Routing using Local Information: Introduction to Geographic Routing

Réseaux & Communication

Alain Cournier Stéphane Devismes

Université de Picardie Jules Verne

October 26, 2026



Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

Preamble

This lesson is mainly based on the chapter

"Theory and Practice of Geographic Routing [10],"

by Stefan Ruhrup,

from the book "*Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols*" [9].

Definition

Geographic routing is a technique to deliver a message to a node in a network over multiple hops by means of position information.

Geographic routing is also known as position-based routing or geometric routing in the literature.

Hypotheses

Geographic routing algorithms work nearly stateless and apply under the following assumptions:

1. A node can determine its own position, *e.g.*, using a GPS
2. A node is aware of its neighbors' positions, *e.g.*, acquired using local broadcast
3. The position of the destination is known

   Require a *location service* (out of the scope of this course)

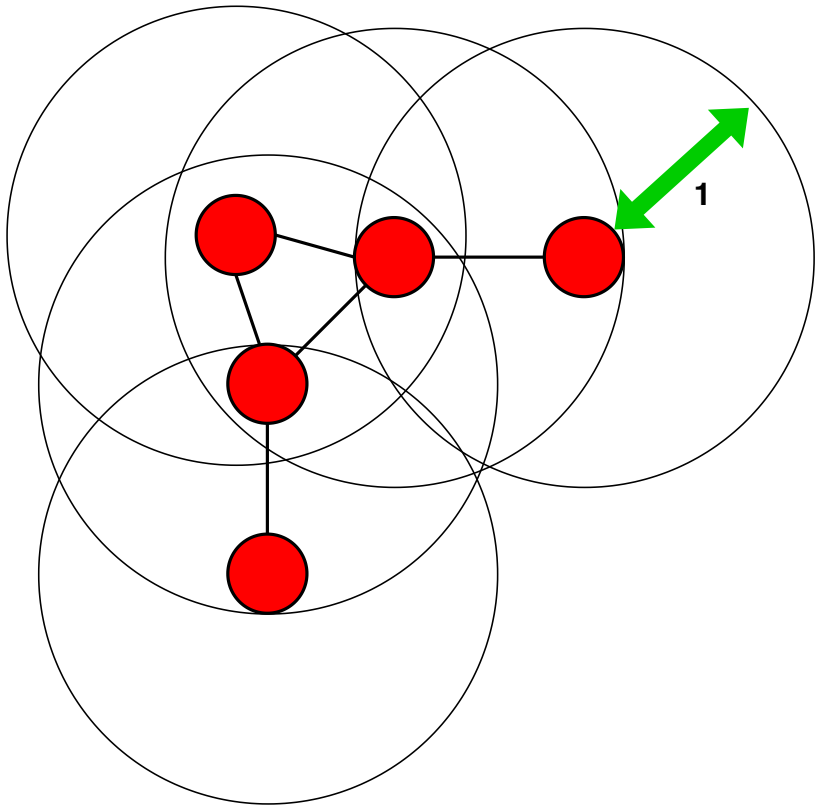
Network Model

Geographic routing is based on geometric criteria and is often used in the context of wireless networks

Network Model

Geographic routing is based on geometric criteria and is often used in the context of wireless networks $\Rightarrow$ **Unit Disk Graphs (UDG)**

Nodes u and v are neighbors $\equiv \|u, v\| \leq 1$[1]



[1] The transmission range is normalized to 1

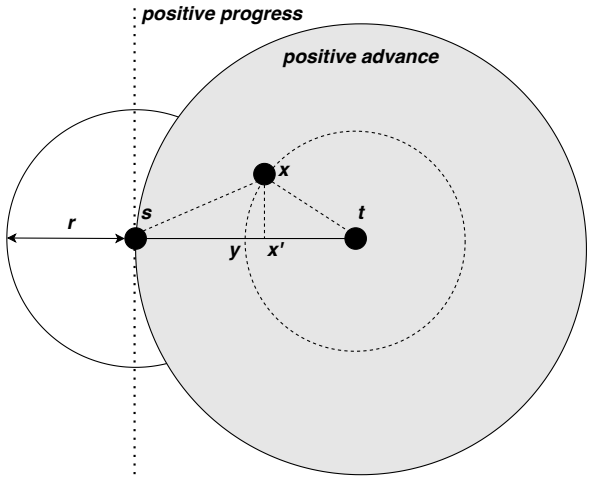
Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

If the node is not the destination, it selects a neighbor for the next hop based on local information.

Routing decisions are **locally optimal**, based on a given criteria.

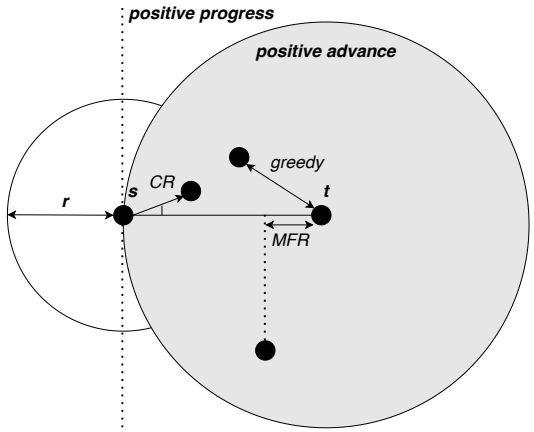
Criteria for the Next Hop Selection



- Progress: the projection of the location of neighbor x on the s-t-line, *i.e.*, $|x', t|$
- Distance to the destination: $|x, t|$
- Advance: $|s, y|$
- Angular distance / angular separation: Absolute angular deviation $\angle_{xst}$[2]

[2]The absolute angular deviation is the smallest angle between two directions, taken as a non-negative value, regardless of clockwise or counterclockwise orientation.

Instances



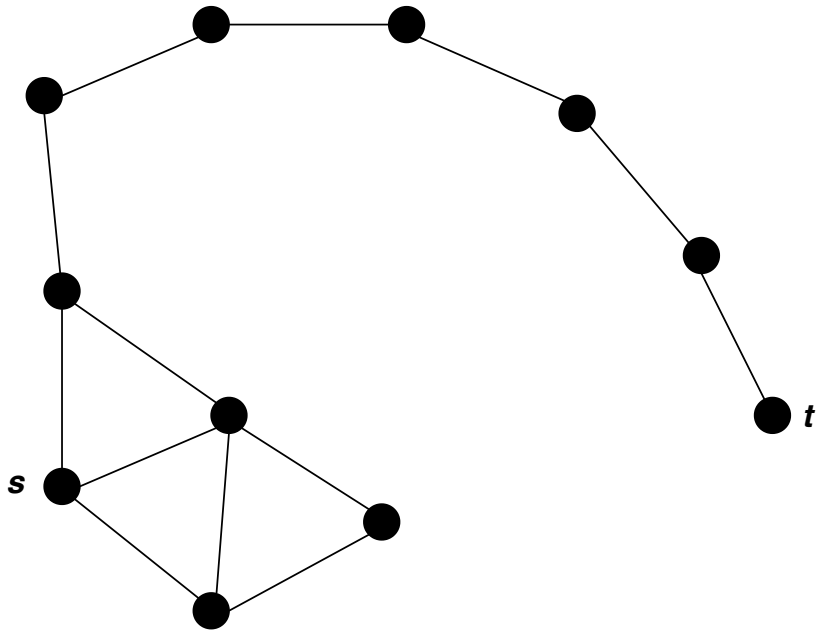
- MFR [12]: choosing the neighbor with **most forwarding progress** among neighbors with positive progress
- Greedy [5]: choosing the neighbor that **minimizes the distance to the destination**, or equivalently that **maximizes the advance** among neighbors with positive advance
- Compass Routing (CR) [7]: choosing the neighbor that **minimizes the angle separation *w.r.t.* the destination**[3] among all neighbors

[3] CR does not require GPS, a compass is sufficient!

Issues with Greedy Forwarding

Loops

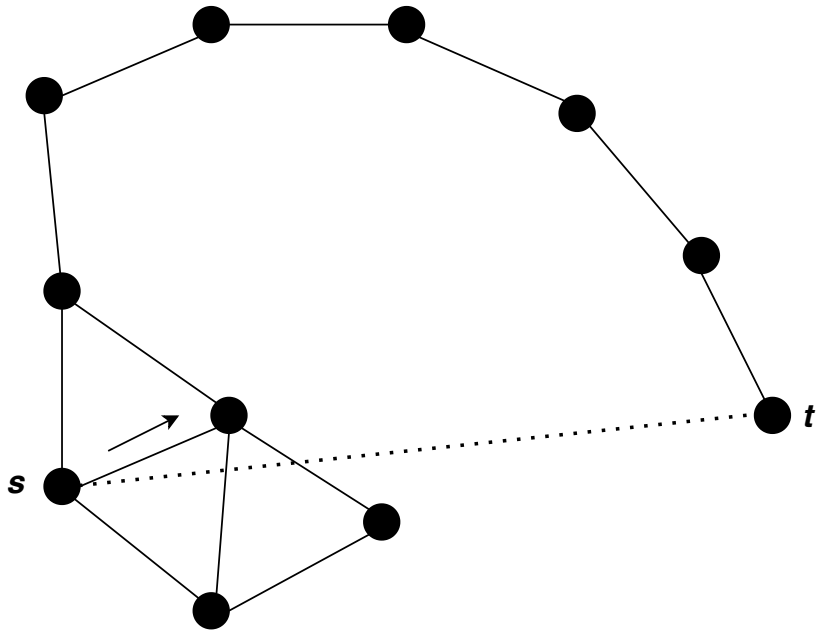
CR may **loop**



Issues with Greedy Forwarding

Loops

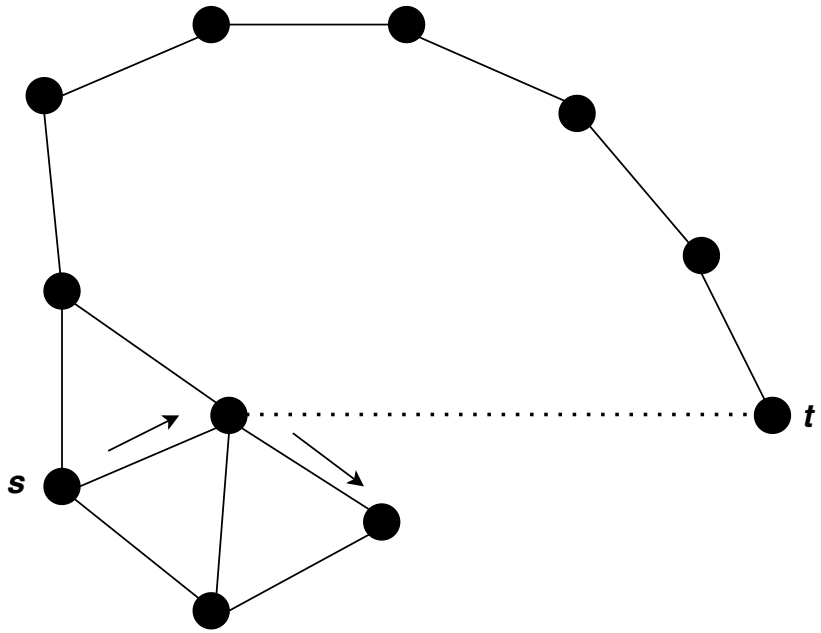
CR may **loop**



Issues with Greedy Forwarding

Loops

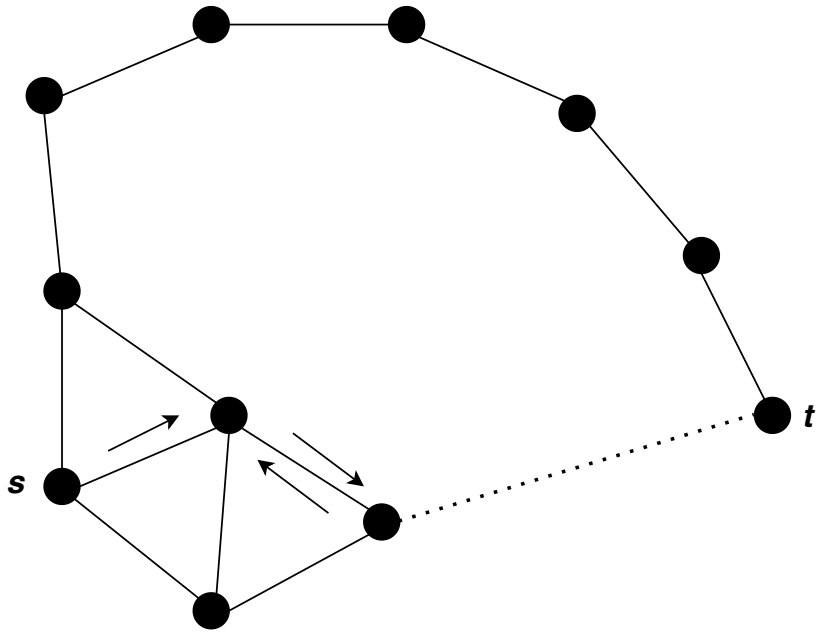
CR may **loop**



Issues with Greedy Forwarding

Loops

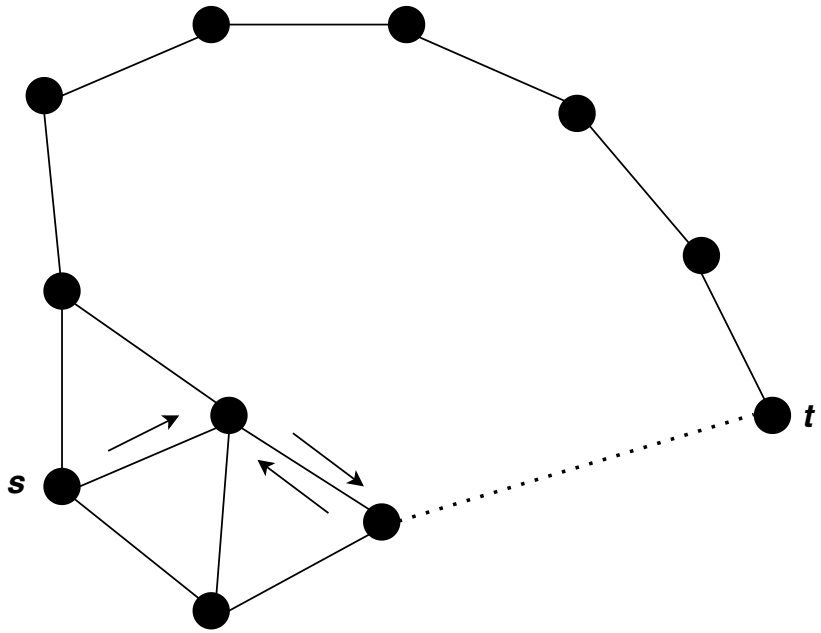
CR may **loop**



Issues with Greedy Forwarding

Loops

CR may **loop**

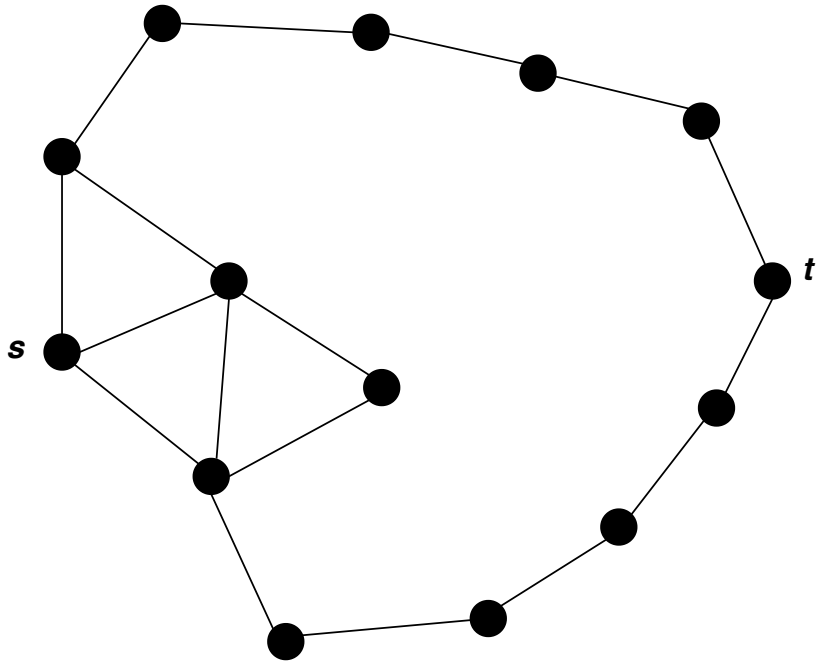


MFR and Greedy are loop-free

Issues with Greedy Forwarding

Dead ends

MFR and Greedy may lead to **dead ends**

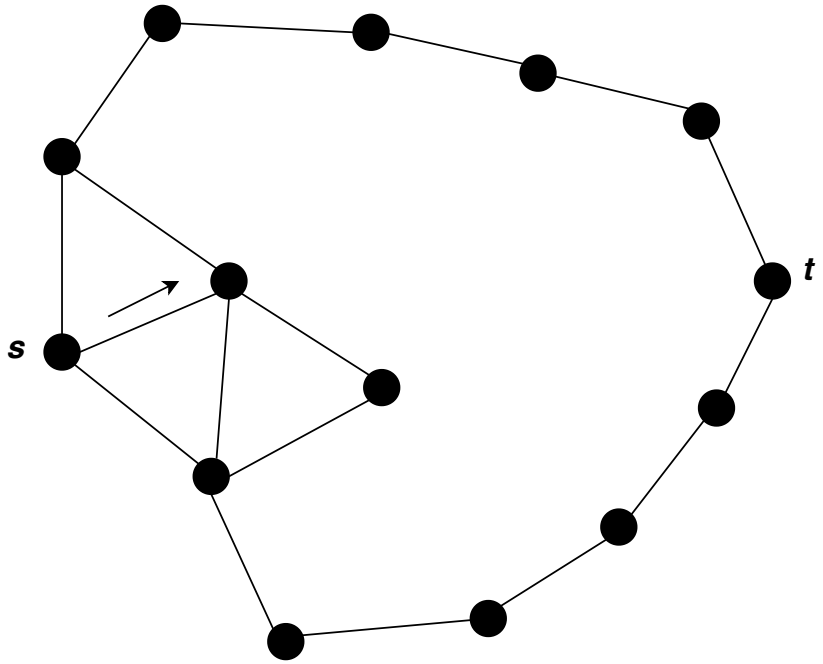


Example with the Greedy Forwarding

Issues with Greedy Forwarding

Dead ends

MFR and Greedy may lead to **dead ends**

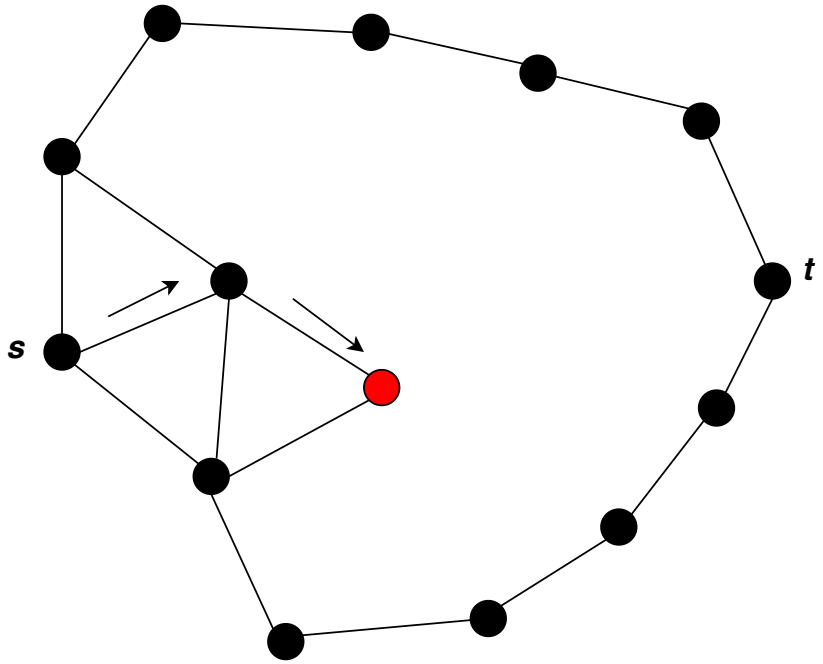


Example with the Greedy Forwarding

Issues with Greedy Forwarding

Dead ends

MFR and Greedy may lead to **dead ends**



Example with the Greedy Forwarding

Advanced Strategies

- 2-hop knowledge (virtual edge $(a, b) = b$ is 2-hop away from a)

  This does not work: the previous counter-example still works

Advanced Strategies

- 2-hop knowledge (virtual edge $(a, b) = b$ is 2-hop away from a)

  This does not work: the previous counter-example still works

- Backward step with taboo list containing all encountered dead ends

  This works! But, the taboo list is stored in the message: the overhead in messages is huge and routes may be very long!

