Distributed Scalable Content Discovery Based on Rendezvous Points

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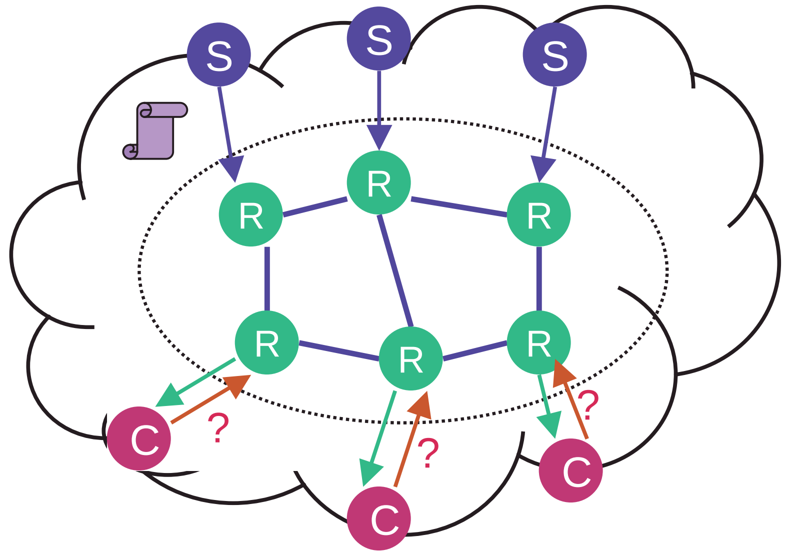
Outline

- Content Discovery System (CDS)
- Thesis statement
- Related work
- Proposed CDS system
- Research plan
- Time line
- Expected contributions

Content Discovery System (CDS)

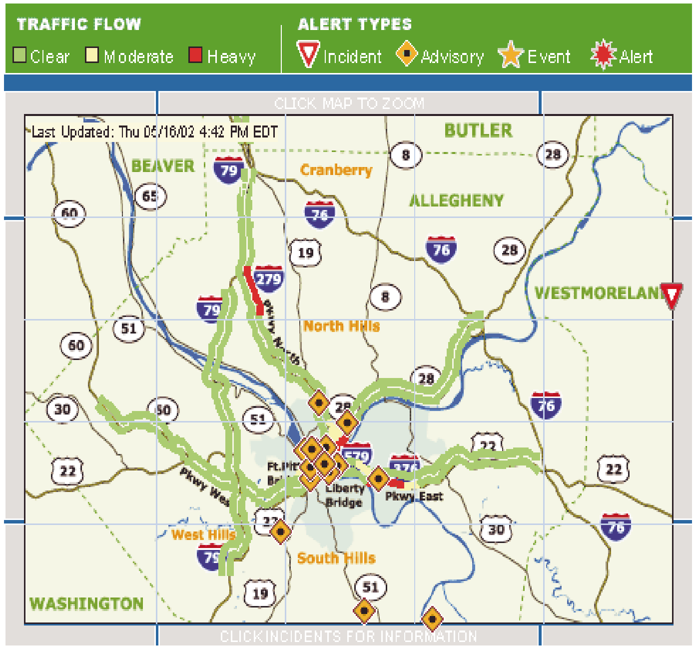
- Distributed system that allows the discovery of contents
  - Three logical entities
  - “content name” discovery
  - Broad definition of “content”
- Example CDS systems
  - Service discovery
  - Peer-to-peer object sharing
  - Pub/sub systems
- Separation of content discovery and content delivery



S: content providers (servers)
C: content consumers(clients)
R: content resolvers

Example: A Highway Monitoring Service

- Allows users to discover traffic status observed by cameras and sensors
  - What is the speed around Fort Pitt tunnel?
  - Are there any accidents on I-279?
  - What sections around Pittsburgh are congested?
- Characteristics of this service
  - Support large number of devices
  - Devices must update frequently
  - Support high query rate



Snapshot from: Traffic.com

Thesis Statement

In this thesis, I propose a distributed and scalable approach to content discovery that supports flexible and efficient search of dynamic contents.

CDS Properties

- Contents must be searchable
  - Find contents without knowing the exact names
  - Contents can be dynamic
  - Content names are not hierarchical
- Scalability
  - System performance remains as load increases
- Distributed and robust infrastructure
  - No centralized administration
- Generic software layer
  - Building block for high level applications

Related Work

- Existing systems have difficulties in achieving both scalability and rich functionality
- Centralized solution
  - Central resolver(s) stores all the contents
  - Supports flexible search
  - Load concentration at the central site
  - Single point-of-failure.
- Distributed solution
  - Graph-based schemes
  - Tree-based schemes
  - Hash-based schemes

Distributed Solutions

- Graph-based systems
  - Resolvers organized into a general graph
    - Registration flooding scheme
    - Query broadcasting scheme
  - Not scalable
  - Robust infrastructure

- Tree-based systems
  - Resolvers organized into a tree
  - Scale well for hierarchical names
    - E.g., DNS
    - Hard to apply to non-hierarchical names
  - Robustness concern
  - Load concentration close to the root

