Web Caching and Content Distribution: A View From the Interior

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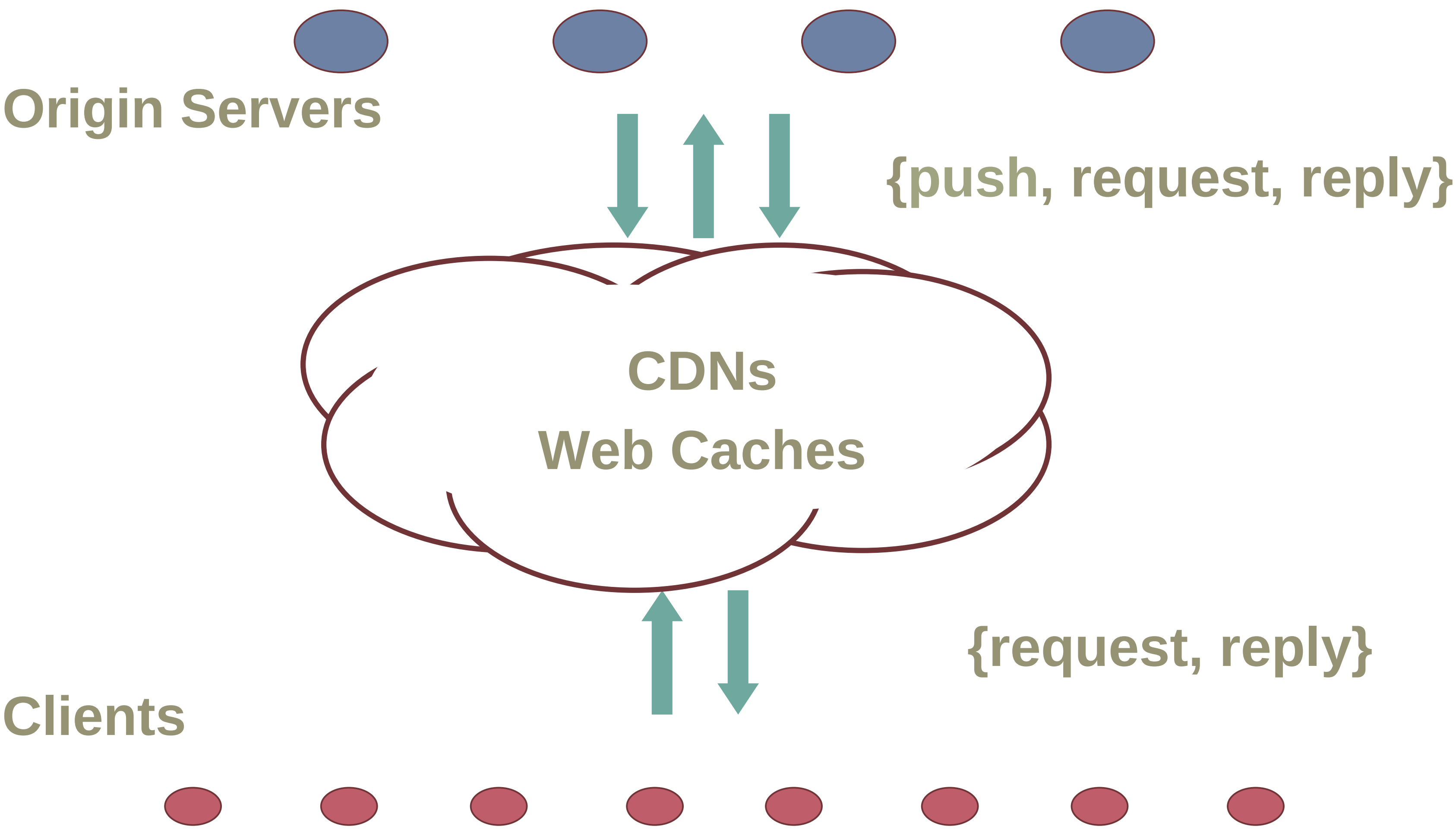
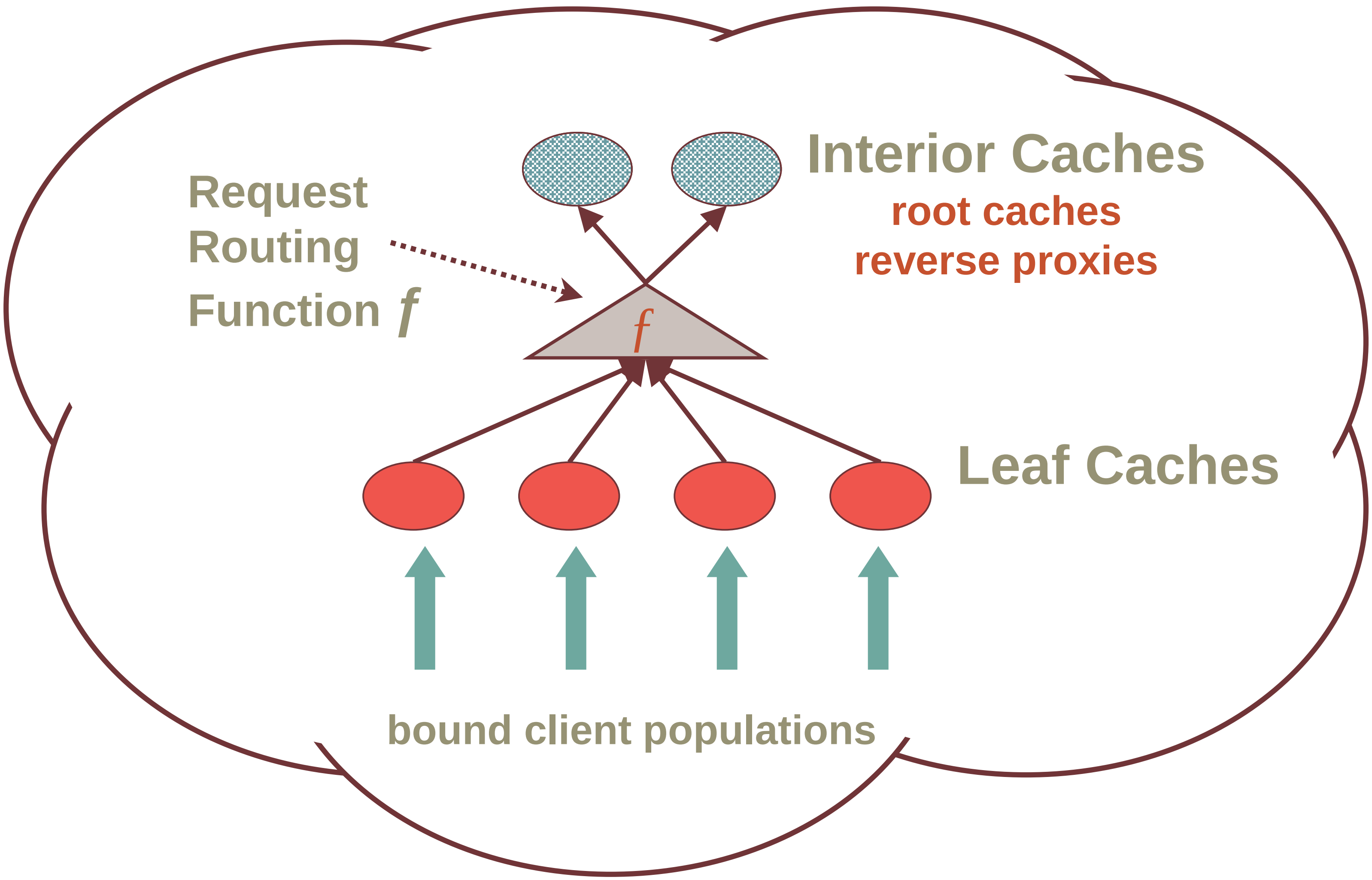
Overview

- Analytical tools have evolved to predict behavior of large-scale Web caches.
  - Are results from existing large-scale caches consistent with the predictions?
    - NLANR
  - What do the models predict for Content Distribution/Delivery Networks (CDNs)?
- Goal: answer these questions by extending models to predict *interior* cache behavior.

Generalized Cache/CDN (External View)



Generalized Cache/CDN (Internal View)



Goals and Limitations

- Focus on *interior cache* behavior.
  - Assume leaf caches are ubiquitous.
  - Model CDNs as interior caches.
- Focus on *hit ratio* (percentage of accesses absorbed by the "cloud").
  - Ignore push replication; at best it merely reduces some latencies by moving data earlier.
- Focus on "typical" *static* Web objects.
  - Ignore streaming media and dynamic content.

Outline

- Analytical model
  - applied to interior nodes of cache hierarchies
  - applied to CDNs
- Implications of the model for CDNs in the presence of ubiquitous leaf caching
- Match model with observations from the NLANR cache hierarchy
- Conclusion

Analytical Model

- [Wolman/Voelker/Levy et. al., SOSP 1999]
  - refines [Breslau/Cao et. al., 1999], and others
- Approximates *asymptotic* cache behavior assuming Zipf-like object popularity
  - caches have sufficient capacity
- Parameters:
  - λ = per-client request rate
  - μ = rate of object change
  - p_c = percentage of objects that are cacheable
  - α = Zipf parameter (object popularity)

Cacheable Hit Ratio: the Formula

- C_N is the hit ratio for cacheable objects achievable by population of size N with a universe of n objects.

$$C_N = \int_1^n \frac{1}{Cx^\alpha}\left(\frac{1}{1 + \frac{\mu C x^\alpha}{\lambda N}}\right) dx$$

$$C = \int_1^n \frac{1}{x^\alpha} dx$$

[Wolman/Voelker/Levy et. al., SOSP 99]

Inside the Hit Ratio Formula

Approximates a sum over a universe of *n* objects...

