The University of New Mexico

Secure Algorithms and Data Structures for Massive Networks

Jared Saia

Joint work with: Amos Fiat(U. Tel Aviv), Valerie King(U. Vic), Erik Vee (IBM Labs), Vishal Sanwalani(U. Waterloo), and Maxwell Young(UNM)

What is Security?

Security: Designing algorithms and data structures which are **provably** robust to attack

- *Attack*: An adversary controls a constant fraction of nodes in the network
- *Robust:* Critical invariants provably maintained despite efforts of adversary to disrupt them

Our Adversary

- Controls constant fraction of the nodes in the network
- Mostly Omniscient
- Computationally unbounded

Scalable Security

- In massive networks, number of nodes, n, can be millions
- Thus want *scalable* algorithms:
  - Bandwidth: each node can send and process only polylog n bits
  - Latency: polylog n
  - Memory: polylog n

Outline

- Motivation
- Our Results, Scalable and Secure:
  - Data Structures
    - Distributed Hash Table
  - Algorithms
    - Leader Election, Byzantine Agreement, Global Coin Toss
- Future Work

Motivation

- Scalability: Peer-to-peer, ad hoc, wireless networks can have hundreds of thousands of nodes
- Security: These networks are vulnerable
  - No admission control
  - Economic, social and political incentives to attack
  - Adversary can take over many,many nodes (e.g. zombienets) and use them maliciously

Motivation

- Why computationally-unbounded adversary?
  - Dangerous to assume certain problems are intractable (e.g. quantum computation can solve factoring)
  - Many real-world adversaries have access to significant computational and/or human resources (e.g. governments, companies, zombienets)
  - Theoretically interesting

DHTs

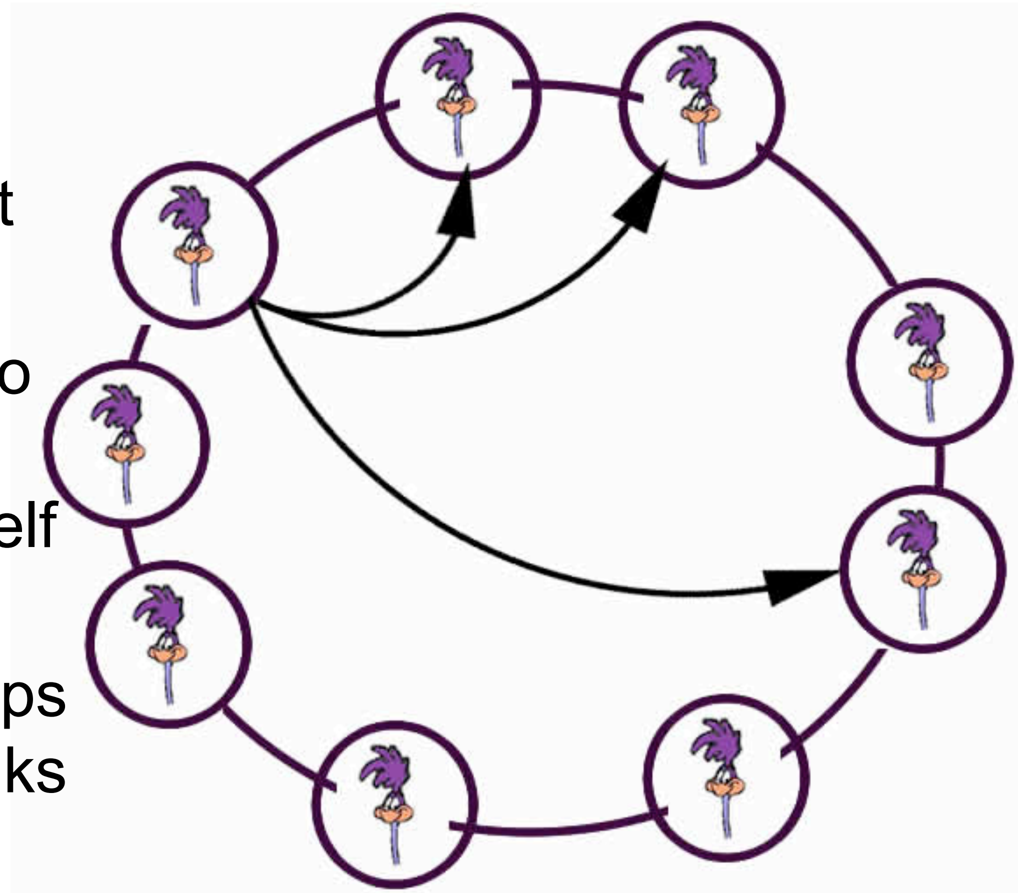
- A distributed hash table (DHT) is a structured peer-to-peer network that provides:
  - Content storage and lookup

- Many DHTs: Chord, CAN, Tapestry, Viceroy, Khorde, Kelips, Kademlia, etc.

