Web Caching

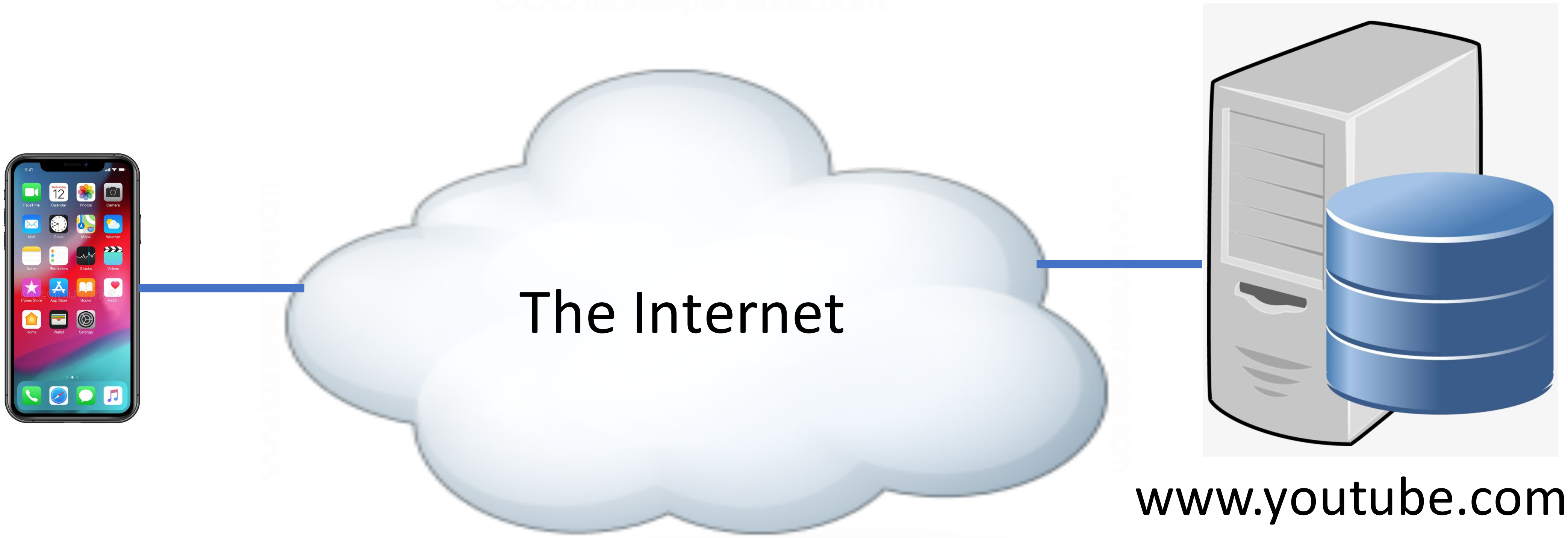
COS 316: Principles of Computer System Design

Lecture 9

Amit Levy & Ravi Netravali

Downloading a Web Page

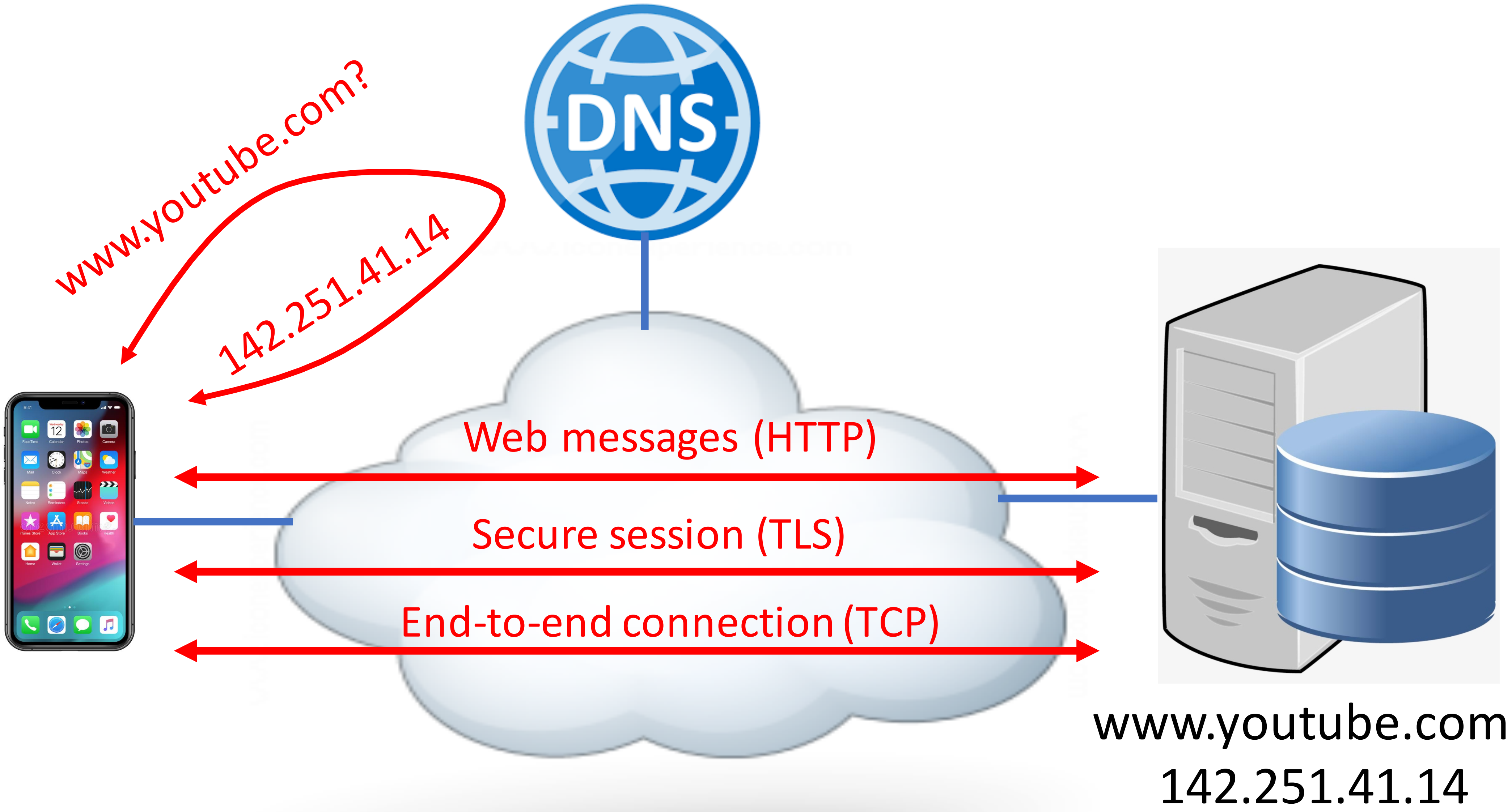
User visits https://www.youtube.com



The Internet

www.youtube.com

Downloading a Web Page (https://www.youtube.com)



Multiple Problems

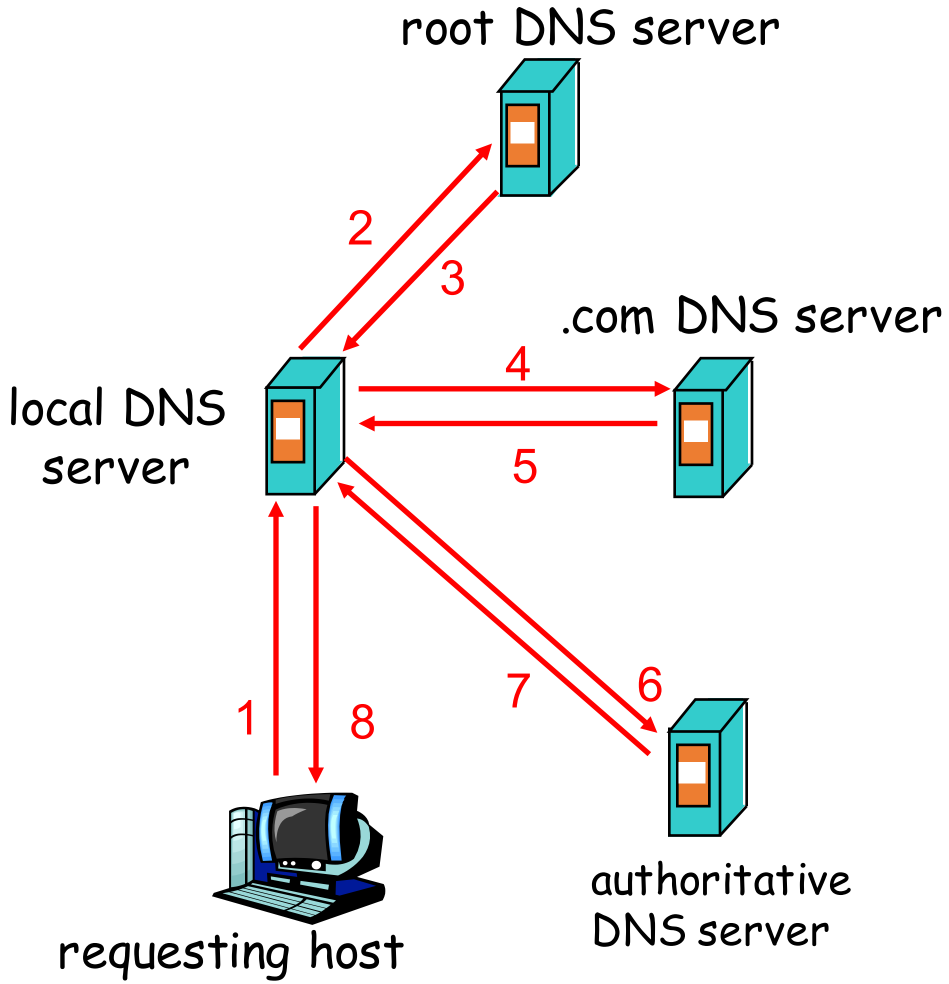
- User latency
  - Round-trips to query multiple DNS servers
  - Multiple round-trips with the Web server
  - Delivery of a (possibly large) Web item
- Server overhead
  - Handling many requests from many clients
  - Financial costs to deploy enough servers
- Network bandwidth
  - Traffic on many links in multiple networks
  - Financial costs for the affected networks

Caching to the Rescue: Domain Name System

- What to cache?
  - Mapping of popular names to IP addresses
    - E.g., www.youtube.com → 142.251.41.14
  - Mapping of *parts* of names to DNS server IPs
    - E.g., .com top-level domain → 192.26.92.30

