Structured Overlays:

Attacks, Defenses, and all things Proximity

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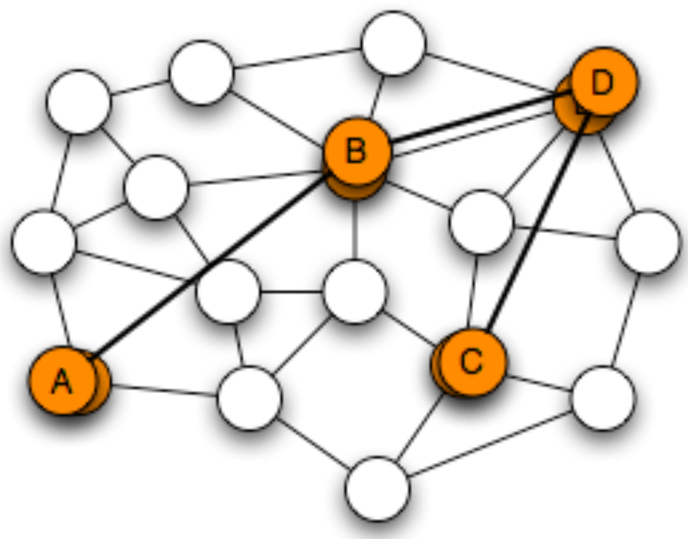
Our roadmap

- General overview of Overlays / DHTs
  - Chord [13]
  - Pastry [7]
- Location, Location, Location
- General Attacks and Defenses
- Eclipse Attacks: Churn as Shelter [4]
- Targeted Attacks: LocationGuard [11]

What is an Overlay Network?



Logical Network that sits "on top of" another network.

Can be *structured*, or *unstructured*.

Used for P2P systems, multicast broadcasts, etc.

Distributed Hash Table (DHT)

- Decentralized network where each node takes responsibility for a certain portion of a *keyspace*. Example: [0, 2^{160}-1].
- Given a *key*, any member of the DHT should be able to efficiently lookup whatever node is responsible for that key.
- For our purposes, we can think of a DHT as being an overlay network on top of the Internet, with Overlay **`NodeID = hash(IP address)`**

The “Big 4” DHTs

- **Chord** [13] (MIT)
- **Pastry** [7] (Microsoft)
- **CAN** [9] (UC Berkeley)
- **Tapestry** [14] (UC Santa Barbara)

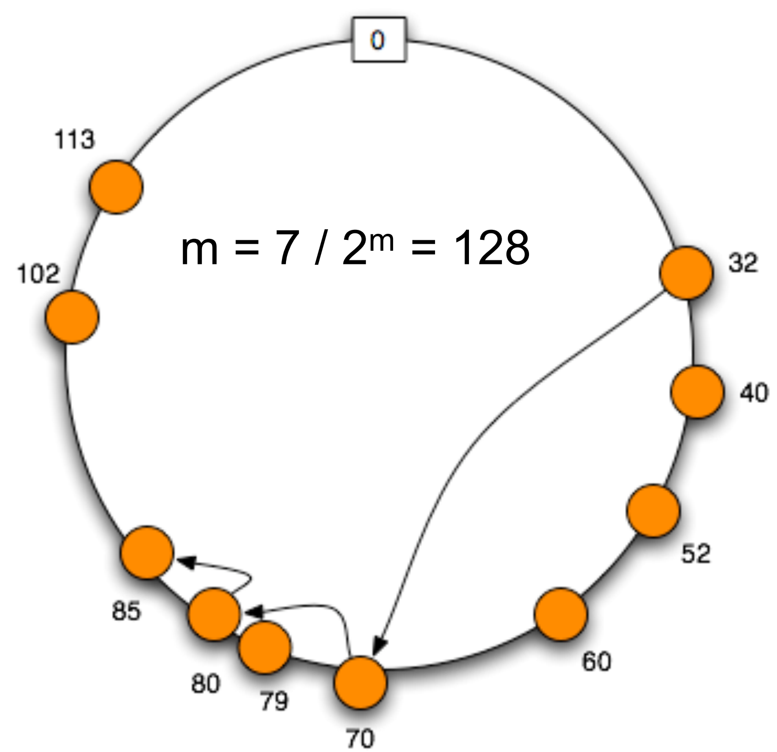
- All released roughly the same time ~ 2001
- Numerous others variants since then…

Chord

- Use a hash function to map each node and key into an m-bit identifier circle, modulo 2^m.
- Key *k* is assigned to the first node whose identifier is equal to or greater than *k*.
- Nodes keep track of their successors, predecessors along the ring, in addition to log(n) other nodes on the ring.

Chord Routing Example

Node 32 looks up key 82



Node 32 Finger Table		
Start	Interval	Node
33	33-33	40
34	34-35	40
36	36-39	40
40	40-47	40
48	48-63	52
64	64-95	70 ←
96	96-31	102
Successor		40
Predecessor		113

Chord Overview

- Very nice, easy-to-analyze properties:
  - *O*(log(n)) **overlay** hops to perform lookup
  - *O*(log(n)) sized routing tables
  - *O*($\log^2$(n)) steps to join a network
- Extremely reliable in event of node **failure**
  - Can record multiple predecessors, successors
  - Handles concurrent joins/leaves well
- No fudging with extra parameters!

Pastry

- Also uses a ring structure
- Performs lookups with:
  - Routing Table (Chord's Finger Table)
  - Leaf Set (Chord's Successors/Predecessors)
  - Neighborhood Set (More on this later)
- Keys thought of as sequence of digits with base 2^b. Route lookups to "numerically closest" node, rather than successor node.

Pastry Routing, Single Hop

b = 2 Example

Base = $2^b = 2^2 = 4$

11032111

31123001

10233033

NodeId 10233102

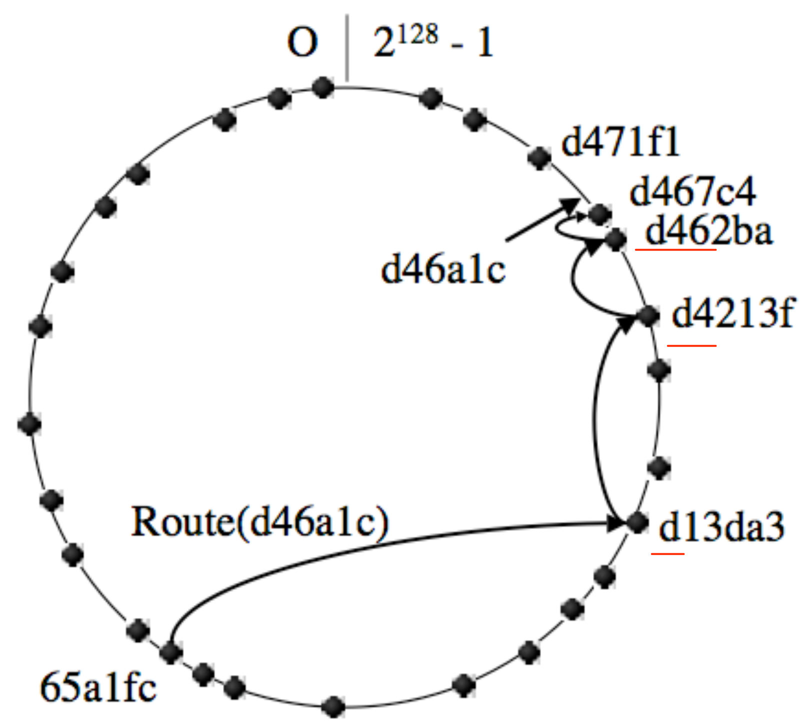
Leaf set	SMALLER	LARGER	
10233033	10233021	10233120	10233122
10233001	10233000	10233230	10233232

Routing table

-0-2212102	1	-2-2301203	-3-1203203
0	1-1-301233	1-2-230203	1-3-021022
10-0-31203	10-1-32102	2	10-3-23302
102-0-0230	102-1-1302	102-2-2302	3
1023-0-322	1023-1-000	1023-2-121	3
10233-0-01	1	10233-2-32	
0		102331-2-0	
		2	

Pastry Routing, Total Path

- Different view with b = 4
- Lookup key d46a1c from node 65a1fc
- At each step, matching prefix gets larger



Pastry Overview

- Configuration parameters
- Slightly harder analysis (still reasonable)
  - $O(\log_{2^b}(n))$ overlay hops
  - $\log_{2^b}(n)(2^b-1)$ sized routing tables
  - $2^{b+1}(\log_{2^b}(n))$ messages for a proper join
- Routing tables are **proximity-optimized**
  - Potentially faster lookups in practice
  - Standard Chord makes no such optimizations

Proximity Neighbor Selection

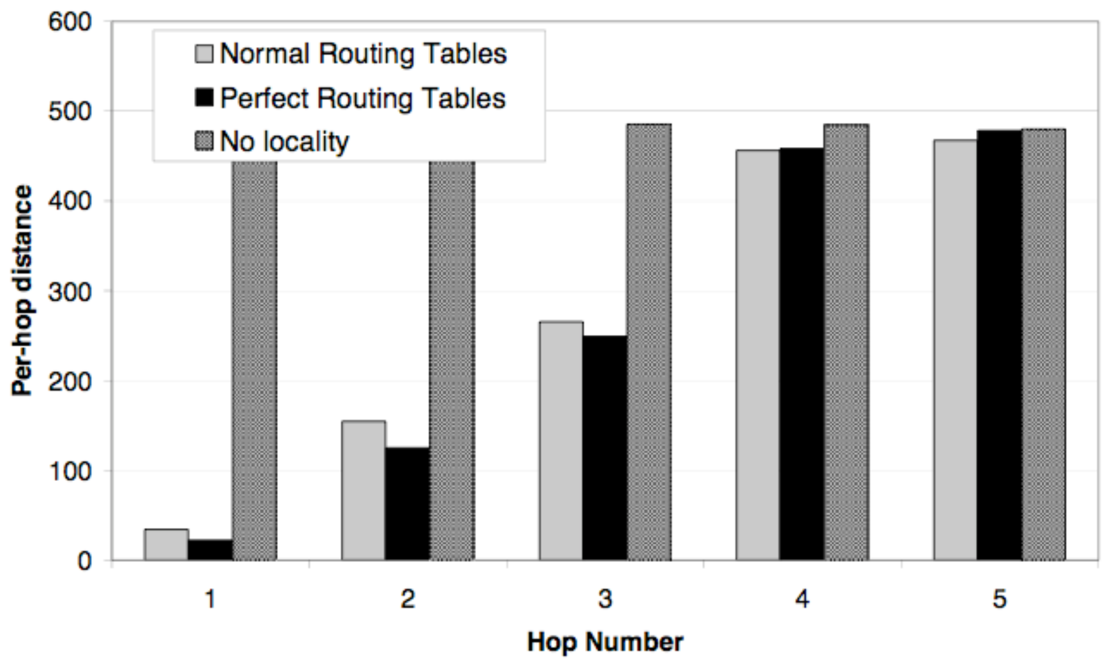
- Many choices for upper entries of the routing tables, which node do we pick?
  - Pick the one closest to us **in the network**
  - Use proximity metric: networks hops / latency

Routing Table

Many Choices - Close Proximity
….
….
….
….
Few Choices - Not-as-close Proximity

Proximity Affects Hops [3]

Many nodes to choose from for the initial hops, so we can probably get very close neighbors.