Advanced Strategies

- 2-hop knowledge (virtual edge $(a, b) = b$ is 2-hop away from a)

  This does not work: the previous counter-example still works

- Backward step with taboo list containing all encountered dead ends

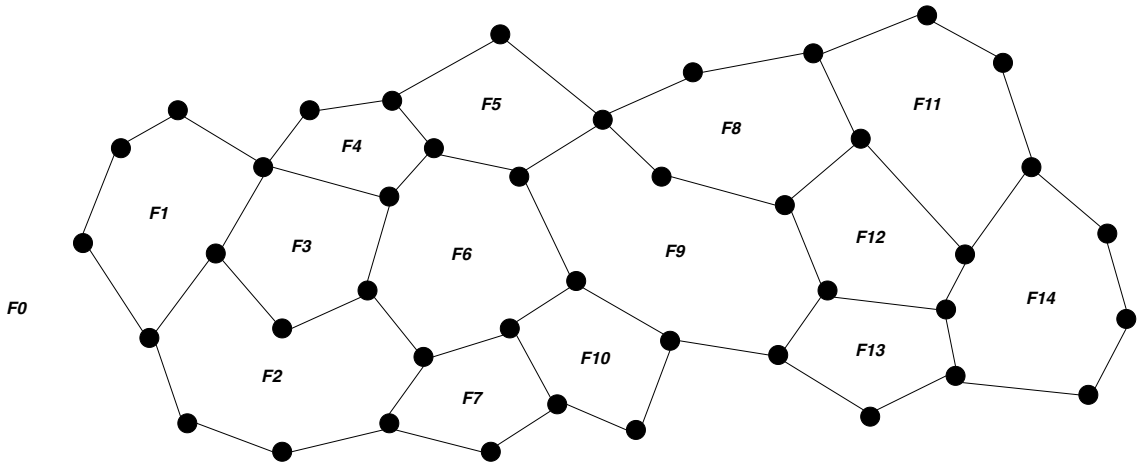
  This works! But, the taboo list is stored in the message: the overhead in messages is huge and routes may be very long!

- **Using faces in planarized UDG**

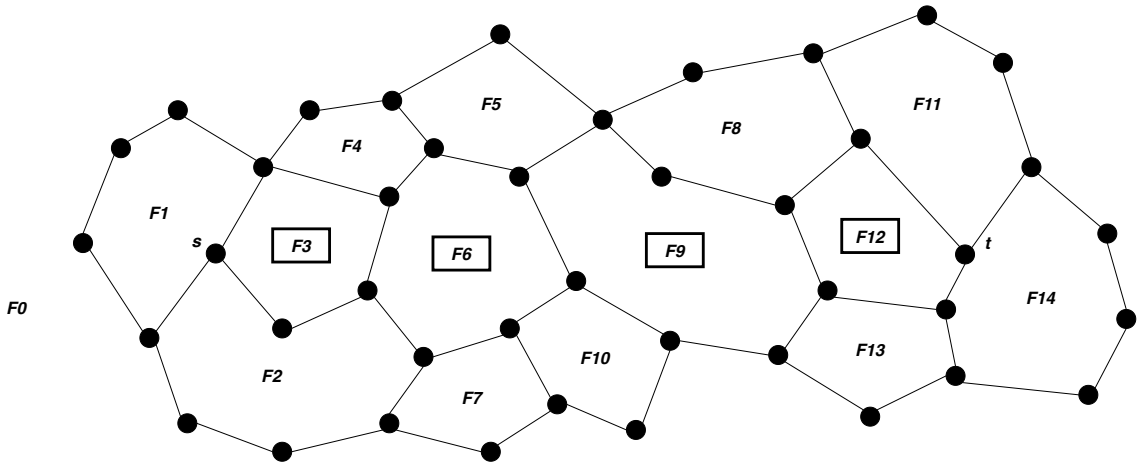
Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

Faces in (UDG) Planar Graphs

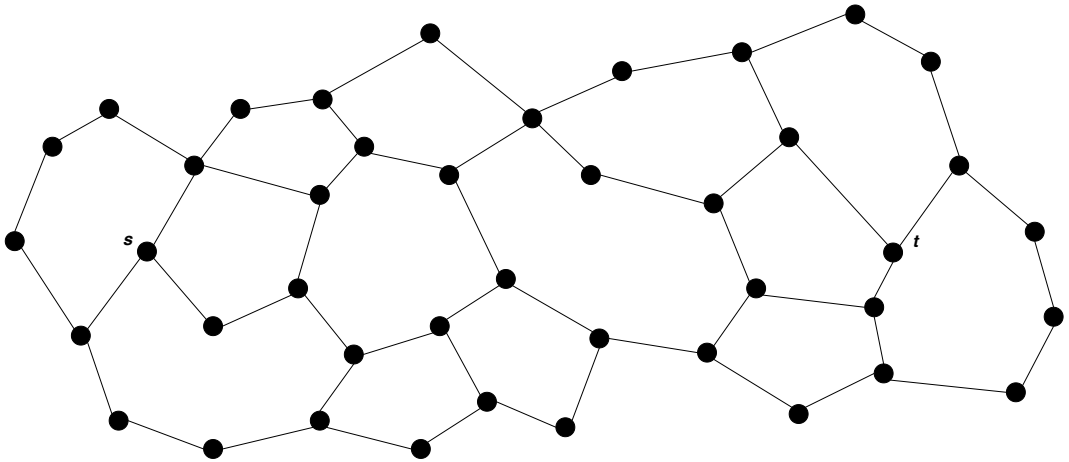


Faces in (UDG) Planar Graphs

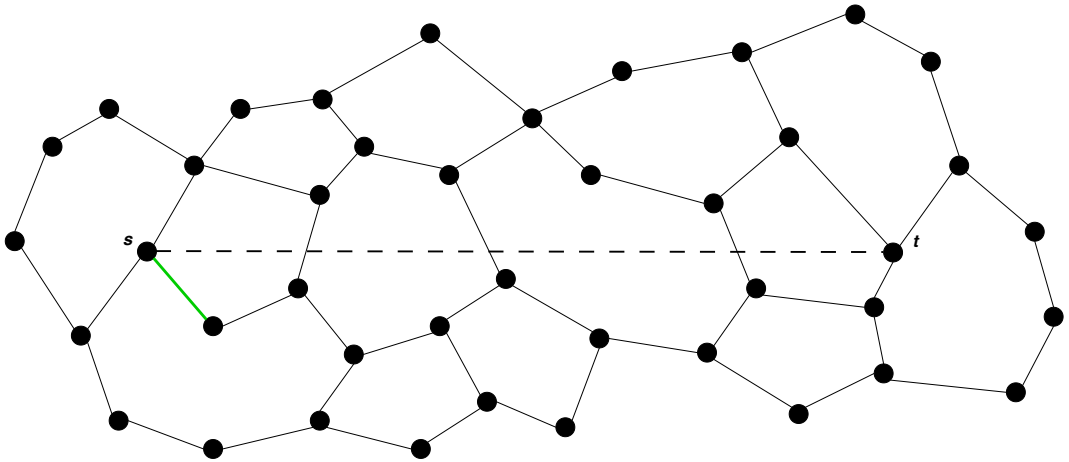


Idea: traverse faces toward the destination using the left-hand or right-hand rule

Face Routing, Kranakis *et al.* [7]



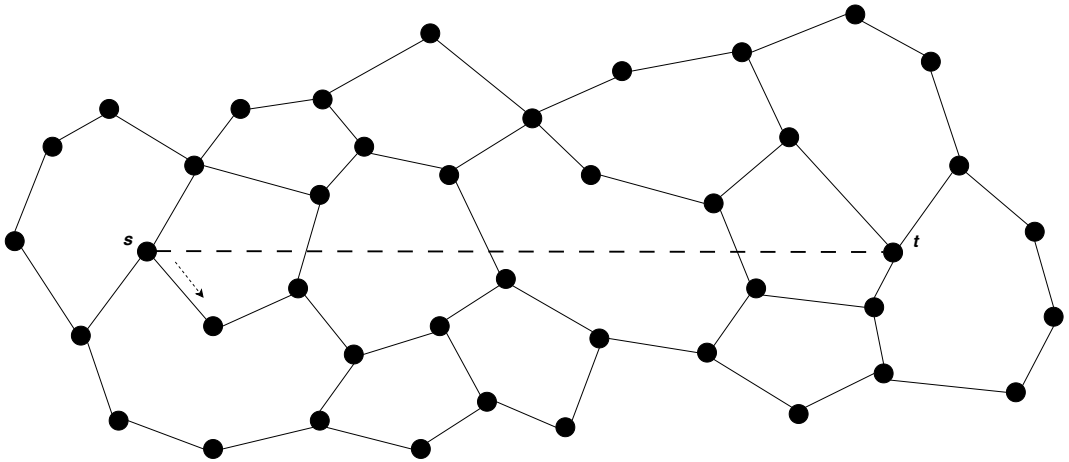
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)

cw = clockwise ccw = counterclockwise

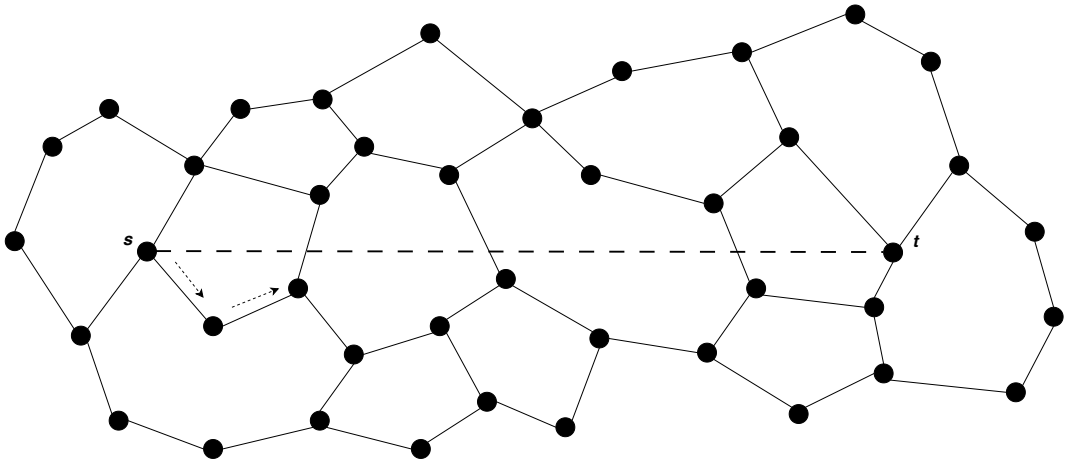
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.

cw = clockwise ccw = counterclockwise

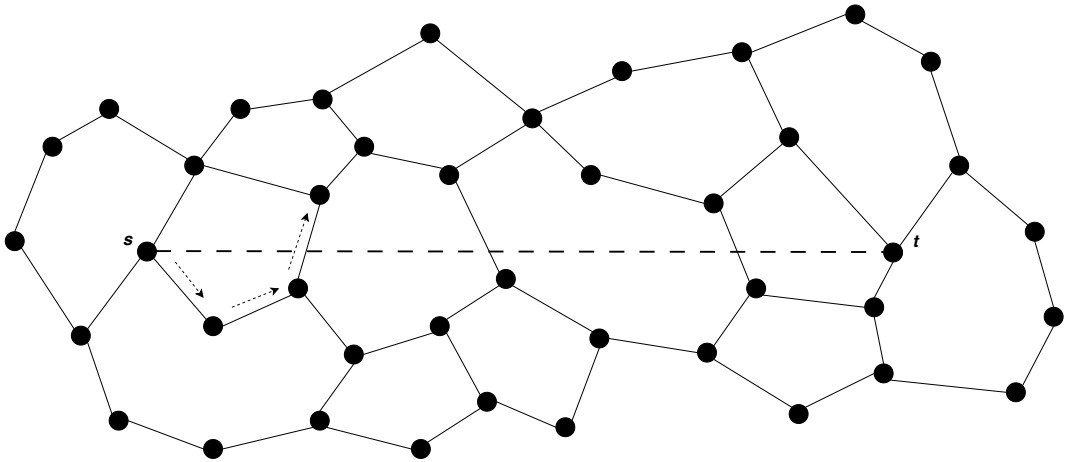
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.

cw = clockwise ccw = counterclockwise

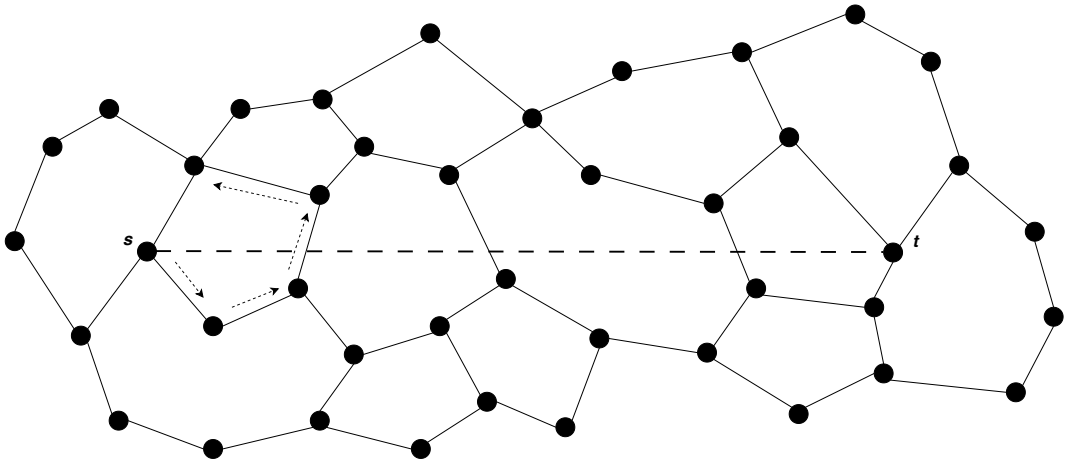
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.

cw = clockwise ccw = counterclockwise

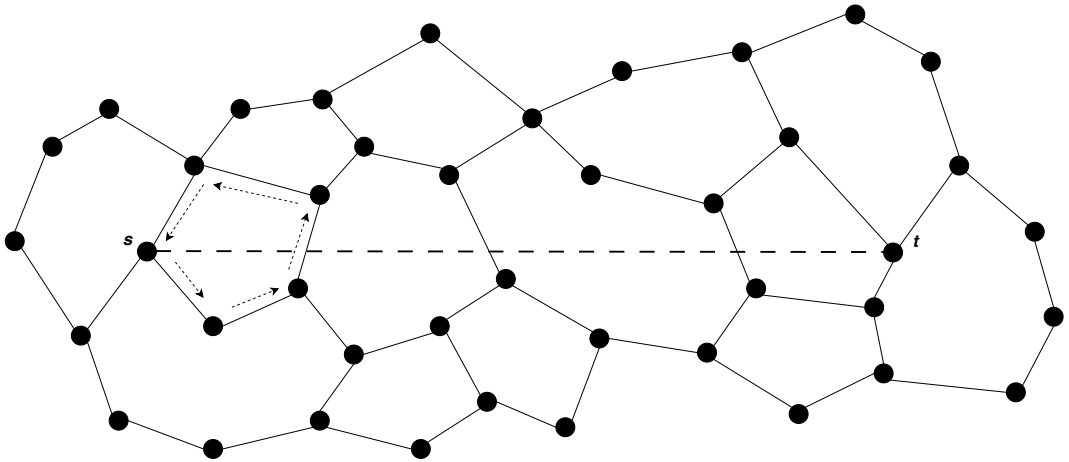
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.

cw = clockwise ccw = counterclockwise

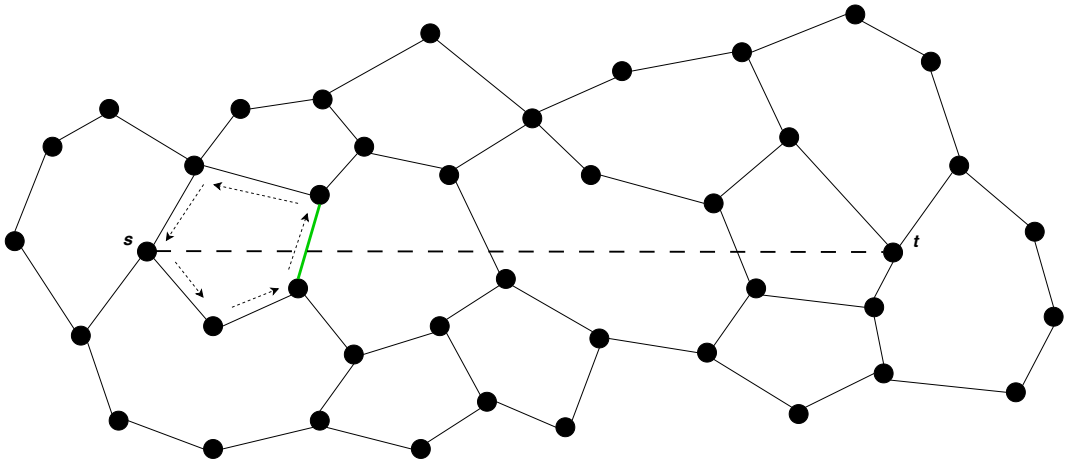
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.