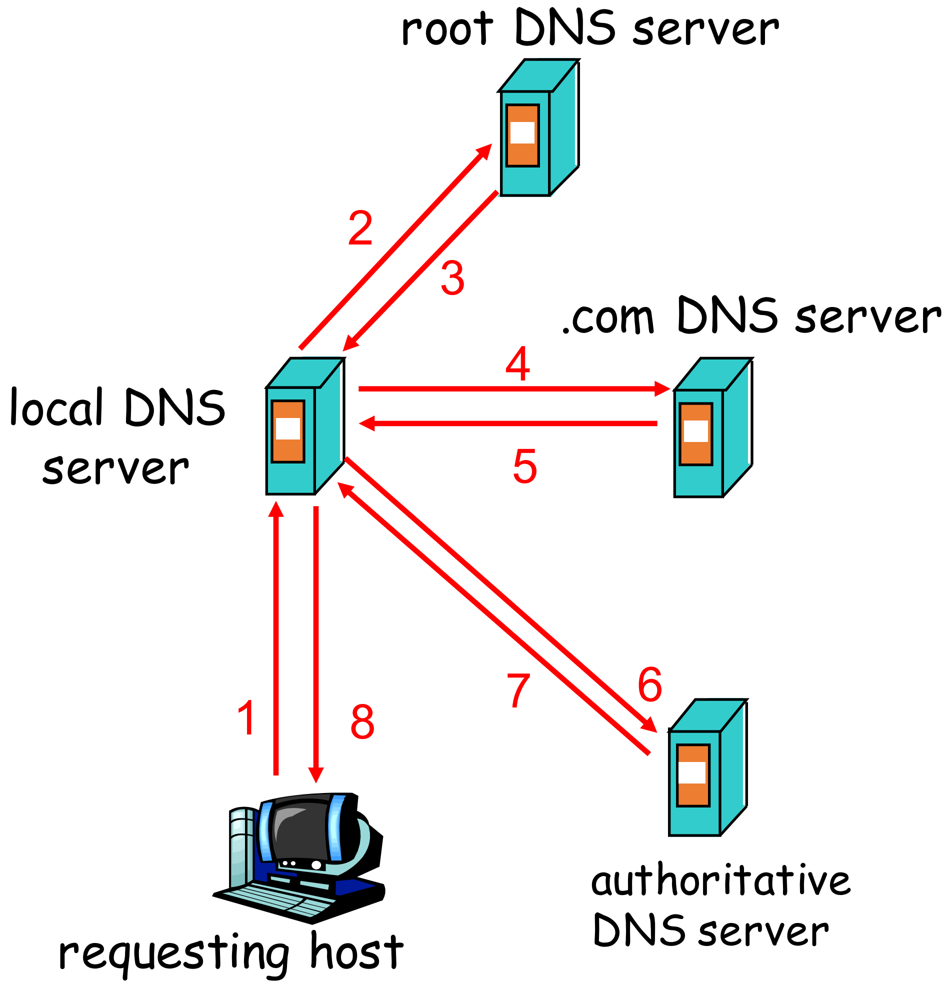
Caching to the Rescue: Domain Name System

- What to cache?
  - Mapping of popular names to IP addresses
    - E.g., www.youtube.com → 142.251.41.14
  - Mapping of *parts* of names to DNS server IPs
    - E.g., .com top-level domain → 192.26.92.30



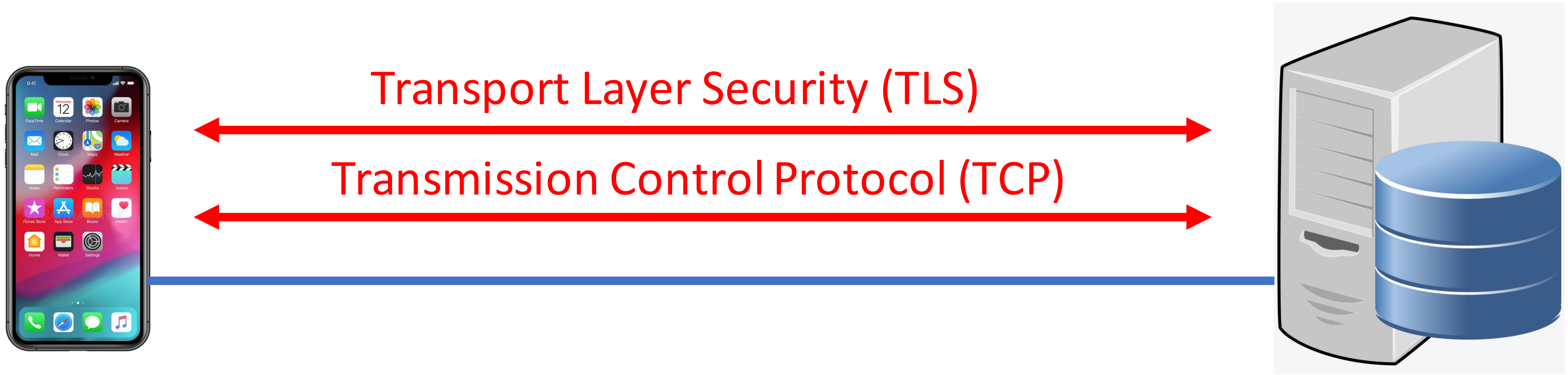
Caching to the Rescue: Domain Name System

- What to cache?
  - Mapping of popular names to IP addresses
    - E.g., www.youtube.com → 142.251.41.14
  - Mapping of *parts* of names to DNS server IPs
    - E.g., .com top-level domain → 192.26.92.30
- Where to cache?
  - Local DNS server (e.g., for the campus)
  - Client machine (e.g., user's browser)
- How to avoid stale information?
  - Cached entries have a limited "time to live"



Caching to the Rescue: Communication Channel

- End-to-end communication
  - TLS: confidentiality, integrity, and authenticity
  - TCP: ordered, reliable delivery of byte stream
- Establishing the channel is expensive
  - Communication delays, creating data structures, and computing keys
- Exploit temporal locality by reusing the channels

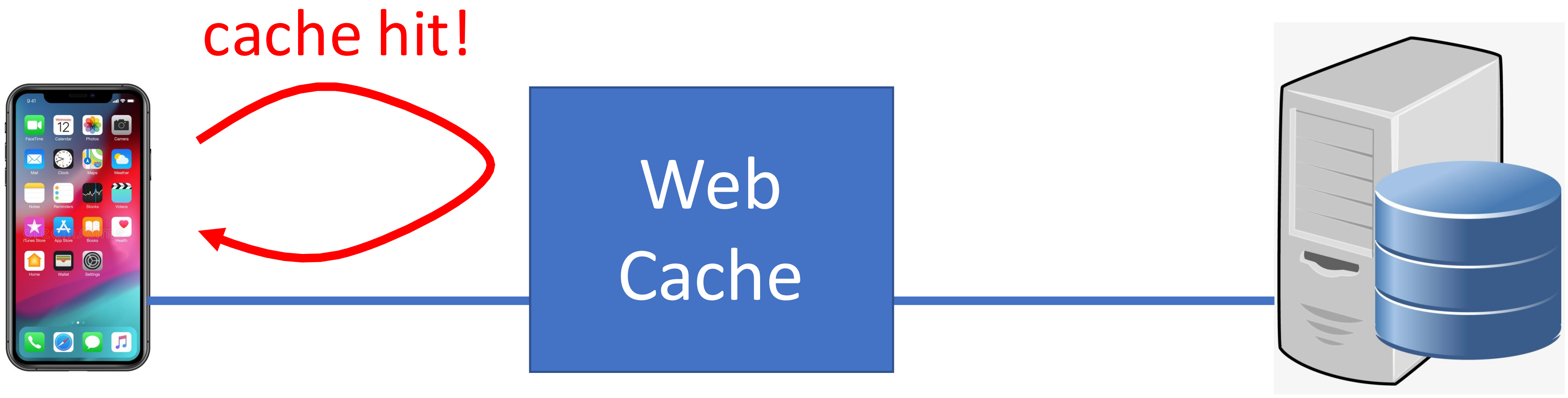


Transport Layer Security (TLS)

Transmission Control Protocol (TCP)

Caching to the Rescue: Web Items

- Cache Web items closer to the client
  - Reduce latency
  - Reduce server overhead
  - Reduce use of network bandwidth



cache hit!

