Democratizing content distribution

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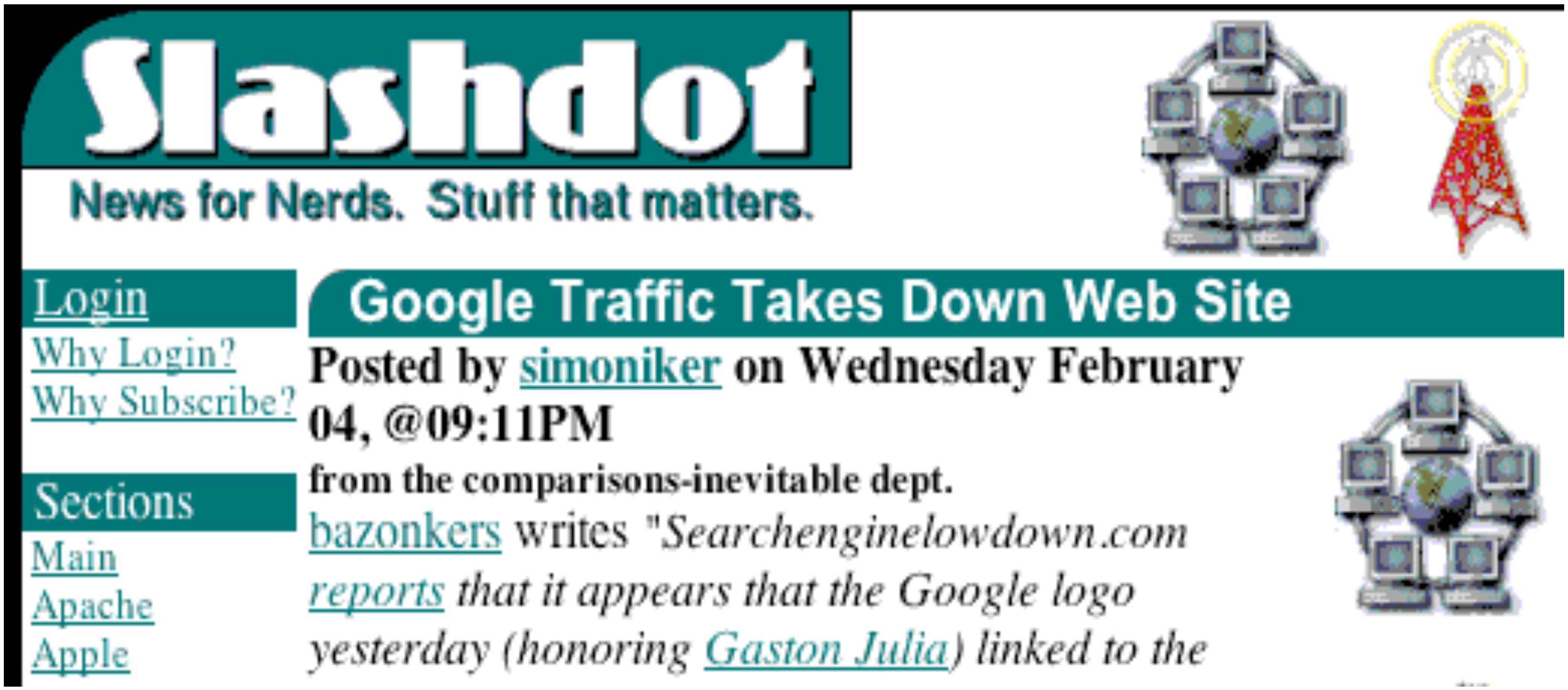
Overloading content publishers

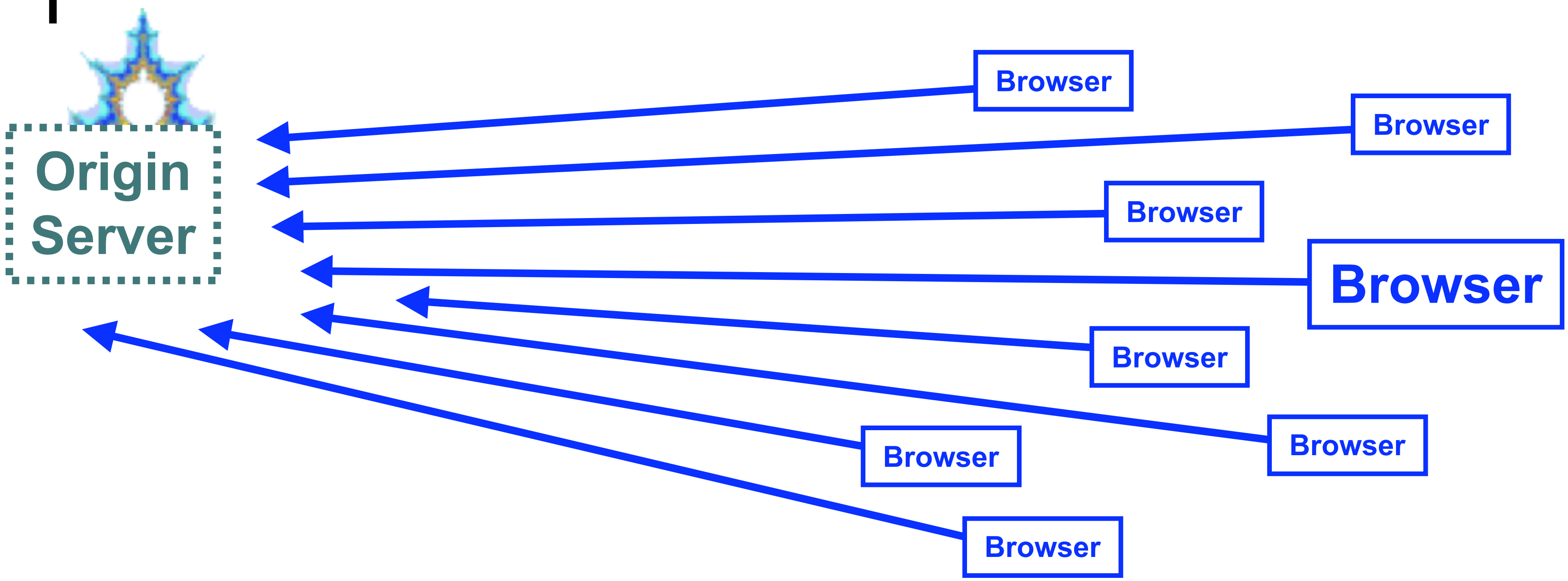
- Feb 3, 2004: Google linked banner to “julia fractals”
- Users clicked onto University of Western Australia web site
- …University’s network link overloaded, web server taken down temporarily…

Adding insult to injury…



- Next day: Slashdot story about Google overloading site
- …UWA site goes down again

Insufficient server resources

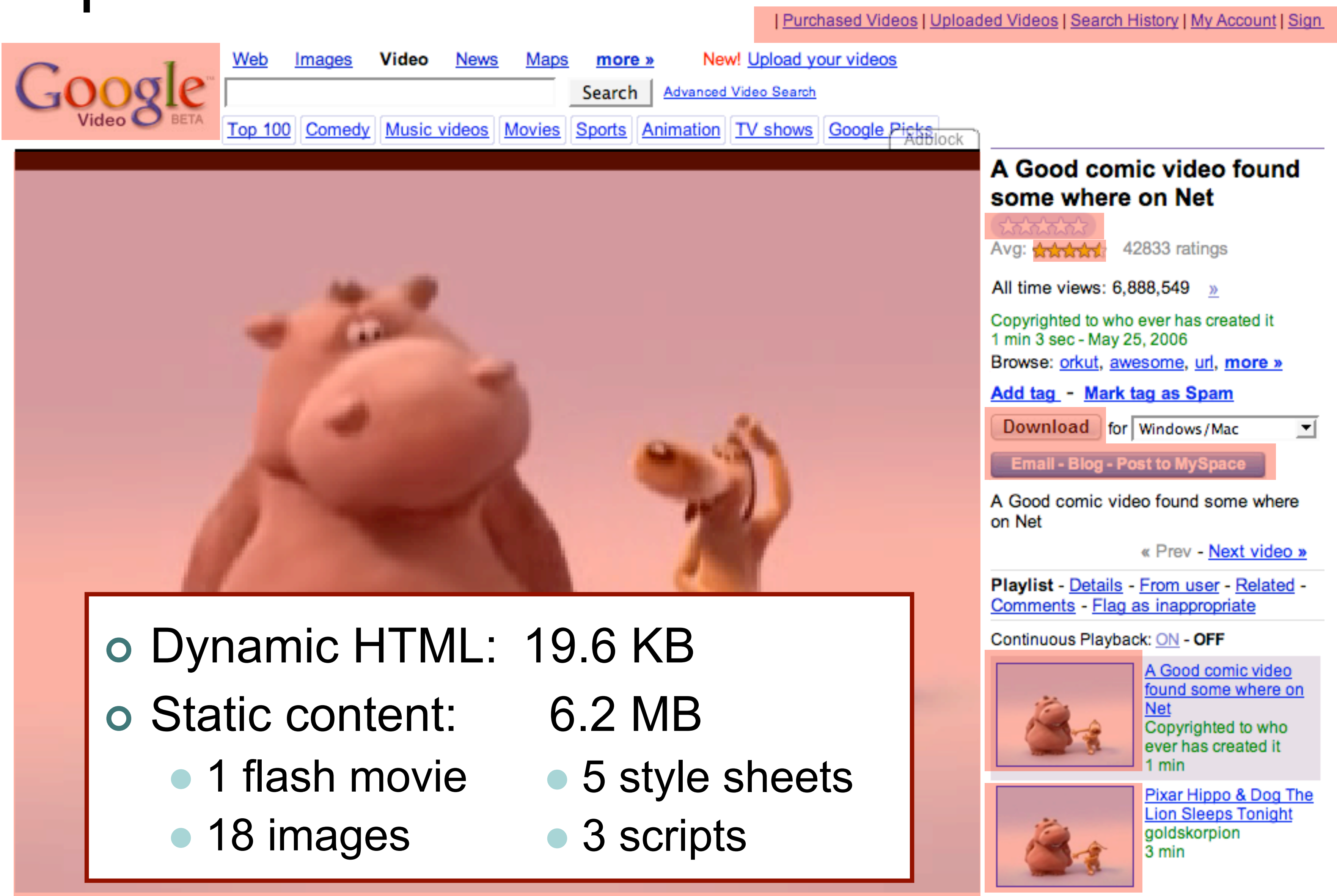


- Many clients want content
- Server has insufficient resources
- Solving the problem requires more resources

Serving large audiences possible…

- Where do their resources come from?
  - Must consider two types of content separately
    - Static
    - Dynamic

Static content uses most bandwidth



- Dynamic HTML: 19.6 KB
- Static content: 6.2 MB
  - 1 flash movie
  - 18 images
  - 5 style sheets
  - 3 scripts

Serving large audiences possible…

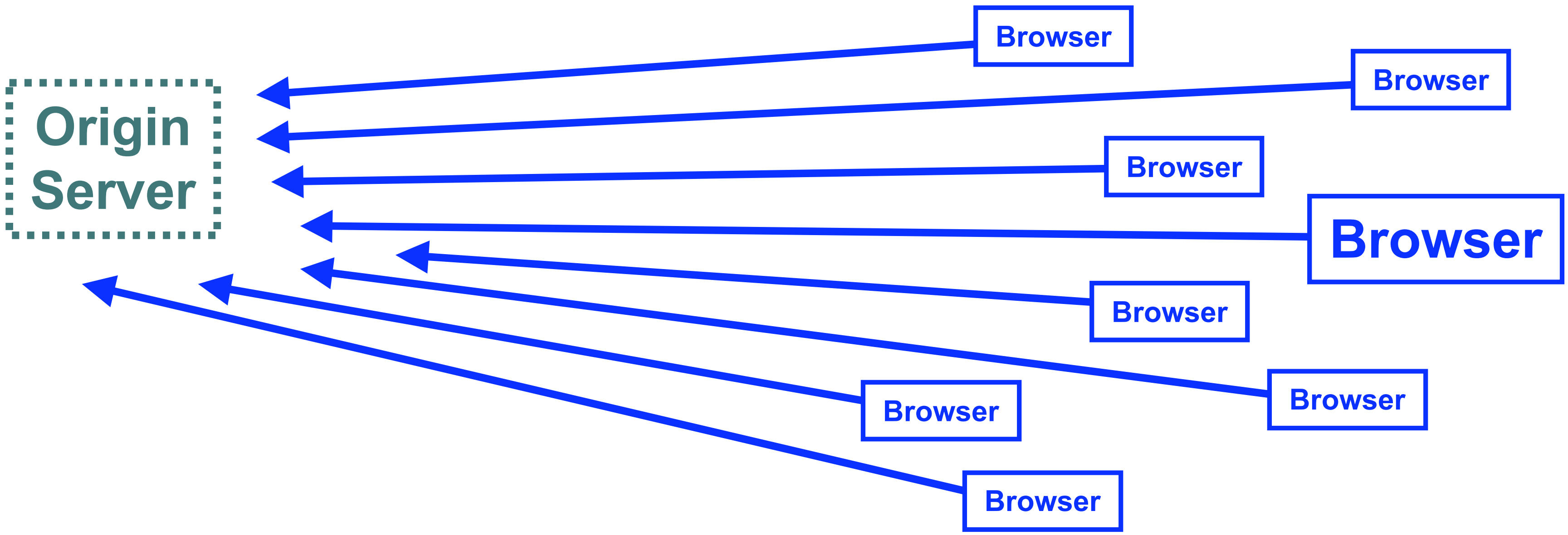
- How do they serve static content?

Content distribution networks (CDNs)

Centralized CDNs

- Static, manual deployment
- Centrally managed
- Implications:
  - Trusted infrastructure
  - Costs scale linearly

Not solved for little guy



- Problem:
  - Didn’t anticipate sudden load spike (flash crowd)
  - Wouldn’t want to pay / couldn’t afford costs

Leveraging cooperative resources

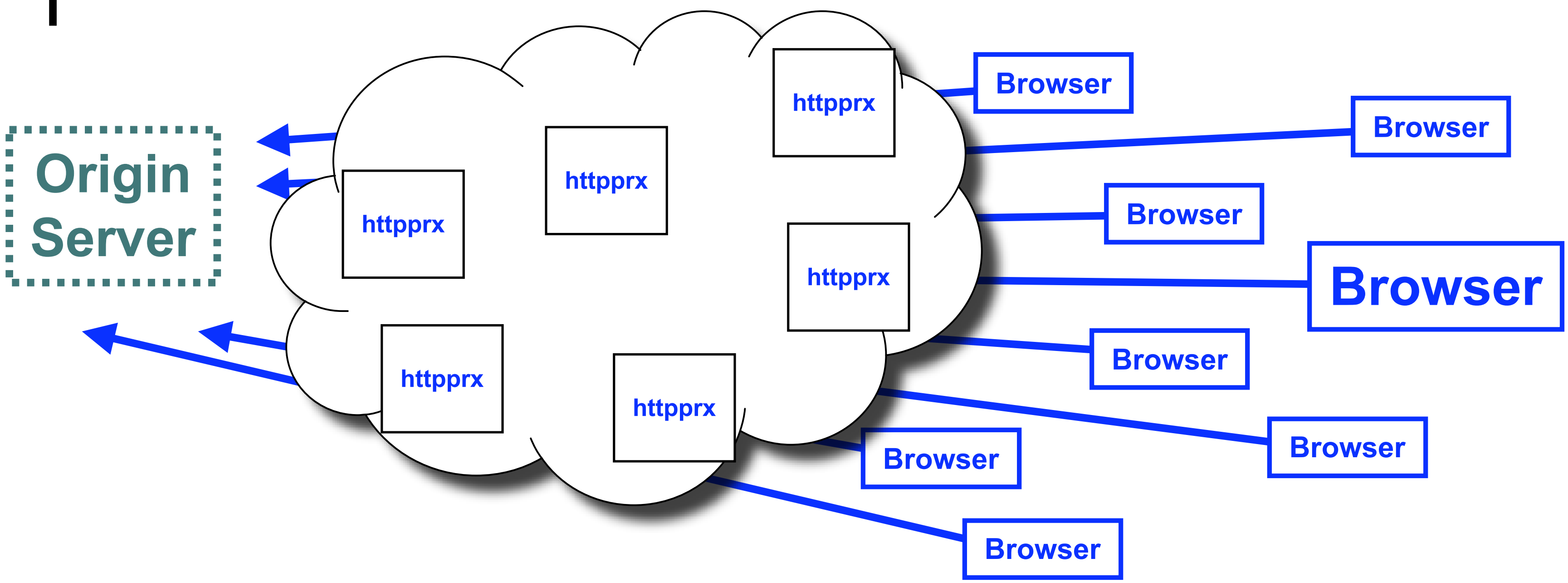
- Many people want content
- Many willing to mirror content
  - e.g., software mirrors, file sharing, open proxies, etc.
- Resources are out there

…if only we can leverage them

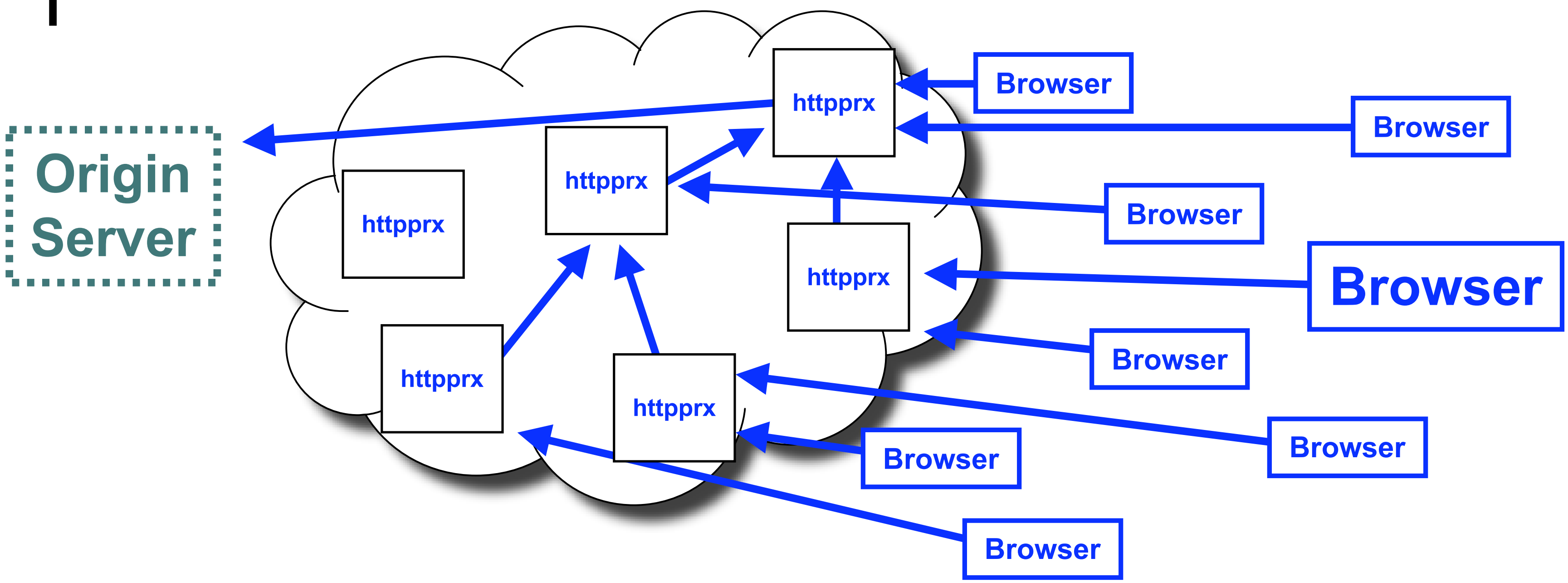
- Contributions

Theme throughout talk: How to leverage previously untapped resources to gain new functionality

Proxies absorb client requests



Proxies absorb client requests



- Reverse proxies handle all client requests
- Cooperate to fetch content from one another