cw = clockwise ccw = counterclockwise

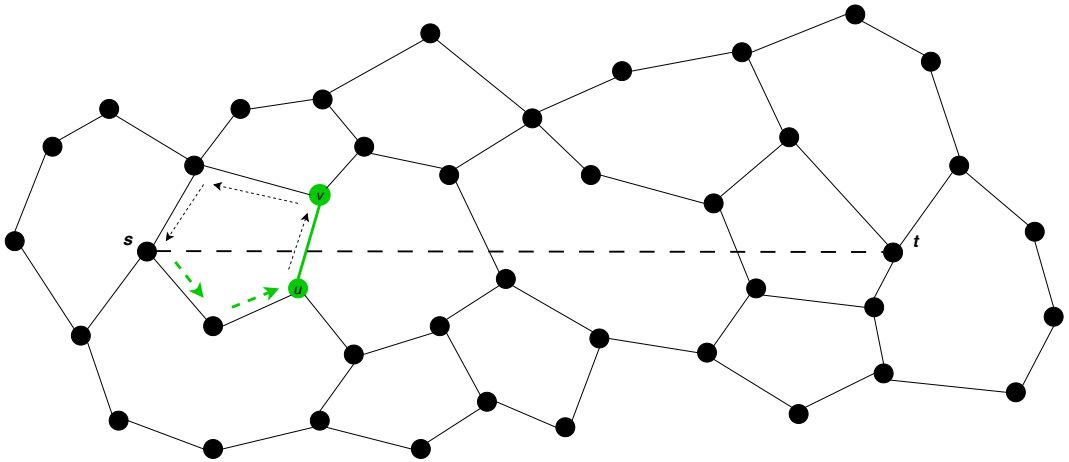
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.

cw = clockwise ccw = counterclockwise

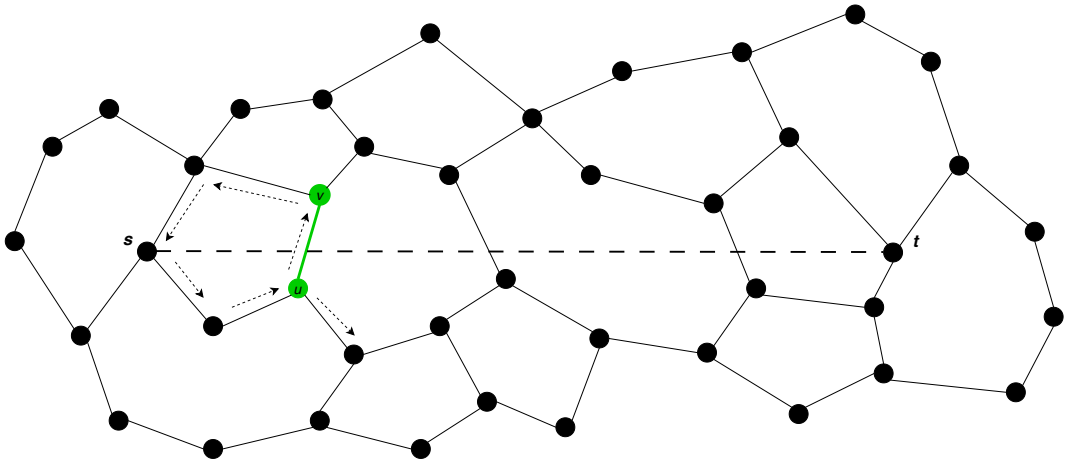
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

cw = clockwise ccw = counterclockwise

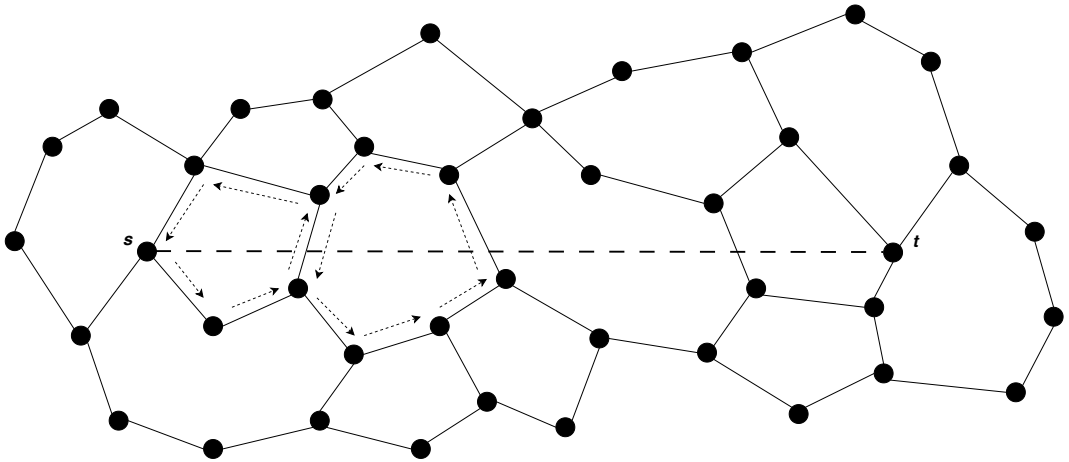
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

cw = clockwise ccw = counterclockwise

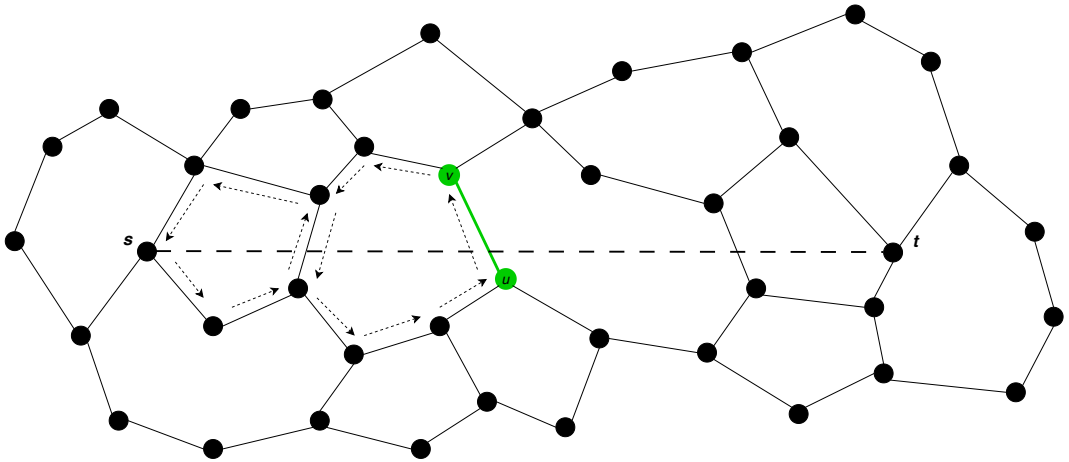
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

cw = clockwise ccw = counterclockwise

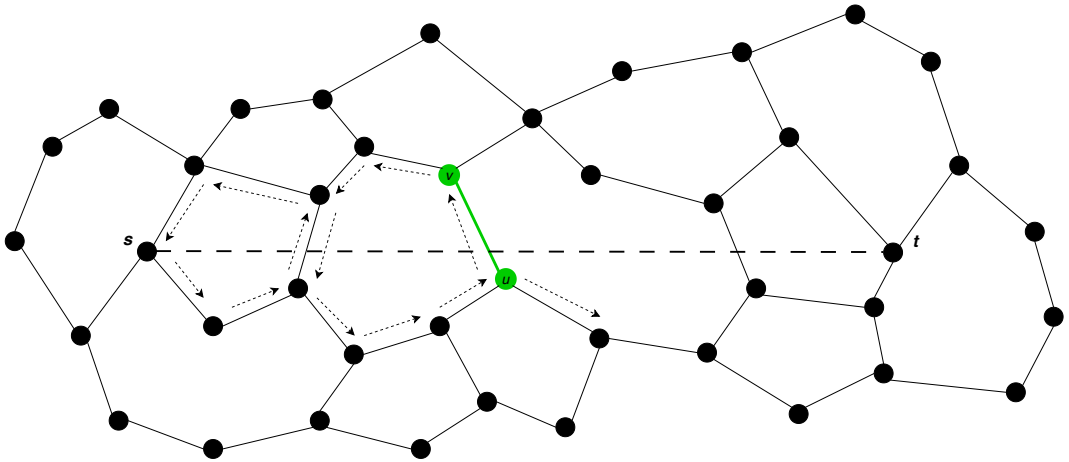
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

$$\text{cw} = \text{clockwise} \qquad \text{ccw} = \text{counterclockwise}$$

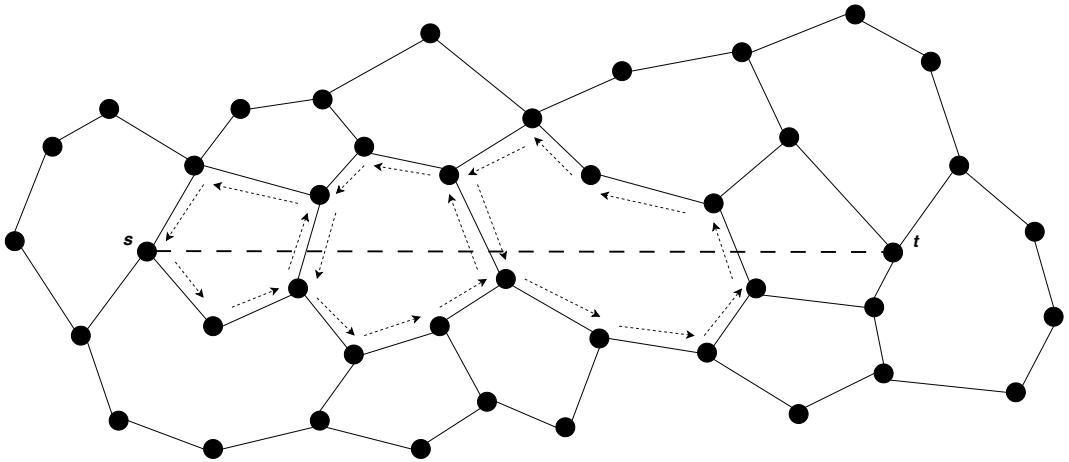
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

$$\text{cw} = \text{clockwise} \qquad \text{ccw} = \text{counterclockwise}$$

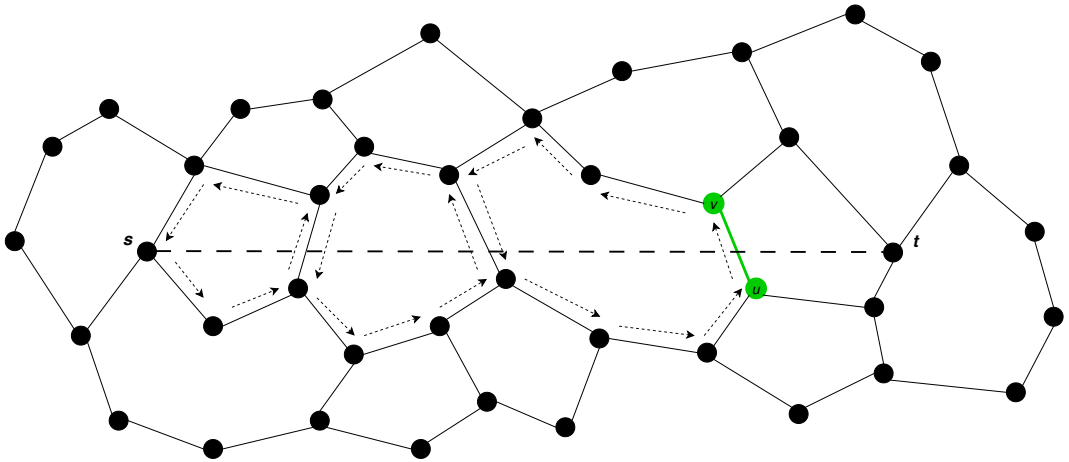
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

cw = clockwise ccw = counterclockwise

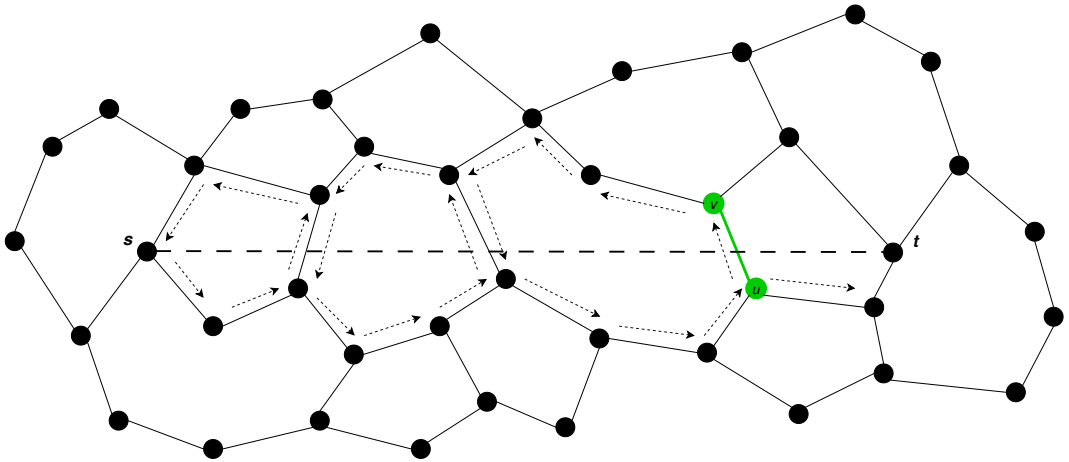
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

$$\text{cw} = \text{clockwise} \qquad \text{ccw} = \text{counterclockwise}$$

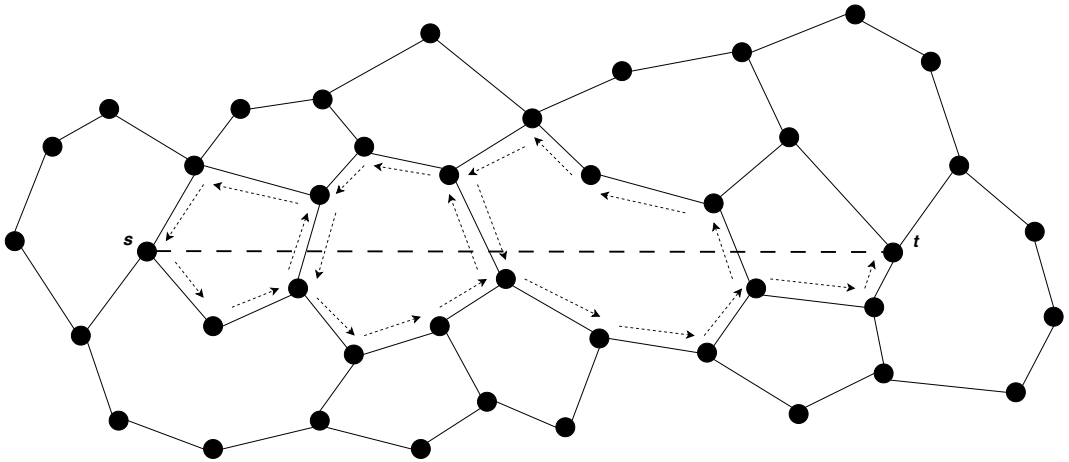
Face Routing, Kranakis *et al.* [7]



1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

$$\text{cw} = \text{clockwise} \qquad \text{ccw} = \text{counterclockwise}$$

Face Routing, Kranakis *et al.* [7]

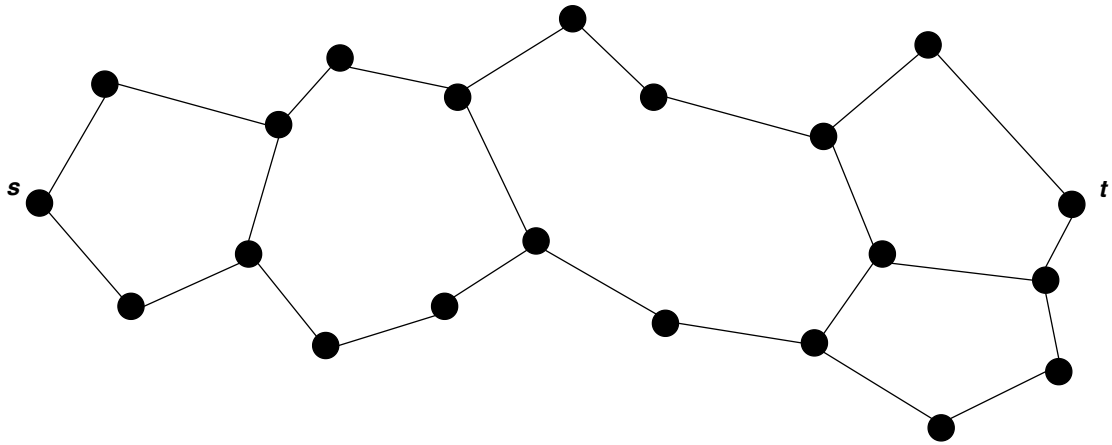


1. Select the next hop v in the cw (or ccw) direction from (s, t)
2. Traverse the current face by selecting, at each vertex, the cw (or ccw) successor of the predecessor, until returning to the starting arc or reaching t.
3. If t is reached, terminate. Otherwise, among all traversed arcs intersecting $\overline{st}$, select the arc (u, v) whose intersection point x is closest to t.
4. Route the packet to u and restart from Step 2, considering v as the predecessor of u.

cw = clockwise ccw = counterclockwise

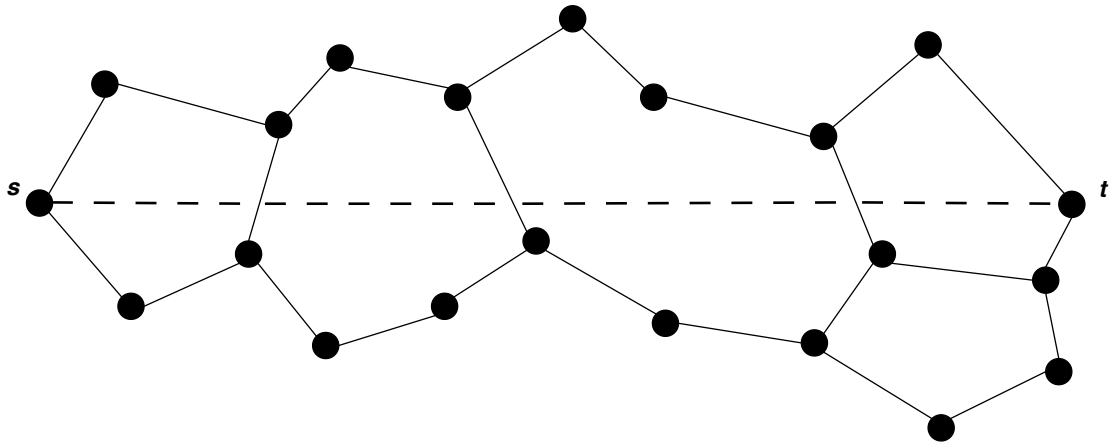
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



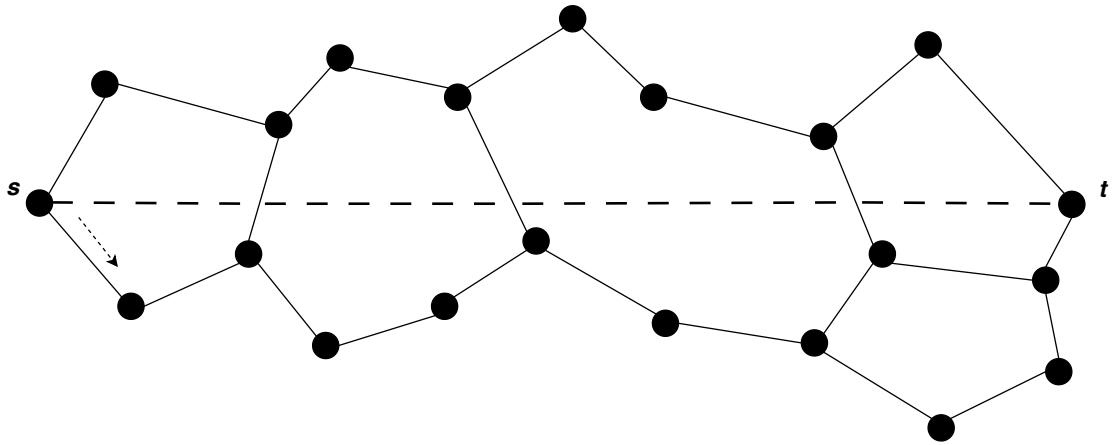
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