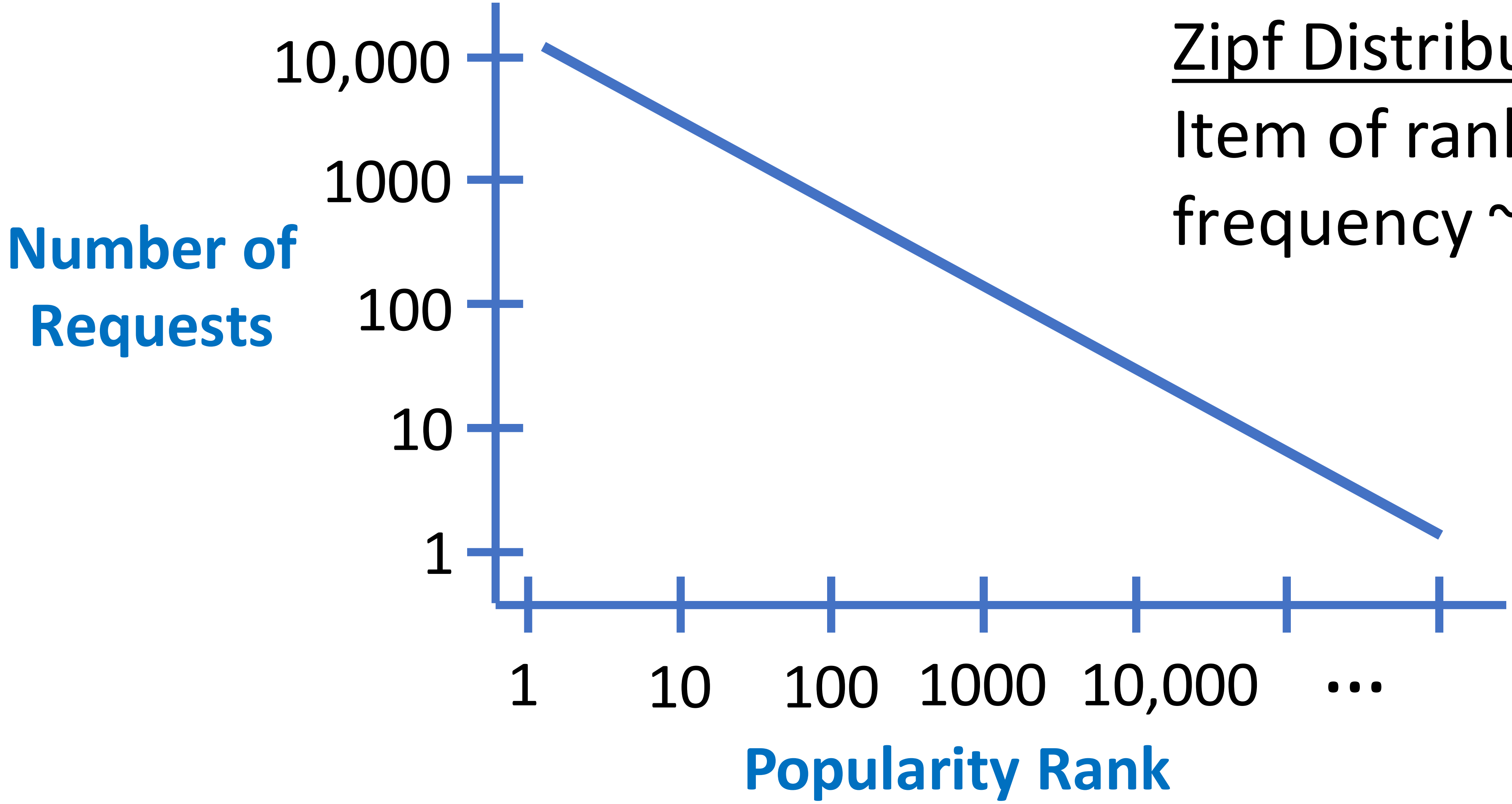
Web Cache

Web Caching: Outline

- Cache replacement
  - Popularity distributions
  - Replacement algorithms
- Cache consistency
  - Dynamic items
  - Cache validation
- Cache placement
  - Client’s web browser
  - Client’s network
  - Server’s network
  - Third party (CDN)
- Content Distribution Network

Cache Replacement

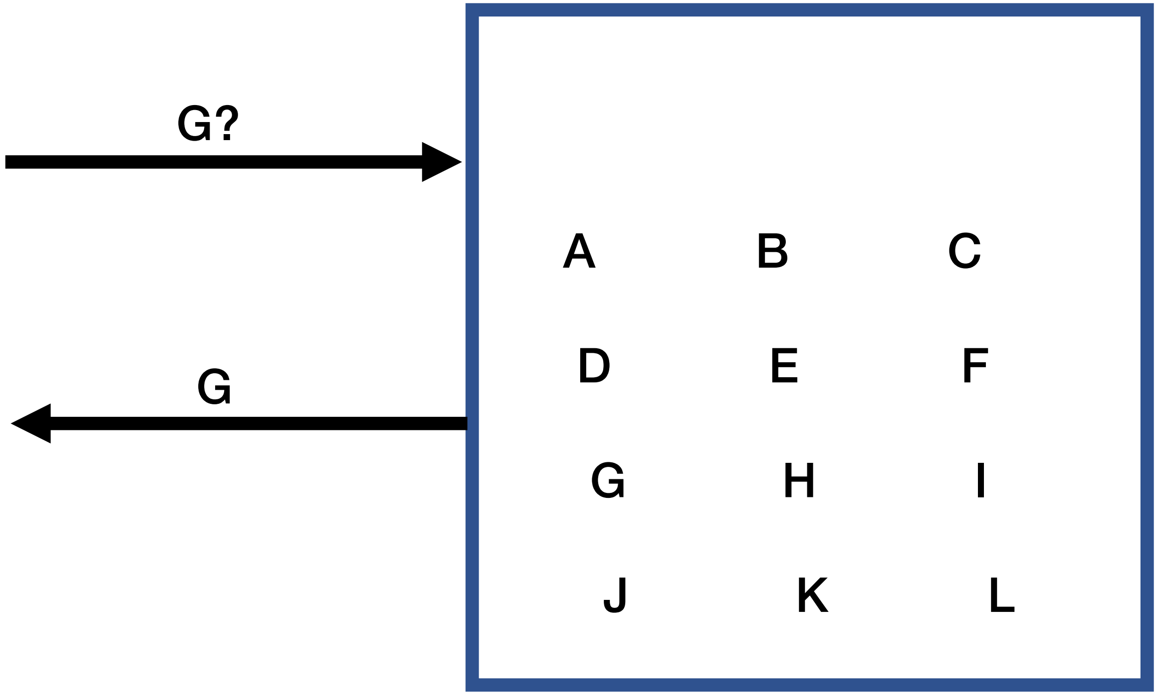
Web Caching Should Work Well!



<u>Zipf Distribution</u>

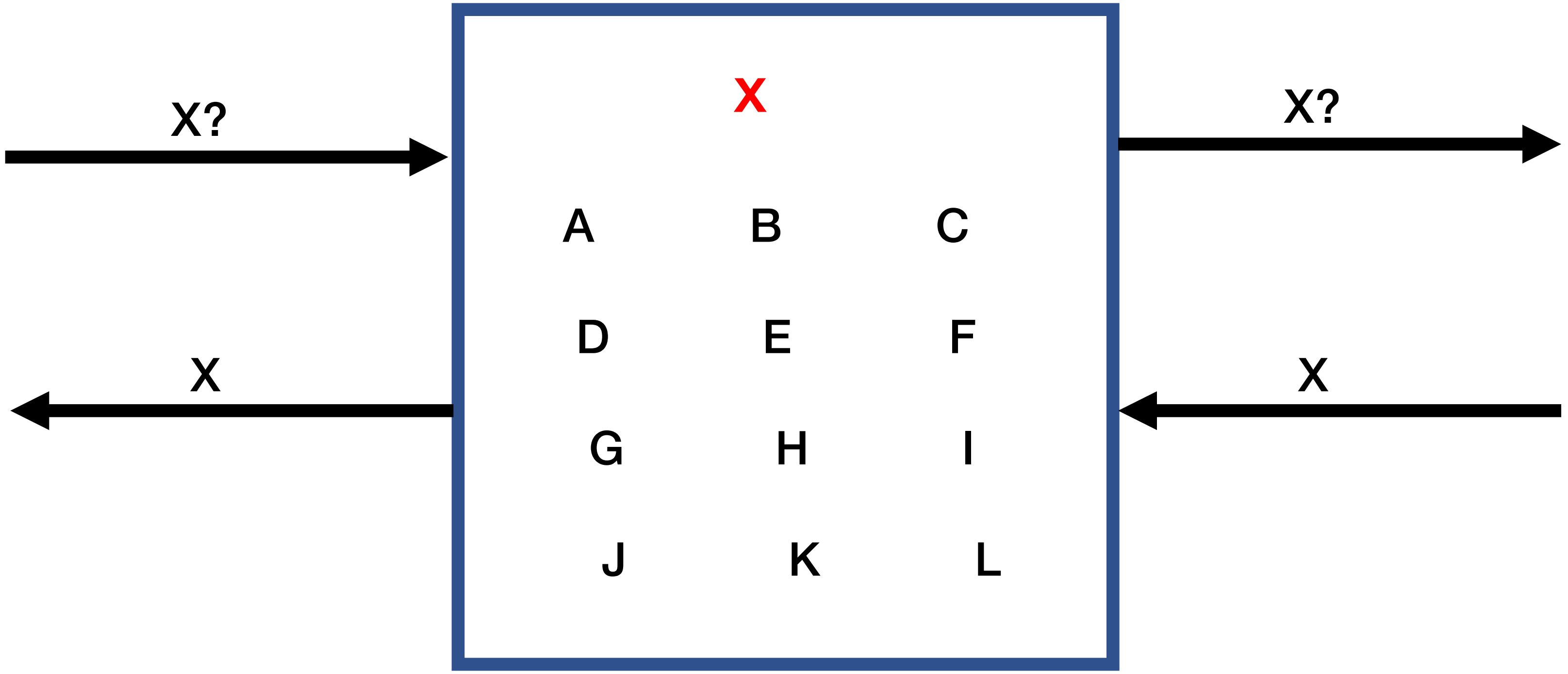
Item of rank *k* has frequency ~ *1/k^a*

Web Cache Hit



On cache hit, retrieve the object from the cache!

Web Cache Miss



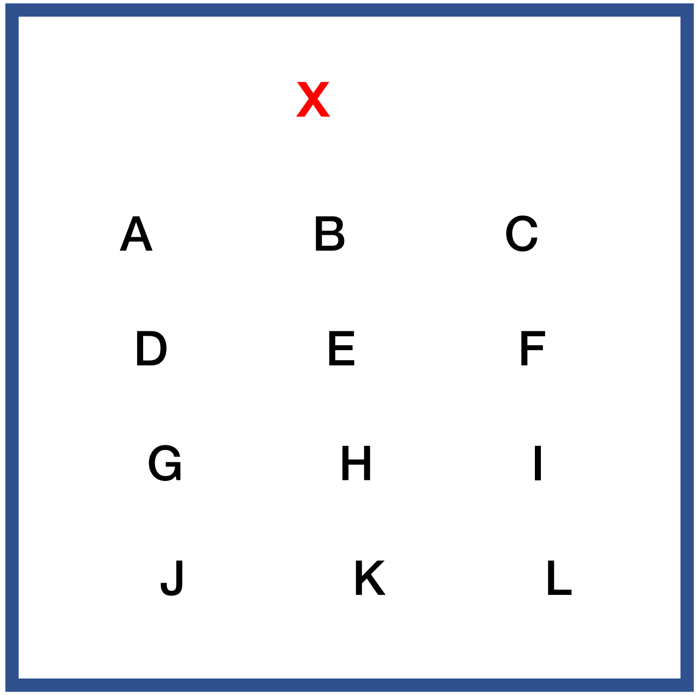
If I want to store X, what do I get rid of to make space?

Cache Replacement Algorithms

- Which object to evict?
  - Least likely to be used again soon
  - Least expensive to fetch again

- Example algorithms
  - First in first out (FIFO)
  - Least recently used (LRU)
  - Least frequently used (LFU)

- (Note: all fully associative today)



Cache Replacement: First-In-First-Out (FIFO)

- Evict objects added to cache longest ago
- Very simple!

- Three-item cache example:
    - Request stream: a, b, a, c, a, d, a, e, a, f, g

- Can we do better?