...of the probability of access to each object *x*...

…times the probability *x* was accessed since its last change.

$$C_N = \int_1^n \frac{1}{Cx^{\alpha}} \left(\frac{1}{1 + \frac{\mu C x^{\alpha}}{\lambda N}} \right) dx$$

C is just a normalizing constant for the Zipf-like popularity distribution (a PDF).

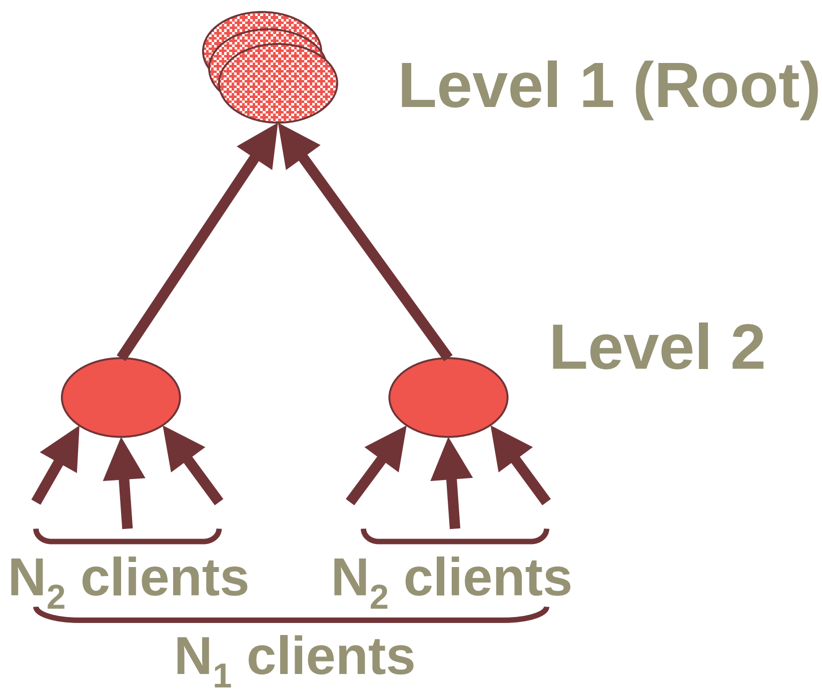
$$C = \int_1^n \frac{1}{x^{\alpha}} dx$$

$C = 1/\Omega$

in [Breslau/Cao 99]

$0 < \alpha < 1$

An Idealized Hierarchy



Assume the trees are symmetric to simplify the math.

Ignore individual caches and solve for each level.

Hit Ratio at Interior Level *i*

- C_N gives us the hit ratio for a complete subtree covering population N
- The hit ratio predicted at level i or at any cache in level i is given by:

$$\frac{\text{hits at level } i}{\text{requests to level } i} = \frac{h_i}{r_i} = \frac{Rp_c(C_{N_i} - C_{N_{i+1}})}{r_{i+1} - h_{i+1}}$$

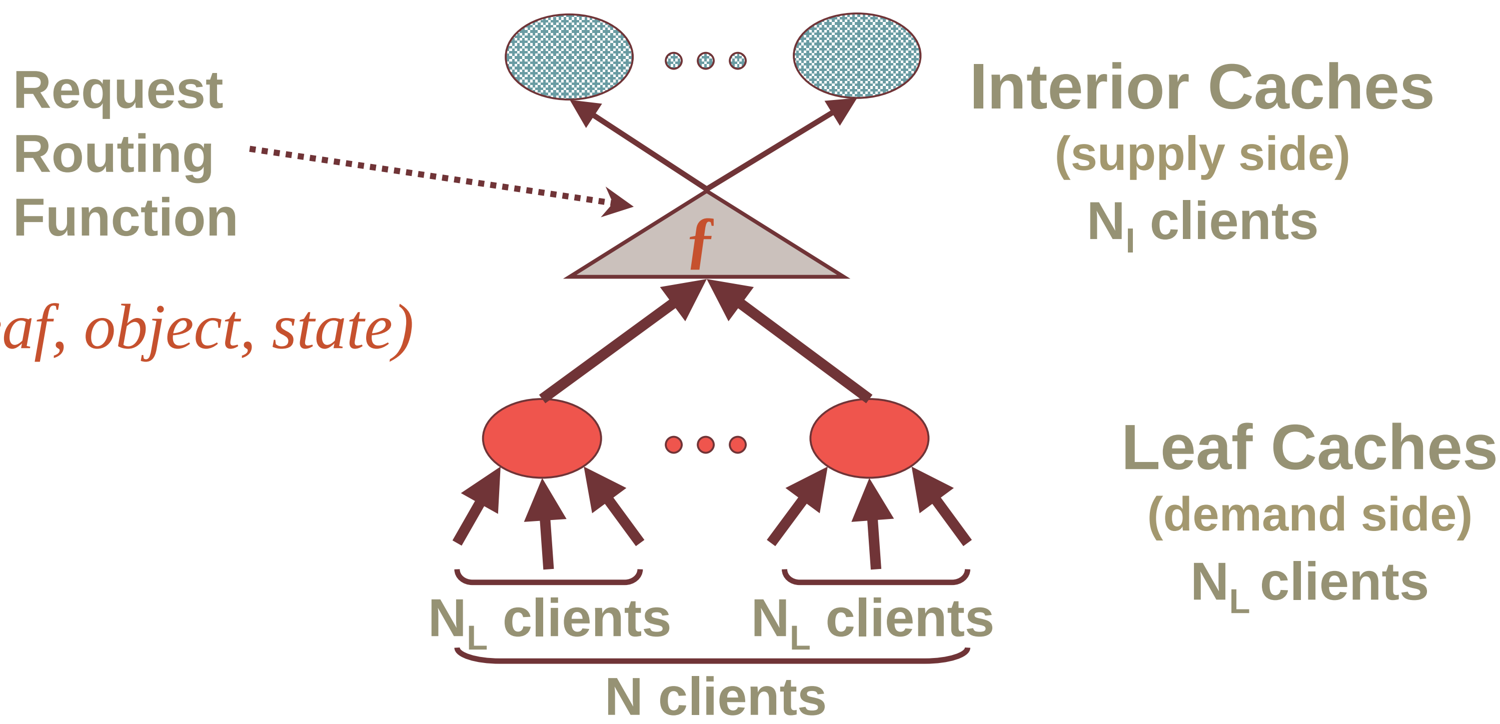
"the hits for N_i (at level *i*) minus the hits captured by level *i+1*, over the miss stream from level *i+1*"

Root Hit Ratio

- Predicted hit ratio for cacheable objects, observed at root of a two-level cache hierarchy (i.e. where $r_2 = Rp_c$):

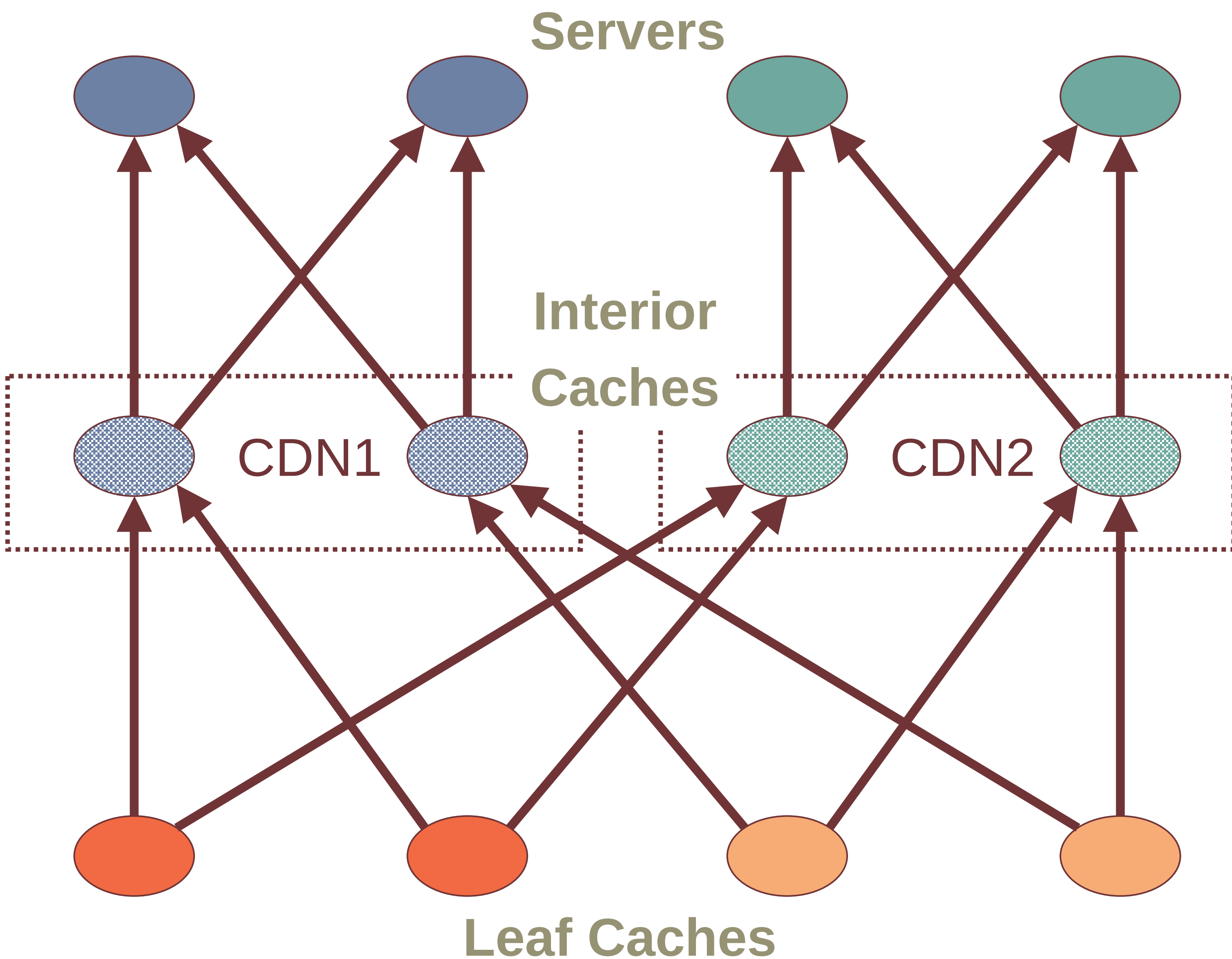
$$\frac{h_1}{r_1} = \frac{C_{N_1} - C_{N_2}}{1 - C_{N_2}}$$

