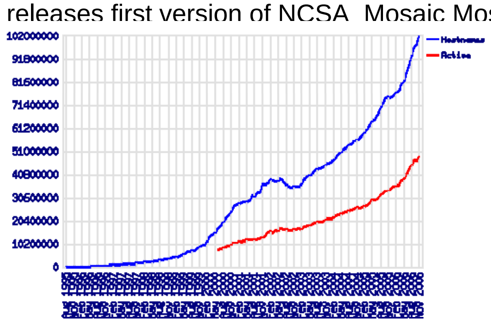
15-441 Computer Networking
Caching, CDN, Consistent Hashing, P2P

Web history

- 1945: Vannevar Bush, “As we may think”, Atlantic Monthly, July, 1945.
  - describes the idea of a distributed hypertext system.
  - a “memex” that mimics the “web of trails” in our minds.
- 1989: Tim Berners-Lee (CERN) writes internal proposal to develop a distributed hypertext system
  - connects “a web of notes with links”.
  - intended to help CERN physicists in large projects share and manage information
- 1990: Tim BL writes graphical browser for Next machines.

Web history (cont)

- 1992
  - NCSA server released
  - 26 WWW servers worldwide
- 1993
  - Marc Andreessen releases first version of NCSA Mosaic Mosaic version released f
  - Web (port 80) traf
  - Over 200 WWW s
- 1994
  - Andreessen and c Communications (



Typical Workload (Web Pages)

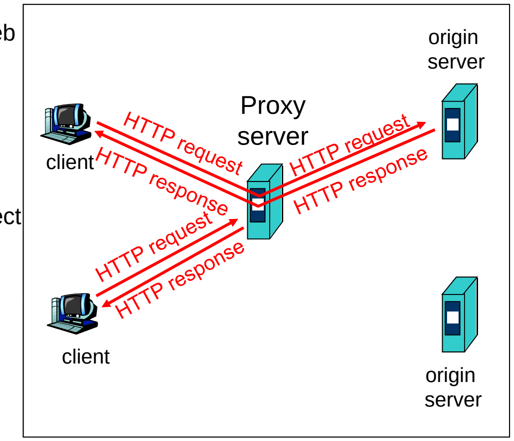
- Multiple (typically small) objects per page
- File sizes
  - Heavy-tailed
    - Pareto distribution for tail
    - Lognormal for body of distribution
- Embedded references
  - Number of embedded objects also pareto

    $Pr(X>x) = (x/x^m)^{-k}$
- This plays havoc with perform
- Solutions?

> - Lots of small objects means & TCP
>   - 3-way handshake
>   - Lots of slow starts
>   - Extra connection state

Web Proxy Caches

- User configures browser: Web accesses via cache
- Browser sends all HTTP requests to cache
  - Object in cache: cache returns object
  - Else cache requests object from origin server, then returns object to client



No Caching Example (1)

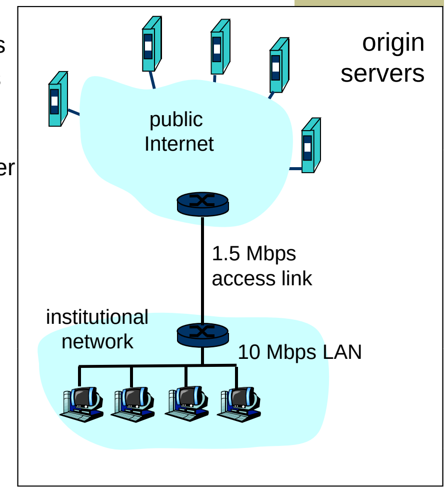
Assumptions

- Average object size = 100,000 bits
- Avg. request rate from institution's browser to origin servers = 15/sec
- Delay from institutional router to any origin server and back to router = 2 sec

Consequences

- Utilization on LAN = 15%
- Utilization on access link = 100%
- Total delay = Internet delay + access delay + LAN delay

= 2 sec + minutes + milliseconds



No Caching Example (2)

