Bloofi: A Hierarchical Bloom Filter Index with Applications to Distributed Data Provenance

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Outline

- Problem
- Bloofi
  - Description
  - Search
  - Maintenance
- Distributed Data Provenance
- Experimental results
- Conclusions and future work

Problem

- Federated cloud environment
- Semi-independent clouds
- Each cloud keeps control of its data
- Data needs to be shared on demand

- Given a set of sets (the clouds)
- Find all the sets (clouds) that contain a given element X

Challenges

- Number of participants is high
- Broadcasting a query is expensive
- Processing each query at all locations is expensive
- Creating a global distributed index is not possible
  - Individual clouds maintain control of the data
  - Volume and rate of data insertion is high

Our Solution

- Each cloud maintains a Bloom filter of its data
- Bloom filters shared with a central location
- Construct a Bloom Filter Index (Bloofi) at central location
- Queries are processed first at central location, and sent only to the clouds that (might) have the answer

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Bloom Filters

- Bit array of size *m*
- *k* hash functions with range [0,*m*-1]

Insert x: $h_1(x) = 2$
$h_2(x) = 9$
$h_3(x) = 5$

0	0	1	0	0	1	0	0	0	1	0	0

0 1 2 …………………………………. m-1

Bloom Filters

- Bit array of size *m*
- *k* hash functions with range [0,*m*-1]

Query y: $h_1(y) = 2$
$h_2(y) = 9$
$h_3(y) = 4$

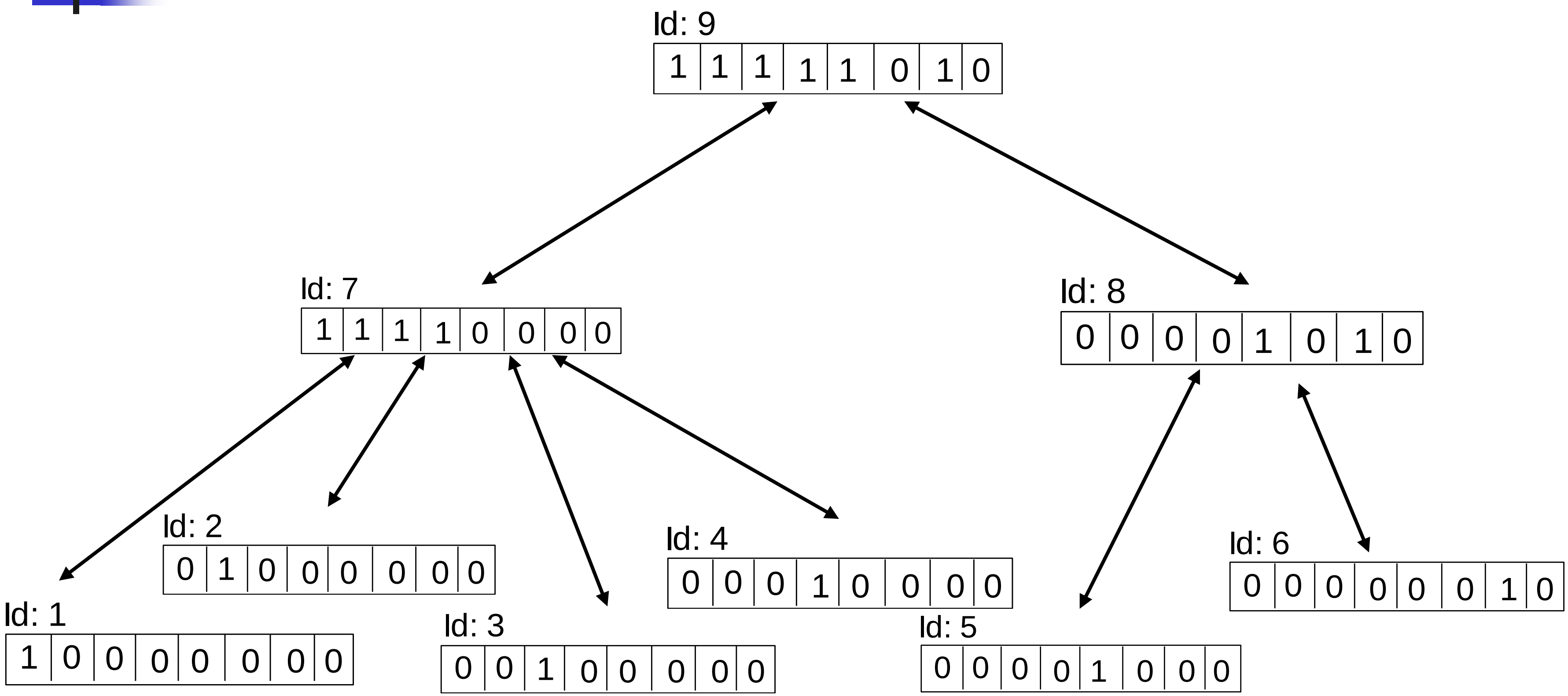
0	0	1	0	~~0~~	1	0	0	0	1	0	0

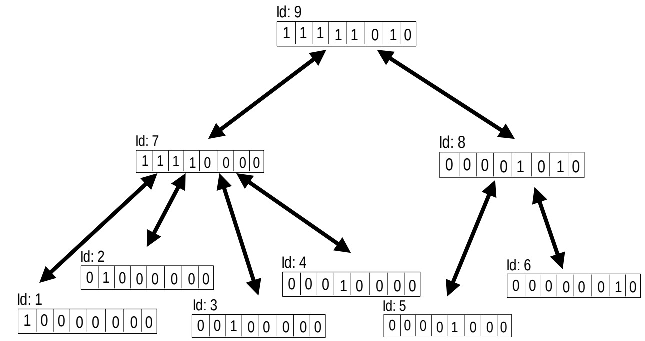
0 1 2 ………………………………… m-1

Bloom Filters Advantages

- Compact representation of sets
- Efficient insertion and testing
- Probability of false negatives = 0
- Trade-off between size of filter and false positive probability

