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On Content Indexing for Off-Path Caching in Information-Centric Networks

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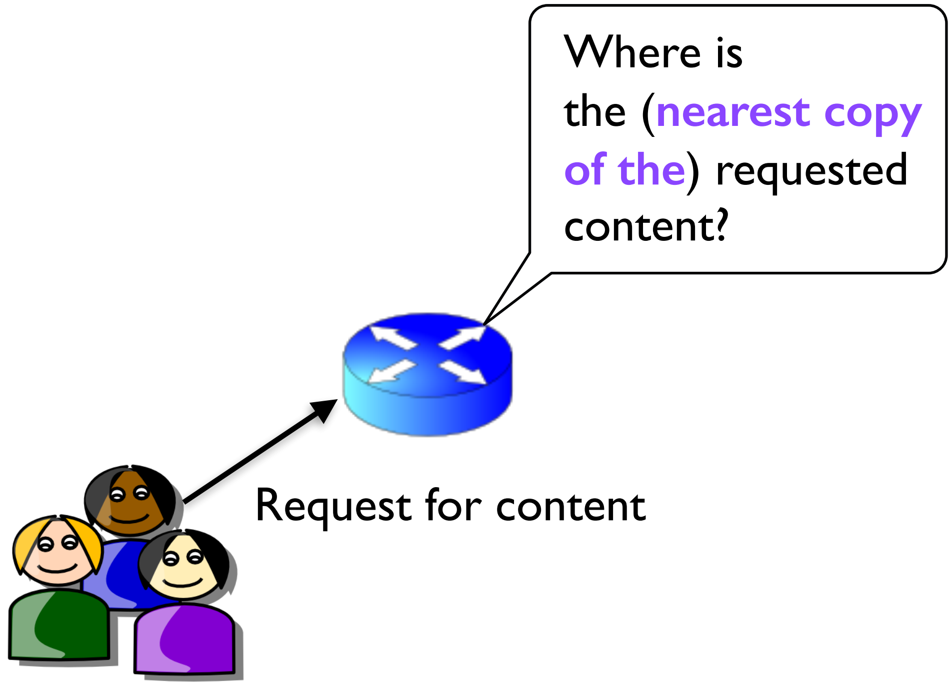

Where is the (nearest copy of the) requested content?
Request for content

Name resolution service in ICN

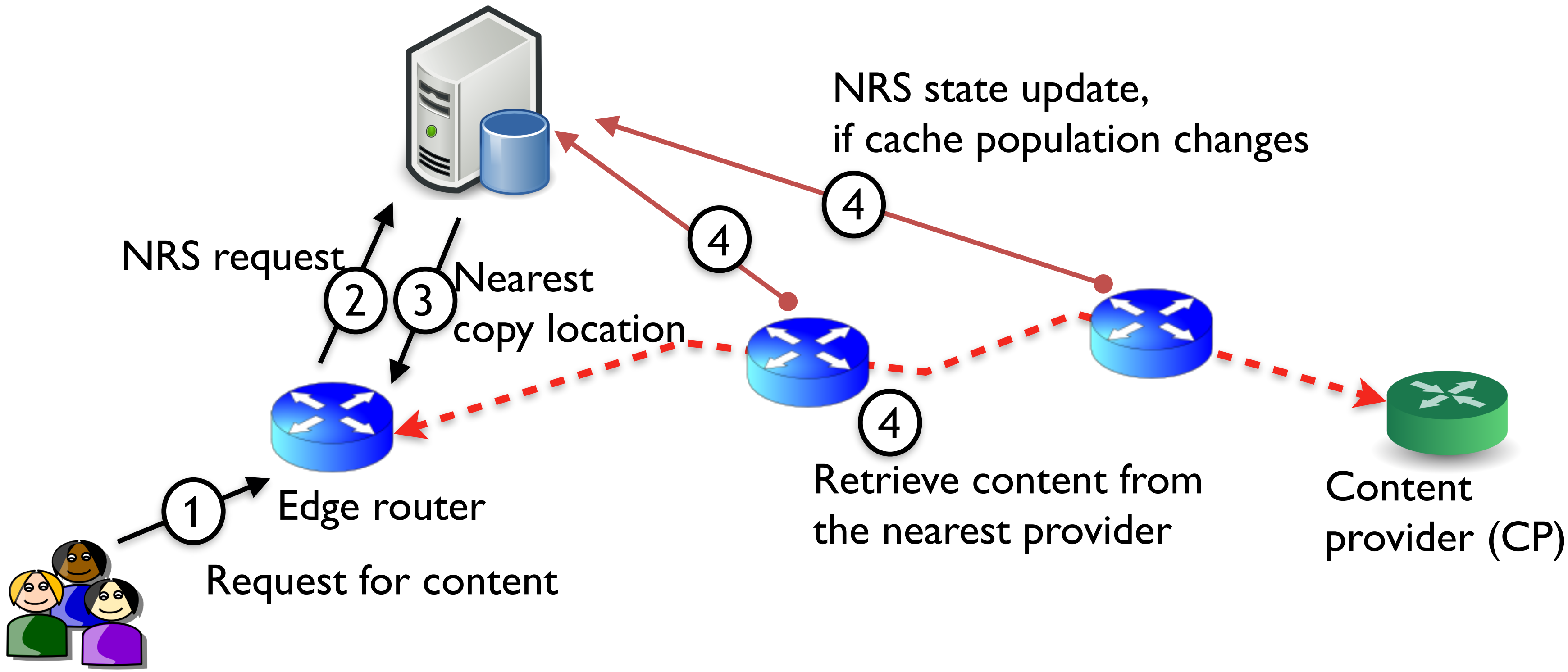
- **Standalone service (look-up by name)**
  - Directory service, *Name Resolution Server (NRS)*
  - NRS maps names to locators and routing is done using locators
  - 🙂 Nearest-copy routing
  - ☹️ Scalability (temporary copies, update, storage, lookup)
- **Name-based routing**
  - Route on names
  - 🙂 No need for an infrastructure
  - ☹️ Resolution guarantee?