Hash-based Lookup Systems

- Resolvers form an overlay network based on hashing
  - E.g., Chord, CAN, Pastry, Tapestry
- Provide a simple name lookup mechanism
  - Associating content names with resolver nodes
    - No flooding or broadcasting
- Do not support search
  - Clients must know the exact name of the content
- Our system utilizes the hash-based lookup algorithms

Proposed CDS system

- Basic system design
  - Naming scheme
  - Resolver network
  - Rendezvous Point (RP) based scheme
- System with load balancing
  - Load concentration problem
  - Load Balancing Matrices (LBM)

Attribute-Value Based Naming Scheme

- Content names and queries are represented with AV-pairs
  - Attributes may be dynamic
  - One attribute may depend on another attribute
- Searchable
  - Query is a subset of the matched name
  - $2^n - 1$ matched queries for a name that has n AV-pairs
- Example queries
  - find out the speed at I-279, exit 4, in Pittsburgh
  - find the highway sections in Pittsburgh that speed is 45mph

Service description (SD)

```
Camera number = 5562
Camera type = q-cam
Highway = I-279
   Exit = 4
City = pittsburgh
Speed = 45mph
Road condition = dry
```

Query 1:

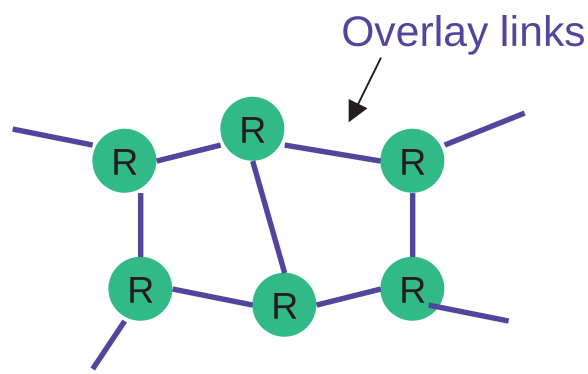
```
Highway = I-279
   Exit = 4
City = pittsburgh
```

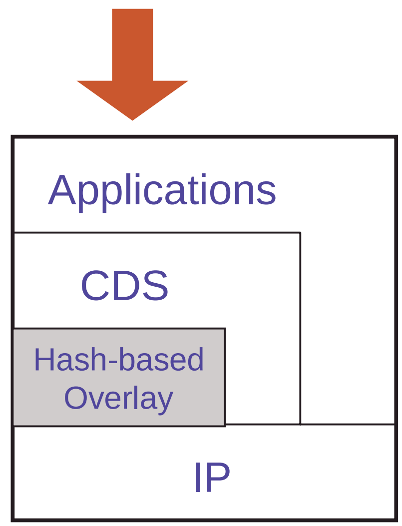
Query 2:

```
City = pittsburgh
Speed = 45mph
```

Hash-based Resolver Network

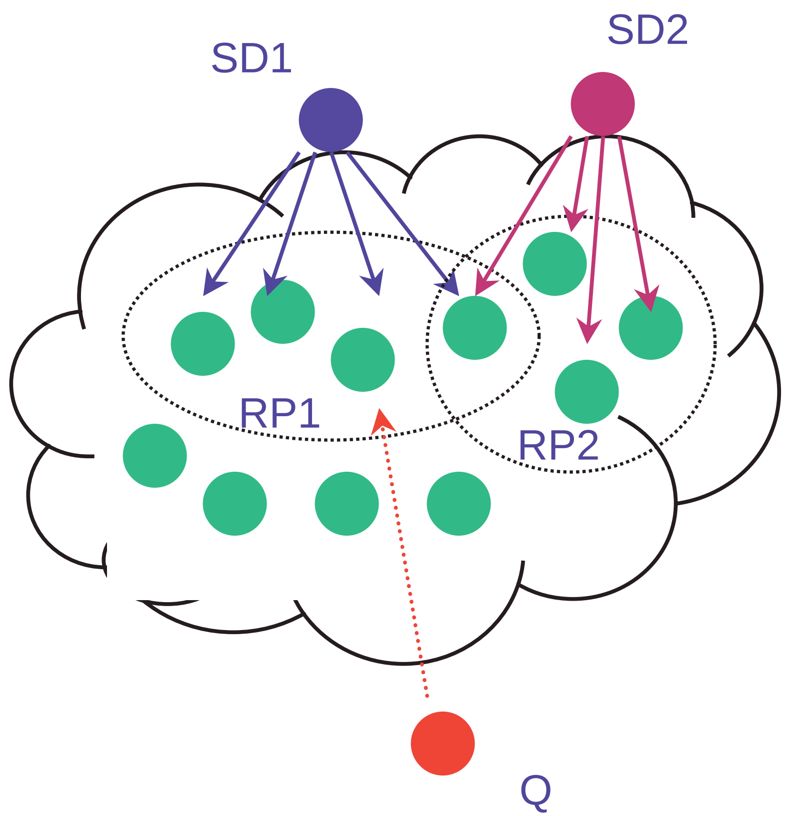
- Resolvers form a hash-based overlay network
  - Use Chord-like mechanisms
  - Node ID computed based on a hash function H
  - Node ID based forwarding within the overlay
    - Path length is *O(log Nc)*
- CDS is decoupled from underlying overlay mechanism
  - We use this layer for content distribution and discovery