Generalizing to CDNs

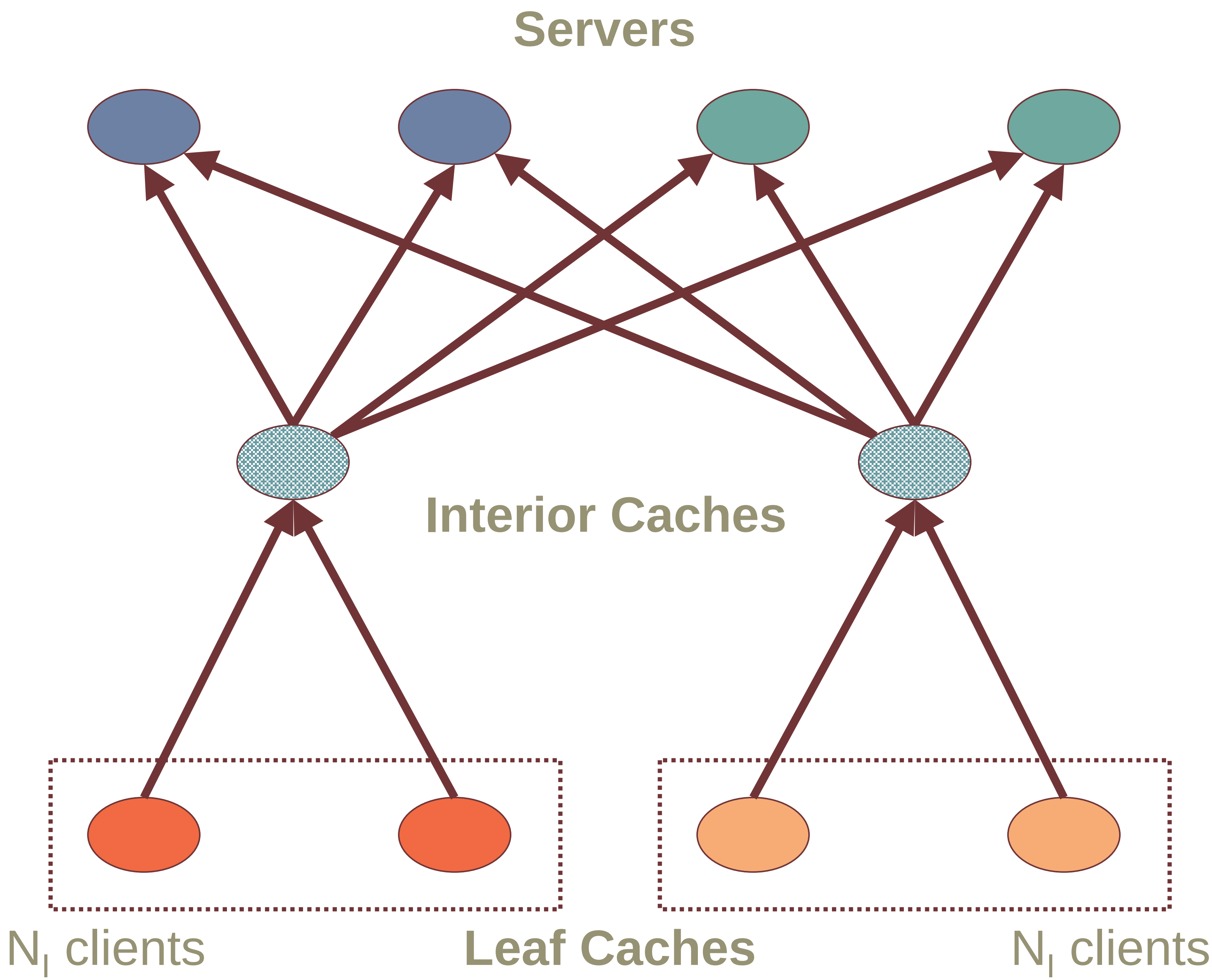


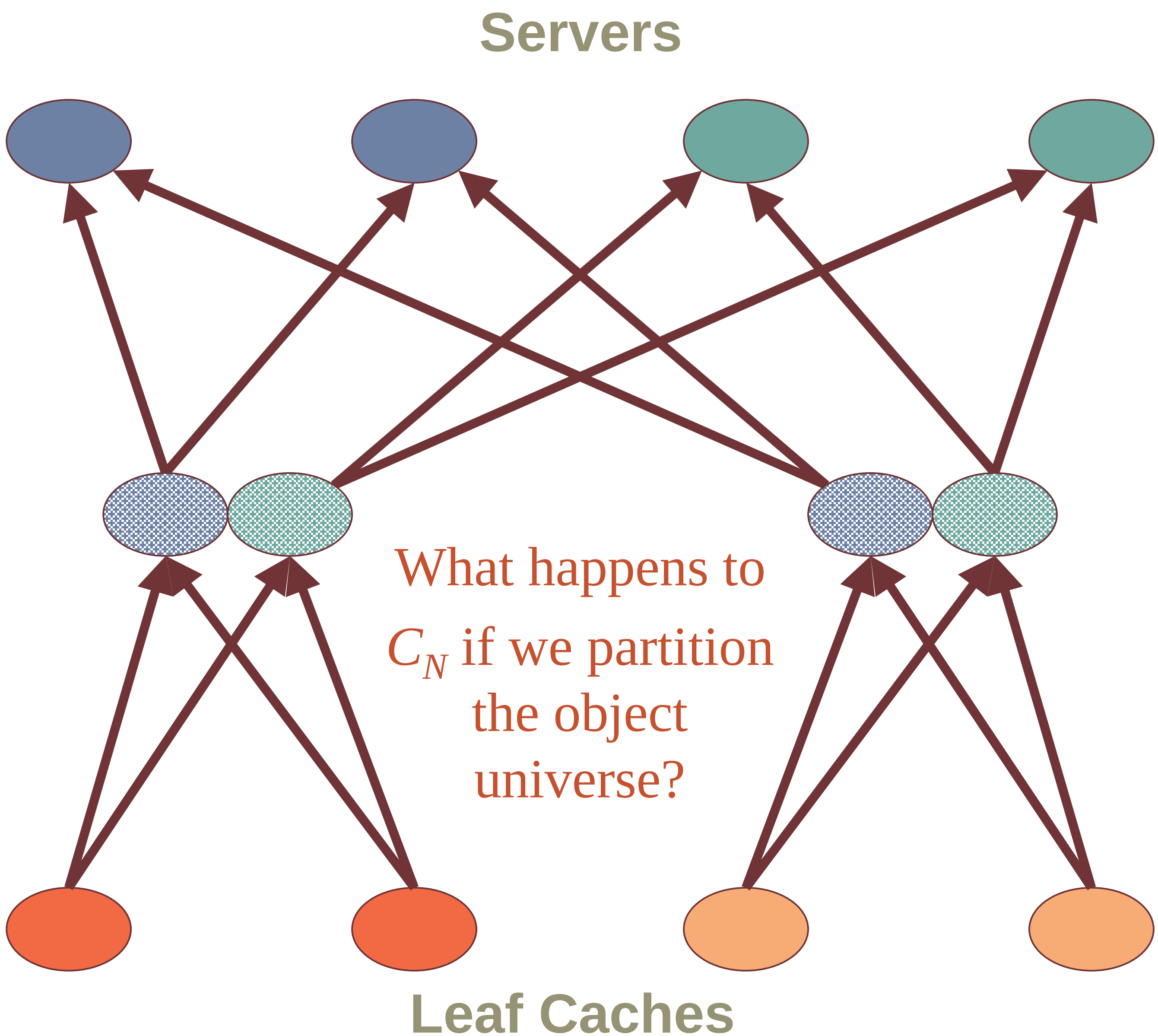
f(leaf, object, state)

Symmetry assumption: *f* is stable and “balanced”.

