The Versatility of TTL Caches: Service Differentiation and Pricing

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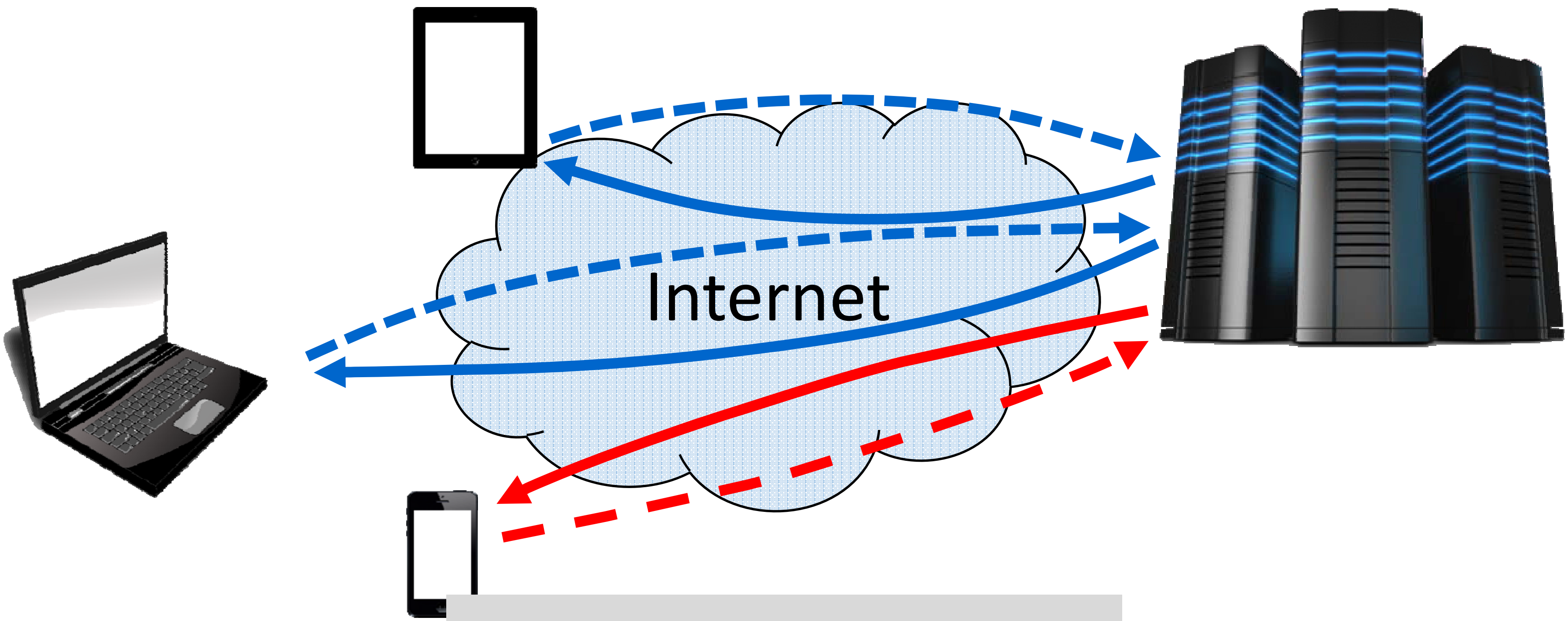
Internet today