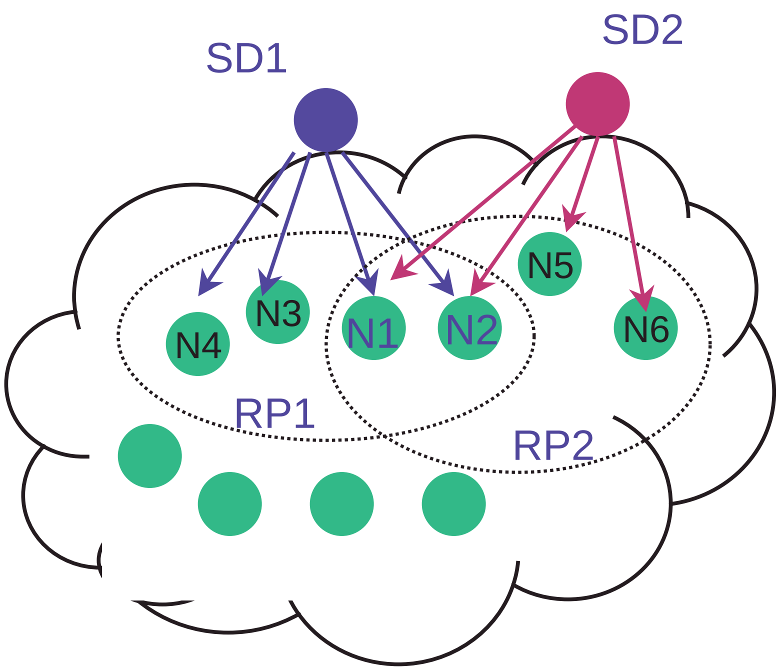
Rendezvous Point (RP) -based Approach

- Distribute each content name to a set of resolver nodes, known as RPs
  - Queries are sent to proper RPs for resolution
- Guidelines
  - The set should be small
  - Use different set for different names
  - Ensure that a name can be found by all possible matched queries



Registration with RP nodes

- Hash each AV-pair individually to get a RP node ID
  - Ensures correctness for queries
  - RP set size is *n* for a name with *n* AV-pairs
- Full name is sent to each node in the RP set
  - Replicated at *n* places
- Registration cost
  - *O(n)* messages to *n* nodes



SD1: {a1=v1, a2=v2, a3=v3, a4=v4)
SD2: {a1=v1, a2=v2, a5=v5, a6=v6)

H(a1=v1) = N1, H(a2=v2) = N2

Resolver Node Database

- A node becomes the specialized resolver for the AV-pairs mapped onto it
  - Each node receives equal number of AV-pairs
    - $k = N_d / N_c$
- Size of the name database is determined by the number of names contain each of the *k* AV-pair

$$t = \sum_{i=1}^{k} N_{av_i}$$

- Contain the complete AV-pair list for each name
  - Can resolve received query completely

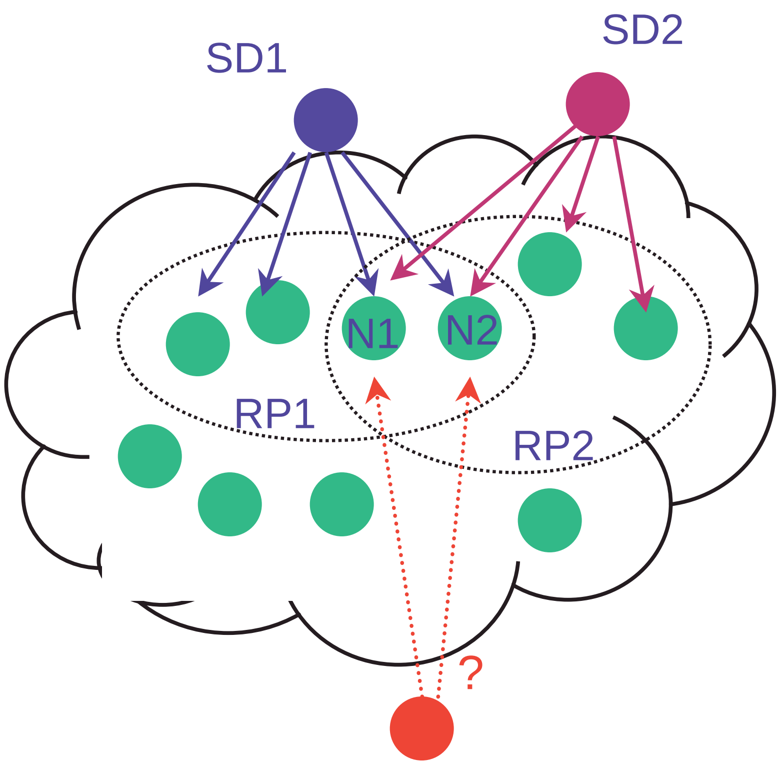
N_d: Number of different AV-pairs
N_c: Number of Resolver nodes
N_{avi}: Number of names that contain av_i