Our contribution

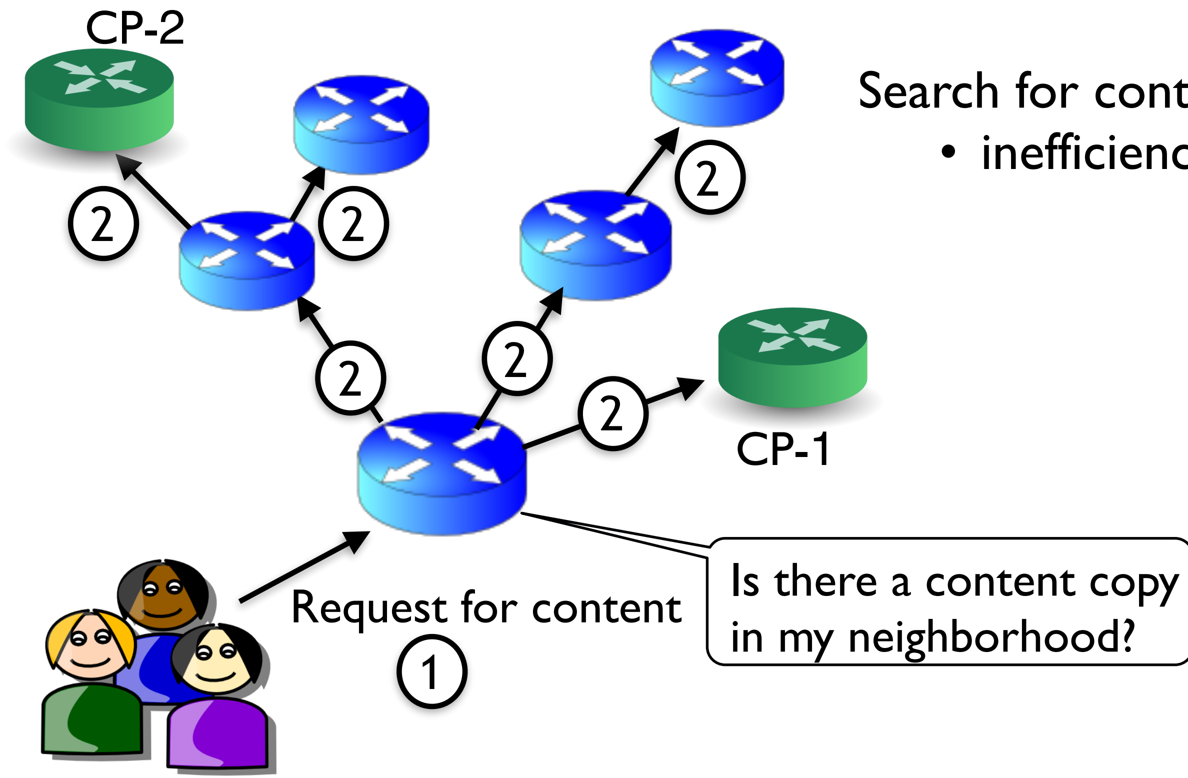
- Partial NRS to balance the tradeoff between **scalability** and **resolution guarantee**: *can we have an NRS that indexes only some of the content but brings most of the benefits?*

- We identify **which items to index** to decrease the content delivery cost under a limit on maximum number of items to be indexed

