BUFFALO: Bloom Filter Forwarding Architecture for Large Organizations

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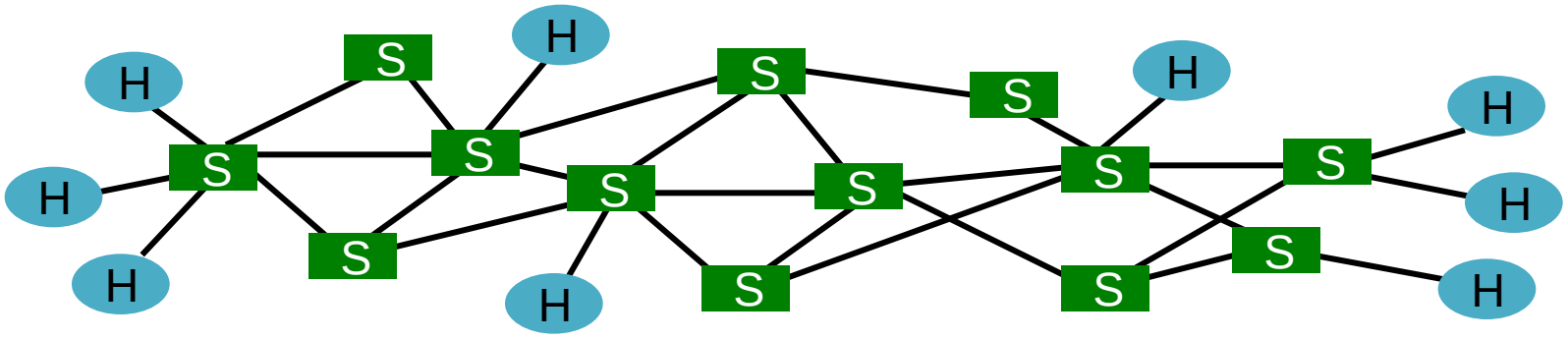
Large-scale SPAF Networks

- Large network using flat addresses
  - Simple for configuration and management
  - Useful for enterprise and data center networks
- SPAF:Shortest Path on Addresses that are Flat
  - Flat addresses (e.g., MAC addresses)
  - Shortest path routing (link state, distance vector)

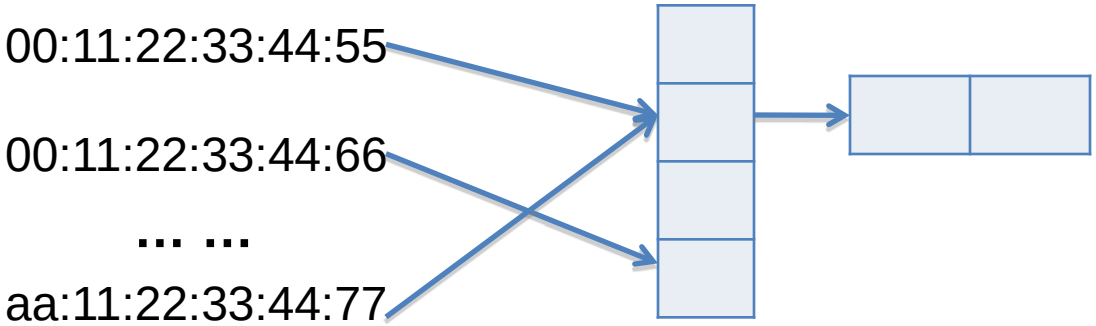


Scalability Challenges

- Recent advances in control plane
  - E.g., TRILL, SEATTLE
  - Topology and host information dissemination
  - Route computation
- Data plane remains a challenge
  - Forwarding table growth (in # of hosts and switches)
  - Increasing link speed