Least Recently Used (LRU)

- Evict object used longest ago
  - “Objects used more recently are more likely to be accessed again”
  - Exploits temporal locality

- Implementation: Update access time for every hit

- Three-item cache example:
  - Request stream: a, b, a, c, a, d, a, e, a, f, g
  - Request stream: h, h, h, i, j, k, h

Least Frequently Used (LFU)

- Evict object with fewest hits
  - “Objects used more often are more likely to be accessed again”
  - If tie, use LRU

- Implementation: Update access count for every hit

- Three-item cache example:
  - Request stream: a, b, a, c, a, d, a, e, a, f, g
  - Request stream: h, h, h, i, j, k, h
  - Request stream: l, l, m, n, o, m

Clairvoyant (Belady): Offline Optimal Caching

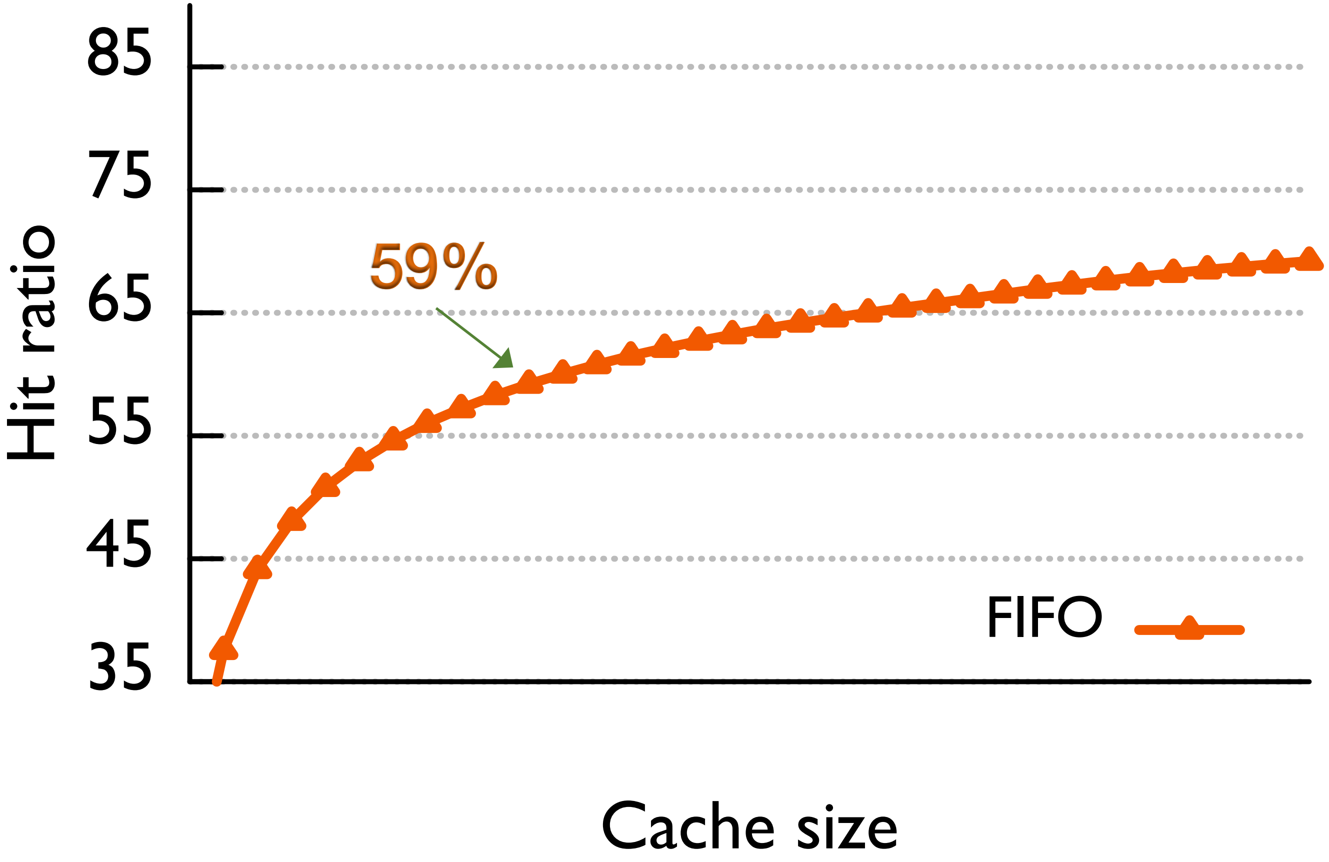
- What is the best a caching algorithm could do?
- Offline: uses knowledge of the future
  - (Can’t use in practice)

- Evict the object with the furthest **next** access time
  - Worst object to keep in the cache

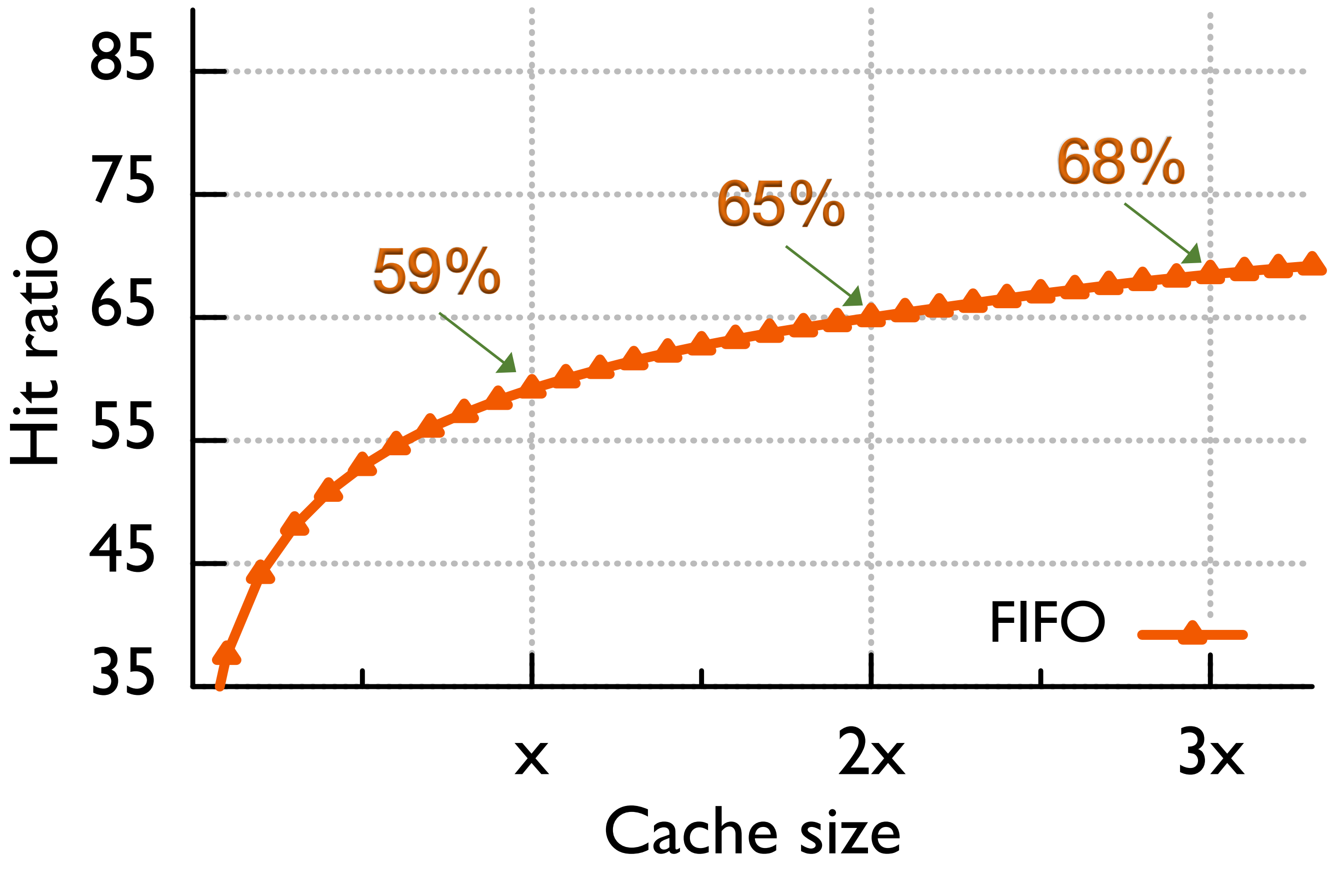
- Three-item cache example:
  - Request stream: h, h, h, i, j, k, h
  - Request stream: l, l, m, n, o, m

Edge Cache with Different Sizes

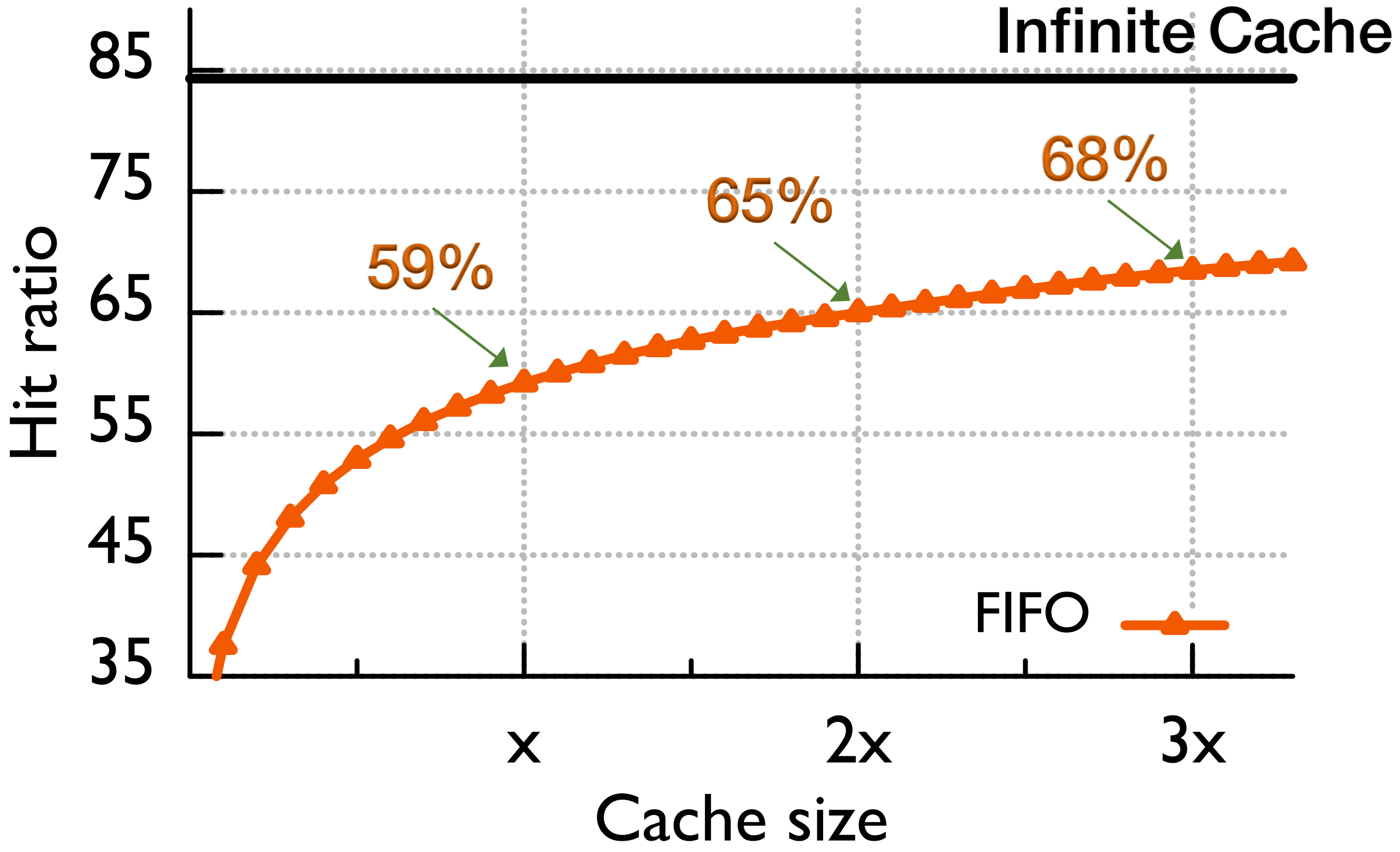
From “An Analysis of Facebook Photo Caching,” at Symposium on Operating System Principles, 2013.