Bloofi: A **B**loo**m** **F**ilter **I**ndex

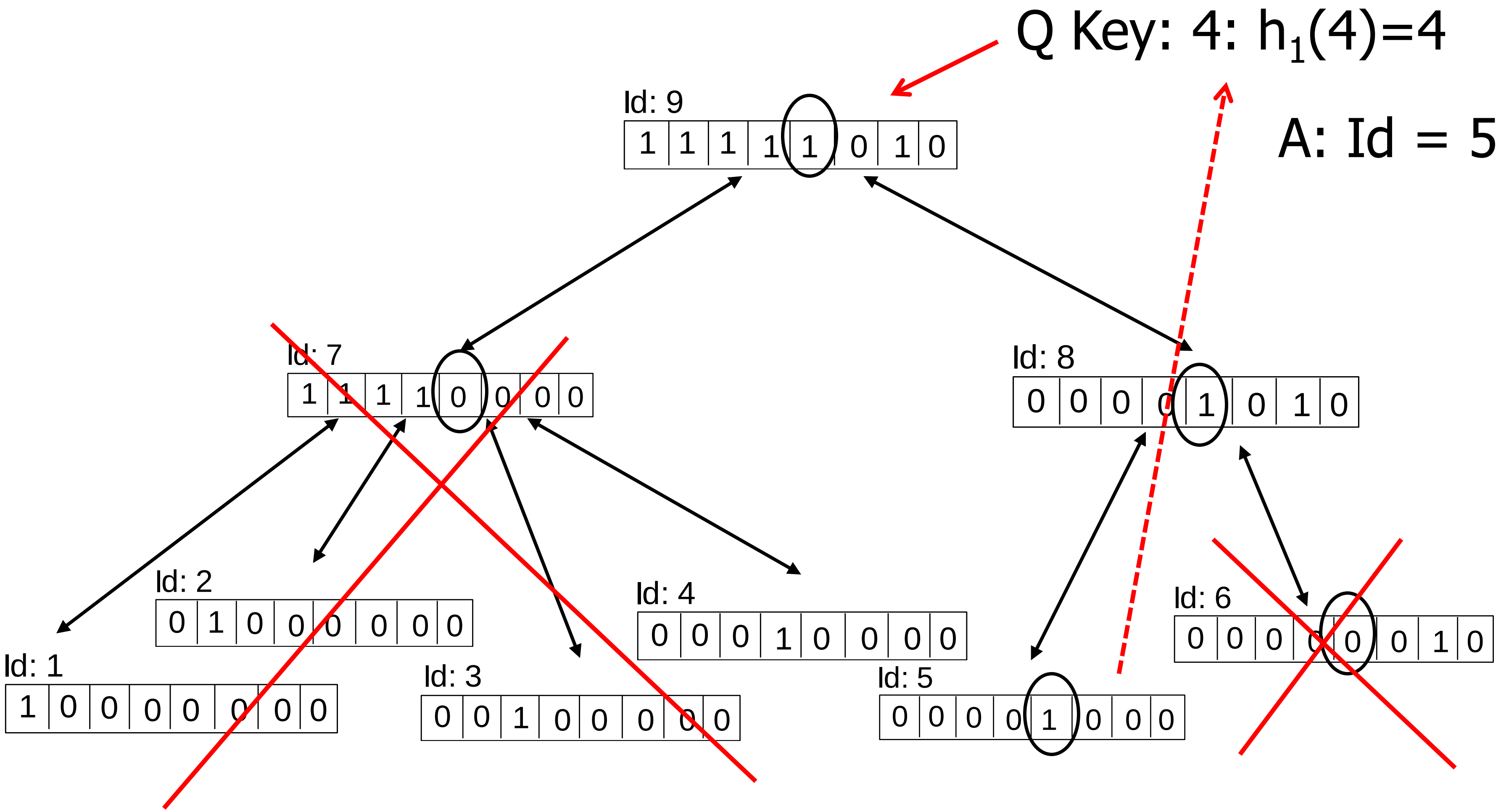




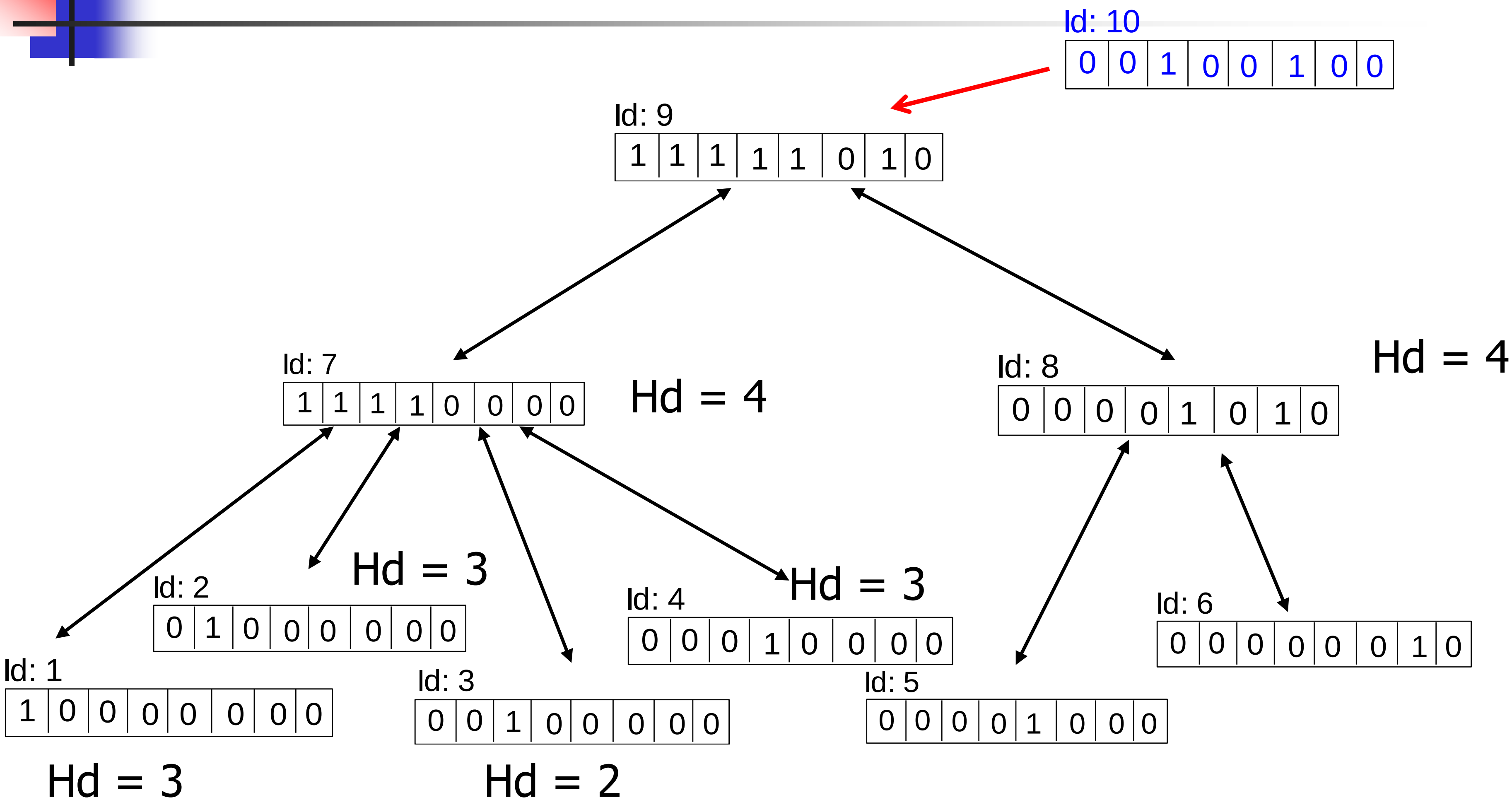
Bloofi Invariants

- Each Bloom filter value represents the *union* of all subsets in the subtree => useful for pruning during search
- Balanced tree
- Each non-root node has between *d* and 2*d* descendants
- Each node has 1 value

