Trading off bandwidth for memory in a future, information-centric Internet

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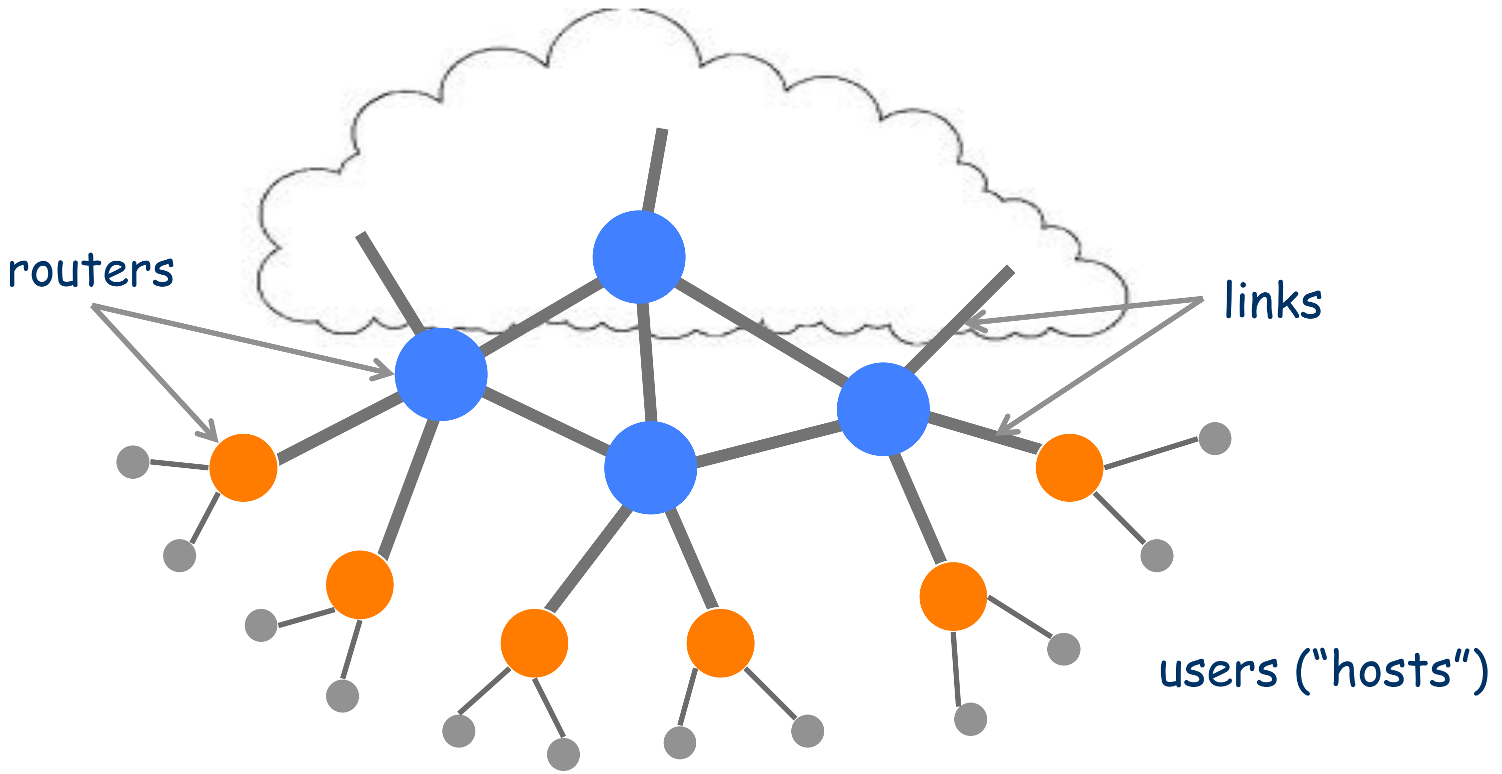
Engineering the Internet

- the Internet is a "network of networks", a set of routers interconnected by links allowing communication between hosts
- the traffic engineer's task: how much capacity (eg, link bandwidth) and how it should be shared to satisfy demand



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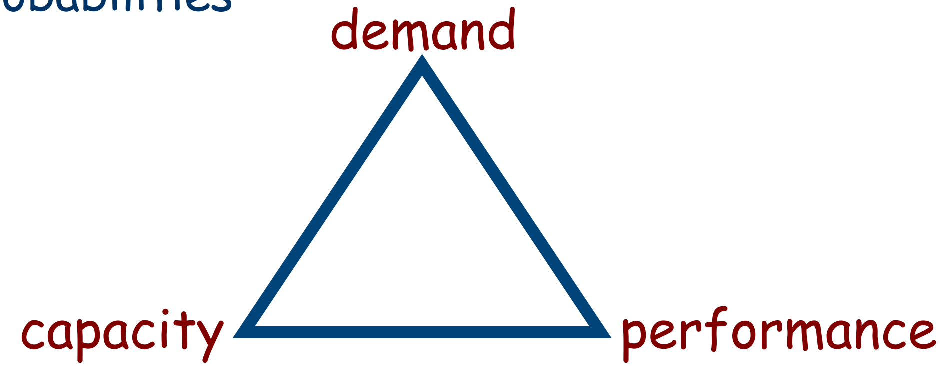
- understanding a three-way relation between
  - demand: a succession of packet flows generated by diverse applications, typically modelled as a stochastic process
  - capacity: how much, but also how it is shared by different flows
  - performance: time to download, communication quality,... expressed in terms of probabilities



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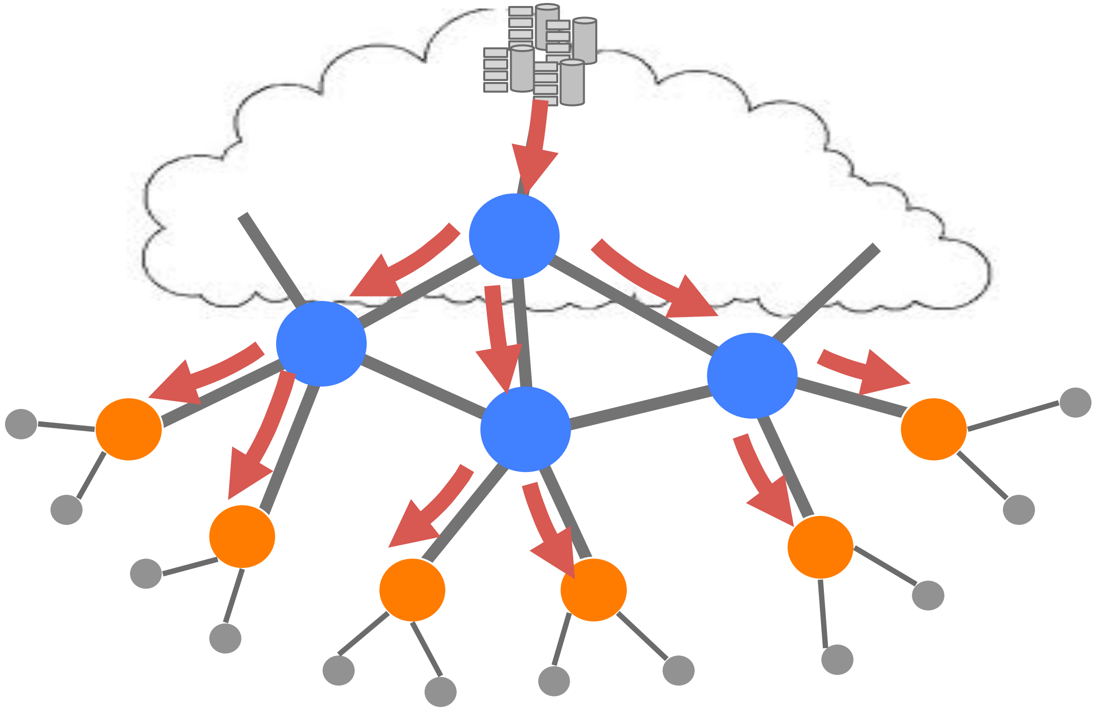
- this talk is about a traffic engineering issue in a future information-centric network

Outline

1. engineering an information-centric Internet
2. NDN: a proposed information-centric network architecture
3. modelling cache performance
4. evaluating the memory-bandwidth tradeoff

An information-centric network

- more than 90% of Internet traffic is content retrieval
  - web pages, documents,... and videos
- network performance and costs are highly dependent on where the content is stored
  - eg, in remote servers or local cache memories



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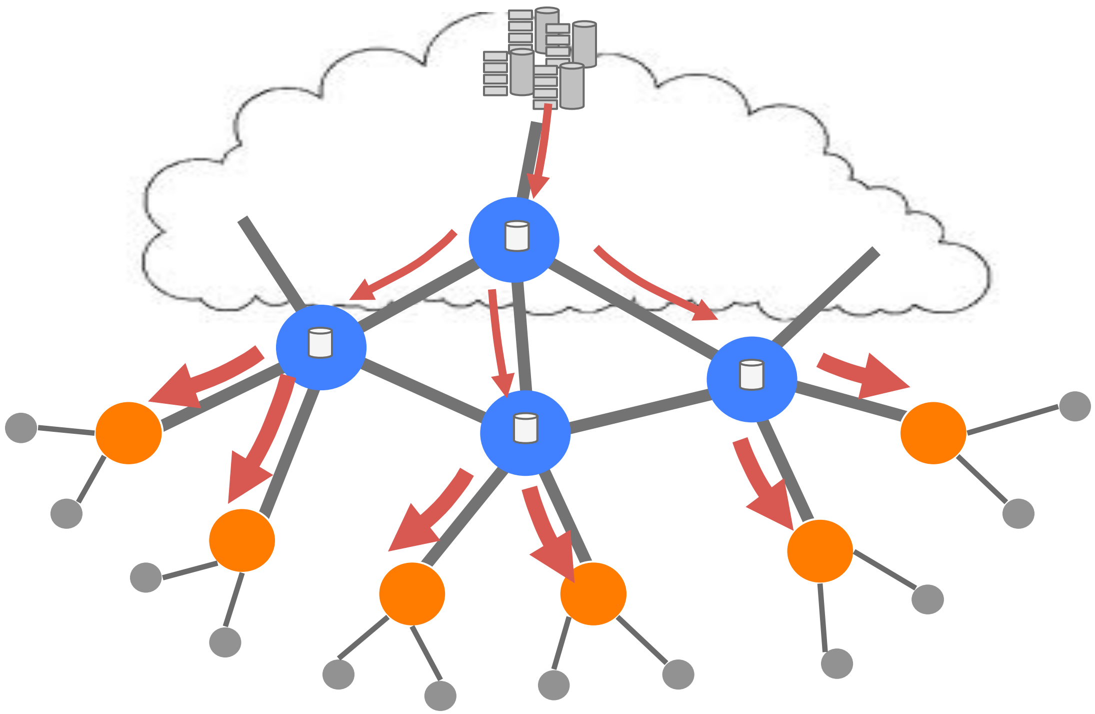