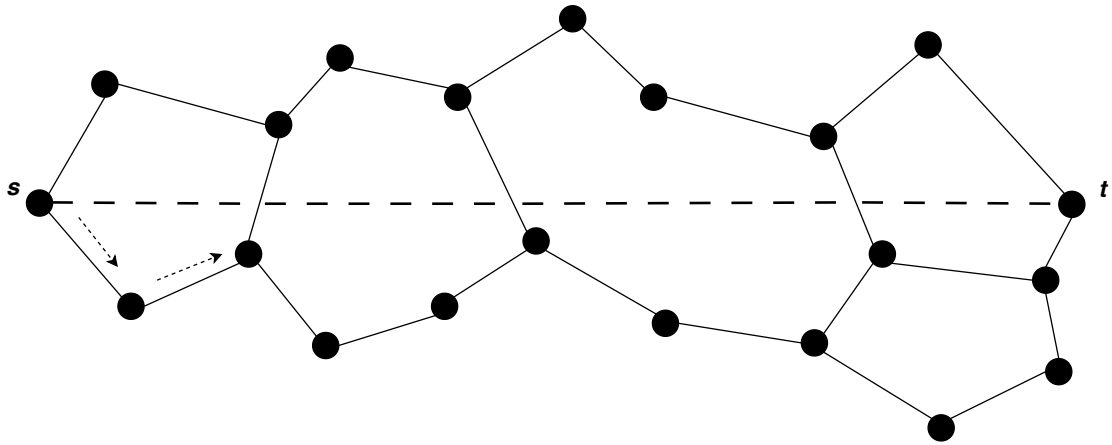
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



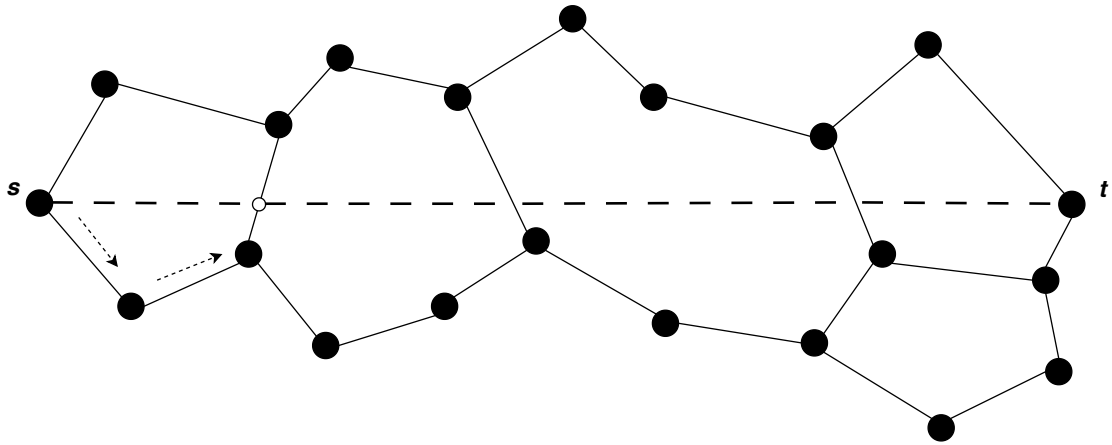
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



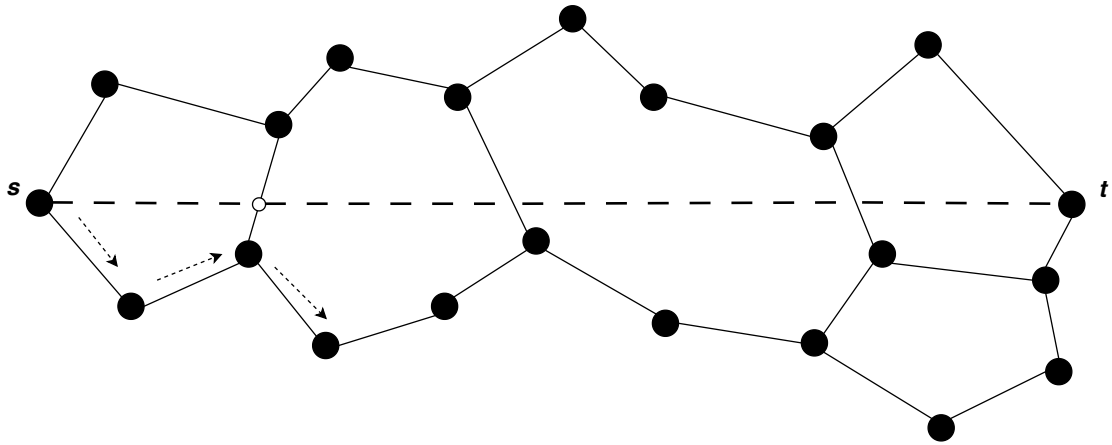
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



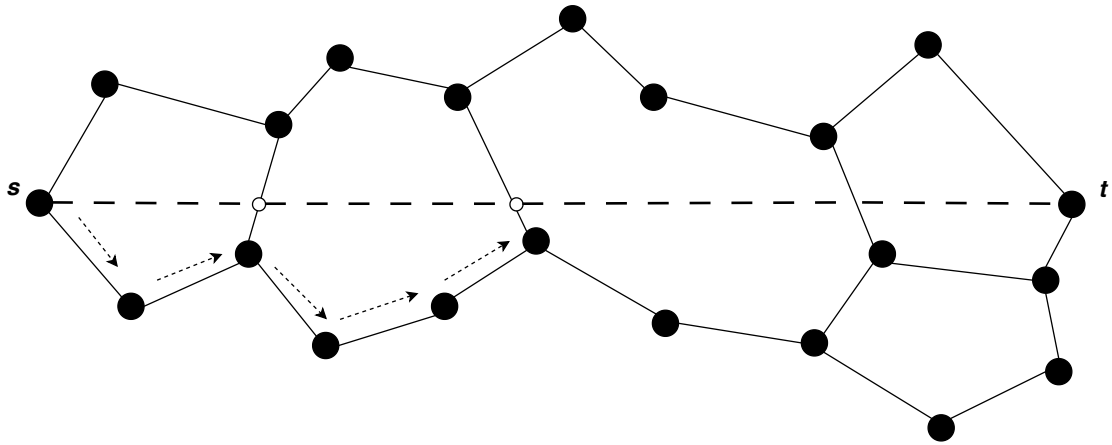
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



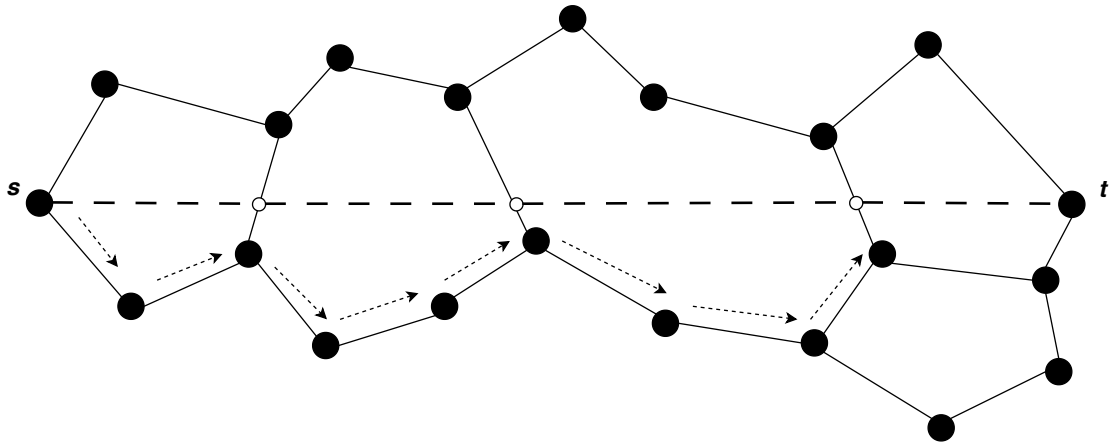
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the *s*-*t*-line**



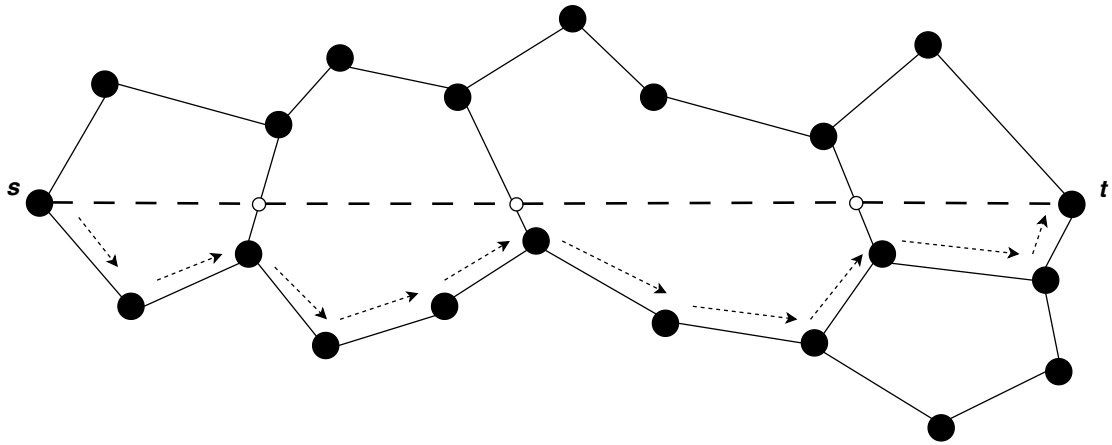
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the *s*-*t*-line**



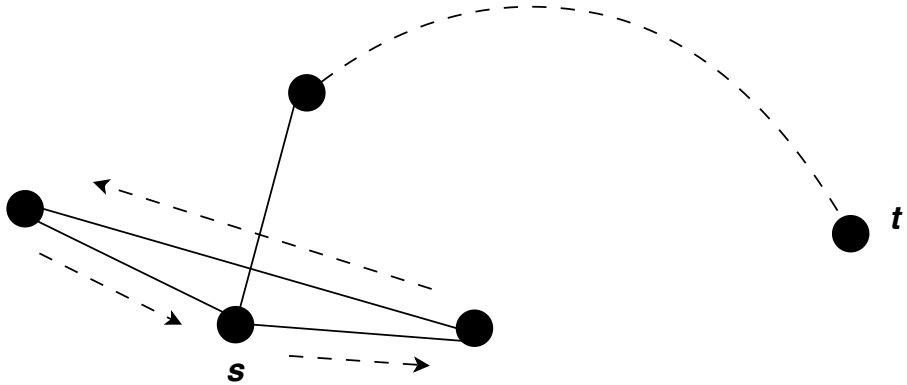
Improved Strategy: Face-2 Routing, Bose *et al.* [2]

Face change **right before crossing the s-t-line**



Planarity Assumption

Planarity is mandatory to ensure the delivery guarantee



Mixed Strategy

- Greedy is efficient but delivery is not guaranteed
- Face Routing guarantees delivery but is inefficient

Mix both: **Greedy-Face-Greedy** (GFG), Datta *et al.* [3]

Principle of GFG

Two modes: Greedy and Face

- Start in greedy mode
- In case of dead end, store the distance d to the destination t and switch to face mode
- Switch back to greedy mode when finding a node u such that $|u, t| < d$

GFG Algorithm

Values stored in the packet:

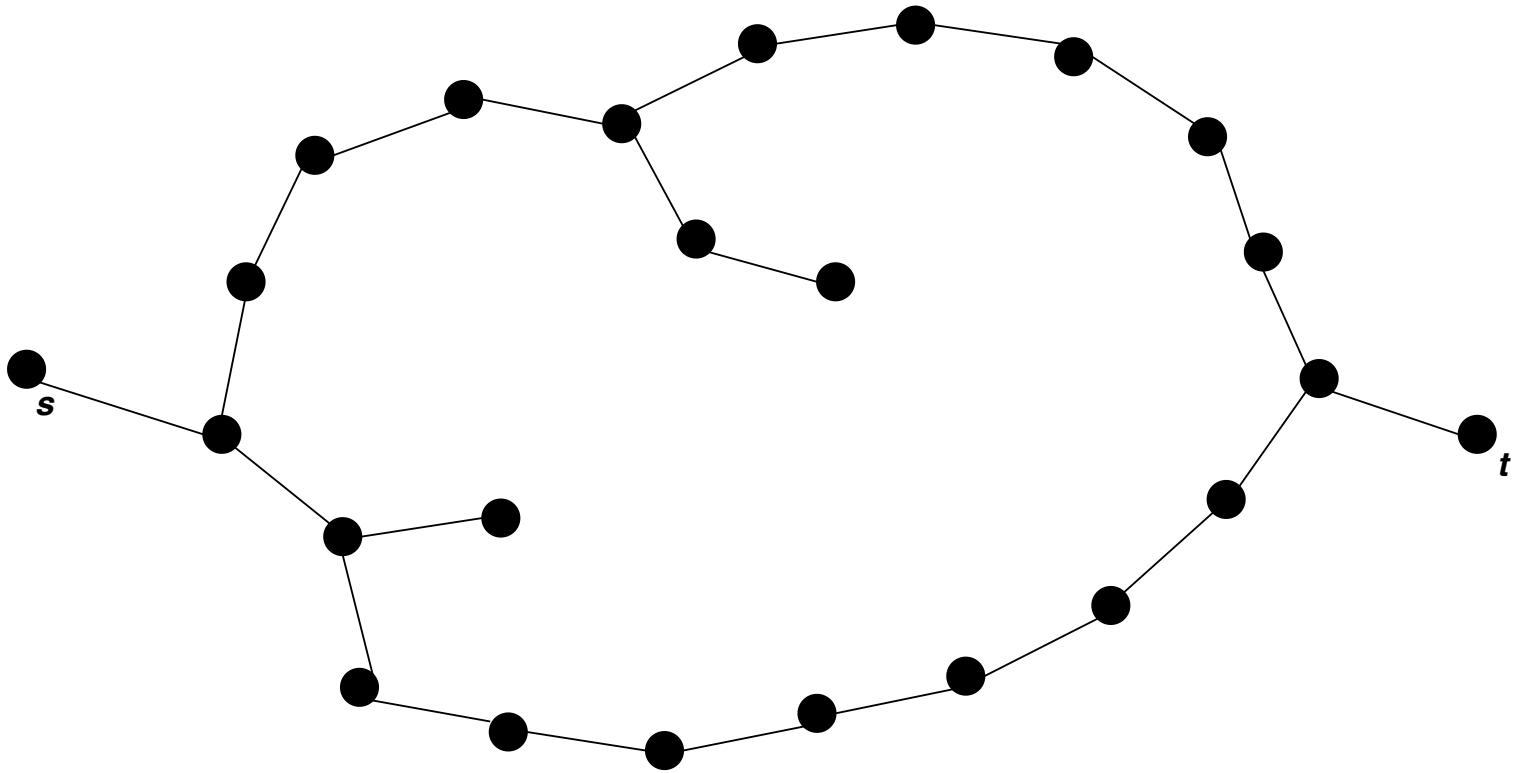
t: the target position; $mode \in \{Greedy, Face\}$, initialized to $Greedy$; p: the previous hop

e_f: first edge of the current face; d_f: distance to target (in the face mode)

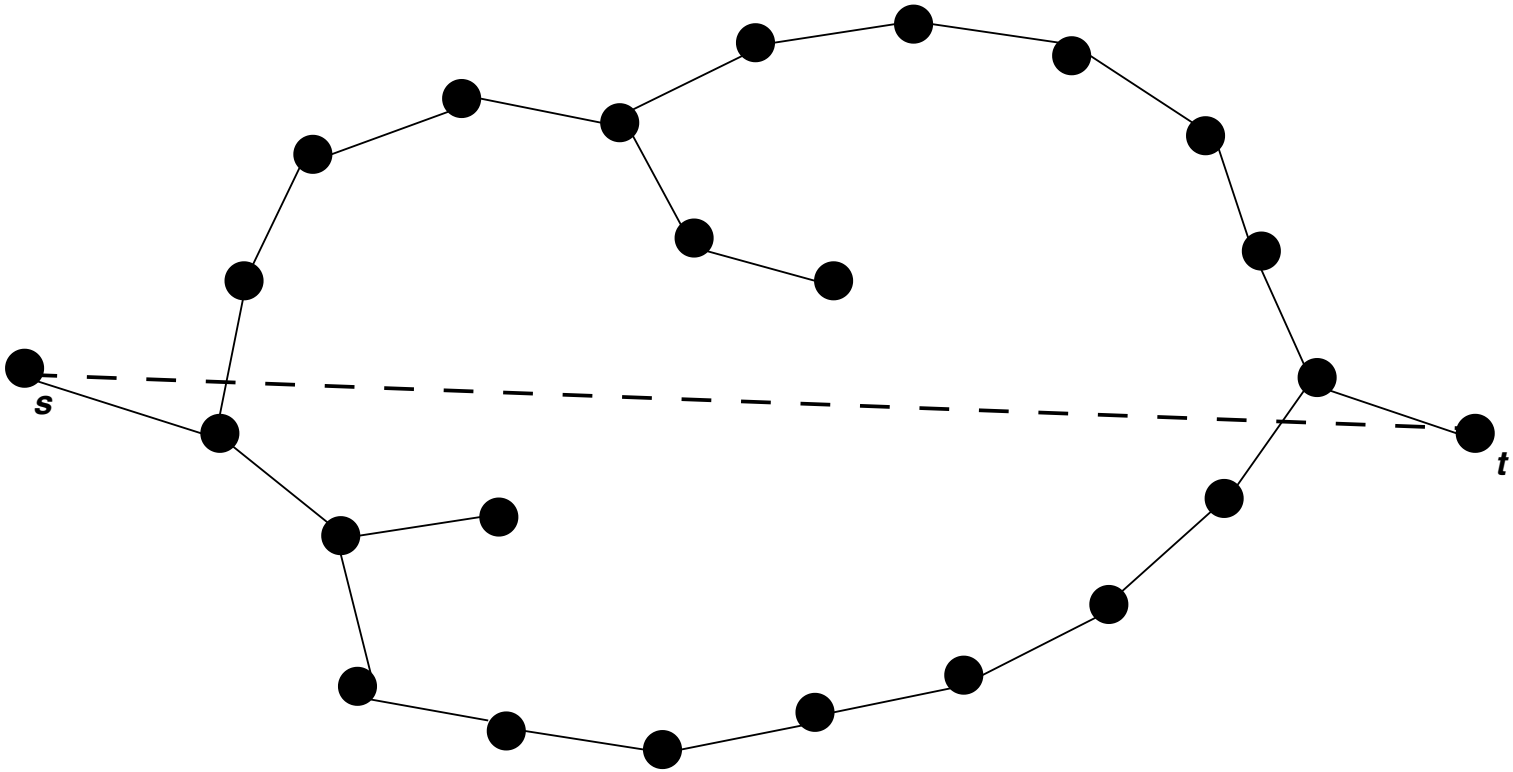
Code:

```
Let u be the current position
if u = t then
    deliver the packet
else
    if mode = Greedy then                                          ▷ Greedy Mode
        if u is a dead end then                                    ▷ Switch to the Face Mode
            Select next hop v in ccw direction from (u, t)
            d_f ← |u, t|; e_f ← (u, v); p ← u                      ▷ To prepare the next hop
            mode ← Face
        else
            Select next hop v according to the greedy rule
        end if
    else                                                           ▷ Face Mode
        if there is a neighbor w with |w, t| < d_f then            ▷ Switch to the Greedy Mode
            Select next hop v according to the greedy rule; mode ← Greedy
        else
            Select next hop v in ccw direction from (u, p)
            If (u, v) = e_f then return   ▷ The packet is dropped: the destination is unreachable
            p ← u                                                  ▷ To prepare the next hop
        end if
    end if
    Send the packet to v
end if
```