A comparison of settings

Centralized CDNs

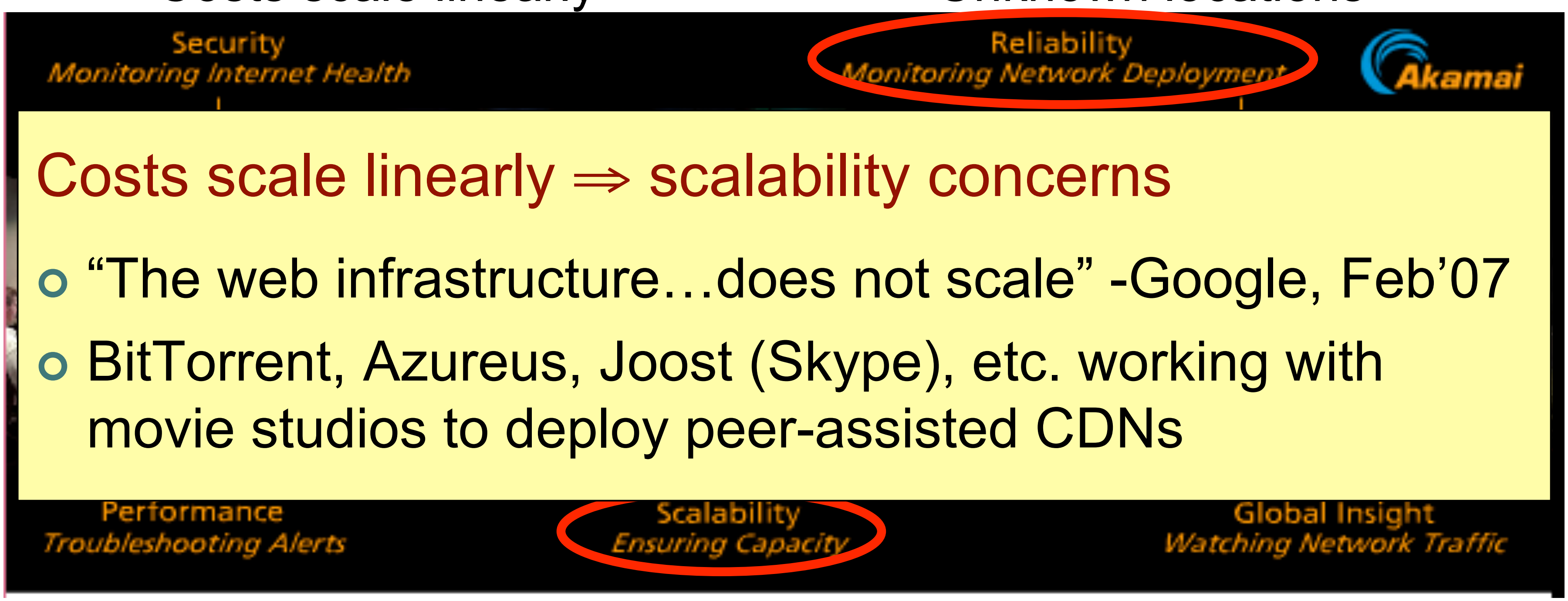
- Static, manual deployment
- Centrally managed
- Implications:
  - Trusted infrastructure
  - Costs scale linearly

Decentralized CDNs

- Use participating machines
- No central operations
- Implications:
  - Less reliable or untrusted
  - Unknown locations

A comparison of settings

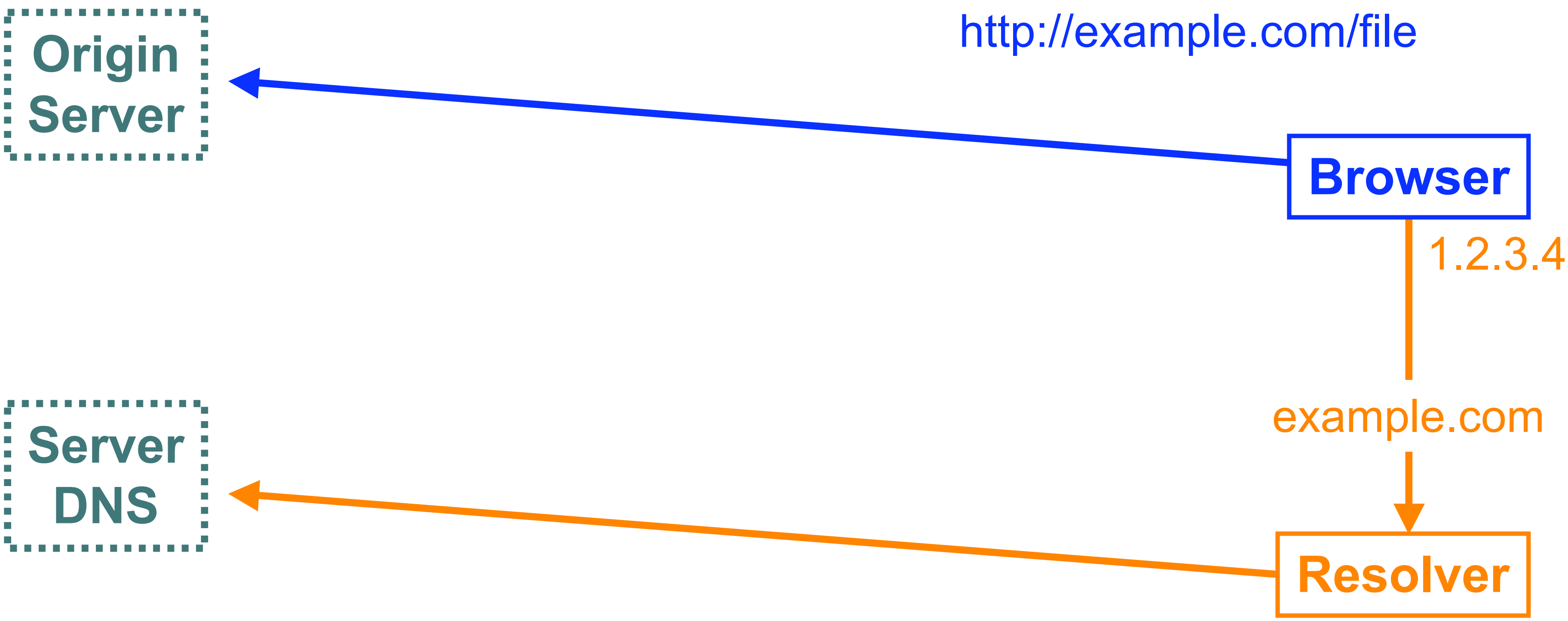
Centralized CDNs	Decentralized CDNs
Static, manual deployment	Use participating machines
Centrally managed	No central operations
Implications:	Implications:
• Trusted infrastructure	• Less reliable or untrusted
• Costs scale linearly	• Unknown locations



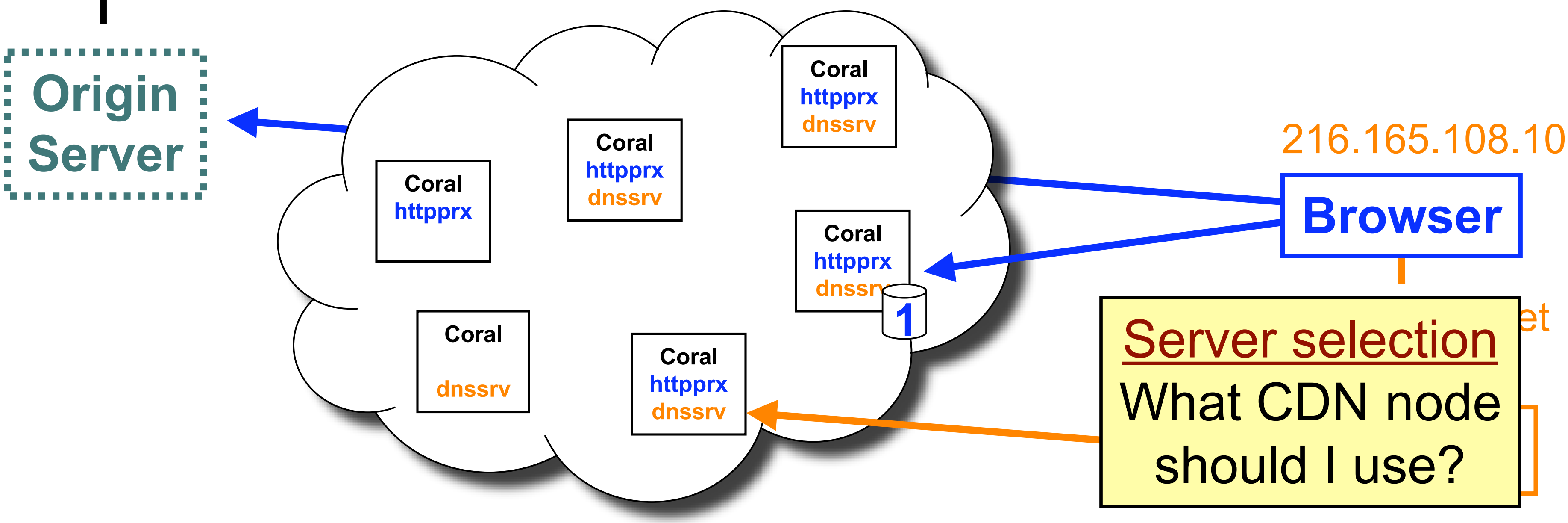
Costs scale linearly ⇒ scalability concerns

- “The web infrastructure…does not scale” -Google, Feb’07
- BitTorrent, Azureus, Joost (Skype), etc. working with movie studios to deploy peer-assisted CDNs

Getting content



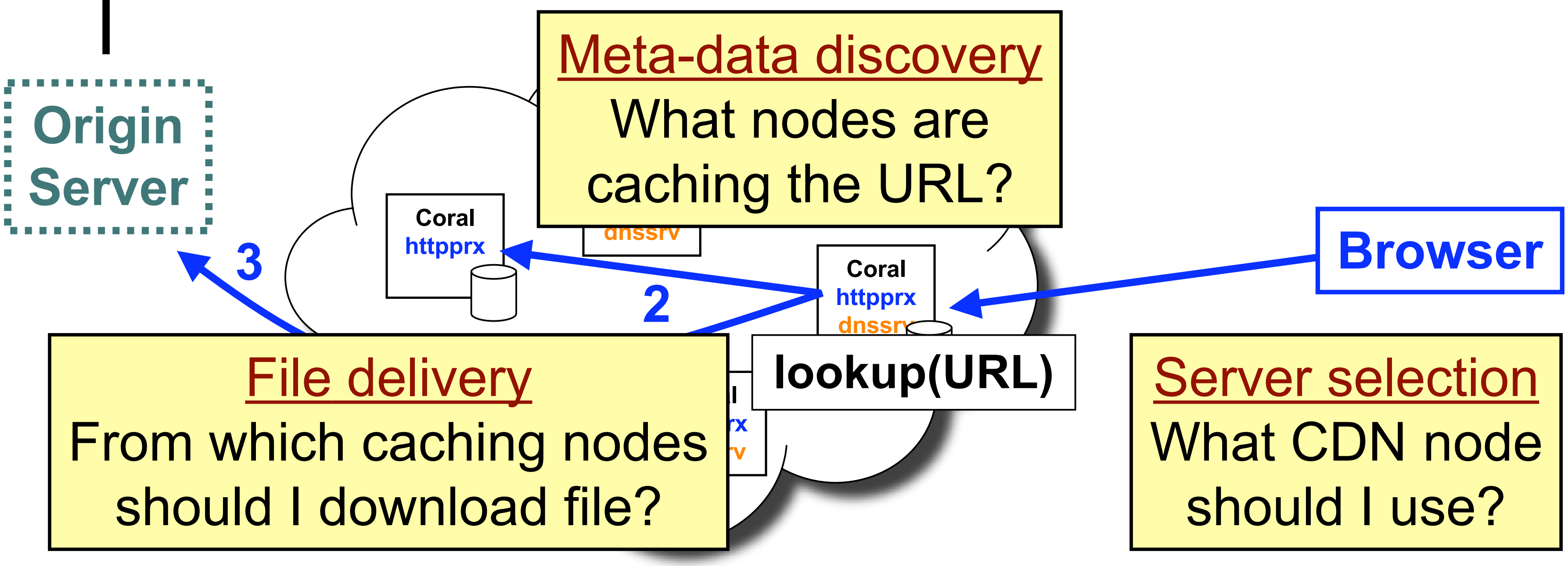
Getting content with CoralCDN



- Participants run CoralCDN software, no configuration
- Clients use CoralCDN via modified domain name

  example.com/file → example.com.nyud.net:8080/file

Getting content with CoralCDN



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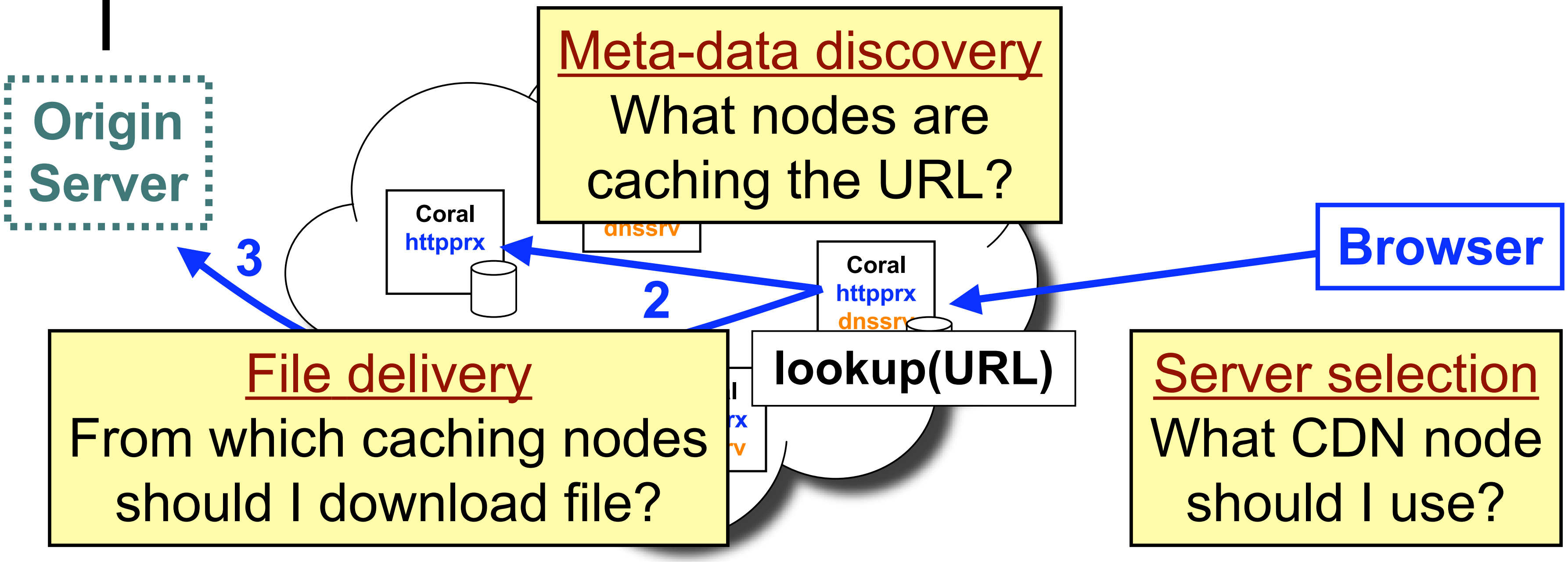
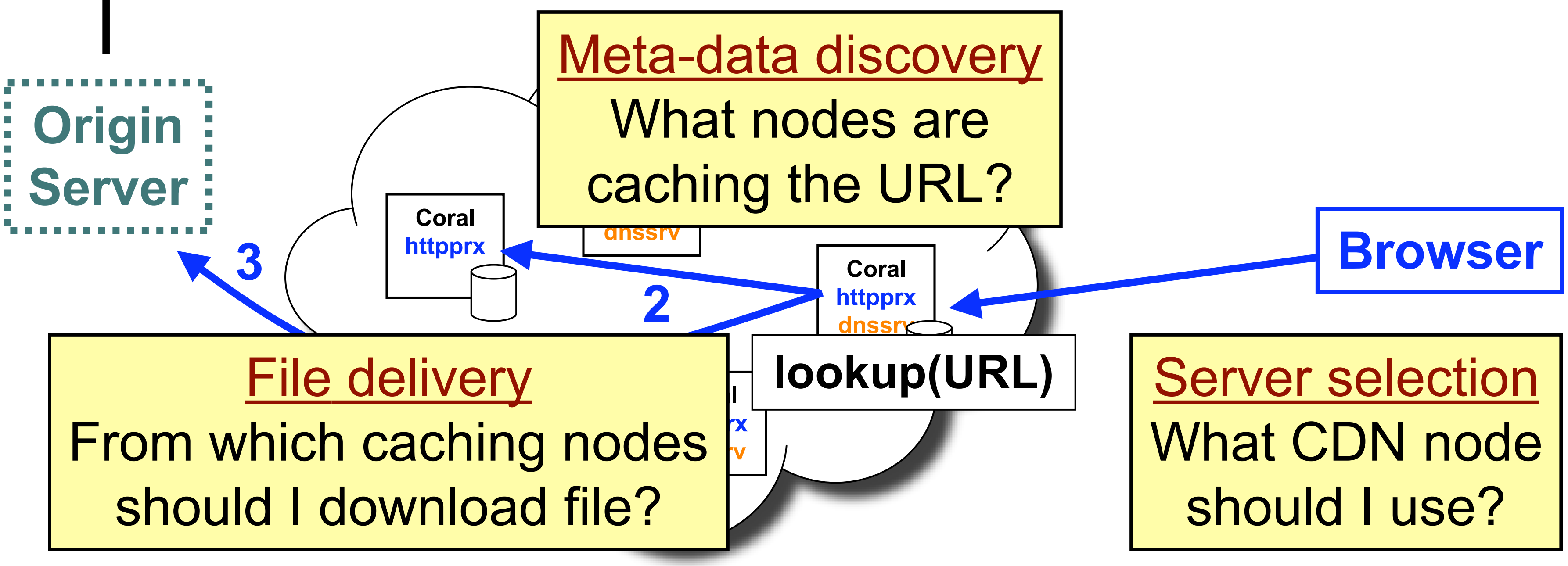


- Goals
  - Reduce load at origin server
  - Low end-to-end latency
  - Self-organizing

Getting content with CoralCDN

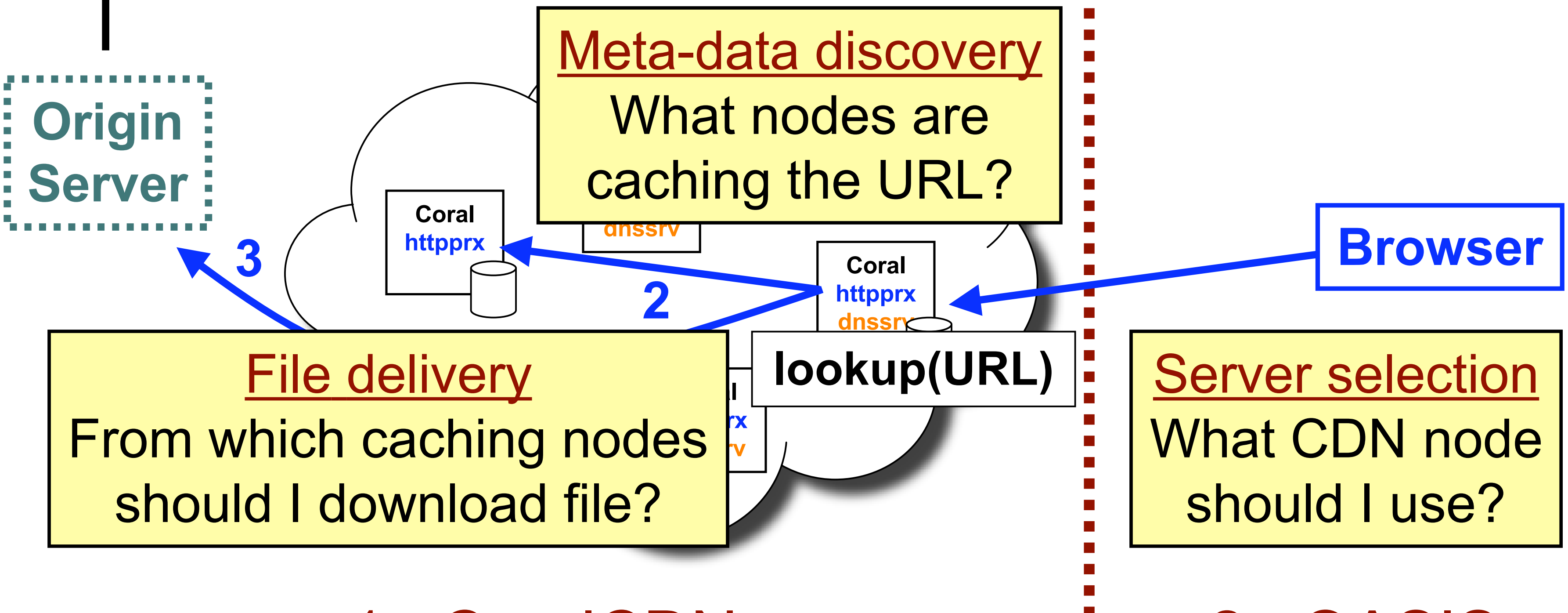


- Why participate?
  - Ethos of volunteerism
  - Cooperatively weather peak loads spread over time
  - Incentives: Better performance when resources scarce

