ICN traffic control and network performance

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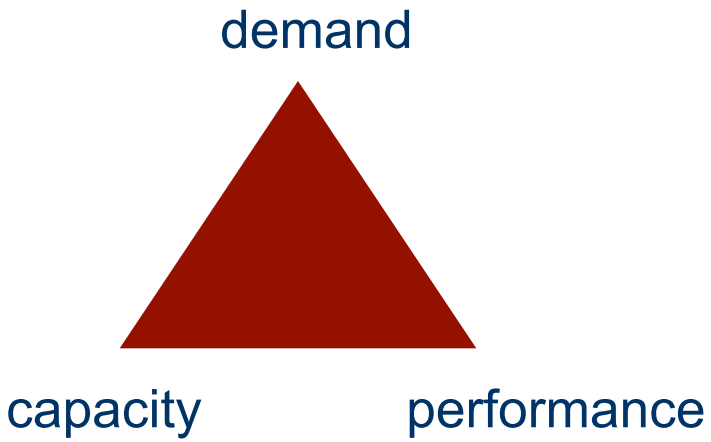
Traffic control is...

- how to realize performance objectives
- at least cost
- accounting for traffic characteristics (multi-service)
- by traffic engineering...
- and resource sharing mechanisms
    - congestion control
    - queue management
    - overload controls
    - ...
- i.e., traffic control is the basis for quality of service (QoS)

The dual role of QoS

- perform effective traffic control
  - to meet diverse application requirements
  - for delay, jitter, loss, throughput,...
- create a viable business model for the network operator
  - a range of differentiated services
  - to maximize revenue and avoid commoditization
- a source of some confusion!

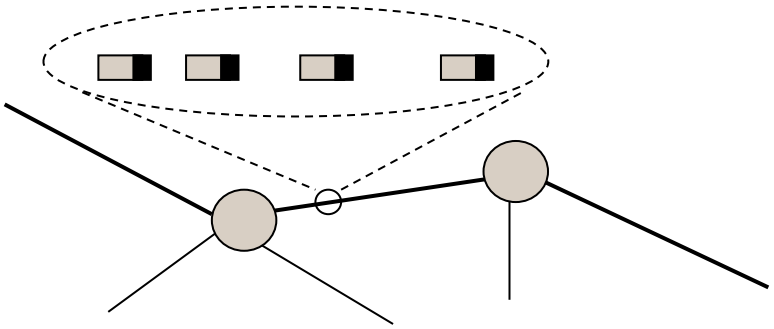


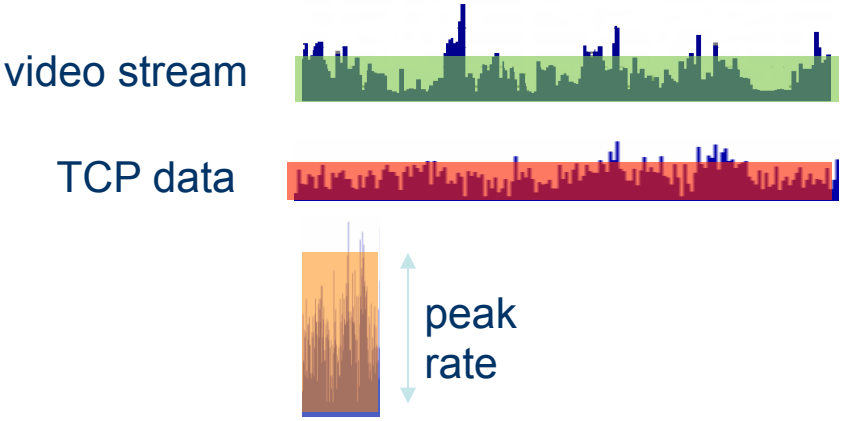
Outline

- Internet traffic control
- ICN traffic control
- Impact of in-network caching

Understanding traffic at flow level

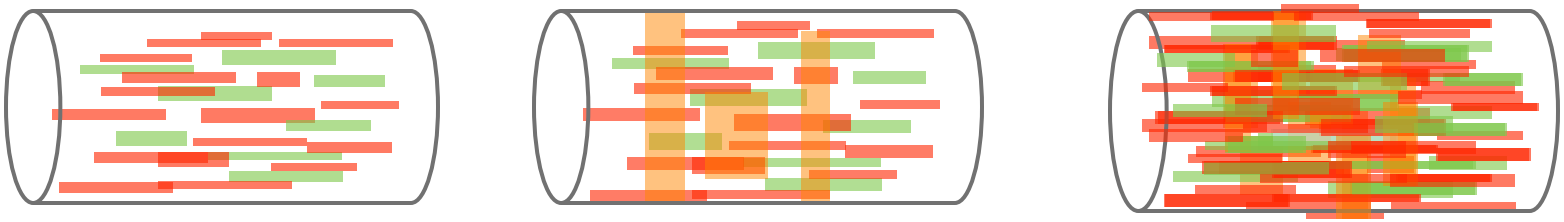
- users experience quality at flow level
  - a flow is an instance of some application (document transfer, voice signal,...)
  - a set of packets with like header fields, local in space and time
- flows of four types
  - conversational, streaming, interactive data, background
  - with different requirements for latency, integrity, throughput
  - and different traffic characteristics – rates, volumes,...





Bandwidth sharing regimes

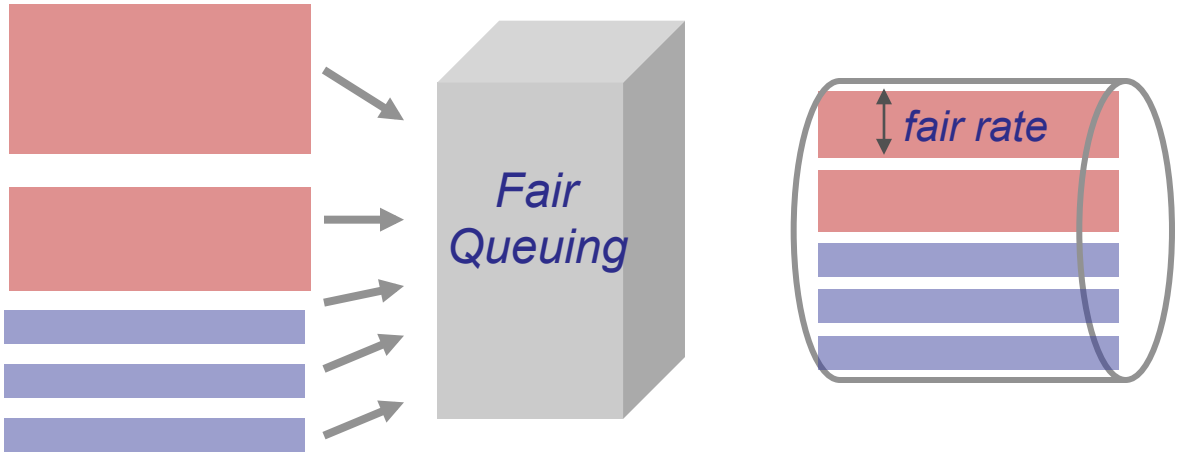
- three regimes



- transparent regime:
  - all flows suffer negligible loss, no throughput degradation
- elastic regime:
  - some high rate flows can saturate residual bandwidth; without control these can degrade quality for all other flows
- overload regime:
  - traffic load is greater than capacity; all flows suffer from congestion unless they are handled with priority

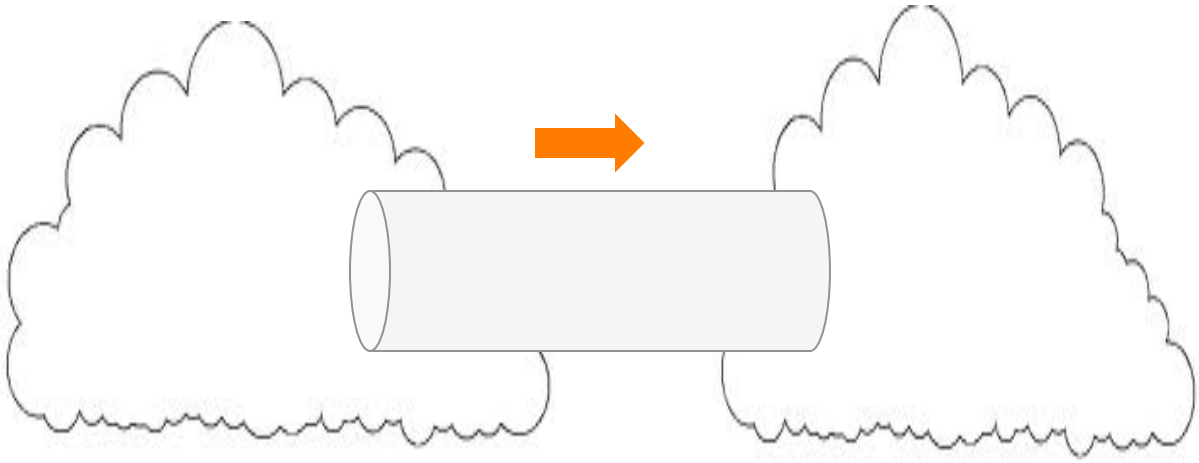
Internet traffic control

- rather than Intserv, DiffServ, MPLS TE,…
  routers should impose per-flow fair sharing and not rely on end-system implemented congestion control
- fair queuing is feasible and scalable…
  … and realizes implicit service differentiation…
  … for network neutral traffic control
- fairness is an expedient, not a socio-economic objective

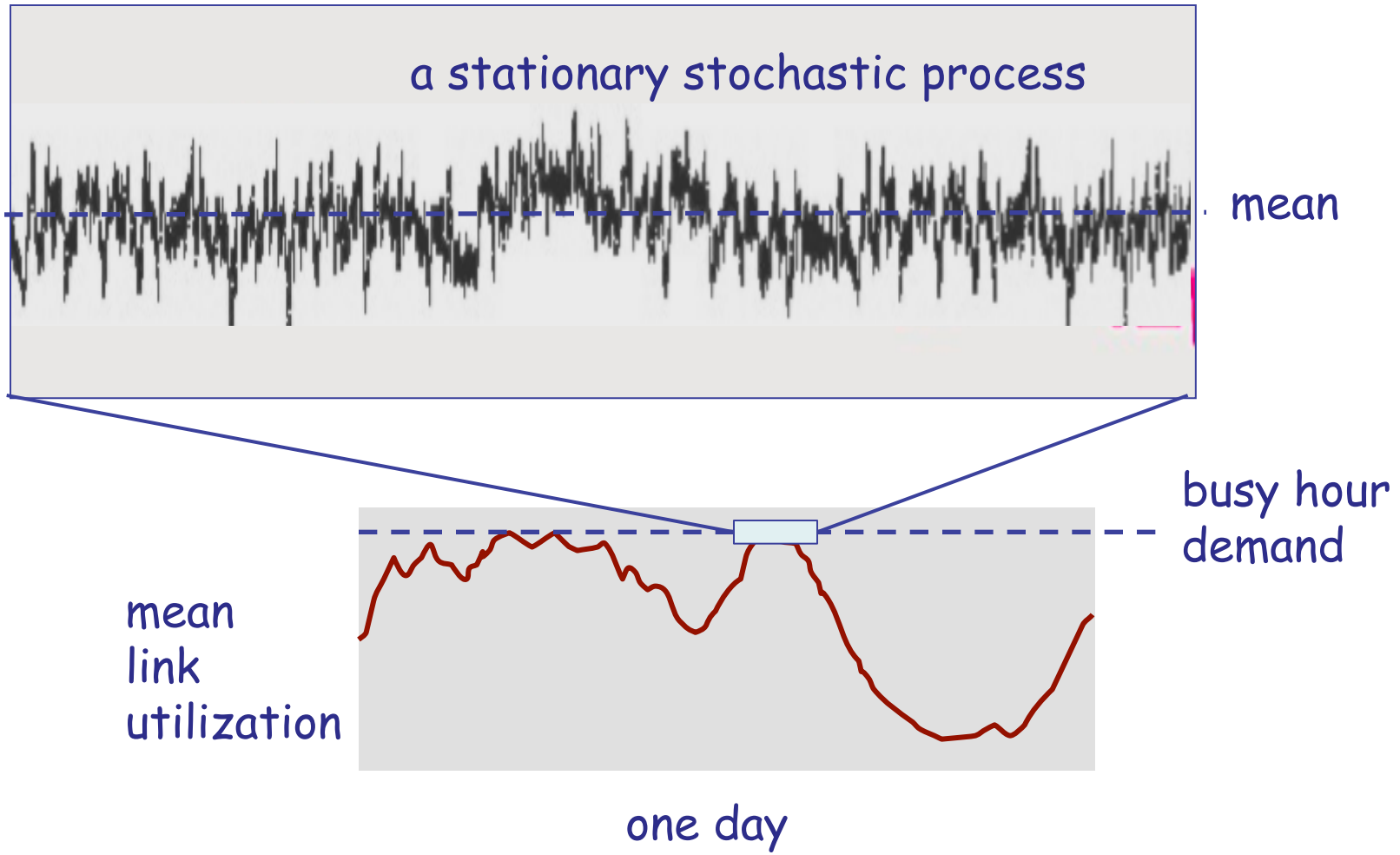


Statistical bandwidth sharing

- ie, statistical multiplexing with elastic traffic
- consider a network link handling flows between users, servers, data centers,...
- define, link load = flow arrival rate x mean flow size / link rate
  = packet arrival rate x mean packet size / link rate
  = link utilization



Traffic variations and stationarity



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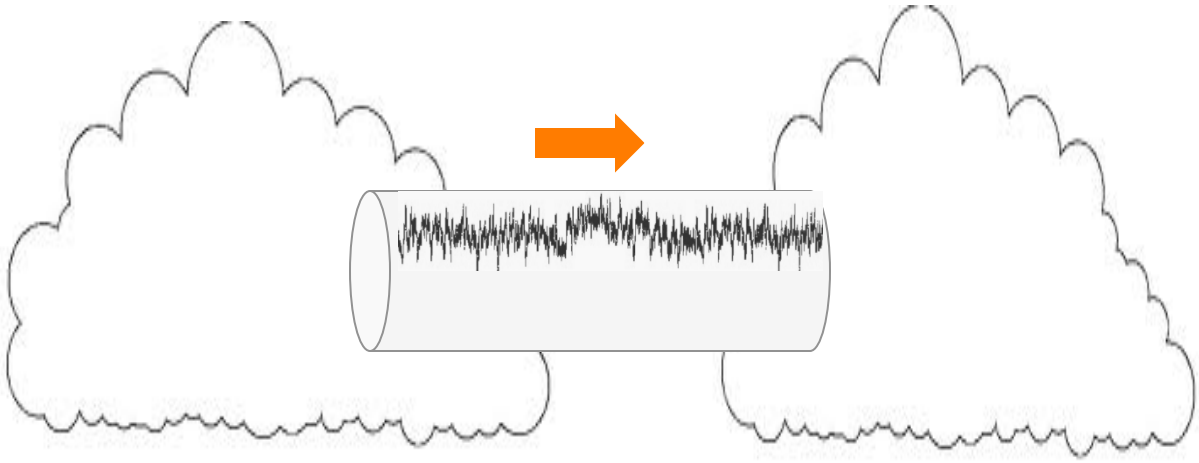
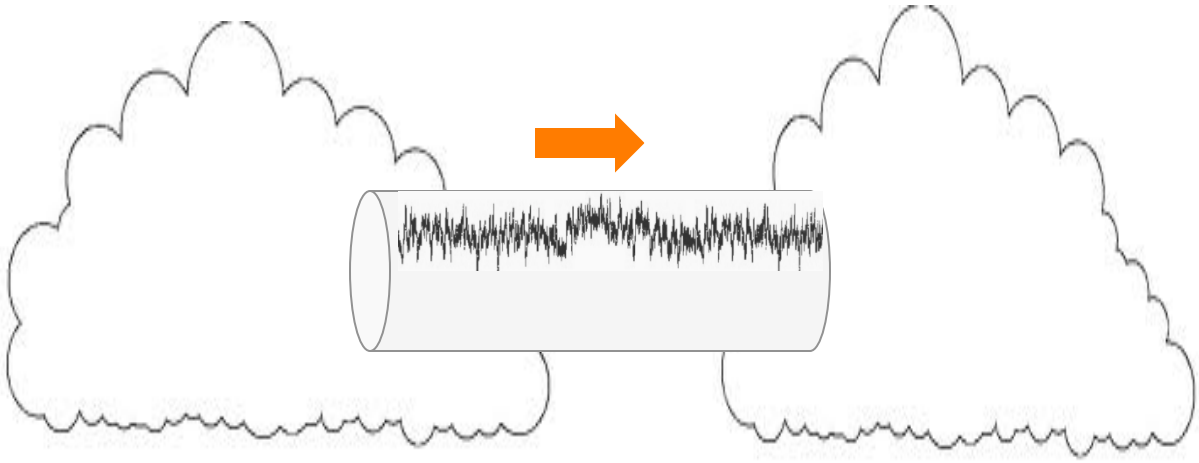
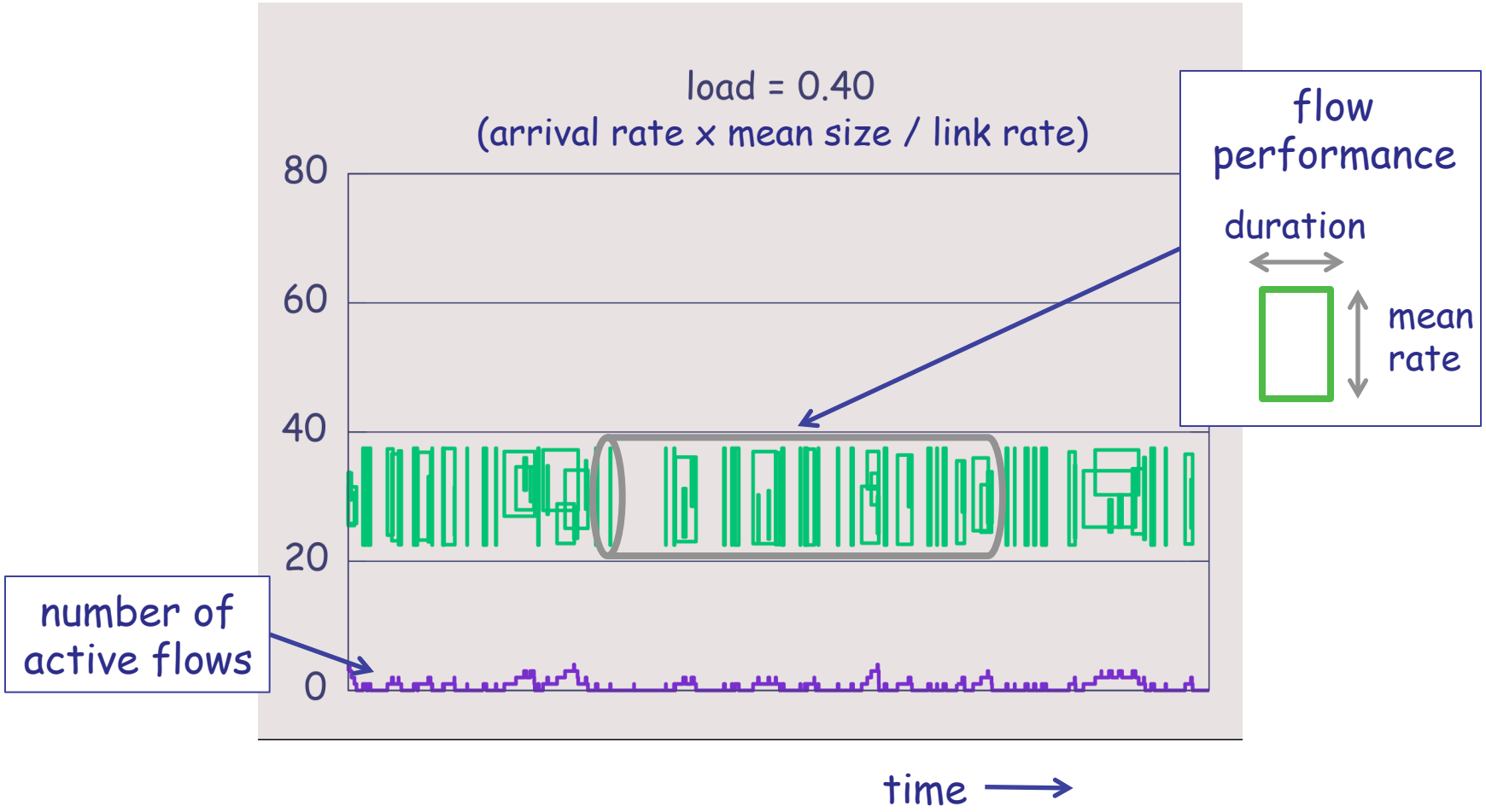


Bandwidth sharing performance

- in the following simulation experiments, assume flows
  - arrive as a Poisson process
  - have exponential size distribution
  - instantaneously share link bandwidth fairly
- results apply more generally thanks to insensitivity