NRS-based operation in ICN

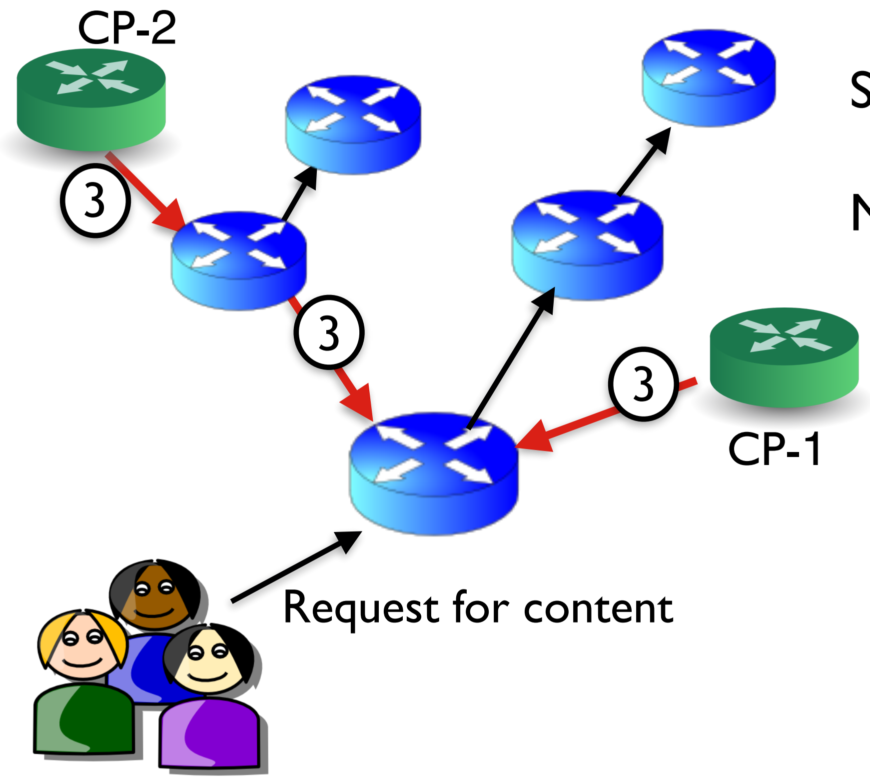


Operation without an NRS in ICN



Search for content in the neighborhood
- inefficiency in content discovery

Operation without an NRS in ICN



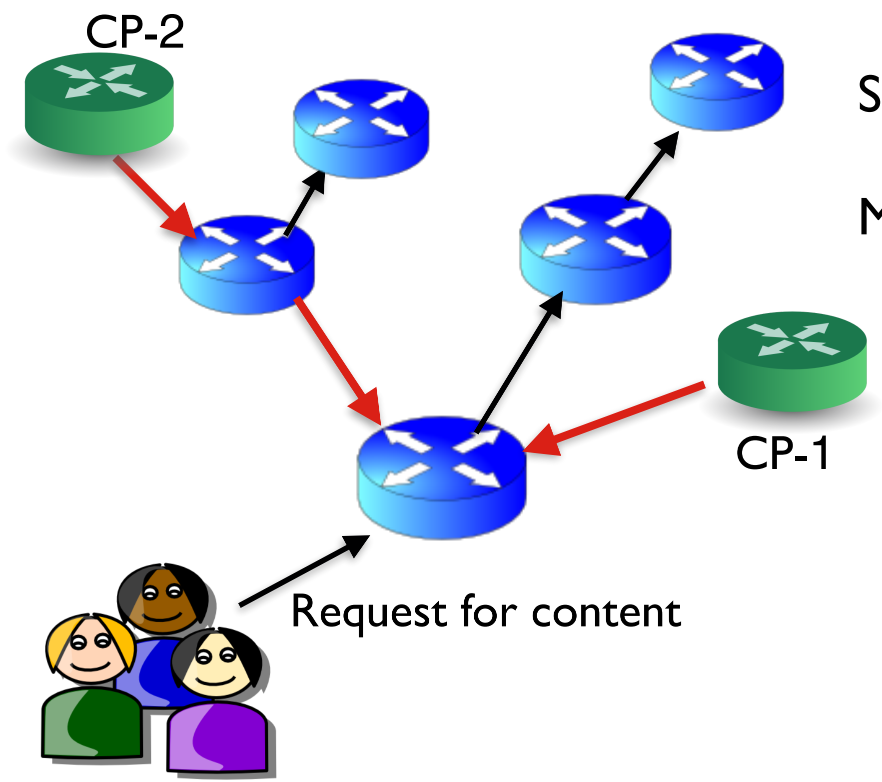
Search for content in the neighborhood

- inefficiency in content discovery

Multiple content providers routing content

- inefficiency in content retrieval

Operation without an NRS in ICN



Search for content in the neighborhood
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Multiple content providers routing content
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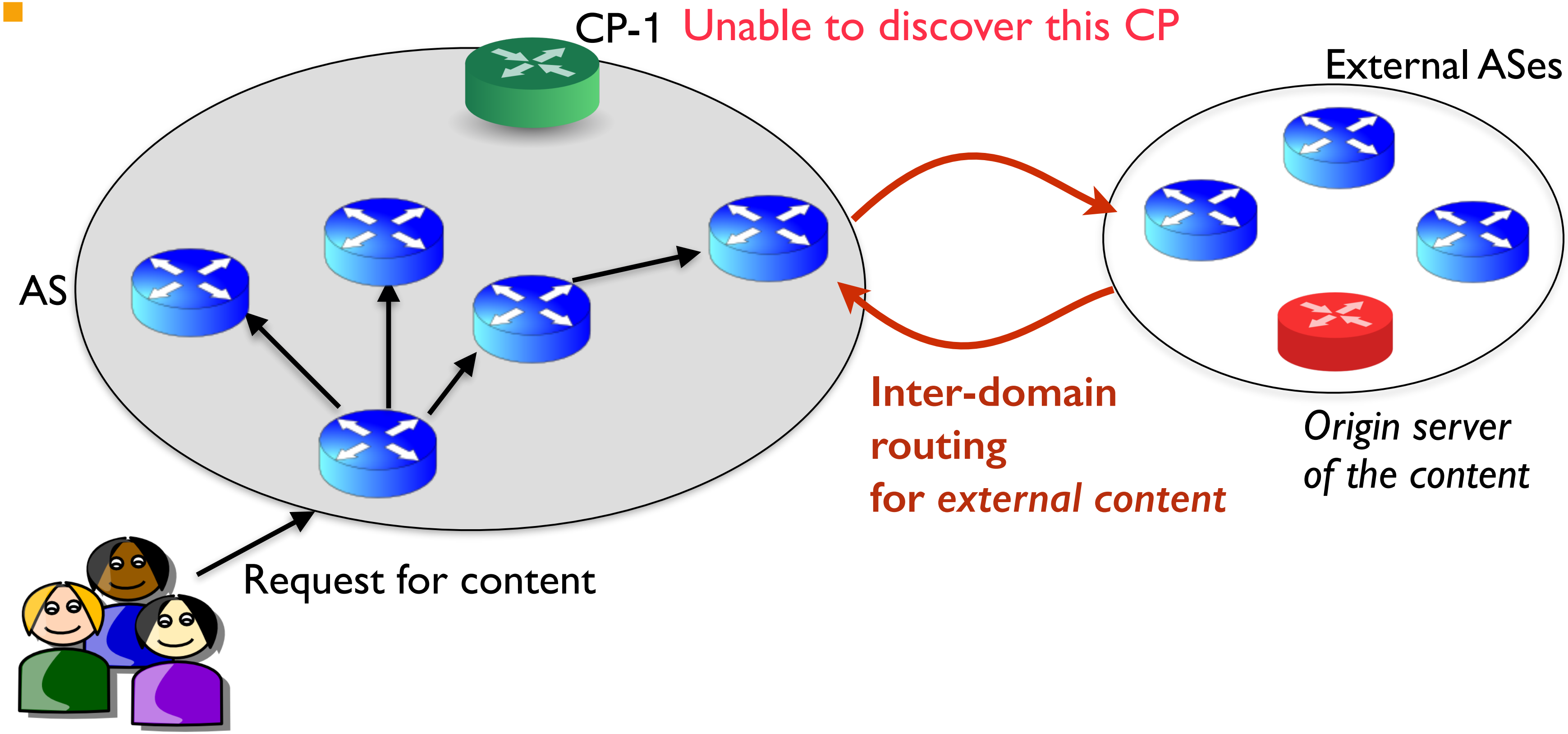
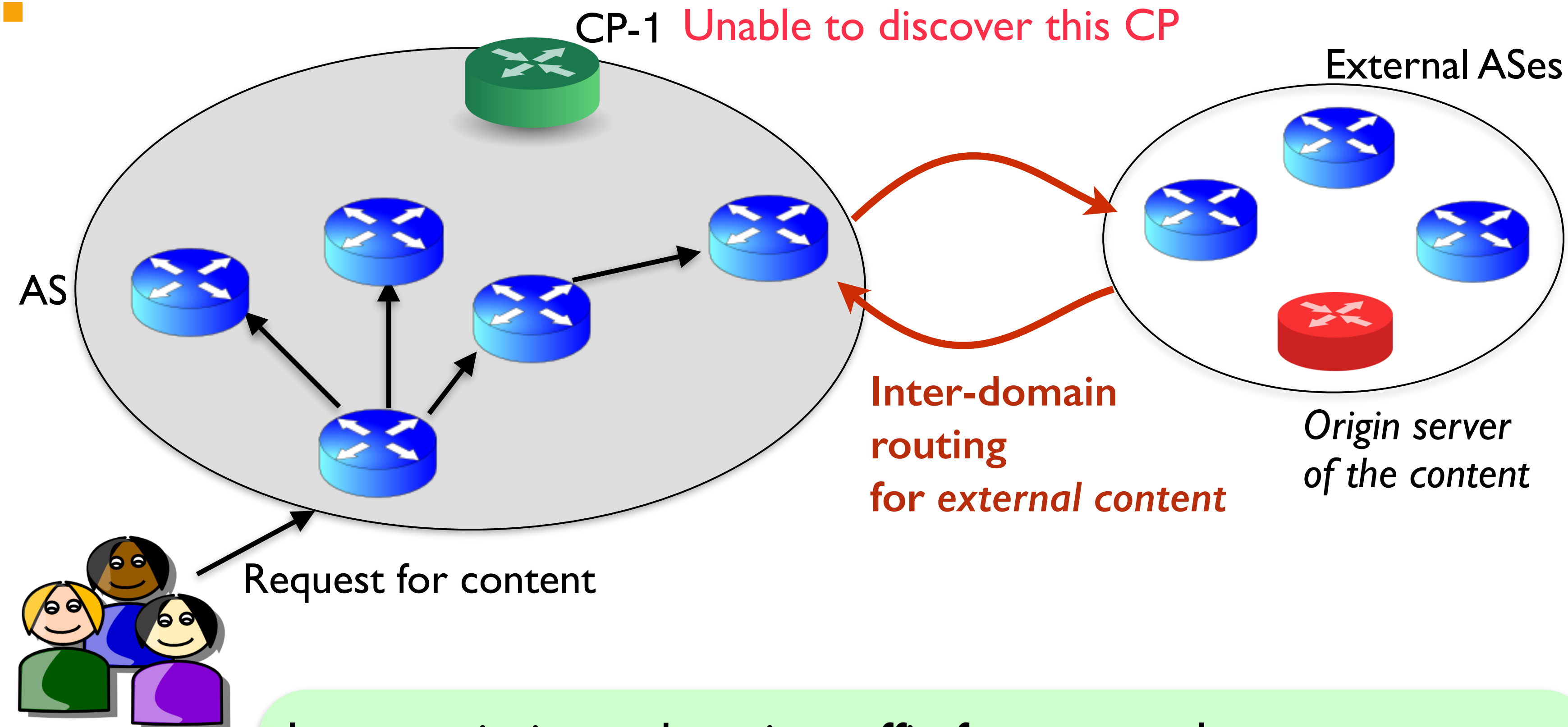
Bandwidth inefficiency