This talk

[IPTPS '03] [NSDI '04]

[NSDI '06]



1. CoralCDN
2. OASIS

3. Using these for measurements: Illuminati [NSDI '07]
4. Finally, adding security to leverage more volunteers

“ Real deployment ”

Powered By PLANETLAB

- Currently deployed on 300-400 PlanetLab servers
  - CoralCDN running 24 / 7 since March 2004

- An open CDN for *any* URL:

  example.com/file → example.com.nyud.net:8080/file

“ Real deployment ”

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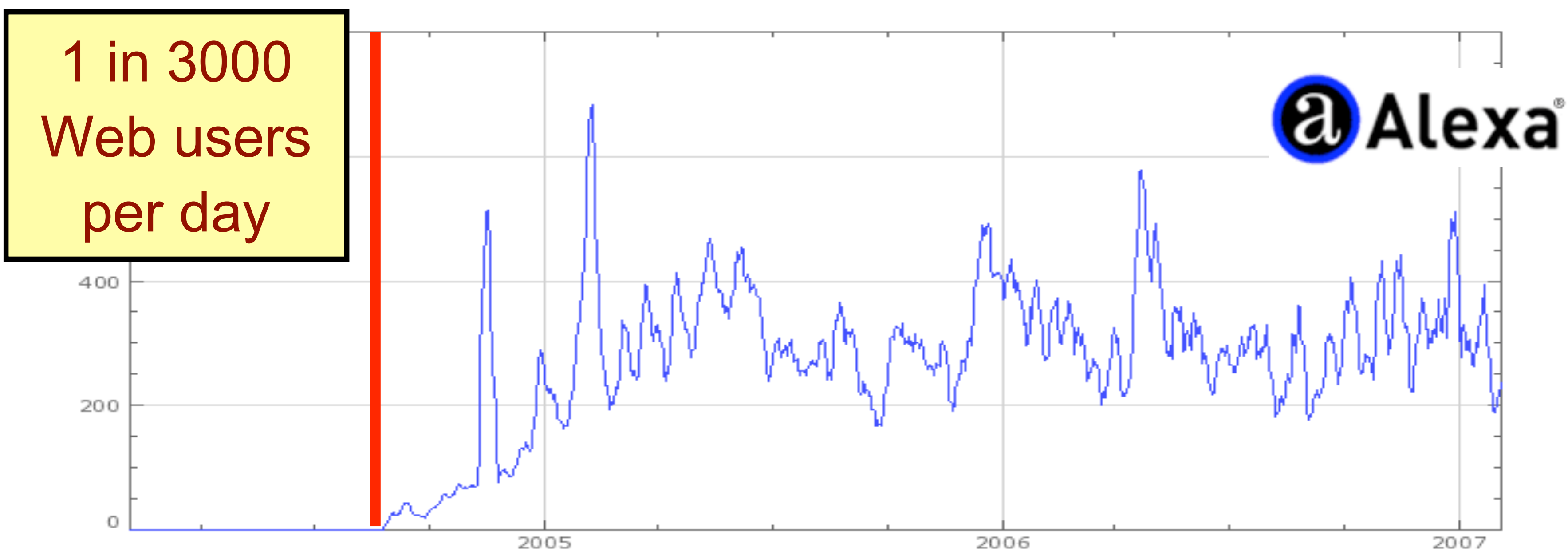

This talk

[IPTPS '03]
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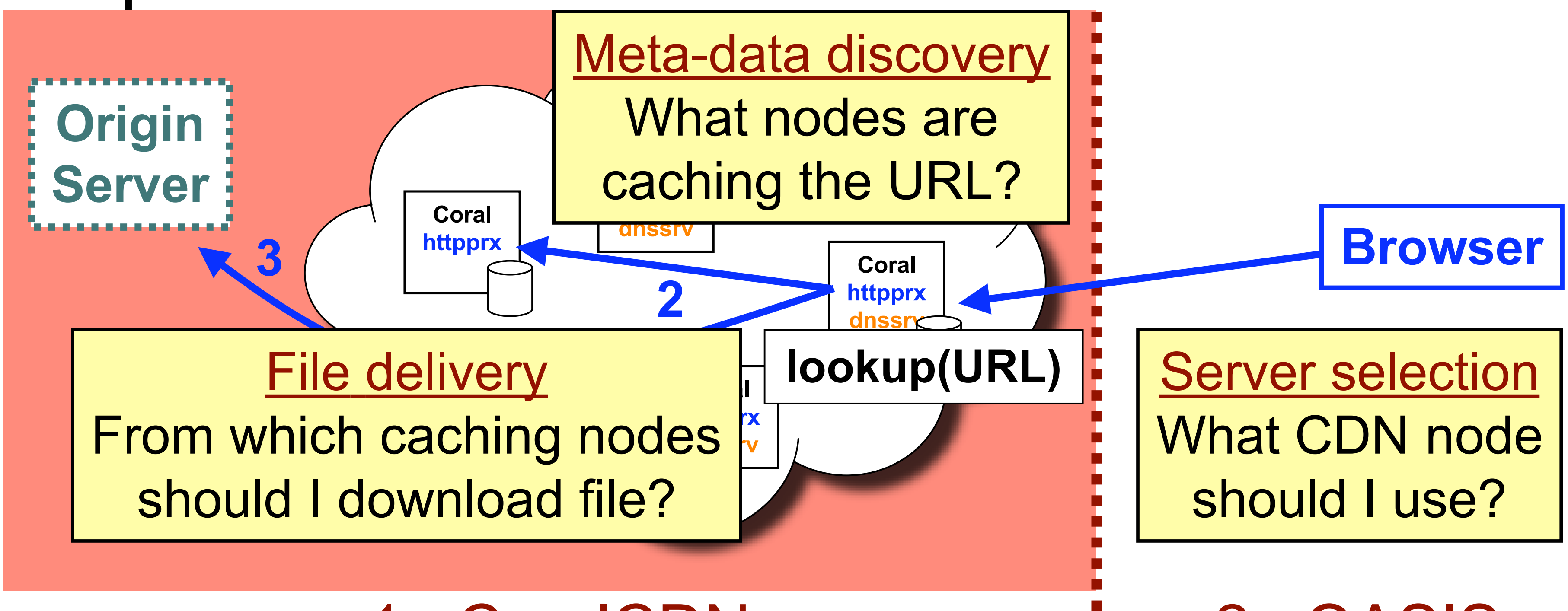

1. CoralCDN
2. OASIS
3. Using these for measurements: Illuminati [NSDI '07]
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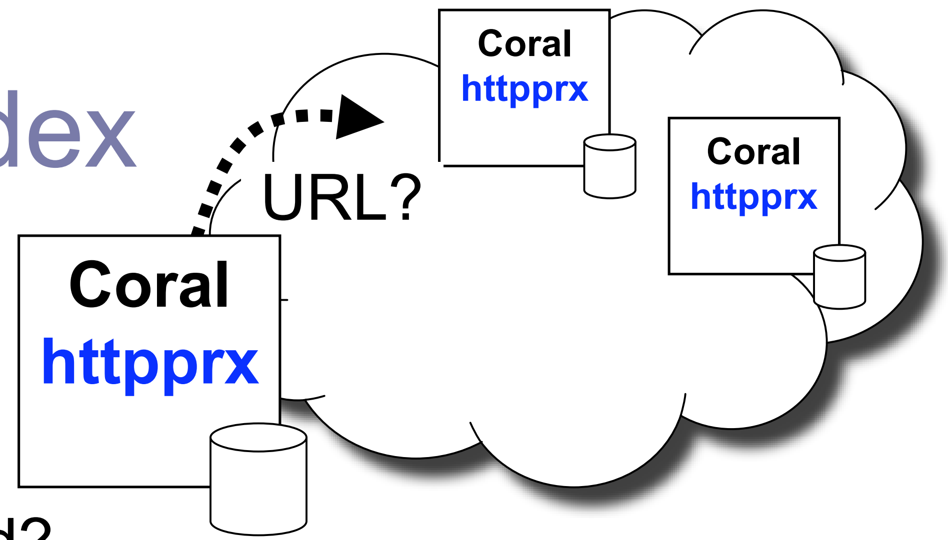
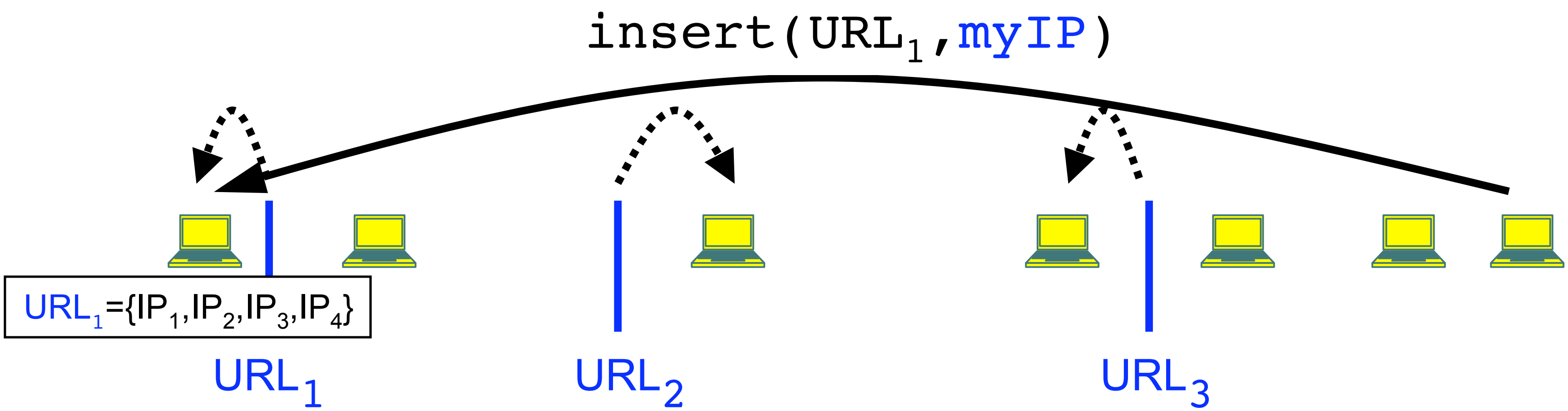
We need an index



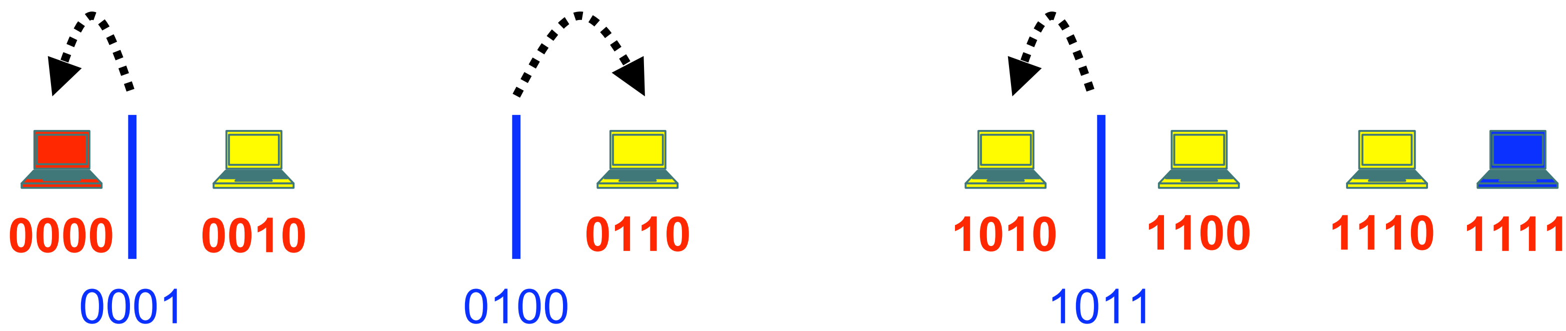
- Given a URL:
  - Where is the data cached?
  - Map name to location: URL ⇒ {IP_1, IP_2, IP_3, IP_4}
  - `lookup(URL)` ⇒ Get IPs of caching nodes
  - `insert(URL,myIP,TTL)` ⇒ Add me as caching URL for TTL seconds
- Can't index at central servers
  - No individual machines reliable or scalable enough
- Need to distribute index over participants

Strawman: distributed hash table (DHT)



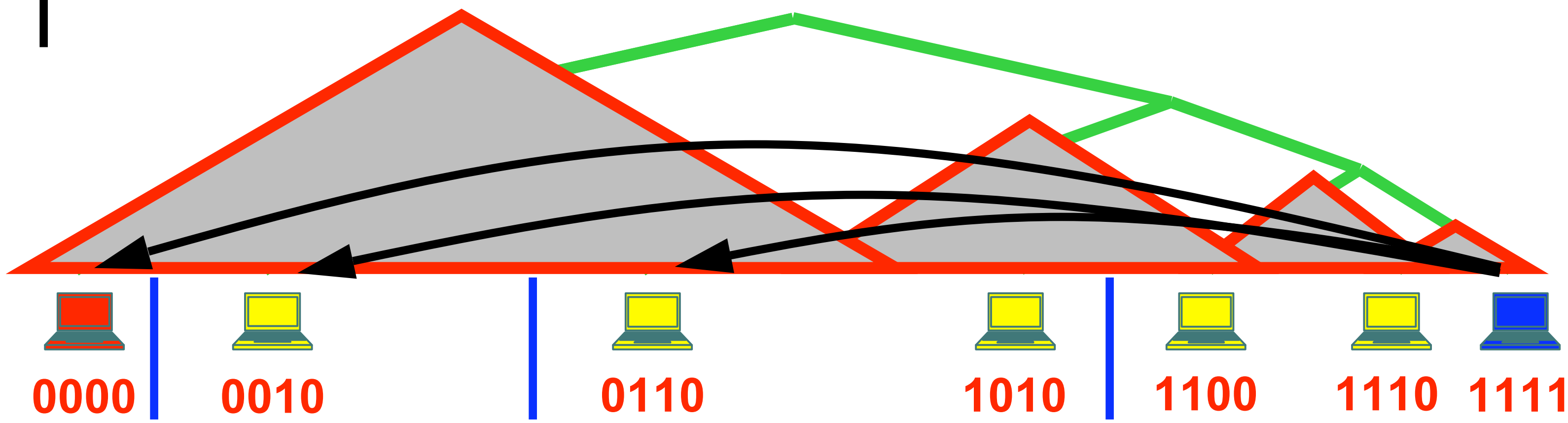
- Use DHT to store mapping of URLs (keys) to locations
- DHTs partition key-space among nodes
- Contact appropriate node to lookup/store key
  - Blue node determines red node is responsible for URL
  - Blue node sends lookup or insert to red node

Strawman: distributed hash table (DHT)



- Partitioning key-space among nodes
  - Nodes choose random identifiers: hash(IP)
  - Keys randomly distributed in ID-space: hash(URL)
  - Keys assigned to node nearest in ID-space
    - Minimizes *XOR(hash(IP),hash(URL))*

Strawman: distributed hash table (DHT)



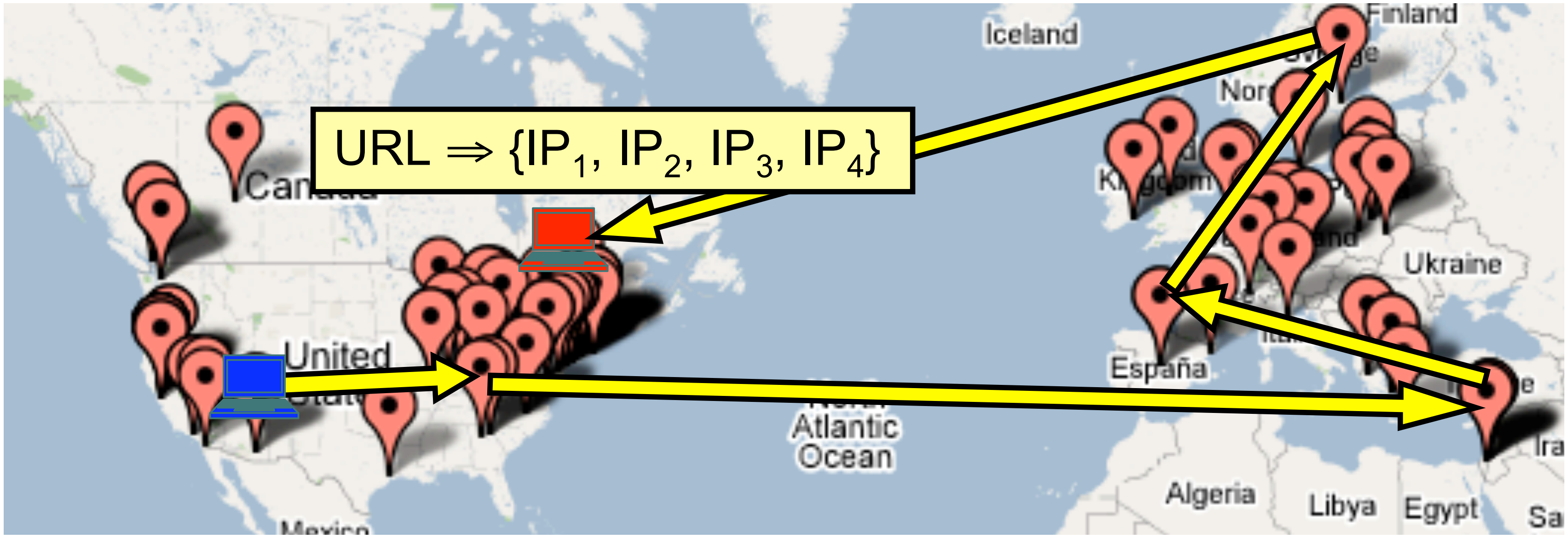
- Provides "efficient" routing with small state

  If *n* is # nodes, each node:

  - Monitors *O(log n)* peers
  - Discovers closest node (and URL map) in *O(log n)* hops
  - Join/leave requires O(log n) work

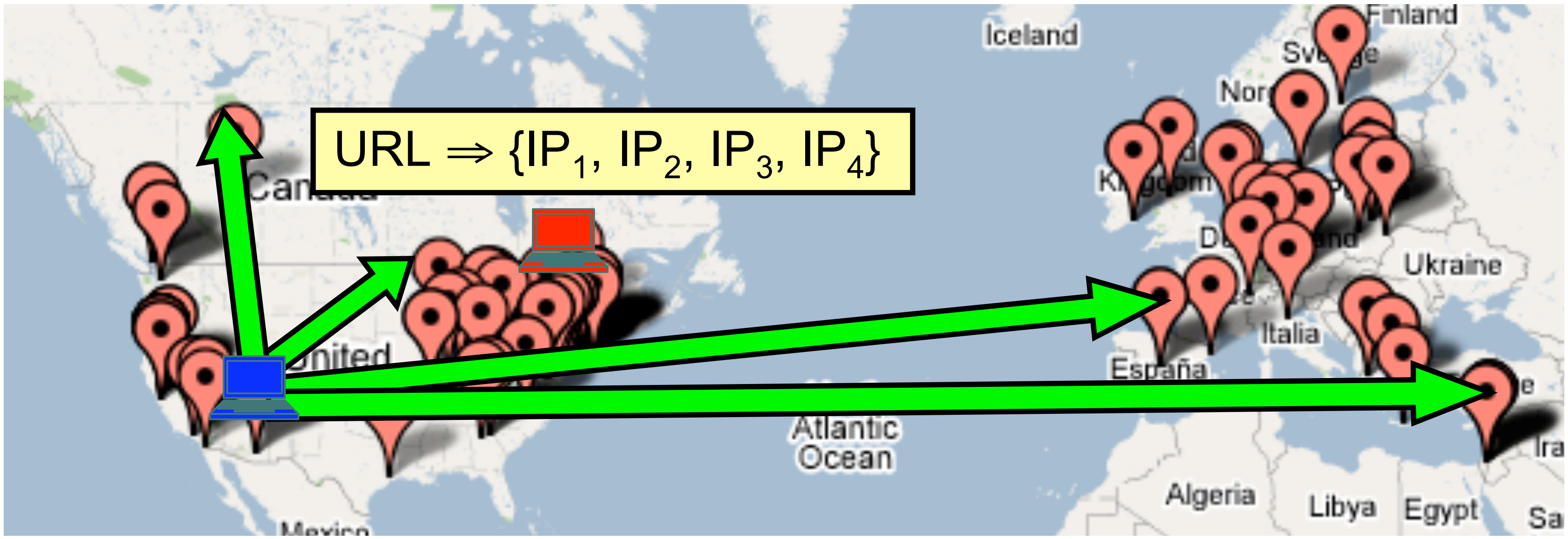
- Spread ownership of URLs evenly across nodes

Is this index sufficient?



