Scalable routing

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CS 538 October 3 2013

How do we route in really big networks?

Classic shortest-path routing

$\Omega(n)$ memory per node

- at least store next hop to *n* destinations

$\Omega(n)$ messages per node per unit time

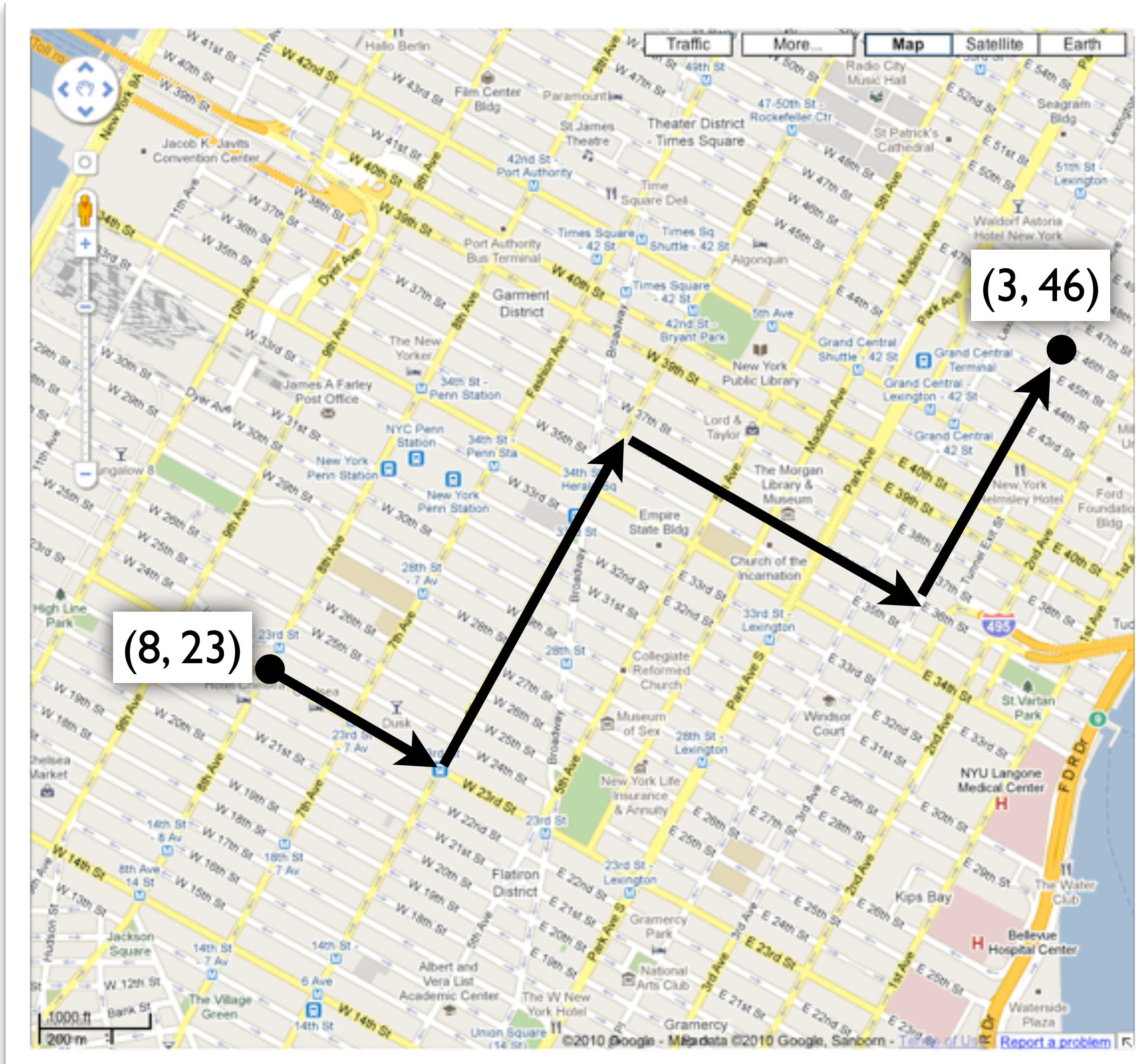
- assuming each node moves once per unit time
- also must recompute routes each of these times

if n = 1,000,000,000 and "unit time" = one day,

- ≈100–10,000x more fast path mem. than routers today
- 11,600 updates per second
- 4.4 Mbit/sec if updates are 50 bytes

How can we scale better than $\Omega(n)$ per node?

Routing in Manhattan



Recipe for scaling

1. Convert name to address
   - name: arbitrary
   - address: hint about location
   - conversion uses distributed database (e.g., DNS)
2. Nodes have partial view of network
3. To route, combine partial view with dest. address

Challenge: how do we summarize the network in the partial view and address?

- And what *exactly* are we trying to achieve?

Key goals

Addresses are small

Node state is small

Routes are short

- stretch = $\frac{\text{route length}}{\text{shortest path length}}$

How does Manhattan routing do?

- Assume square grid of *n* nodes ($\sqrt{n} \times \sqrt{n}$)
- Address is (street, avenue); nodes store neighbors' addr.
- Address size: $2\log_2(\sqrt{n}) = \log_2 n$
- Node state: $\approx 4\log_2 n$
- Route length: shortest (stretch 1) *if we know address!*

Outline

Scalable routing in structured networks

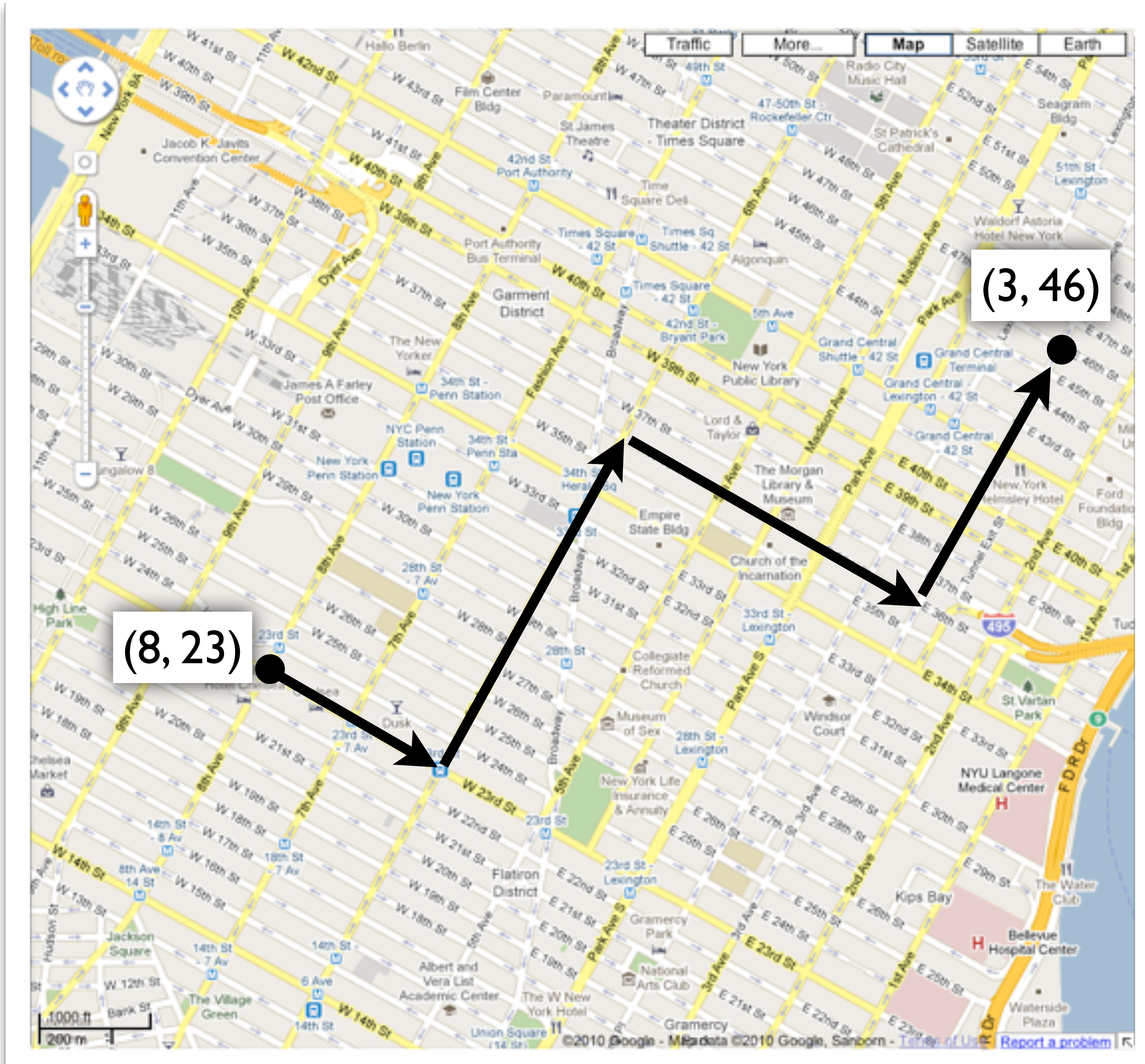
- Manhattan routing
- Greedy routing
- NIRA