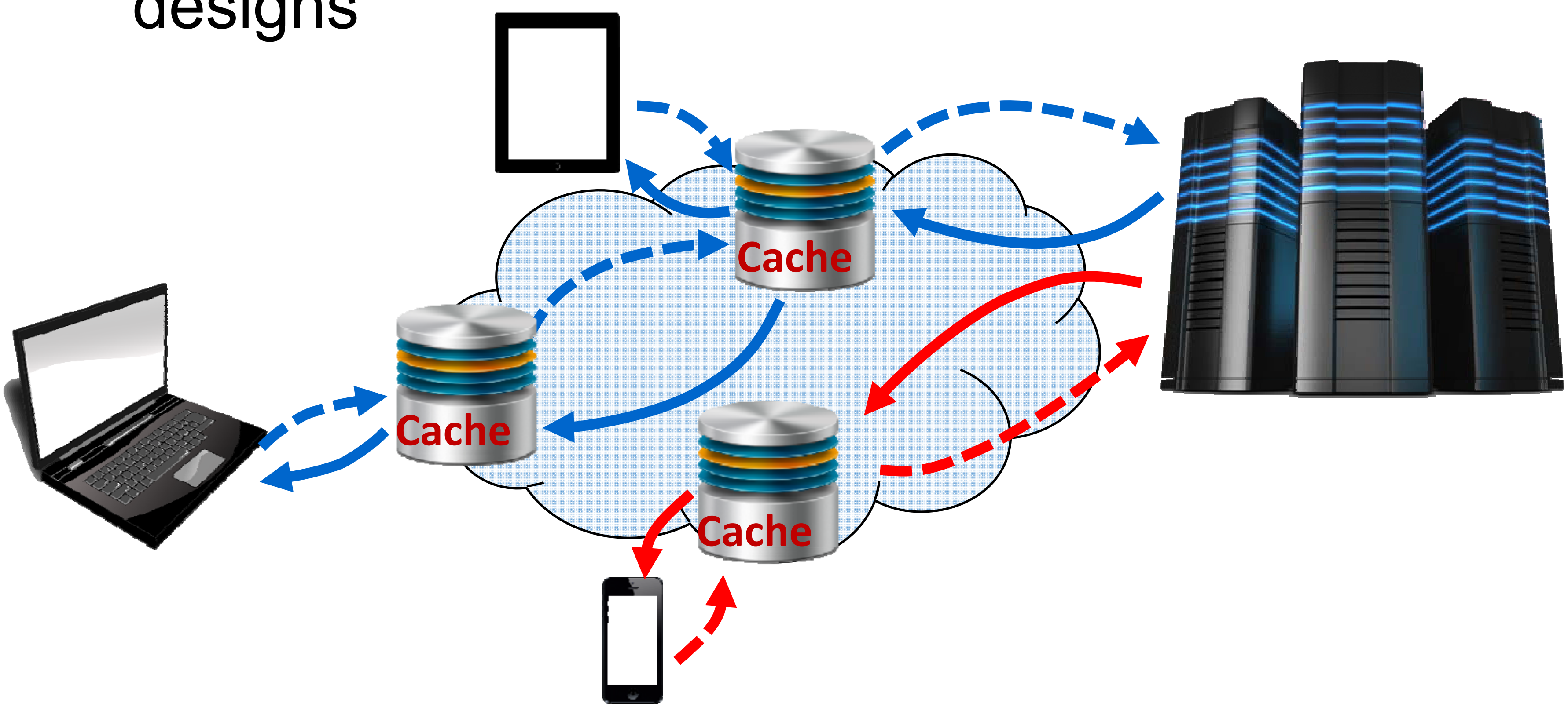
- primary use of Internet – content delivery
- point-to-point communication - users know *where* content is located



Does not scale!

New paradigm: content centric networks

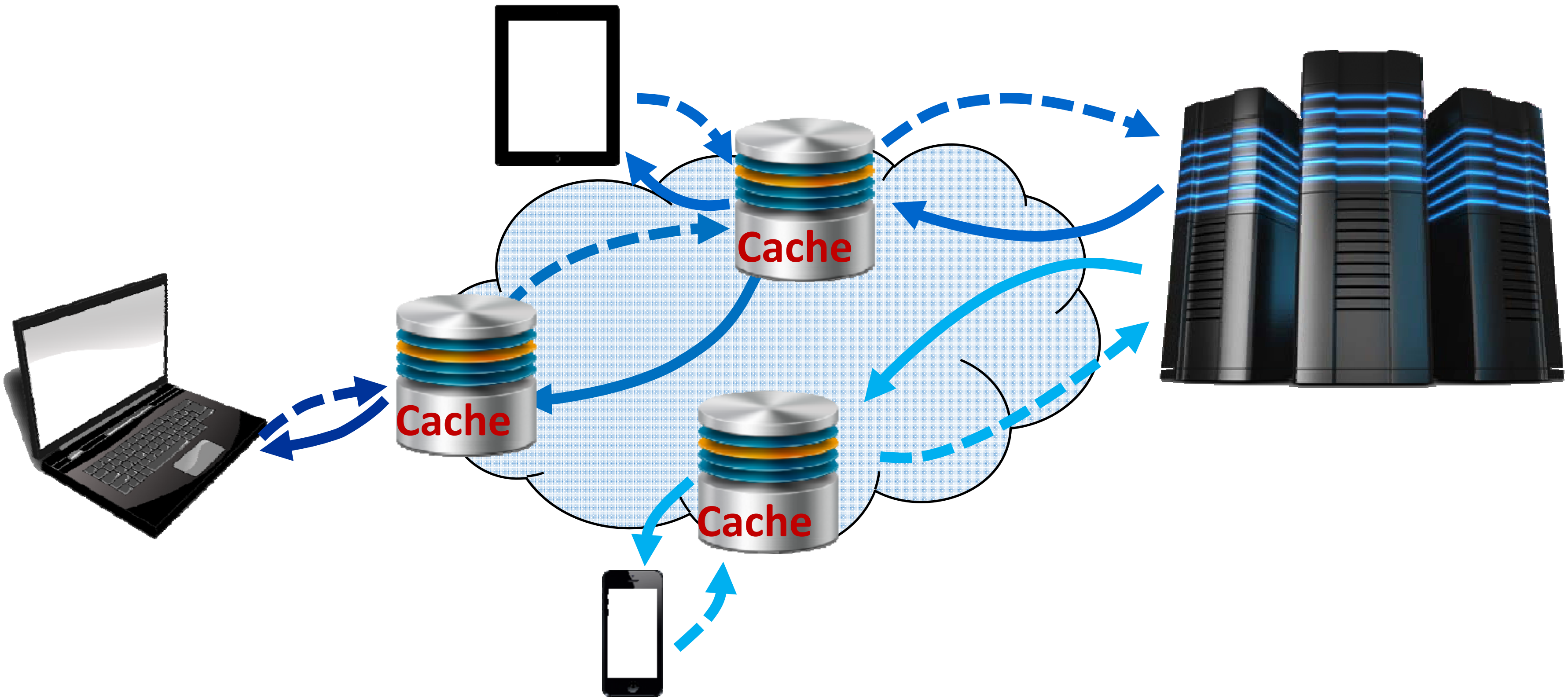
- users request what they want
- content stored at edge of network, in network
- diversity of users, content → driving CCN designs



