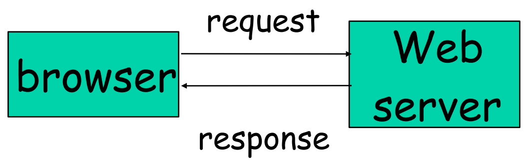
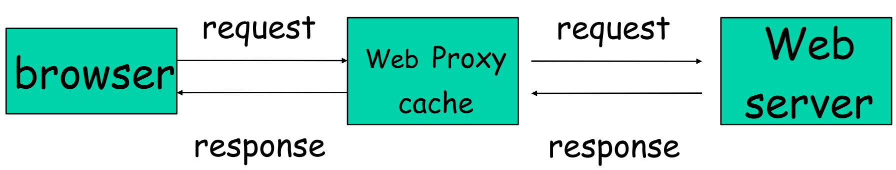
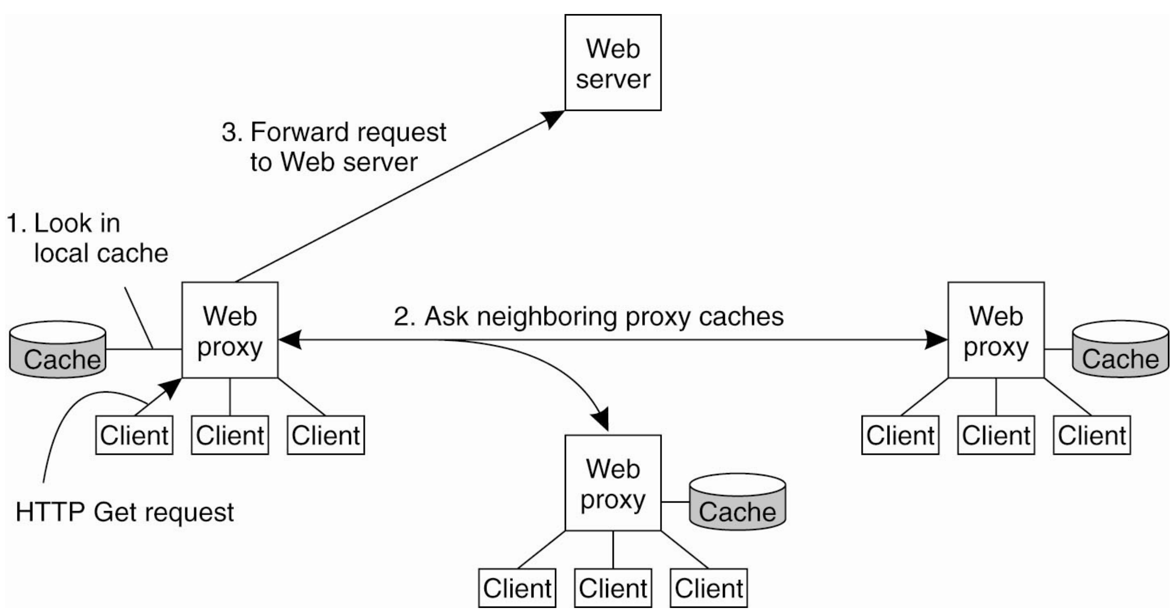
Web Caching

- Example of the web to illustrate caching and replication issues
  - Simpler model: clients are read-only, only server updates data





Web Proxy Caching



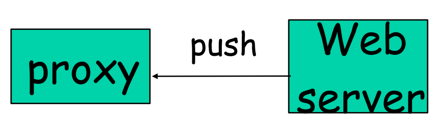
- The principle of cooperative caching.

Consistency Issues

- Web pages tend to be updated over time
  - Some objects are static, others are dynamic
  - Different update frequencies (few minutes to few weeks)
- How can a proxy cache maintain consistency of cached data?
  - Send invalidate or update
  - Push versus pull

Push-based Approach

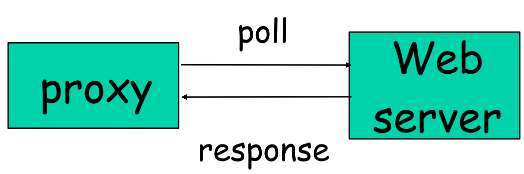
- Server tracks all proxies that have requested objects
- If a web page is modified, notify each proxy
- Notification types
  - Indicate object has changed [invalidate]
  - Send new version of object [update]
- How to decide between invalidate and updates?
  - Pros and cons?
  - One approach: send updates for more frequent objects, invalidate for rest