- We focus on Chord

Chord

- Each peer in Chord has an ID which locates it on the unit circle.
- Each peer maintains links to peers at geometrically increasing distances from itself
- Thus, each peer can reach any other peer in O(log n) hops while maintaining O(log n) links

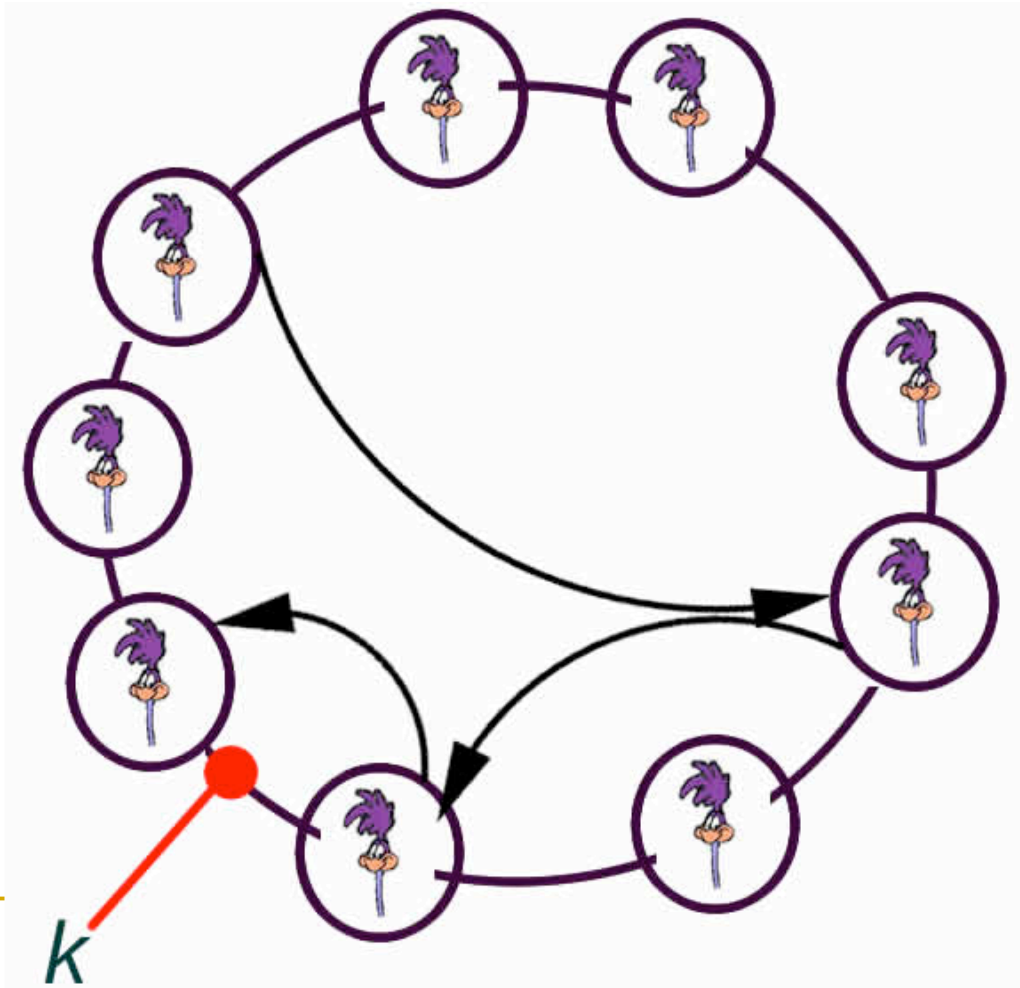


Chord

- *Successor protocol enables storage and lookup of data items*

- For *a point k, successor(k)* returns peer, *p*, which minimizes clockwise distance between *k* and *p*.

