Challenges and Opportunities in Exascale-Computing Interconnects

Manolis Katevenis and Nikolaos Chrysos

FORTH-ICS and Univ. of Crete, Greece

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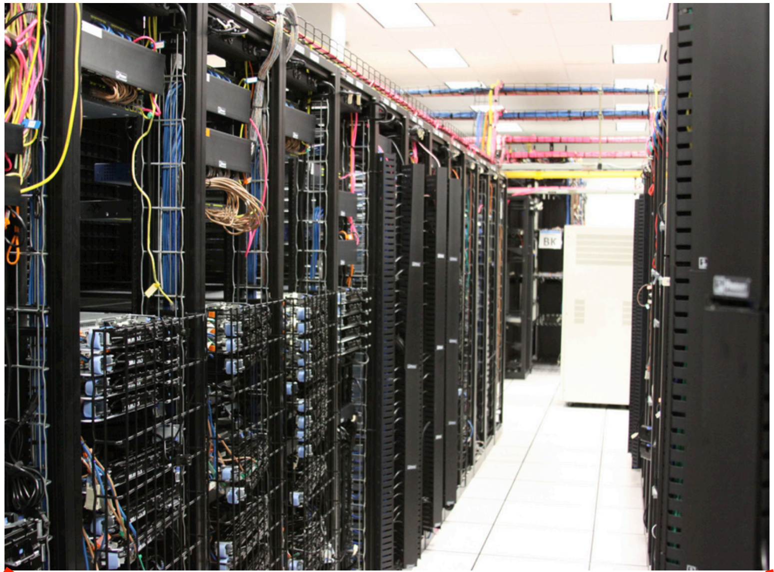
Outline

- Warehouse-scale datacenters and supercomputers
- Traffic characteristics in commercial datacenters
- Efficient congestion control: an old, unresolved problem
- Multipathing: benefits & issues
- RDMA: optimizing data copying
- Global virtual address space & routing

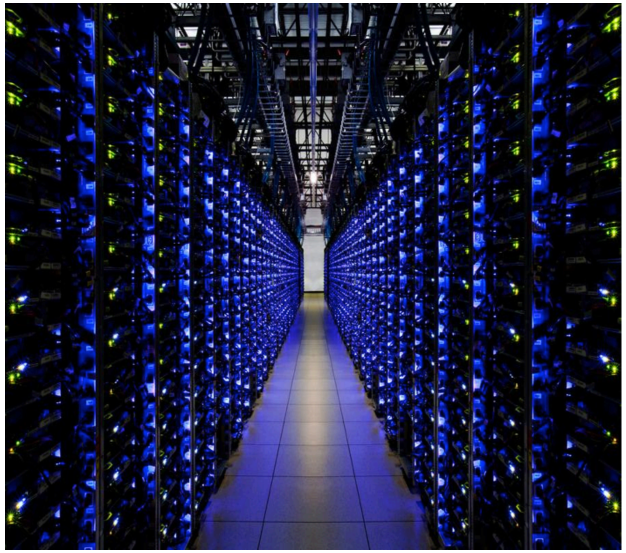
Datacenters: big-data stores of information society



What is a "datacenter"

A rack: 25-40 servers

Enterprise: a-few-hundred servers



Commercial datacenter:

Many-thousand servers

Supercomputers have similarities with datacenters

- Large scale installations
- Exploit massive parallelism
- … but designed to perfection
  - Custom one-off hardware vs. the economies of scale that rule in datacenters

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TOP500 list as of Nov. 2015

1. Tianhe-2 (MilkyWay-2) : 54.9 PFLOP/S @ 17.8 MW
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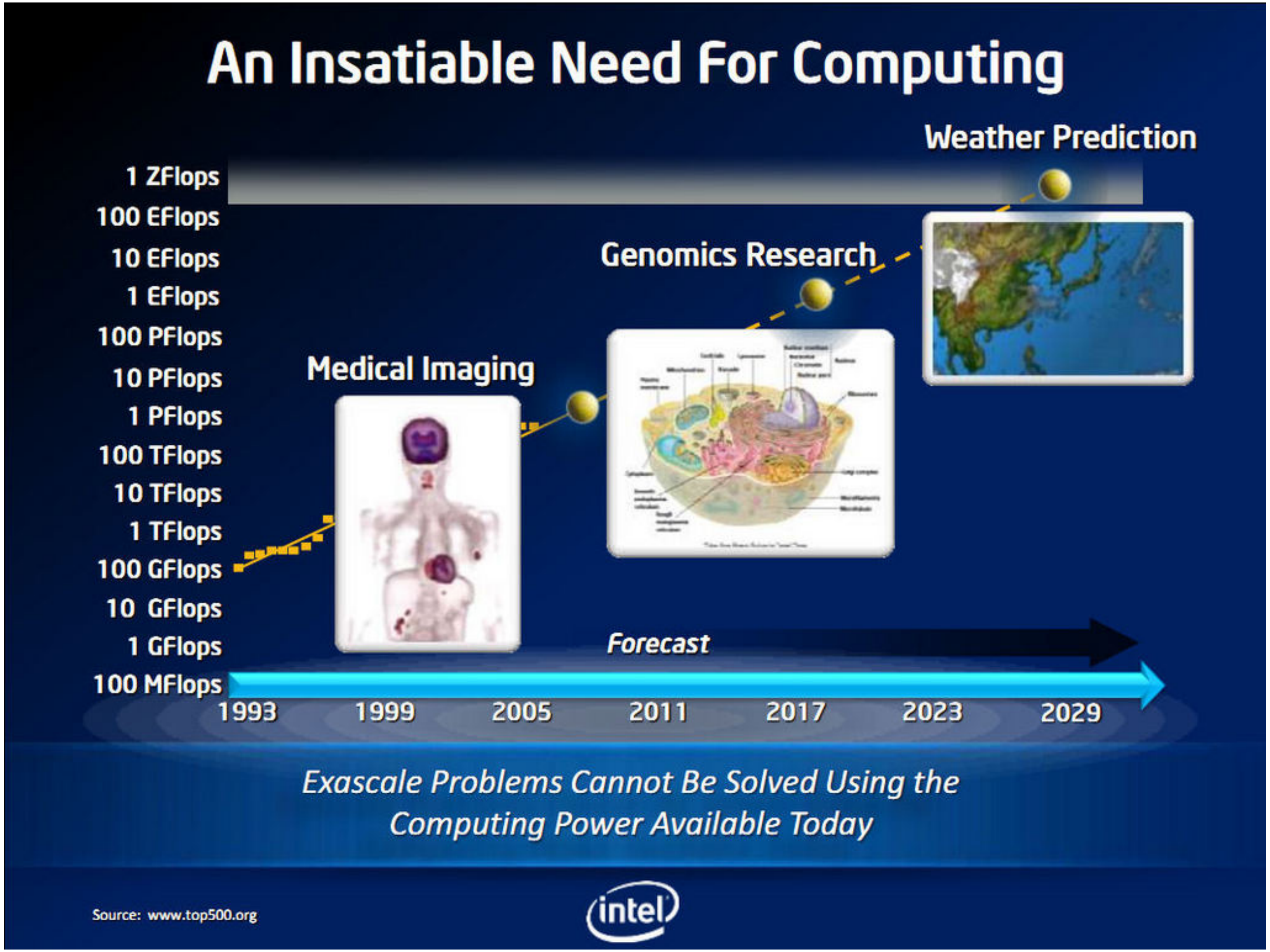
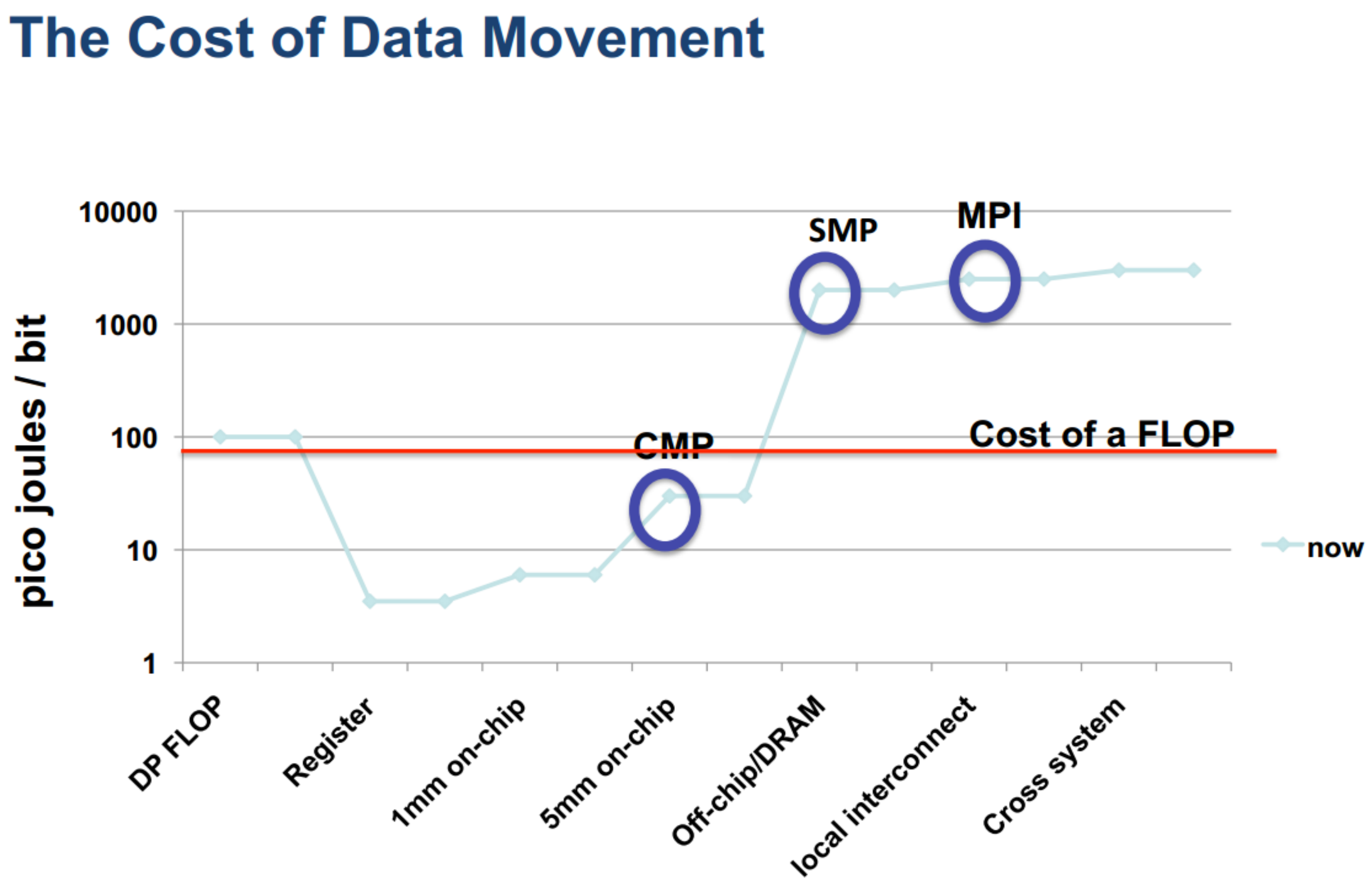
Google's power estimated at 40 PFLOPS in 8 Datacenters (2012)