Performance of fair shared link



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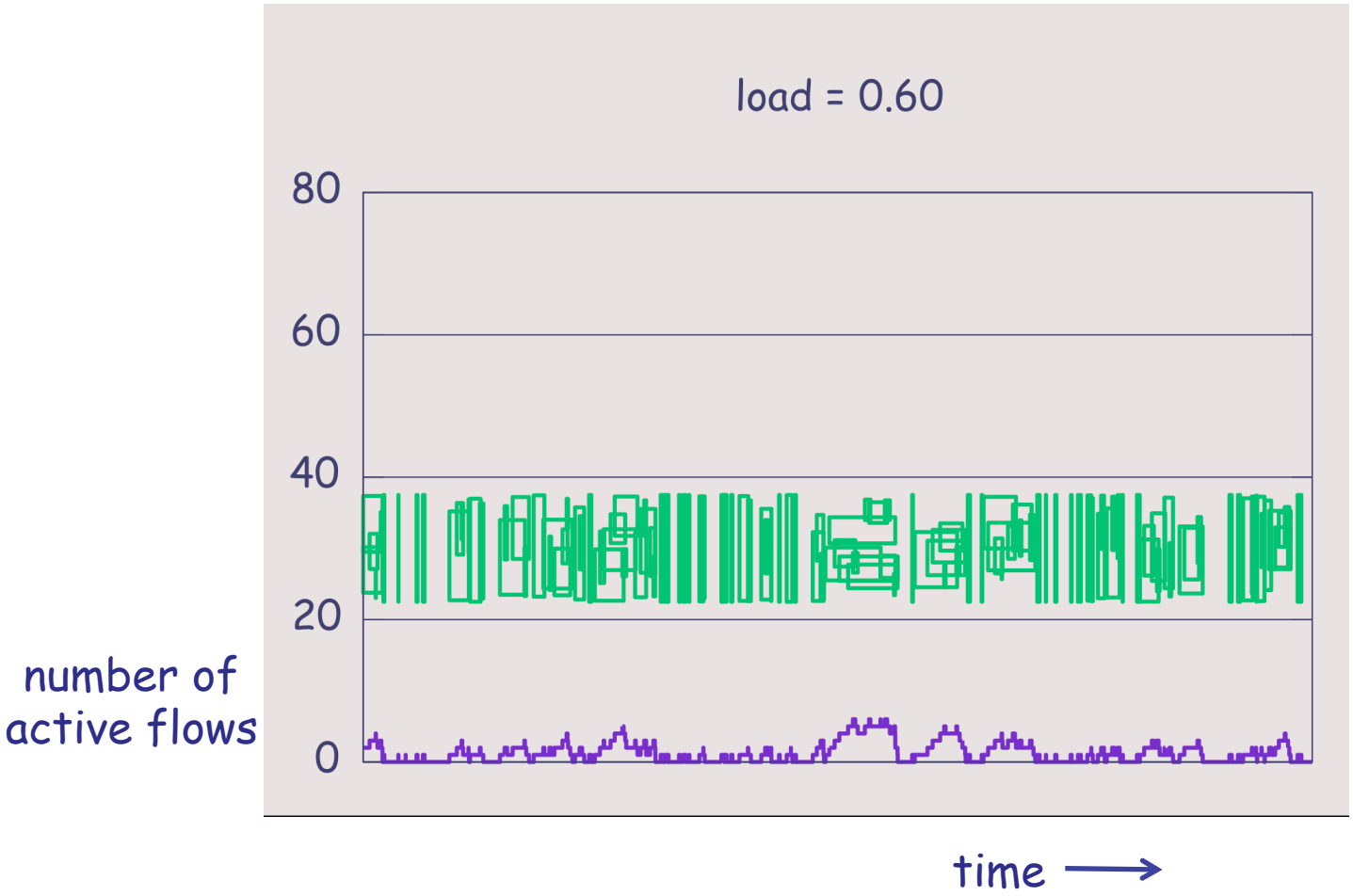

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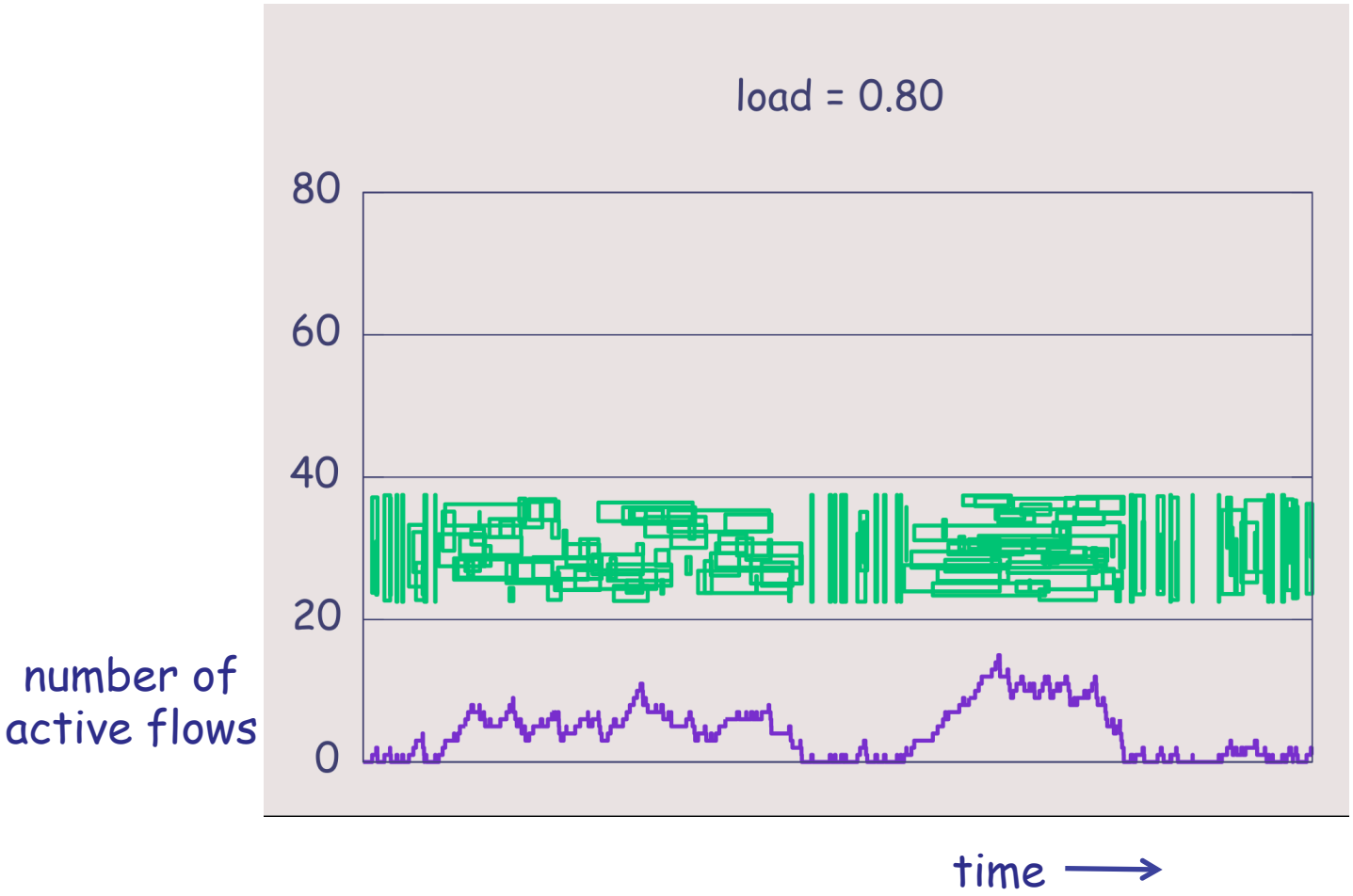

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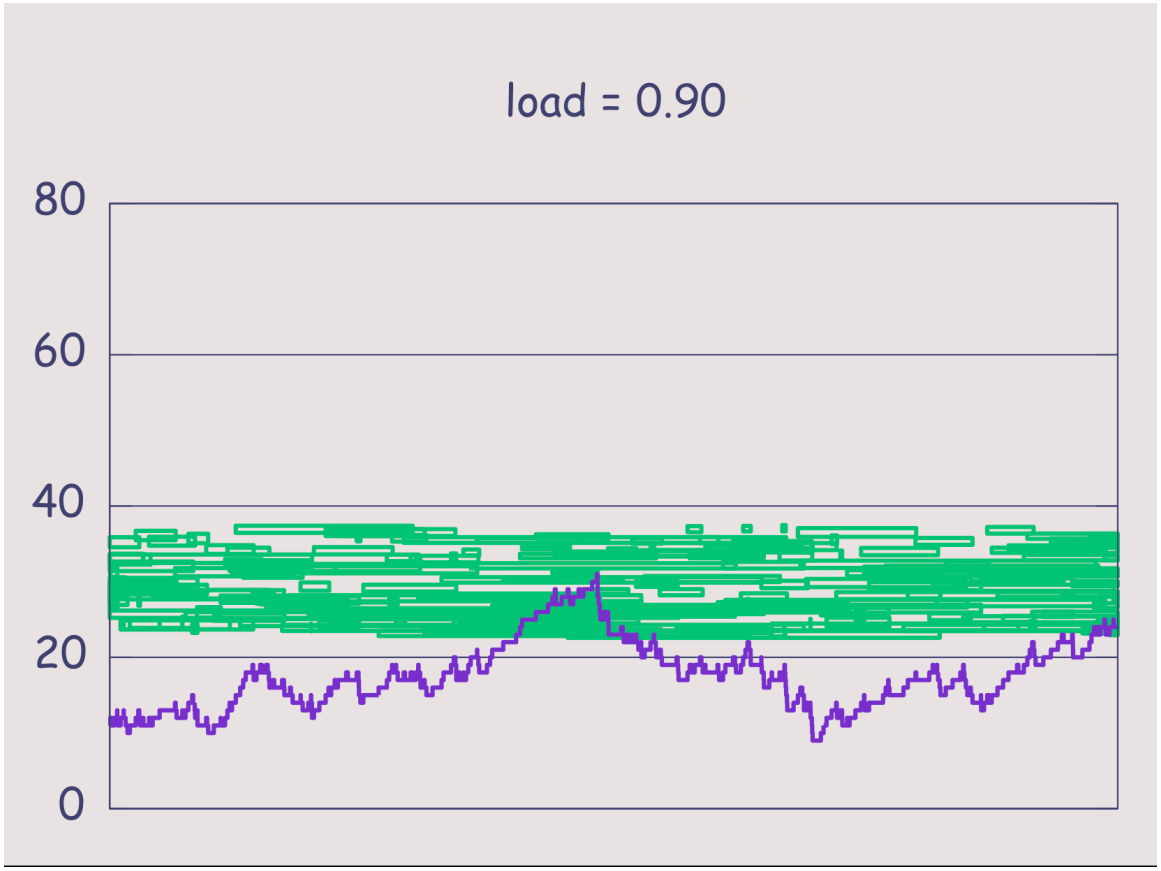

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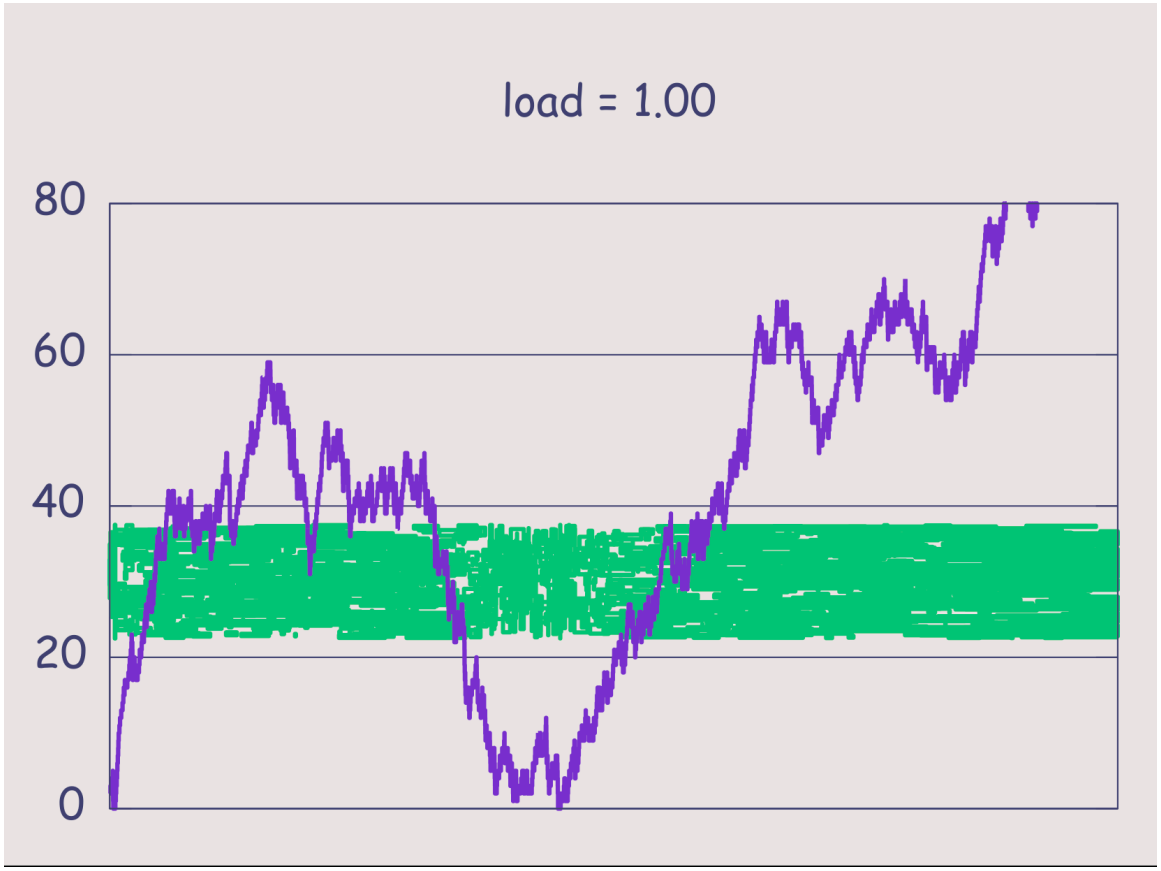
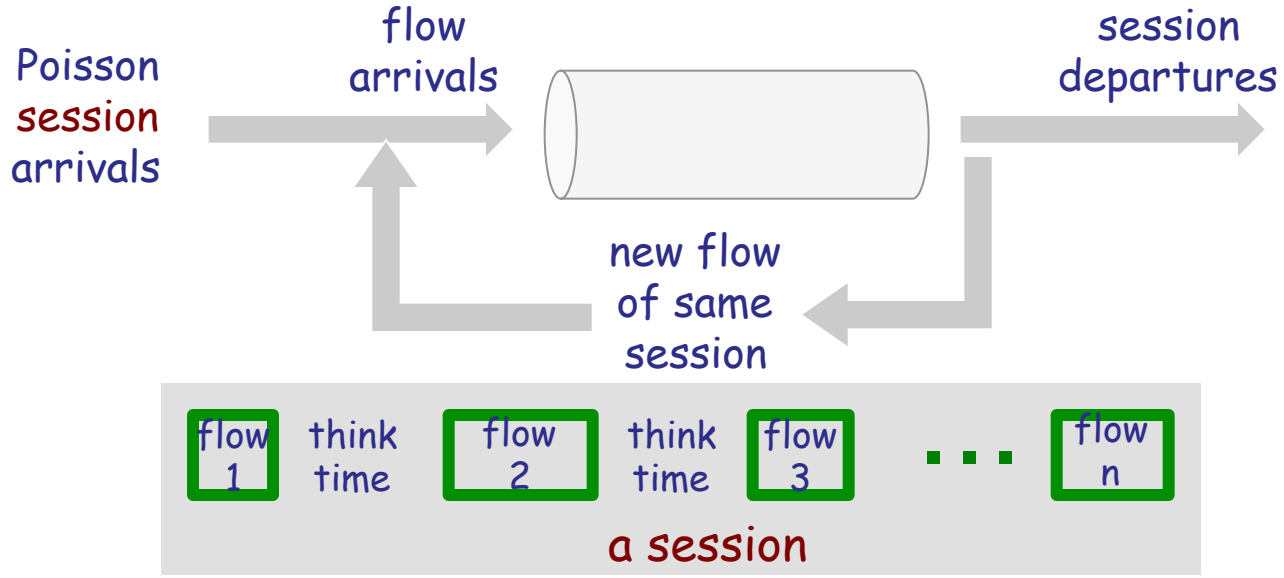


Observations

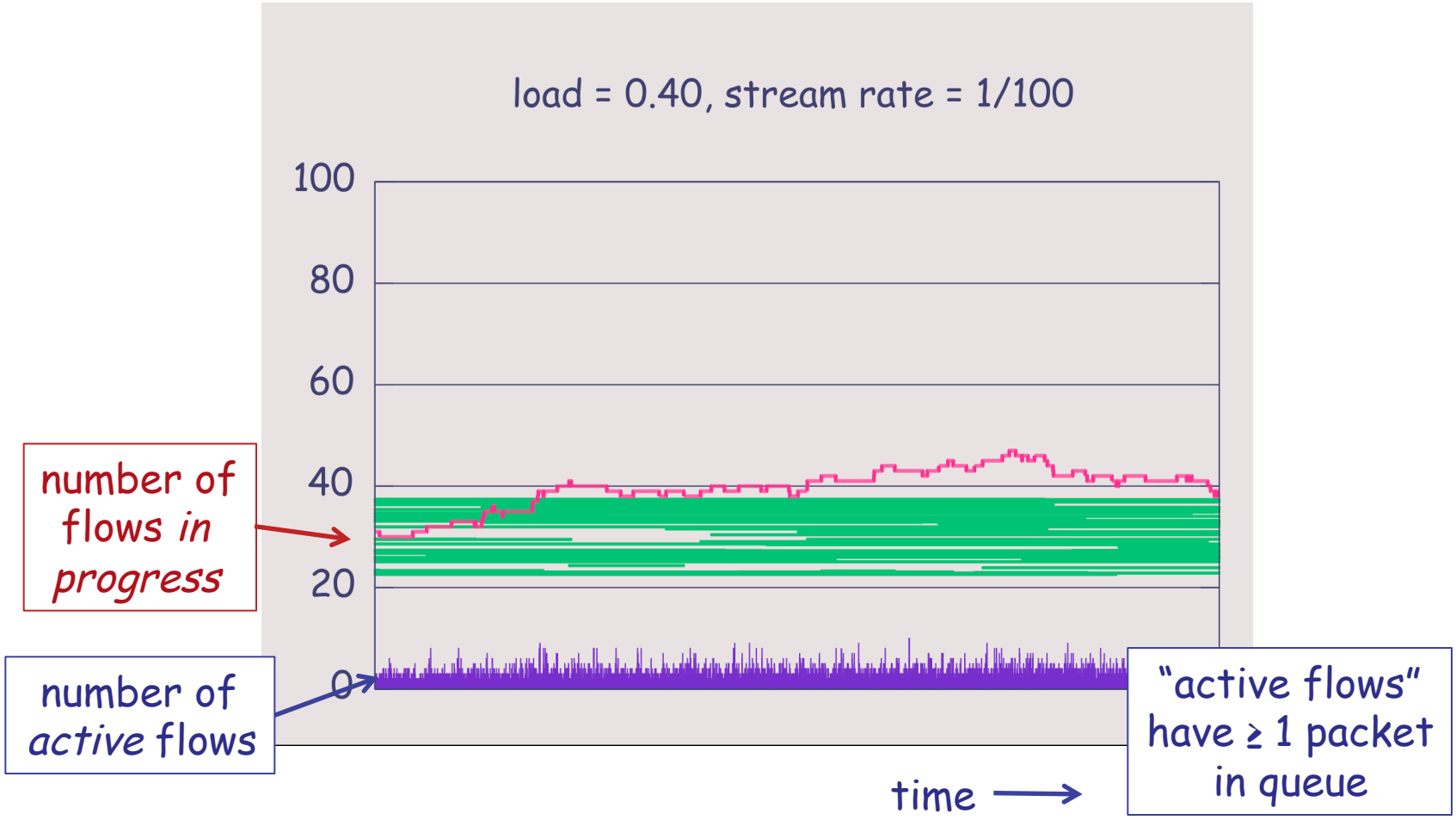
- the number of flows using a fairly shared link is small until load approaches 100% (*for any link capacity*)
- therefore, fair queuing schedulers are feasible and scalable
- our simulations make Markovian assumptions but the results for the number of active flows are true for much more general traffic [Ben-Fredj et al, Sigcomm 2001]



More simulations

- on Internet core links (≥ 10 Gbps), the vast majority of flows cannot use all available capacity; their rate is constrained elsewhere on their path (eg, ≤ 10 Mbps)
- consider a link shared by flows whose maximum rate is only 1% of the link rate
  - conservatively assume these flows emit packets as a Poisson process at rate proportional to the number of flows in progress

Performance with rate limited flows



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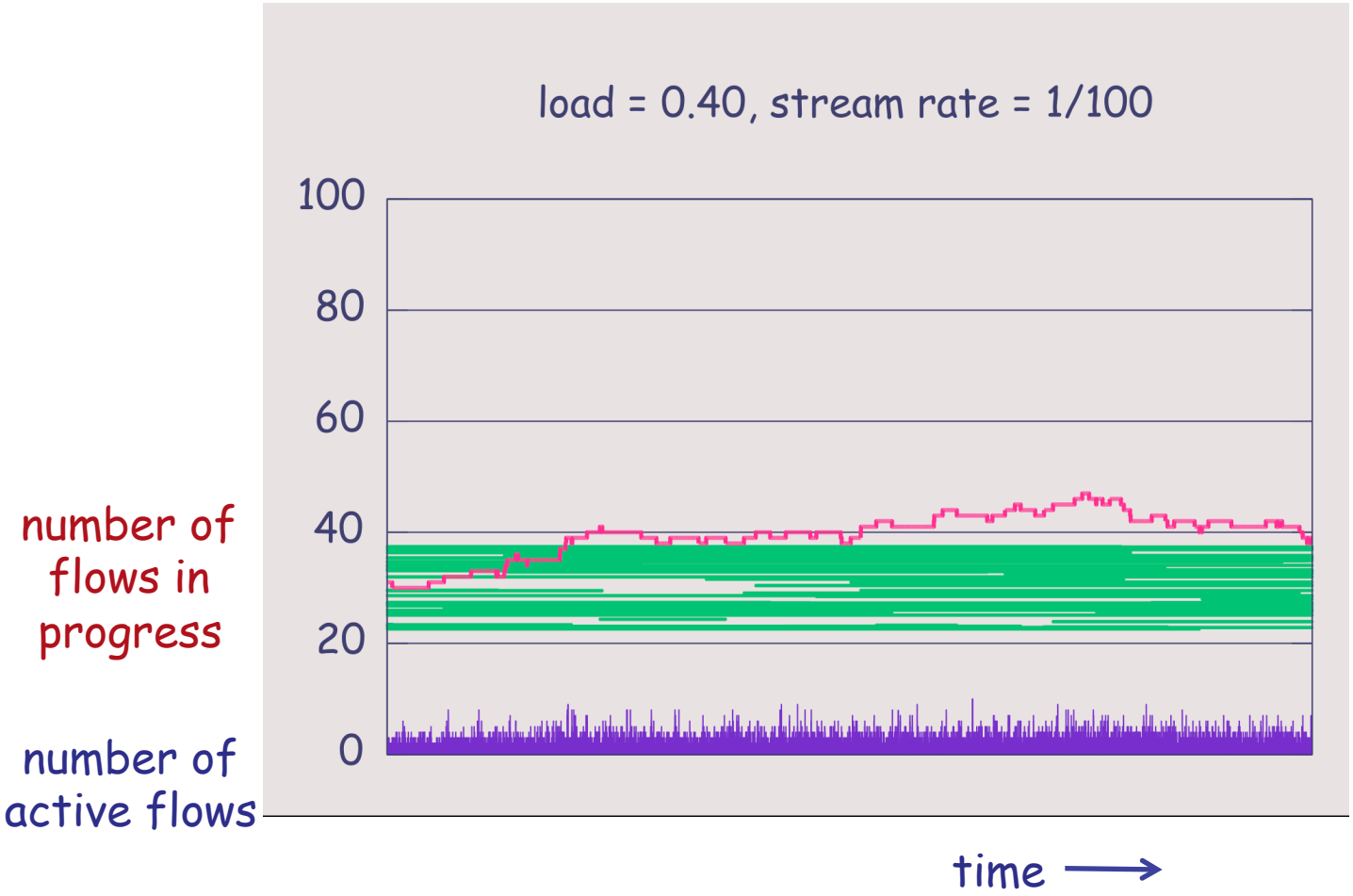