GFG: Example

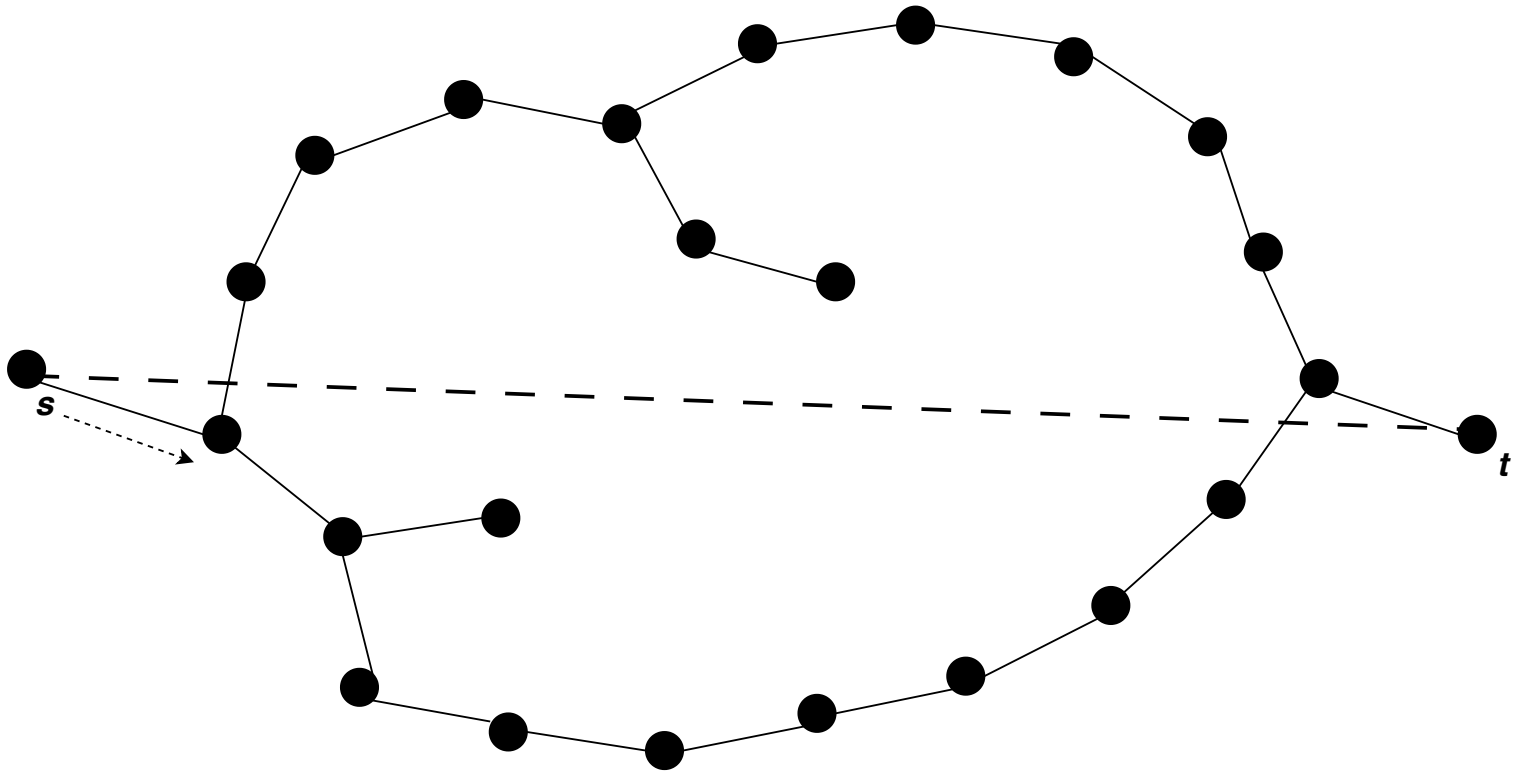


GFG: Example



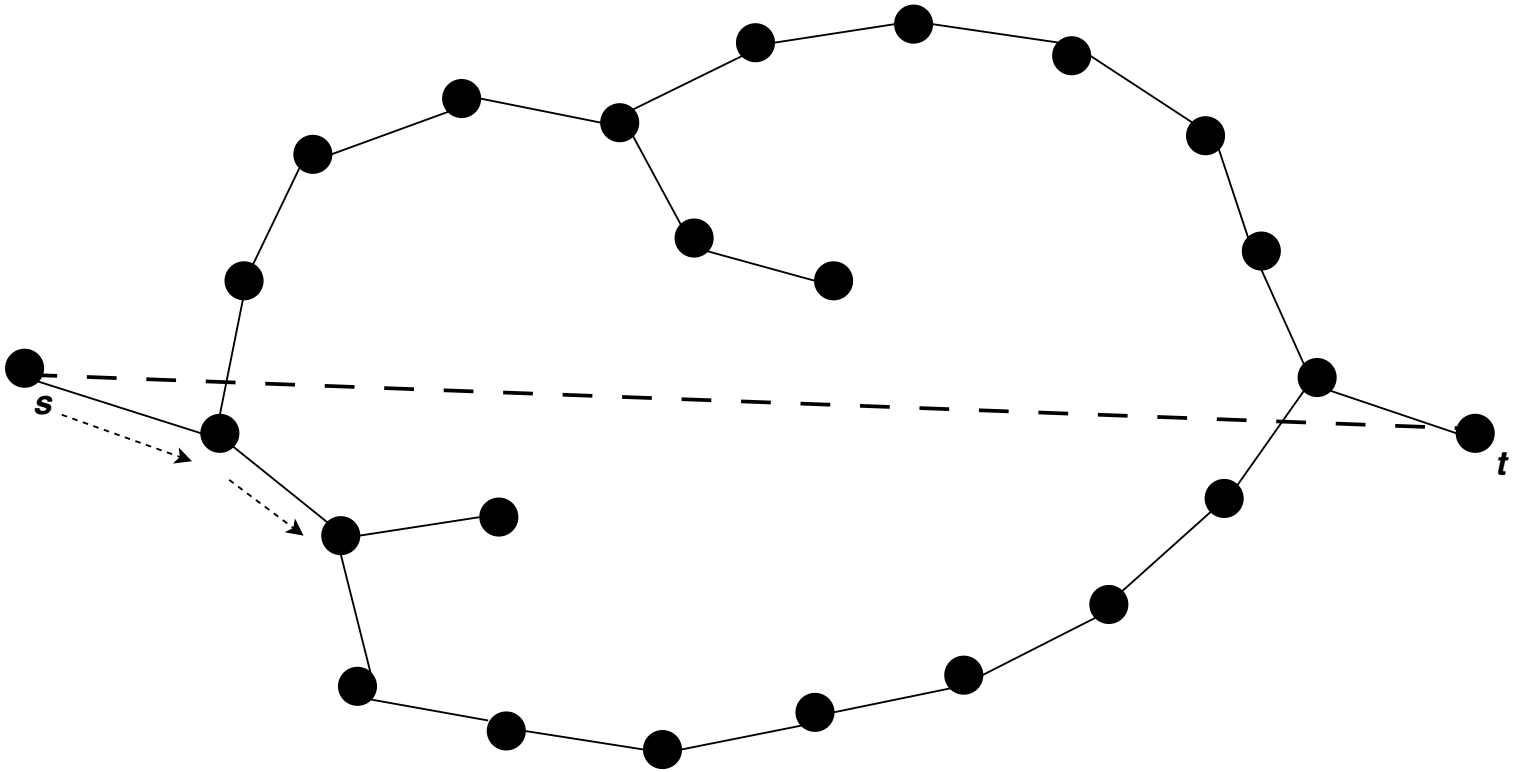
Greedy

GFG: Example



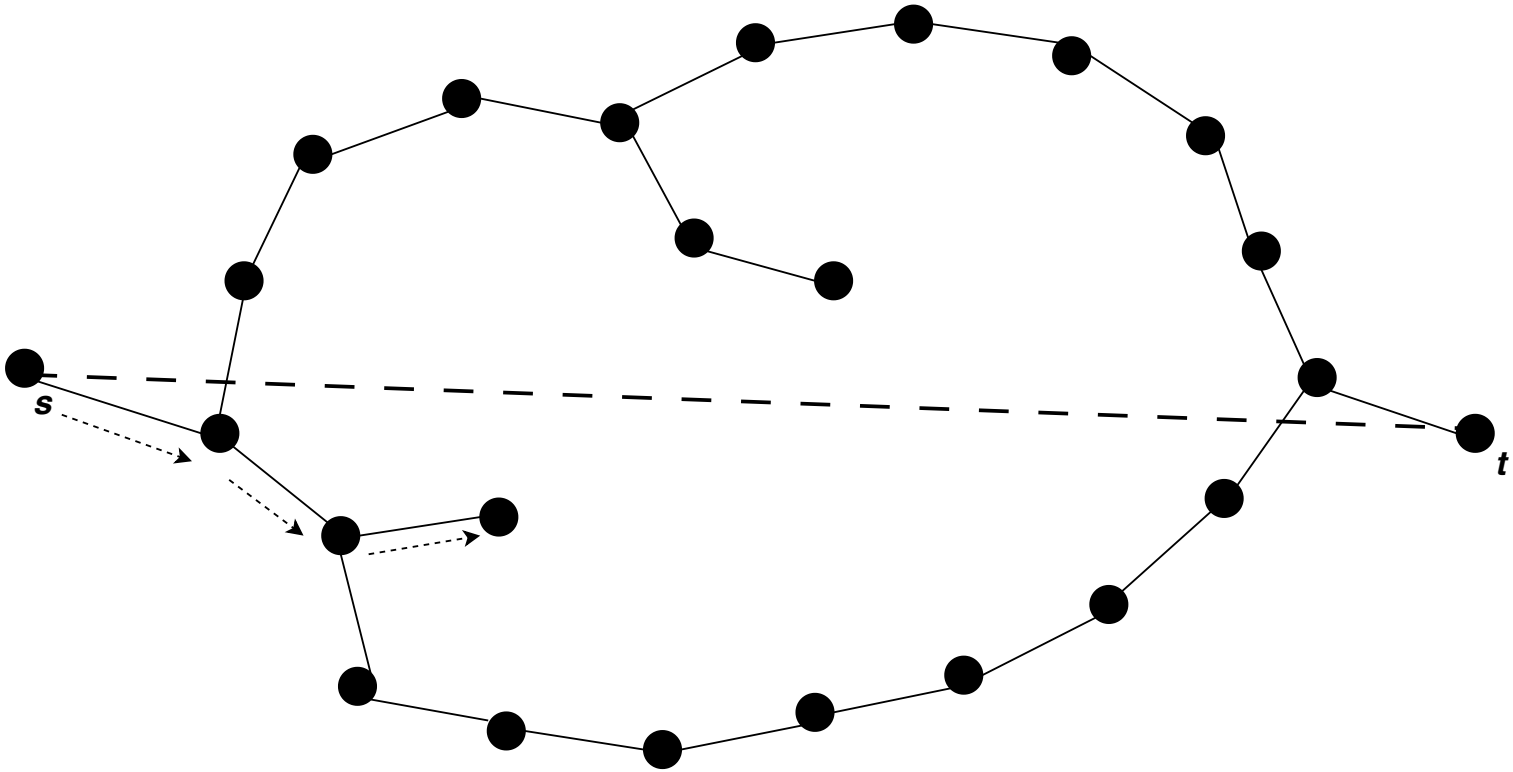
Greedy

GFG: Example



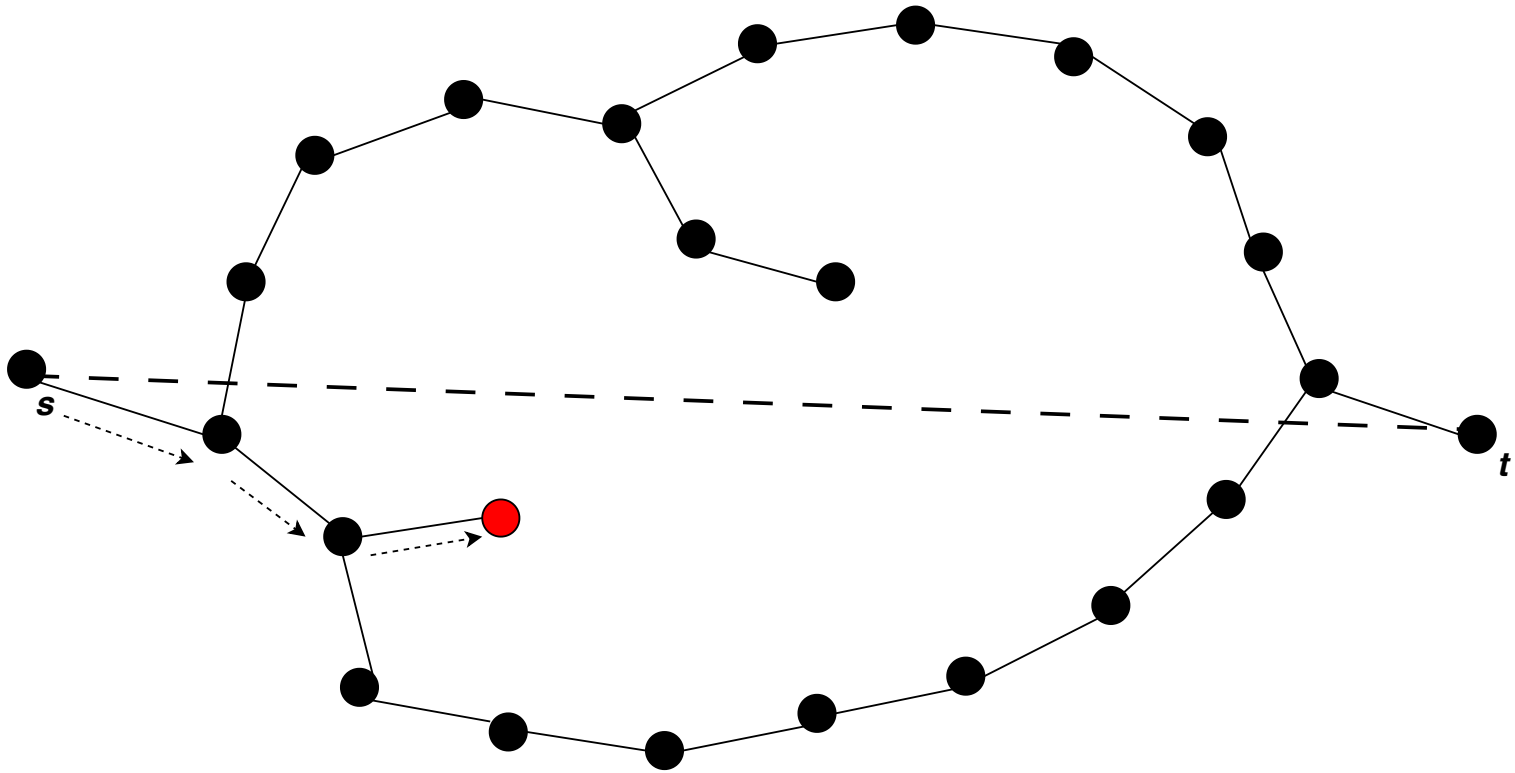
Greedy

GFG: Example



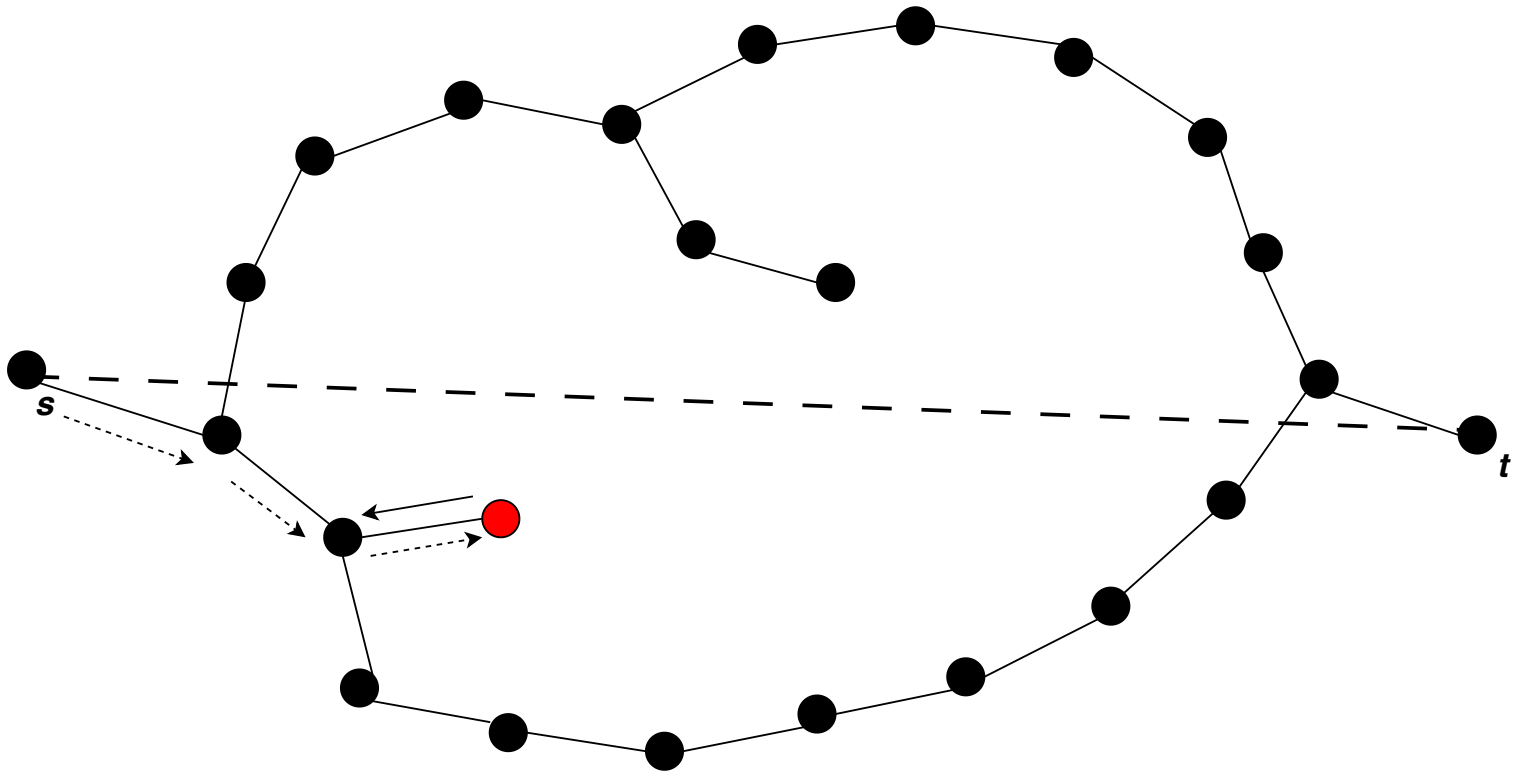
Greedy

GFG: Example



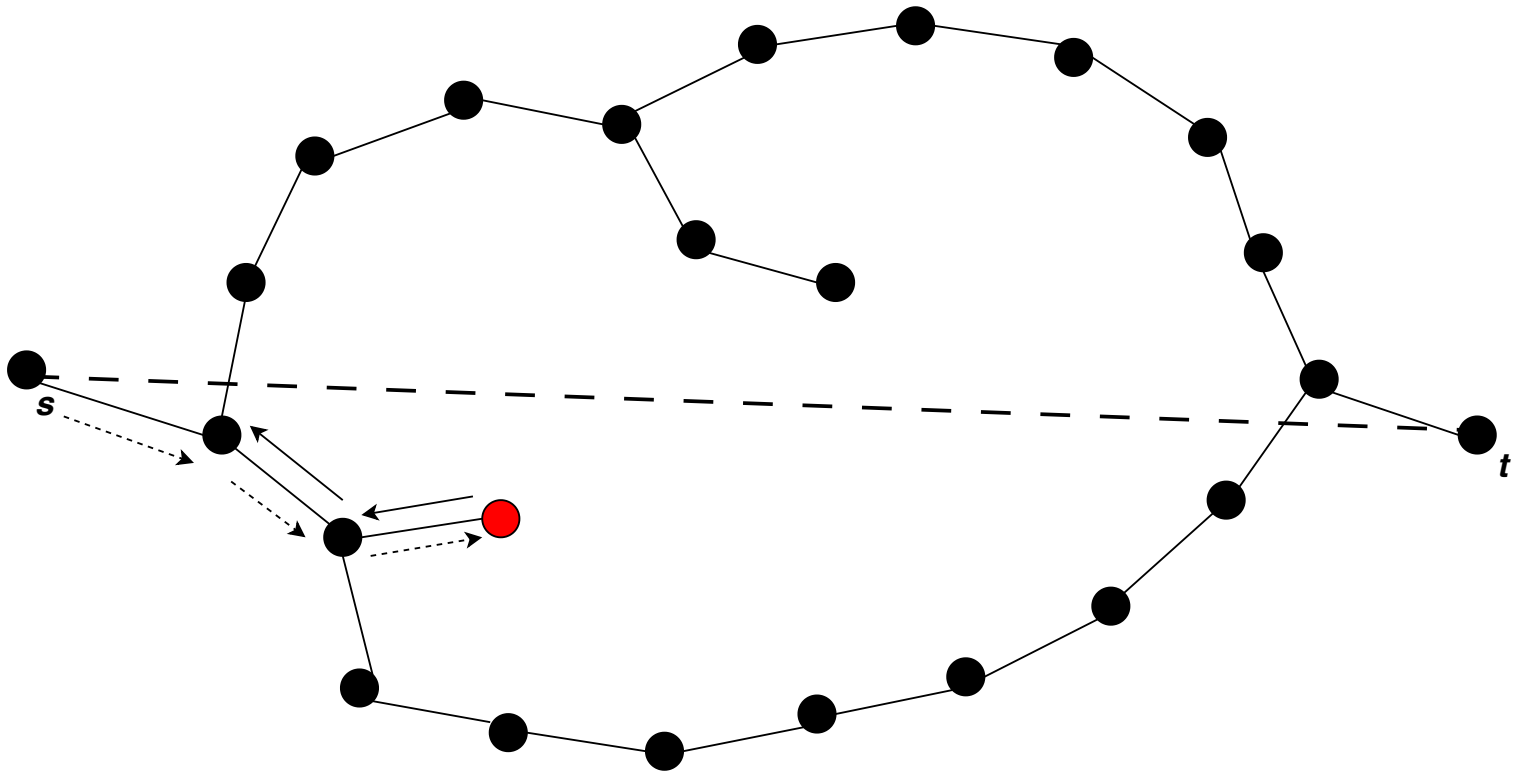
Greedy → Face

GFG: Example



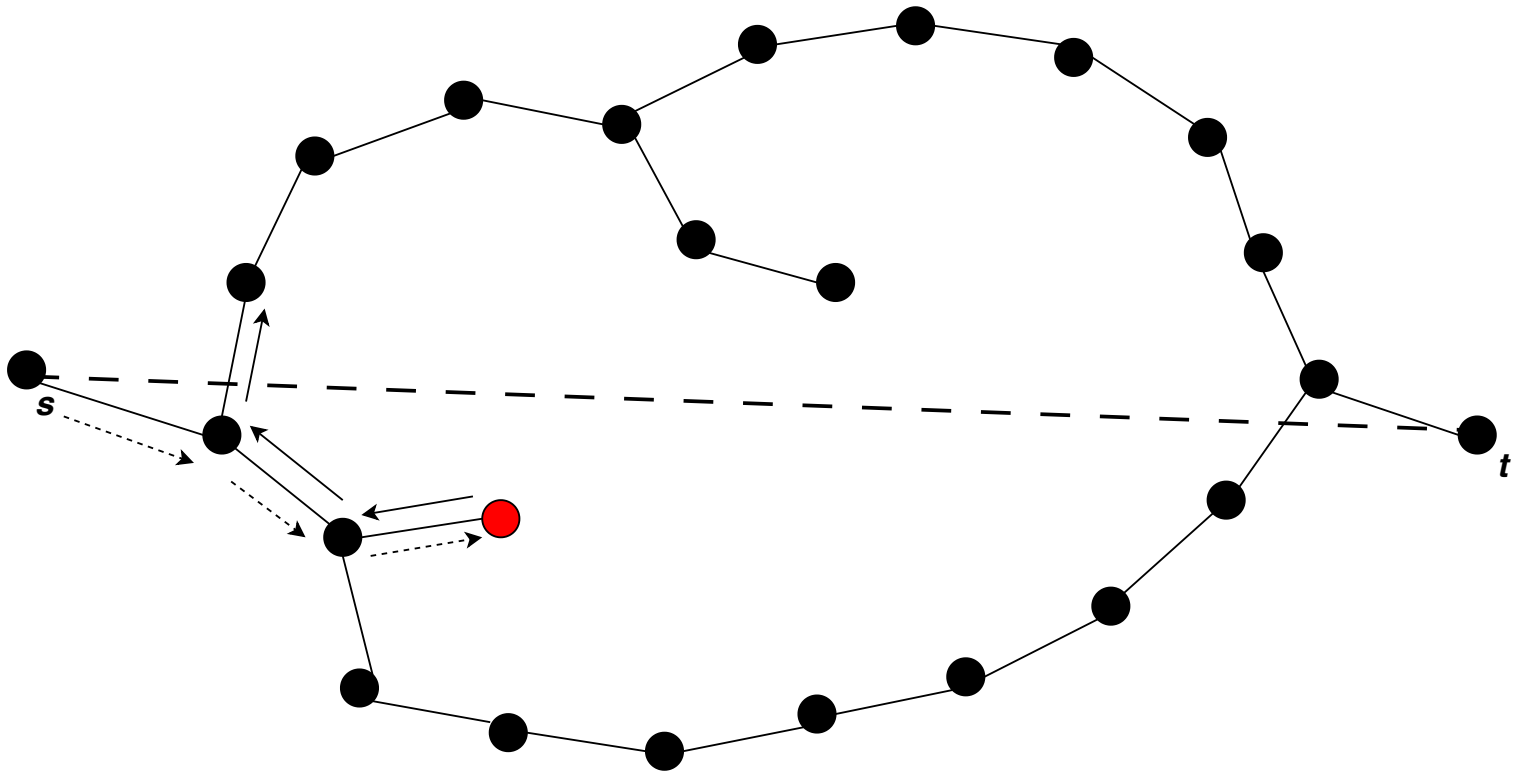
Face

GFG: Example



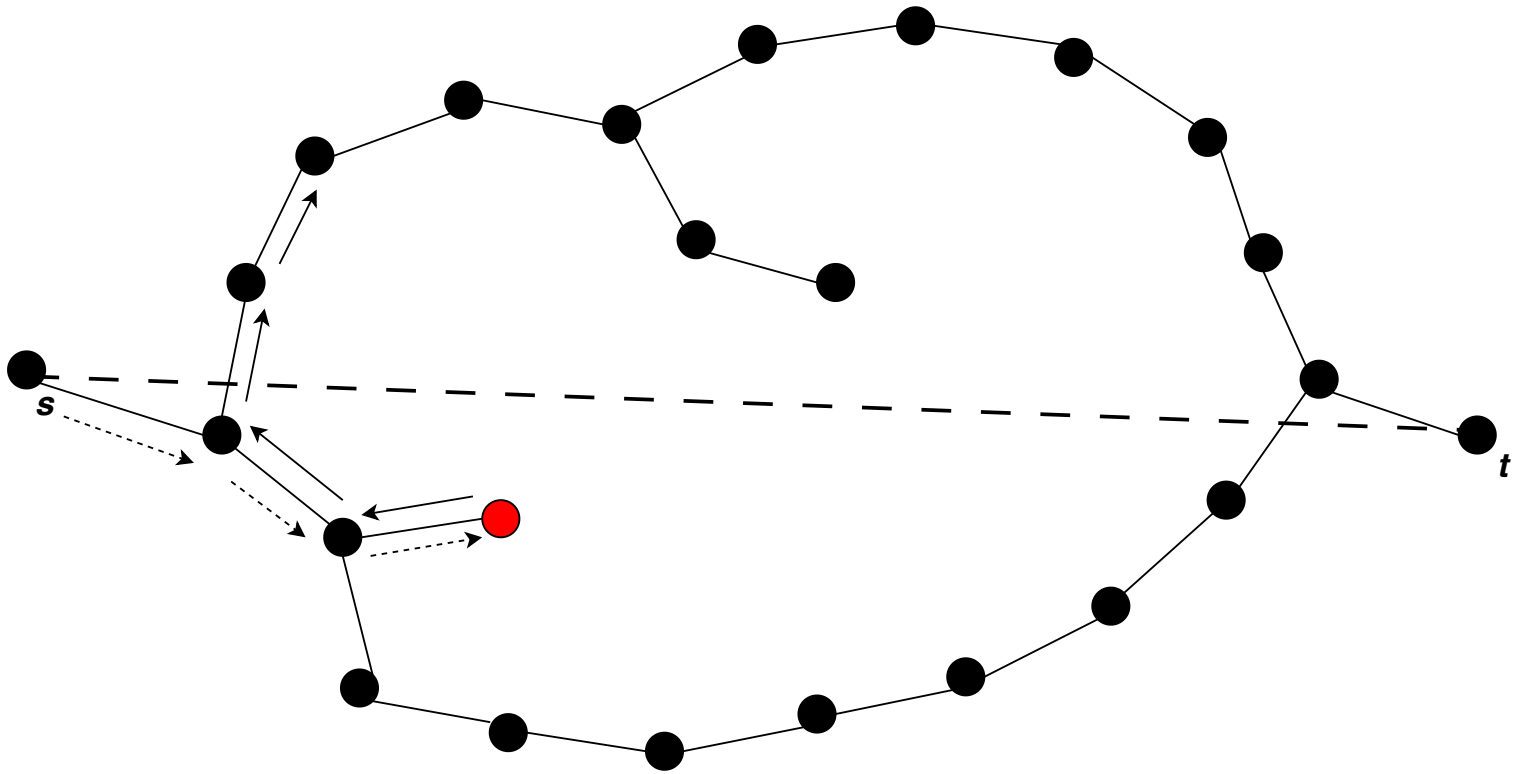
Face

GFG: Example

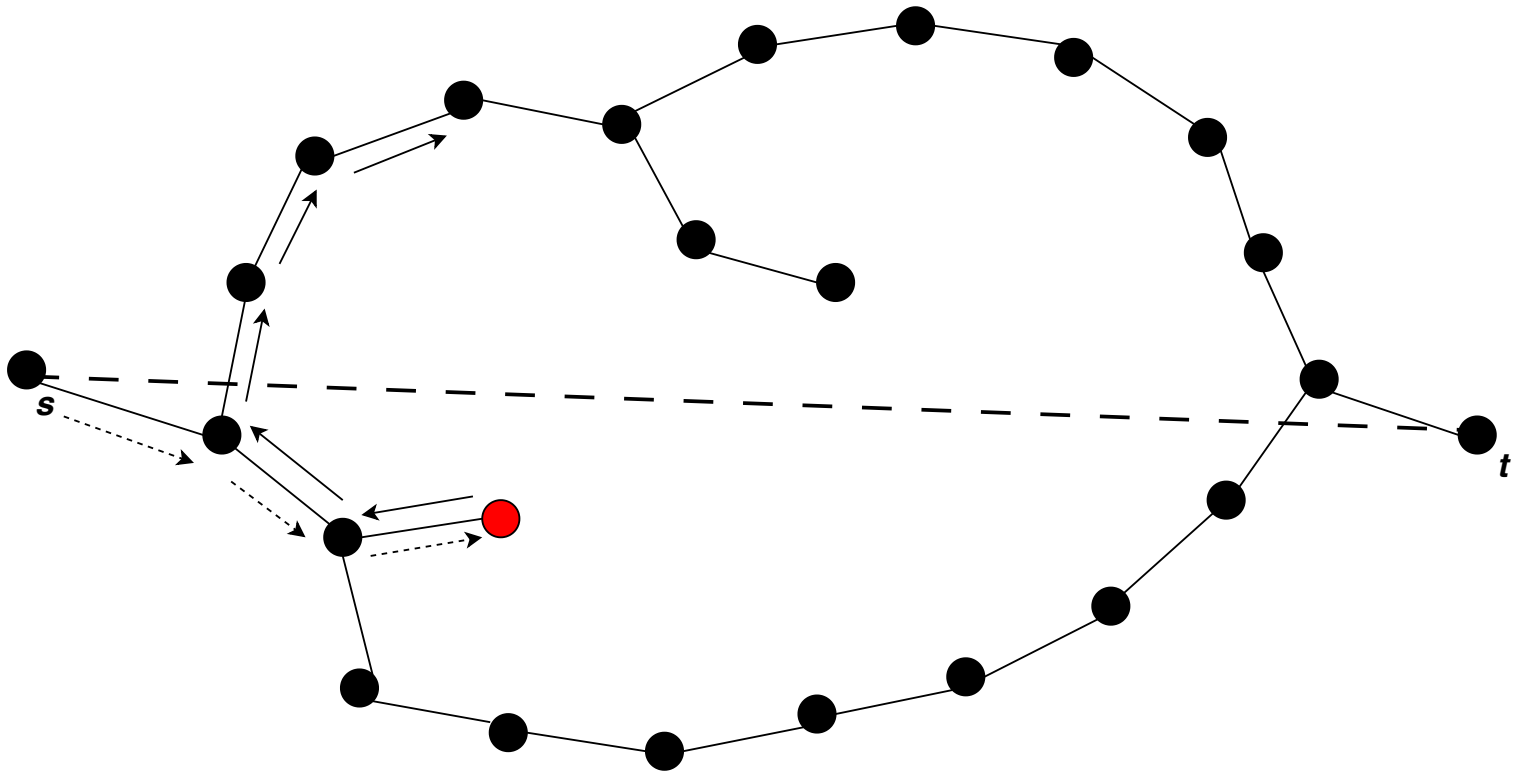


Face

GFG: Example

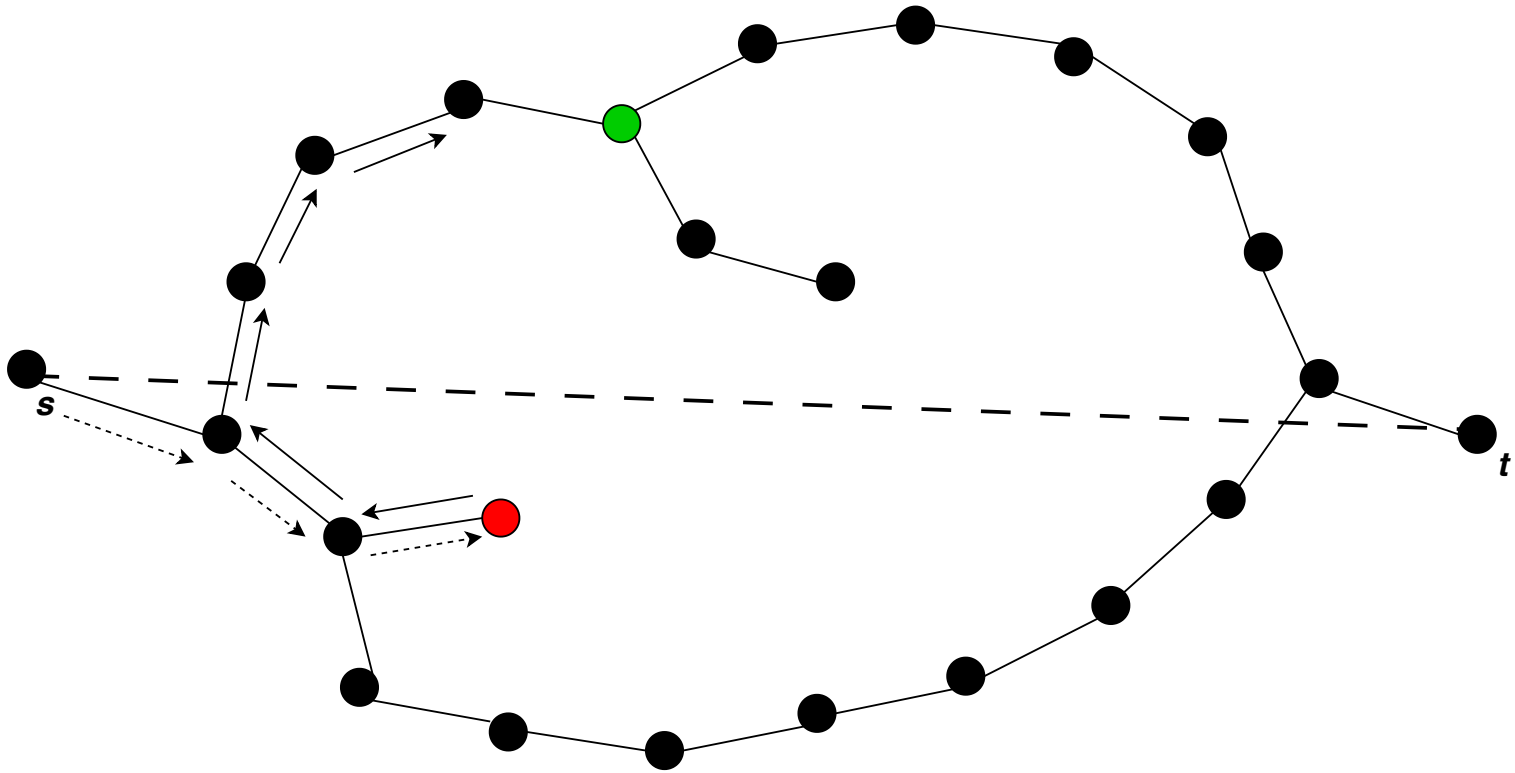


GFG: Example



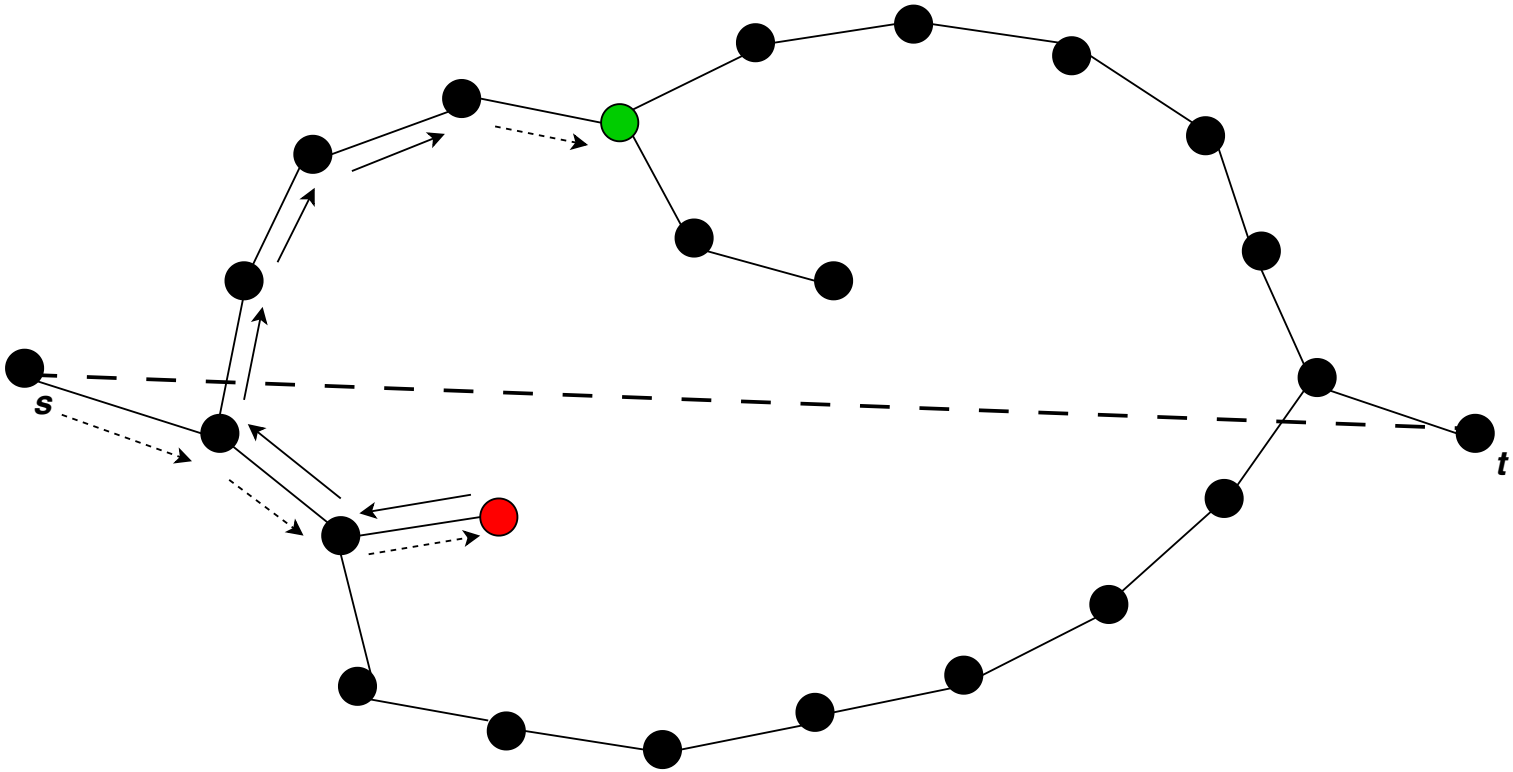
Face

GFG: Example



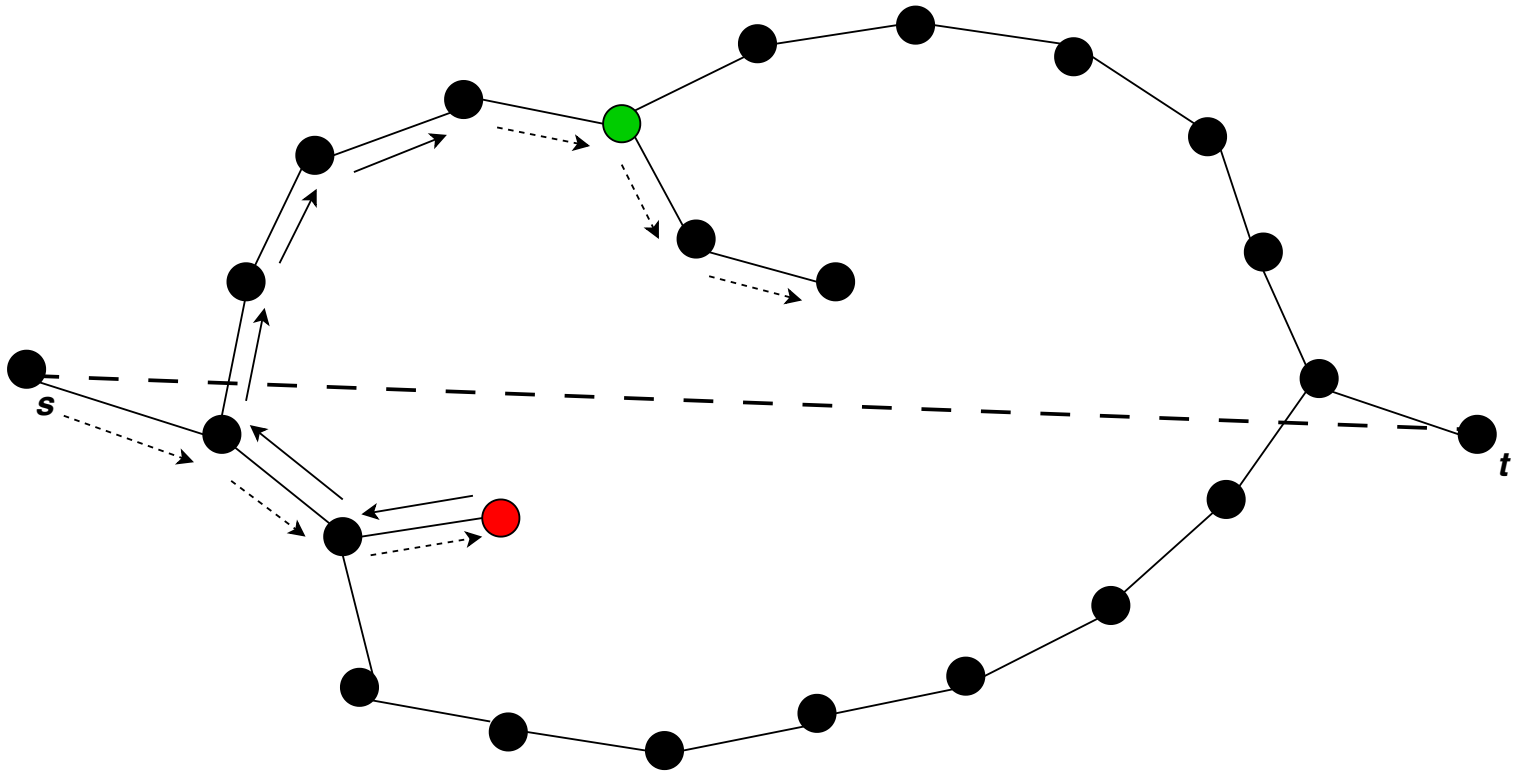
Face → Greedy

GFG: Example



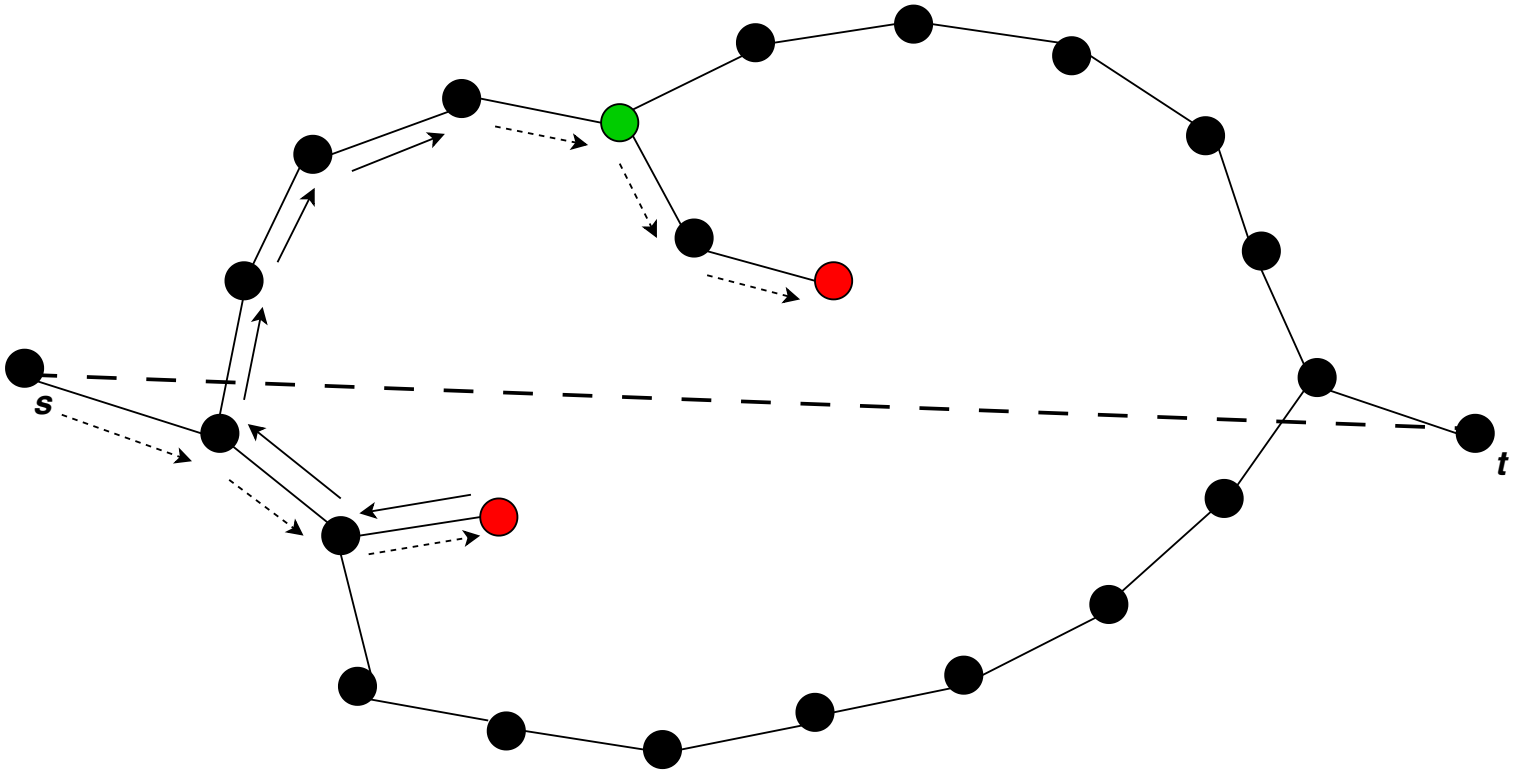
Greedy

GFG: Example



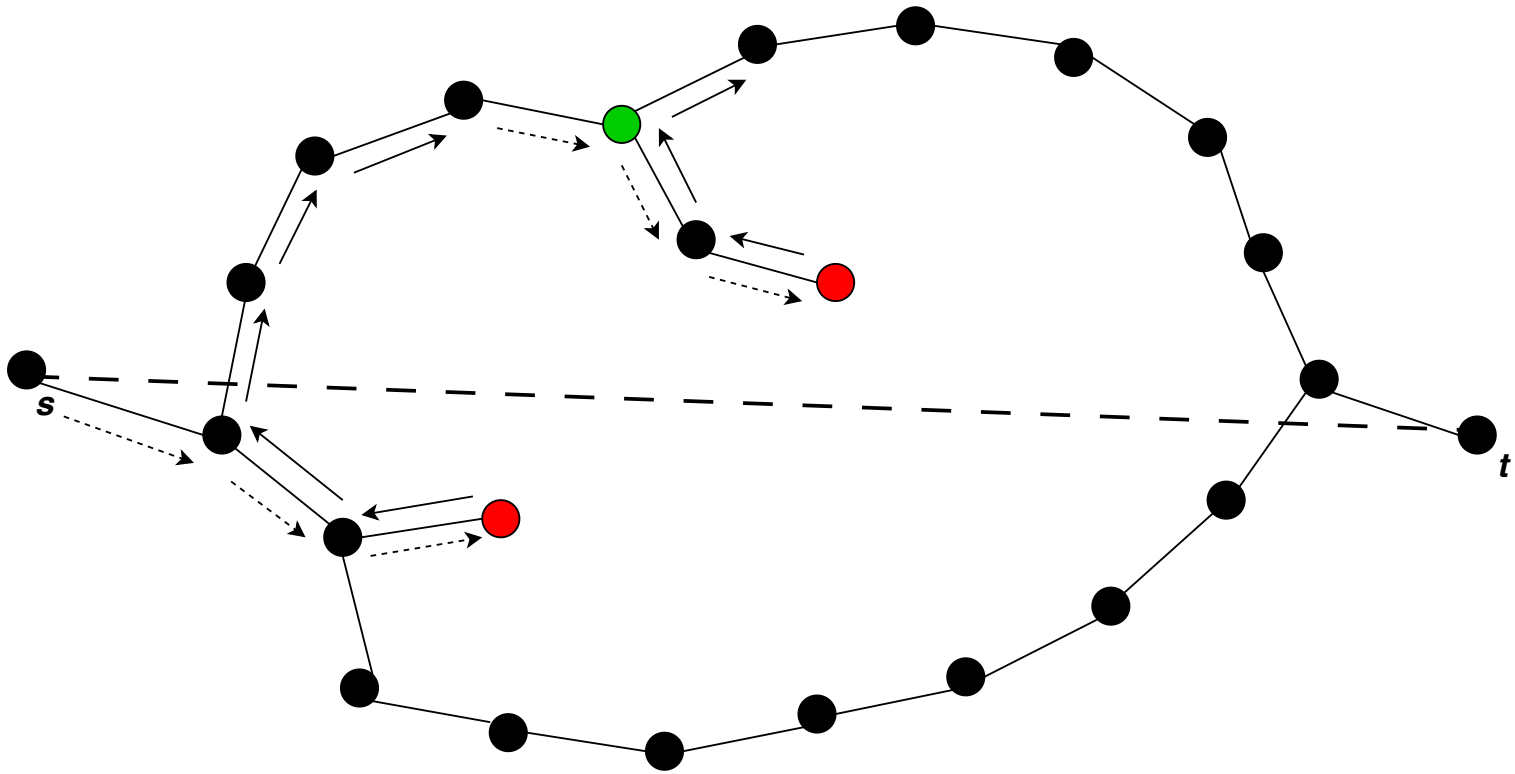
Greedy

GFG: Example



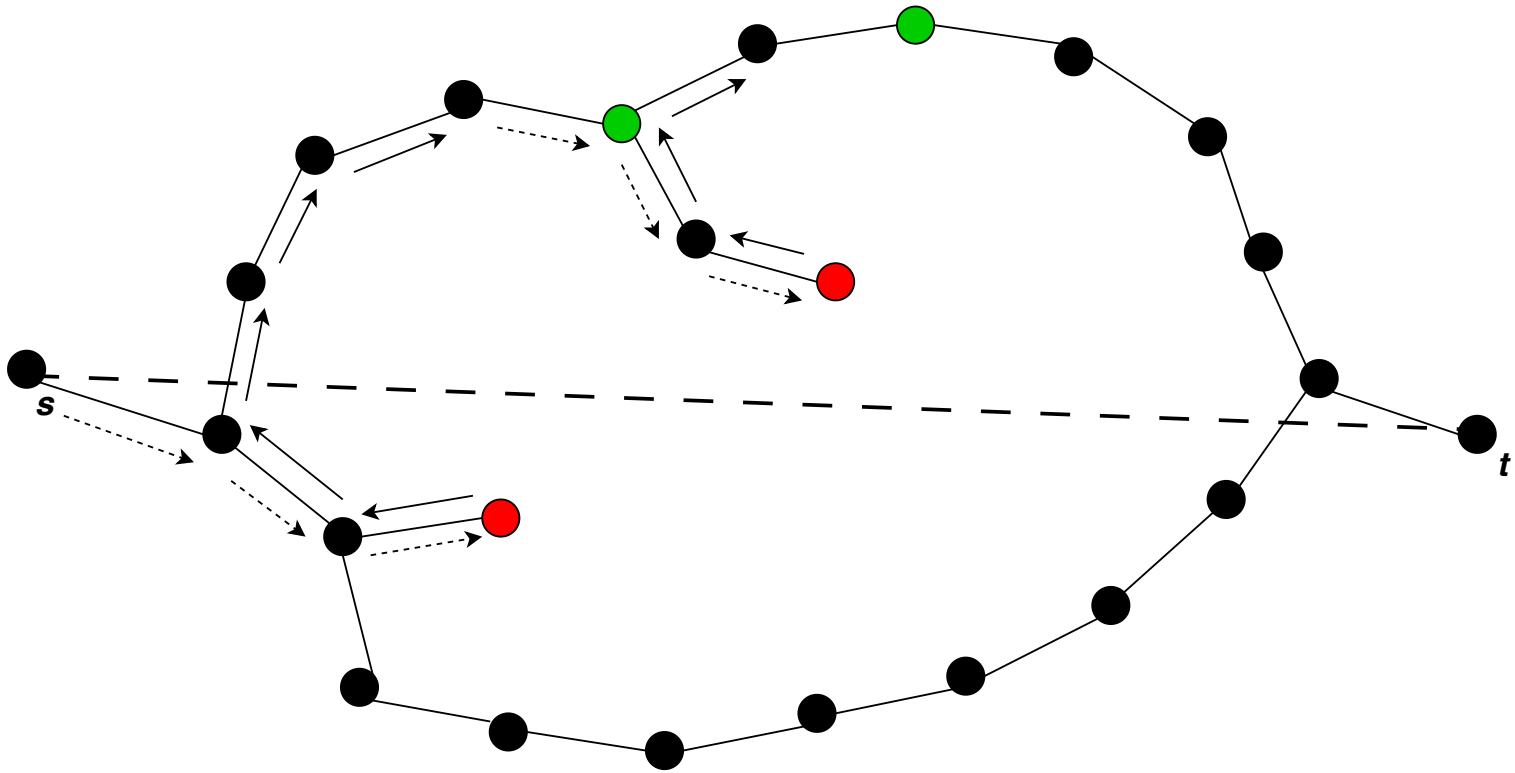
Greedy → Face

GFG: Example



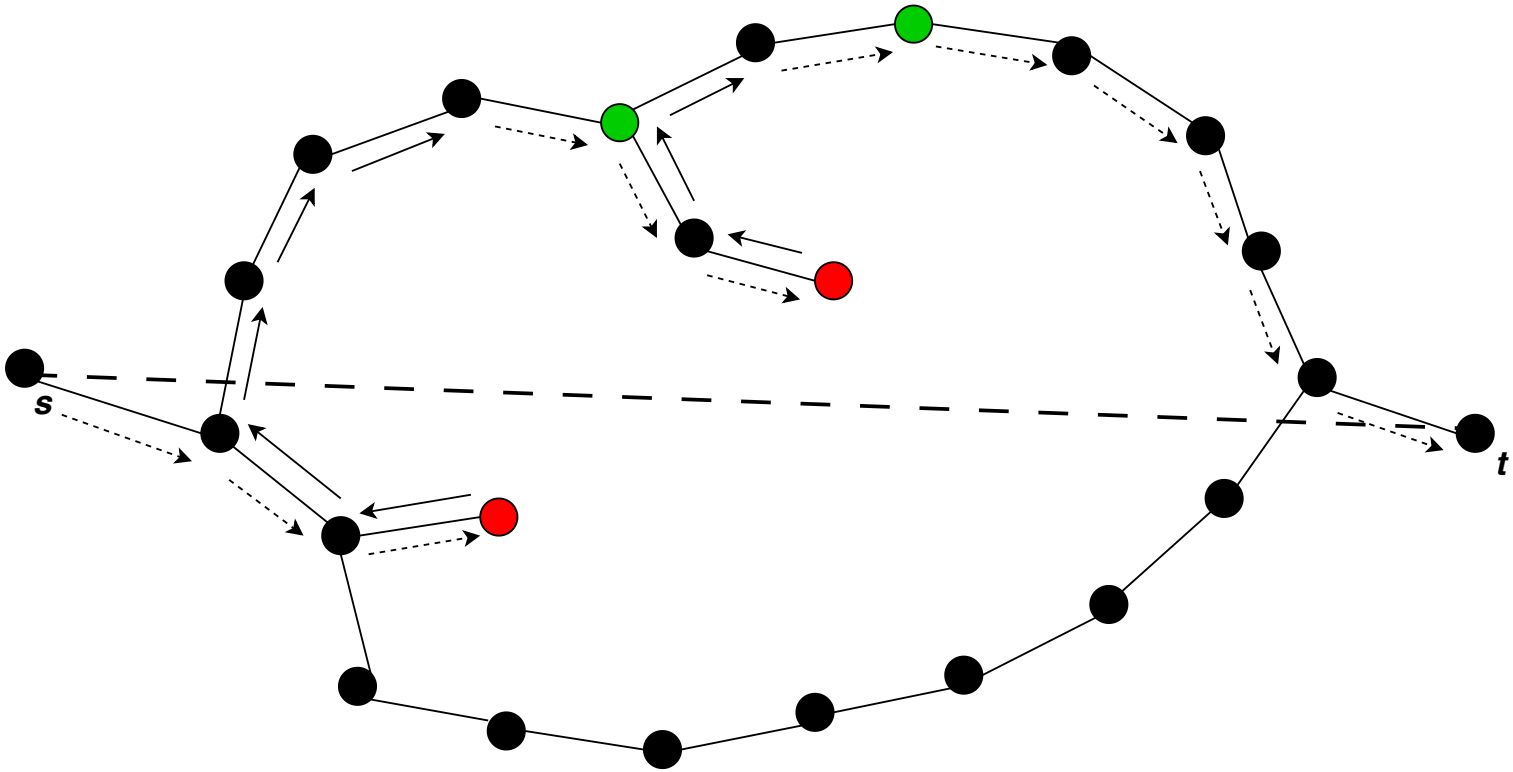
Face

GFG: Example



Face → Greedy

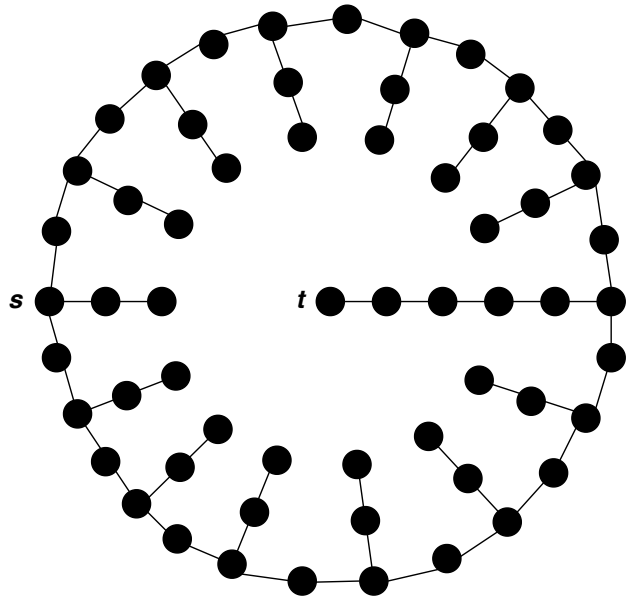
GFG: Example



Greedy

Lower bound [8]

$\Omega(k^2)$ for a shortest path of length $O(k)$



- External ring of length $2k$
- $O(k)$ "branches" of length $\Theta(k)$

From s, at least k nodes of the external ring and $O(k)$ "branches" are visited before reaching t

Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

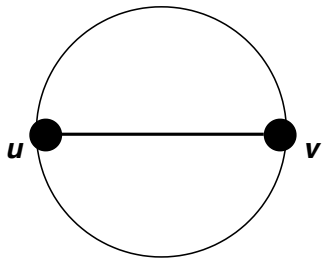
Planarization Techniques

1. Gabriel Graphs [6]
2. Relative Neighborhood Graphs [13]
3. Delaunay Triangularization [4]

Gabriel Graphs [6]

A **Gabriel graph** of a given point set S is defined as follows: $\forall u, v \in S$, it contains the edge $\{u, v\}$ if the Thales' circle on $\{u, v\}$ is empty.

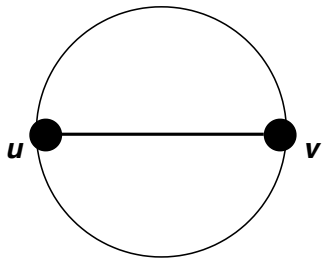
Thales' circle (also called the Gabriel circle) on $\{u, v\}$ = the circle having $\{u, v\}$ as diameter.



Gabriel Graphs [6]

A **Gabriel graph** of a given point set S is defined as follows: $\forall u, v \in S$, it contains the edge $\{u, v\}$ if the Thales' circle on $\{u, v\}$ is empty.

Thales' circle (also called the Gabriel circle) on $\{u, v\}$ = the circle having $\{u, v\}$ as diameter.

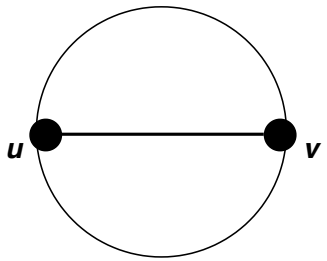


Gabriel graphs are planar and connected.

Gabriel Graphs [6]