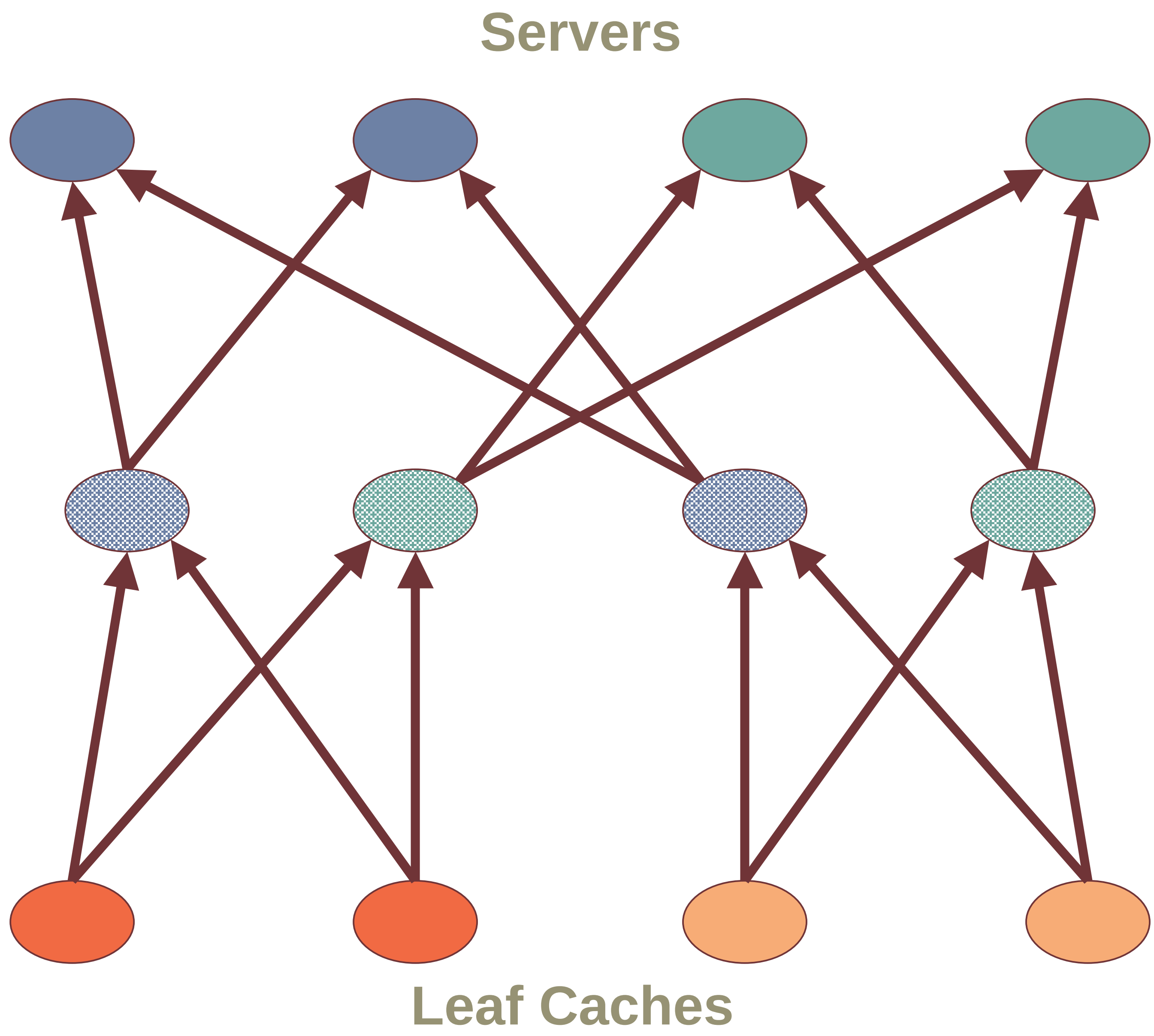


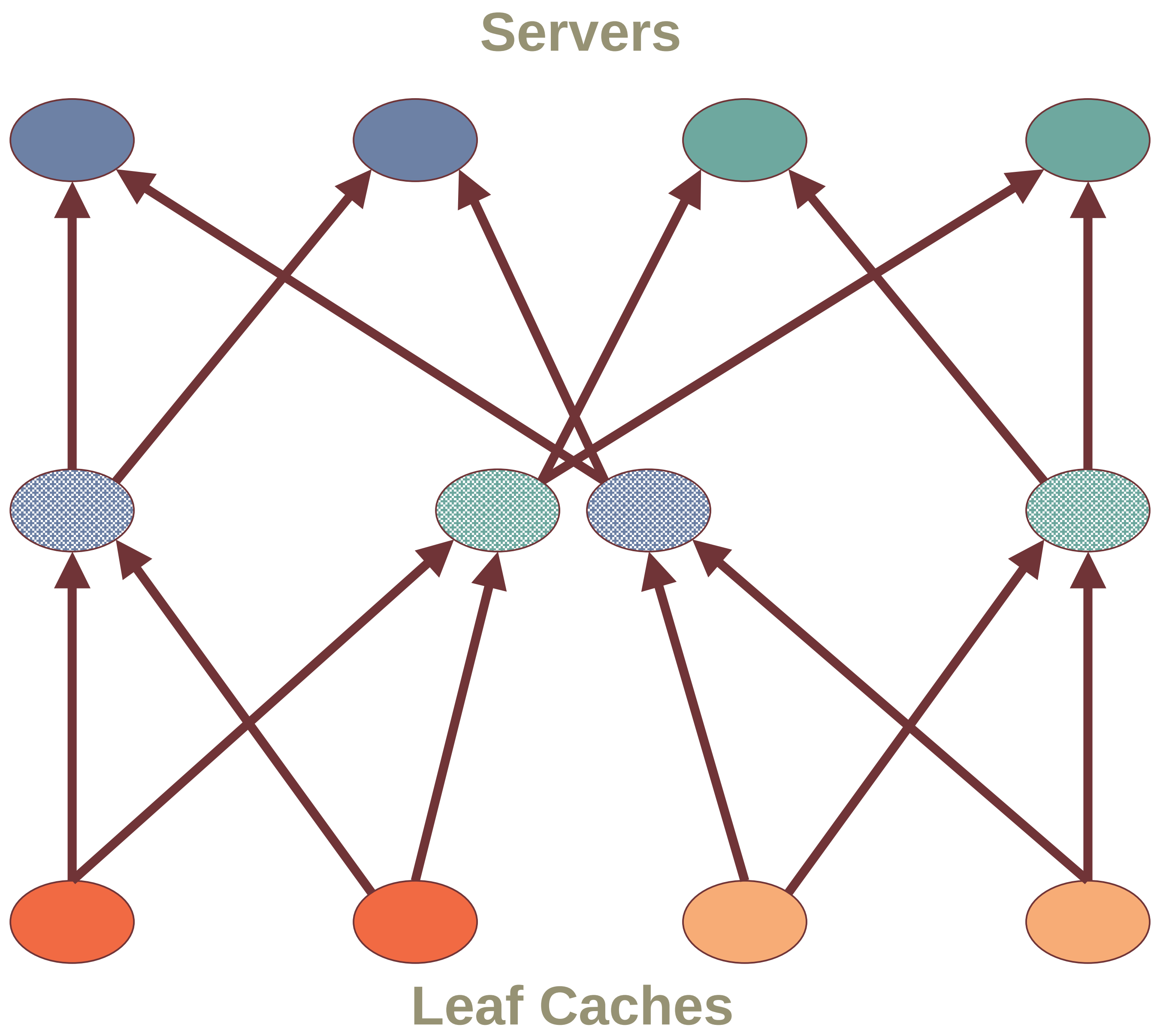
Servers
Interior
Caches
CDN1
CDN2
Leaf Caches