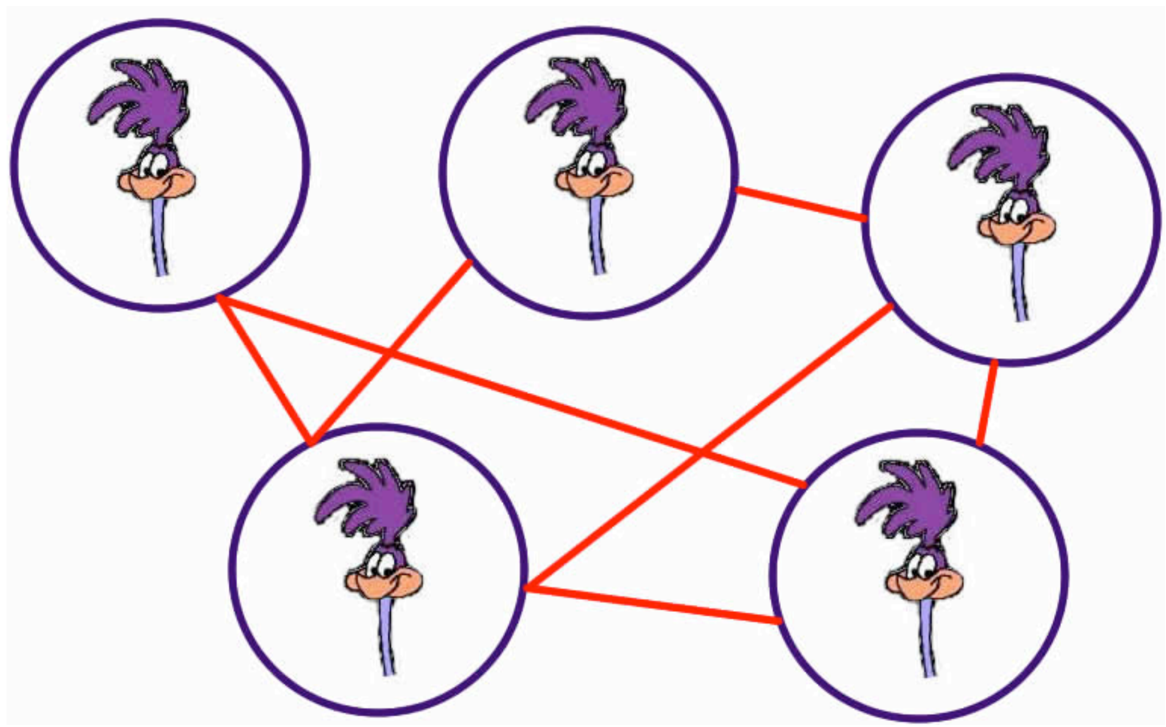
- If *k* is the key for a data item; *successor(k)* is the peer that stores that data item.



Introducing: Coyotus Adversarius

An adversary can: spam, hog bandwidth, delete nodes, etc.

Wiley “the Adversary” Coyote



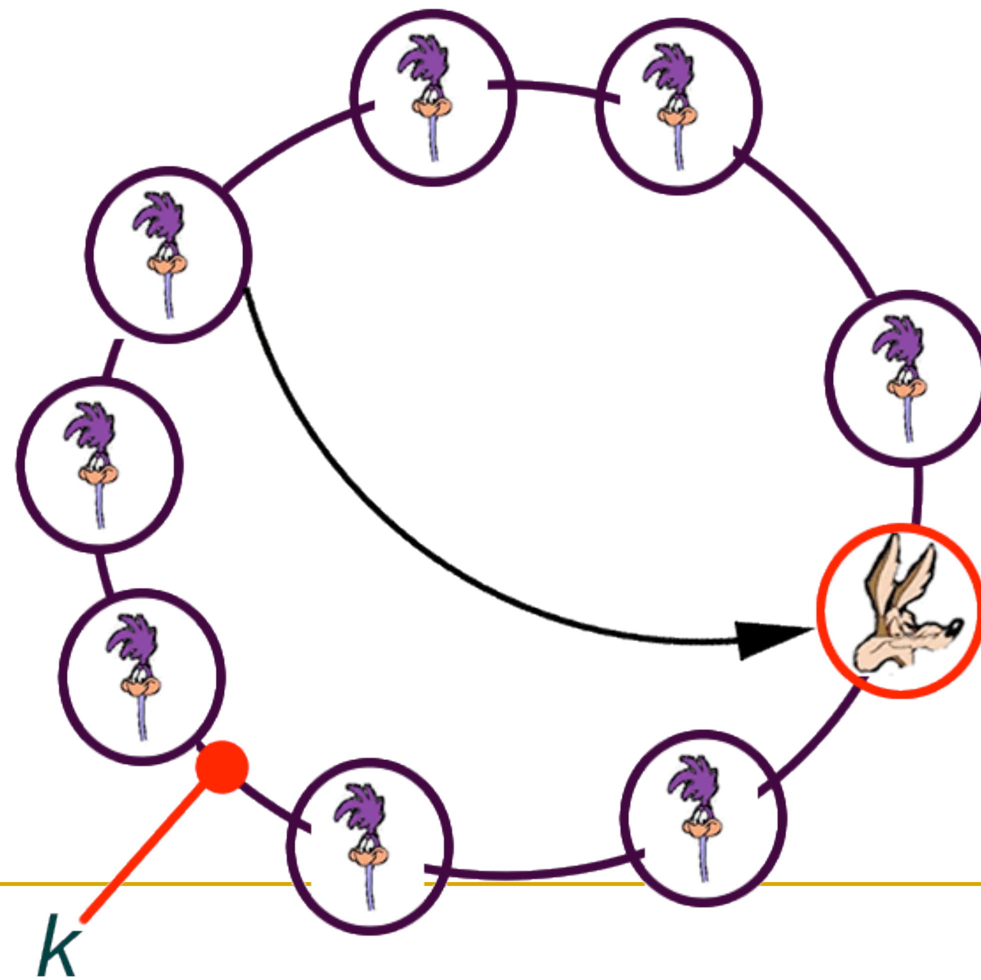
Road Runner Net

Chord is Vulnerable

- Chord is robust to random node deletion. But it is not robust to adversarial attack.