Computing power must scale together w. society needs



Data movement is a massive wall in the road to exascale



Courtesy: Horst Simon, Lawrence Berkeley NationalLaboratory

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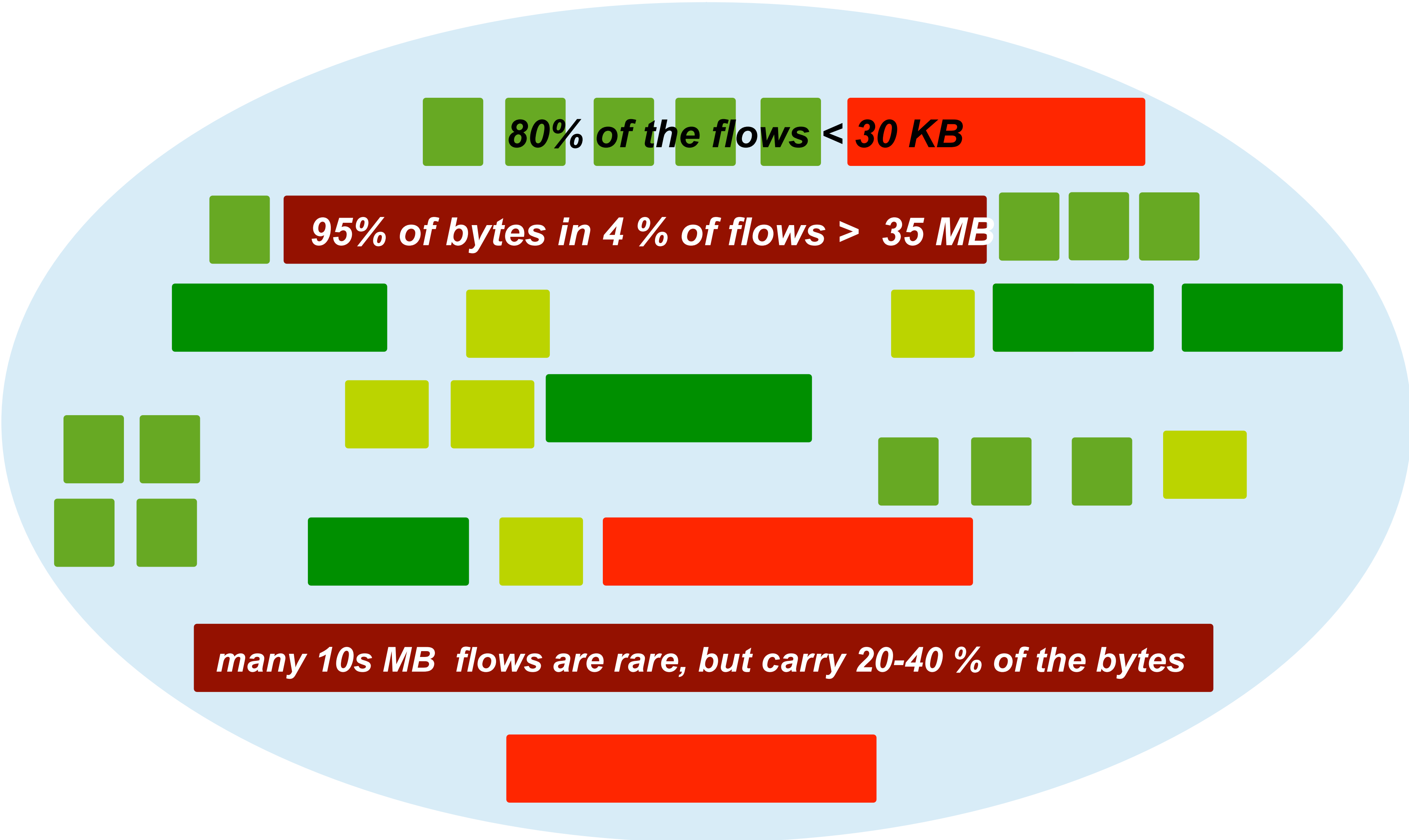
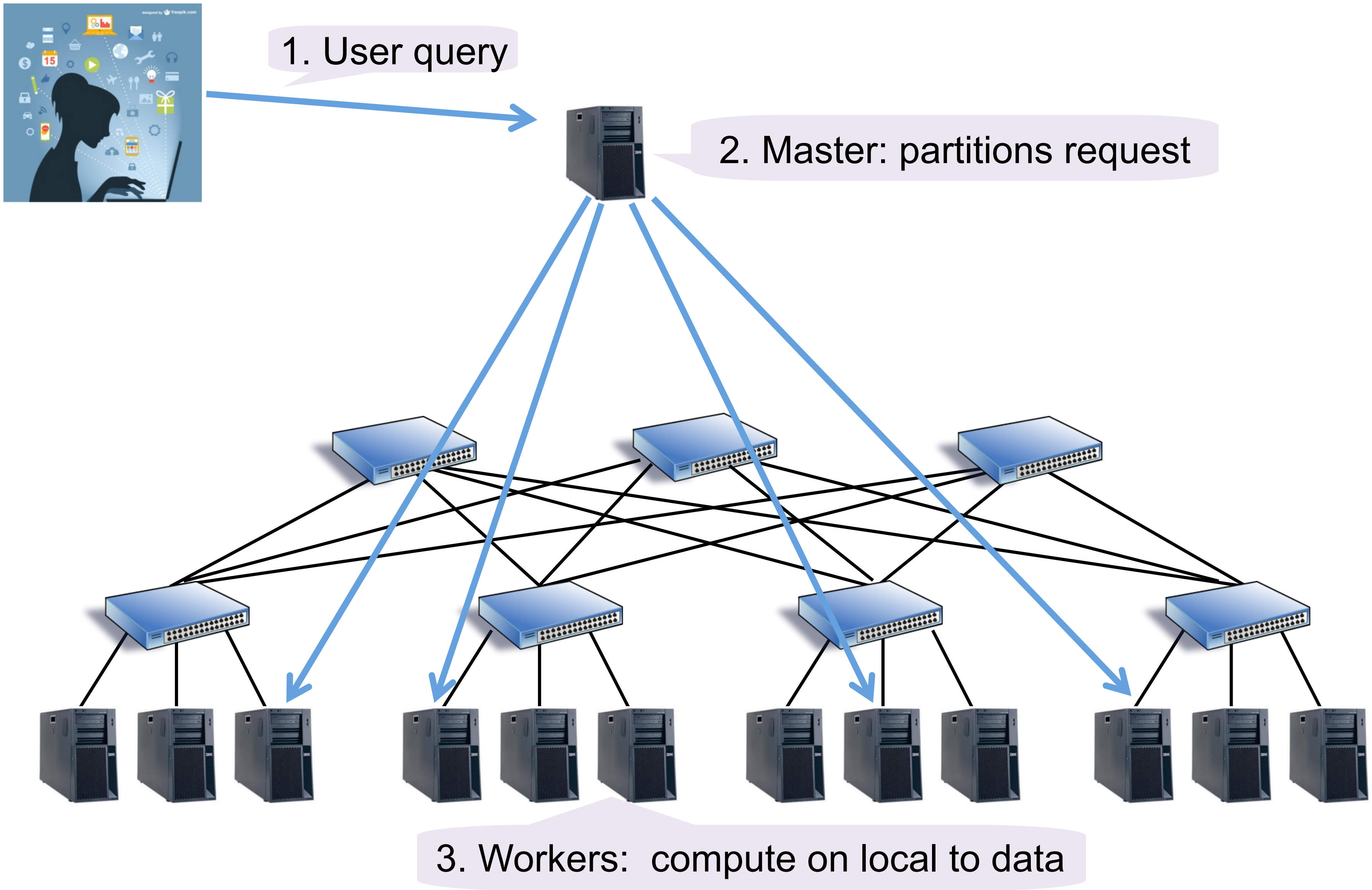
Flow sizes in commercial datacenters



Sources of large flows: storage/ VM migration/ checkpointing..

Online data intensive (OLDI) app's working on big-data



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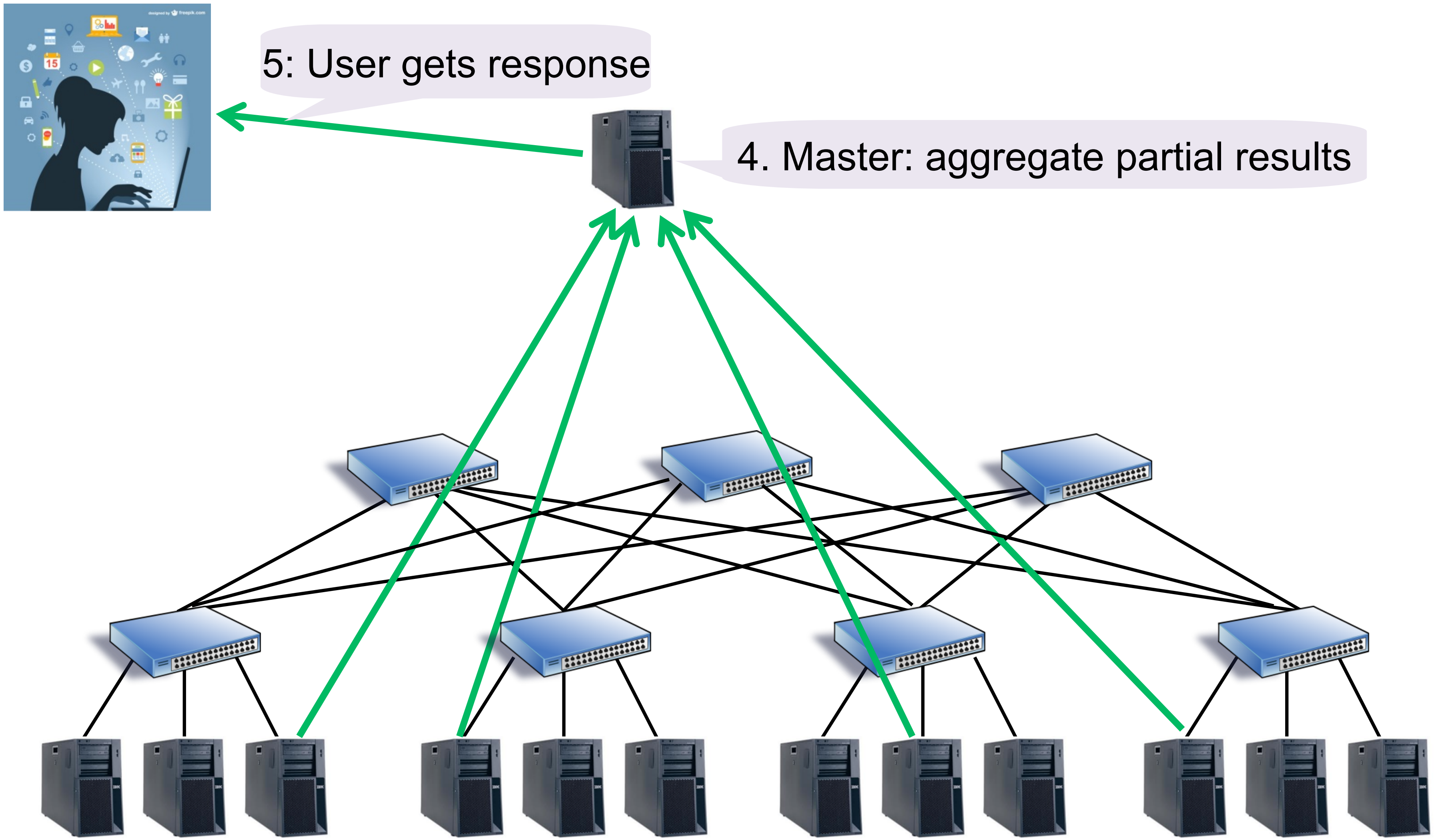
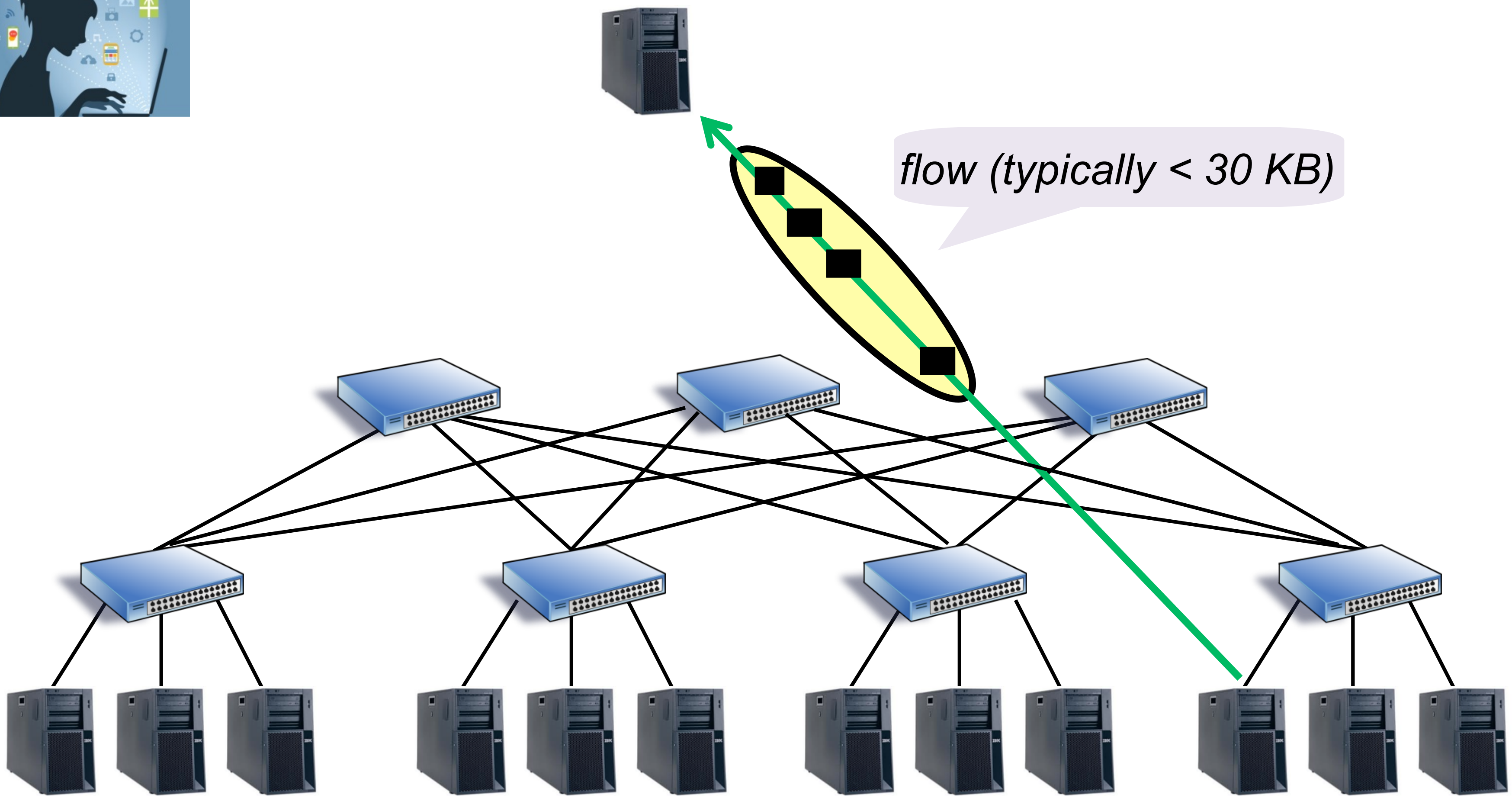
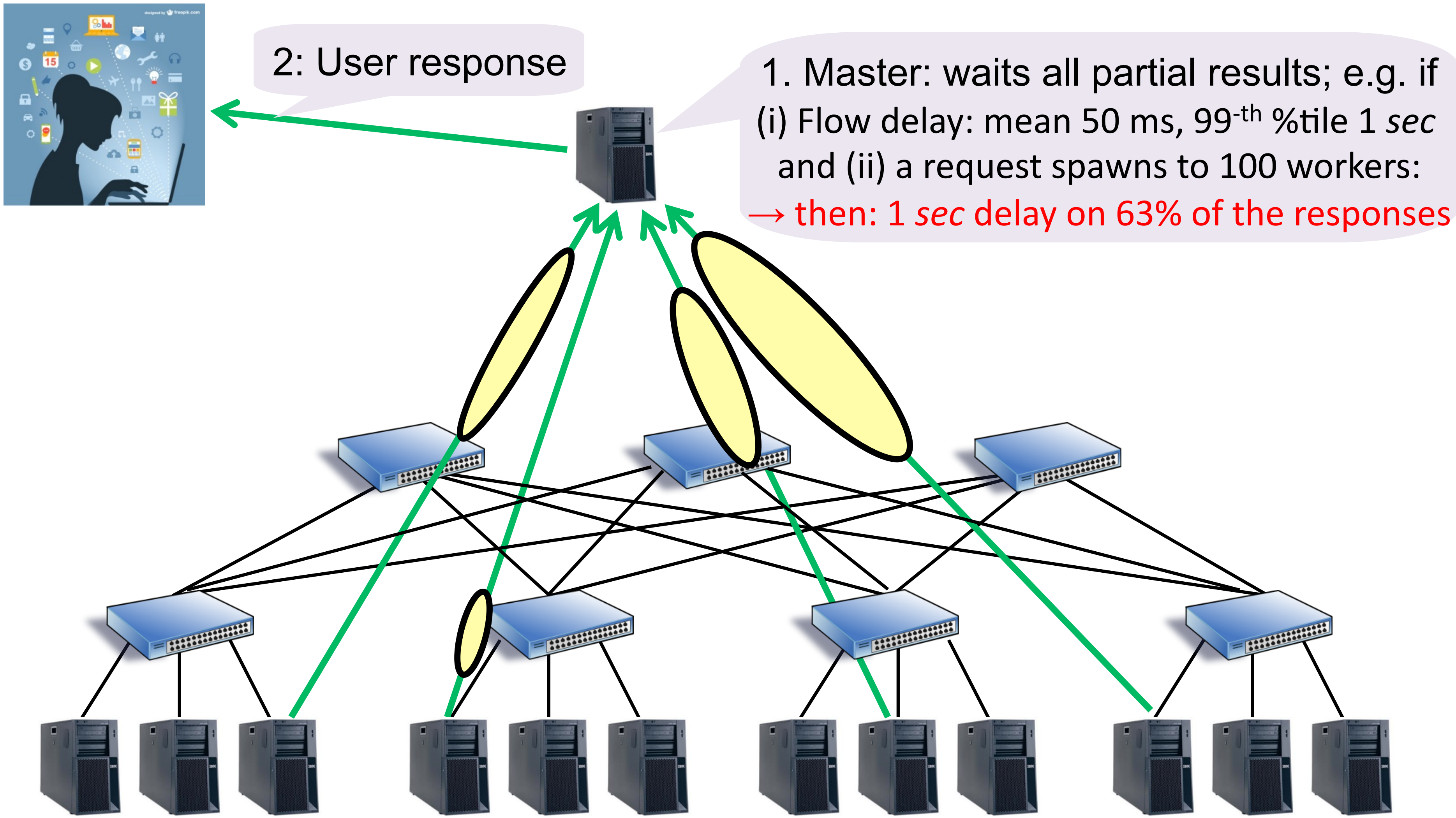