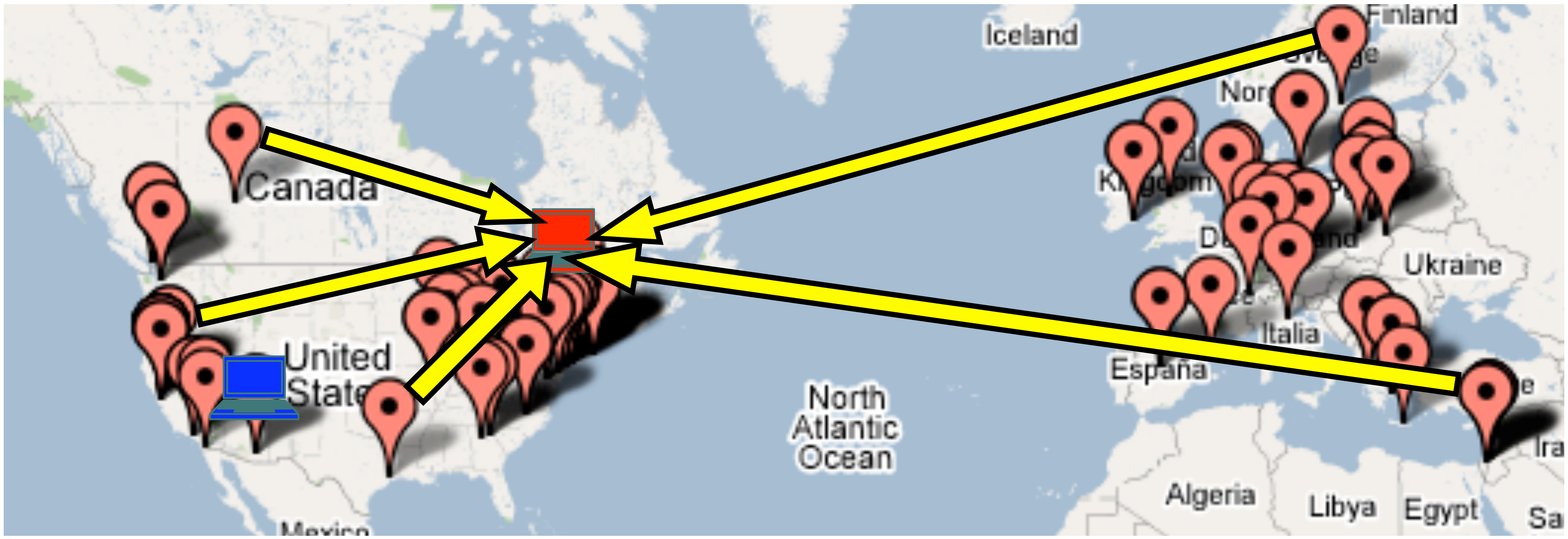
- **Problem:** Random routing

Is this index sufficient?



- Problem: Random routing
- Problem: Random downloading

Is this index sufficient?



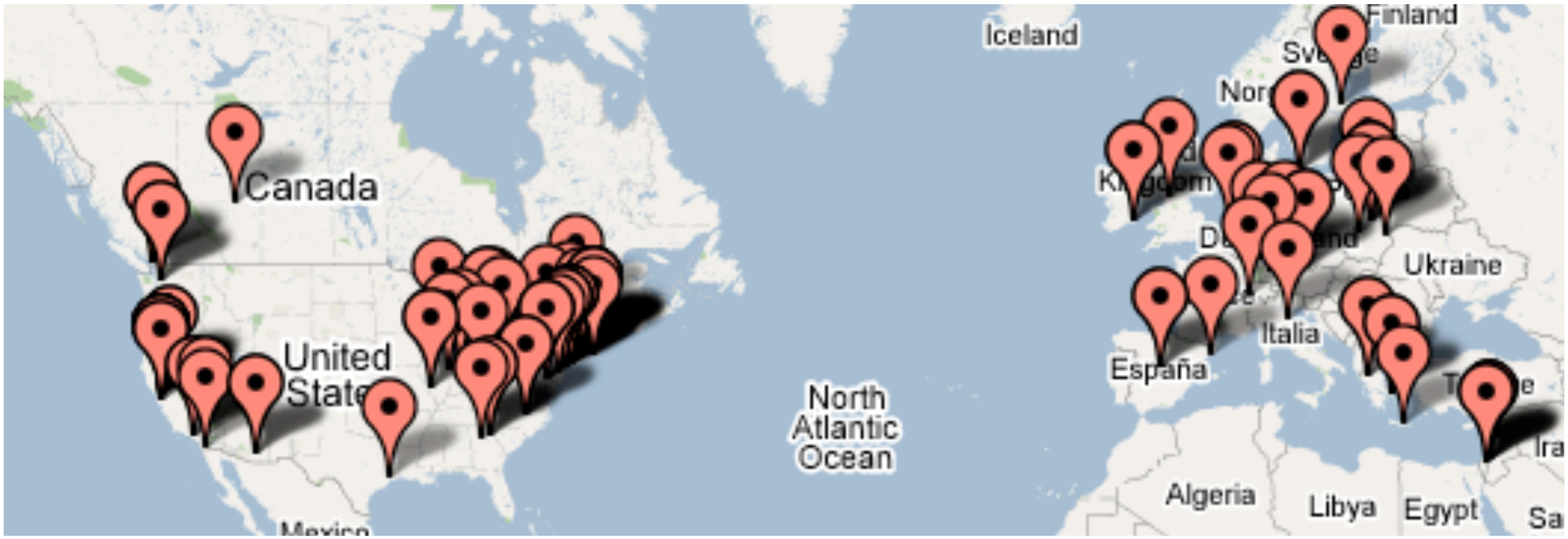
- Problem: Random routing
- Problem: Random downloading
- Problem: No load-balancing for single item
  - All `insert` and `lookup` go to same closest node

Don't need hash-table semantics

- DHTs designed for hash-table semantics
  - Insert and replace: URL ⇒ IP_{last}
  - Insert and append: URL ⇒ {IP_1, IP_2, IP_3, IP_4}

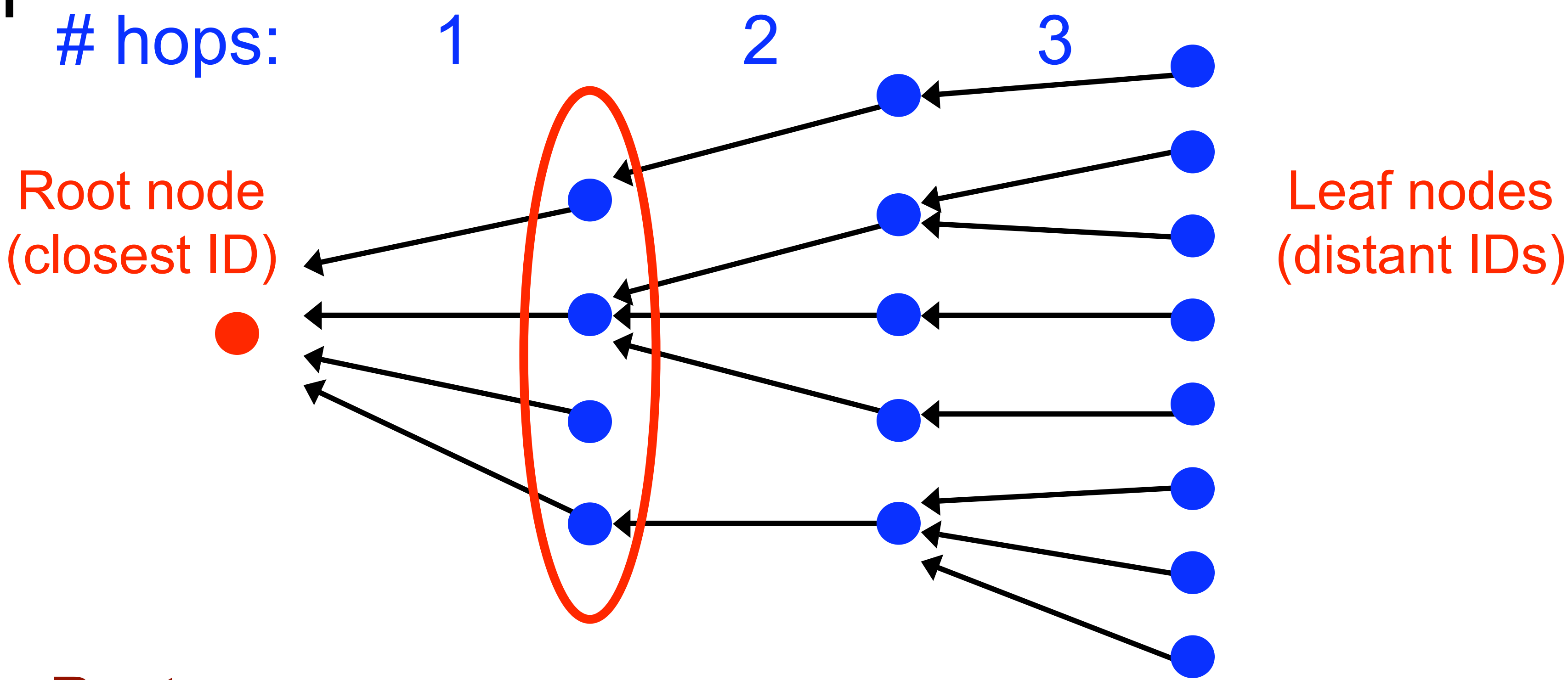
- We only need few values
  - `lookup`(URL) ⇒ {IP_2, IP_4}
  - Preferably ones close in network

Next…



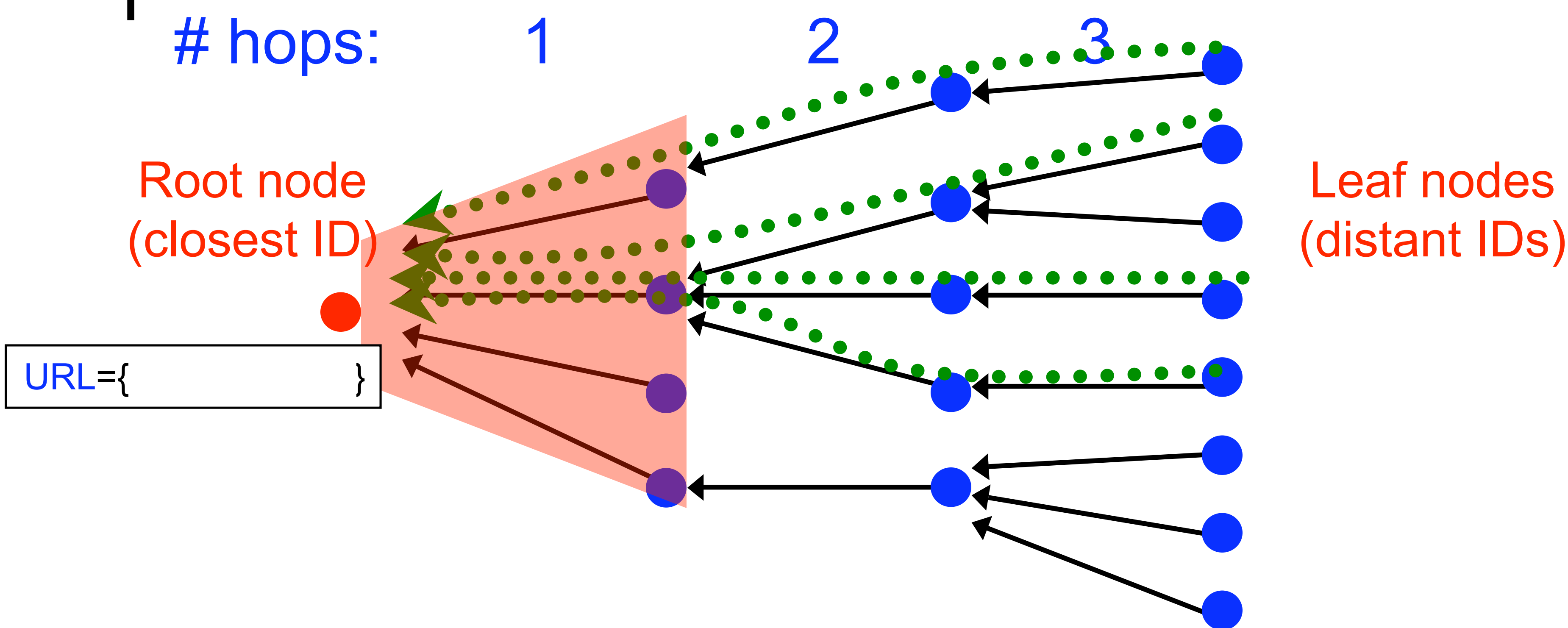
- Solution: Bound request rate to prevent hotspots
- Solution: Take advantage of network locality

Prevent hotspots in index



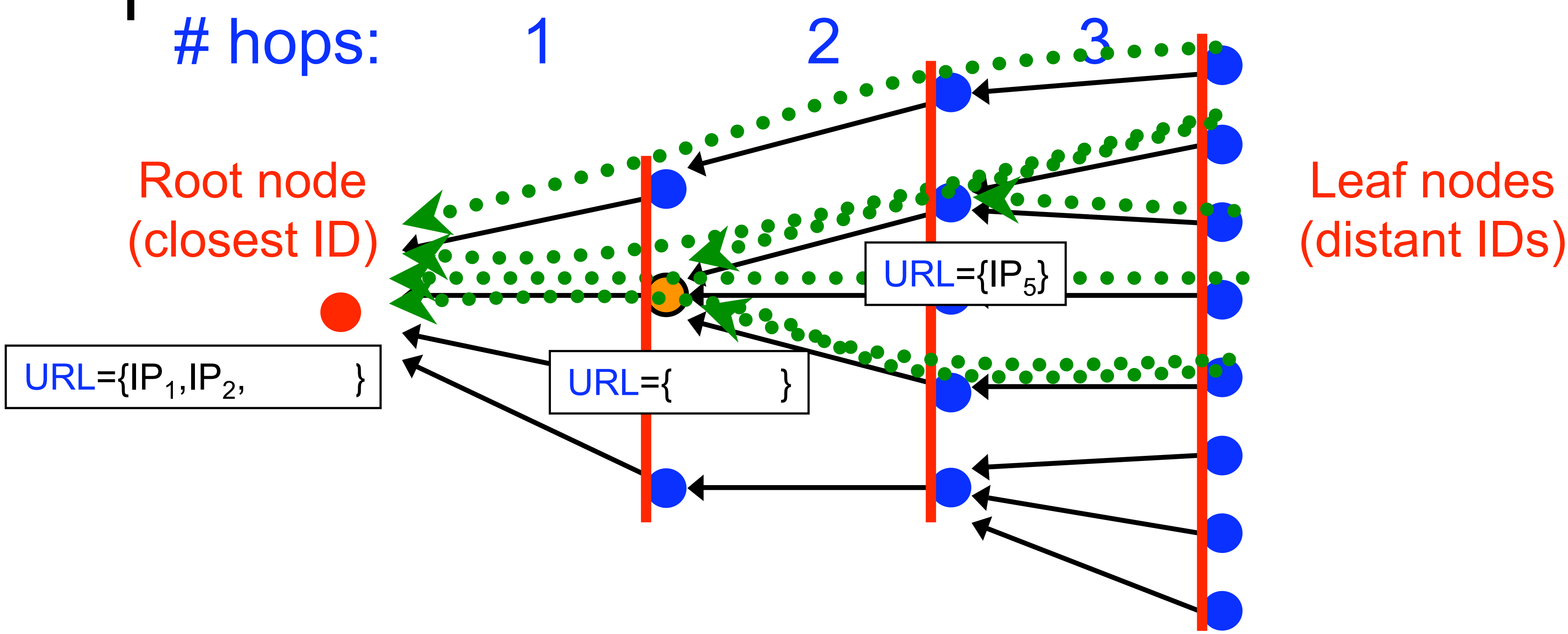
- Route convergence
  - *O(log n)* nodes are 1 hop from root

Prevent hotspots in index



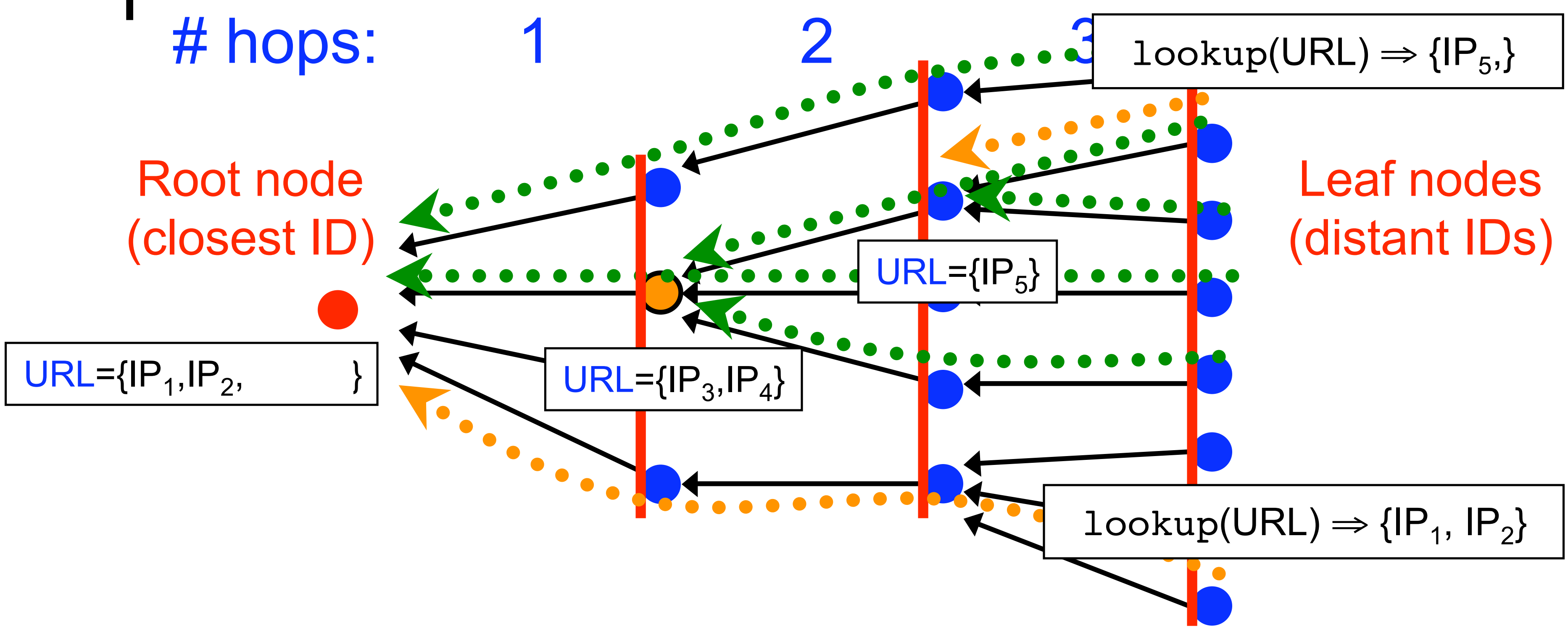
- Route convergence
  - *O(log n)* nodes are 1 hop from root
- Request load increases exponentially towards root

Rate-limiting requests



- Bound rate of inserts towards root
  - Nodes leak through at most β inserts per min per URL
- Locations of popular items pushed down tree
  - Refuse if already storing max # “fresh” IPs per URL