N1:
(a1=v1)
SD1: a1=v1, a2=v2, a3=v3, a4=v4
SD2: a1=v1, a2=v2, a5=v5, a6=v6
SD3: a1=v1, …
…
(a7=v7)
…

N2:
(a2=v2)
SD1: a2=v2, a1=v1, a3=v3, a4=v4
SD2: a2=v2, a1=v1, a5=v5, a6=v6
SD4: a2=v2, …
…

Query Resolution

- Client applies the same hash function to *m* AV-pairs in the query to get the IDs of resolver nodes
  - Query can be resolved by any of these nodes
- Query optimization algorithm
  - Client selects a node that has the best performance
    - E.g., probe the database size on each node
- Query cost
  - *O(1)* query message
  - *O(m)* probe messages



Q:{a1=v1, a2=v2}

H(a1=v1) = N1, H(a2=v2) = N2

Load Concentration Problem

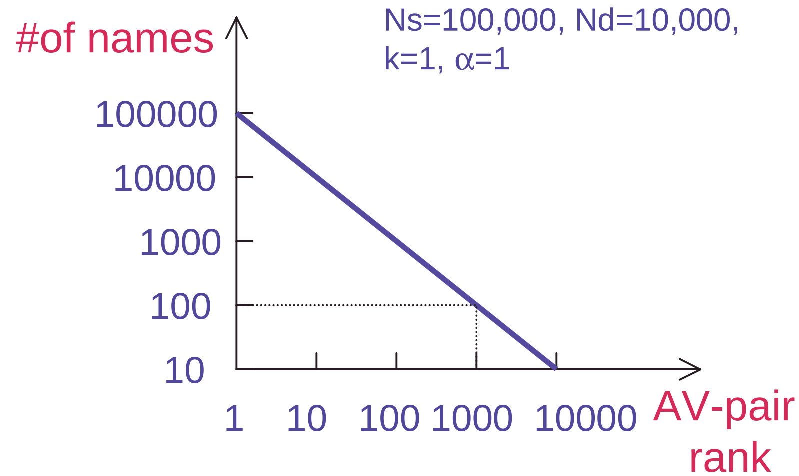
- Basic system performs well under balanced load
  - Registrations and queries processed efficiently
- However, one node may be overloaded before others
  - May receive more names than others
    - Corresponds to common AV-pairs in names
  - May be overloaded by registration messages
  - May be overloaded by query messages
    - Corresponds to popular AV-pairs in queries

Example: Zipf distribution of AV-pairs

- Observation: some AV-pairs are very popular, and many are uncommon
  - E.g. `speed=45mph` vs. `speed=90mph`
- Suppose the popularity distribution of AV-pairs in names follow a Zipf distribution
- Example:
  - 100,000 names have the most popular AV-pair
    - Will be mapped onto one node!
  - Each AV-pair ranked from 1000 to 10000 is contained in less than 100 names

$$N_{av_i} = N_s \cdot k \cdot \frac{1}{i^{\alpha}}$$

Ns: total number of names
Nd: number of different AV-pairs
i: AV-pair rank(from 1 to Nd)
k: constant
α: constant near 1



CDS with Load Balancing

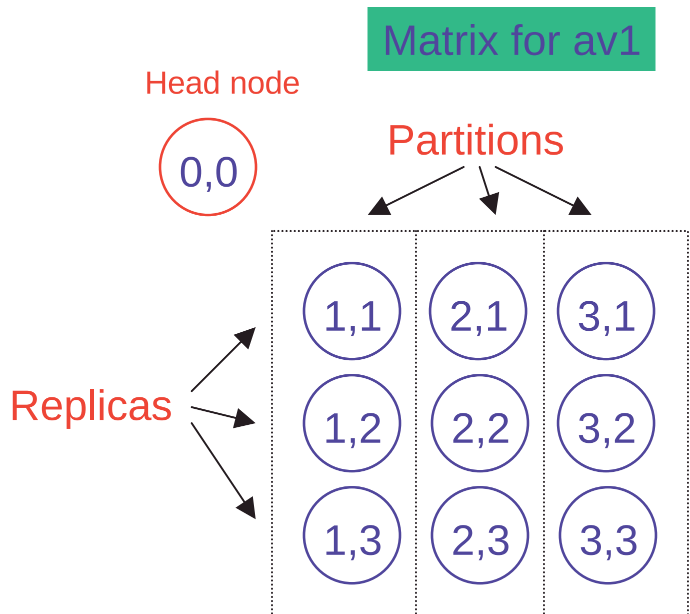
- Intuition
  - Use a set of nodes for a popular AV-pair
- Mechanisms
  - Partition when registration load reaches threshold
  - Replicate when query load reaches threshold
- Guideline
  - Must ensure registrations and queries can still find RP nodes efficiently

Thresholds maintained on each node

T_{SD} : Maximum number of content names can host
T_{reg} : Maximum sustainable registration rate
T_{q} : Maximum sustainable query rate

Load Balancing Matrix (LBM)

