Geographic Routing without Planarization

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Greedy Distributed Spanning Tree Routing (GDSTR)

- New geographic routing algorithm
  - DOES NOT require planarization
  - uses spanning tree, not planar graph
  - low maintenance cost
  - better routing performance than existing algorithms

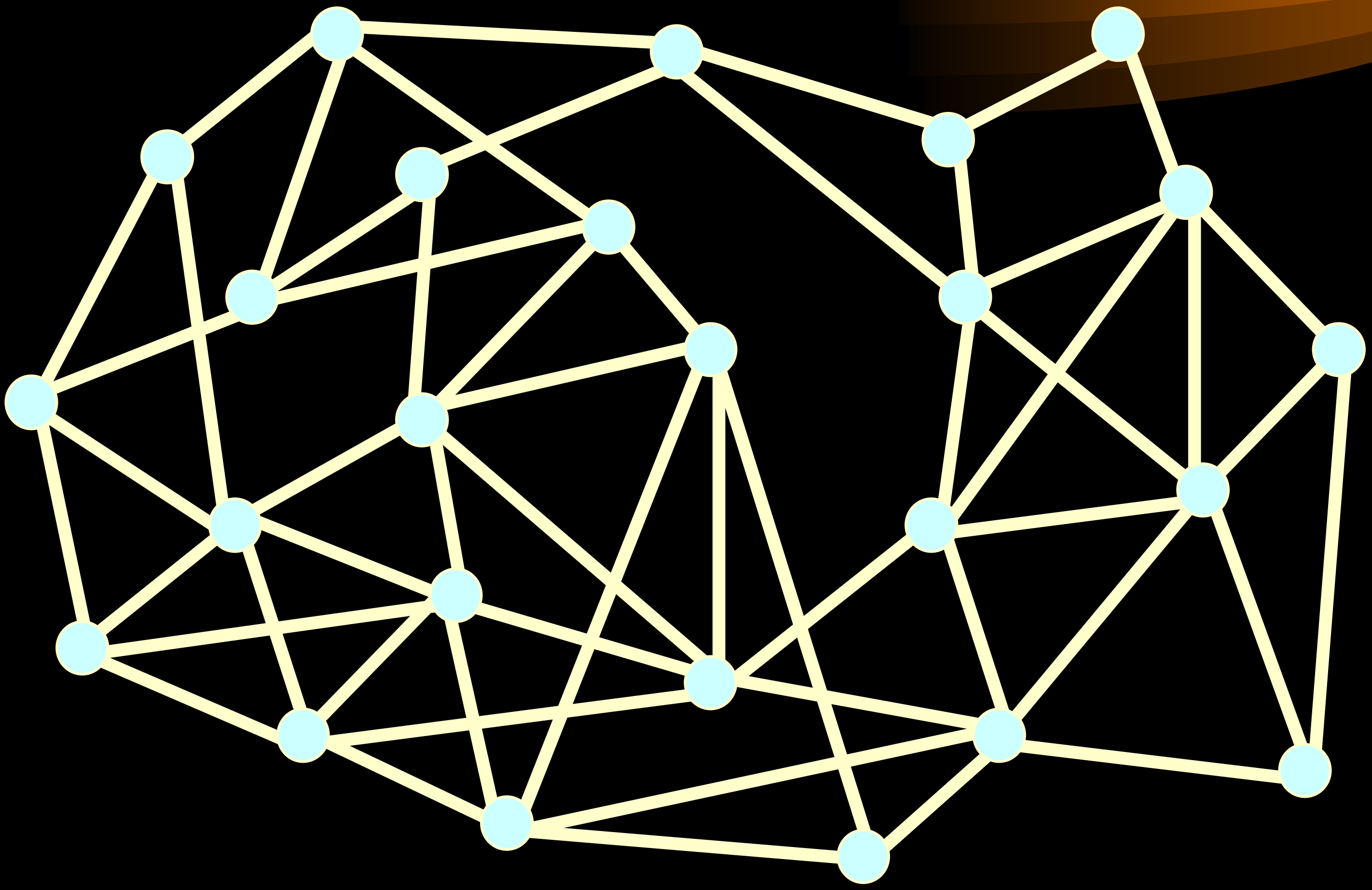
Overview

- Background
- Problem
- Approach
- Simulation Results
- Conclusion

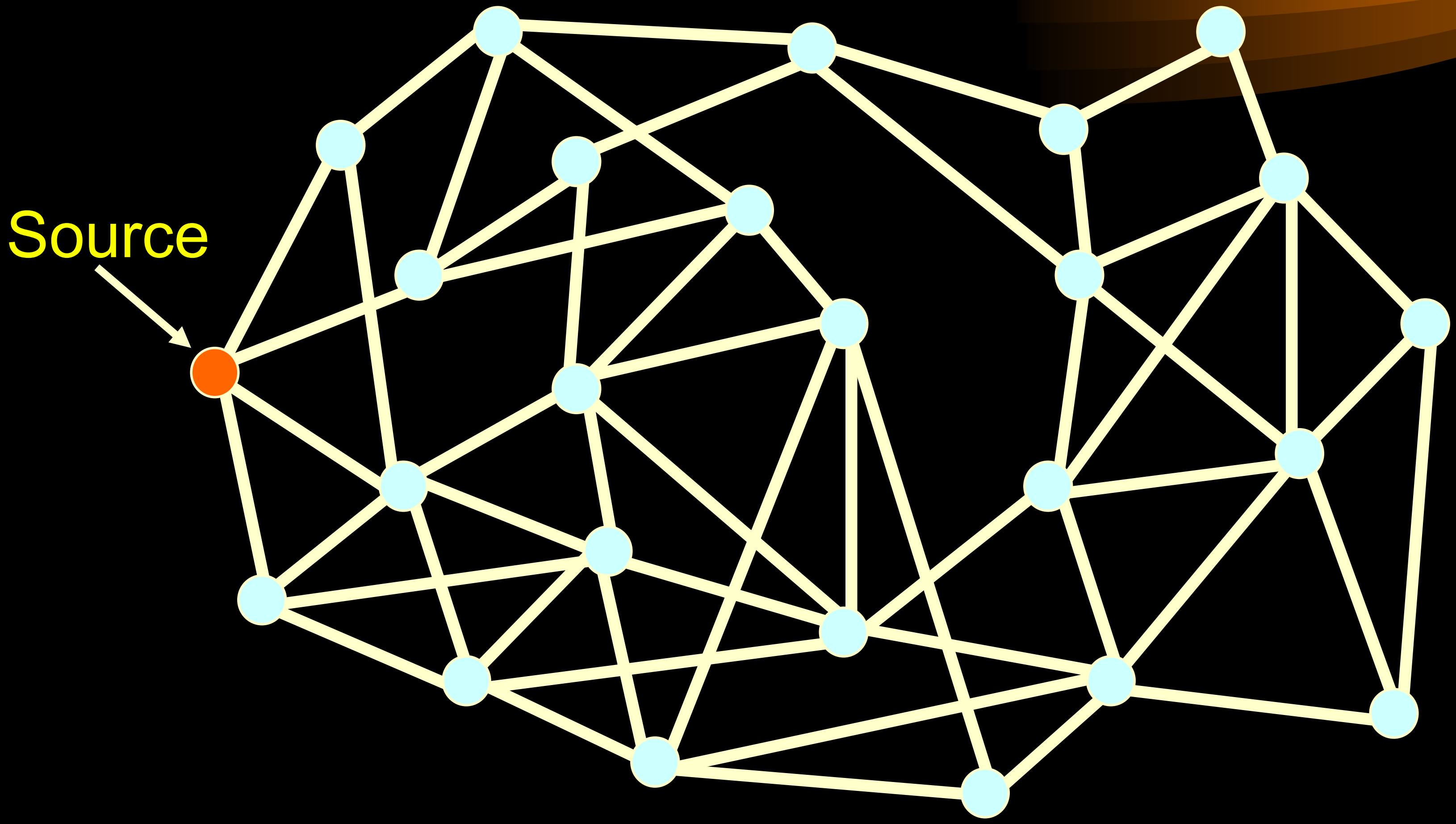
Geographic Routing

- Wireless nodes have *x-y* coordinates
  - can use virtual coordinates (Rao et al. 2003)
- Nodes know coordinates of immediate neighbors
- Packet destinations specified with *x-y* coordinates
- In general, forward packets greedily

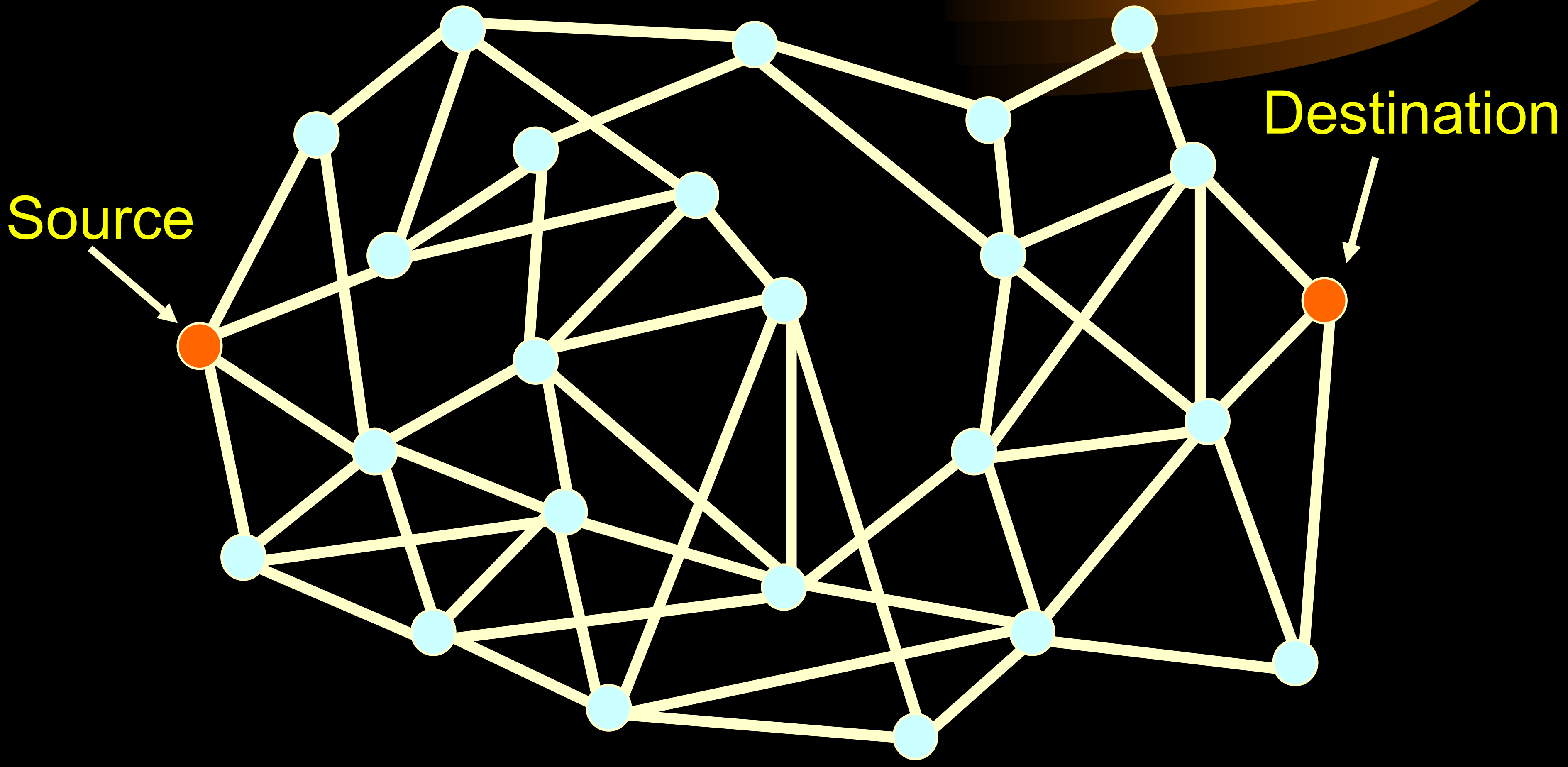
Geographic Routing



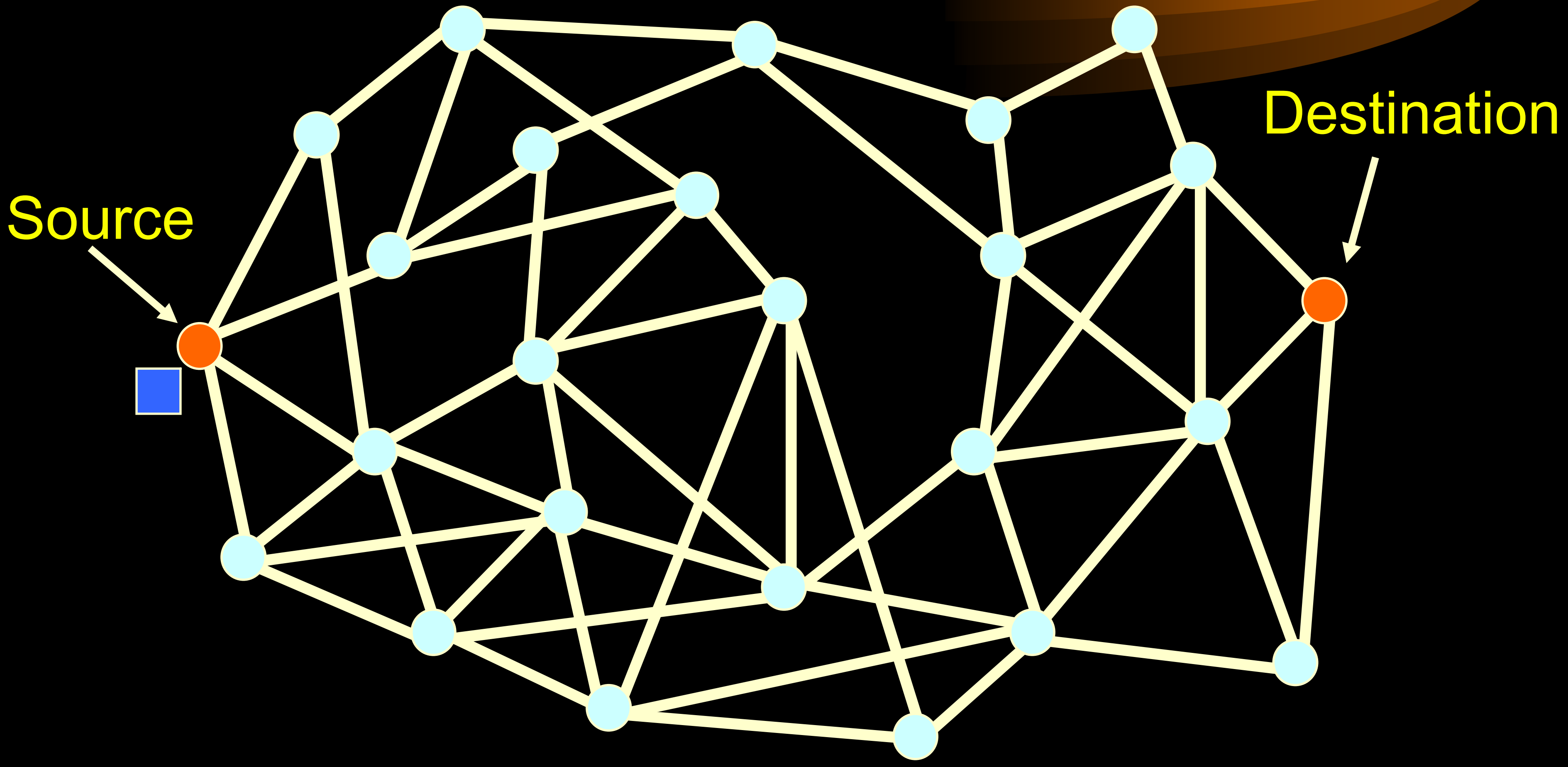
Geographic Routing



Geographic Routing



Greedy Forwarding



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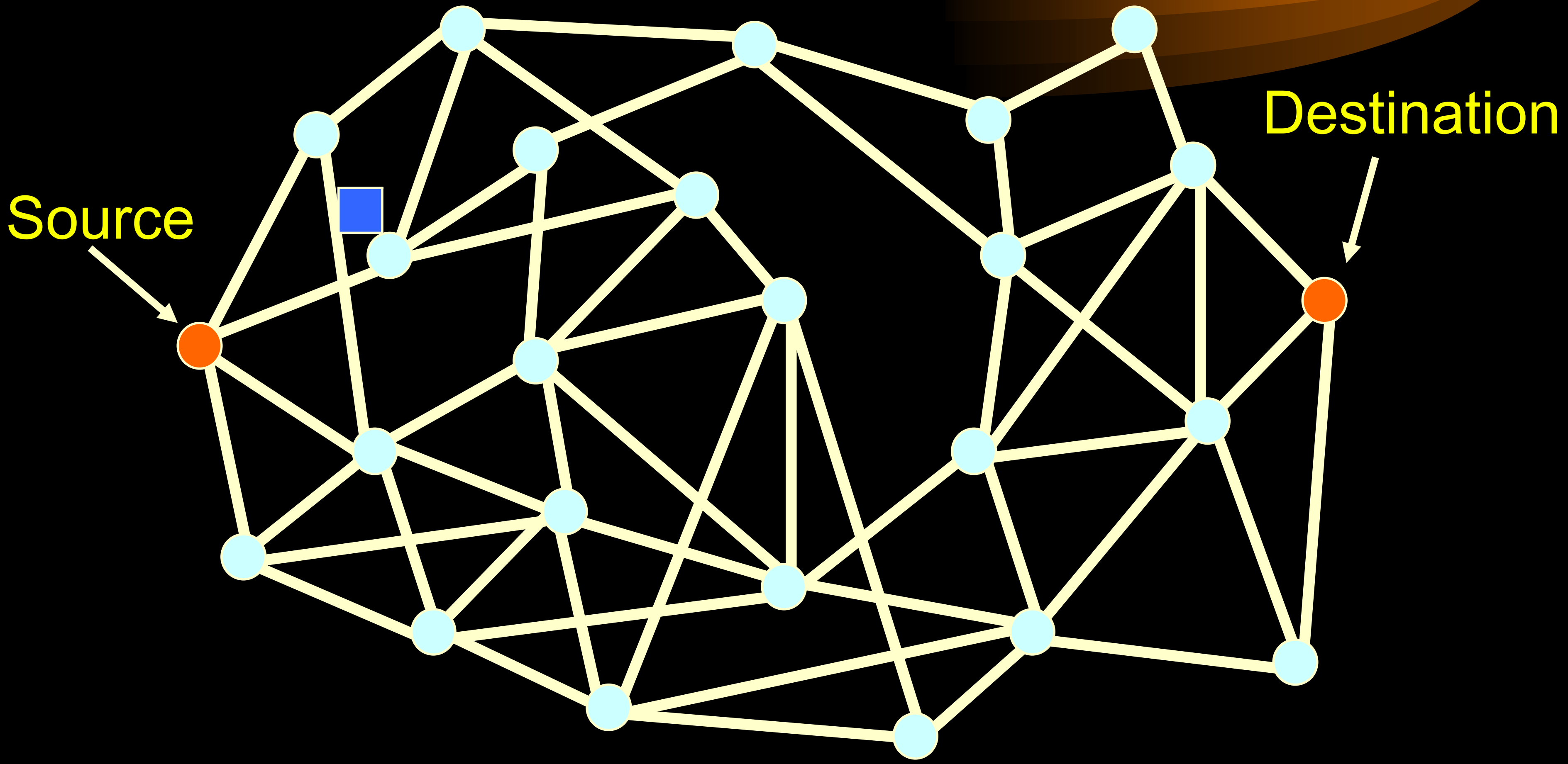

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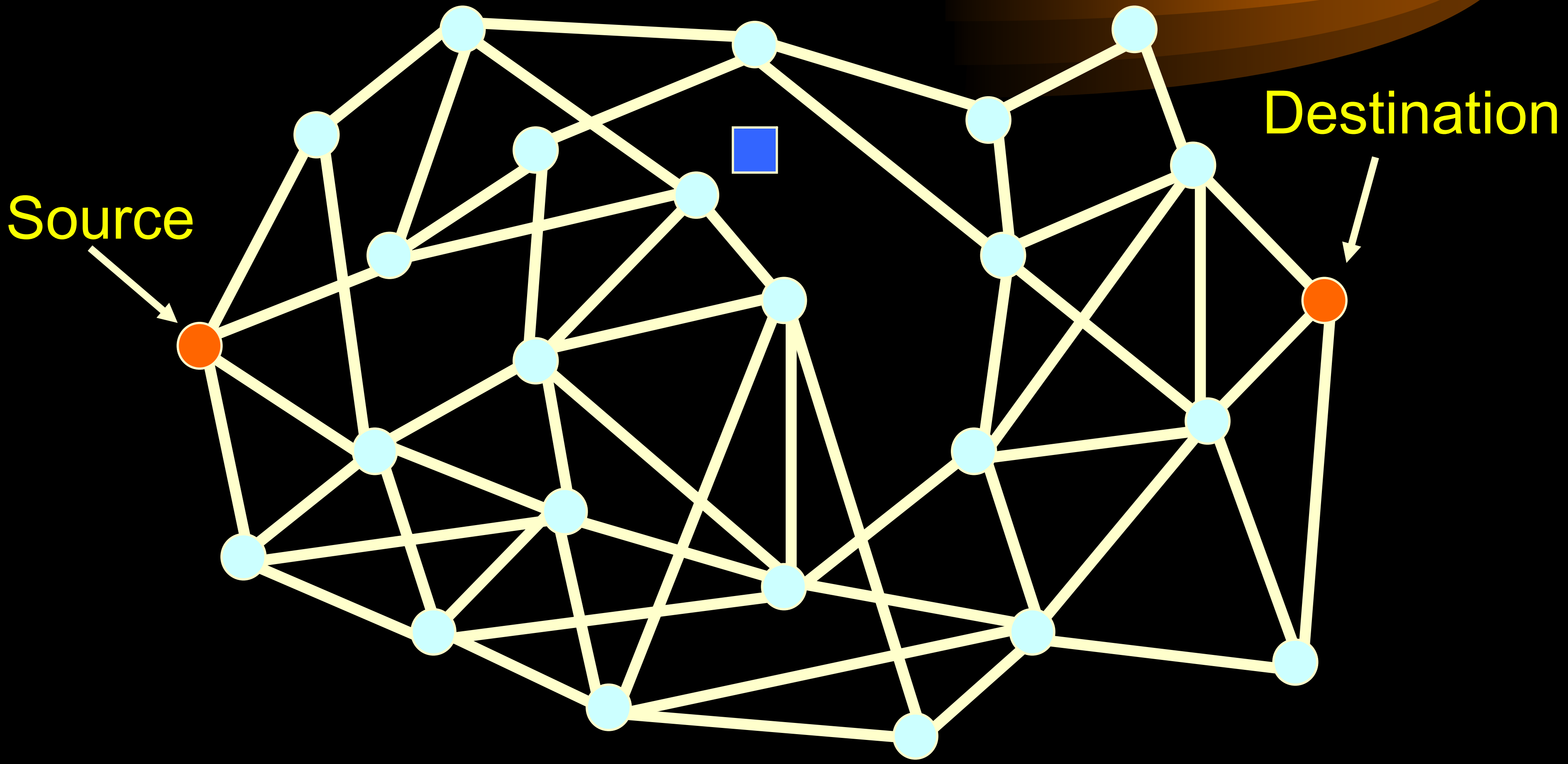