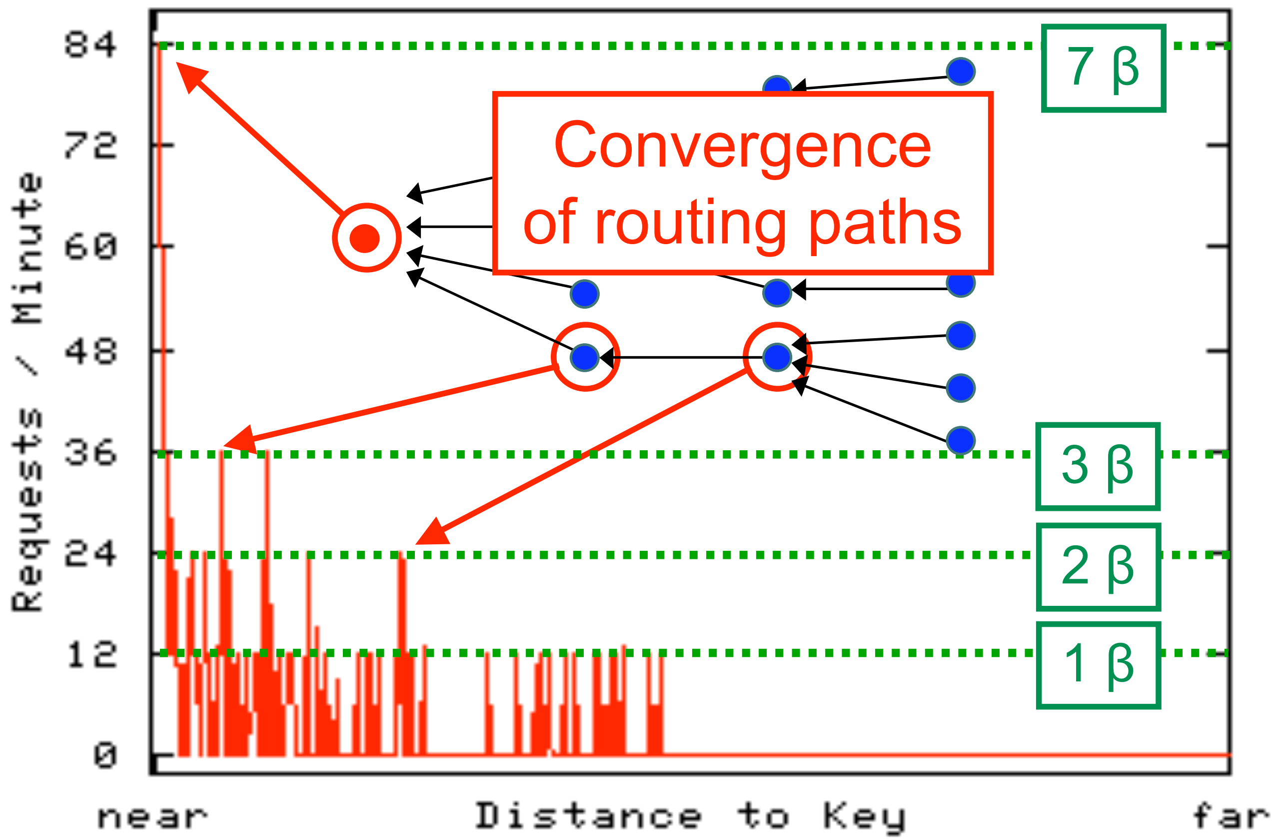
Rate-limiting requests



- **High load:** Most stored on path, few on root

Theorem: Fixing *b* bits per hop, root receives $\beta \cdot (2^b - 1) \cdot \left\lceil \frac{\log_{b+1} n}{b} \right\rceil$ insertion requests per time period

Wide-area results follow analytics

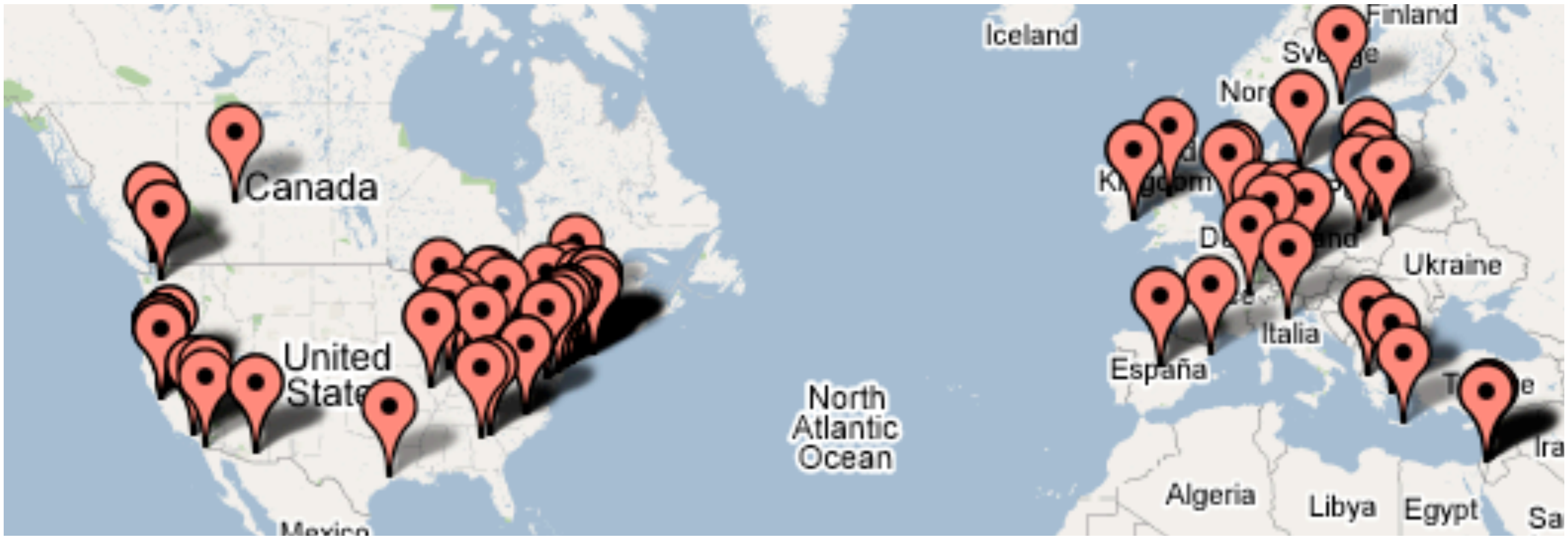


494 nodes on PlanetLab

$$\lceil \log_2(494) \rceil = 9$$

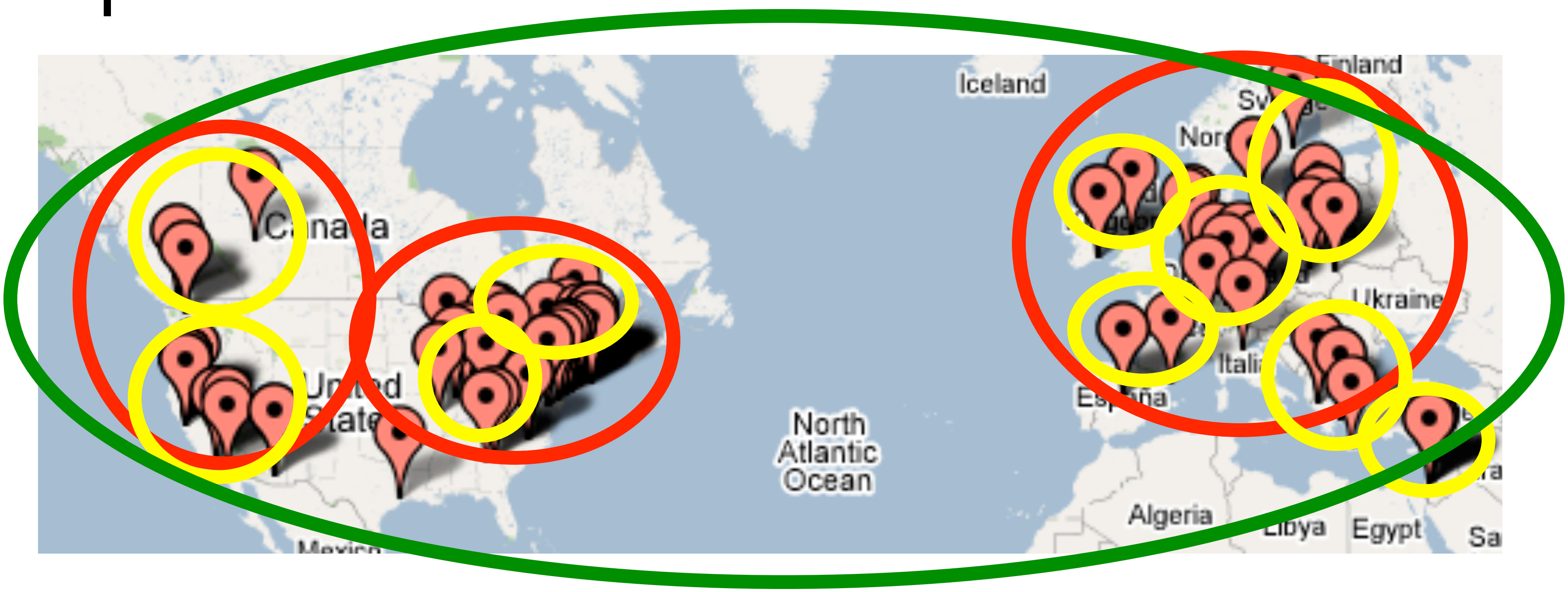
- Nodes aggregate request rate: ~12 million / min
- Rate-limit per node (β): 12 / min
- Requests at closest fan-in from 7 others: 83 / min

Next…



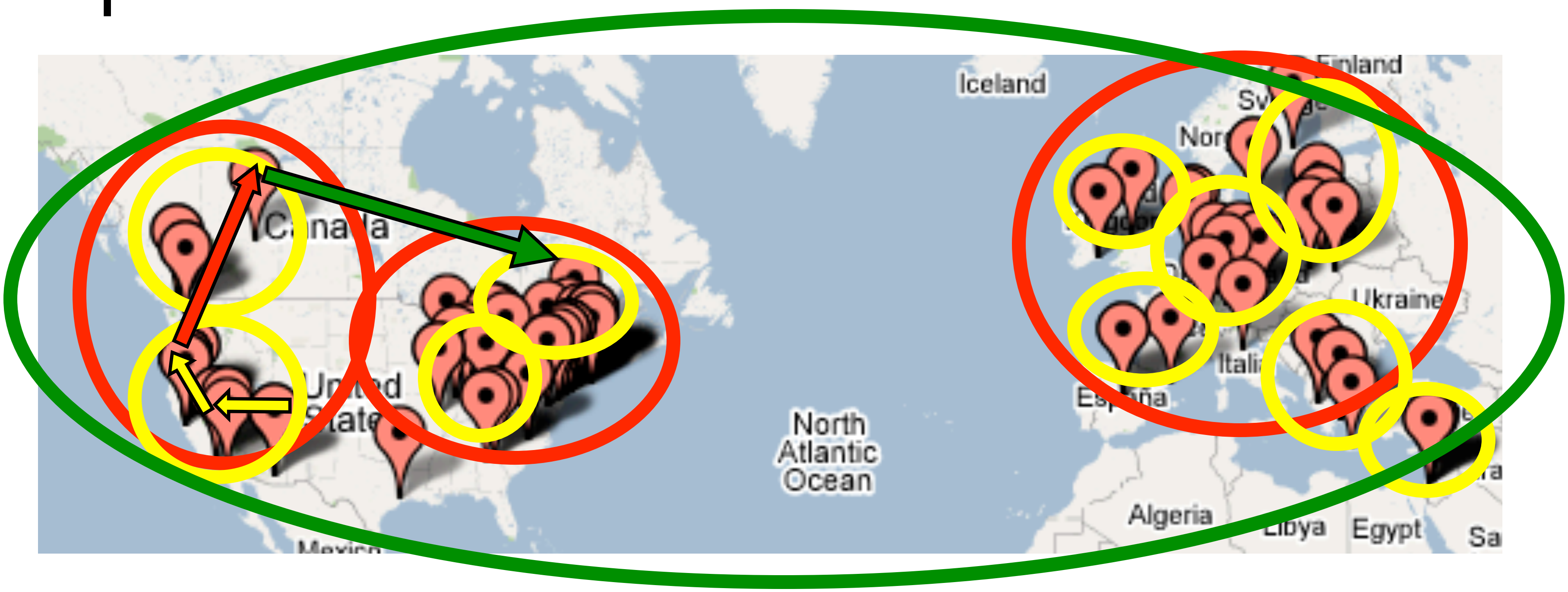
- Solution: Bound request rate to prevent hotspots
- Solution: Take advantage of network locality

Cluster by network proximity



- Organically cluster nodes based on RTT
- Hierarchy of clusters of expanding diameter
- Lookup traverses up hierarchy
  - Route to node nearest ID in each level

Cluster by network proximity



- Organically cluster nodes based on RTT
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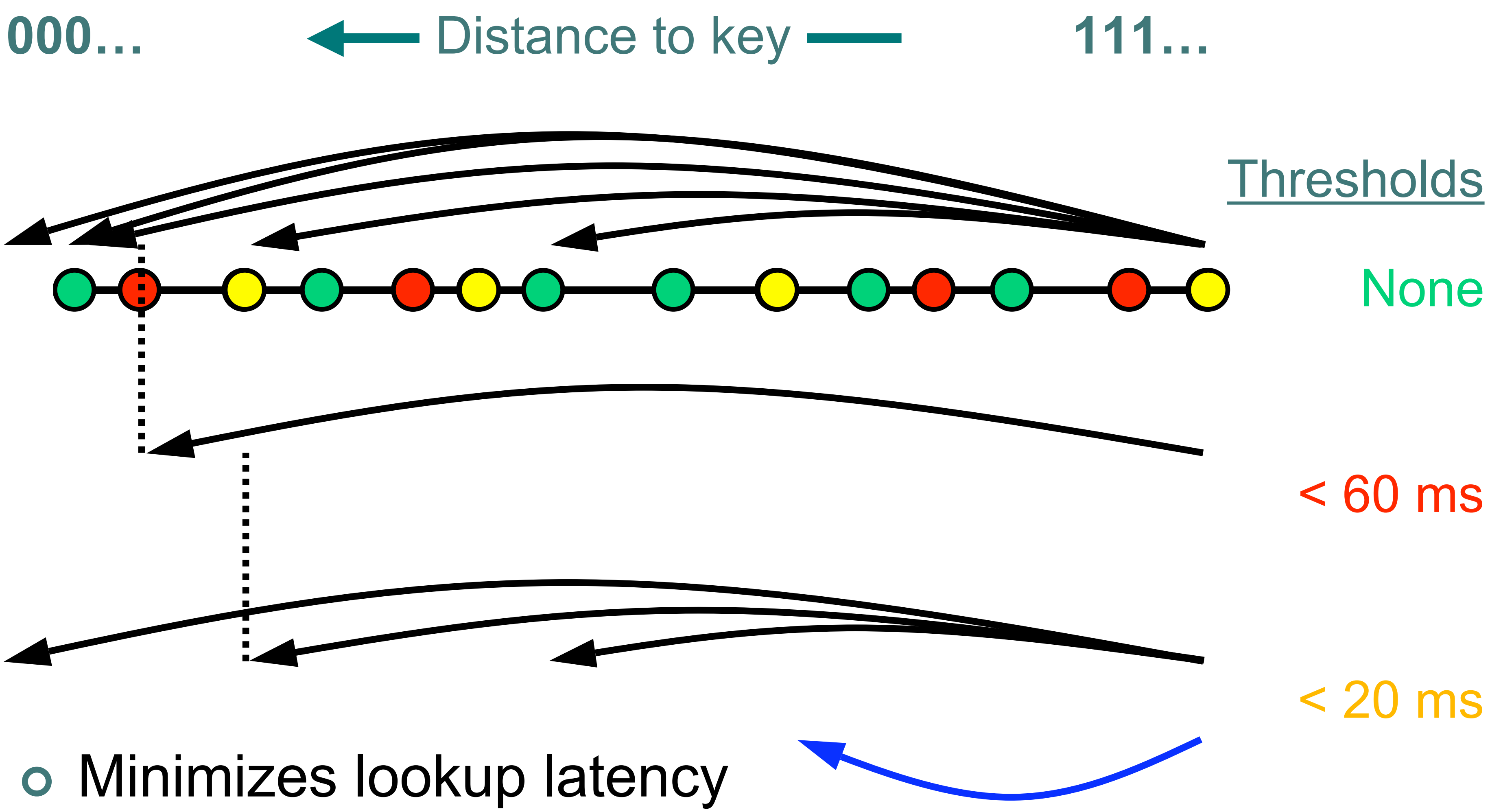
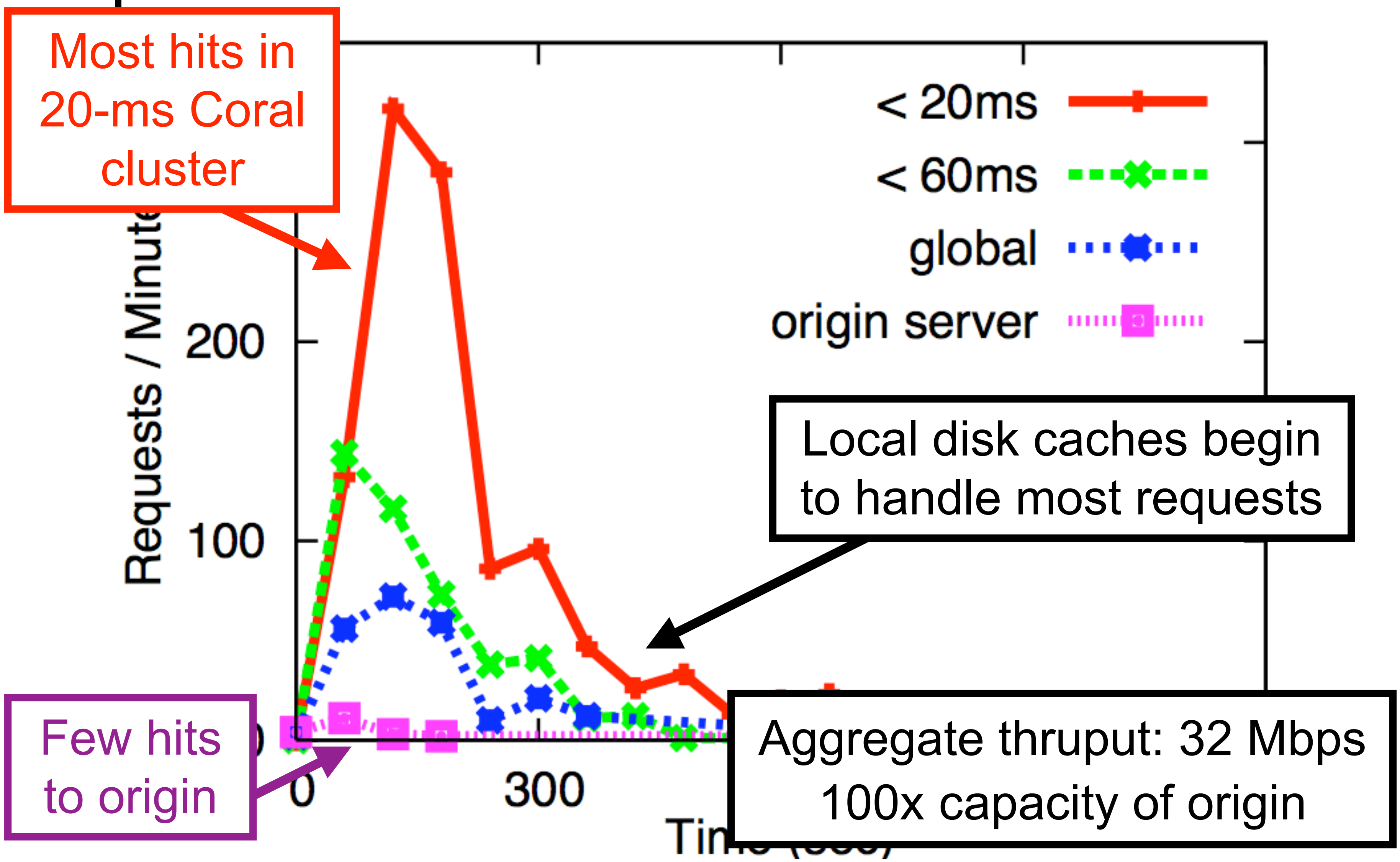
Preserve locality through hierarchy