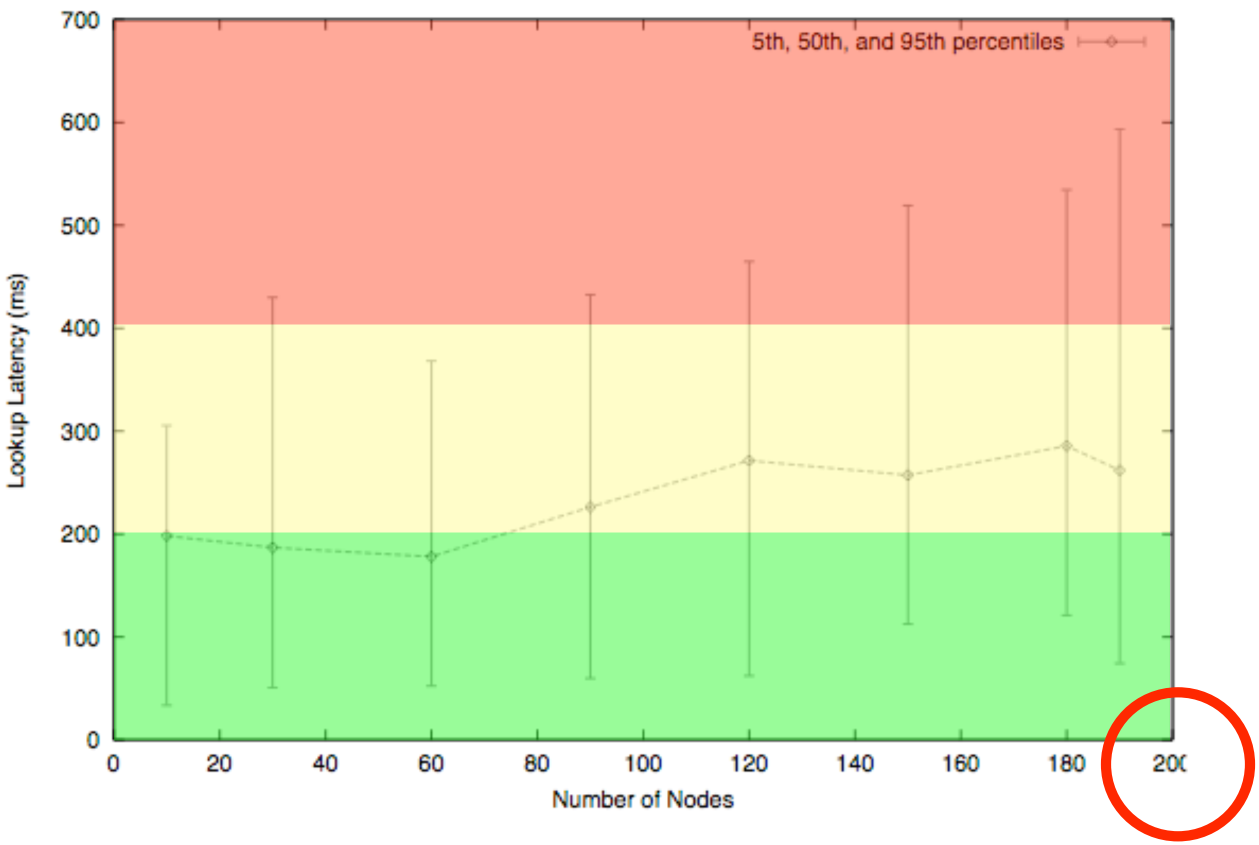


No Proximity for Chord?

- Chord uses a **constrained** table
  - No wiggle room to proximity optimize table entries without violating the rules
  - Can we still use proximity even if we're stuck with a constrained table?
- Proximity Route Selection
  - At route-time, compromise some progress in the overlay lookup if shorter network trip

Is constrained “good enough”?

Latency data from [13], no proximity consideration



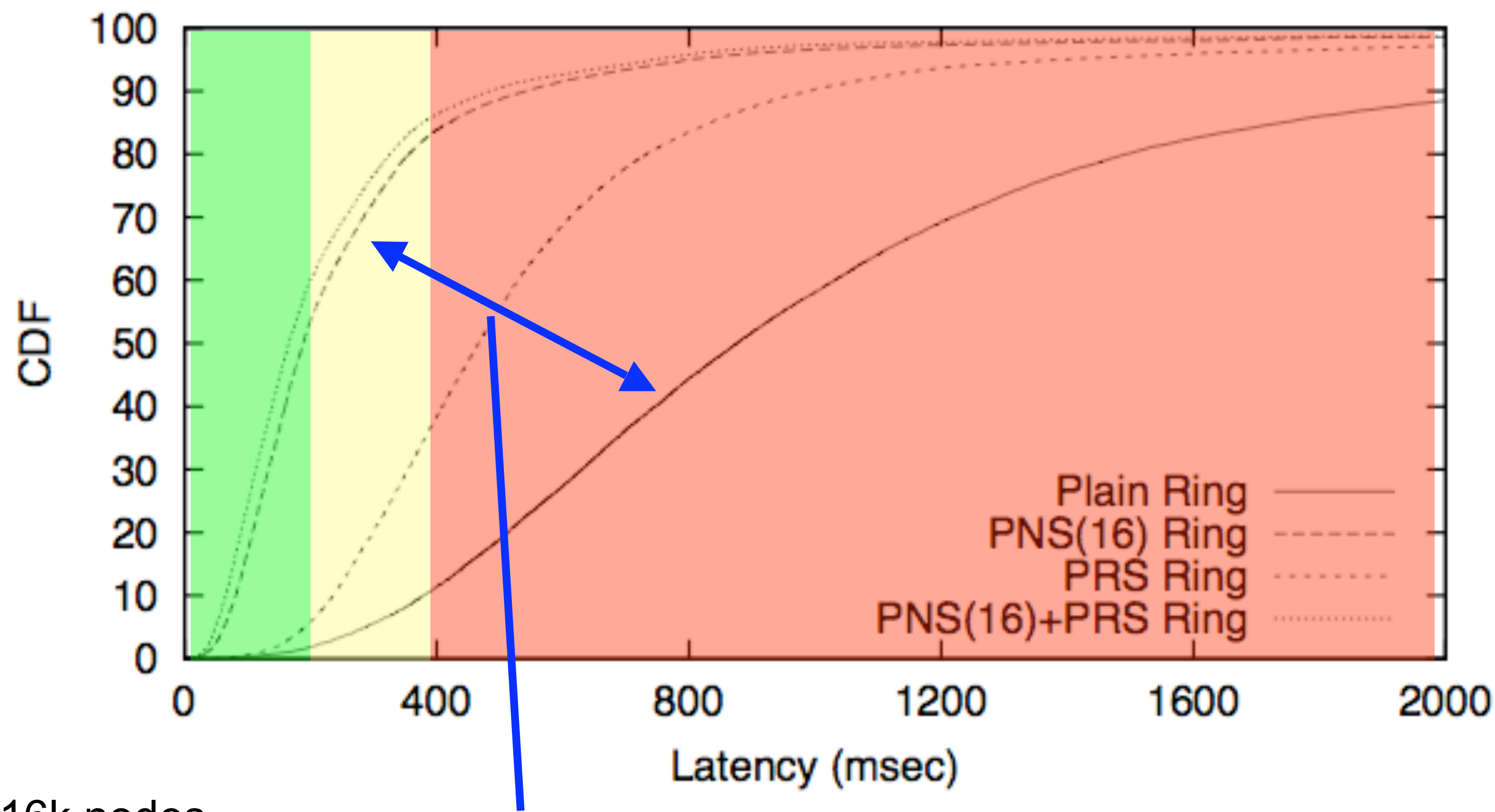
Bulk Transfer

VOIP

Gaming

!!!

How about a 2nd opinion? [6]



16k nodes

Using a proximity-optimized table has DRASTIC effect on lookup time!

The Adversarial Model

- Assume the network layer is secure.
- Freeloader Model
  - Not coordinated with other adversaries
  - Simply drops routing requests
  - Can handle adversarial nodes as failed nodes
- How many freeloaders before our lookups begin to fail?

