Vivaldi
Practical, Distributed Internet Coordinates

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Overview

Circa 2001: file sharing networks extremely popular

- harness huge numbers of machines
- but don’t scale well (at least asymptotically)

Academics study how to build scalable peer-to-peer systems.

- Chord, Pastry, OceanStore, ...

How can we make them perform better in practice?

- predict round trip times with Vivaldi

P2P circa 2001: an exciting social development

- Internet users cooperating to share, for example, music files.
  - Napster, Gnutella, Morpheus, KaZaA, ...
- Lots of attention from the popular press (and the RIAA!)
  - “The ultimate form of democracy on the Internet.”
  - “The ultimate threat to copyright protection on the Internet.”
- Not much new technologically.

What is a P2P System?

- System without any central servers.
  - Every node is a server
  - No particular node is vital to the network
  - Nodes all have the same functionality
- Huge number of nodes, many node failures
- Enabled by technology improvements

P2P: useful for building reliable services?

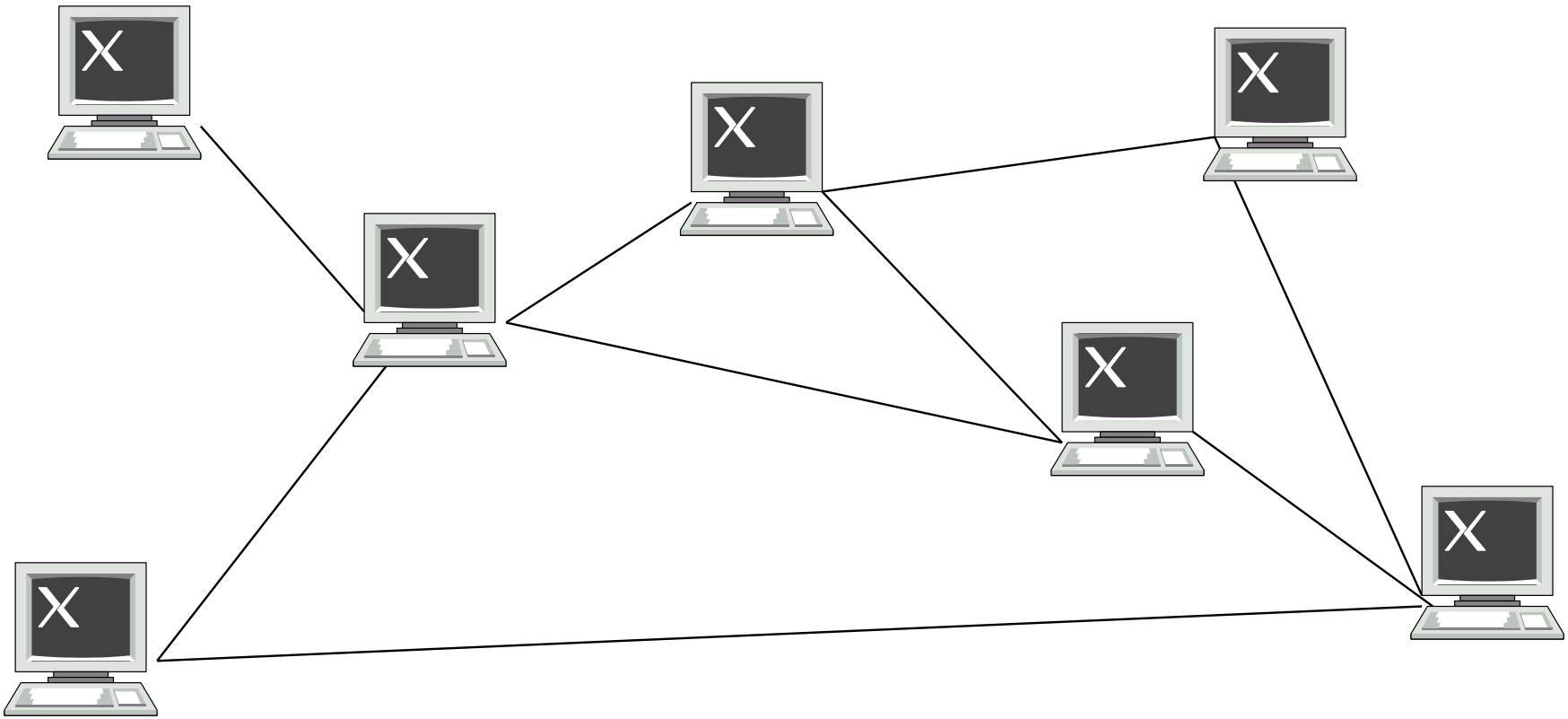
- Many critical services use the Internet.
  - Hospitals, some government agencies, etc.
  - (but not other Agencies)
- Non-Internet systems exist at large scales too.
  - corporations, government agencies, etc.
- Can we build large-scale robust distributed services?
  - Node and communication failures
  - Load fluctuations (e.g., flash crowds)
  - Attacks (including DDoS)

The promise of P2P computing

- Reliability: no central point of failure.
  - Many replicas
  - Geographic distribution
- High capacity through parallelism
  - Many disks
  - Many network connections
  - Many CPUs
- Automatic configuration
- Useful in public and proprietary settings

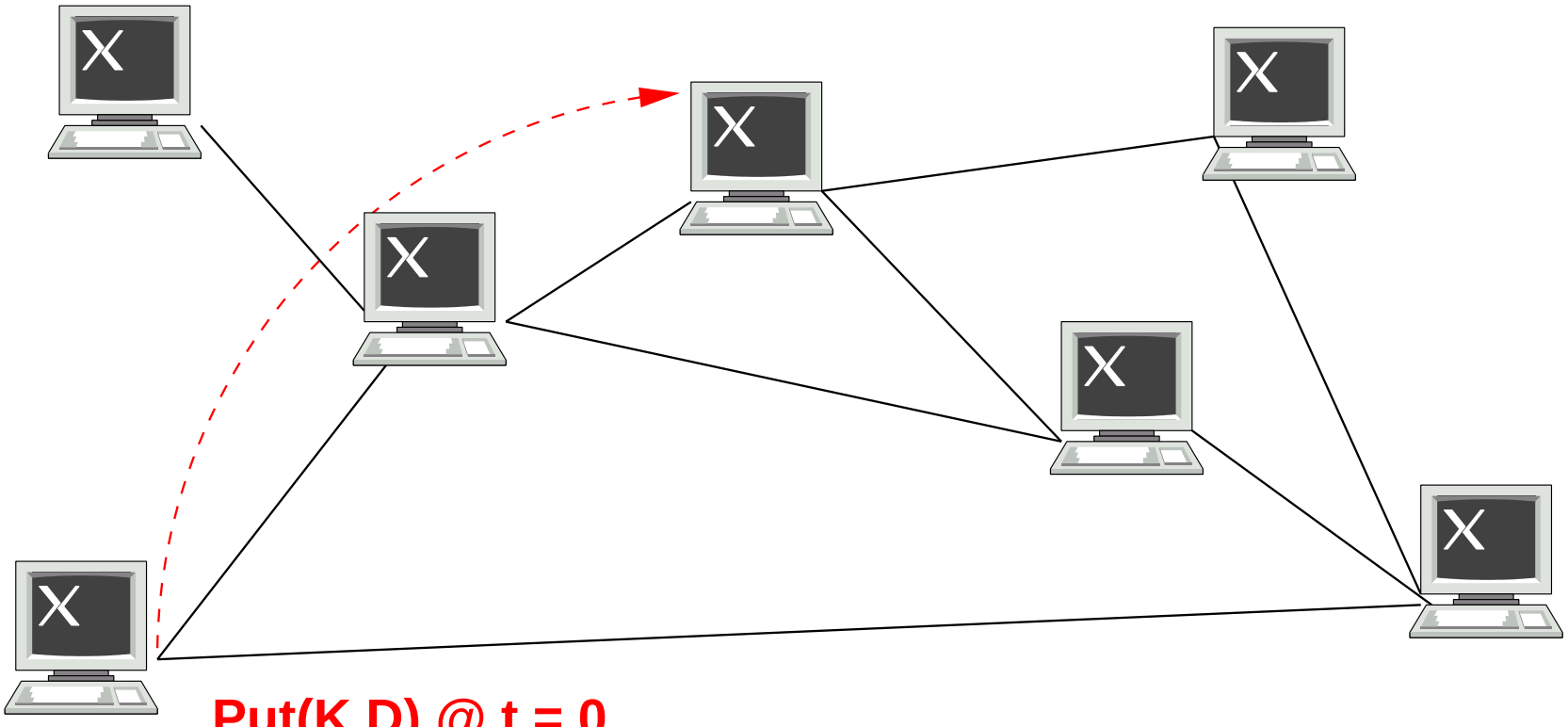
Distributed Hash Table

- Building block for “principled” peer-to-peer systems.



- DHTs provide location service: map key to a set of machines.

DHT as Location and Rendezvous Service



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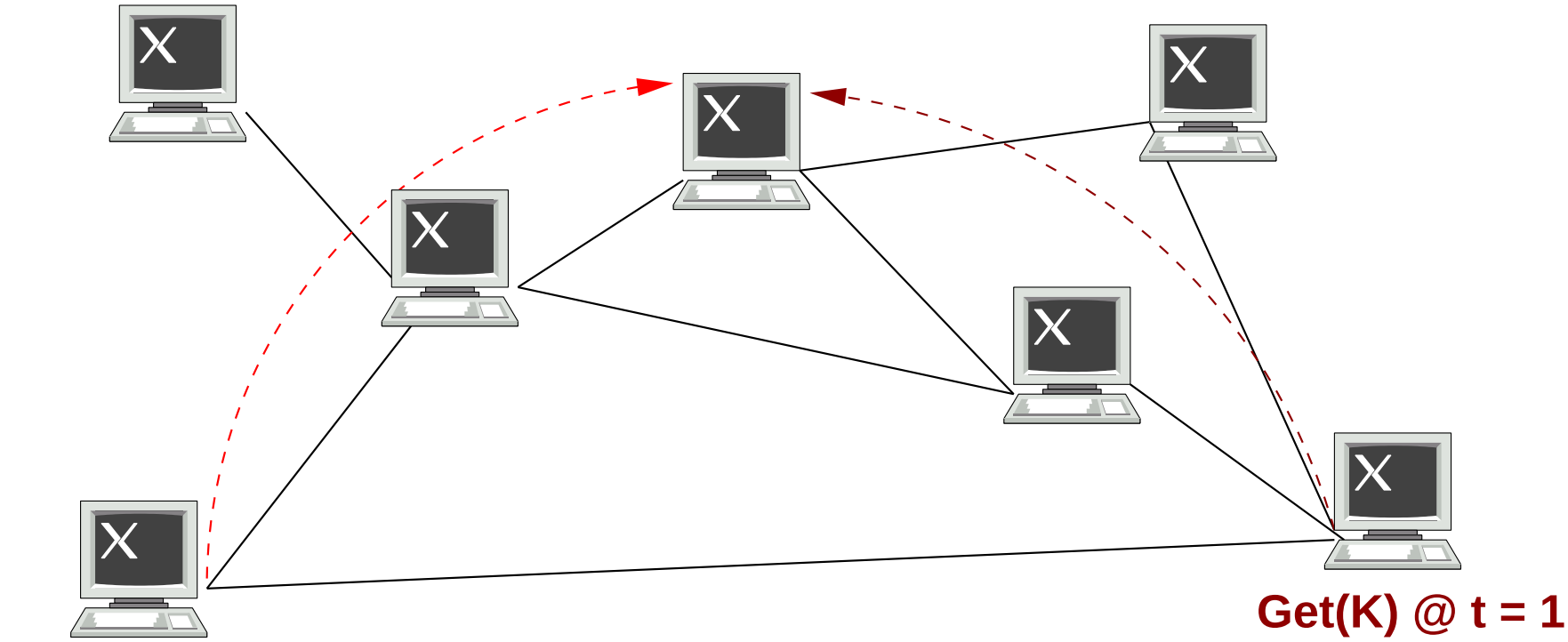


DHT as Location and Rendezvous Service

Many useful primitives can be and have been built on top of this rendezvous.

- File sharing
- Web cache
- Archival/Backup storage
- Censor-resistant stores
- DB query and indexing
- Event notification
- Naming systems
- Communication primitives

We will concentrate on storage.

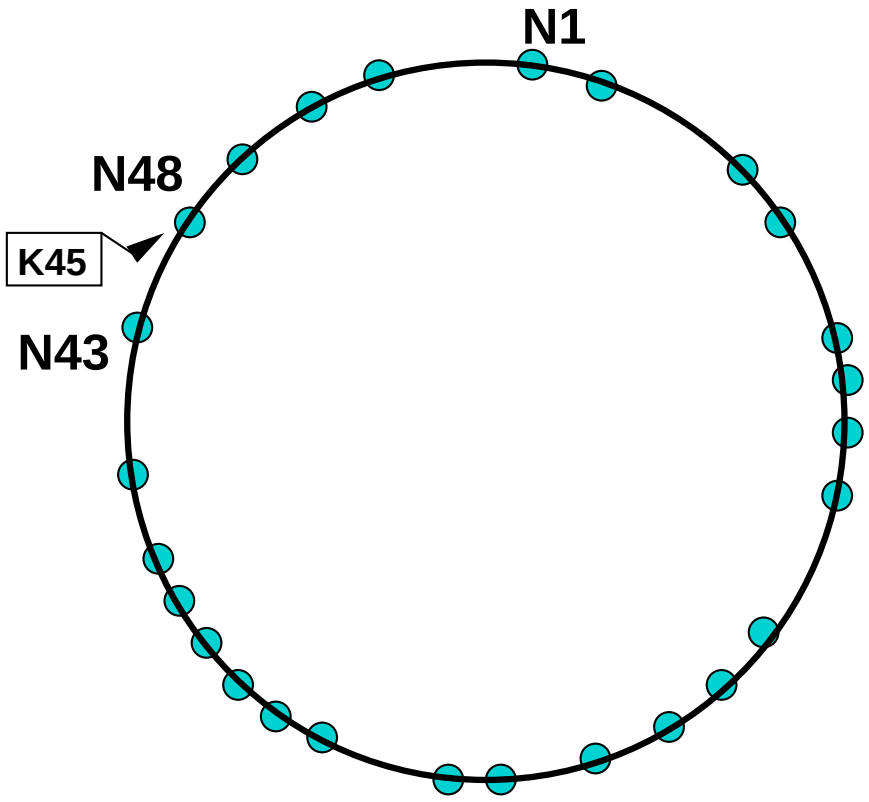
- but first, how to implement DHT?

Chord: One Peer-to-Peer System

Developed at MIT in 2000.
Recipe differs from others, but flavor is same.

- Assign nodes and keys big identifiers (SHA1 hashes).
- Traverse identifier space during lookup.
- Provide lookup first; layer storage on top.

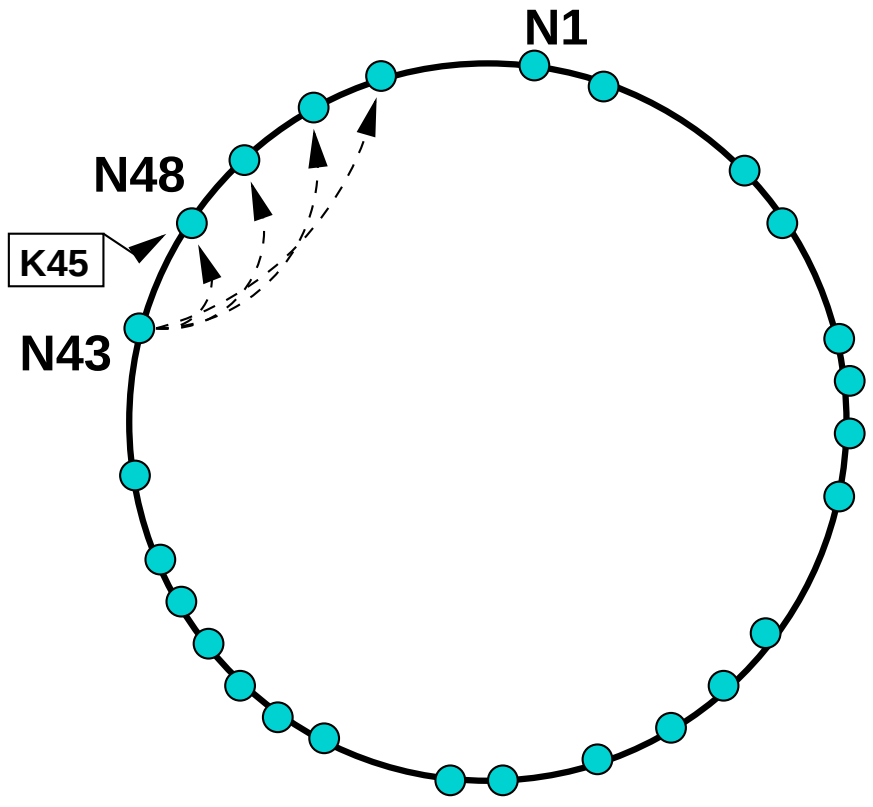
Chord: Successor Defines Ownership



Identifier space arranged in a *logical* ring.

- A key's *successor* is first node clockwise after key on ring.
- That node is the owner of the key.

Chord: Successors Ensure Correctness



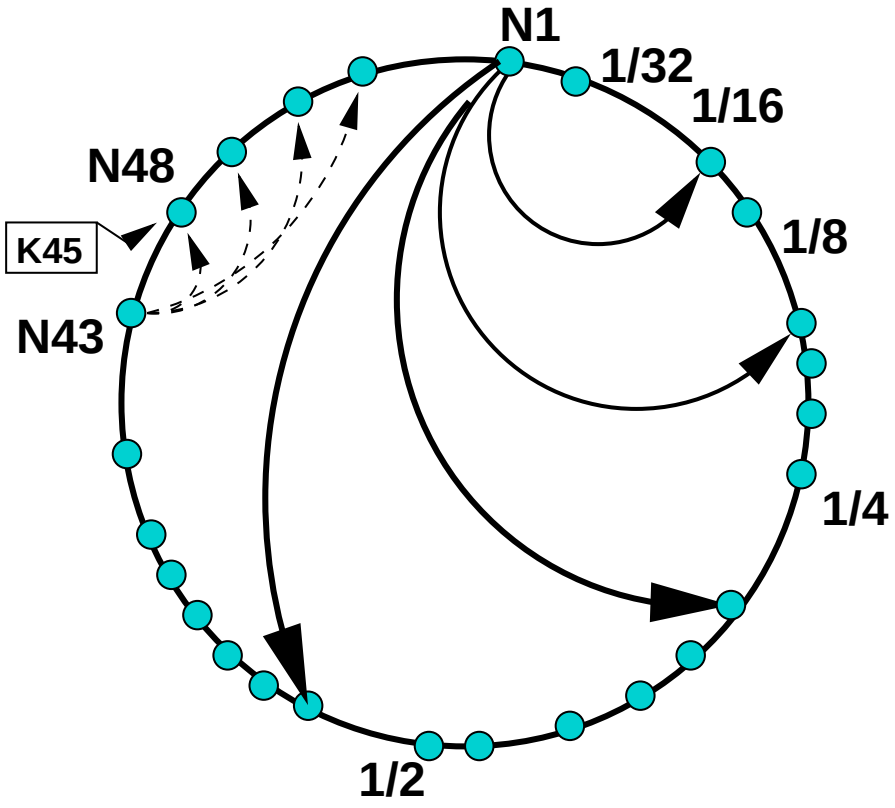
Nodes maintain list of *r* successors.

- On failure of node *n*, successor takes over keys.
- Nodes ping predecessors regularly to detect failure.

Can traverse ring by following successors.

- a bit slow if there are millions of nodes.