Partial results are usually small



User is best satisfied if all partial results arrive on time



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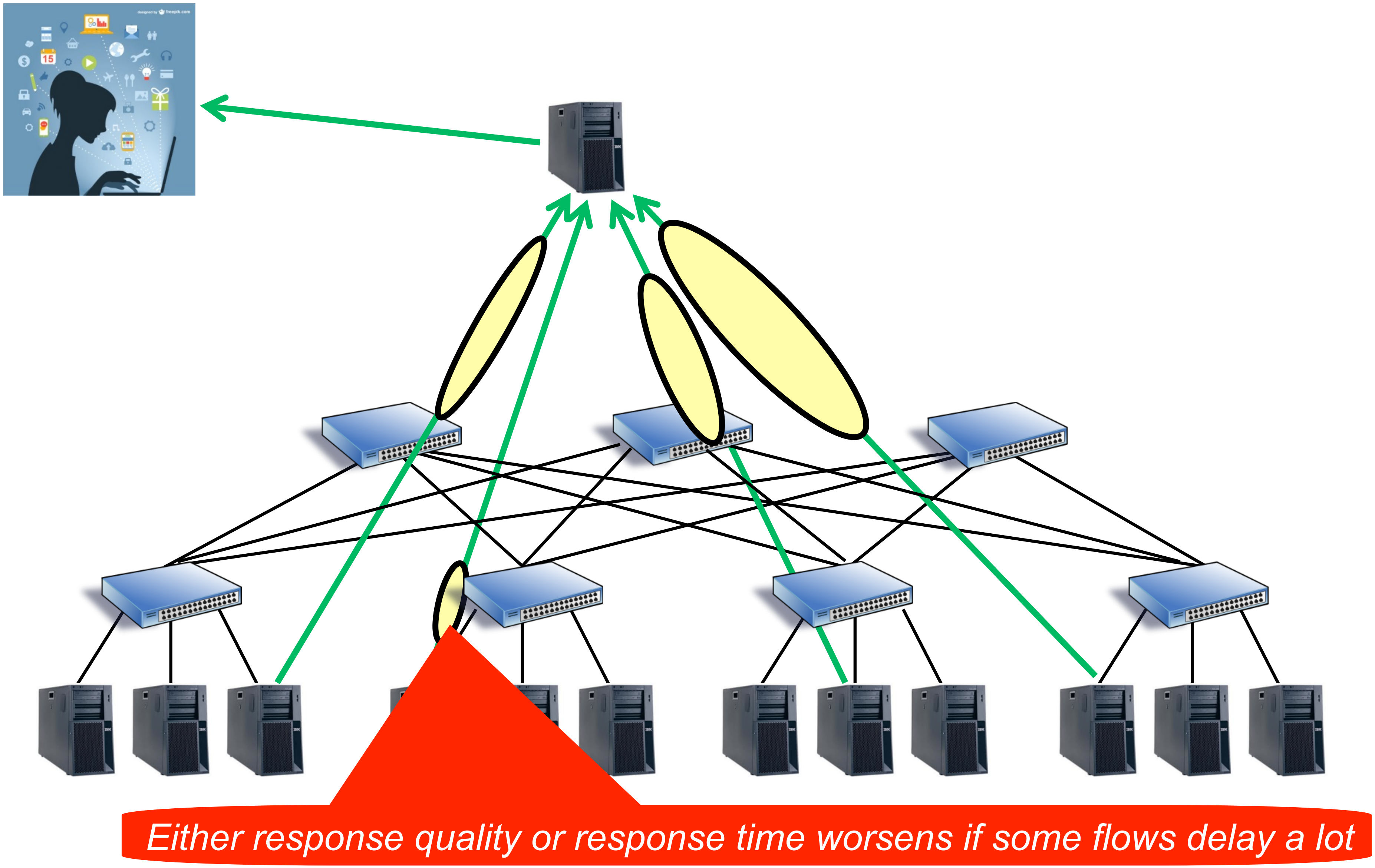
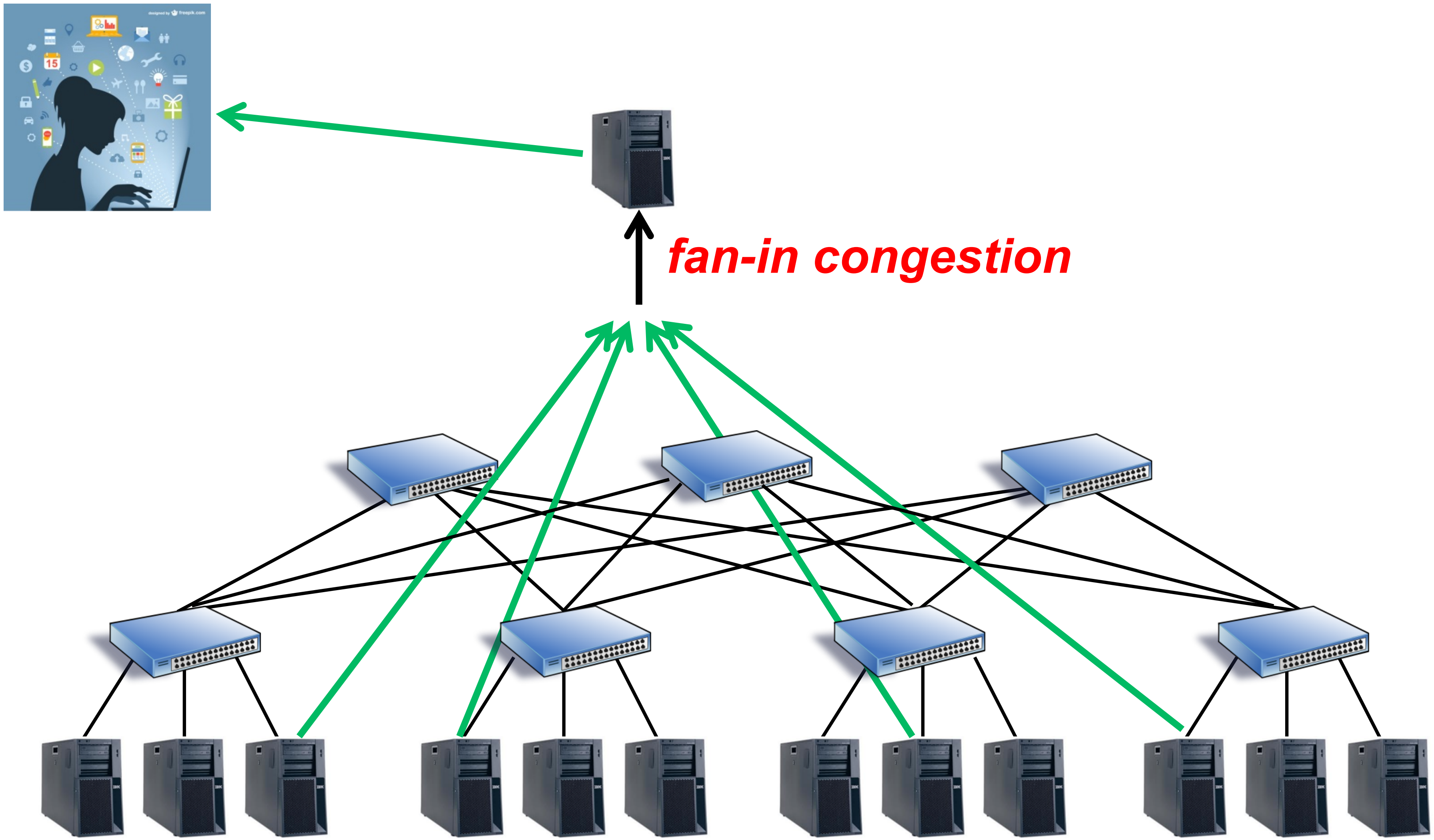
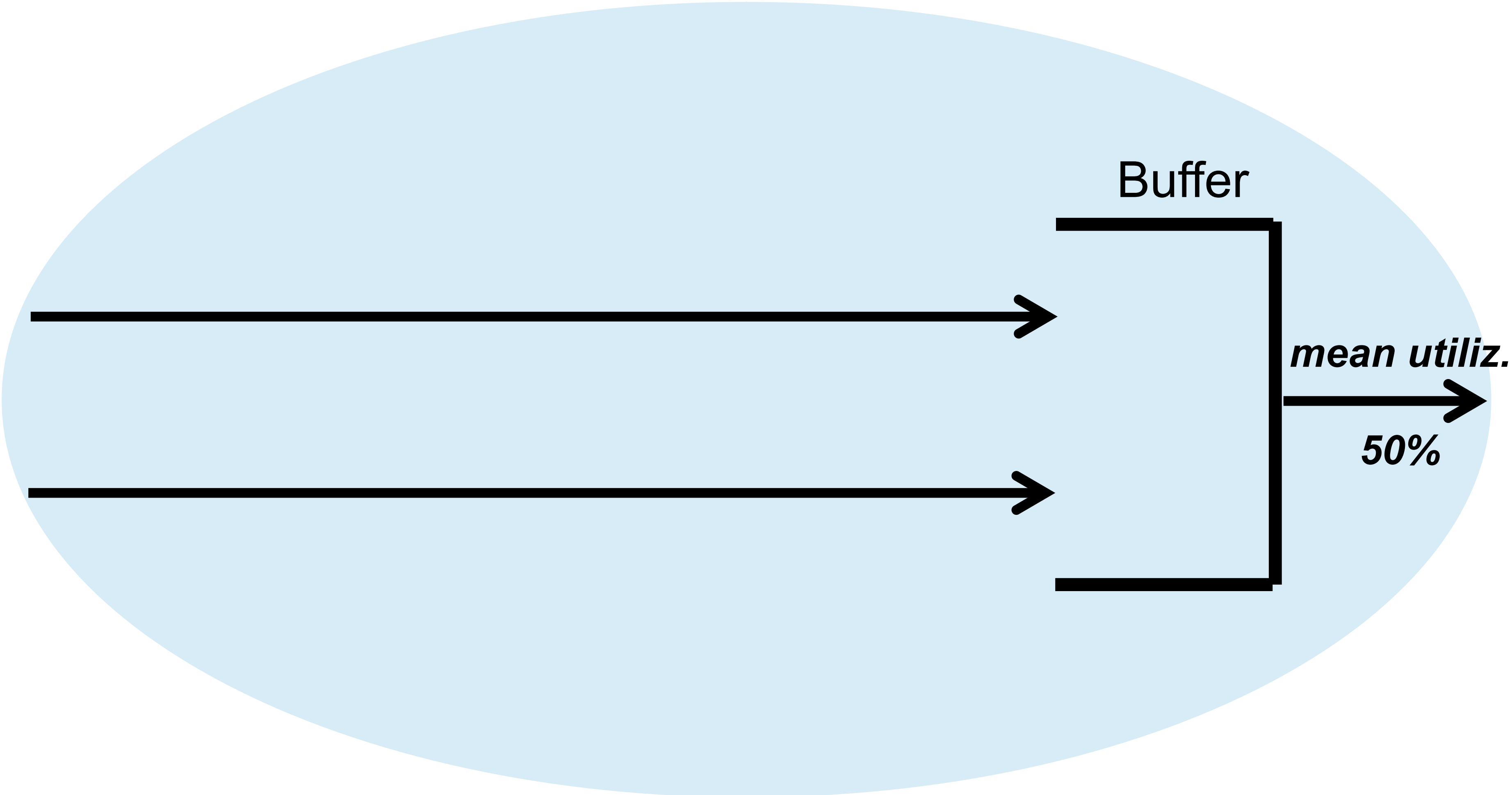