State of the Art

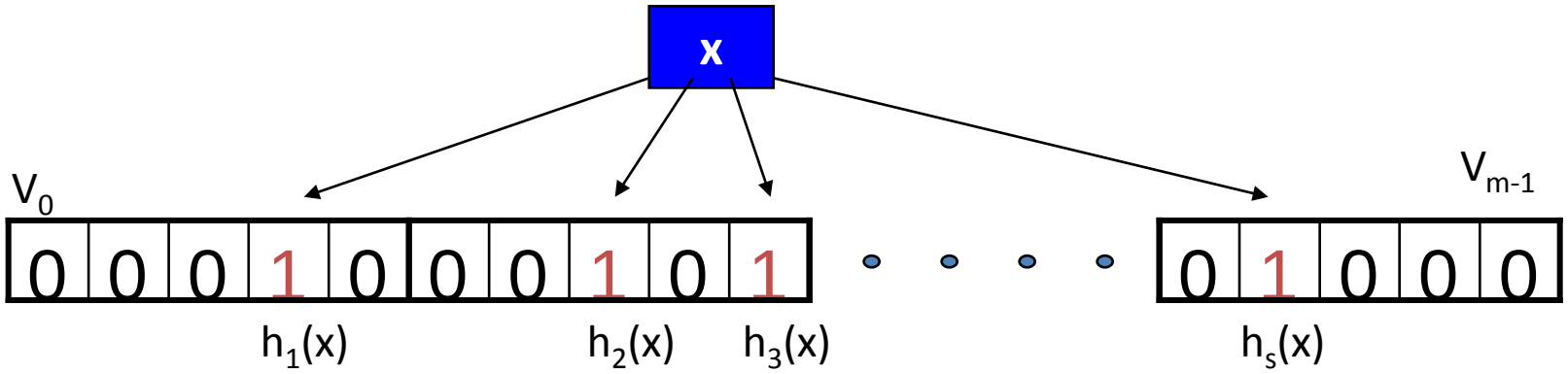
- Hash table in SRAM to store forwarding table
  - Map MAC addresses to next hop
  - Hash collisions: extra delay



- Overprovision to avoid running out of memory
  - Perform poorly when out of memory
  - Difficult and expensive to upgrade memory

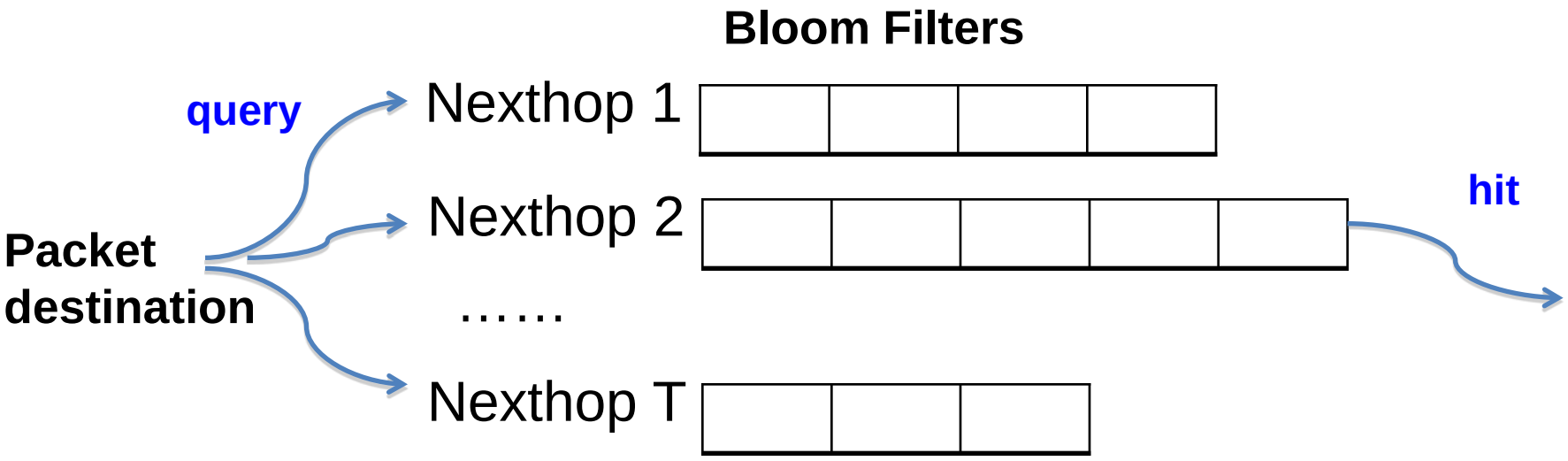
Bloom Filters

- Bloom filters in fast memory (SRAM)
  - A compact data structure for a set of elements
  - Calculate *s* hash functions to store element *x*
  - Easy to check membership
  - Reduce memory at the expense of false positives



BUFFALO: Bloom Filter Forwarding

- One Bloom filter (BF) per next hop
  - Store all addresses forwarded to that next hop



BUFFALO Challenges

How to optimize memory usage?

- Minimize the false-positive rate

How to handle false positives quickly?