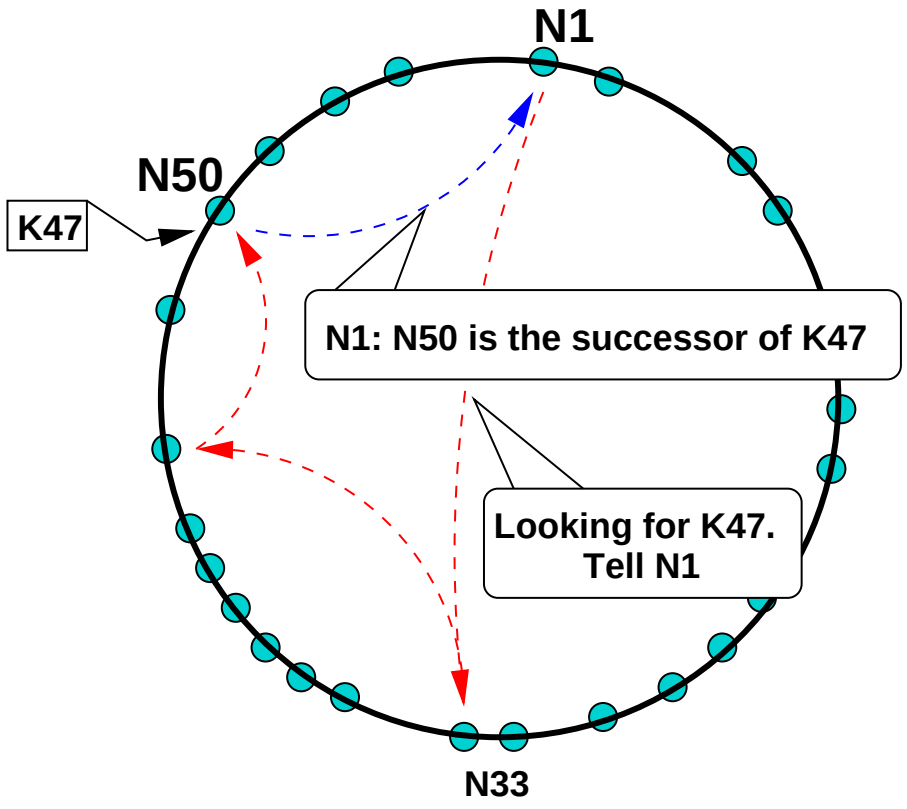
Chord: Fingers Speed Lookups



Nodes maintain pointers to larger hops around the ring.

- Like using skip lists in a linked list.
- *O*(log *N*) exponentially-distributed fingers.

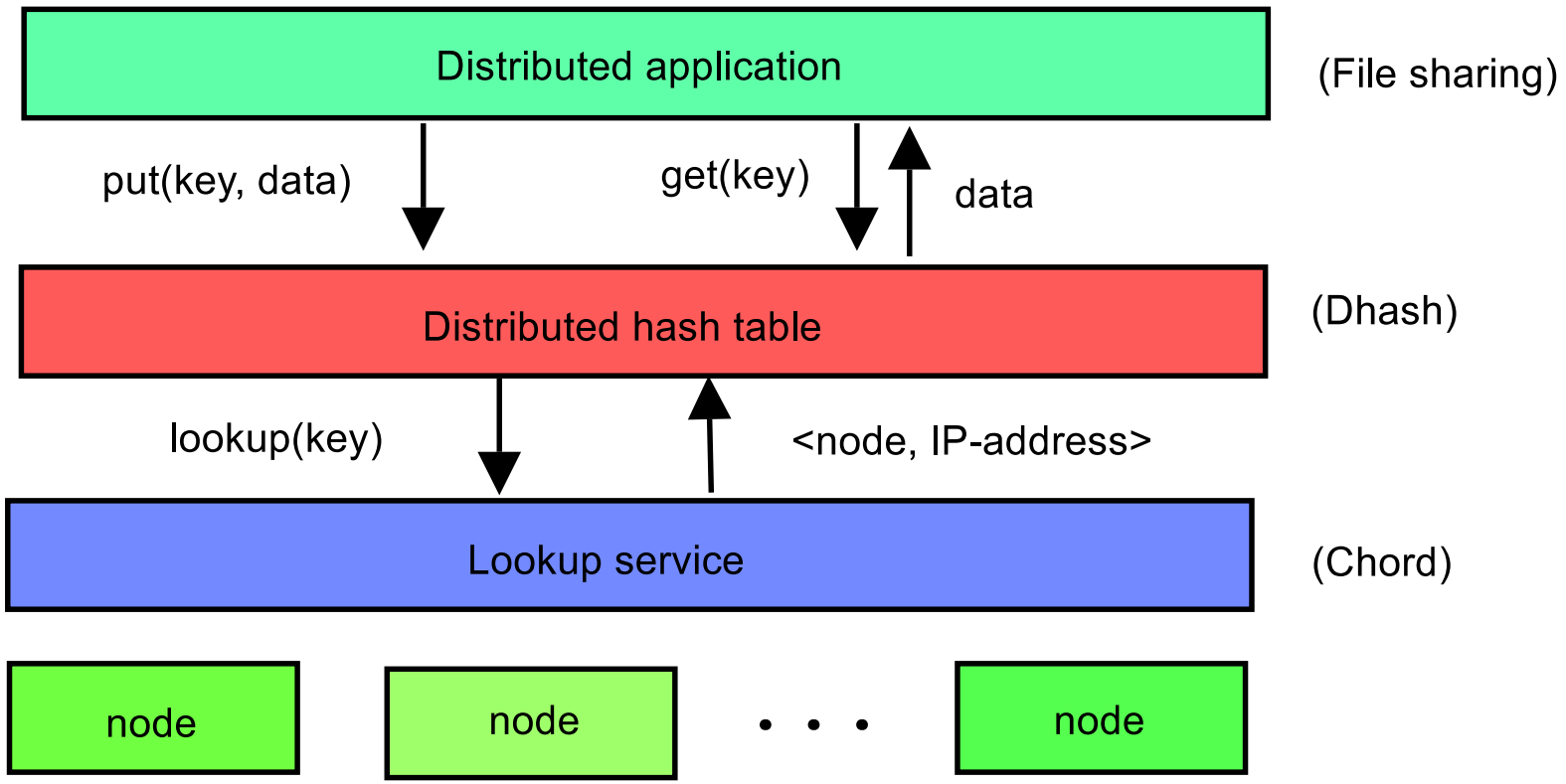
Chord: Lookup Requires log *N* Hops



Each hop halves the distance to the key.

DHash: a Storage Infrastructure

Now we have lookup; add storage (and then apps).



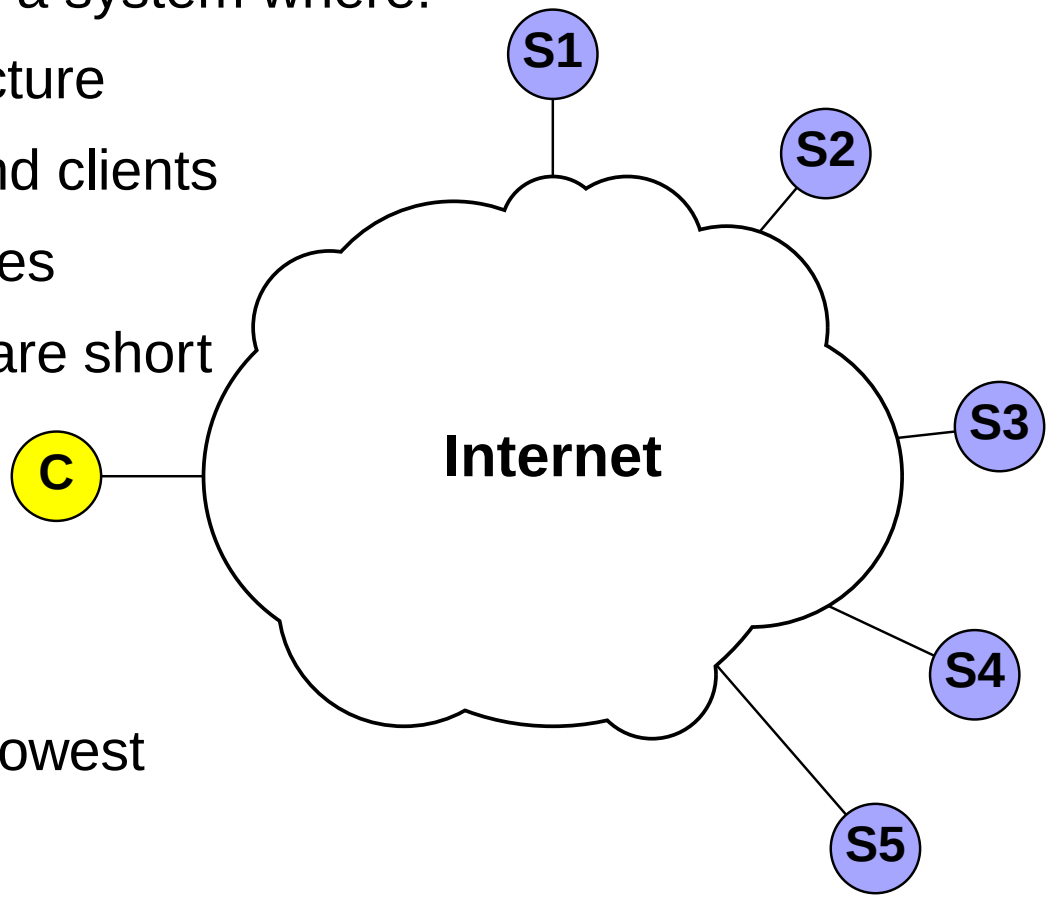
To fetch a block in DHash:

- Block replicated on *r* successors of key
- Use Chord (DHT) to find servers responsible for block
- Download block from one of those servers. Which?

Problem: Predicting Round Trip Times on Internet

Example: server selection in a system where:

- no centralized infrastructure
- nodes act as servers and clients
- many thousands of nodes
- exchanges with server are short
- server choice changes for each exchange



Want to choose server with lowest round trip time to client.

How?

Possible Solutions

- Can avoid predictions, wasting time or bandwidth:
  - measure RTT on demand
  - measure RTT in advance
  - talk to multiple servers at once
- Can predict using synthetic coordinates as in GNP (Infocom 2002).

Synthetic Coordinates with GNP

GNP assigns Euclidean coordinates to nodes such that coordinate distance predicts round trip time.

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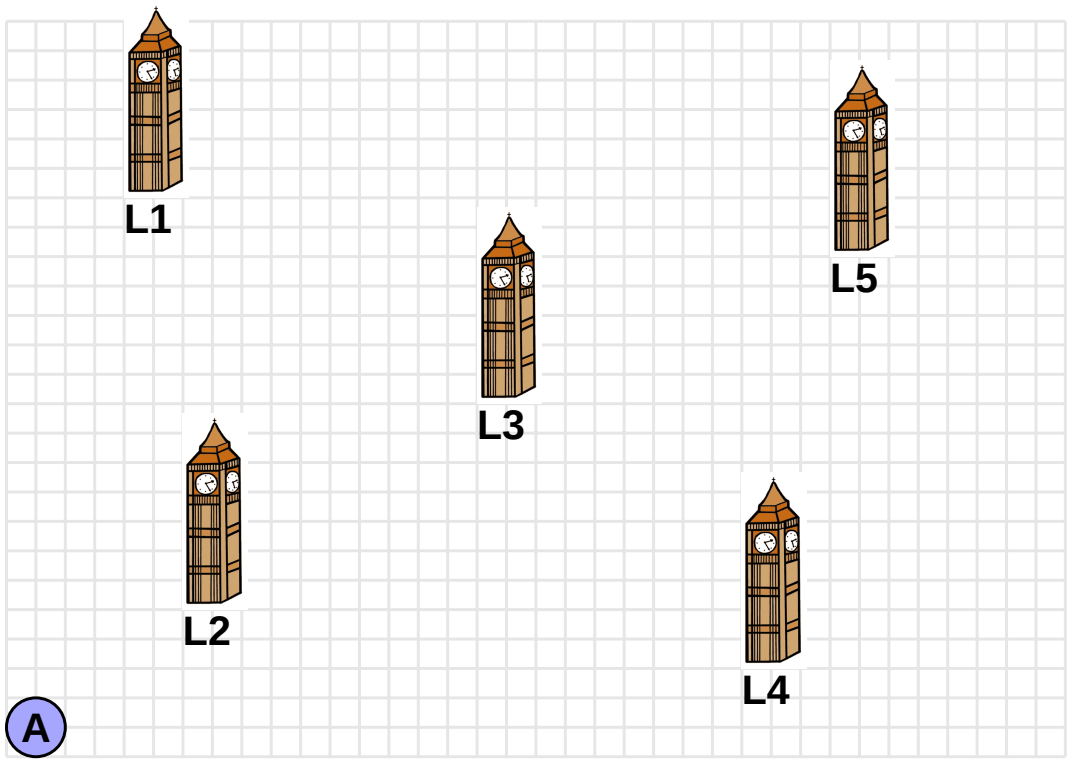
Node A pings landmarks to compute its own position.

	Coord	Dist
L1	(40,320)	
L2	(60,180)	
L3	(160,250)	
L4	(250,160)	
L5	(280,300)	



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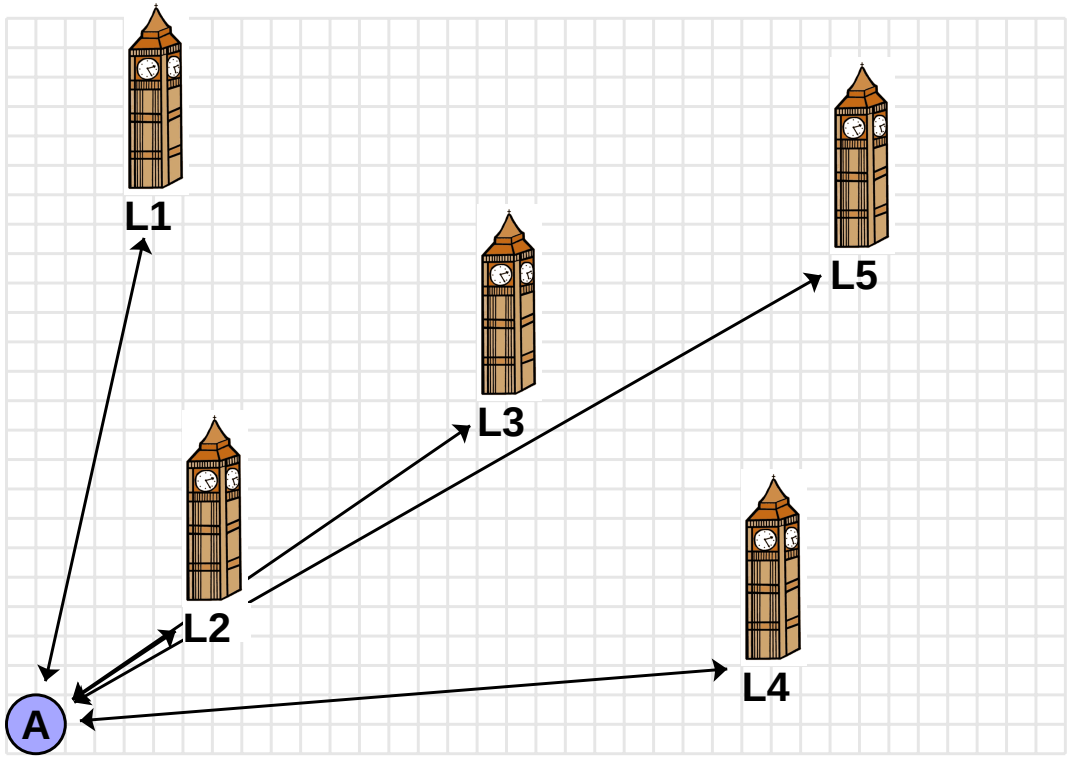

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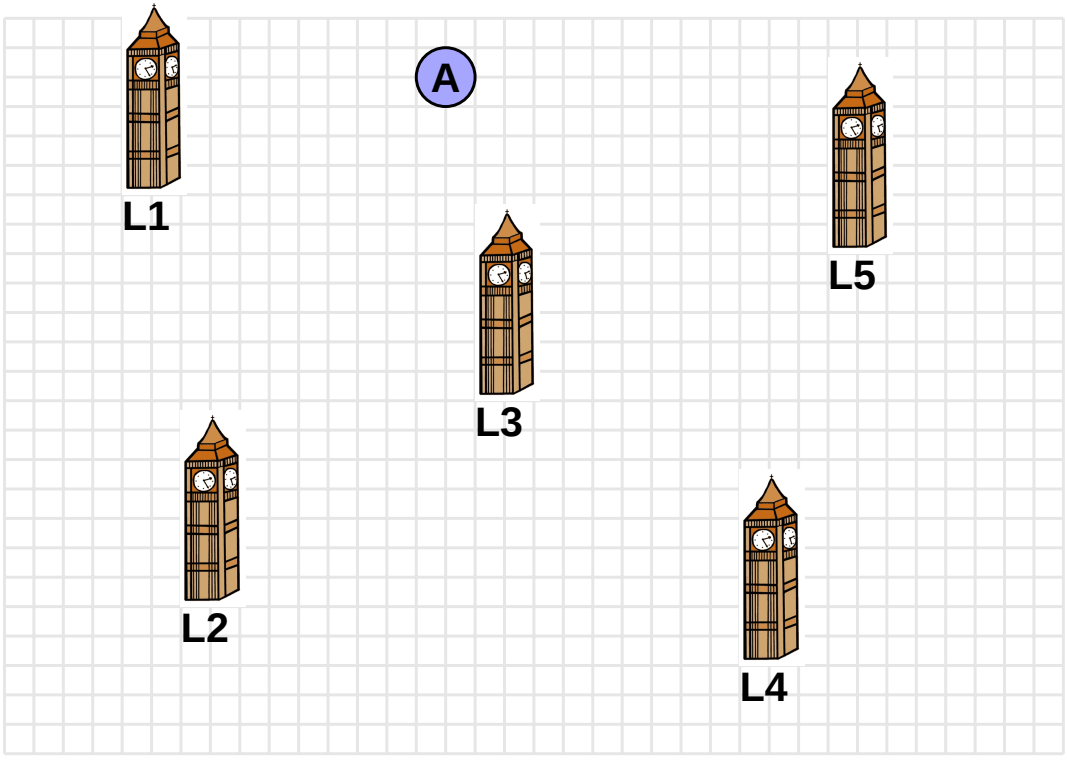

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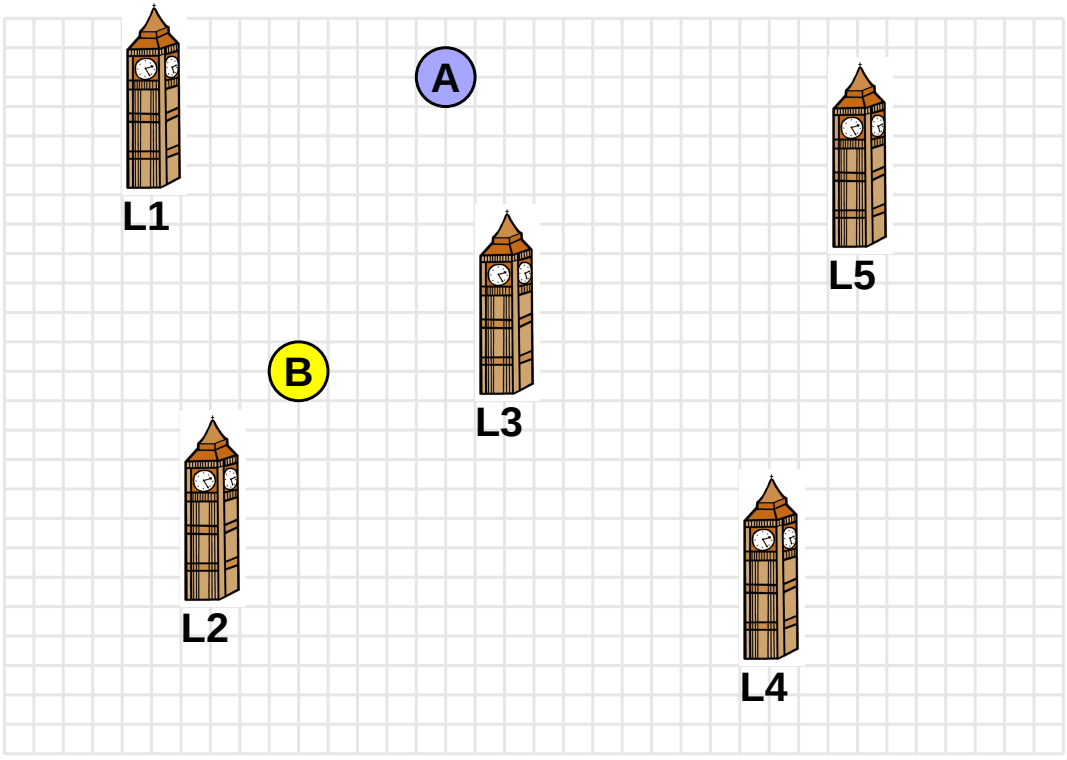