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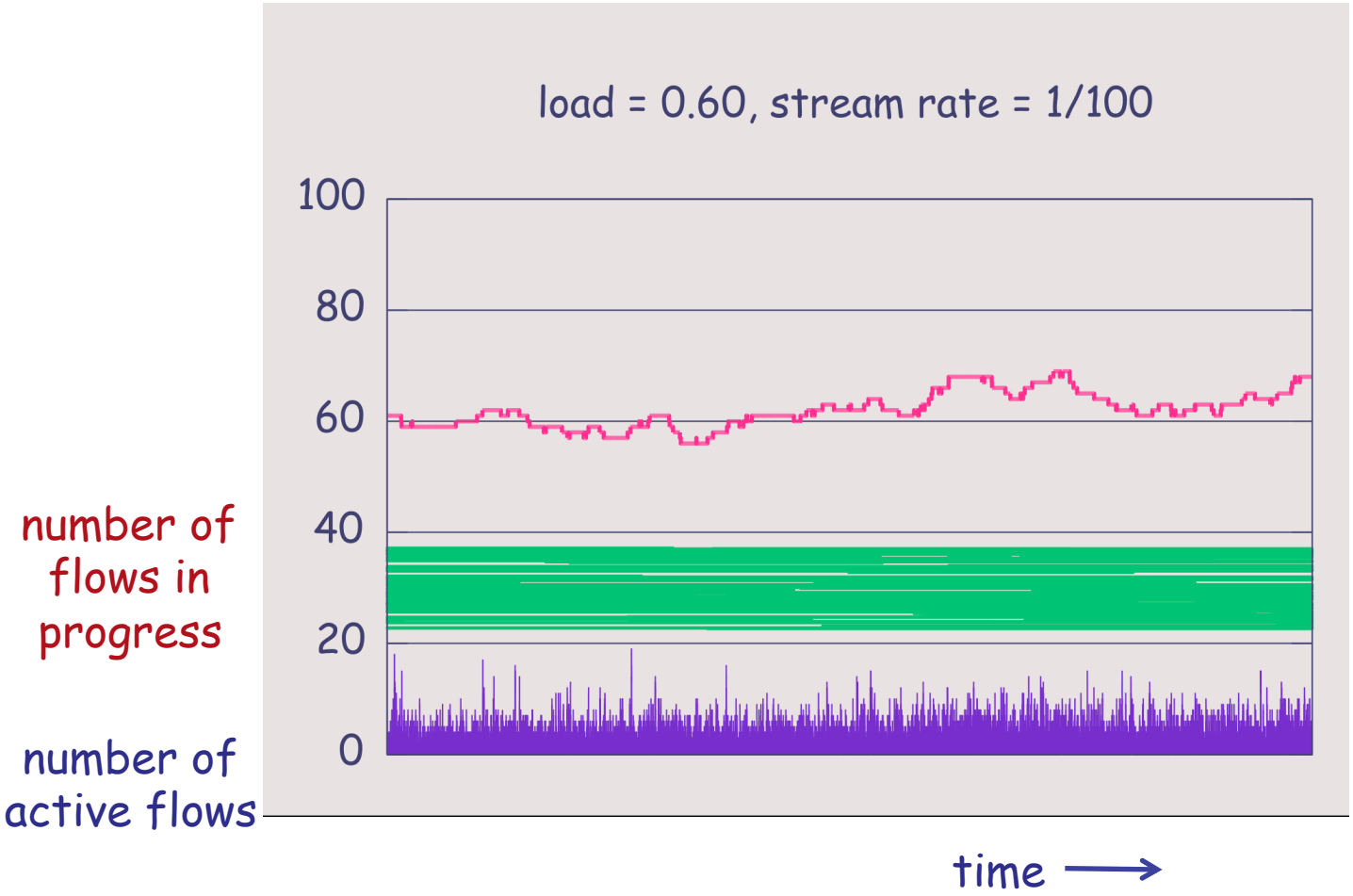

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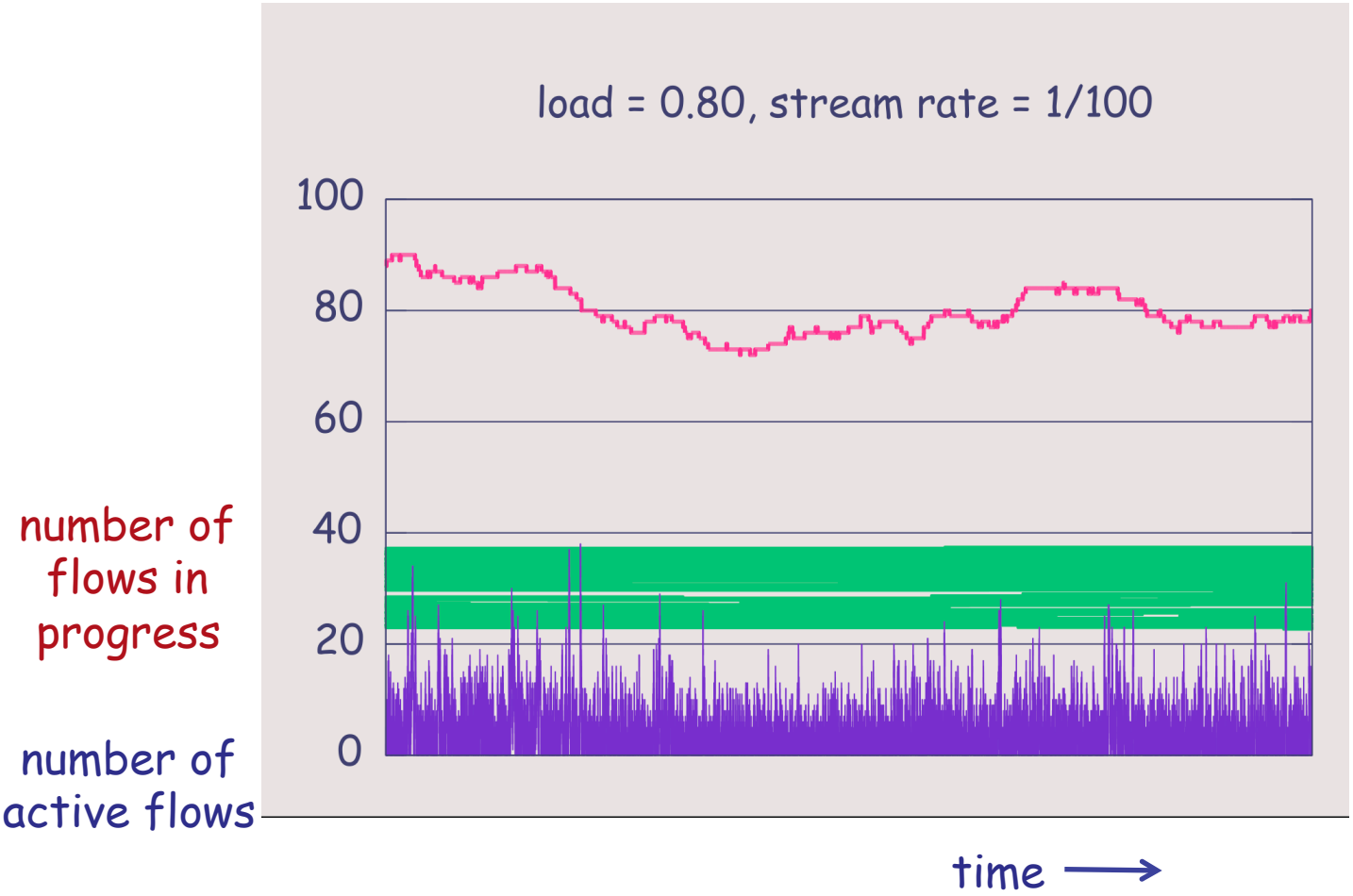

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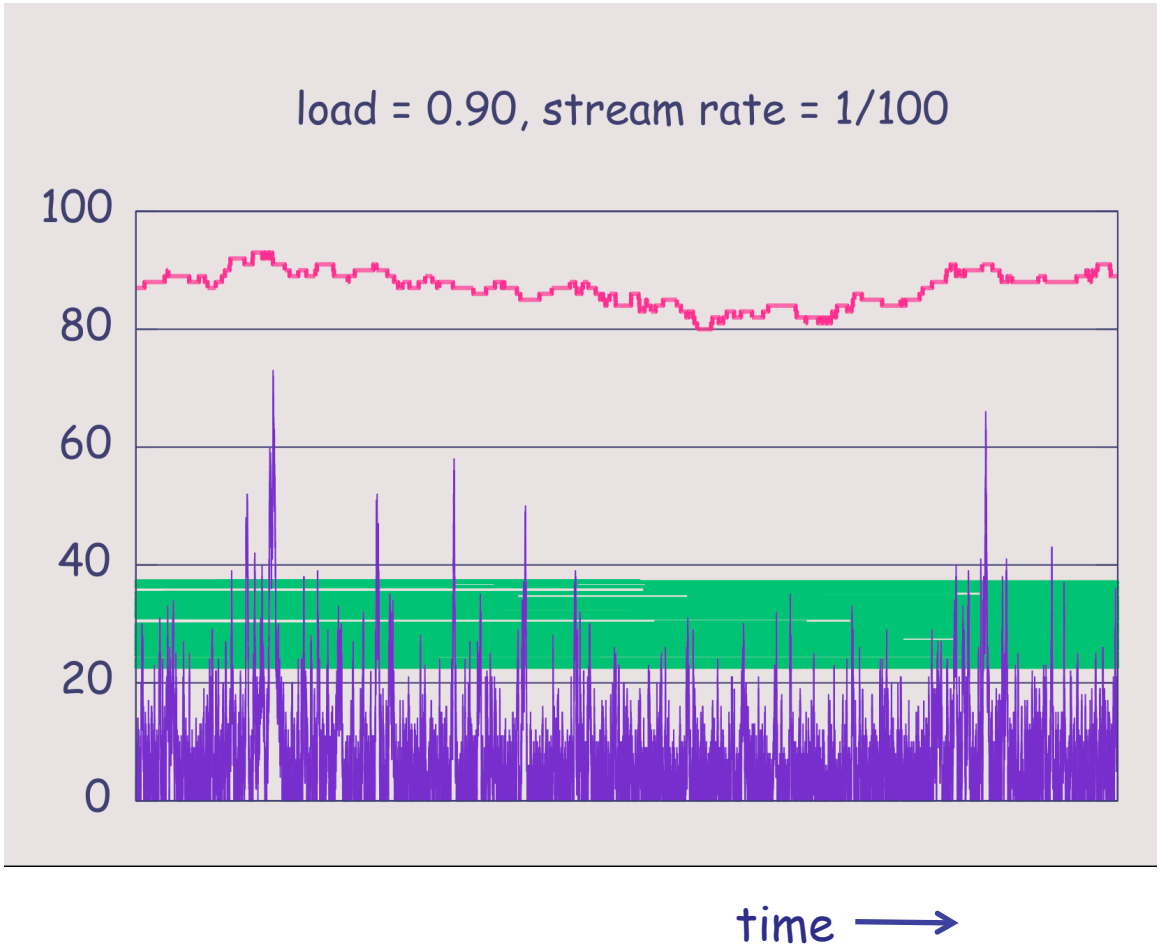

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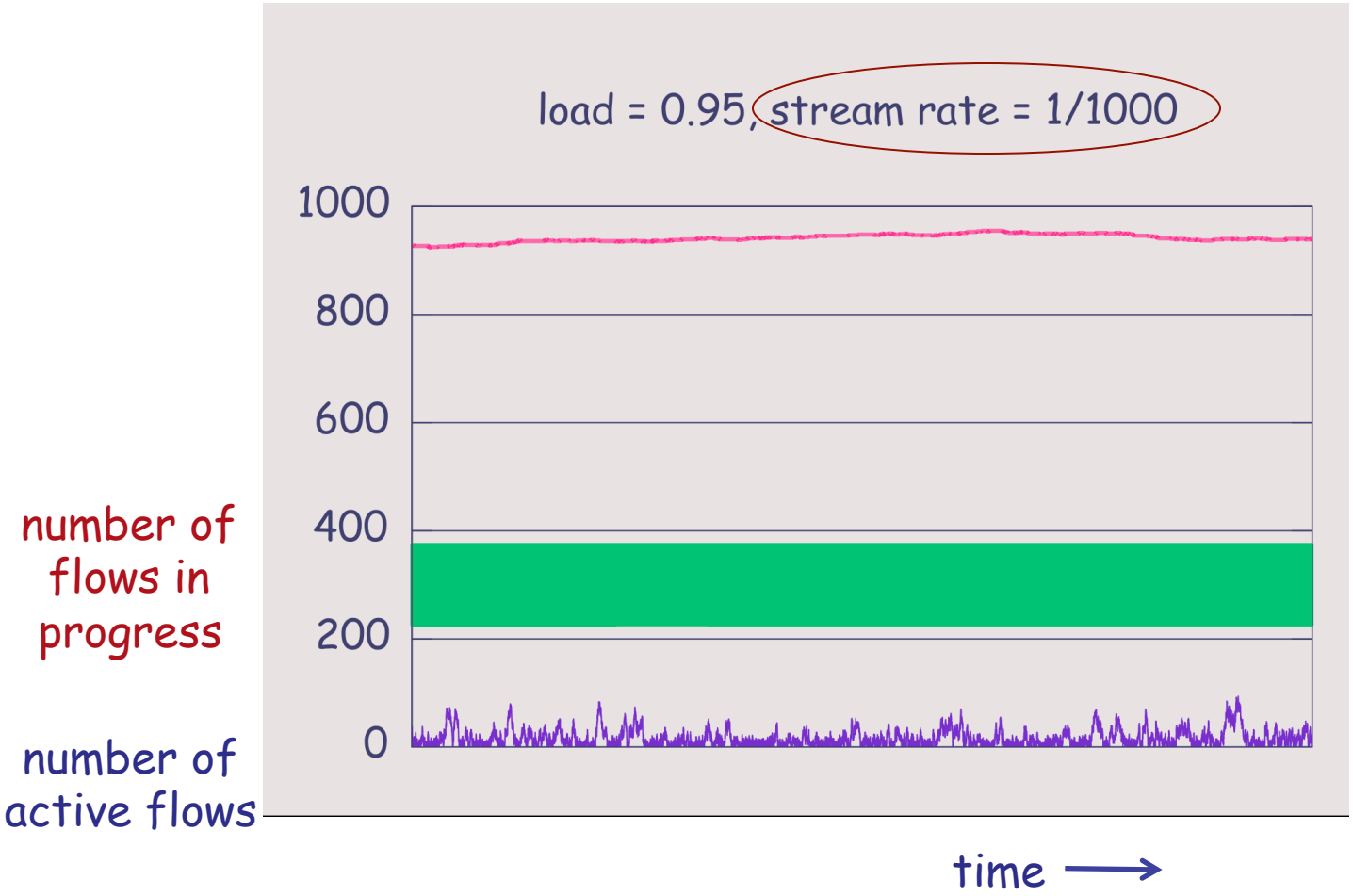


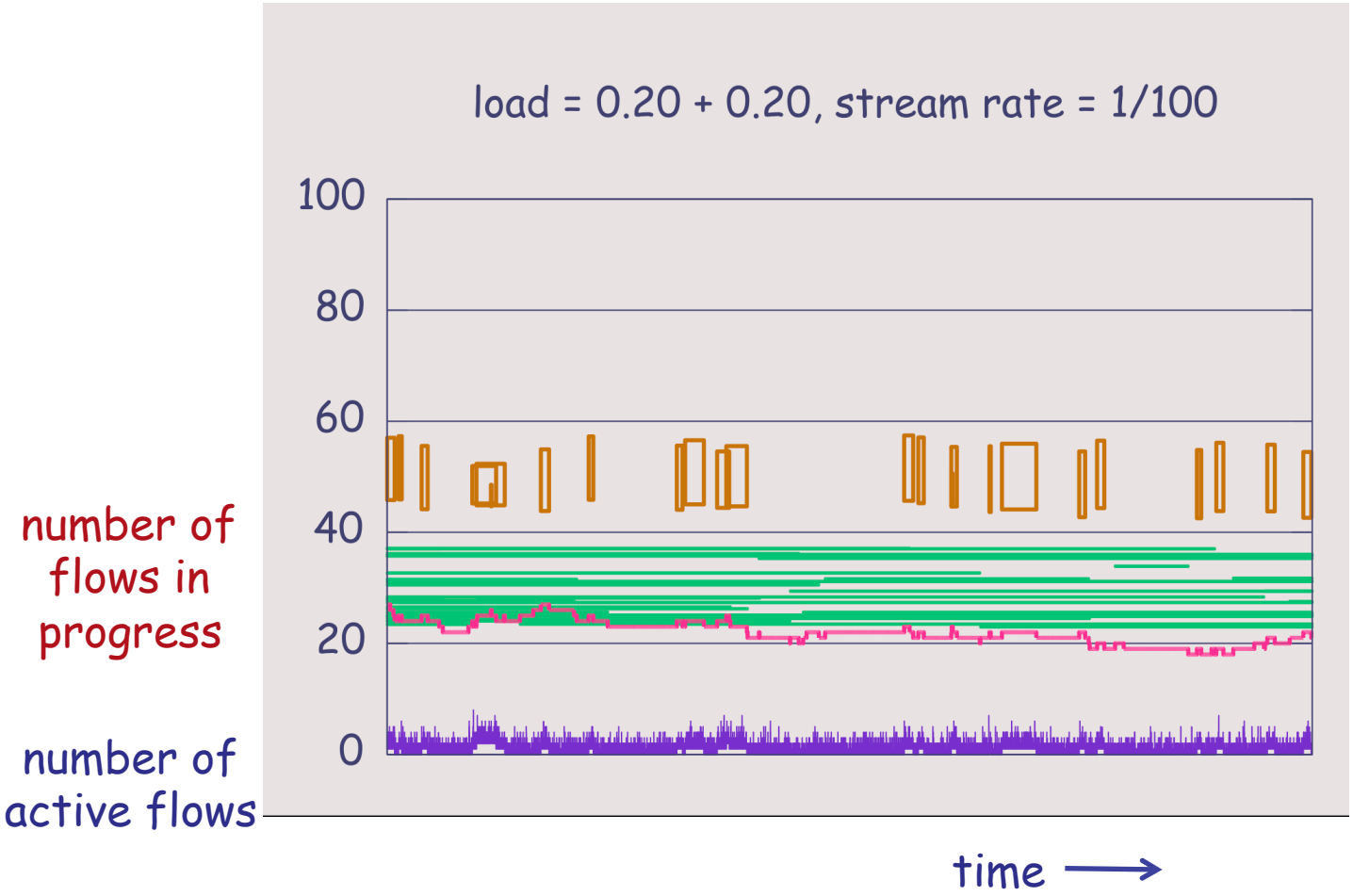
Observations 2

- most flows are not elastic and emit packets at their peak rate
- these flows are "active", and need to be scheduled, only when they have a packet in the queue
- the number of *active* flows is small until load approaches 100%
- fair queuing is feasible and scalable, even when the number of flows *in progress* is very large

More simulations

- links may be shared by many rate limited flows and a few elastic flows
- consider a link shared by 50% of traffic from flows whose peak rate is 1% of link rate and 50% elastic traffic