Edge Cache with Different Sizes

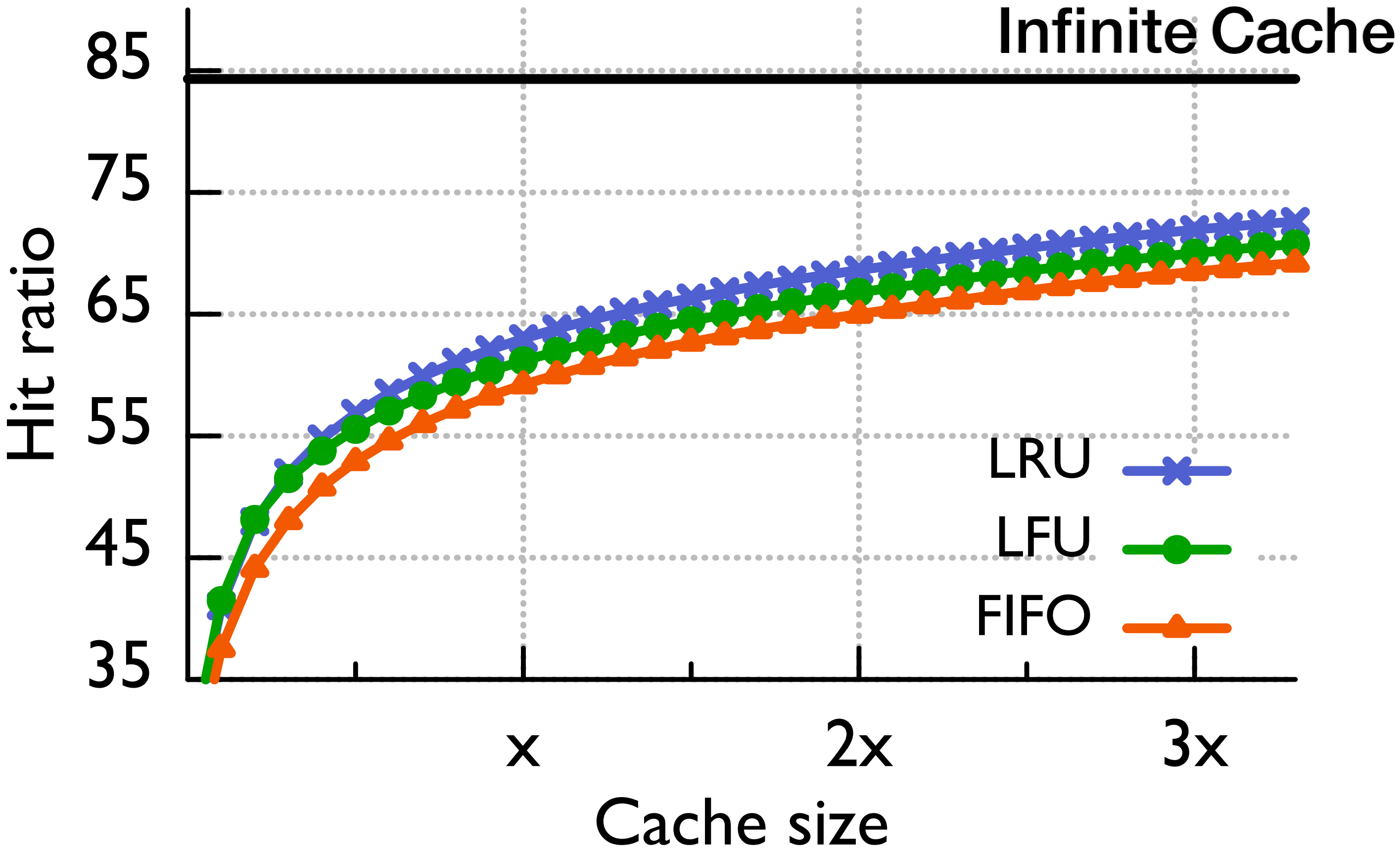


Edge Cache with Different Sizes



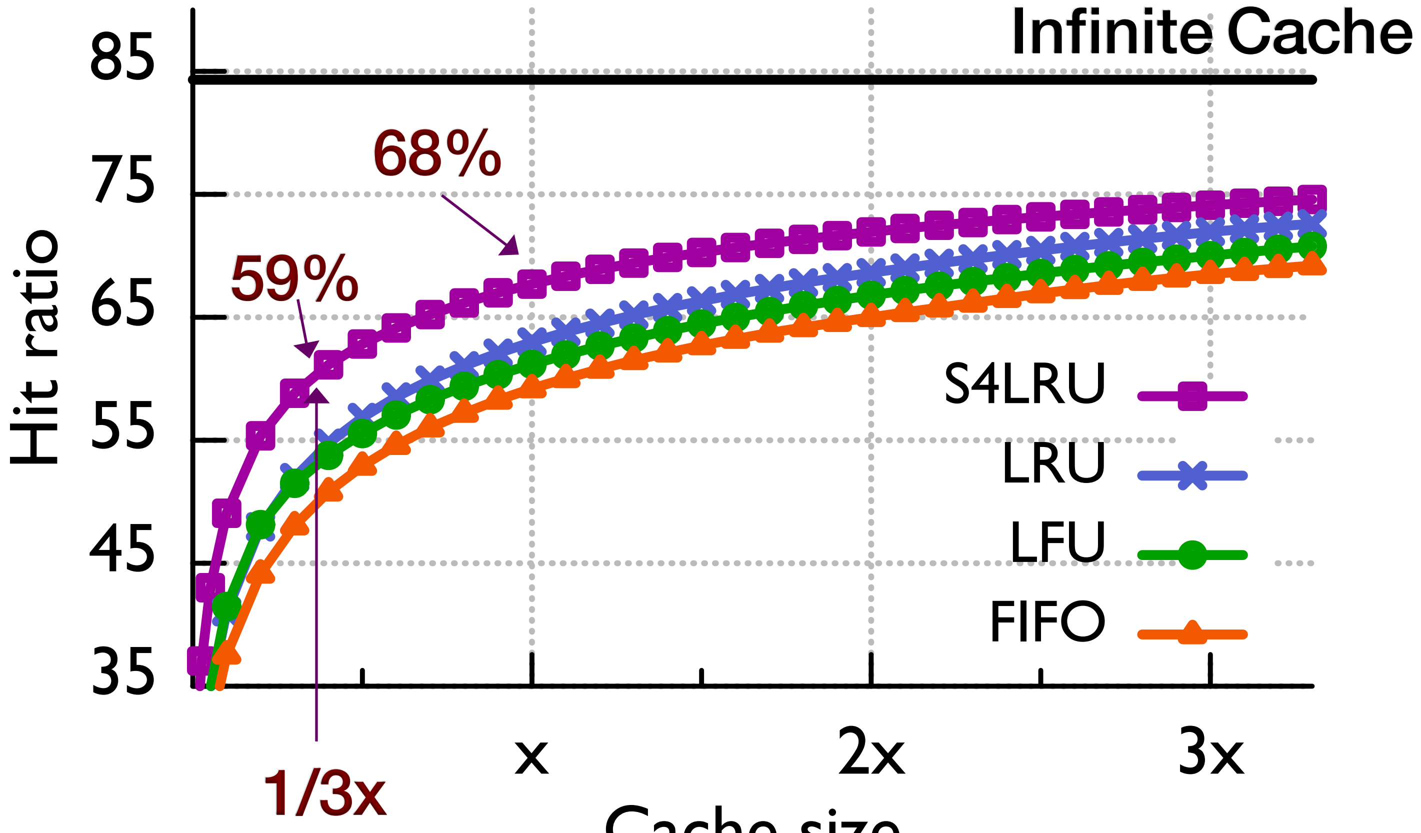
- “Infinite” size ratio needs 45x of capacity