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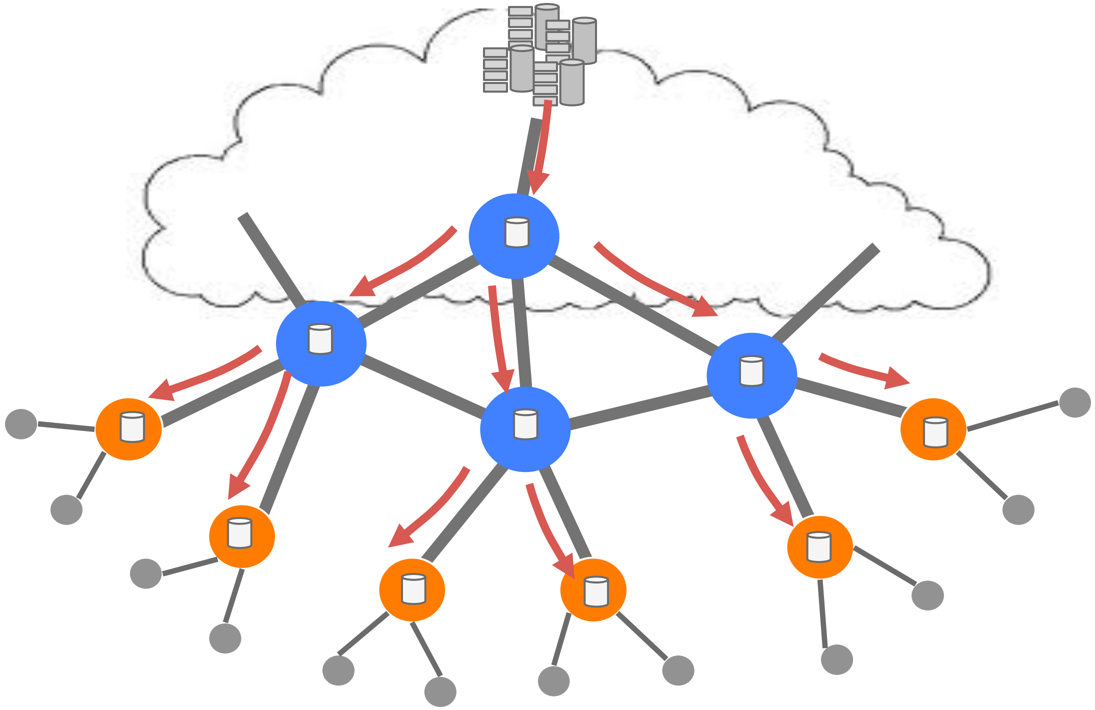

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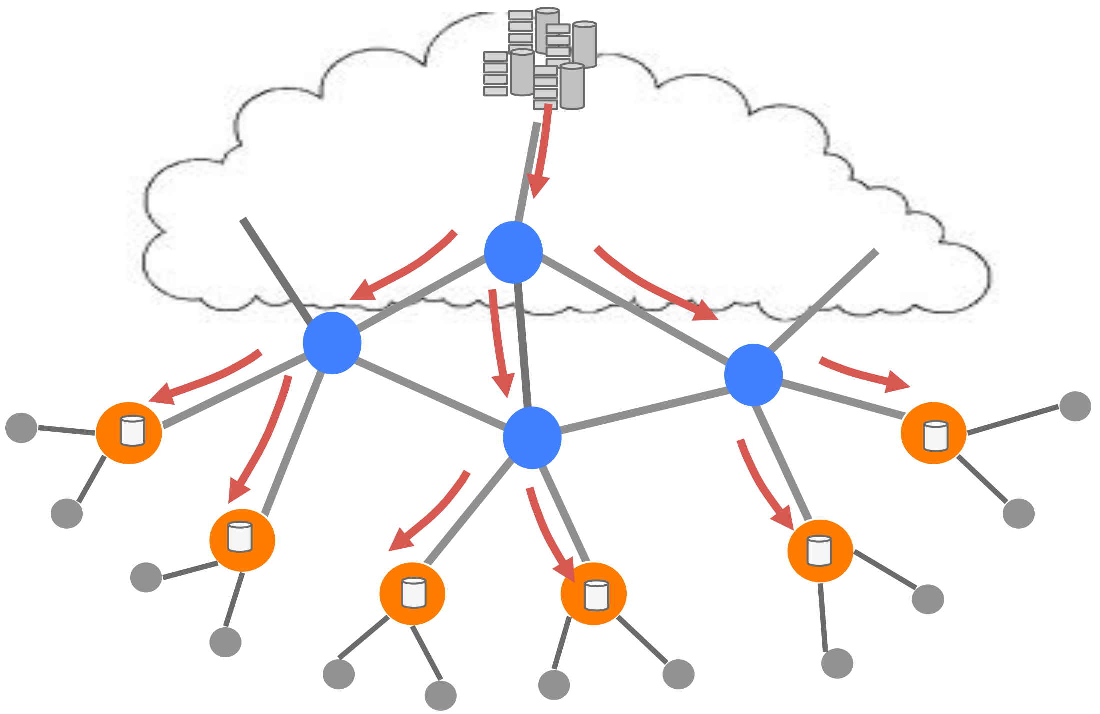
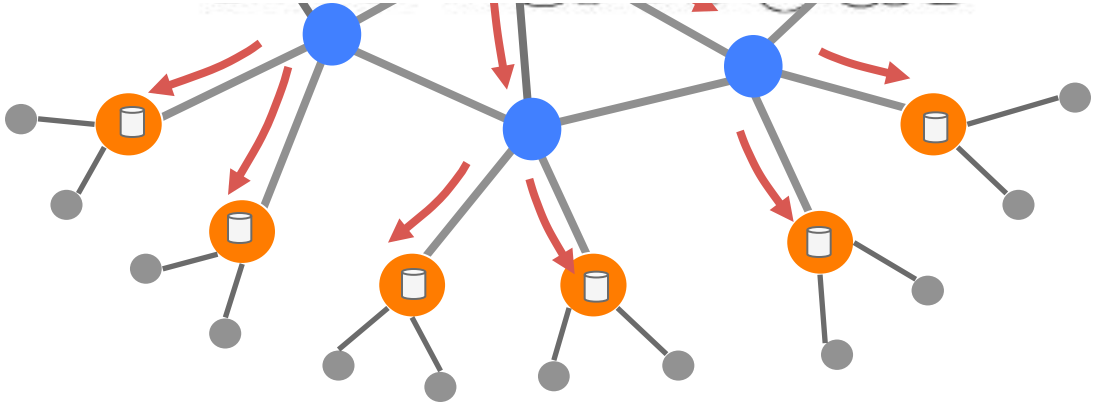


An information-centric network

- more than 90% of Internet traffic is content retrieval
  - web pages, documents, ... and videos
- network performance and costs are highly dependent on where the content is stored
  - eg, in remote servers or local cache memories
- what is the optimal memory-bandwidth tradeoff?
  - bigger caches means more hits and less network traffic
- can this tradeoff be achieved incrementally or do we need a new Internet architecture ?



Towards a new Internet architecture

- IP, the Internet Protocol, was designed some 40 years ago
  - some brilliant design decisions
    - connectionless packet switching, the "end-to-end principle", a layered architecture,...
  - but continuing success may be due more to Moore's law
    - increasing processing power, middle boxes, overlays, over-provisioning,...
- the Internet was not designed for present needs...
  - from 200 hosts in 1980 to more than 10^9 in 2014
  - from messaging, Telnet, FTP... to Web, social networks, video,...
- ... leading to some serious problems
  - viruses, attacks, phishing, identity theft, cyber crime,...
  - unreliable performance, difficult mobility management,...
  - a network hard to engineer, operate and troubleshoot
  - an improvised business model

Incremental change or a "clean slate" design

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Incremental change or a "clean slate" design

- since 2005, much world-wide research on new Internet architectures, deliberately ignoring the existing network
- proposals include:
  - new architectural principles (eg, other than layering)
  - network virtualization
  - improved network management
  - ...
  - a network focused on content retrieval
- two major trends emerge from this effort
  - software-defined networks (virtualization, network management)
  - information-centric networking (content retrieval)
- the first is not clean slate, some argue the second can also be realized by incremental changes to IP