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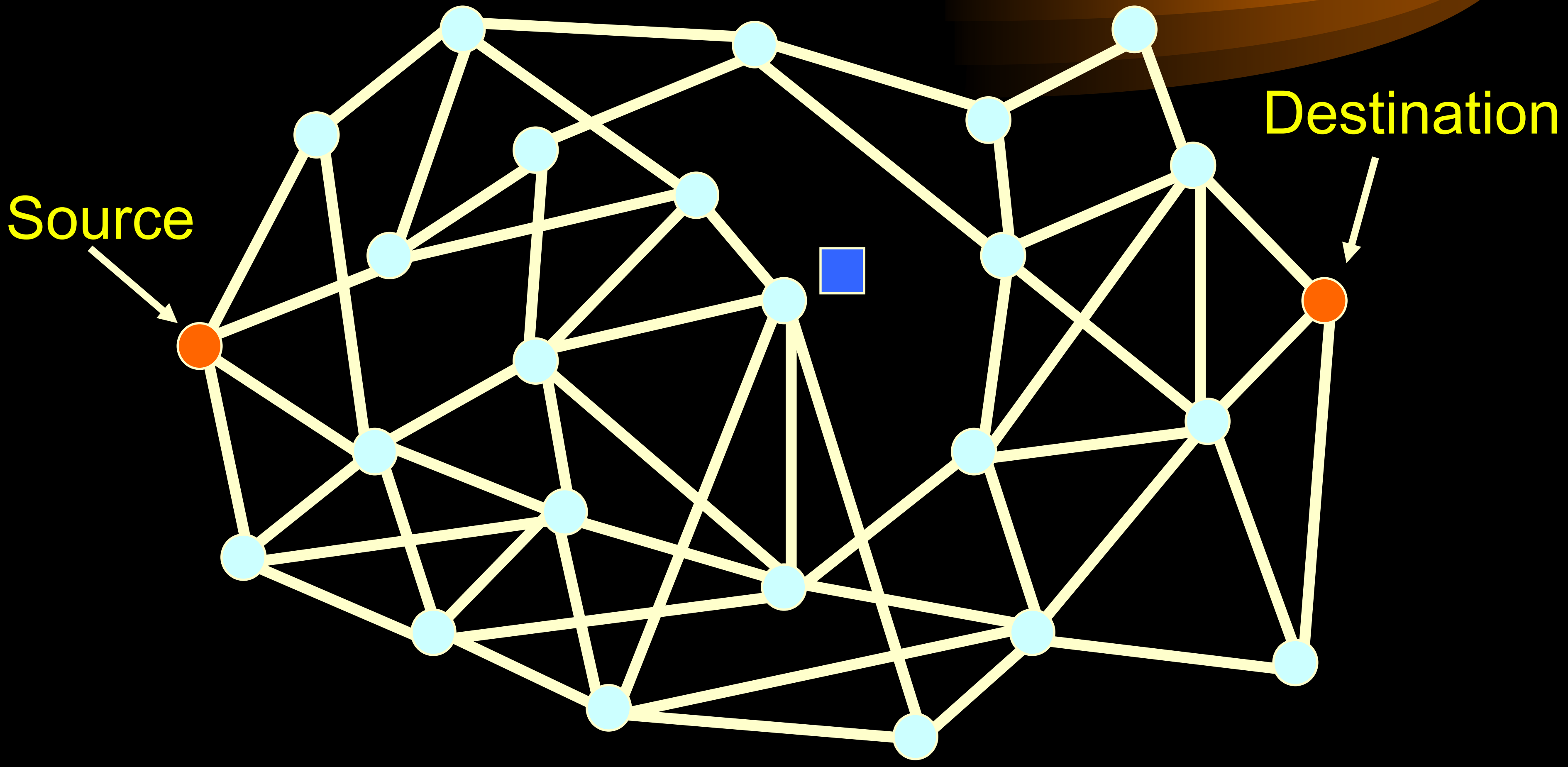
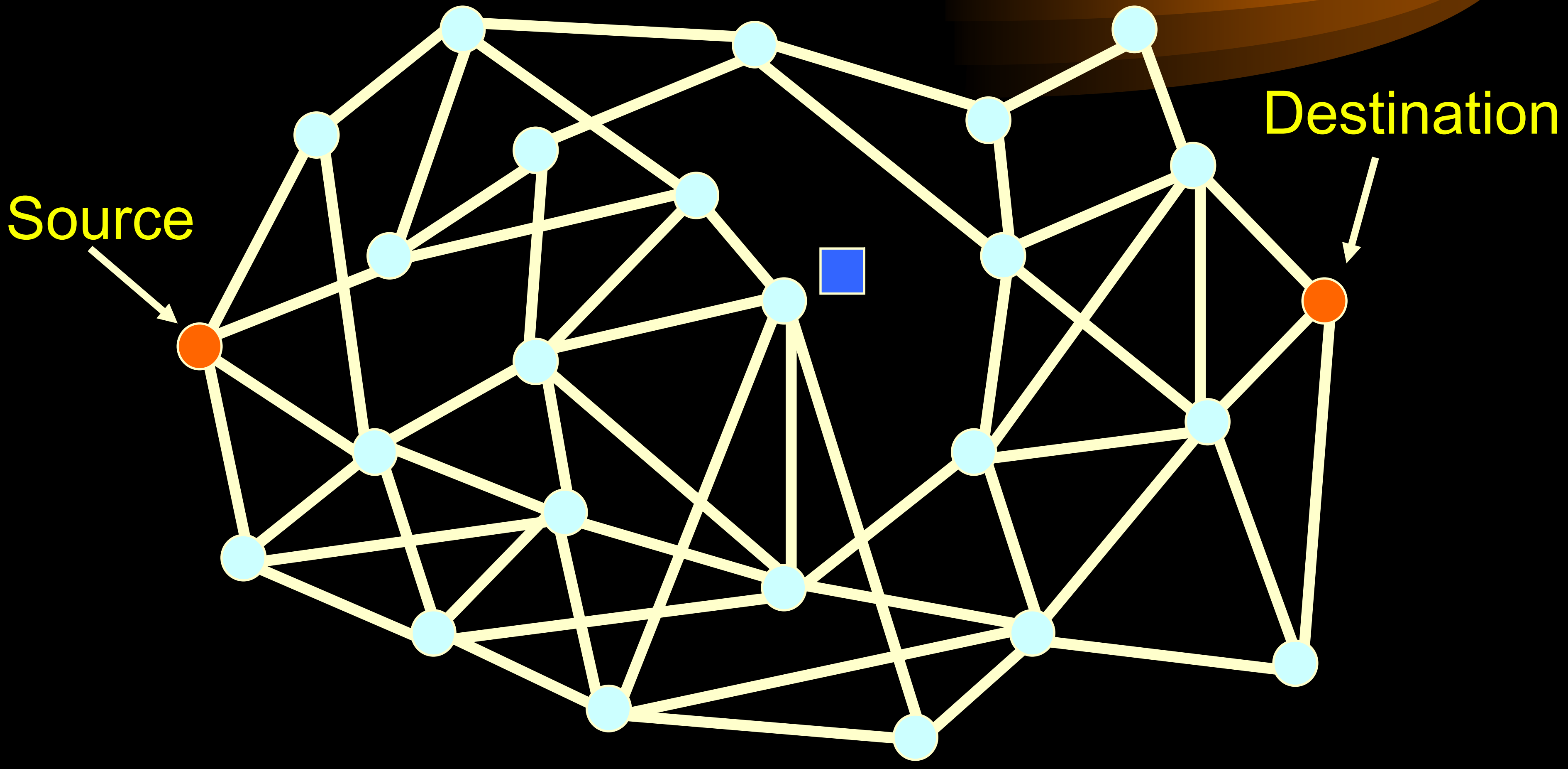
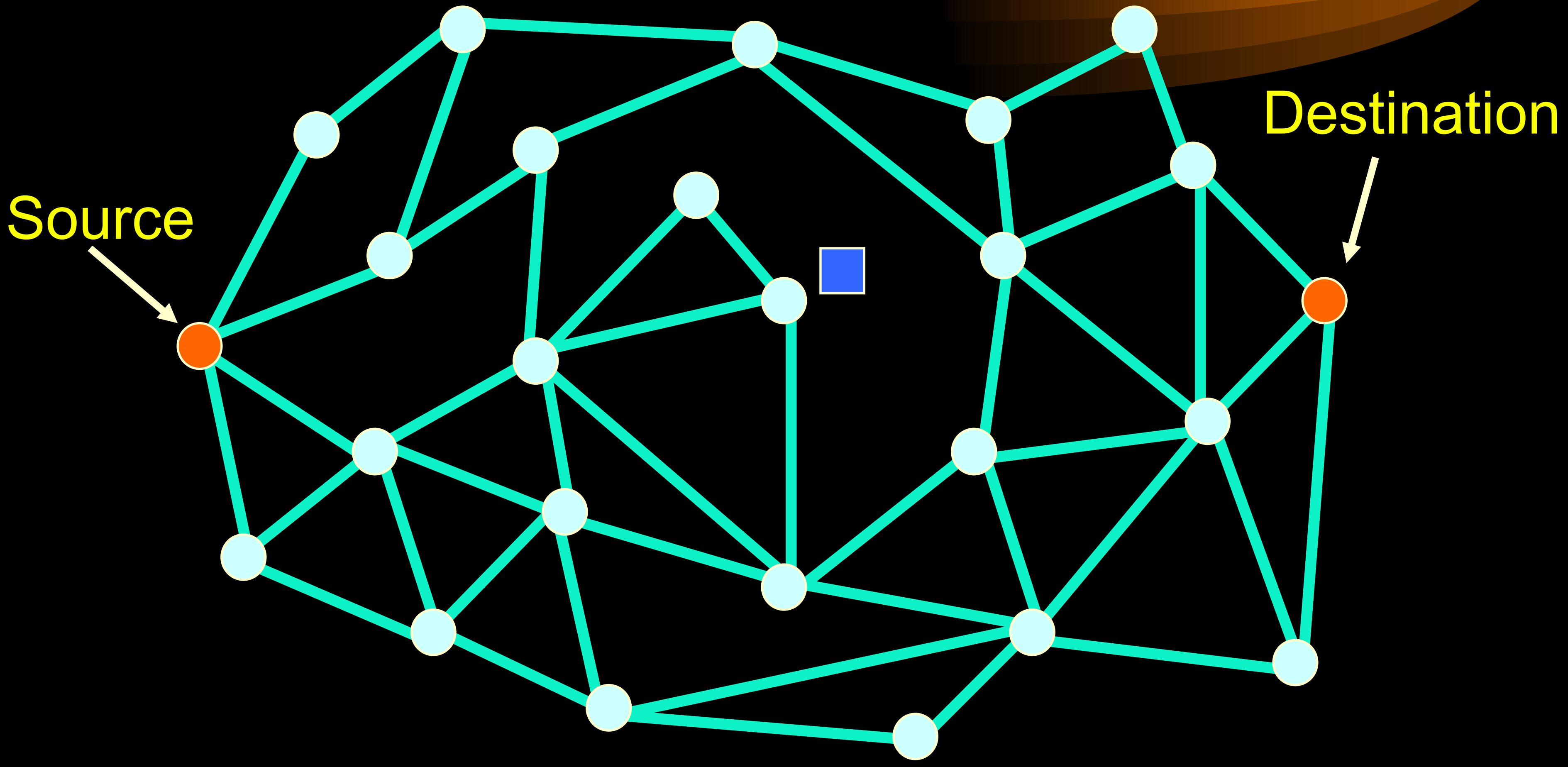


Geographic Routing: Dealing with Dead Ends

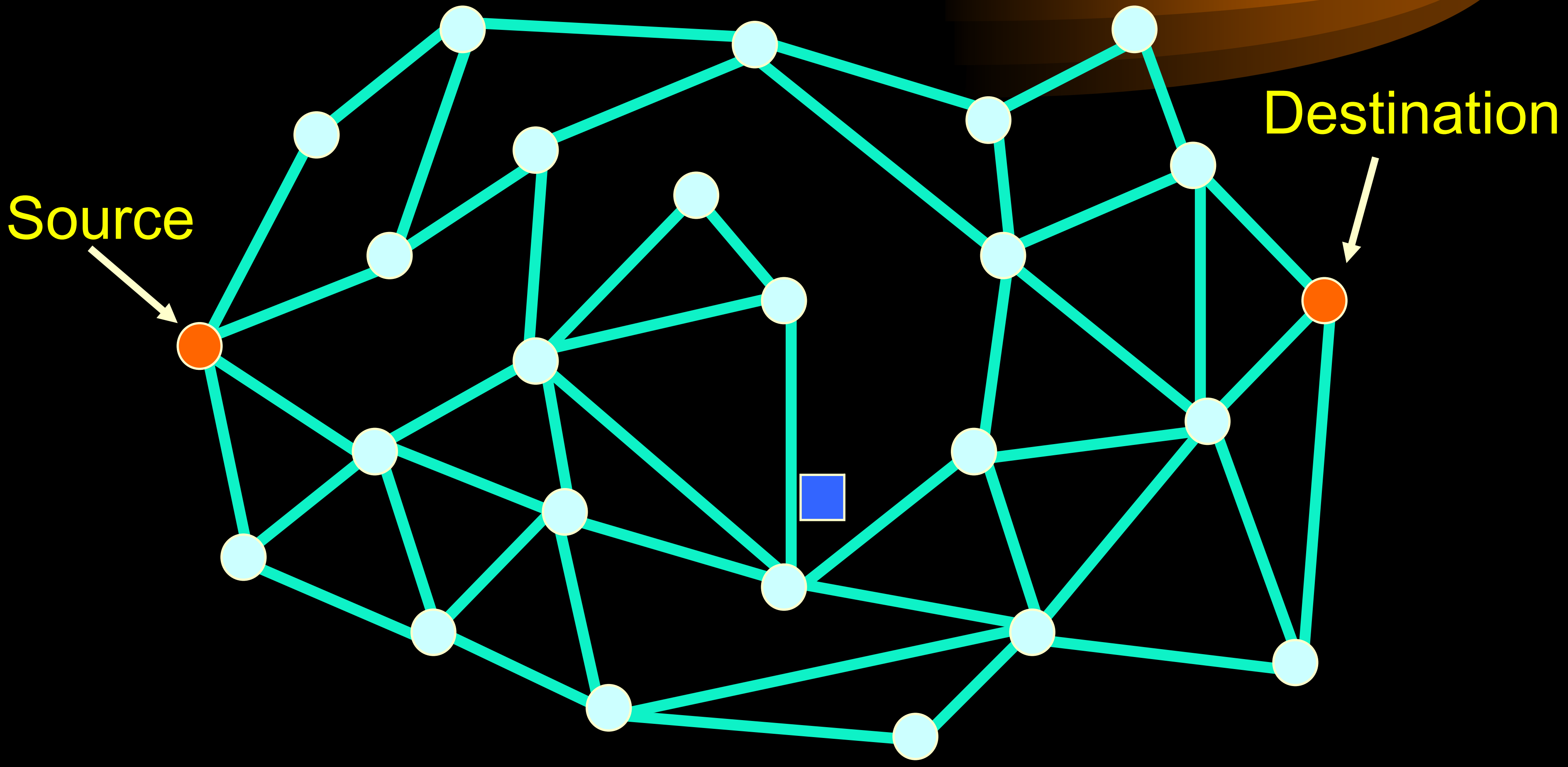


Whoops. Dead end!

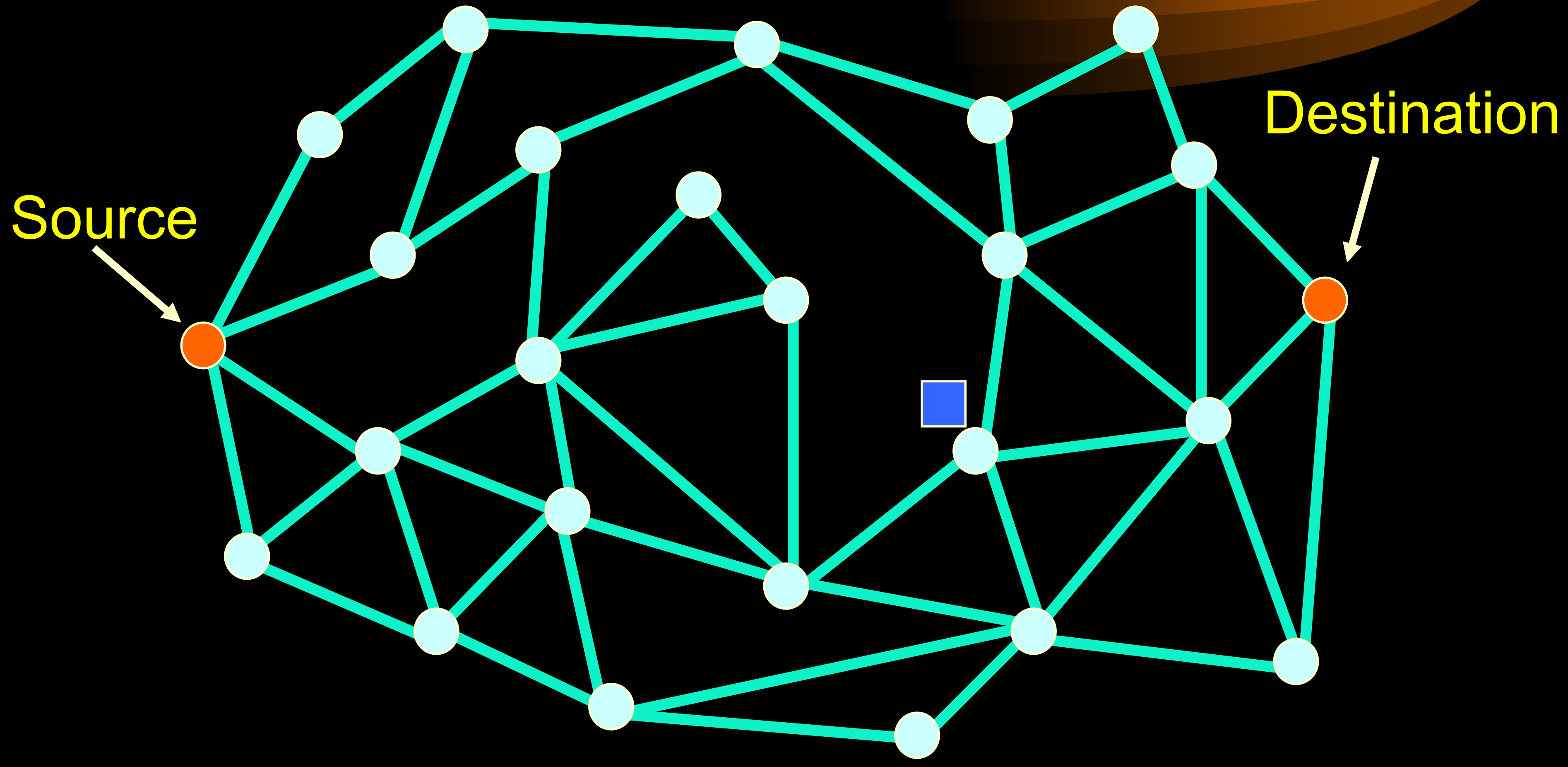
Face Routing



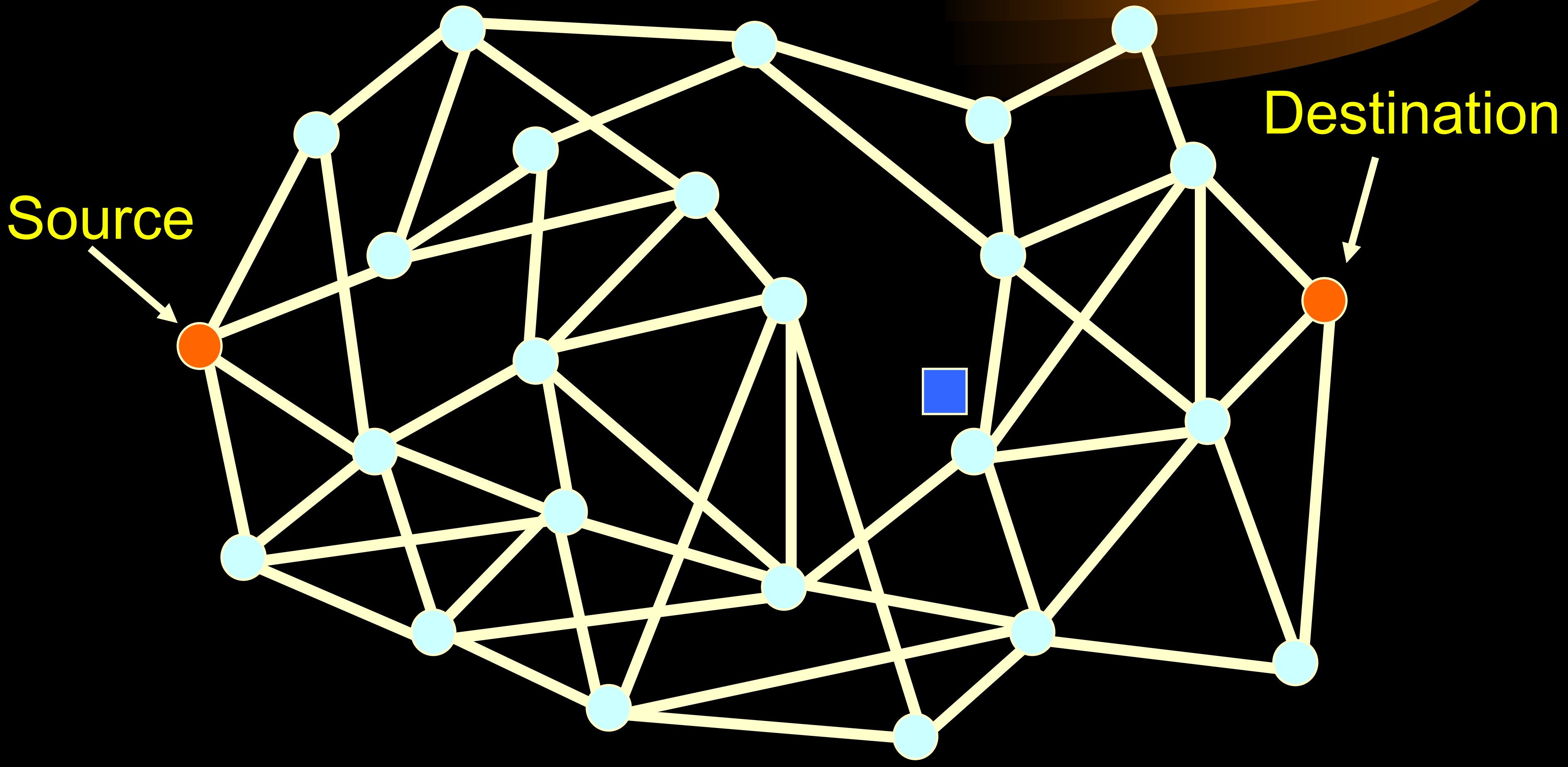
Face Routing



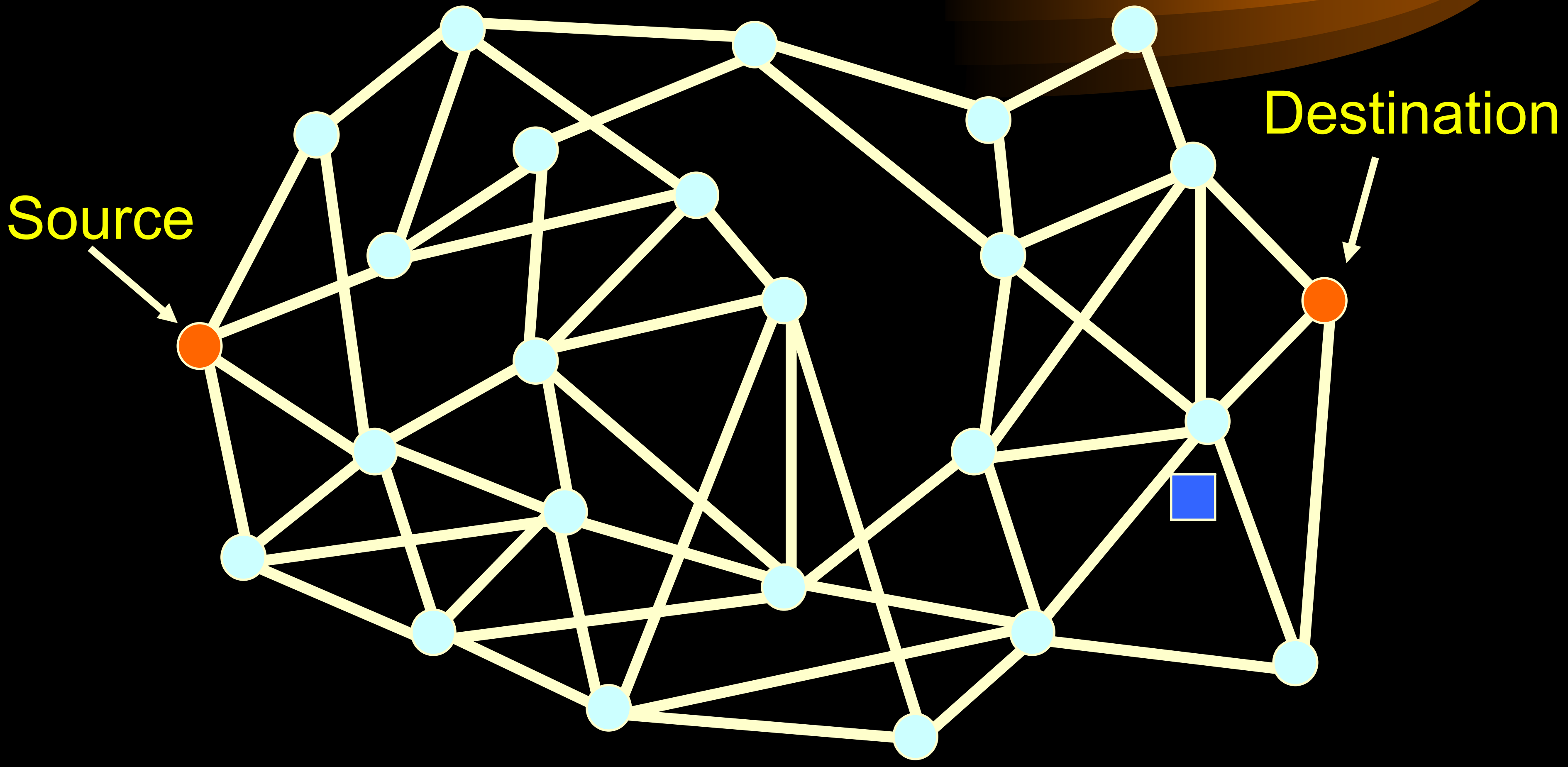
Face Routing



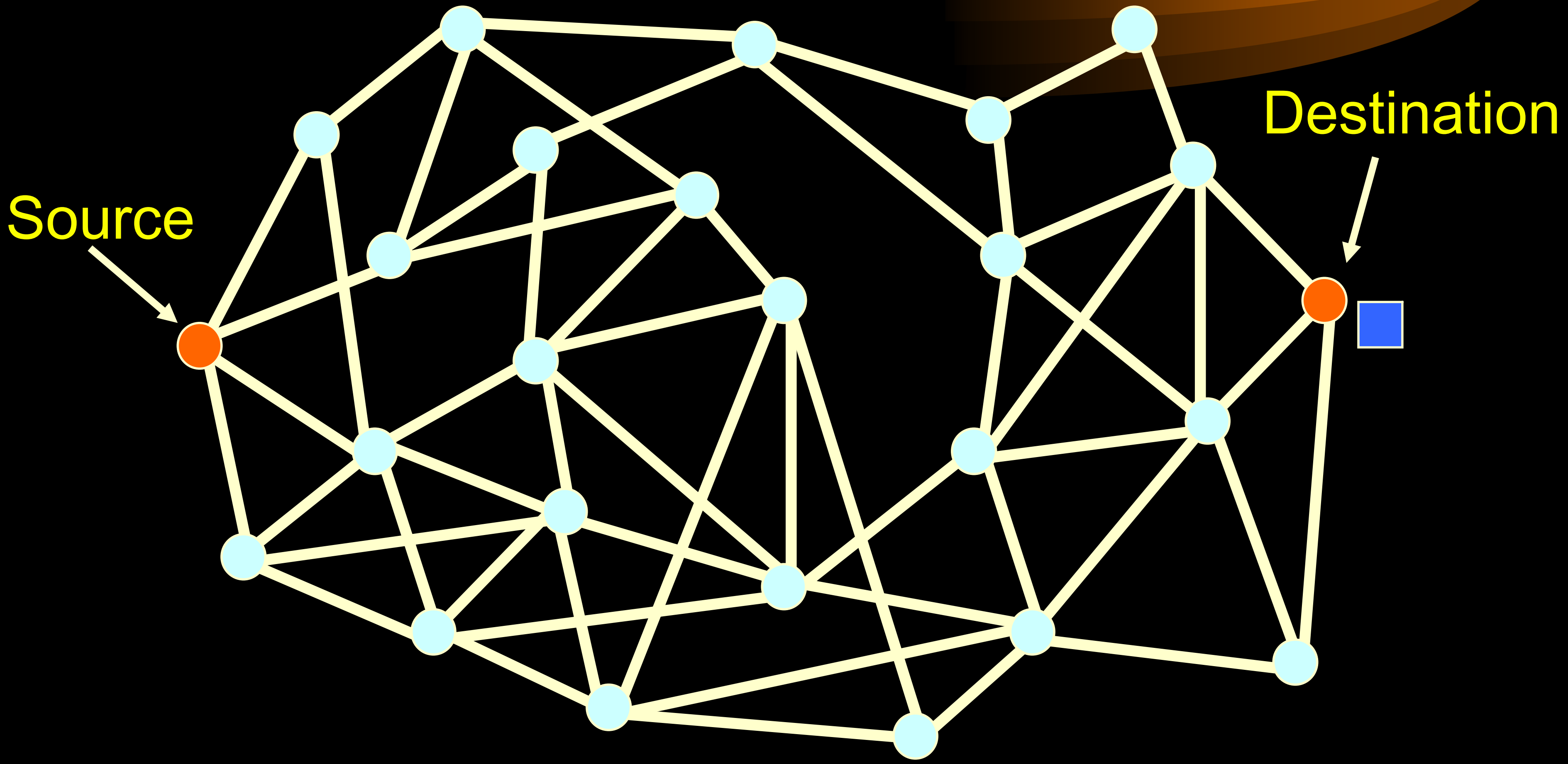
Back to Greedy Forwarding



Back to Greedy Forwarding



Back to Greedy Forwarding



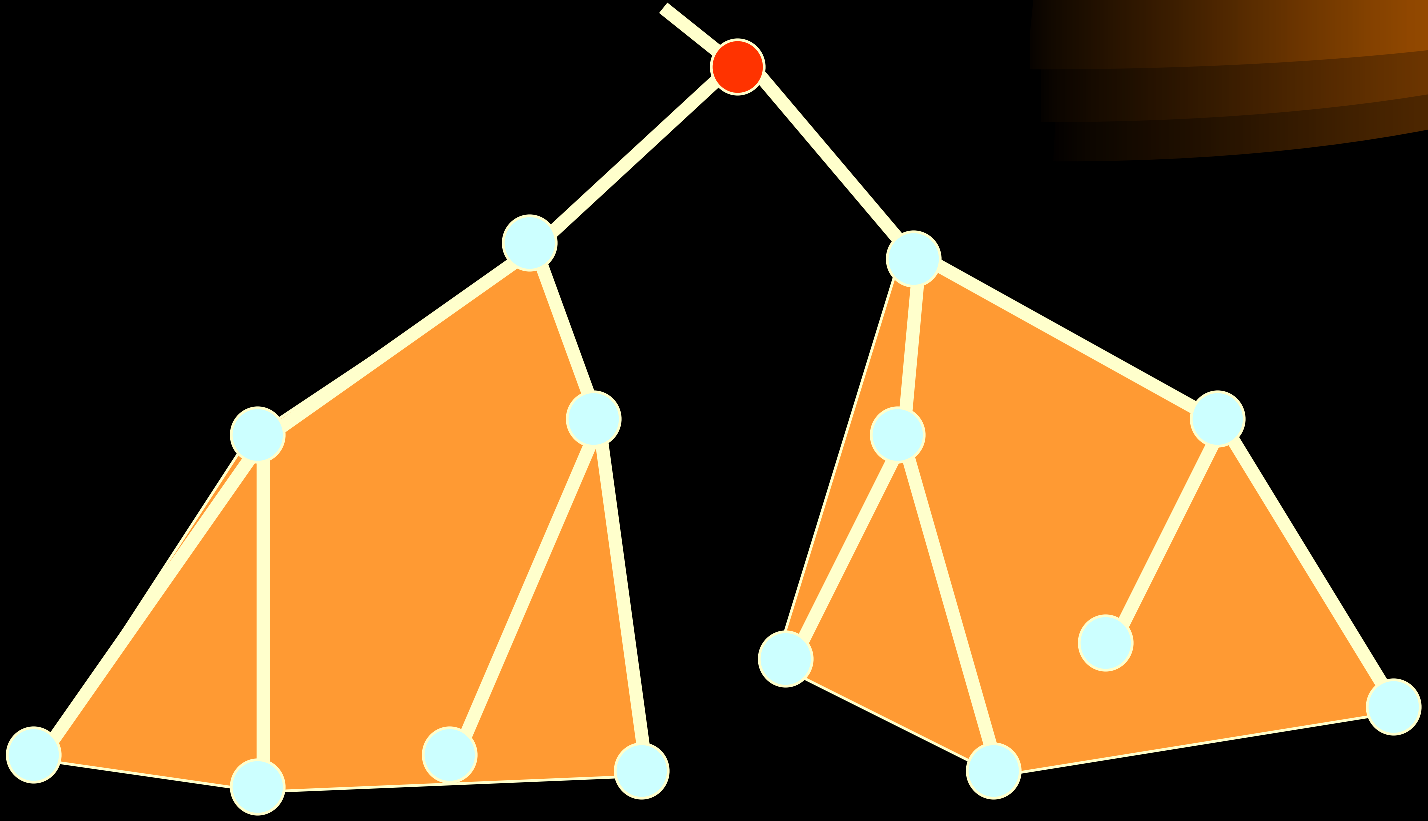
Planarization is Costly!