Edge Cache with Different Algos



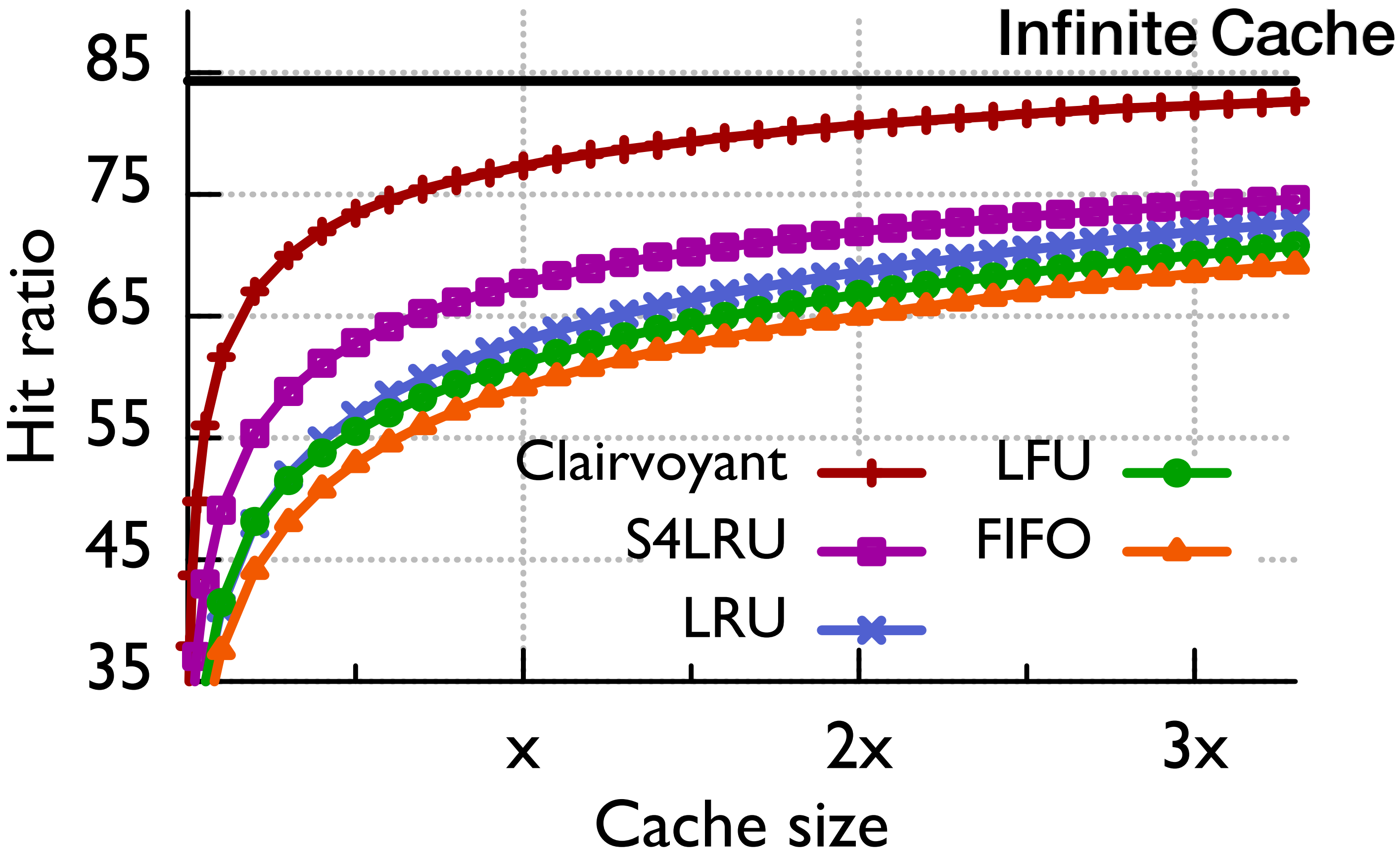
- LRU > LFU > FIFO

Edge Cache with Different Algorithms



- **S4LRU** is a more complex algorithm, uses recency and frequency

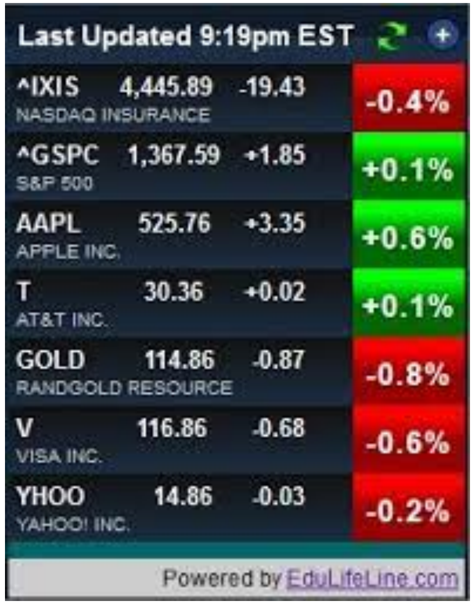
Edge Cache with Different Algos



- Clairvoyant (Bélády) shows we can do much better!

Cache Consistency

Some Web Content is Not Cacheable



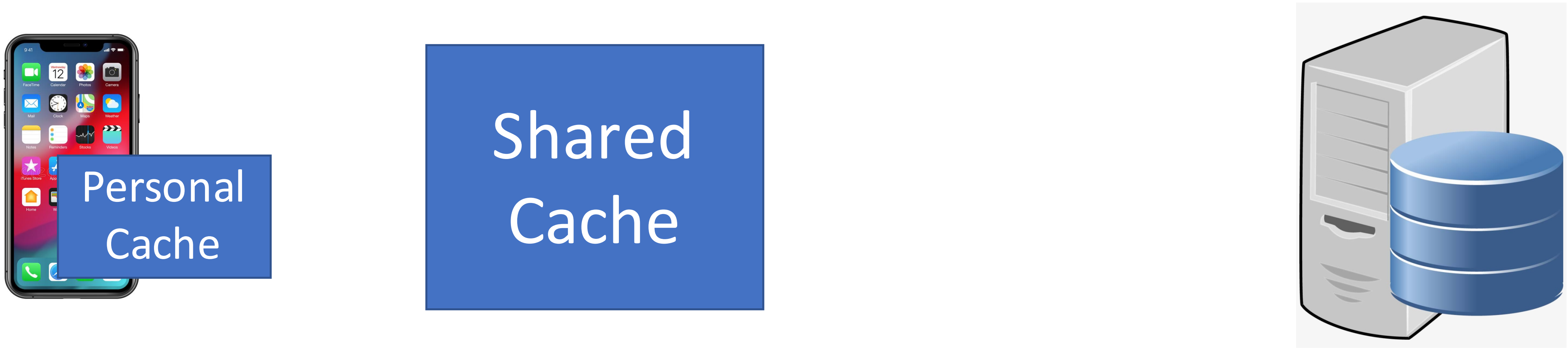
Last Updated 9:19pm EST

^IXIS NASDAQ INSURANCE	4,445.89	-19.43	-0.4%
^GSPC S&P 500	1,367.59	+1.85	+0.1%
AAPL APPLE INC.	525.76	+3.35	+0.6%
T AT&T INC.	30.36	+0.02	+0.1%
GOLD RANDGOLD RESOURCE	114.86	-0.87	-0.8%
V VISA INC.	116.86	-0.68	-0.6%
YHOO YAHOO! INC.	14.86	-0.03	-0.2%

Powered by EduLifeLine.com

- Dynamic content
  - E.g., stock prices, scores, web cams
- Content generated by scripts
  - Results depend on the specific parameters
  - E.g., https://www.google.com/search?q=php+script+url
- Personalized content
  - E.g., based on cookie sent by the browser
- Encrypted content
  - Cannot decrypt without the appropriate key

Cache Consistency Challenges



Personal Cache

Shared Cache

<u>Web cache needs to know</u>

- Whether to cache an item
- How long to cache an item
- Whether to check an item’s freshness
- Whether it is okay to return a stale item
- Whether the item has sensitive data

Cache Consistency Challenges

Personal Cache

Shared Cache

<u>Web cache needs to know</u>

- Whether to cache an item
- How long to cache an item
- Whether to check an item’s freshness
- Whether it is okay to return a stale item
- Whether the item has sensitive data

<u>Server knows the content</u>

- Whether the item is dynamic
- How often the item changes
- Whether the item has changed
- Whether stale information is useful
- Whether item contains sensitive data

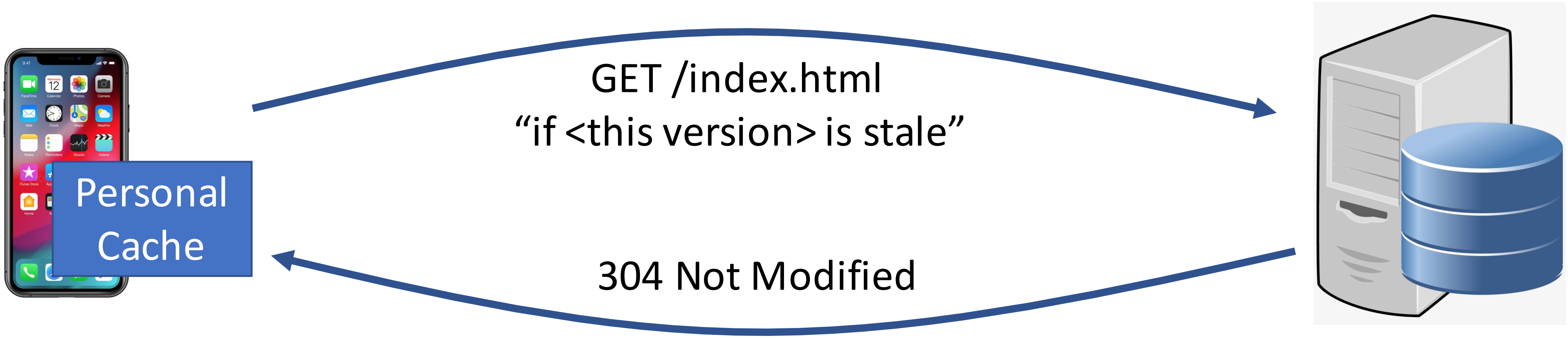
Scalability challenge: the server cannot remember every client that has cached an item

HTTP Response Header for Cache Control

- Whether to cache
  - no store: no cache should store it
- Who should cache
  - private: only a private cache (e.g., browser)
  - public: any cache, including shared ones
- How long to cache
  - max-age=N: for N seconds
  - must-revalidate: check with the server (don’t return stale item)

Cache-Control: public, max-age=86400, must-revalidate

Cache Validation: Client Checks Freshness

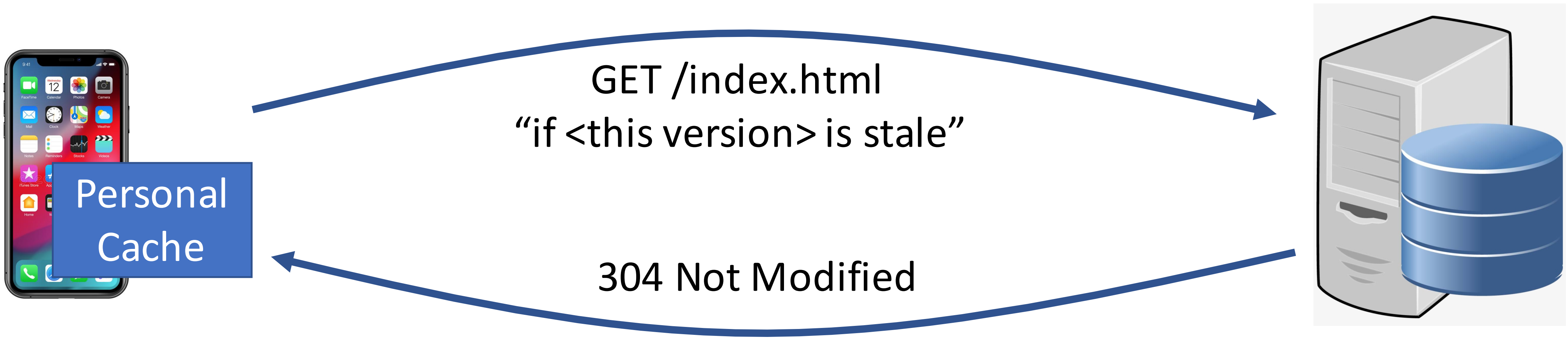


Personal Cache

GET /index.html
“if <this version> is stale”

304 Not Modified

Cache Validation: Client Checks Freshness



Personal Cache

GET /index.html
“if <this version> is stale”

304 Not Modified

How do they identify the “version”?