- No memory/payload overhead

How to handle routing dynamics?

- Make it easy and fast to adapt Bloom filters

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Optimize Memory Usage

- Consider fixed forwarding table
- Goal: Minimize overall false-positive rate
  - Probability one or more BFs have a false positive
- Input:
  - Fast memory size *M*
  - Number of destinations per next hop
  - The maximum number of hash functions
- Output: the size of each Bloom filter
  - Larger BF for next-hops with more destinations

Constraints and Solution

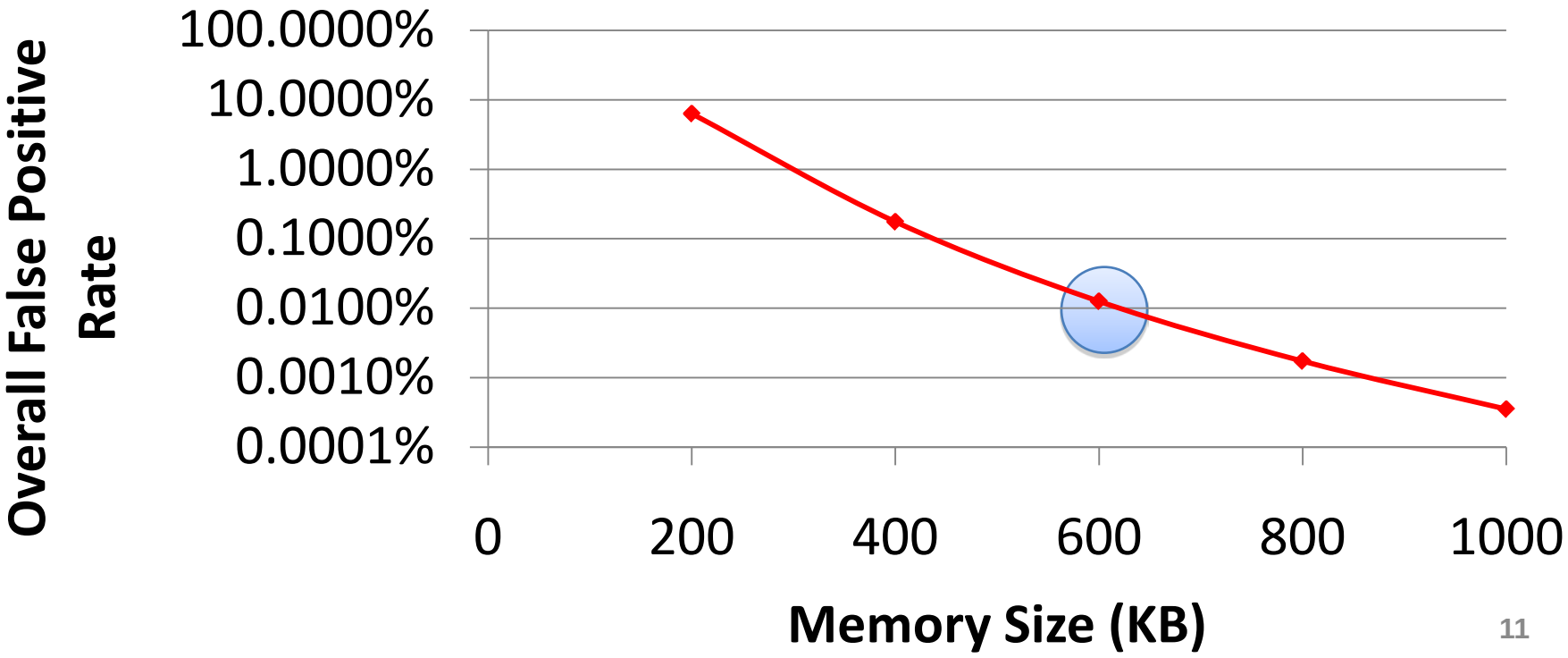
- Constraints
  - Memory constraint
    - Sum of all BF sizes $\leq$ fast memory size M
  - Bound on number of hash functions
    - To bound CPU calculation time
    - Bloom filters share the same hash functions
- Proved to be a convex optimization problem
  - An optimal solution exists
  - Solved by IPOPT (Interior Point OPTimizer)

Minimize False Positives

– Forwarding table with 200K entries, 10 next hop

– 8 hash functions

– Optimization runs in about 50 msec



Comparing with Hash Table

- Save 65% memory with 0.1% false positives
- More benefits over hash table
  - Performance degrades gracefully as tables grow
  - Handle worst-case workloads well