- Planarization is hard for real networks
  - GG and RNG don’t work
- Planarization is complicated & costly!
  - CLDP (Kim et al., 2005)

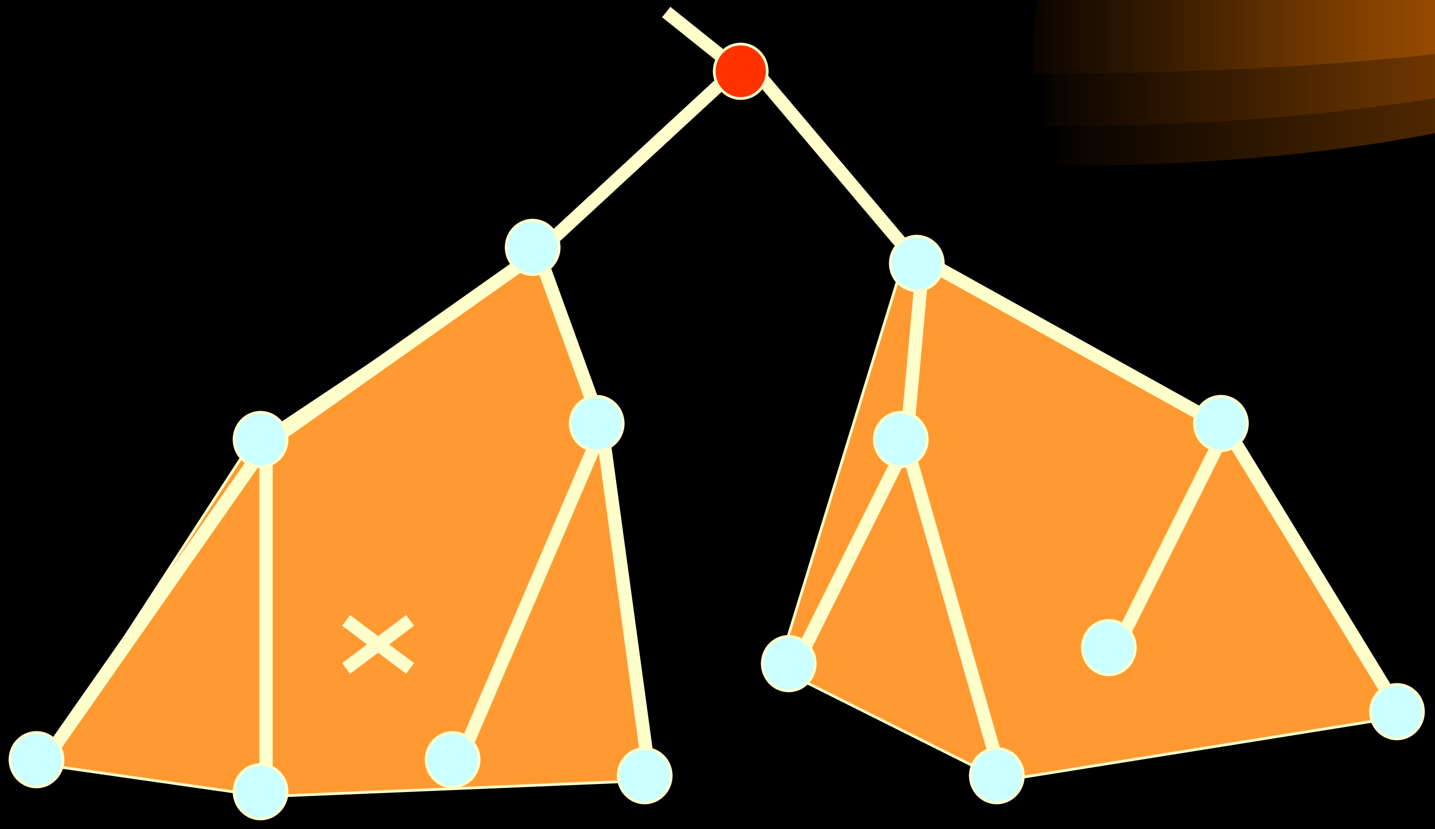
Greedy Distributed Spanning Tree Routing (GDSTR)

- Route on a spanning tree
- Use convex hulls to “summarize” the area covered by a subtree
  - convex hulls tells us what points are possibly reachable
  - reduces the subtree that must be traversed (smaller search problem)