A **Gabriel graph** of a given point set S is defined as follows: $\forall u, v \in S$, it contains the edge $\{u, v\}$ if the Thales' circle on $\{u, v\}$ is empty.

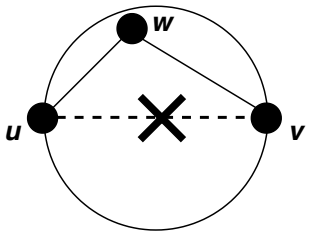
Thales' circle (also called the Gabriel circle) on $\{u, v\}$ = the circle having $\{u, v\}$ as diameter.



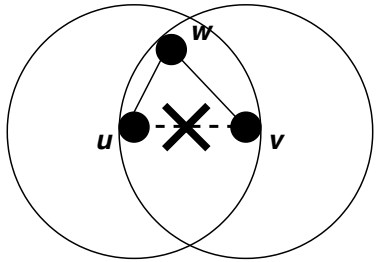
Gabriel graphs are planar and connected.

This construction rule can be applied locally to a node's 1-hop neighborhood in order to extract a planar subgraph.

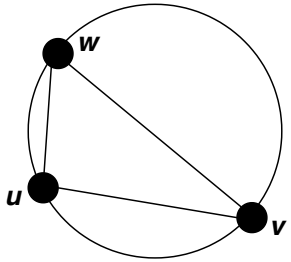
Planarization Techniques



(1)

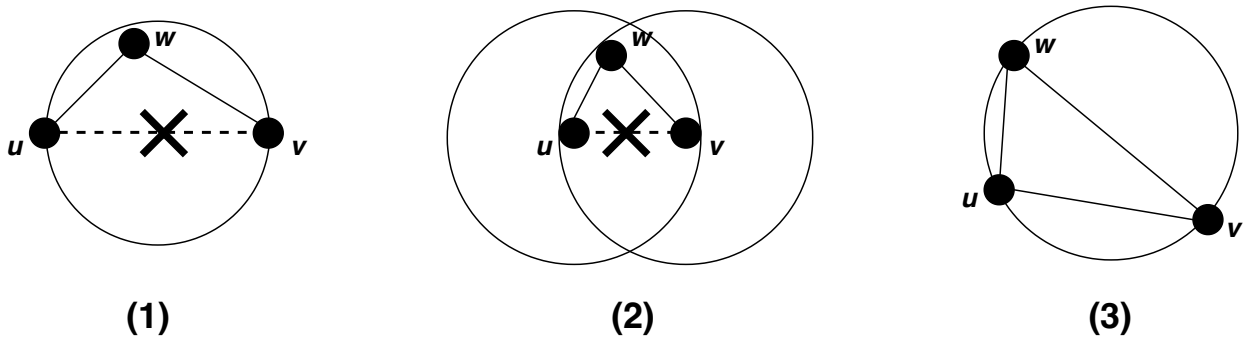


(2)



(3)

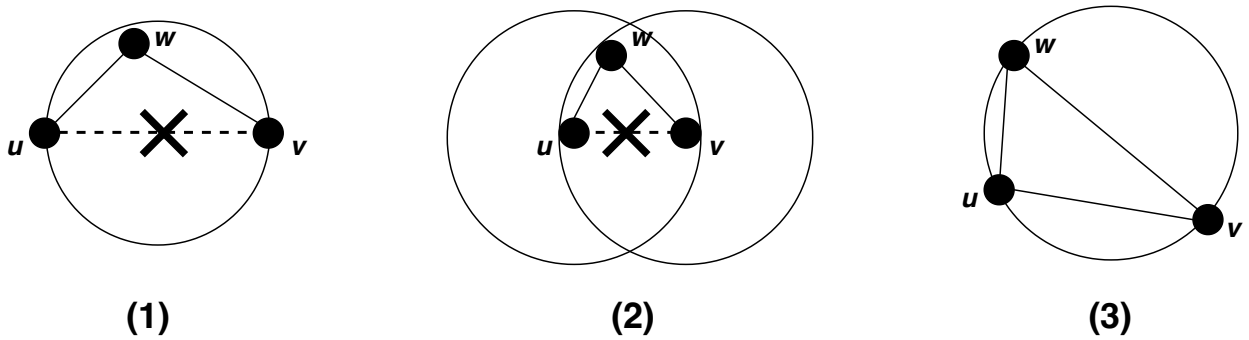
Planarization Techniques



1. Gabriel Graphs [6]: remove an edge $\{u, v\}$ if Thales' circle on $\{u, v\}$ contains another node w.

   Applying the Gabriel Graphs criterion to a unit disk graph yields a planar and connected graph, if the unit disk graph is connected.

Planarization Techniques



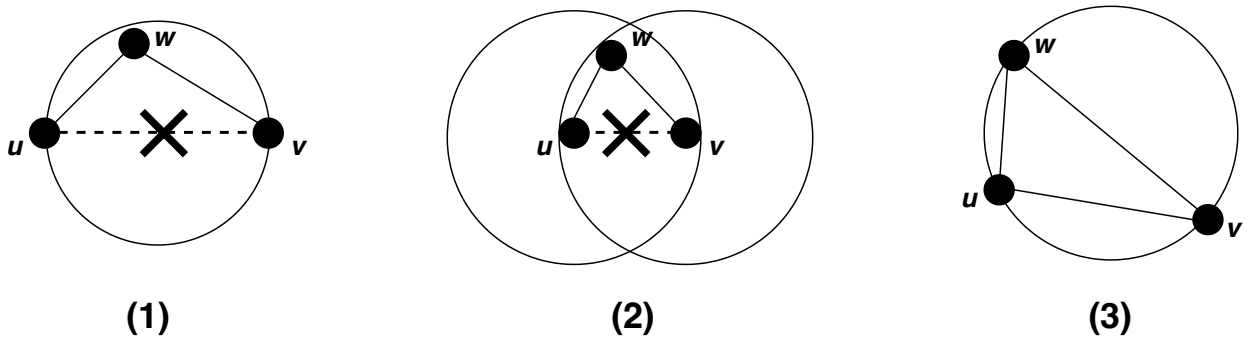
1. Gabriel Graphs [6]: remove an edge $\{u, v\}$ if Thales' circle on $\{u, v\}$ contains another node w.

   Applying the Gabriel Graphs criterion to a unit disk graph yields a planar and connected graph, if the unit disk graph is connected.

2. Relative Neighborhood Graphs [13]: remove an edge $\{u, v\}$ if if the intersection of the two circles with radius $|u, v|$ centered at u and v contains another node w

   Applying the RNG criterion to a unit disk graph yields a planar and connected graph, if the unit disk graph is connected.

Planarization Techniques



1. Gabriel Graphs [6]: remove an edge $\{u, v\}$ if Thales' circle on $\{u, v\}$ contains another node w.

   Applying the Gabriel Graphs criterion to a unit disk graph yields a planar and connected graph, if the unit disk graph is connected.

2. Relative Neighborhood Graphs [13]: remove an edge $\{u, v\}$ if if the intersection of the two circles with radius $|u, v|$ centered at u and v contains another node w

   Applying the RNG criterion to a unit disk graph yields a planar and connected graph, if the unit disk graph is connected.

3. Delaunay Triangularization [4]: the Delaunay triangulation of a given point set contains all triangles whose circumcircle is empty.

Stretch Factor

Planarization removes (omit) crossing edges $\Rightarrow$ **Detours**

