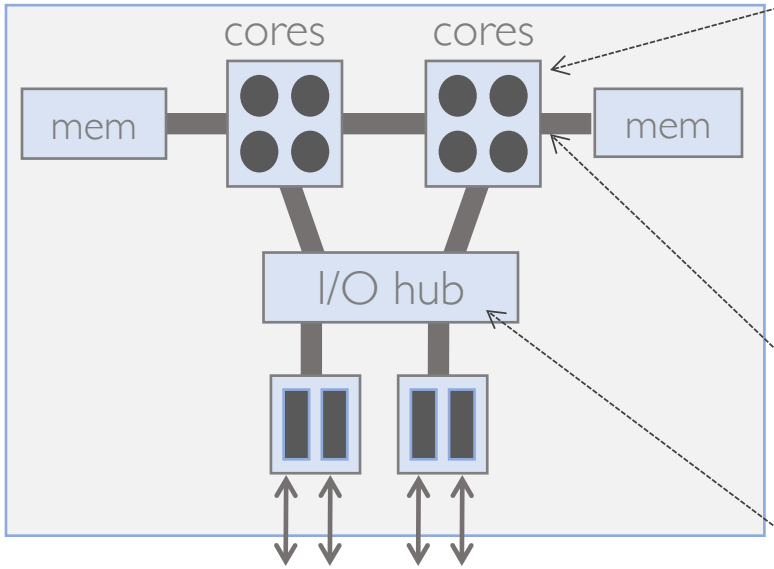
Packet processing in a server



Per packet,

1. core polls input port
2. NIC writes packet to memory
3. core reads packet
4. core processes packet (*address lookup, checksum, etc.*)
5. core writes packet to port

Packet processing in a server



8x 2.8GHz

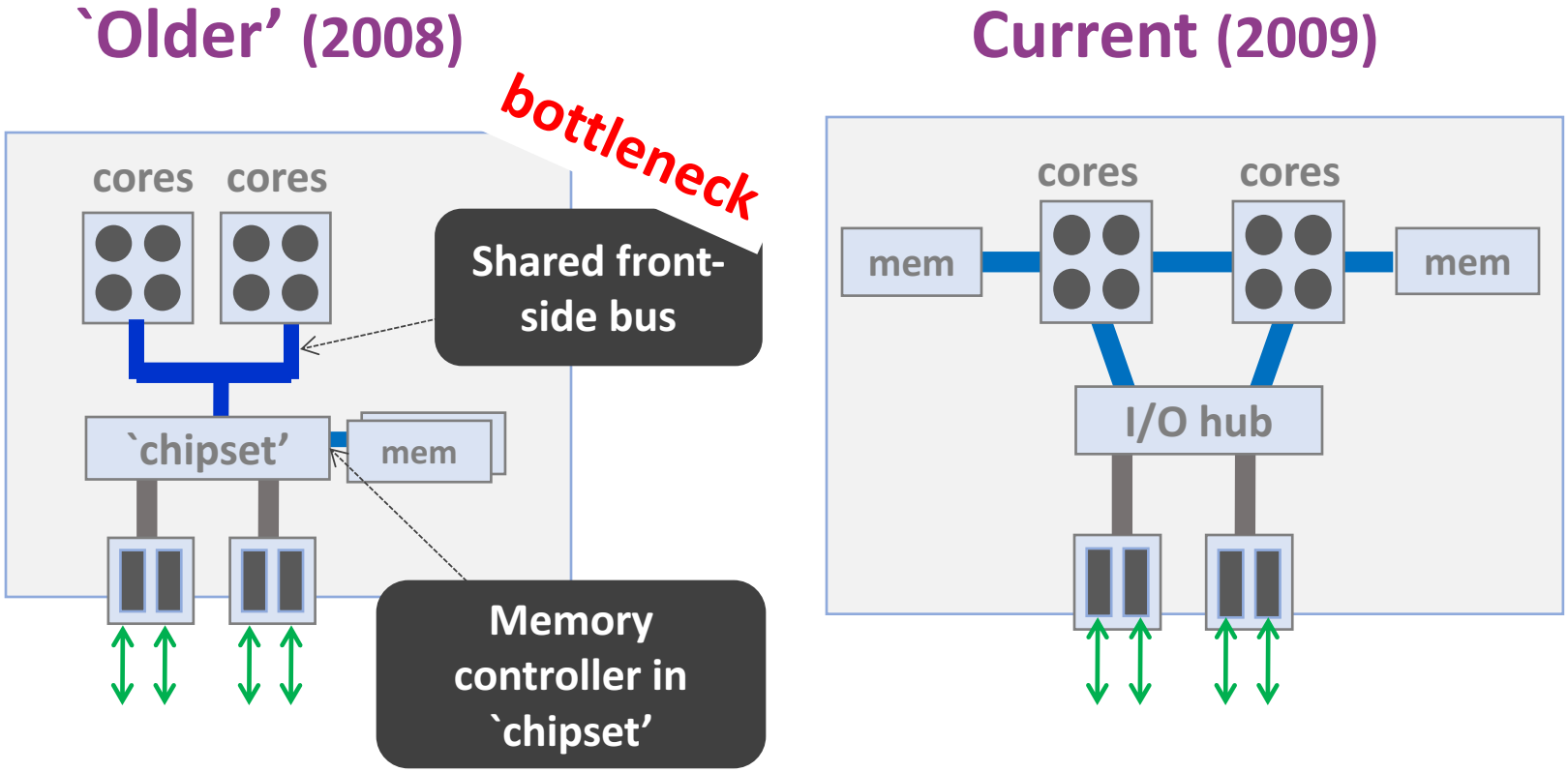
Assuming 10Gbps with all 64B packets
→19.5 million packets per second
→ one packet every 0.05 µsecs
→~1000 cycles to process a packet

Today, 200Gbps memory

Today, 144Gbps I/O

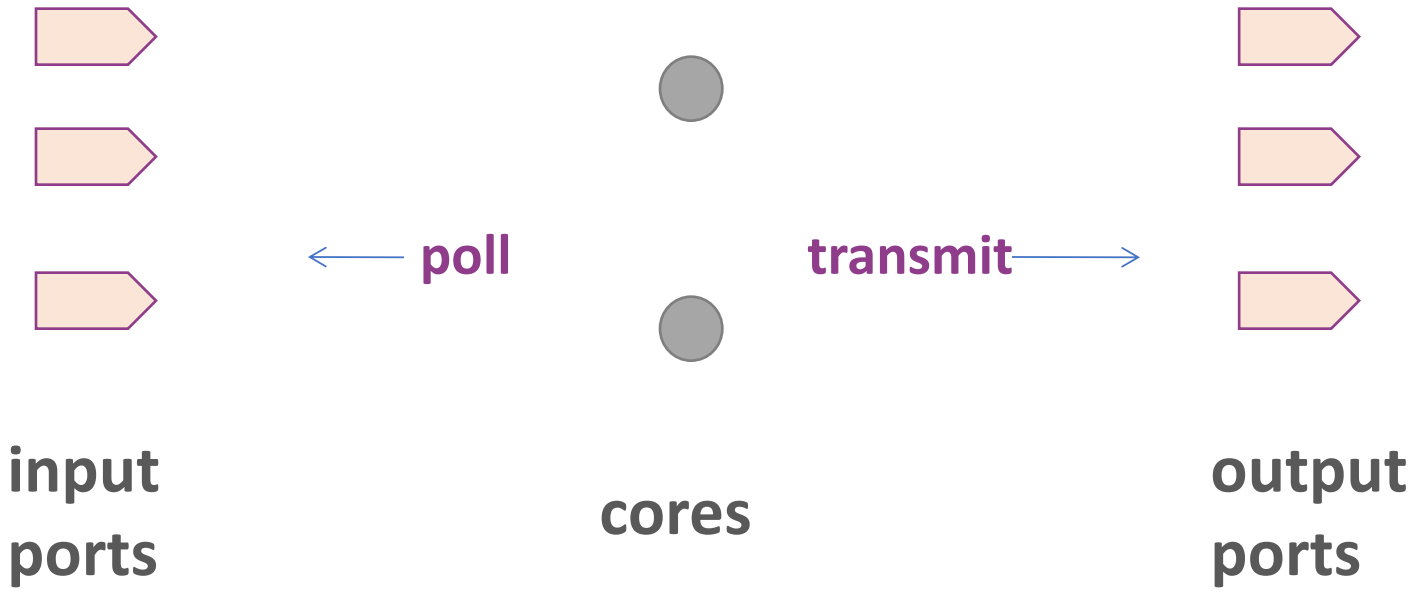
Suggests efficient use of CPU cycles is key!