Scalable routing in arbitrary networks

- Hierarchy
- Compact routing

Structured networks

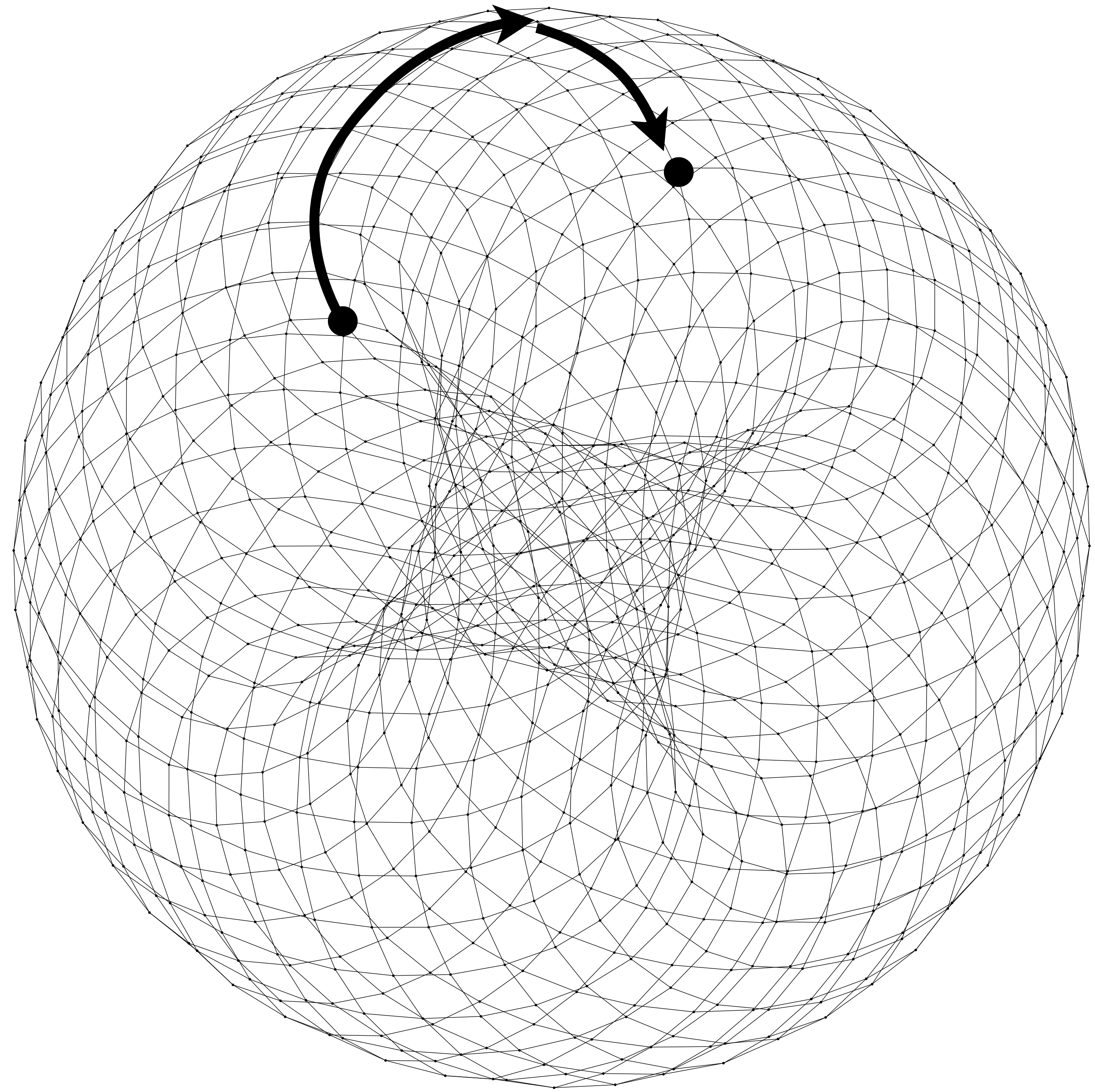
Grid



Torus

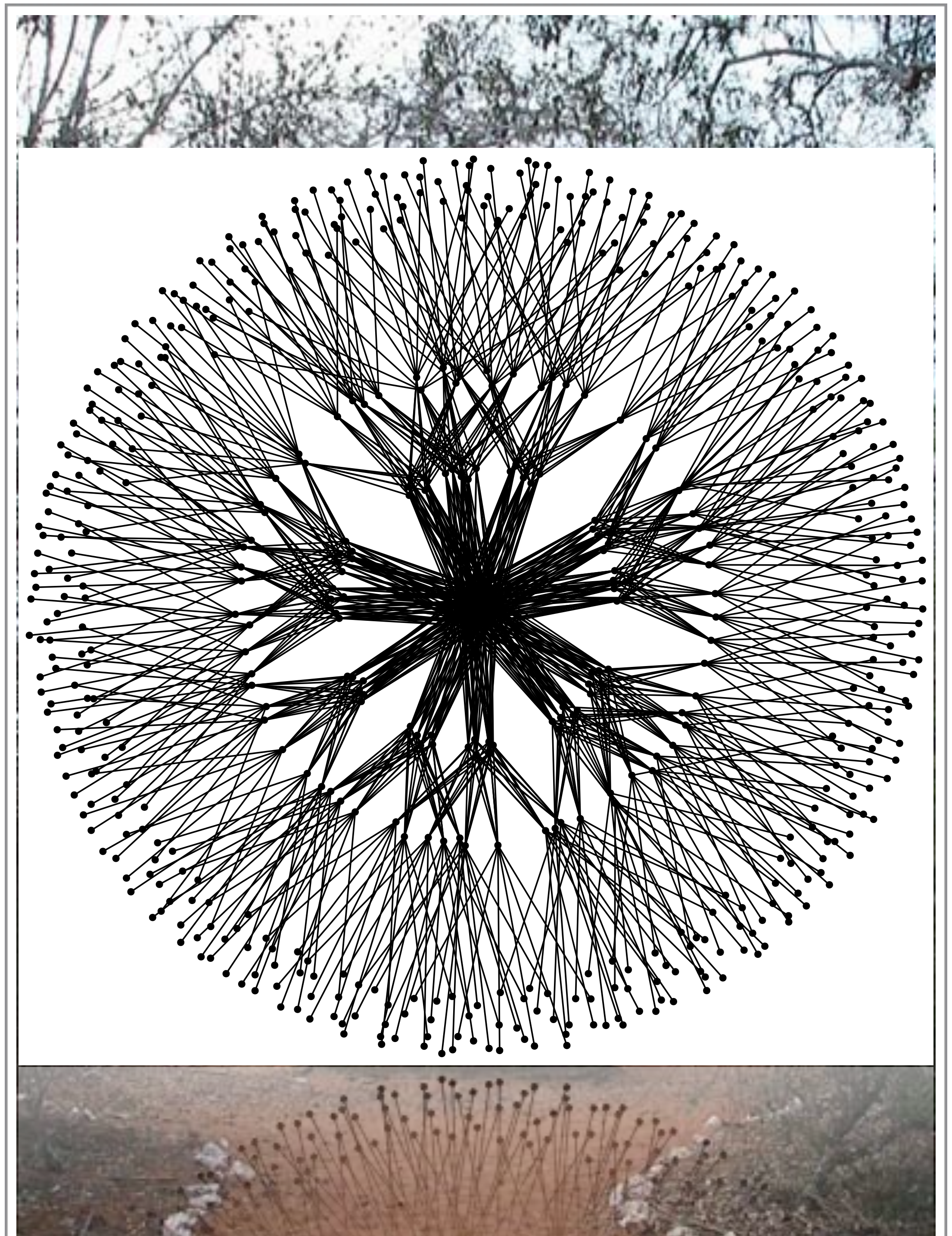
3D Torus

[Cray T3D press shot via hexus.net]

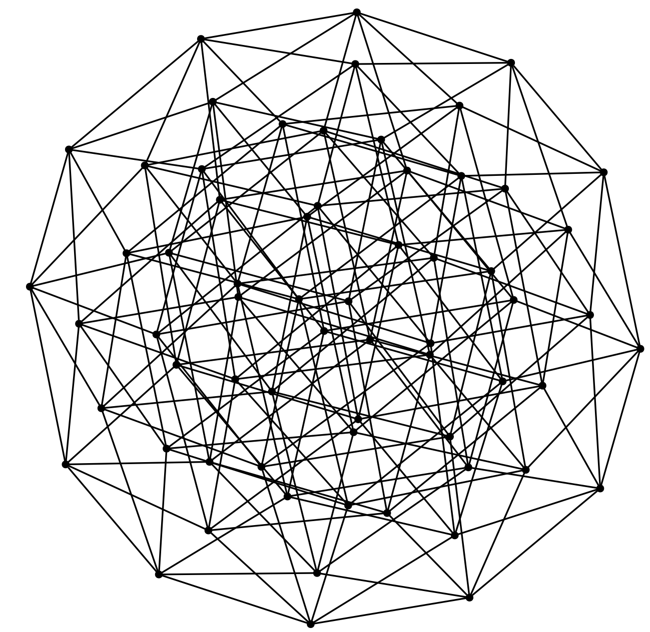


2D Torus

A plethora of structured graphs!

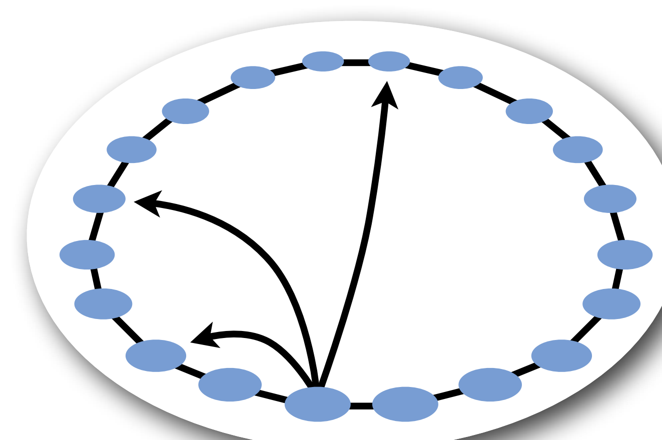


Hypercube
Supercomputers,
distributed hash tables



Fat tree
Supercomputers,
data centers

Small world
distributed hash tables



Greedy routing

Technique common in many structured networks

Scheme:

- Each node knows addresses of itself & neighbors
- Given two addresses, can estimate "distance" between them: dist(s,t)
- Forwarding at node v: send to neighbor w which minimizes dist(v,w) + dist(w,d)

What structure does this require?

- Compact addresses that can "summarize" location
- Good estimator of distance dist(s,t)

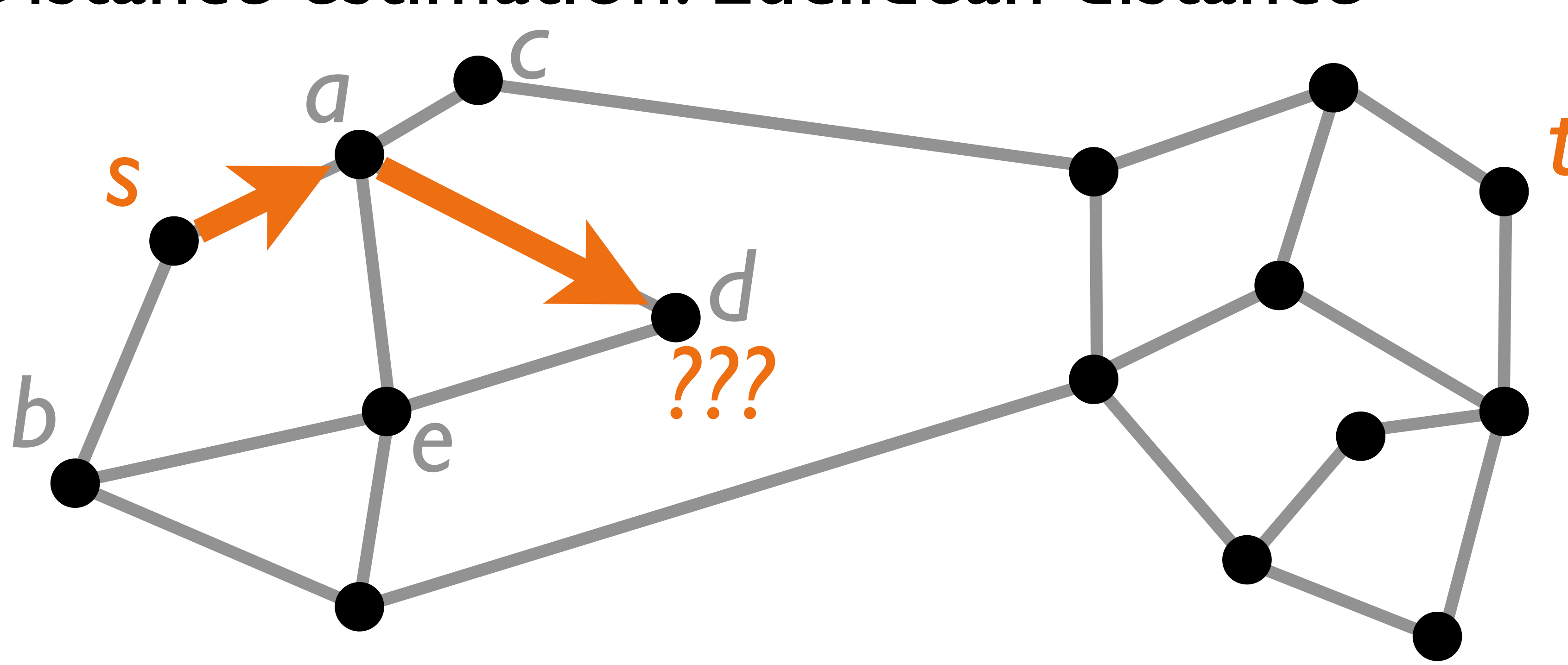
Greedy routing examples

#1: Manhattan routing

- Address: (*x*, *y*) coordinate on grid
- Distance 'estimation' of (*x*, *y*) to (*x'*, *y'*) = |*x*-*x'*| + |*y*-*y'*|

#2: Greedy geographic routing

- Address: physical location (e.g., (*x*,*y*) coord. from GPS)
- Distance estimation: Euclidean distance



If local minima in dist(), we're stuck!