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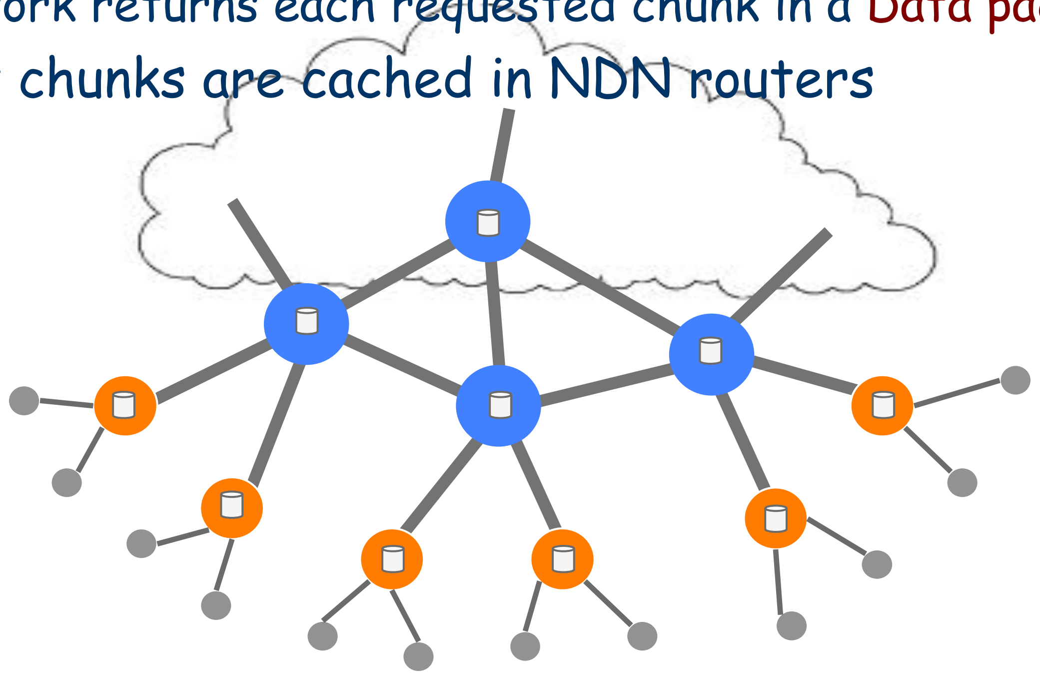
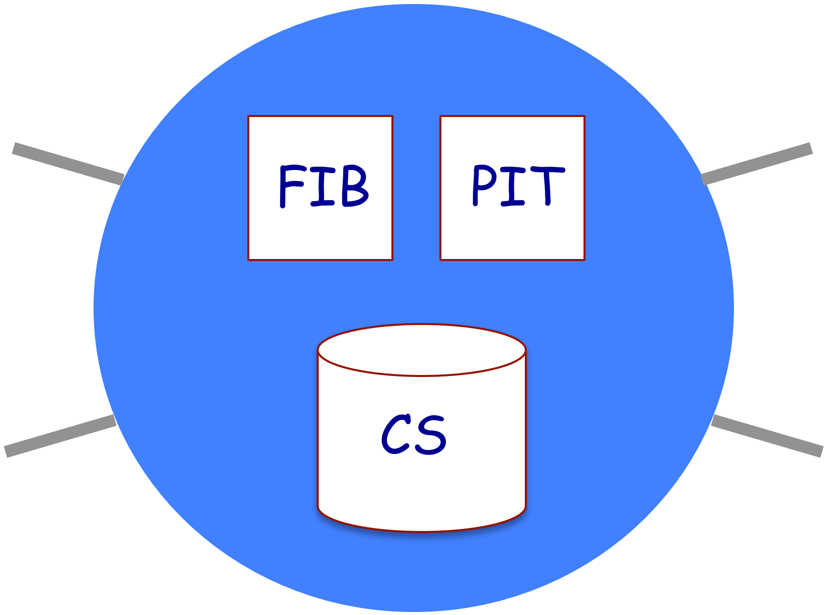
Named data networking (NDN)

- initially proposed by Jacobson et al. (Palo Alto Research Center) as content-centric networking (CCN), currently developed in NSF project called NDN
- instead of addresses, packets have names
  - users request a content chunk (eg, 4KB) with an Interest packet
  - network returns each requested chunk in a Data packet
- content chunks are cached in NDN routers



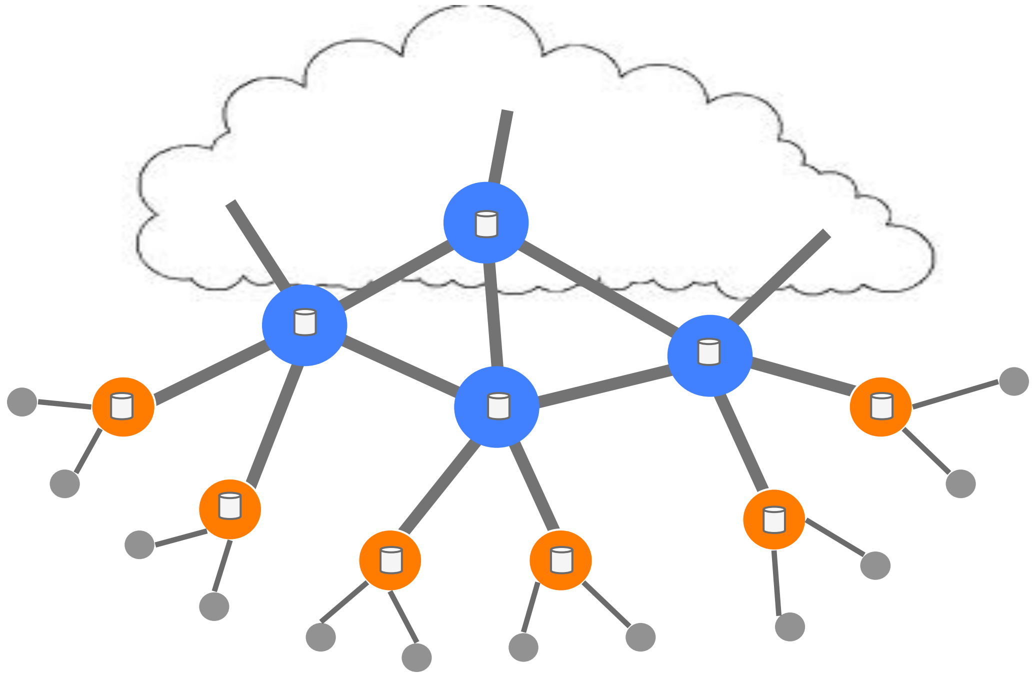
Forwarding in an NDN router

- a Forwarding Information Base (FIB) indicates useful output(s) for every name received in Interest packets
- a Pending Interest Table (PIT) records requesting input for each Interest until Data packet is received
- a Content Store (CS) temporarily caches returned Data



NDN saves bandwidth

- a content chunk cached in the CS can be downloaded directly
  - on receipt of Interest, first check content store
- simultaneous multicasting (eg, live video) realized using PIT entry
  - if content chunk name is already in PIT, do not send Interest, add new input for future Data transmission



A new ICN architecture or enhanced IP?

- Information-centric networking (eg, NDN) has compelling advantages over IP
  - saves bandwidth through deferred and simultaneous multicast
  - simplifies mobility management
  - facilitates network security by data encryption, as necessary
- on the other hand,
  - the Internet already saves bandwidth by caching: so-called Content distribution networks (CDNs) are already widely deployed
  - name-based forwarding brings severe scalability issues
  - currently there are no "killer applications" that make ICN (eg, NDN) an obvious winner
- the choice partly depends on cost-effectiveness
  - how should one engineer a network of caches?
  - what exactly is the memory-bandwidth tradeoff?

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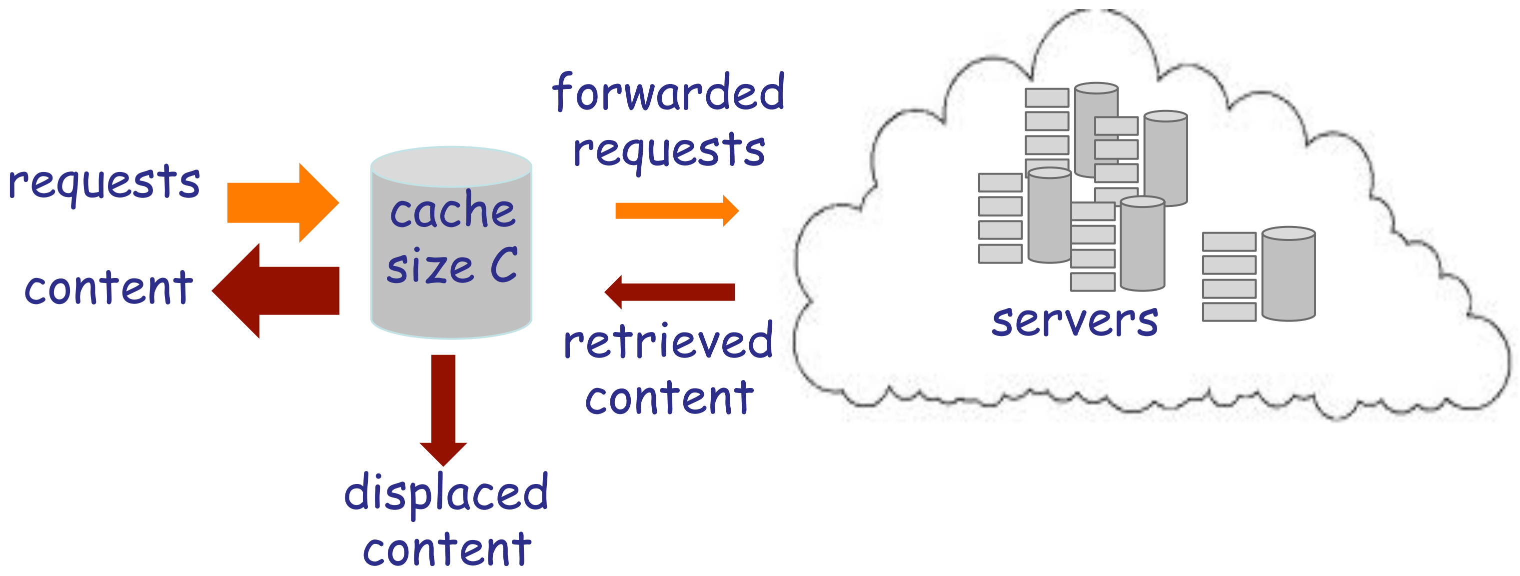
Engineering a content cache

- demand: a request process for content items of different popularities
- capacity: size and a replacement policy to keep most useful items in cache
- performance: the "hit rate" = proportion of requests served by cache