Operation without an NRS in ICN

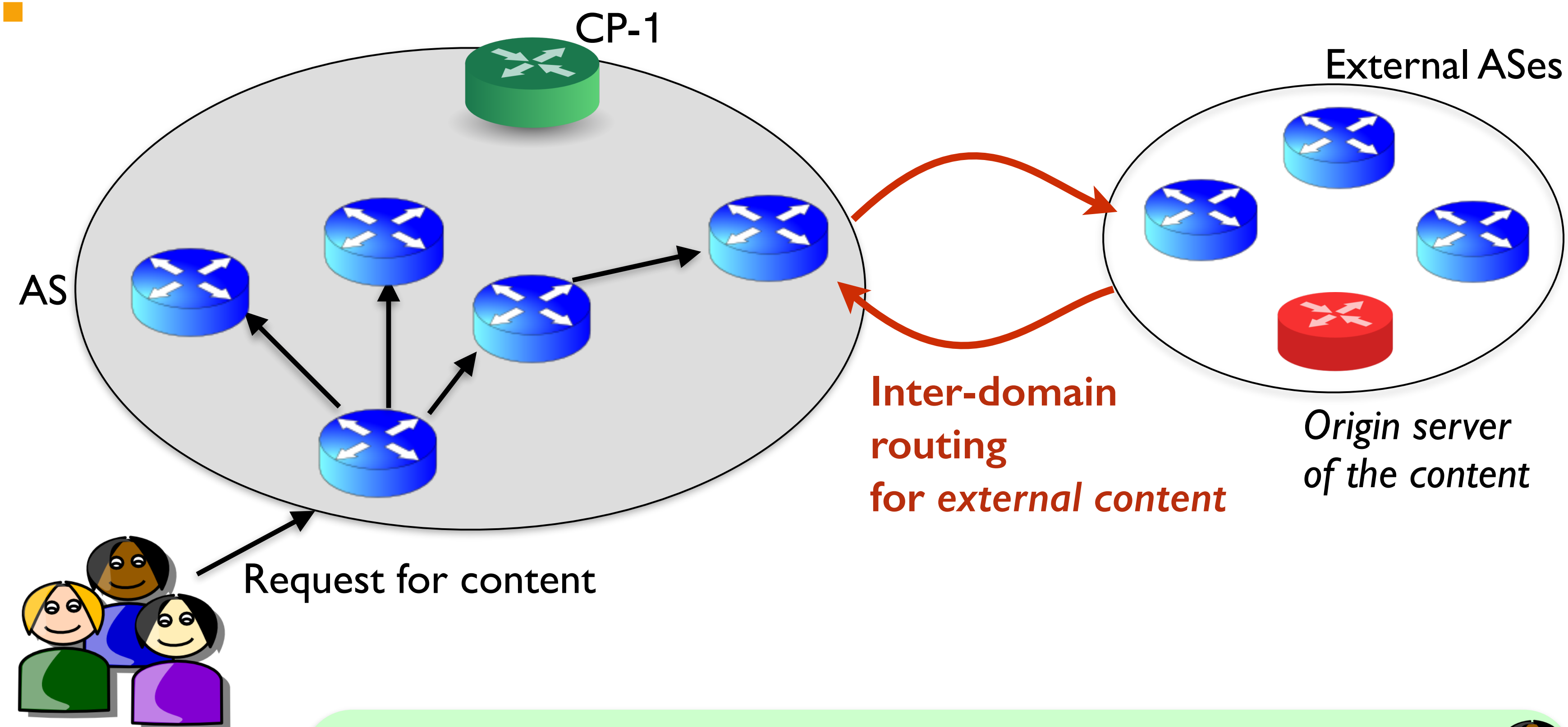


Operation without an NRS in ICN



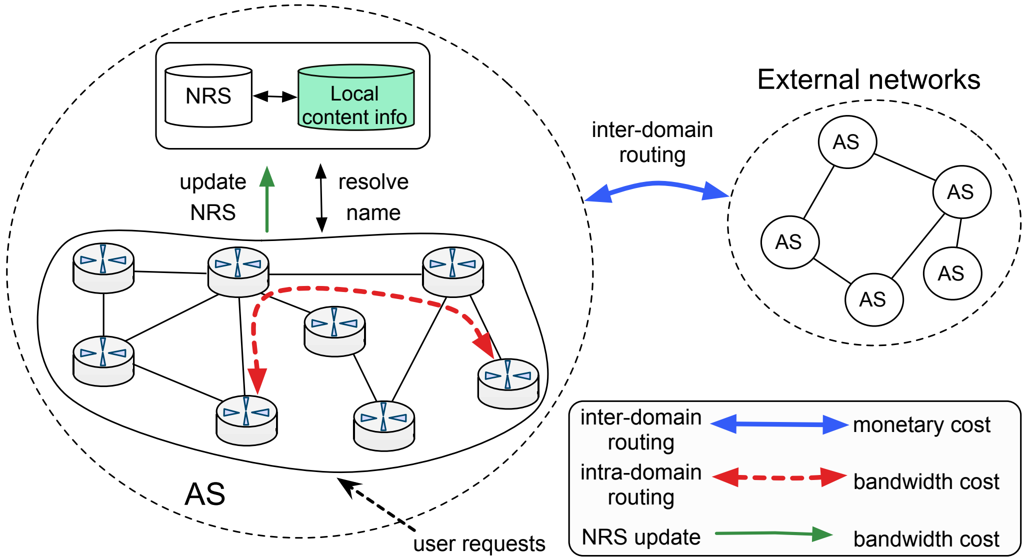
Increase in inter-domain traffic for external content:
monetary inefficiency