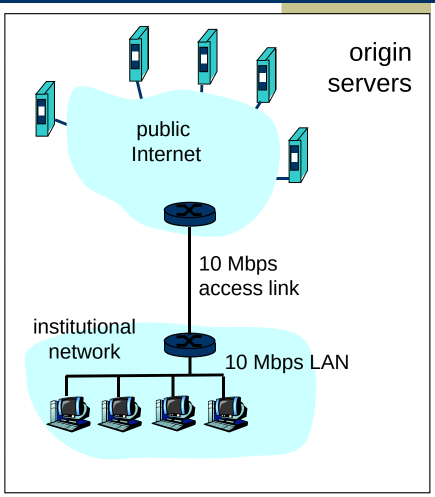
Possible solution

- Increase bandwidth of access link to, say, 10 Mbps
- Often a costly upgrade

Consequences

- Utilization on LAN = 15%
- Utilization on access link = 15%
- Total delay = Internet delay + access delay + LAN delay

= 2 sec + msecs + msecs



W/Caching Example (3)

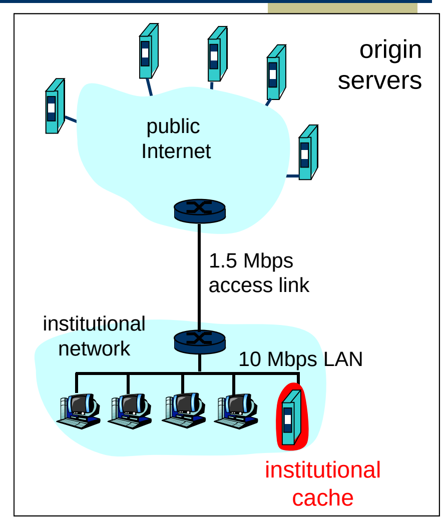
Install cache

- Suppose hit rate is .4

Consequence

- 40% requests will be satisfied almost immediately (say 10 msec)
- 60% requests satisfied by origin server
- Utilization of access link reduced to 60%, resulting in negligible delays
- Weighted average of delays

= .6*2 sec + .4*10msecs < 1.3 secs



HTTP Caching

- Clients often cache documents
  - Challenge: update of documents
  - If-Modified-Since requests to check
    - HTTP 0.9/1.0 used just date
    - HTTP 1.1 has an opaque “entity tag” (could be a file signature, etc.) as well
- When/how often should the original be checked for changes?
  - Check every time?
  - Check each session? Day? Etc?
  - Use Expires header
    - If no Expires, often use Last-Modified as estimate

Example Cache Check Request

GET / HTTP/1.1

Accept: */*

Accept-Language: en-us

Accept-Encoding: gzip, deflate

If-Modified-Since: Mon, 29 Jan 2001 17:54:18 GMT

If-None-Match: "7a11f-10ed-3a75ae4a"

User-Agent: Mozilla/4.0 (compatible; MSIE 5.5; Windows NT 5.0)

Host: www.intel-iris.net

Connection: Keep-Alive

Example Cache Check Response

HTTP/1.1 304 Not Modified

Date: Tue, 27 Mar 2001 03:50:51 GMT

Server: Apache/1.3.14 (Unix) (Red-Hat/Linux) mod_ssl/2.7.1 OpenSSL/0.9.5a DAV/1.0.2 PHP/4.0.1pl2 mod_perl/1.24

Connection: Keep-Alive

Keep-Alive: timeout=15, max=100

ETag: "7a11f-10ed-3a75ae4a"

Problems

- Over 50% of all HTTP objects are uncacheable – why?
- Not easily solvable
  - Dynamic data → stock prices, scores, web cams
  - CGI scripts → results based on passed parameters
- Obvious fixes
  - SSL → encrypted data is not cacheable
    - Most web clients don’t handle mixed pages well →many generic objects transferred with SSL
  - Cookies → results may be based on passed data
  - Hit metering → owner wants to measure # of hits for revenue, etc.
- What will be the end result?