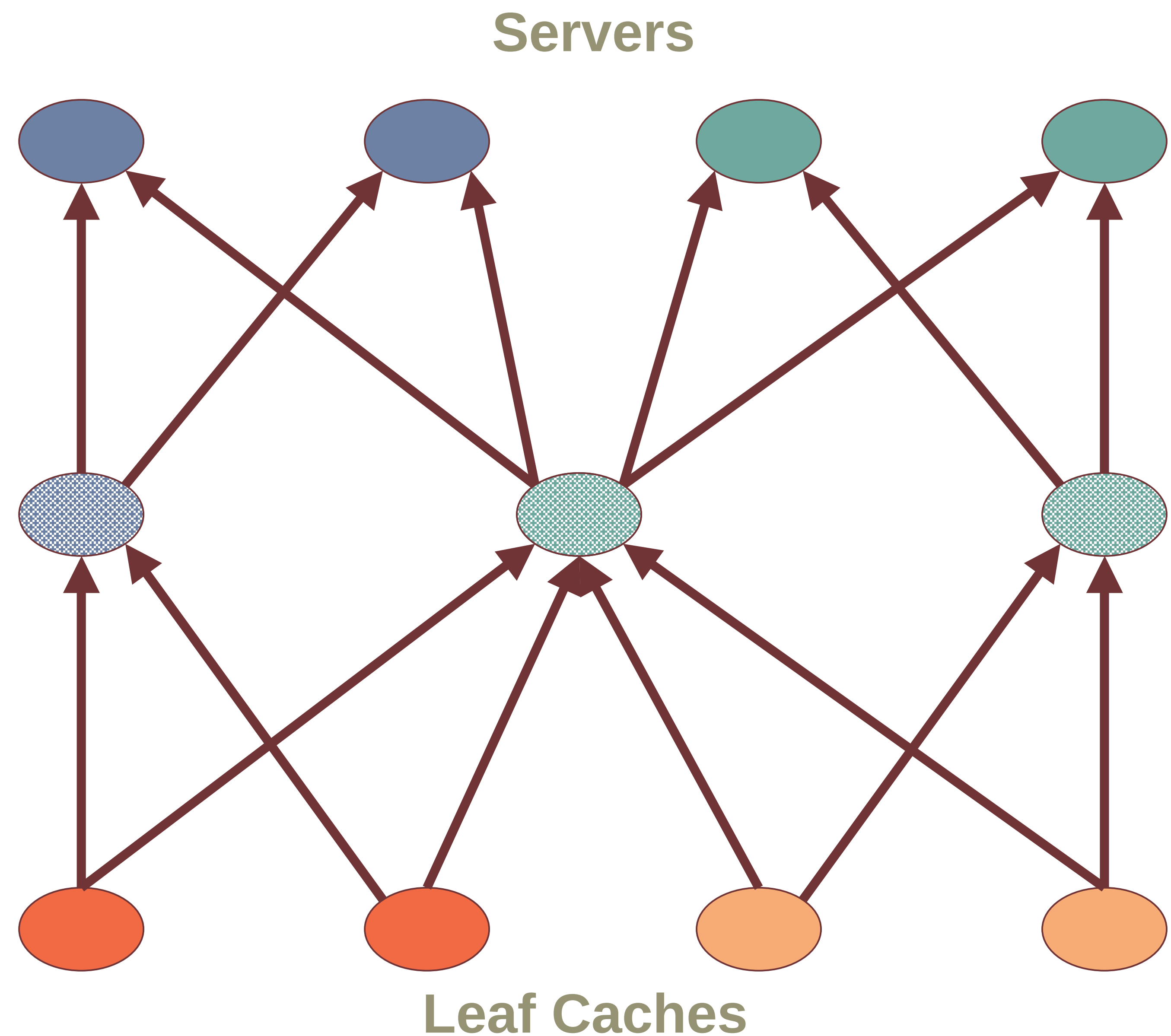

Servers
Interior Caches
N_l clients
Leaf Caches
N_l clients

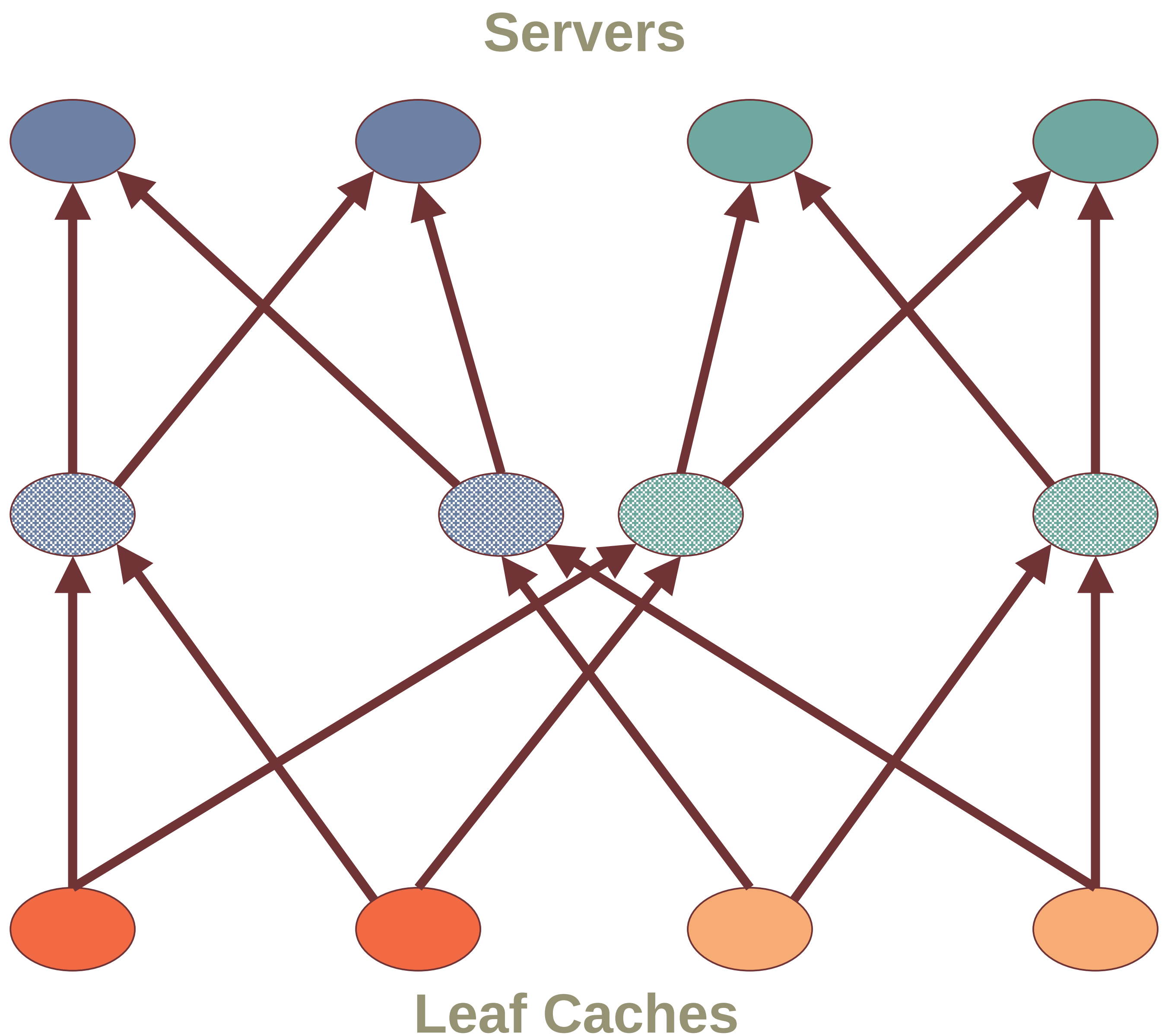


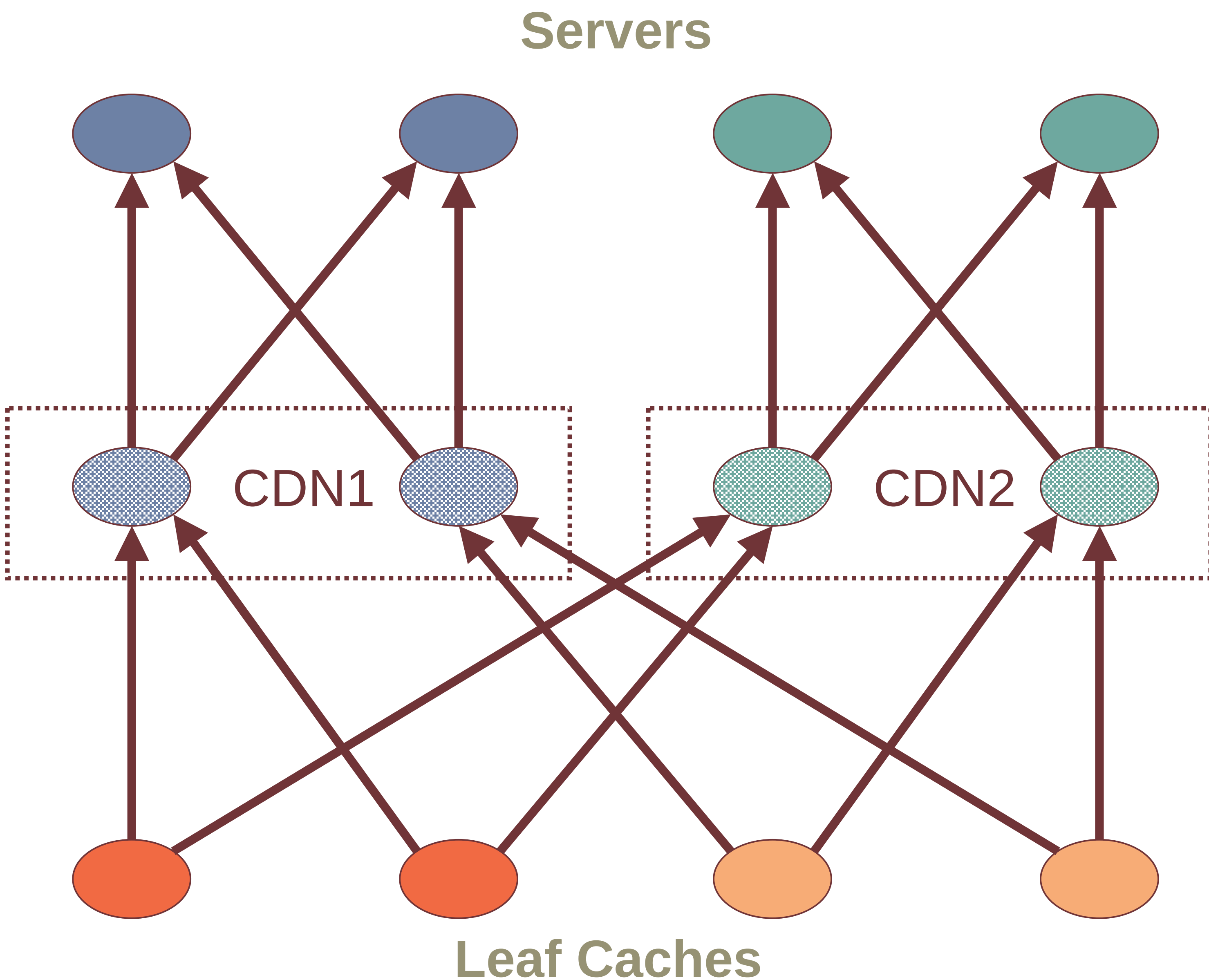
What happens to C_N if we partition the object universe?


Servers
Leaf Caches


Servers
Leaf Caches


Servers
Leaf Caches


Servers
Leaf Caches


Servers
CDN1
CDN2
Leaf Caches

Hit ratio in CDN caches

- Given the symmetry and balance assumptions, the cacheable hit ratio at the interior (CDN) nodes is:

$$\frac{C_{N_I} - C_{N_L}}{1 - C_{N_L}}$$

N_I is the covered population at each CDN cache.
N_L is the population at each leaf cache.