Performance of link with elastic and rate limited flows



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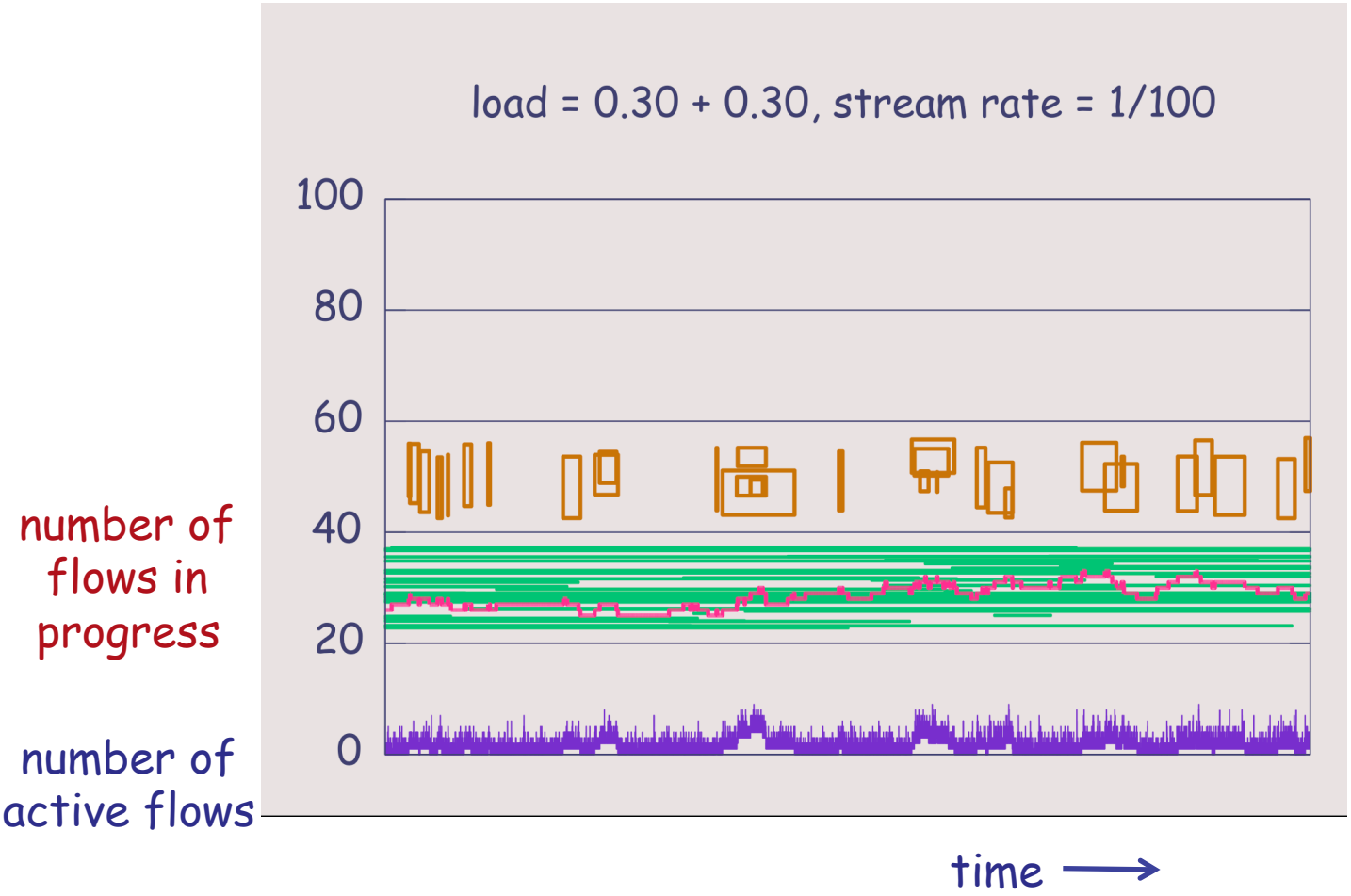

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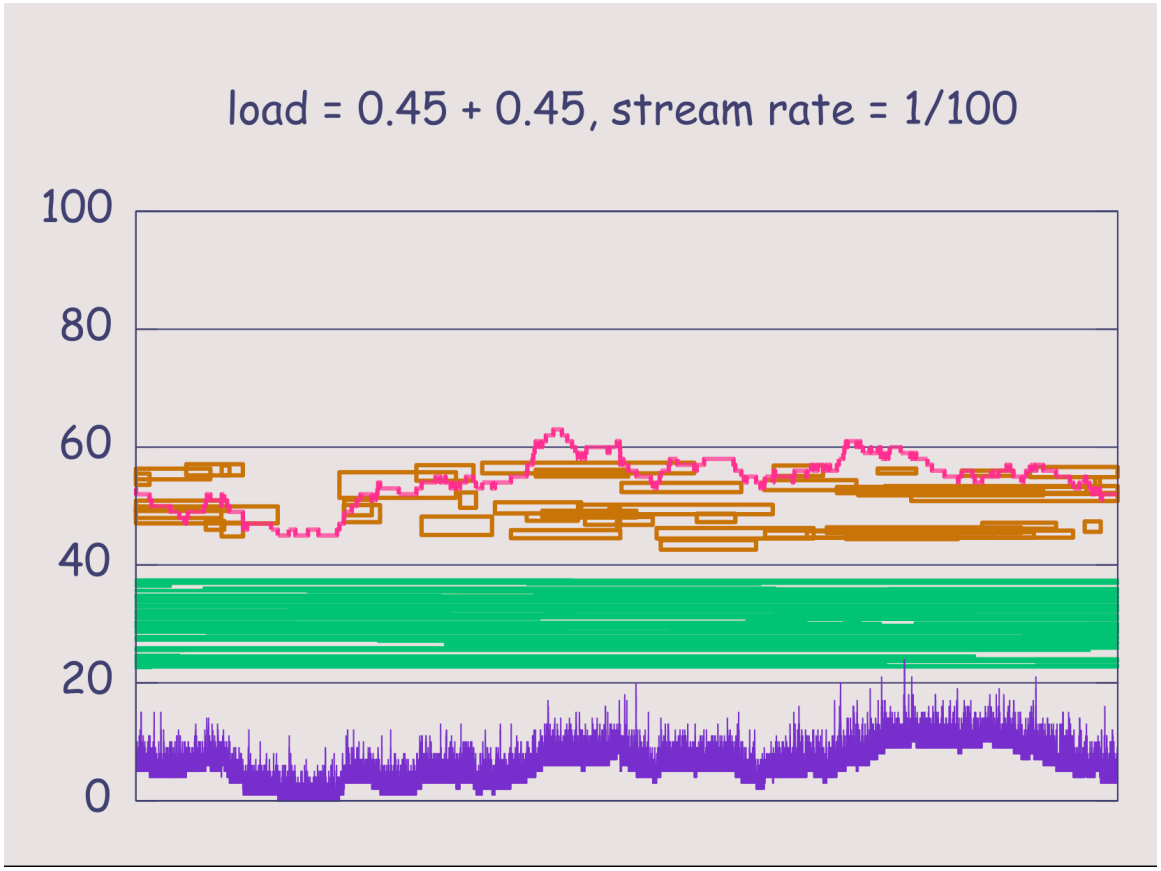


Observations 3

- the number of *active* flows is small (<100) with high probability until load approaches 100%
- therefore, fair queuing is feasible and scalable
- fair queuing means packets of limited peak rate flows see negligible delay:
  - they are delayed by at most 1 round robin cycle
  - this realizes implicit service differentiation since conversational and streaming flows are in the low rate category

Congestion collapse and the "law of the jungle"

- Wikipedia: the Internet was saved in 1987 from congestion collapse by TCP congestion control
- but transport protocols are becoming less and less TCP friendly, so are we again in danger of congestion collapse?
- the answer is
  - "not really", if flow peak rates are limited to ~1-10% of link capacity
  - "not at all", if routers implement fair sharing
- the real cause of congestion collapse is load > 1
  - the number of flows in progress continues to grow while per-flow throughput → 0
- cf. Bonald et al. "*Is the "law of the jungle" sustainable for the Internet?*", Infocom 2009

Recommendation for traffic control

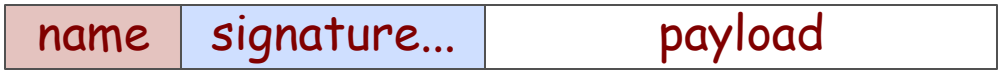
- implement per-flow fair queuing in router queues
  - this is scalable and feasible (though more complex than FIFO)
  - and realizes implicit service differentiation
  - view fairness as an *expedient* not a socio-economic objective
- apply traffic engineering to ensure load is not too close to 100% and overload controls in case this fails
- access networks need more than fair sharing - but see "Bufferbloat" where fair queuing is the preferred solution

Outline

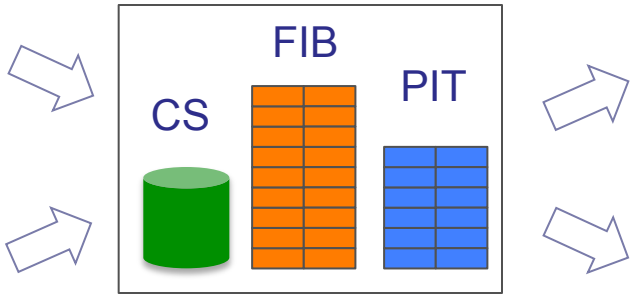
- Internet traffic control
- ~~ICN~~ CCN traffic control
- Impact of in-network caching

Content-centric networking (CCN)

- a new Internet architecture proposed by Jacobson [CoNext 2009]
  - "named data networking": packets have names, not addresses!
- users emit Interests 

- network returns Data 

- using pending Interest table (PIT), forwarding information base (FIB), content store (CS)
  - PIT remembers forwarded Interests and where they came from
  - FIB determines where to forward Interests from name prefix
  - CS is a cache that locally stores popular content

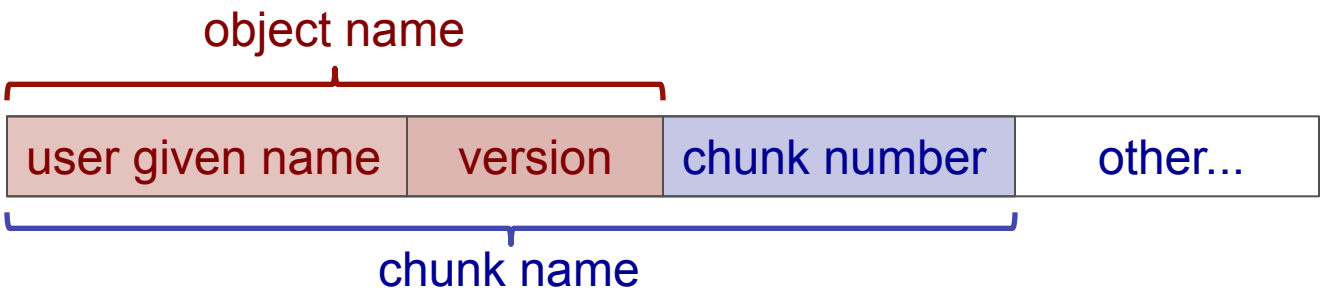


CCN and traffic control

- [CoNext 2009] says
  - "no queues in CCN routers, LRU replaces FIFO"
  - "flow balance removes need for in-path congestion control "
- we disagree ! CCN traffic control is still to be defined
  - a mixture of network mechanisms and end-system protocols
- objectives of traffic control in the core
  - ensure real time flows suffer negligible delay
  - control bandwidth sharing between high rate flows
- we propose a flow-aware traffic control framework
  - borrowing and adapting mechanisms from IP
  - proposing some new, CCN-specific mechanisms

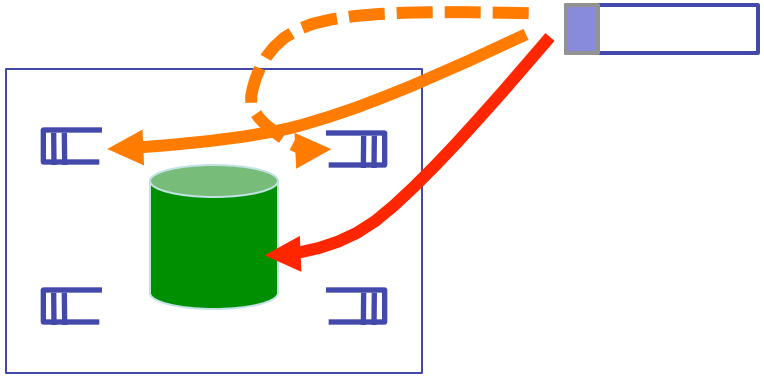
Flow identification in ICN

- flow identified by object name
- possible in CCN where name is in header
  - since hierarchical packet name includes object name
- assume this is possible in ICN in general
  - though PURSUIT, NetInf use flat names for objects and it is not clear that names appear in packet headers
- NB. flow thus includes all downloads of same content object from multiple sources to multiple receivers, as observed at a given point in the network



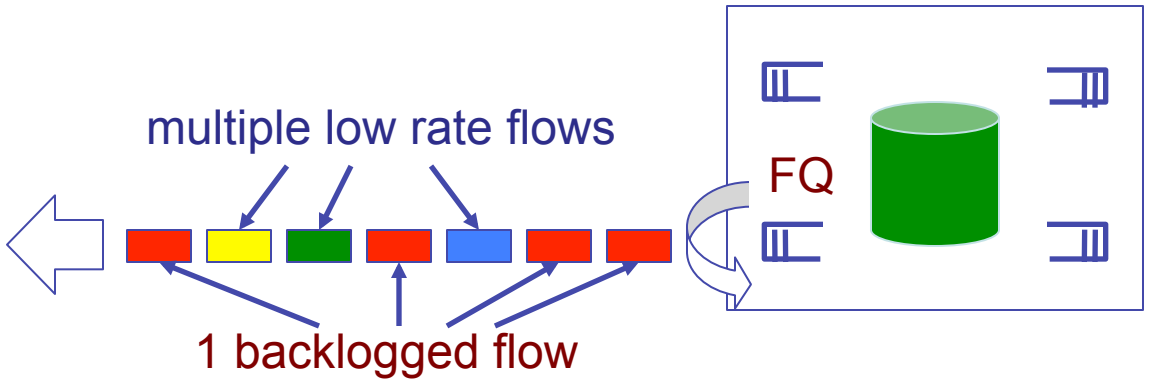
Distinguishing buffers and content store

- to significantly reduce upstream traffic, the content store must have a capacity measured in terabytes
  - eg, 25 TB for a YouTube hit rate of 50%
- an IP buffer is considered large when sized for the bandwidth delay product, ie, less than one gigabyte
  - eg, 10 Gb/s link, 240 ms RTT ⇒300 MB
- buffers and content store have different technologies
  - for different capacity and access speed requirements
- in CCN, on arrival of a Data packet do the following in parallel
  - cache, if appropriate
  - place in buffer on relevant faces
  - discard, applying buffer mgt



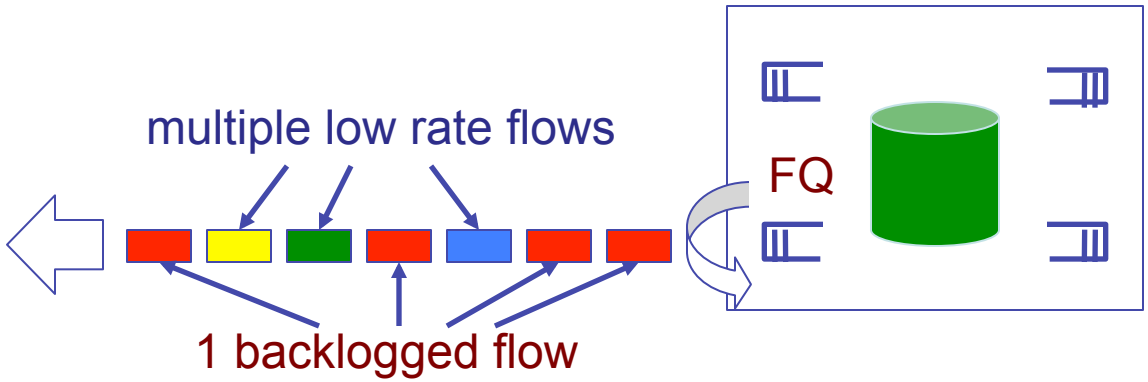
Flow-aware networking

- identify flows by object name…
  - included in chunk name and parse-able
- … on-the-fly, locally, e.g., at a given face
  - all packets with the same object name belong to one flow
- at each face apply per-flow fair queuing with longest queue drop
  - to ensure low latency for real time applications
  - to control bandwidth sharing between elastic downloads
- arguably, the only requirements for a neutral Internet!



Realizing fair queuing

- for example, apply deficit round robin (DRR) and stochastic fairness (SFQ), as implemented in the Linux kernel
- complexity determined by number of "active flows", ie, flows that currently have one or more packets in the buffer
- typically less than 100 flows are active
  - a small number of high rate backlogged flows
  - a small number of packets from many low rate flows
- thus, per-flow fair queuing is feasible and scalable!

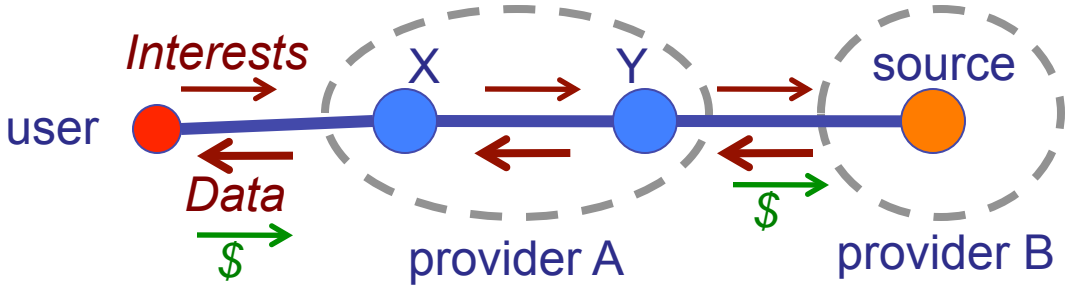


Outline

- Internet traffic control
- ~~ICN~~ CCN traffic control
  - some specific CCN mechanisms
- Impact of in-network caching

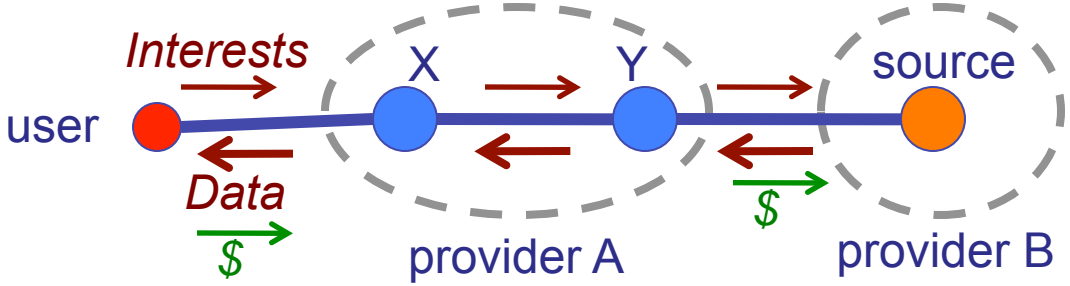
"Interests buy data"

- a proposed direction of charging:
  - user pays provider A, A pays provider B,..., for *delivered* Data
  - not excluding flat rates, peering,...
- brings return on investment and an incentive to invest
  - in transmission capacity (to be able to sell Data)
  - in cache memory to avoid paying repeatedly for popular content
- no charge for Interests but an incentive to avoid buying Data that can't be sold (ie, delivered downstream) due to congestion...



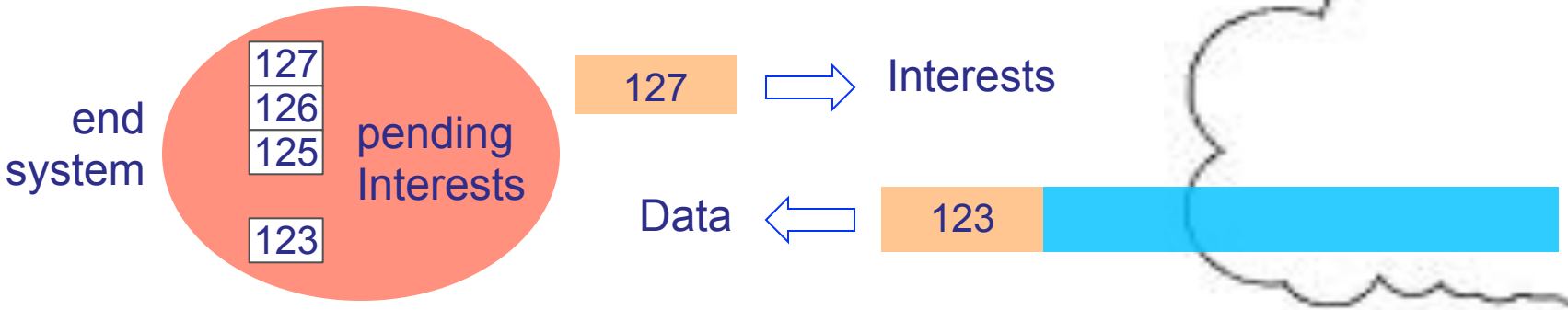
Interest discard

- a particularity of CCN: Interests follow the same path as Data
- a router can therefore participate in congestion control by shaping the flow of Interests
- we propose Interest discard:
  - routers monitor congestion on the downstream link
  - discard upstream Interests in excess of current fair rate
  - all in the same line card
- avoids buying data that cannot be sold (because of insufficient link capacity), and stops abusive emission of Interests



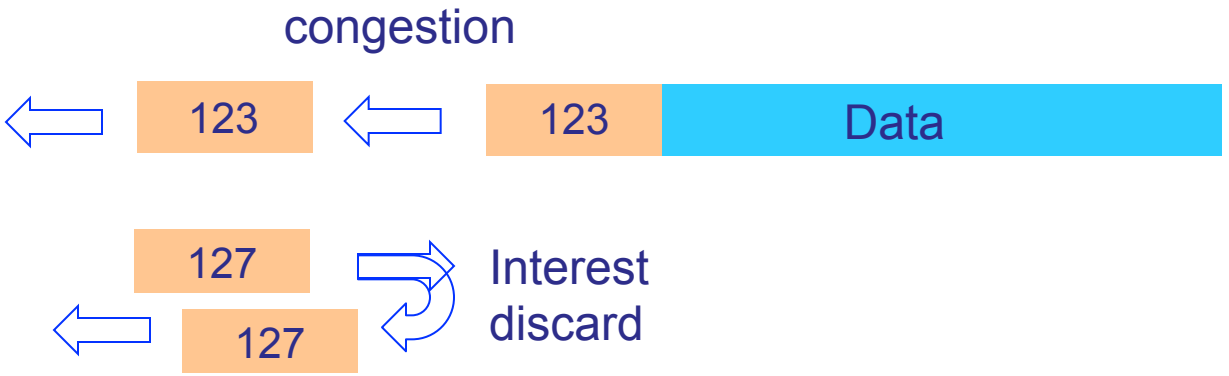
End-system behaviour

- receivers control download rate by Interest emissions
- since fairness is imposed, network performance is broadly independent of user emission strategies
- greedy strategies are OK
  - users can emit Interests as fast as they like without impacting other flows or reducing network capacity
- additive increase, multiplicative decrease (ie, like TCP) is probably better
  - for simpler management of pending Interests in end systems
  - but aggressive parameters are OK (low loss, high throughput)



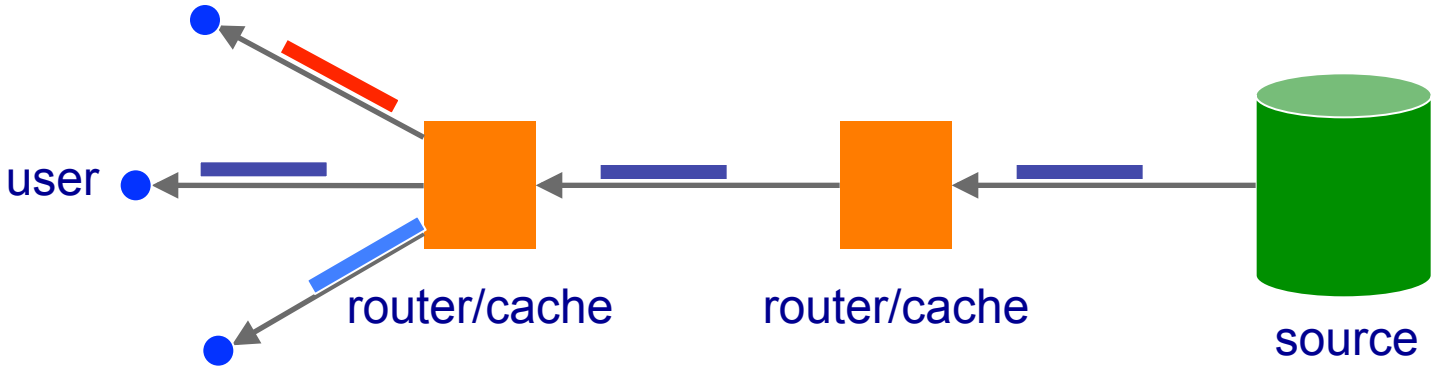
Explicit congestion notification

- for effective AIMD, we require fast congestion notification
  - but sequence is not preserved in CCN
  - triple duplicate ACK won't work!
- we propose an explicit congestion notification:
  - in case of DRR drop or Interest discard, return Data header
- for fast PIT update in routers and user equipment
  - instead of waiting for a time out
- simulations show smaller PIT and better throughput fairness



Multicasting

- fair queuing does not adversely impact multicast in CCN
- eg, same live streaming flow requested by several users
  - multicast by Interest aggregation (and caching)
  - no problem with FQ! streaming flows have low latency, low loss
- eg, same video download by several users asynchronously
  - multiple flows would be treated by FQ as one (possible degradation)
  - but multiple parallel flows for same object are eliminated by caching



Proposed traffic control framework

- flow-aware networking is a complete traffic control for CCN
- "Interests buy Data" implies a rational direction of charging
- some requirements
  - explicit object name in packet headers
  - (approximate) fair queuing in face buffers
  - traffic engineering and overload controls to ensure load < 90%
- some enhancements
  - Interest discard to avoid buying excess Data
  - explicit congestion notification by Data payload discard
- see "Flow-Aware traffic control for a content-centric network," S. Oueslati, J. Roberts, and N. Sbihi, in Proc of IEEE Infocom 2012
- there are other proposals...