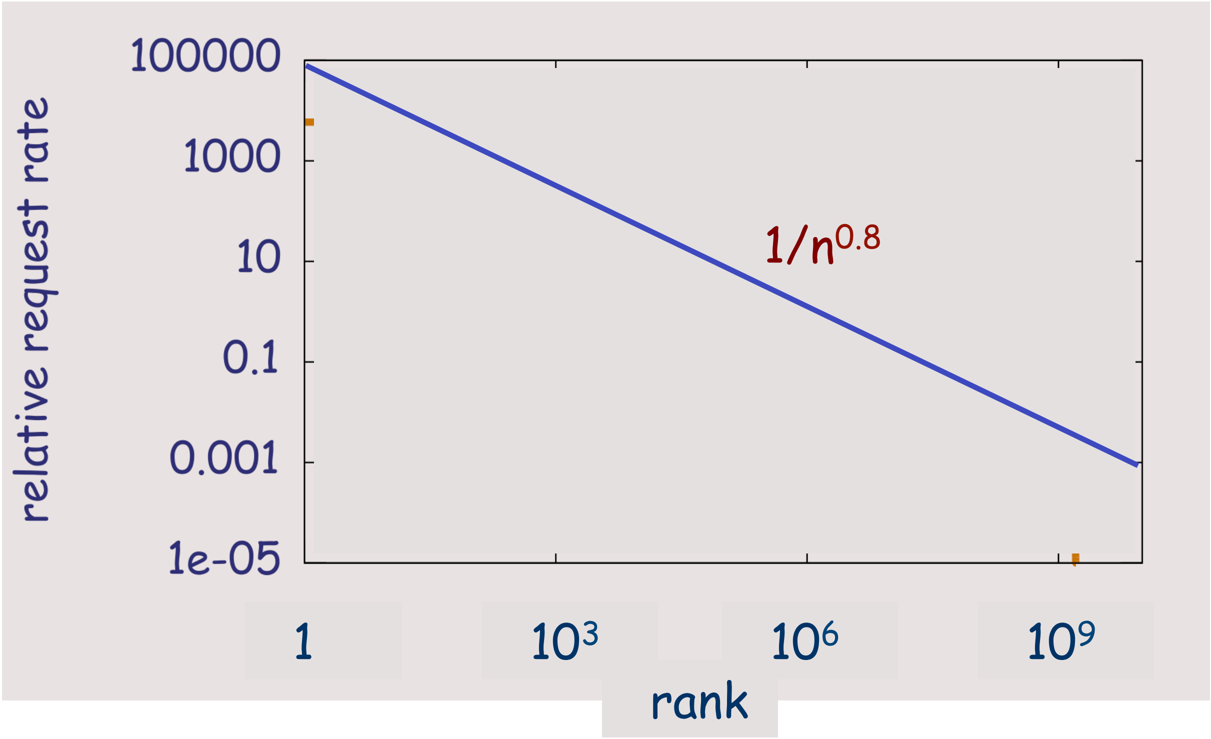


The Internet traffic mix

- in 2014, more than 96% of Internet traffic is content
- video counts for 60%, file sharing 20%, web, etc 20%
- video includes YouTube, Netflix, live video, webcams,...
- vast catalogues
  - ~10^{11} web pages ≈ O(1 petabyte), ie, 10^{15} bytes
  - ~10^{6} torrents ≈ O(1 petabyte)
  - ~10^{8} YouTubes ≈ O(1 petabyte)
  - ~10^{4} VoD items ≈ O(1 terabyte), ie, 10^{12} bytes
- but highly skewed demand
  - a relatively small number of highly popular items
  - popularity typically follows a generalized Zipf law...

Zipf popularity

- popularity is measured by request arrival rate
- measurements reveal popularity decreases as a power law:
  - request rate of n^{th} most popular object ∝ $1/n^{\alpha}$
  - typically, $\alpha \approx 0.8$



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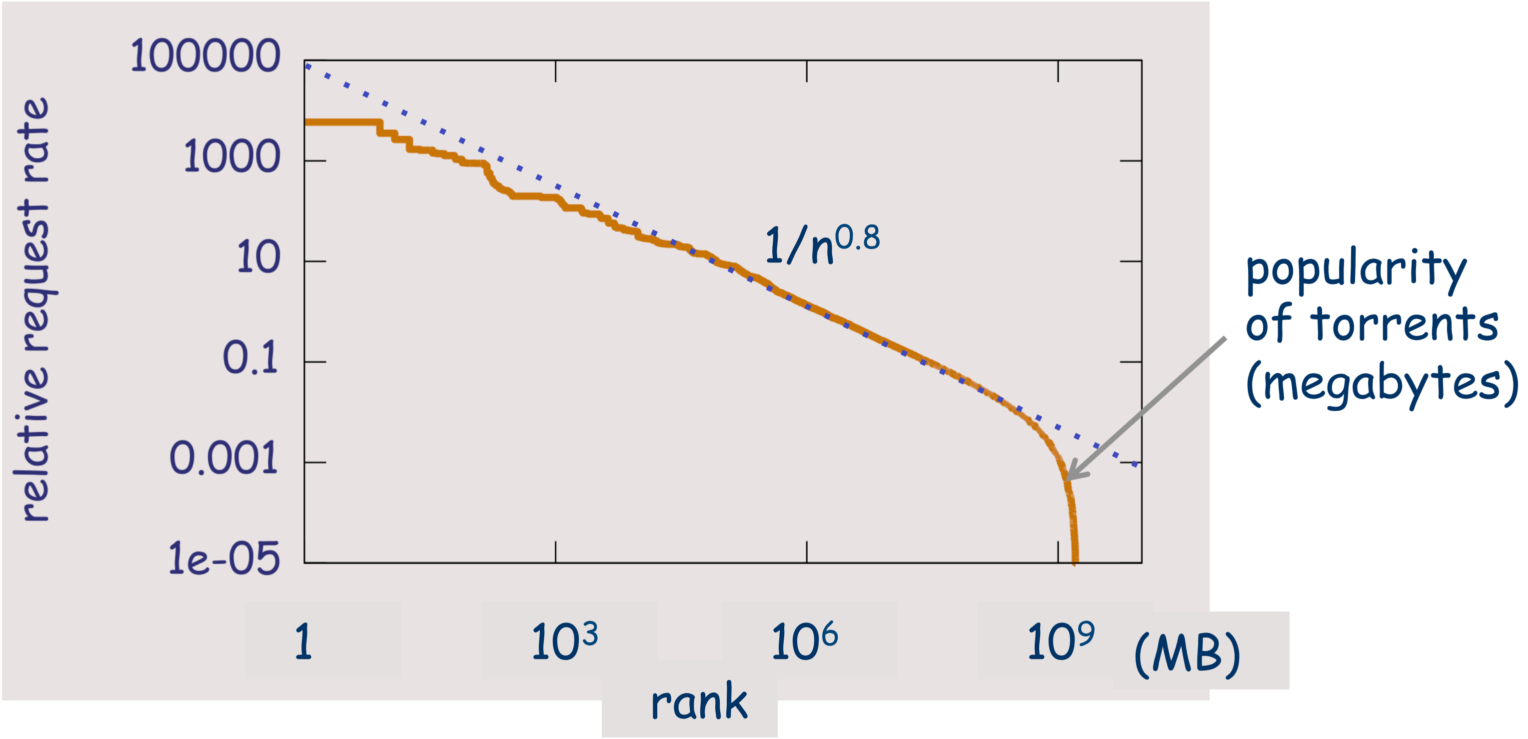

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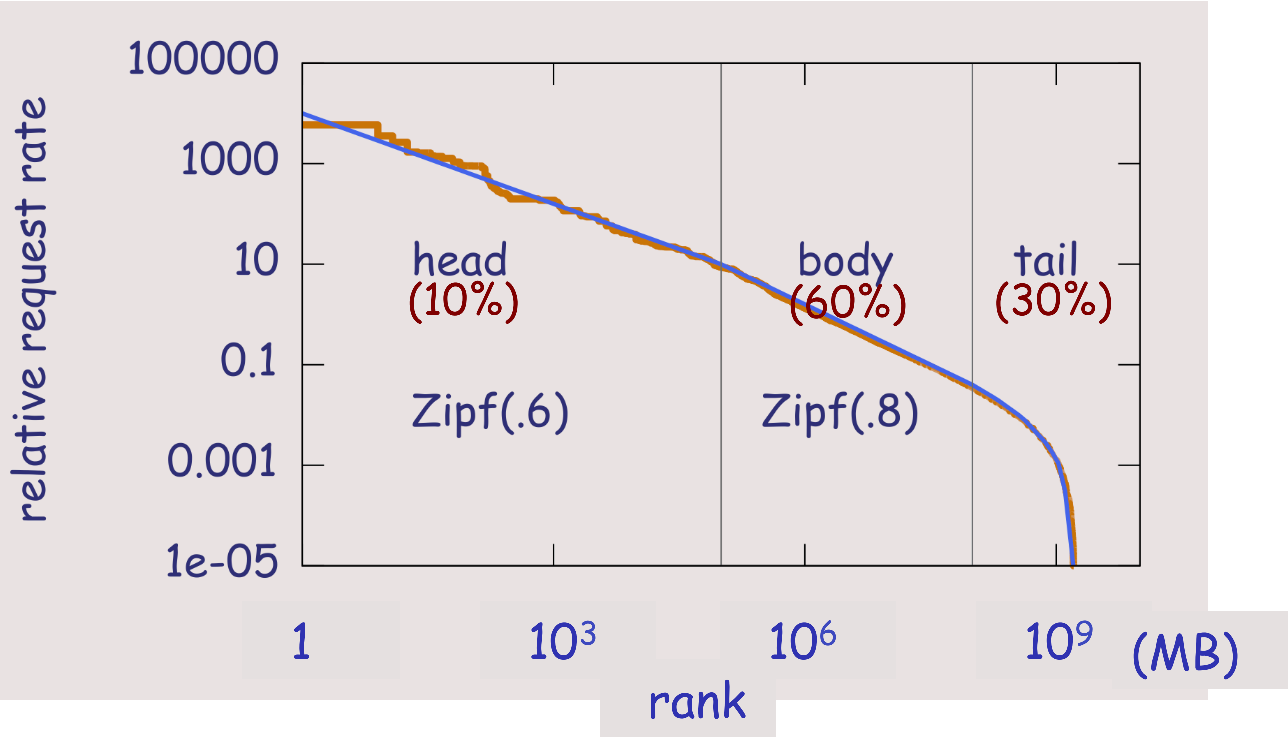
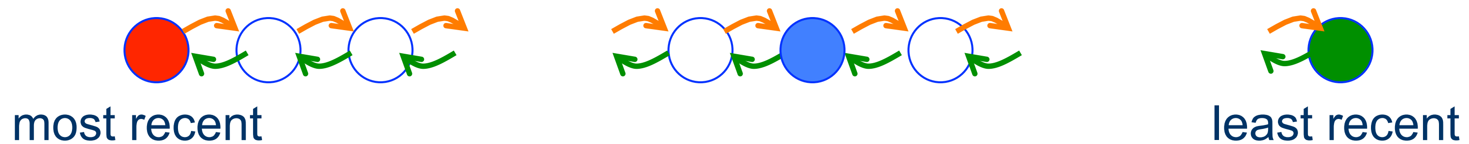


Modelling the request process: the independent reference model (IRM)

- assume a fixed catalogue of N objects
- requests arrive sequentially and any request is for object n with probability $\propto q(n)$ for $1 \leq n \leq N$
  - eg, $q(n) = 1/n^{\alpha}$
- ignores time locality, ie, assumes catalogue and popularities remain fixed over time
- a problem arises when trying to estimate $q(n)$
  - reliable statistics require long measurement periods
  - but catalogue and object popularities change
- the law for torrents avoids the time locality problem but ignores space locality since torrent trackers are global