Push-based Approaches

- Advantages
  - Provide tight consistency [minimal stale data]
  - Proxies can be passive
- Disadvantages
  - Need to maintain state at the server
    - Recall that HTTP is stateless
    - Need mechanisms beyond HTTP
  - State may need to be maintained indefinitely
    - Not resilient to server crashes

Pull-based Approaches



- Proxy is entirely responsible for maintaining consistency
- Proxy periodically polls the server to see if object has changed
  - Use if-modified-since HTTP messages
- Key question: when should a proxy poll?
  - Server-assigned *Time-to-Live (TTL)* values
    - No guarantee if the object will change in the interim

Pull-based Approach: Intelligent Polling

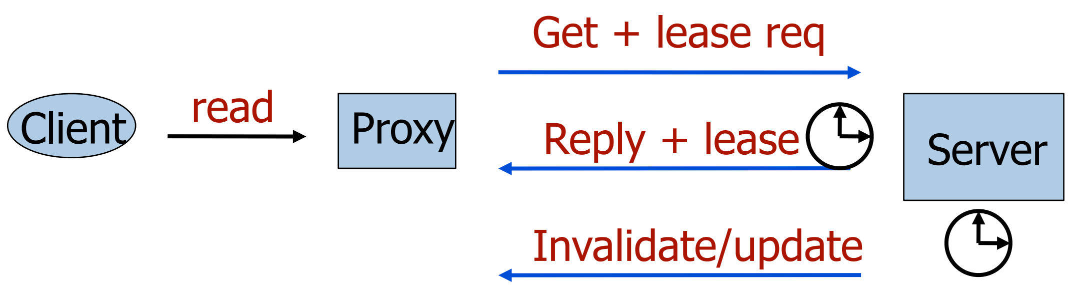
- Proxy can dynamically determine the refresh interval
  - Compute based on past observations
    - Start with a conservative refresh interval
    - Increase interval if object has not changed between two successive polls
    - Decrease interval if object is updated between two polls
    - Adaptive: No prior knowledge of object characteristics needed

Pull-based Approach

- Advantages
  - Implementation using HTTP (If-modified-Since)
  - Server remains stateless
  - Resilient to both server and proxy failures
- Disadvantages
  - Weaker consistency guarantees (objects can change between two polls and proxy will contain stale data until next poll)
    - Strong consistency only if poll before every HTTP response
  - More sophisticated proxies required
  - High message overhead

A Hybrid Approach: Leases

- Lease: duration of time for which server agrees to notify proxy of modification
- Issue lease on first request, send notification until expiry
  - Need to renew lease upon expiry
- Smooth tradeoff between state and messages exchanged
  - Zero duration => polling, Infinite leases => server-push
- Efficiency depends on the *lease duration*



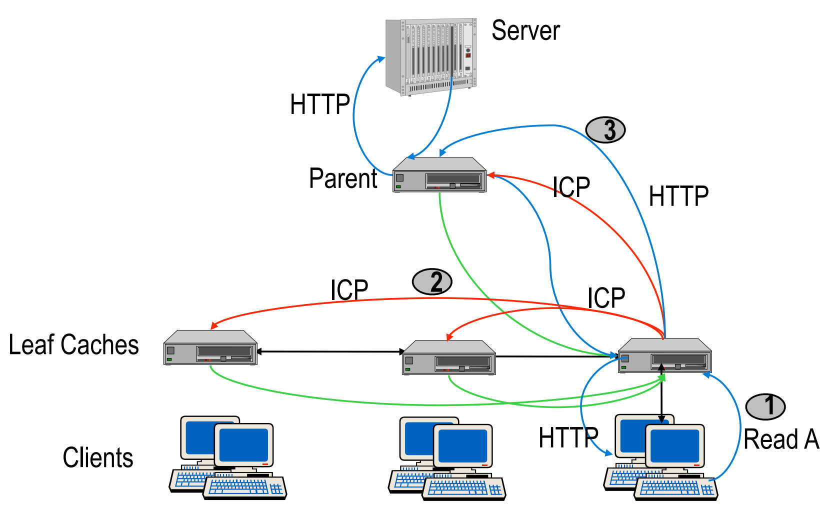
Policies for Leases Duration

- Age-based lease
  - Based on bi-modal nature of object lifetimes
  - Larger the expected lifetime longer the lease
- Renewal-frequency based
  - Based on skewed popularity
  - Proxy at which objects is popular gets longer lease
- Server load based
  - Based on adaptively controlling the state space
  - Shorter leases during heavy load