Lesson#1: *multi-core alone isn't enough*



Hardware need: avoid shared-bus servers

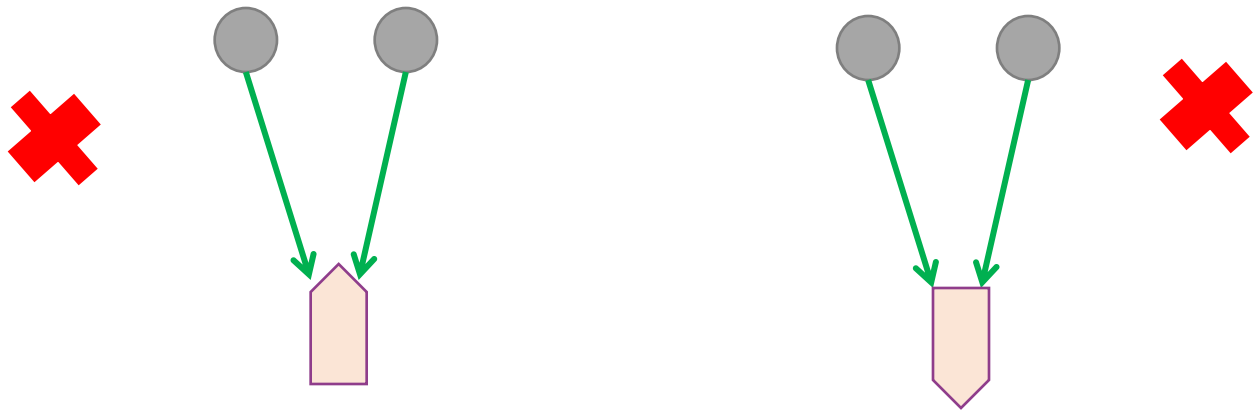
Lesson#2: *on cores and ports*



How do we assign cores to input and output ports?

Lesson#2: *on cores and ports*

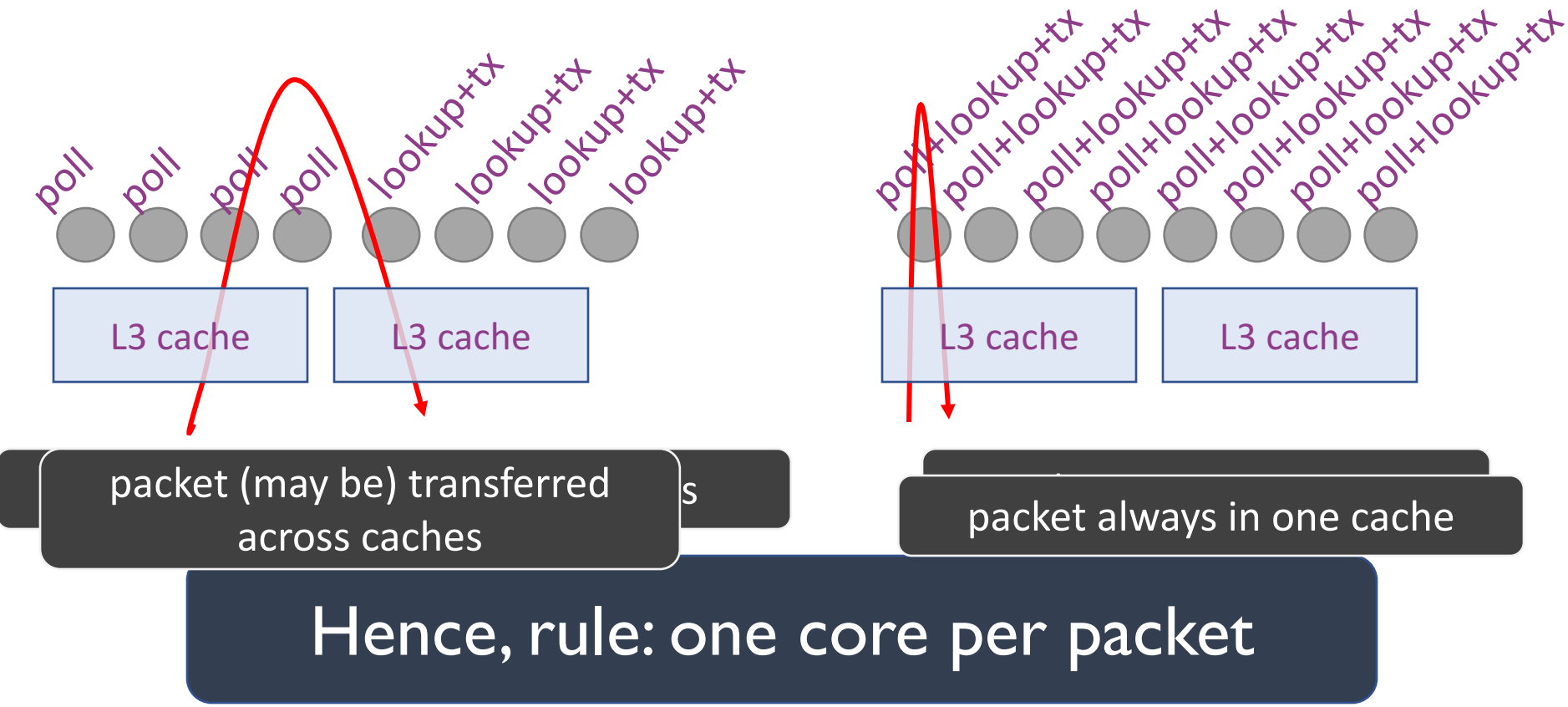
Problem: **locking**



Hence, rule: one core per port

Lesson#2: *on cores and ports*

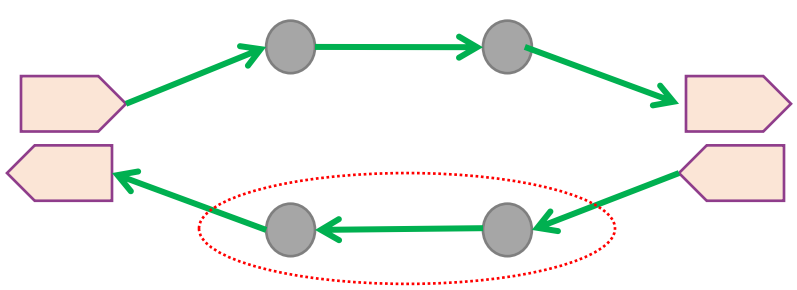
Problem: **inter-core communication, cache misses**



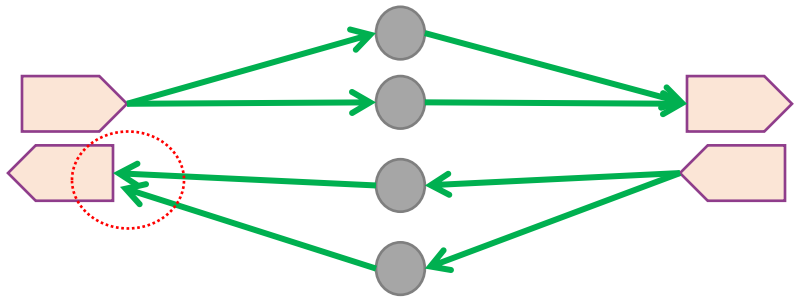
Hence, rule: one core per packet

Lesson#2: *on cores and ports*

- **two rules:**
  - one core per port
  - one core per packet
- **problem: often, can't simultaneously satisfy both**



✖ *one core per packet*

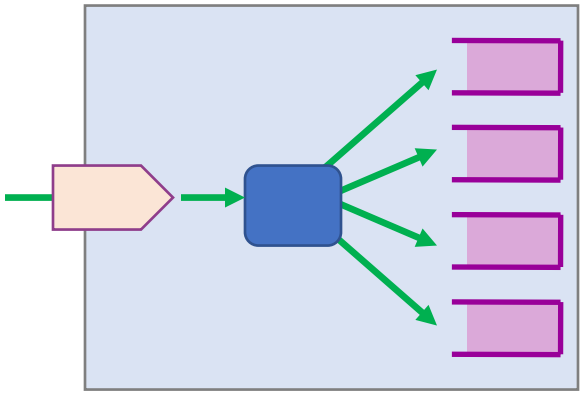


✖ *one core per port*

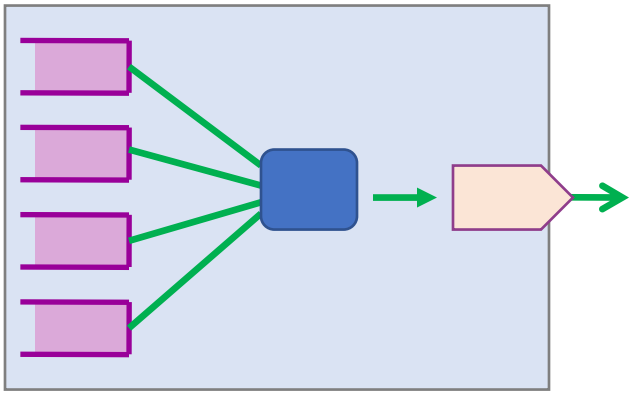
- solution: use *multi-Q* NICs

Multi-Q NICs

- **feature on modern NICs (for virtualization)**
  - port associated with multiple queues on NIC
  - NIC demuxes (muxes) incoming (outgoing) traffic
  - demux based on hashing packet fields (e.g., source+destination address)