Analysis

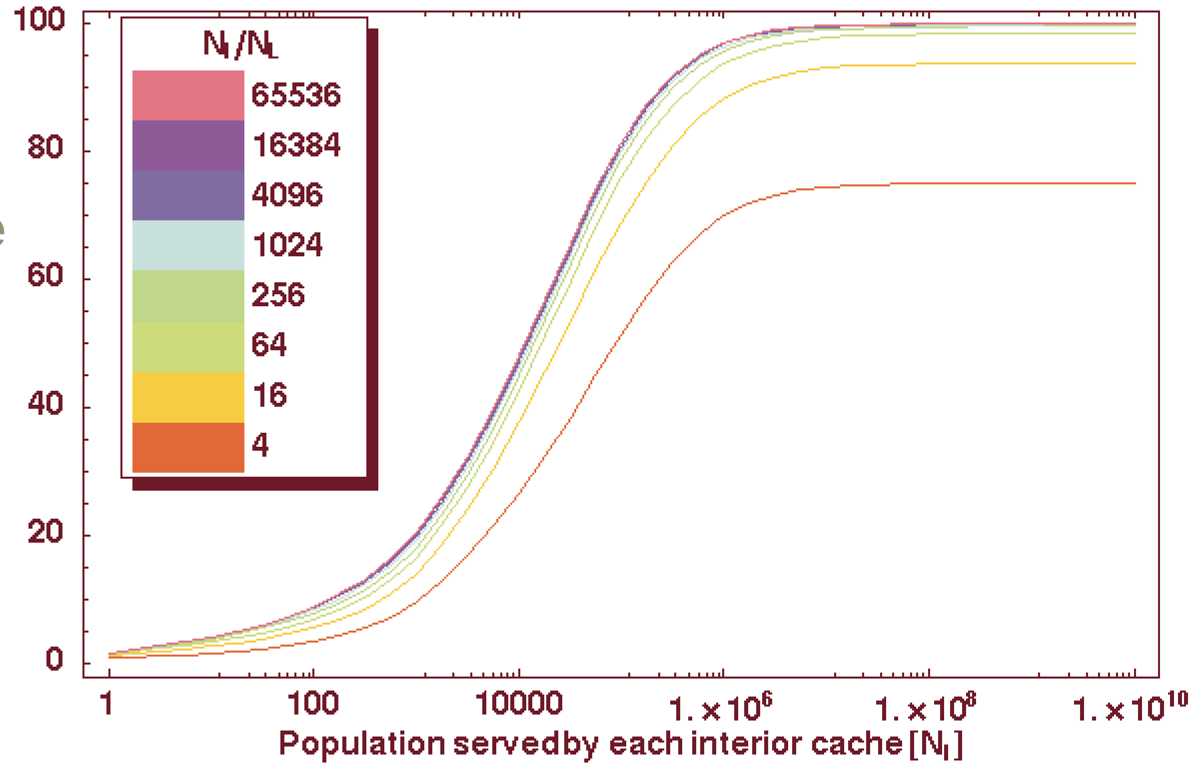
- We apply the model to gain insight into interior cache behavior with:
  - varying leaf cache populations (N_L)
    - *e.g., bigger leaf caches*
  - varying ratio of interior to leaf cache populations (N_I/N_L)
    - *e.g., more specialized interior caches*
  - Zipf α parameter changes
    - *e.g., more concentrated popularity*

Analysis (cont'd)

- Fixed parameters (unless noted otherwise):
  - λ (client request rate) = 590 reqs./day
  - μ (rate of object change) =
    - once every 14 days (popular objects, 0.3%)
    - once every 186 days (unpopular objects)
  - p_c (percent of requests cacheable) = 60%
  - α (Zipf parameter - object popularity) = 0.8

Cacheable interior hit ratio observed at interior level fixing interior/leaf population ratio

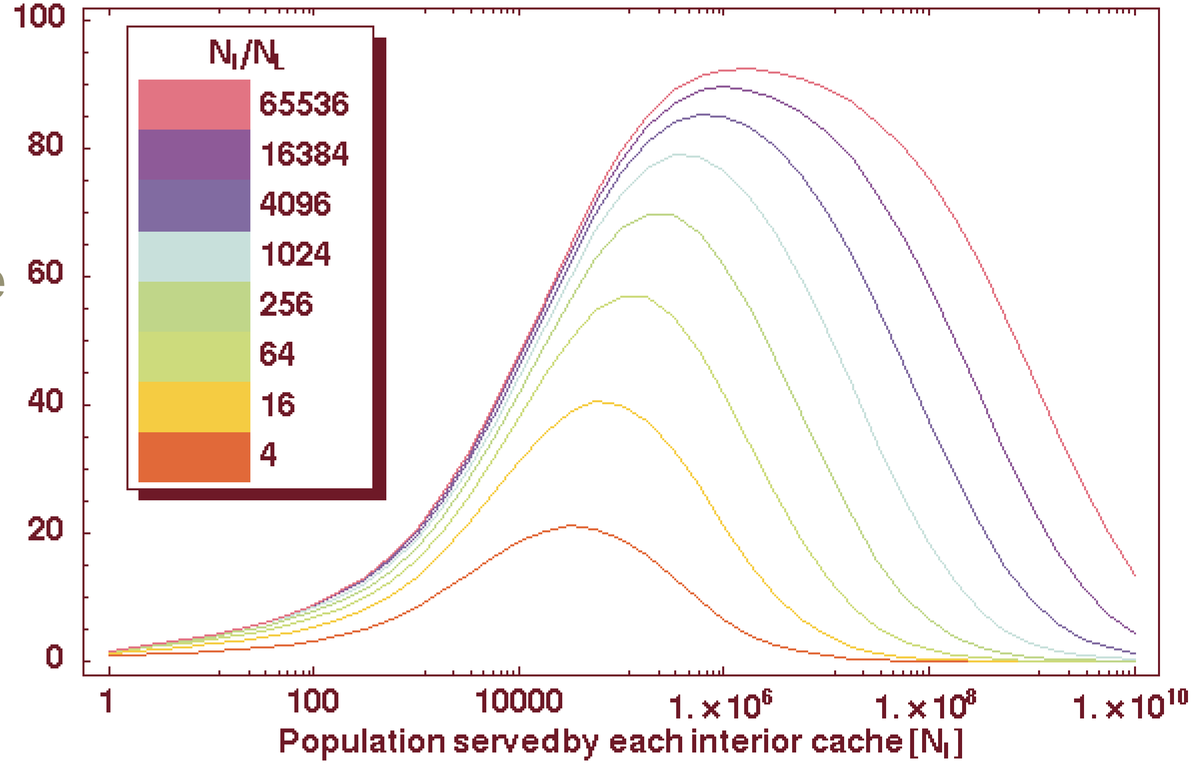
cacheable hit ratio



increasing N_I and N_L -->

Interior hit ratio
as percentage of all cacheable requests, fixing interior/leaf population ratio