Caching Proxies – Sources for Misses

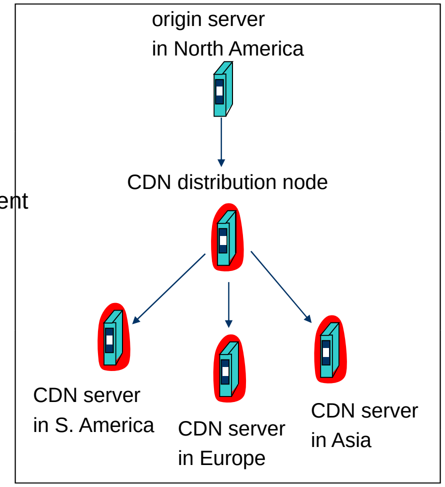
- Capacity
  - How large a cache is necessary or equivalent to infinite
  - On disk vs. in memory → typically on disk
- Compulsory
  - First time access to document
  - Non-cacheable documents
    - CGI-scripts
    - Personalized documents (cookies, etc)
    - Encrypted data (SSL)
- Consistency
  - Document has been updated/expired before reuse
- Conflict
  - No such misses

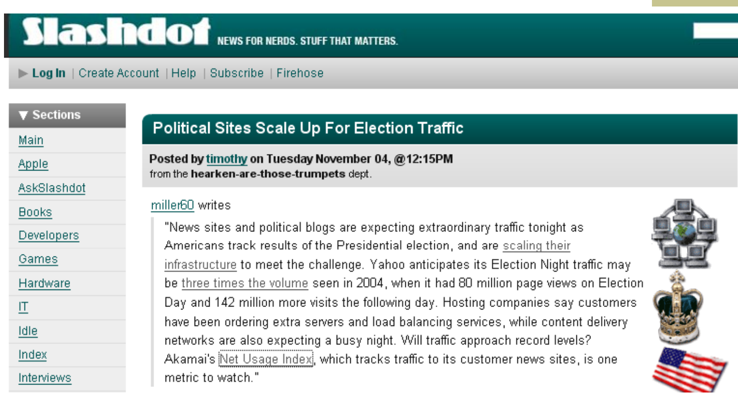
Content Distribution Networks (CDNs)

- The content providers are the CDN customers.

Content replication

- CDN company installs hundreds of CDN servers throughout Internet
  - Close to users
- CDN replicates its customers' content in CDN servers. When provider updates content, CDN updates servers





http://www.akamai.com/html/technology/nui/news/index.html

Content Distribution Networks & Server Selection

- Replicate content on many servers
- Challenges
  - How to replicate content
  - Where to replicate content
  - How to find replicated content
  - How to choose among know replicas
  - How to direct clients towards replica

Server Selection

- Which server?
  - Lowest load → to balance load on servers
  - Best performance → to improve client performance
    - Based on Geography? RTT? Throughput? Load?
  - Any alive node → to provide fault tolerance
- How to direct clients to a particular server?
  - As part of routing → anycast, cluster load balancing
    - Not covered ☹
  - As part of application → HTTP redirect
  - As part of naming → DNS

Application Based

- HTTP supports simple way to indicate that Web page has moved (30X responses)
- Server receives Get request from client
  - Decides which server is best suited for particular client and object
  - Returns HTTP redirect to that server
- Can make informed application specific decision
- May introduce additional overhead → multiple connection setup, name lookups, etc.
- While good solution in general, but…
  - HTTP Redirect has some design flaws – especially with current browsers

Naming Based

- Client does name lookup for service
- Name server chooses appropriate server address
  - A-record returned is “best” one for the client
- What information can name server base decision on?
  - Server load/location → must be collected
  - Information in the name lookup request
    - Name service client → typically the local name server for client

How Akamai Works

- Clients fetch html document from primary server
  - E.g. fetch index.html from cnn.com
- URLs for replicated content are replaced in html
  - E.g. <img src=“http://cnn.com/af/x.gif”> replaced with <img src=“http://a73.g.akamaitech.net/7/23/cnn.com/af/x.gif”>
- Client is forced to resolve aXYZ.g.akamaitech.net hostname