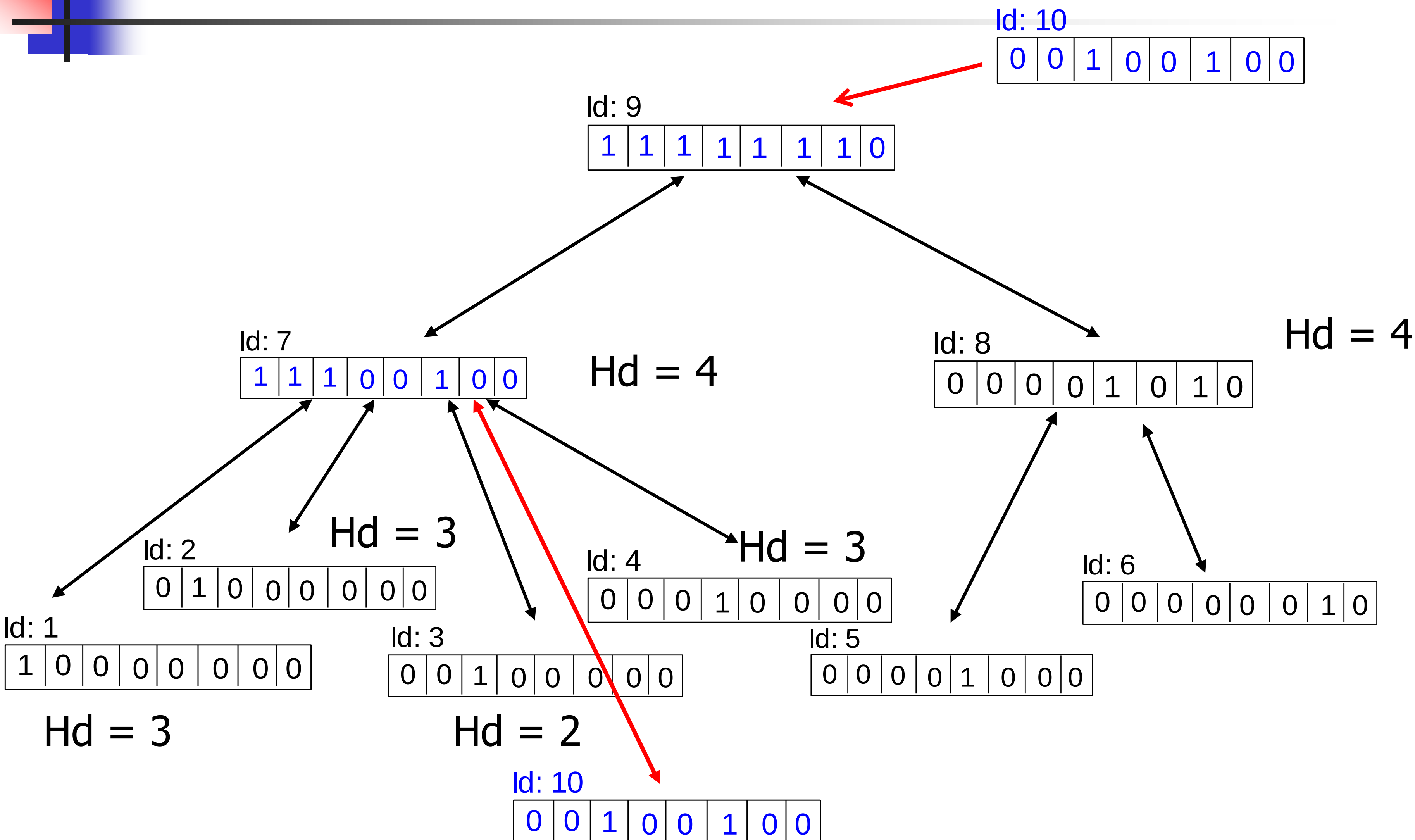
Bloofi Search



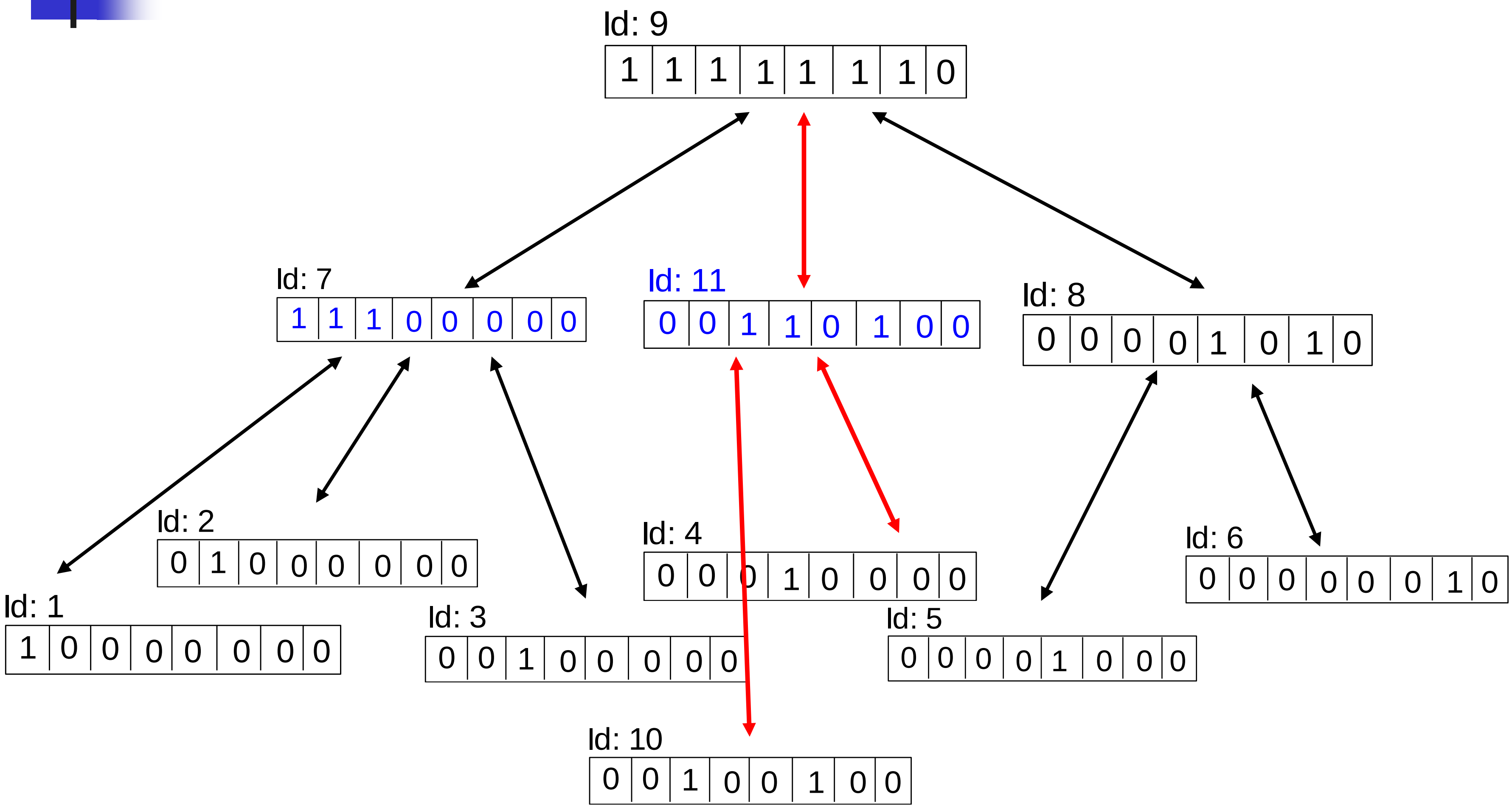
Bloofi Insert



Bloofi Insert



Bloofi Split



Bloofi Properties

- Search cost is $O(d*\log_d N)$ in general and $O(N)$ in worst case
- Storage cost is $O(N/d)$