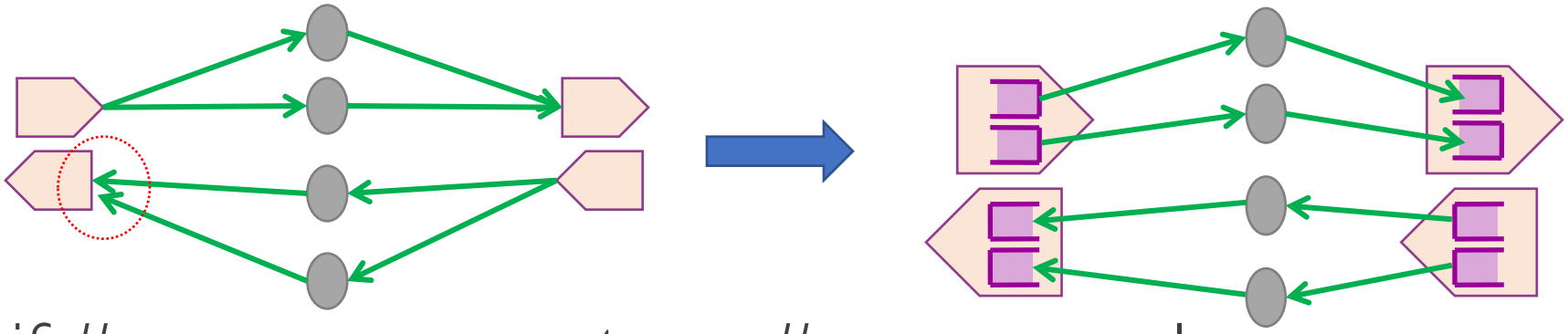
Multi-Q NIC: incoming traffic



Multi-Q NIC: outgoing traffic

Multi-Q NICs

- feature on modern NICs (for virtualization)
- repurposed for routing
  - rule: one core per ~~port~~ **queue**
  - rule: one core per packet



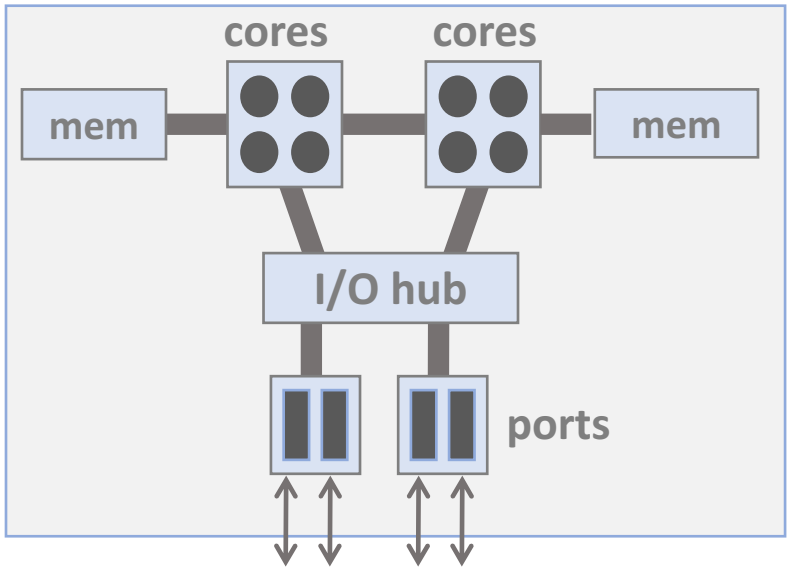
- if #queues per port == #cores, can always enforce both rules

Lesson#2: *on cores and ports*

recap:

- **use multi-Q NICs**
  - with modified NIC driver for lock-free polling of queues
- **with**
  - one core per queue (avoid locking)
  - one core per packet (avoid cache misses, inter-core communication)

Lesson#3: book-keeping



1. core polls input port
2. NIC writes packet to memory
3. core reads packet
4. core processes packet
5. core writes packet to out port

and packet descriptors

problem: excessive per packet book-keeping overhead

- solution: batch packet operations
  - NIC transfers packets in batches of `k'

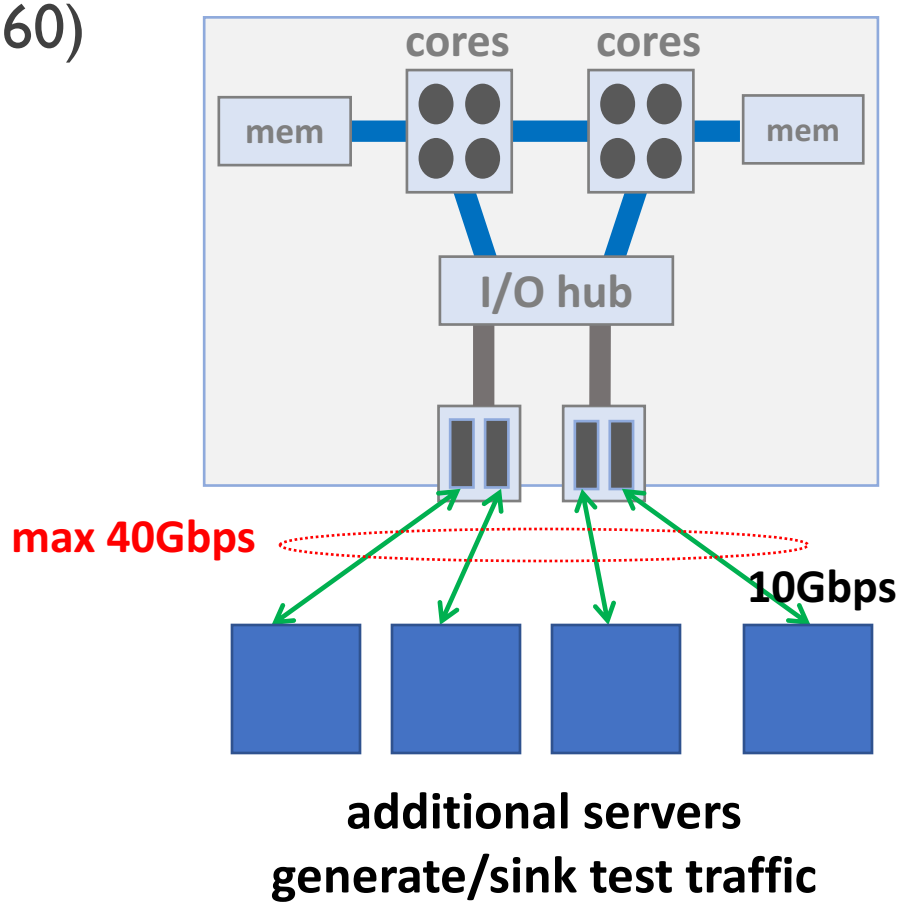
Recap: routing on a server

Design lessons:

1. parallel hardware
   - at cores *and* memory *and* NICs
2. careful queue-to-core allocation
   - one core per queue, per packet
3. reduced book-keeping per packet
   - modified NIC driver w/ batching

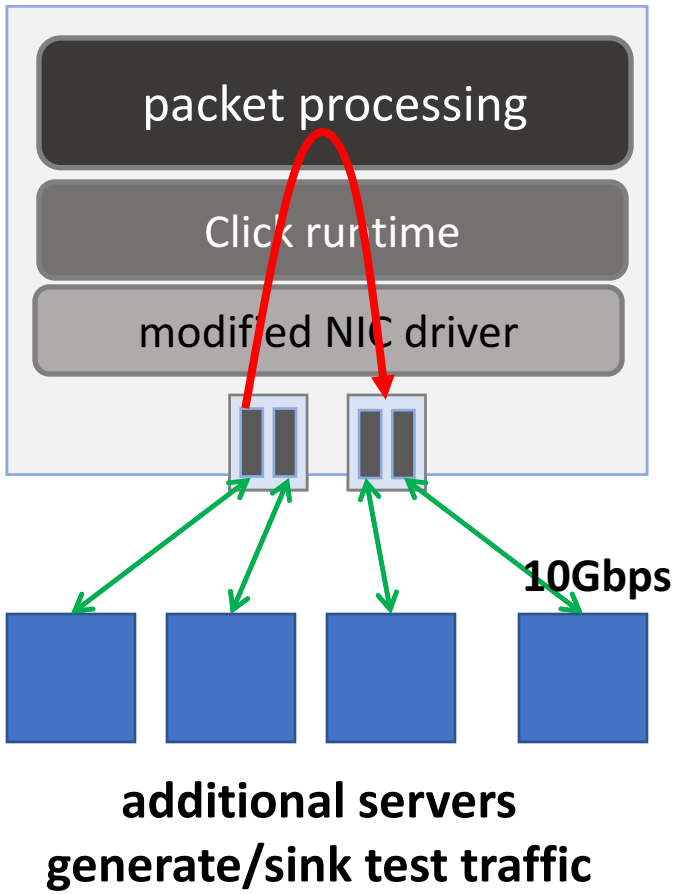
Single-Server Measurements

- test server: Intel Nehalem (X5560)
  - dual socket, 8x 2.80GHz cores
  - 2x NICs; 2x 10Gbps ports/NIC