Try One Lookup…

Fraction of lazy nodes

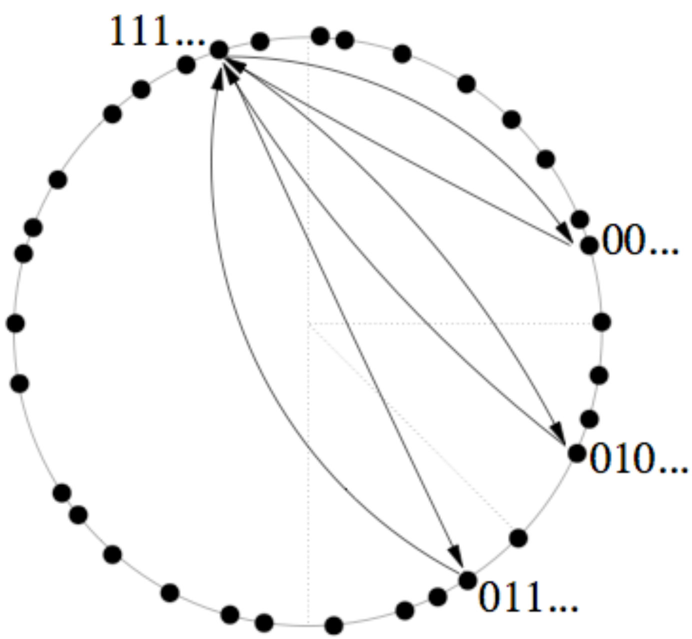
$$\Pr(success) = (1 - f)^M$$

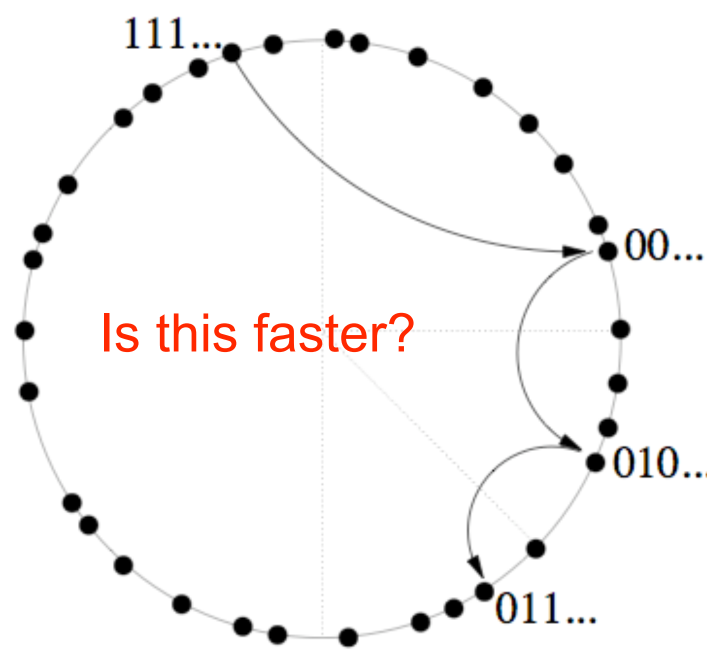
Expected number of overlay hops

$$\Pr(failure) = 1 - (1 - f)^M$$

Discover a lookup failure

- How long until we realize lookup failed?
  - Depends - Iterative or Recursive Routing?





Try, try again

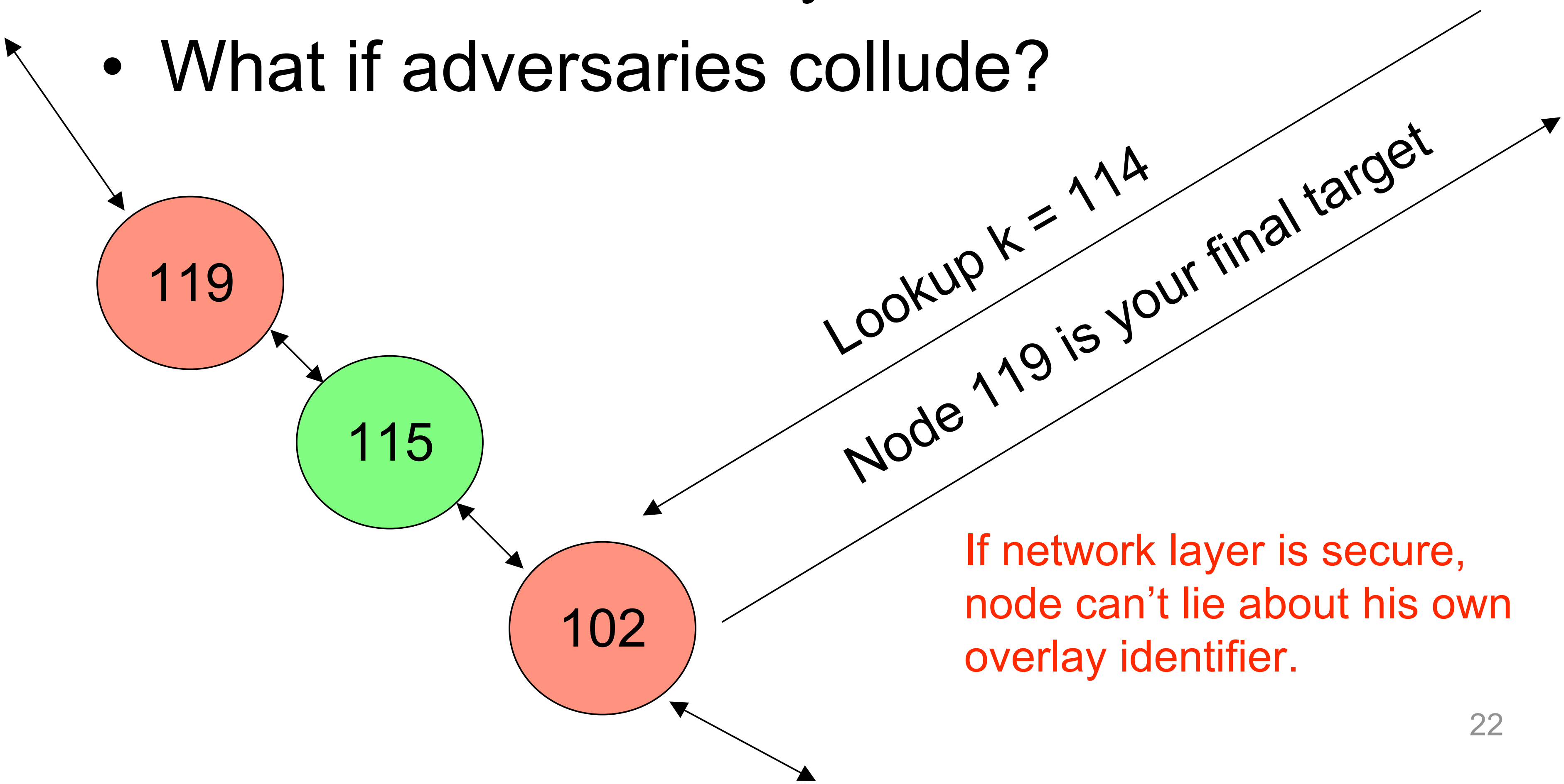
- If a single lookup fails, hand to a neighbor and let him try: *redundant routing*.
- Final success rests on overlay structure and resulting *independent paths* to target

$$\Pr(failure) \le (1-(1-f)^M)^I$$

Assumes we don't care about latency!!!

Stronger Adversary

- What if our adversary can lie?
- What if adversaries collude?



If network layer is secure, node can't lie about his own overlay identifier.

How to detect lying

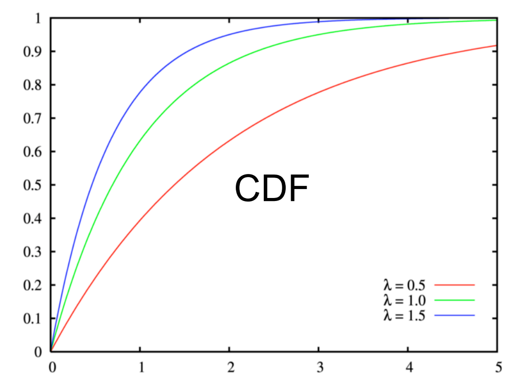
- At intermediate hop, next hop always needs to get closer the key
- At final hop, the final node ID should be *reasonably* close to the lookup key.
  - Assuming uniform hash, distance between nodes follows an **exponential distribution**.
  - Declare shenanigans if lookup result is not close enough to the key value.

DHT Probability

Distance is **Exponential Distribution**

PDF

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x} & , \ x \geq 0 \\ 0 & , \ x < 0 \end{cases}$$



Reason: Walking along outer ring, frequency of node occurrences is a **Poisson Process**

$$p(x;\lambda) = \frac{e^{-\lambda}\lambda^{x}}{x!} \qquad \lambda = 1$$

← Rate w/ interval of one n^{th} of the ring

↑ Probability of “x” occurrences within one interval

Simplistic Lie Detection

Pr(Travel around $(1/n)^{th}$ of ring without seeing a node) = e^{-1}

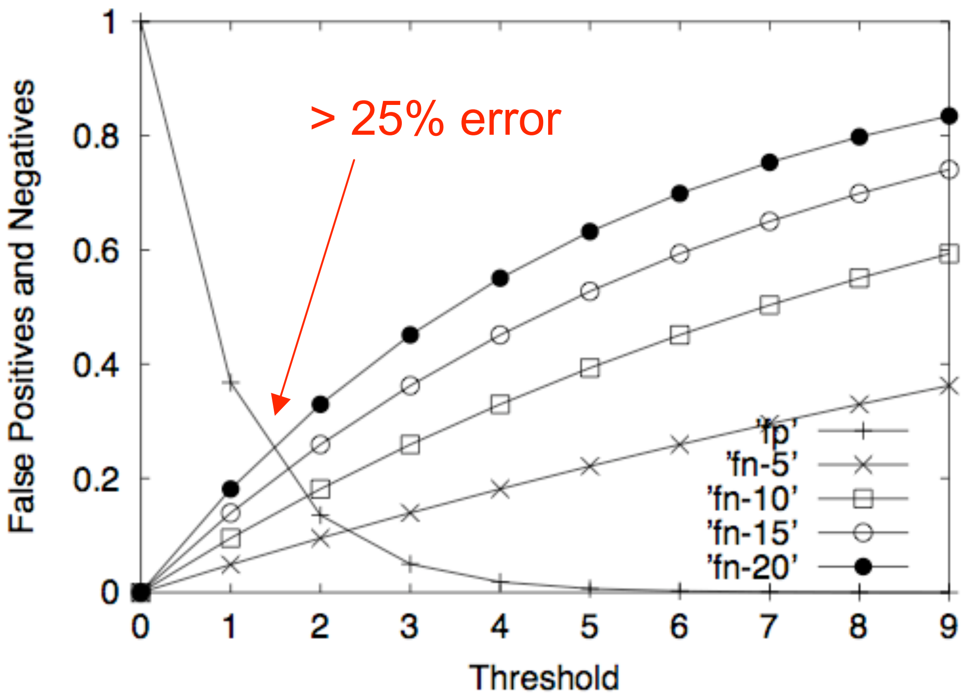
Pr(Travel around $(T/n)^{th}$ of ring without seeing a node) = e^{-T}

Simple algorithm:

```
    Pick a threshold, T.
    If distance(node, key) ≥ T/n
         Declare Shenanigans!
```

Simplistic Lie Detection [12]

False Positives and False Negatives are substantial



Other (more complicated) ways to significantly reduce the error.