Caching for content delivery

Decreases

- ❑ delays
- ❑ banwidth consumption
- ❑ server loads



New Challenges

Content Providers

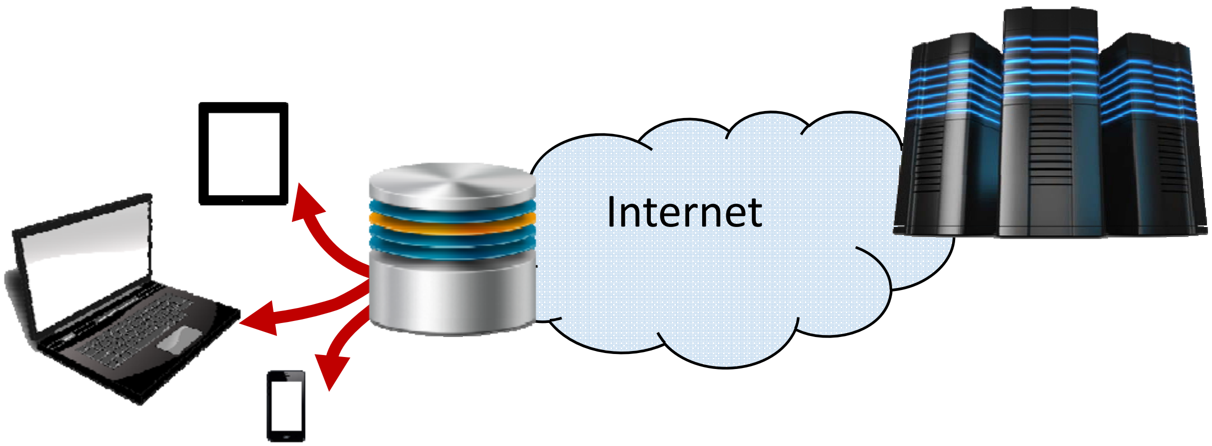
hulu
YouTube
NETFLIX
HBO GO
amazon

Content Distribution Networks

Akamai
Azion technologies
Limelight NETWORKS
fastly
Level(3) COMMUNICATIONS

Users

Service differentiation



- not all content equally important to providers/users
- content providers have different service demands
- economic incentives for CDNs
- current cache policies (mostly) oblivious to service requirements

This has given rise to alphabet soup

LACS GDSF ASA

PSC k-LRU RPAC

PRR RAND LFU DWCS

LARC LRU LFRU PBSTA

RMARK

ARC FIFO SAIU

LRV

2Q CAR SIZE LIRS

TOW DSCA

CLOCK

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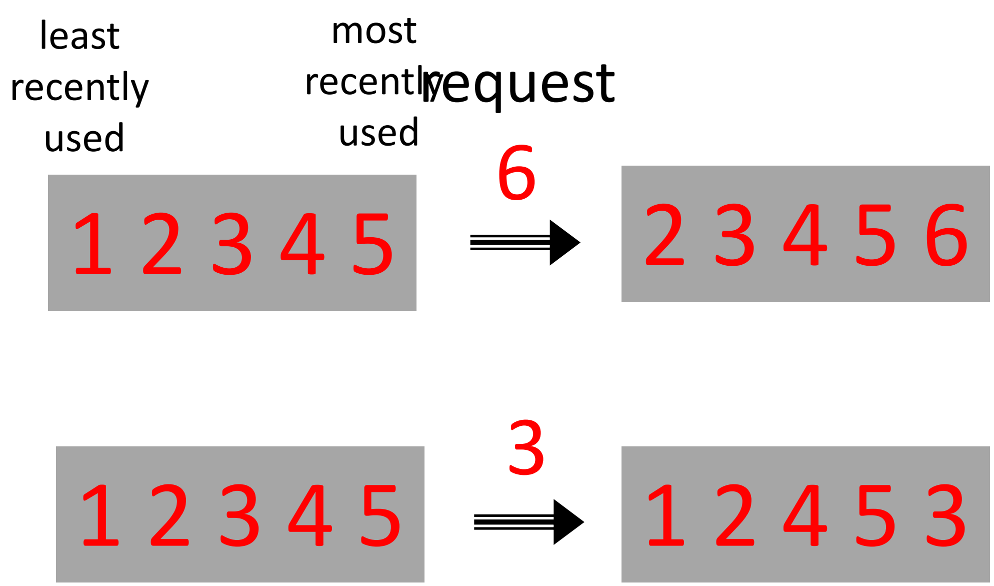
LRU (least recently used)