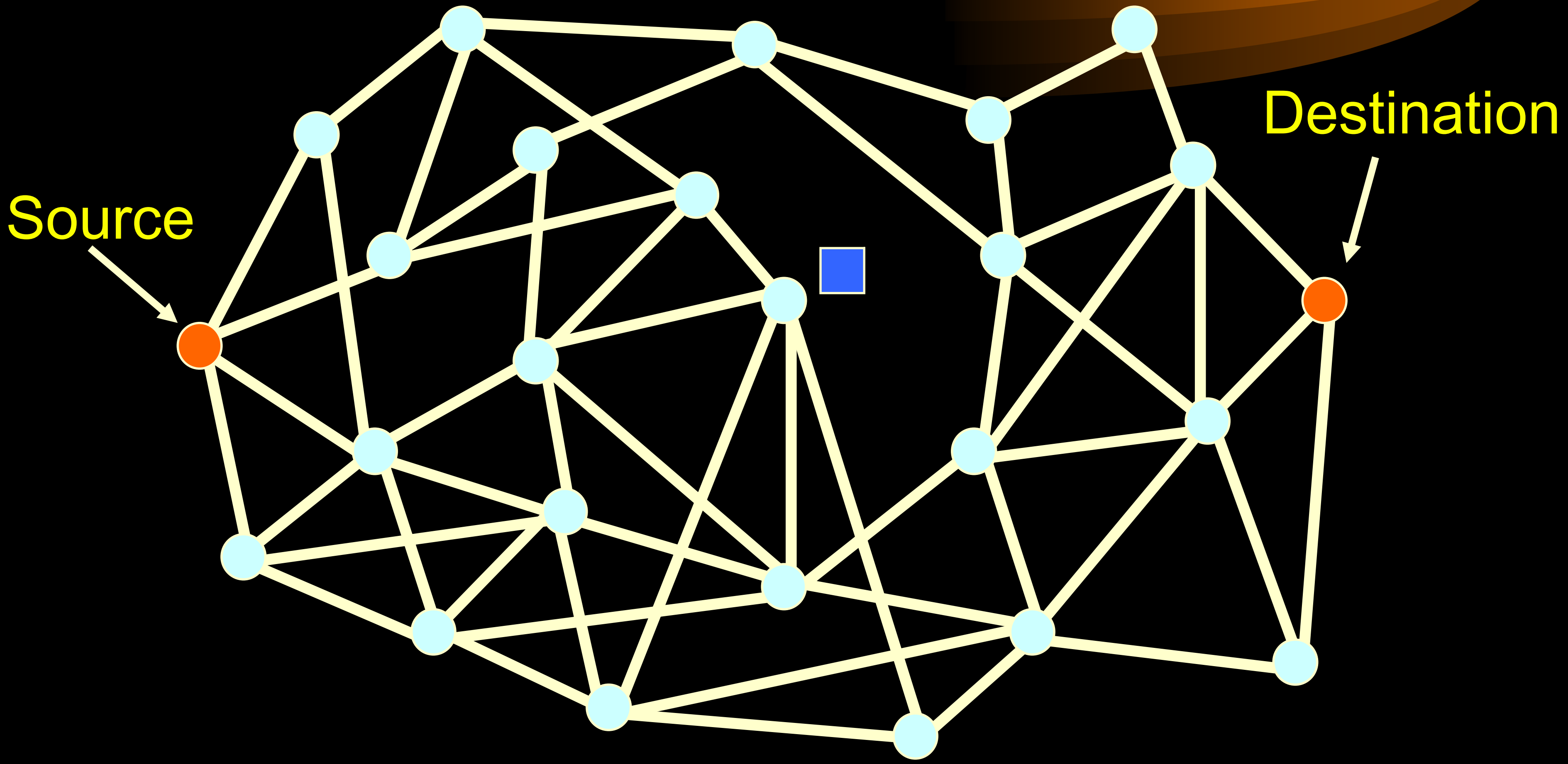
Hull Tree



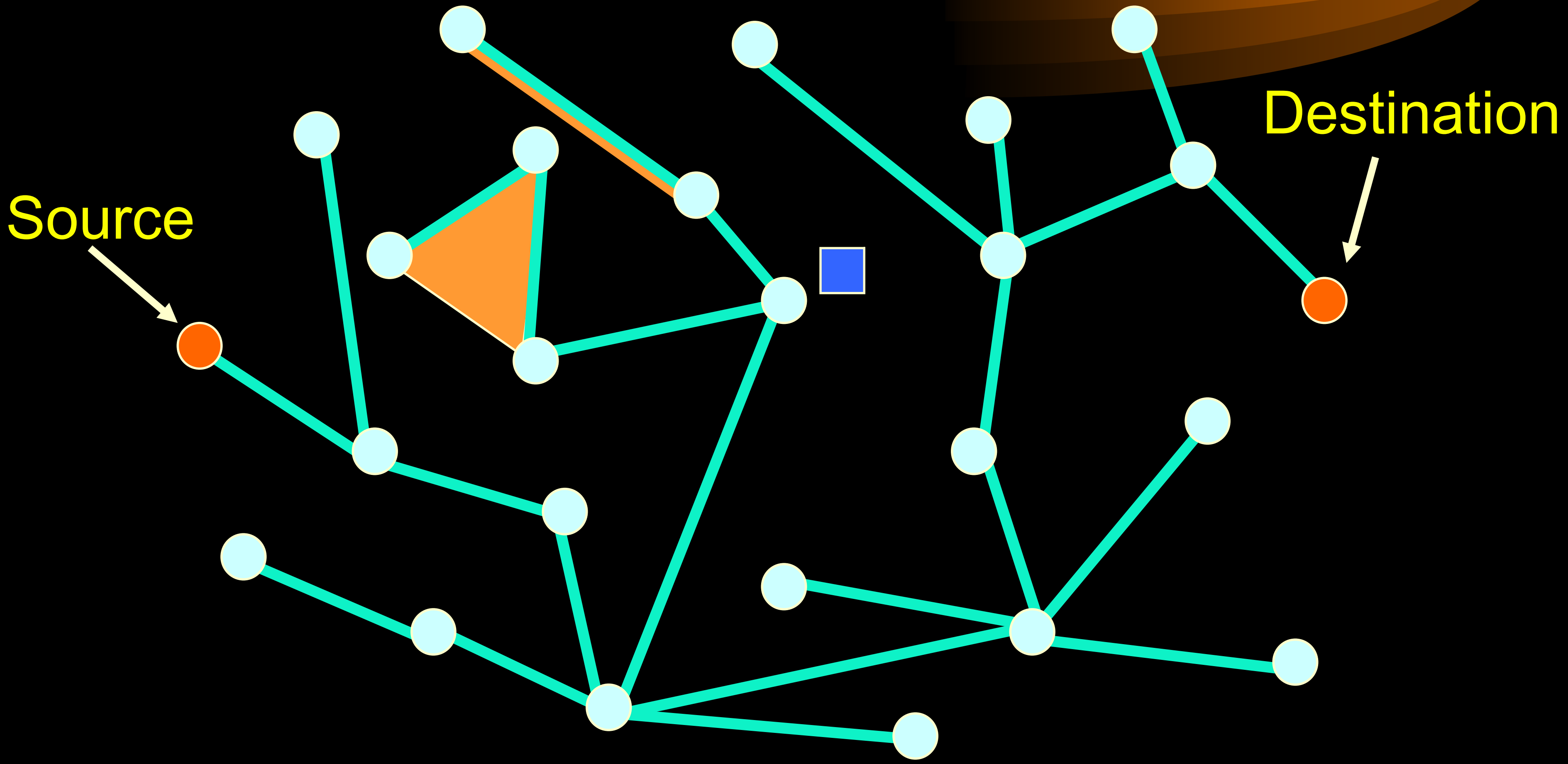
Hull Tree



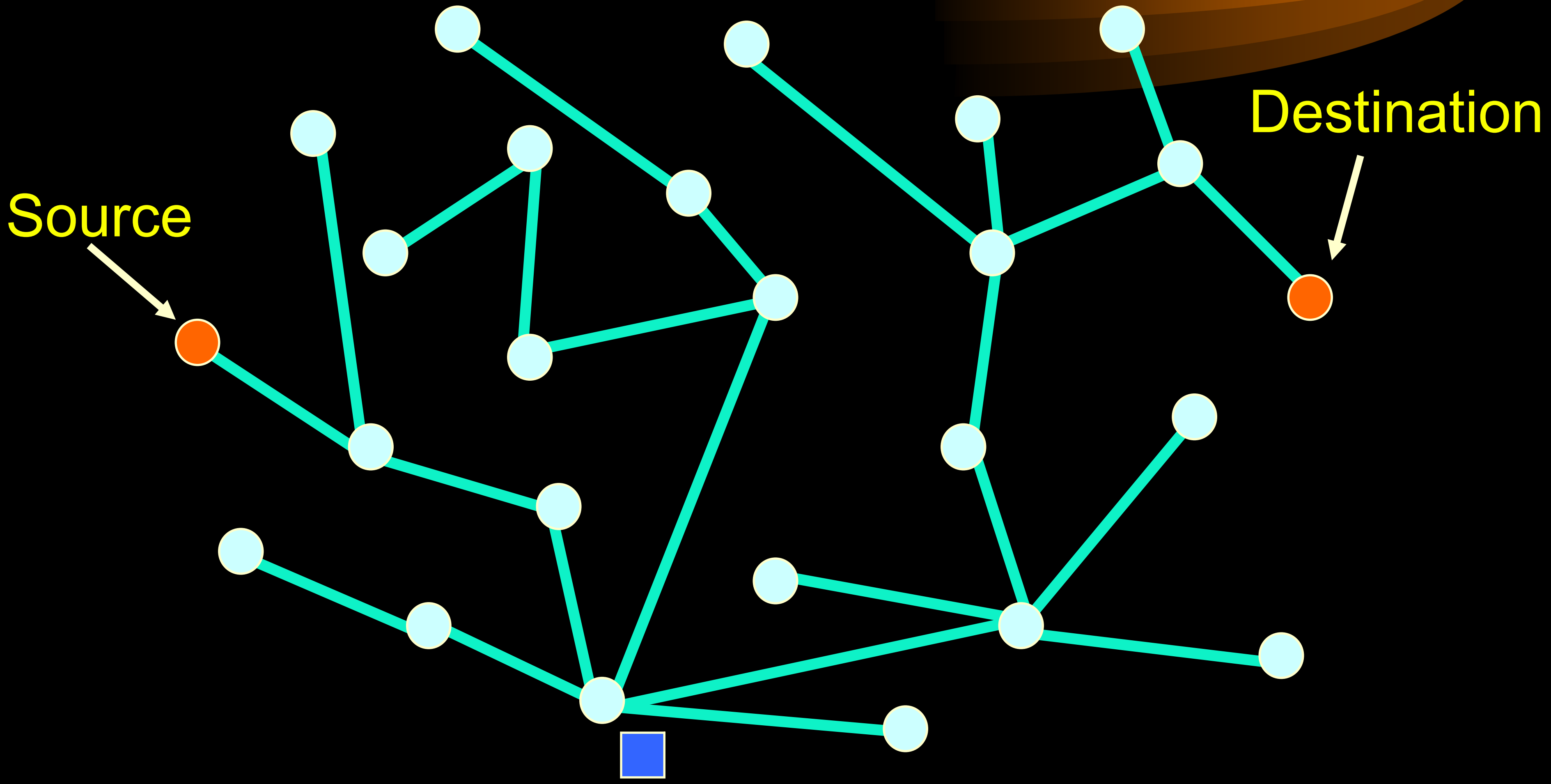
GDSTR Example



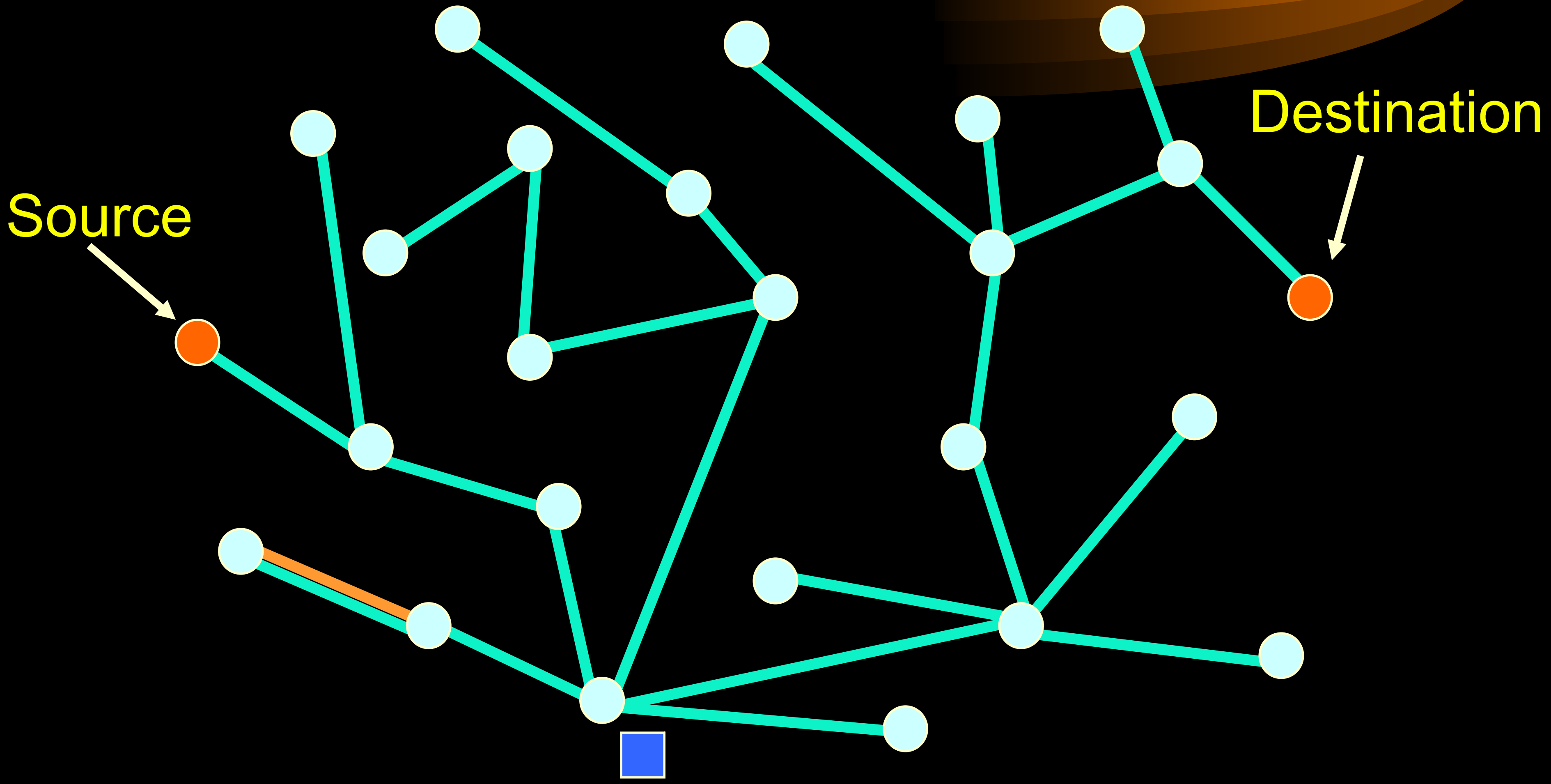
GDSTR Example



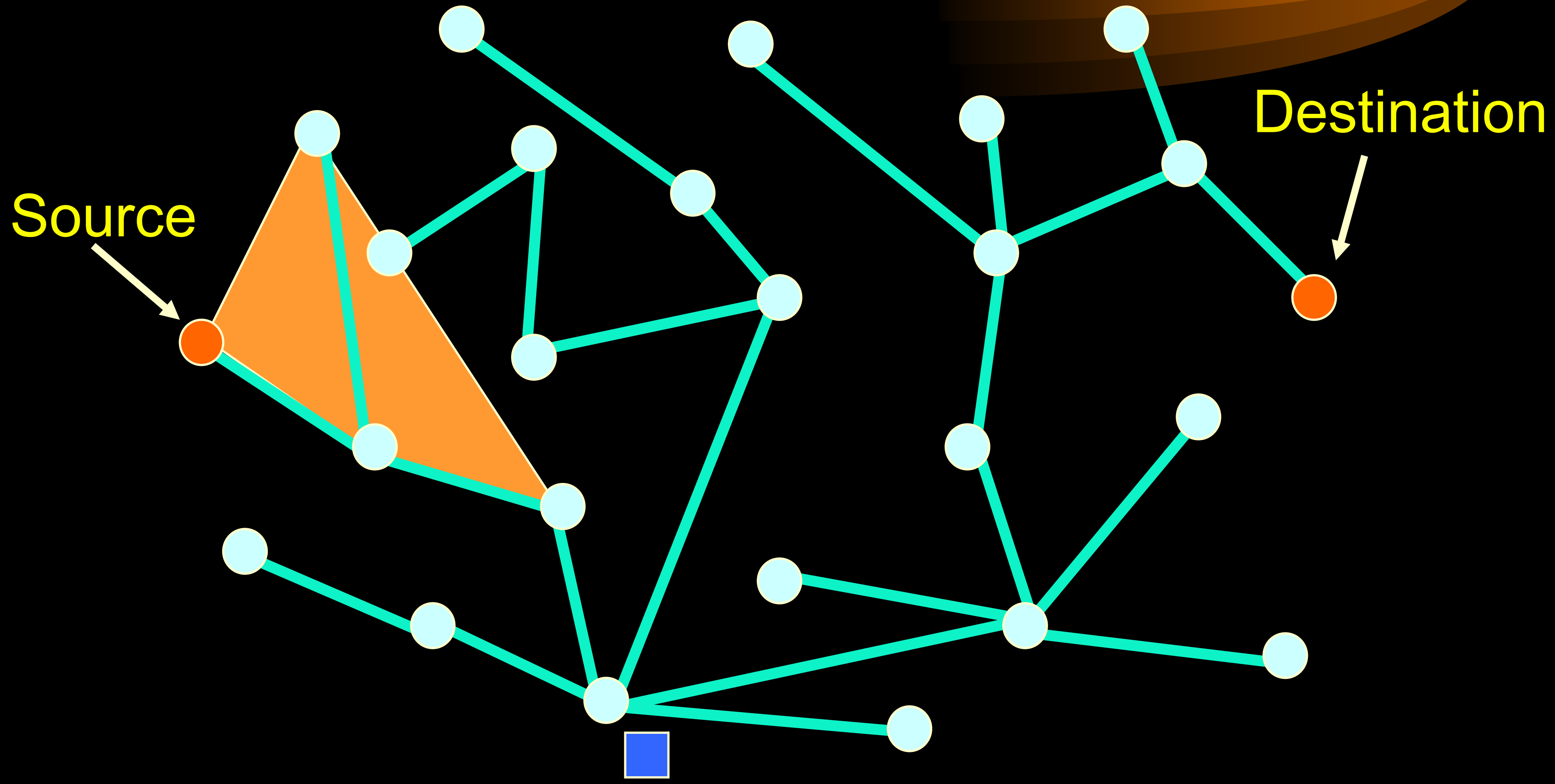
GDSTR Example



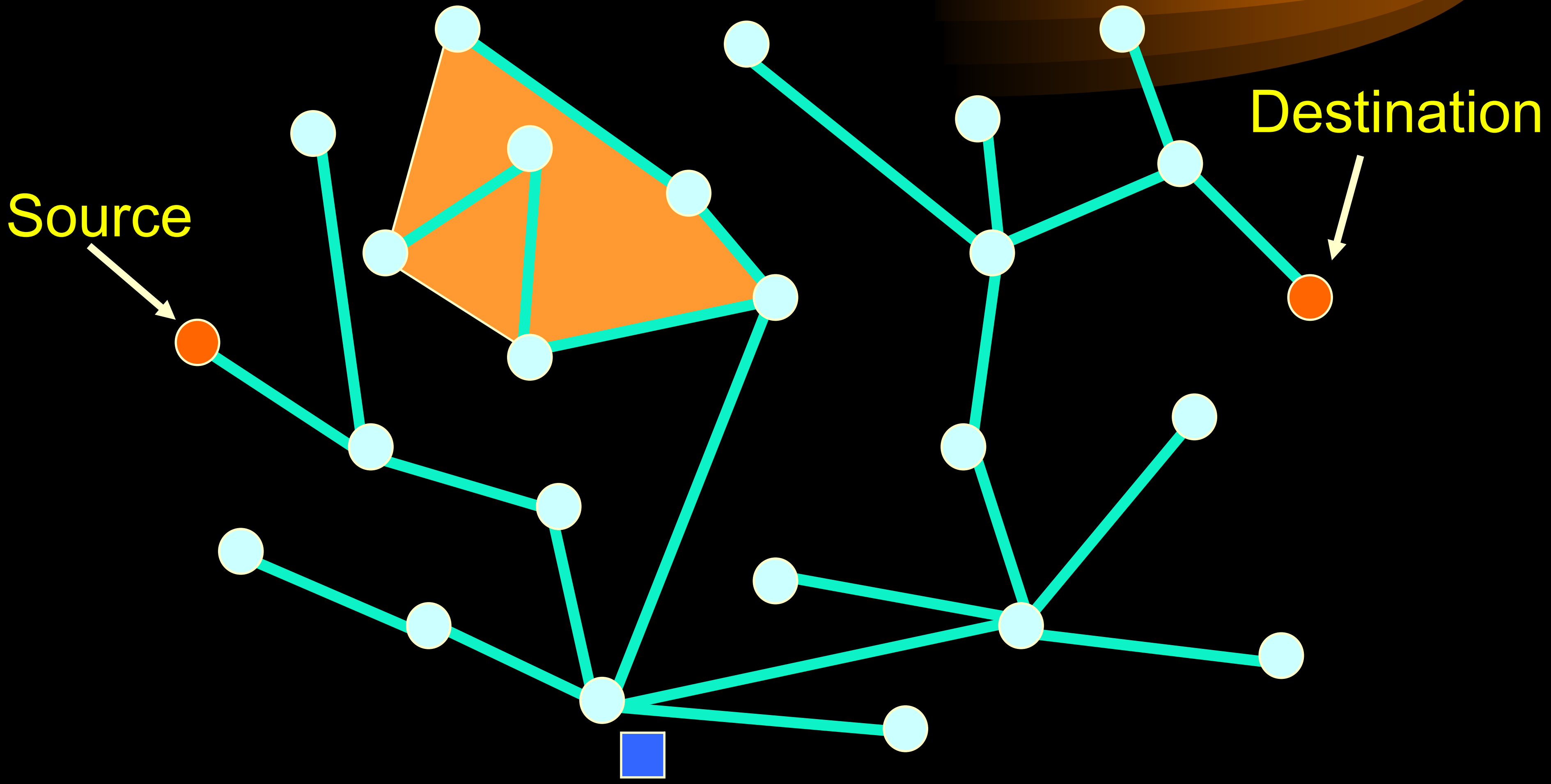
GDSTR Example



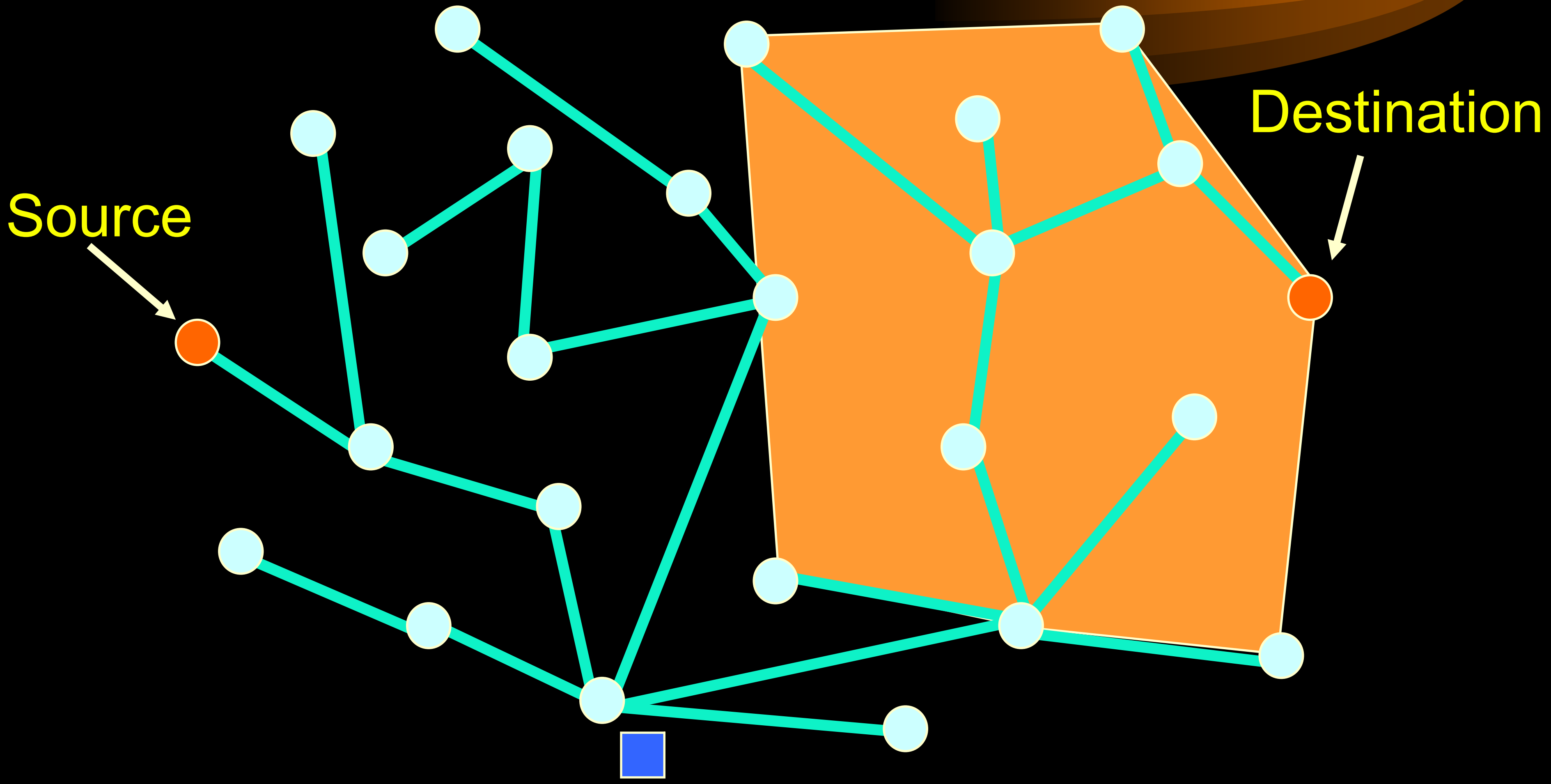
GDSTR Example



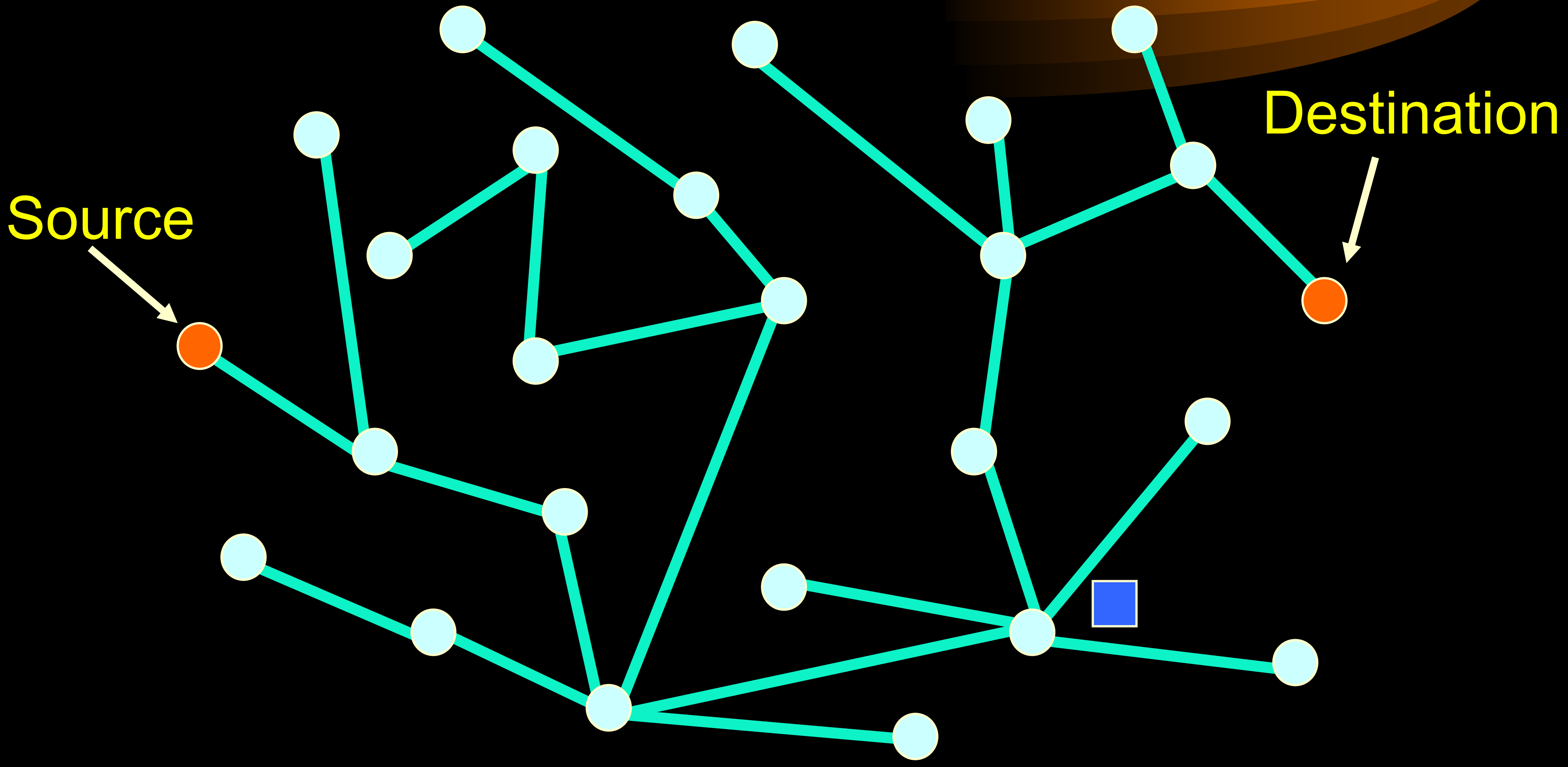
GDSTR Example



GDSTR Example



GDSTR Example



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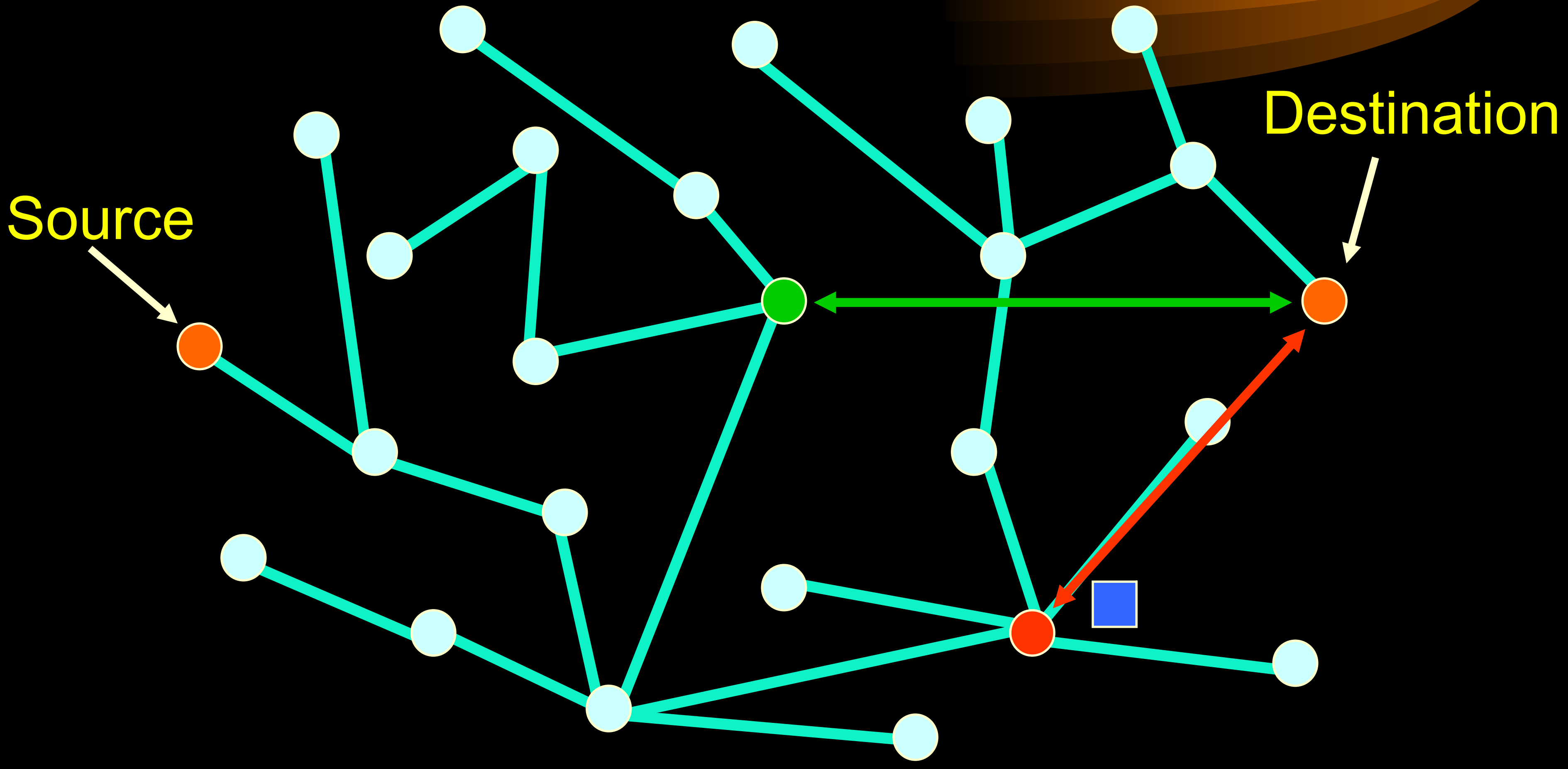
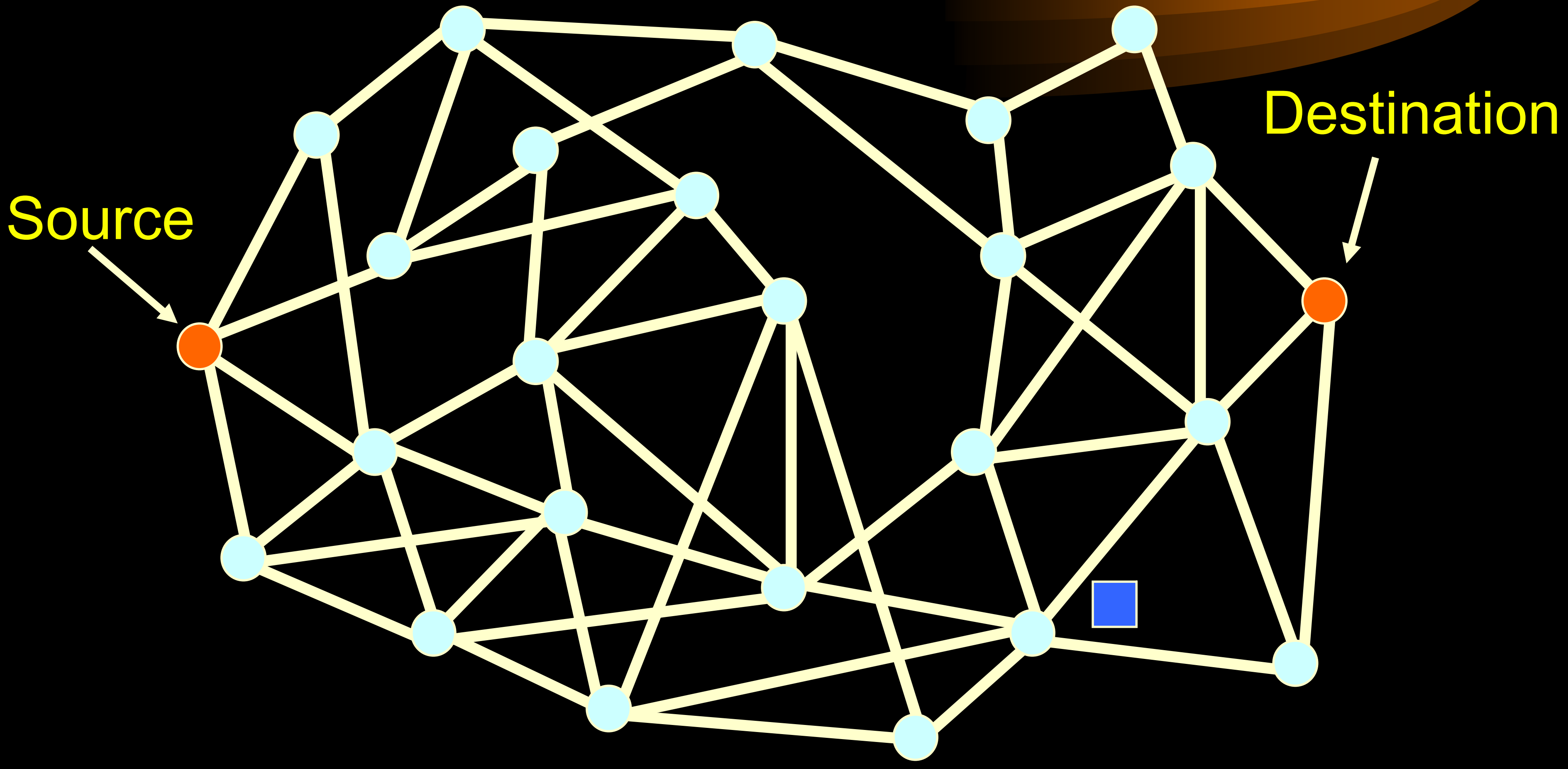
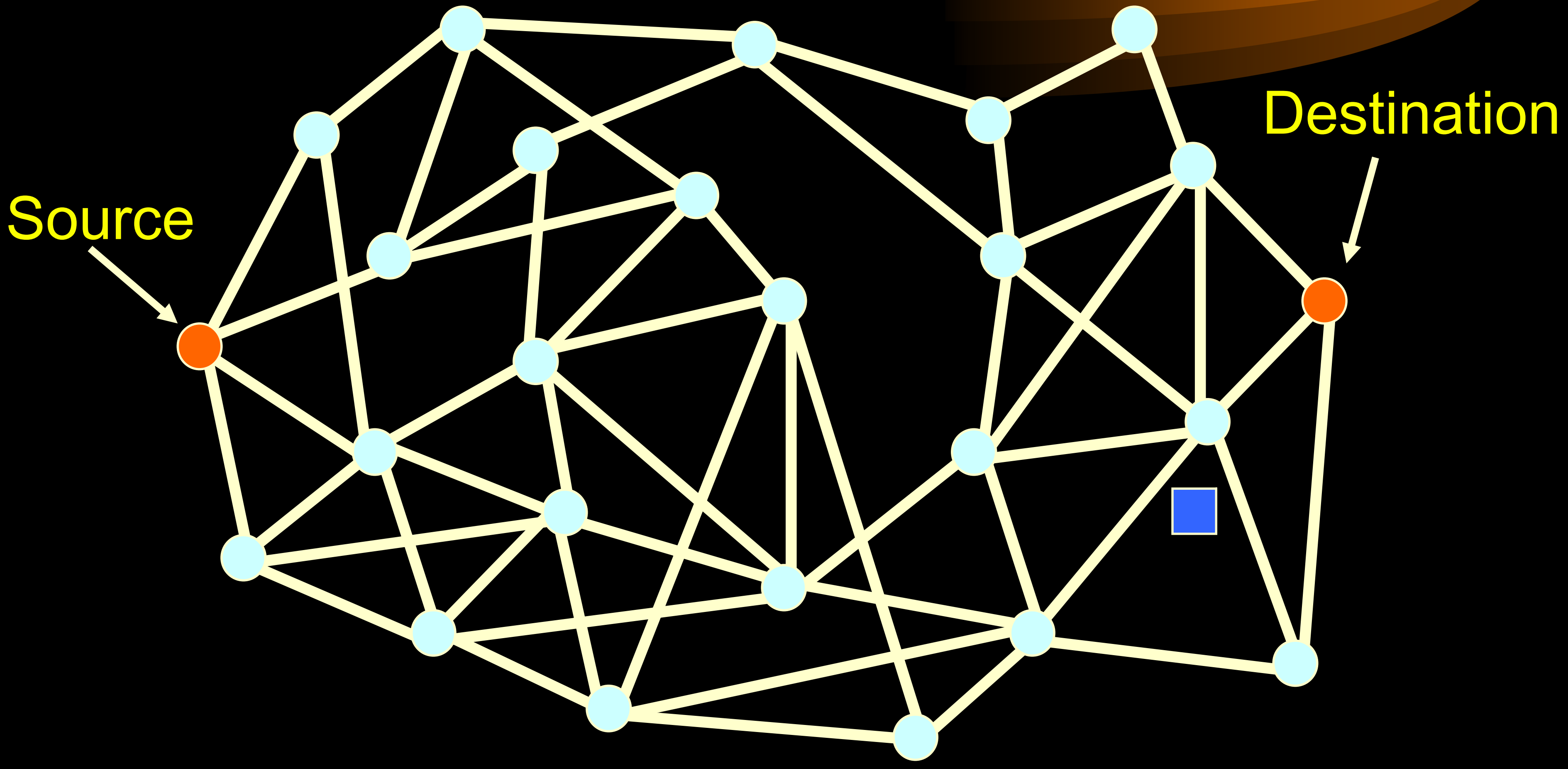