Final Word on Lie Detection

- If we need to lookup one key in particular, error rates are probably too high
- If we can replicate functionality among many nodes (*r* file replicas), unlikely that:
  - False negatives on all lies
  - False positives on all well-behaved nodes
- Works for optimized or constrained routing

More Powerful Adversaries

- Until now, assumed that if ***f*** fraction of the overlay is malicious means ***f*** fraction of my routing table points to adversaries.
- What if adversaries can "poison" routing tables to increase their influence?

The Sybil Attack [5]

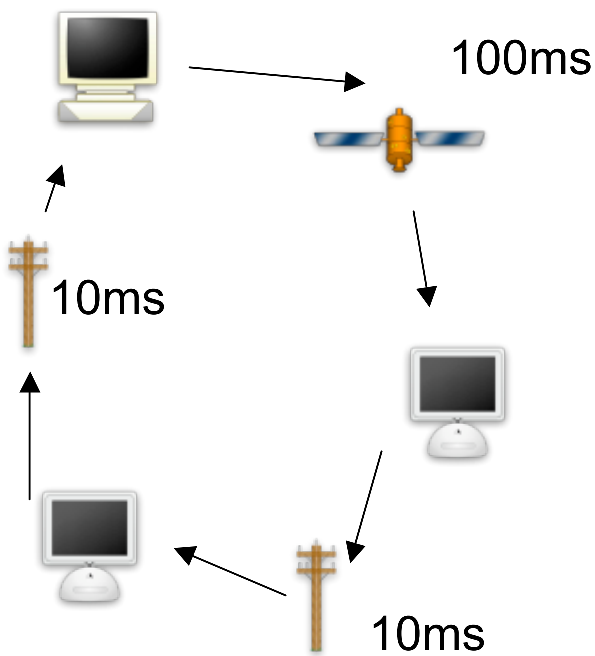
- Without a trusted third party, one attacker may assume an unbounded number of identities on the overlay network.
- Chord and Pastry imply trust of IANA to somewhat mitigate this
  - Owners of large IP space yield more power
  - Will really become a problem with IPv6

The Eclipse Attack [10]

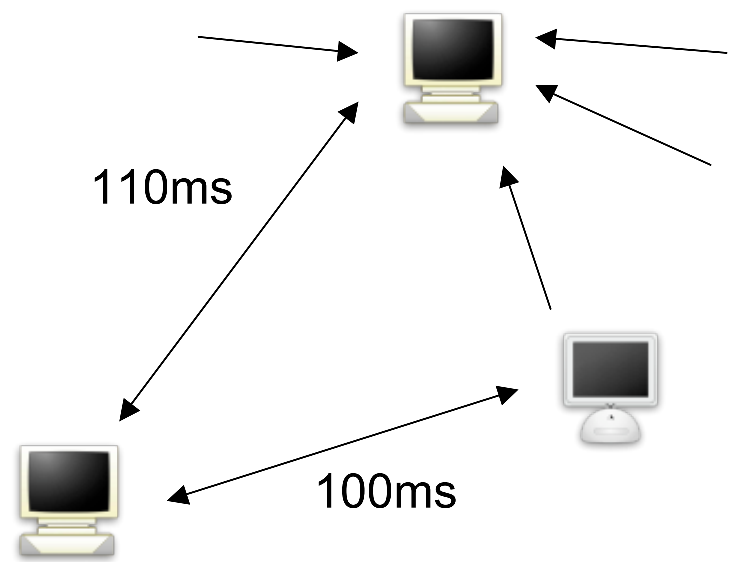
- If an attacker can "appear" to be closer than good nodes in the underlying network, the attacker will be chosen to populate the proximity-optimized table.
- Not nearly as effective on a constrained routing table, since routing table IDs are chosen by strict rules.

How to “appear” closer

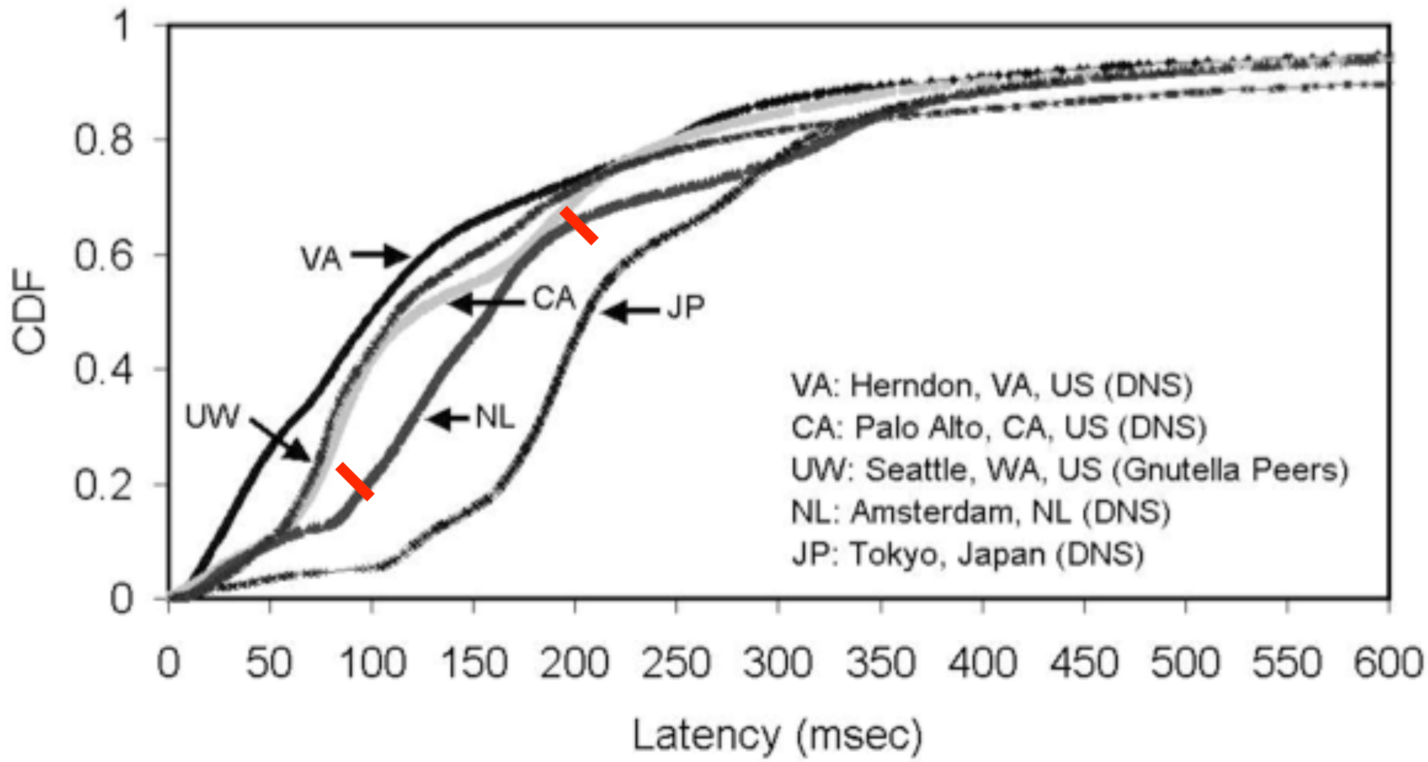
The Internet isn’t a Euclidian space, use alternate reply routes!



Launch DoS attacks against good nodes to slow them down slightly



C’mon -- is this feasible? [6]



Over 40% of requests within 100ms latency

Feasibility Test

- From home cable modem, performed 50 pings of www.google.com
  - Average Round Trip: 29.429ms
- 1 minute later, 50 pings again, this time performing two downloads over SSL.
  - Average Round Trip: 127.107ms

Difference ~ 100ms -- This attack is VERY feasible!!

The Eclipse Attack

- This attack is DEVASTATING against overlays with optimized routing tables
- If we assume malicious nodes can always use proximity in their favor, initial tests show adversary can achieve 100% routing table control with $f = 20\%$
- More details tomorrow by Dan

Shelter from Eclipse Attack

- Solution #1 [2]
  - Use optimized routing table unless we detect lying. Then switch to highly redundant and constrained routing table.
- But…
  - Redundancy causes a lot of overhead.
  - No proximity considerations may cause unacceptable delay.