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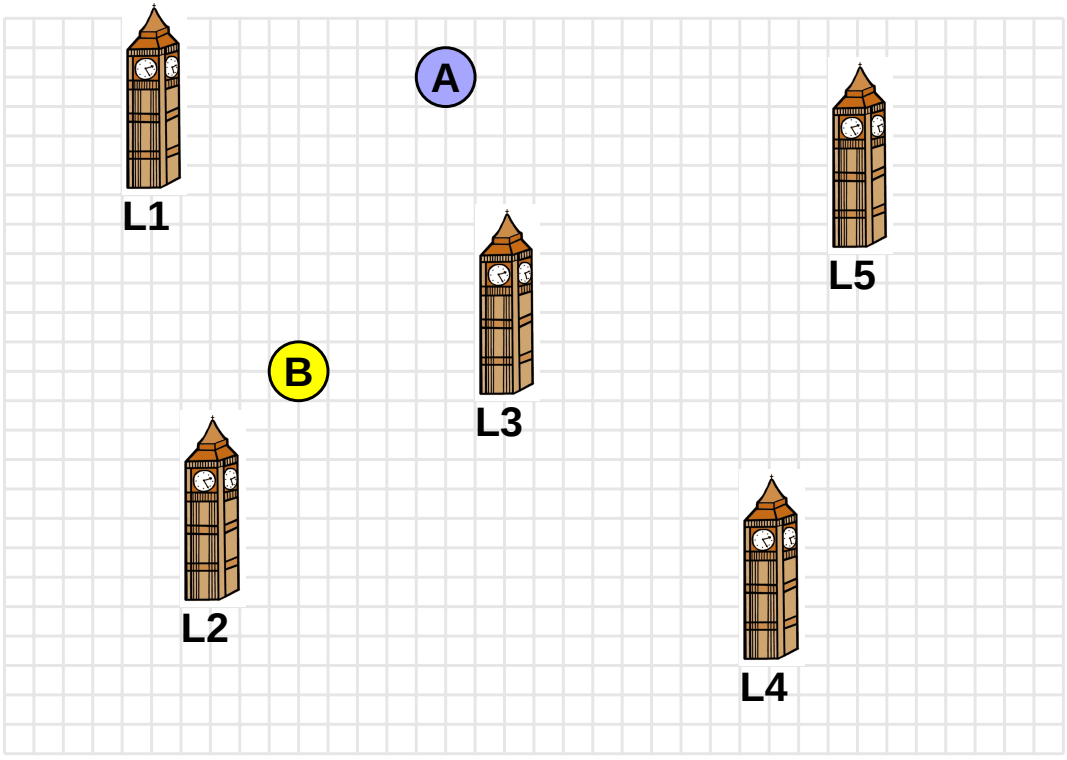
Node B does the same.

RTT between A and B is predicted by the distance between their coordinates, *without direct measurement.*



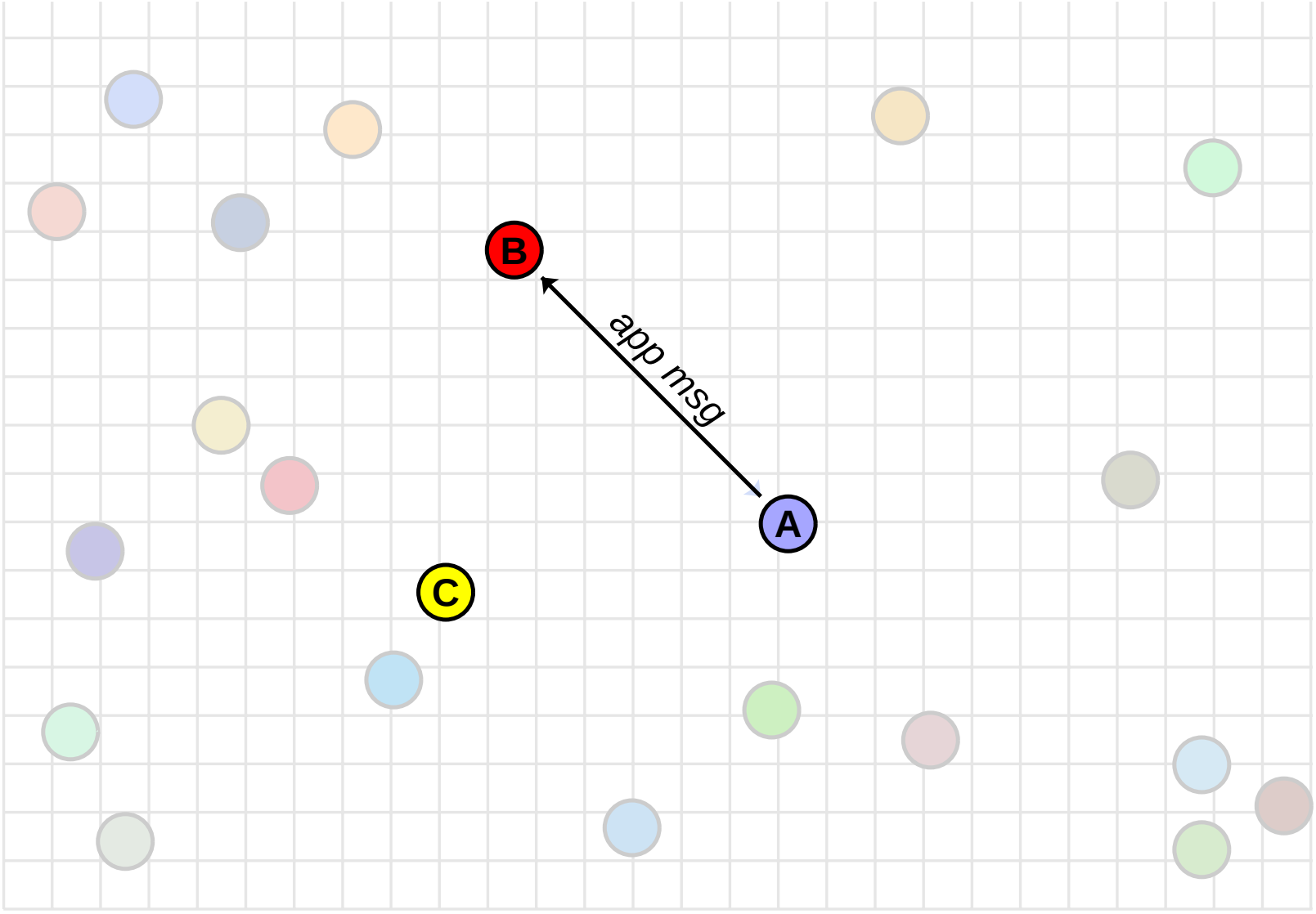
Vivaldi Overview

Vivaldi is a decentralized method for computing synthetic coordinates

- Piggyback on application traffic
- Node updates its own coordinates in response to sample
- Each node need only contact a small fraction of the other nodes

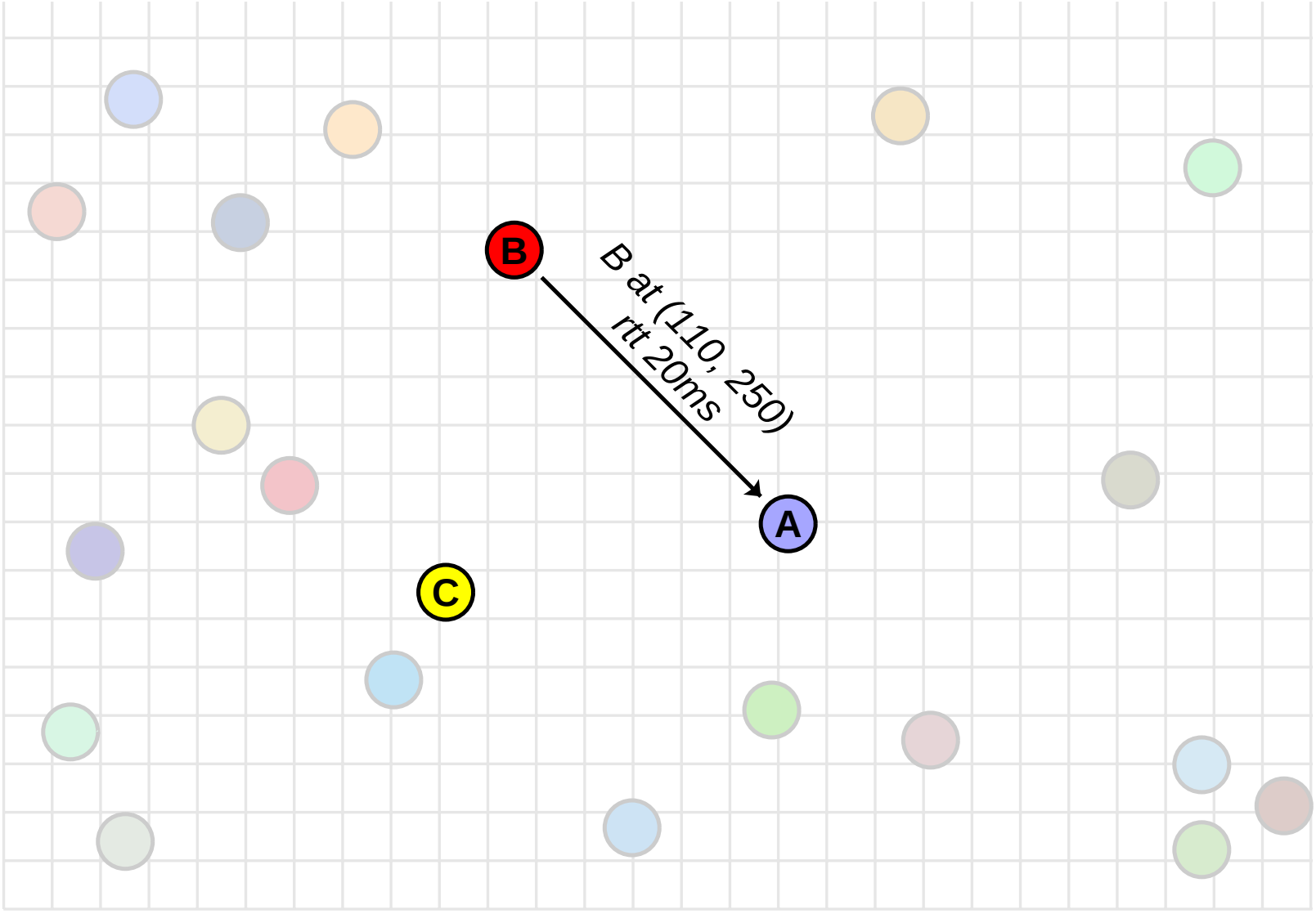
Vivaldi Example

Follow node A through a sequence of communications.



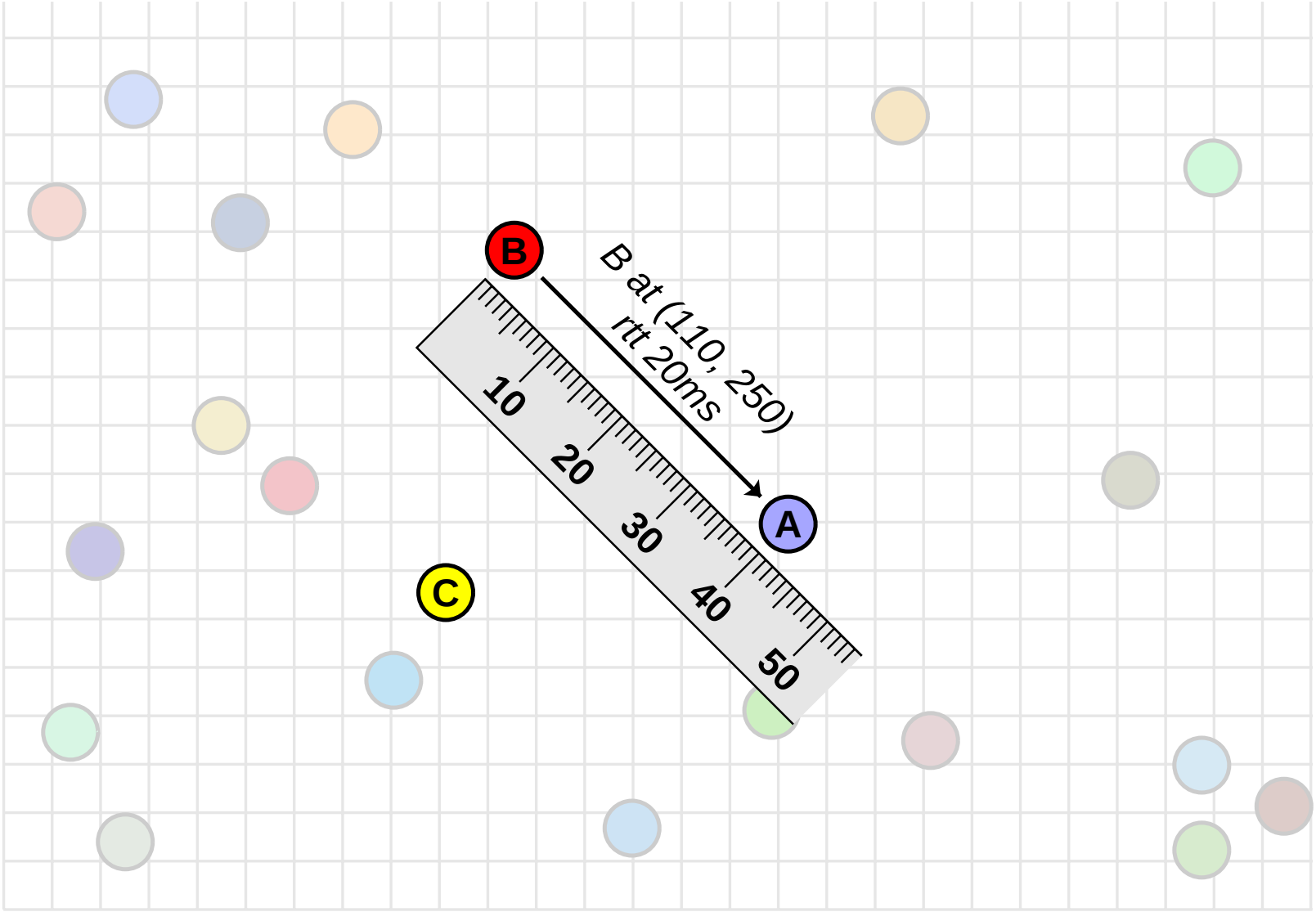
Vivaldi Example

A obtains B's coordinates, RTT.



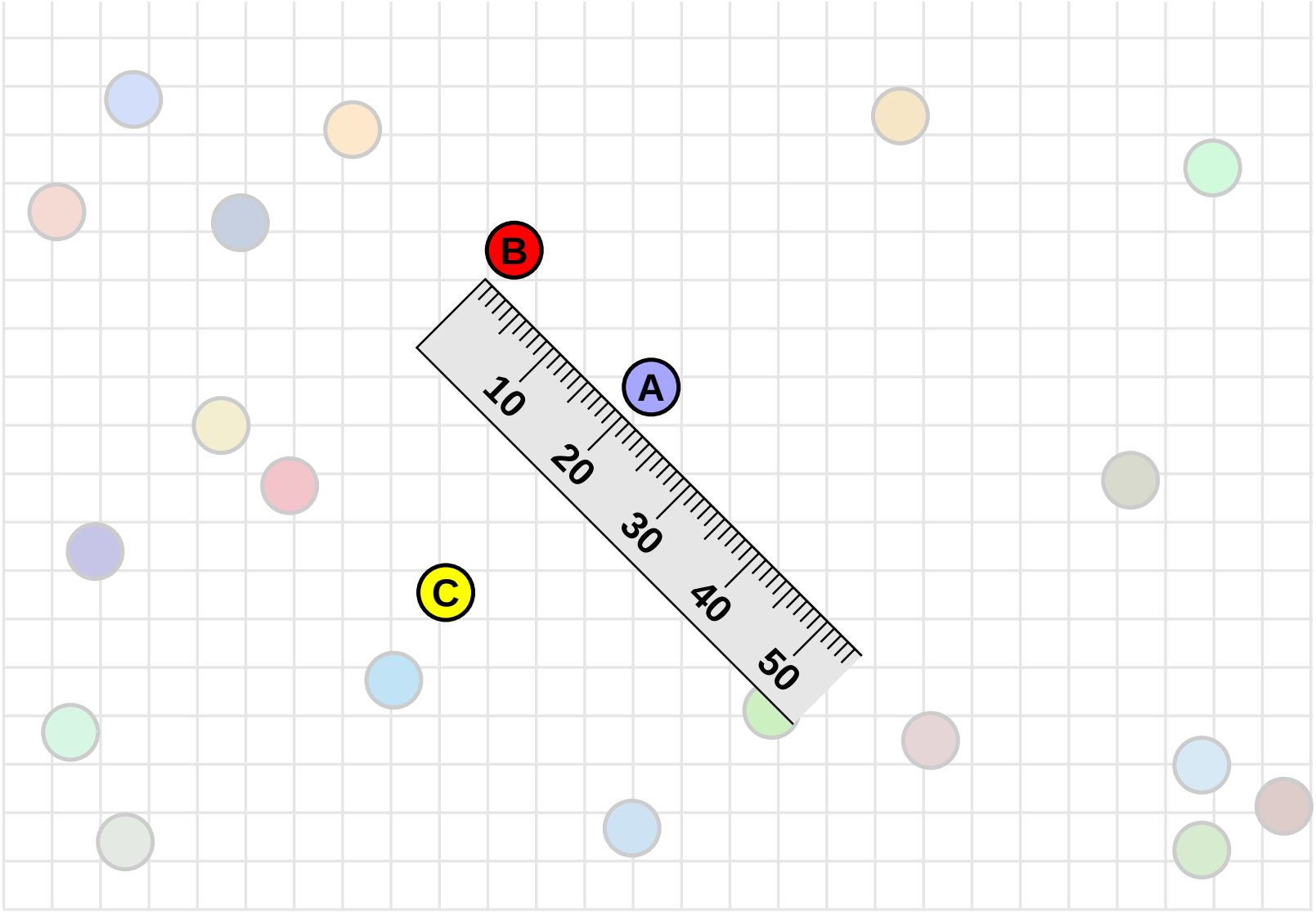
Vivaldi Example

A computes distance to B in coordinate space.