Compute close to data & flows are small ..but netw. suffers



“No problem: my network logs show 50% utilization”



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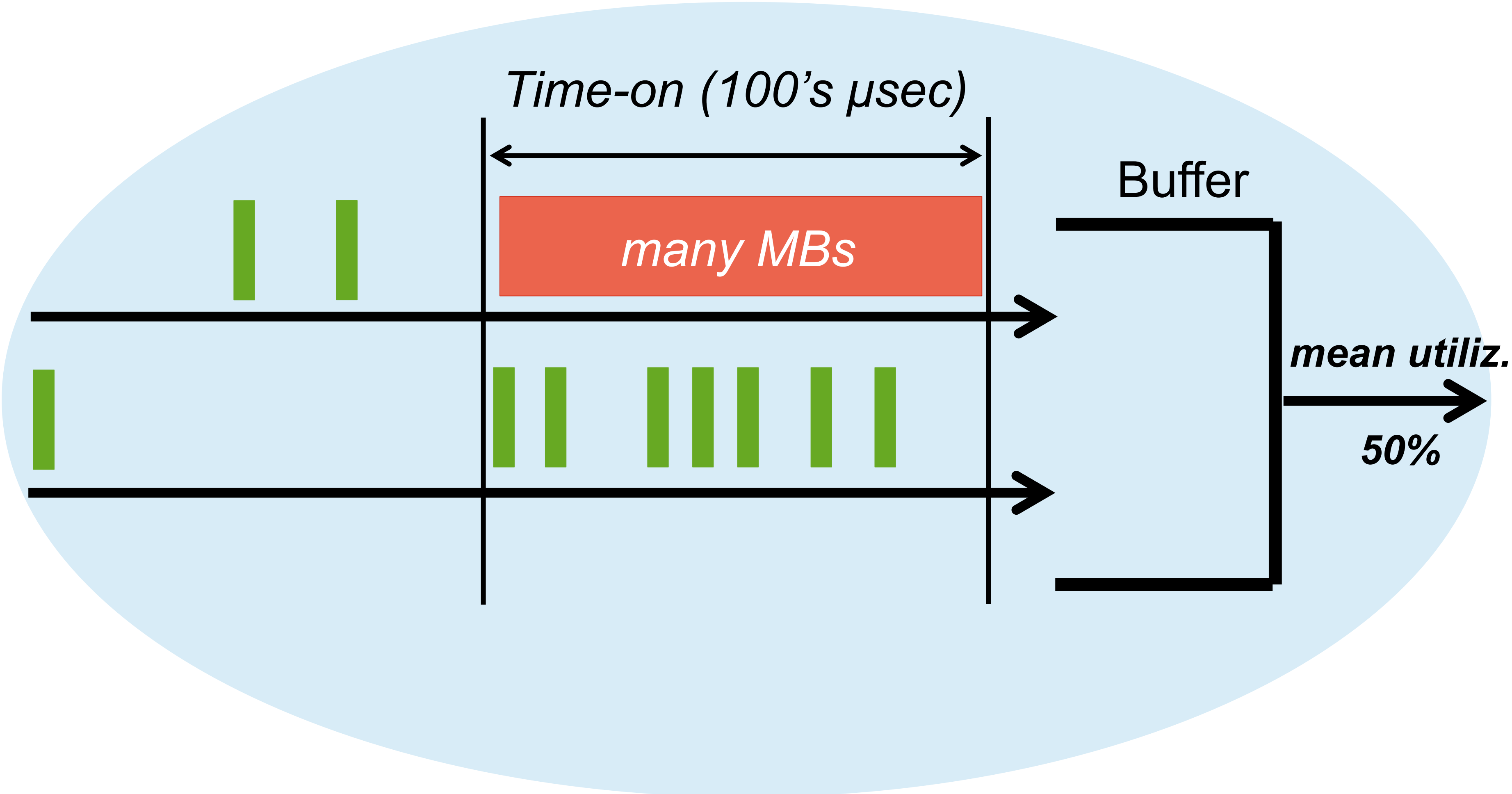

But bursty large flows & fan-in → strong fights @ short time scale

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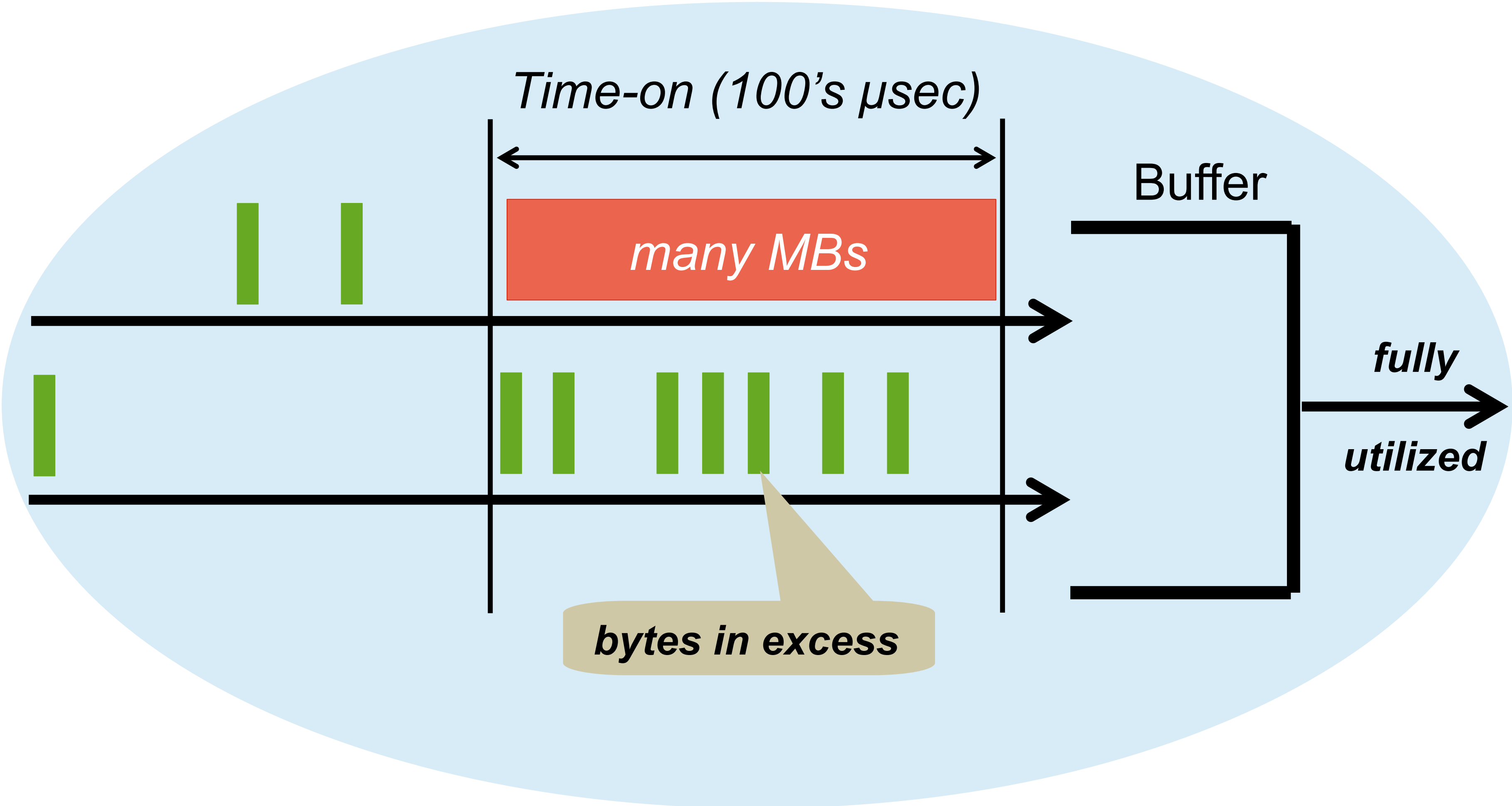

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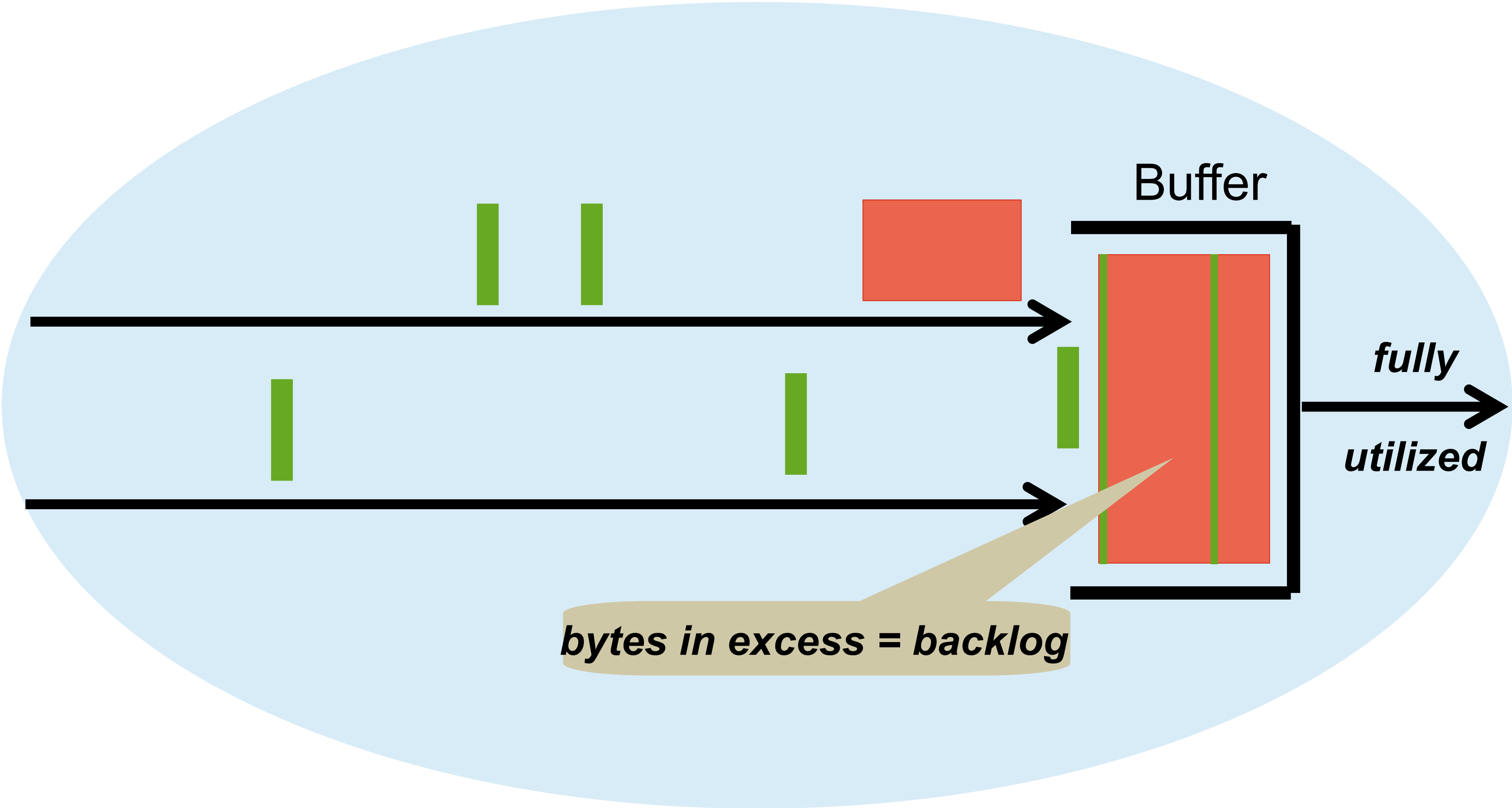
Big problem: buffers will backlog