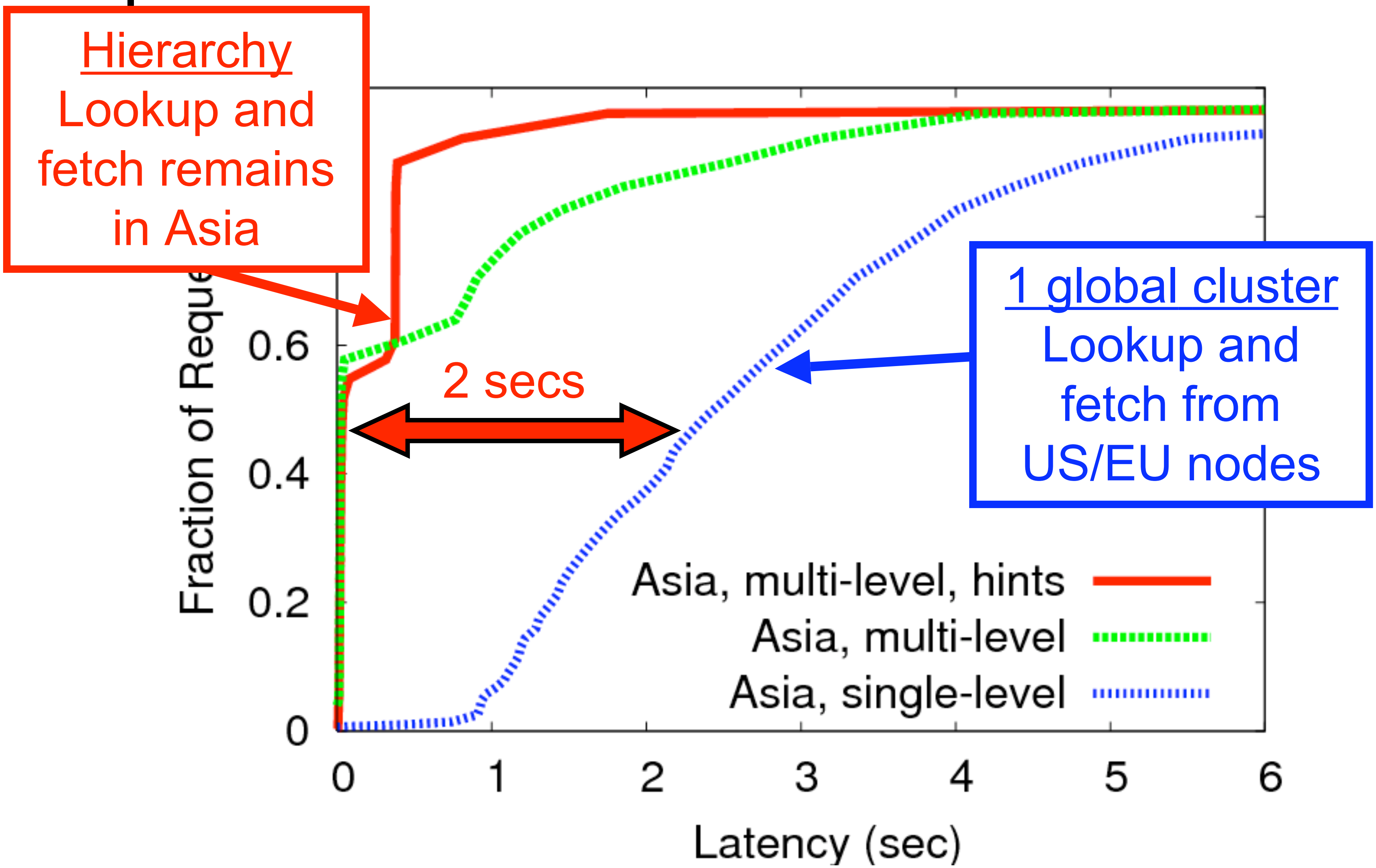


- Minimizes lookup latency
- Prefer values stored by nodes within faster clusters

Reduces load at origin server



Clustering benefits e2e latency



CoralCDN's deployment

Powered By PLANETLAB

- Deployed on 300-400 PlanetLab servers
- Running 24 / 7 since March 2004

Current daily usage

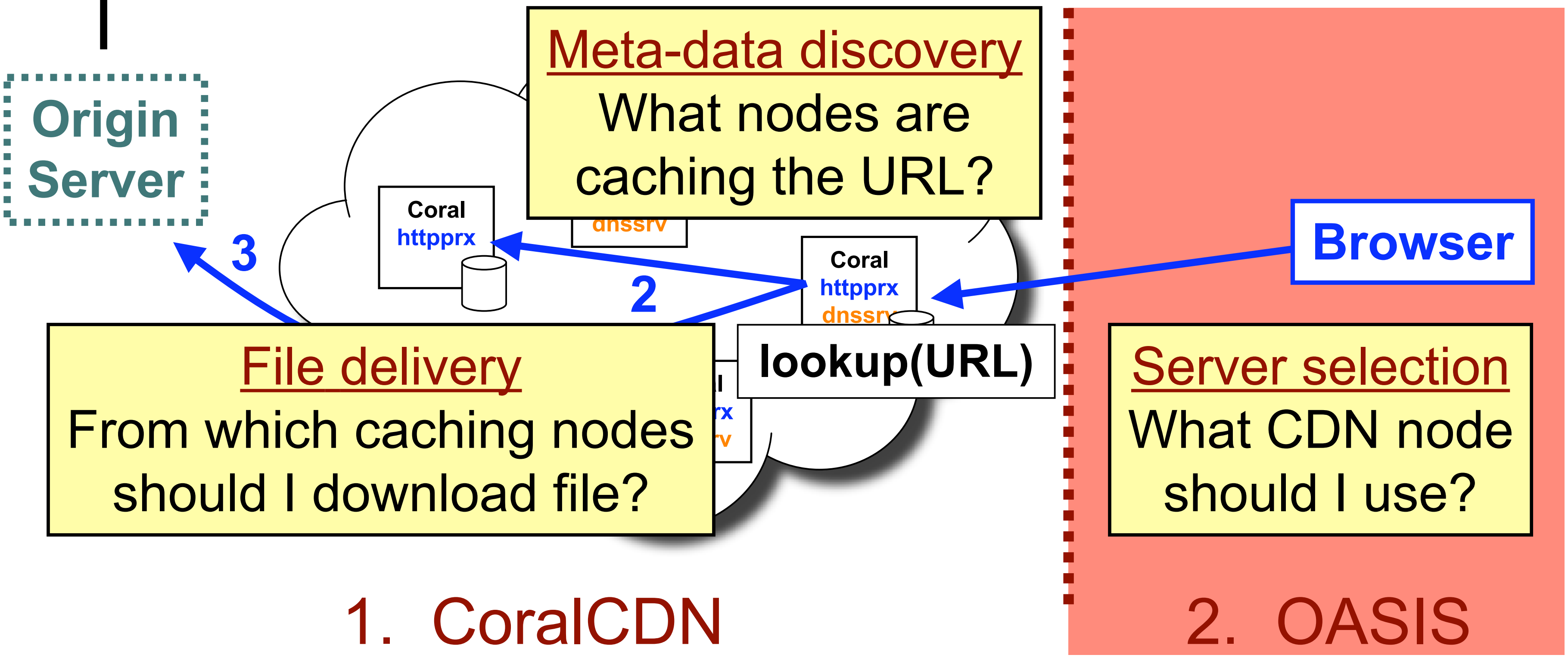
- 20-25 million HTTP requests
- 1-3 terabytes of data
- 1-2 million unique client IPs
- 20K-100K unique servers contacted (Zipf distribution)

- Varied usage
  - Servers to withstand high demand
  - Portals such as Slashdot, digg, …
  - Clients to avoid overloaded servers or censorship

This talk

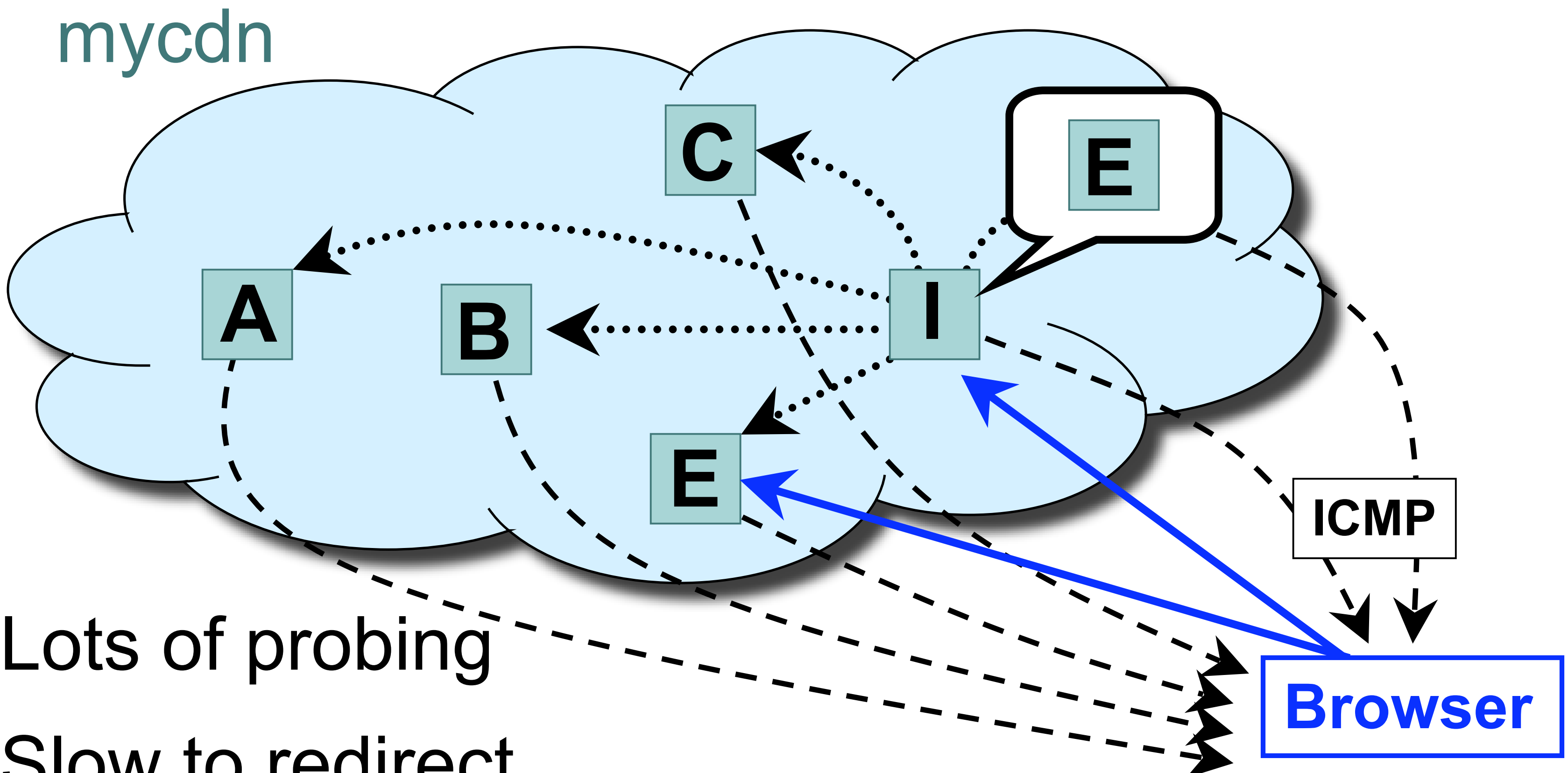
[IPTPS '03]
[NSDI '04]

[NSDI '06]



3. Using these for measurements: Illuminati [NSDI '07]
4. Finally, adding security to leverage more volunteers

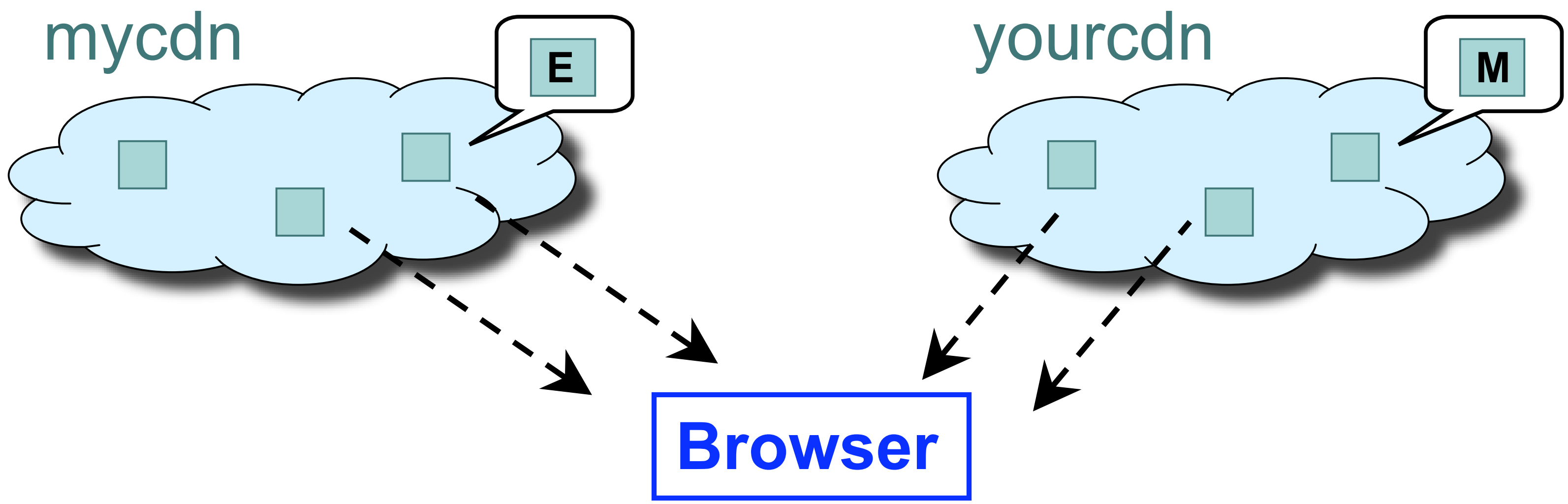
Strawman: probe to find nearest



- Lots of probing
- Slow to redirect
  - Negates goal of faster e2e download

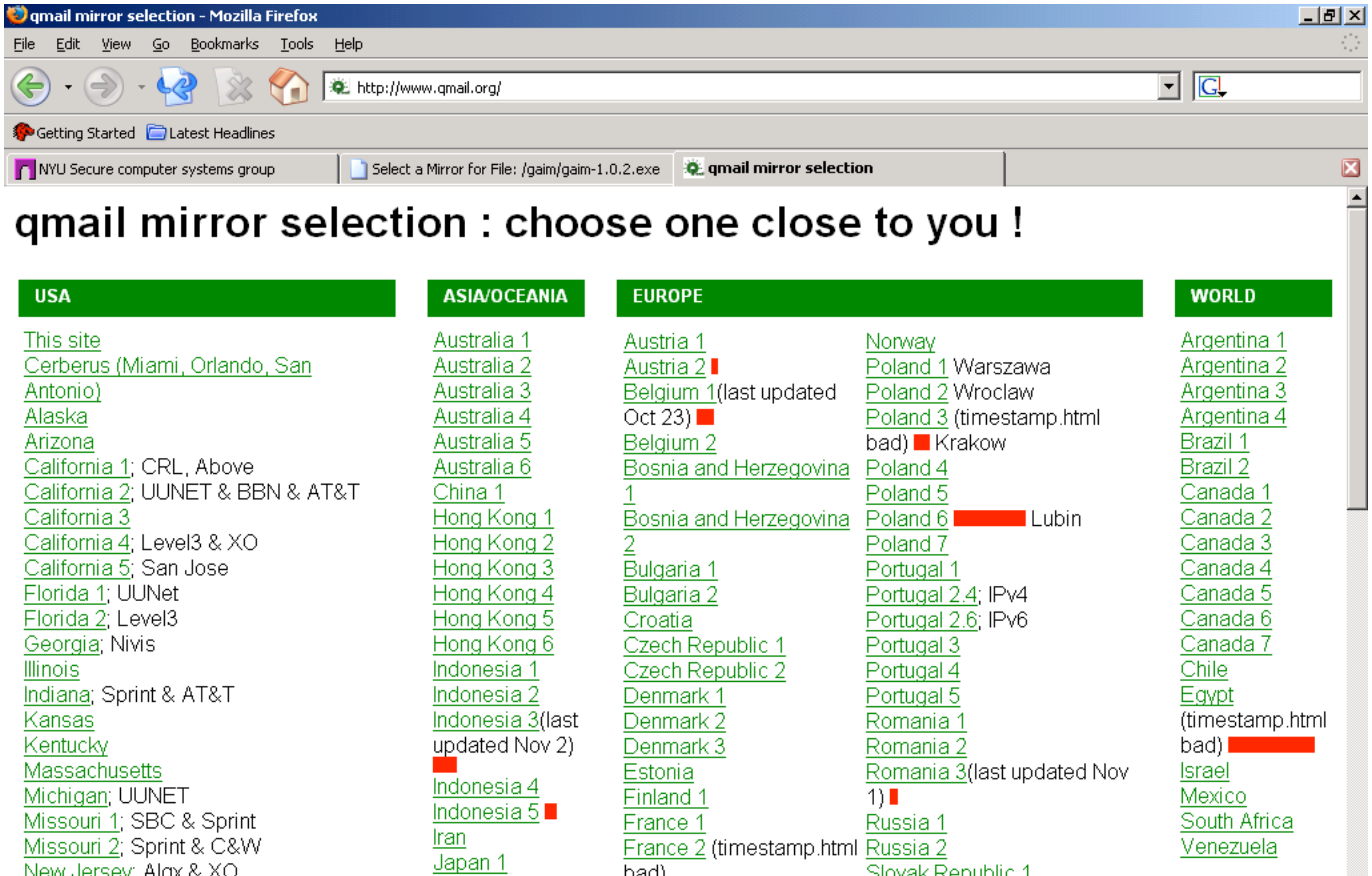
⇒ Cache after first lookup?

What about *yourcdn*?

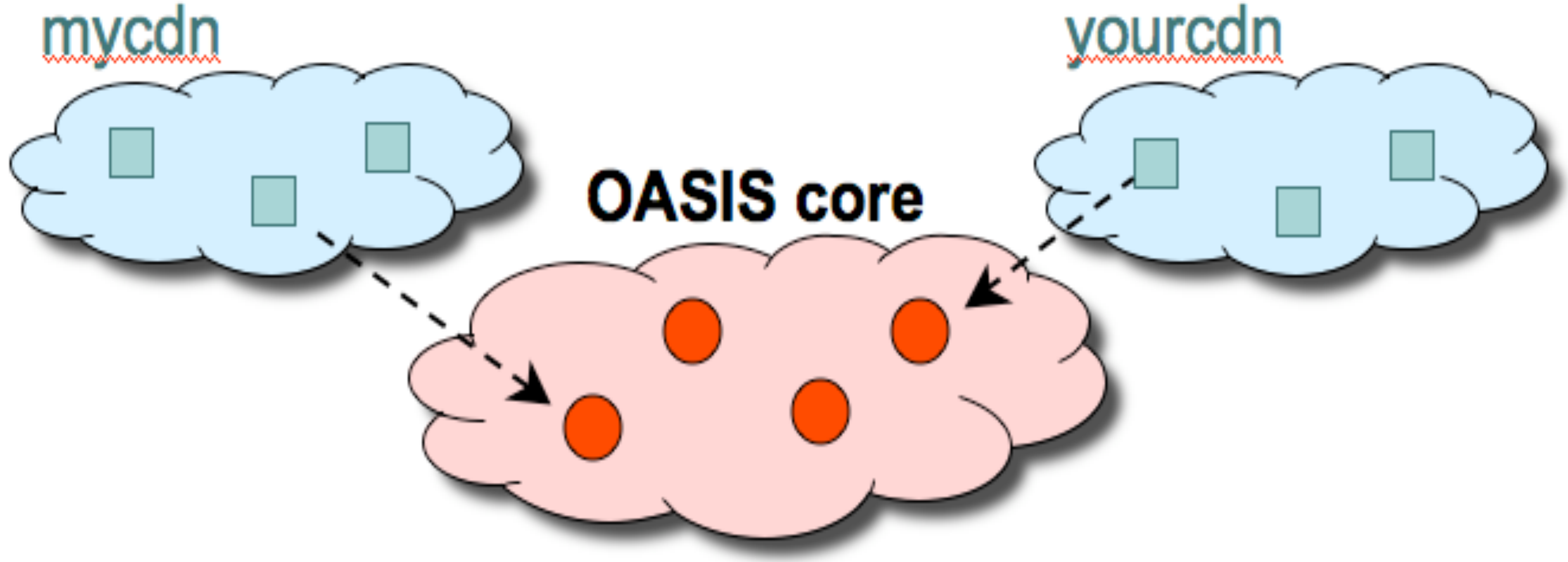


- Lots of probing
- Slow to redirect
- Every service pays same cost

Whither server-selection?