- Use a matrix of nodes to store all names that contain one AV-pair
  - RP Node → RP Matrix
- Columns are used to share registration load
- Rows are used to share query load
- Matrix expands and contracts automatically based on the current load
  - Self-adaptive
  - No centralized control



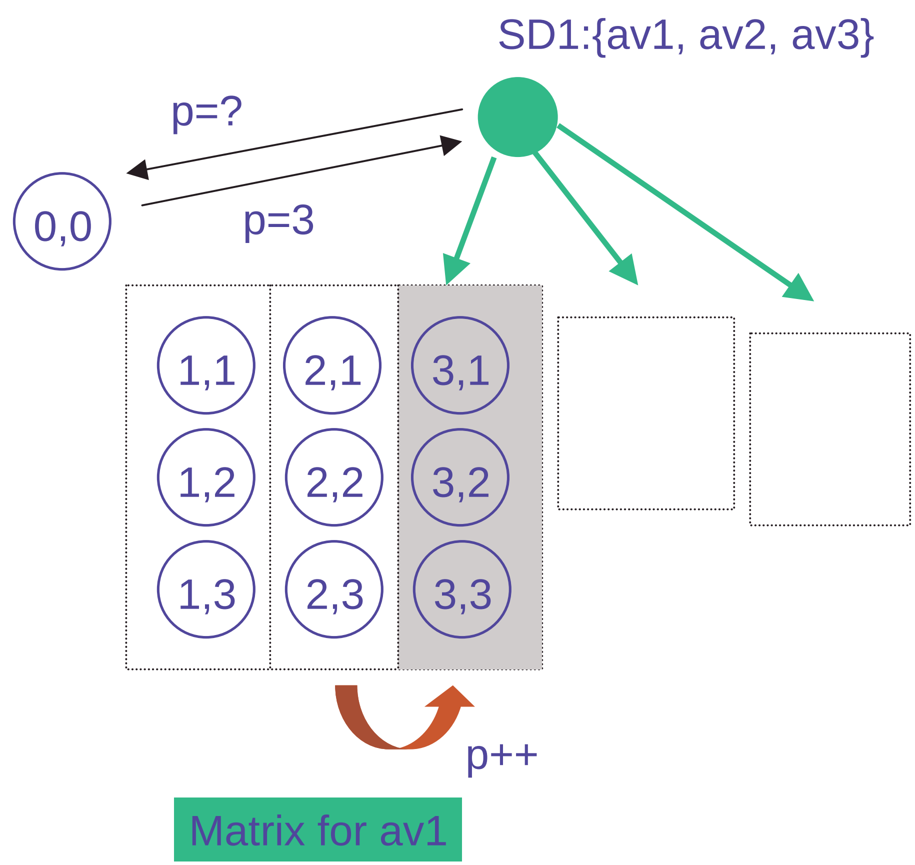
Nodes are indexed

$N_1^{(p,r)} = H(av1, p, r)$

Head node: $N_1^{(0,0)}$=H(av1, 0, 0), stores the size of the matrix (p, r)