Cooperative Caching

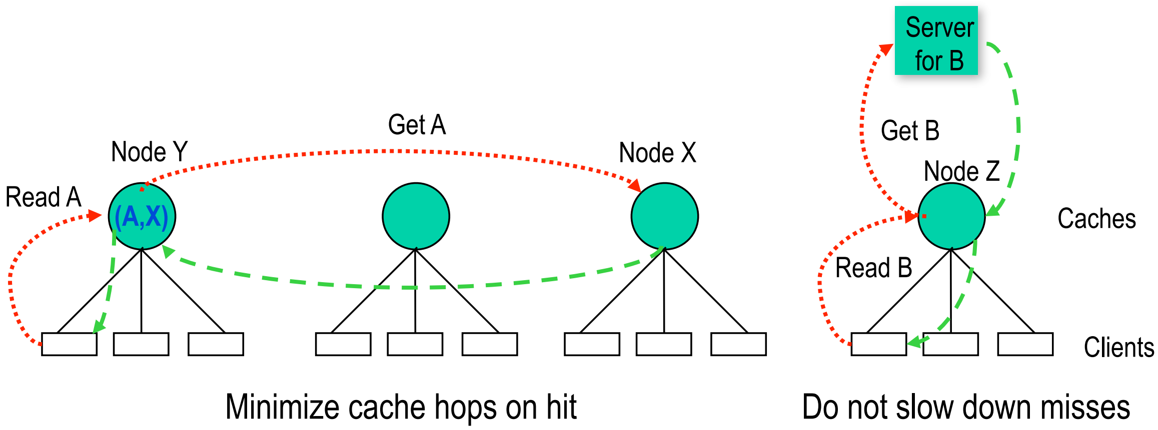
- Caching infrastructure can have multiple web proxies
  - Proxies can be arranged in a hierarchy or other structures
    - Overlay network of proxies: content distribution network
  - Proxies can cooperate with one another
    - Answer client requests
    - Propagate server notifications

Hierarchical Proxy Caching



Examples: Squid, Harvest

Locating and Accessing Data



Properties

- Lookup is local
- Hit at most 2 hops
- Miss at most 2 hops (1 extra on wrong hint)

Edge Computing

- Web caches effective when deployed close to clients
  - At the "Edge" of the network
- Edge Computing: paradigm where applications run on servers located at the edge of the network
- Benefits
  - Significantly lower latency than "remote" cloud servers
  - Higher bandwidth
  - Can tolerate network or cloud failures
- Complements cloud computing
  - Cloud providers offer edge servers as well as cloud servers

Edge Computing Origins

- Origins come from mobile computing and web caching
- Content delivery networks
  - Network of edge caches deployed as commercial service
  - Cache web content (especially rich content: images, video)
  - Deliver from closest edge proxy server

- Mobile computing
  - devices has limited resources, limited battery power
  - computational offload: offload work to more capable edge server
  - low latency offload important for interactive mobile applications
  - edge server sends results to the mobile

Content Delivery Networks

- Global network of edge proxies to deliver web content
  - edge clusters of varying sizes deployed in all parts of the world
  - Akamai CDN: 120K servers in 1100 networks, 80 countries
- Content providers are customers of CDN service
  - Examples: news sites, image-rich online stores, streaming sites
  - Decide what content to cache/offload to CDN
  - Embed links to cdn content: http://cdn.com/company/foo.mp4
  - Consistency responsibility of content providers
- Users access website normally
  - Some content fetched by browser from CDN cache