- Insert cost and delete cost are $O(d\log_d N)$
- Update cost is $O(\log_d N)$

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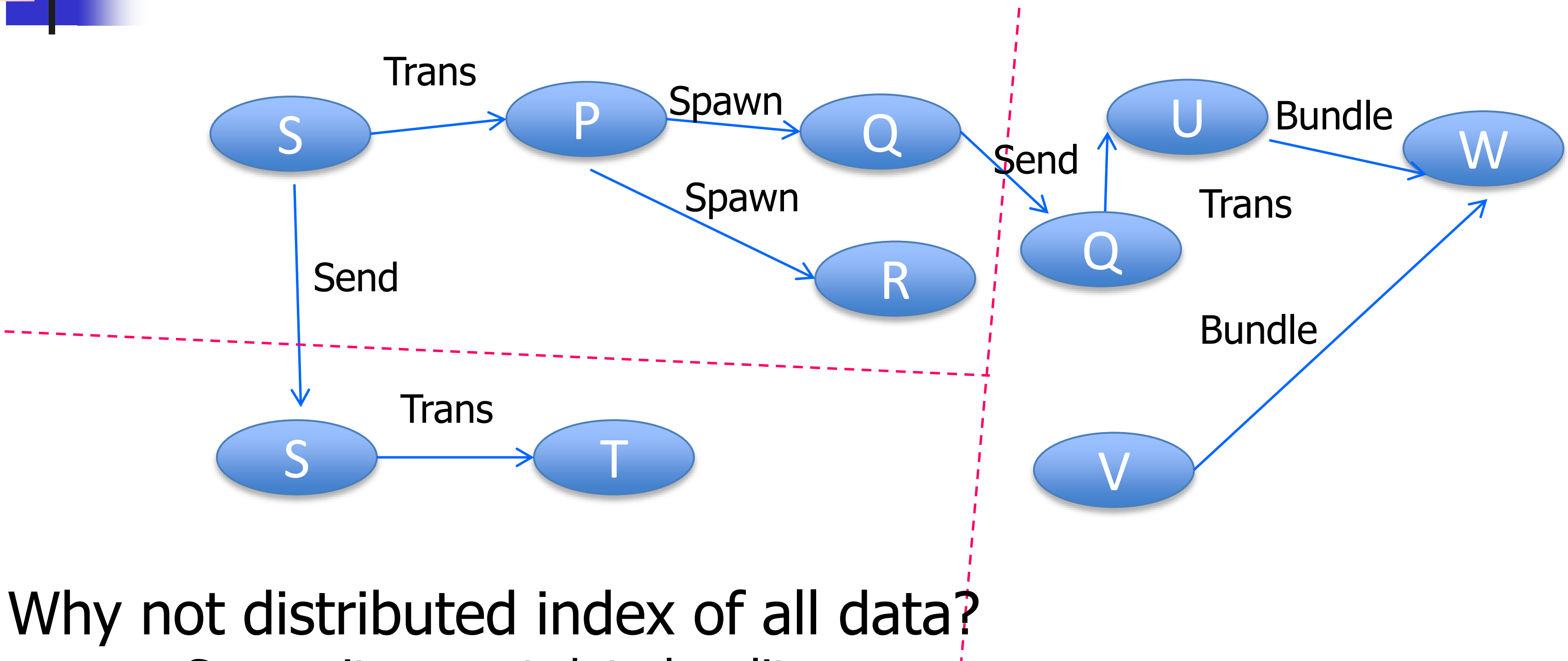
Distributed Data Provenance



Why not distributed index of all data?