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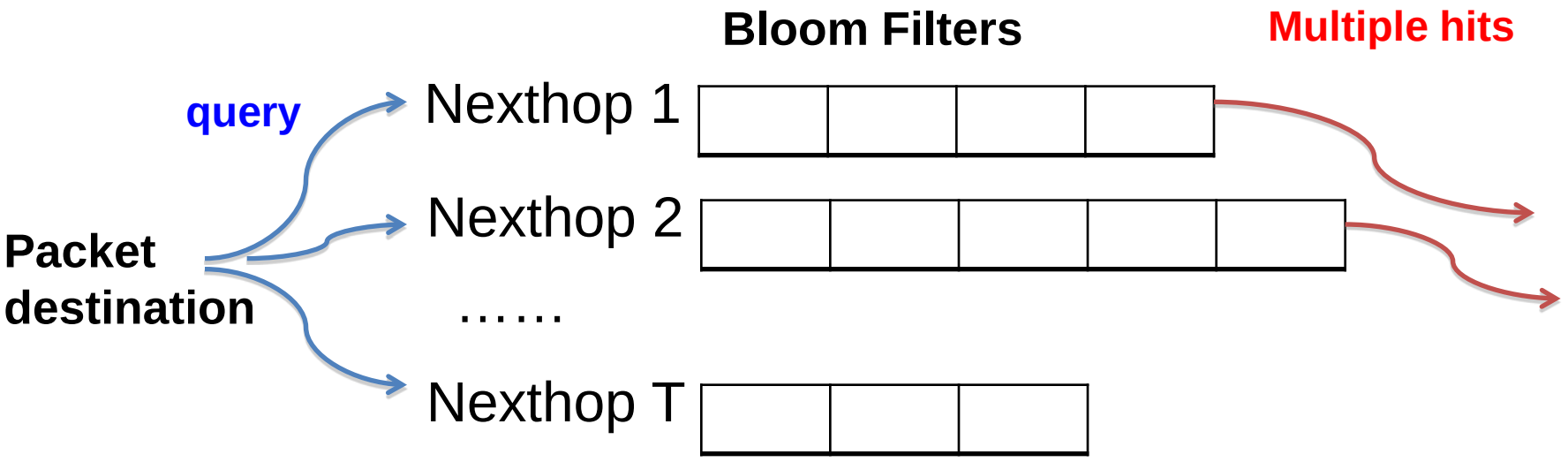
False Positive Detection

- Multiple matches in the Bloom filters
  - One of the matches is correct
  - The others are caused by false positives

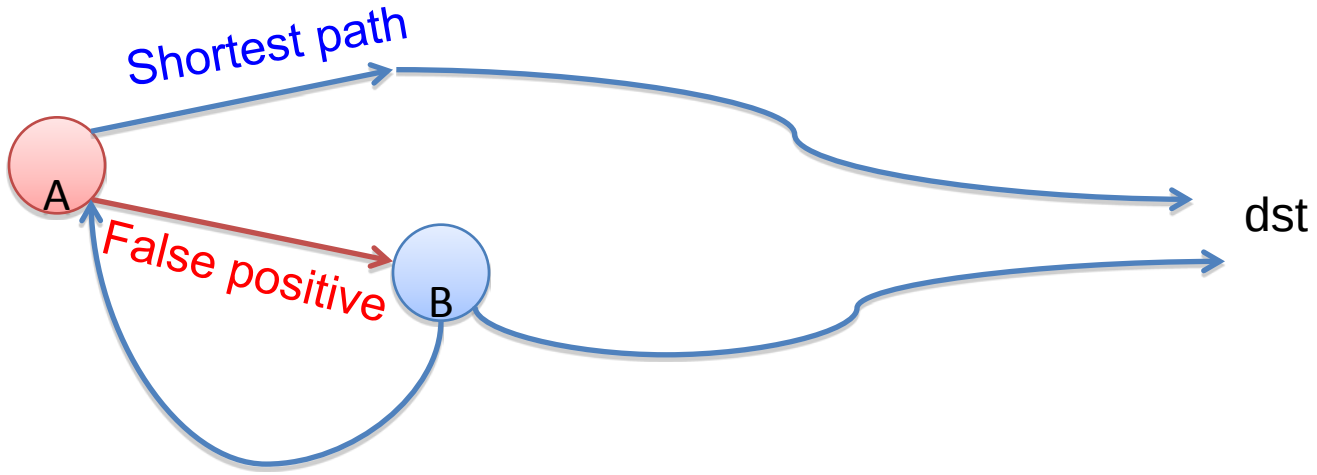


Handle False Positives

- Design goals
  - Should not modify the packet
  - Never go to slow memory
  - Ensure timely packet delivery
- BUFFALO solutions
  - Exclude incoming interface
    - Avoid loops in “one false positive” case
  - Random selection from matching next hops
    - Guarantee reachability with multiple false positives