- classic cache management policy
- contents ordered by recency of usage
- miss – remove least recently used content
- hit – move content to front



Challenges

- how to provide differentiated services
  - to users
  - to content providers
- how to make sense of universe of caches
- how to design cache policies

Answer: Time-to-Live (TTL) caches

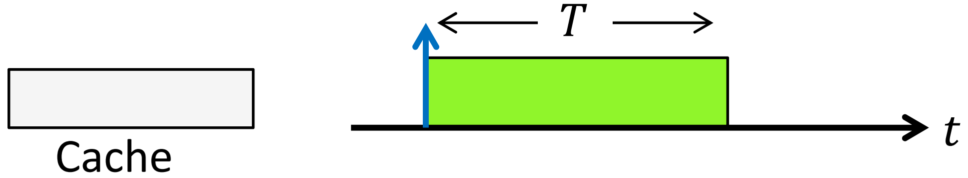
Outline

- introduction
- TTL caches
- differentiated services: utility driven caching
  - per content
  - per provider
- incentivizing caches
- conclusions, future directions

Time-to-live (TTL) caches

TTL cache

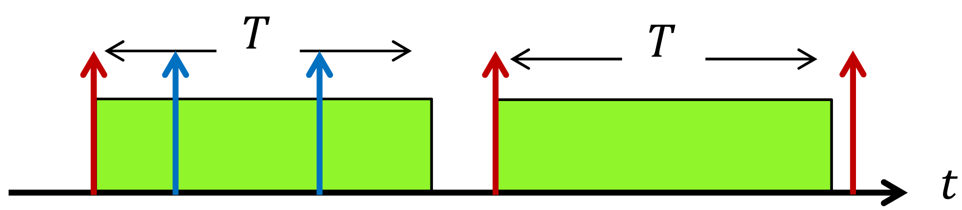
- associate timer with every content
  - set on miss
  - remove content when timer expires



- versatile tool for modeling caches
- versatile mechanism for cache design/configuration
- two types of TTL caches
  - reset, non-reset

Non-reset TTL cache

- timer set on cache miss



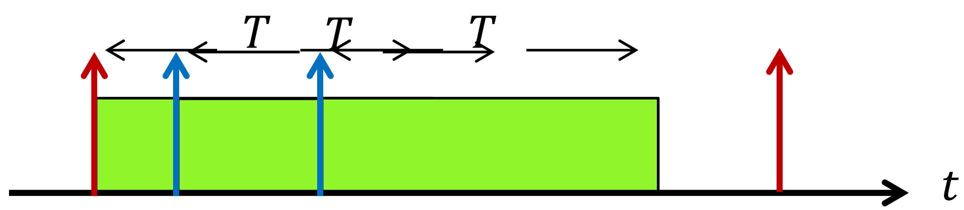
- TTL non-reset hit probability (content i):

$$h_i = 1 - \frac{1}{1 + \lambda_i T_i}$$

λ_i - request rate (Poisson)

Reset TTL cache

- timer reset at every request



- TTL reset hit probability (content i):

$$h_i = 1 - e^{-\lambda_i T_i}$$

Characteristic time approximation
(Fagin, 77)

Cache size B; request rate $\lambda_i, i = 1, \dots, N$

- LRU – model as reset TTL cache

$$\sum_i \left(1 - e^{-\lambda_i T}\right) = B$$

- FIFO – model as non-reset cache

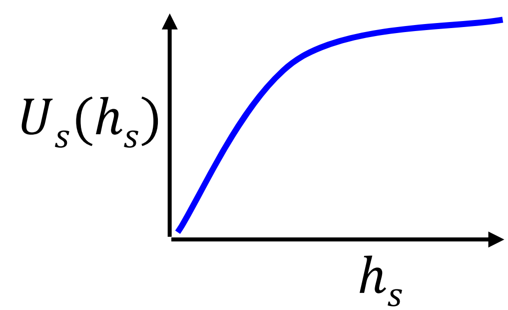
$$\sum_i \left(1 - \frac{1}{1 + \lambda_i T}\right) = B$$