Replacement policies

- 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 request arrival

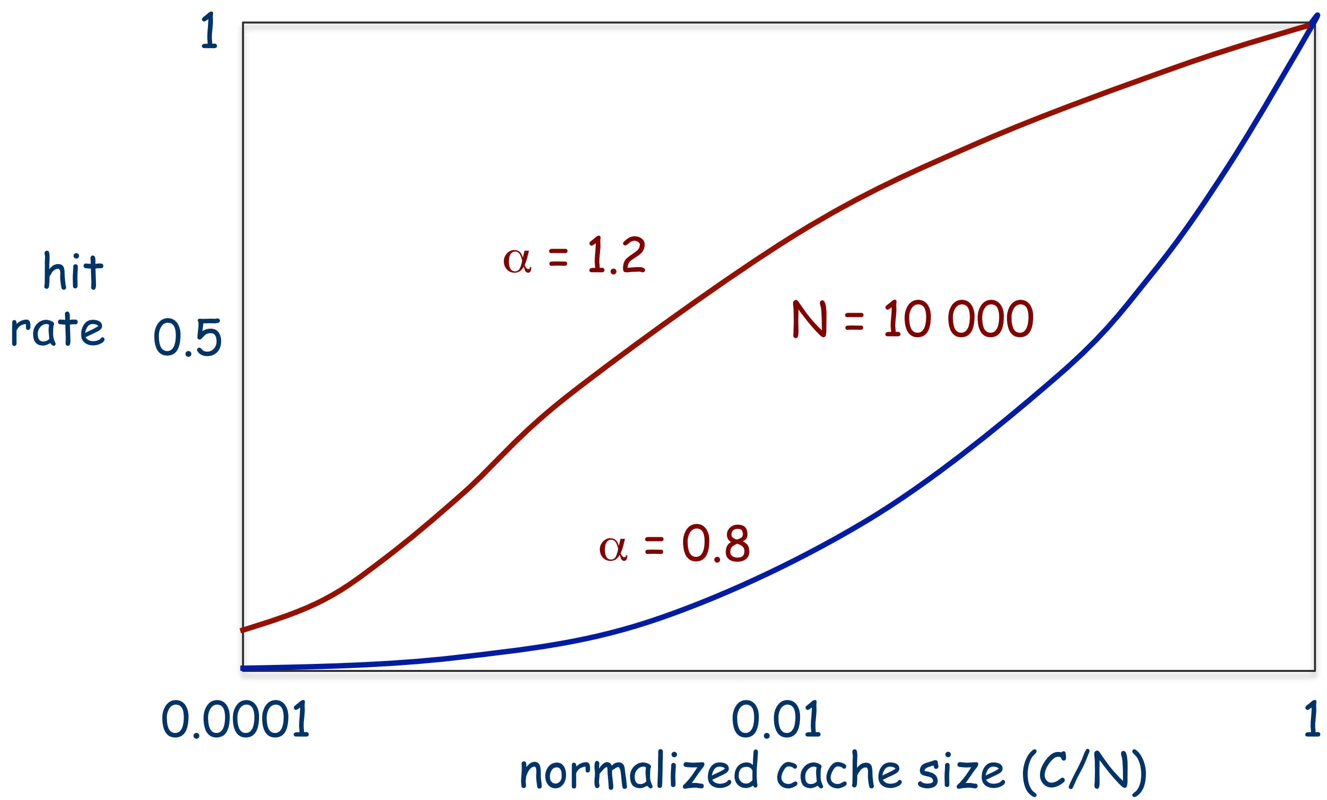


Calculating LRU hit rates (Che *et al.*, 2002)

- 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, $C = \sum_n \mathbf{1}\{\text{object } n \text{ is in cache}\}$
- taking expectations, $C = \sum_n h(n) = \sum_n (1 - \exp\{-q(n)t_C\})$
- solving numerically for t_C yields $h(n)$
- the approximation is very accurate and we know why (Fricker, Robert & Roberts, 2012)

LRU hit rate for $q(n) = 1/n^{\alpha}$

- strong impact of Zipf parameter α



LRU cache performance

- strong impact of Zipf parameter α
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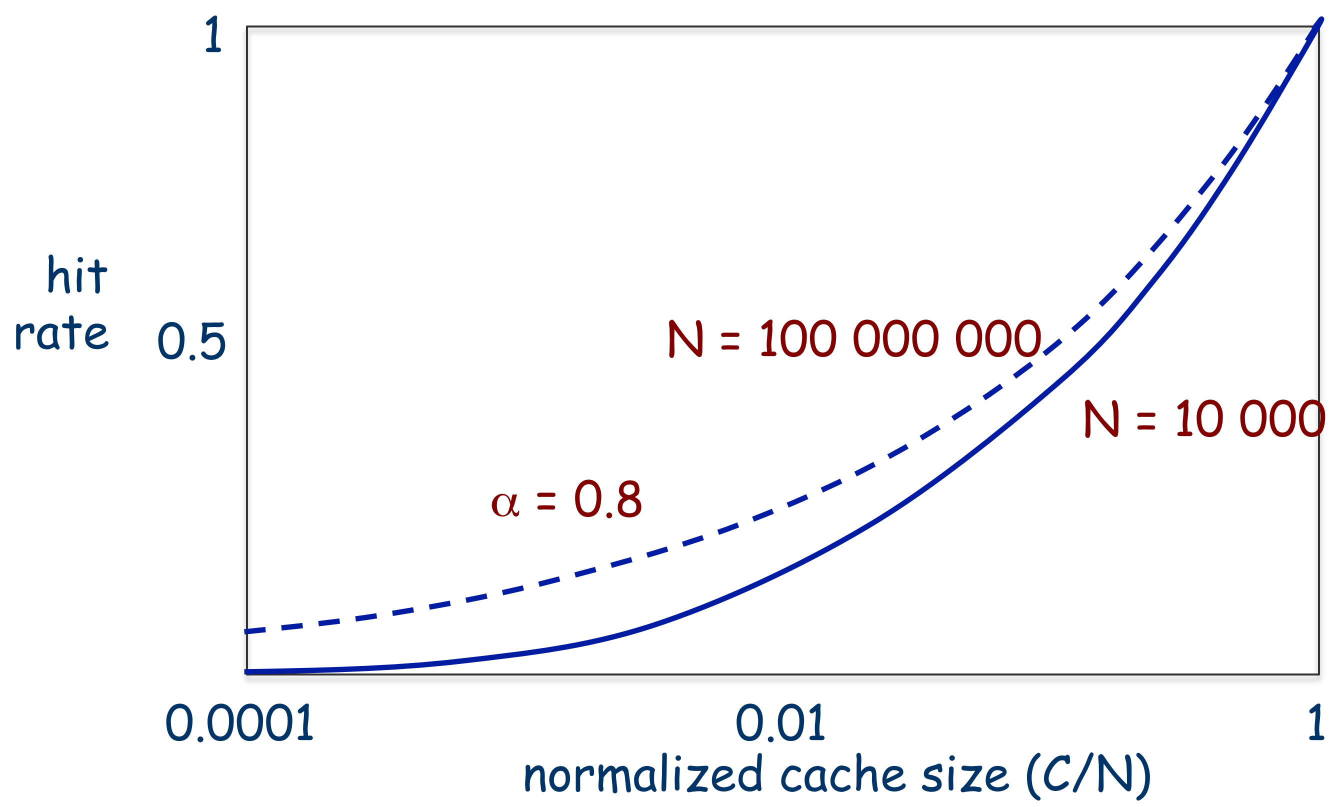

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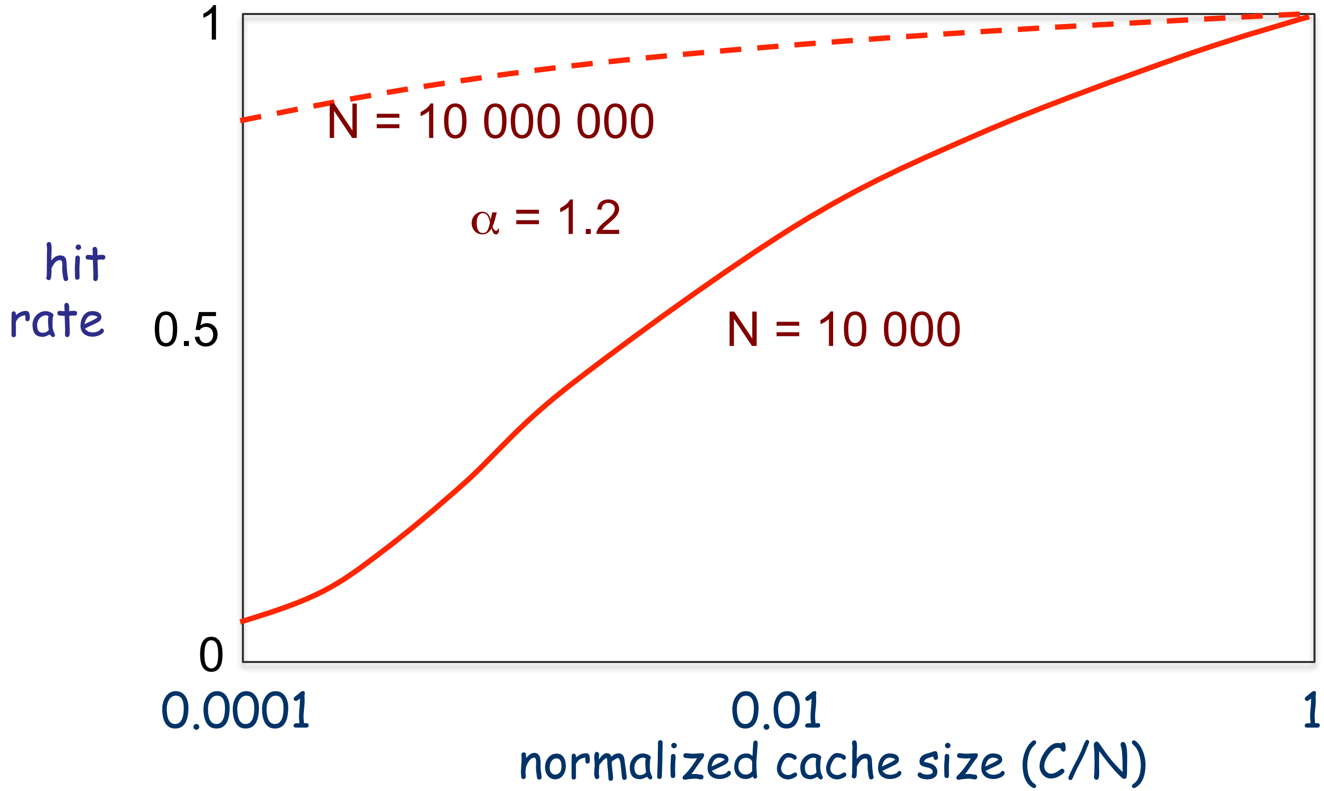