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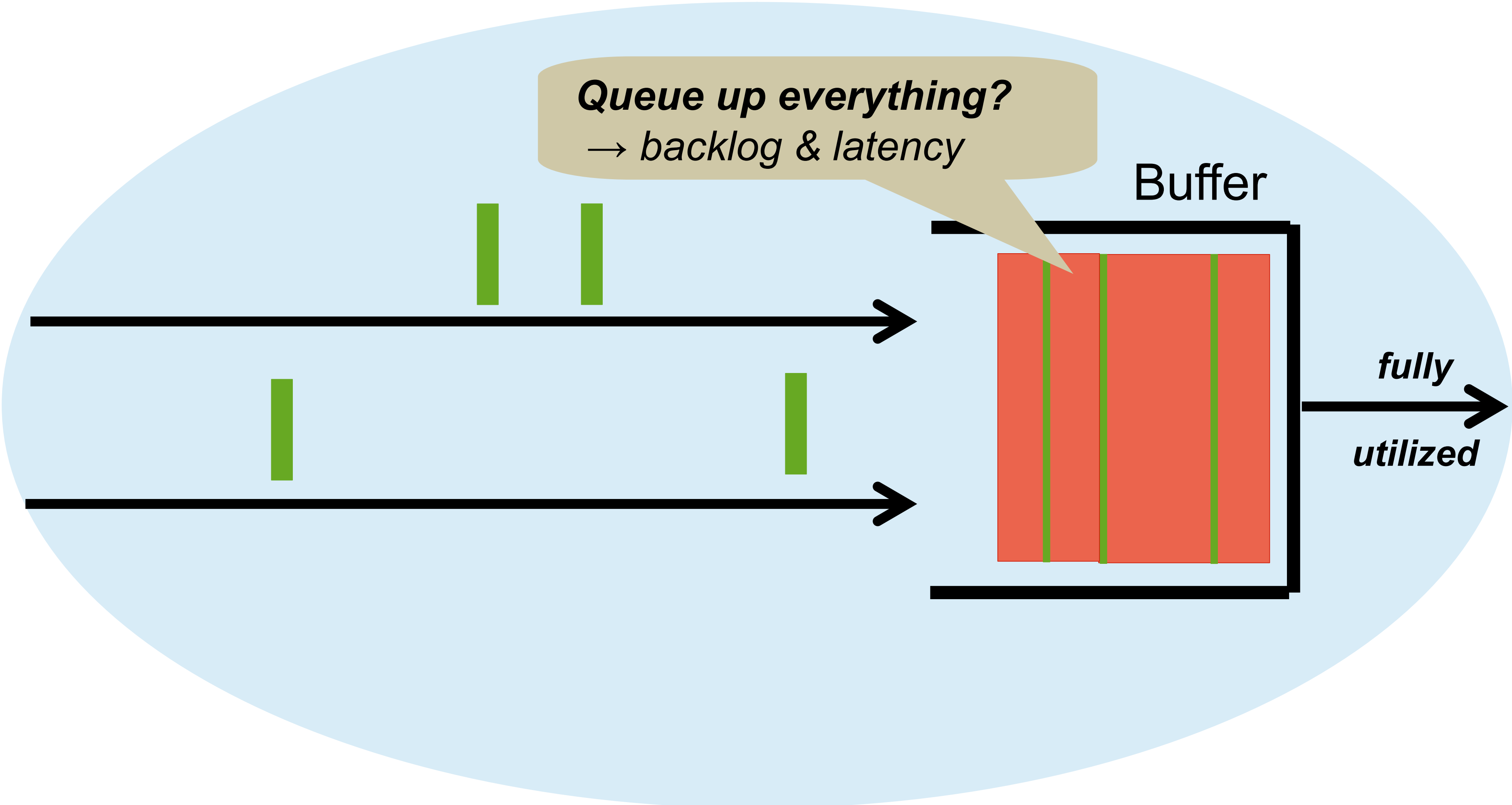

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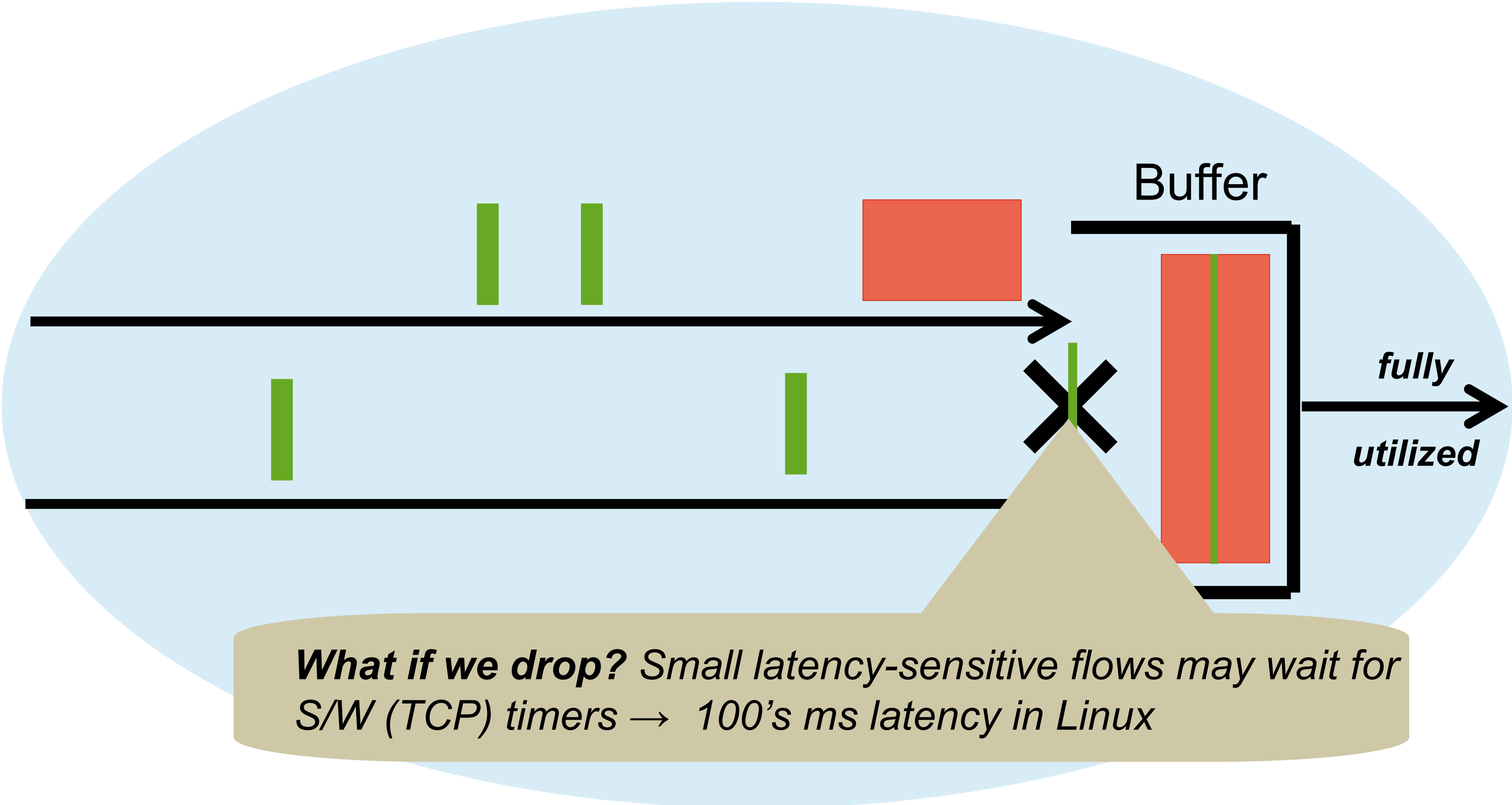

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Network congestion: an old unresolved problem

- Effects
  - Unacceptable latencies
  - Productivity (throughput) reduction
- Need to live with it (hard) … or take measures

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  - Conservative rate (window) control to ensure stability
    - converges to approximately fair rates after several RTTs
  - Cannot avoid backlogs & drops : recovery w. sluggish S/W retransmissions
    - bad for latency-critical flows
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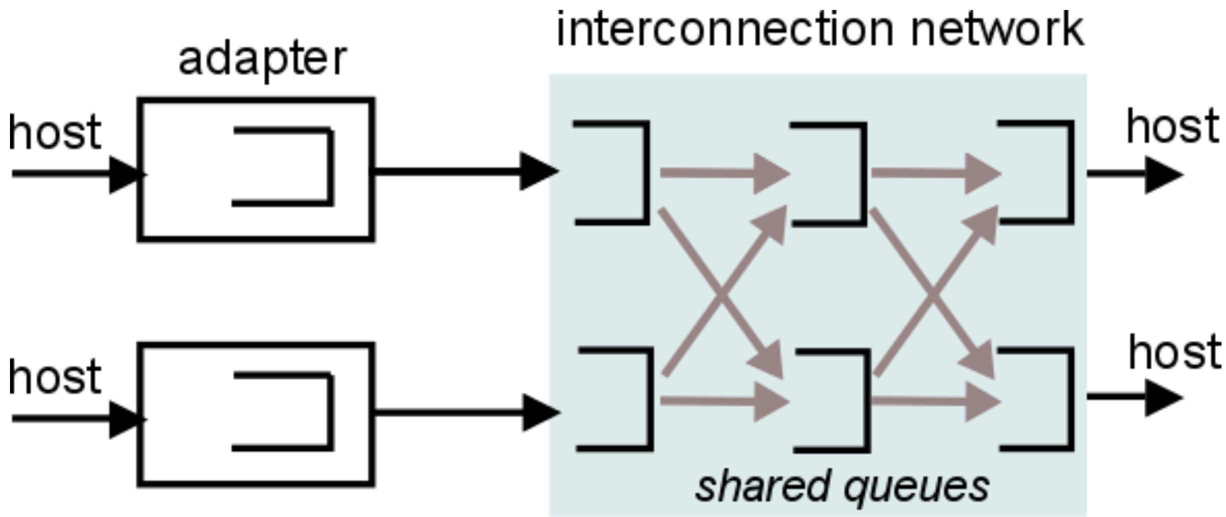
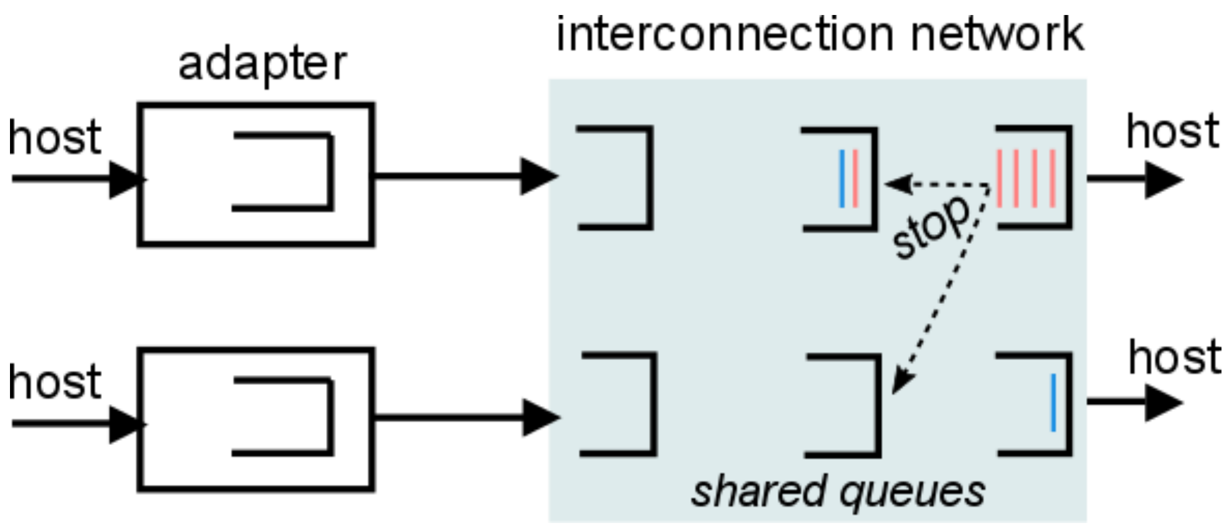
  - Long lat. (10's μsec) & many copies at hosts: ***can do much better w. RDMA***

Multistage interconnection network : abstract view



- One shared queue per switching element
- Multiple paths to destination

First measure: link-level flow control to avoid packet drops



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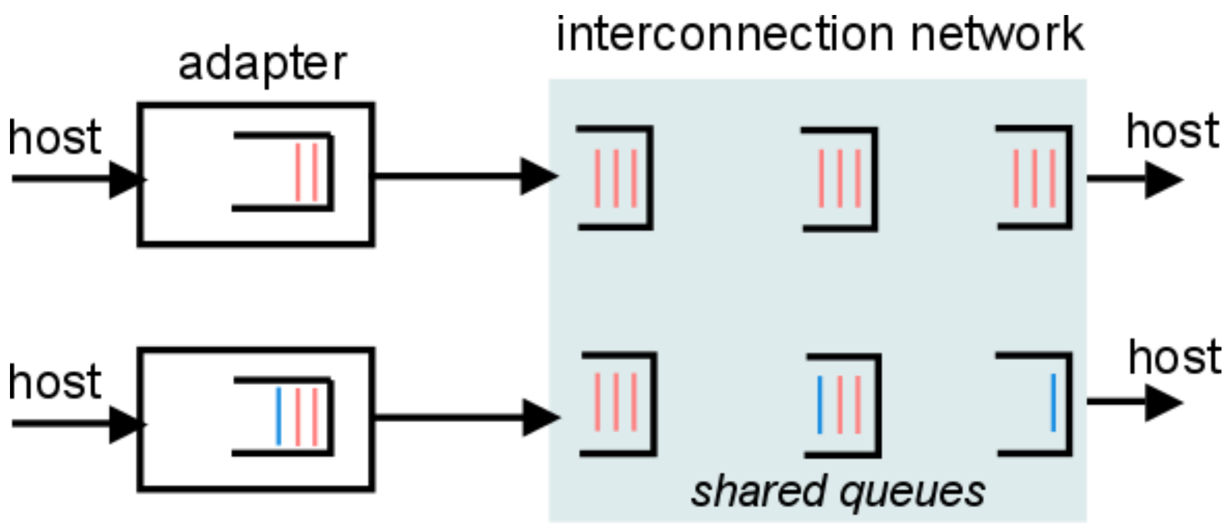
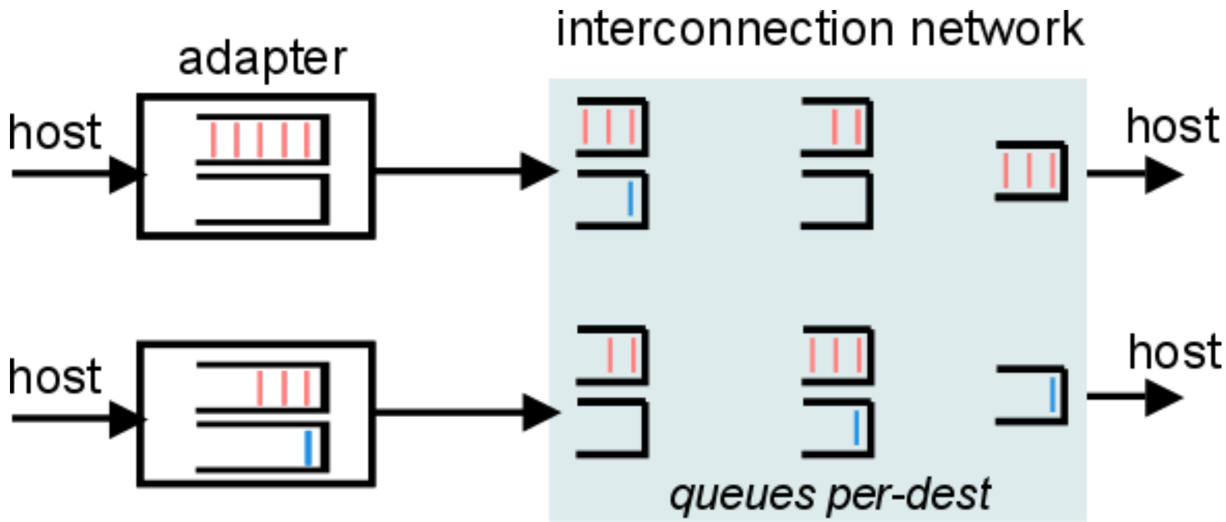