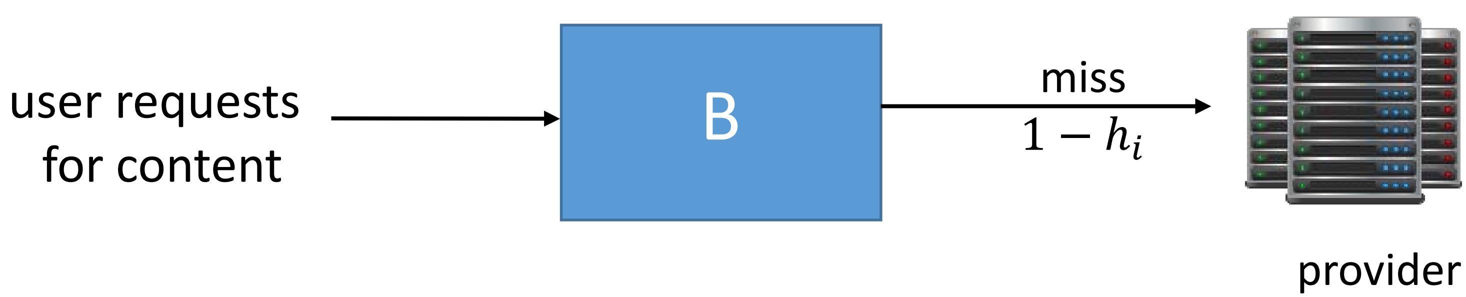
- T – *cache characteristic time*
- asymptotically exact as $N, B \to \infty$; accurate for $B > 100$
- extends to many cache policies

Providing differentiated services

Model

- single cache, size B
- N contents, request rates $\{\lambda_i\}$
- h_i: hit probability of content i
- each content has ***utility***, function of hit probability $U_i(h_i)$
  - concave, increasing





Cache utility maximization

$$\begin{aligned} \underset{h_i}{\text{maximize}} \quad & \sum_{i=1}^{N} U_i(h_i) \\ \text{such that} \quad & \sum_{i=1}^{N} h_i = B \\ & 0 \le h_i \le 1, \quad i = 1, 2, \ldots, N. \end{aligned}$$

Utility-based caching

- cost/value tradeoff
  - $U_i(h_i) = V_i(h_i) - C_i(h_i)$
- fairness implications
  - e.g. Proportionally fair w.r.t. hit probability
- cache markets
  - contract design

Cache utility maximization

$$
\begin{aligned}
\underset{h_i}{\text{maximize}} \quad & \sum_{i=1}^{N} U_i(h_i) \\
\text{such that} \quad & \sum_{i=1}^{N} h_i = B \\
& 0 \le h_i \le 1, \quad i = 1, 2, \ldots, N.
\end{aligned}
$$

Can we use this framework to model existing policies?

Reverse Engineering

Can we obtain same statistical behavior as LRU, FIFO using timers? What utilities?

LRU

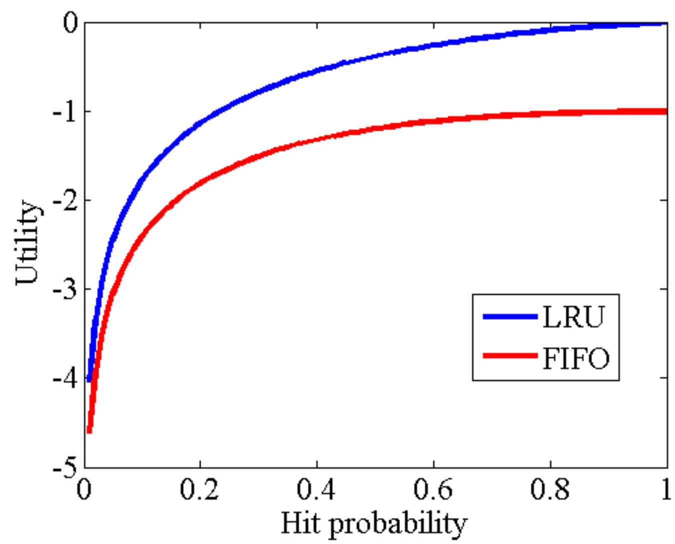
$$U_i(h_i) = \lambda_i \mathrm{li}(1 - h_i)$$

$$\mathrm{li}(x) = \int_0^x \frac{\mathrm{d}t}{\ln t}$$

logarithmic integral

FIFO

$$U_i(h_i) = \lambda_i(\log h_i - h_i)$$



Dual Problem

- Lagrangian function:

$$L(\boldsymbol{h}, \alpha) = \sum_{i=1}^{N} U_i(h_i) - \alpha\left[\sum_{i=1}^{N} h_i - B\right]$$