How Akamai Works

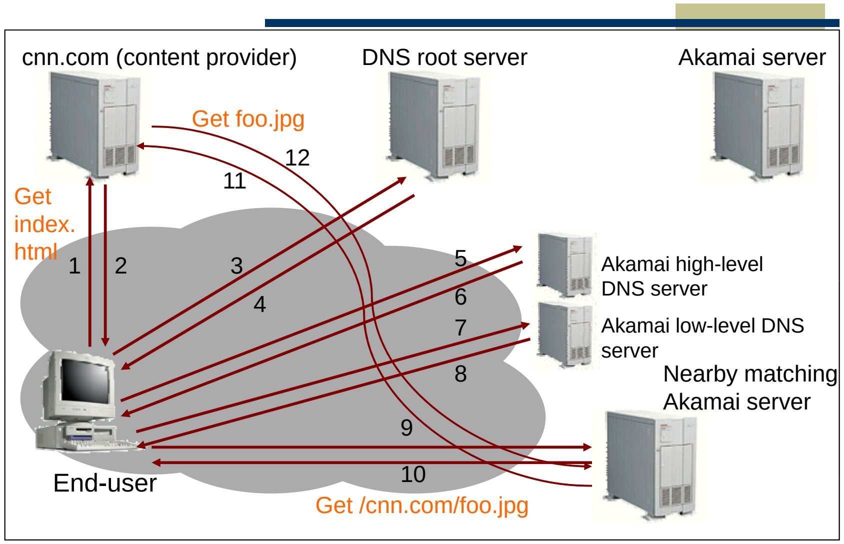
- How is content replicated?
- Akamai only replicates static content (*)
- Modified name contains original file name
- Akamai server is asked for content
  - First checks local cache
  - If not in cache, requests file from primary server and caches file

* (At least, the version we're talking about today. Akamai actually lets sites write code that can run on Akamai's servers, but that's a pretty different beast)

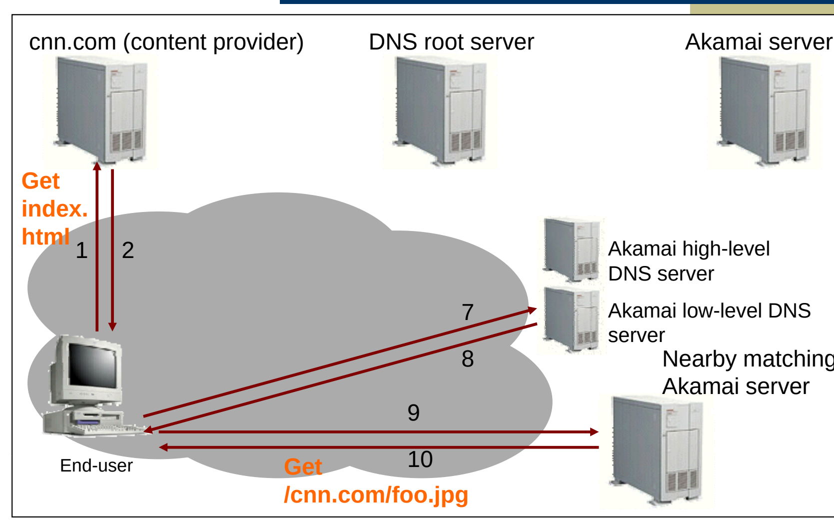
How Akamai Works

- Root server gives NS record for akamai.net
- Akamai.net name server returns NS record for g.akamaitech.net
  - Name server chosen to be in region of client's name server
  - TTL is large
- G.akamaitech.net nameserver chooses server in region
  - Should try to chose server that has file in cache - How to choose?
  - Uses aXYZ name and hash
  - TTL is small → why?

How Akamai Works



Akamai – Subsequent Requests



Simple Hashing

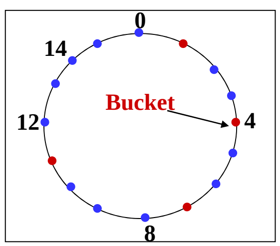
- Given document XYZ, we need to choose a server to use
- Suppose we use modulo
- Number servers from 1…n
  - Place document XYZ on server (XYZ mod n)
  - What happens when a servers fails? n → n-1
    - Same if different people have different measures of n
  - Why might this be bad?