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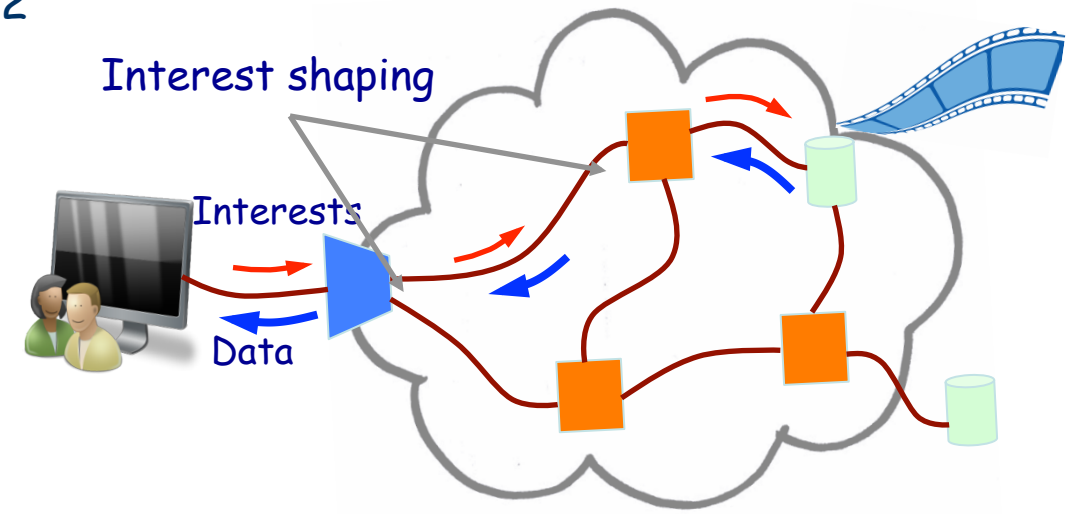
- Internet traffic control
- ~~ICN~~ CCN traffic control
  - some specific CCN mechanisms
  - other proposals
- Impact of in-network caching

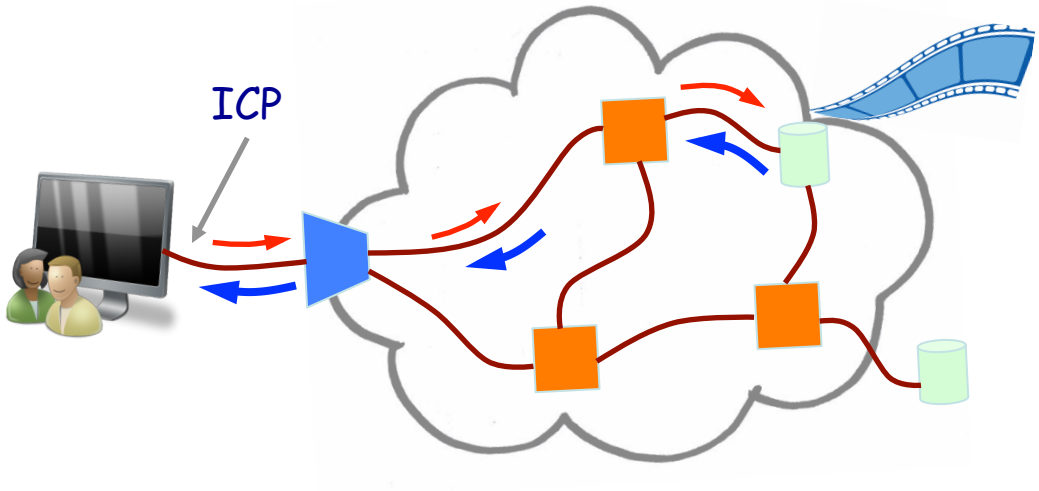
Flow-aware CCN by Interest shaping

- control Data flow sharing by shaping Interest flows
- shape Interests in same line card as controlled Data
  - cf. "An effective hop-by-hop Interest shaping mechanisms for CCN" by N. Rozhnova and S. Fdida, NOMEN 2012
- shape Interests in previous line card, using PIT adaptation
  - cf. "Joint Hop-by-Hop and Receiver-Driven Interest Control Protocol for Content-Centric Networks", C. Carofiglio et al., ICN 2012



Receiver-driven transport protocol

- Interest control protocol
  - additive increase, multiplicative decrease Interest window
  - loss detection by adaptive time-out
  - analysis for stability proof and parameter setting
  - experimental implementation and validation
  - cf. "ICP: Design and evaluation of an Interest control protocol for content-centric networking", G. Carofiglio et al., NOMEN 2012



Receiver-driven transport protocol

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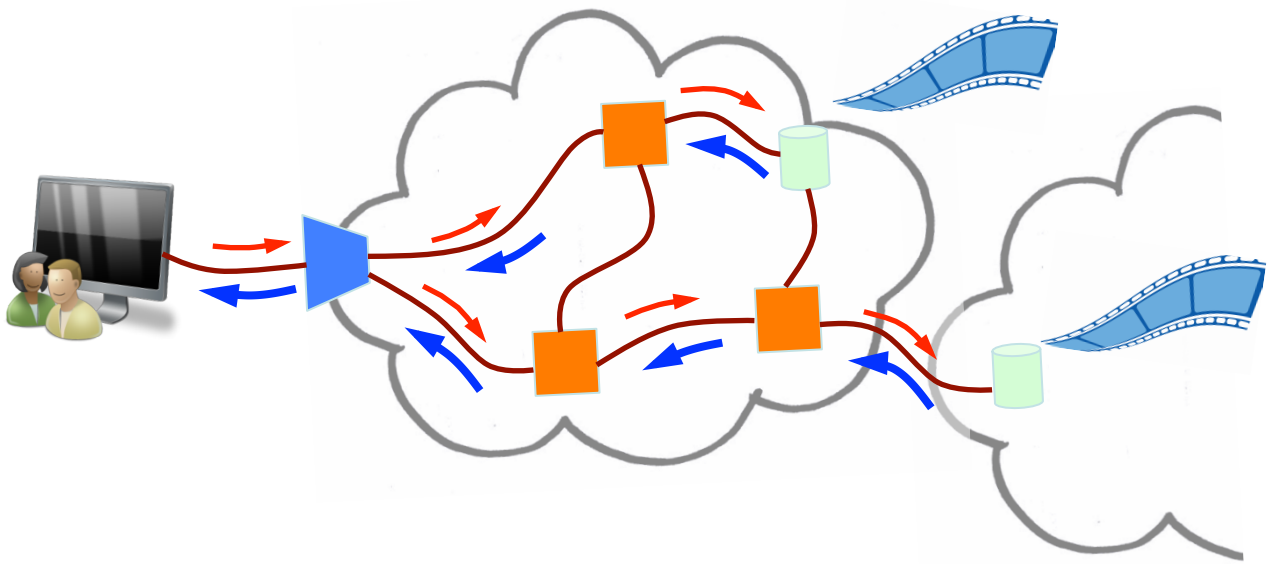
  - analysis for stability proof and parameter setting
  - experimental implementation and validation
  - cf. "ICP: Design and evaluation of an Interest control protocol for content-centric networking", G. Carofiglio et al., NOMEN 2012
- used in conjunction with Interest shaping
  - cf. "Joint Hop-by-Hop and Receiver-Driven Interest Control Protocol for Content-Centric Networks", C. Carofiglio et al., ICN 2012

Multipath forwarding

- adaptive and multipath routing via Interest shaper/PIT coupling
- to use multiple sources of content including on-path caches
  - remote adaptive AQM for RTT dependent probabilistic window decrease
  - unique window, per path RTT estimation
  - cf "Multipath congestion control in content-centric networks", G. Carofiglio et al., NOMEN 2013



"Traffic control" in other ICN architectures

- SAIL/NetInf: use TCP or borrow ICP from CCN…
  - cf. Deliverable 3.2 NetInf Content Delivery and Operations, 2012
- PURSUIT: ConTug is a receiver driven transport protocol
  - cf. Tech Report TR 12-002
- CONET: ICTP is receiver driven and TCP-like
  - cf. "Transport layer issues in information-centric networks", S. Salsano et al., ICN 2012

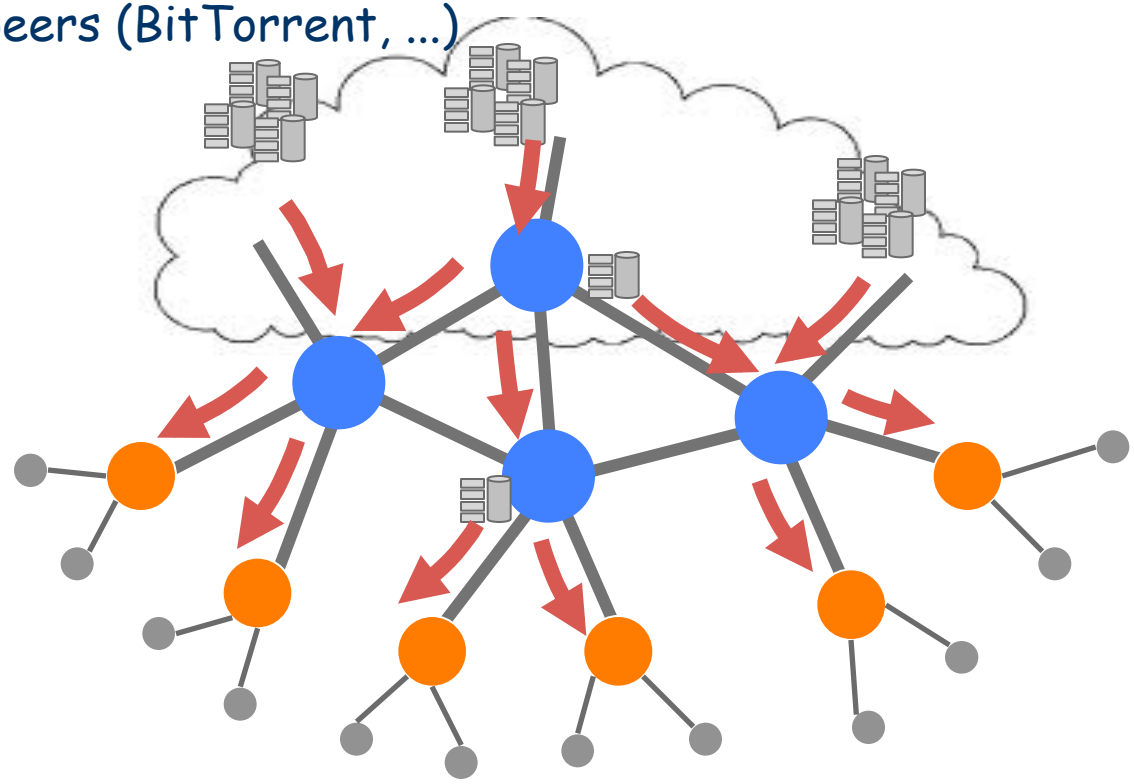
- all seem to rely on end-system congestion control; some use segment names that don't allow flow-awareness
- congestion control is complicated by multi-source delivery (due mainly to in-network caching)

Outline

- Internet traffic control
- ICN traffic control
- Impact of in-network caching

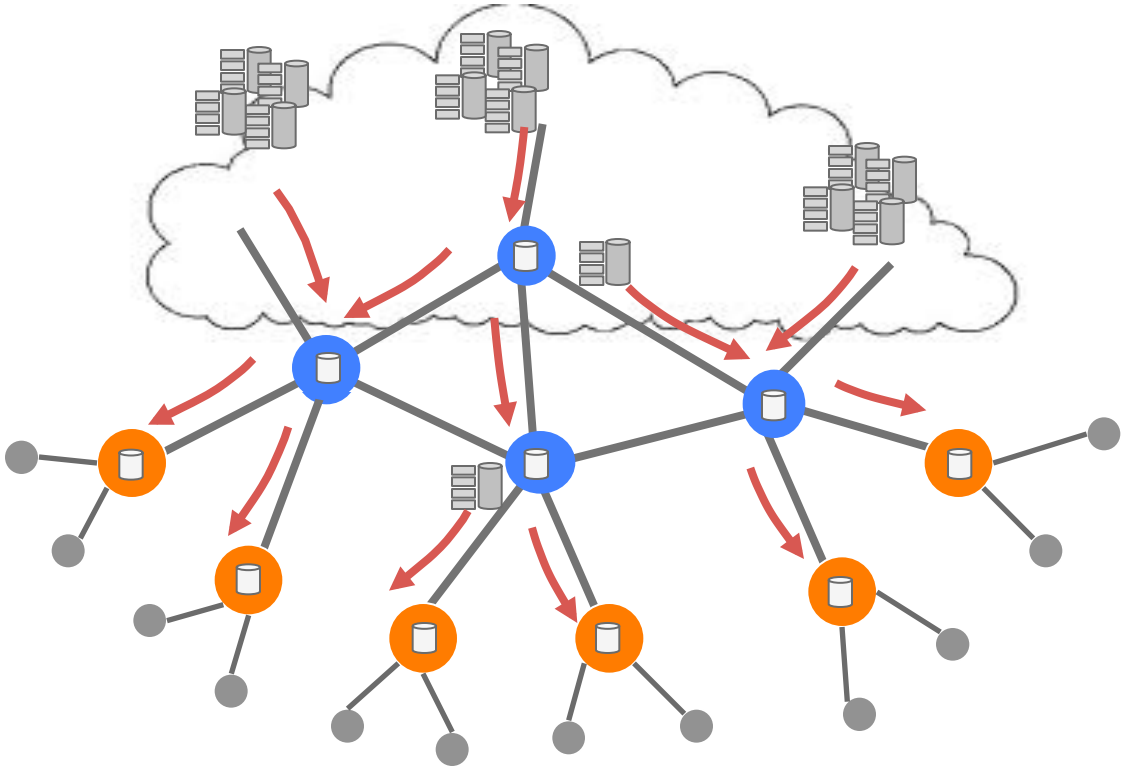
Content traffic in the Internet

- more than 90% of traffic in an ISP network is content delivery
  - from large scale data centers (Google, Facebook,...,)
  - from "content distribution networks" (Akamai, Limelight,...)
  - from peers (BitTorrent, ...)



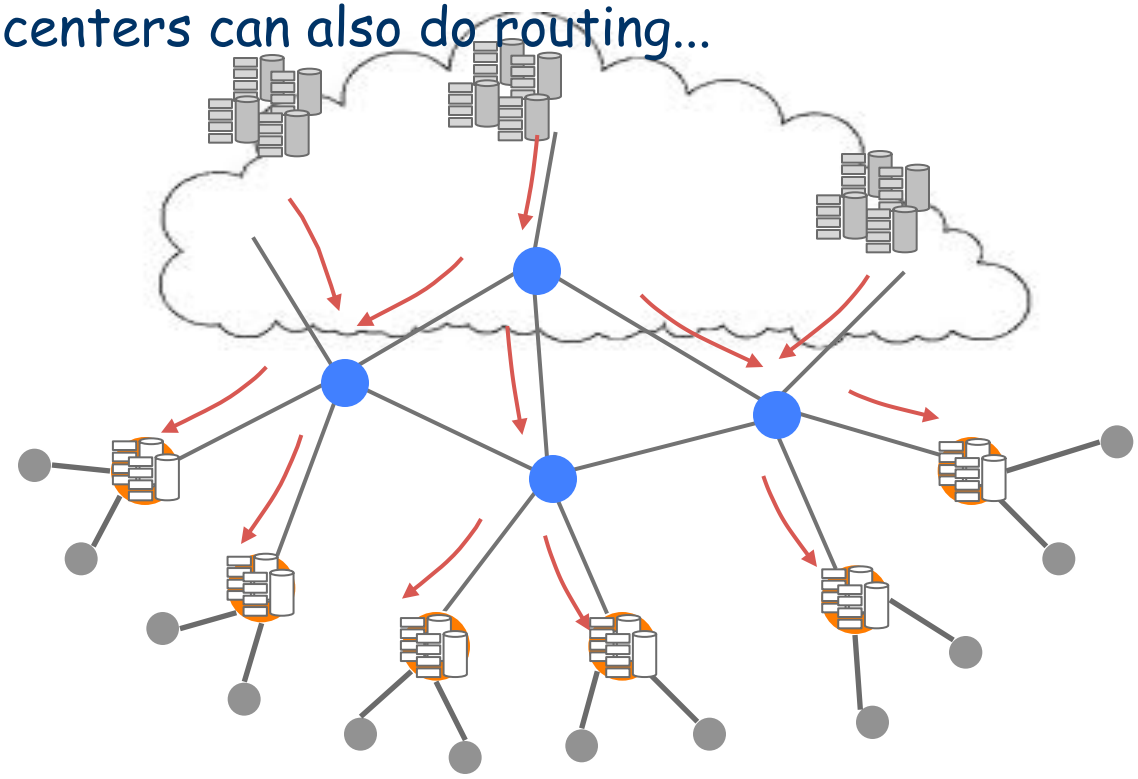
Traffic reduction in an information-centric network

- eg, equip routers with a "content store"
- cache popular content to realize a more favourable memory-bandwidth tradeoff



Or, is this vision flawed?

- router content stores are limited in size by technology while effective traffic reduction requires VERY large caches
- and content delivery is a business needing compute power
- and data centers can also do routing…



Outline

- Internet traffic control
- ICN traffic control
- Impact of in-network caching
  - performance of an LRU cache

LRU replacement

- when a cache is full, some objects must be removed to make room for new ones, eg,
  - least recently used (LRU): replace the object that has not been requested for the longest time
  - random: replace any object chosen at random
  - least frequently used (LFU): only cache the most popular objects
  - ...
- LFU is optimal among policies that cannot see into the future
- LRU appears as a reasonable compromise between complexity and performance
  - objects are indexed by a linked list that evolves at each reqest arrival

Content mix

- Cisco: "96% of traffic is content transfer"
- web, file sharing, user generated content, video on demand
- billions of objects, petabytes of content!

	share	objects	size	volume
web	.18	10^{11}	10 KB	1 PB
file sharing	.36	10^{5}	10 GB	1 PB
UGC	.23	10^{8}	10 MB	1 PB
VoD	.23	10^{4}	100 MB	1 TB

The independent reference model (IRM)

- assume a fixed population of N objects
- requests arrive sequentially and any request is for object n with probability $\propto q(n)$ for $1 \leq n \leq N$

- equivalently, for computing the hit rate,
  assume Poisson arrivals of requests for object n at rate $q(n)$ for $1 \leq n \leq N$

Validity of the independent reference model

- the IRM ignores changes in popularity over time
  - eg, new videos appear, are popular for a time and then disappear
- but, assuming cache content churn occurs at a faster time scale, IRM is reasonable for short periods
  - this is like the stationarity assumption in teletraffic
- accounting for "temporal locality" is more important when estimating the popularity law q(n)
  - measurements over a week may not be relevant for estimating hit rates in the busy period
- q(n) estimation also needs to account for "spatial locality"
  - what's popular in France is not necessarily popular in Norway,...