- Timestamp
  - When the item was modified by the server
  - E.g., Last-Modified: Wed, 21 Oct 2015 07:28:00 GMT
- Version number
  - Entity tag provided by the server
  - E.g., ETag: "33a64df551425fcc55e4d42a148795d9f25f89d4"

Cache Placement

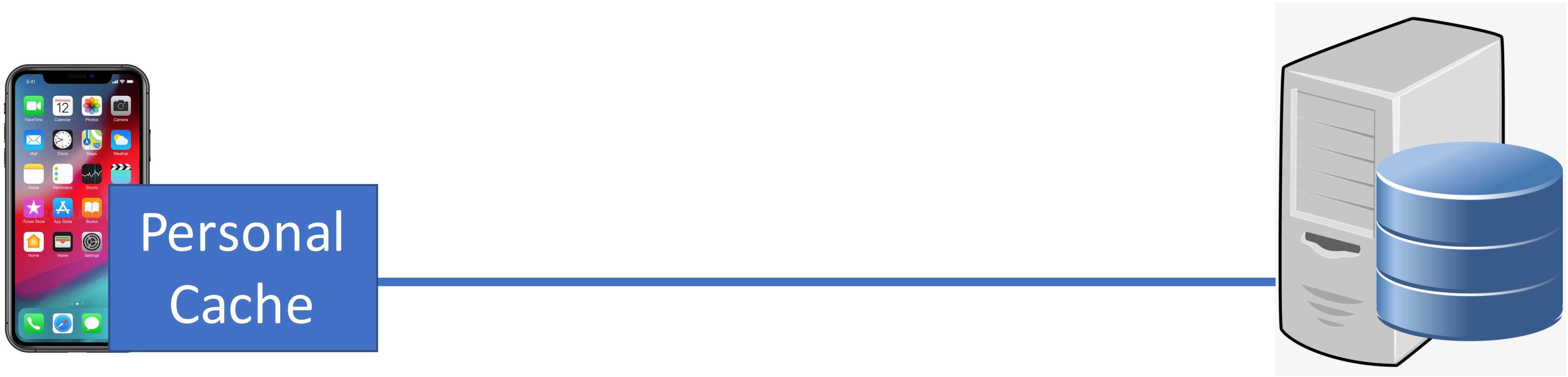
Client Machine (e.g., Browser)

Advantages

- Very low latency
- Preserves access bandwidth
- Available when disconnected

Disadvantages

- Low hit rate due to “cold” misses
- Many cache consistency checks
- Incomplete logs at the server



Personal Cache

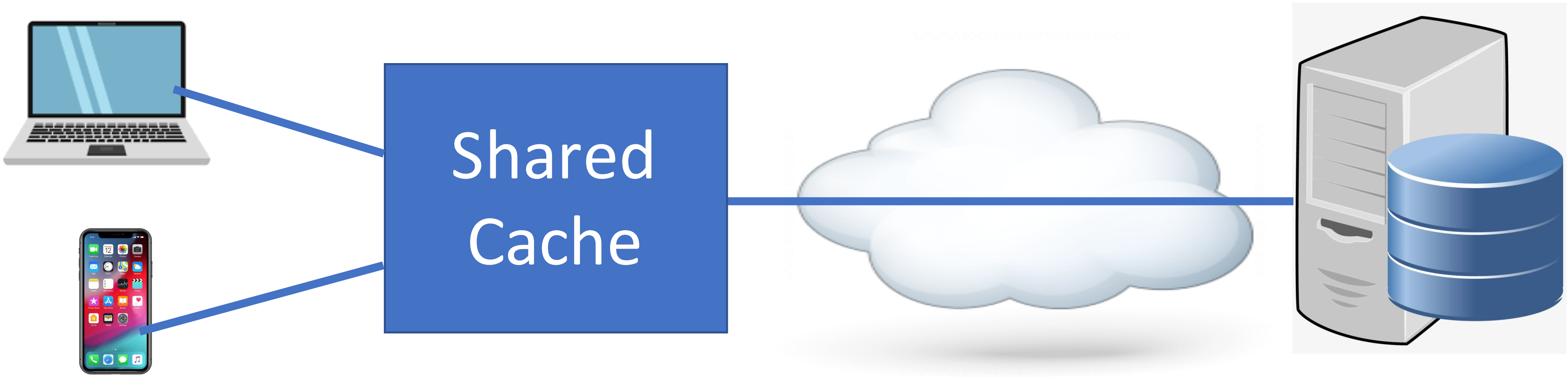
Client Network (Forward Proxy Cache)

Advantages

- Low latency
- Preserves enterprise bandwidth
- Hits for locally popular content

Disadvantages

- Cost to deploy the cache
- Many consistency checks
- Incomplete logs at the server



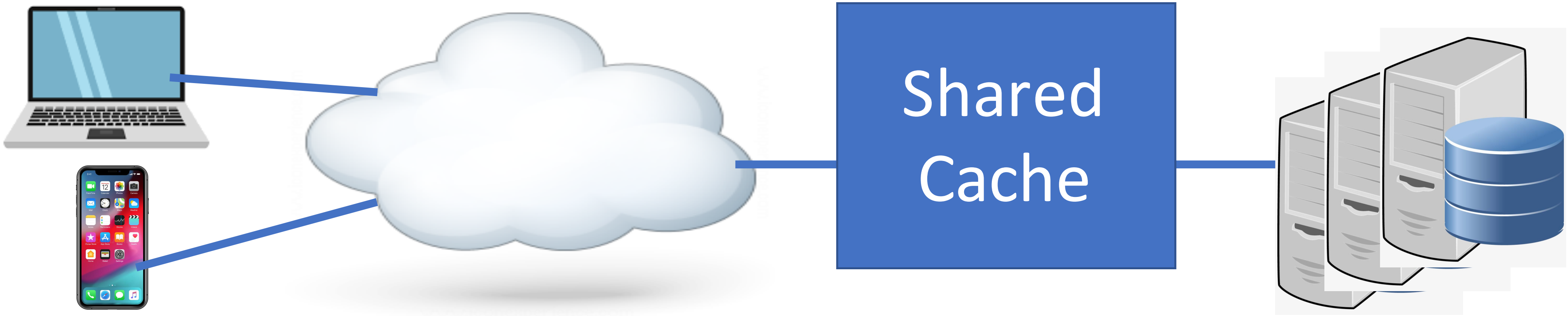
Server Network (Reverse Proxy Cache)

Advantages

- High hit rate across global users
- Greater cooperation with server
- Complete request logs for server
- Preserves server bandwidth

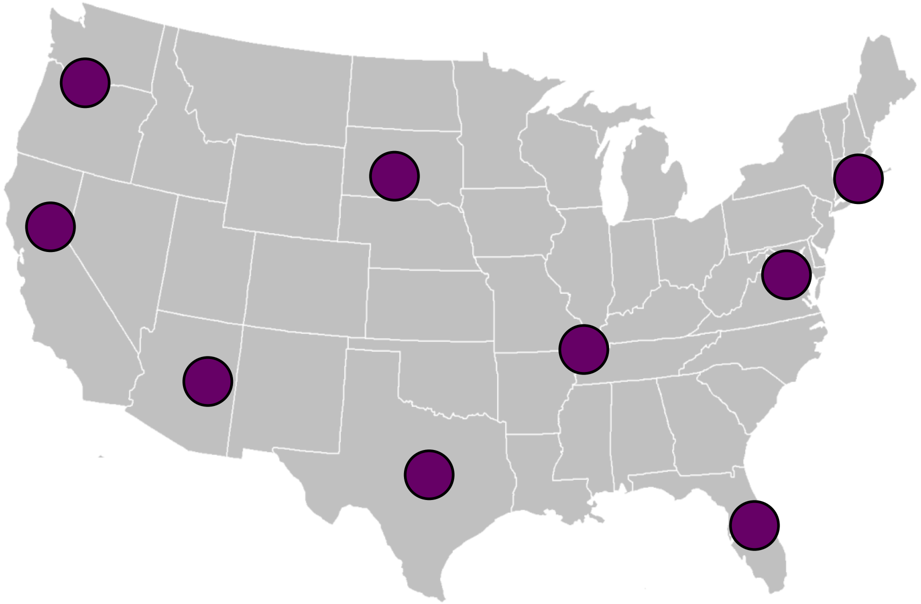
Disadvantages

- Costs to deploy the cache
- Does not reduce latency much
- Consumes wide-area bandwidth



Content Distribution Network (CDN)

- Outsourced caching infrastructure
  - Caching for clients and servers
  - Dedicated equipment and software
  - Trained staff, best practices, etc.
- Coordination with the server
  - Generating non-cacheable content
  - Providing detailed measurement data
- Smart cache placement
  - Many caches: handle large request load
  - Close to many clients: reduce latency