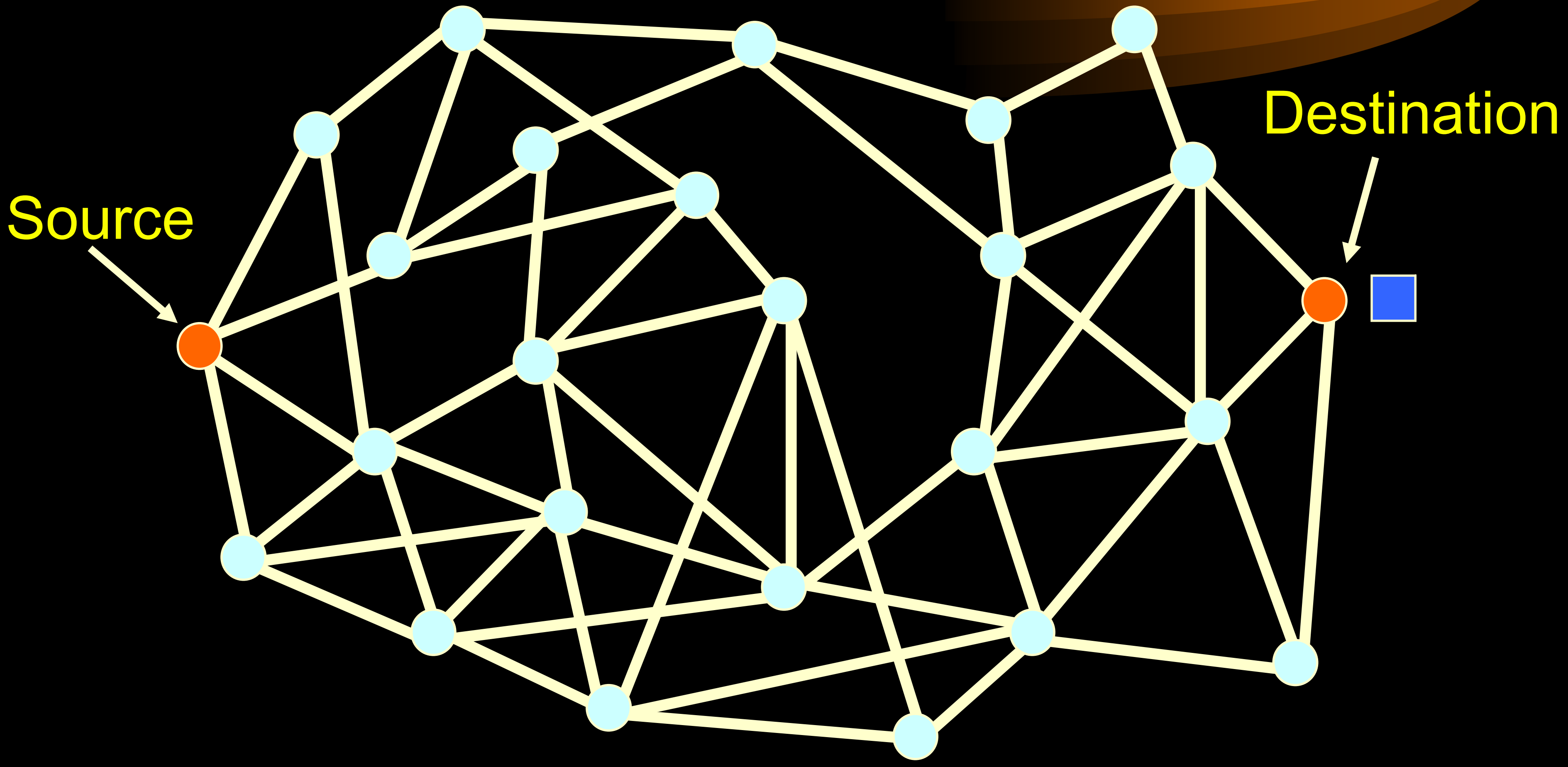
Revert to Greedy Forwarding



Revert to Greedy Forwarding



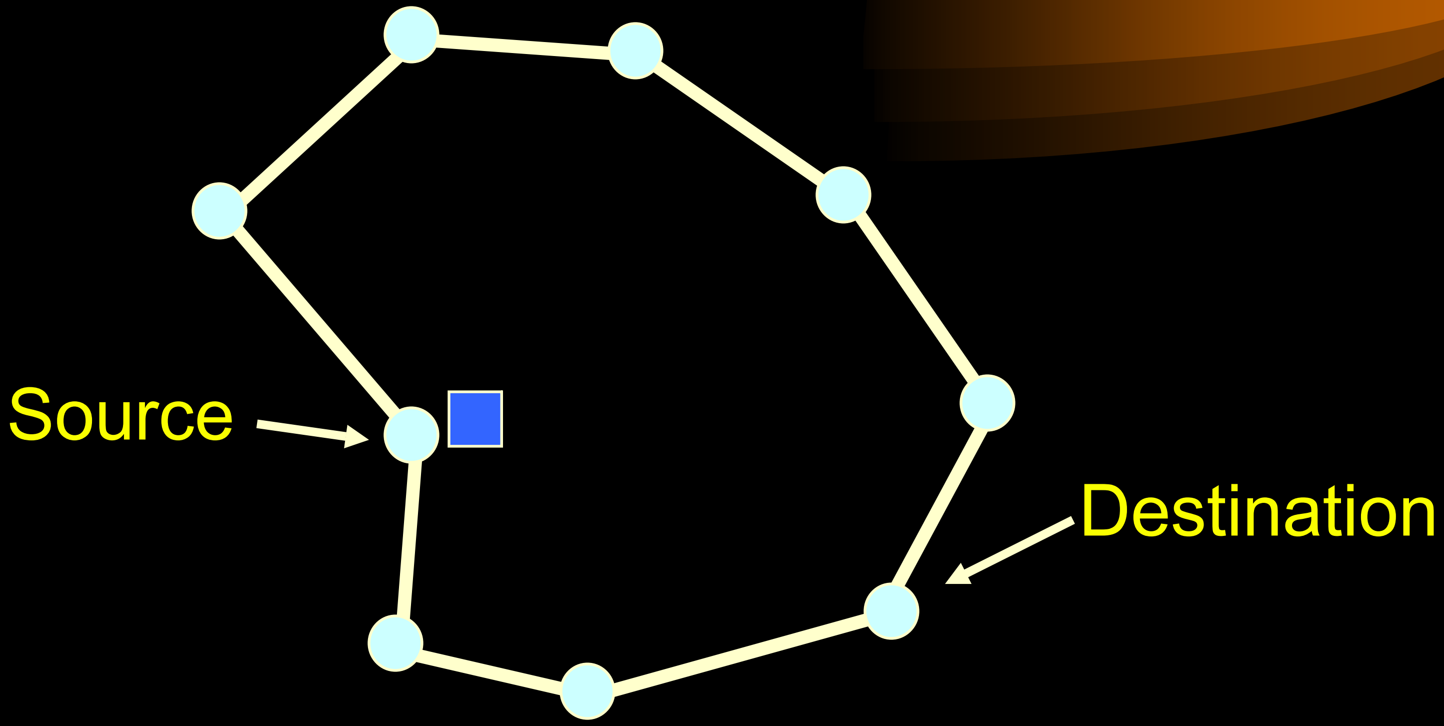
Revert to Greedy Forwarding



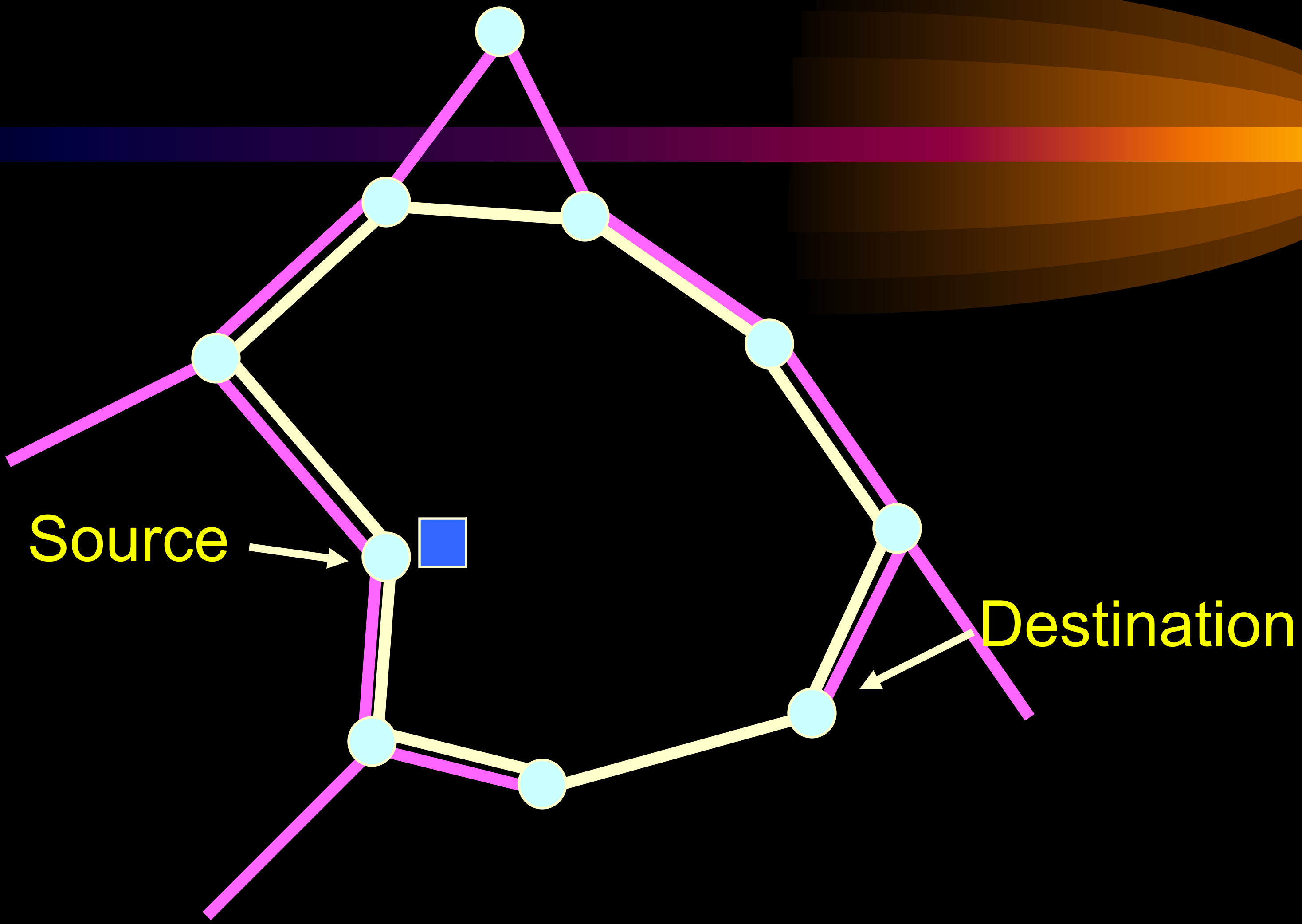
Issues

- Choosing forwarding direction
  - multiple hull trees
- Undeliverable packets
  - conflict Hulls

Using Multiple Trees

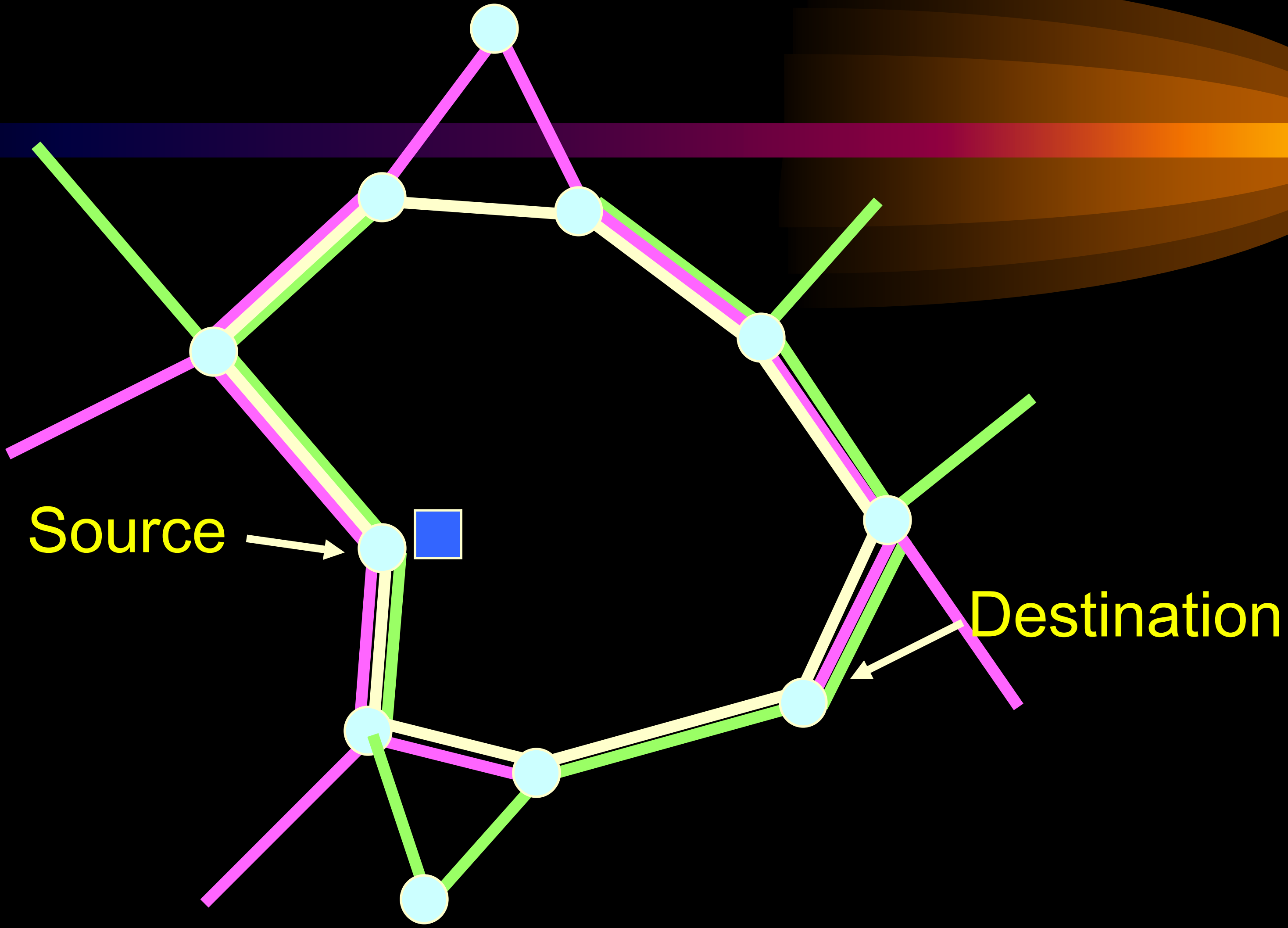


Using Multiple Trees



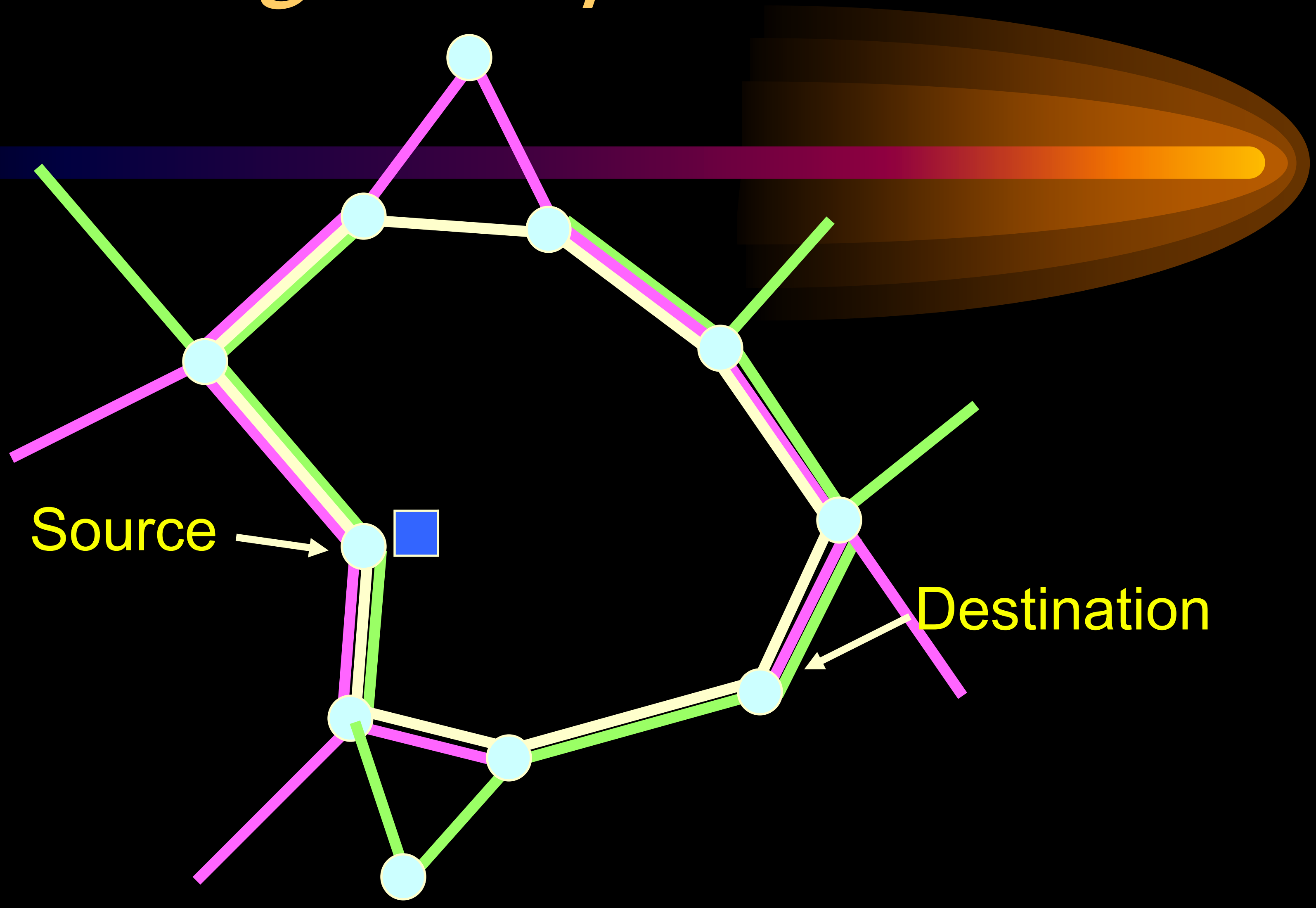
With one tree, may be forced to route in “bad” direction.

Using Multiple Trees



Two extremal-rooted trees are usually sufficient to “approximate” a void

Using Multiple Trees



Pick tree with root closest to the destination

Summary: Routing

- Try greedy forwarding
- Dead end:
  - choose tree
  - record start node
  - traverse subtree
- If possible, revert to greedy forwarding
- Back to start node: packet undeliverable

Theorem

Given a pair of nodes *s* and *t* in connected graph *G*, GDSTR guarantees packet delivery from *s* to *t*.

Building Hull Trees

- Convex hull info in *keepalive* messages
- Choose roots:
  - minimal and maximal x-coordinates
- Want compact trees
  - minimal hop count from root
- Aggregate convex hulls from leaves to root
- Conflict hull info percolates from root to leaves

Simulation Results

- Measured 2 routing metrics:
  - Path Stretch
  - Hop Stretch
- Topologies
  - range of network densities (average node degree)
  - larger networks up to 5,000 nodes
    - low/high density
    - low/high obstacle density

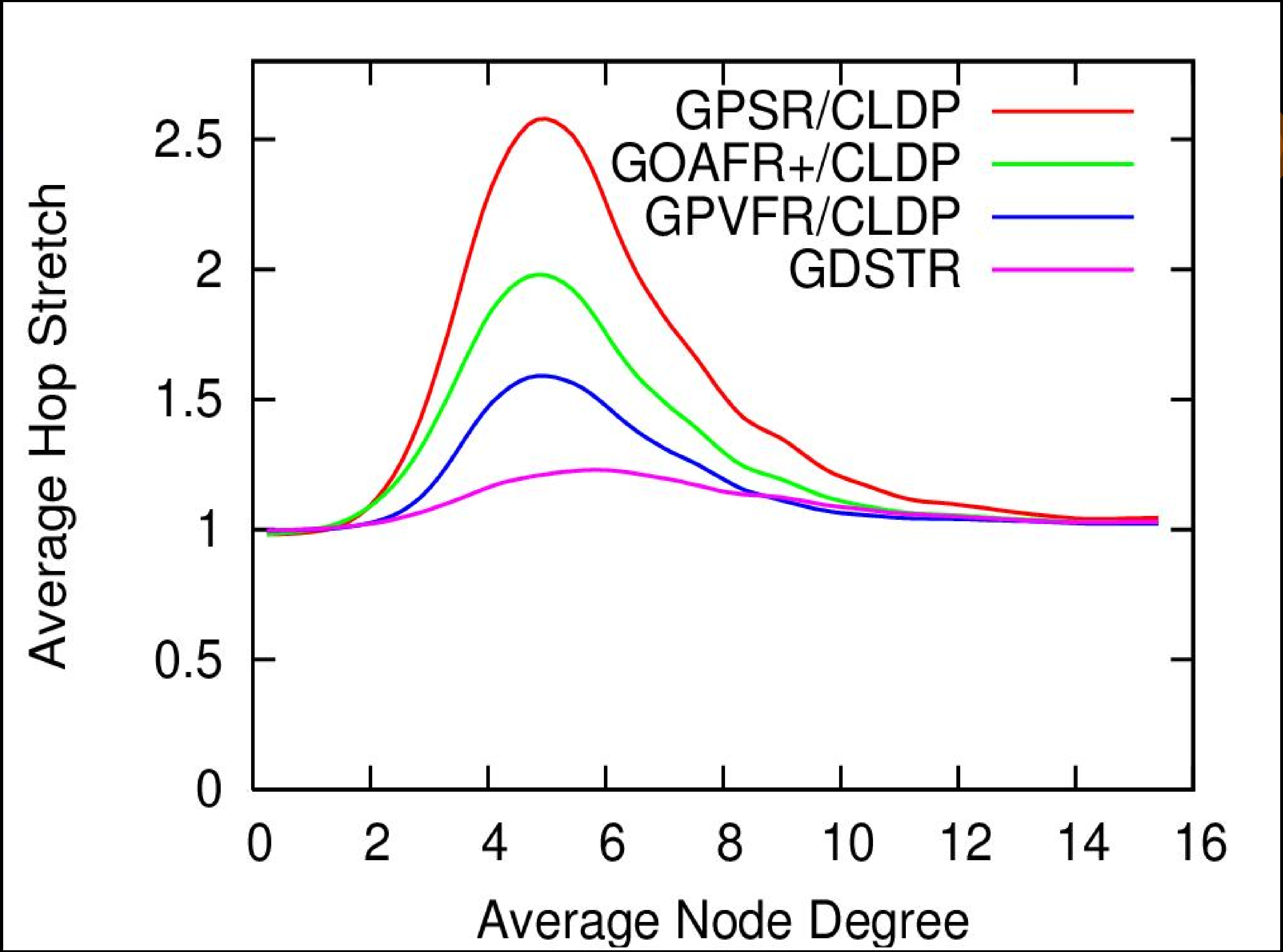
Simulation Results

- Compare with
  - GPSR (Karp, 2001),
  - GOAFR+ (Kuhn, 2003) and
  - GPVFR (Leong et al., 2005)

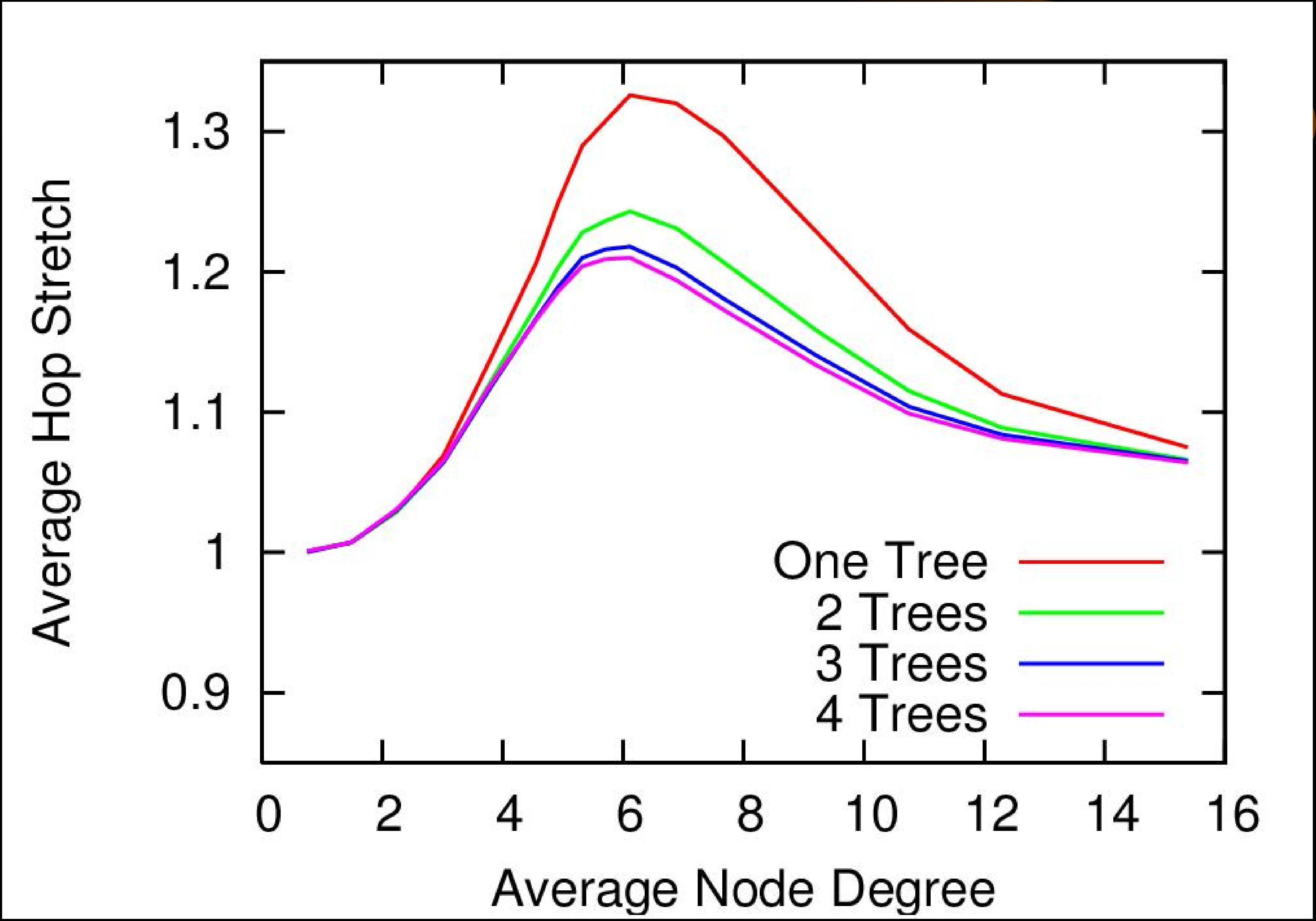
under CLDP planarization (Kim et al., 2005)

- Measured costs and compared with CLDP:
  - storage
  - bandwidth

Hop Stretch


GPSR/CLDP
GOAFR+/CLDP
GPVFR/CLDP
GDSTR
Average Hop Stretch
0
0.5
1
1.5
2
2.5
0
2
4
6
8
10
12
14
16
Average Node Degree

Hop Stretch

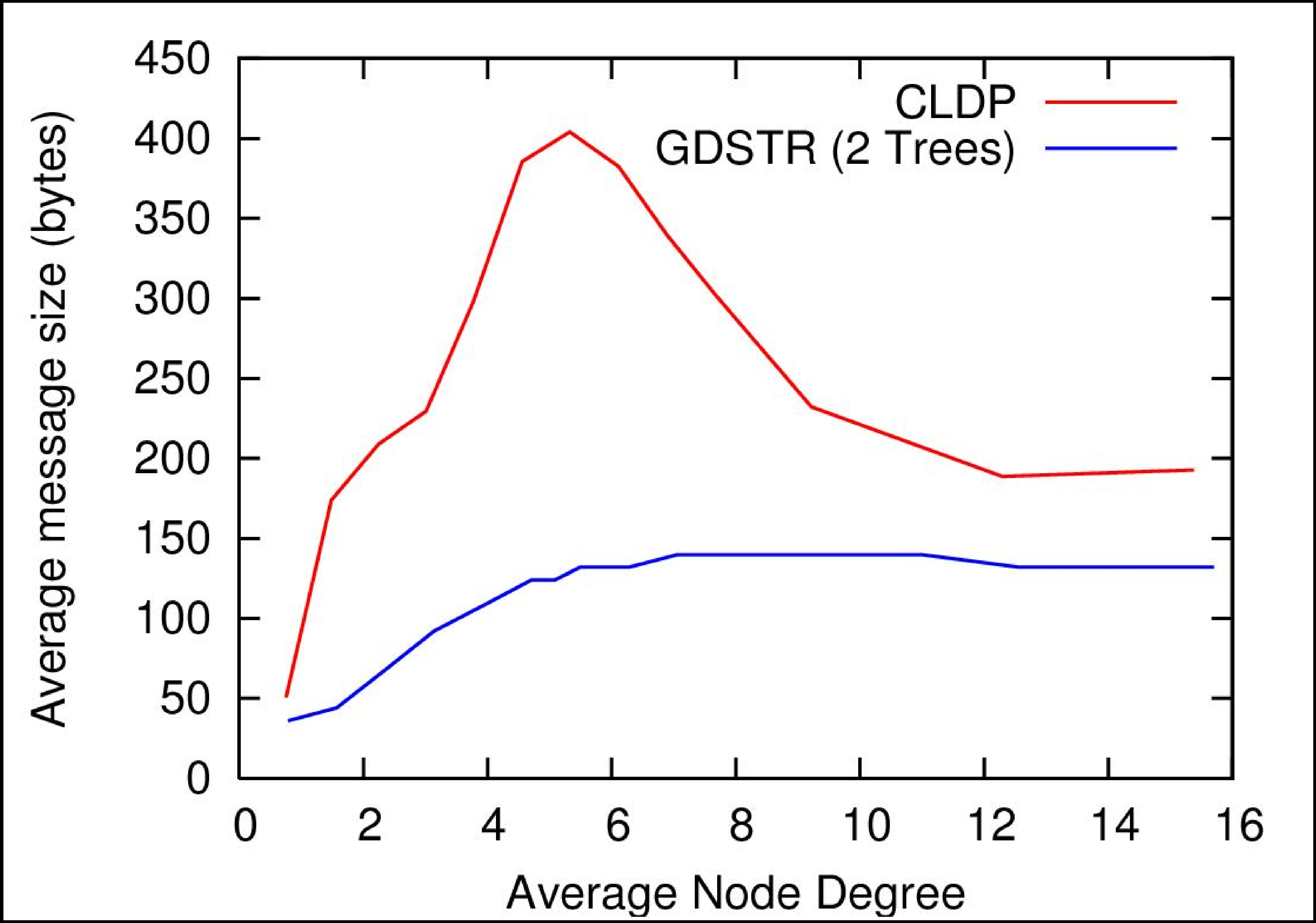


Average Hop Stretch
1.3
1.2
1.1
1
0.9
0
2
4
6
8
10
12
14
16
Average Node Degree
One Tree
2 Trees
3 Trees
4 Trees

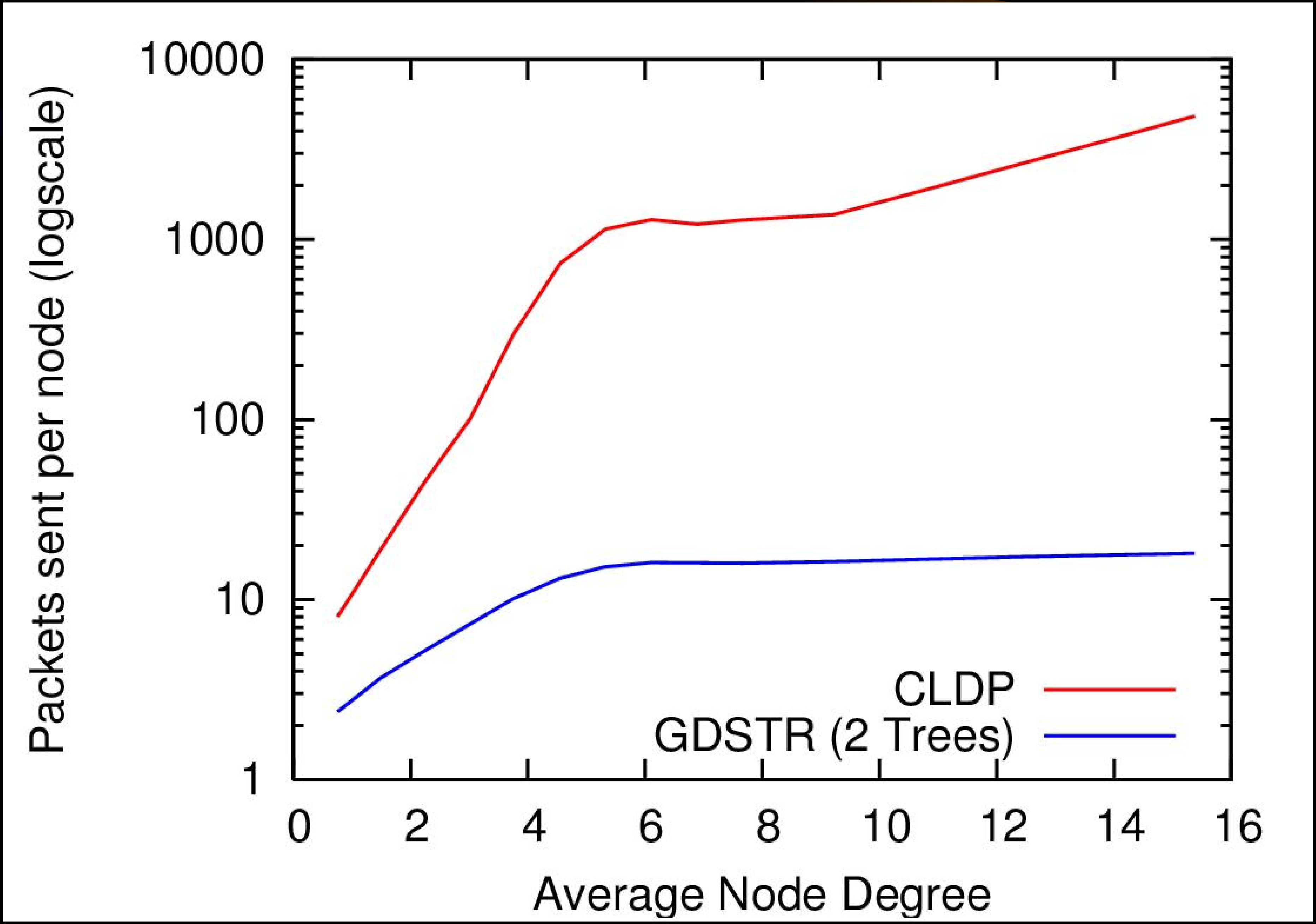
Costs

- Computation:
  - convex hull computation: *O(log n)* operations [Graham’s scan]
- Storage: < 1 kb
- Bandwidth