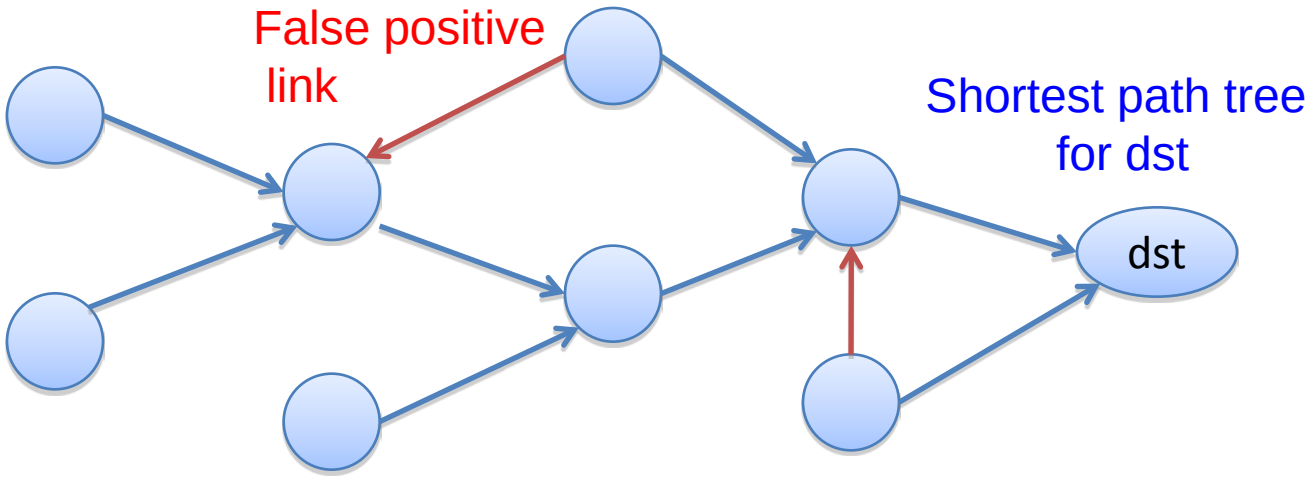
One False Positive

- Most common case: one false positive
  - When there are multiple matching next hops
  - Avoid sending to incoming interface
- Provably at most a two-hop loop
  - Stretch <= *Latency(AB)+Latency(BA)*