Shelter from Eclipse Attack

- Solution #2 [10]
  - Perform auditing of all nodes to determine that their in-degree and out-degree are appropriate
  - May allow for us to retain the use of our optimized routing table
  - Dan will address this in depth tomorrow

Churn as Shelter [4]

- Completely off-the-wall solution (if you ask me)
- Force nodes to leave and rejoin the overlay at regular intervals
- When nodes rejoin, Overlay **`NodeID = hash(random || IP)`**, so both the victim and adversary are put in new random location within the overlay.
- Rejoins are staggered to maintain stability

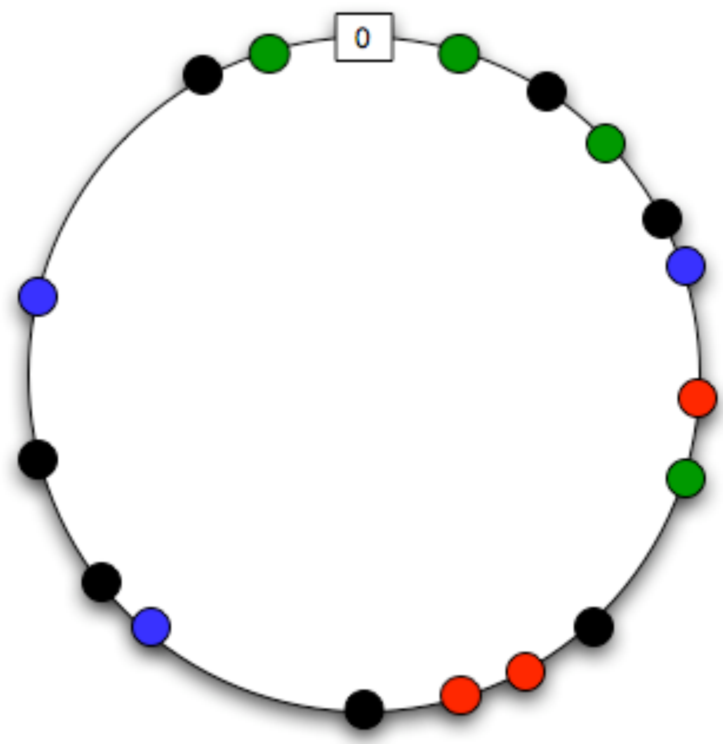
Churn as Shelter

Cert(timestep 100 - nonce '0xf01b')
Cert(timestep 101 - nonce '0xb33f')
Cert(timestep 102 - nonce '0x4e33')
Cert(timestep 103 - nonce '0xa30b')

At time *t*, group *g* uses:

$$t - ((t - \frac{gk}{G}) \bmod k)$$

Group 0 - ID = hash('0xf01b' II IP)
Group 1 - ID = hash('0xb33f' II IP)
Group 2 - ID = hash('0x4e33' II IP)
Group 3 - ID = hash('0xa30b' II IP)



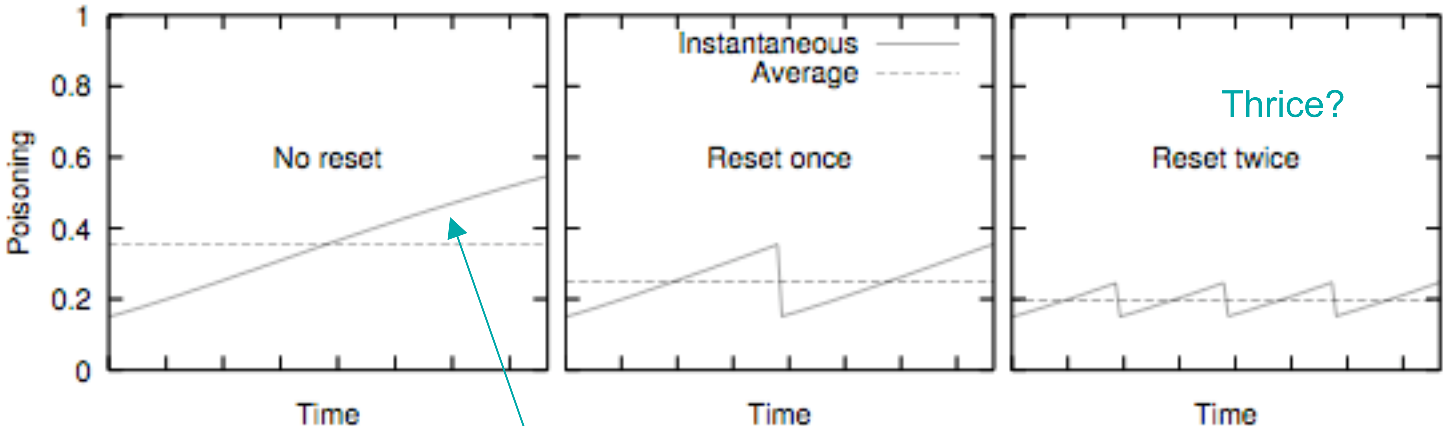
G = 4 total groups
k = 4 timesteps per epoch

Tale of 2 Routing Tables

- Constrained Routing Table (CONS)
  - No proximity consideration
  - Highly redundant
  - Can precompute CONS for next time epoch
- Churn-Optimized Routing Table (CHURN)
  - Proximity consideration
  - Flushed at the beginning of every epoch
  - Changes and Updates are rate-limited

The Intuition

- Forced rejoins (resets) reduce average poisoning level in the CHURN table



Poisoning has flat slope due to limiting of the update rates

Not all updates made equal

If you can poison one entry, which one should it be?

Routing table

-0-2212102	1	-2-2301203	-3-1203203
0	1-1-301233	1-2-230203	1-3-021022
10-0-31203	10-1-32102	2	10-3-23302
102-0-0230	102-1-1302	102-2-2302	3
1023-0-322	1023-1-000	1023-2-121	3
10233-0-01	1	10233-2-32	
0		102331-2-0	
		2	

$$\frac{1}{2^b} = \frac{1}{4}$$

routes affected

$$\left(\frac{1}{2^b}\right)^7 = \frac{1}{16384}$$

Upper entries carry exponentially more importance, both in an attack and in an optimization on node initiating a lookup on the overlay!!

How do you measure poisoning?

A

Routing table

-0-2212102	1	-2-2301203	-3-1203203
0	1-1-301233	1-2-230203	1-3-021022
10-0-31203	10-1-32102	2	10-3-23302
102-0-0230	102-1-1302	102-2-2302	3
1023-0-322	1023-1-000	1023-2-121	3
10233-0-01	1	10233-2-32	
0		102331-2-0	
		2	

B

Routing table

-0-2212102	1	-2-2301203	-3-1203203
0	1-1-301233	1-2-230203	1-3-021022
10-0-31203	10-1-32102	2	10-3-23302
102-0-0230	102-1-1302	102-2-2302	3
1023-0-322	1023-1-000	1023-2-121	3
10233-0-01	1	10233-2-32	
0		102331-2-0	
		2	

"Churn" Metric

Measure by fraction of poisoned entries:

Poisoning(A) = Poisoning(B) ~~ 1 / 25

Measure by effective control over routing table:

Poisoning(A) = **1/4**

Poisoning(B) = **1/25**

Can “Churn” be the answer?

- We are essentially giving up **some** optimization for **some** protection against eclipse attacks.
- We need to quantify this trade-off!

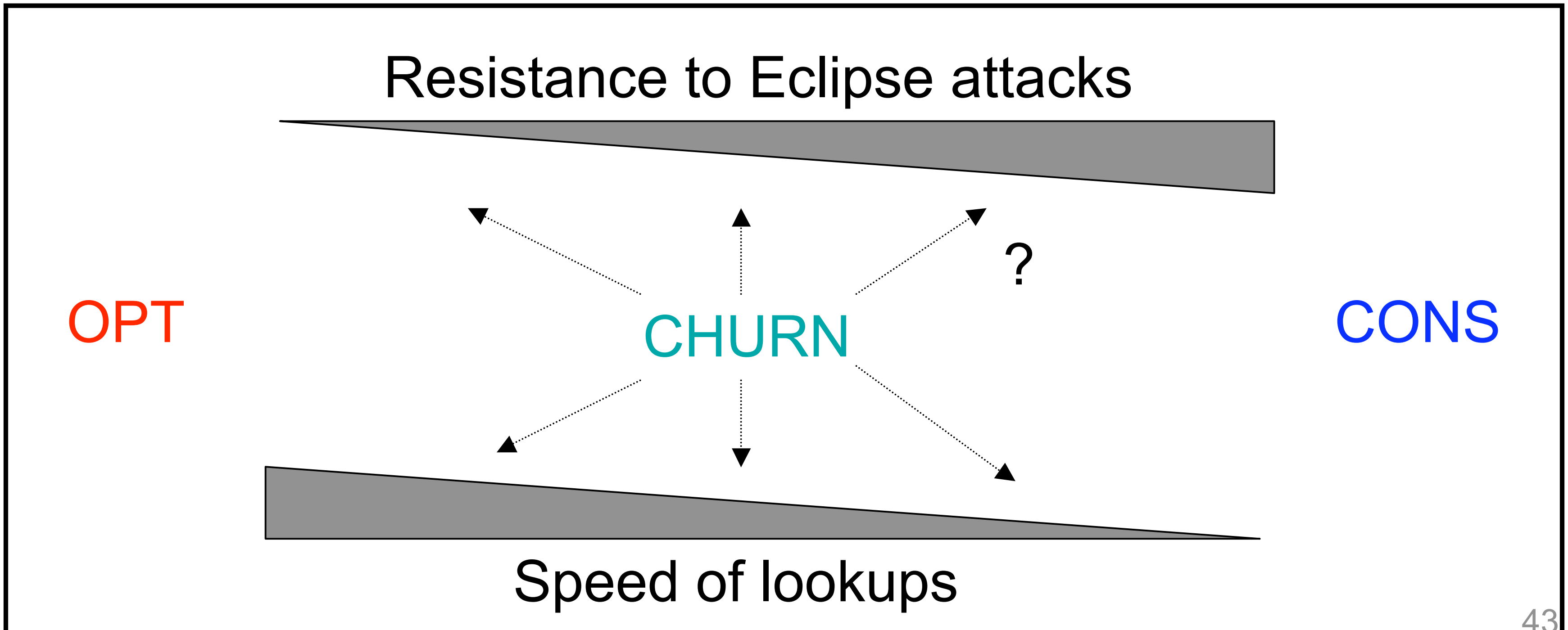
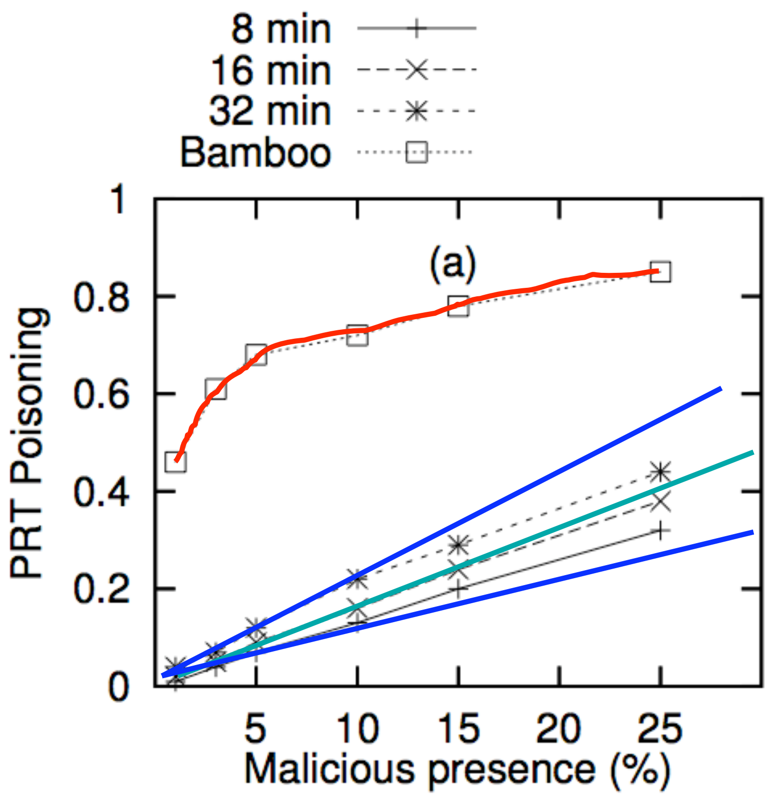