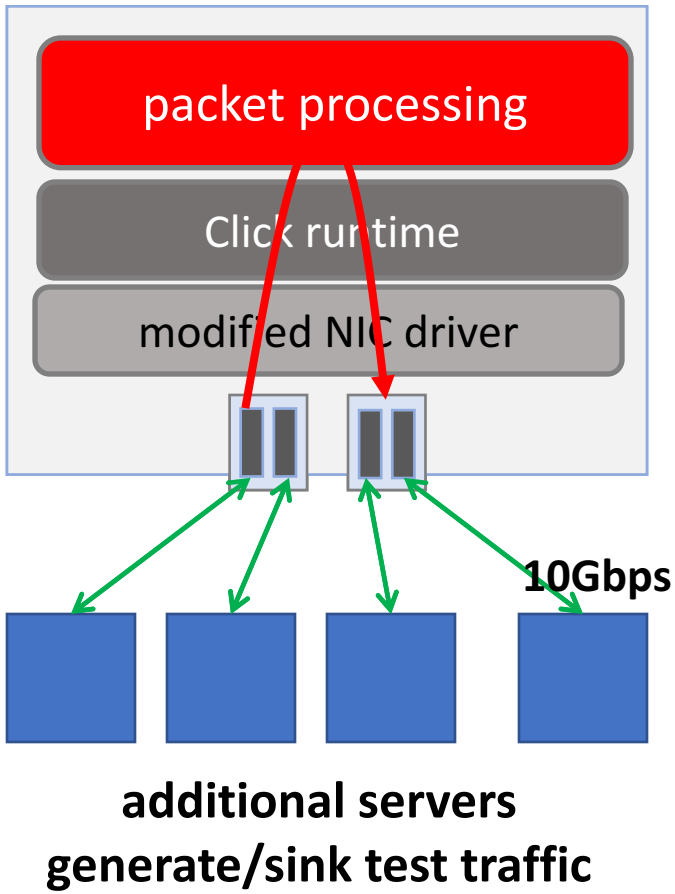
Single-Server Measurements

- **test server: Intel Nehalem (X5560)**
  - dual socket, 8x 2.80GHz cores
  - 2x NICs; 2x 10Gbps ports/NIC
- **software: kernel-mode Click [TOCS'00]**
  - with modified NIC driver (batching, multi-Q)



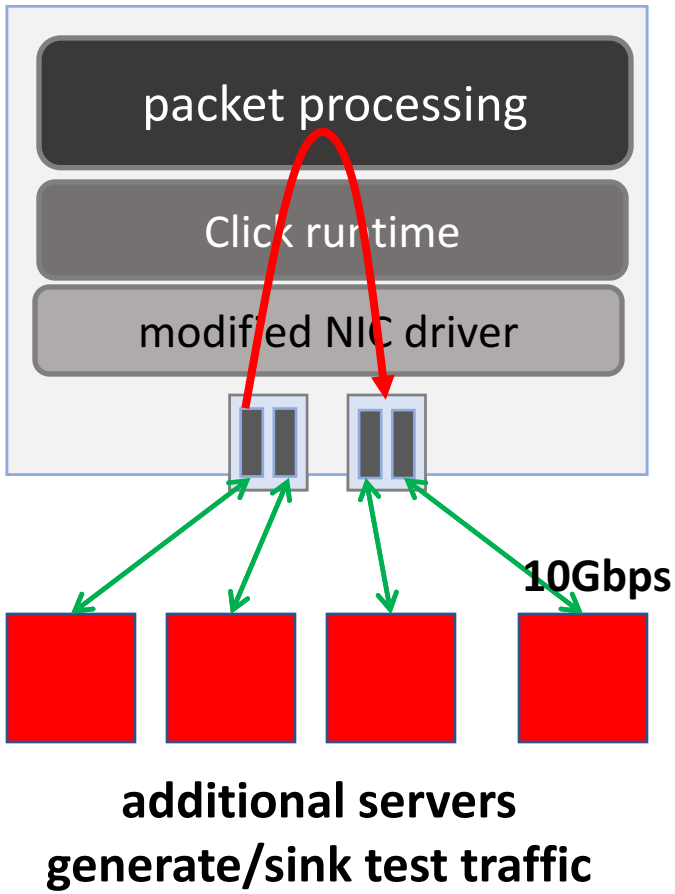
Single-Server Measurements

- test server: Intel Nehalem (X5560)
- software: kernel-mode Click [TOCS'00]
  - with modified NIC driver
- packet processing
  - static forwarding (no header processing)
  - IP routing
    - trie-based longest-prefix address lookup
    - ~300,000 table entries [RouteViews]
    - checksum calculation, header updates, etc.

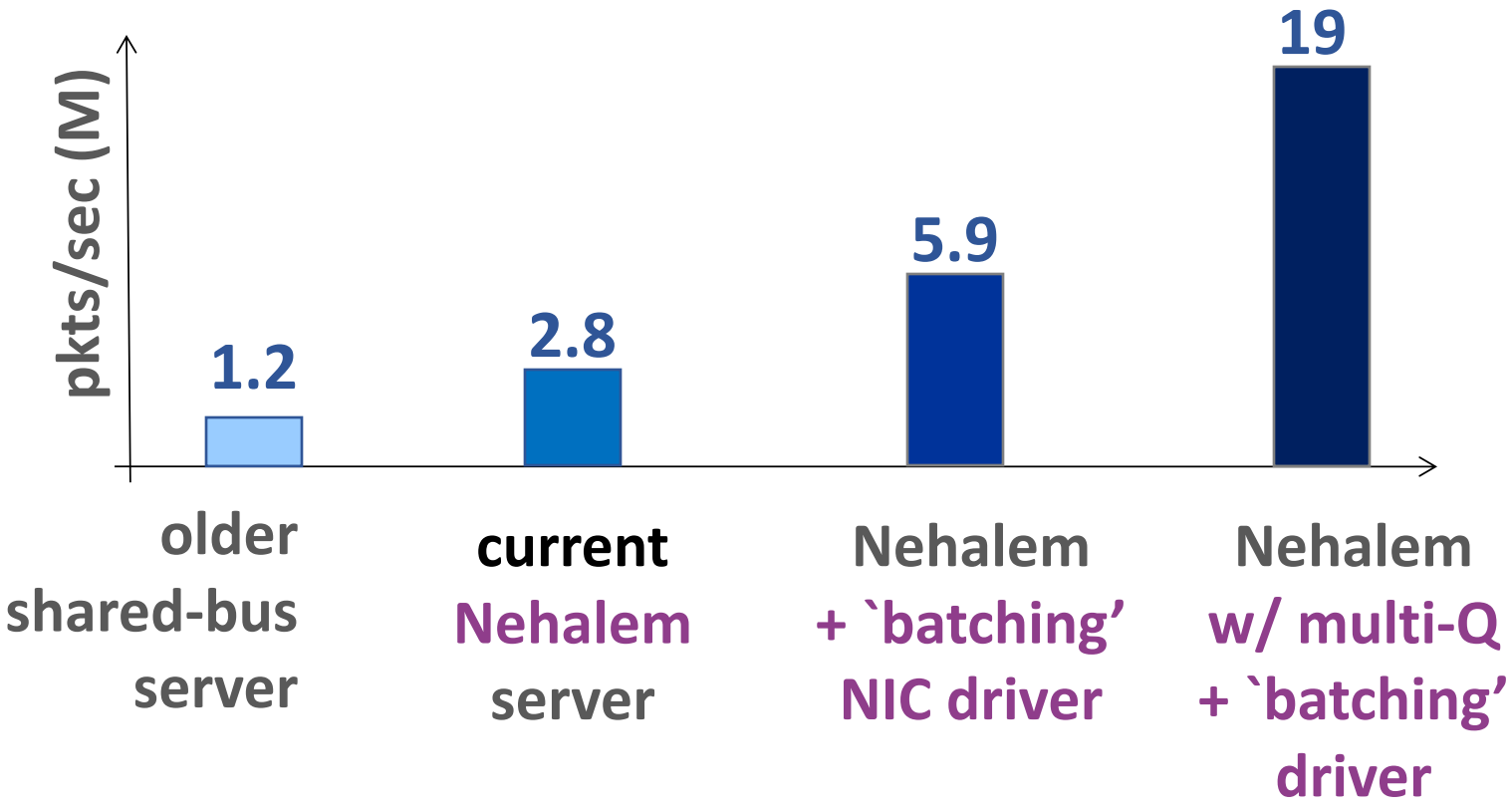


Single-Server Measurements

- test server: Intel Nehalem (X5560)
- software: kernel-mode Click [TOCS'00]
  - with modified NIC driver
- packet processing
  - static forwarding (no header processing)
  - IP routing
- input traffic
  - all min-size (64B) packets
    (maximizes packet rate given port speed R)
  - realistic mix of packet sizes [Abilene]