Adversarial peers might:

- not forward requests
- corrupt data
- etc.



Our Goals

Design variant of Chord which is*:*

- *Robust:* ensure correctness of *successor* protocol even under attack

- *Scalable*: bandwidth, latency and memory are polylogarithmic in the network size

S-Chord

- *Theorem: S-Chord* is *robust*, whp, for any time period during which:
  - there are always z peers in the network for some integer z
  - there are never more than $(1/4-\varepsilon)z$ adversarial peers in the network for positive ε
  - number of peer insertions and deletions is no more than z^k for some tunable parameter k

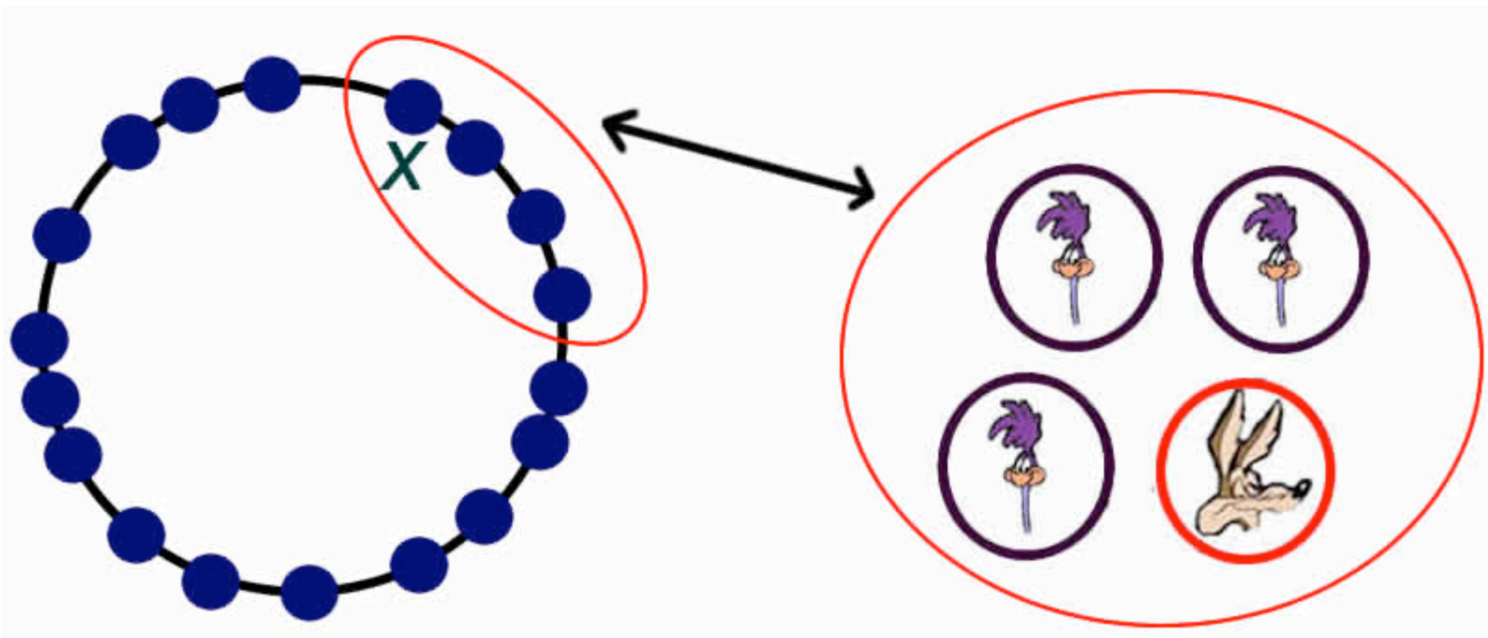
Our Result

- *Robust*:
  - Correctness of successor protocol guaranteed
- Scalable:
  - Resources required by S-Chord are only a polylogarithmic factor greater than Chord in bandwidth, latency, and linking costs