Content popularity

- Zipf law popularity
  - request rate for n^{th} most popular object, $q(n) \propto 1/n^{\alpha}$
- web page popularity Zipf(α), $.64 < \alpha < .83$
- file sharing Zipf(a), $.75 < \alpha < .82$
- user generated content Zipf(α), $.56 < \alpha < .88$
- video on demand Zipf(α), $.65 < \alpha < 1.2$, Weibull, ...

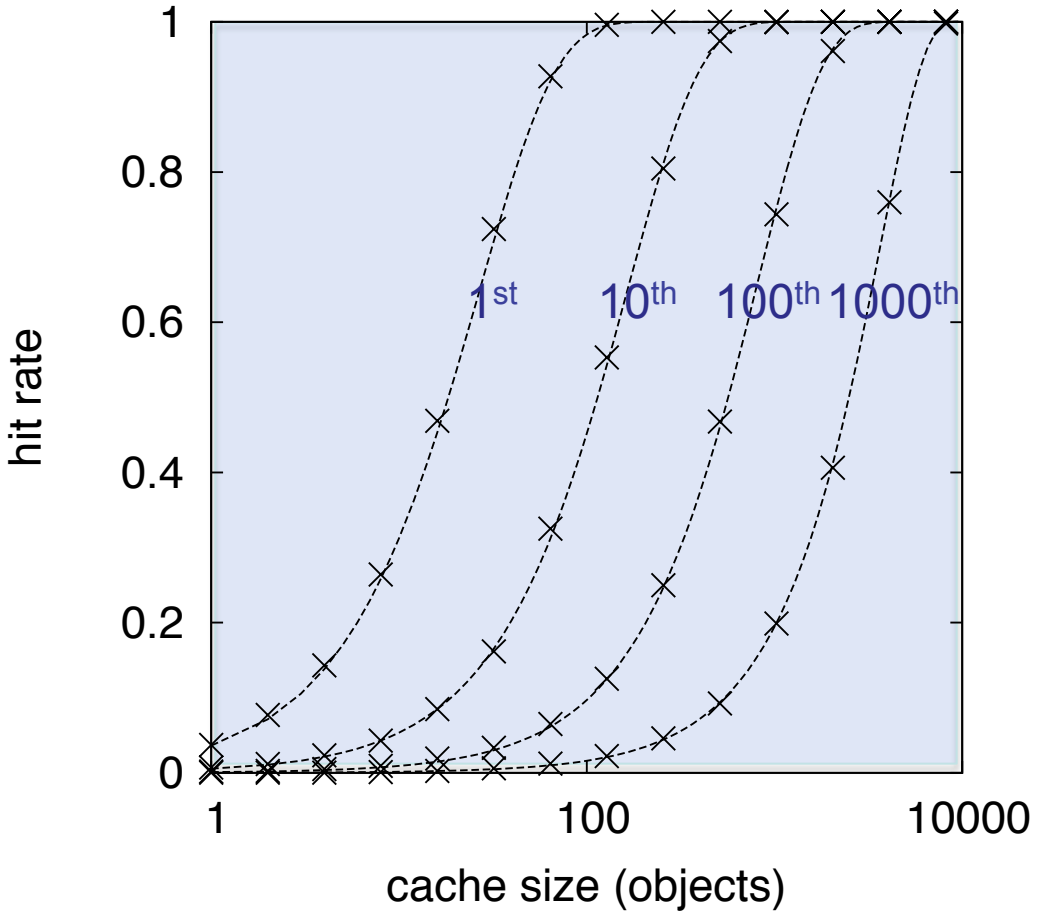
- for our evaluations, we suppose
  - Zipf(.8) for web, file sharing, UGC
  - Zipf(.8) or Zipf(1.2) for VoD

Calculating LRU hit rates (Che, Tung and Wang, 2002)

- cache size C objects, popularity of object $n \propto q(n)$
- assume "independent reference model" or, equivalently, Poisson request arrivals at rate $q(n)$ for object n
- "characteristic time" T_C is time for C different objects to be requested
- assume random variable T_C is approximately deterministic, $T_C \sim t_C$
- then, hit rate for object n is $h(n) = 1 - \exp\{-q(n)t_C\}$
- now, $C = \sum_n \mathbf{1}\{\text{object n is in cache}\}$
- taking expectations, $C = \sum_n h(n) = \sum_n (1 - \exp\{-q(n)t_C\})$
- solving numerically for t_C yields $h(n)$

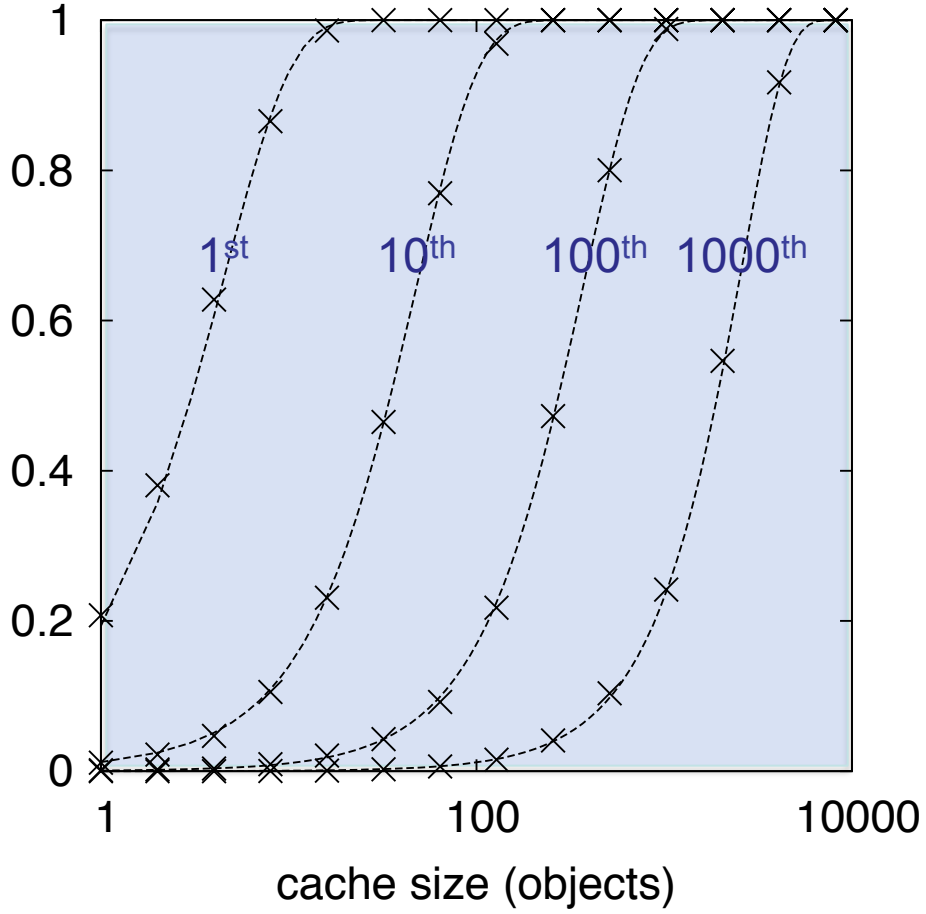
Accuracy of Che approximation

- 10000 objects, Zipf(.8) popularity



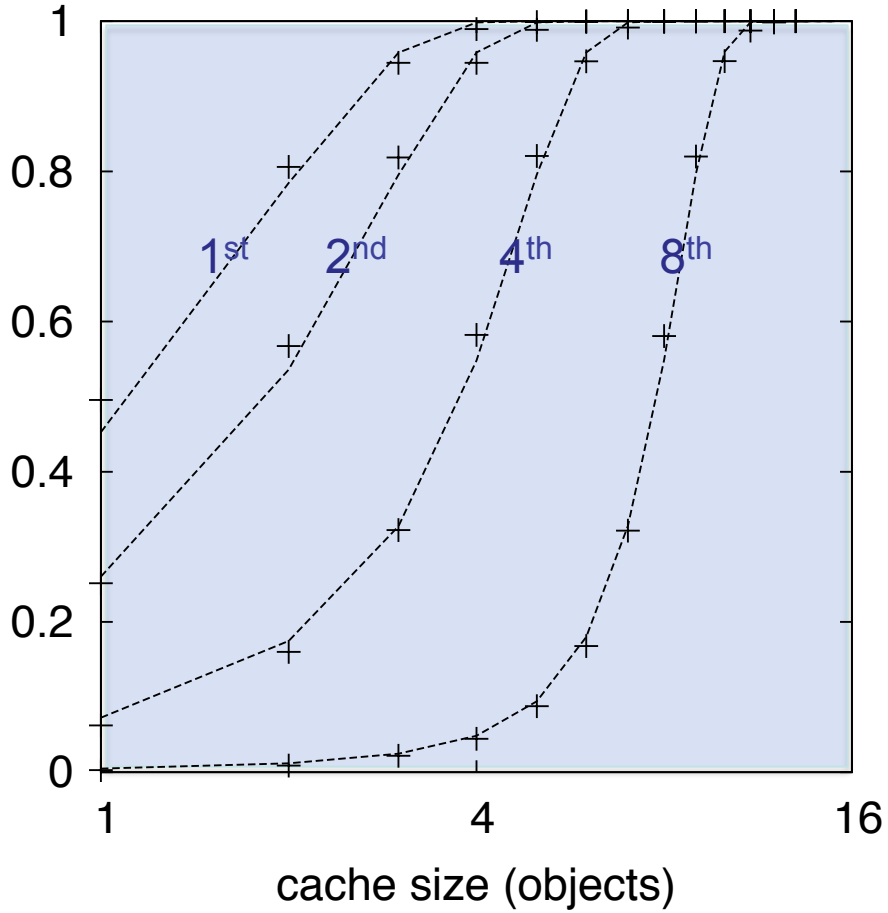
Accuracy of Che approximation

- 10000 objects, Zipf(1.2) popularity



Accuracy of Che approximation

- 16 objects, geometric(.5) popularity

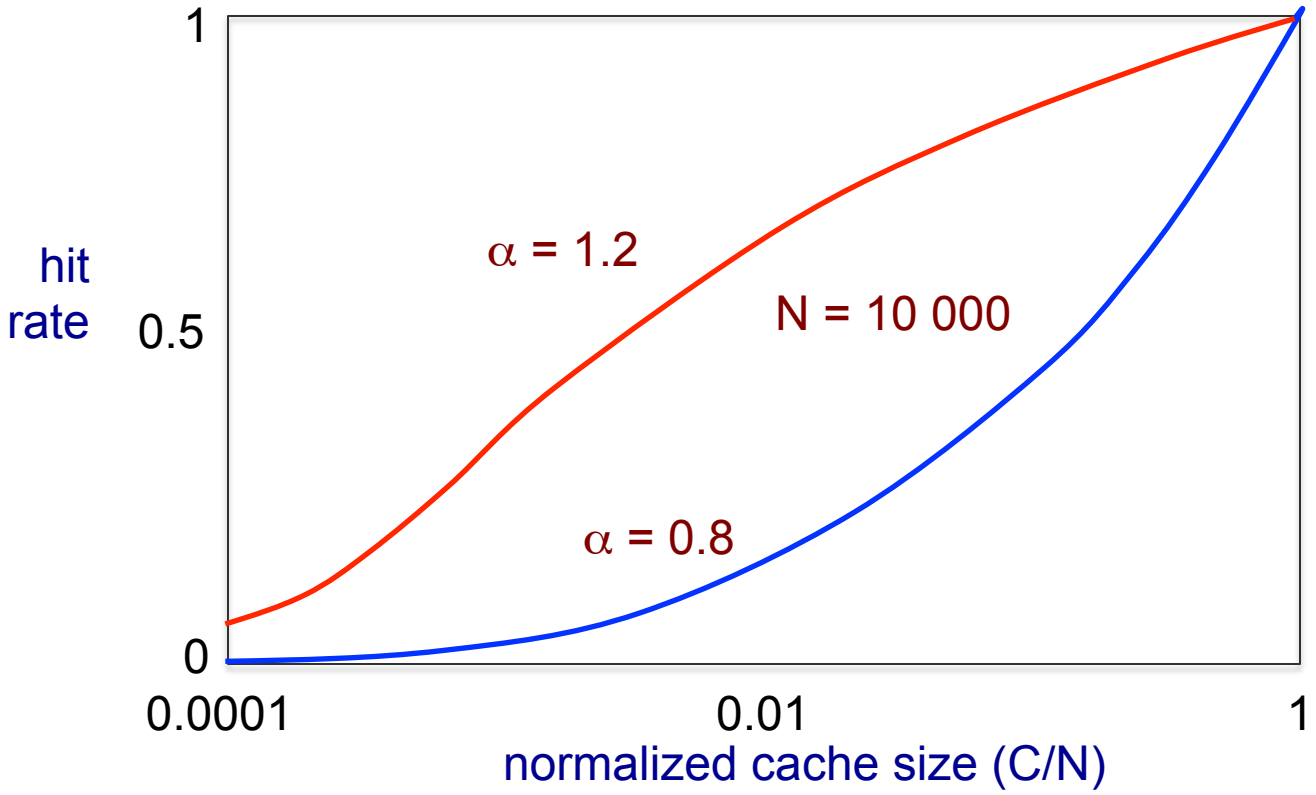


Accuracy of Che approximation

- we can explain accuracy of Che approximation
  - central limit theorem for number of distinct object requests in (0,t)
  - approximate complementary error function (erfc) by a step function
- cf. C. Fricker et al., A versatile and accurate approximation for LRU cache performance. ITC 24, 2012.

LRU cache performance

- strong impact of Zipf parameter α
- strong impact of object population N



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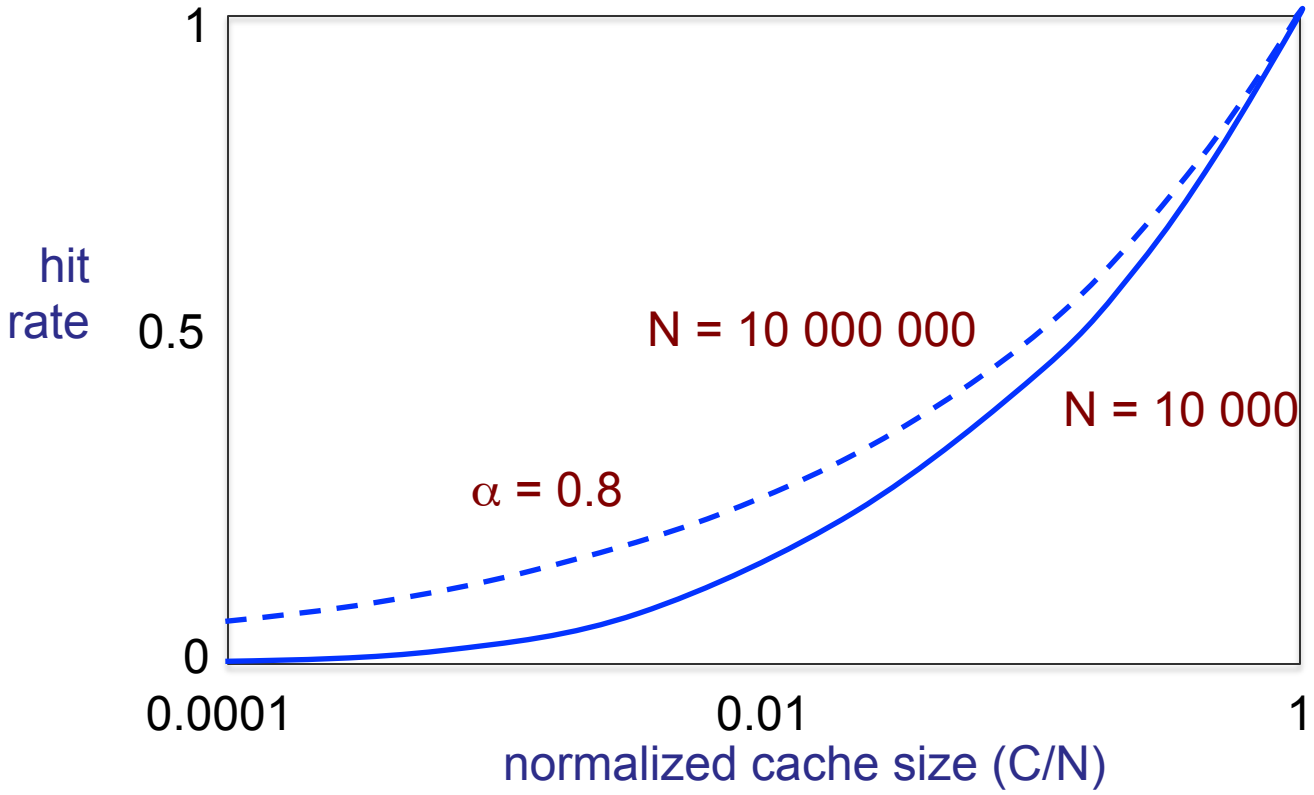

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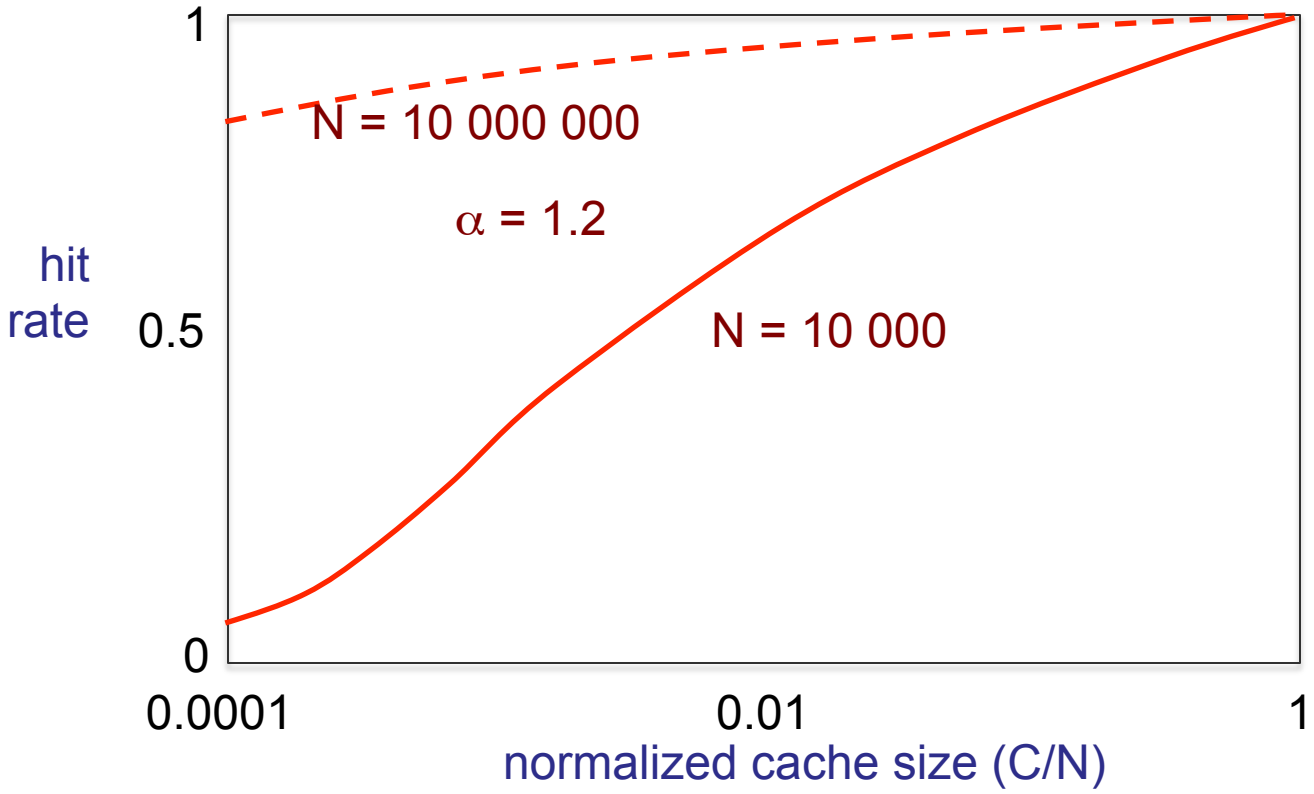


Content mix (recap)

- Cisco: "96% of traffic is content transfer"
- web, file sharing, user generated content, video on demand
- billions of objects, petabytes of content!