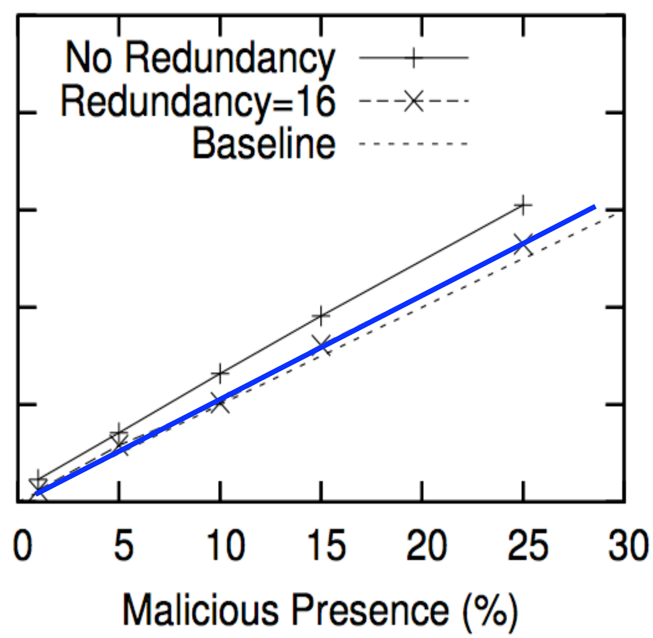
Table Poisoning in an Attack

OPT -- CHURN -- CONS

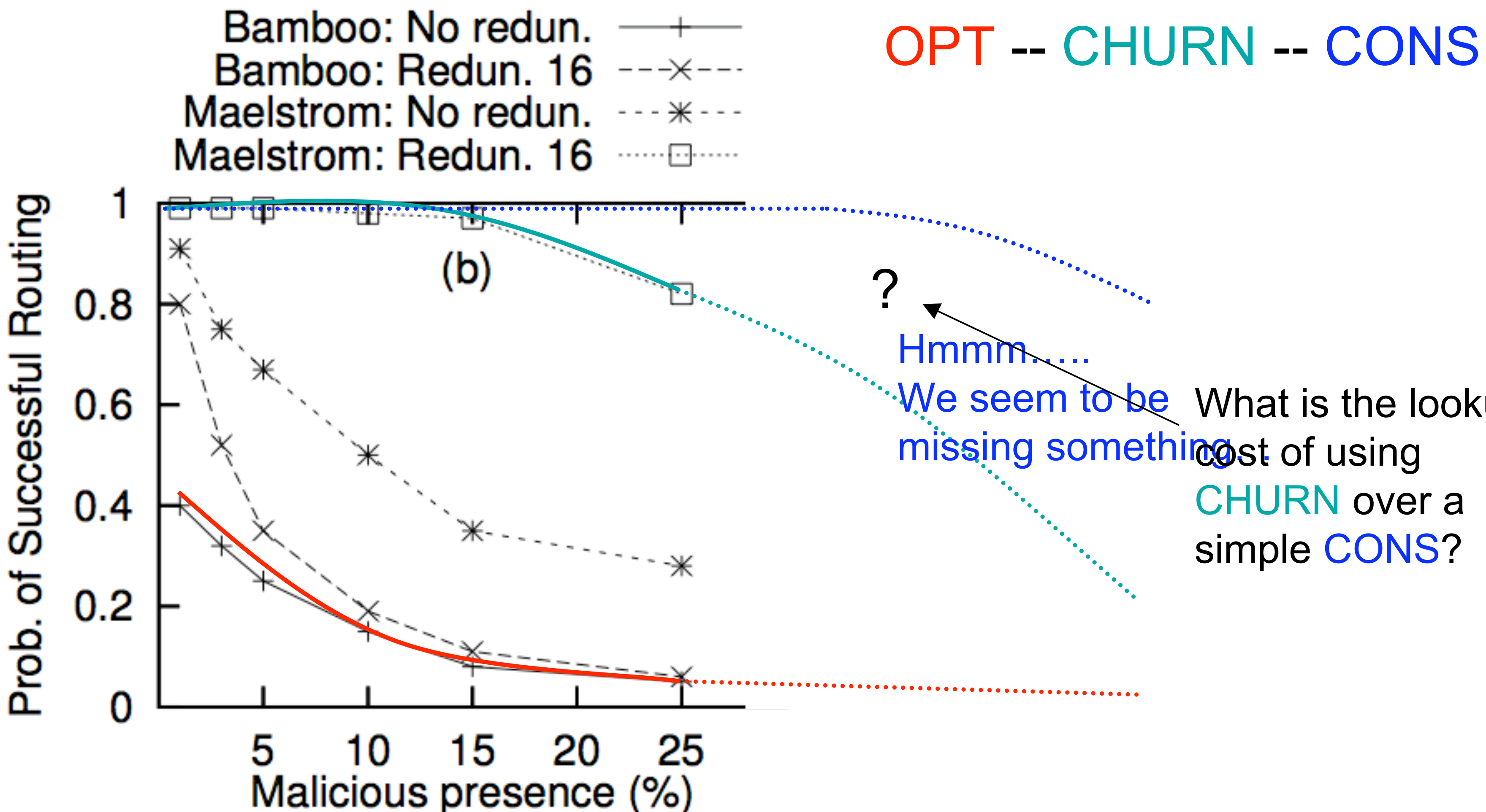


Still lose additional **20**% of table entries over CONS

.5



Lookup Success in an Attack



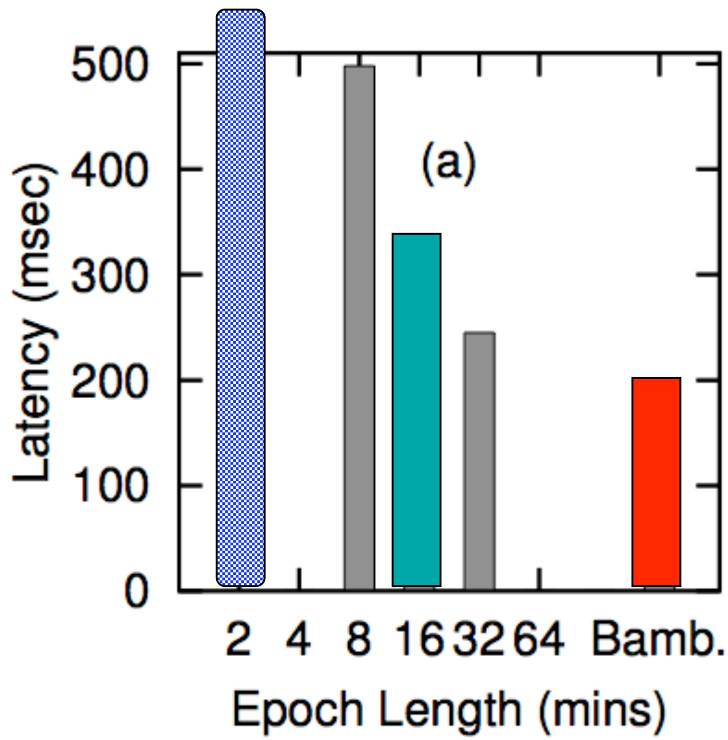
What is the lookup cost of using CHURN over a simple CONS?

CHURN resistance to attack

- Churn gives us “some” shelter against Eclipse attacks as compared to a fully optimized routing table (OPT)
- Using only a constrained (CONS) routing table presumably performs much better in the face of an Eclipse attack
  - Not particularly clear as to exactly where CHURN sits between CONS and OPT when handling Eclipse attacks

CHURN in good conditions

- What if there is no attack? How much do we pay for using CHURN in lieu of OPT? How much better is CHURN than simply using CONS?