- Some sites want data locality
- Different storage solutions at each site
- All data not created equal, not all data should go to the "headquarters"

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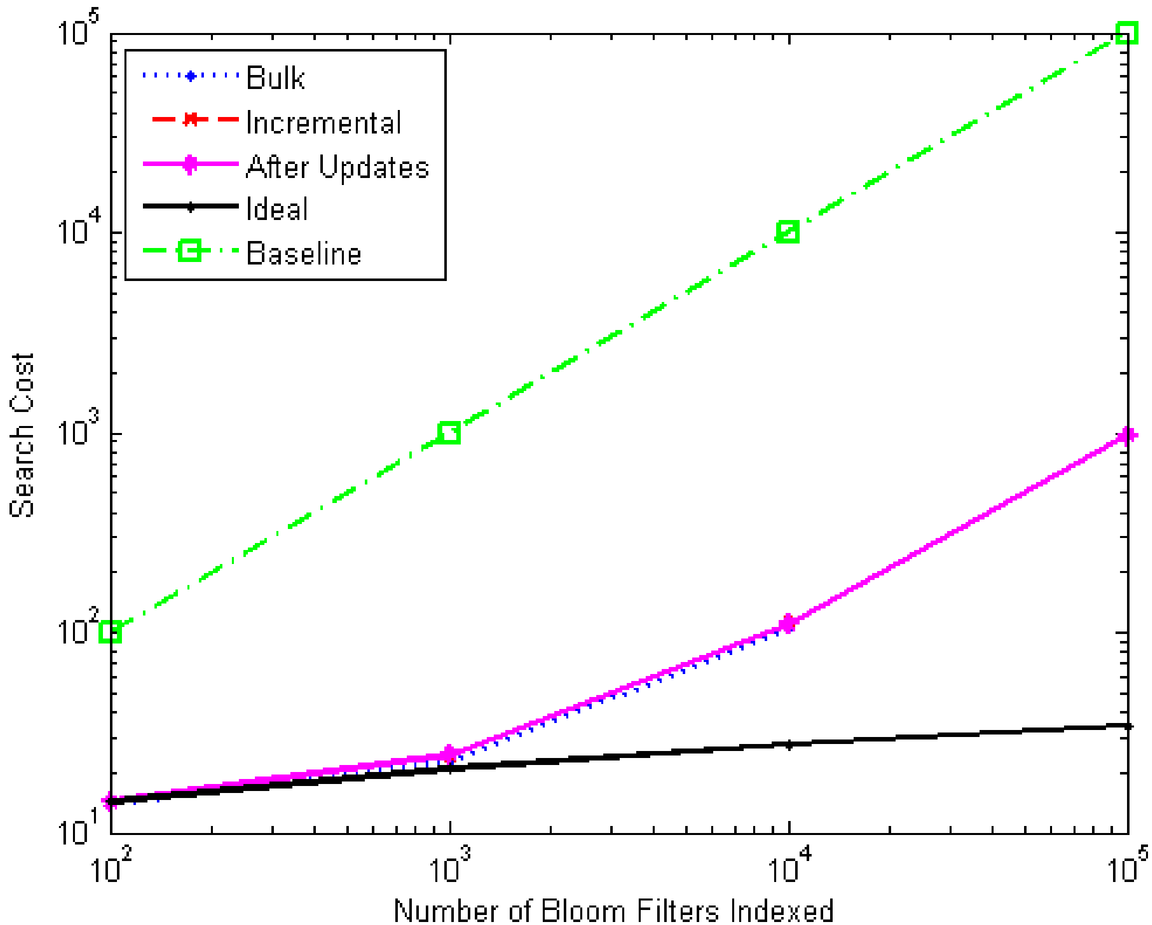
Experiments Set-up

- Simulator written in Java
  - Uses open-source Bloom filter impl [Skjegstad]
- Experiments run on a Dell Latitude E6510 2.76GHz Intel Core I7 CPU, 4 GB RAM
- Performance metrics:
  - Search cost – nb Bloom filters searched to find *all* matches
  - Search time – time to find *all matches*
  - Maintenance cost – nb of nodes accessed during insert/delete/update
- Compare with "baseline" case – no index