Multiple False Positives

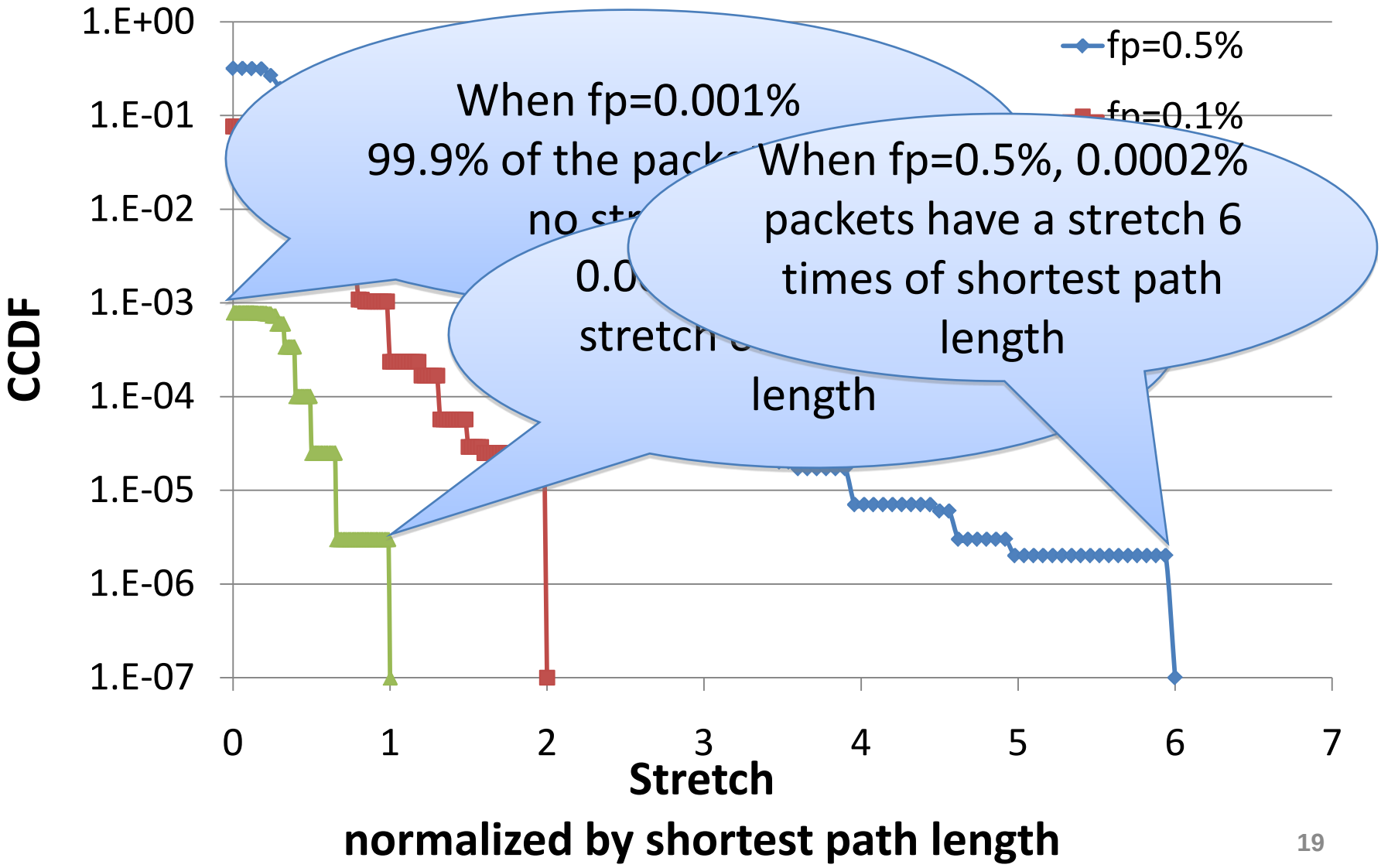
- Handle multiple false positives
  - Random selection from matching next hops
  - Random walk on shortest path tree plus a few false positive links
  - To eventually find out a way to the destination



Stretch Bound

- Provable expected stretch bound
  - With k false positives, proved to be at most $O(3^{k/3})$
  - Proved by random walk theories
- However, stretch bound is actually not bad
  - False positives are independent
  - Probability of *k* false positives drops exponentially
- Tighter bounds in special topologies
  - For tree, expected stretch is polynomial in *k*