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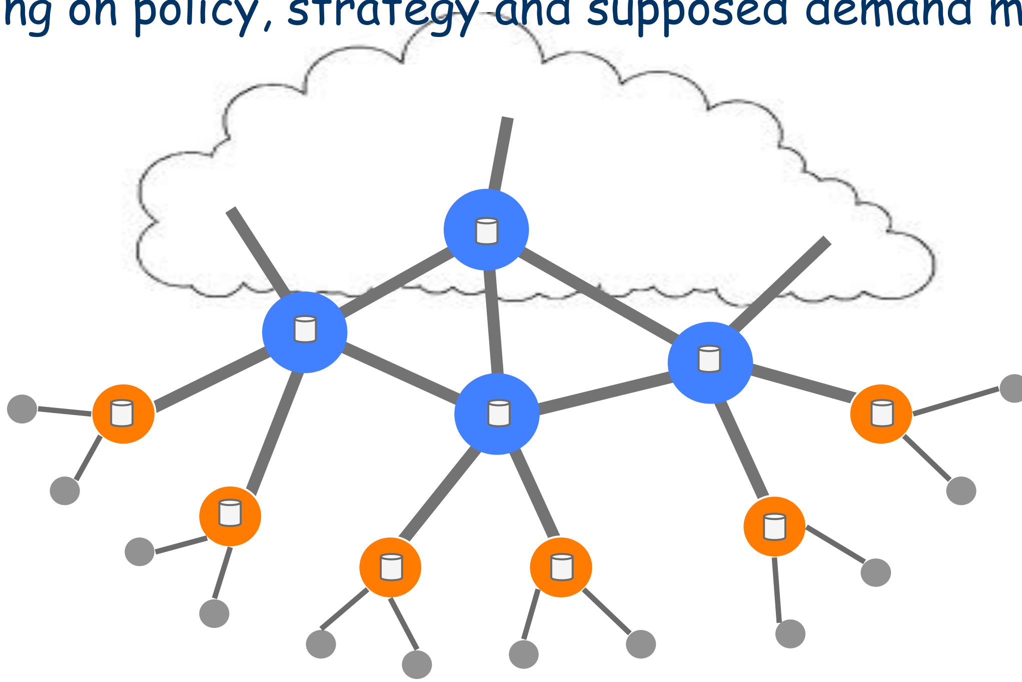
In-network caching or caches at the edge only?

- in NDN, caches are distributed through the network
  - given a "cache budget", the optimal distribution depends on cooperative placement policy and Interest forwarding strategy
- recent research suggests the difference between the optimum and simply caching at the edge may only be slight
  - depending on policy, strategy and supposed demand model



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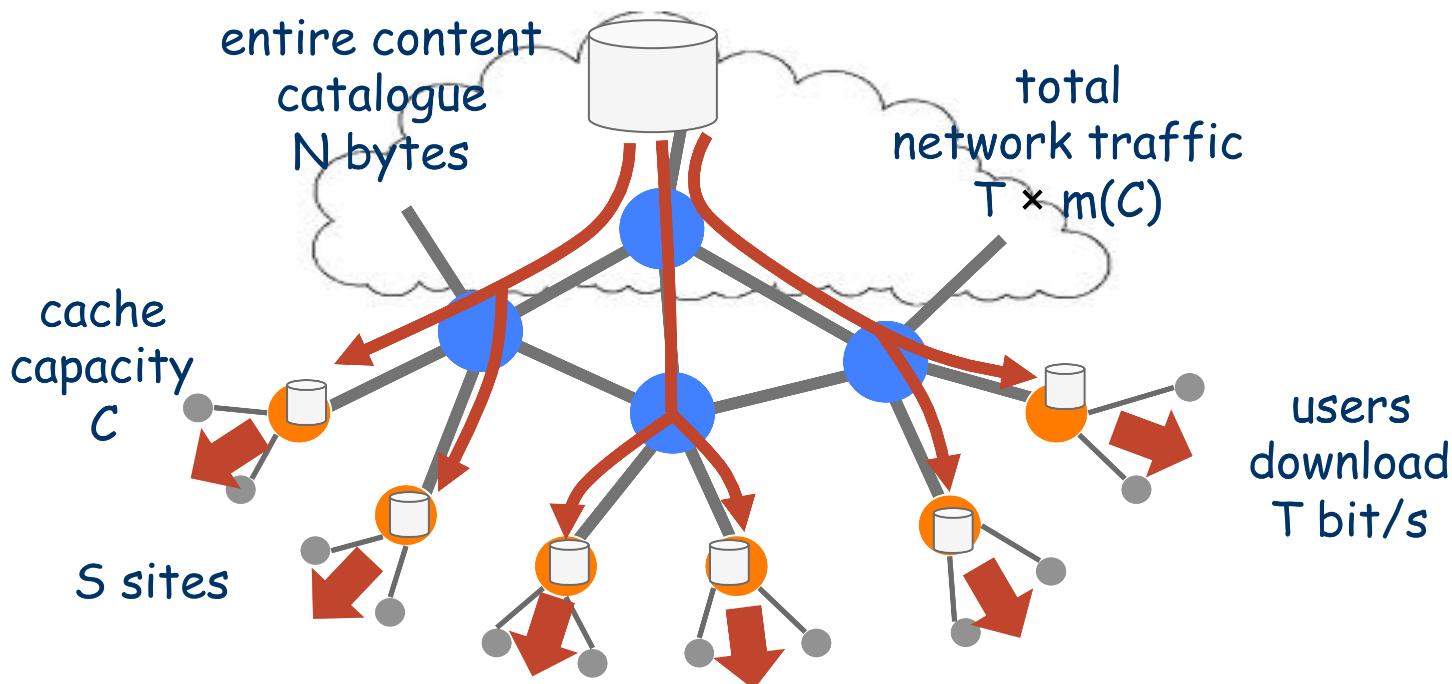
- recent research suggests the difference between the optimum and simply caching at the edge may only be slight
  - depending on policy, strategy and supposed demand model
- the cache budget is a key parameter but this is not a given
  - eg, if memory is very cheap, edge caching is clearly preferable
  - the optimal cache budget in fact depends on the memory-bandwidth tradeoff

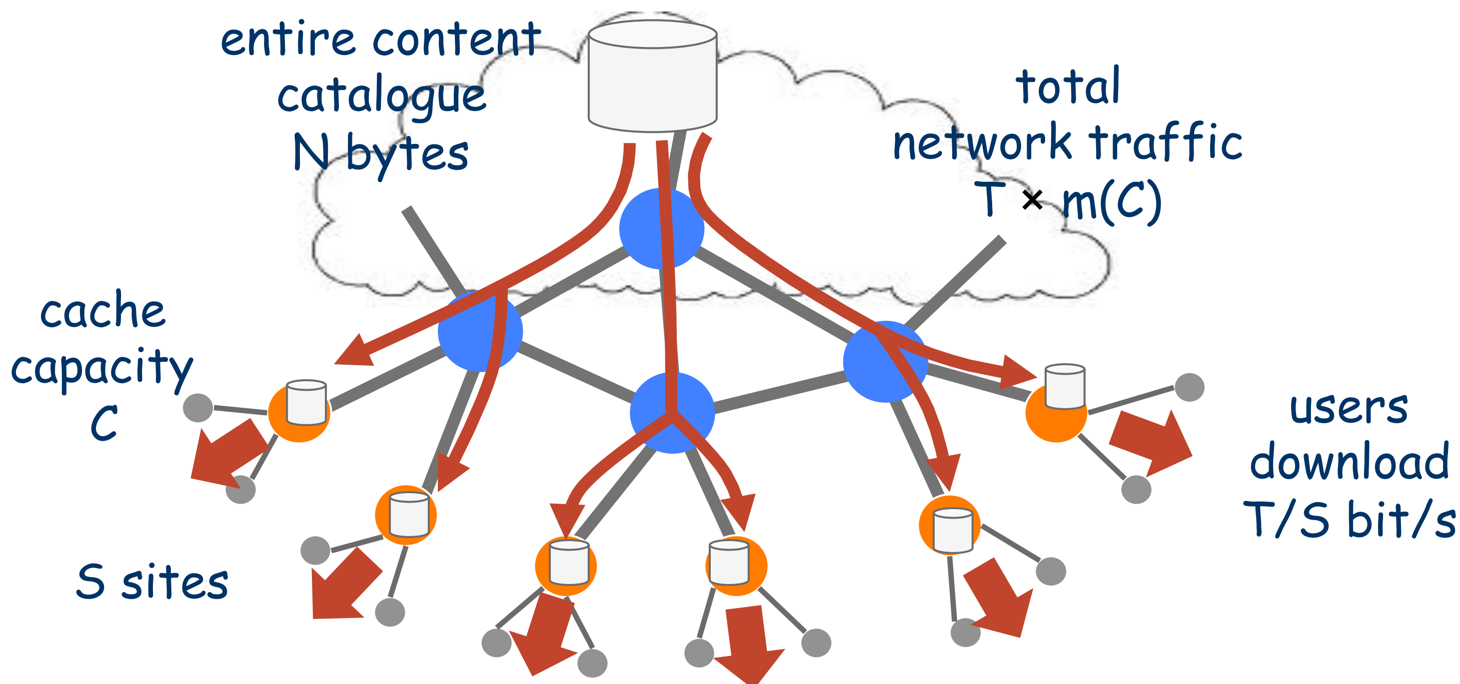
Tradeoff at the edge

- a simple symmetric network model
- cost of edge caching = $C \times S \times k_m$
  - C = cache size, S = number of sites, k_m = unit cost of memory
- cost of bandwidth = $T \times m(C) \times k_b$
  - T = total demand (bit/s), $m(C)$ = miss rate, k_b = unit cost of bandwidth