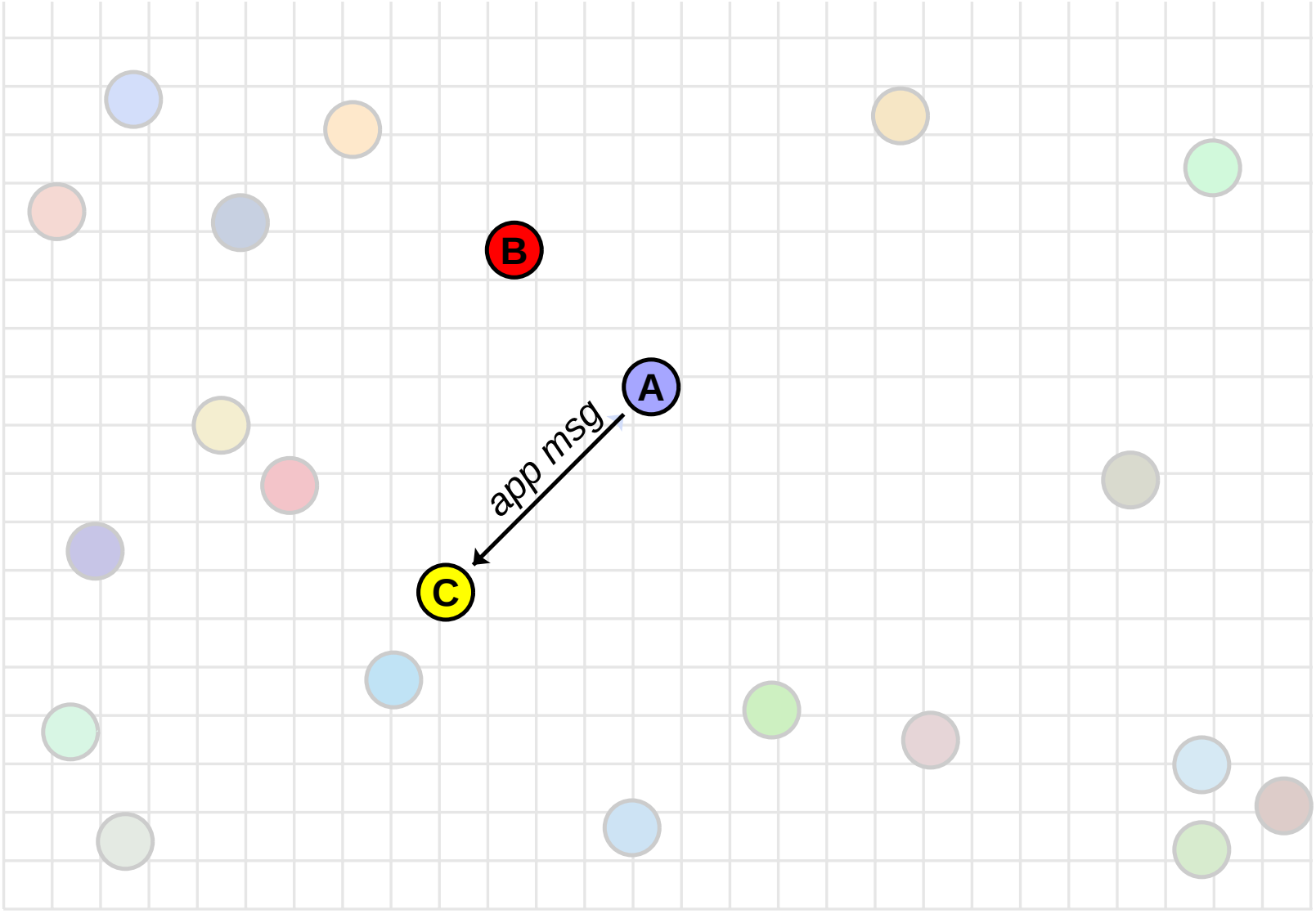
Vivaldi Example

A adjusts coordinates so distance matches actual RTT.



Vivaldi Example

Follow node A through communication with C.



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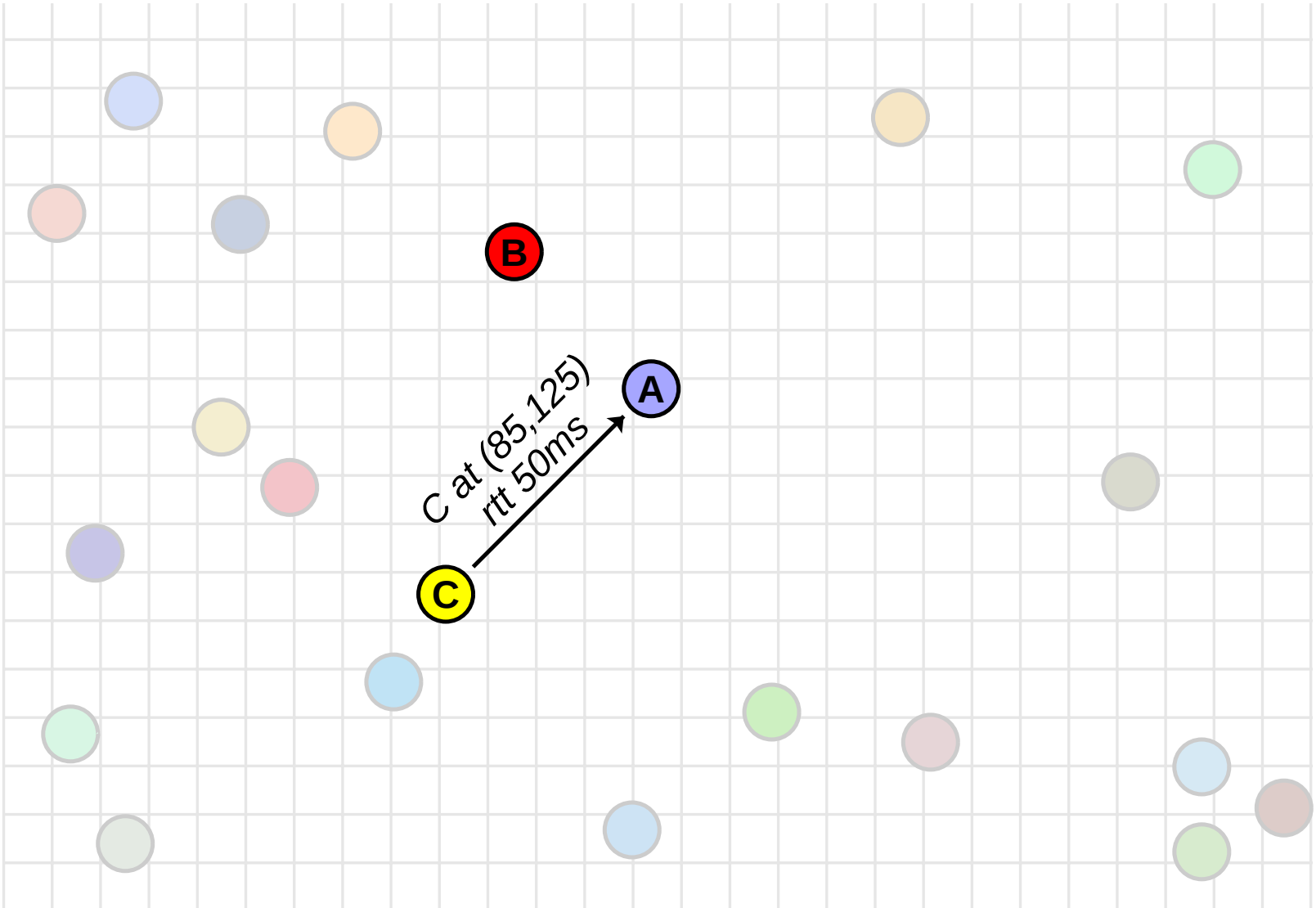

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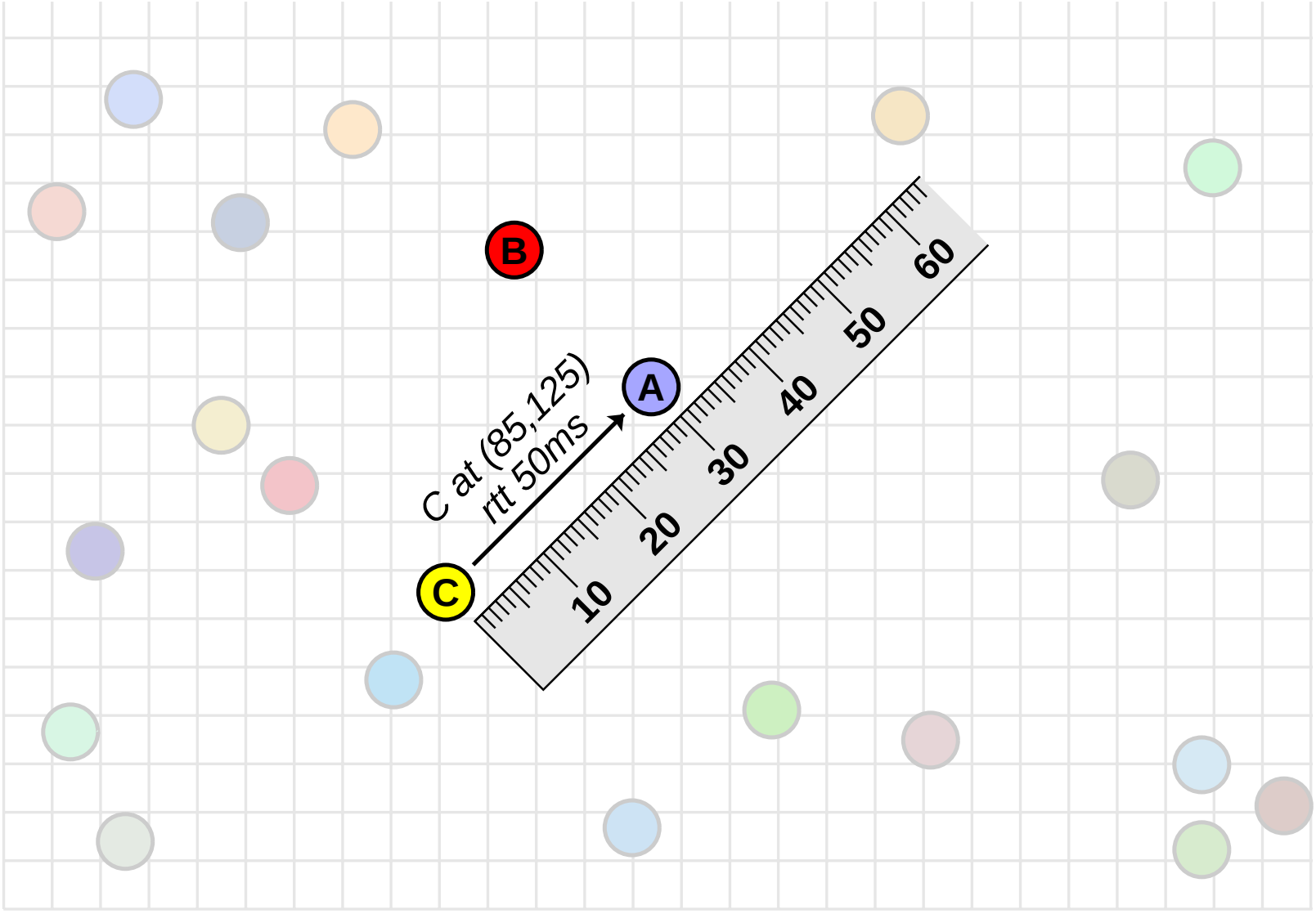
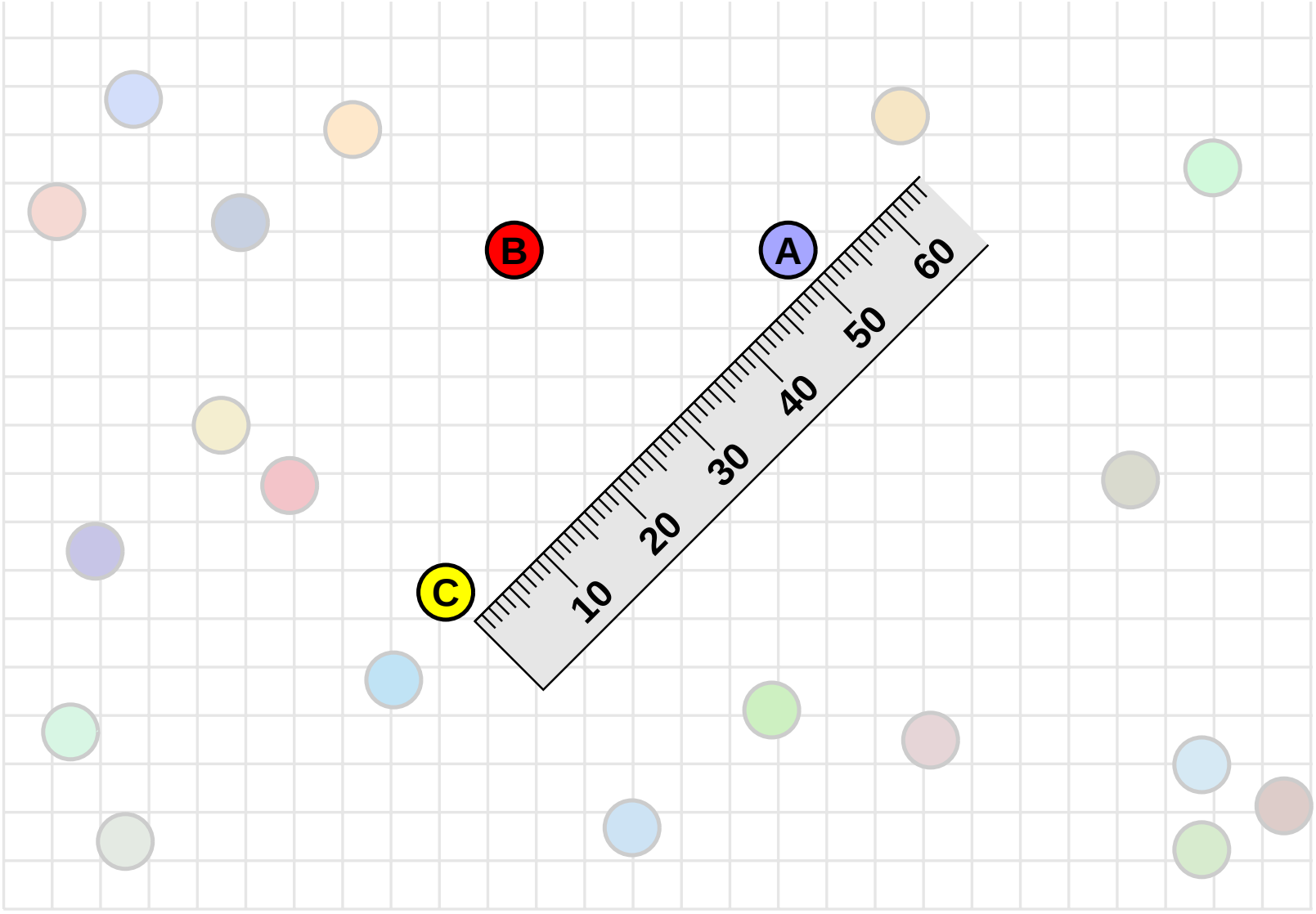


Vivaldi Example

A adjusts coordinates so distance matches actual RTT.
(Now A is wrong distance from B.)



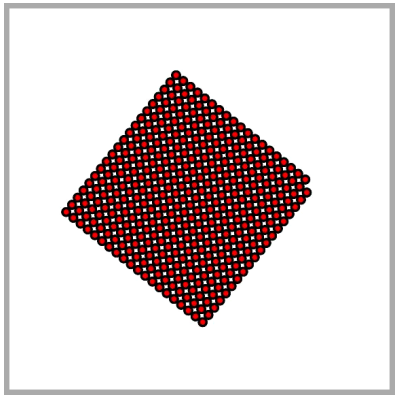
Challenges of Decentralization

Without centralized control, must consider:

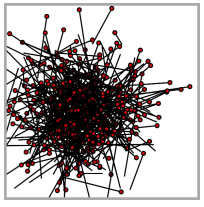
- will the system converge to an accurate coordinate set?
- how long will the system take to converge?
- will the system be disturbed by new nodes joining the system?

Tuning Vivaldi: Convergence

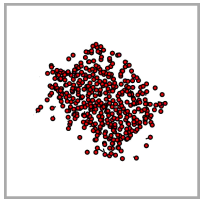
- Run Vivaldi on round trip times derived from grid.



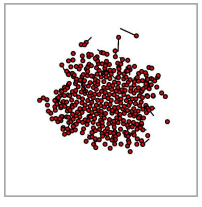
- As described, algorithm never converges.



- To cause convergence, damp motion.

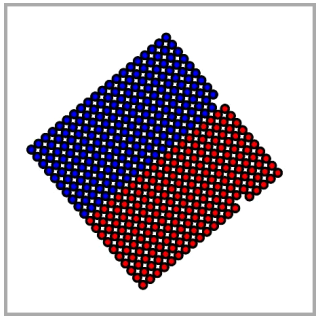


- To speed convergence, vary damping with estimate of prediction accuracy.

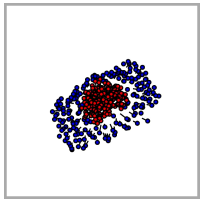


Tuning Vivaldi: Naive Newcomers

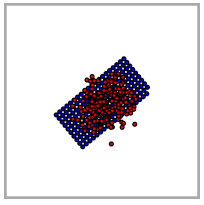
- Run Vivaldi on round trip times derived from grid.
  Blue nodes start first, stabilize.
  Red nodes join the system.



- High-accuracy nodes are displaced by new, low-accuracy nodes joining the system



- To avoid this, vary damping with ratio of local node's accuracy and sampled node's accuracy.



Vivaldi Algorithm

Given the coordinates, round trip time, and accuracy estimate of a node:

- Update local accuracy estimate.
- Compute ‘ideal’ location.
- Compute damping constant δ using local and remote accuracy estimates.
- Move δ of the way toward the “ideal” location.

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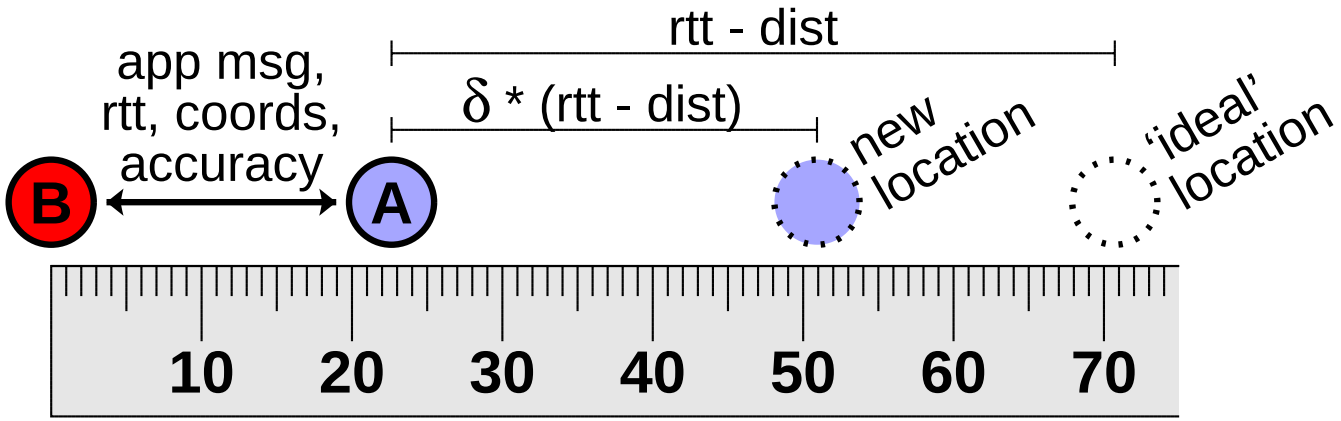


Evaluating Synthetic Coordinates on the Internet

- Cannot evaluate by comparing to “correct” coordinate set.
- Evaluate *predictions* made using a coordinate set.
- Predictions of Internet will never be perfect.
  - violations of triangle inequality, ...

Evaluating Vivaldi on the Internet

- How accurate are Vivaldi's predictions?
- How quickly does Vivaldi converge to a coordinate set?
- How quickly can Vivaldi adapt to network changes?
- How does choice of coordinate space affect error?
- How does Vivaldi work in real-world apps?