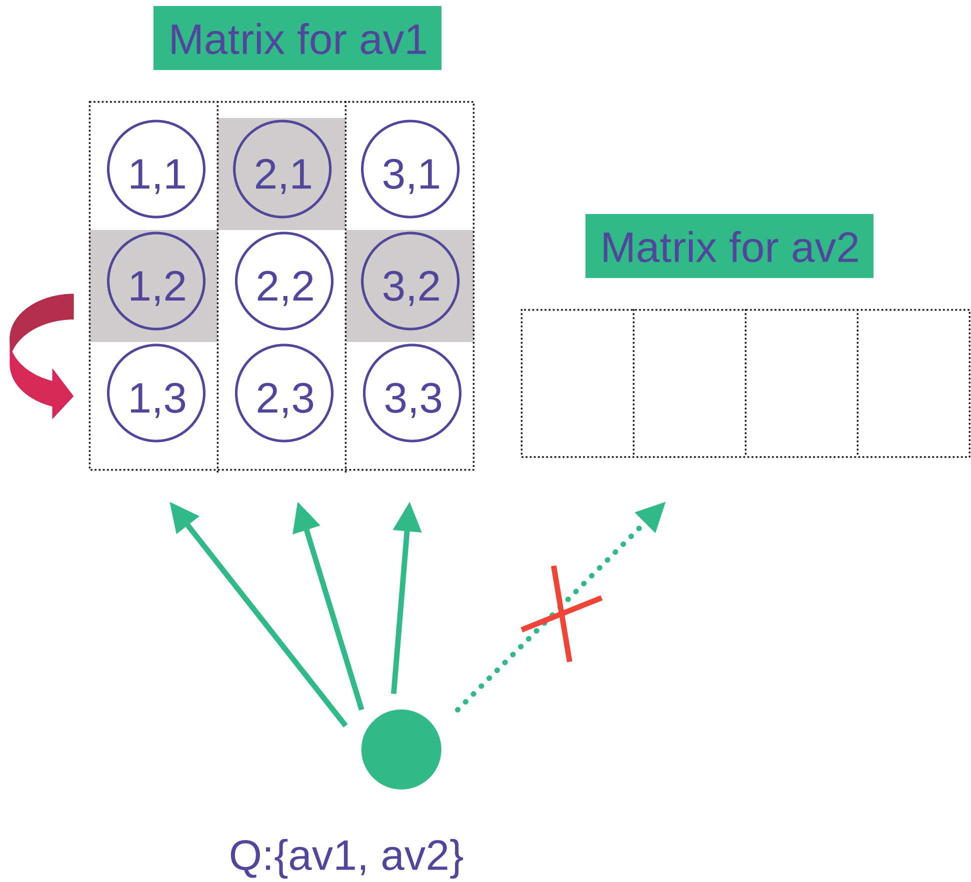
Registration

- New partitions are introduced when the last column reaches threshold
  - Increase the p value by 1
  - Accept new registrations
- Discover the matrix size (p, r) for each AV-pair
  - Retrieve from head node $N_1^{(0,0)}$
  - Binary search to discover
  - Use previously cached value
- Send registration to nodes in the last column
  - Replicas
- Each column is a subset of the names that contain av1



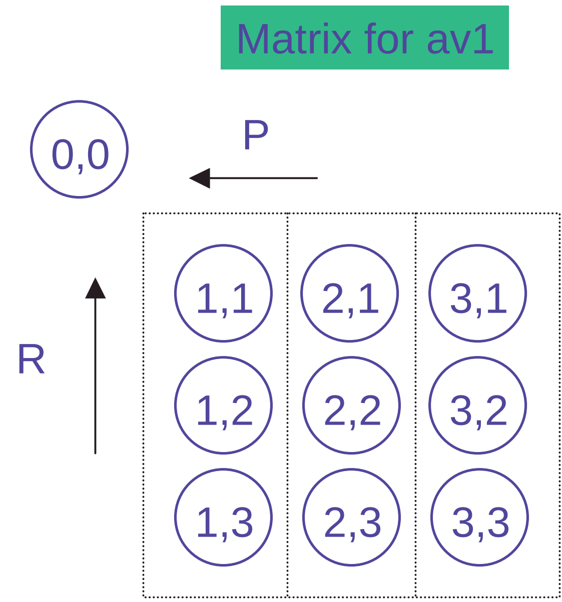
Query

- Select a matrix with the fewest columns
  - Small p → few partitions
- Sent to one node in each column
  - To get all the matched contents
- Within each column, sent to a random node
  - Distribute query load evenly
- New replicas are created when the query load on a node reaches threshold
  - Increase r value by 1
  - Duplicate its content at node $N_1^{(p,r+1)}$
  - Future queries will be shared by r+1 nodes in the column



Matrix Compaction

- Smaller matrix is more efficient for registrations and queries
- Matrix compaction along P dimension
  - When earlier nodes in each row have available space
    - Push
    - Pull
  - Decrease p value by 1
- Matrix compaction along R dimension
  - When observed query rate goes below threshold
  - Decrease r value by 1
- Must maintain consistency



System Properties

- From a resolver node point of view
  - Load observed is upper bounded by thresholds
- From whole system point of view
  - Load is spread across all resolvers
  - System does not reject registrations or queries until all resolvers reach thresholds
- Registration cost for one AV-pair
  - *O(r_i)* registration messages, where r_i is the number of rows in the LBM

$$r_i = \frac{Q_{av\,i}}{T_q}$$

- Query cost for one AV-pair
  - *O(p_i)* query messages, where p_i is the number of columns in the LBM

$$p_i = \max\left(\frac{N_{av\,i}}{T_{SD}}, \frac{R_{av\,i}}{T_{reg}}\right)$$

Matrix Effects on Registration and Query

- Matrix grows as registration and query load increase
  - Number of resolver nodes in one matrix
    - $m_i = r_i\ p_i$
- Matrices tend not to be big along both dimensions
  - Matrix with many partitions gets less queries
    - Query optimization algorithm
    - Large p → small r
  - Matrix with fewer partitions gets more queries
    - Small p → large r
    - Replication cost small
- Will study the effects in comprehensive system evaluation

Roadmap

- Content Discovery System (CDS)
- Thesis statement
- Related work
- Proposed CDS system
- Research plan
- Time line
- Expected contributions

Implementation Plan

- Simulator implementation
  - For evaluation under controlled environment
  - Plan to use Chord simulator as a starting point
- Actual implementation
  - Implement CDS as a generic software module
  - Deploy on the Internet for evaluation
  - Implement real applications on top of CDS