Greedy Perimeter Stateless Routing

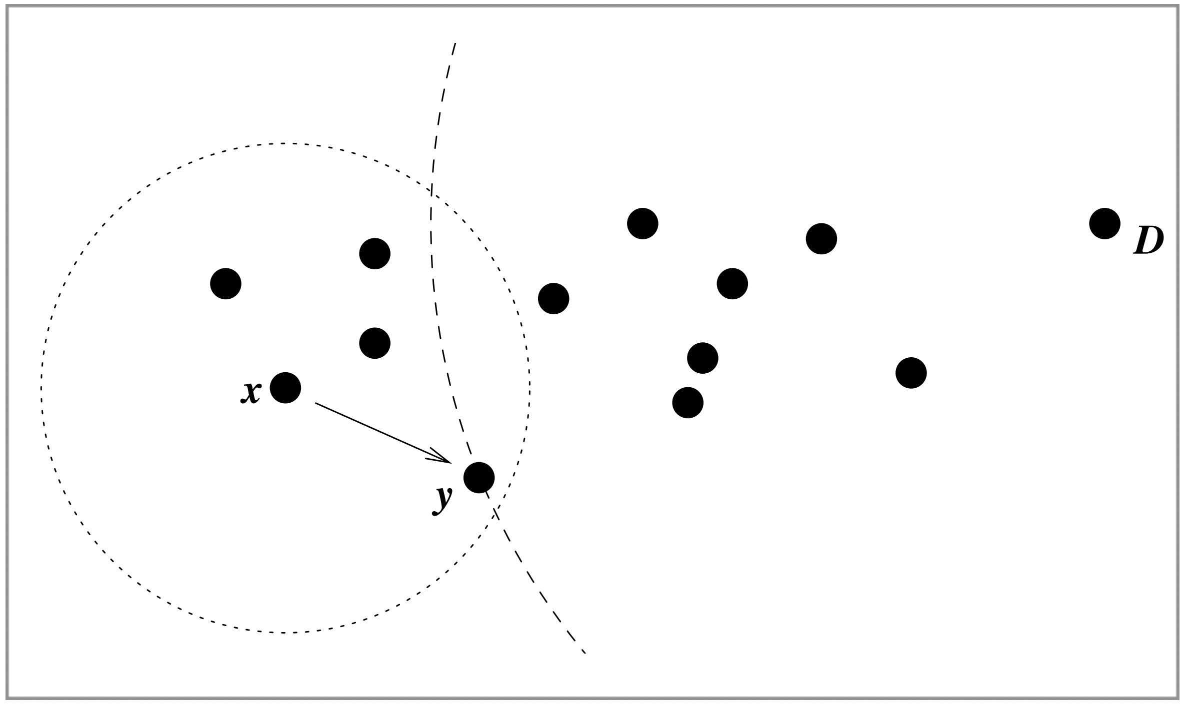
[Karp, Kung, MobiCom '00]

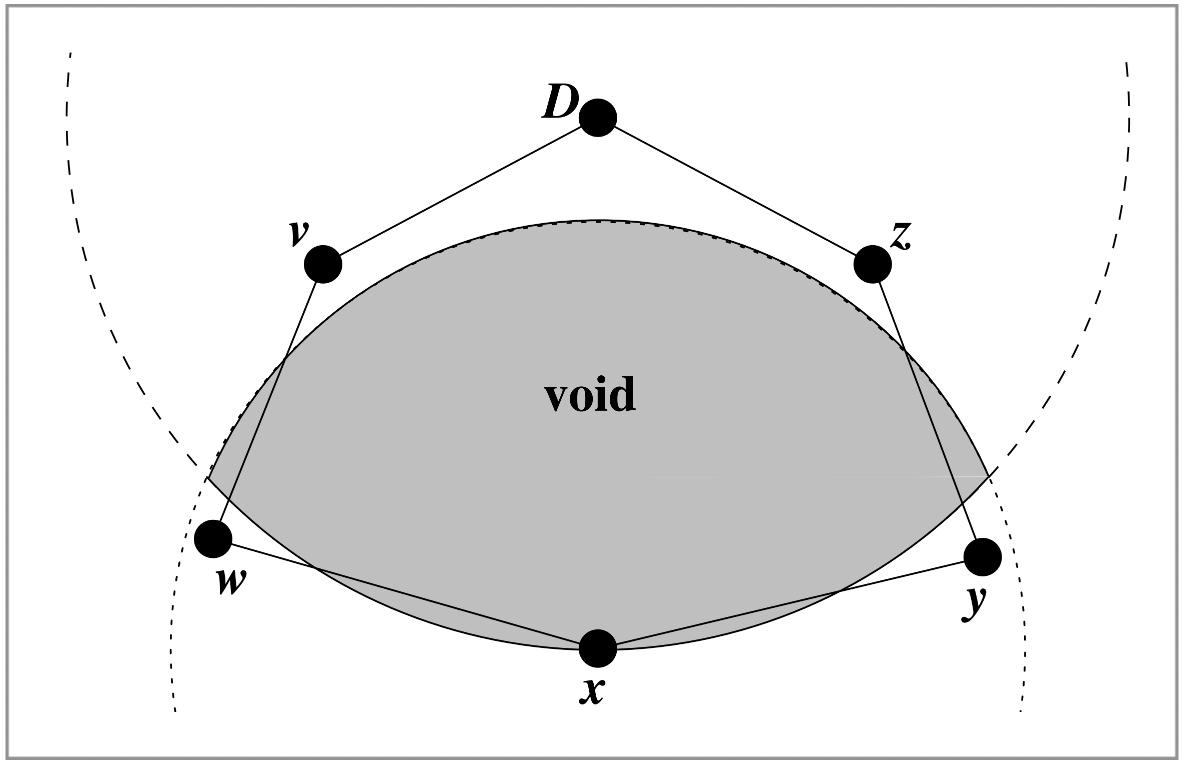
Address is physical location, e.g., from GPS

Distance estimate is Euclidean distance

If we get stuck...

- = no neighbor is closer to destination *D* than we are!
- Then planarize graph and traverse perimeter of void

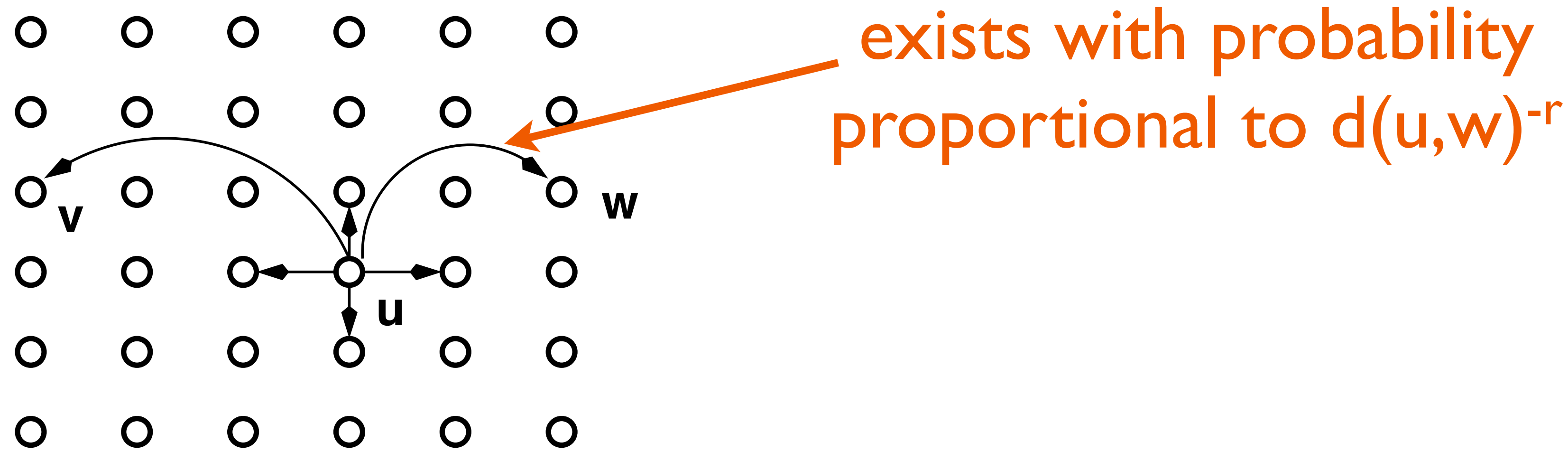




Greedy example #3: Small worlds

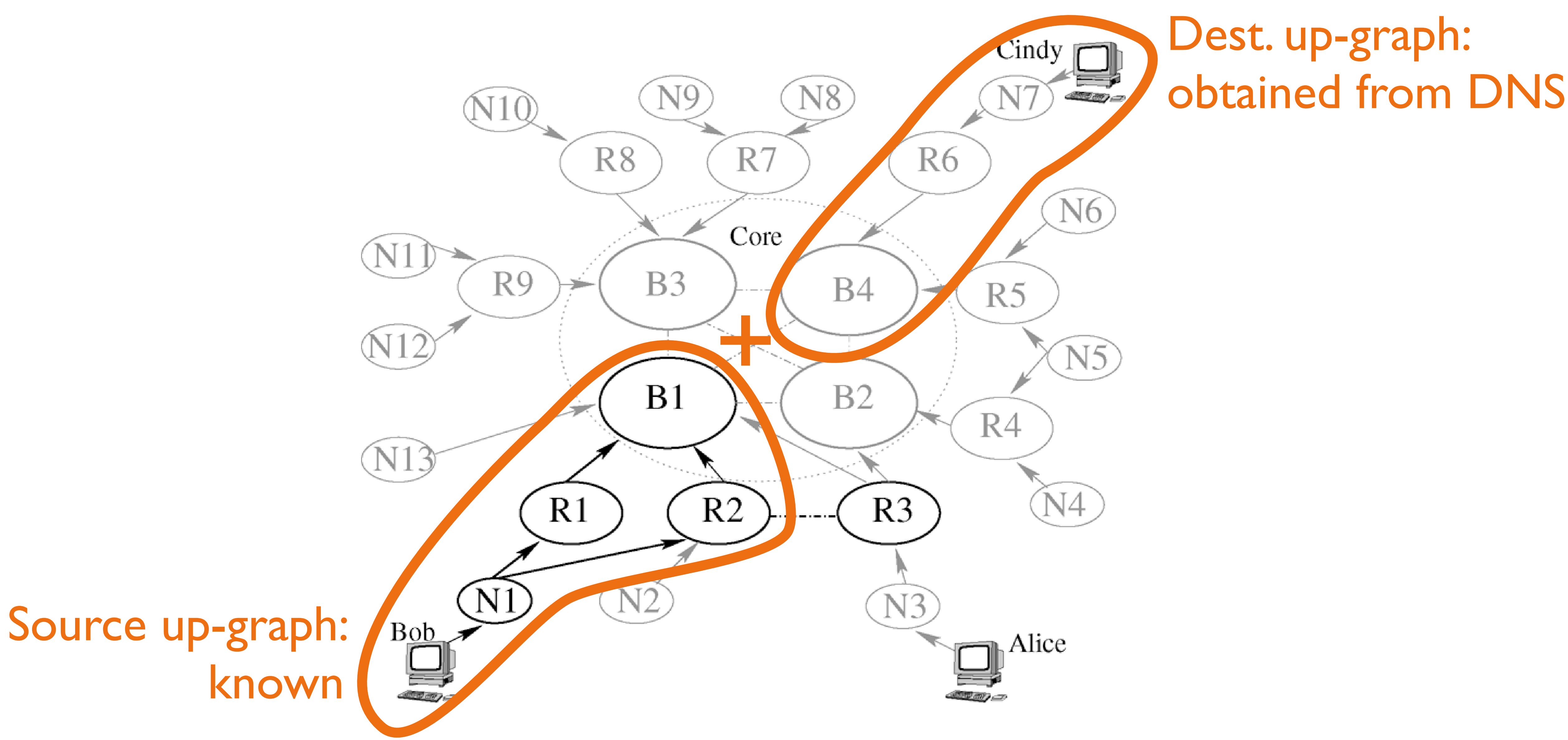
"Small world" effect demonstrated by Milgram ['67]