Dual variable

- optimality condition:

$$\frac{\partial L}{\partial h_i} = U_i'(h_i) = \alpha$$

- inverse

$$\boldsymbol{h_i} = \boldsymbol{U_i}'^{-1}(\boldsymbol{\alpha})$$

LRU Utility Function

- optimality condition:

$$h_i = {U_i}'^{-1}(\alpha)$$

- TTL approximation

$$h_i = 1 - e^{-\lambda_i T}$$

- let hit probability decrease in α, increase in T
- let $T = 1/\alpha$

$$U_i(h_i) = \lambda_i \mathrm{li}(1 - h_i)$$

Fairness properties

- weighted proportional fairness

$$U_i(h_i) = \lambda_i \log h_i$$

yields $h_i \propto \lambda_i$

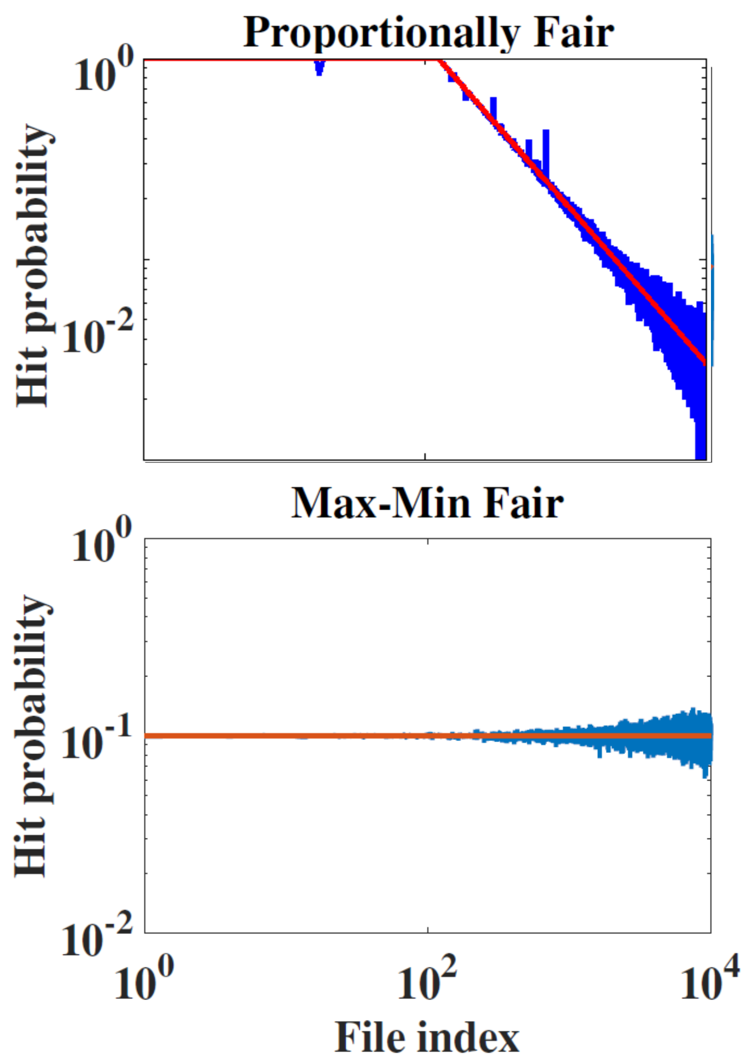
- max-min fairness – limit as $\beta \to \infty$

$$U_i(h_i) = \lim_{\beta \to \infty} \frac{h_i^{1-\beta}}{1-\beta}$$

yields $h_i = B/N$

Evaluation

- 10,000 contents
- cache size 1000
- Zipf popularity, parameter 0.8
- 10^7 requests



Cache utility maximization

$$\begin{aligned} \underset{h_i}{\text{maximize}} \quad & \sum_{i=1}^{N} U_i(h_i) \\ \text{such that} \quad & \sum_{i=1}^{N} h_i = B \\ & 0 \le h_i \le 1, \quad i = 1, 2, \ldots, N. \end{aligned}$$

Q: How do we control hit probabilities?

A: TTL cache; control hit probabilities through timers

Cache utility maximization

$$\max_{T_i} \sum_{i=1}^{N} U_i(h_i(T_i))$$

$$s.t. \sum_{i}^{N} h_i(T_i) \leq B$$

On-line algorithms

- dual algorithm
- primal algorithm
- primal-dual algorithm

Setting timer in dual

- TTL-reset cache:

$$\boldsymbol{h_i = 1 - e^{-\lambda_i T_i}}$$

- optimality condition:

$$\boldsymbol{h_i = {U_i}'^{-1}(\alpha)}$$

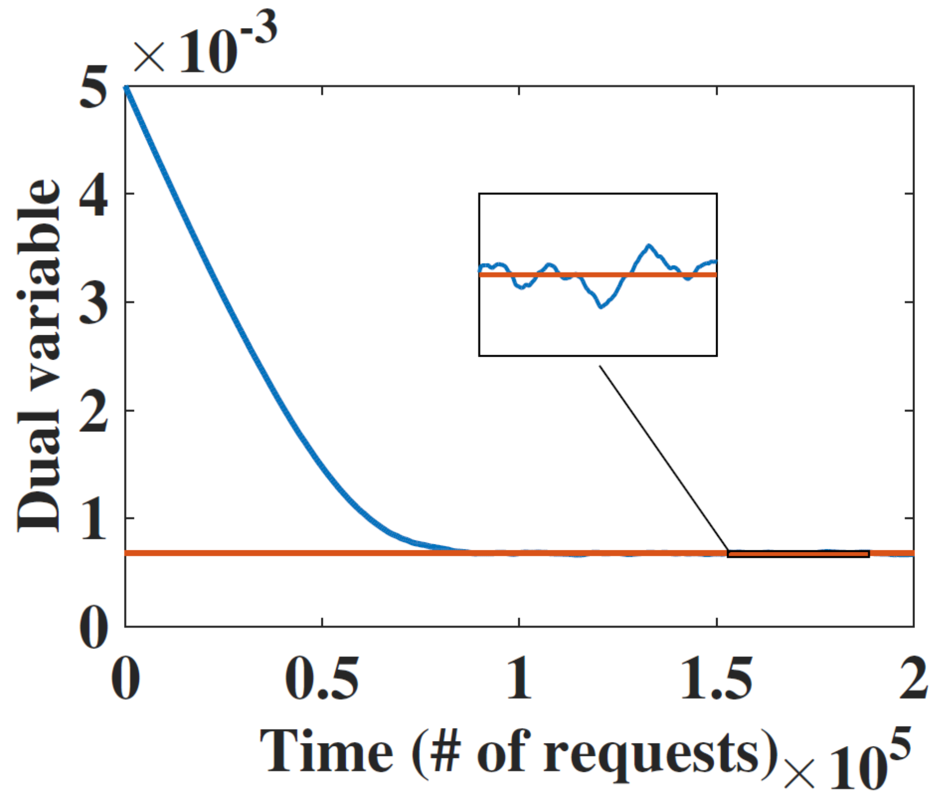
$$\Rightarrow$$

$$\boldsymbol{T_i} = -\frac{\boldsymbol{1}}{\boldsymbol{\lambda_i}}\log\left(1 - \boldsymbol{{U_i}'^{-1}(\alpha)}\right)$$

- find α via gradient descent; update at each request
- estimate $1/\lambda_i$ using sliding window

Convergence: dual algorithm

- 10,000 contents
- cache size 1000
- Zipf popularity, parameter 0.8
- 10^7 requests



Primal algorithm

- primal problem replaces buffer constraint with soft "cost" constraint

$$\max_{T_i} \sum_{i=1}^{N} U_i(T_i) - C\left(\sum_{i=1}^{N} h_i(T_i) - B\right)$$

with convex cost function C

- similar style on-line algorithm

Summary

- utility-based caching enables differentiated services
- TTL cache provides flexible mechanism for deploying differentiated services
- simple online algorithms require no apriori information about:
  - number of contents
  - popularity
- framework captures existing policies
  - e.g. LRU and FIFO

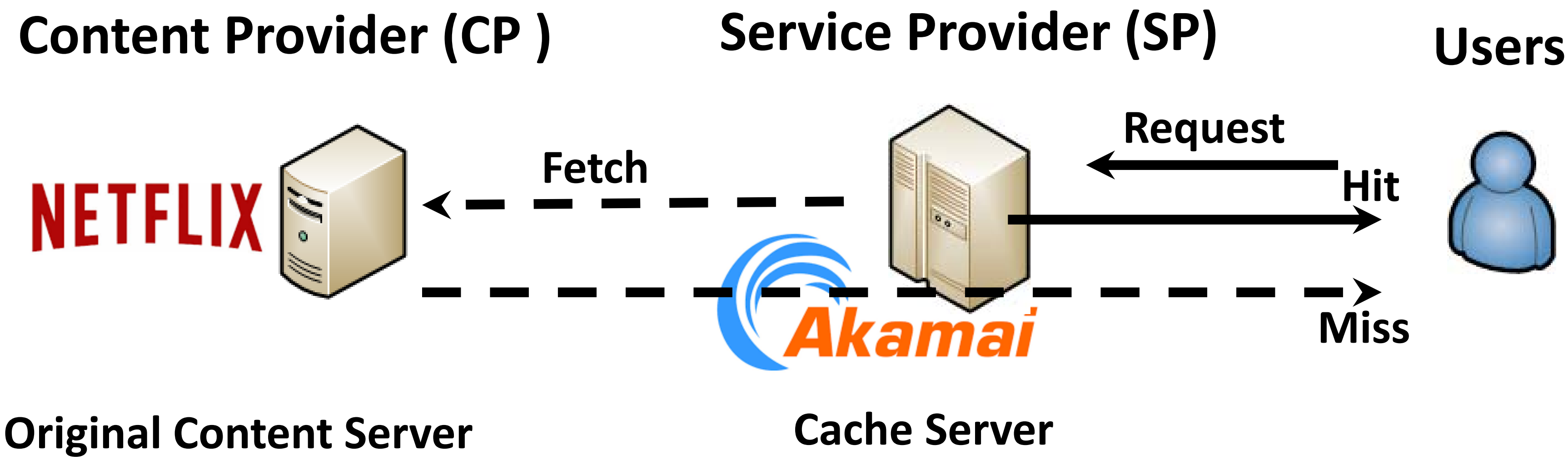
Other issues

- provider-based service differentiation
- monetizing caching

Differentiated monetization of content

- focused on
  - user/content differentiation
  - CP differentiation
- how can SPs make money?
  - contract structure?
  - effect of popularity?