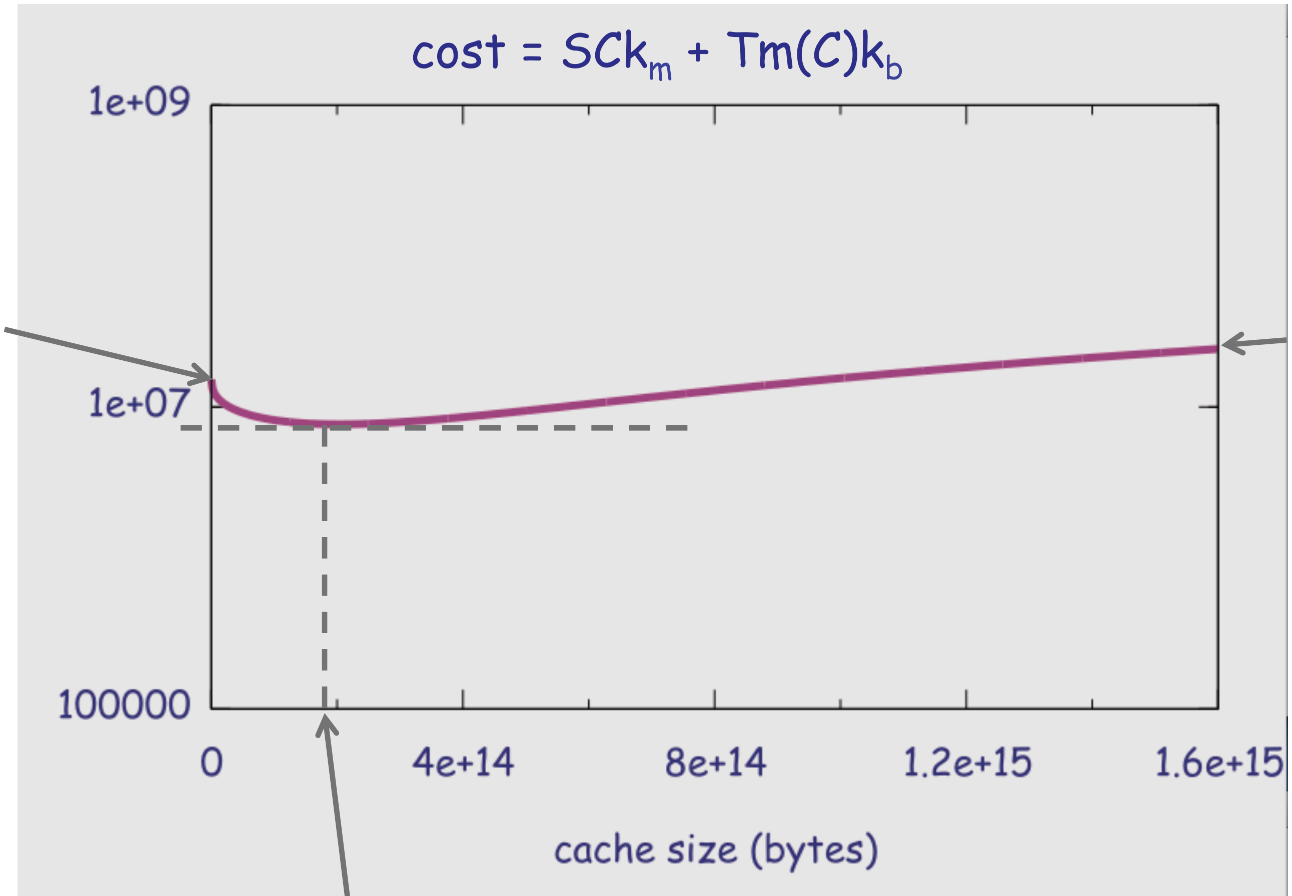


Tradeoff at the edge

- example data
  - empirical popularity law for torrents
  - N = 1.6 petabyte, T = 1 Tb/s, S = 100
  - k_m = .15 € per GB per month, k_b = 15 € per Mb/s per month



Costing the tradeoff

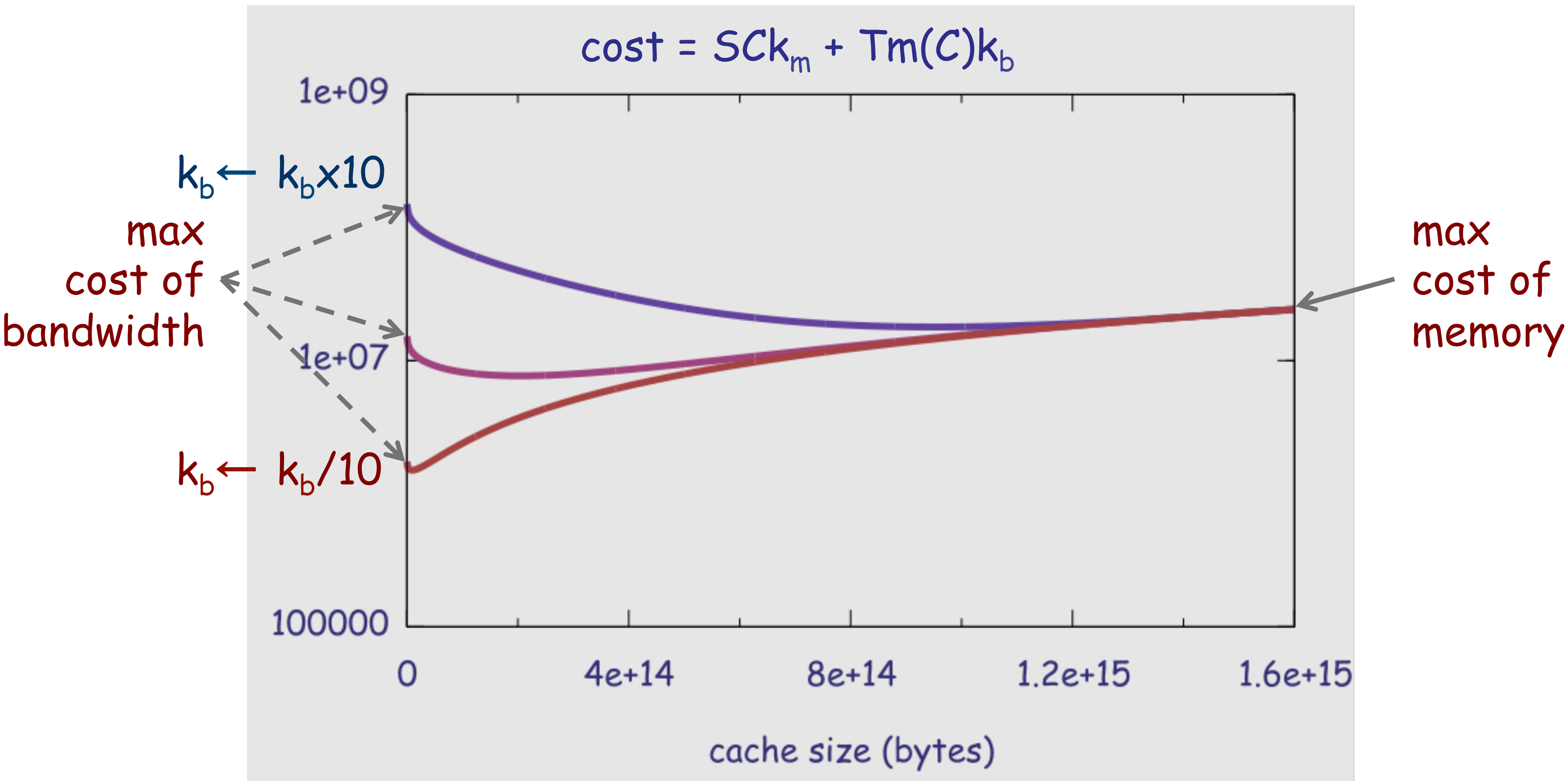


max cost of bandwidth ($C = 0$)

max cost of memory ($C = 1.6 \times 10^{15}$)

optimal size (hit rate ≈ 0.7)