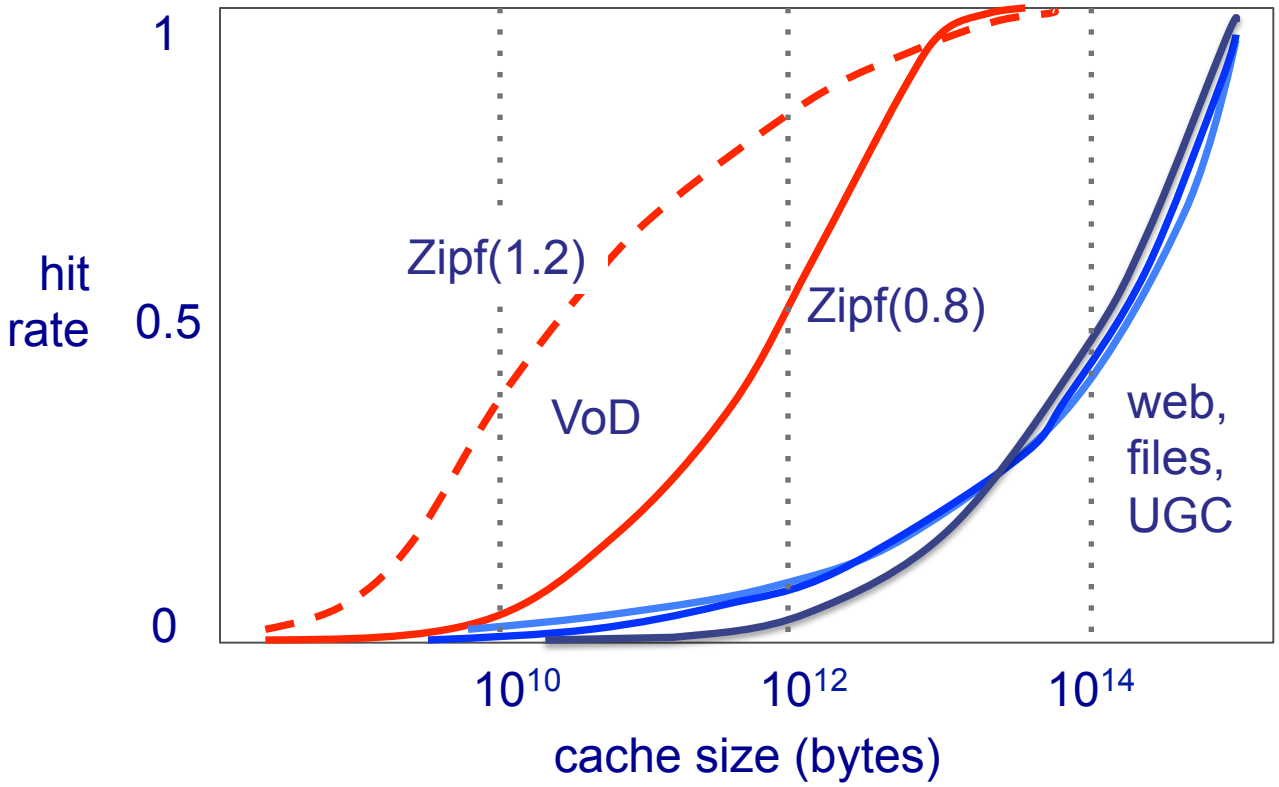
	share	objects	size	popularity
web	.18	10^{11}	10 KB	$1/n^{.8}$
file sharing	.36	10^{5}	10 GB	$1/n^{.8}$
UGC	.23	10^{8}	10 MB	$1/n^{.8}$
VoD	.23	10^{4}	100 MB	$1/n^{.8}$ or $1/n^{1.2}$

Generalized Che approximation

- cache size C bytes, popularity of object n of type i is $q_i(n)$, size of this object is $\theta_i(n)$
- assume "independent reference model »
- "characteristic time" T_C is time for different objects of total size C to be requested, assume $T_C \sim t_C$
- then, hit rate for type i object n is $h_i(n) \approx 1 - \exp\{-q_i(n)t_C\}$
- now, $C = \sum_i \sum_n 1\{\text{type i object \#n present}\}\ \theta_i(n)$
- taking expectations, $C = \sum_i \sum_n h_i(n)\ \theta_i(n)$
  $= \sum_i \sum_n (1 - \exp\{-q_i(n)t_C\})\ \theta_i(n)$
- solving for t_C yields the $h_i(n)$

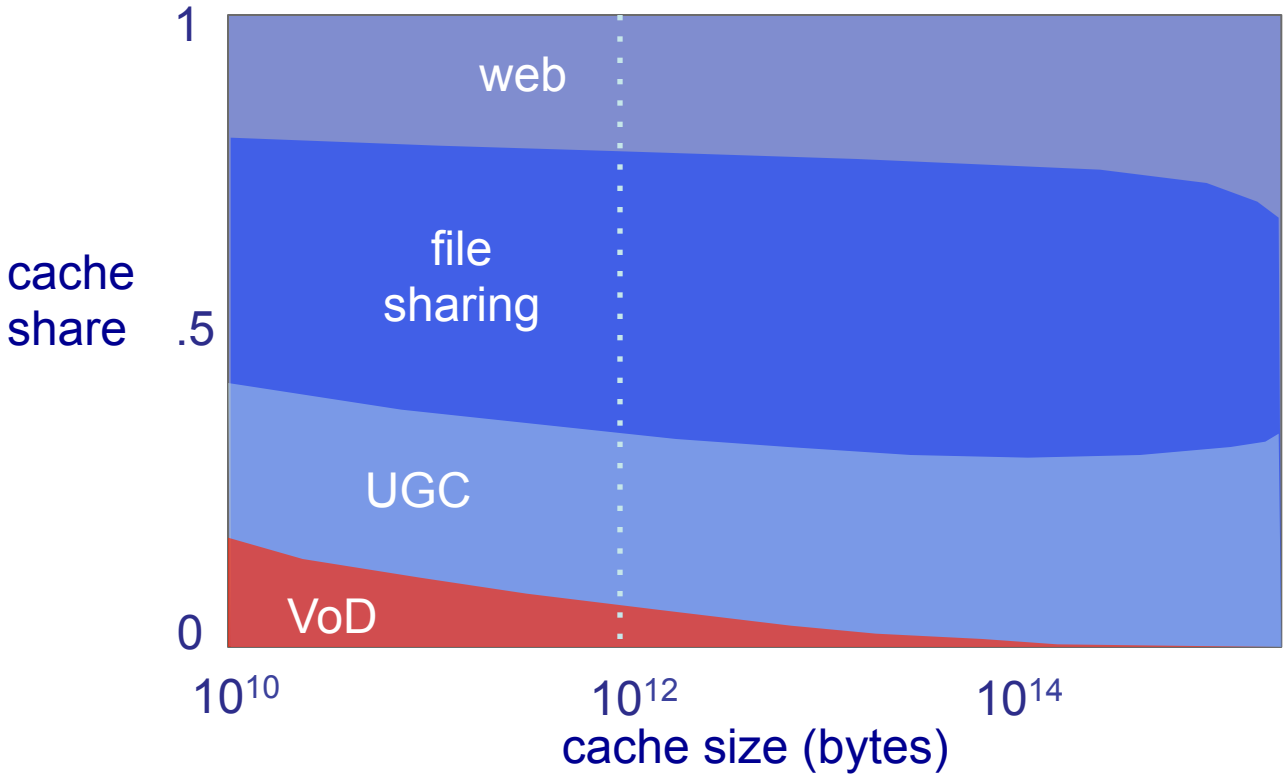
Per content type hit rates

- for web, file sharing and UGC, we need $O(10^{14})$ cache size
- for VoD, $O(10^{12})$ cache size yields high hit rates



Cache occupancy by type of content – VoD popularity is Zipf(1.2)

- disproportionate cache use, e.g., for 1 TB cache:
  - 95% share for web, files and UGC for only 5% hit rate
  - VoD hit rate is 85% but only uses 5% of cache capacity



Is ubiquitous caching really a good idea?

- router cache cannot be very big, $O(10^{12})$ bytes, say
  - for cheap but rapid storage in a large number of ICN routers
- significant VoD hit rate but heavy polution from other types
- it would be more effective to specialize cache for VoD

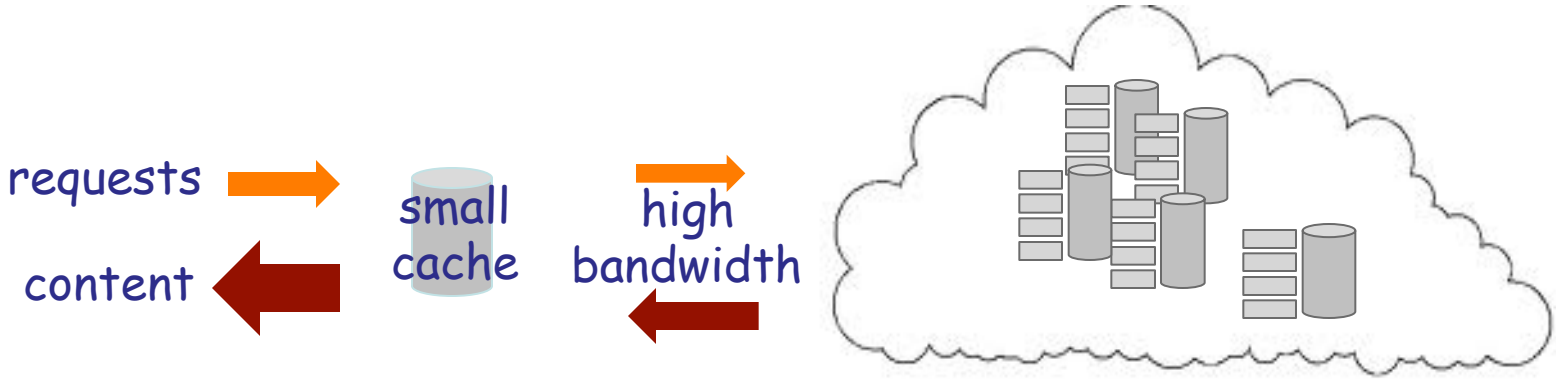
- eg, assume 1 TB cache
  - shared cache hit rate = .17
  - dedicated VoD cache hit rate = .23 (ie, all VoD traffic)

Outline

- Internet traffic control
- ICN traffic control
- Impact of in-network caching
  - performance of an LRU cache
  - the memory-bandwidth cost tradeoff

Evaluating the memory-bandwidth tradeoff

- assuming the "independent reference model"
- accounting for a very large content catalogue...
  - web pages, user-generated content, file sharing, video
  - petabytes of content
- and highly dispersed content item popularities
  - Zipf-like behaviour with exponent < 1
- an example from BitTorrent trackers... [Dan & Carlsson, IPTPS 2010]



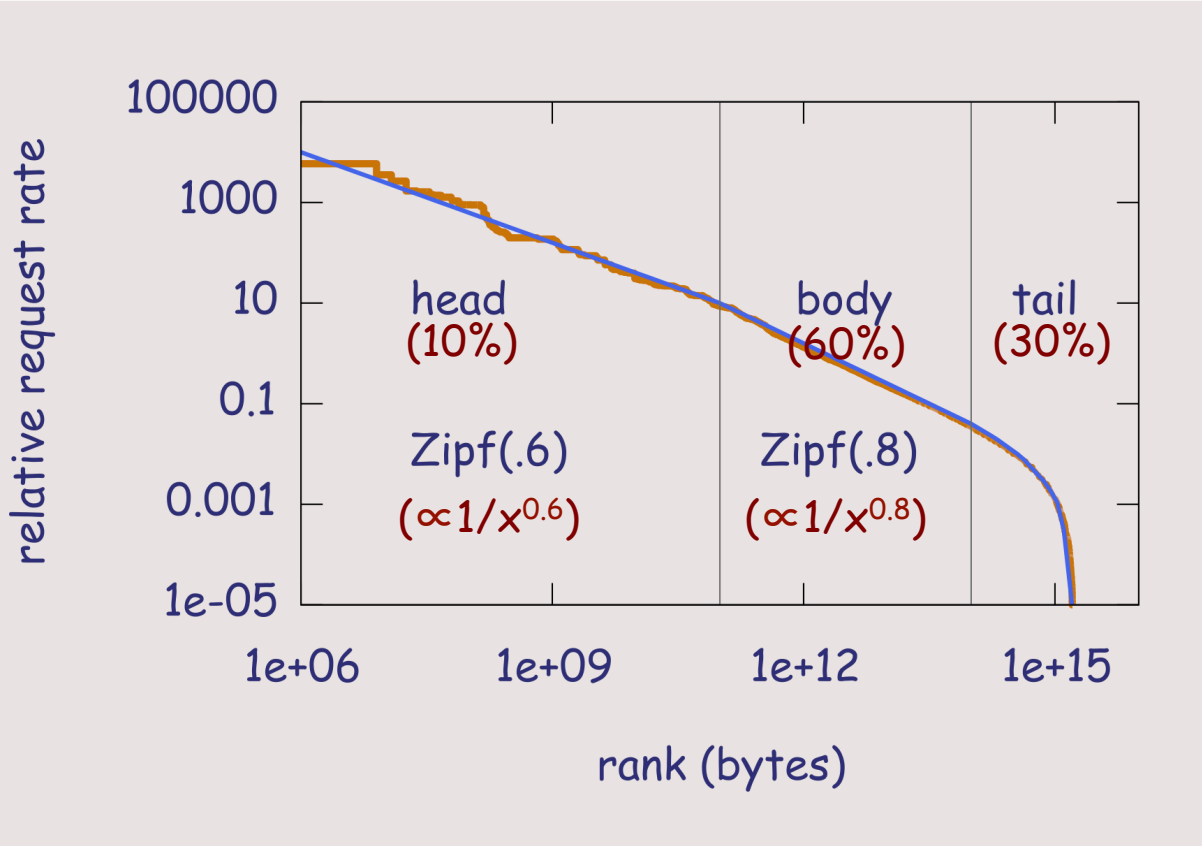
A popularity law for torrents

- the number of BitTorrent leechers is a measure of instantaneous popularity
- assume q(n) is request rate for torrent n; we assume

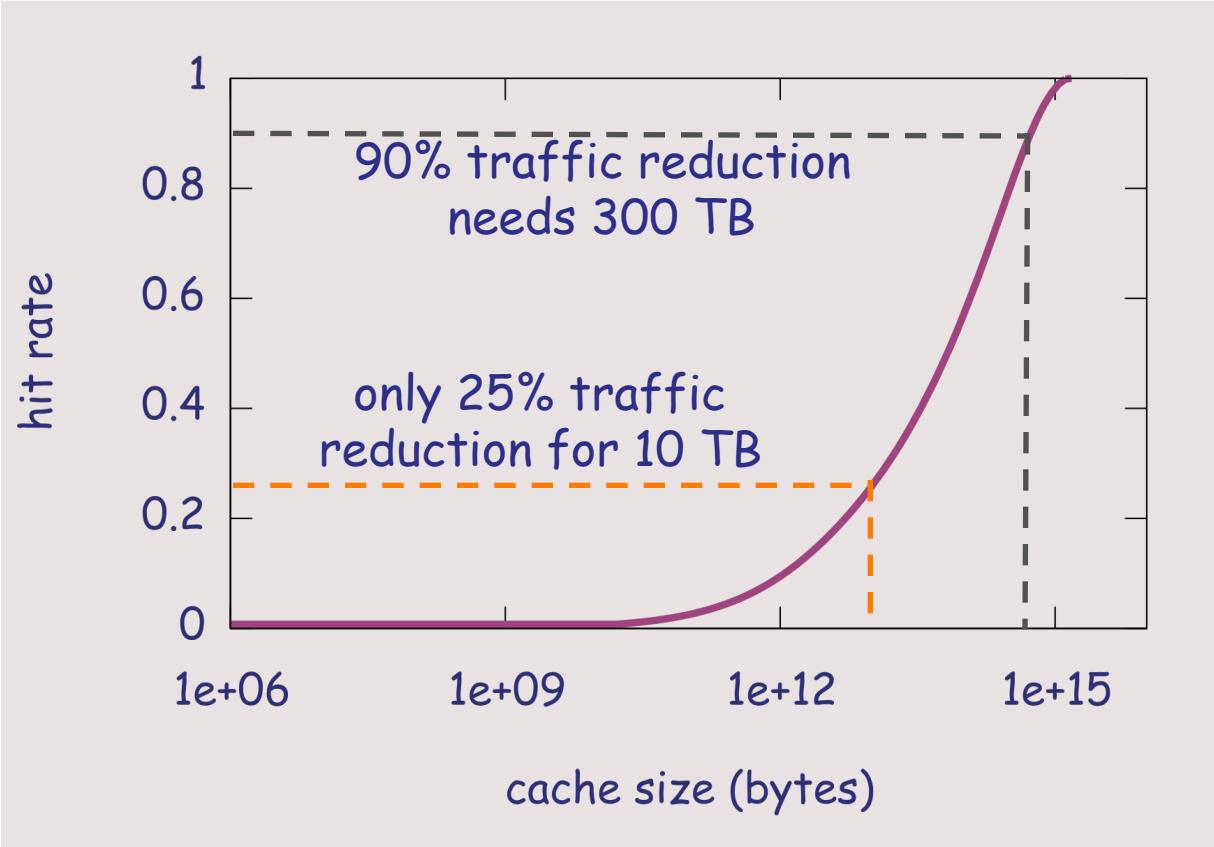
$$q(n) \propto l(n) / s(n)$$

  where l(n) is number of leechers, s(n) is torrent size
- l(n) and s(n) can be derived by "scraping" trackers
  - cf. G. Dan and N. Carlsson. Power-law revisited: large scale measurement study of p2p content popularity, IPTPS 2010
- NB. other popularity measurements are carried out over a period (eg, most watched videos in 1 week) and do not account for temporal locality

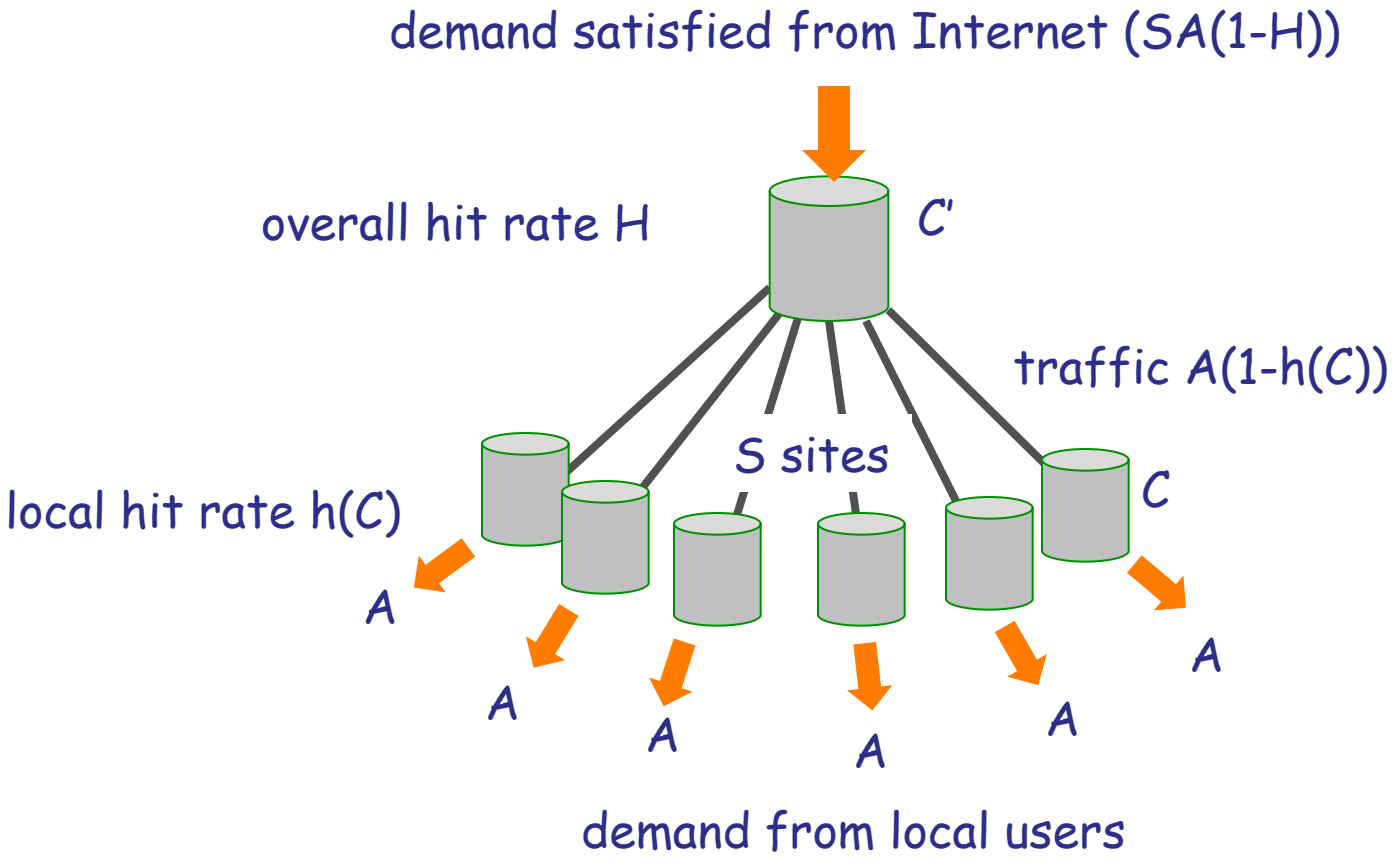
A popularity law for torrents



LRU hit rate versus cache size for torrents



A two-layer cache hierarchy



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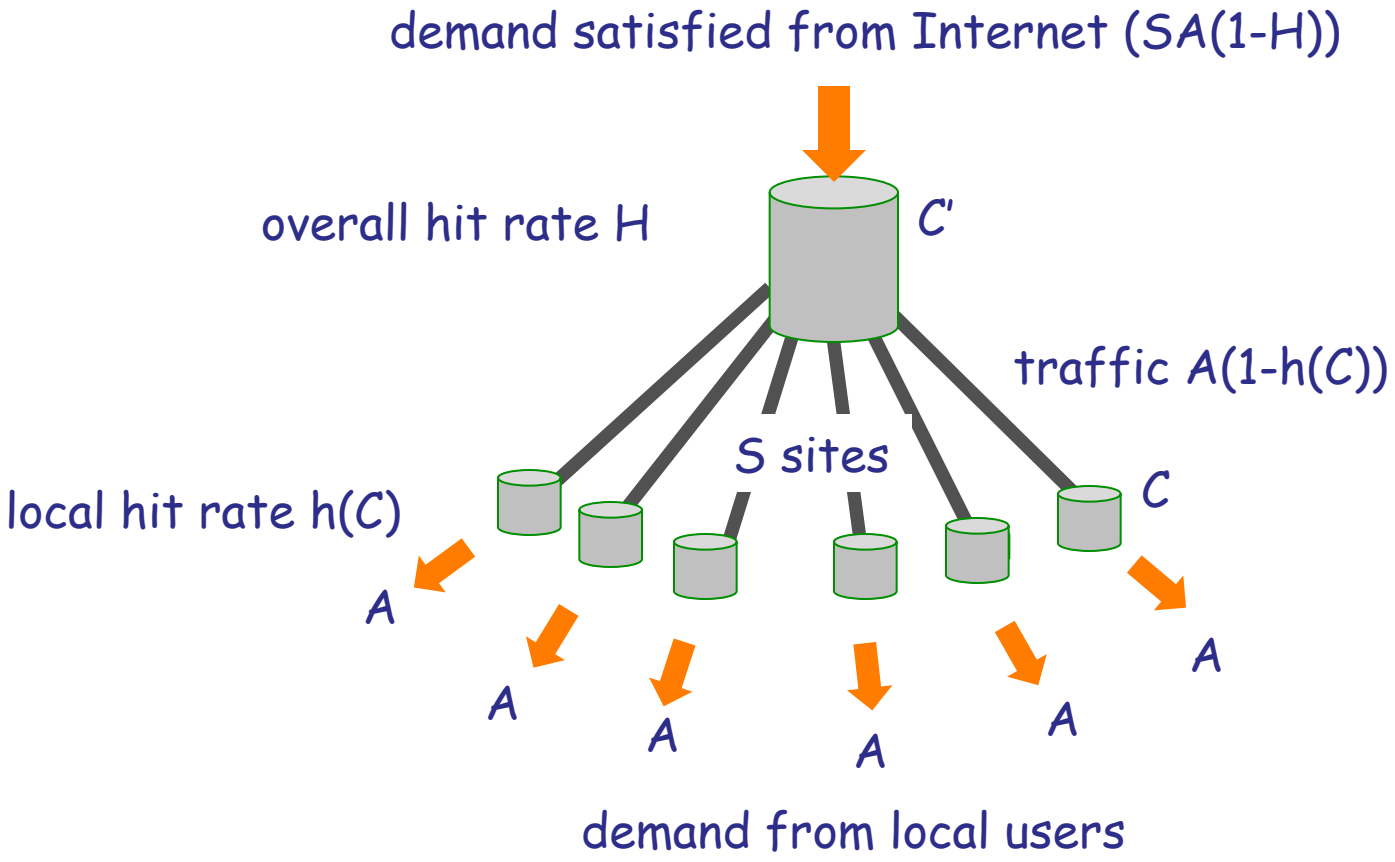
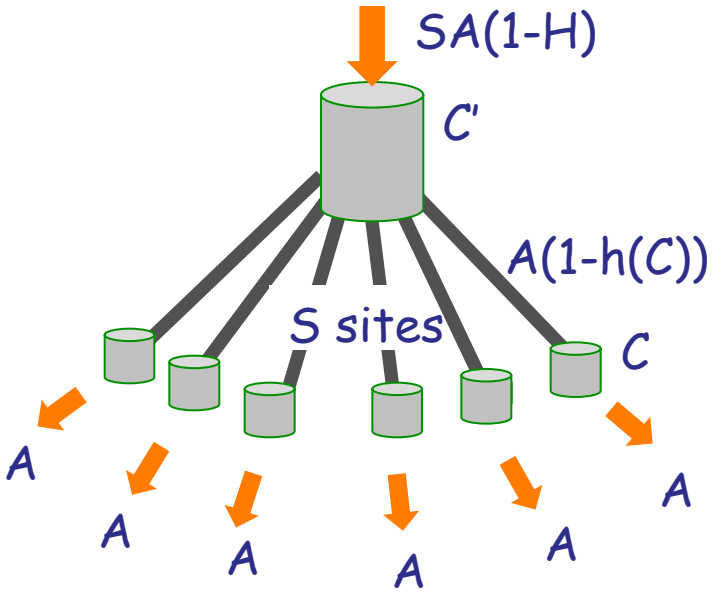