Stretch in Campus Network



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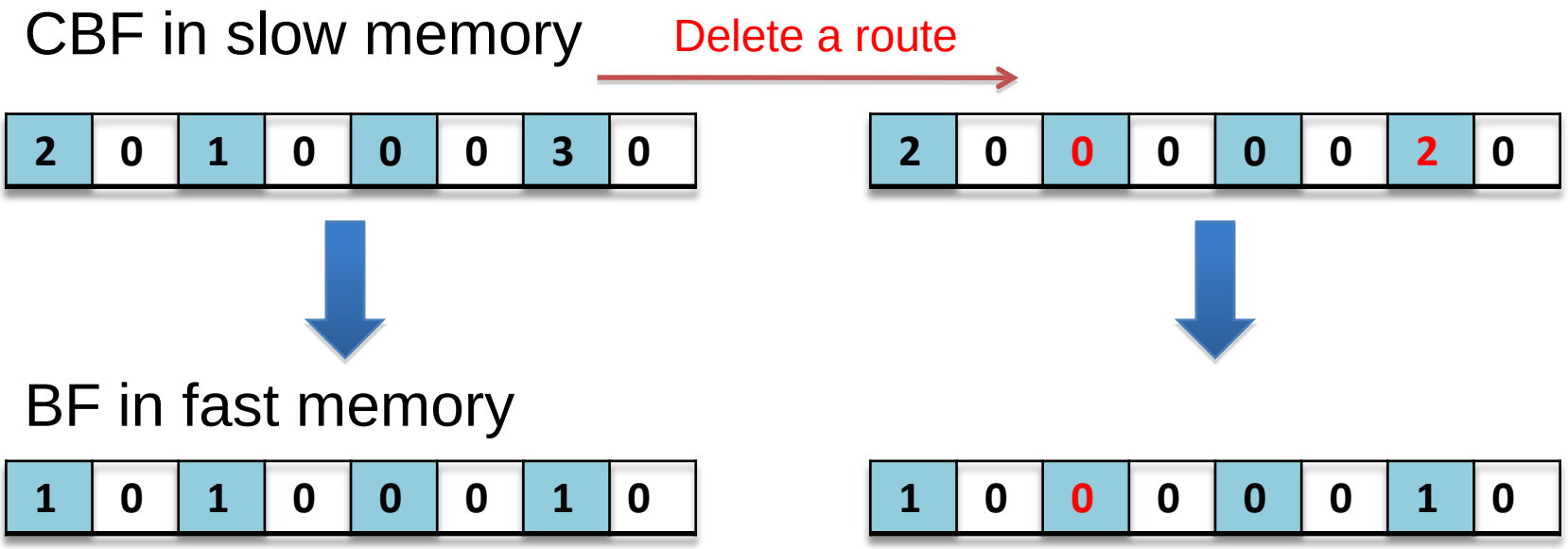
Problem of Bloom Filters

- Routing changes
  - Add/delete entries in BFs
- Problem of Bloom Filters (BF)
  - Do not allow deleting an element
- Counting Bloom Filters (CBF)
  - Use a counter instead of a bit in the array
  - CBFs can handle adding/deleting elements
  - But, require more memory than BFs

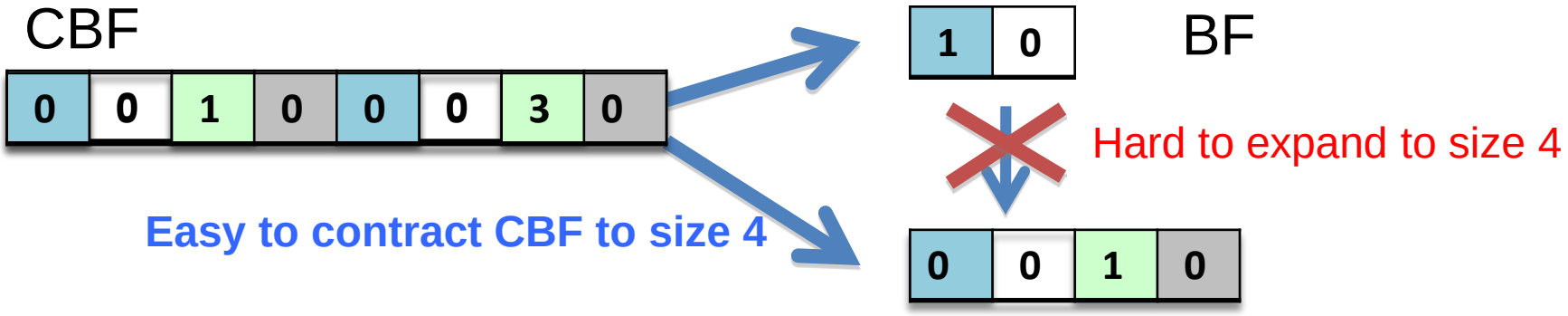
Update on Routing Change

- Use CBF in slow memory
  - Assist BF to handle forwarding-table updates
  - Easy to add/delete a forwarding-table entry