Consistent Hash

- "view" = subset of all hash buckets that are visible
- Desired features
  - Smoothness – little impact on hash bucket contents when buckets are added/removed
  - Spread – small set of hash buckets that may hold an object regardless of views
  - Load – across all views # of objects assigned to hash bucket is small

Consistent Hash – Example

- Construction
  - Assign each of C hash buckets to random points on mod 2^n circle, where, hash key size = *n.*
  - Map object to random position on unit interval
  - Hash of object = closest bucket

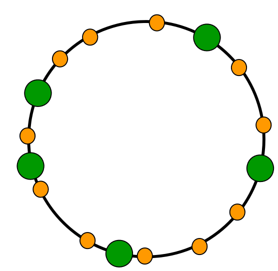


- Monotone → addition of bucket does not cause movement between existing buckets
- Spread & Load → small set of buckets that lie near object
- Balance → no bucket is responsible for large number of objects

Consistent Hashing

- **Main idea:**
  - map both keys and nodes to the same (metric) identifier space
  - find a "rule" how to assign keys to nodes

Ring is one option.



Consistent Hashing

- The consistent hash function assigns each node and key an *m*-bit identifier using SHA-1 as a base hash function
- **Node identifier:** SHA-1 hash of IP address
- **Key identifier:** SHA-1 hash of key

Identifiers

- *m* bit identifier space for both keys and nodes
- **Key identifier:** SHA-1(key)

  Key="LetItBe" $\xrightarrow{\text{SHA-1}}$ ID=60

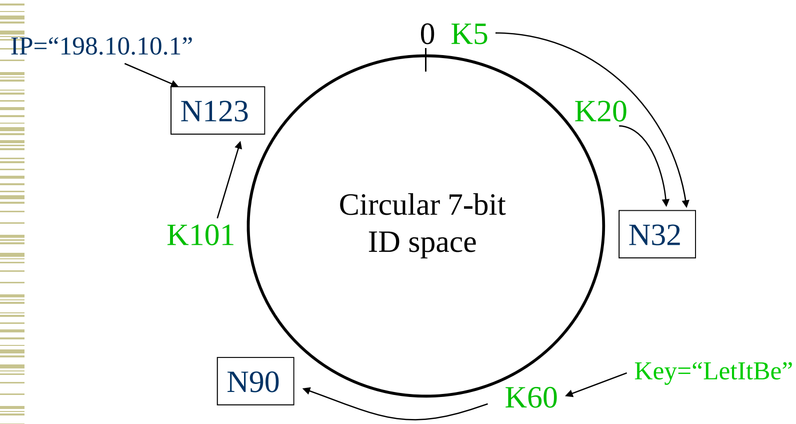
- **Node identifier:** SHA-1(IP address)

  IP="198.10.10.1" $\xrightarrow{\text{SHA-1}}$ ID=123

- How to map key IDs to node IDs?

Consistent Hashing Example

Rule: A key is stored at its successor: node with next higher or equal ID



Consistent Hashing Properties

- **Load balance:** all nodes receive roughly the same number of keys
- For *N* nodes and *K* keys, with high probability
  - each node holds at most $(1+\varepsilon)K/N$ keys
  - (provided that K is large enough compared to N)

Consistent Hash – Example

- Construction
  - Assign each of C hash buckets to random points on mod 2^n circle, where, hash key size = *n.*
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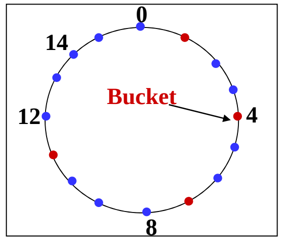

- Monotone → addition of bucket does not cause movement between existing buckets
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Load Balance

- Redirector knows all CDN server Ids
- Can track approximate load (or delay)
- To balance load:
  - W_i = Hash(URL, S_i) for all I
  - Sort W_i
  - From high to low find first server with low enough load
- How should “load” be measured?