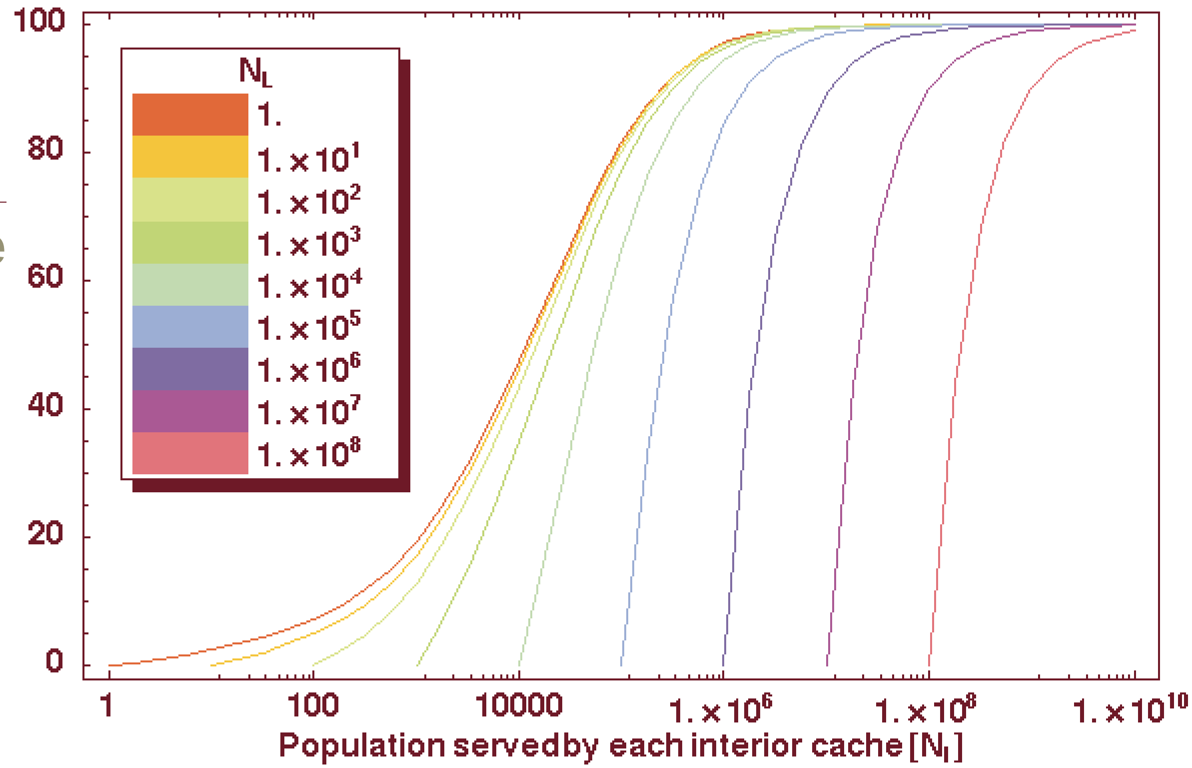
marginal cacheable hit ratio



increasing N_I and N_L -->

Cacheable interior hit ratio fixing leaf population

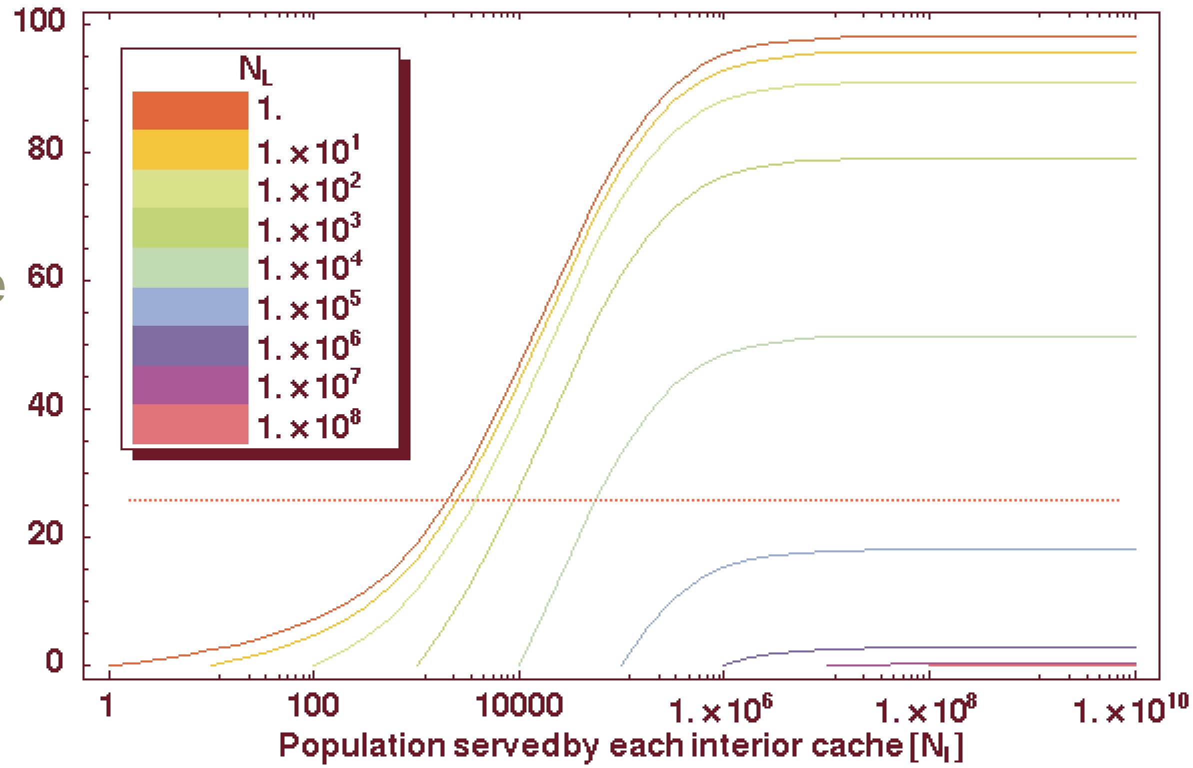
cacheable hit ratio



increasing "bushiness" -->

Cacheable interior hit ratio as percentage of all requests fixing leaf population

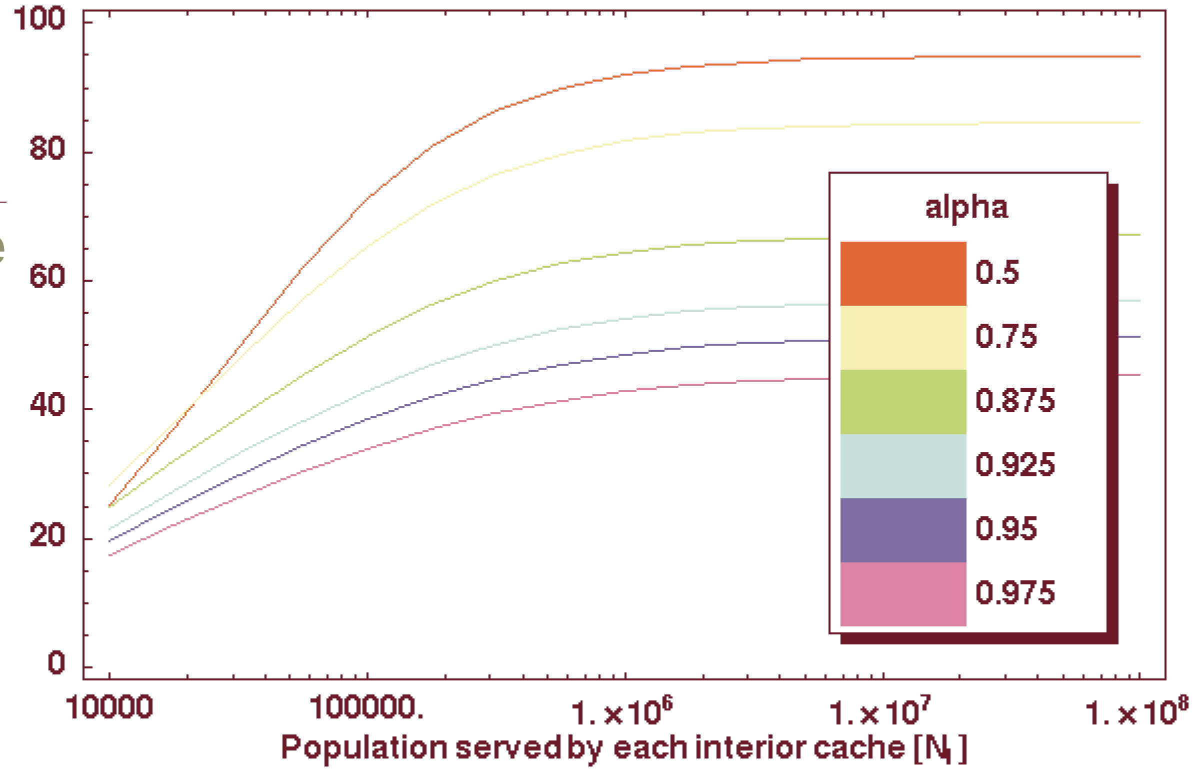
marginal cacheable hit ratio



increasing “bushiness” -->

Cacheable interior hit ratio as percentage of all requests varying Zipf α parameter

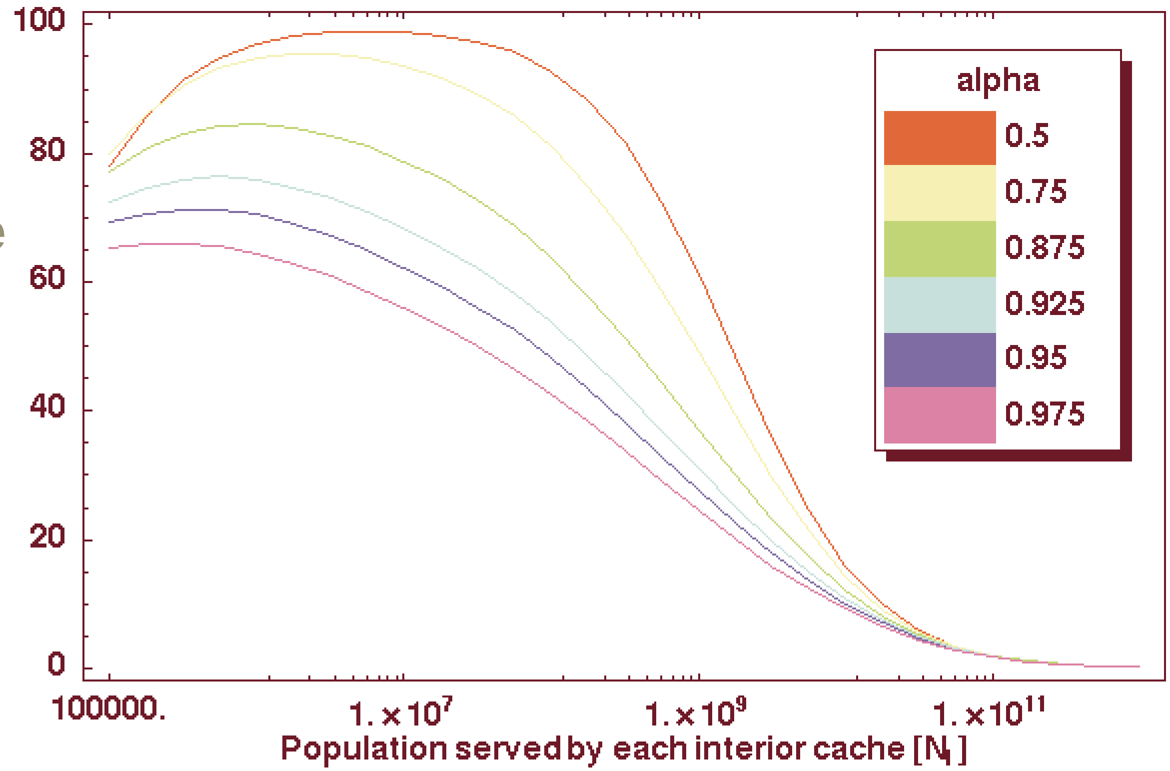
cacheable hit ratio



N_L fixed at 1024 clients

Cacheable interior hit ratio as percentage of all requests varying Zipf α parameter

cacheable hit ratio



N_I/N_L fixed at 64K

Conclusions (I)

- Interior hit ratio captures effectiveness of upstream caches at reducing access traffic filtered by leaf/edge caches.
  - Hit ratios grow rapidly with covered population.
- Edge cache populations (N_L) are key: is it one thousand or one million?
  - With large N_L, interior ratios are deceptive.
  - At $N_L = 10^5$, interior hit ratios might be 90%, but the CDN sees less than 20% of the requests.