Kleinberg's model: *n* x *n* lattice, plus long range edges



Result: greedy routing finds short ($O(\log^2 n)$) paths with high probability if and only if $r = 2$

Non-greedy: NIRA [Yang et al '07]

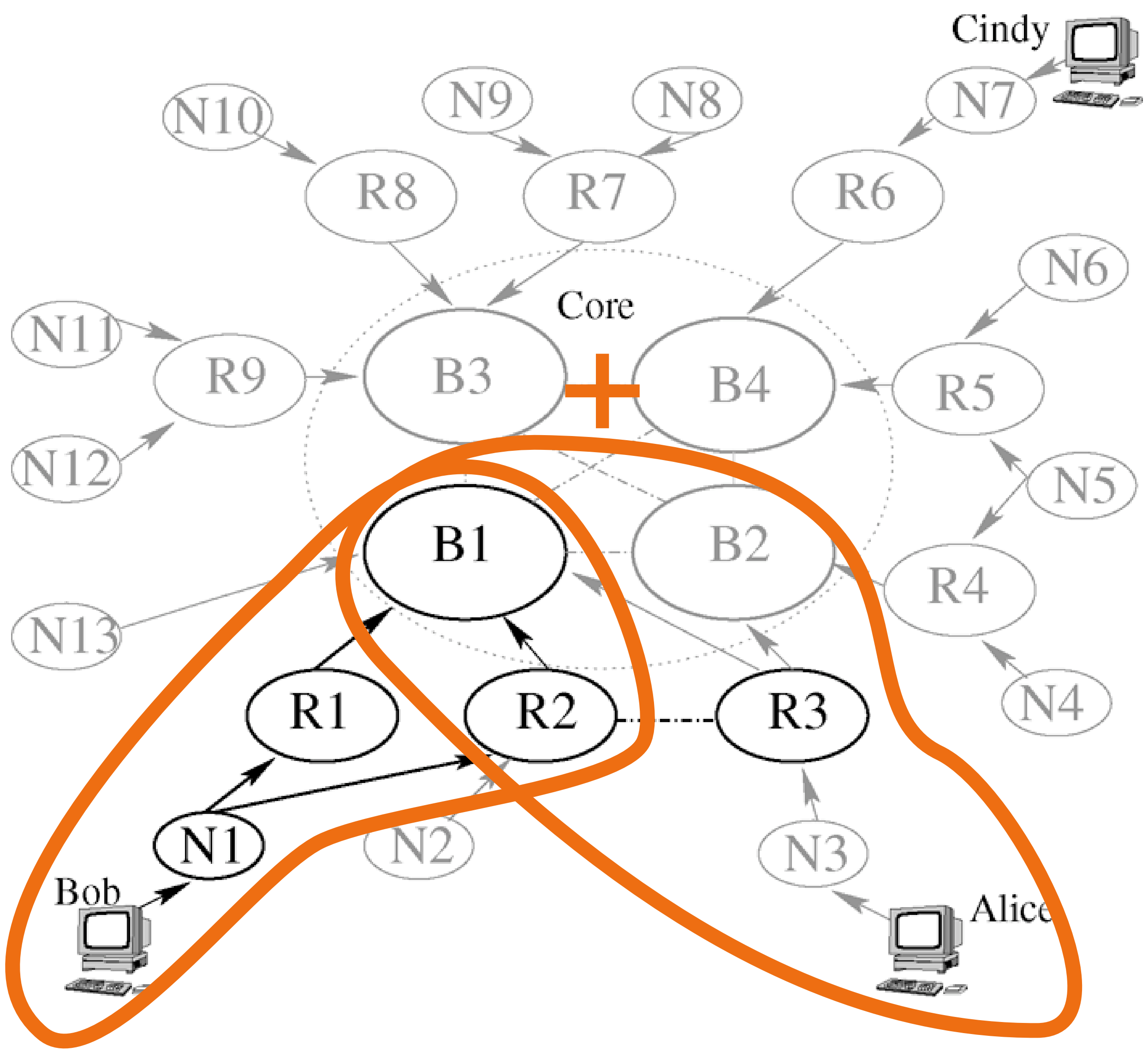


Assumes a graph with a "core"

- routes go up to core (provider links), over (peering links), and down (customer links)
- i.e., "valley-free"

Non-greedy: NIRA [Yang et al '07]

Dest. up-graph: obtained from DNS



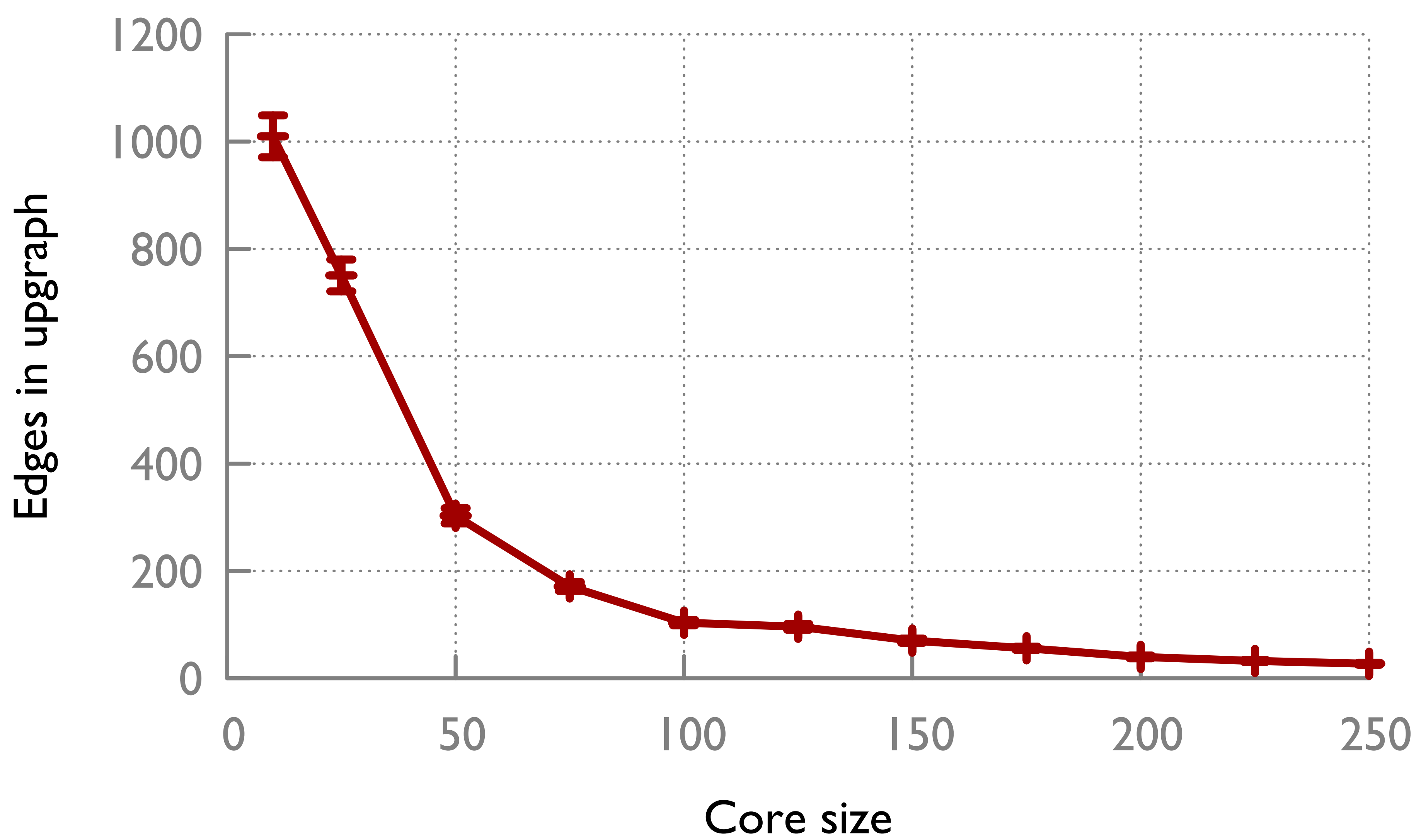
Source up-graph: known

Assumes a graph with a "core"

- routes go up to core (provider links), over (peering links), and down (customer links)
- i.e., "valley-free"

NIRA key ideas

Up-graphs are small



[Calculation using 2013 CAIDA Internet topology data]

NIRA key ideas

Up-graphs are small

Union of source and dest subgraphs is all we need

- exploits Internet's current structure to find good paths

Address is effectively a subgraph, not just a number!

- here "address" means "destination-specific location info"

Q: How well does NIRA satisfy our goals?