- Assumption:
  - Every direct link is a private communication channel

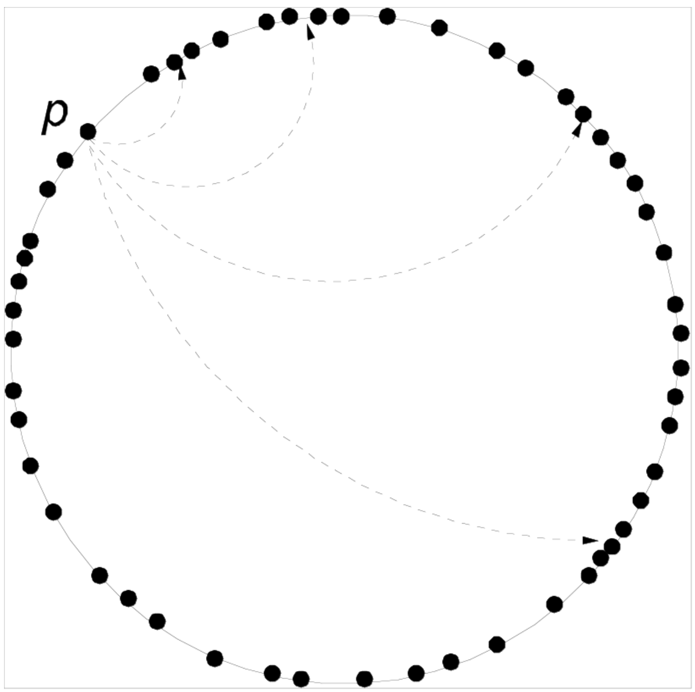
Main Idea: Trustworthy Small Sets

- For point x on the unit circle, define the *swarm*, $S(x)$, to be set of peers whose ID's are located within clockwise distance of $\Theta((\ln n)/n)$ from x

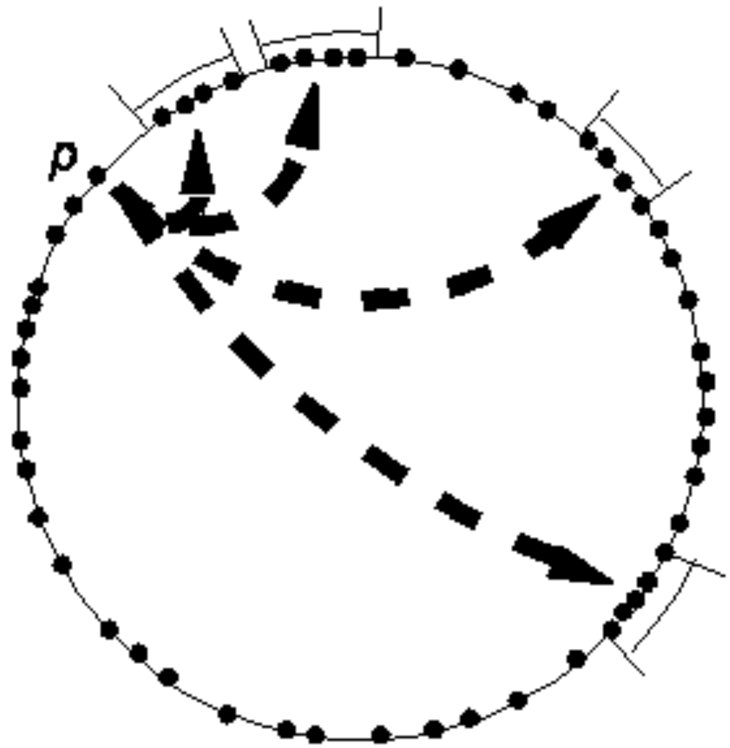


Swarm Links

- Whenever a peer p links to a single peer in Chord, p links to a set of O(logn) peers (a swarm) in S-Chord



Chord



S-Chord

Swarm Goodness Invariant

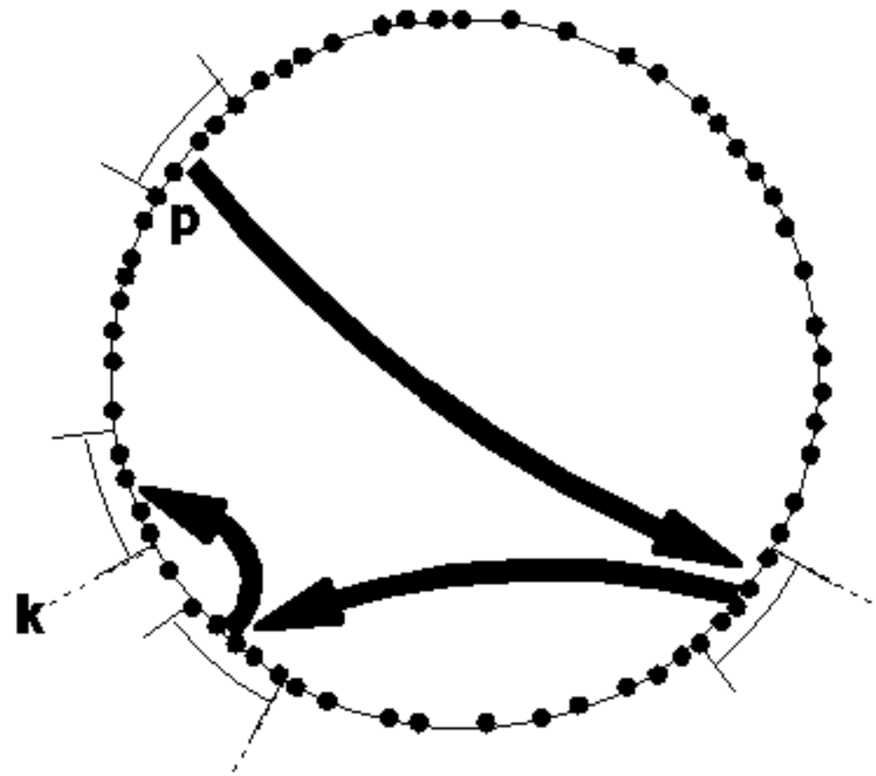
- Call a swarm *good* if it contains at least a 3/4 fraction of good peers and $\Theta(\log n)$ peers total
- Critical invariant maintained by our DHT is that all swarms are good
- We can use this invariant to implement the *successor* protocol robustly, using majority filtering