Costing the tradeoff



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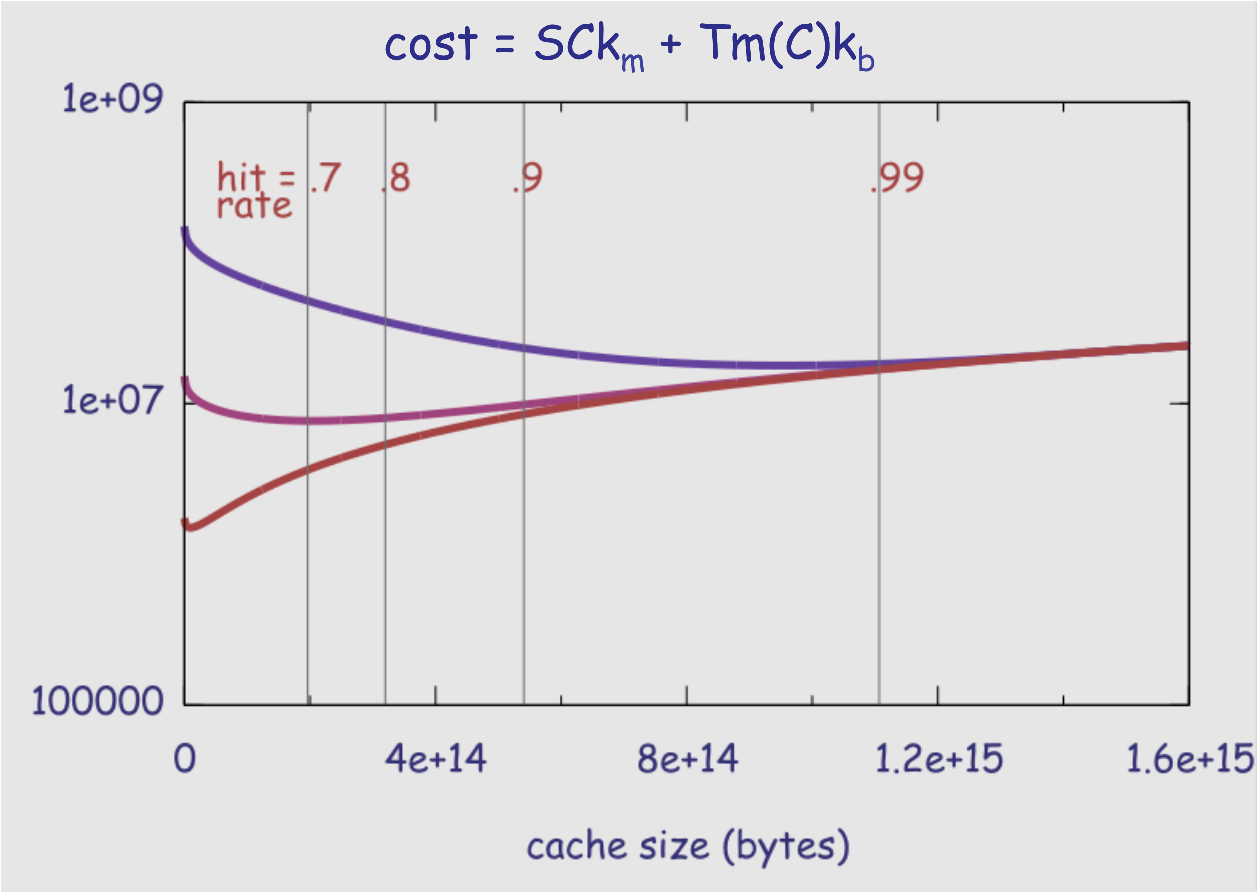
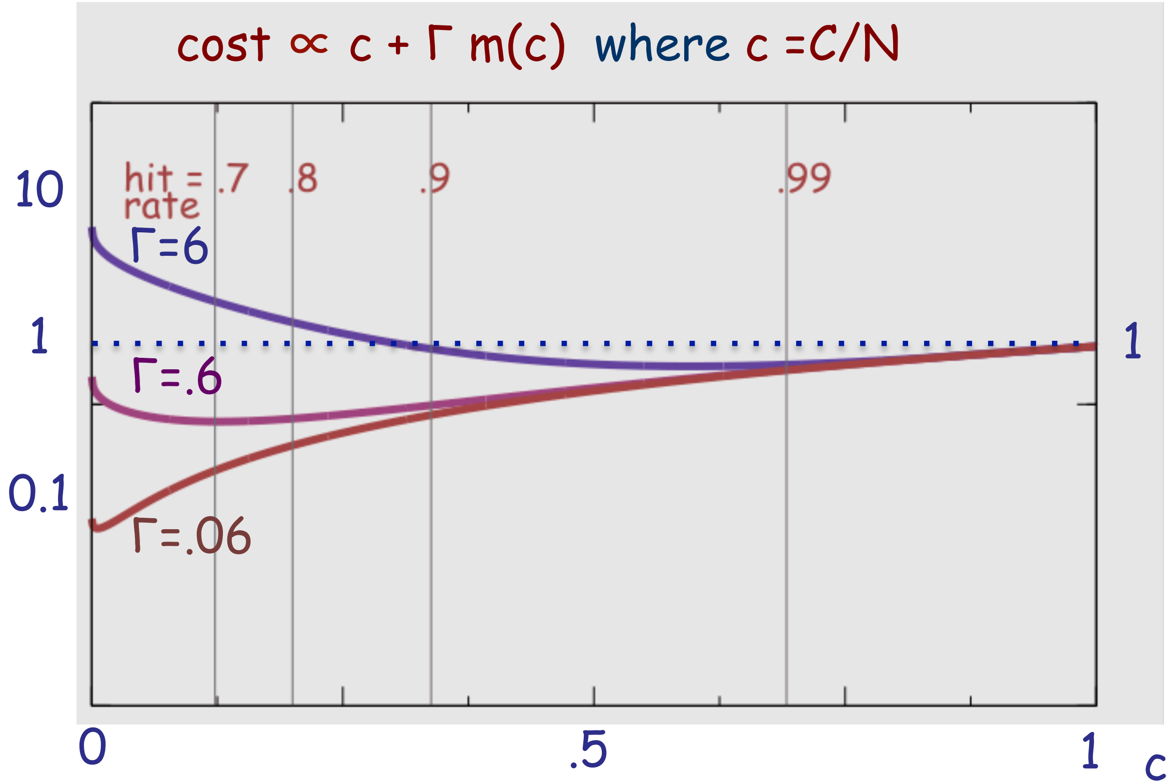


Observations on tradeoff

- key factor is $\Gamma = Tk_b / SNk_m$ where N is catalogue size
  - Γ = max bandwidth cost/ max storage cost



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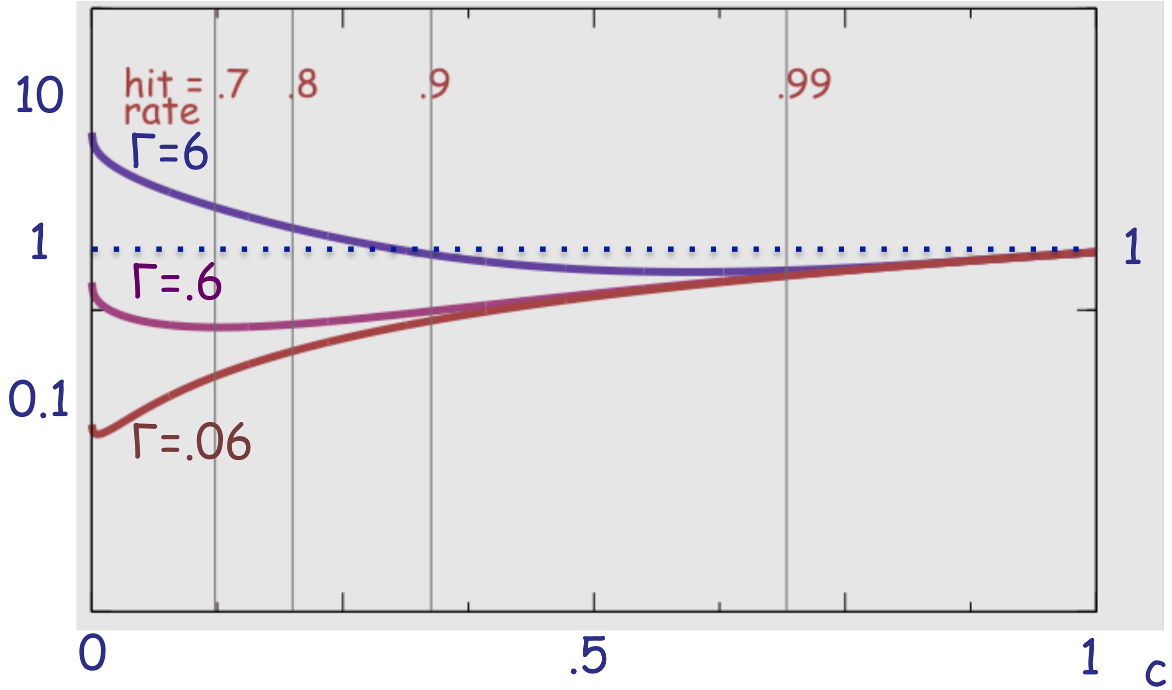

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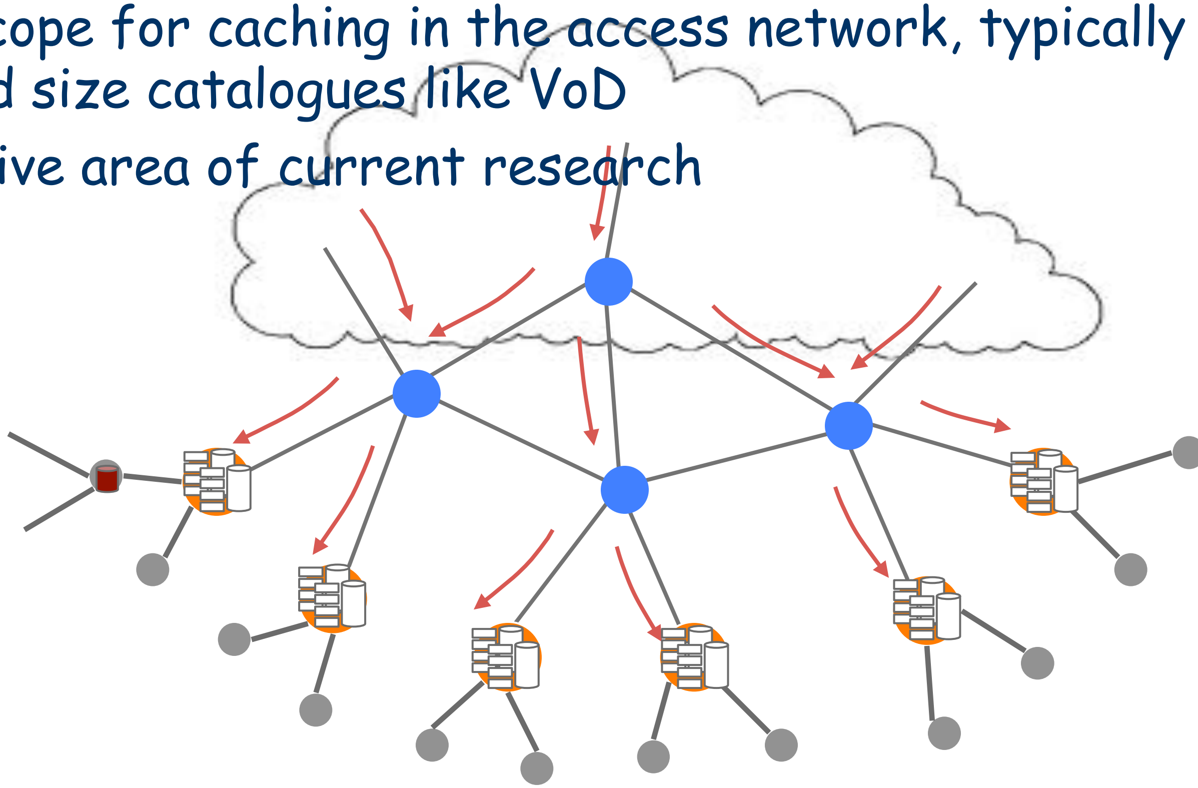
- cost trends $\Rightarrow$ Γ is increasing with time
  - k_m decreases by 40% each year
  - k_b decreases by 20% each year
- there is scope for optimizing position of edge caches
  - S large for small catalogue (eg, VoD, N = $O(10^{12})$)
  - S small for large catalogue (eg, torrents, etc, N = $O(10^{15})$)

Is the future Internet a network of data centers?

- edge routers become data centers, storing huge amounts of content and performing multiple data processing functions, including routing
- still scope for caching in the access network, typically for limited size catalogues like VoD
- an active area of current research



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- conclusions

- traffic engineering and the Internet
  - relating demand, capacity and performance
  - for capacity planning and effective resource sharing
  - a new caching dimension for an information-centric network
- the Internet has become information-centric
  - new architectures are proposed (eg, Named Data Networking)
  - though IP might still be made to evolve
- cache performance is critical in information-centric networks
  - depends on content catalogue size and popularity distributions
  - Che: a method for calculating the hit rate for LRU replacement
- optimal structure depends on the memory–bandwidth tradeoff
  - caching at the edge appears better than in-network caching
  - with scope for specialized caches in the access network