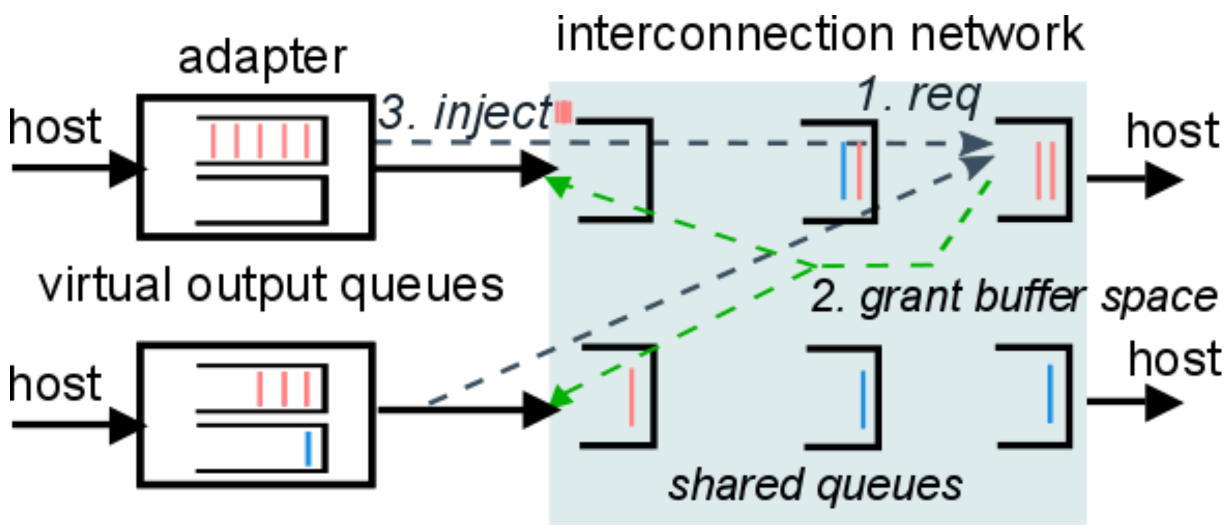
- Packets held in upstream buffer when downstream buffer full
  – Lossless networks: CEE (pause-based), Infiniband (credit-based)
- New problems
  – HOL blocking: nobody in Q can move because head packet is blocked
  – *Many* network buffers fill up not only at hotspot
    - Bad for latency-critical flows

A "high-end" accompanying measure: per-destination Qs



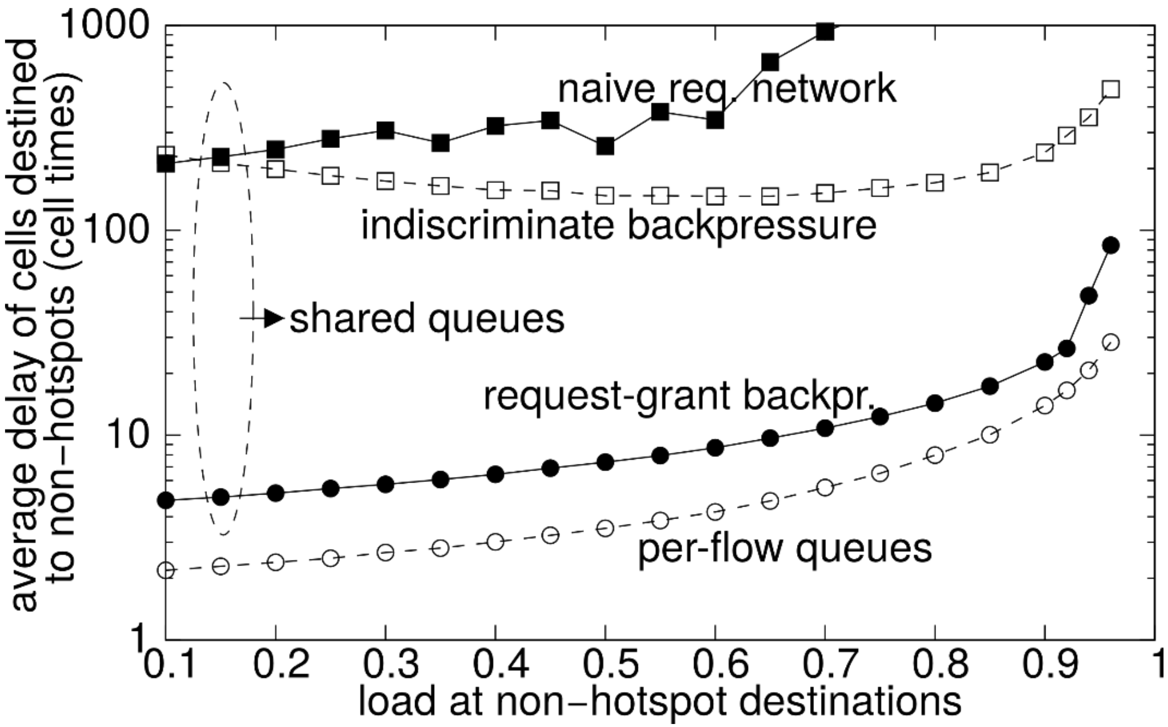
- Separate queues inside the network for every destination (Katevenis 1987, Sapunjis & Katevenis 2003)
  - Perfect isolation if link-level flow control stops only the queues of misbehaving flows (destinations)
  - Non-congested flows progress at full speed
- But cost of switching elements grows with network size

A sometimes affordable alternative: buffer reservations



- At high loads, reserve network buffer resources before injecting packets (Chrysos & Katevenis 2006, IBM 100G server-rack fabric 2014)
  - Packets wait at virtual output (per-dest) queues in front of network
- Shared in-fabric queues never exert backpressure
  - No HOL blocking and no backlogs
- But complicated schedulers & per-dest request queues (counters)

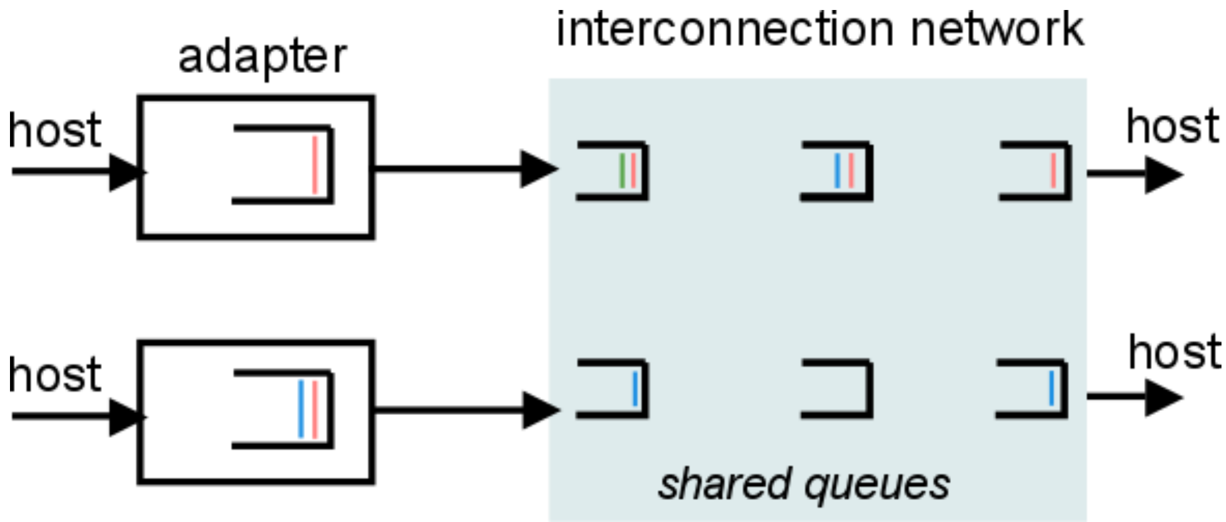
Simple flow control vs. per-flow queues vs. req-grant



Delay of innocent (non-congested) packets w. 1 congested dest

- Request-grant backpr. & per-flow queues best performance
  - small latencies for innocent cells – no backlogs & no HOL blocking in
- Simple flow control (indiscr. bkpr.) → innocent flows suffer
  - ~ 2 orders of magnitude higher latency

Dynamically allocated (per-flow) queues



- Regional Explicit Congestion Notification (RECN – *Duato e.a.* HPCA 2005)
- Key insights:
  – Under normal conditions: one queue per link suffices

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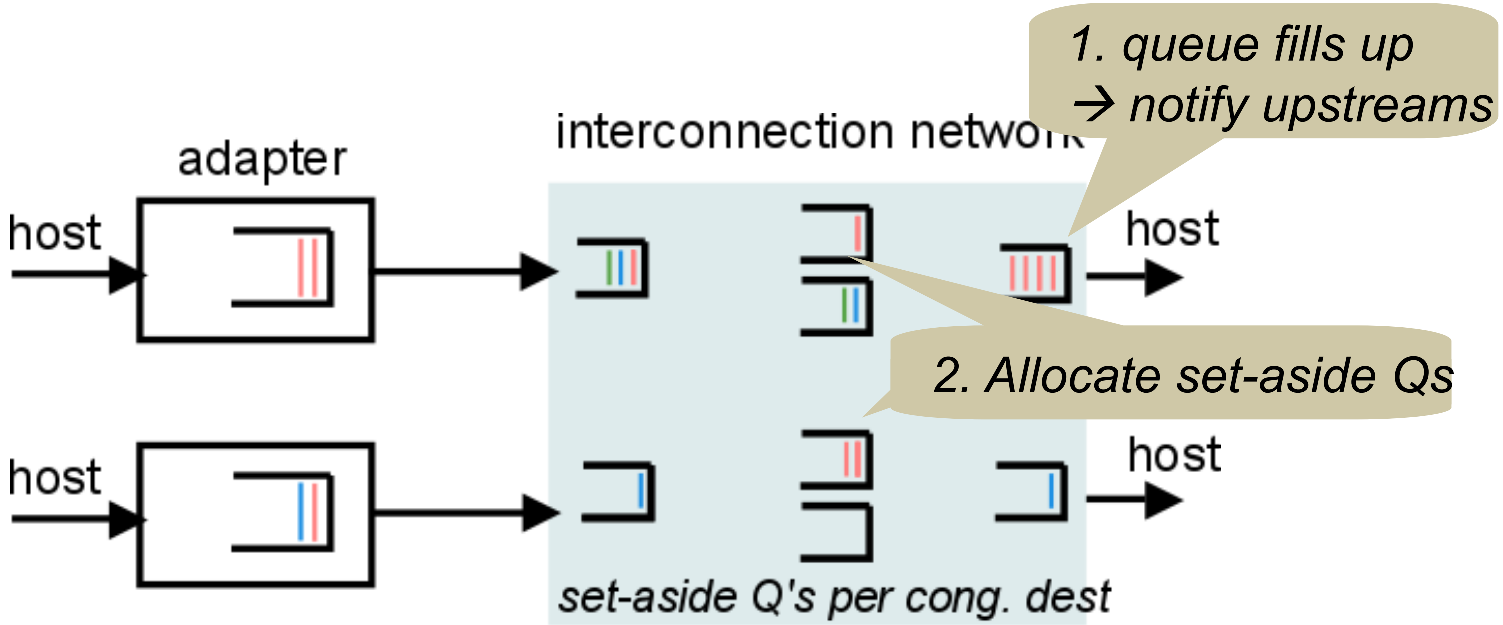