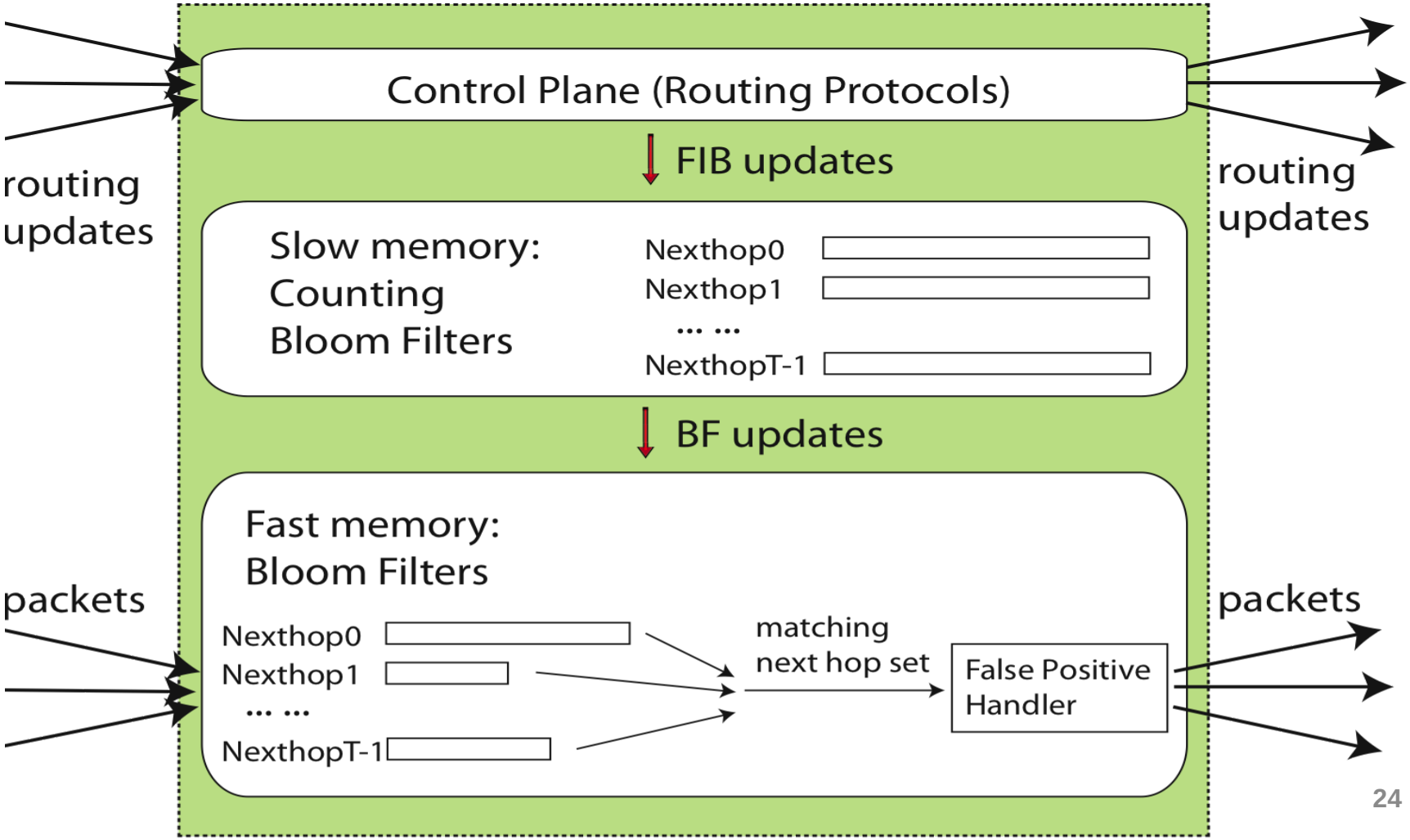
Occasionally Resize BF

- Under significant routing changes
  - # of addresses in BFs changes significantly
  - Re-optimize BF sizes
- Use CBF to assist resizing BF
  - Large CBF and small BF
  - Easy to expand BF size by contracting CBF



BUFFALO Switch Architecture

– Prototype implemented in kernel-level Click



Prototype Evaluation

- Environment
  - 3.0 GHz 64-bit Intel Xeon
  - 2 MB L2 data cache, used as fast memory size *M*
- Forwarding table
  - 10 next hops
  - 200K entries

Evaluation Results

- Peak forwarding rate
  - 365 Kpps, 1.9 µs per packet
  - 10% faster than hash-based *EtherSwitch*
- Performance with FIB updates
  - 10.7 µs to update a route
  - 0.47 s to reconstruct BFs based on CBFs
    - On another core without disrupting packet lookup
    - Swapping in new BFs is fast

Conclusion

- Three properties of BUFFALO
  - Small, bounded memory requirement
  - Gracefully increase stretch with the growth of forwarding table
  - Fast reaction to routing updates
- Key design decisions
  - One Bloom filter per next hop
  - Optimizing of Bloom filter sizes
  - Preventing forwarding loops
  - Dynamic updates using counting Bloom filters

- Thanks!
- Questions?