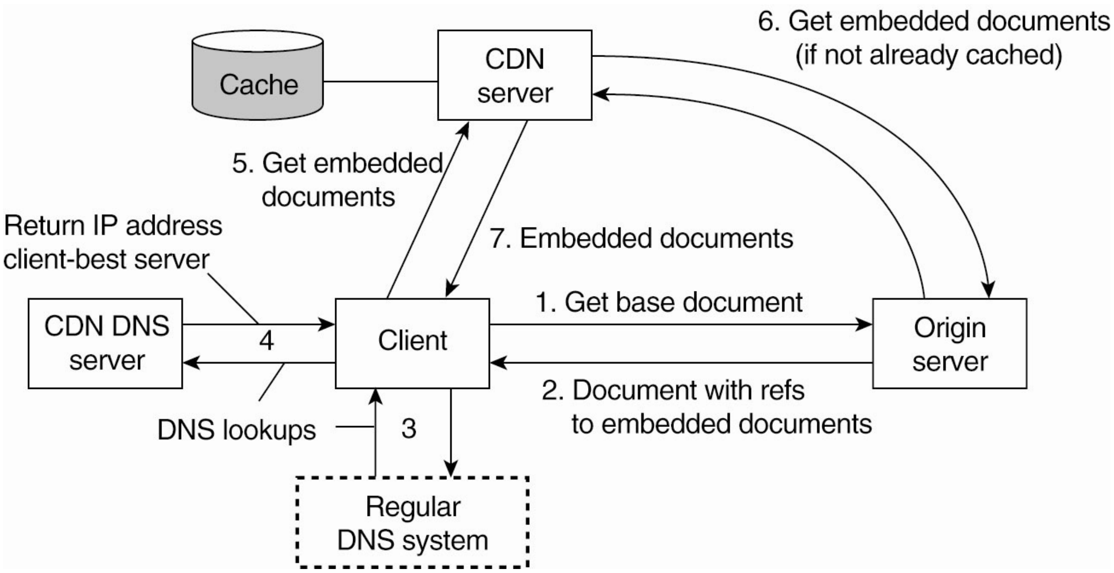
CDN Request Routing

- Web request need to be directed to nearby CDN server
- Two level load balancing
  - Global: decide which cluster to use to serve request
  - Local: decide which server in the cluster to use
- DNS-based approach is common
  - Special DNS server: resolve www.cnn.com/newsvideo.mp4
  - DNS checks location of client and resolves to IP address of nearby CDN server
  - Different users will get resolved to different edge locations

CDN Issues

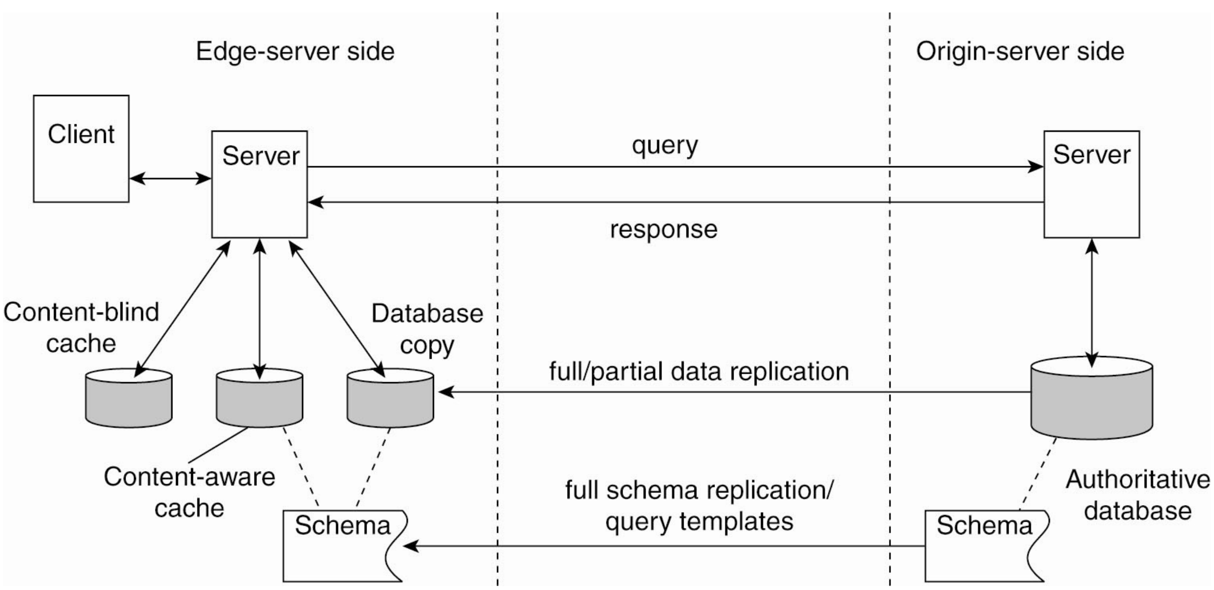
- Which proxy answers a client request?
  - Ideally the "closest" proxy
  - Akamai uses a DNS-based approach
- Propagating notifications
  - Can use multicast or application level multicast to reduce overheads (in push-based approaches)
- Active area of research
  - Numerous research papers available

CDN Request Processing



- The principal working of the Akamai CDN.