Operation without an NRS in ICN



- Bandwidth inefficiency
- Data access latency
- Monetary inefficiency

A closer look from an AS' viewpoint

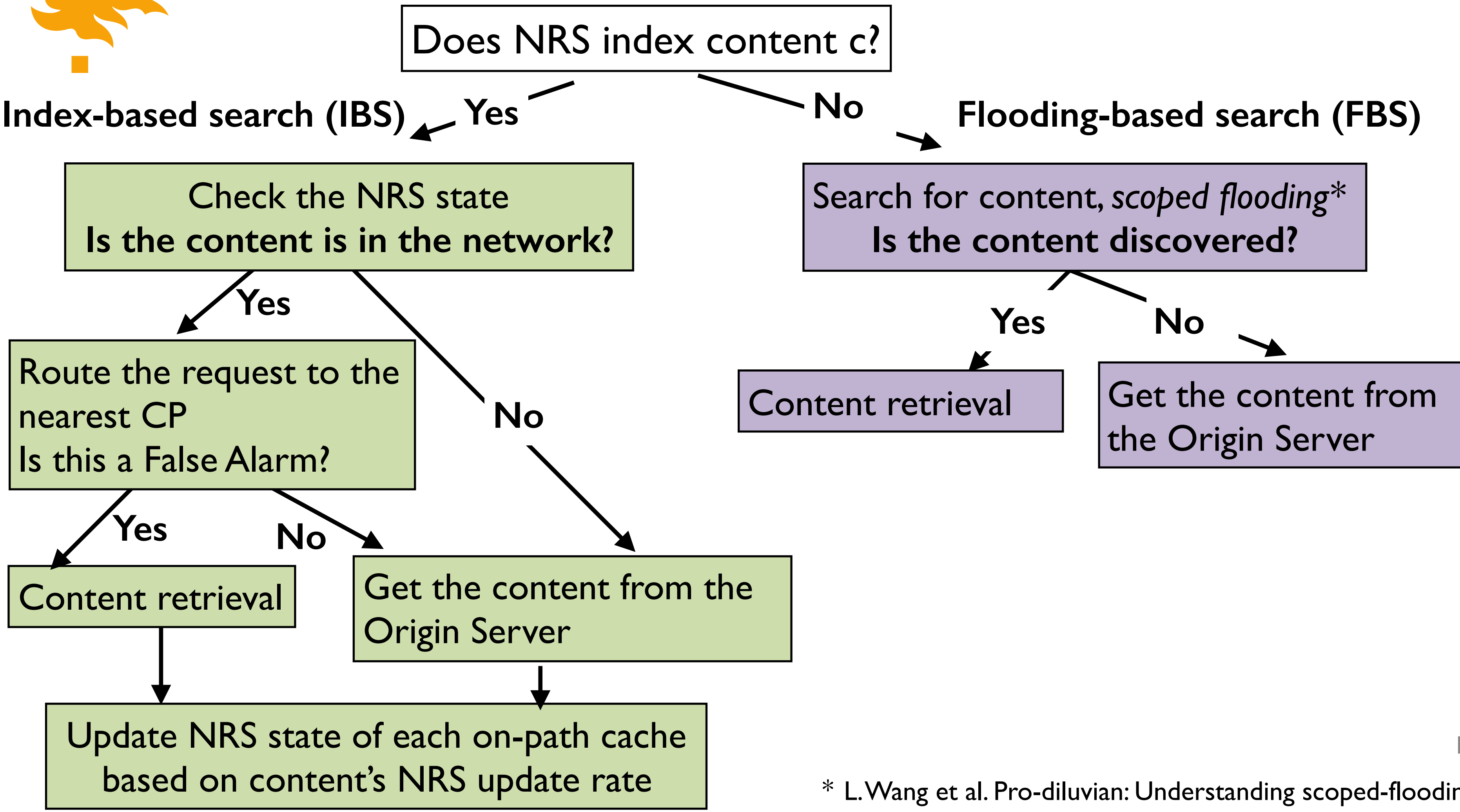


- Local vs. external content (origin server in the AS, or outside AS)
- To improve scalability:
    - NRS indexes only some fraction(w) of all content catalogue (K)
    - Routers update the NRS not upon every single change in their cache, but based on calculated rates under certain *false positive* and *negative* probabilities according to rate-distortion theory proposed in Azimdoost et al.

Which items to index by NRS?

- Calculate the **cost of content delivery** with NRS and without NRS
- **Indexing gain** is the difference between the cost
- Index the ones with the highest indexing gain

Cost of content delivery: discovery and retrieval



* L. Wang et al. Pro-diluvian: Understanding scoped-flooding for content discovery in ICN. In ACM ICN, 2015.

NRS-based content delivery: more formally

System state: <Content state, NRS state>

		NRS state, $S_{NRS}(k)$			Content is retrieved from
		NRS indexes c_k		NRS does not index c_k	
		0	1	NA	
Content state $S(k)$	0	Fetch from the origin $p_{00}=(1-\alpha_k)(1-P_k)(1-\varepsilon^1)$	IBS, fetch from the origin $p_{01}=(1-\alpha_k)(1-P_k)\varepsilon^1$	FBS, fetch from the origin $p_{0na}=(1-\alpha_k)(1-P_k)$	AS, if local content External AS, if external content
	1	Fetch from the origin $p_{10}=(1-\alpha_k)P_k(1-\varepsilon^0)$	IBS $p_{11}=(1-\alpha_k)P_k\varepsilon^0$	FBS, fetch from the origin $p_{1na}=(1-\alpha_k)P_k$	AS, if discovered or local External AS, if external and not discovered

- Above steps are taken if the content is NOT in the edge cache
- Content is expected to be in the cache with probability $\boldsymbol{\alpha}$: Che's approximation

NRS-based content delivery: more formally

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NRS indexes the content

NRS-based content delivery: more formally

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False alarm

NRS-based content delivery: more formally

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False negative

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Rely on IBS

NRS-based content delivery: more formally

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Rely on FBS

NRS-based content delivery: more formally

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Cost of IBS, FBS, and fetching from the origin server:

# of transmissions of the message x the message size:

- IBS: expected hop distance between the nearest content provider and a randomly selected requesting node
- FBS: # of nodes receiving the message for a certain search scope (2 or 3 hops)
- Origin server:
  - expected hop distance between a randomly-selected router and a content provider
  - inter-AS routing cost (assumption: NRS has the origin server info)