Evaluation Methodology

Use simulator seeded with real Internet measurements.

- pairwise RTTs for 192 PlanetLab nodes
- use RTT matrix as input to simulator
- run various algorithms on simulator

Each Vivaldi node queries others as fast as it can

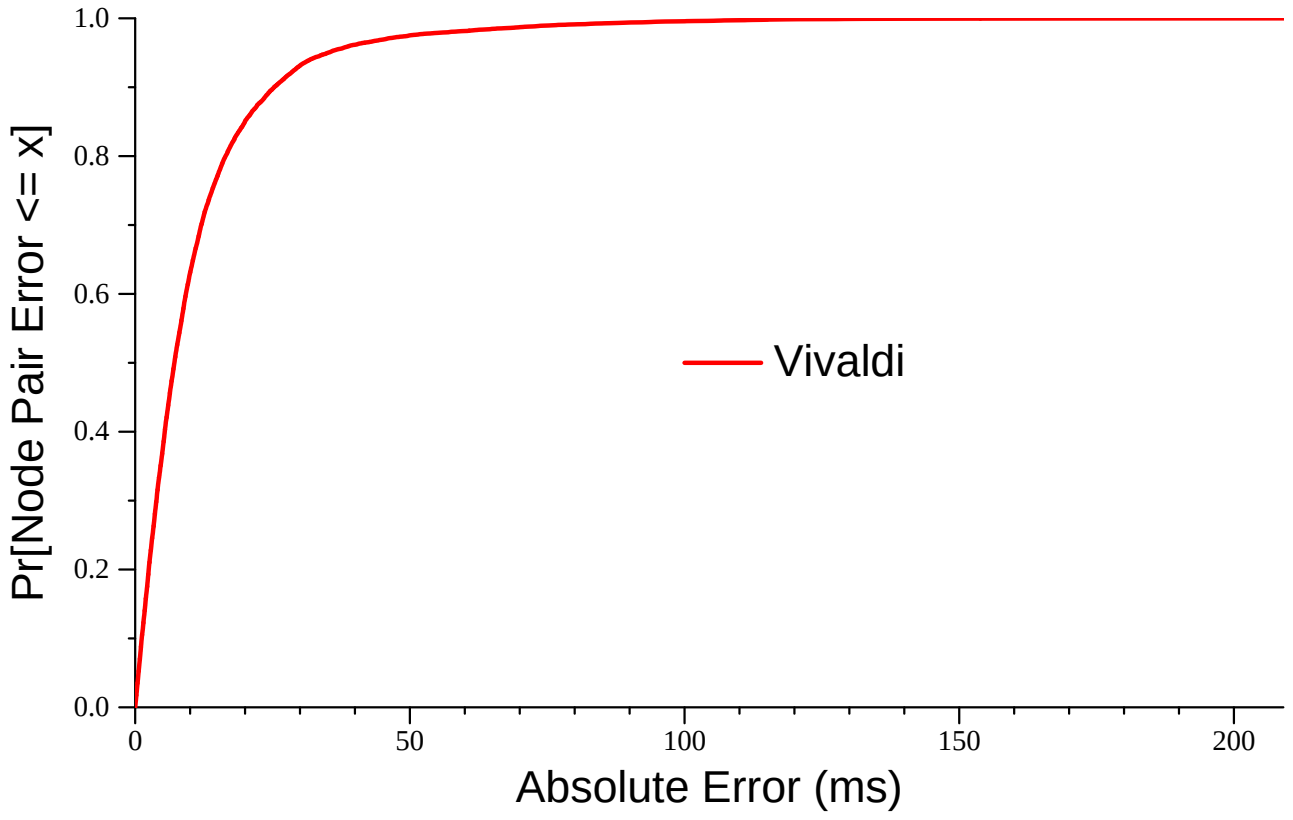
- one message outstanding at a time
- each node has a small fixed neighbor set

Vivaldi's Absolute Prediction Error

Look at distribution of absolute prediction error, defined as

$$\left|\text{actual RTT} - \text{predicted RTT}\right|,$$

over all node pairs in the system.



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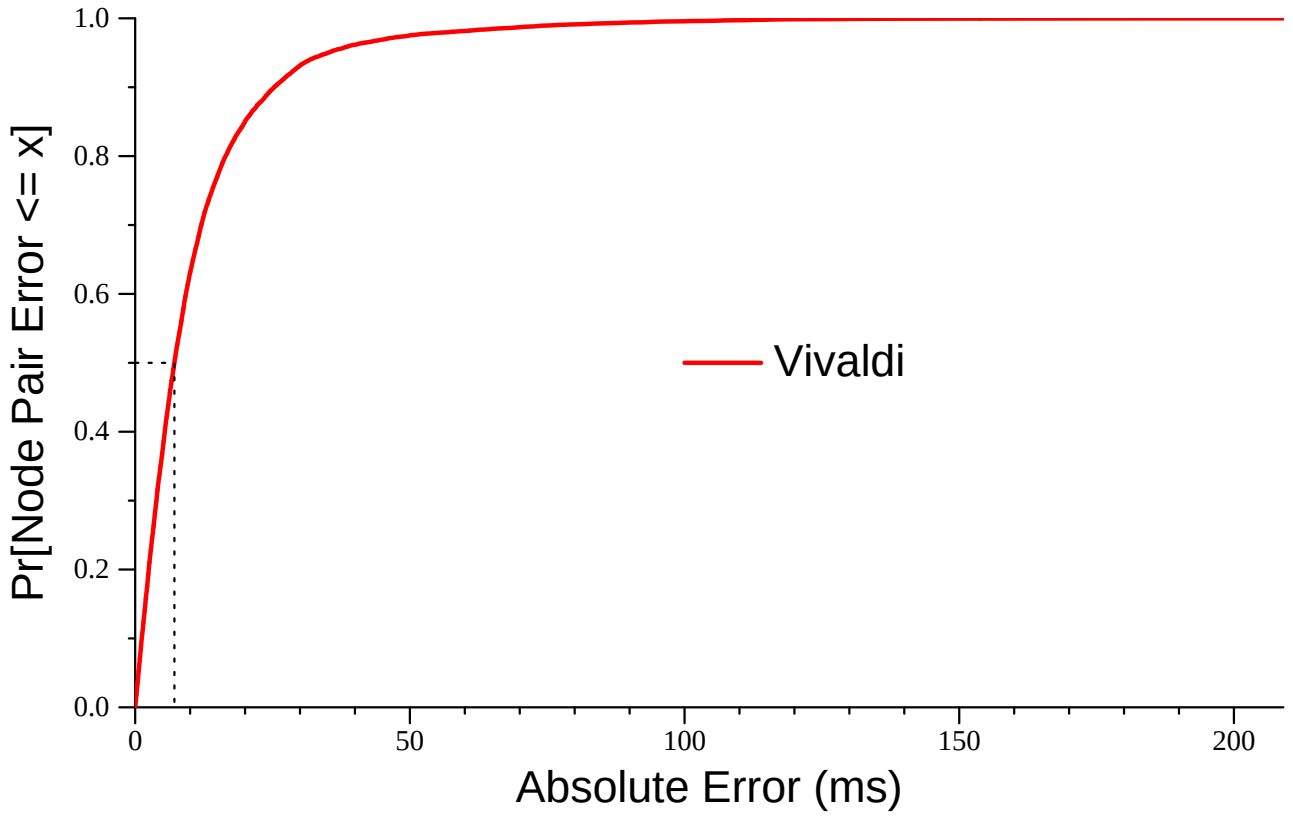

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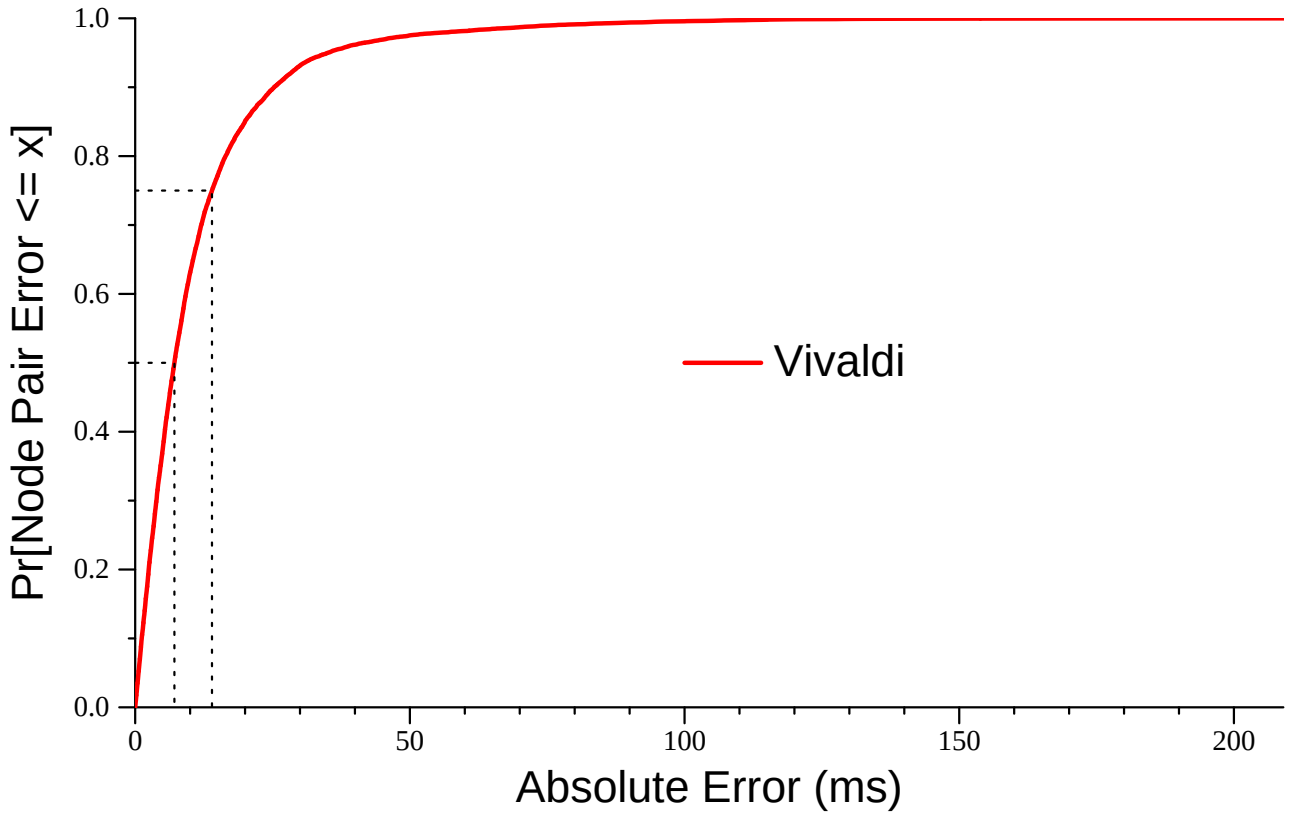

Vivaldi's Relative Prediction Error

Look at relative error, defined as

$$\frac{|\text{actual RTT} - \text{predicted RTT}|}{\min(\text{actual RTT}, \text{predicted RTT})},$$

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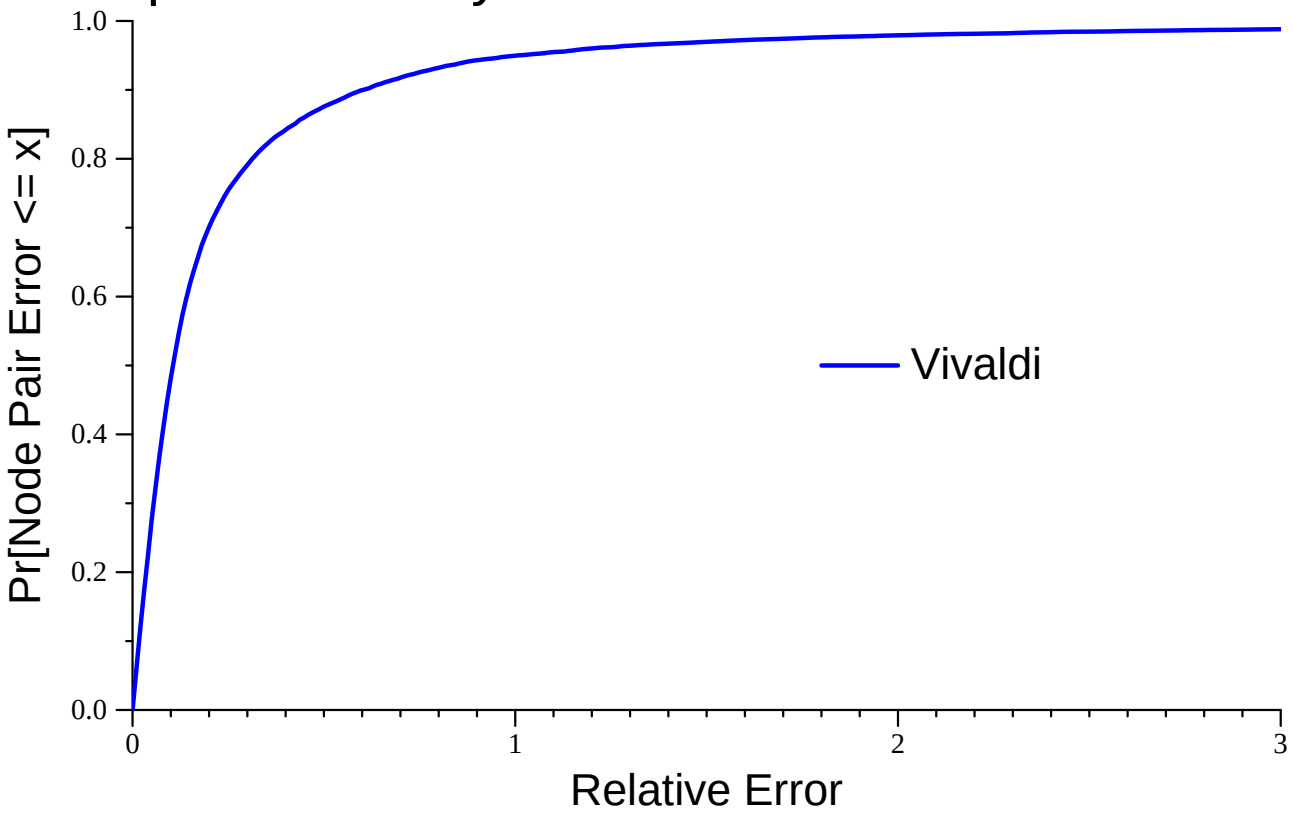

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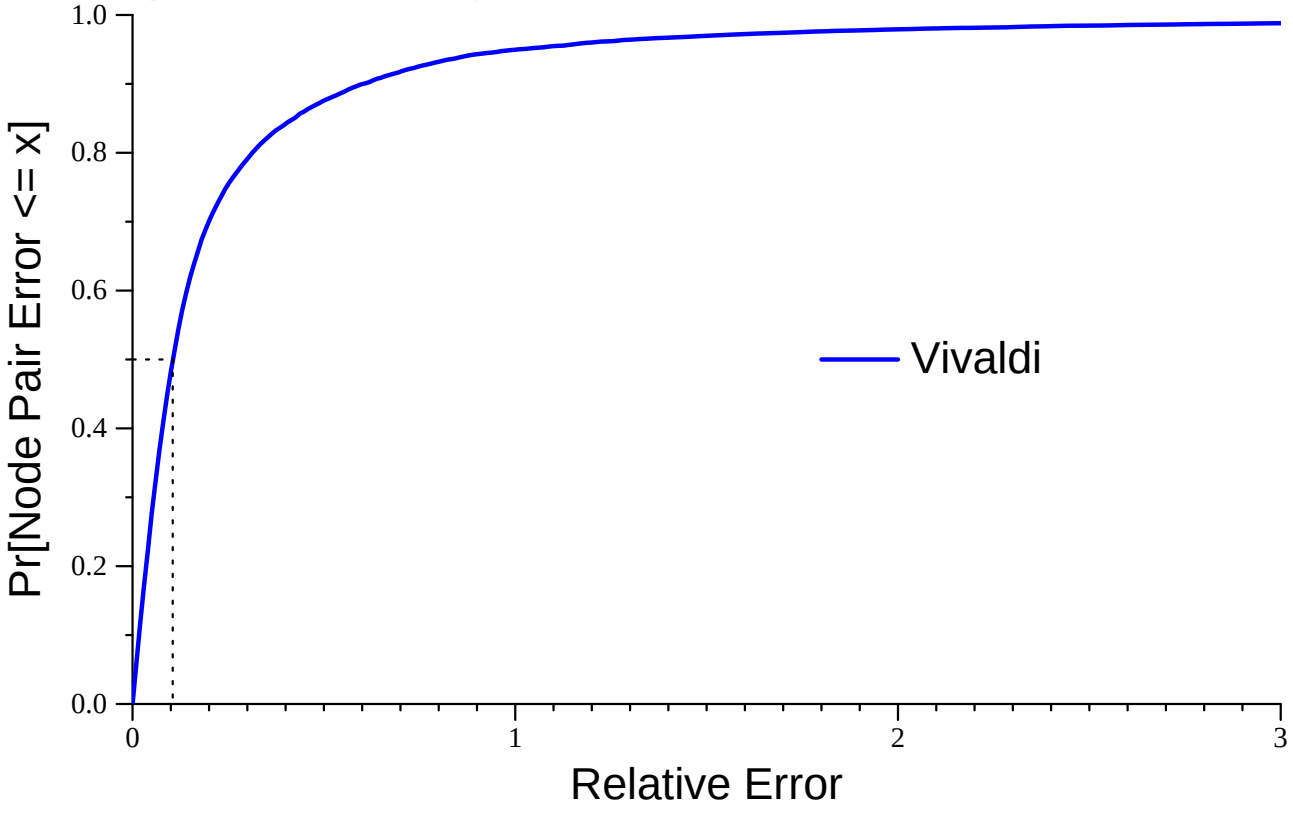