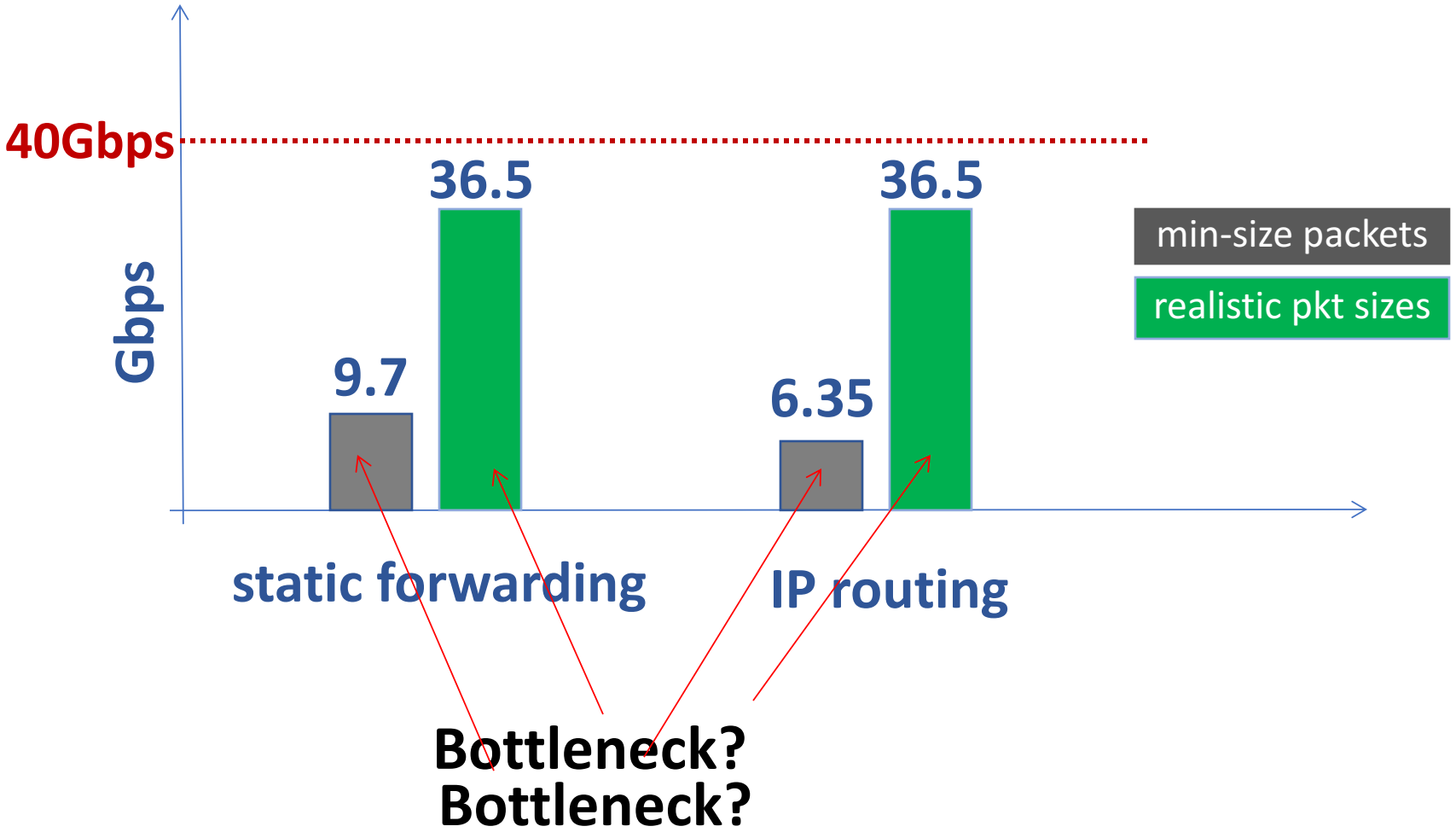


Factor analysis: design lessons



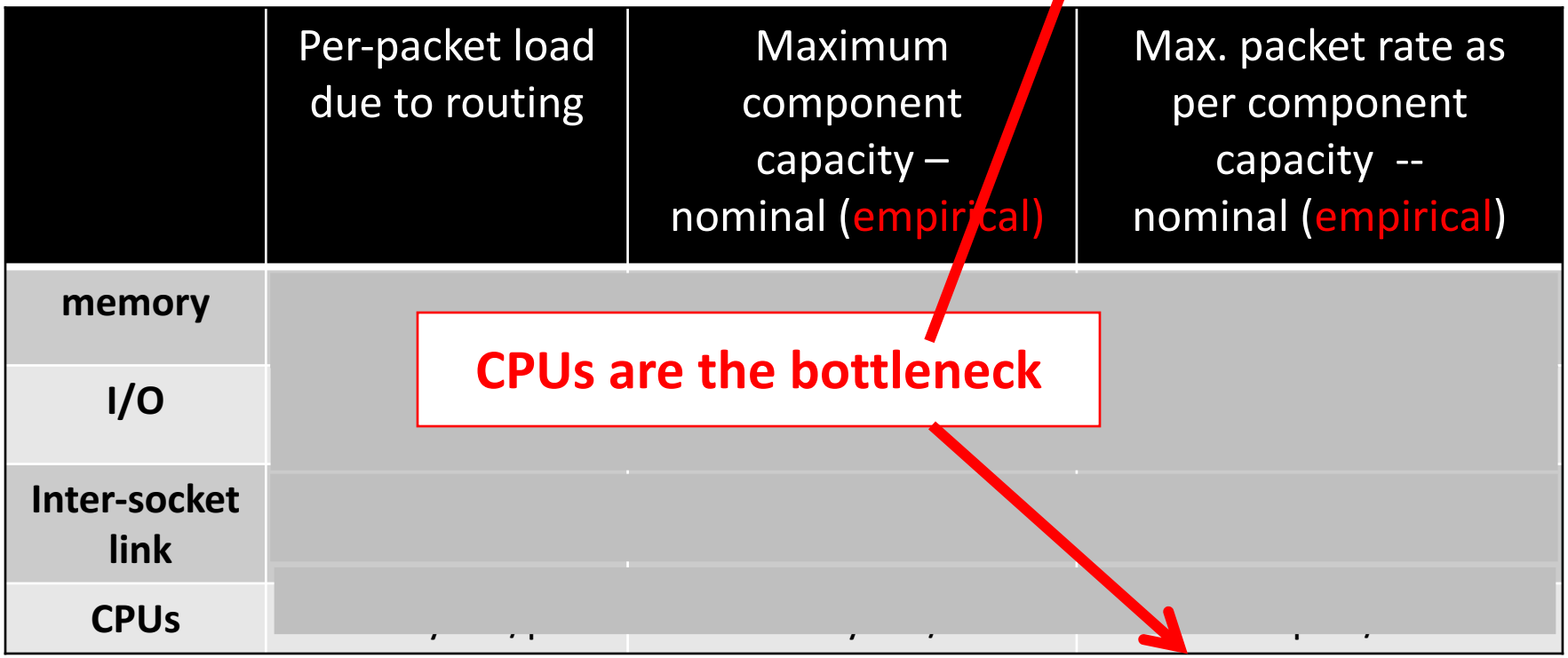
Test scenario: static forwarding of min-sized packets

Single-server performance



Bottleneck analysis (64B pkts)

Recall: max IP routing = 6.35Gbps → 12.4 M pkts/sec

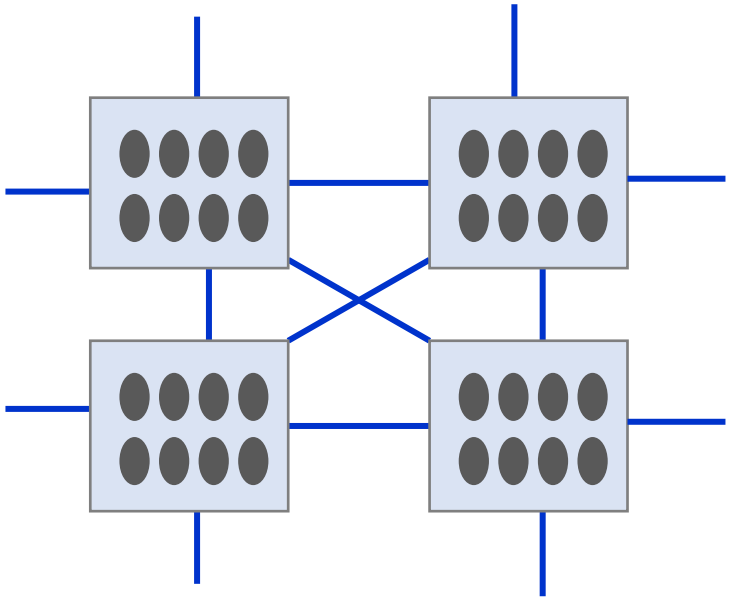


Test scenario: IP routing of min-sized packets

Recap: single-server performance

	R	NR
current servers (realistic packet sizes)	1/10 Gbps	36.5 Gbps
current servers (min-sized packets)	1	6.35 (CPUs bottleneck)

Recap: single-server performance



With newer servers? (2010)