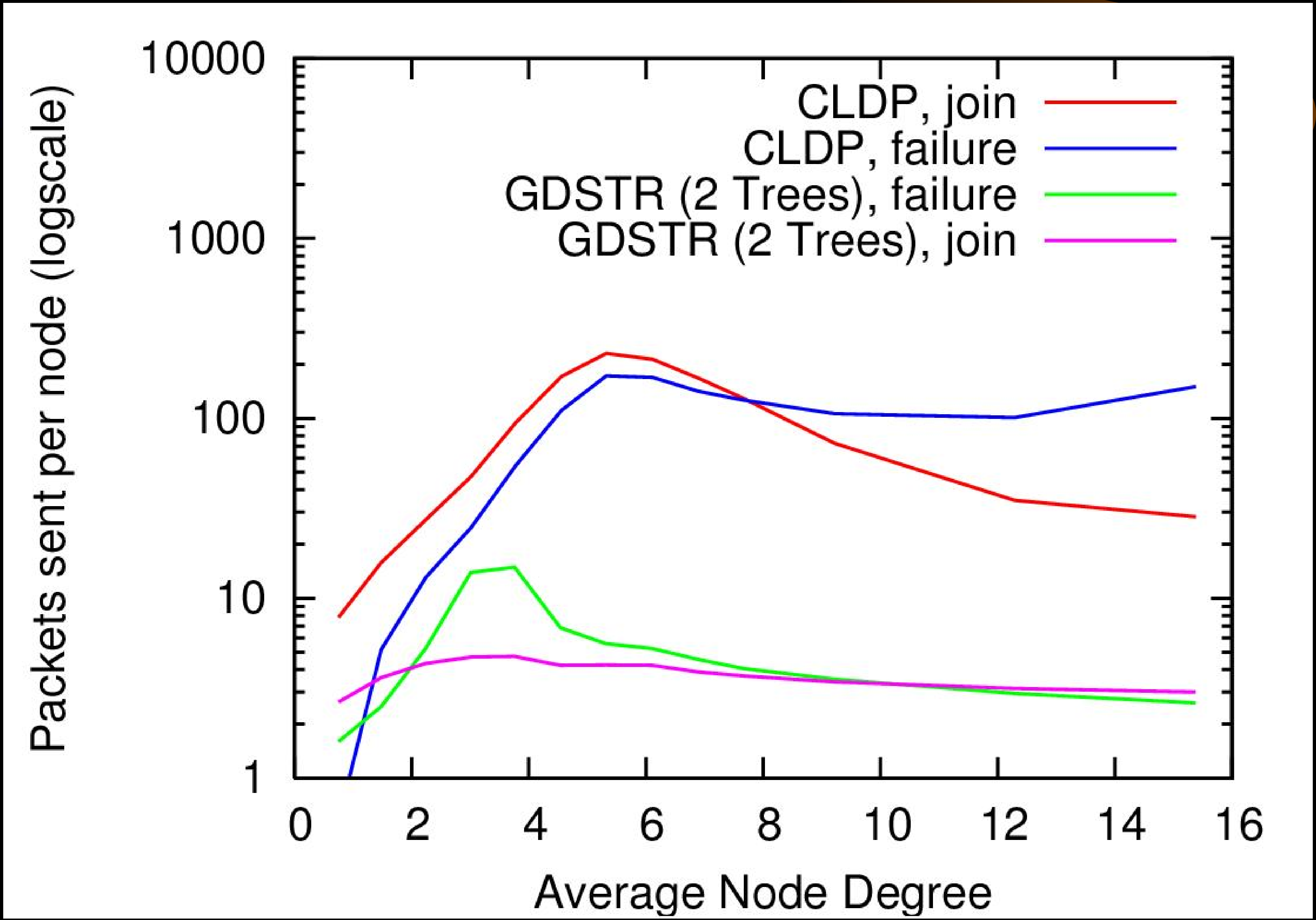
Message Sizes



Messages for Startup



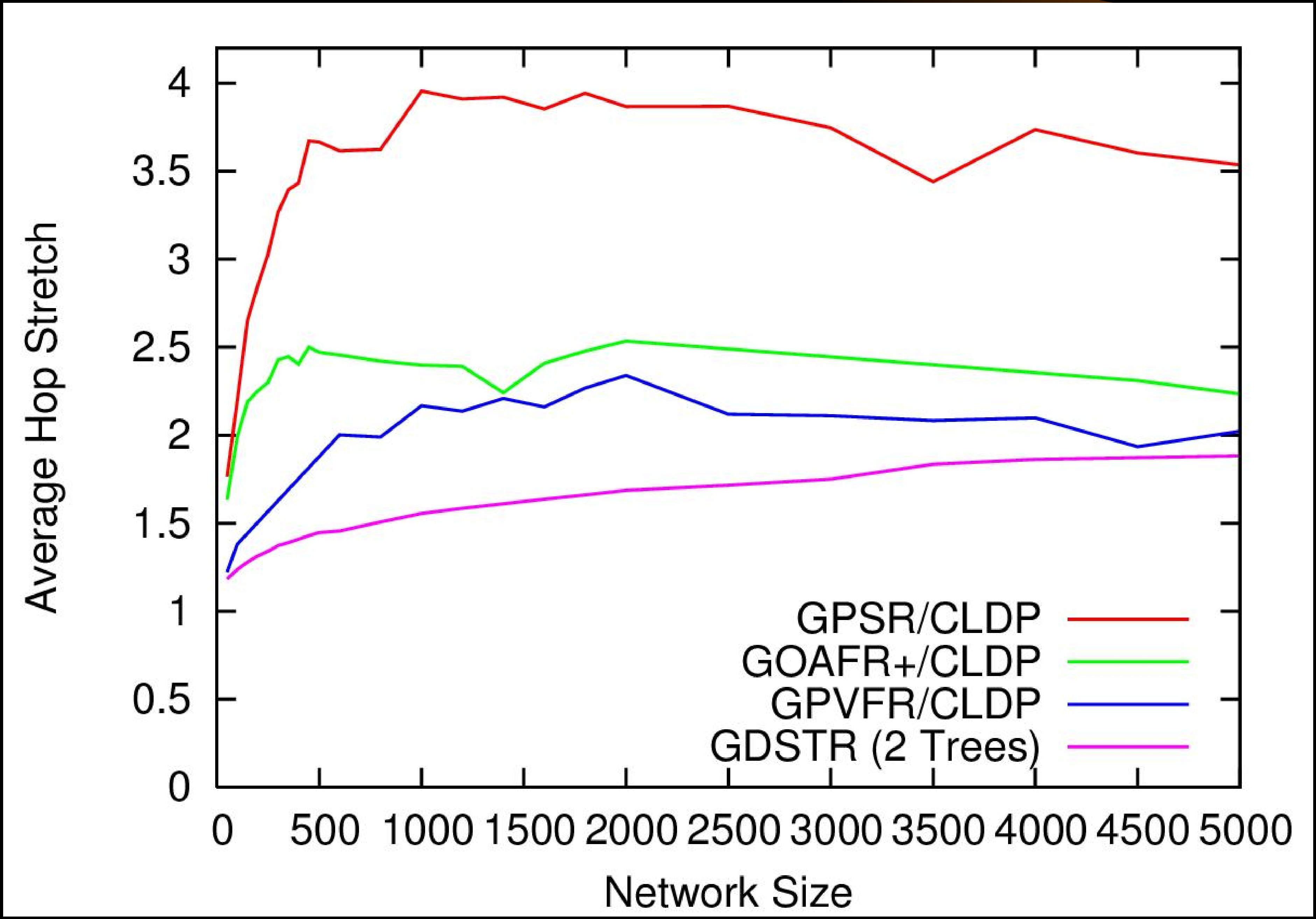
Messages for Stabilization



Summary

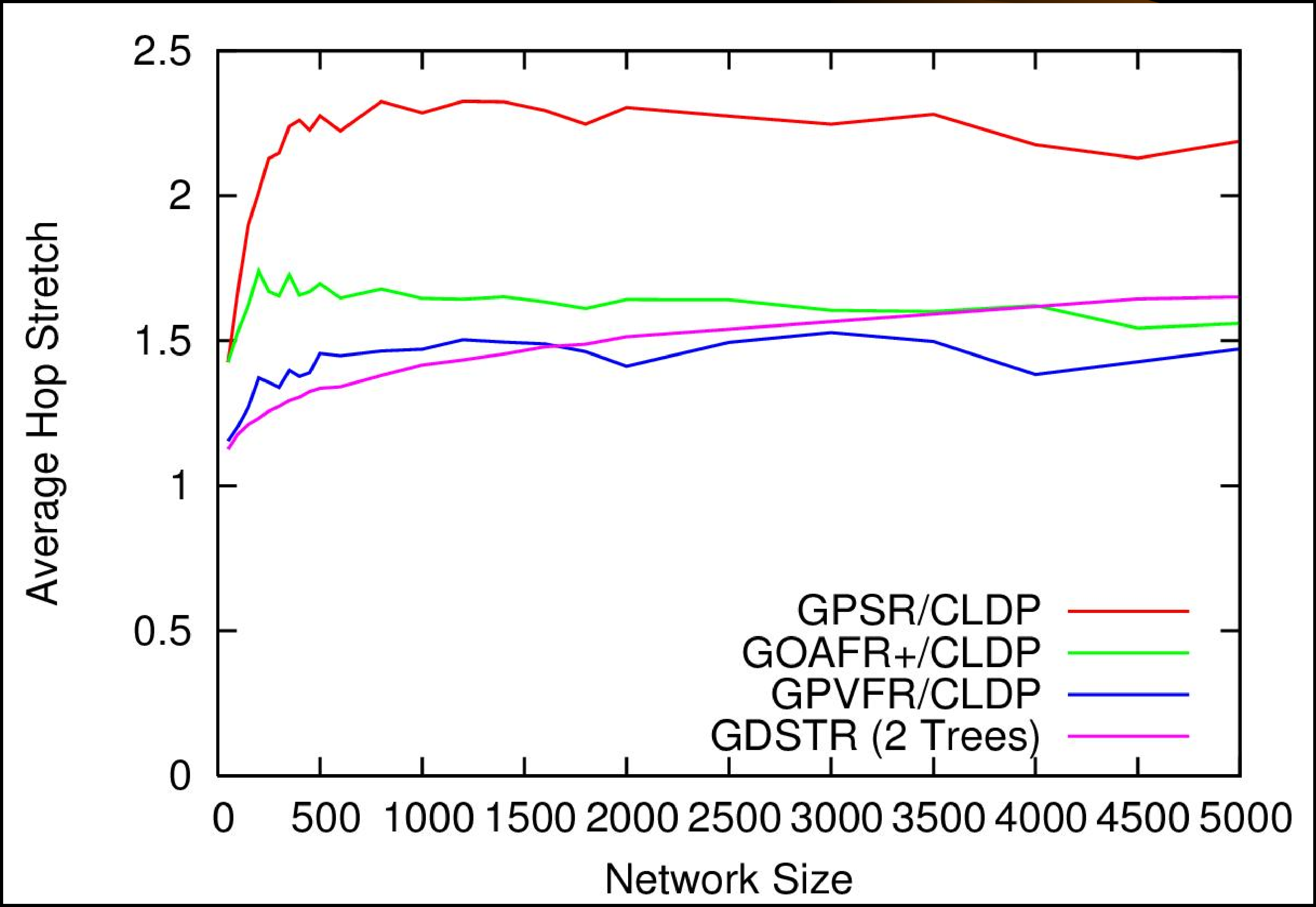
- Maintenance cost one order of magnitude less than CLDP (face routing)
- Better routing performance (stretch) – up to 20% better

Large Voids



Average Hop Stretch
0
0.5
1
1.5
2
2.5
3
3.5
4
Network Size
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
GPSR/CLDP
GOAFR+/CLDP
GPVFR/CLDP
GDSTR (2 Trees)

Small Voids


Average Hop Stretch
2.5
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Network Size
GPSR/CLDP
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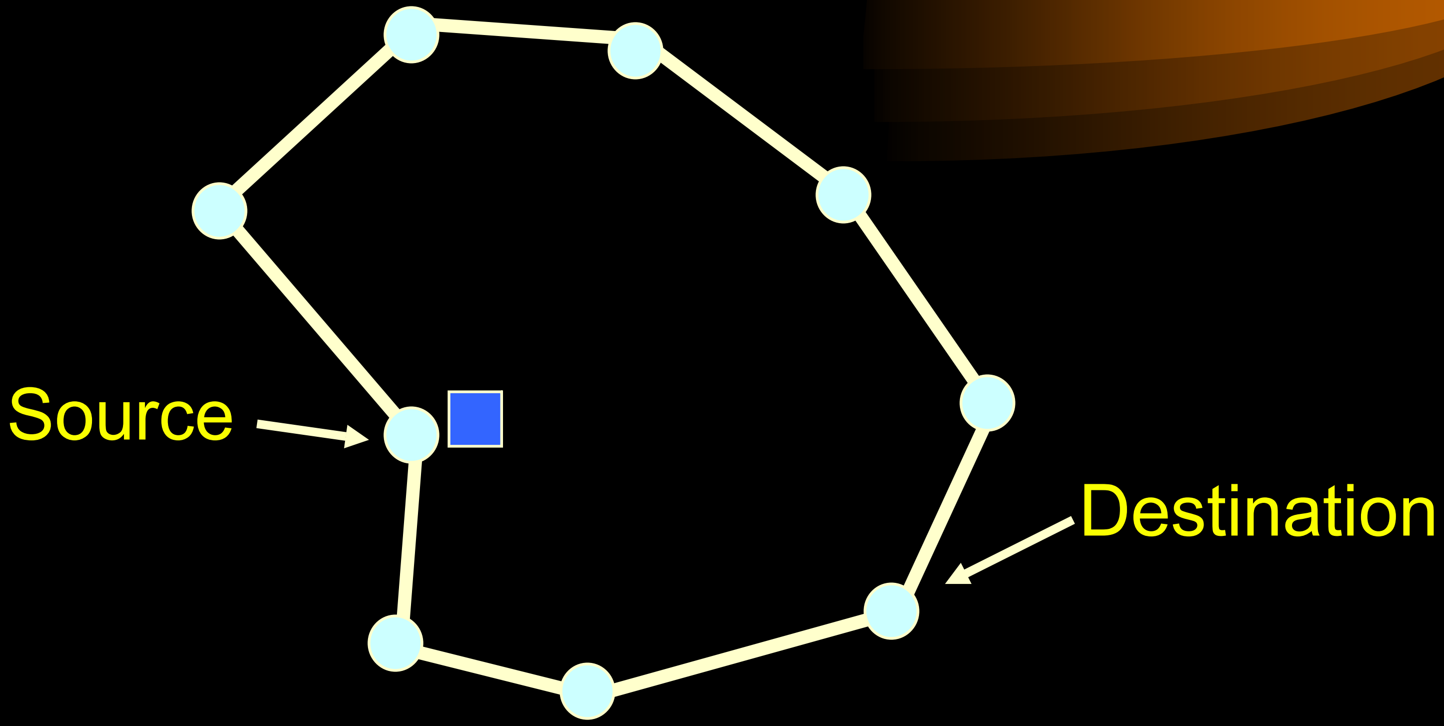
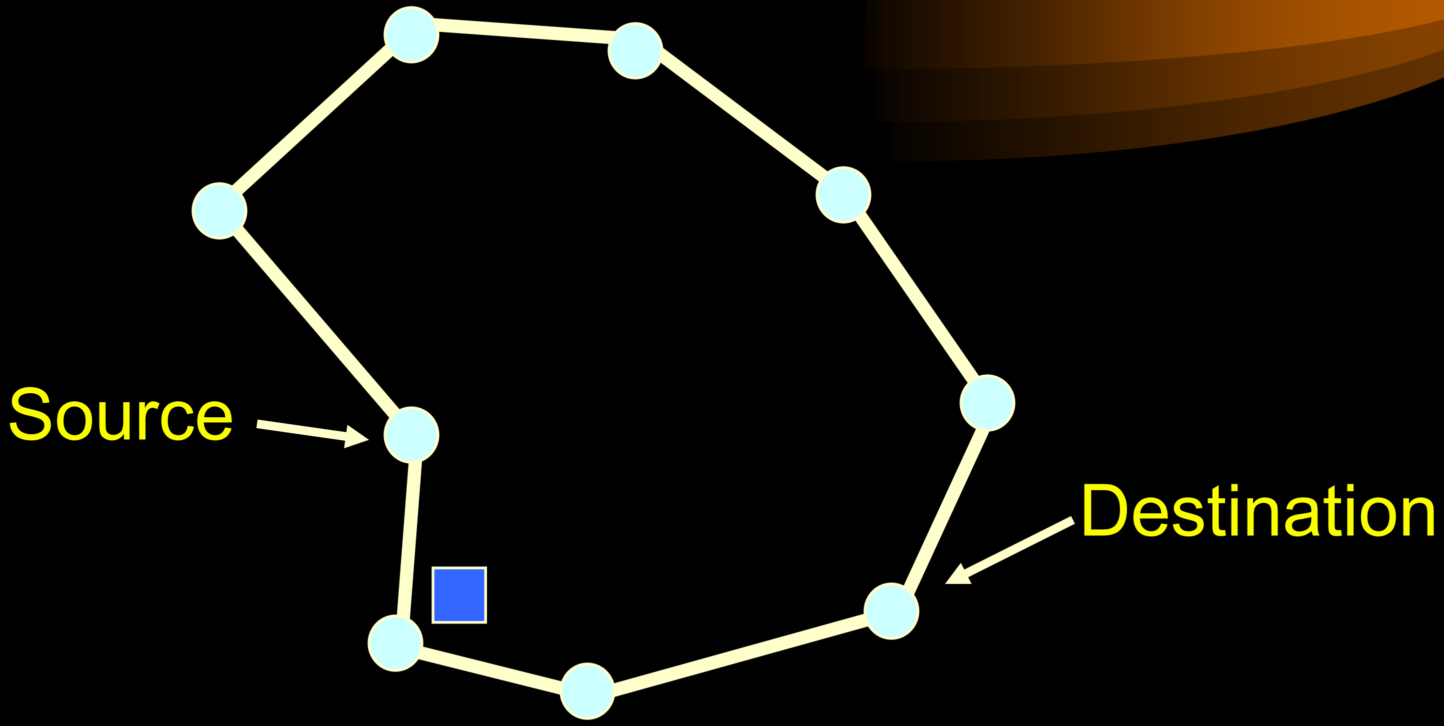
Explaining Performance