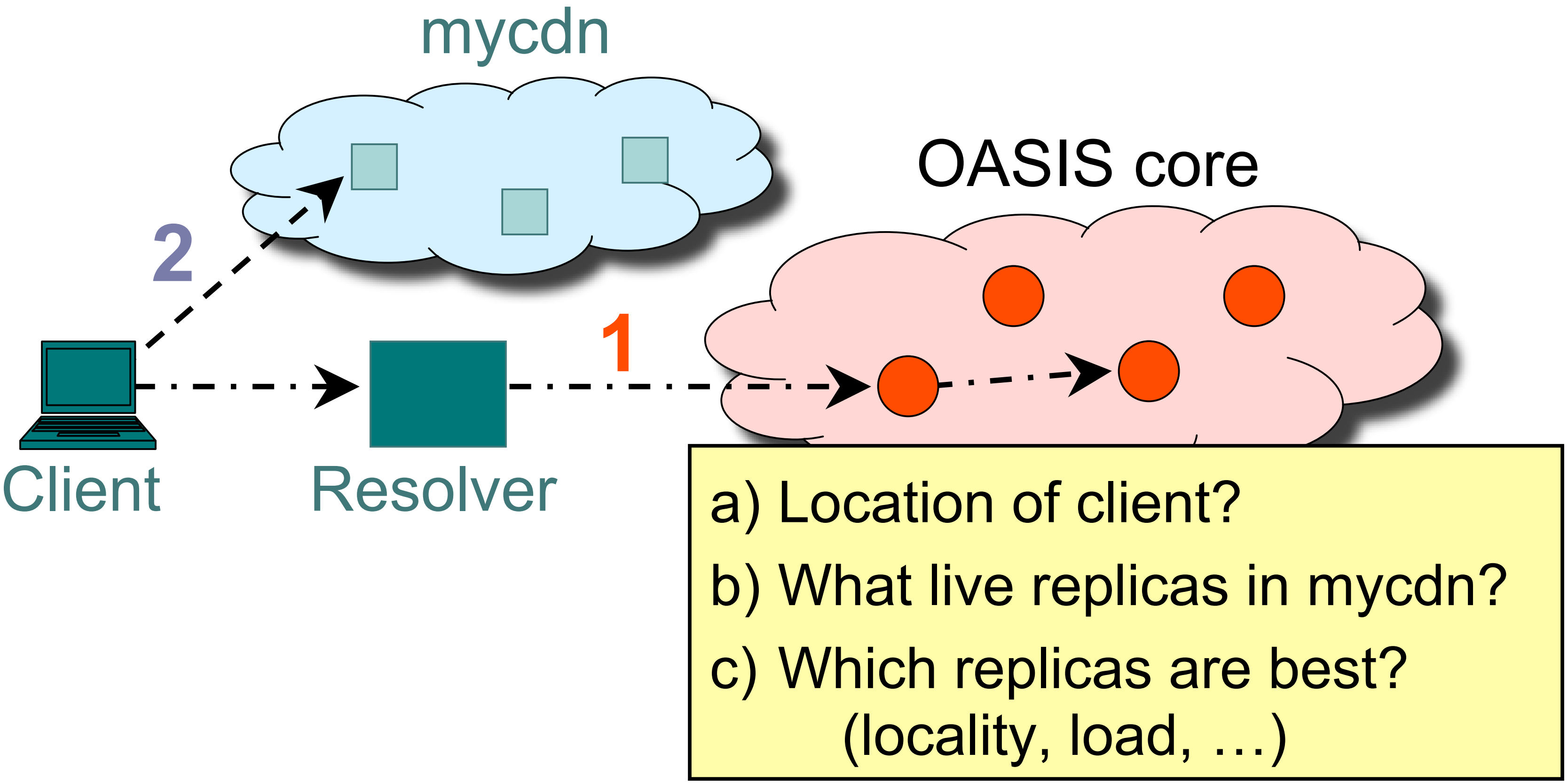


Goal: Knew answer without probing on critical path



- OASIS: a shared server-selection infrastructure
  - Amortize measurement cost over services' replicas
    - Total of ~20 GB/week, not per service
    - More nodes ⇒ higher accuracy and lower cost each
  - In turn, services benefit from functionality

If had a server-selection infrastructure…



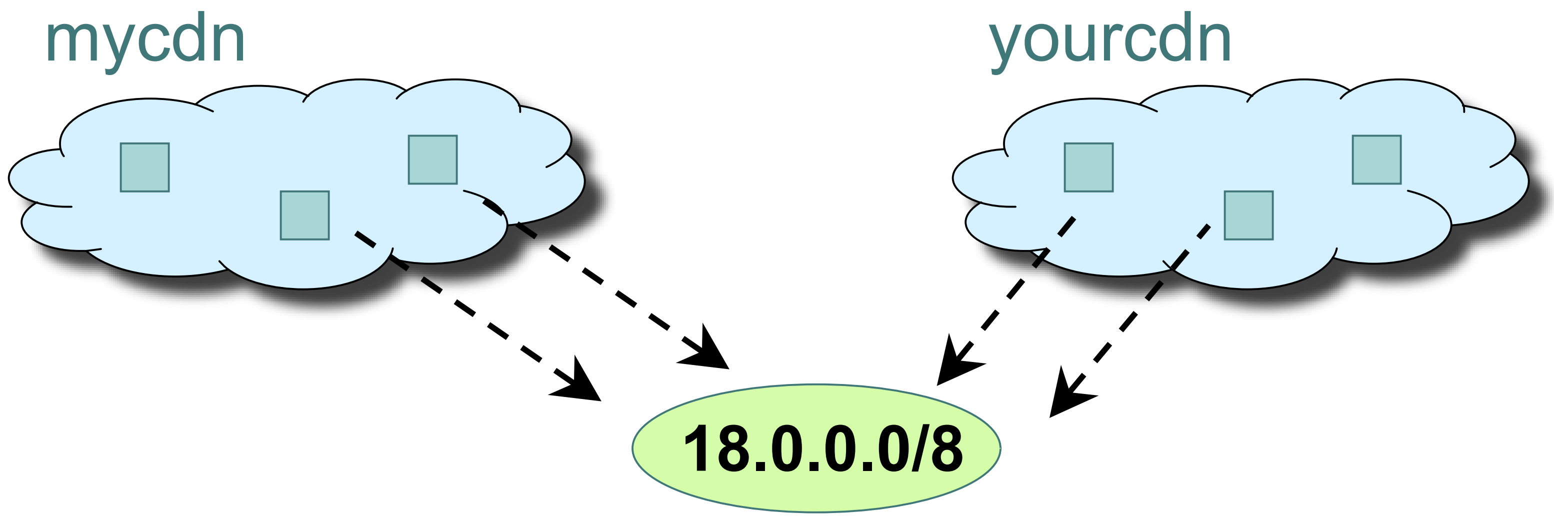
1. Client issues DNS request for ***mycdn**.nyuld.net*
2. OASIS redirects client to nearby application replica

What would this require?

- Measure the entire Internet in advance
  - Reduce the state space
  - Intermediate representation for locality
  - Detect and filter out measurement errors

- Architecture to organize nodes and manage data

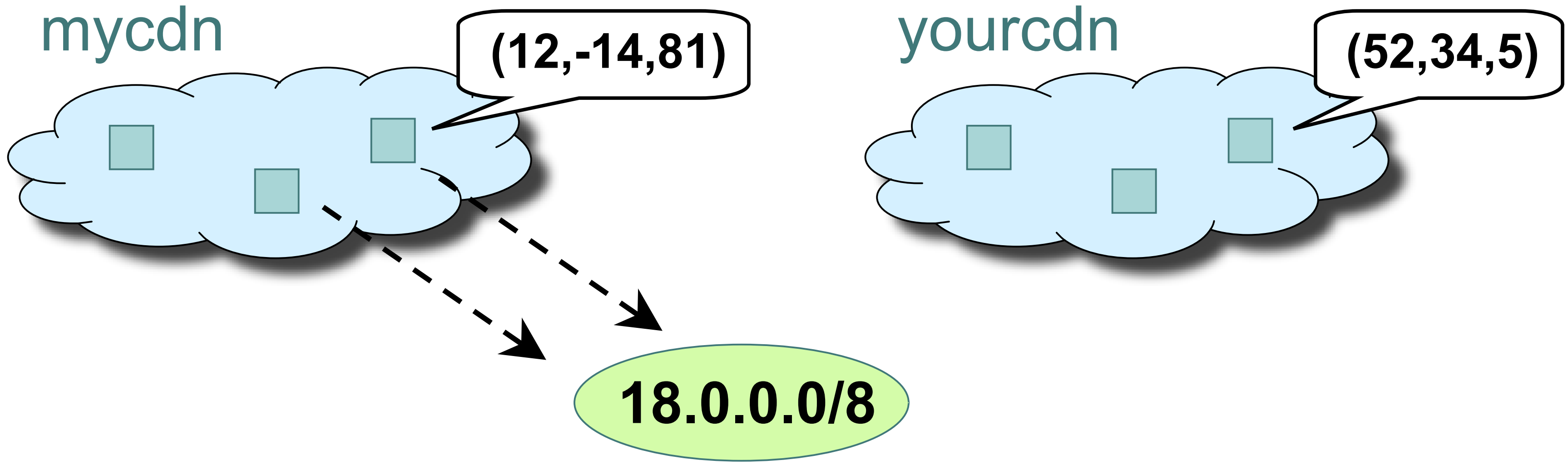
Reduce the state space



- 3-4 orders of magnitude by aggregating IP addresses
- [IMC '05]: nodes in same IP prefix are often close
  - 99% of prefixes with same first three-octets (x.y.z.*)
- Dynamically split prefixes until at same location

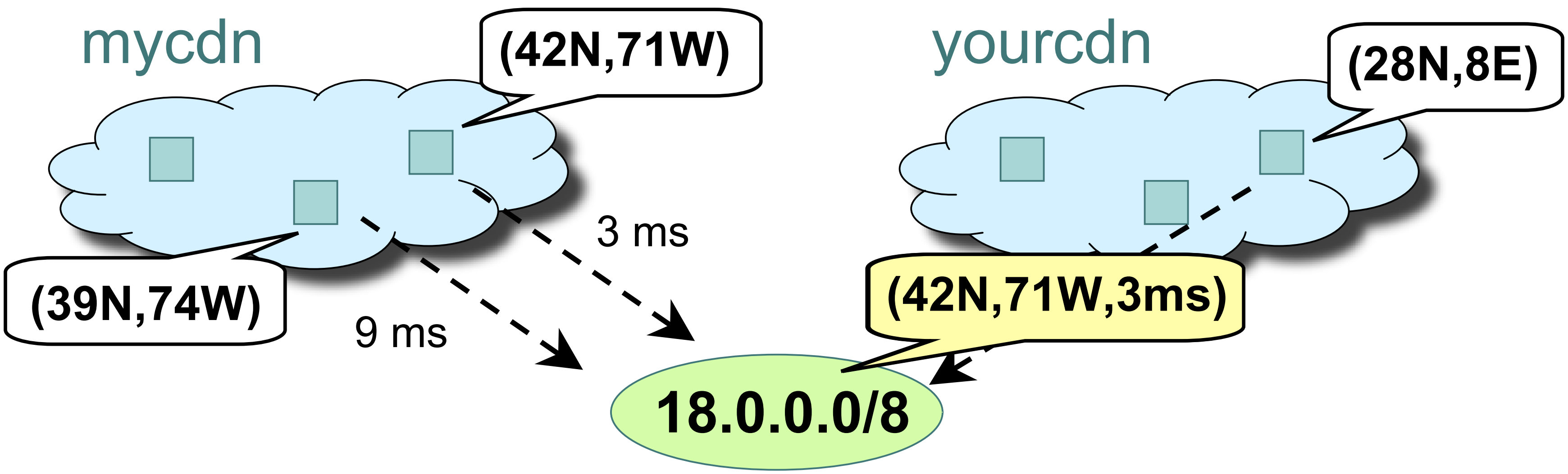
Representing locality

[IPTPS '05]



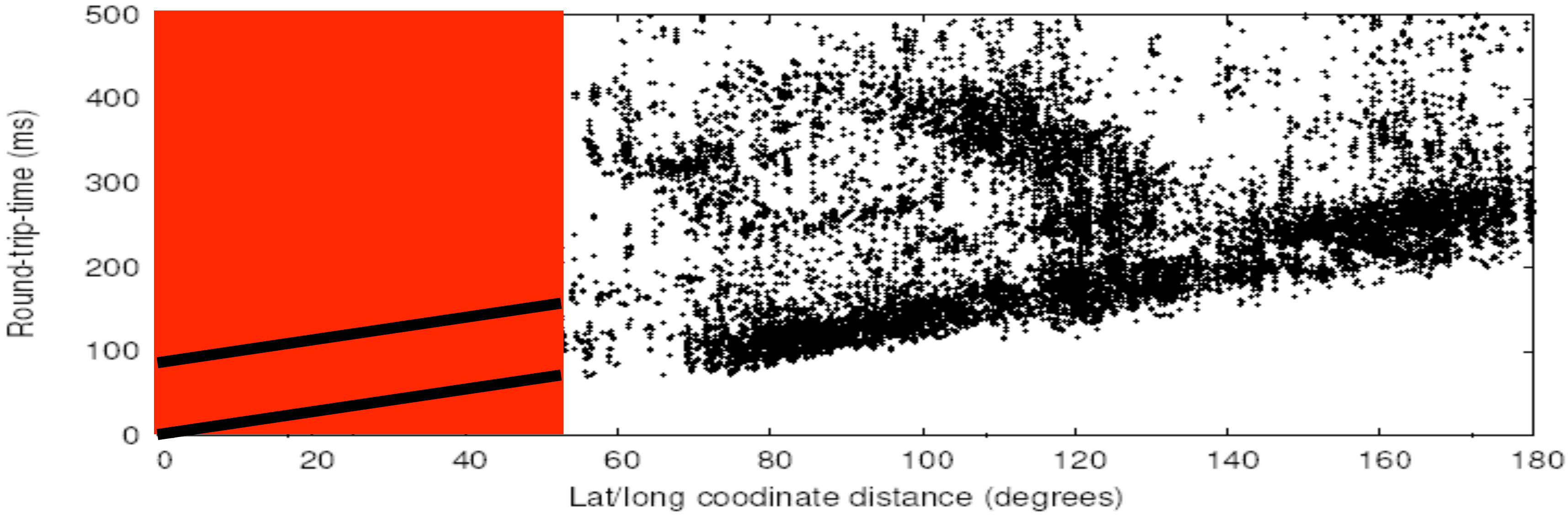
- Use virtual coordinates?
  - Predicts Internet latencies, fully decentralized
  - But designed for clients participating in protocol
  - Cached values useless: Coordinates drift over time

Representing locality



- Combine geographic coordinates with latency
  - Add't assumption: Replicas know own geo-coords
  - RTT accuracy has real-world meaning
    - Check if new coordinates improve accuracy

Representing locality

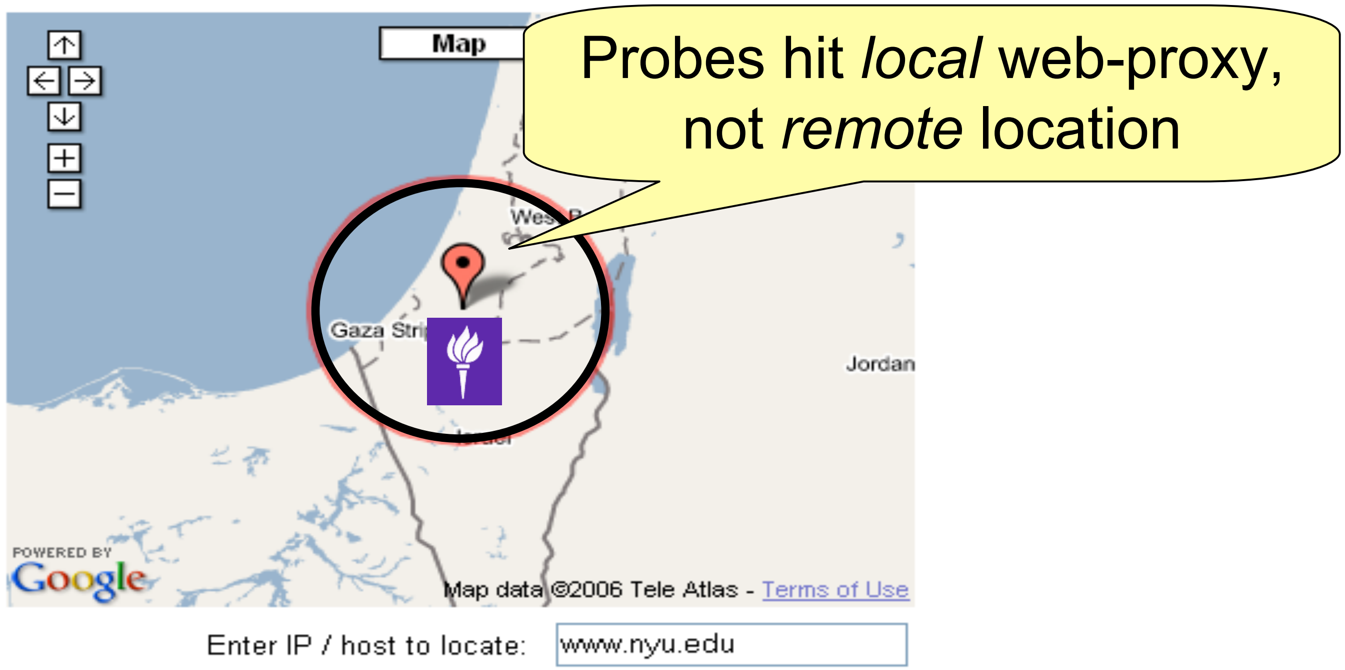


Correlation b/w geo-distance and RTT

Designing for high-density deployments

More nodes participate ⇄ Higher accuracy

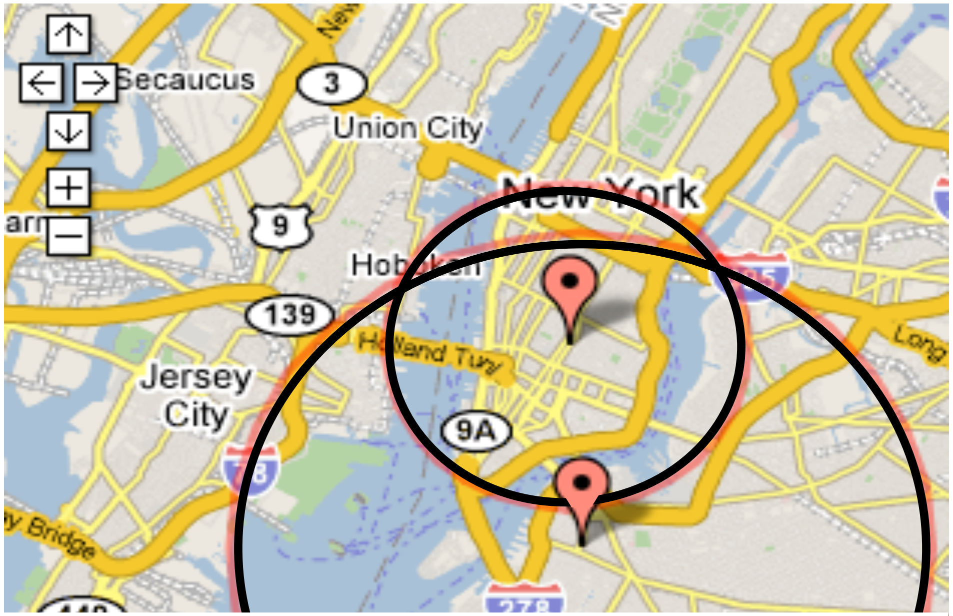
Measurements have errors



Israeli node 3 ms from NYU ?