Successor

- If All Swarms are good, can robustly implement Successor with majority filtering
- Takes $O(\log^3 n)$ messages naively

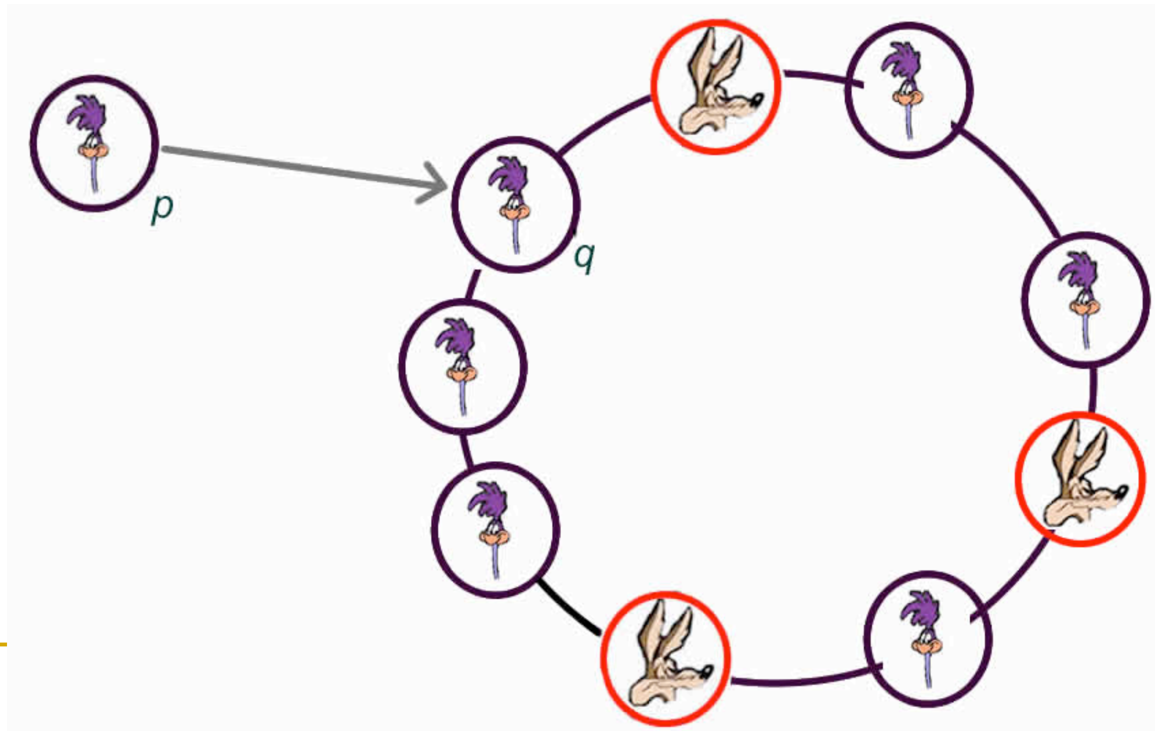
Our improvements:

- Can do in $O(\log^2 n)$ messages in expectation
- Can also do with $O(1)$ bit blowup in expectation using Rabin fingerprinting and error-correcting codes



Join Protocol

- Join protocol maintains Swarm Goodness Invariant
- When a peer joins, it must establish its own links and links of other peers must be updated too
- We assume that a joining peer knows some good peer in the network



Join Protocol

- Adversary selects IP addresses so we can't use these to determine proper location for a peer in our DHT
- Thus, when a new peer *p* joins the network, it is assigned an ID by a pre-existing swarm *S* in the network
- S needs a way to come to consensus on the ID of *p.*

Selecting a random ID

- Use techniques from secure multiparty computation to allow a good swarm S to agree on a random number between 0 and 1
- Can do this even if a computationally unbounded adversary controls a 1/4 fraction of the peers in the swarm
- Requires private communication channels between all peers in the swarm

A Problem

- Random ID selection will insert bad peers at random locations
- However, adversary can target a swarm and keep adding peers to the network, discarding those that land outside the targeted swarm, until there is a majority of bad peers in that swarm
- Adversary only needs to add O(z) peers before it will be able to take over some swarm

Solution

- [S ’05] shows that if each joining peer is rotated with two other peers selected u.a.r. that the bad peers will be sufficiently scattered so that they can not take over a swarm (for z^k insertions)

- [KS ’04] give an algorithm for selecting a peer u.a.r. from the set of all peers in a DHT. Algorithm can be run by a good swarm to come to consensus on two peers selected u.a.r.