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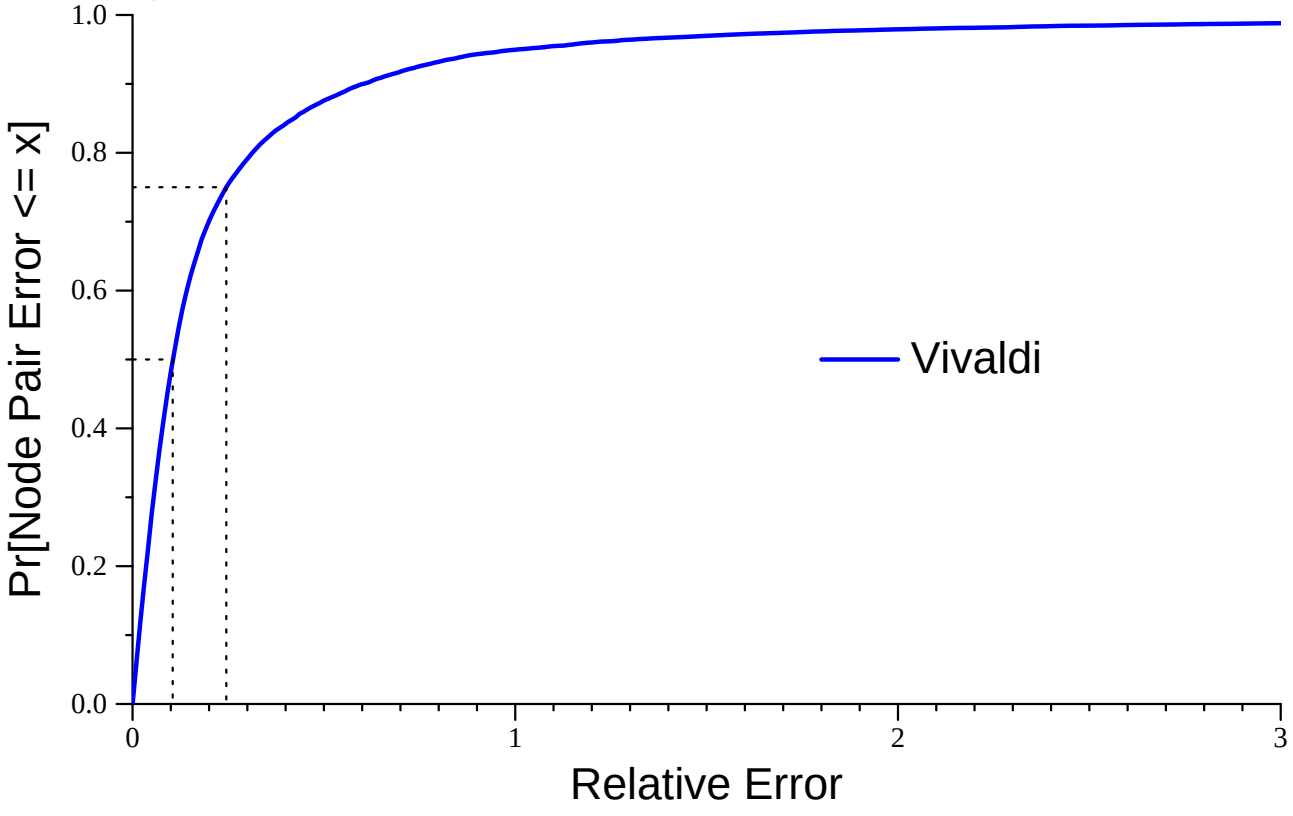
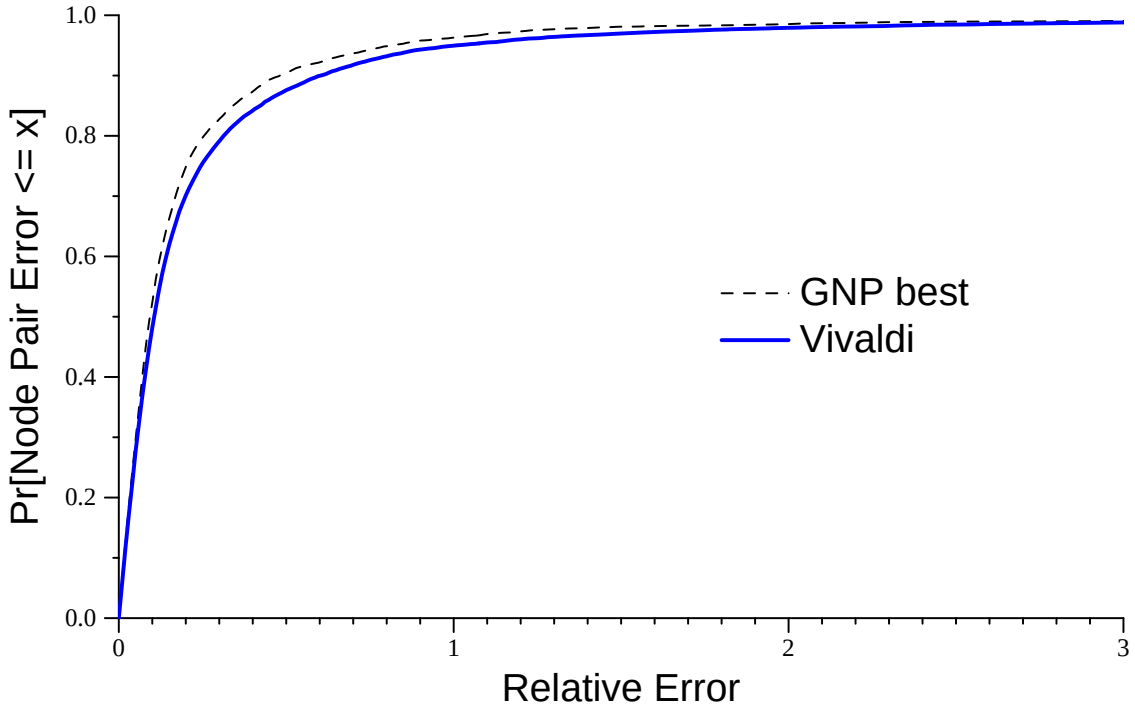


Vivaldi Compared to GNP on Relative Error

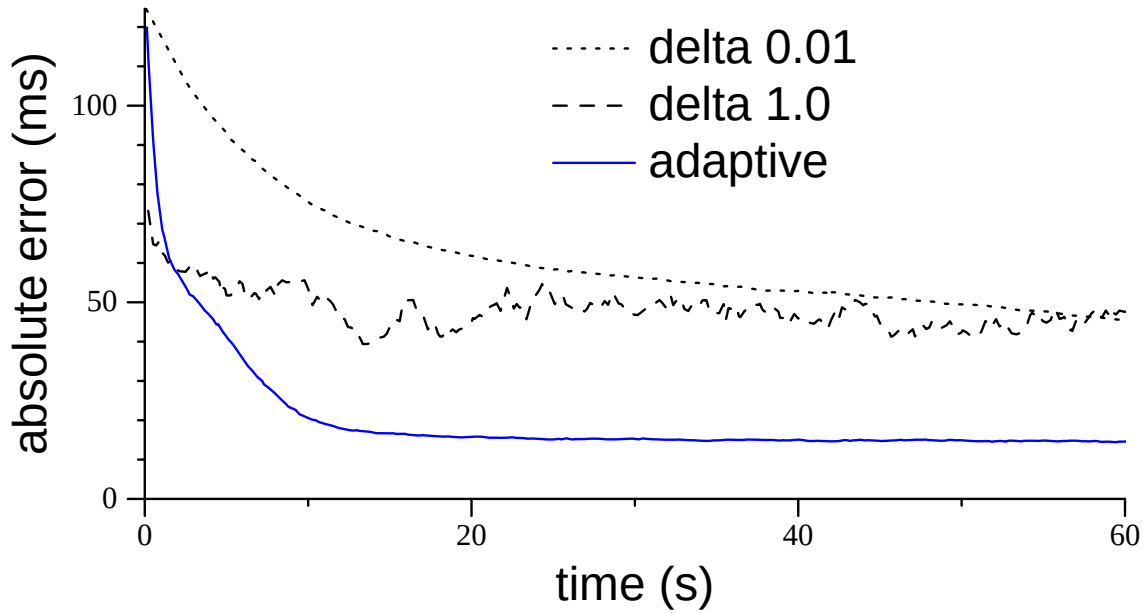
Compare to GNP's predictions.

- GNP sensitive to landmark choice. Use best of 64 random landmark sets.



Vivaldi's Convergence Time

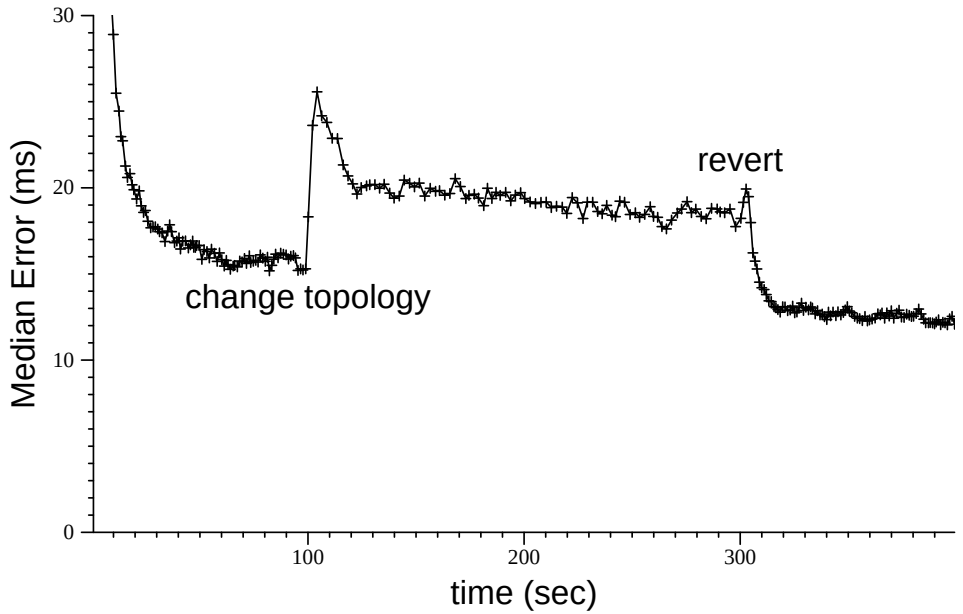
- Depends on choice of δ, the damping constant.



- Using adaptive δ, Vivaldi converges in under 20 seconds (60 measurements per node).

Vivaldi's Time to Adapt to Network Changes

- Vivaldi nodes are always adjusting their coordinates.
- Test adapting speed with synthetic topology change: lengthen one link by factor of ten.



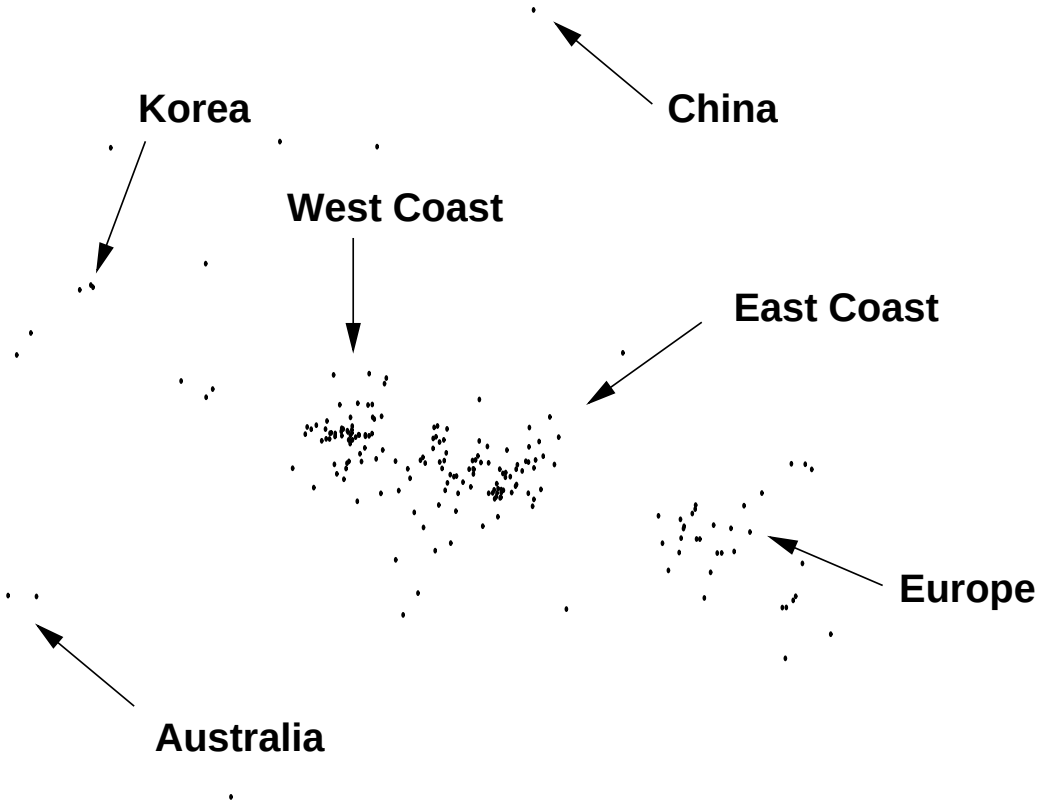
- Vivaldi adapts in about twenty seconds.

Other Coordinate Spaces

- *A priori*, it's not clear why *any* coordinate system should fit the Internet well.
- GNP showed that Euclidean coordinates work well.
- Why do they work?
- Are there better coordinate systems?
  - Obvious other candidates: globe, 3D, 4D, ...

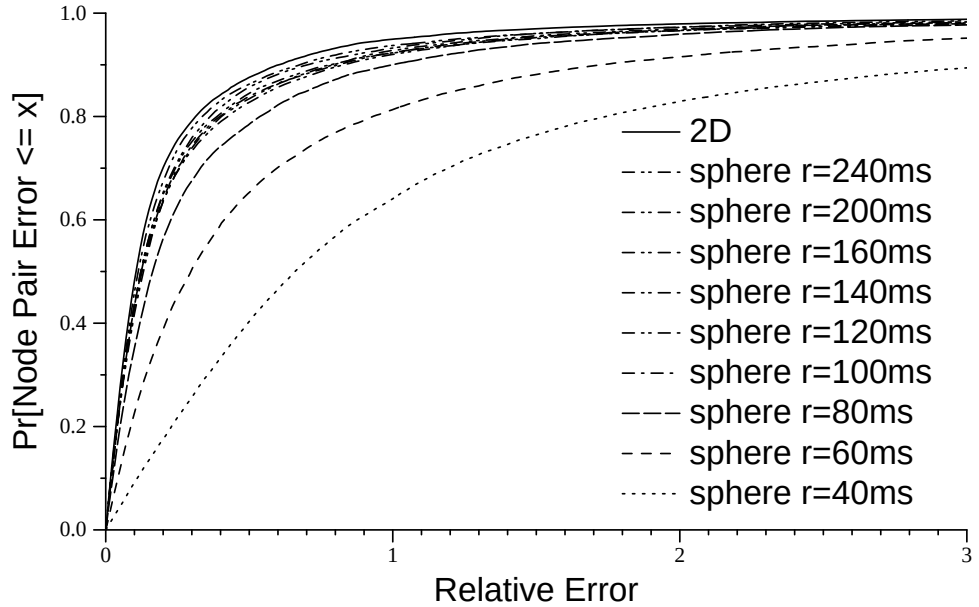
Vivaldi's 2D Assignment for PlanetLab

Placement in 2D mirrors physical geography.



Globe Coordinates vs. 2D Euclidean

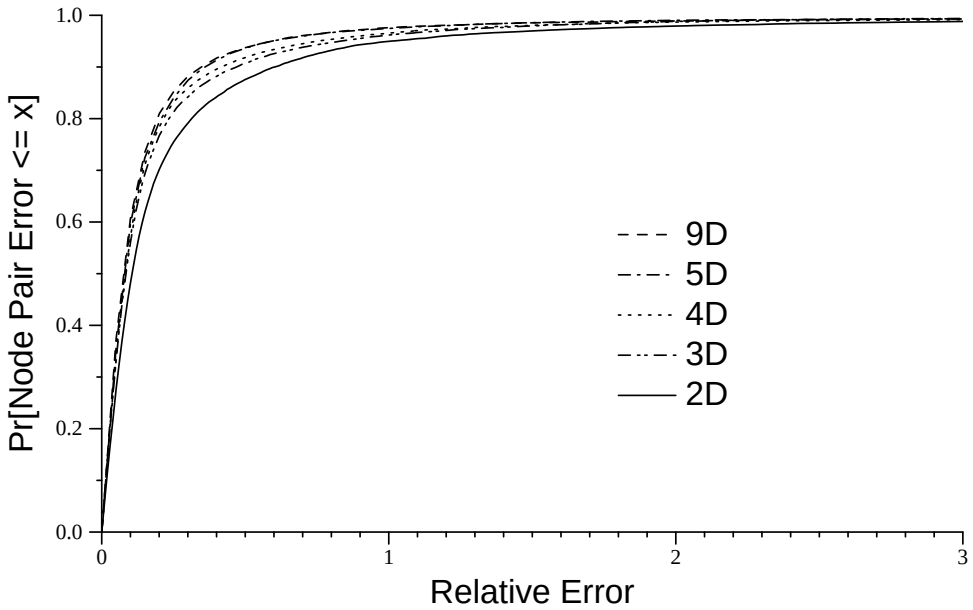
- Globe coordinates (latitude, longitude) place nodes on surface of a sphere.
- Great circle distance between two nodes on the sphere depends on radius.



- Coordinate sets are using one part of the sphere as a rough approximation to a 2D plane.

Higher Euclidean Dimensions

- If two are good, more should be better.



- Why are they better?

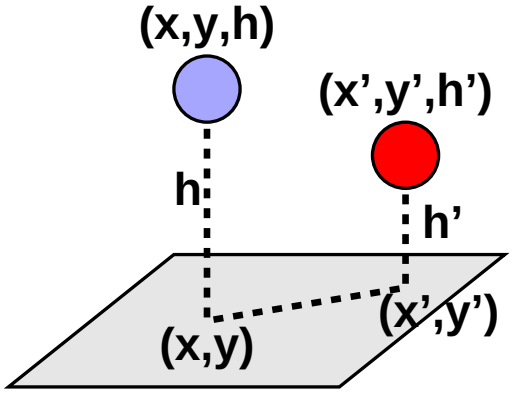
Higher Euclidean Dimensions Explained

- In 2D, some nodes need to be farther away from all others.
- In 3D, these “hard-to-place” nodes can move up or down from the 2D plane to get away from everyone.
- Each new dimension adds an independent direction.
- Accomodates per-node overhead: server load, access links.

Problem: how can we accomodate “hard-to-place” nodes without an arbitrary number of dimensions?

Height Vectors

- Give “hard-to-place” nodes their own way to get away from everyone.
- Height vectors place nodes at some height above a 2D transit plane.
- Directly models per-node overhead.

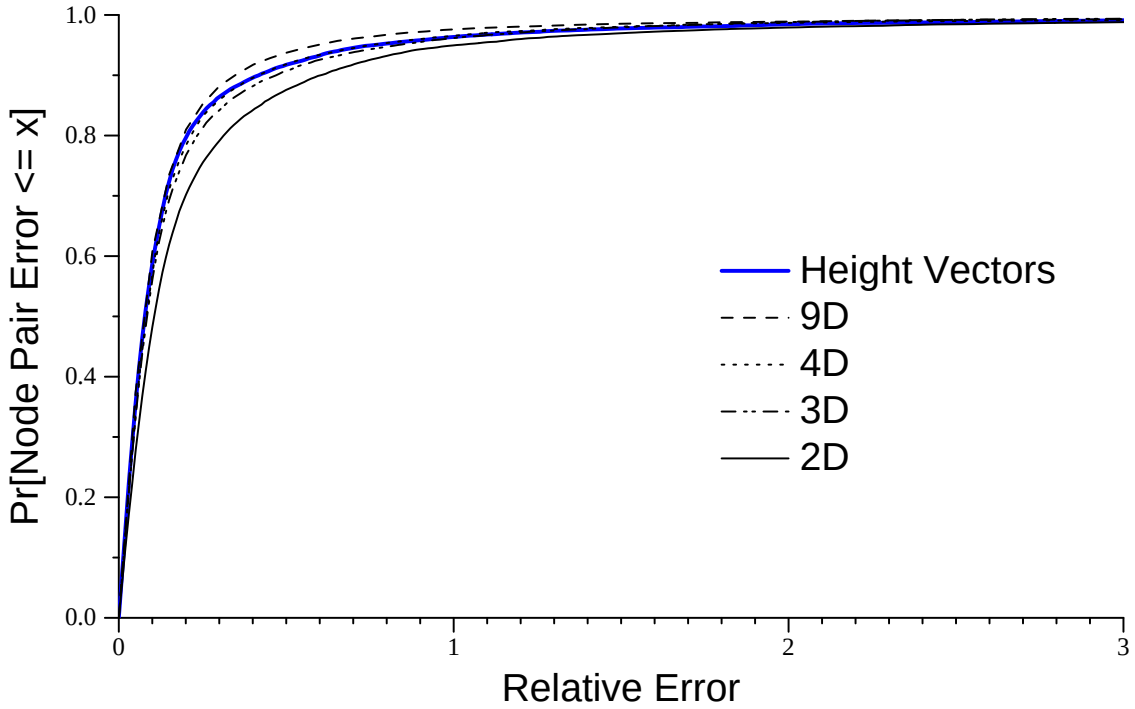


- Distance from (x, y, h) to (x', y', h') is

$$h + \sqrt{(x - x')^2 + (y - y')^2} + h'.$$

Height Vectors Work Well

- Height Vectors outperform 2- and 3-D Euclidean.