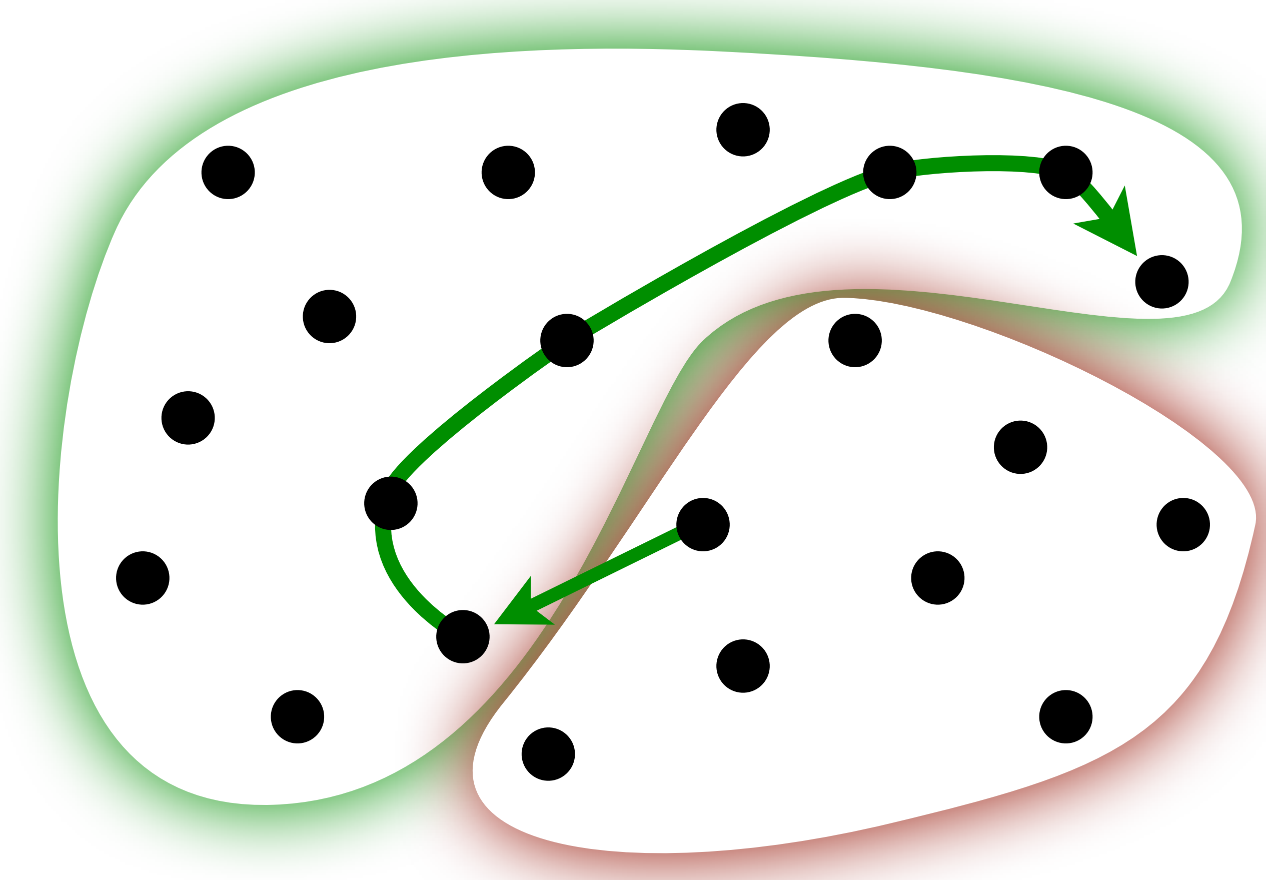
- small address
- small node state
- low stretch

But what if our network
does not have a
“special” structure?

Technique in practice: Hierarchy

No structure? Make one!

- 2-level hierarchy: nodes in clusters
- each node knows how to reach one node of each cluster and all nodes in its own cluster



Problems:

- Some paths very long
- Location-dependent addresses (as in earlier techniques)

128.112.128.81

Fundamental tradeoffs

Can we achieve our key goals?

- Low state
- Low stretch (short paths)
- Short addresses

Or, does scalability force us to give something up?

Compact routing theory

Given arbitrary graph, scheme must:

- Construct state (forwarding tables) at each router
- Specify forwarding algorithm:
  - Input: Forwarding table, incoming packet
  - Output: Packet's next hop (+ optionally change header)

Goals:

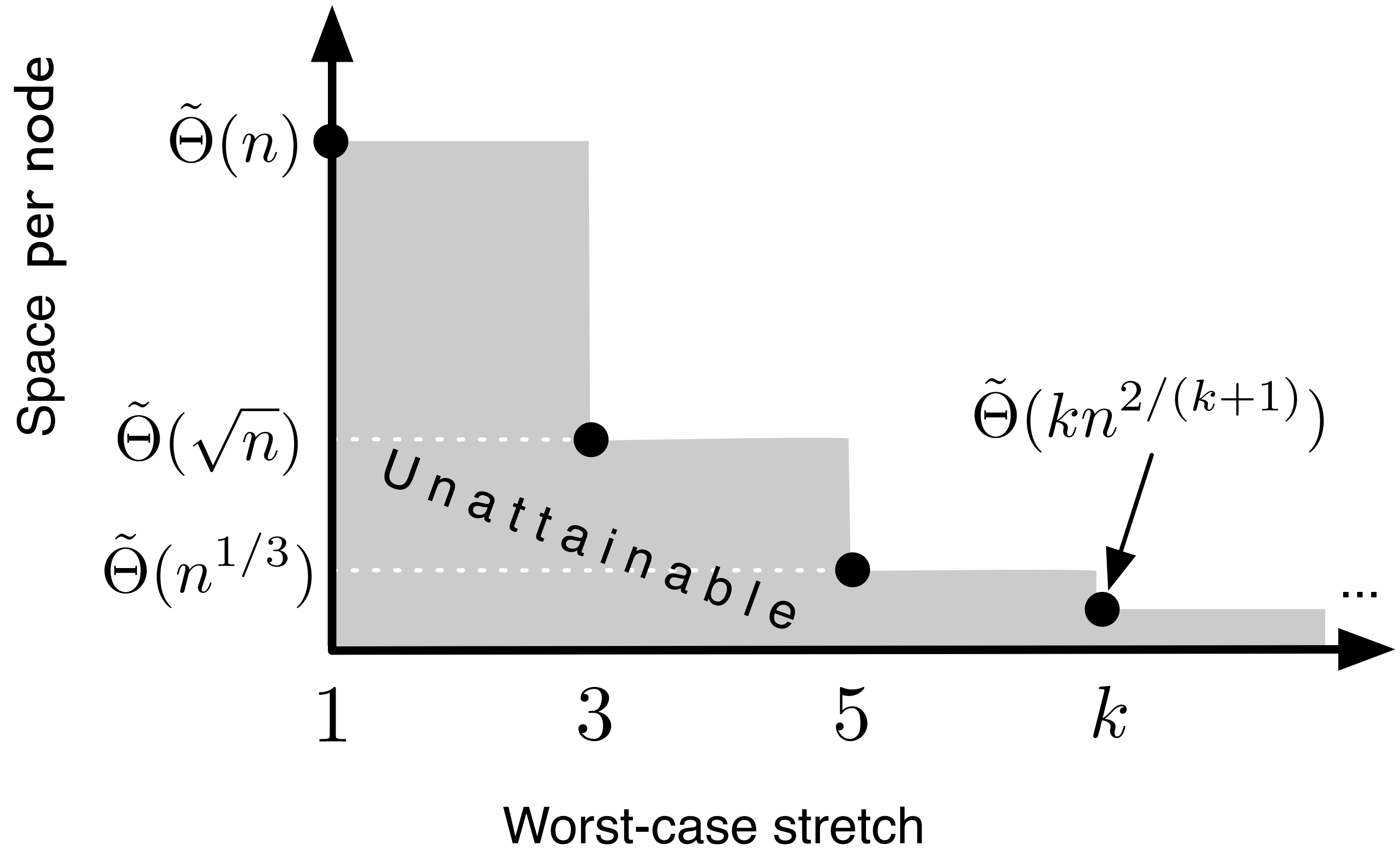
- Minimize maximum state at each router (FIB memory)
- Minimize maximum stretch:

$$\max_{s,t} \frac{s \rightsquigarrow t \text{ route length}}{s \rightsquigarrow t \text{ shortest path length}}$$

- Reasonably small packet headers (e.g., O(log *n*))

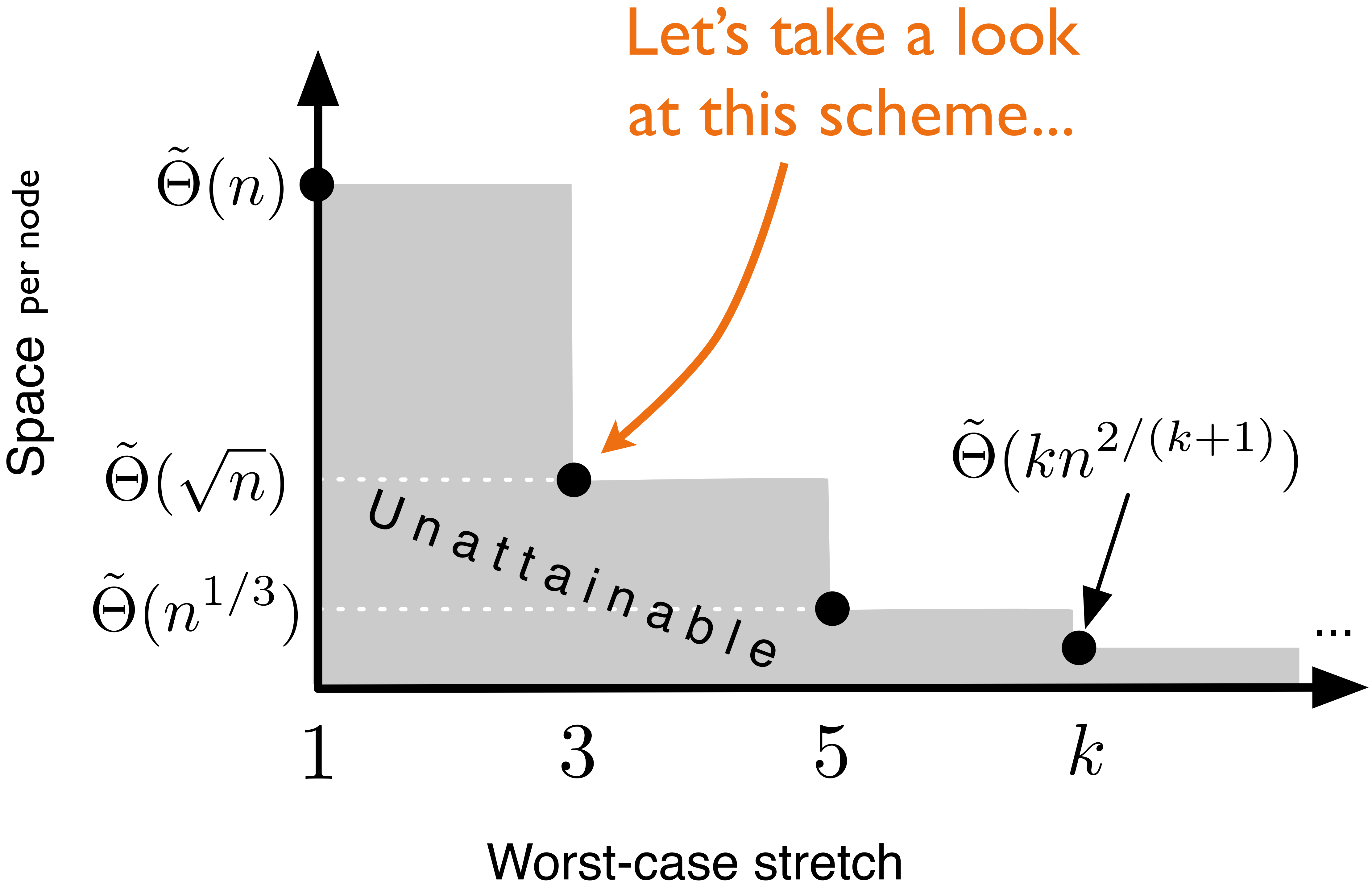
Compact routing theory

[Peleg & Upfal '88,
Awerbuch et al. '90,
...,
Cowen '99,
Thorup & Zwick '01,
Abraham et al. '04]



Name-dependent	Addresses assigned by routing protocol
Name-independent	Arbitrary ("flat") names e.g., DNS or MAC address