- Combining these two results allows us to maintain the Swarm Goodness Invariant w.h.p for z^k peer joins.

Join Protocol

- The JOIN algorithm assumes that peer *p* knows some correct peer *q*
- *p* first contacts peer *q* with a request to join the network.
- *q* alerts *S(q)* to this request and the peers in *S(q)* choose a random ID for *p* using secure computation
- Two peers, p_1 and p_2, are then selected uniformly at random and then p, p_1 and p_2 are rotated

All swarms are good - Pf Intuition

- Good peers are “well spread” on the unit circle since their lifetimes are independent of locations
- Whenever a new peer is added, there is a small random perturbation of the peer locations on the unit circle
- This ensures that the bad peers are also well spread on the circle
- Thus every swarm has a majority of good peers

Handling different estimates

- So far we have assumed that all peers know ln n and (ln n)/n exactly – this is clearly unrealistic
- However, using standard techniques, we can ensure that each peer has high and low estimates of these quantities
- Using these estimates, the protocols remain essentially the same and all previous results hold.

DHT Conclusion

- S-Chord provably preserves functionality of Chord even in the face of massive adversarial attack.
- For n peers in the network, the resource costs are :
  - $O(\log n)$ latency and expected $\Theta(\log^2 n)$ messages per lookup
  - $\Theta(\log n)$ latency and $\Theta(\log^3 n)$ messages per peer join operation
  - $O(\log^2 n)$ links stored at each peer

Outline

- Motivation
- Our Results, Scalable and Secure:
  - Data Structures
    - Distributed Hash Table
  - **Algorithms**
    - **Leader Election, Byzantine Agreement, Global Coin Toss**
- Future Work

Leader Election

- In the leader election problem, there are n processors, 1/3 of which are bad
- Bad processors are controlled by an adversary which selects them before game starts
- Goal: Design algorithm which ensures a good processor is elected with constant probability

Leader Election

- Communication occurs in rounds, bad processors get to see messages of all good players before they send their messages
- Every processor has a unique ID - the ID of the sender of a message is explicitly known by the receiver
- Each processor has access to private random bits which are not known to the adversary or the other processors

Our Goal

- Previous results: can solve this problem in small number of rounds but require that each processor send and process a number of bits which is linear in n
- Our goal: an algorithm which is *scalable*: each good processor sends and processes a number of bits which is at most polylogarithmic in n (*exponential decrease*)

Our Result

- Assume there are n processors and strictly less than 1/3 are bad. Our algorithm elects, with constant probability, a leader from the set of good processors such that:
  - Exactly one good processor considers itself the leader
  - A 1-o(1) fraction of the good processors know this leader
  - Every good processor sends and processes only a polylogarithmic number of bits
  - The number of rounds required is polylogarithmic in n

Sampling

- Result: almost all (1-o(1) fraction) of the good processor know the leader
- Using sampling, we can bootstrap this to ensure that w.h.p, all good processors know the leader
- However can only do this if
  - Have private communication channels
  - Restrict number of messages bad nodes can send

Techniques Used

- Our algorithm makes use of a “tournament” graph which has expander-like properties.
- Each bottom node of this graph corresponds to a small set of randomly chosen processors
- Processors advance up the graph as they win local elections

Techniques Used

- Q: How to ensure that the winner of some lower election knows its competitors at the next higher election?
- A: Idea: Use watcher sets: sets of nodes that watch an election but don't participate.
- Hard part: setting up these watcher sets so that most of them can't be taken over by the adversary.

Extensions

- We can easily extend our result to elect with a set of O(logn) processors such that with high probability, a majority of these peers are good
- This allows us to securely compute several other problems w.h.p. e.g., majority vote, Byzantine agreement, etc.

Conclusion

- We’ve described provable secure and scalable
  - Data Structures: Distributed Hash Table(DHT)
  - Algorithms: Leader Election, Byzantine Agreement, Global Coin Toss
- Our algorithms are robust against a computationally unbounded, omniscient adversary that controls a constant fraction of the network

Future Work

- Robustification: Can we take other algorithms and make them robust without blowing up number of messages by too much?
  - E.g. Worm detection, Collaborative Filtering, Auctions, Voting Protocols, Spectral Decomposition
- Practical Applications: Can we simplify the algorithms enough so they can be successfully deployed on real networks?

That's all folks!