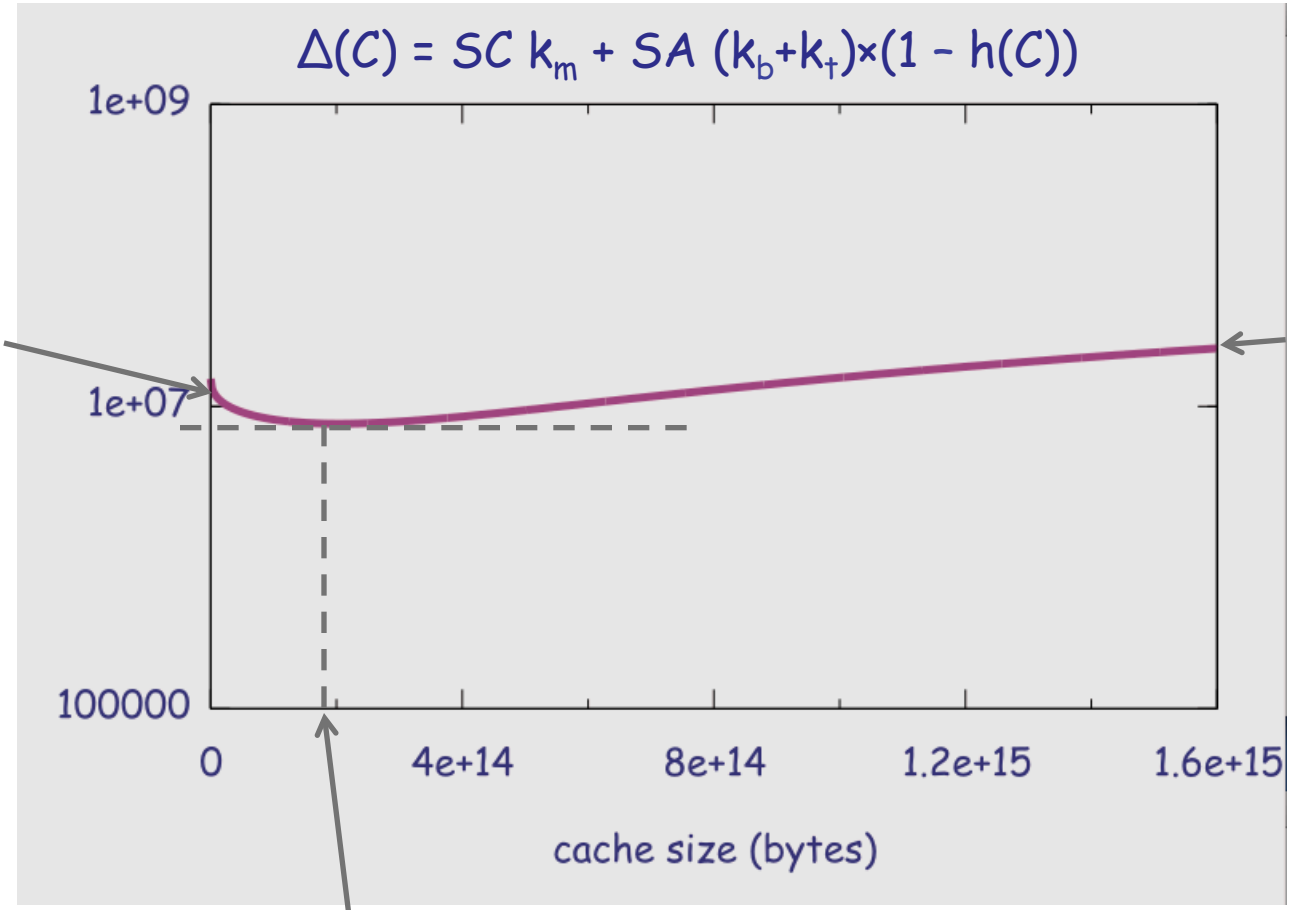
Cost evaluation

- cost = Internet + access + caches + bandwidth
- assume A, S fixed, C' contains all content (ie, $H = 1$)
- a monthly cost of caching
  - memory: k_m per GB $\Rightarrow k_m(SC+C')$
  - traffic: k_t per Mb/s $\Rightarrow k_t(SA+SA(1-h(C)))$
- a monthly cost of bandwidth
  - bandwidth: k_b per Mb/s $\Rightarrow k_b SA(1-h(C))$
- cost variation as C varies:

  $\Delta(C) = SC\,k_m + SA\,(k_b+k_t)\times(1 - h(C))$
- cost "guesstimates":
  - k_m = €0.15 per GB
  - k_t+k_b = €15 per Mb/s



Costing the tradeoff

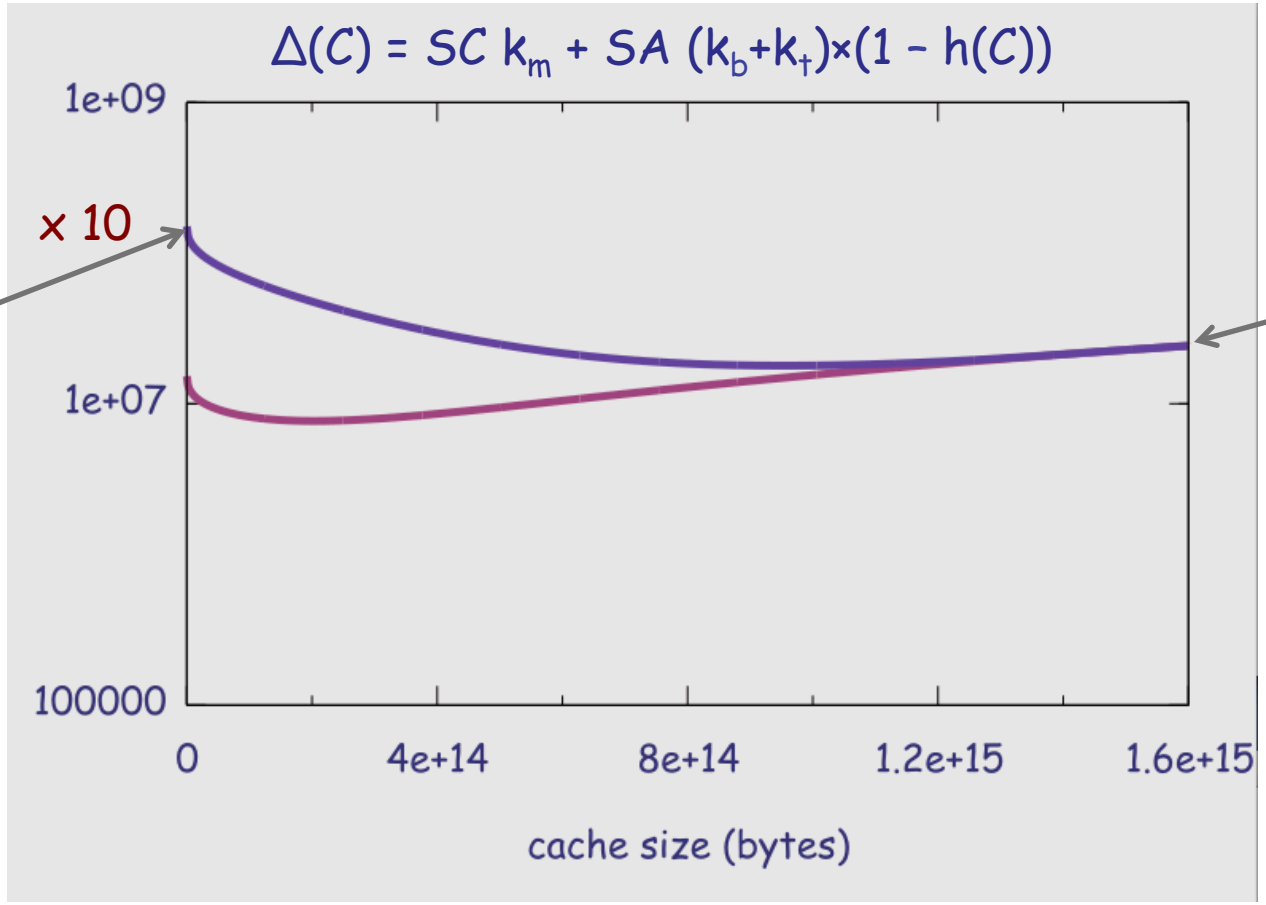


max cost of bandwidth ($C = 0$)

max cost of memory ($C = 1.6\times10^{15}$)

optimal size

Costing the tradeoff



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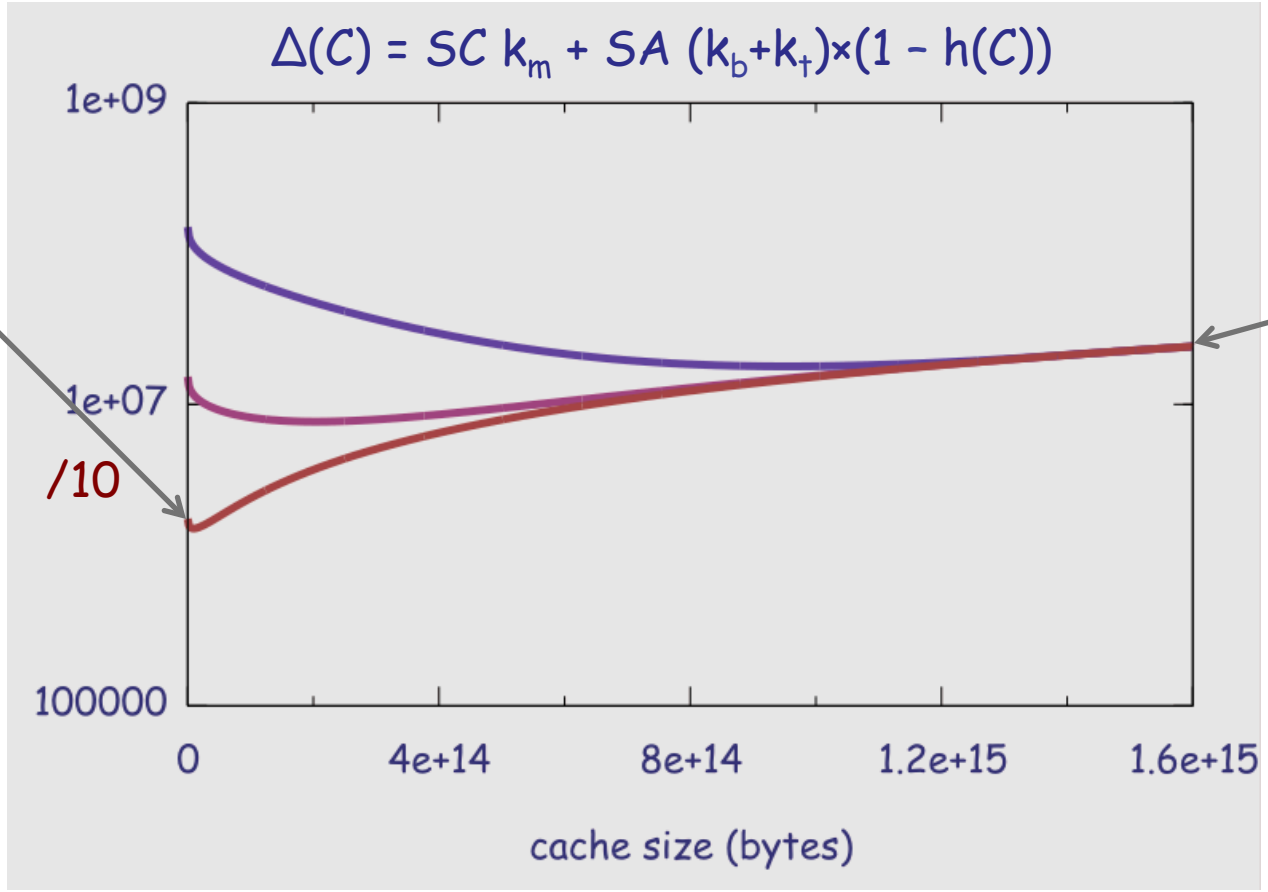
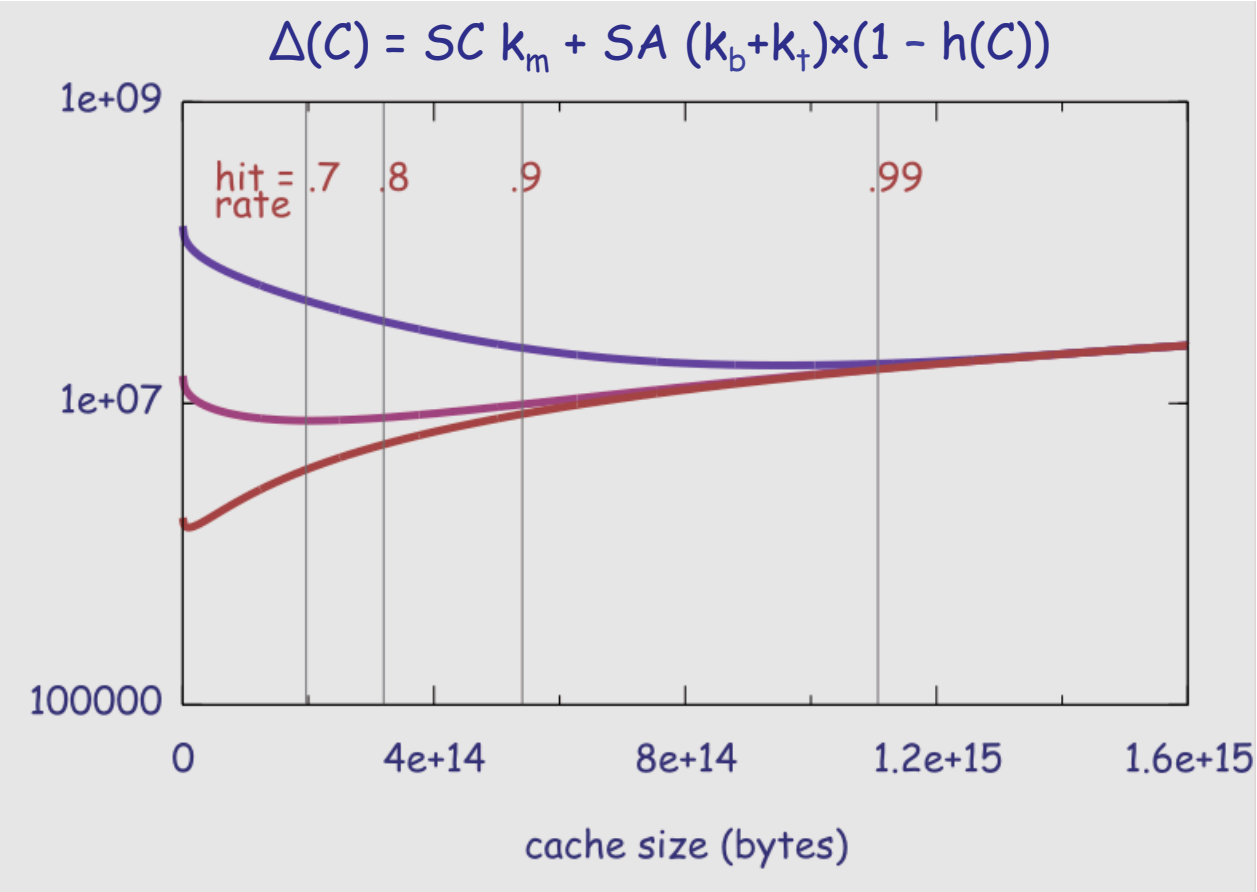


max cost of bandwidth

/10

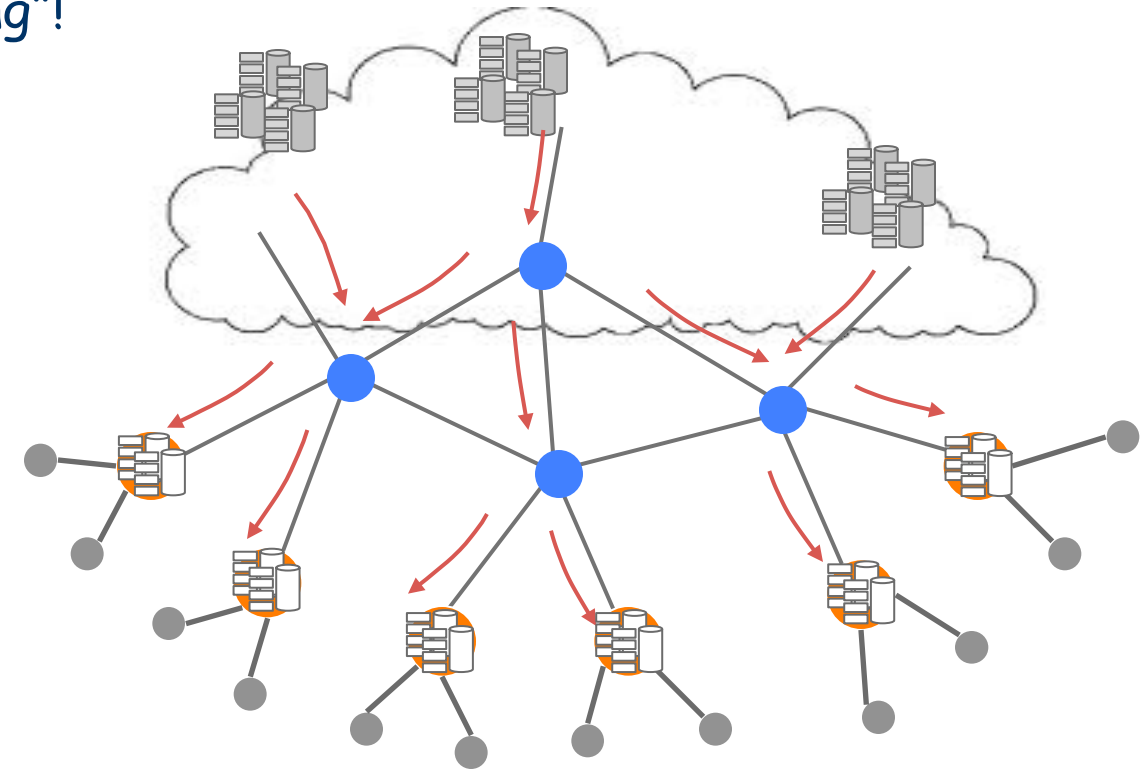
max cost of memory

Costing the tradeoff



Large storage, low bandwidth

- using best guess cost data suggests large (~petabyte) stores capturing more than 90% of content traffic are cost effective
- instead of "routers that do caching", we have "data centers that do routing"!



Outline

- Internet traffic control
- ICN traffic control
- Impact of in-network caching
- Conclusions

ICN as a flow-aware network of data centers

- flow aware traffic control
  - per-flow fair queuing in router buffers
  - implicit service differentiation and no reliance on user cooperation
  - need to ensure link load < 0.9 by TE and overload controls
- transposition of flow-aware control to ICN
  - need flow identifier – object name in packet headers…
  - and "interests buy data", interest discard, ECN…
  - and receiver-based congestion control
- the role of in-network caching
  - reduces traffic by caching popular content close to users
  - but content catalogues are huge and popularity is widely dispersed
  - very large caches are necessary and cost effective
- a future ICN based on data centers that also do routing!