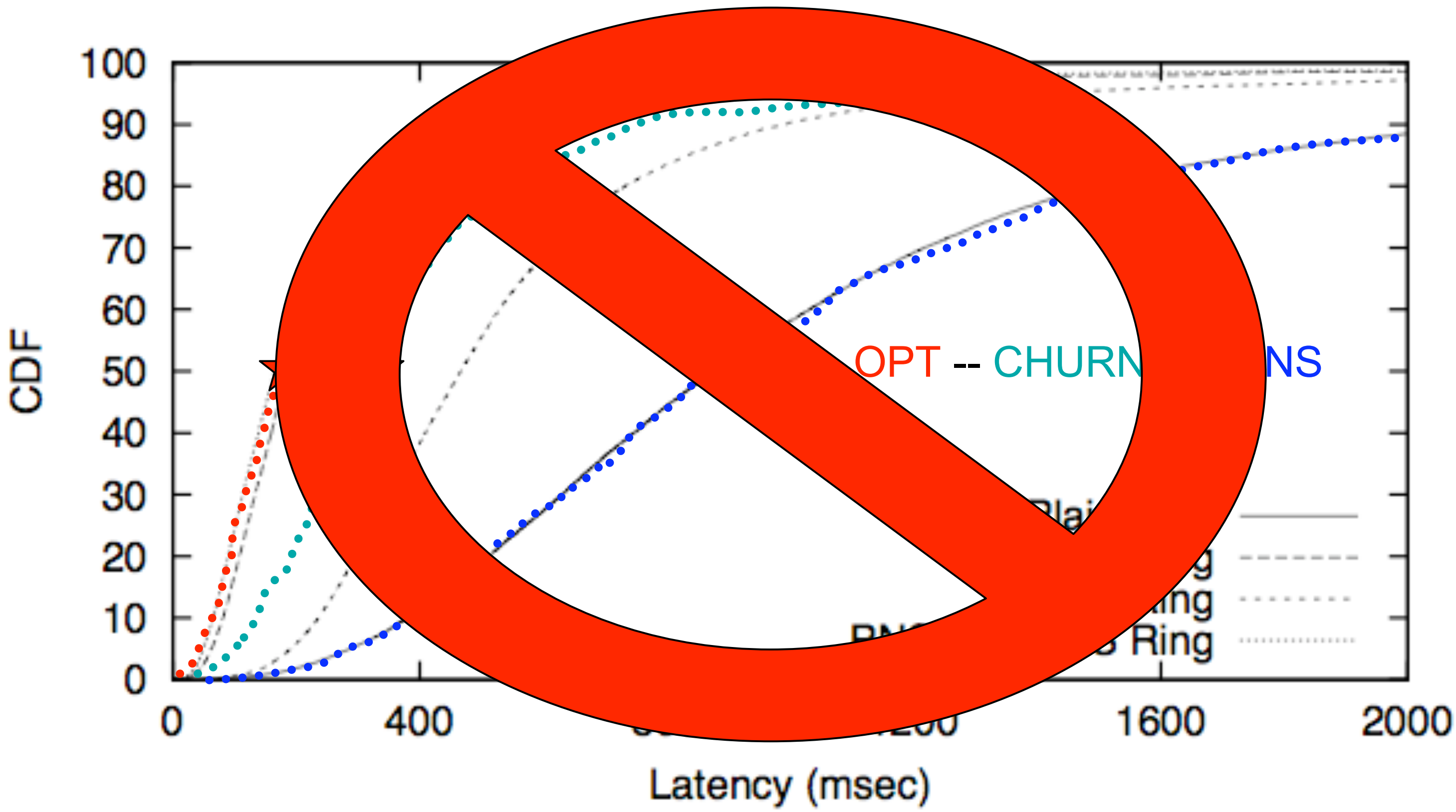


OPT -- CHURN -- CONS

Hmm….

Can we at least make an educated guess?

Cost of CHURN



There is absolutely no reason why I should have to do this guesswork!

Cost of CHURN

- It's just not clear how much faster this hybrid approach is over a CONS table.
- Can CHURN keep up with applications that demand low latency?
  - Difference between 200ms and 400ms is substantial for applications like VOIP.
  - If your application easily tolerates 600ms of delay with CHURN, couldn't it probably handle 1000ms just as easily?

Final word on CHURN

- In well-behaved network:
  - How much faster is CHURN than CONS?
  - How much faster is OPT than CHURN?
- Under Eclipse attack:
  - How much safer is CONS than CHURN?
  - How much safer is CHURN than OPT?

The only question that was well addressed in the paper -- did they sell it to you?

Different Adversarial Model

- Until now, we assumed that our adversary wanted to cause as much havoc as possible on the overlay as a whole
- What if our adversary is less greedy?
  - We consider the example where our overlay is used as a distributed file system
  - Can our adversary **target** one particular file so as to deny us access to it?

DHT File Systems

- Farsite [1]
- OceanStore [8]

- Generally protect data with cryptography
- Adversary can still launch DoS attack against specific files
- An attack of this nature is analogous to censorship over a distributed file system

LocationGuard [11]

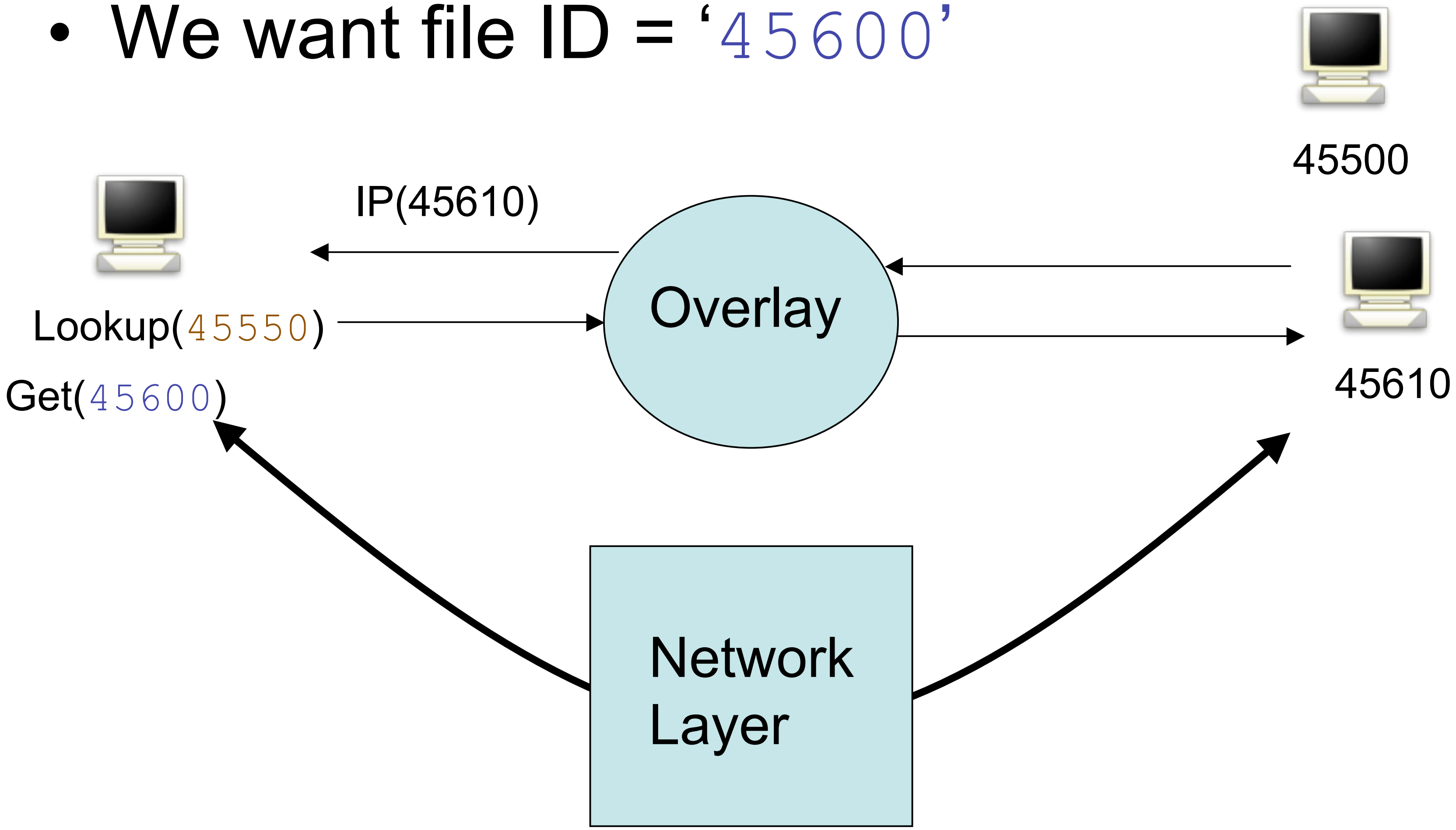
- Adversary can’t target a specific file if he doesn’t know what to look for
- Assume we have *i* replicas of a file on an overlay
- We first protect our filename with a *LocationKey*

$$Identifier_i = E_k(filename \,\|\, i)$$

We still don’t want to perform a simple ***Lookup(Identifier$_i$)*** -- why not??

LookupGuard

- We want file ID = '45600'



LookupGuard

- How much we can shift our lookup value and still find the right node?
- Use same probabilistic properties that were used to detect lying!

$$\Pr(safe) = e^{-rN} \longrightarrow r \le \frac{-\ln(\Pr(safe))}{N}$$

Amount of (relative) shift in lookup value

Total number of nodes in the overlay

Obfuscation Example

- N = 1 million (2^{20})
- Want a correct lookup 999,999 times out of 1 million tries

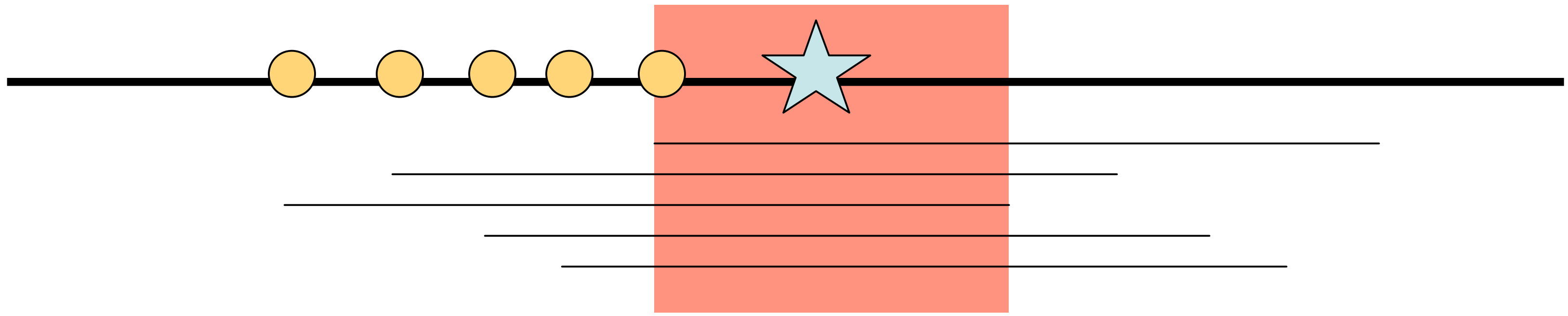
$$r \leq \frac{-\ln(1-2^{-20})}{2^{20}} \rightarrow r \leq 2^{-40}$$

Suppose a Chord ring of keyspace 2^{160}

Max safe obfuscation offset = $(2^{160})(2^{-40})$ = $\mathbf{2^{120}}$

Sieve Attack

- Given enough queries, can't the adversary *sieve* the space to discover the true token?