NRS-based content delivery: more formally

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Cost for discovery, retrieval and NRS update

$$\text{Content discovery cost: } \phi_k = \begin{cases} l^{req}(\alpha_k\phi^c + (p_{11}+p_{01})\phi_k^{\mathrm{IBS}} + (1-p_{11})\phi^{\mathrm{ori}}), & \text{if } x_k = 1 \quad (2) \\ l^{req}(\alpha_k\phi^c + \phi^{\mathrm{FBS}} + (p_{0na}+p_{1na}(1-\gamma_k^{\mathrm{FBS}}))\phi^{\mathrm{ori}}), & \text{if } x_k = 0 \quad (3) \end{cases}$$

$$\text{Content retrieval cost: } \beta_k = \begin{cases} s_k(\alpha_k\phi^c + p_{11}\phi_k^{\mathrm{IBS}} + (1-p_{11})\phi^{\mathrm{ori}}), & \text{if } x_k = 1 \quad (4) \\ s_k(\alpha_k\phi^c + p_{1na}\gamma_k^{\mathrm{FBS}} n_k\phi_k^{\mathrm{IBS}} + (p_{0na}+p_{1na}(1-\gamma_k^{\mathrm{FBS}}))\phi^{\mathrm{ori}}), & \text{if } x_k = 0 \quad (5) \end{cases}$$

$$\text{NRS update cost: } \psi_k = \begin{cases} R_k(\varepsilon^1,\varepsilon^0)l^{up}\phi^{\mathrm{up}}, & \text{where } l^{up} = \log K_\omega + \log N + 1, \text{ if } x_k = 1 \quad (6) \\ 0, & \text{if } x_k = 0 \quad (7) \end{cases}$$

NRS-based content delivery: more formally

NRS indexes content k

NRS does not index

$$\text{Content discovery cost: } \phi_k = \begin{cases} l^{req}(\alpha_k \phi^c + (p_{11} + p_{01})\phi_k^{\text{IBS}} + (1 - p_{11})\phi^{\text{ori}}), & \text{if } x_k = 1 \quad (2) \\ l^{req}(\alpha_k \phi^c + \phi^{\text{FBS}} + (p_{0na} + p_{1na}(1 - \gamma_k^{\text{FBS}}))\phi^{\text{ori}}), & \text{if } x_k = 0 \quad (3) \end{cases}$$

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NRS-based content delivery: more formally

Cost of getting the content from cache

Cost of IBS for content k

Search success for FBS for content k

Cost of fetching content k from origin server

$$\text{Content discovery cost: } \phi_k = \begin{cases} l^{req}(\alpha_k\phi^c + (p_{11}+p_{01})\phi_k^{\text{IBS}} + (1-p_{11})\phi^{\text{ori}}), & \text{if } x_k = 1 \qquad (2) \\ l^{req}(\alpha_k\phi^c + \phi^{\text{FBS}} + (p_{0na}+p_{1na}(1-\gamma_k^{\text{FBS}}))\phi^{\text{ori}}), & \text{if } x_k = 0 \qquad (3) \end{cases}$$

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NRS-based content delivery: more formally

n_k: overhead factor

$$n_k = 1 + \rho(N^{\mathrm{FBS}}\alpha_k)$$

$\rho \in [0,1]$ FBS redundancy coefficient

$$\text{Content discovery cost: } \phi_k = \begin{cases} l^{req}(\alpha_k\phi^c + (p_{11} + p_{01})\phi_k^{\mathrm{IBS}} + (1-p_{11})\phi^{\mathrm{ori}}), & \text{if } x_k = 1 \quad (2) \\ l^{req}(\alpha_k\phi^c + \phi^{\mathrm{FBS}} + (p_{0na} + p_{1na}(1-\gamma_k^{\mathrm{FBS}}))\phi^{\mathrm{ori}}), & \text{if } x_k = 0 \quad (3) \end{cases}$$

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Cost for discovery, retrieval, and NRS update

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Rate of update for meeting certain false positive and negative rates *Azimdoost et al.*

l^{up}: NRS update message (payload) size

Indexing for minimum content delivery cost

Decision variable:

- index content k or not, x_k

Objective:

- minimize the expected cost of content delivery over all requests from within this AS

Constraints:

- subject to total number of items to be indexed Kw

Indexing for minimum content delivery cost

Utility for item k

$$
\begin{aligned}
U_k &= q_k(\phi_k + \beta_k) + \psi_k \\
\phi_k &= l^{req}(\alpha_k \phi^c + (p_{11} + p_{01})\phi_k^{\mathrm{IBS}}) + x_k((1-p_{11})\phi^{\mathrm{ori}}) \\
&\quad + (1-x_k)(\phi^{\mathrm{FBS}} + (p_{0na} + p_{1na}(1-\gamma_k^{\mathrm{FBS}}))\phi^{\mathrm{ori}})) \\
\beta_k &= \alpha_k s_k \phi^c + s_k(p_{11}\phi_k^{\mathrm{IBS}} + (x_k((1-p_{11})\phi^{\mathrm{ori}}) \\
&\quad + (1-x_k)(p_{1na}\gamma_k^{\mathrm{FBS}} n_k \phi_k^{\mathrm{IBS}}) + (p_{0na} + p_{1na}(1-\gamma_k^{\mathrm{FBS}}))\phi^{\mathrm{ori}})) \\
\psi_k &= x_k R_k(\varepsilon^1, \varepsilon^0) l^{up} \phi^{\mathrm{up}}
\end{aligned}
$$

Optimization problem

$$
\min \sum_{k=1}^{K} U_k \qquad s.t. \sum_{k=1}^{K} x_k \leqslant K_\omega .
$$

Indexing gain for item k

$$
\Delta U_k = U_k(x_k = 0) - U_k(x_k = 1)
$$

Select the first Kw items

Performance analysis

- Which items to index?
- How much can we benefit with increasing NRS size?
- How is ICN performance affected?
  - cache hits
  - inter-domain traffic
  - data access latency

Setting

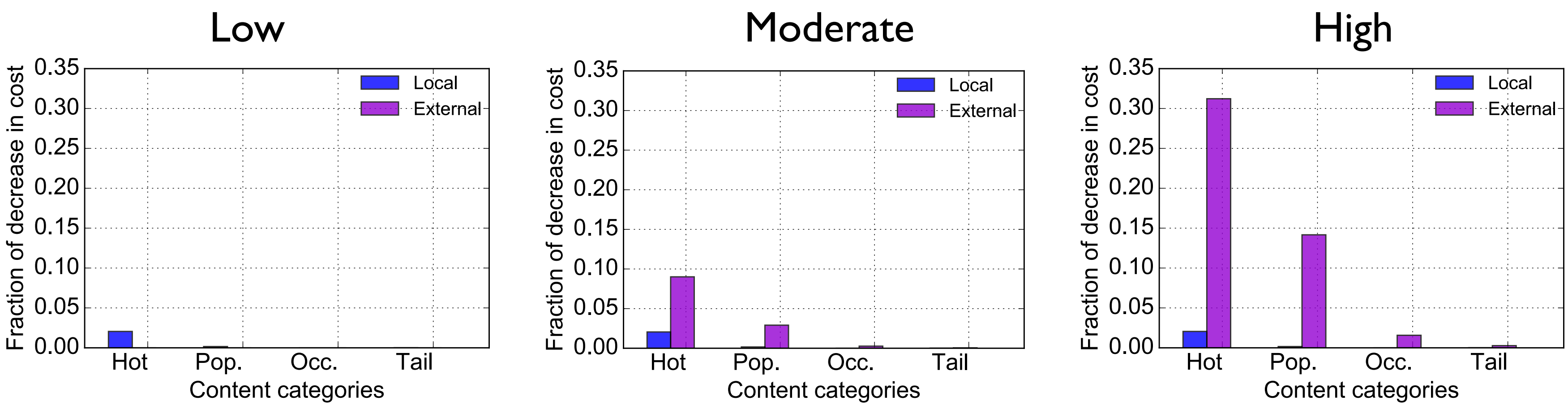
- ICARUS simulator, available at https://icarus-sim.github.io/
- Realistic AS topologies from Rocketful project (N: # routers)
- Local content: 30% of the requested contents (K: # content)
- Content popularity categories: h*ot*, *popular, occasional, far tail* as in *K. Mokhtarian et al.*
- Network's cache capacity
  - small cache: 10^{-2} K/N
  - large cache 10^{-1} K/N