4x cores, 2x memory, 2x I/O

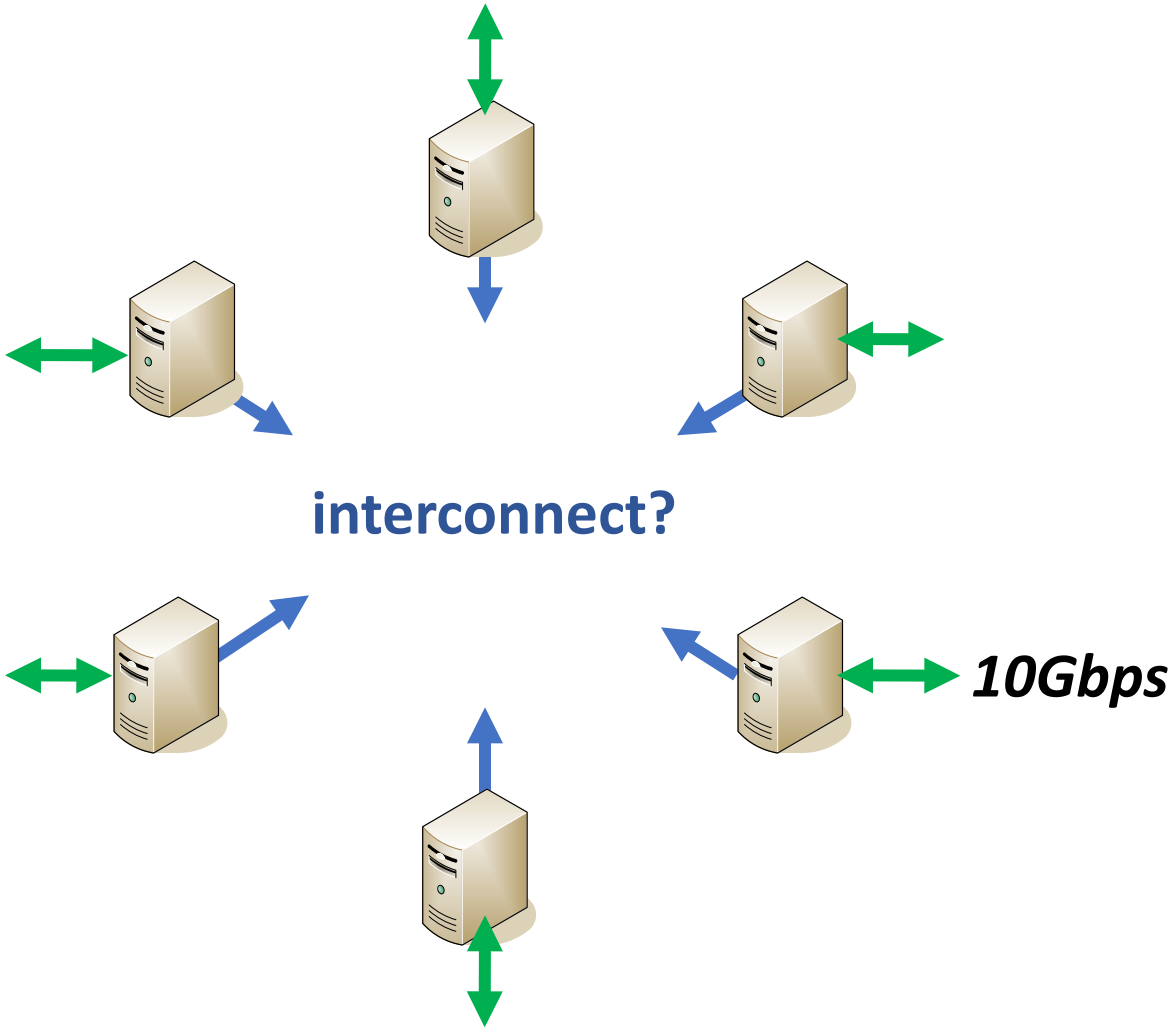
Recap: single-server performance

	R	NR
current servers (realistic packet sizes)	1/10 Gbps	36.5 Gbps
current servers (min-sized packets)	1	6.35 (CPUs bottleneck)
upcoming servers –estimated (realistic packet sizes)	1/10/40	146
upcoming servers –estimated (min-sized packets)	1/10	25.4

Practical Architecture: Goal

- scale software routers to multiple 10Gbps ports
- example: 320Gbps (32x 10Gbps ports)
  - higher-end of edge routers; lower-end core routers

A cluster-based router today



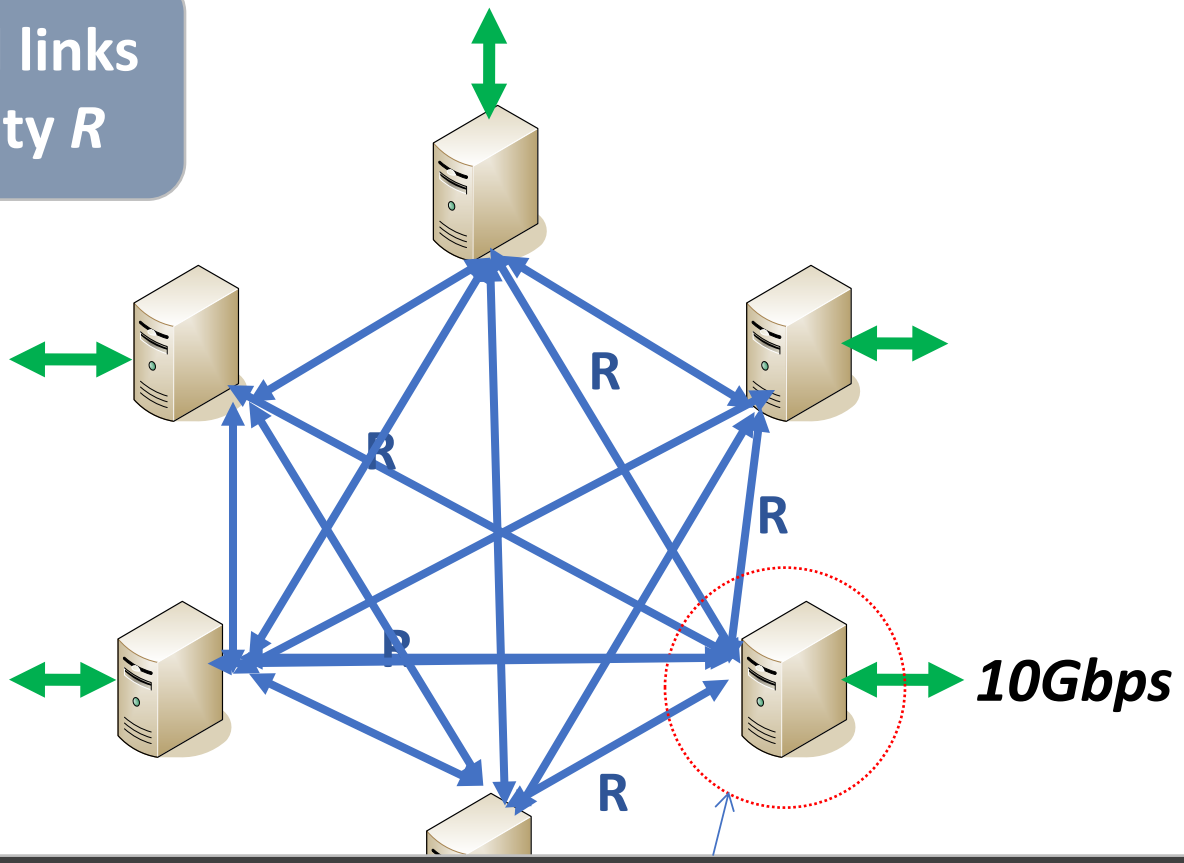
Interconnecting servers

Challenges

- any input can send up to R *bps* to any output

A naïve solution

N^2 internal links of capacity R



problem: commodity servers cannot accommodate NxR traffic

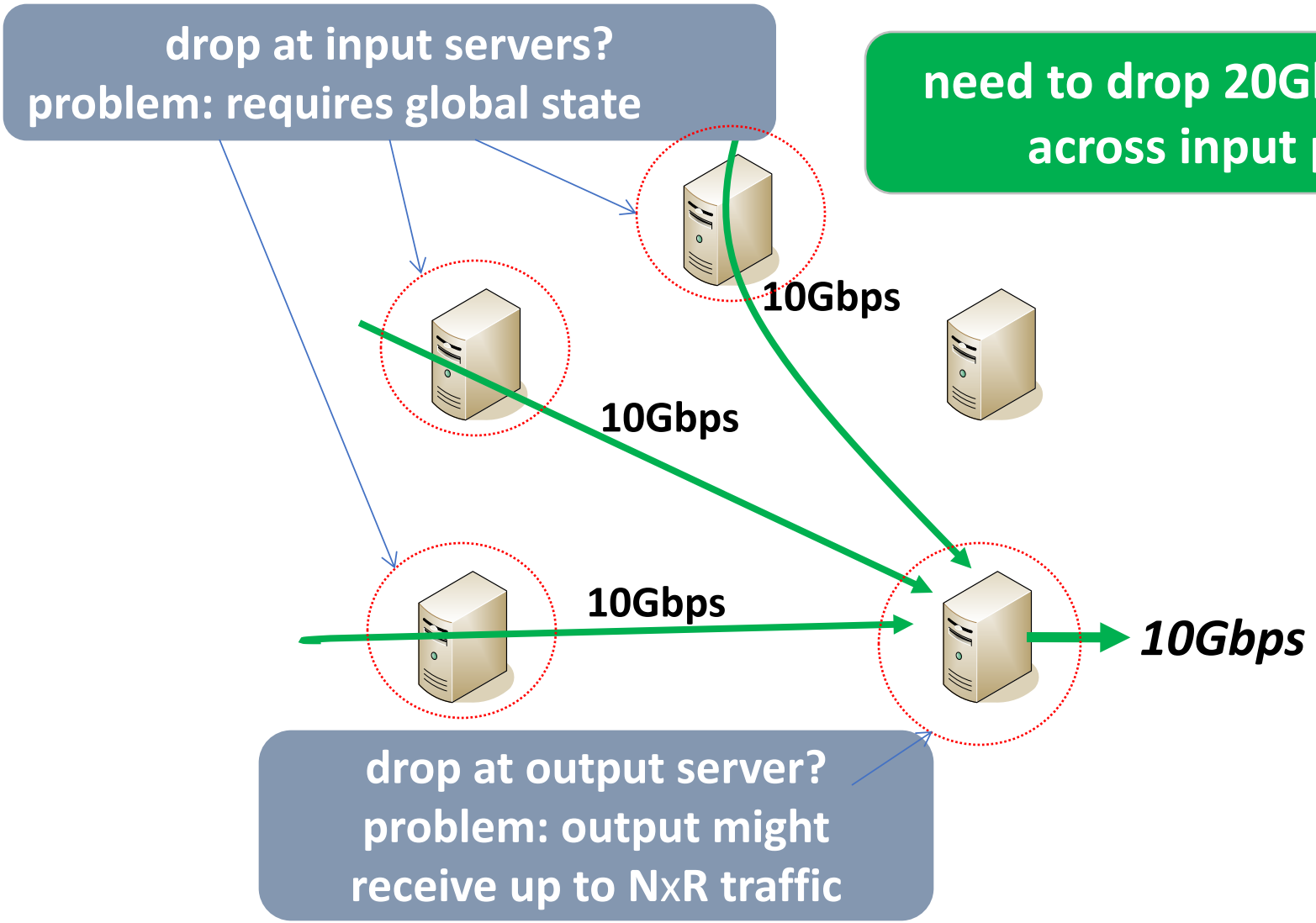
Interconnecting servers

Challenges

- any input can send up to R *bps* to any output
  - but need a lower-capacity interconnect
  - *i.e.*, fewer (<N), lower-capacity (<R) links per server