Per request cost and benefit



- benefit per request hit b
- cost per request miss c

Key: how should SP manage cache?

Formulating as utility optimization

$$U(h) = \lambda b h \; - \lambda c(1-h) - P(h)$$

$P(h)$ - payment to cache provider

Q: how should SP manage cache? pricing schemes?

Service contracts

Contracts specify pricing $P(h)$ per content

- nonrenewable contracts
- renewable contracts
  - occupancy-based
  - usage-based

Non-renewable contracts

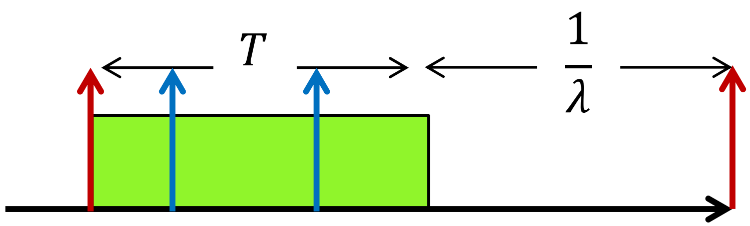
- on-demand contract upon cache miss
  - no content pre-fetching
  - contract for time T linear price pT
    - proportional to TTL, per-unit time charge p
- potential inefficiency
  - content evicted upon TTL timer expiration

  $\Longrightarrow$ miss for subsequent request
- how long to cache content?

Non-renewable contracts

- value accrual rate to content provider

$$U = \lambda \frac{b\lambda T + c}{\lambda T + 1}$$



- payment rate to cache provider

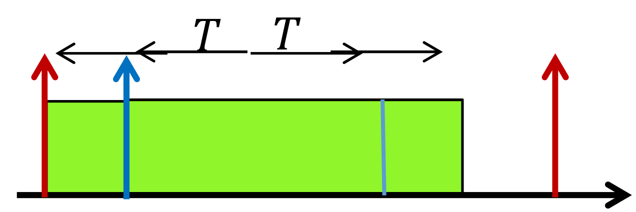
$$P = p \frac{T}{T + 1/\lambda}$$

Rule: cache if $\lambda(b + c) > p$; $T^* = \infty$

otherwise not

Occupancy-based renewable contracts

- on-demand contract on every cache request
  - o pre-fetching
  - o at request, pay
    - pT if miss
    - px, if time since last request $x < T$



- CP pays for time content in cache

Rule: cache if $\lambda(b + c) > p$; $T^* = \infty$

otherwise not

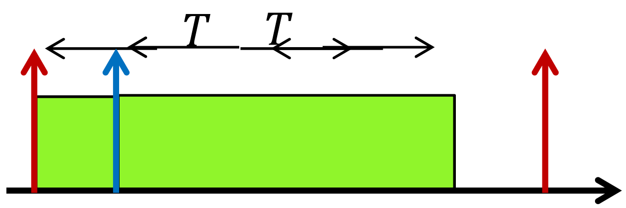
same as non-renewable contract

Observations

- both contracts occupancy based; pay for time in cache
- renewable contract more flexible
    - allows contract renegotiation
- results generalize to renewal request processes

Usage-based renewable contracts

- on-demand contract on every cache request
  - o no pre-fetching
  - o at request, always pay pT



- price - pT per request

Rule: cache if $\lambda(b+c) > p$

$$T^* = \frac{1}{\lambda} \ln \frac{\lambda(b+c)}{p}$$

otherwise not

Observations

Usage-based pricing

- provides better cache utilization than occupancy-based pricing
  - T^* decreasing function of λ, p; increasing function of b, c
- better incentivizes cache provider

Summary

- TTL cache versatile construct for
  - modeling/analysis
  - design/configuration
  - adaptive control
  - pricing
- TTL combined with utility-based optimization
  - provides differentiated cache services
  - shares caches between content providers
  - provides incentives for cache providers

Future directions

- differentiated services in a multi-cache setting
  - presence of router caches
  - multiple edge caches
- relaxation of assumptions
  - Poisson, renewal → stationary
  - arbitrary size content
- pricing
  - non-linear pricing
  - market competition among cache providers
- unified cache, bandwidth, processor allocation framework

Thank you