Evaluation Plan

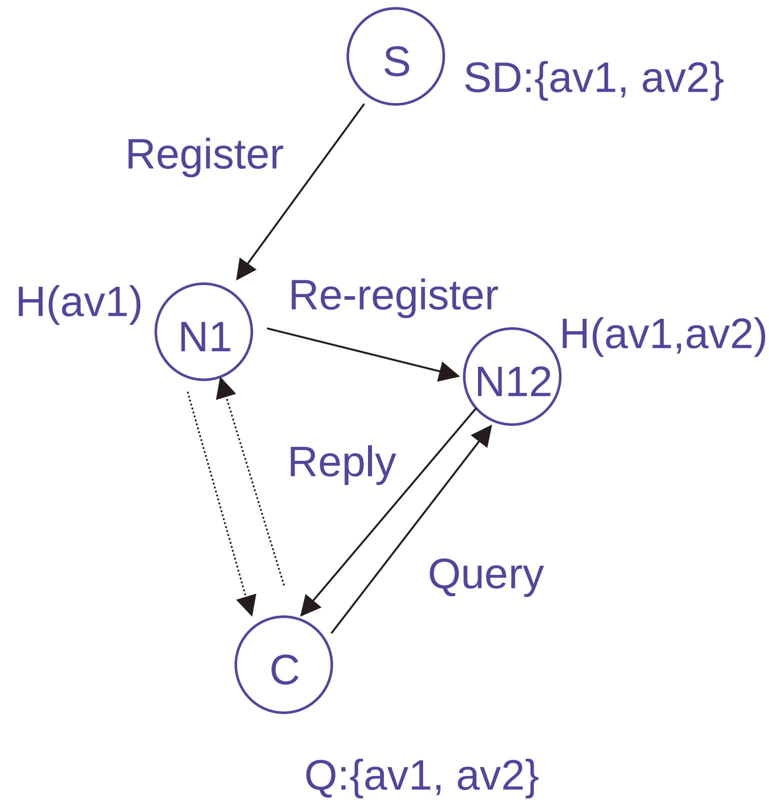
- Work load generation
  - Synthetic load
    - Use known distributions to model AV-pair distribution in names and queries
  - Benchmarks
    - Take benchmarks used in other applications, e.g., databases
  - Collect traces
    - Modify open source applications to obtain real traces
- Performance metrics
  - Registration and query response time
  - Success/blocking rate
  - System utilization

System Improvements

- Performance
  - Specialized resolvers
    - Combine AV-pairs
  - Search within a matrix
- Functionality
  - Range search
    - Auxiliary data structure to index the RP nodes
  - Database operations
    - E.g., "project", "select", etc.

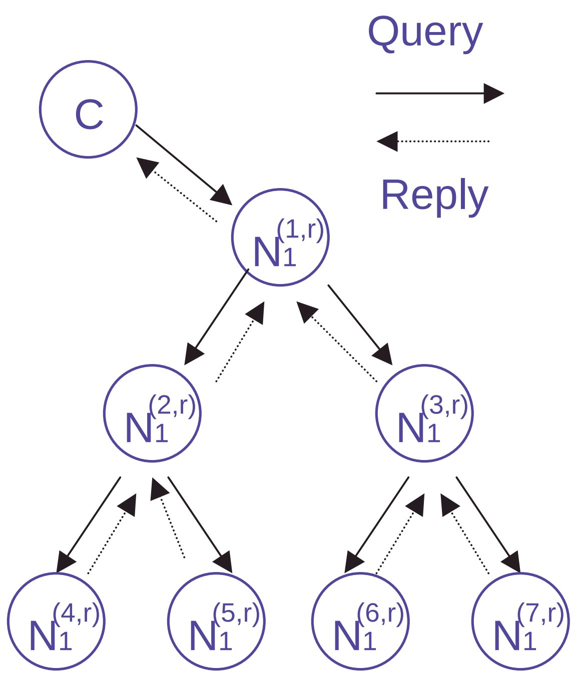
Specialized Resolvers

- Problem
  - All the RP matrices corresponding to a query are large, but the number of matched contents is small
    - Q:{device=camera, location=weh7110}
- Idea
  - Deploy resolvers that correspond to the AV-pair combination
- Mechanism
  - First level resolver monitors query rate on subsequent AV-pair
  - Spawn new node when reaches threshold
  - Forward registration to it



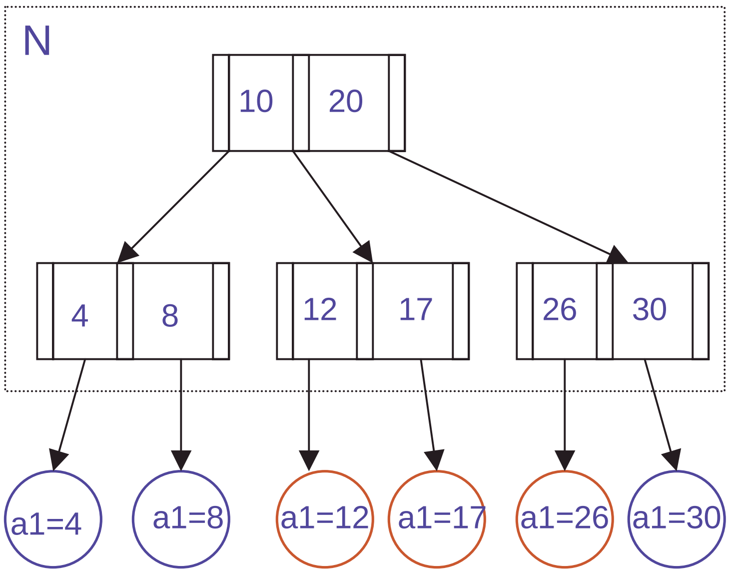
Improve Search Performance within LBM

- For a query, the selected matrix may have many partitions
  - Reply implosion
- Organize the columns into logical trees
  - Propagate query from root to leaves
  - Collect results at each level
    - Can exercise "early termination"