CDN Hosting of Web Applications



Mobile Edge Computing

- Use case: Mobile offload of compute-intensive tasks
- Example: augmented reality, virtual reality (mobile AR/VR)
  - mobile phone or headset has limited resources, limited battery
  - Low latency / response times for interactive use experience
  - mobile devices may lack a GPU or mobile GPU may be limited

- Today's smartphones are highly capable (multiple cores, mobile GPU, neural processor)
  - mobile offload more suitable for less capable devices (e.g., AR headset)
- 5G cellular providers: deploy edge servers near cell towers
  - industrial automation, autonomous vehicles

Edge Computing Today

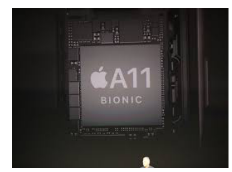
- Emerging approach for latency-sensitive applications
- Edge AI: run AI (deep learning) inference at edge
  - home security camera sends feed, run object detection
- Low latency offload: autonomous vehicles, smart city sensors, smart home etc.
- Edge computing as an extension to cloud
  - Cloud regions augmented by local regions
    - Local regions are edge clusters that offer normal cloud service (but at lower latency) E.g., AWS Boston region
  - Internet of Things (IoT) data processing sevices

Specialized Edge Computing

- Edge accelerators: special hardware to accelerate edge tasks on resource constrained edge servers
  - Nvidia Jetson GPU, Google edge Tensor processing Unit (TUP), Intel Vision Processing Unit (VPU)
- Example: IoT ML inference on edge accelerators
  - Efficient inference on resource-constrained edge servers

Google Edge TPU

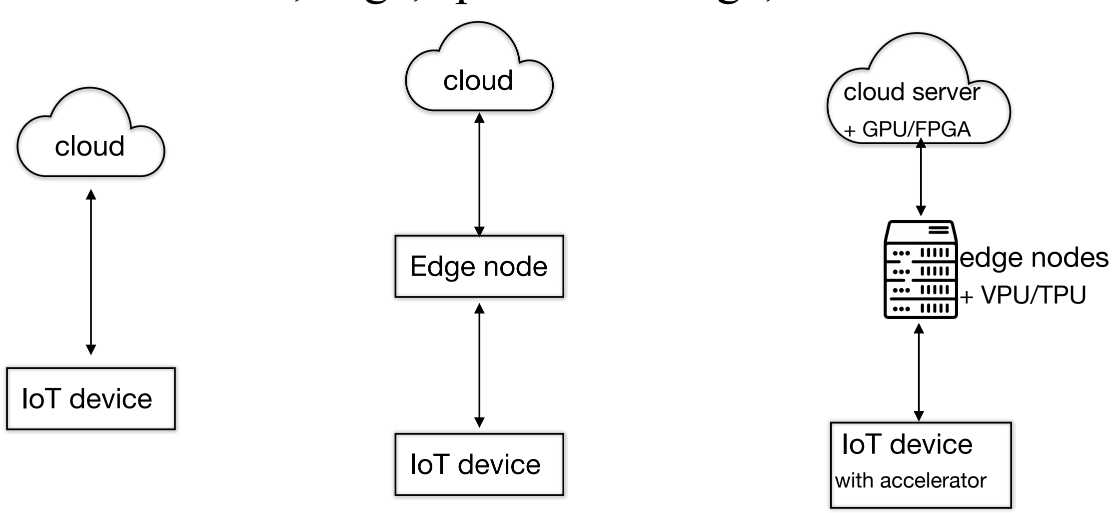
Nvidia Jetson Nano GPU



Apple Neural Engine

Cloud and Edge Architectures

- Offload to cloud, edge, specialized edge,



Traditional cloud (2-tier) | Traditional edge (3-tier) | Specialized (3-tier)