- must cope with overload

Overload


drop at input servers?
problem: requires global state
need to drop 20Gbps; (fairly across input ports)
10Gbps
10Gbps
10Gbps
10Gbps
drop at output server?
problem: output might receive up to NxR traffic

Interconnecting servers

Challenges

- any input can send up to R *bps* to any output
  - but need a lower-capacity interconnect
  - *i.e.,* fewer (<N), lower-capacity (<R) links per server

- must cope with overload
  - need distributed dropping without global scheduling
  - processing at servers should scale as R, not NxR

Interconnecting servers

Challenges

- any input can send up to R *bps* to any output
- must cope with overload

With constraints (due to commodity servers and NICs)

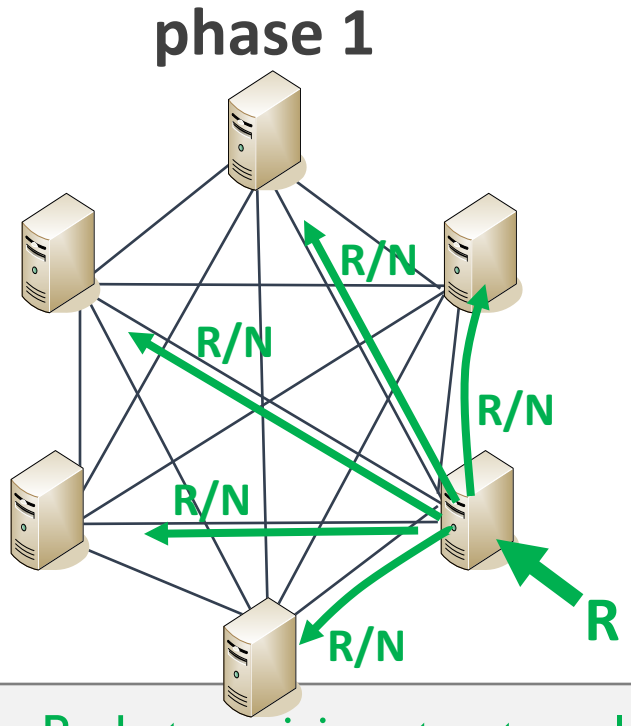
- internal link rates ≤ *R*
- per-node processing: $c_x R$ *(small c)*
- limited per-node fanout

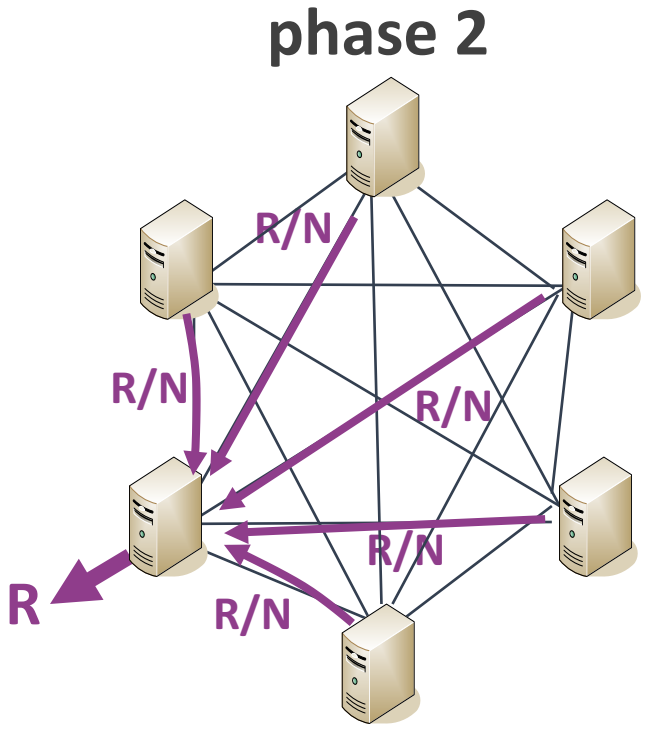
Solution: Use Valiant Load Balancing (VLB)

Valiant Load Balancing (VLB)

- Valiant *et al.* [STOC'81], communication in multi-processors
- applied to data centers [Greenberg'09], all-optical routers [Kesslassy'03], traffic engineering [Zhang-Shen'04], *etc.*
- idea: random load-balancing across a low-capacity interconnect

VLB: operation





Packets arriving at external port are uniformly load balanced

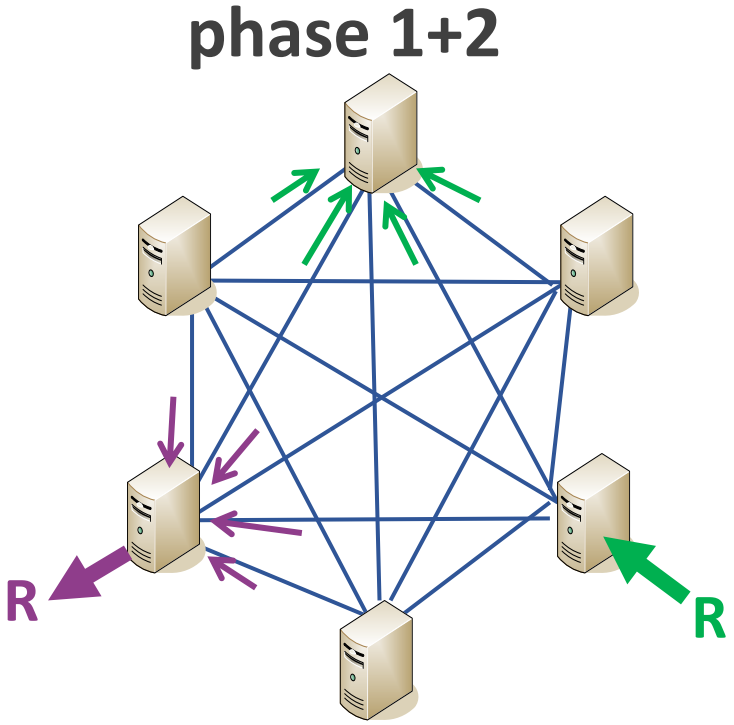
- N^2 internal links of capacity R/
- each server receives up to R *b*