Compact routing theory

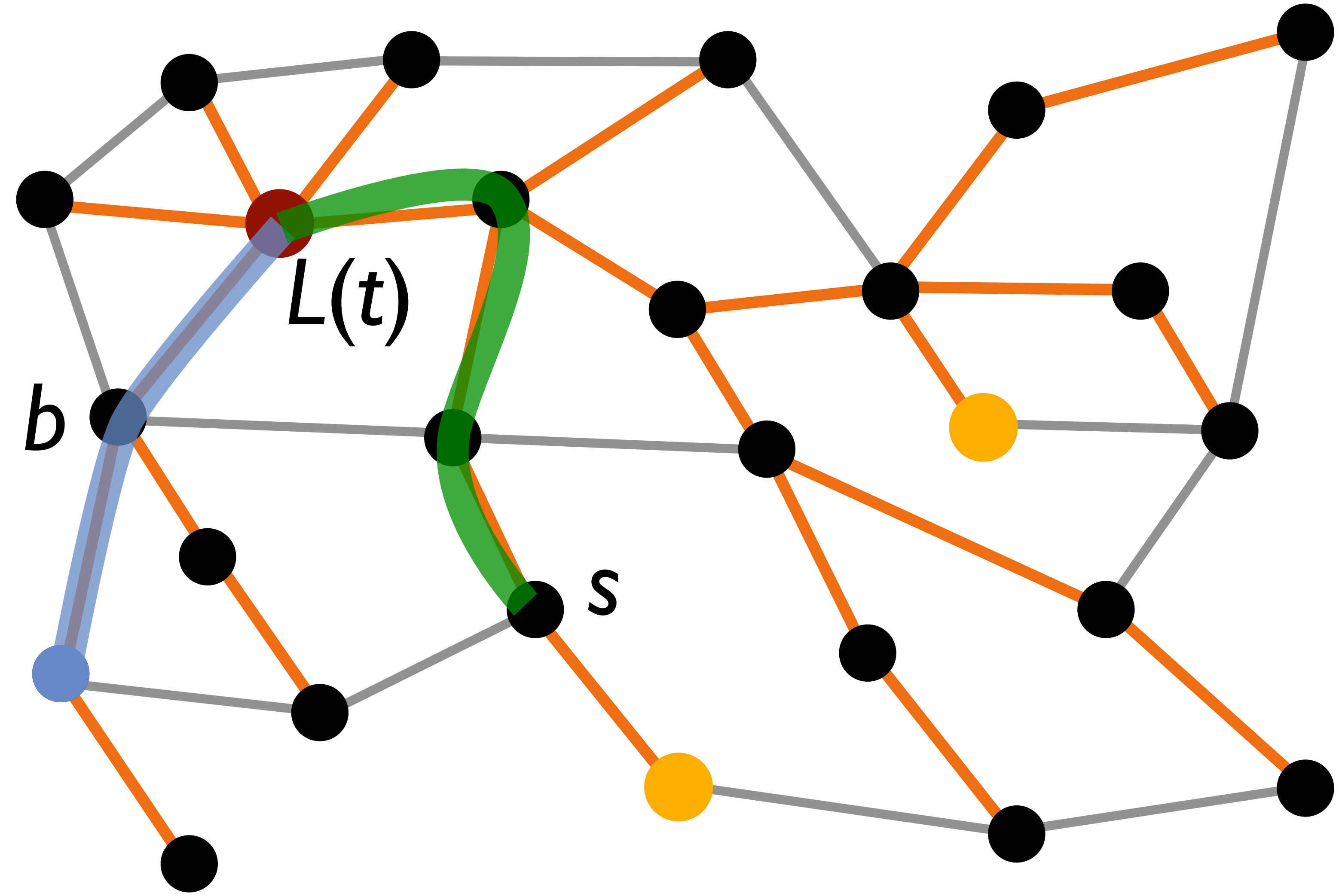


Landmarks

Everyone knows shortest path to landmarks.

Used to define address:

addr(t) = ($L(t)$,b,t)



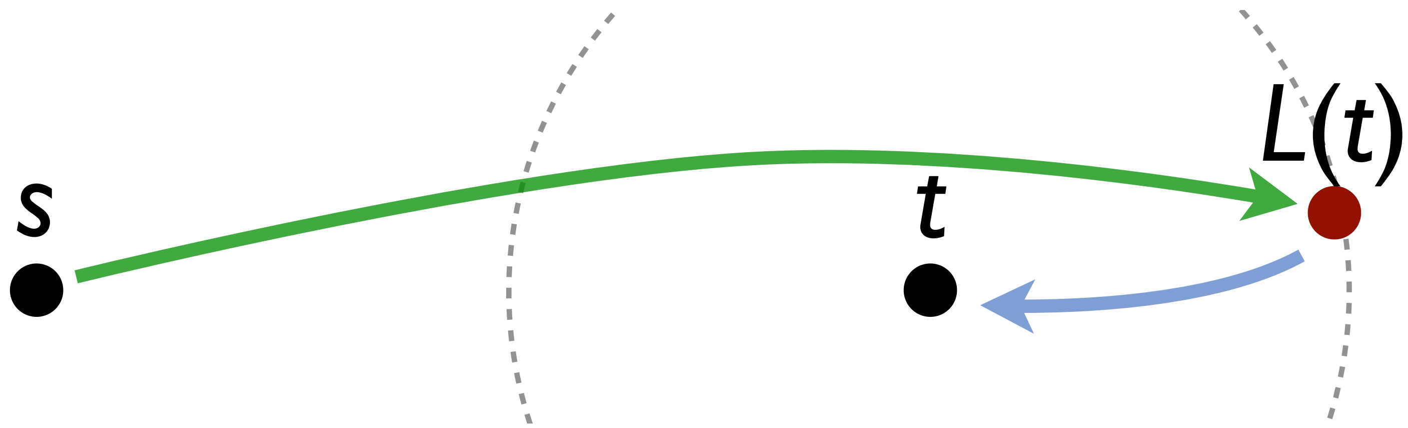
route length = dist. to landmark + dist. to t

$\leq d(s,t) + d(t,L(t)) + d(L(t),t)$

triangle inequality

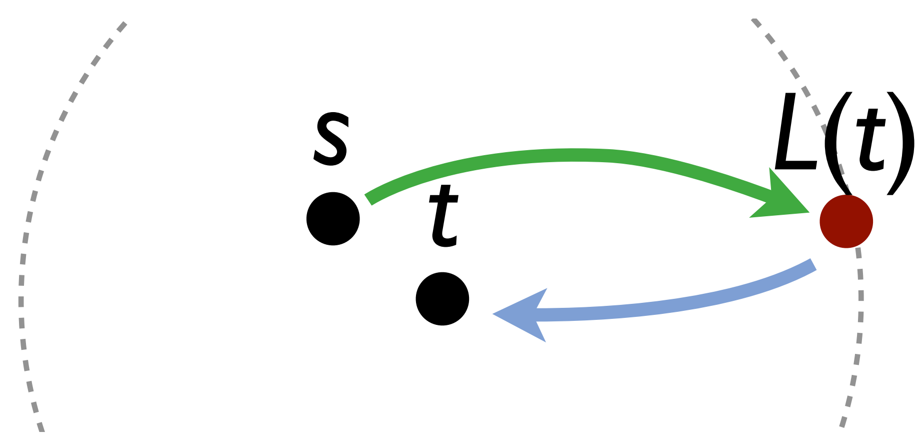
Stretch analysis

Case 1: $d(s,t) \geq d(t,L(t))$: further than landmark



- route length $\leq d(s,t) + d(t,L(t)) + d(L(t),t) \leq 3d(s,t)$

Case 2: $d(s,t) < d(t,L(t))$: closer than landmark



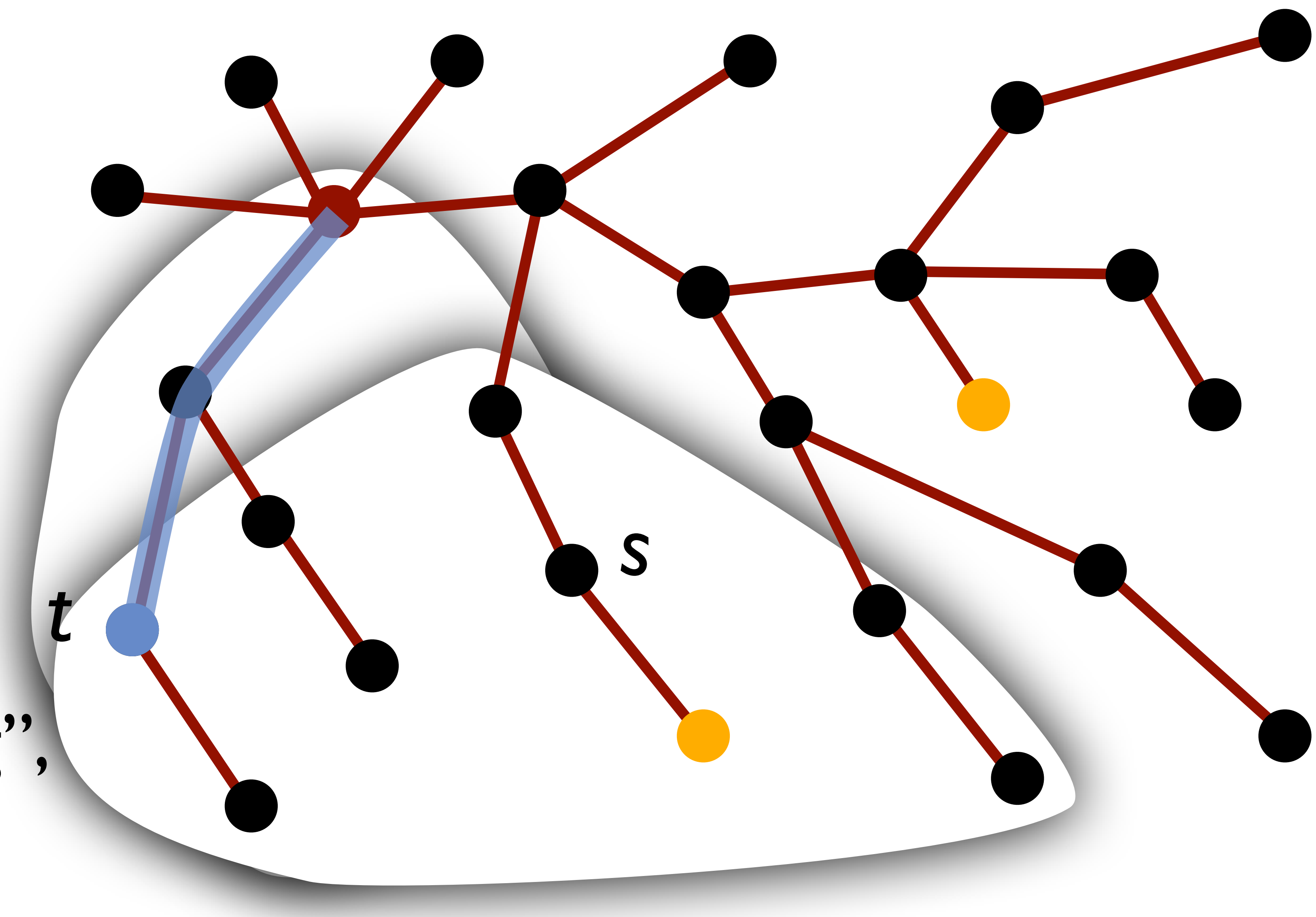
- Trouble!
- Idea: in Case 2, just remember the shortest path.

Vicinities

~~$V(s)$ = nodes t s.t. $d(s,t) < d(t,L(t))$~~

$V(s)$ = nodes t s.t. $d(s,t) < d(s,L(s))$

Requires "handshaking", but convenient to implement



How big are $V(t)$?

Need a landmark in my vicinity.

$\tilde{\Theta}(\sqrt{n})$ random landmarks: $\tilde{\Theta}(\sqrt{n})$-size vicinities

Tool: Chernoff bound

"The sum of many small independent random variables is almost always close to its expected value."