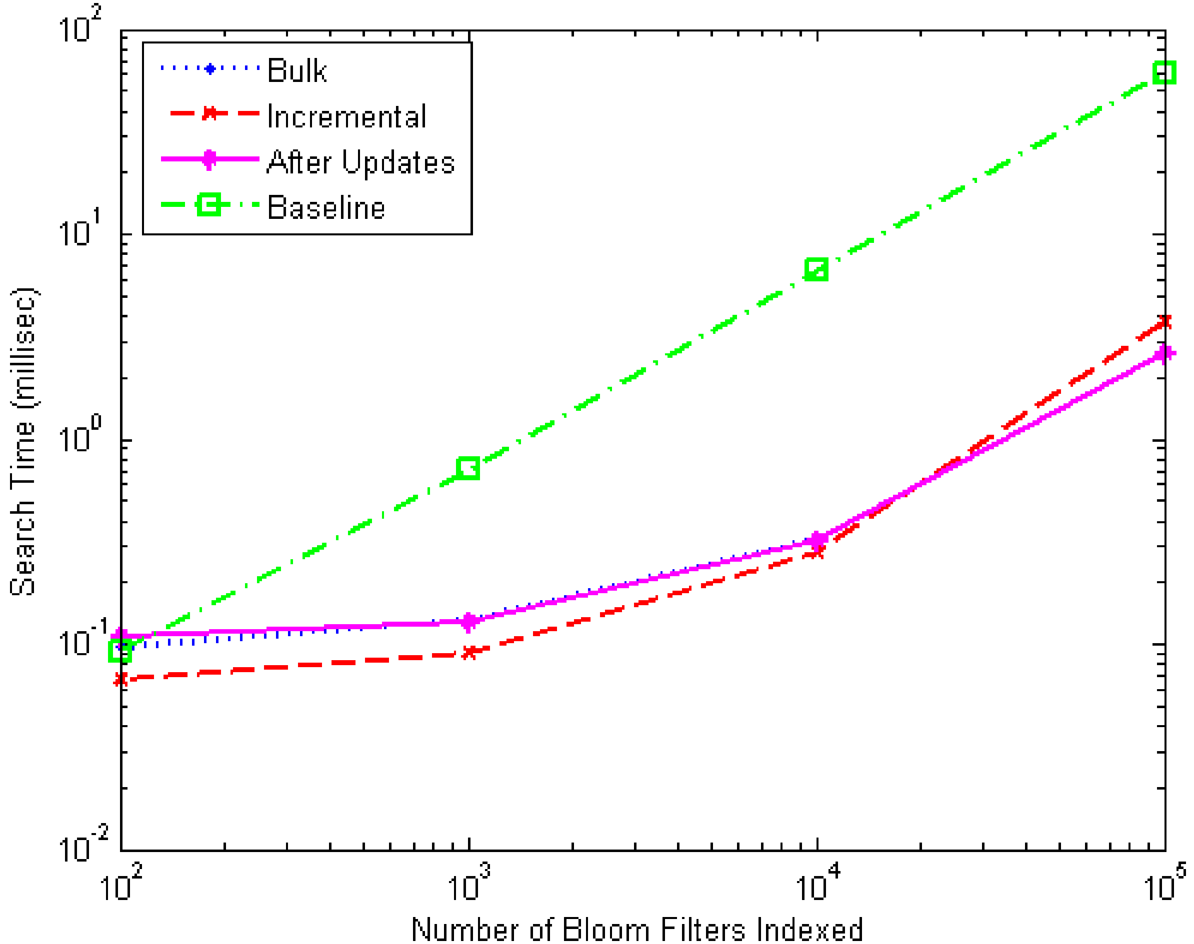
Parameters

Parameter	Range of values	Default Value
N –Nb of Bloom filters	100-100,000	1000
d – Bloofi order	2-22	2
Bloom filter size (bits)	1000-1,000,000	100,992
Bloofi construction method	Iterative / bulk	Iterative
Similarity metric	Hamming/ Jaccard /Cosine	Hamming
Data distribution	Random/nonrandom	Nonrandom