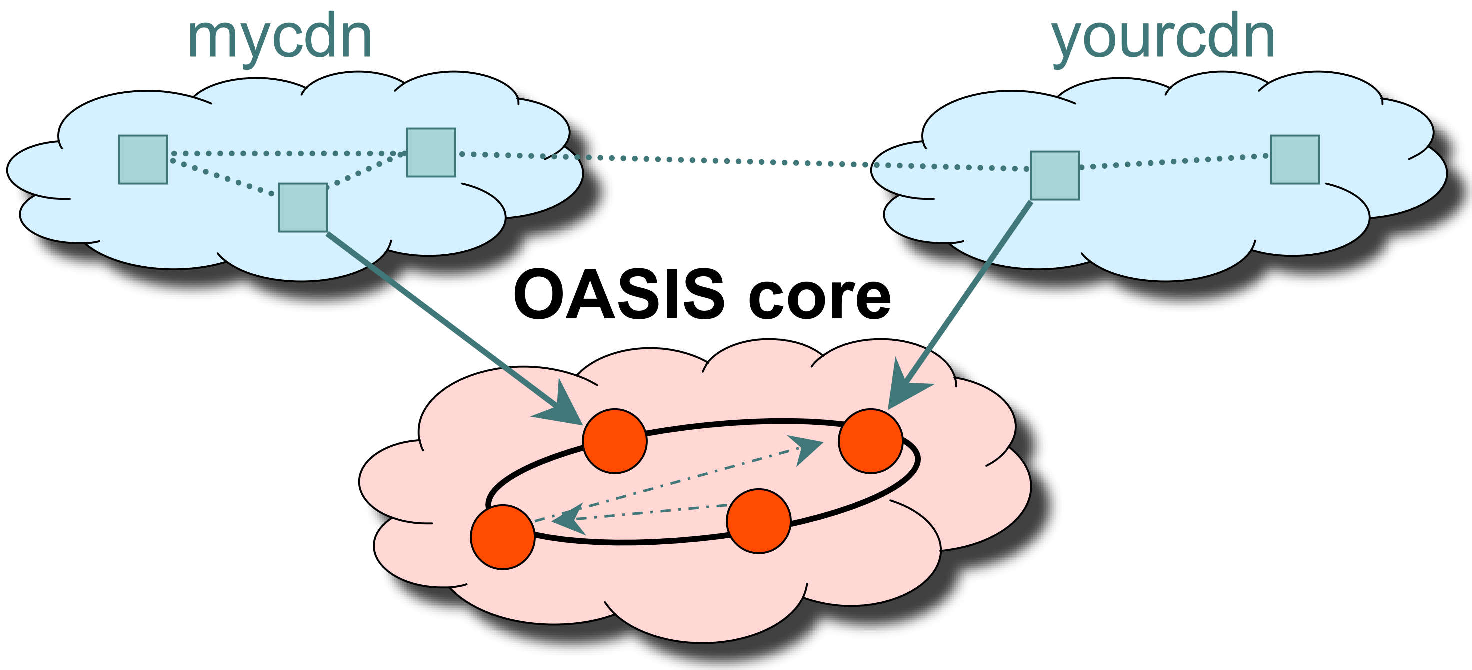
- Many conditions cause wildly wrong results
- Need general solution robust against errors

Finding measurement errors



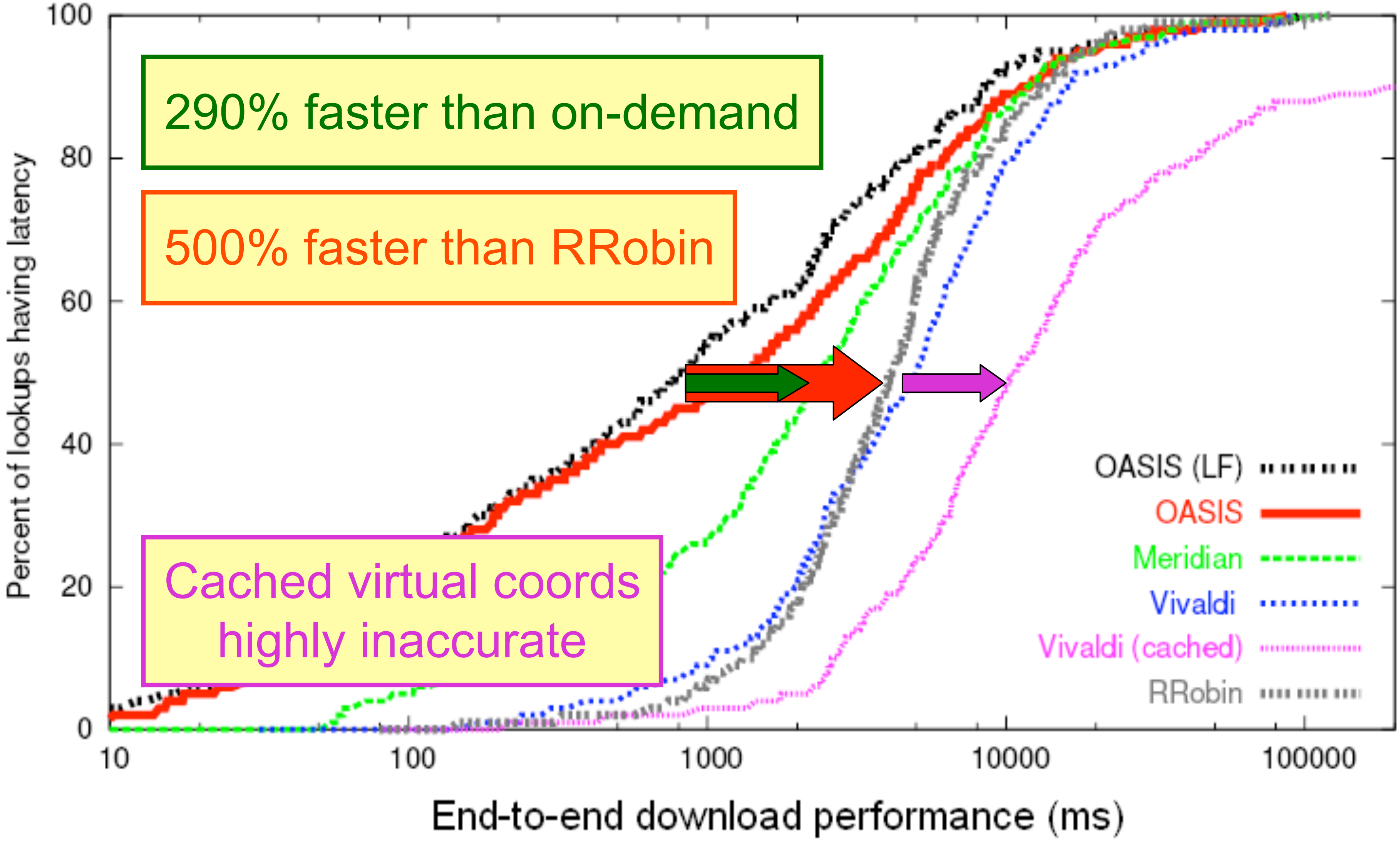
- Require measurement agreement
  - At least two results from different services must satisfy constraints (e.g., speed of light)

Engineering… (Lessons from Coral)



- OASIS core
  - Global membership view
  - Epidemic gossiping
    - Scalable failure detection
    - Replicate network map
  - Consistent hashing
    - Probing assignment, liveness of replicas
- Service replicas
  - Heartbeats to core
  - Meridian overlay for probing
    - $O(\log^2 n)$ probes finds closest

E2E download of web page



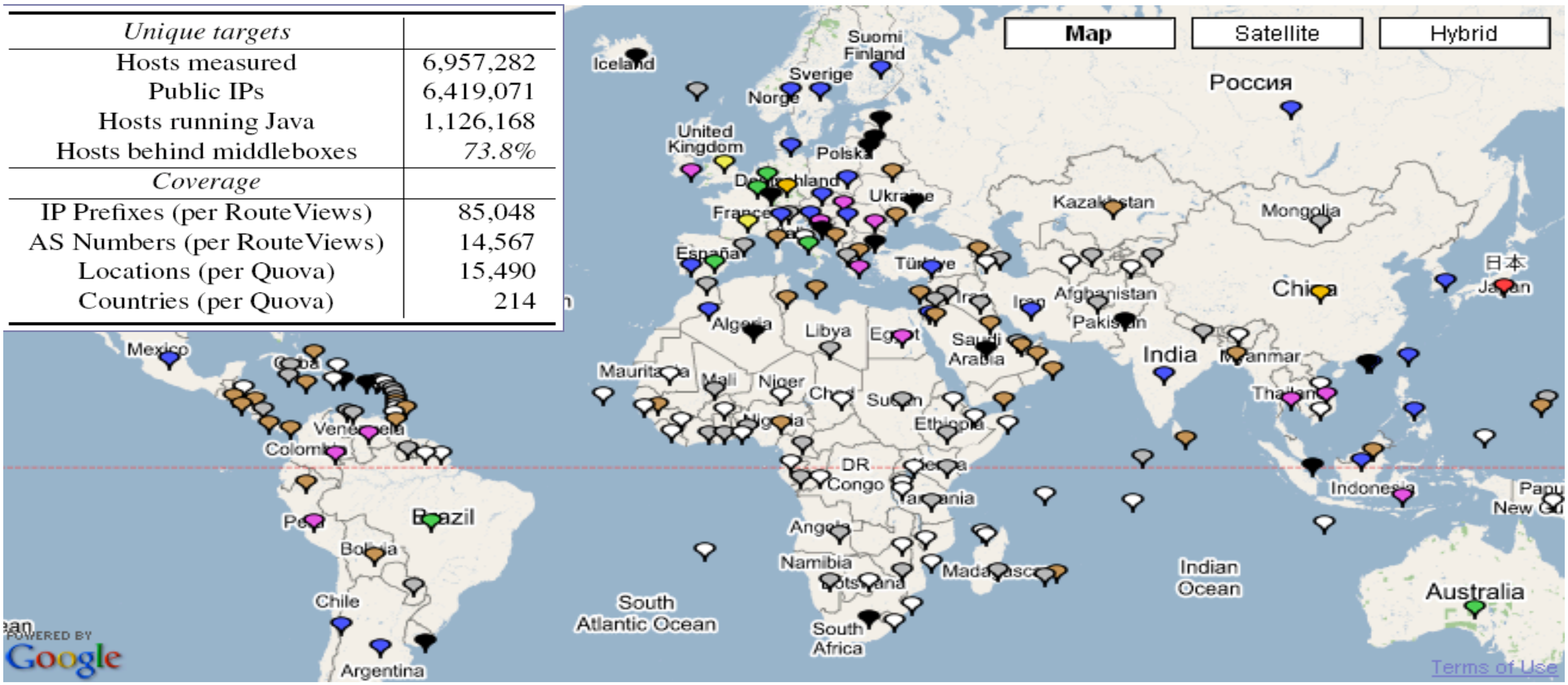
Deployed with thousands of replicas

- **AChord** topology-aware DHT (KAIST)
- **Chunkcast** block anycast (Berkeley)
- **CoralCDN** content distribution (NYU)
- **DONA** data-oriented network anycast (Berkeley)
- **Galaxy** distributed file system (Cincinnati)
- **Na Kika** content distribution (NYU)
- **OASIS:** RPC, DNS, HTTP interfaces
- **OCALA** overlay convergence (Berkeley)
- **OpenDHT** public DHT service (Berkeley)
- **OverCite** distributed library (MIT)
- **SlotNet** overlay routing (Purdue)

Systems as research platforms

- Measurements made possible by CoralCDN
  - Can’t probe clients behind middleboxes
  - CoralCDN clients execute active content

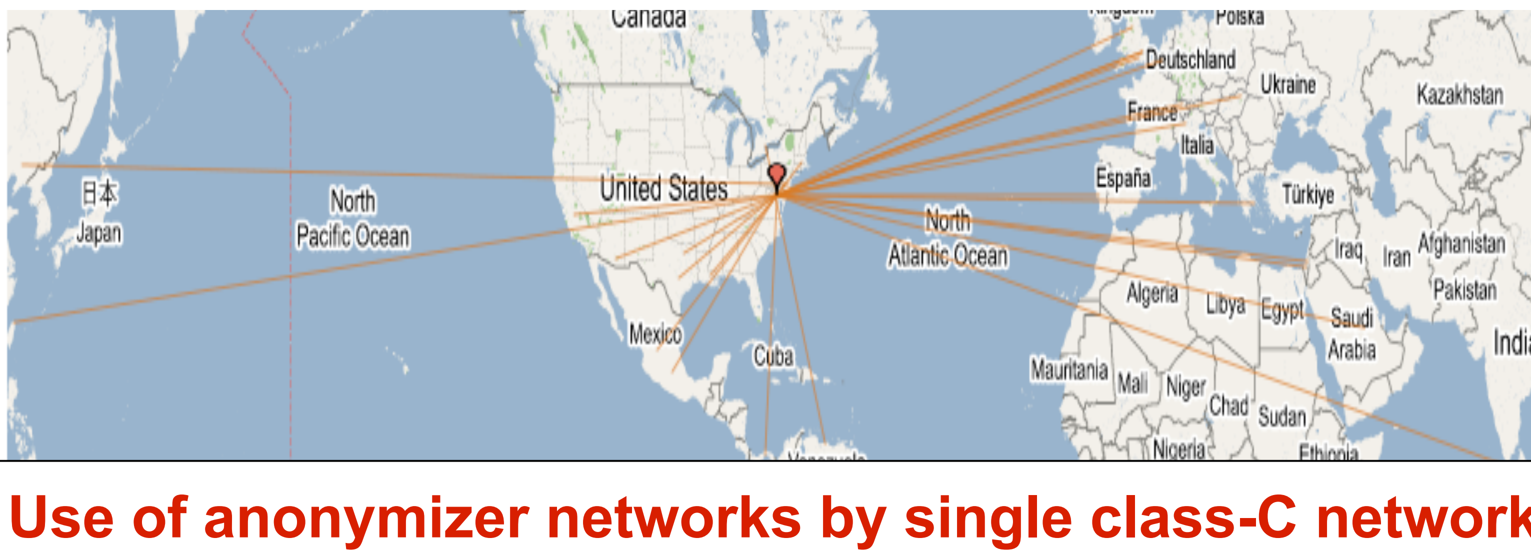
Unique targets	
Hosts measured	6,957,282
Public IPs	6,419,071
Hosts running Java	1,126,168
Hosts behind middleboxes	*73.8%*
Coverage	
IP Prefixes (per RouteViews)	85,048
AS Numbers (per RouteViews)	14,567
Locations (per Quova)	15,490
Countries (per Quova)	214



Measuring the edge: illuminati

[NSDI '07]

- DNS redirection: Clients near their nameservers?
  - Mostly within 20ms; diminishing returns to super-optimize
- Client blacklisting: Safe to blacklist an IP?
  - Quantify collatoral damage: NATs small, DHCP slow
- Client geolocation: Where are clients truly located?
  - Product for real-time proxy detection with Quova



Use of anonymizer networks by single class-C network

Security too…

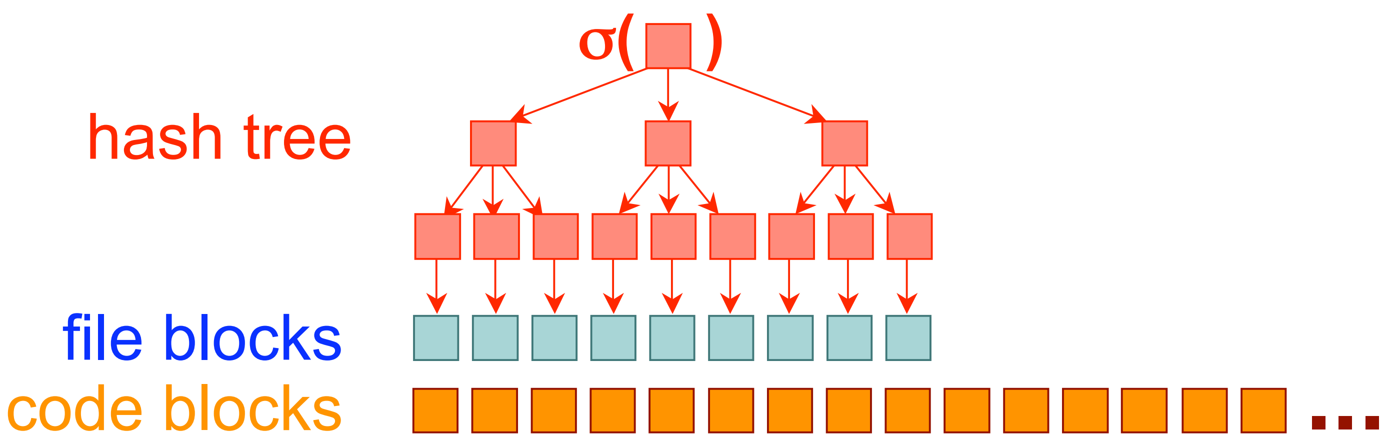
Theme throughout talk: How to leverage previously untapped resources to gain new functionality

- Cooperative content distribution
  - Locate and deliver cached content ⇒ CoralCDN
  - Select good servers ⇒ OASIS
- Adding security enables *untrusted* resources
  - Shark: scaling distributed file systems [NSDI '06]
    - Mutually-distrustful clients use each others' file caches

[S&P '04]

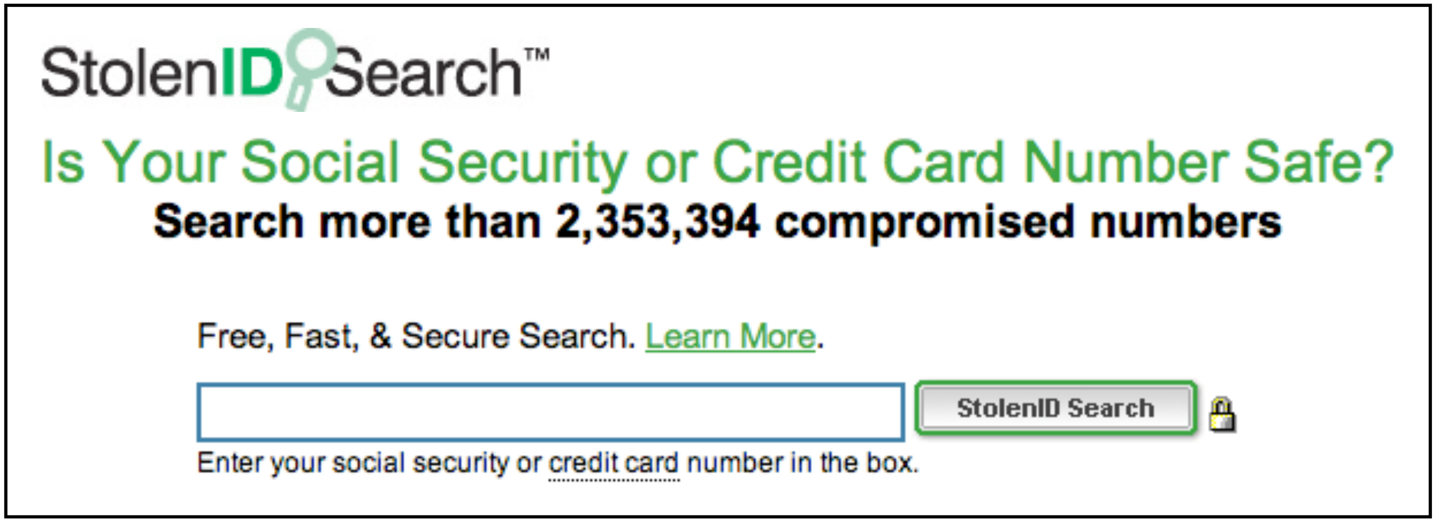
Large-file delivery via rateless erasure codes

- Encode blocks of large file, block negotiation unneeded
  - Exponential number of potential code blocks
- Prevents traditional hash trees for verification



- Instead, hashing based on homomorphic accumulator
  - Given $h(f_1)$, $h(f_2)$, $c_{1+2} = f_1+f_2$, compute $h(c_{1+2}) = h(f_1) \cdot h(f_2)$
- By batching PK operations, can verify at 60 Mbps

Need not be security *or* functionality



- Private matching (PM) [EUROCRYPT '04]
  - Parties compute set intersection (oblivious polynomials)

    P encodes x_i's $\rightleftarrows$ $\forall y_i,\ E(r_i P(y_i) + y_i)$ $\Rightarrow O(n \lg \lg n)$
  - e.g., Passenger manifests ∩ govt. no-fly lists [NSDI '06]
  - e.g., Social path in email correspondence for whitelisting
- Private keyword search (KS) [TCC '05]

Future: Securing and managing distributed systems

- Building and running large-scale systems difficult
  - Security, managability, reliability, scalability, …
  - Especially when decentralized, untrusted, …
  - Hard to reason about, hard to audit, hard to ensure QoS, …
- New architectures
  - Ethane: auditable, secure enterprise networks [Sec ‘06]
- New algorithms
  - Smaller groups with well-defined properties [IPTPS ‘06]
- New tools
  - Tracing transactions across hosts

Research approach

- Today:
  - Techniques for cooperative content distribution
  - Production use for 3 years, millions of users daily

- Generally:
  - New functionality through principled design
    - Distributed algorithms, cryptography, game theory, …
  - Build and deploy real systems
    - Evaluates design and leads to new problems
    - Hugely satisfying to have people use it

Thanks…

www.coralcdn.org

source code (GPL), data, papers available online