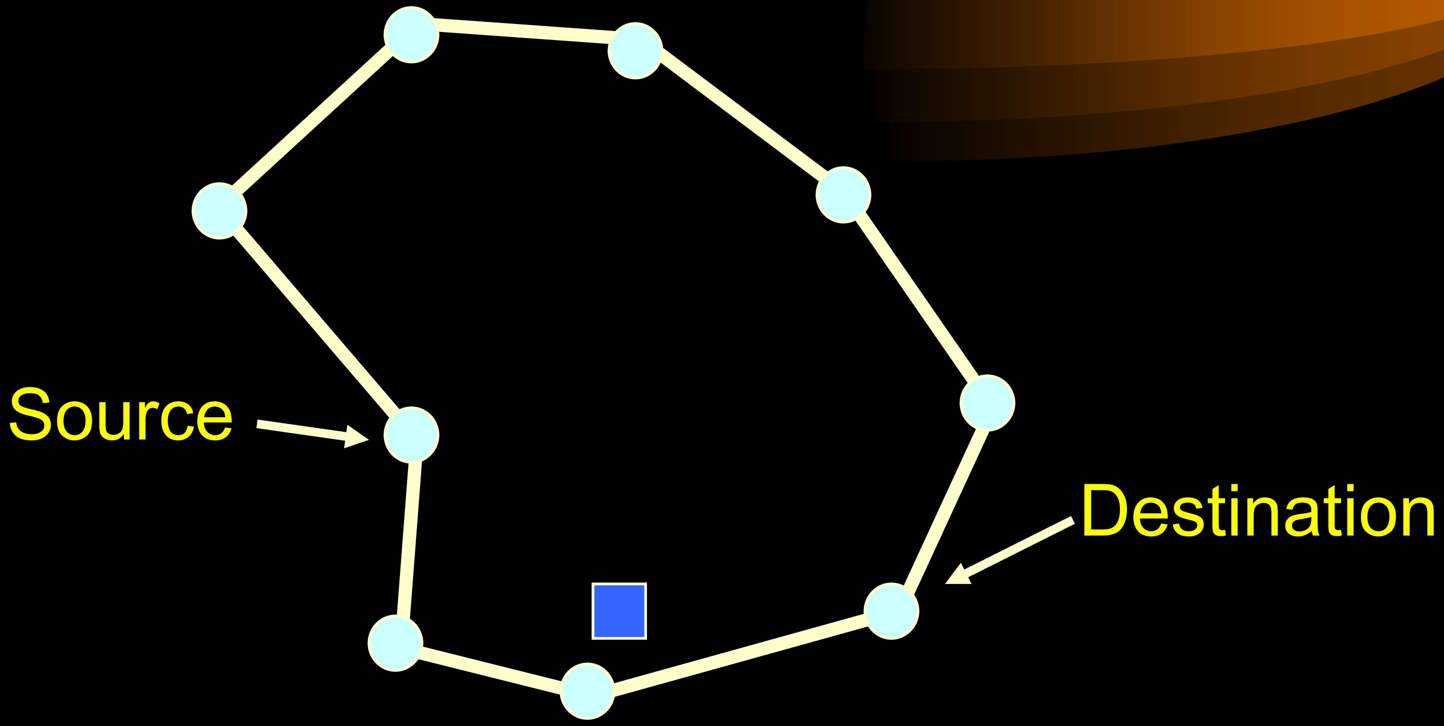
Explaining Performance



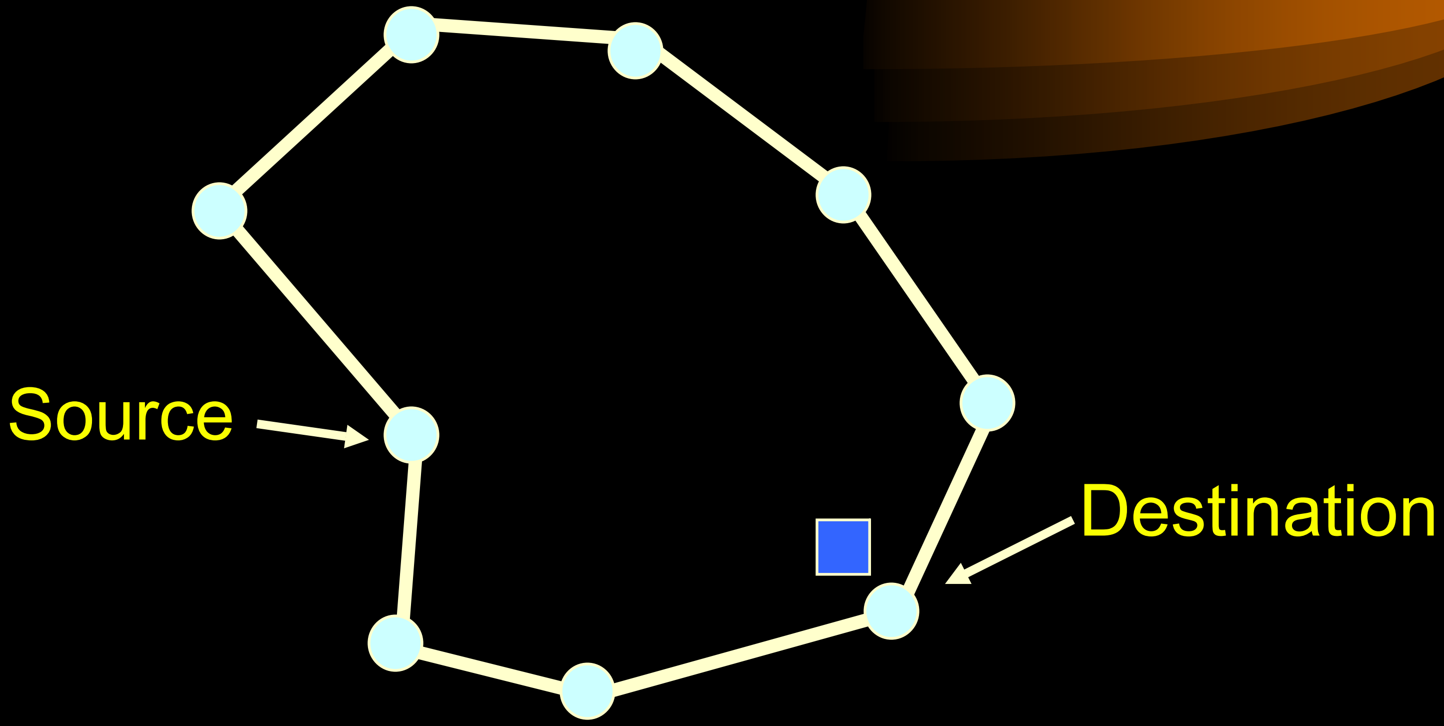
Source

Destination

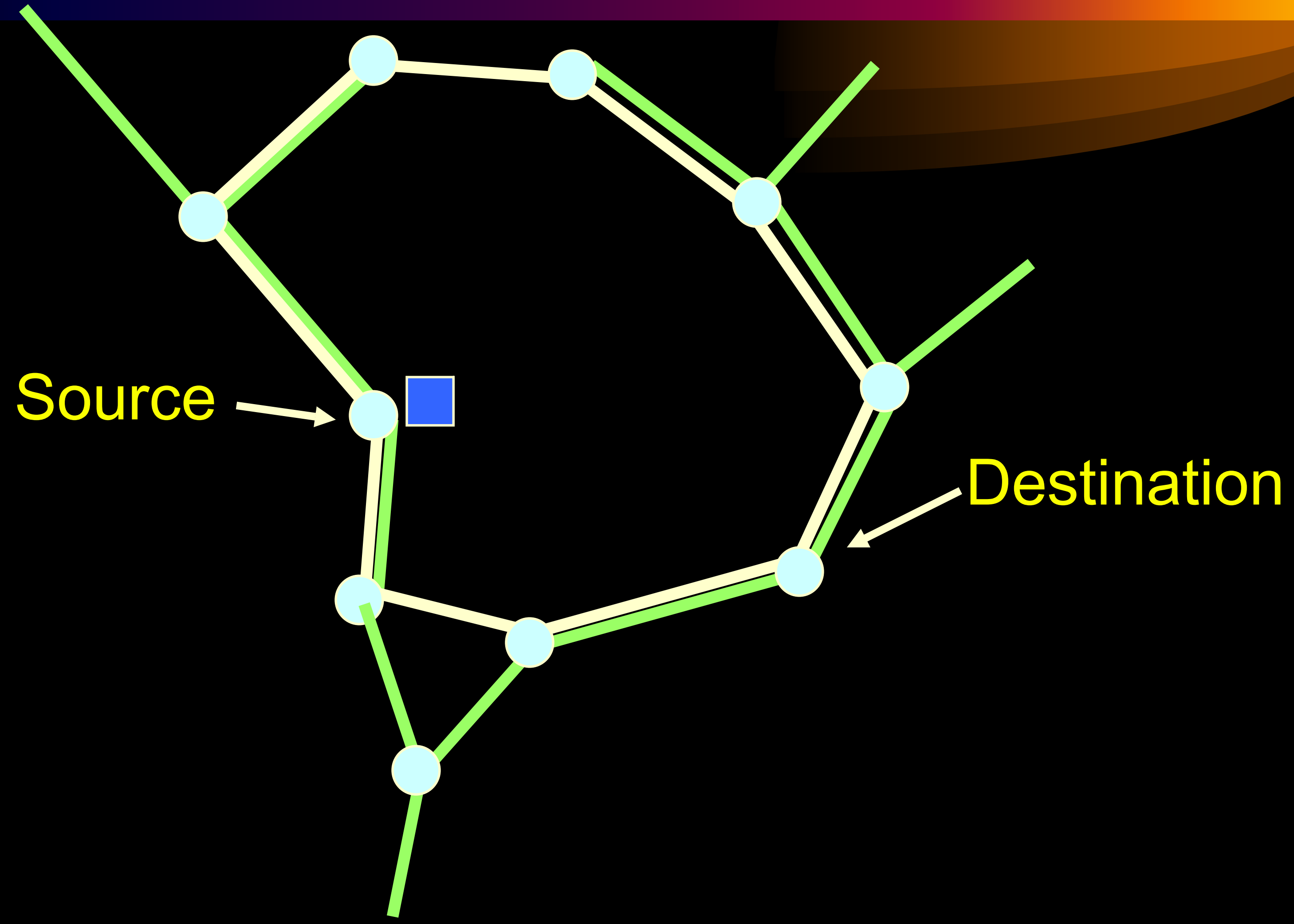
Explaining Performance



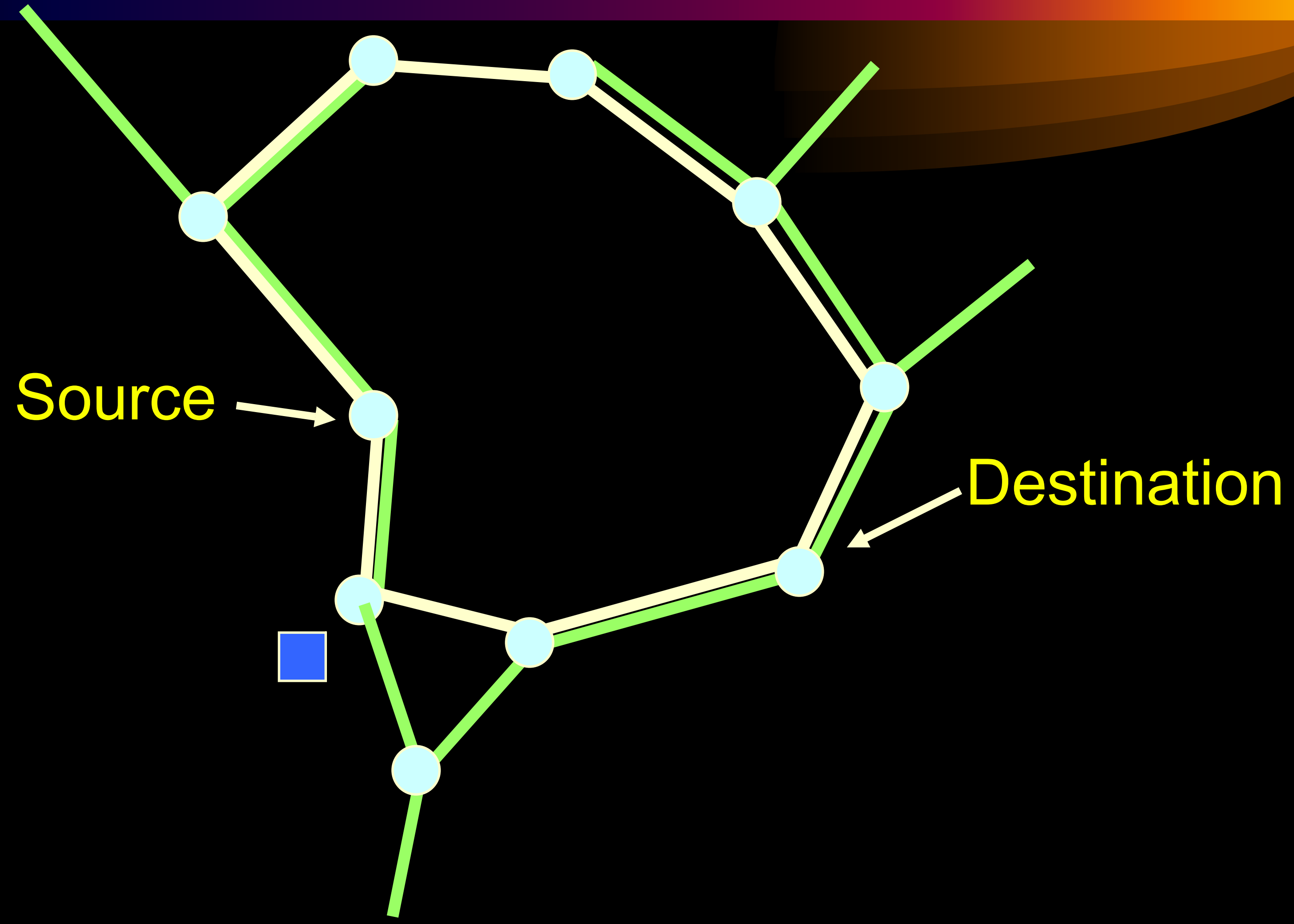
Explaining Performance



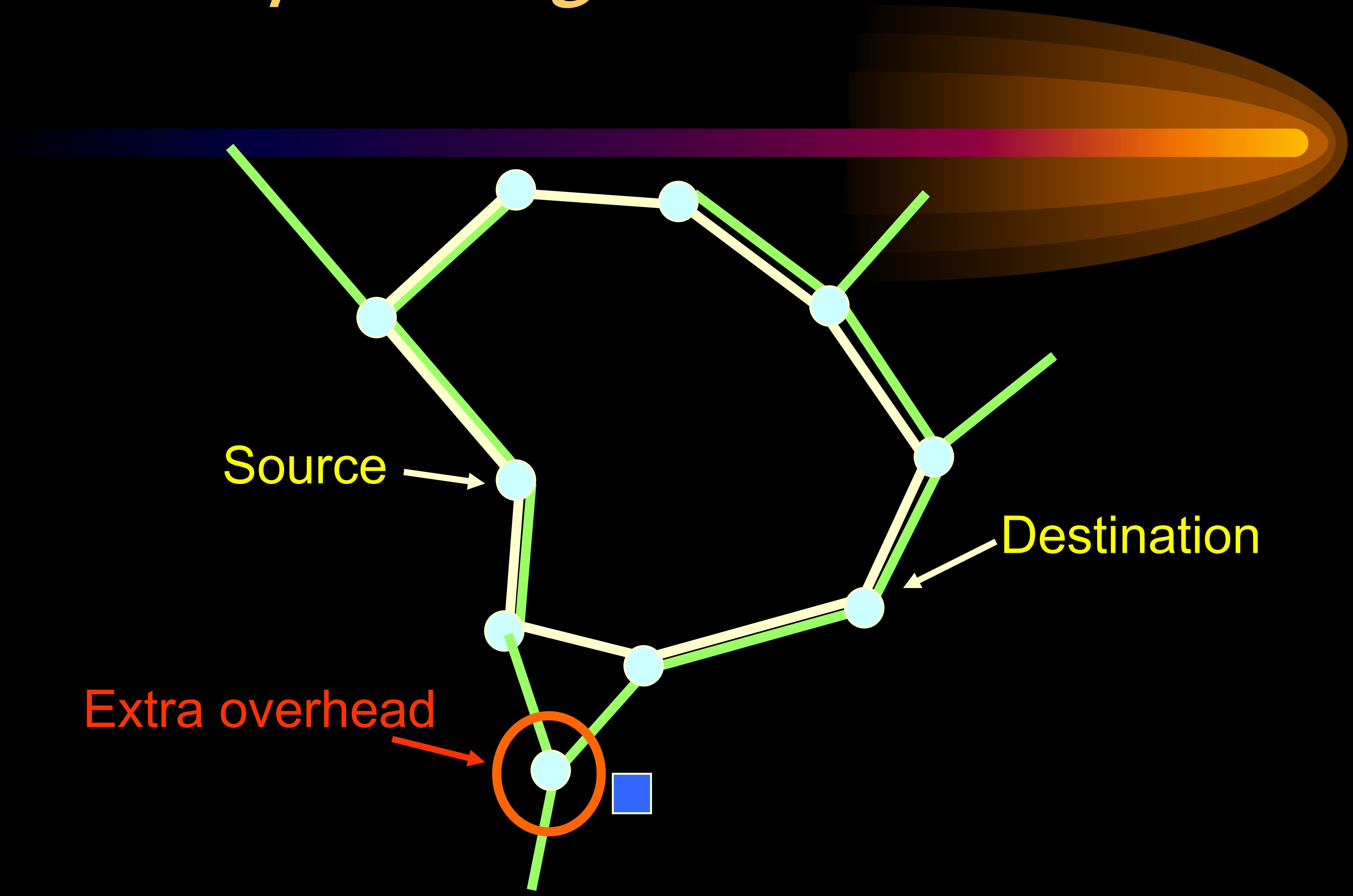
Explaining Performance



Explaining Performance



Explaining Performance



Summary

- Sparse networks
  - GDSTR chooses correct forwarding direction more often than face routing
- Moderately dense networks
  - Faces are small, forwarding direction is inconsequential
  - Trees do not “approximate” small voids well
- Ultra-dense networks
  - Greedy forwarding works all the time!

Conclusion

- Cheaper to maintain two hull trees than a planar graph
- “Global” information allows GDSTR to choose good forwarding direction more often
- GDSTR achieves improved routing stretch at lower maintenance cost than CLDP

Future Work

- Evaluate GDSTR in a practical and mobile setting
- Geographic routing in higher dimensions
  - convex hulls generalizable to higher dimensions

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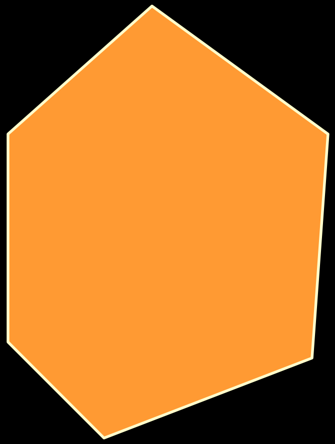
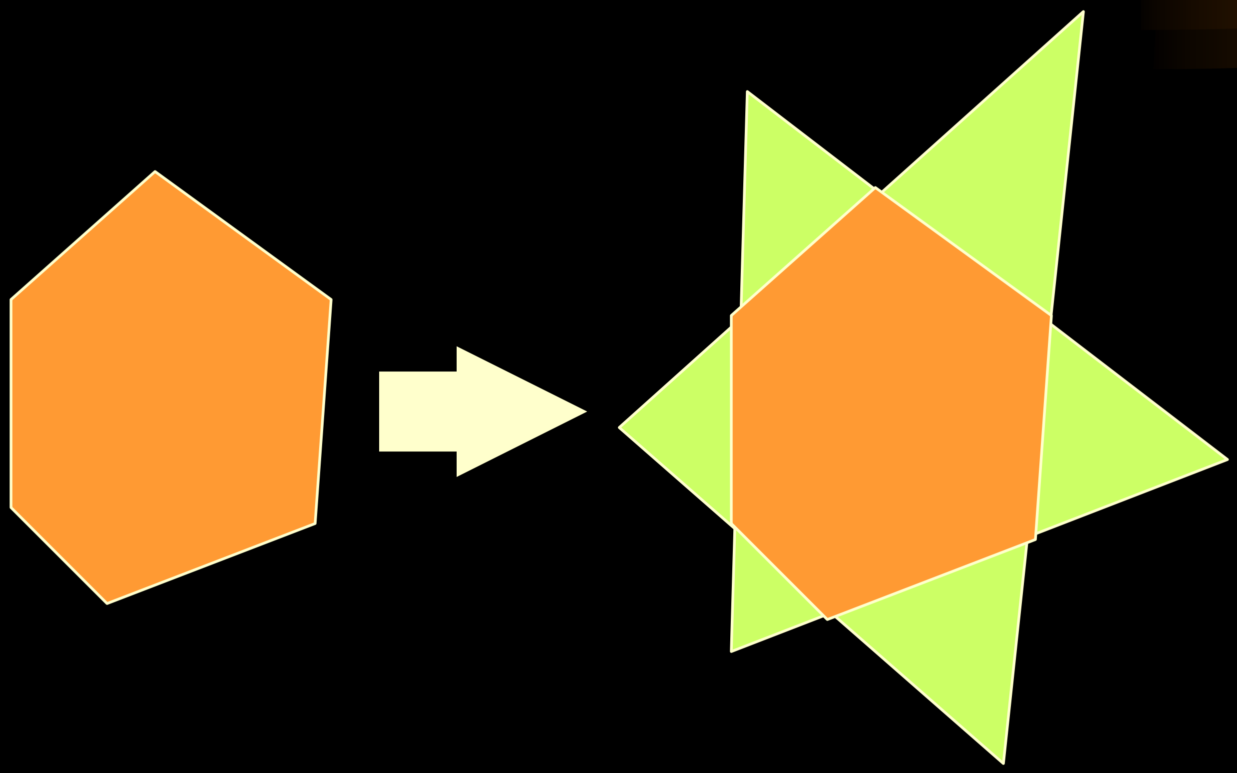
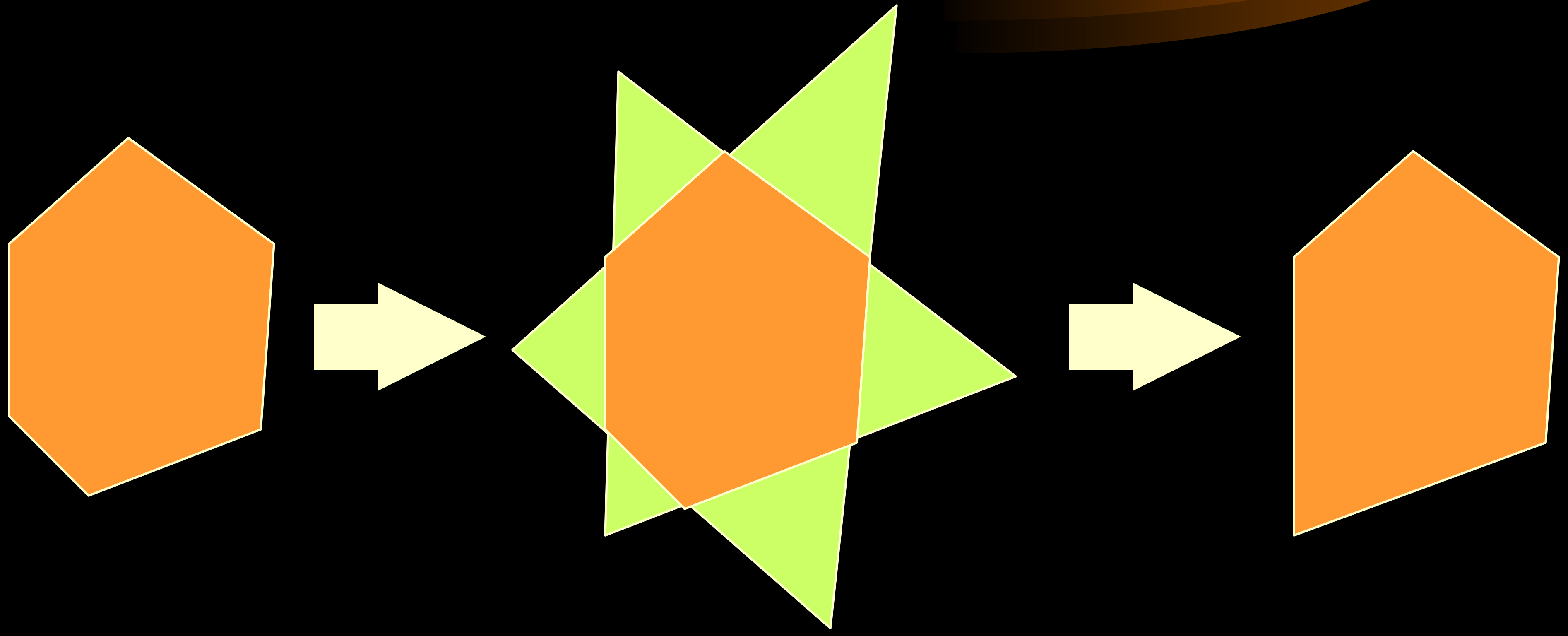
Reducing Convex Hulls



Reducing Convex Hulls



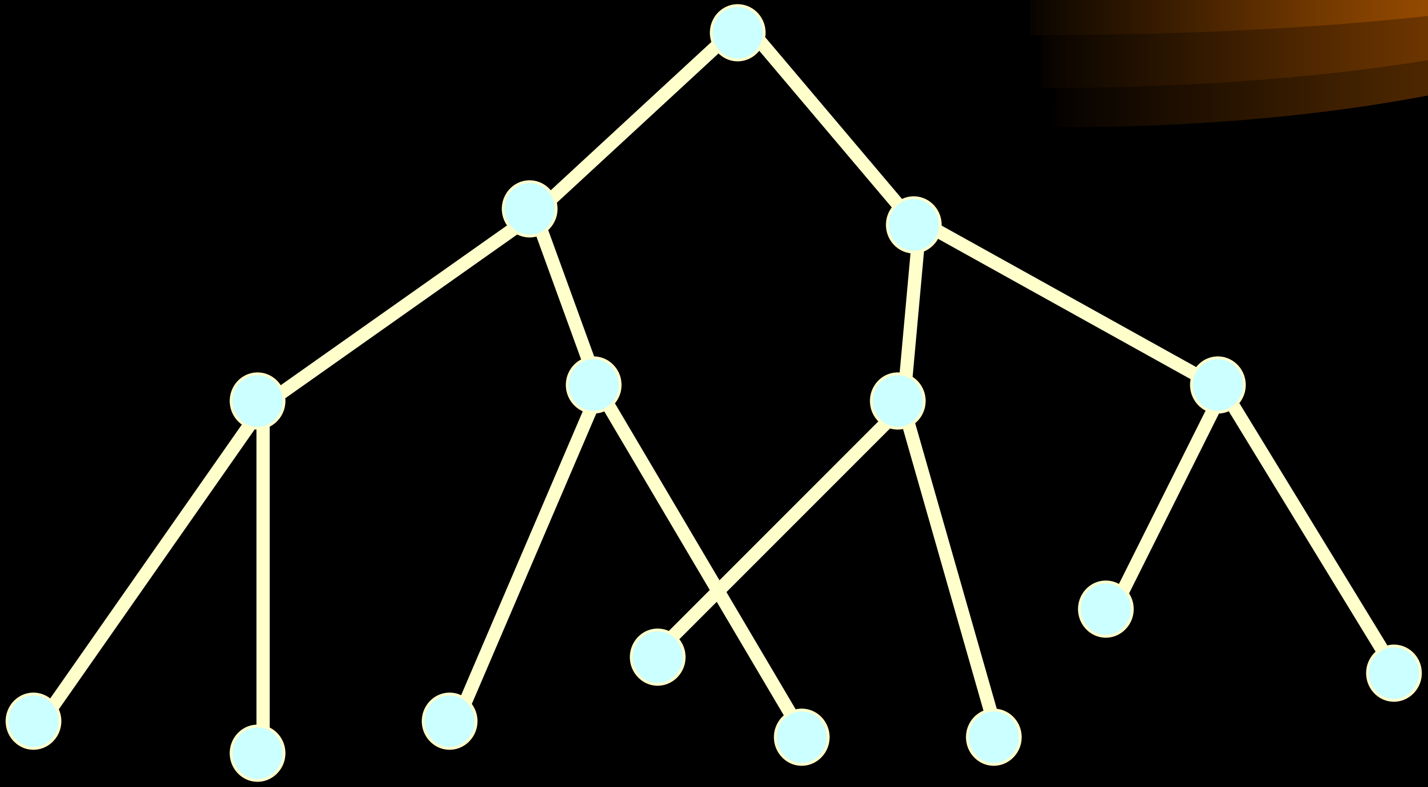
Reducing Convex Hulls



Conflict Hulls

- Undeliverable packets will be forwarded to the root.
- *Conflict hulls* allow us to avoid forwarding to the root
- *Key idea*: parent nodes tell child nodes about other nodes with intersecting hulls

Example: Conflict Hull



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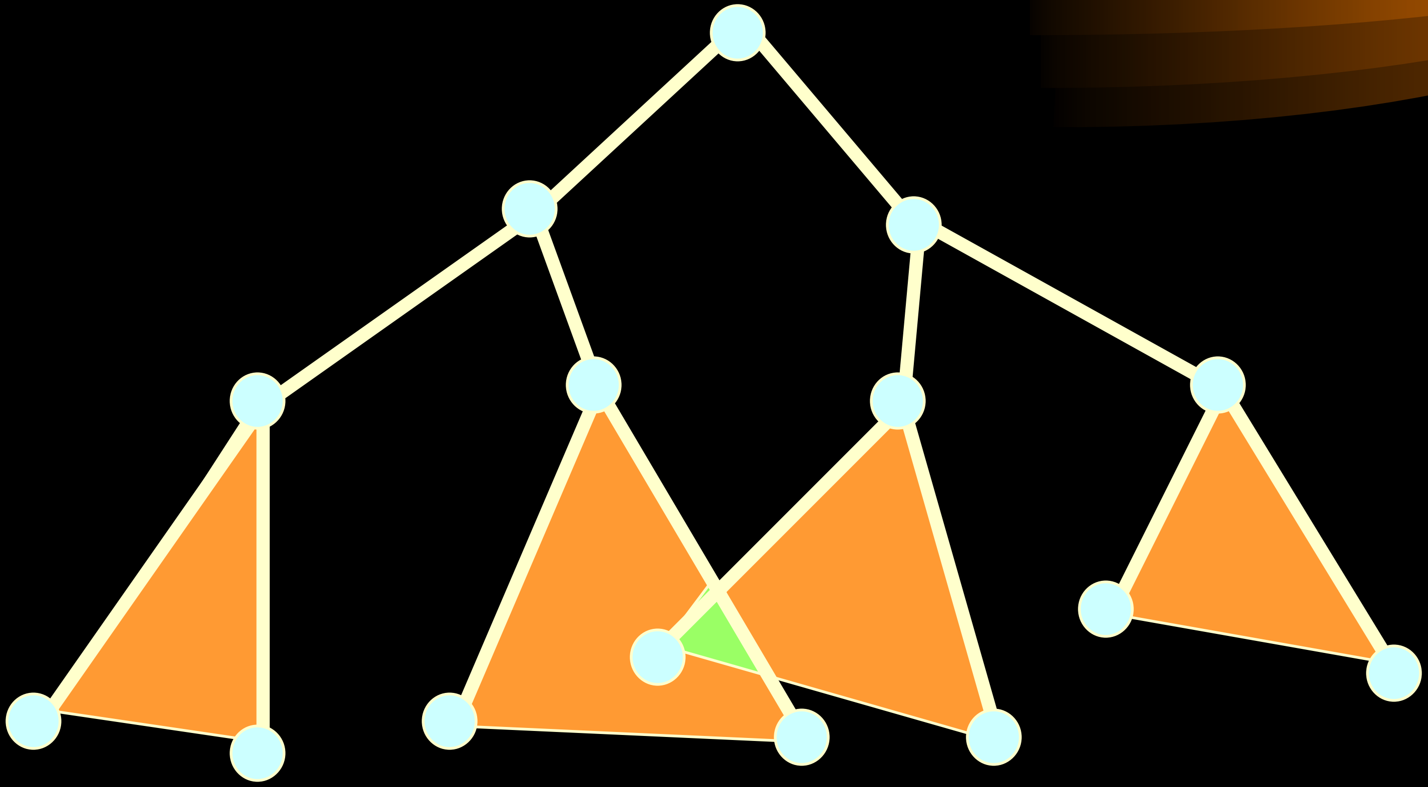

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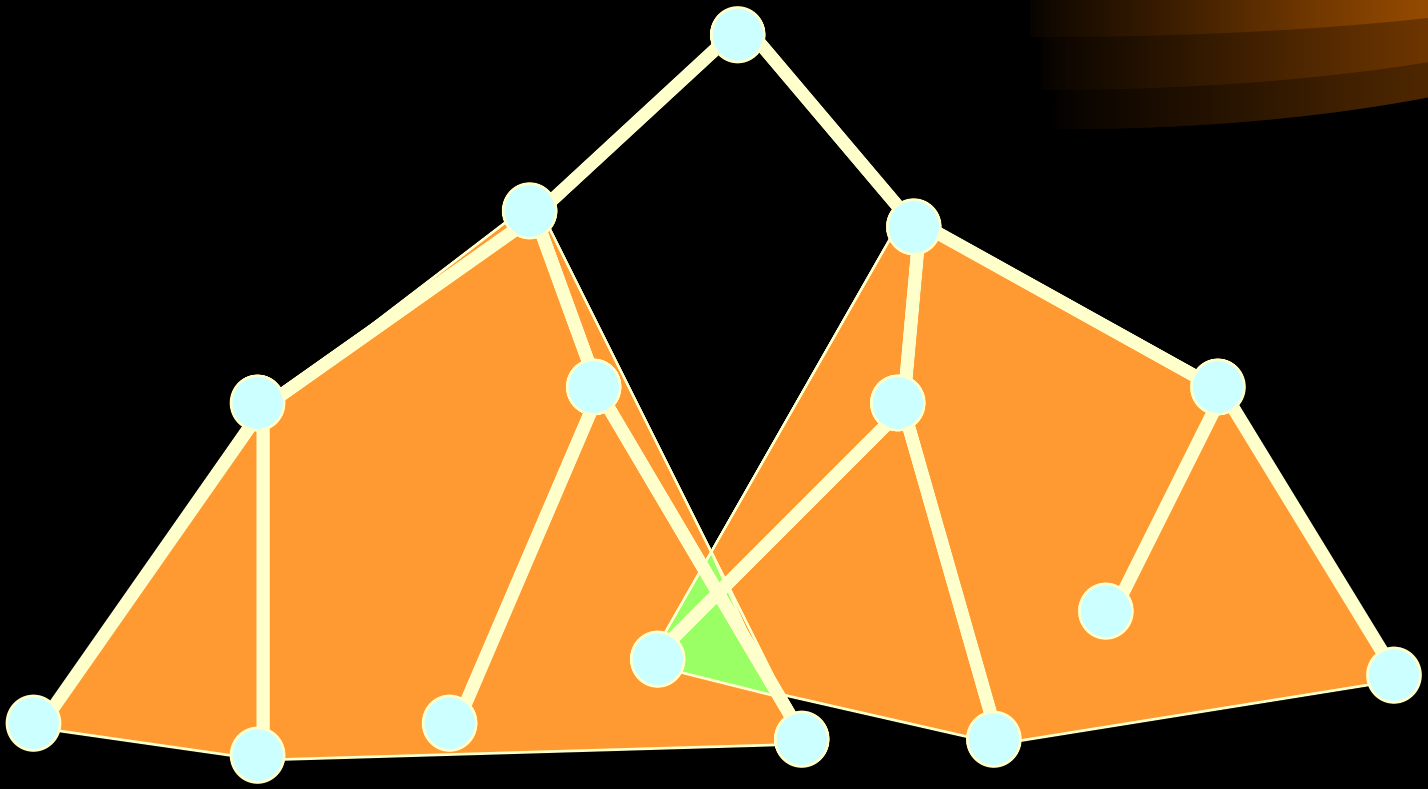