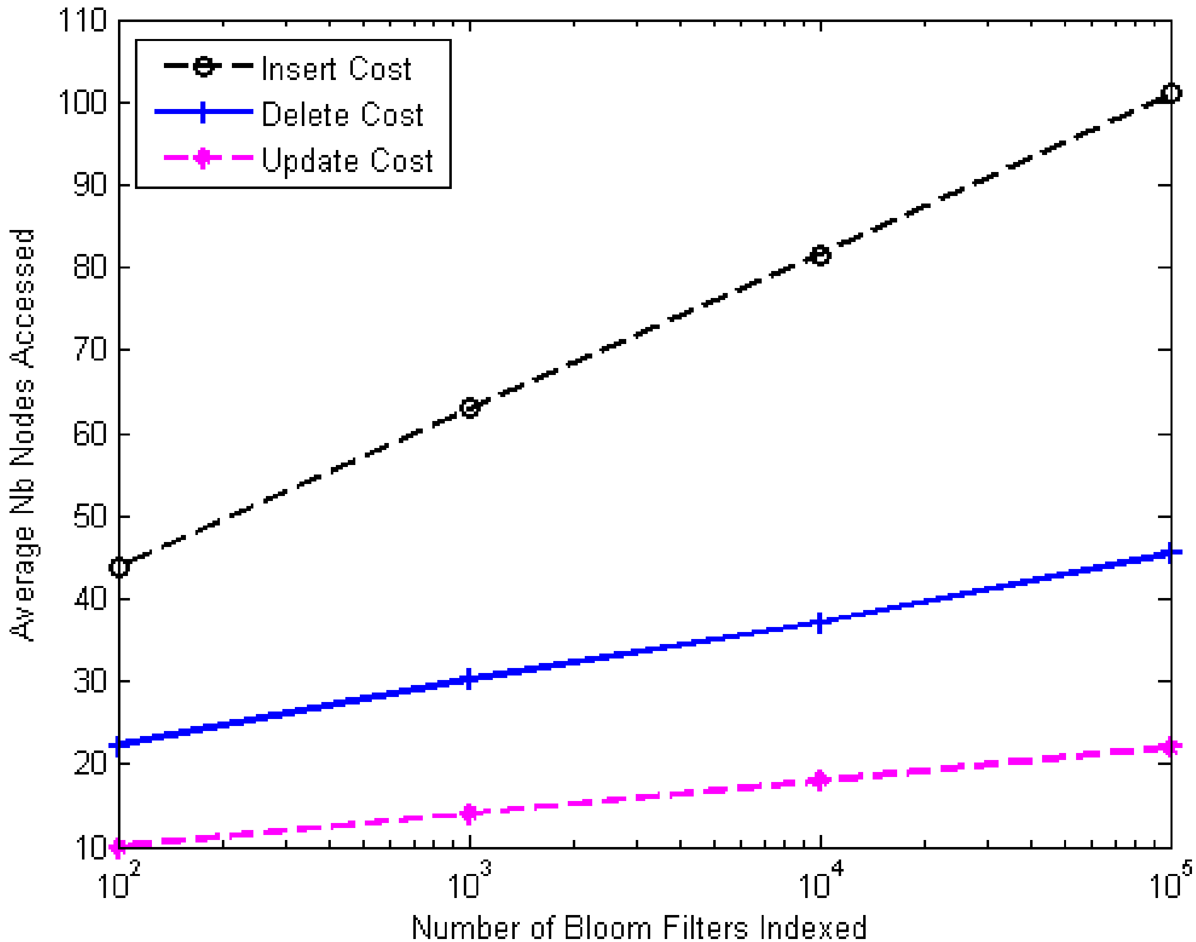
Search Cost vs. N



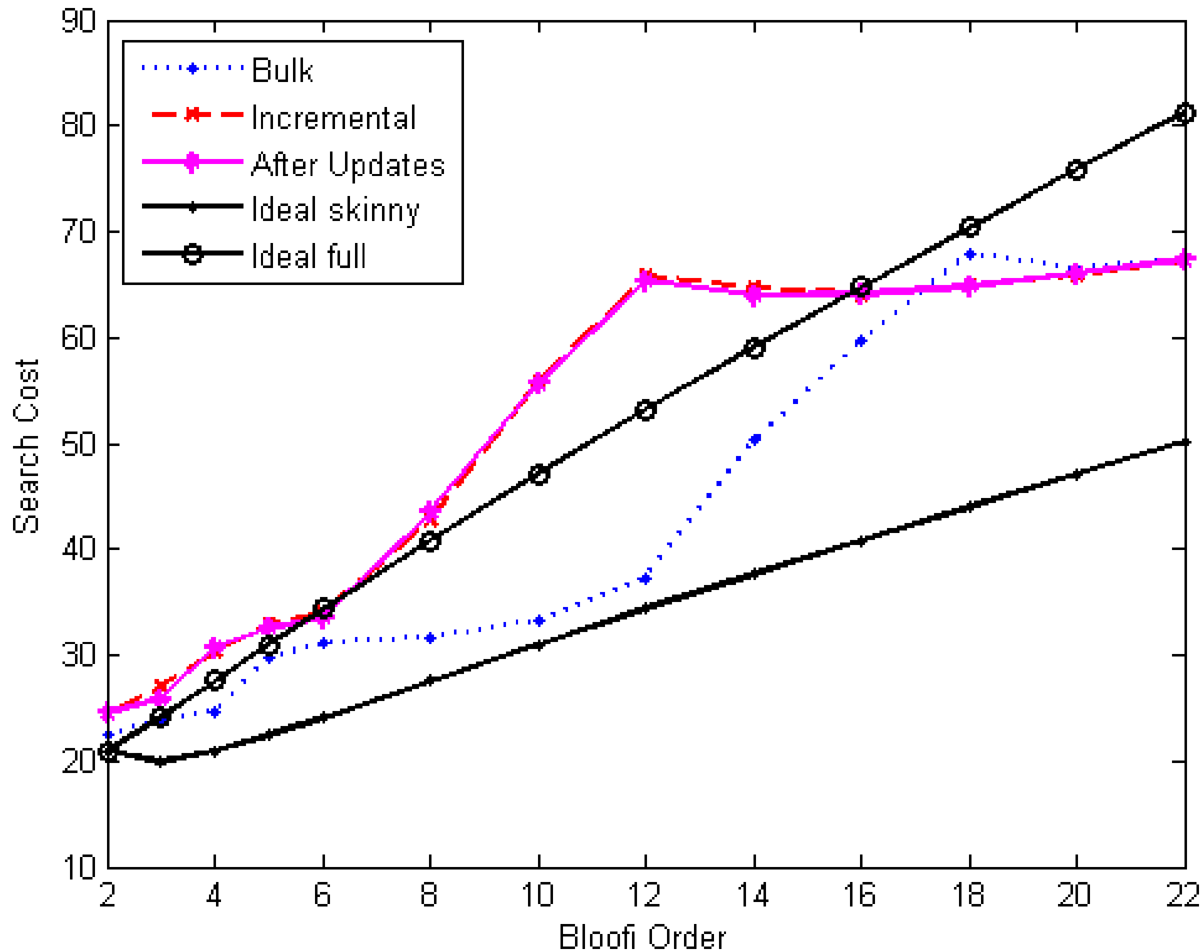
Search Time vs. N



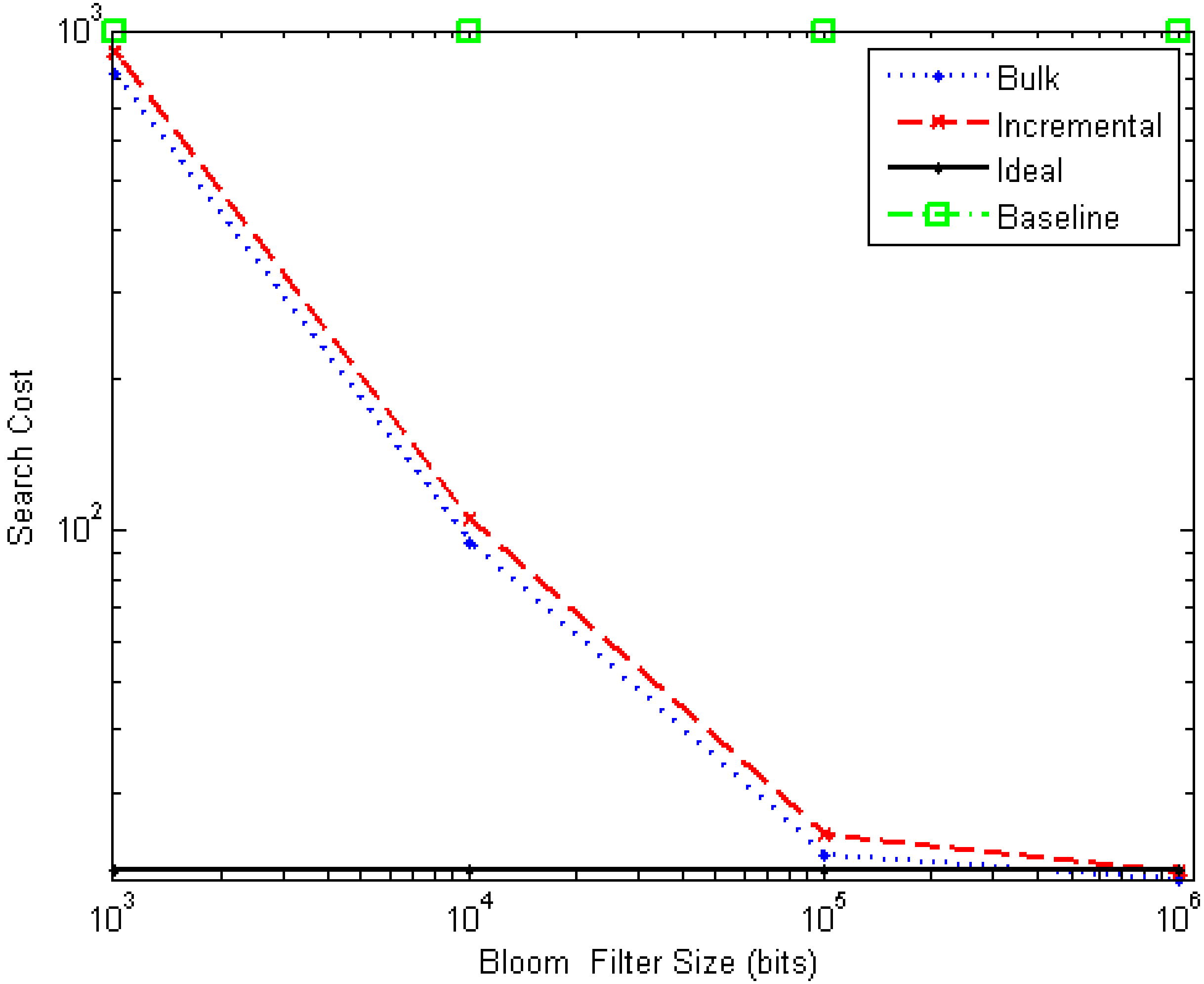
Maintenance Cost vs. N



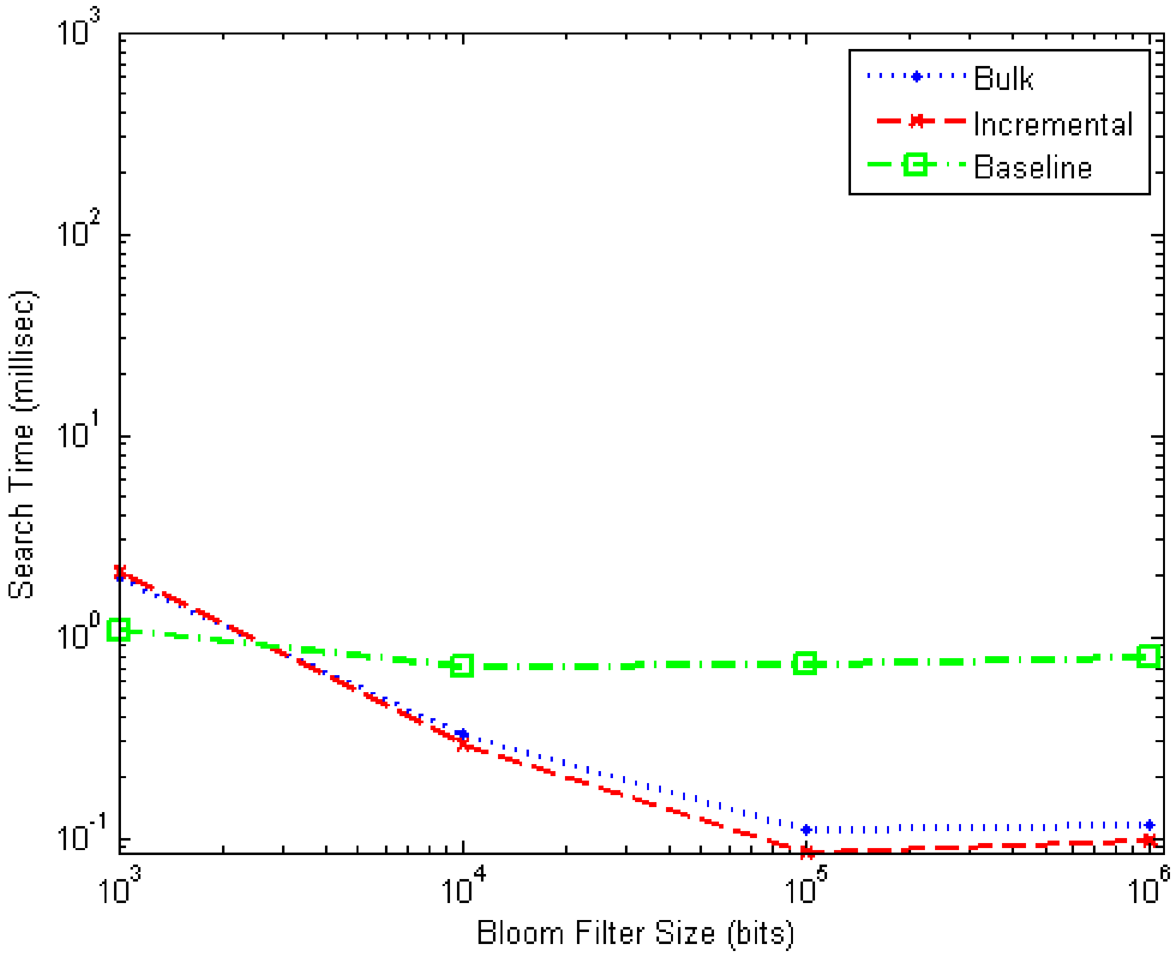
Search Cost vs. *d*



Search Cost vs. Filter Size



Search Time vs. Filter Size



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Related Work

- Bloom filters [Bloom70]
- Bloom filter variants [CM03, DR06, DBN12, Mitzenmacher01, SLP10]
- Bloom filter applications [FCB98, M90, BM02]
- B+trees
- Bitmap indexes [CI98]
- S-trees [Deppisch86]

Conclusions

- Bloofi – a hierarchical index structure for Bloom filters
  - Low search cost (O(N) worst case, O(logN) most cases)
  - Efficient construction and maintenance
  - Low storage cost
- Applications to cloud intelligence

Future work

- Clustering Bloom filters as a routing problem
- Compression
- Consider different Bloom filter sizes at different levels

Thank You!

Questions?