- Impact of inter-AS traffic cost
- Impact of NRS size

Impact of inter-AS traffic cost: fraction of *decrease in cost*

- Let's assume all routers are synchronized, i.e. duplicate responses = 0
- *Low, moderate, high* inter-AS cost

N = 87 routers, AS 1755



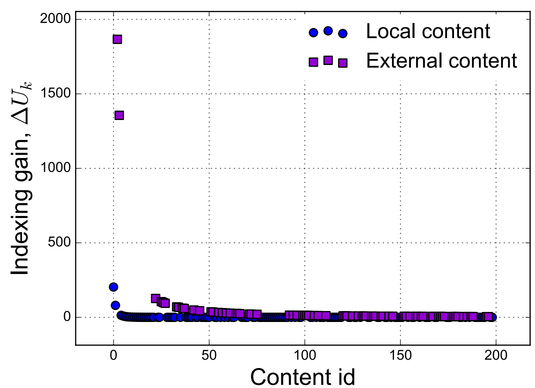
- Higher decrease in cost for more popular content,
- Higher decrease in cost for external content under high inter-AS cost

Impact of inter-AS traffic cost: *indexing gain*

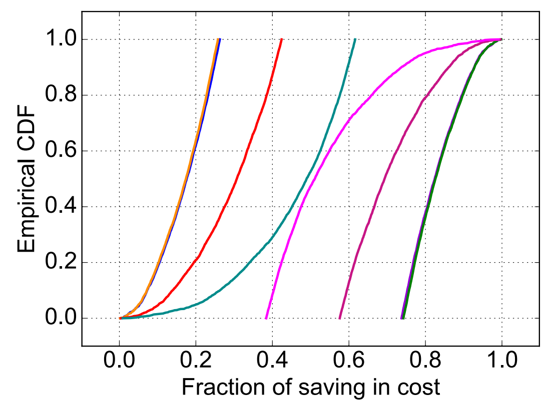
- Content size= 100 Kb, 1 Mb

N = 87 routers, AS 1755

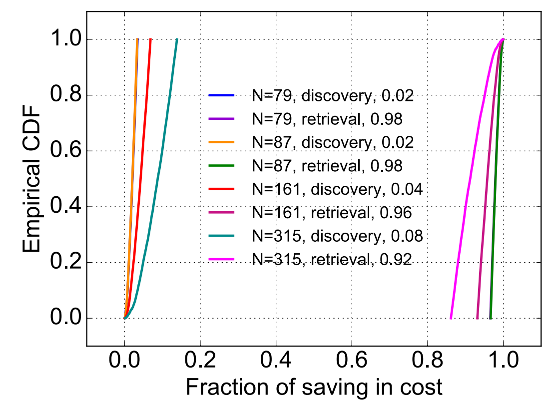
Indexing gain



Content size = 100 Kb



Content size = 1000 Kb



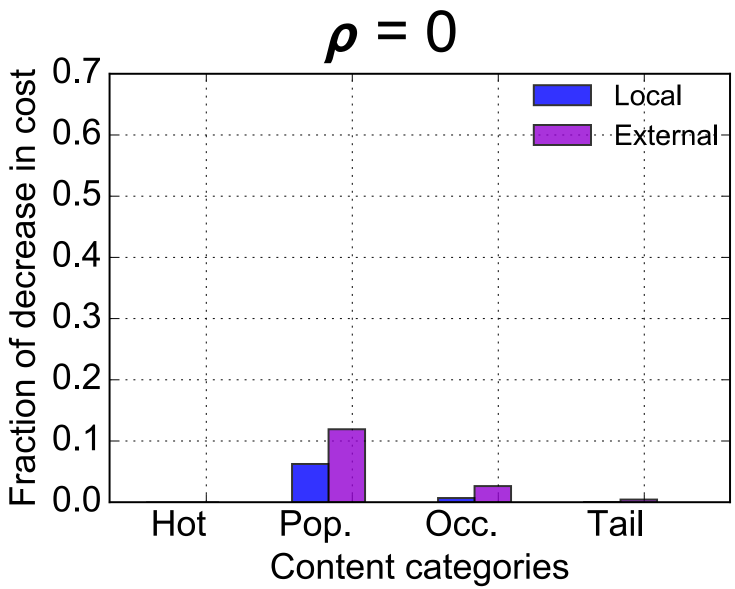
Indexing gain

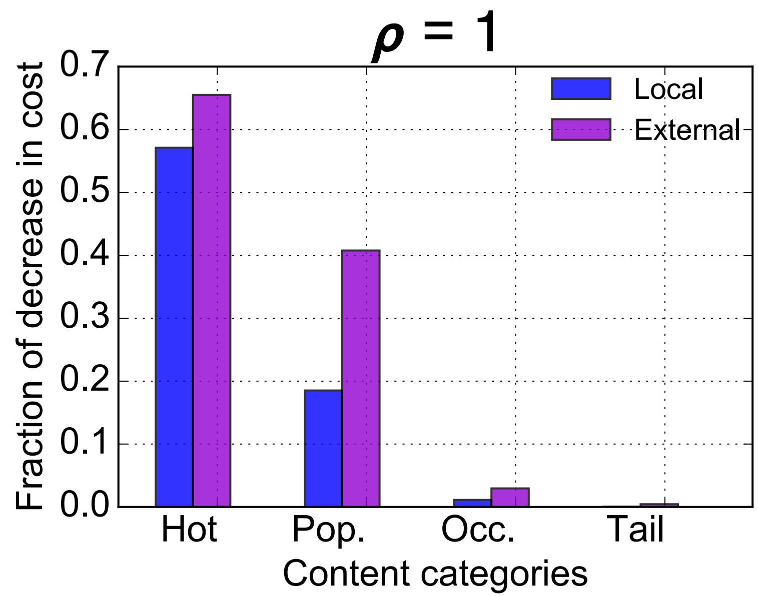
- External content higher (depending on inter-AS routing cost)
- Follows the trend in popularity distribution

Fraction of saving due to discovery and retrieval :

- comparable for small content size
- retrieval cost dominates for larger content size

What if FBS redundancy coefficient ρ is higher?