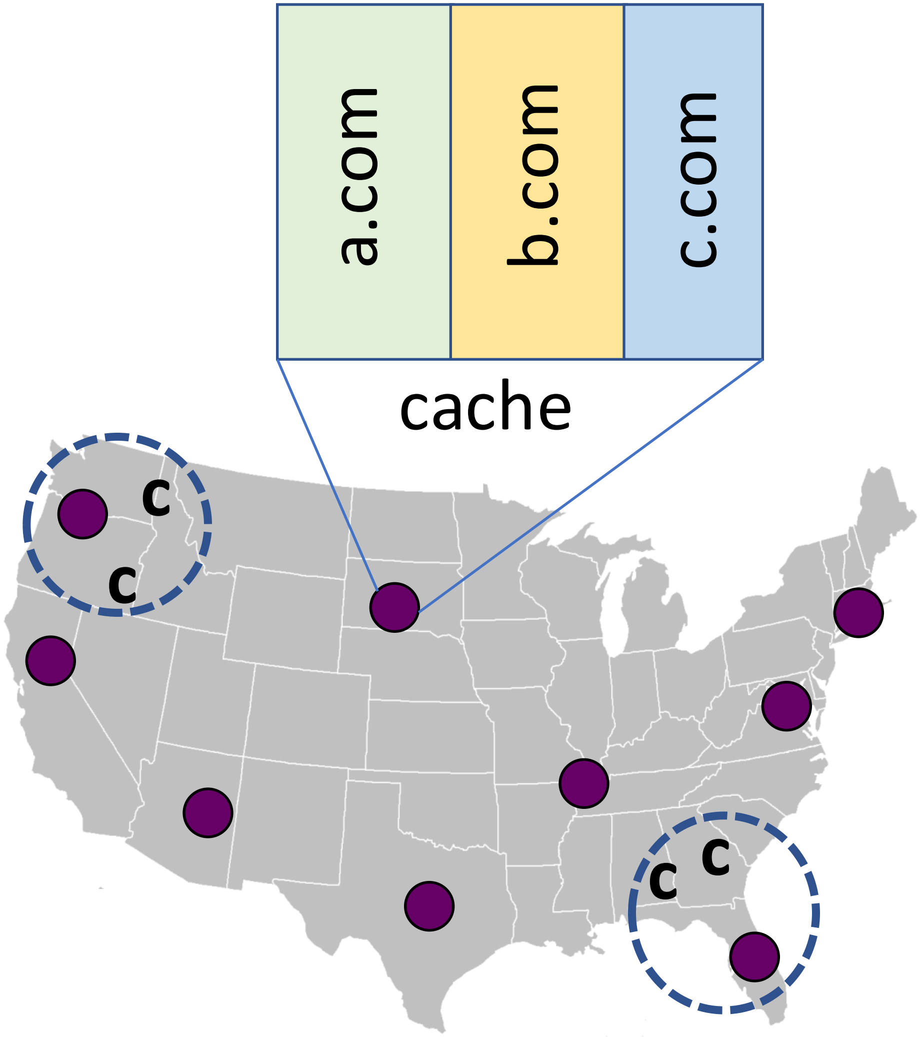


Akamai

More than 4200 locations in 135 countries

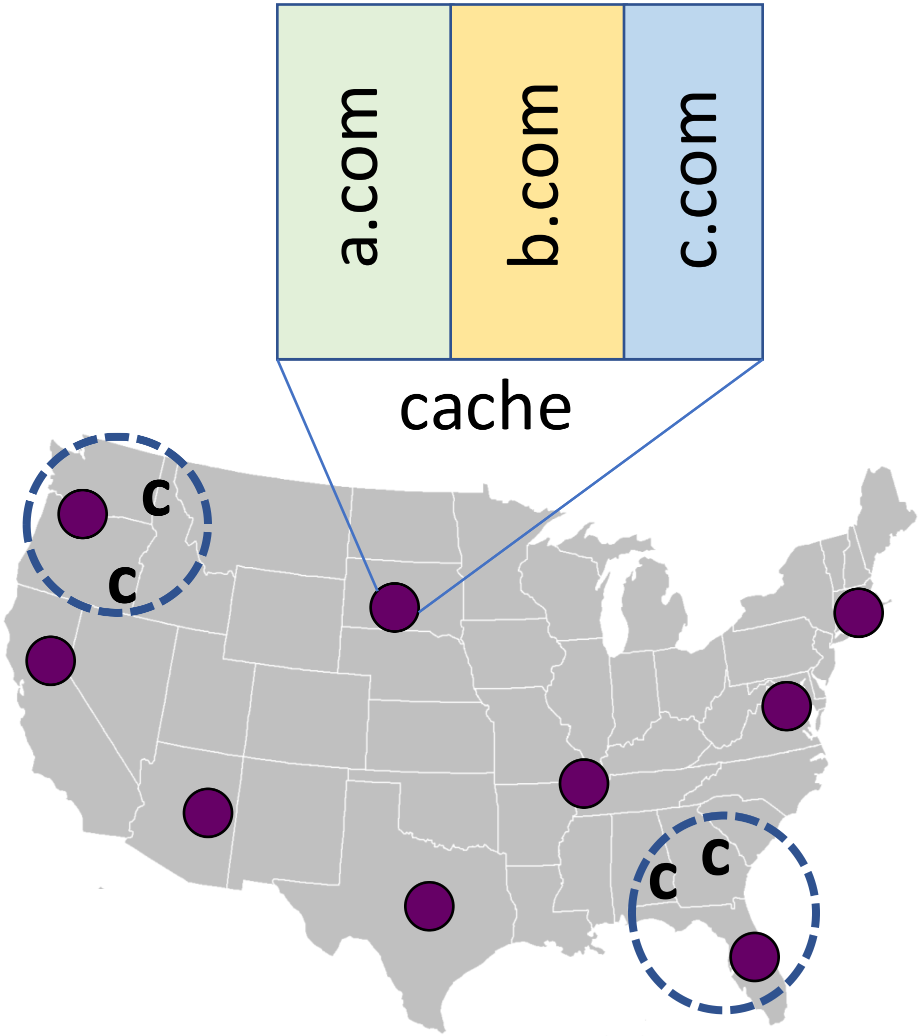
CDN Challenges

- Where to place edge sites?
  - Close to many clients, with reasonable cost
- Where to replicate a server's content?
  - Many edge sites → duplicated data
  - Few edge sites → larger client latency
- How to direct a client to an edge site?
  - Proximity: for low latency
  - Light load: to reduce congestion
- How to manage each cache?
  - Maximize hit rate?
  - Minimize miss penalty?
  - Fairness across origin servers?



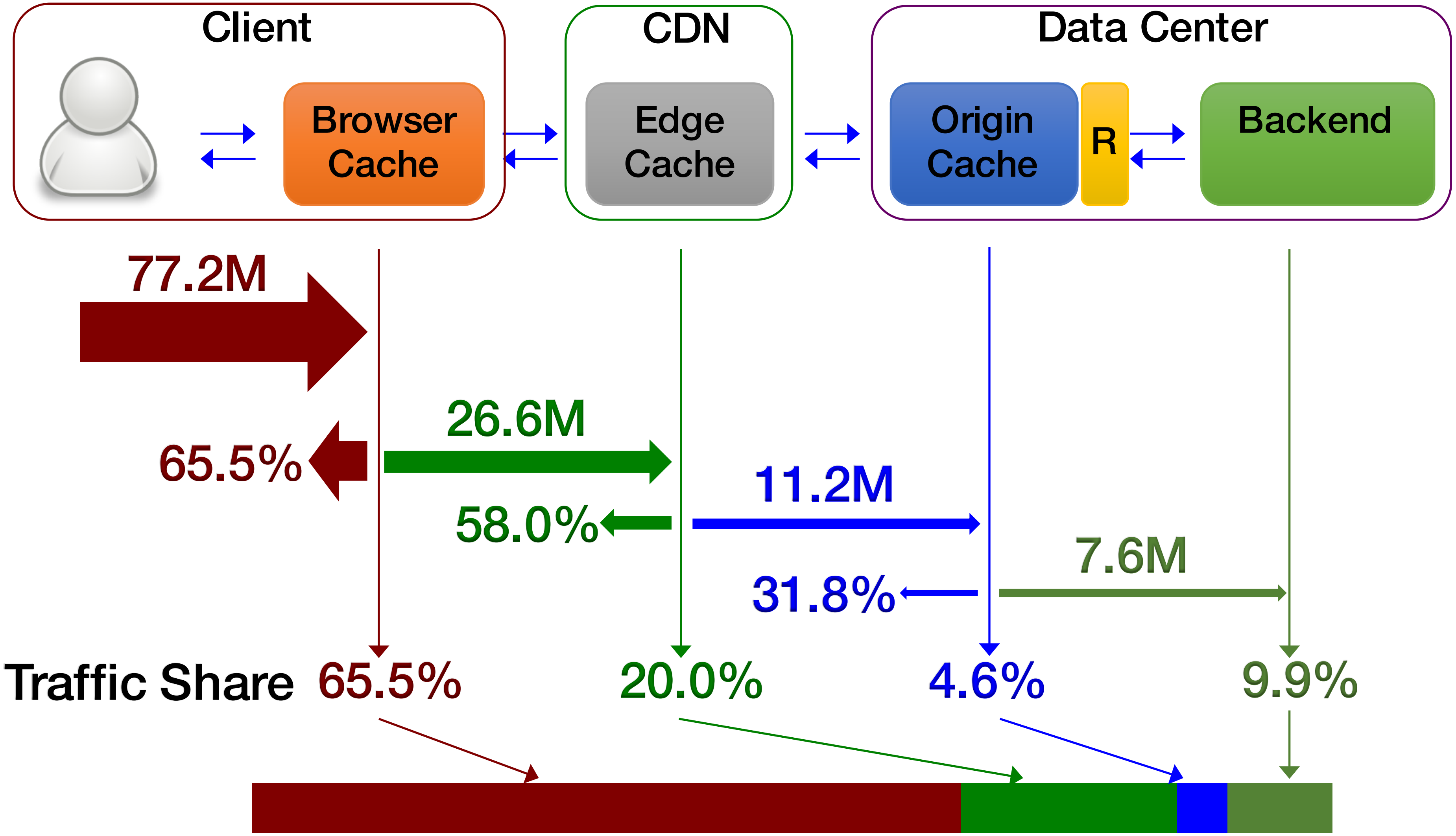
CDN Challenges

- Where to place edge sites?
  - Close to many clients, with reasonable cost
- Where to replicate a server's content?
  - Many edge sites → duplicated data
  - Few edge sites → larger client latency
- How to direct a client to an edge site?
  - Proximity: for low latency
  - Light load: to reduce congestion
- How to manage each cache?
  - Maximize hit rate?
  - Minimize miss penalty?
  - Fairness across origin servers?



CDN Effectiveness

From “An Analysis of Facebook Photo Caching,” at Symposium on Operating System Principles, 2013.



Conclusions

- Downloading a Web page
  - Name resolution, transport connection, secure session, web messages
- Benefits of caching
  - Reduces user latency, server load, and network bandwidth
- Cache replacement
  - Maximize hit rate by trying to predict the future
- Cache consistency
  - Efficient ways to avoid returning unnecessarily stale responses
- Content distribution networks
  - Caching close to clients, while working on behalf of the servers