- N^2 internal links of capacity R/N
- each server receives up to R *bps*

Output server transmits received traffic on external port

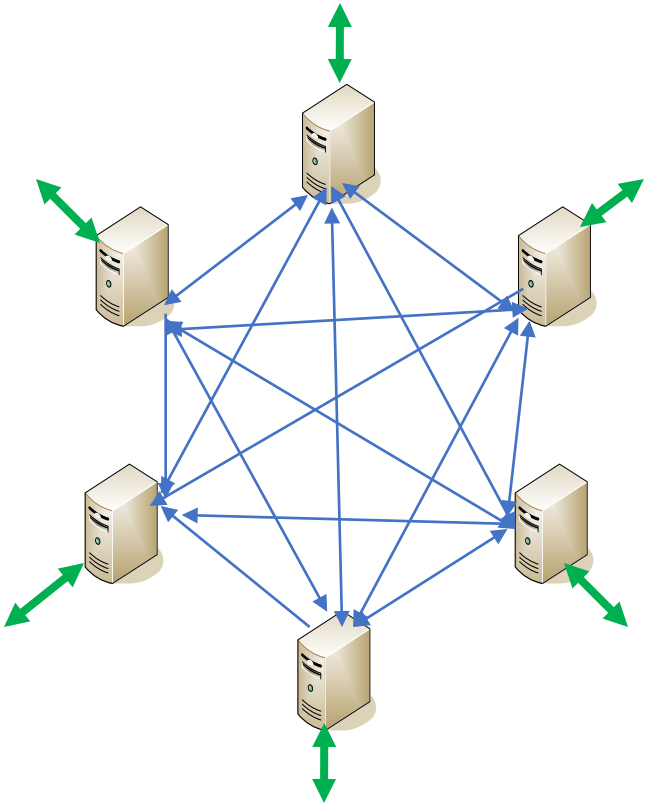
Packets forwarded in two phases

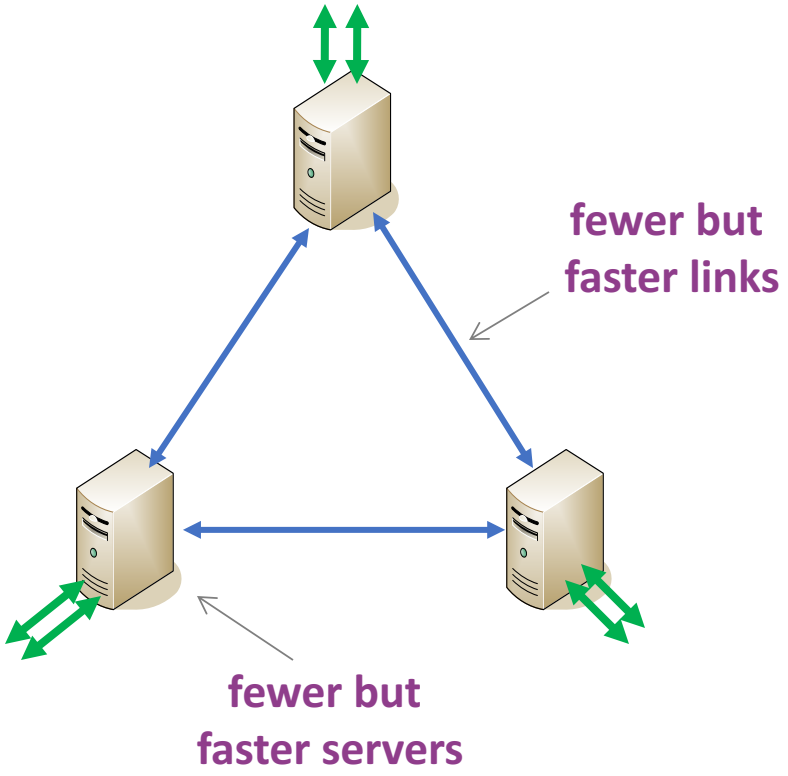
VLB: operation



- N^2 internal links of capacity 2R/N
- each server receives up to 2R bps
- plus R bps from external port
- hence, each server processes up to 3R
- or up to 2R, when traffic is uniform [directVLB, Liu'05]

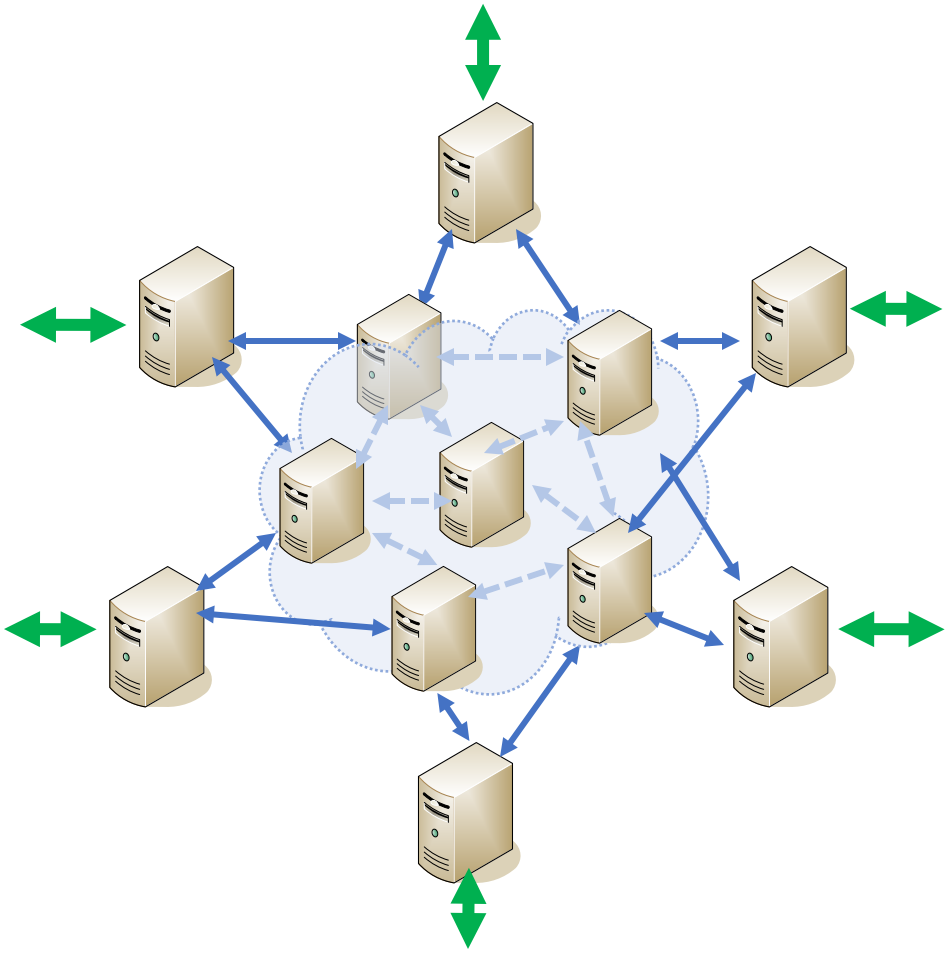
Scaling N: Requires large no. of ports / server





Multiple external ports per server
(if server constraints permit)

Scaling N: Multi-stage interconnect



Use extra servers to form a constant-degree multi-stage interconnect (e.g., butterfly)

Recap: Router cluster

- assign maximum external ports per server
- servers interconnected with commodity NIC links
- servers interconnected in a full mesh if possible
- else, introduce extra servers in a k-degree butterfly
- servers run flowlet-based VLB

Scalability

- **question:** how well does clustering scale for realistic server fanout and processing capacity?

- **metric:** number of servers required to achieve a target router speed

Scalability

Assumptions

- 7 NICs per server
- each NIC has 6 x 10Gbps ports or 8 x 1Gbps ports
- current servers
  - one external 10Gbps port per server
    (i.e., requires that a server process 20-30Gbps)
- upcoming servers
  - two external 10Gbps port per server
    (i.e., requires that a server process 40-60Gbps)

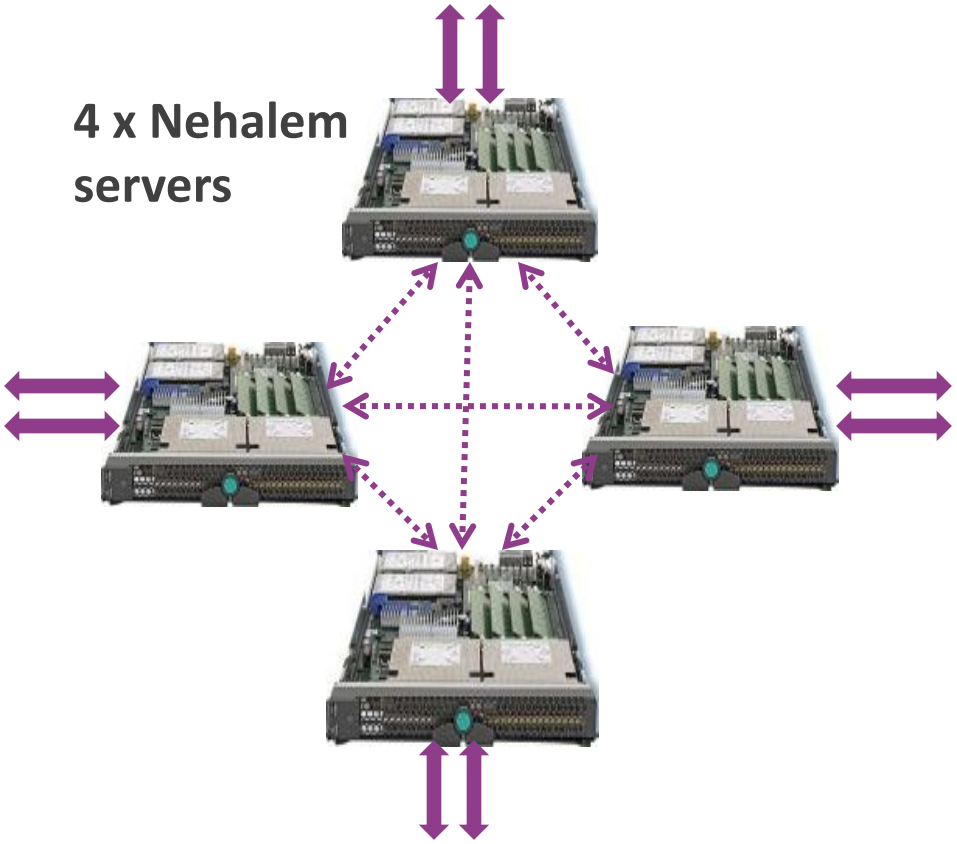
Scalability (computed)

	160Gbps	320Gbps	640Gbps	1.28Tbps	2.56Tbps
current servers	16	32 →	128	256	512
upcoming servers	8	16	32 →	128	256

Transition from mesh to butterfly

Example: can build 320Gbps router with 32 ‘current’ servers

Implementation: the RB8/4



Specs.

- 8x 10Gbps external ports
- form-factor: 4U
- power: 1.2KW
- cost: ~$10k

Key results (realistic traffic)

- 72 Gbps routing
- reordering: 0-0.15%
- validated VLB bounds

What did you all like about this work?

Limitation / trade-offs

- Power
- Form-factor
- Cost
- Packet-reordering
- Increased latency
- High performance only under favorable workloads