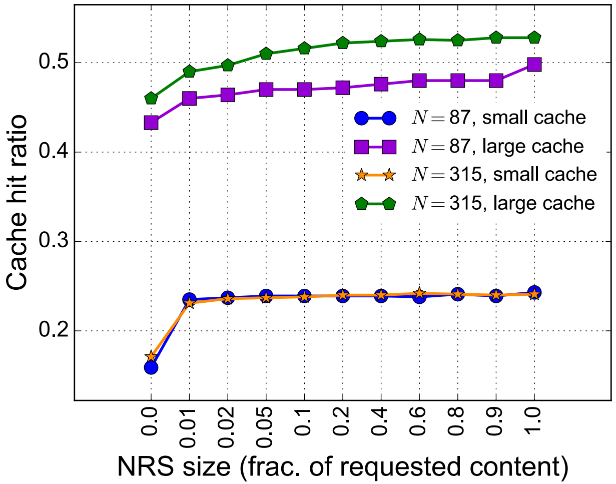


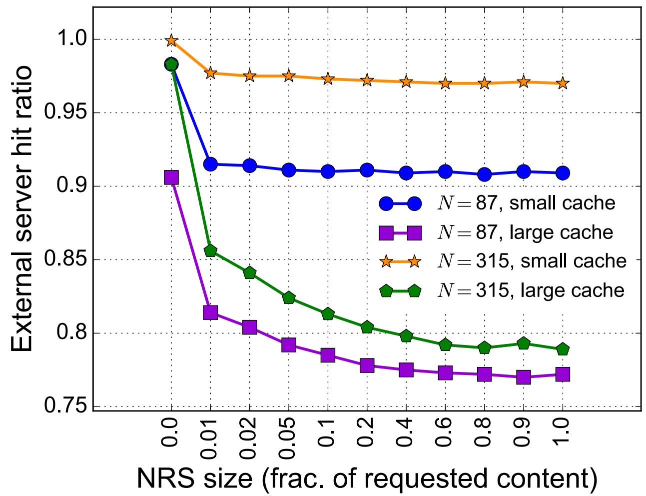
Under large cache regime, bandwidth inefficiency due to multiple content transmissions becomes significant, so does the importance of NRS (up to 65% savings for external, and 55% for local content)!

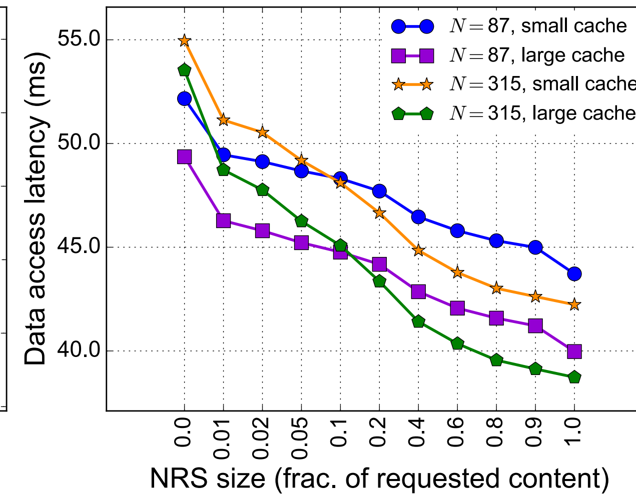
Impact of NRS size

- Content catalogue size: $4x10^4$
- Requests: $5x10^5$ (warmup period: 10^5 requests)
- Content popularity: Zipf with parameter 0.8

Impact of NRS size

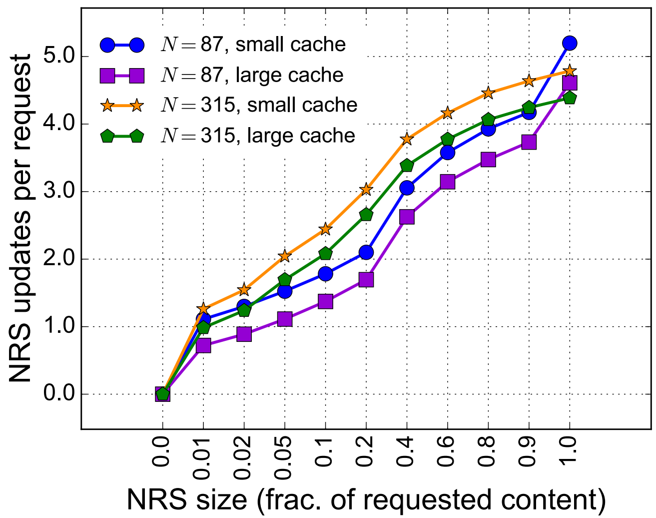


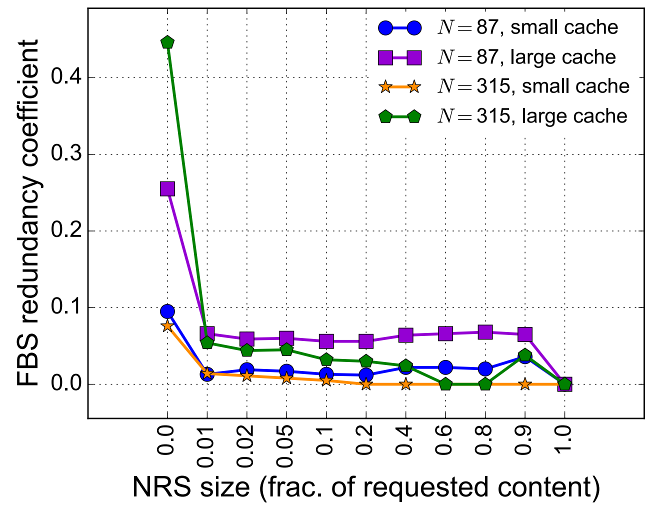




- For small cache, with 1% indexing, cache hit increases from 16-17% to 23%, only marginal increase from 23-24% afterwards
- For larger cache, highest increase in cache hits at 1%, but further increases after 1%
- Highest decrease in inter-domain traffic for the first 1% (intra-AS traffic marginal change)
- Data access latency gets shorter with increasing NRS size due to saving in content discovery time based on FBS

NRS updates and duplicate coefficient





- NRS update cost smaller than average path length due to tolerance to false negatives and positives
- FBS redundancy is about 10% for small cache regime and about 25-45% for larger caches

To sum up

- We proposed a **hybrid name resolution** scheme
  - index the content whose delivery cost decreases the most with NRS,
  - apply content search for other unindexed content
- We determined which items to index based on the calculated cost of content discovery, retrieval, and NRS updates
  - The most significant improvement achieved by **only indexing slight fraction** of content catalogue (~1% for small caches)
  - External content, most popular content
- Future work:
  - Real Internet topology
  - Content discovery can be less aggressive than flooding

Thank you!

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