- Works to view Internet as geographically-accurate core with access links attached.

Evaluating Vivaldi on Chord

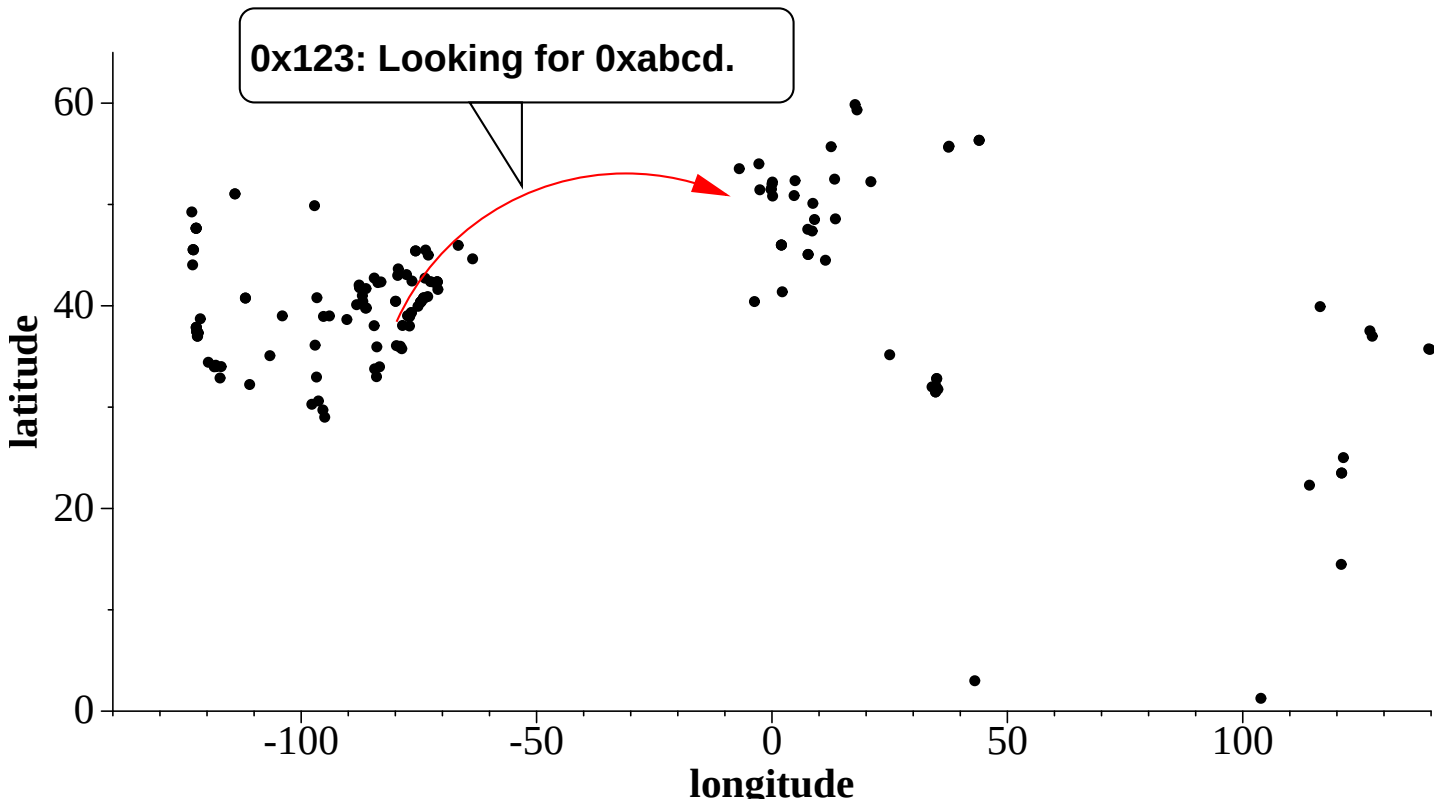
Chord performance is $O(\log n)$ but sluggish.

Can Vivaldi help?

Watching Traffic

Lookups move randomly in the network.

- Node IDs, block keys are assigned (pseudo-)randomly.



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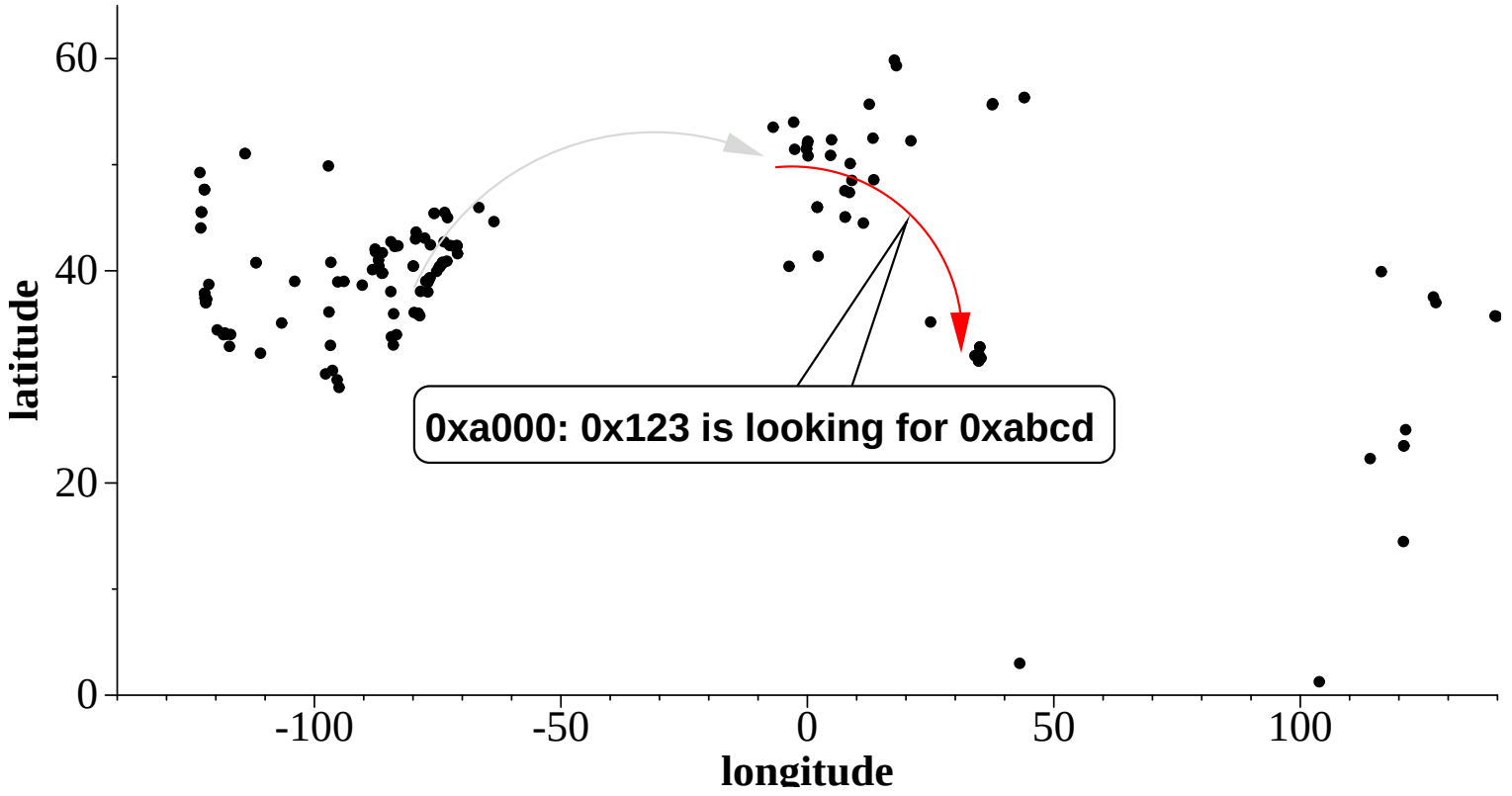

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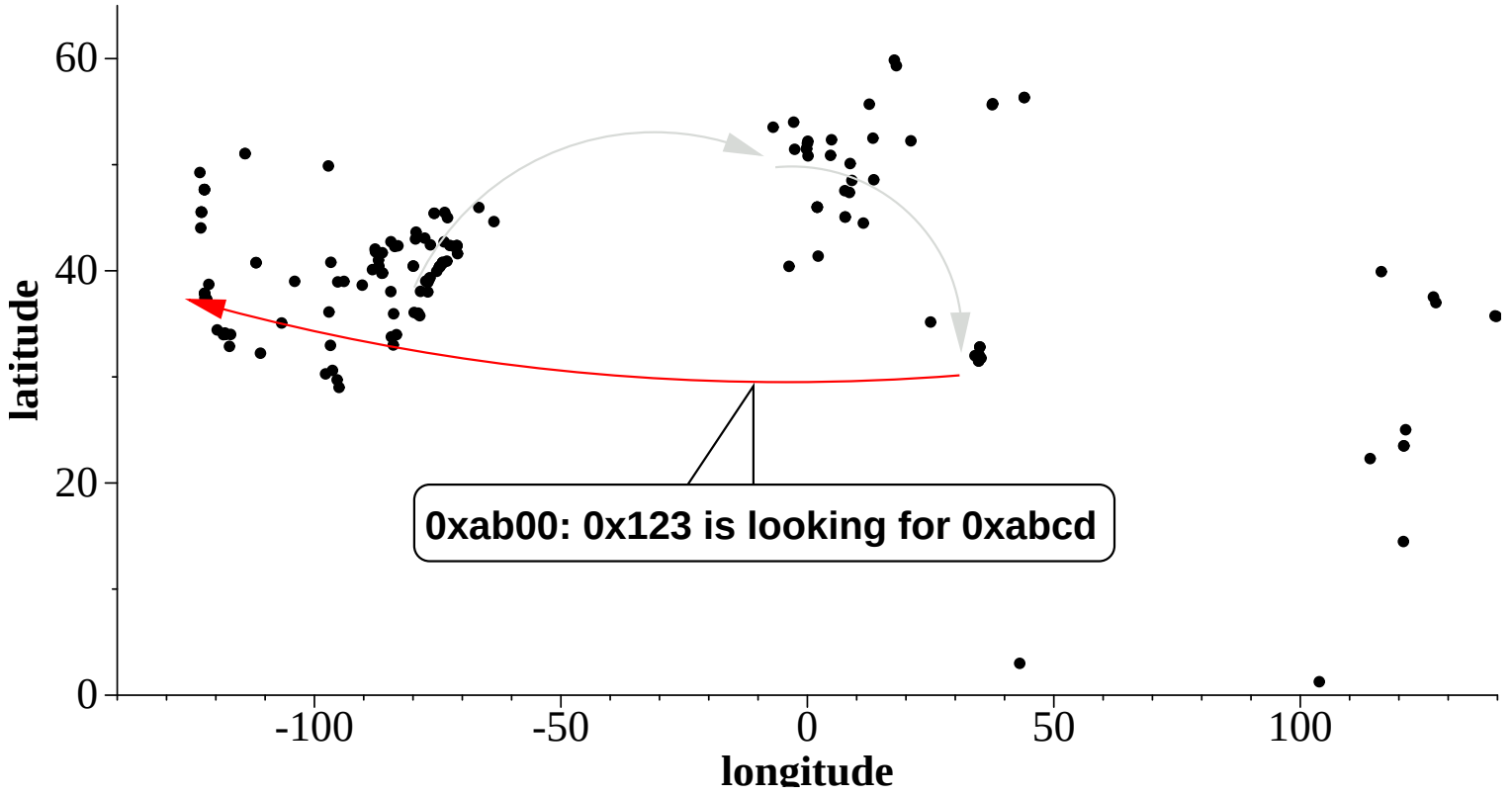

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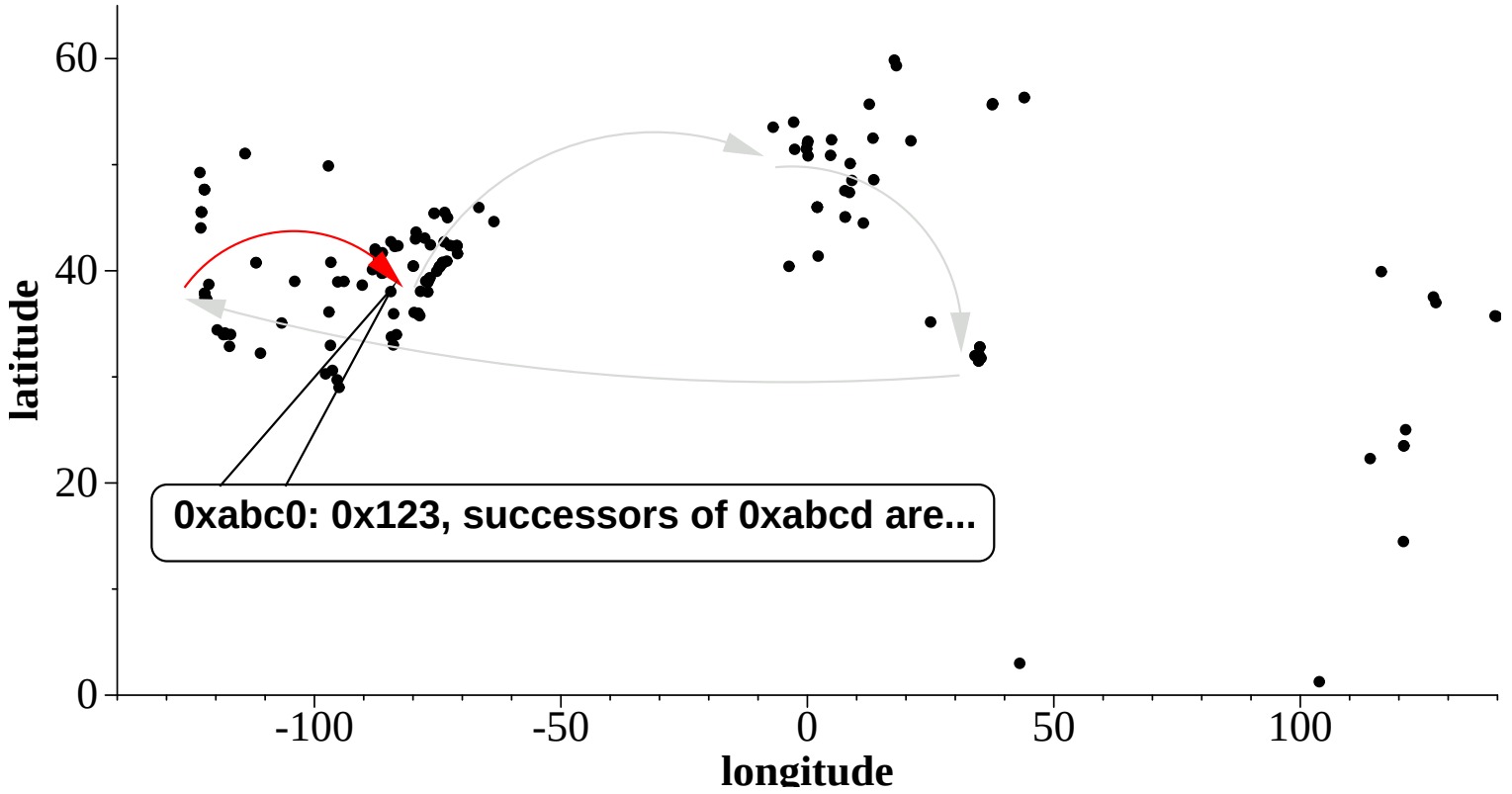
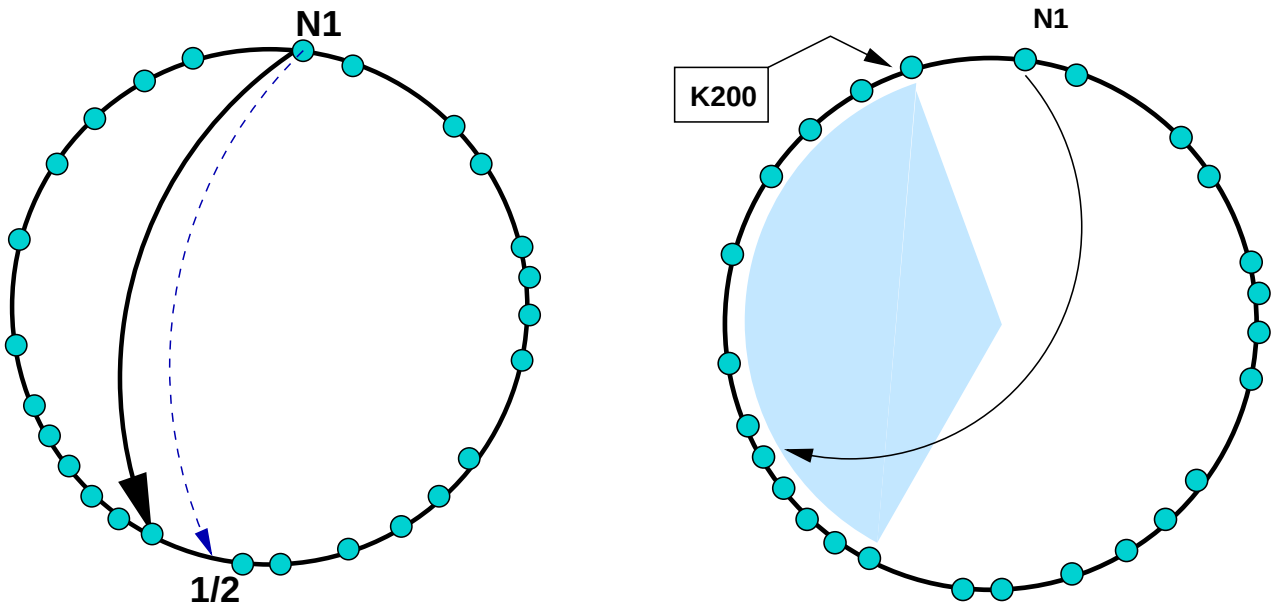
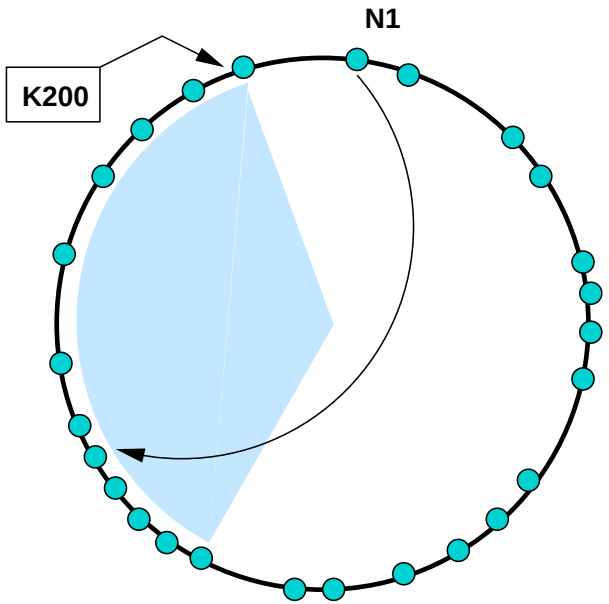


Chord: Shortening Lookup Hops Using Vivaldi



- Relax definition of finger from immediate successor to any node in range.
- Given more choices, can choose nearer neighbors.

Chord: Lookup Using Neighbor Selection



- Each hop now has a range of choices.