Given *x* samples, we expect an adversary to narrow the range to a size of **`((initial range) / x)`**

Sieve Attack

- Obfuscation range is HUGE ~ 2^{120}
- Even after 1 million lookups, adversary has only narrowed range to 2^{100}
- Attack has to be performed on-line, not at all feasible for keyspaces this large

Of course, all of this analysis is meaningless if our adversary owns the keyspace with our file in it…

Inference Attack

- We should further guarantee that an adversary cannot infer statistics from:
  - Lookup frequency
  - End-user IP address
  - File replicas
  - File size
- Important that two adversaries can't tell they own copies of the same original file

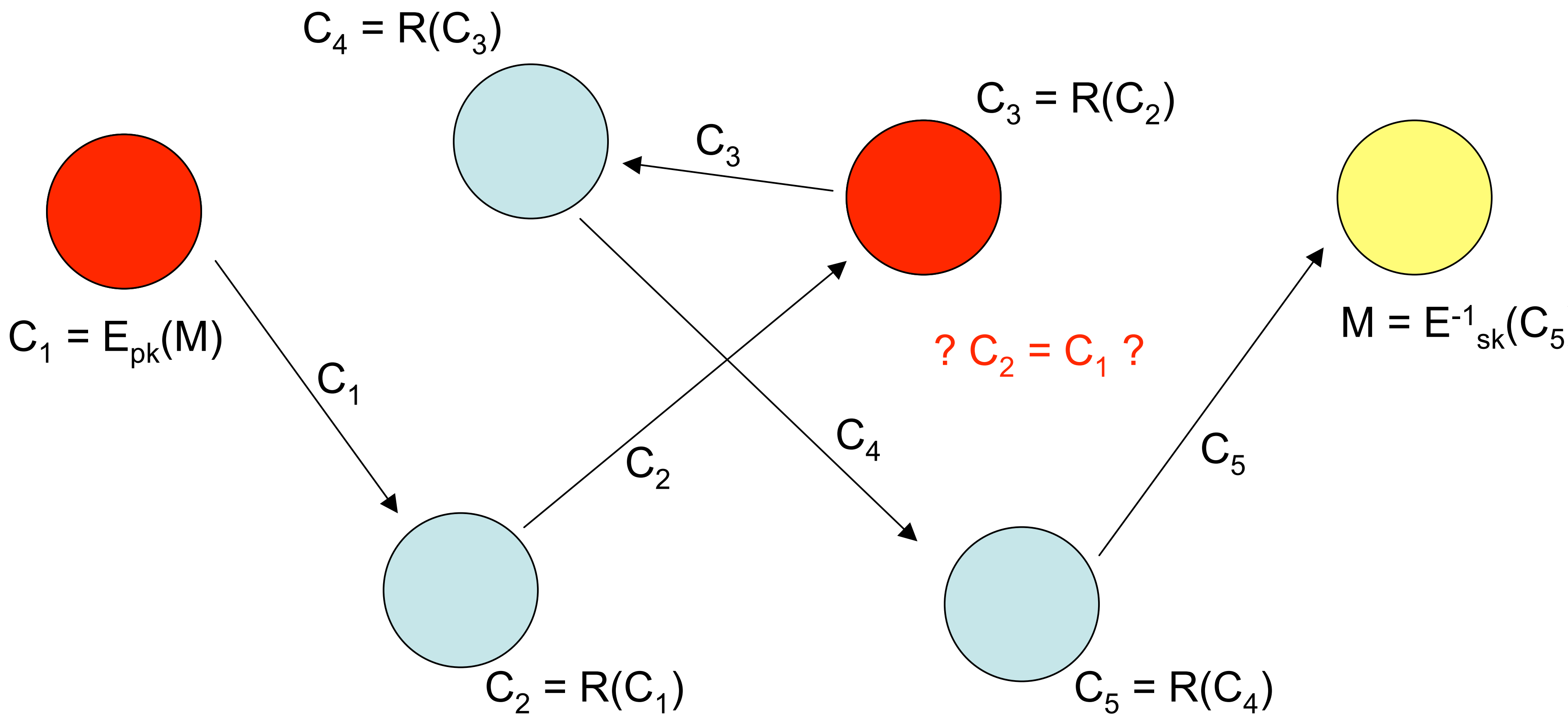
Survivability

- LocationGuard mitigates the DoS attacks of today -- but data will degrade over time!
  - Malicious nodes can corrupt data they control, and churn means that over time adversaries could corrupt a lot
  - Nodes crash (maybe I wrote the code)
- LocationGuard's replication offers no means by which to replenish our data

Universal re-encryption [15]

- Can nodes automatically re-publish data before it degrades?
- Current construction of **universal re-encryption** allows for nodes to re-encrypt without any knowledge of the public key
- Requires the definition of *semantic security under re-encryption*

Universal Re-encryption



Can be done with variation of ElGamal -- construction is not particularly complicated, refer to [15] for more details

The big picture

- We want to design a DHT that is:
  - Highly optimized WRT proximity
  - Resistant to Eclipse Attacks
  - Supports strong data protection (crypto)
  - Is resilient against targeted attacked
  - Has very good survivability for application-level content stored on the overlay

How much free time does everyone have?

References

[1] Adya, W. J. Bolosky, M. Castro, R. Chaiken, G. Cermak, J. R. Douceur, J. Howell, J. R. Lorch, M. Theimer, R. P. Wattenhofer, "FARSITE: Federated, Available, and Reliable Storage for an Incompletely Trusted Environment", 5th OSDI, Dec 2002.

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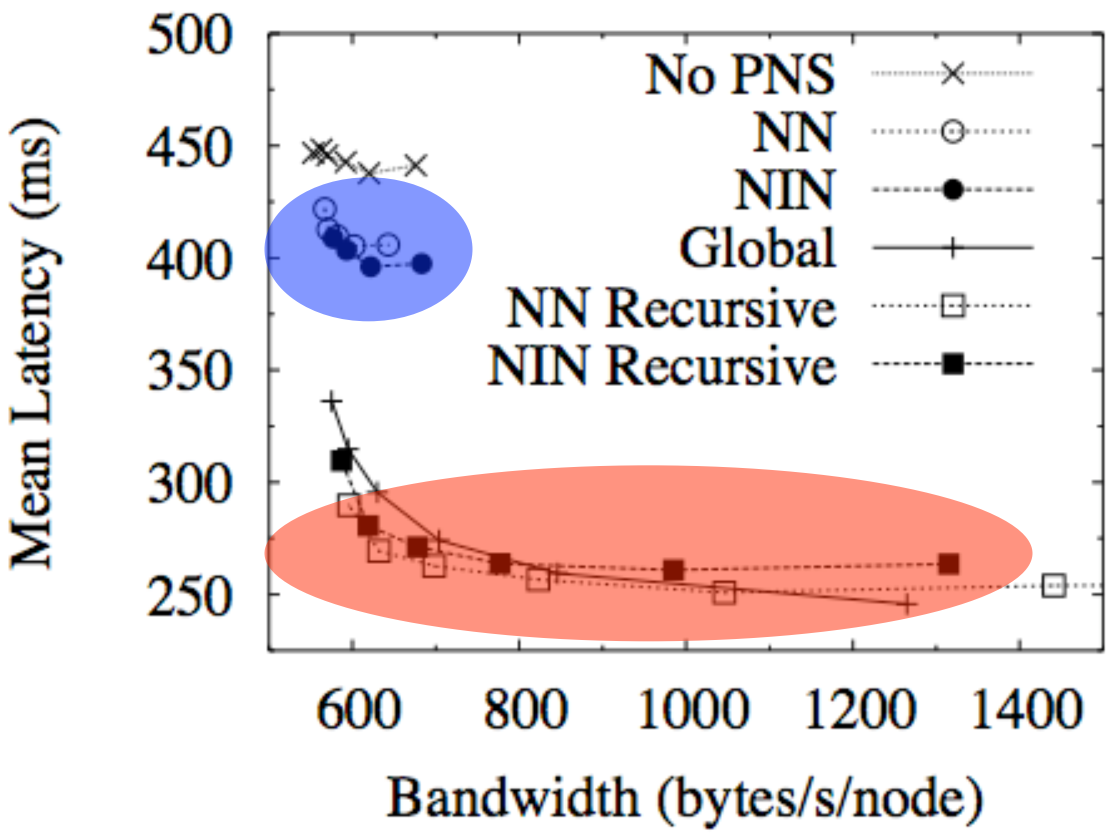
Fin.

After reset, must update quickly

- Global Tuning
  - Perform lookups at random, test your replies
- Local Tuning (Network Neighbor)
  - Ask nodes in your routing table for their tables
- Network Inverse Neighbor
  - Ask nodes in your table for their backpointers
- Recursive variants

Which update method is best?



Just getting our neighbors' routing tables is cheap and easy

But doing random lookups is much more effective!