X_i = m independent (0,1) random variables

$X = \sum X_i$, $E[X] = \mu$

For any $0 \leq \delta \leq 2e - 1,$

$$\Pr[X < (1-\delta)\mu] < e^{-\mu\delta^2/2}$$
$$\Pr[X > (1+\delta)\mu] < e^{-\mu\delta^2/4}$$

See, e.g., Motwani & Raghavan, Theorems 4.1 - 4.3

How many landmarks are enough?

Show that any node *v* always has ~ln *n* landmarks in its vicinity if we use about $\sqrt{c \cdot n \ln n}$ landmarks

$X_i = 1$ if *i*th closest node to *v* is landmark, else $X_i = 0$

$$\Pr[X_i] = \frac{\sqrt{c \cdot n \ln n}}{n}$$

$$E[X] = (\text{Number of nodes in vicinity}) \cdot \Pr[X_i]$$

$$E[X] = \sqrt{c \cdot n \ln n} \cdot \frac{\sqrt{c \cdot n \ln n}}{n}$$

$$= c \ln n$$

Increase *c* to make this arbitrarily small

$$\Pr\left[X < \frac{1}{2} c \ln n\right] < e^{-(c \ln n) \cdot \frac{1}{4} \cdot \frac{1}{2}} = e^{\ln n^{-c/8}} = n^{-c/8}$$

Chernoff bound

Analysis

Stretch

- $\leq$ 3 if outside vicinity (after "handshake")
- = 1 if inside vicinity

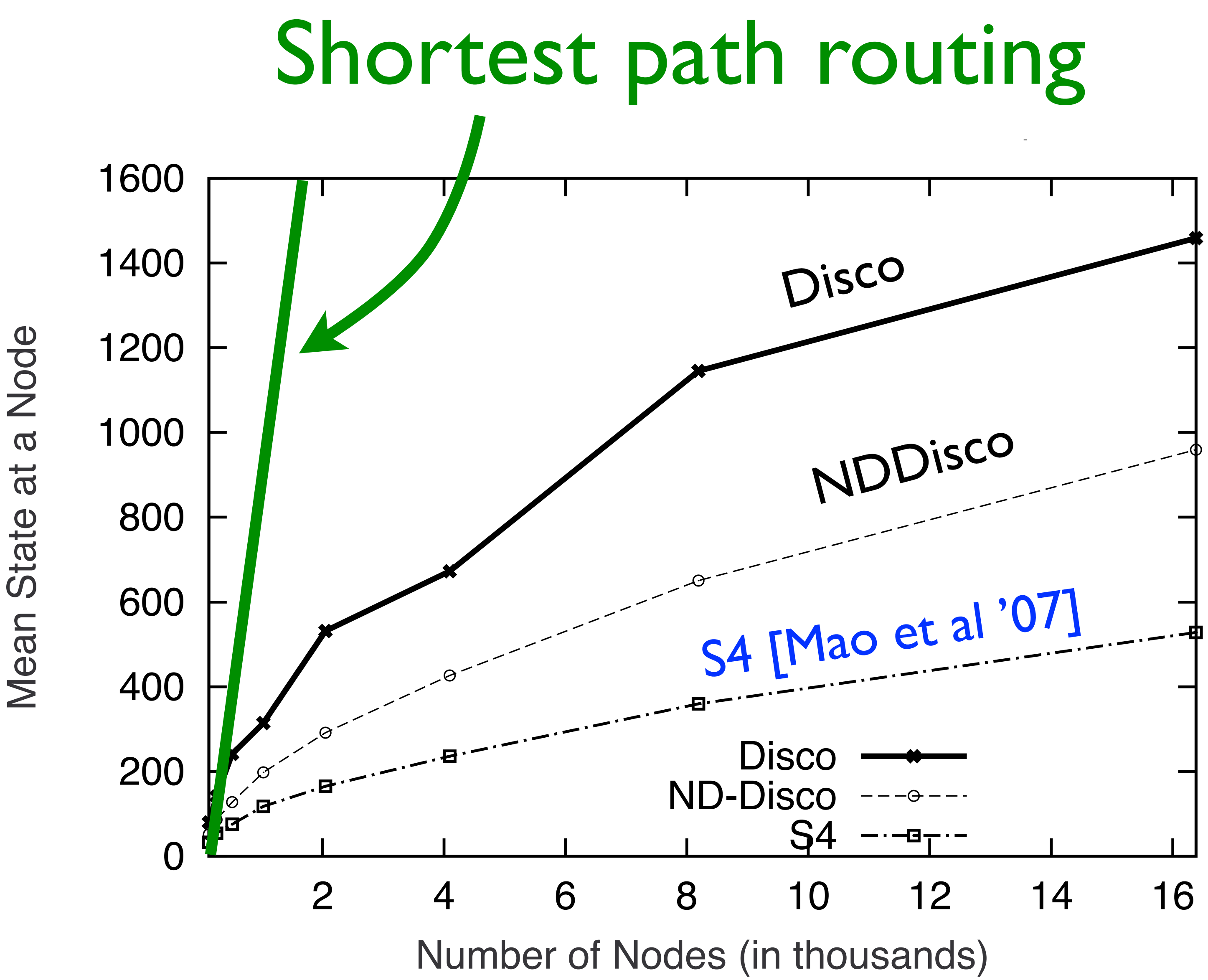
State (data plane)

- Routes to landmarks: $O(\sqrt{n \log n} \cdot \log n) = \tilde{\Theta}(\sqrt{n})$
- Routes within vicinity: $O(\sqrt{n \log n} \cdot \log n) = \tilde{\Theta}(\sqrt{n})$

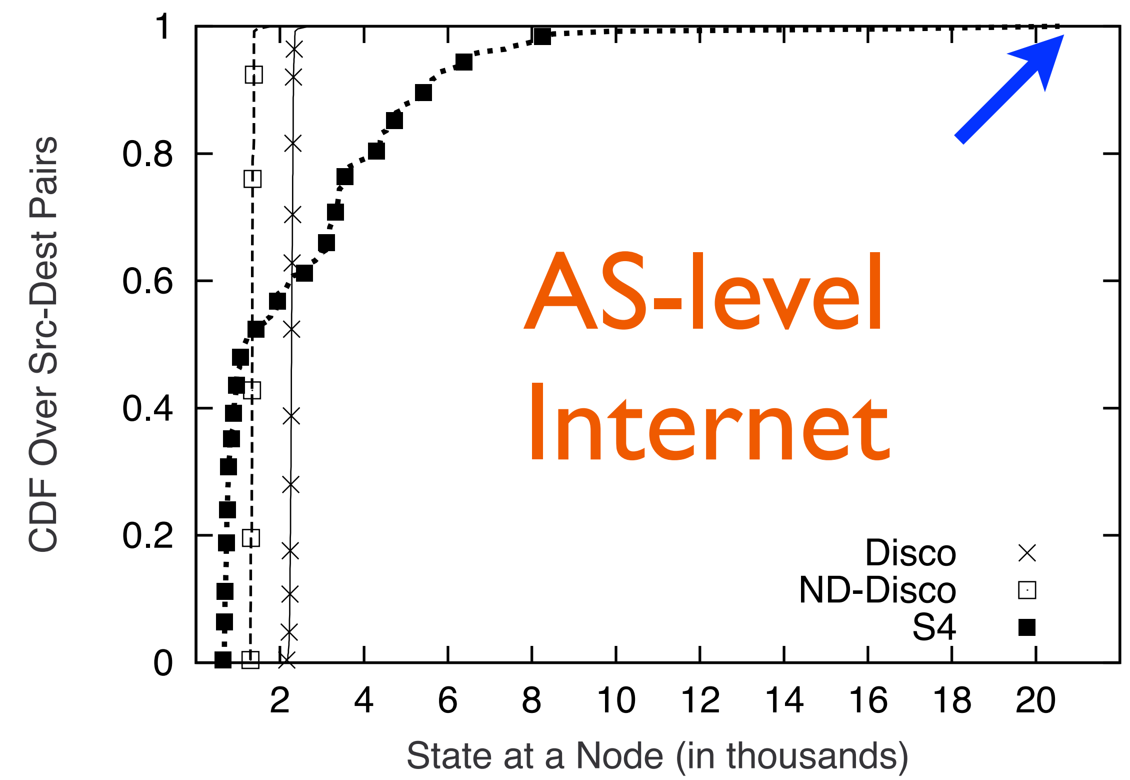
Address size

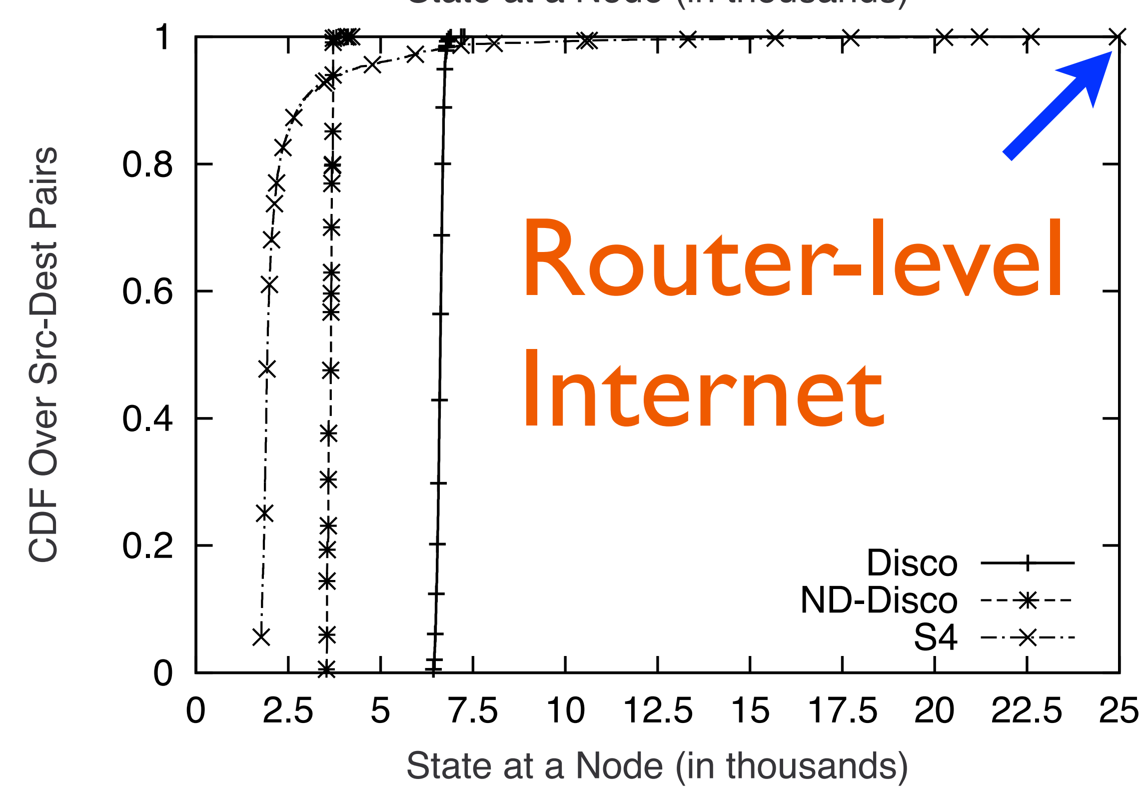
- Simple implementation: depends on path length, but very short in practice
- More complicated/clever storage of route from landmark to destination: $\Theta(\log n)$