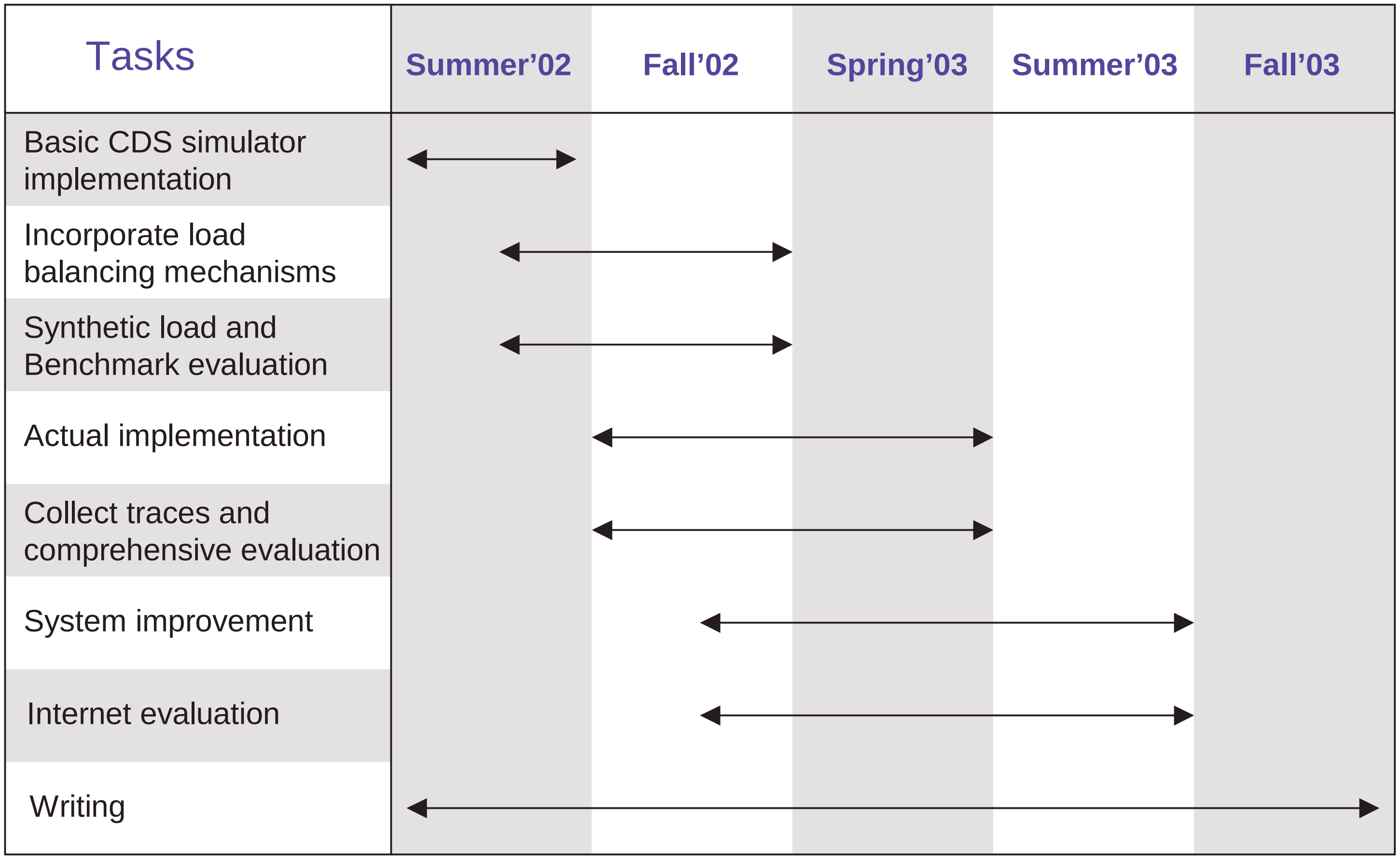
Support for Range Search

- Hash makes range search difficult
  - No node corresponds to a1>26
  - Nodes do not know each other even if share attribute
- Mechanism
  - Use an auxiliary data structure to store the related nodes
    - E.g., B-tree stored on N=H(a1)
  - Registration and query go through this data structure to collect the list of nodes to be visited



Q:{ 8 < a1 < 30}

Time Line


Tasks
Summer'02
Fall'02
Spring'03
Summer'03
Fall'03
Basic CDS simulator implementation
Incorporate load balancing mechanisms
Synthetic load and Benchmark evaluation
Actual implementation
Collect traces and comprehensive evaluation
System improvement
Internet evaluation
Writing

Expected Contributions

- System
  - Demonstrate the proposed CDS provides a scalable solution to the content discovery problem
- Architecture
  - Show content discovery is a critical layer in building a wide range of distributed applications
- Software
  - Contribute the CDS software to the research community and general public