Stretch Factor

Planarization removes (omit) crossing edges $\Rightarrow$ **Detours**

Stretch Factor allows to evaluate the quality of the planarization

Stretch Factor: $\max \frac{\text{shortest path length between } u \text{ and } v \text{ in the subgraph}}{\text{shortest path length between } u \text{ and } v \text{ in the original graph}}$

Comparison

Technique	**Local**[4]	**Stretch Factor**[5][6]
Gabriel Graph	Yes	$\Theta(\sqrt{n})$
RNG	Yes	$\Theta(n)$
Delaunay Triangularization	No	$\Theta(1)$

[4] By Local, we mean using only 1-hop information

[5] n is the number of nodes

[6] Stretch factors come from Bose *et al.* [1]

Comparison

Technique	**Local**[4]	**Stretch Factor**[5][6]
Gabriel Graph	Yes	$\Theta(\sqrt{n})$
RNG	Yes	$\Theta(n)$
Delaunay Triangularization	No	$\Theta(1)$

State-of-the-art: Local variants of the Delaunay Triangularization

[4] By Local, we mean using only 1-hop information

[5] n is the number of nodes

[6] Stretch factors come from Bose *et al.* [1]

Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

Pros and Cons of GFG + planarization

Pros:

- Correctness
  (if the links are reliable)
- Local Information only: small messages and low memory requirements
- Robust
- FIFO
- Fair

Cons:

- Not adaptive
- Load-balancing: many links are not used, in particular due to planarization
- Not efficient
- Unrealistic Model: UDG topology and reliable link

Pros and Cons of GFG + planarization

Pros:

- Correctness
  (if the links are reliable)
- Local Information only: small messages and low memory requirements
- Robust
- FIFO
- Fair

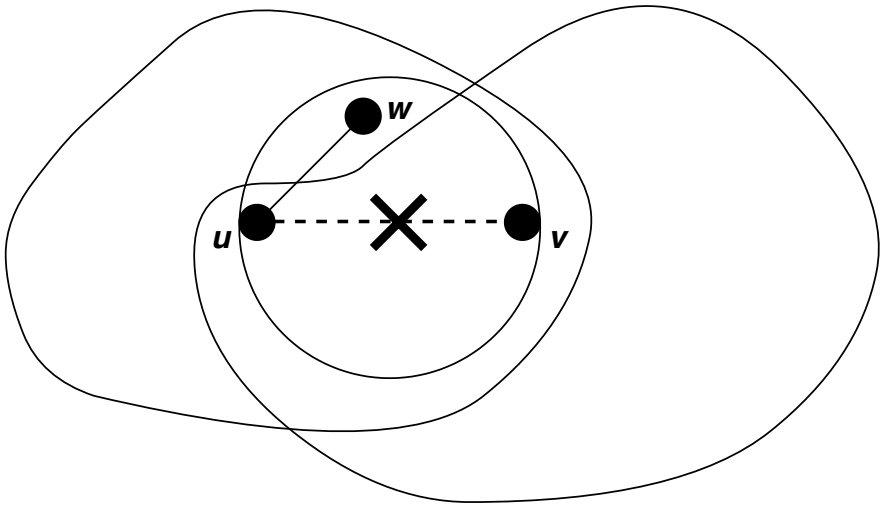
Cons:

- Not adaptive
- Load-balancing: many links are not used, in particular due to planarization
- Not efficient
- **Unrealistic Model: UDG topology and reliable link**

Toward more realistic topologies

GFG works in any planar graph

However, previously introduced planarization techniques may disconnect a non-UDG graph such as a Quasi-UDG.



Other planarization techniques exist

but they are more complex (in particular, not local) and so more costly.

Unreliable links

Greedy (and greedy mode in GFG): designed with respect to distance and does not take lossy links into account.

Idea: adapting greedy (mode) forwarding by considering the reception probability into the criteria that is locally optimized.