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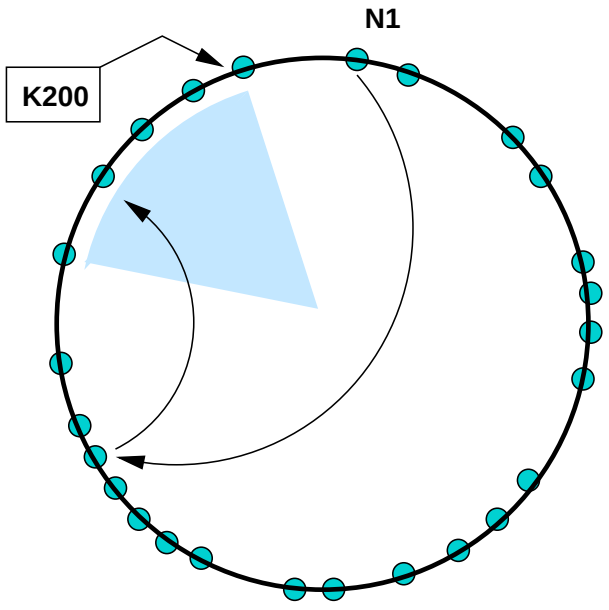

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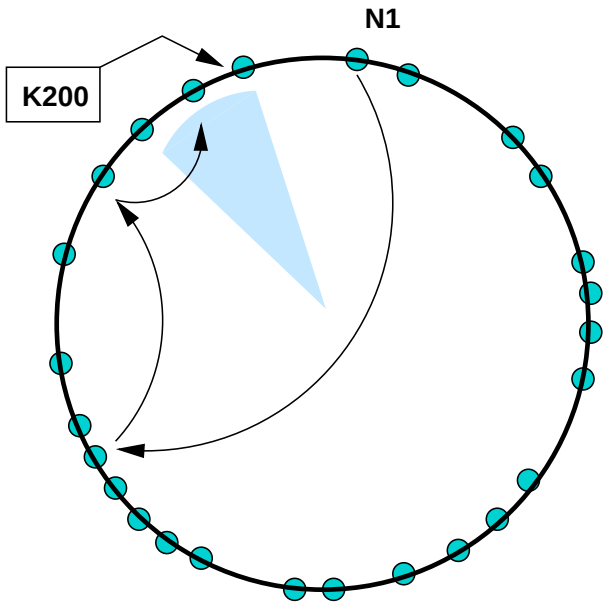

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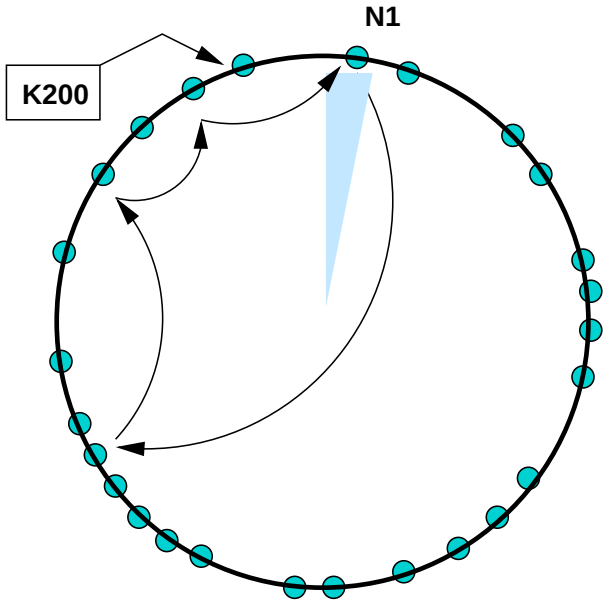
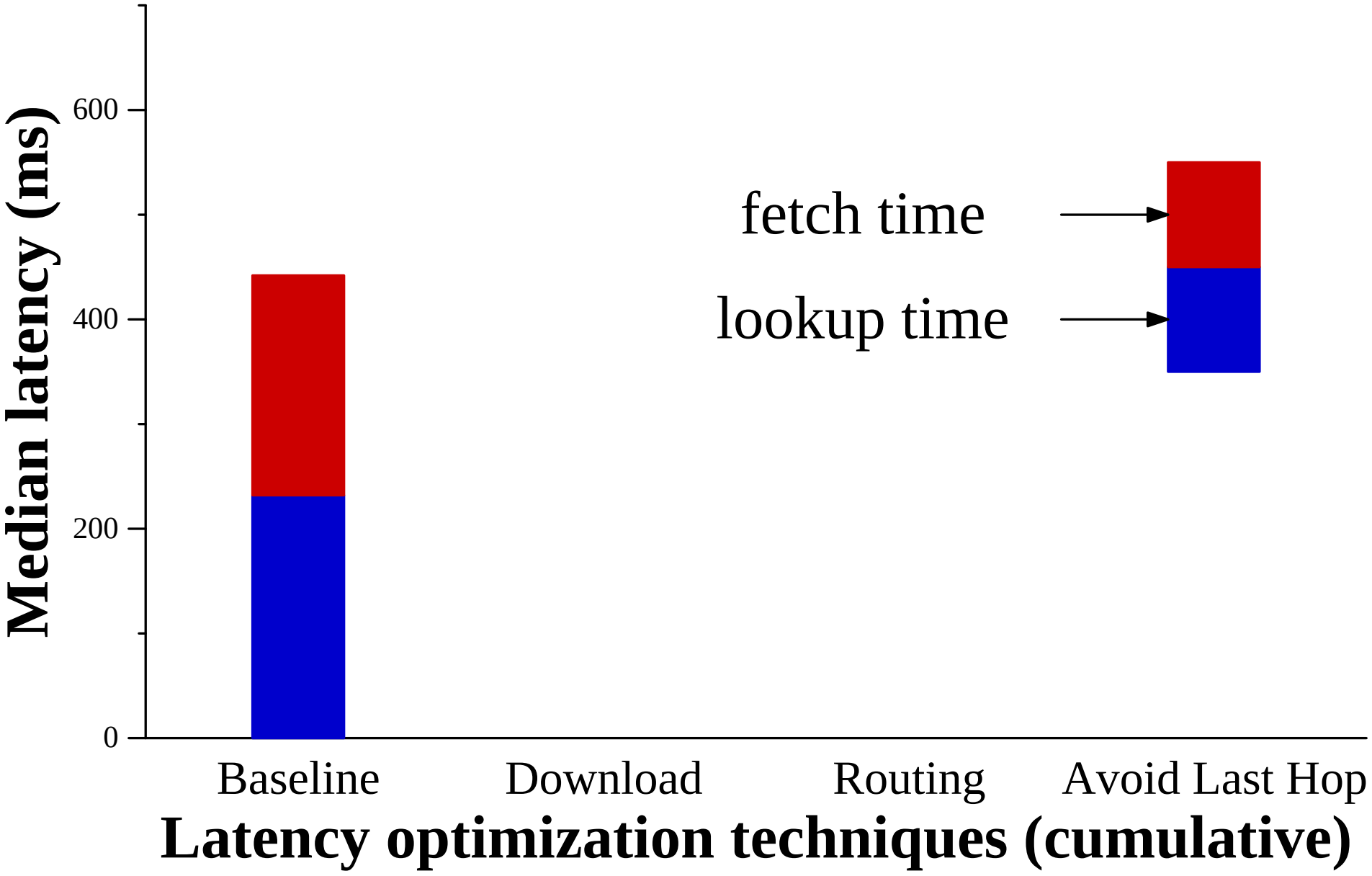


- Each hop now has a range of choices.

Vivaldi Improves Chord and DHash



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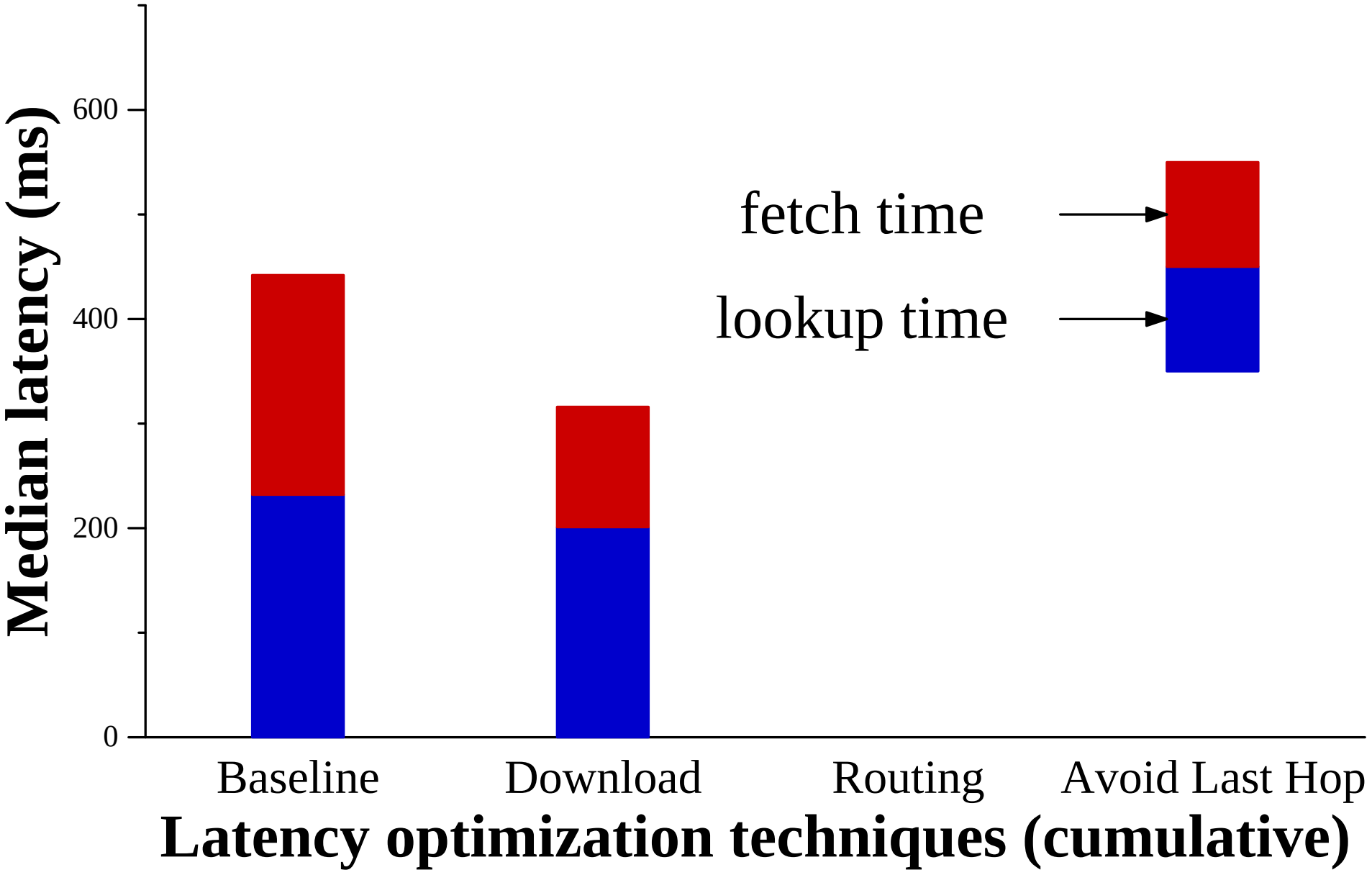

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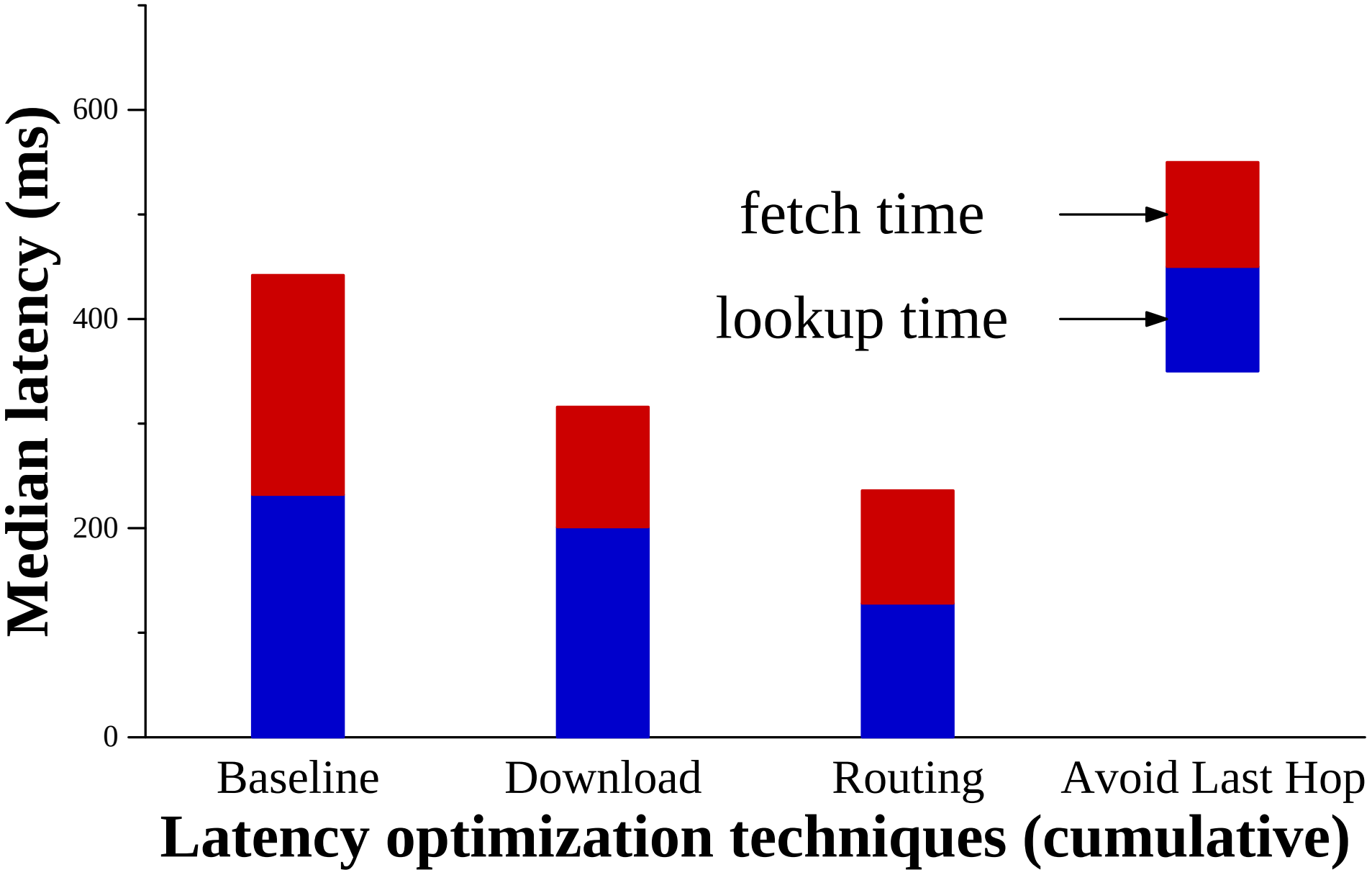

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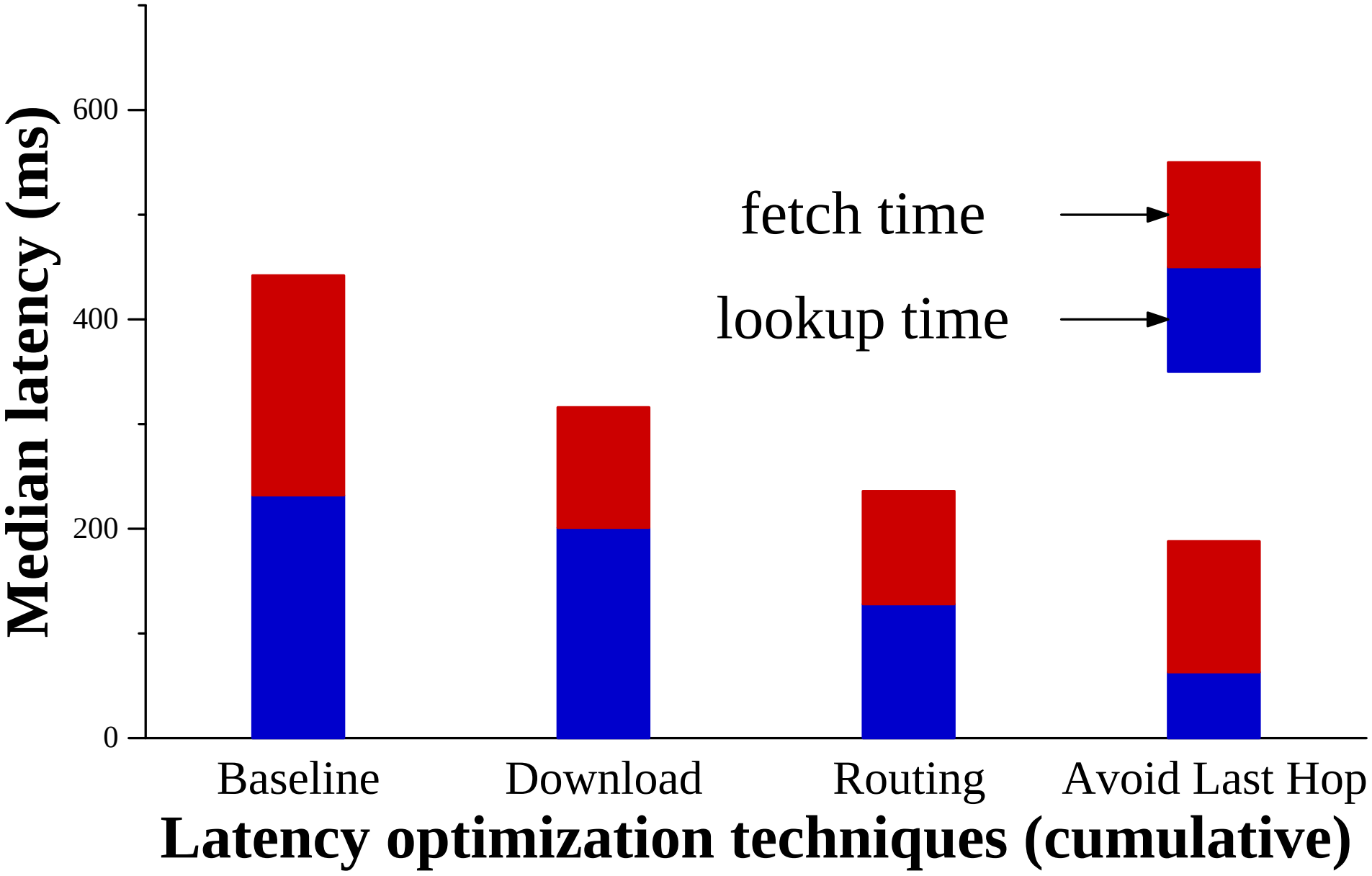

Vivaldi Improves Chord and DHash

Vivaldi improved the performance of Chord and DHash:

- Chord lookups can use nearby neighbors instead of hopping all over the globe.
- DHash replicates blocks on *r* successors of block key.
- DHash can download block from nearest replica.

- Net effect: Vivaldi reduced block fetch time by close to 50% on PlanetLab.

Vivaldi is also used by other systems:

- Bamboo Distributed Hash Table
- SWORD Resource Discovery system
- others in development

Related Work

- Other location techniques (IDMaps, IP2Geo) use static data (AS maps, guesses at physical location).
- Centralized coordinate systems (GNP, Lighthouse) need well-known landmark nodes.
- Decentralized coordinate systems (PIC, NPS) have been developed concurrently.
- Tang and Crovella (IMC 2003) analyze best Euclidean models to use; Shavitt and Tankel (Infocom 2004) suggest using hyperbolic geometries.

Conclusions

Chord is a scalable peer-to-peer system.

Vivaldi:

- accurately predicts round trip time *between node pairs not directly measured*.
- works without centralized infrastructure.
- improves the performance of a Chord and DHash

Height vectors are a promising coordinate space for the Internet.

Links

Chord home page

- `http://pdos.lcs.mit.edu/chord`

Project IRIS (Peer-to-peer research)

- http://project-iris.net

Email

- `rsc@mit.edu`