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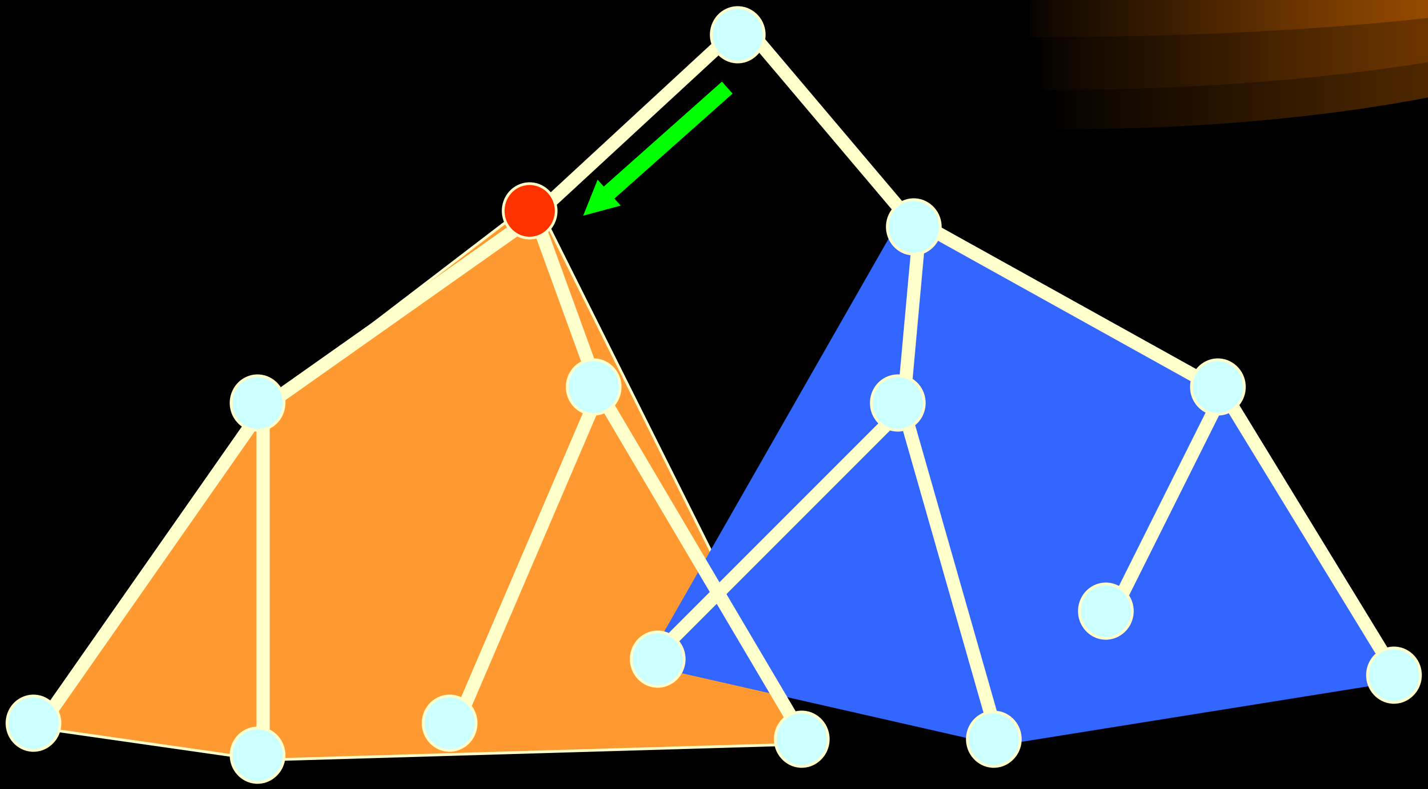
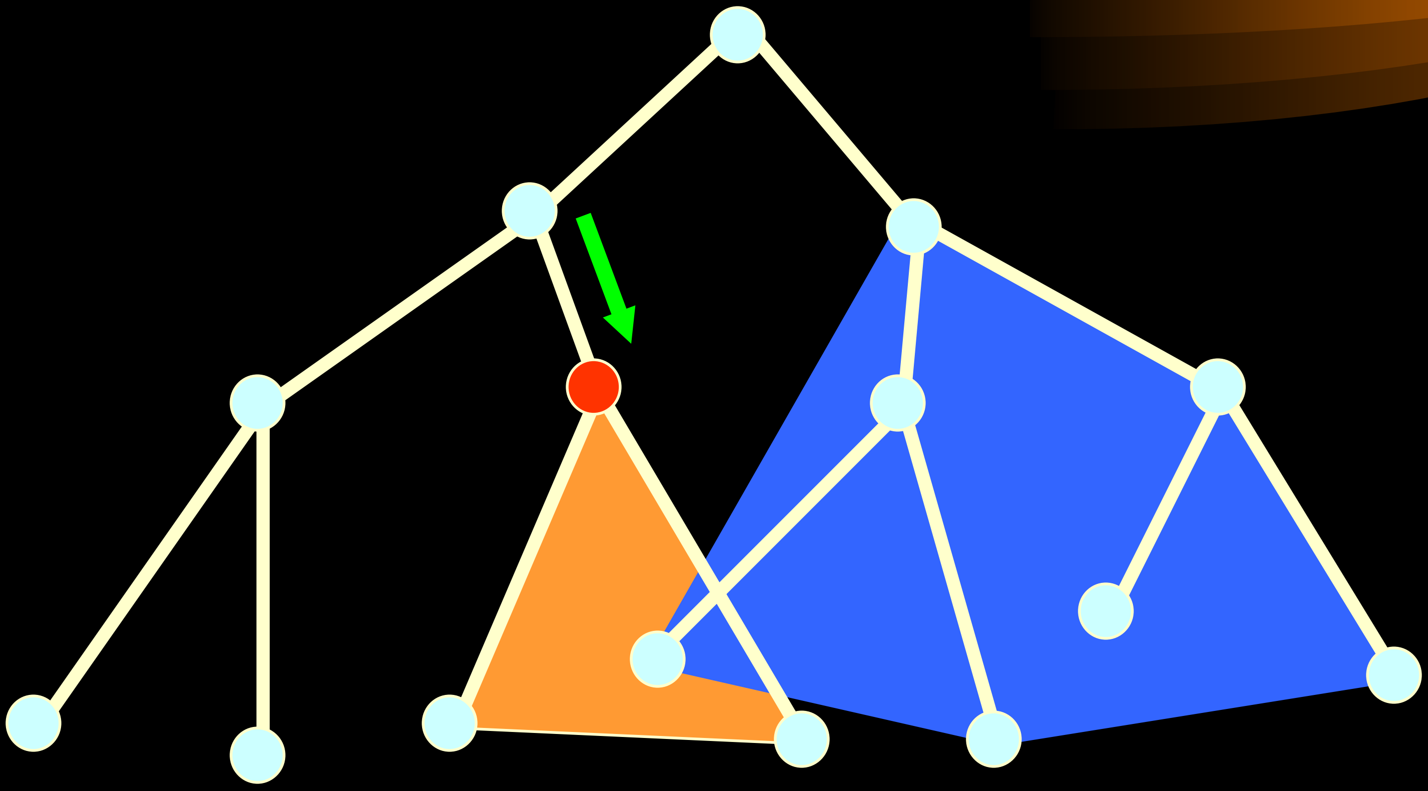
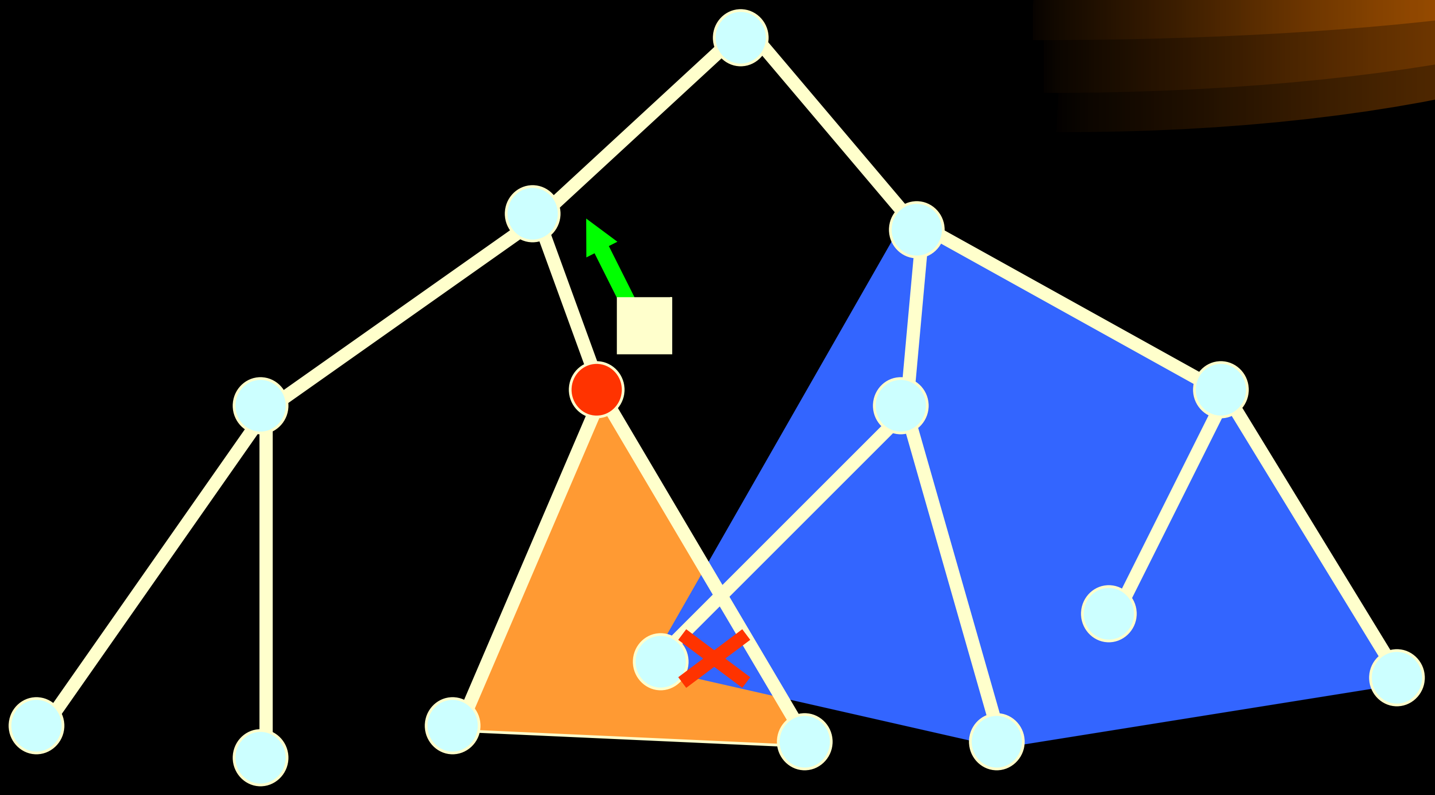


Example: Conflict Hull

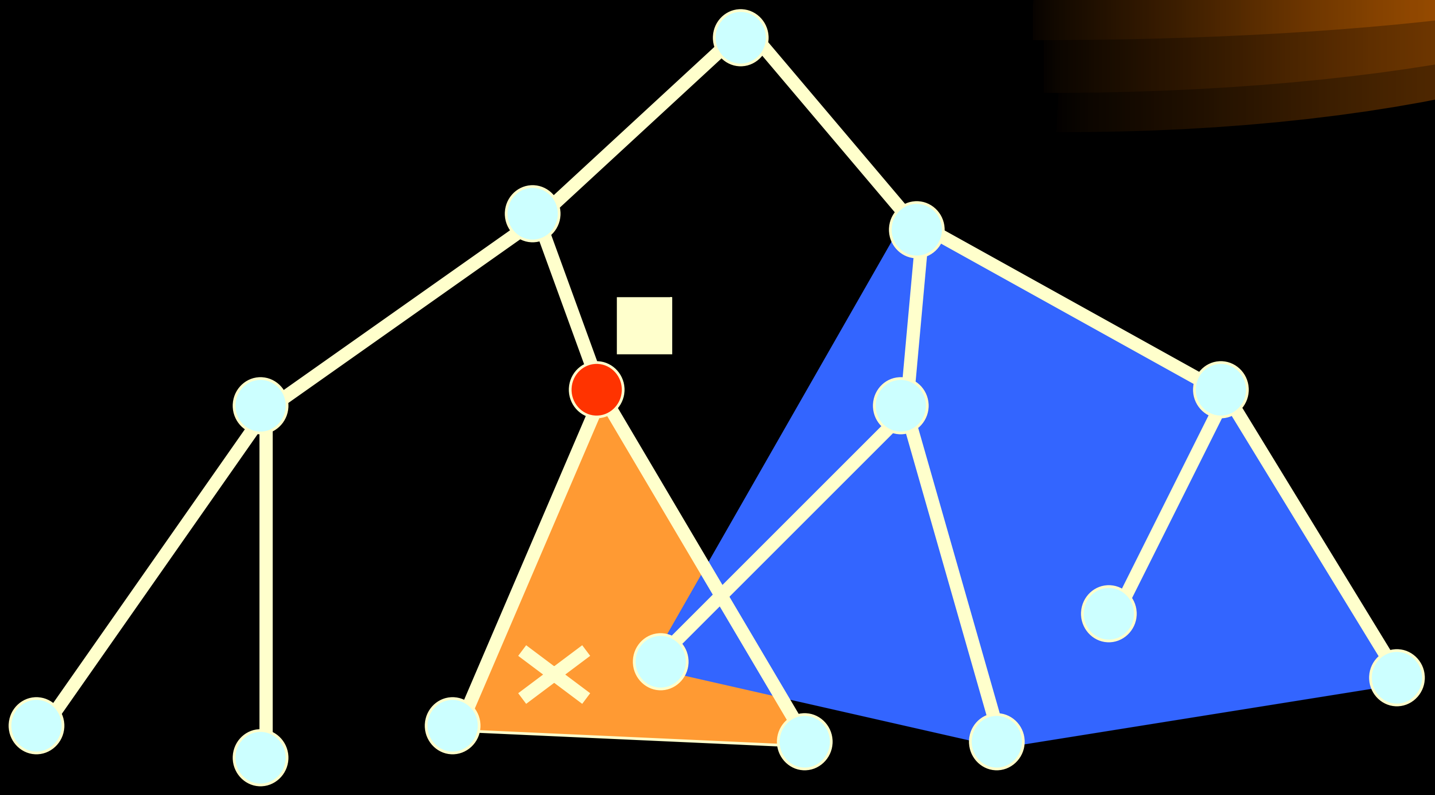


Example: Conflict Hull



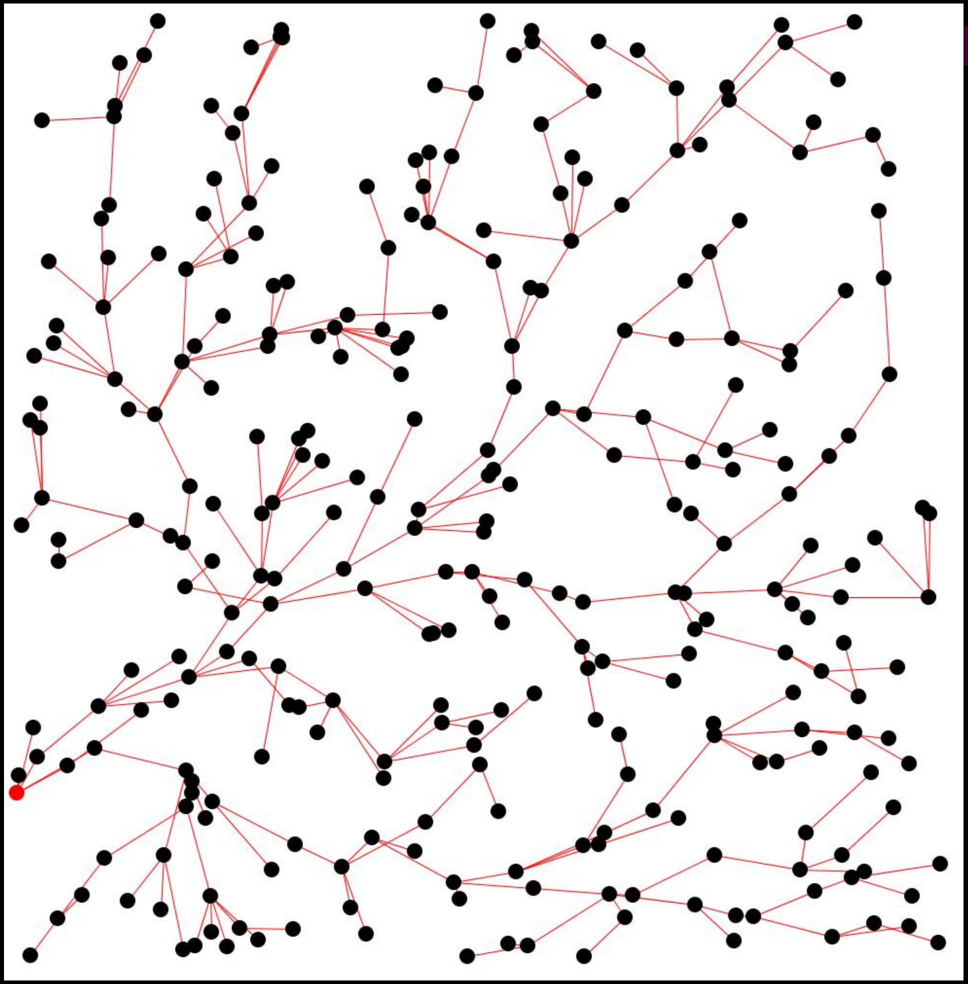
Forward to parent …

Example: Conflict Hull

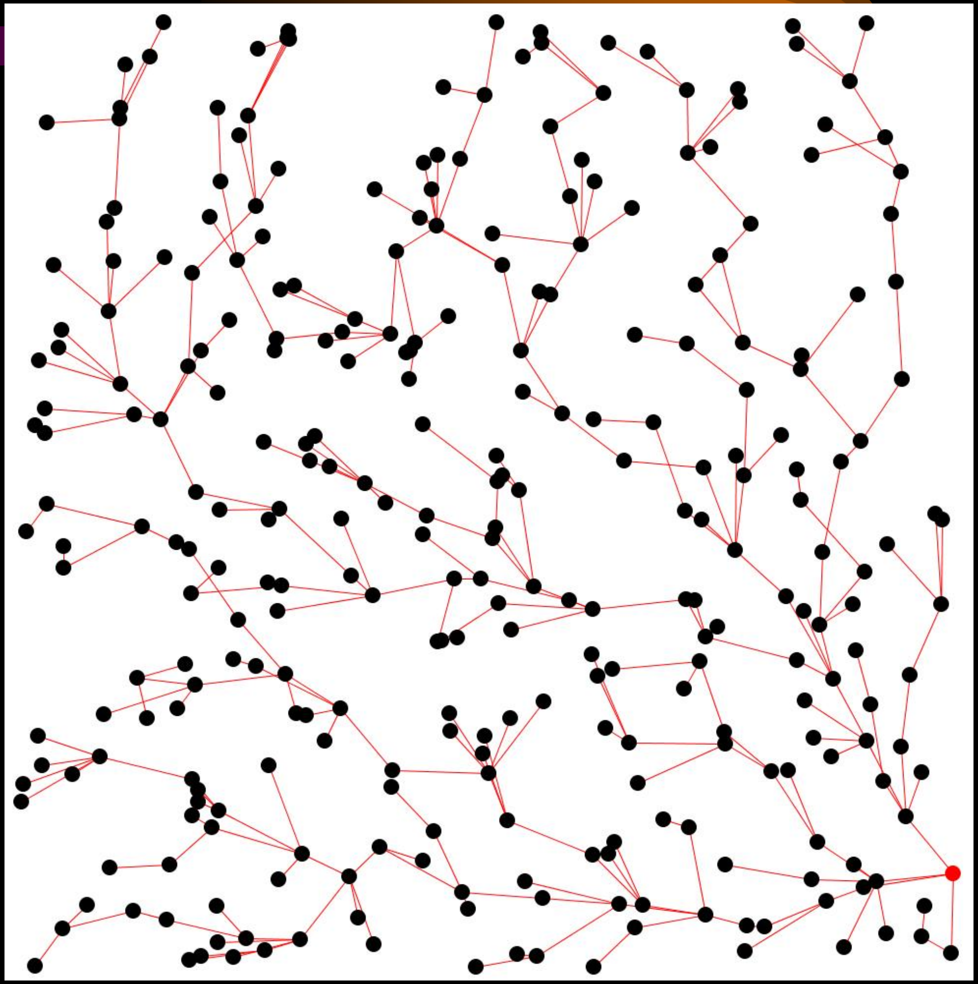


Packet undeliverable!

Example GDSTR Hull Trees

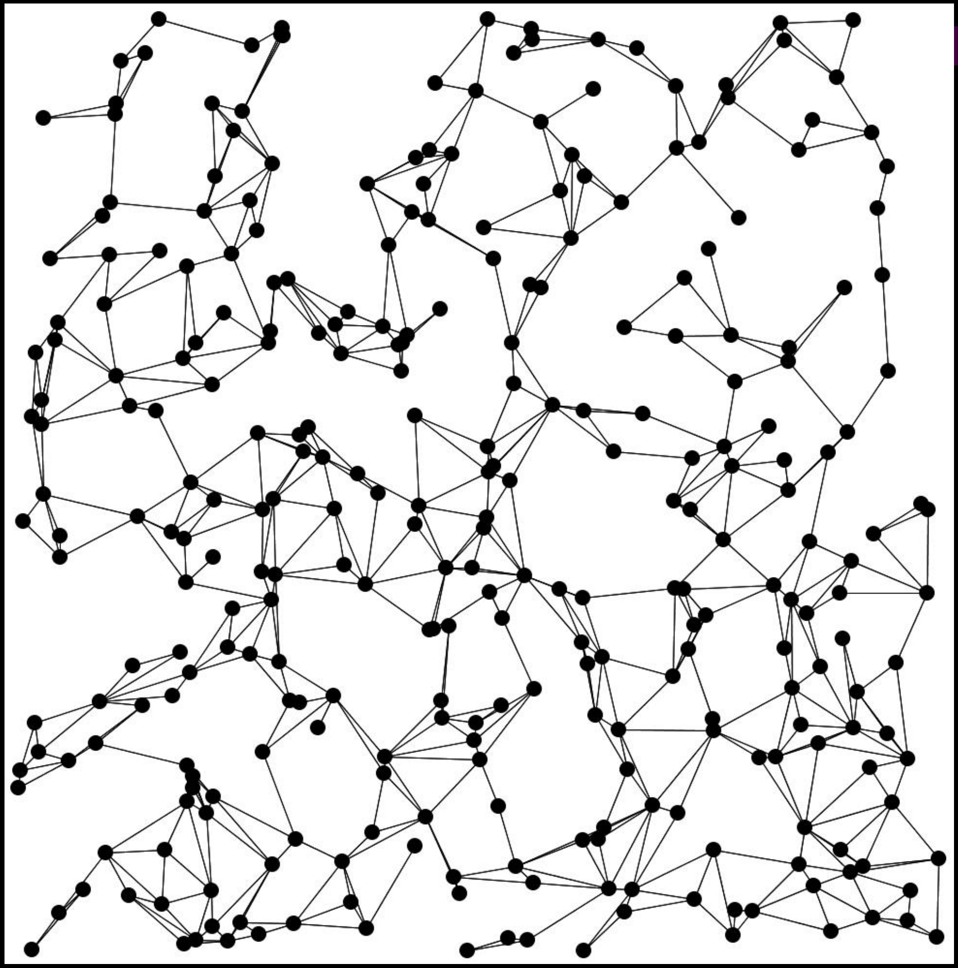


Minimal-x Tree

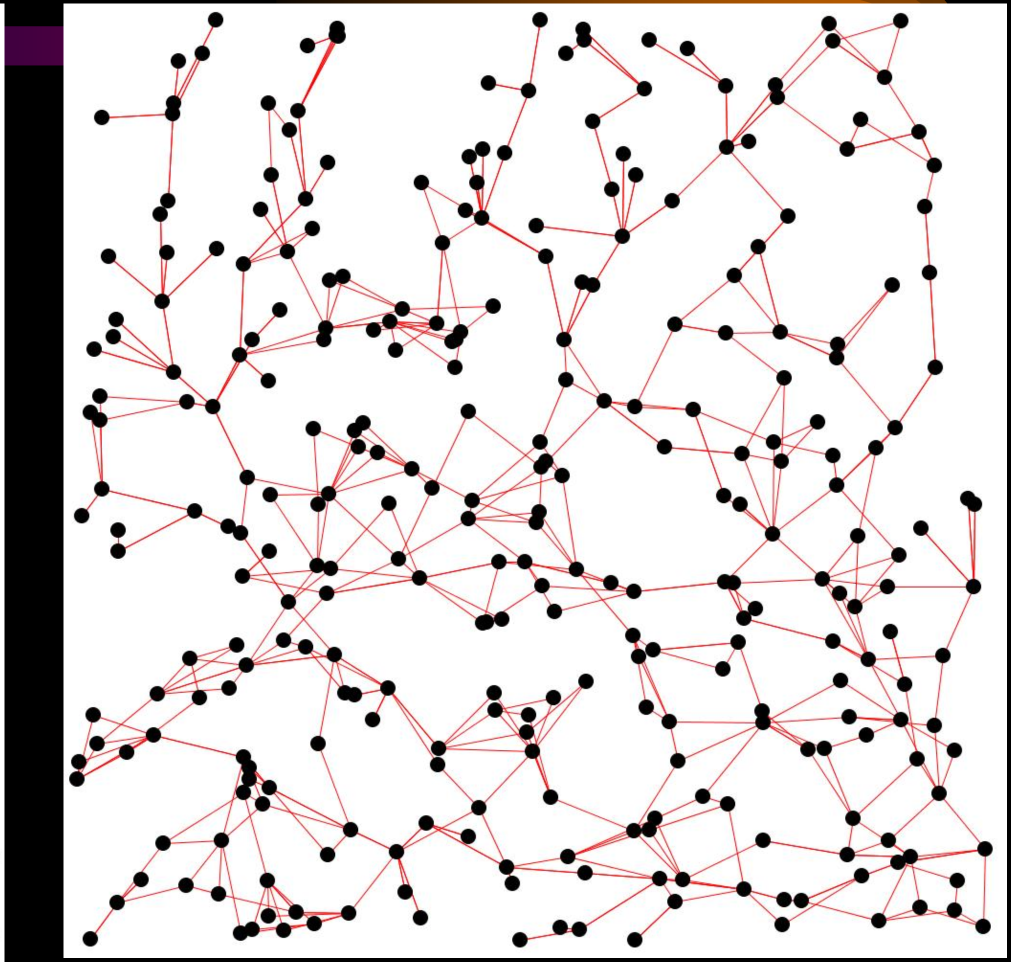


Maximal-x Tree

Comparing Routing Topologies



Planar Graph (CLDP)



Two Trees