Consistent Hashing not just for CDN

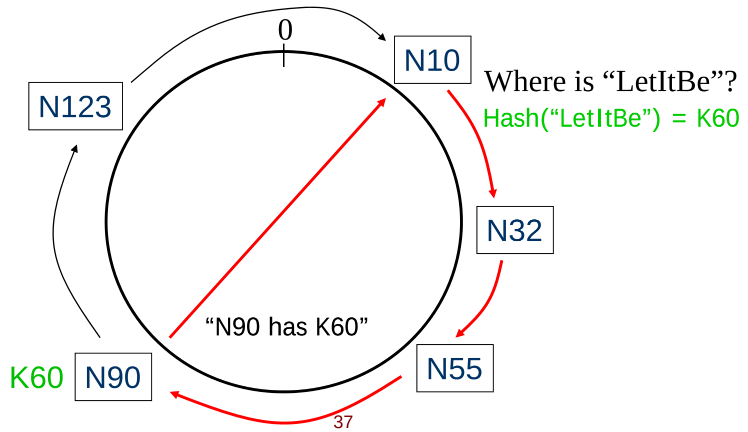
- Finding a nearby server for an object in a CDN uses centralized knowledge.
- Consistent hashing can also be used in a distributed setting
- P2P systems like BitTorrent, e.g., project 3, need a way of finding files.
- Consistent Hashing to the rescue.

Chord: Design Goals

- Load balance: Chord acts as a distributed hash function, spreading keys evenly over the nodes.
- Decentralization: Chord is fully distributed: no node is more important than any other.
- Scalability: The cost of a Chord lookup grows as the log of the number of nodes, so even very large systems are feasible.
- Availability: Chord automatically adjusts its internal tables to reflect newly joined nodes as well as node failures, ensuring that the node responsible for a key can always be found.

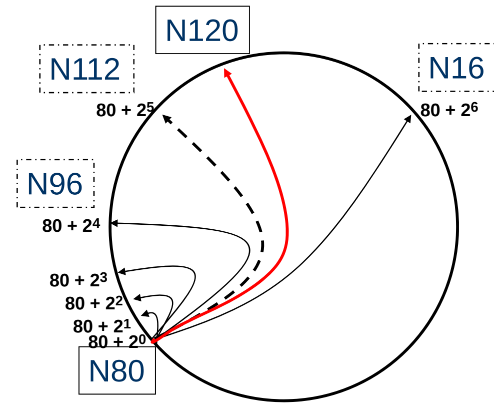
Lookups strategies

- Every node knows its successor in the ring
- Requires *O(N)* lookups



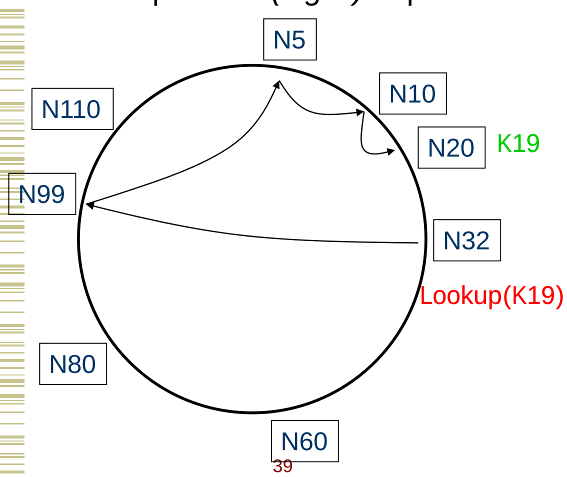
Reducing Lookups: Finger Tables

- Each node knows *m* other nodes in the ring (it has m fingers)
- Increase distance exponentially
- Finger *i* points to successor of $n+2^{i-1}$ i=1..m



Faster Lookups

- Lookups are *O(log N)* hops



N32 finger table

F0 points to successor($32+2^0$) = 60
F1 points to successor($32+2^1$) = 60
F2 points to successor($32+2^2$) = 60
F3 points to successor($32+2^3$) = 60
F4 points to successor($32+2^4$) = 60
F5 points to successor($32+2^5$) = 80
F6 points to successor($32+2^6$) = 99

Look for a node identifier in the finger table that is less then the key identifier and closest in the ID space to the key identifier

Summary of Performance Results

- **Efficient:** *O(log N)* messages per lookup
- **Scalable:** *O(log N)* state per node
- **Robust:** survives massive membership changes