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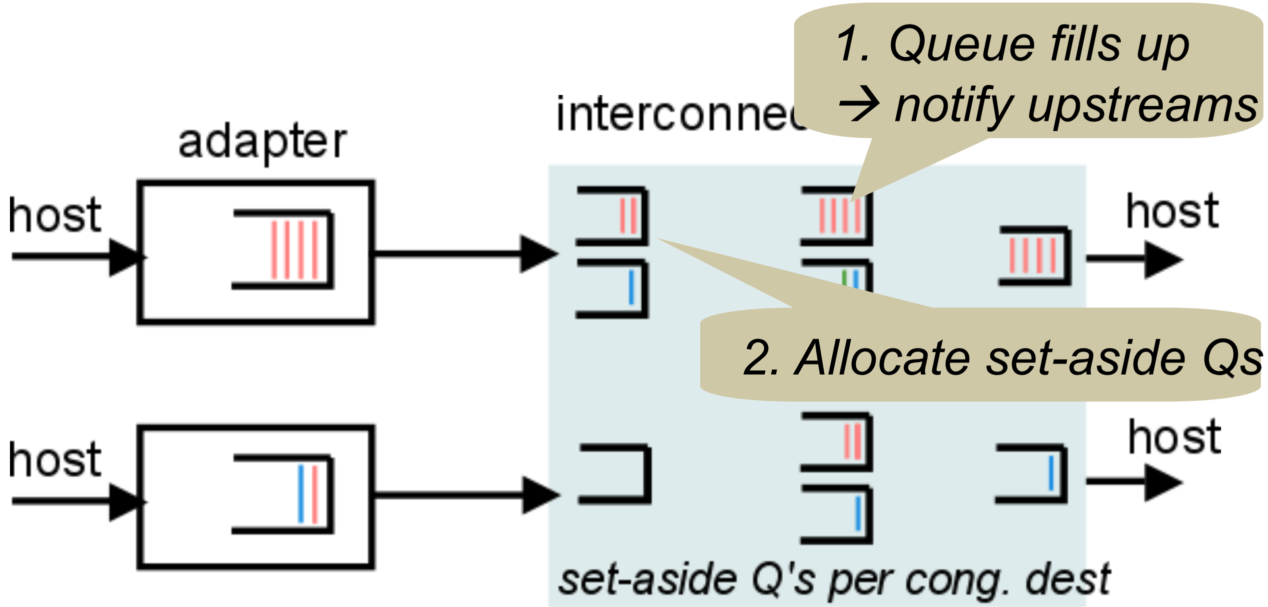

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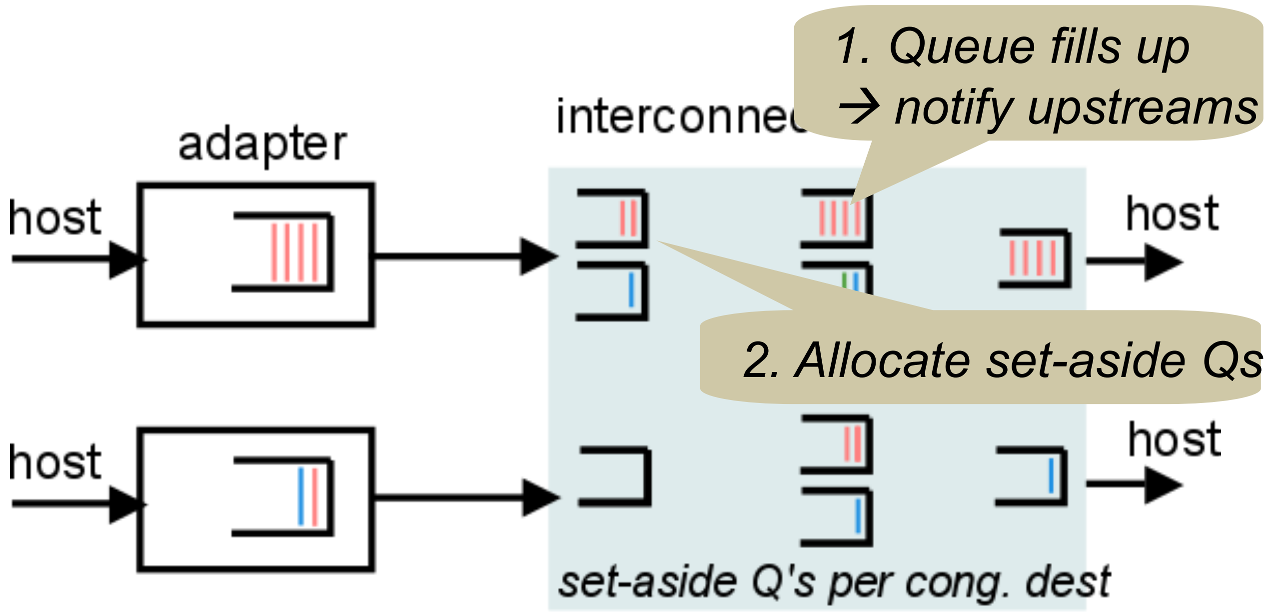

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- Complex link-level ctrl, costly for many concurrent hotspots

Industry-standard solutions

- Quantized Congestion Notification (QCN) for lossless (Converged Enhanced) Ethernet
  - – Congestion points @ netw. links send congestion notifications to sources: → allocate separate queues & rate control flows injections
    - Multiplicative decrease, additive increase ~ TCP
  - – Unfair and complex (*Chrysos e.a.* 2014)

→ Most Ethernet networks are lossy and rely on TCP

- Infiniband congestion control
  - – very hard to tune and stabilize (Gusat *et al.* 2005)
  - – deployment levels: unknown

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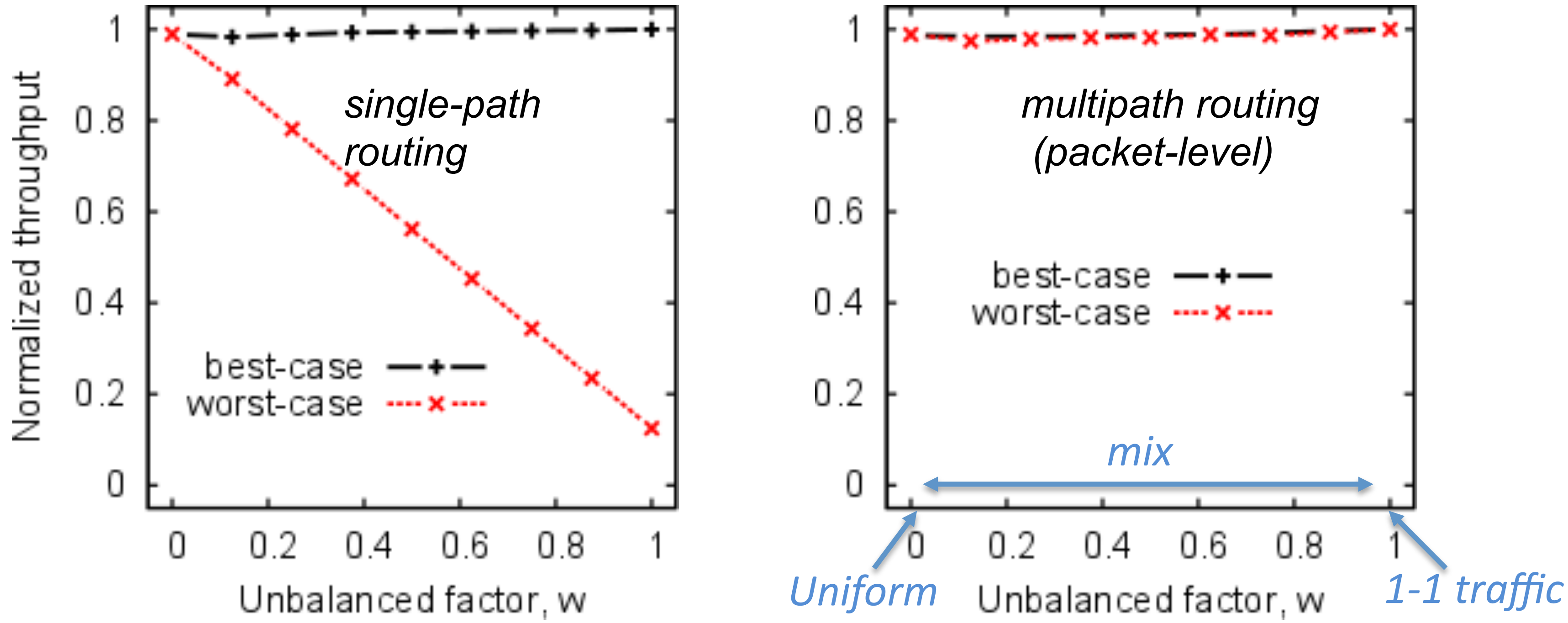
Multipath routing allows to exploit all available capacity

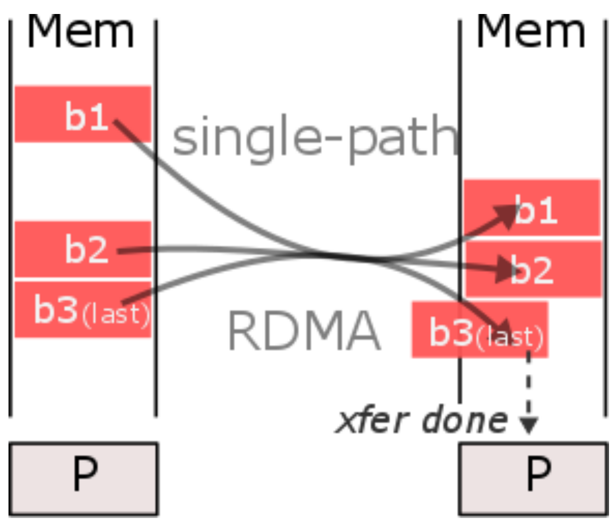


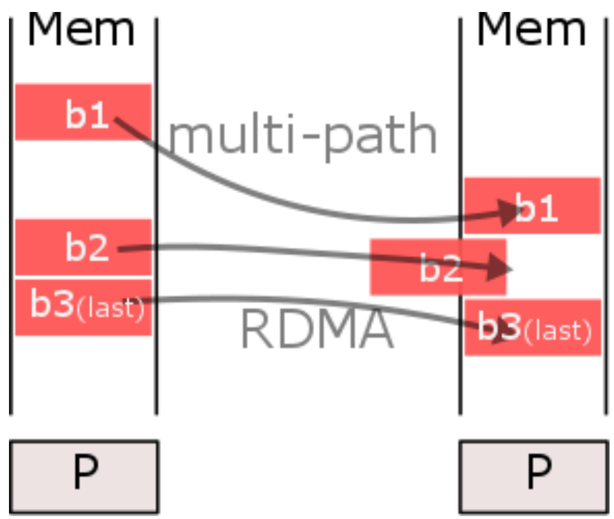
figures test different permutations on full-bisection-BW fat-tree

- Single-path routing: performance varies with spatial orientation of traffic
  - Same happens with industry-standard flow-level multipathing (ECMP routing)
- Packet-level multipathing consistently delivers full throughput

- Multipath Routing is also useful for Resilience

Multipath routing, however, complicates RDMA





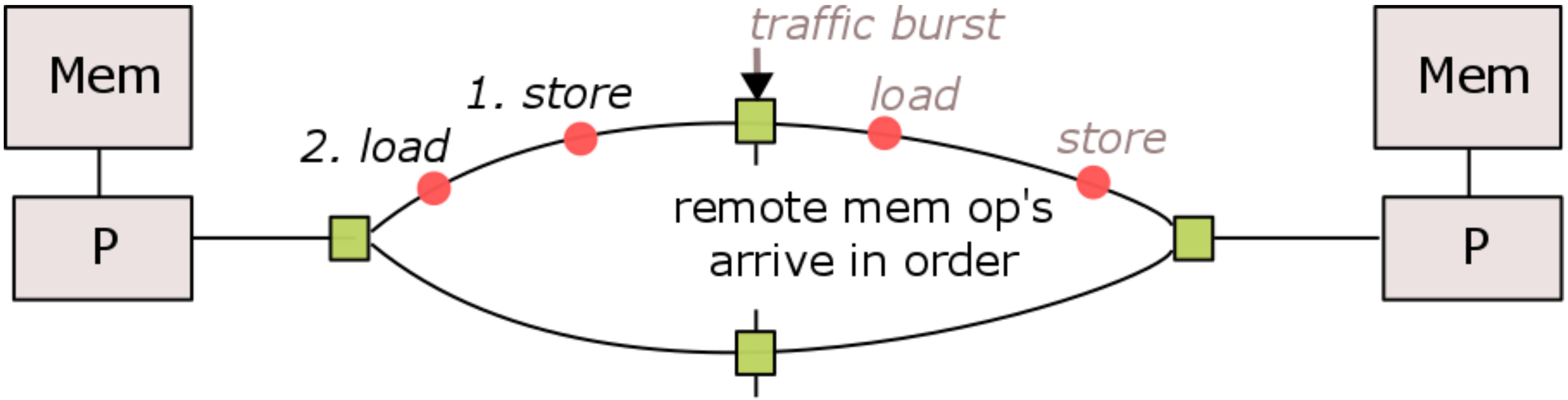
Single-path RDMA

- When dest gets last RDMA packet, it can wake up the processor to pick up the data

Multi-path RDMA

- RDMA packets may arrive out-of-order
  – Need other mechanisms to detect xfer completion

Multipathing also complicates remote memory operations



Remote store & load cmds for one (remote) memory location

- Semantically: “Load” should read what “Store” wrote
  - – OK with single-path routing