State in example networks

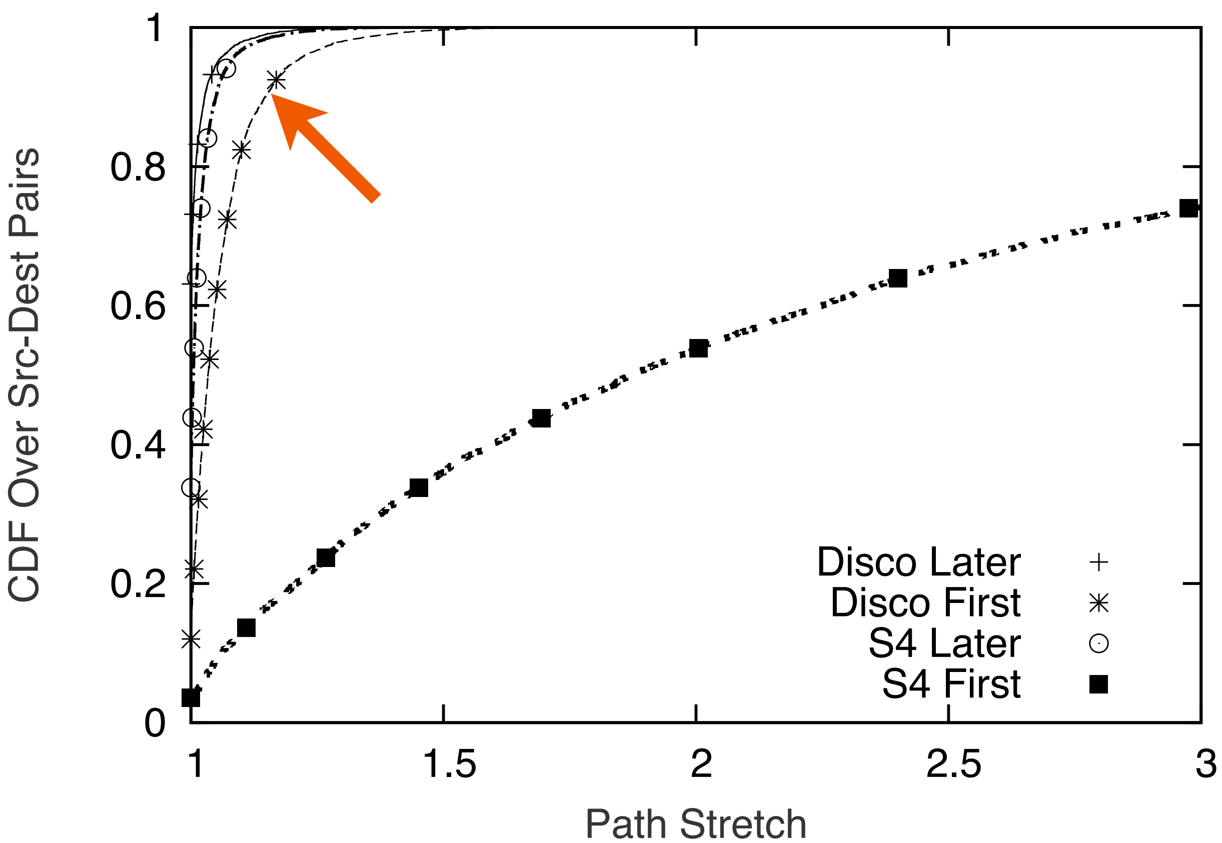


Geometric random graphs

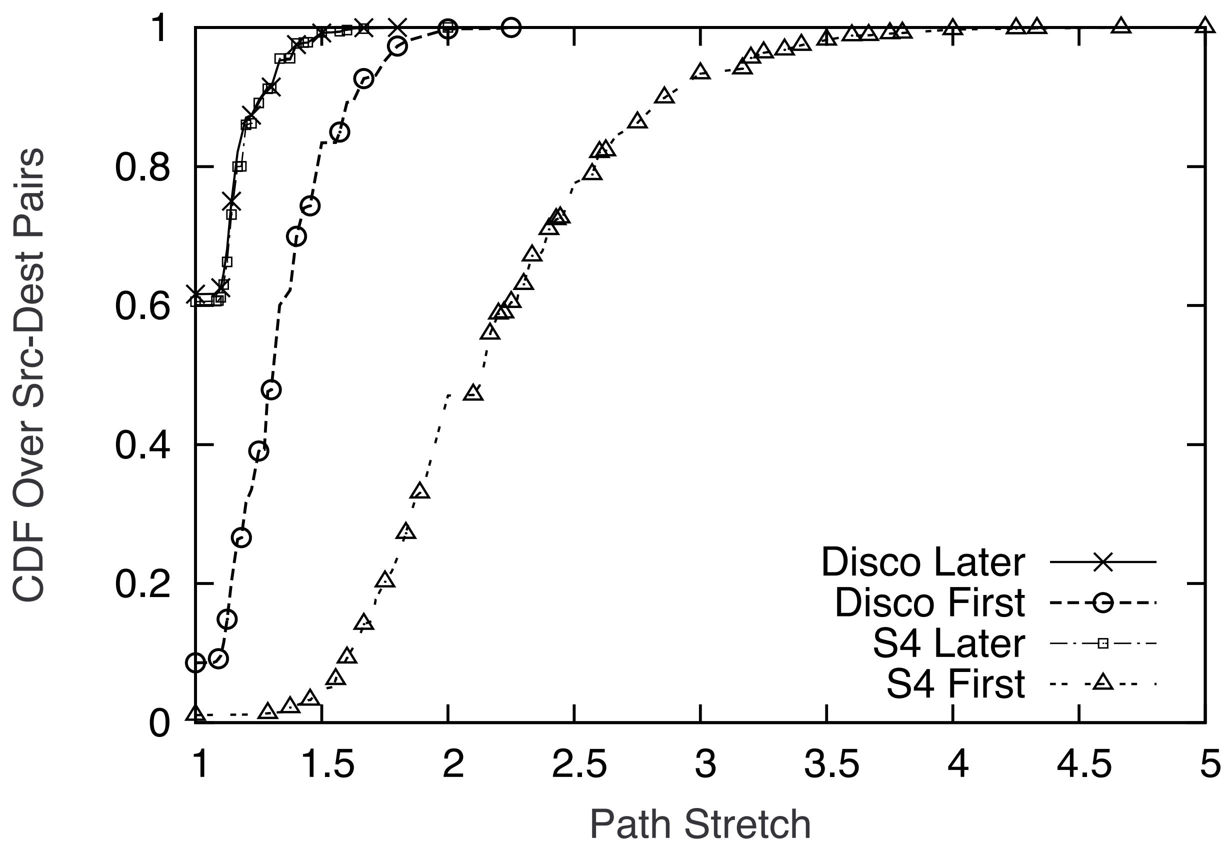




Stretch in example networks



16,000-node Geometric random graph



Router-level Internet topology

What we're not seeing

Routing on flat names with low stretch and state

- we assumed source knows destination address

Other points state-stretch tradeoff space

- we saw state ~$n^{1/2}$, stretch 3

Why you cannot do better than this

- ...in the general case (dense graphs)

Why you can do better than this

- ...if the network is sparse (few edges), as essentially all real networks are

What we're not seeing

Distributed compact routing

- How do you compute FIBs without global view?

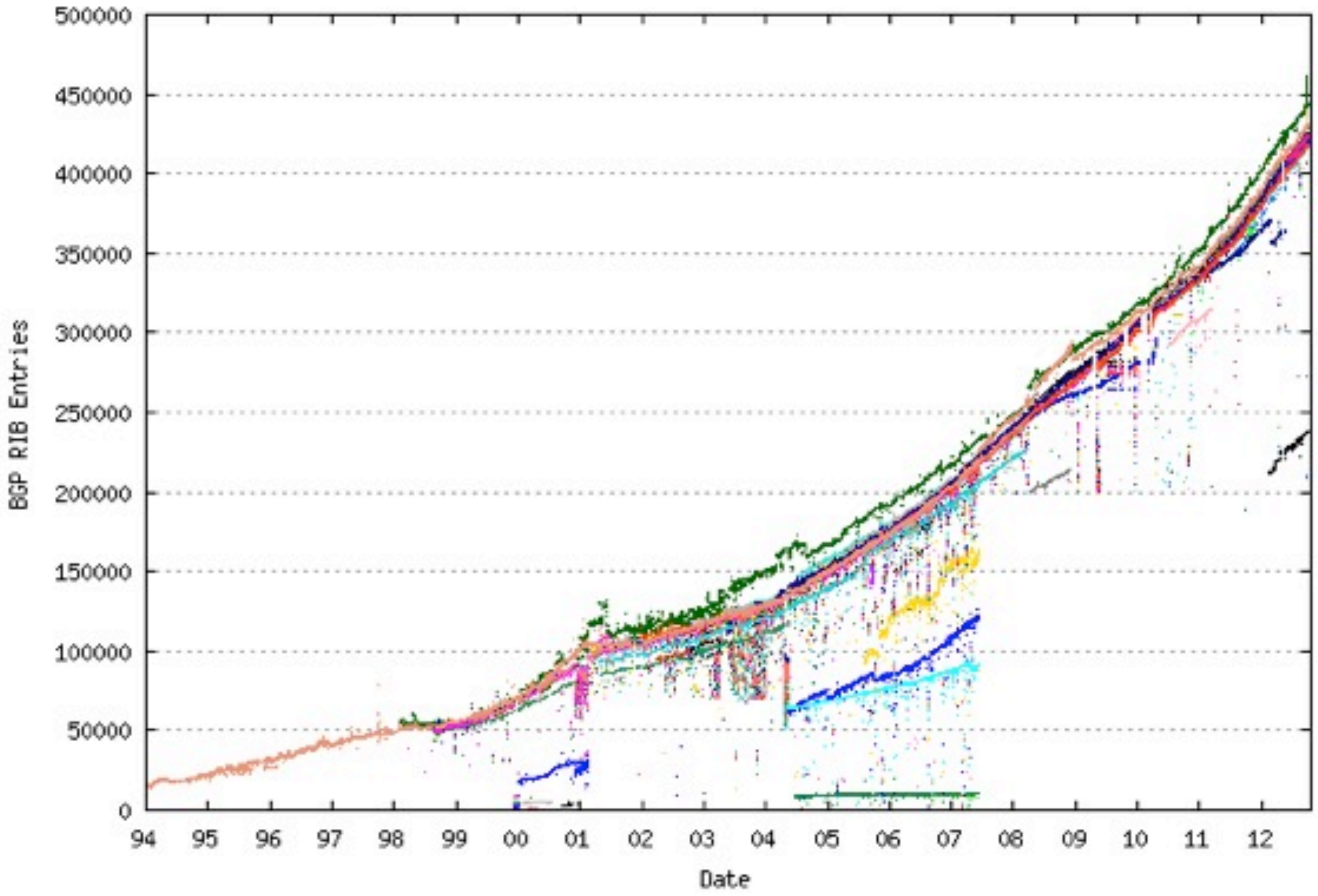
How to handle interdomain routing policies

- no one knows!

Conclusion

Growth of the Internet

There's occasional concern about increasing routing table size on the Internet...



But we seem to manage one way or another. What really matters here?

Key points

Simple shortest-path routing cannot scale

Internet has to do something better than that

- And it does!: Hierarchy (e.g., routing by IP prefix)

Fundamental tradeoff between scalability and stretch of paths

- Internet's use of hierarchy gets us down to "only" 450k forwarding entries at the cost of some latency inflation

Announcements

Steven M. Bellovin, Columbia U

- *"Lawful Hacking: Using Existing Vulnerabilities for Wiretapping on the Internet"*
- 4 pm today in CSL B02

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Next week

- SDN