Joining the Ring

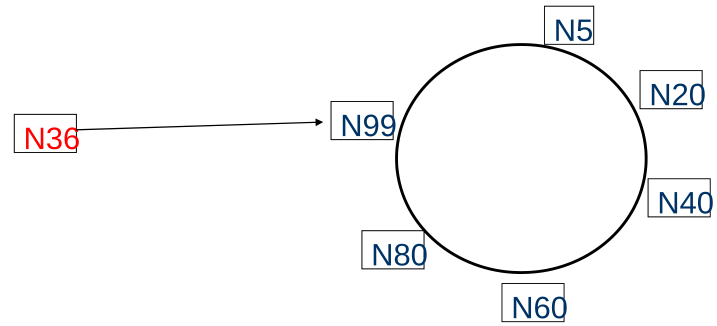
- Three step process
  - Initialize all fingers of new node
  - Update fingers of existing nodes
  - Transfer keys from successor to new node

- Two invariants to maintain
  - Each node's finger table is correctly maintained
  - *successor(k)* is responsible for *k (objects stored in correct place)*

Join: Initialize New Node's Finger Table

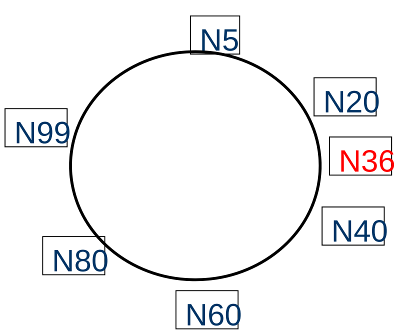
- Locate **any** node *p* in the ring
- Ask node *p* to lookup fingers of new node

1. Lookup(37,38,40,...,100,164)



Join: Update Fingers of Existing Nodes

- New node calls update function on existing nodes

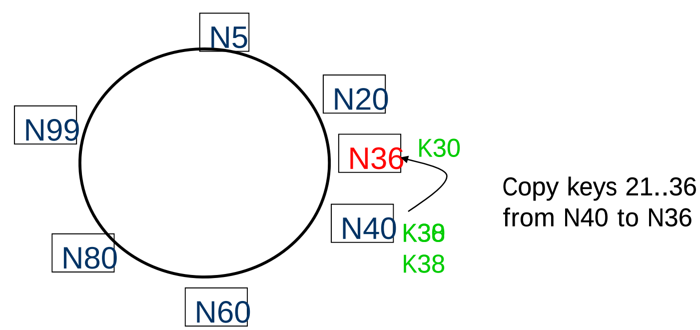


n becomes the ith fingerprint of node p if p precedes n by at least 2^{i-1} and i^{th} finger of node p succeeds n.

Update in $O(\log^2 N)$ expected messages

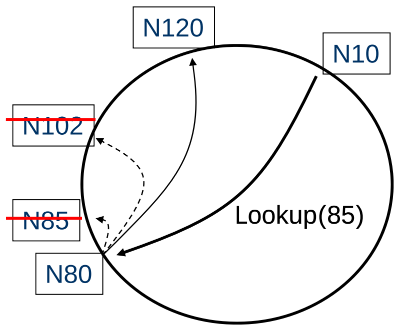
Join: Transfer Keys

- Only keys in the range are transferred



Handling Failures

- **Problem:** Failures could cause incorrect lookup
- **Solution:** *Fallback:* keep track of a list of immediate successors



Handling Failures

- Use successor list
  - Each node knows *r* immediate successors
  - After failure, will know first live successor
  - Correct successors guarantee correct lookups
- Guarantee with some probability
  - Can choose *r* to make probability of lookup failure arbitrarily small

Joining/Leaving overhead

- When a node joins (or leaves) the network, only an fraction of the keys are moved to a different location.
- For *N* nodes and *K* keys, with high probability
  - when node *N*+1 joins or leaves, O(*K*/*N*) keys change hands, and only to/from node *N*+1

Summary

- Caching improves web performance
- Caching only at client is only partial solution
- Content Delivery Networks move data closer to user, maintain consistency, balance load
- Consistent Caching maps keys AND buckets into the same space
- Consistent caching can be fully distributed, useful in P2P systems using structured overlays