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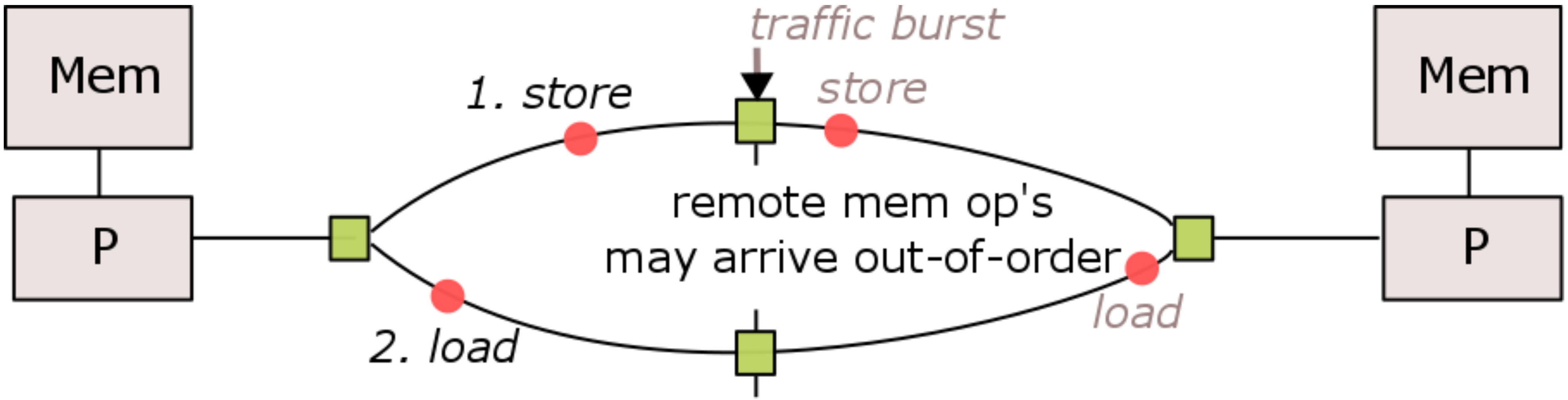

Remote store & load cmds for one (remote) memory location

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  - OK with single-path routing
  - Not necessarily true with multipath routing

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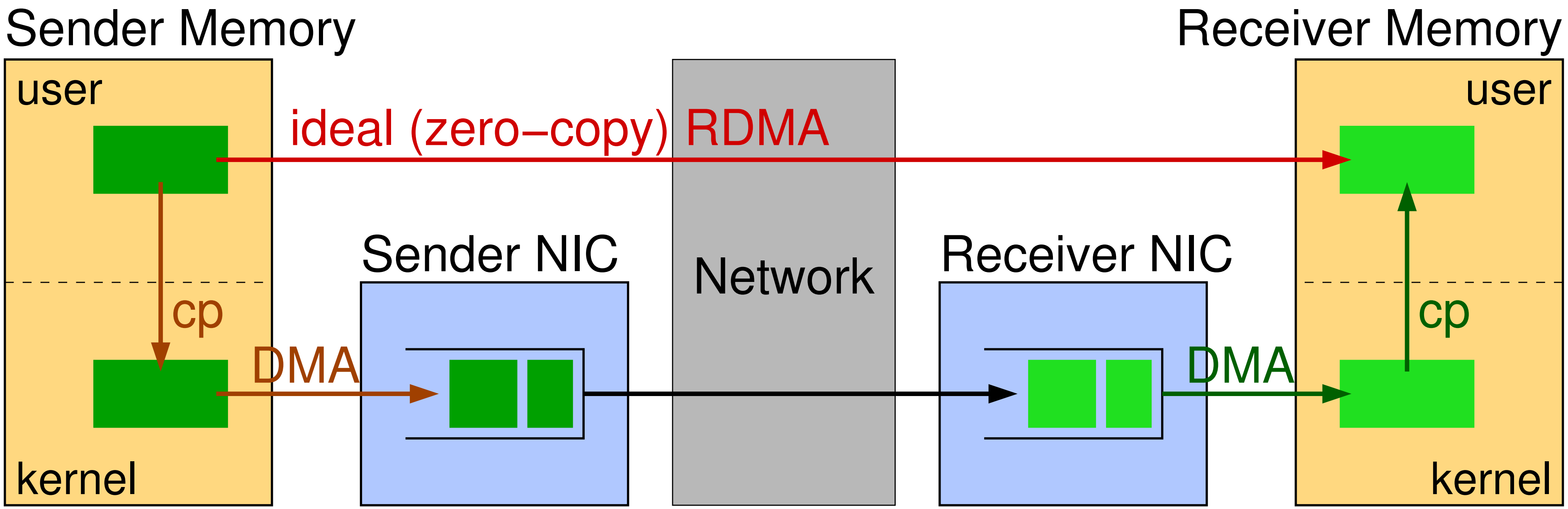
Inefficiencies of traditional "Send" – *how to overcome them*



Up to 5x (!) inefficiencies

- Receiver copy NIC→User – *rcv addresses visible to sender: **R**DMA – PGAS*
- Protection – *virtualized, user-level DMA initiation, IOMMU*
- Buffer Pinning for DMA – *allow RDMA to fail, like page faults for ld/st*
- Send before receive buffer allocated – *fix the API / Application*
- Send buffer reuse immediately after send – *fix the API / Application*

Wish List for an ideal Copy (RDMA) Engine

- User-Level RDMA Initiation:
  - Arguments to be full, arbitrary 64-bit *Virtual* Addresses
  - Control Registers to be virtualized and protected *per-process*
- No System Call necessary:
  - Virtual to Physical Address Translation via *HW MMU's* −not OS
  - Notification of Compl'n-Arrival: *per-process* Mailbox, not interrupt
- (true) Zero-Copy:
  - Any user page as source / destination
  - No need for pinning the src-dst pages in-memory: allow for translation failures during RDMA operation, resuting in notification of incomplete operation −like normal page-faults
  - Also useful for **Resilience**
- Exascale Global Addr. Space: full 64-b virtual addr. (+PID) throughout
- Performance: multi-channel engine; per-channel flow/rate control

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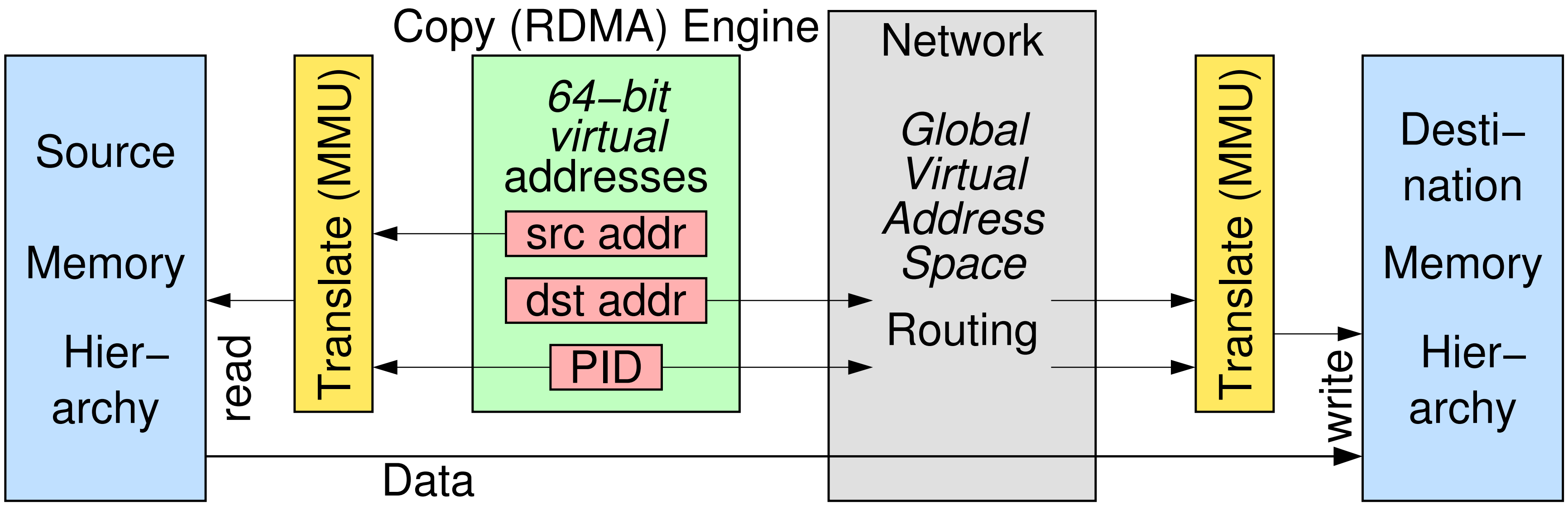
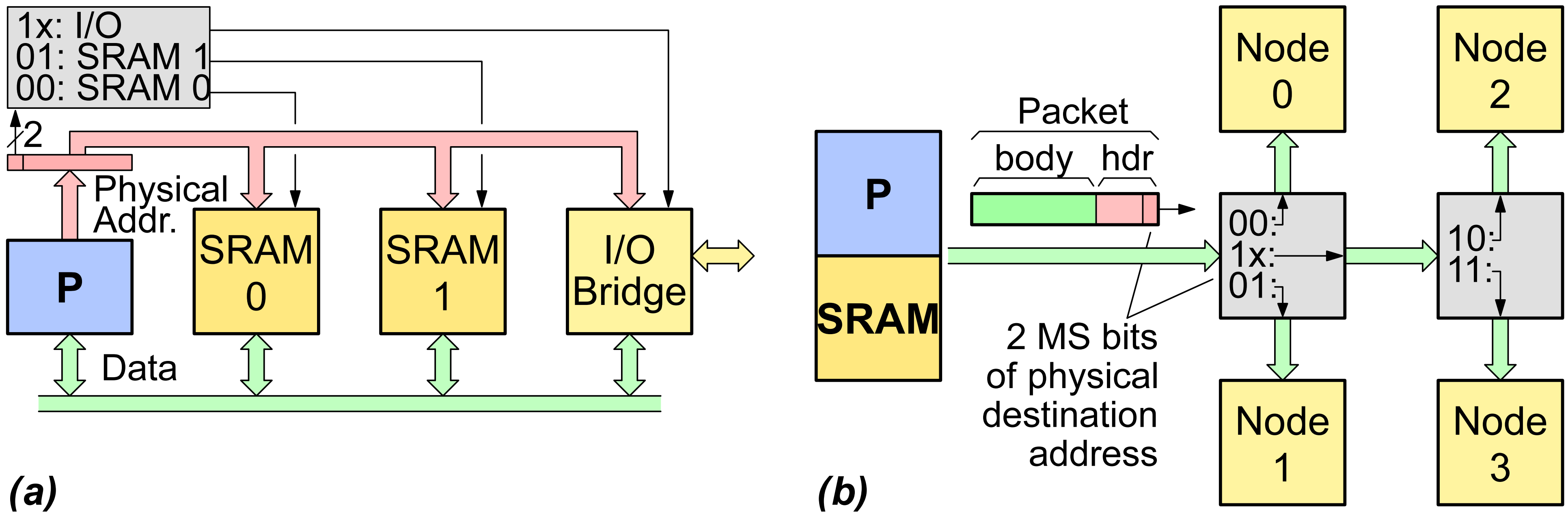
User-Level Commun. in a true Global Virtual Address Space



- GVAS for exascale needs 64-bit addresses, with (global) protection domain identifier either incorporated in them or as extra bits
- Sophisticated network routing based on GVA will allow (large) page (segment) live migration –see "Progressive Address Translation " in Katevenis 2007 paper http://www.ics.forth.gr/carv/ipc/ldstgen_katevenis07.pdf

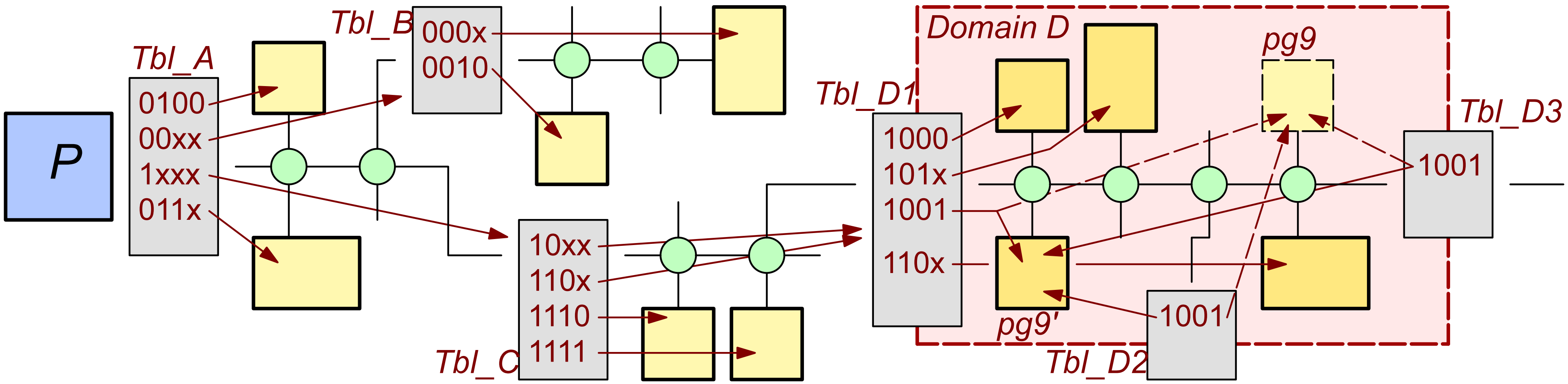
SARC Project (2005-09): Network Routing as Generalization of Address Decoding



- Physical Address Decoding in a uniprocessor
- Geographical Address Routing in a multiprocessor

http://www.ics.forth.gr/carv/ipc/ldstgen_katevenis07.pdf

Progressive Address Translation: Localize Migration Updates



- Packets carry global virtual addresses
- Tables provide physical route (address) for the next few steps
- When page 9 migrates within D, only tables in that domain need updating
- Variable-size-page translation tables look like internet routing tables (longest-prefix matches if we want small-page-within-big-region migration)
- Tables that partition the system, for protection against untrusted operating systems, look like internet firewalls

Conclusions

- Datacenter (and Supercomputer) Interconnects: increasingly important – challenges & opportunities
- Congestion Management: important, hard, unresolved
  - quick feedback, throttle sources, avoid drops, avoid deadlocks
- Multipathing:
  - good performance, useful for Resilience, but out-of-order delivery
- RDMA & Global Virt. Addr. Sp. for optimizing data copying:
  - known techniques, now need to convince industry to adopt them
- Routing: related to address translation and multipathing