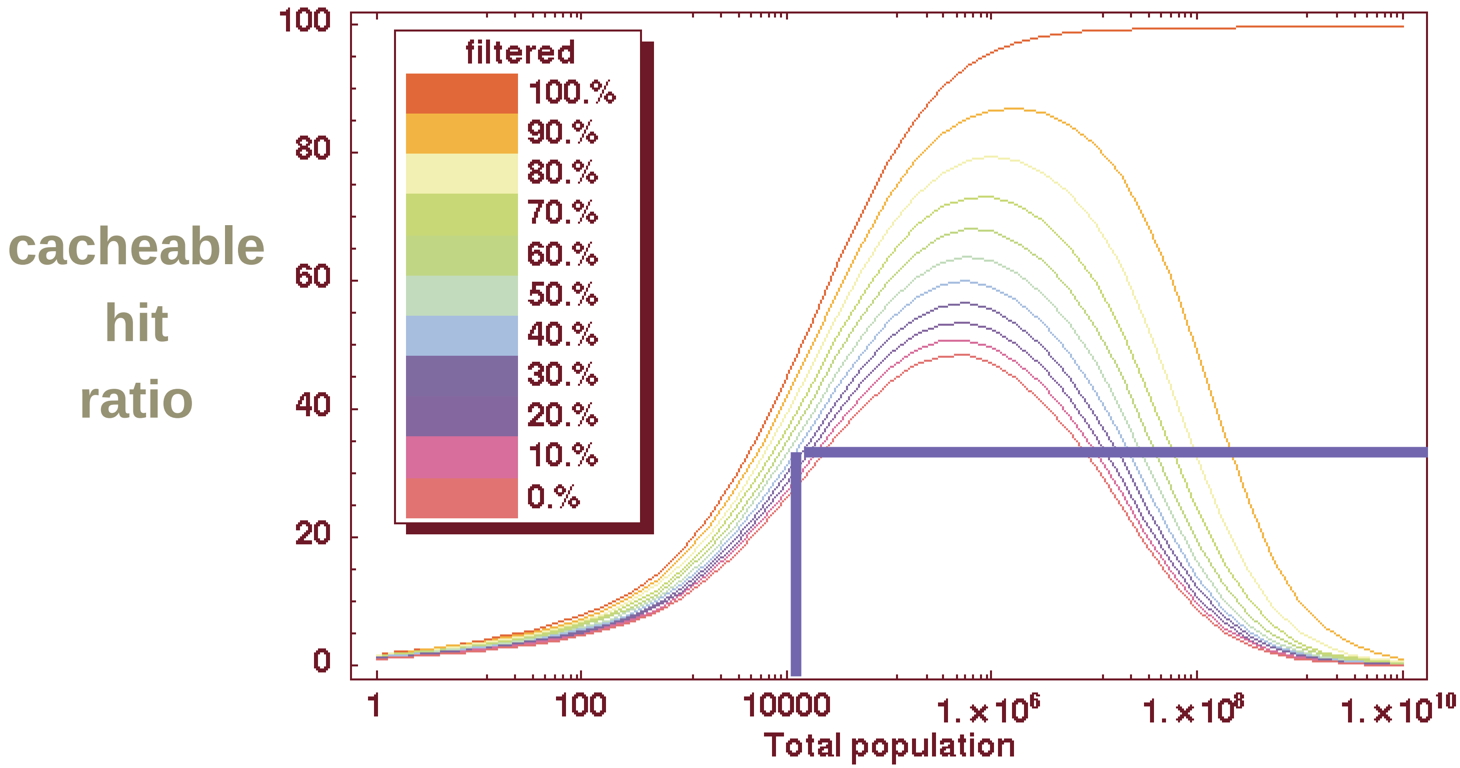
Correlating with NLANR Observations

- *Do the predictions match observations from existing large-scale caches?*
- Observations made from traces provided by NLANR (10/12/99).
  - Observed total hit ratio at (unified) root is 32%
  - 200 of the 914 leaf caches in the trace account for 95% of requests
  - daily request rate indicates population is on the order of tens of thousands
  - *What is the predicted N?*

Model vs. Reality

- NLANR roots cooperate; we filter the traces to determine the *unified* root hit ratio.
- NLANR caches are bounded; traces imply that capacity misses are low at 16GB.
- Analysis assumes the population is balanced across the 200 leaves of consequence.
- Analysis must compensate for objects determined to be uncacheable at a leaf.

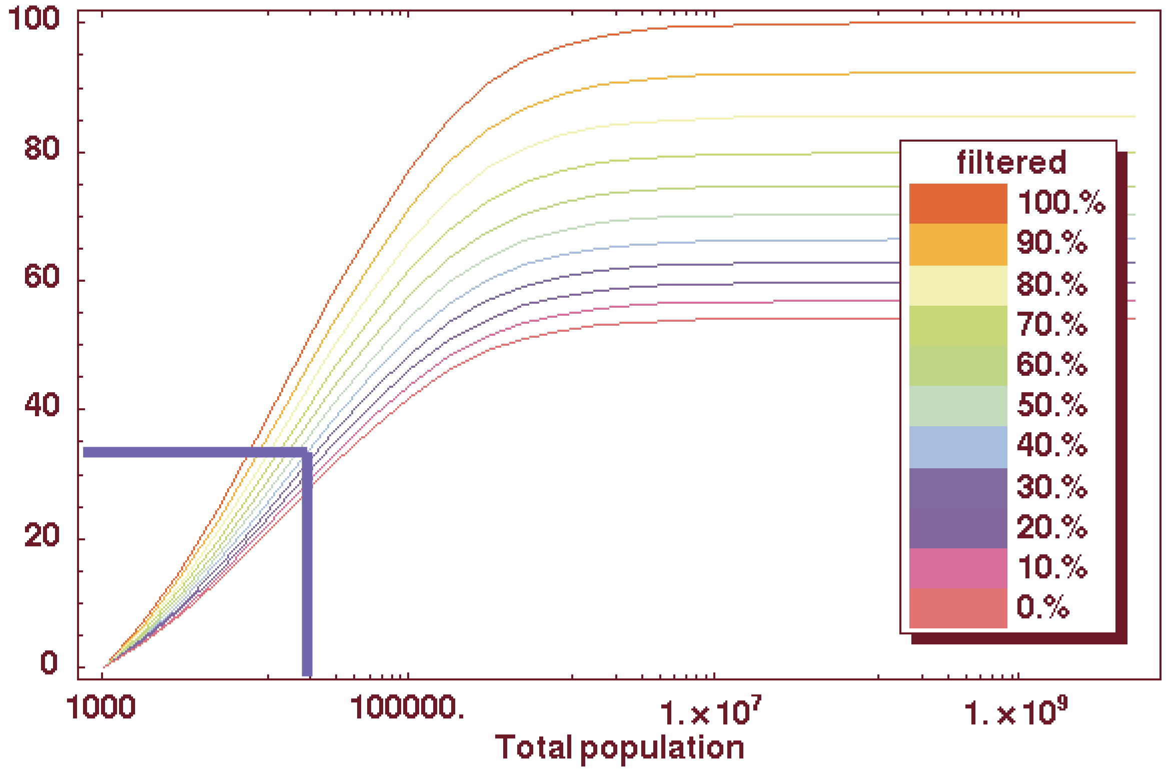
Cacheable interior hit ratio varying percentage of requests detected as uncacheable by leaves



200+ leaf caches

Cacheable interior hit ratio varying percentage of requests detected as uncacheable at request time

cacheable
hit
ratio



1000 clients per leaf cache

Conclusions (II)

- NLANR root effectiveness is around 32% today; it is serving its users well.
- NLANR experiment could validate the model, but more data from the experiment is needed.
  - E.g., covered populations, leaf summaries
- The model suggests that the population covered by NLANR is relatively small.
- With larger N and N_L, higher root hit ratios are expected, with lower marginal benefit.

Modeling CDNs

- If the routing function satisfies three properties:
  - an interior cache sees all requests for each assigned object *x* from a population of size N_I
  - every interior cache sees an equivalent object popularity distribution (*n*/λ held constant)
  - all requests are routed through leaf caches that serve N_L clients
- then interior cacheable hit ratio is:

$$\frac{C_{N_I} - C_{N_L}}{1 - C_{N_L}}$$

Hit ratio with detected uncacheable documents

- p_u is the percentage of uncacheable requests detected *at request time* (and not forwarded to parents):

$$\frac{h_i}{r_i} = \frac{Rp_c(C_{N_i} - C_{N_{i+1}})}{R - h_{i+1} - (1 - p_c)(1 - p_u)r_{i+1}}$$

$$\frac{h_1}{r_2} = \frac{H_{N_1} - H_{N_2}}{1 - H_{N_2} - (1 - p_c)(1 - p_u)}$$

Cache Hierarchies

- As introduced by the Harvest project
  - *k* levels of demand-side caches arranged in a tree (for now)
  - clients are bound to leaves
  - each node's miss stream routes to its parent
- As extended by NLANR (Squid)
  - NLANR-operated root caches cooperate by partitioning URL space

Cache Hierarchies Illustrated