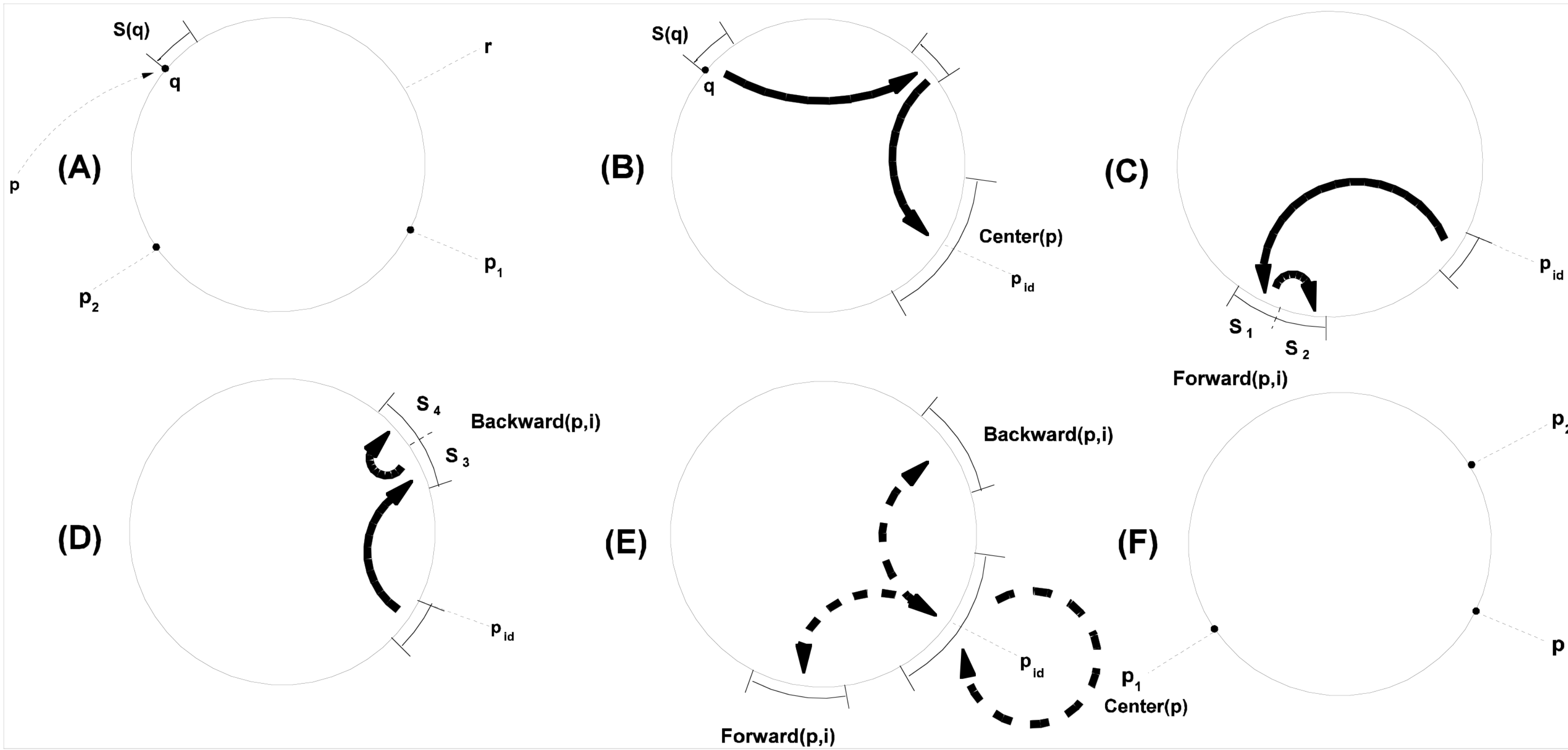
Related Work

- Several results deal with Byzantine attacks on p2p networks.
- Common model: single attack where each peer independently has probability *p<1/2* of becoming Byzantine. [FS ’02, NW ‘03,HK ‘04]
  - Problem: more likely scenario is many Byzantine peers joining the network over time
- Awerbuch and Scheideler [AS ‘04] design a secure distributed naming service which is robust to multiple Byzantine attacks
  - Problem: requires every peer to rejoin the network after O(logn) time steps
  - Their system is *not* a DHT (it is a distributed naming service)

Join Protocol

- All peers in *S(p)* find all the peers in *p*'s Forward and Backward intervals
- In addition, the peers in *S(p)* introduce *p* to all peers, *p'*, in the network such that *p* is now in a Center, Forward or Backward interval for *p'*
- In a similar fashion p_1, p_2 are rotated into their new positions and their new Center, Forward, and Backward intervals are established
- JOIN protocol requires O(log n) latency and O($\log^3$n) messages

Join Protocol



P2P Future Work

- We conjecture that these techniques can be extended to a number of other ring-based DHTs that have a finger-function *f* which satisfies $|f(x) - f(x+\delta)| \leq \delta$ for all positive δ and any point *x* on the unit circle
- Can these protocols or heuristics based on them be used in a practical p2p system? How can the protocols be simplified?
- Can we improve upon the message complexity for the robust successor protocol? Is it possible to either get less than $O(\log^2 n)$ expected messages or prove that this is not possible?