Unreliable links

Greedy (and greedy mode in GFG): designed with respect to distance and does not take lossy links into account.

Idea: adapting greedy (mode) forwarding by considering the reception probability into the criteria that is locally optimized.

Motivation: If a node on the edge of the range with low link quality is selected as a next hop, it might take a few transmission attempts to successfully forward a packet, whereas another node with a smaller advance could be reached on the first try.

Hence, **the criteria for forwarding decisions should include the cost for re-transmissions.**

Estimating the cost for re-transmissions

Packet Retransmission Rate (PRR):

$$\frac{\text{successfully received packets}}{\text{the total number of transmitted packets}} \text{ over a specific time period}$$

$\approx$ a reception probability p for future transmissions

$\approx$ cost for re-transmissions

$\frac{1}{p} \approx$ the expected number of transmissions needed for a successful reception

(if acknowledgments are not taken into account).

A new criteria to deal with a realistic physical layer model

In [11], Seada *et al.* propose to (locally) maximize

$$\text{PRR} \times \text{advance}$$

Essentially, it is a ratio of the advance over the expected number of transmissions

Roadmap

1. Introduction
2. Geographic Greedy Forwarding
3. Planar Graph Routing and Recovery Strategies
4. Planarization
5. Conclusion
6. References

References I

[1] P. Bose, L. Devroye, W. Evans, and D. Kirkpatrick.
On the spanning ratio of gabriel graphs and beta-skeletons.
SIAM Journal on Discrete Mathematics, 20(2):412–427, 2006.

[2] P. Bose, P. Morin, I. Stojmenovic, and J. Urrutia.
Routing with guaranteed delivery in ad hoc wireless networks.
In *Proceedings of the 3rd International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIAL-M'99)*, pages 48–55, 1999.

[3] S. Datta, I. Stojmenovic, and J. Wu.
Internal node and shortcut based routing with guaranteed delivery in wireless networks.
Cluster Computing, 5(2):169–178, 2002.

[4] B. Delaunay.
Sur la sphère vide.
Bulletin de l'Académie des Sciences de l'URSS. Classe des sciences mathématiques et na, 1934(6):793–800, 1934.

[5] G. G. Finn.
Routing and addressing problems in large metropolitan-scale internetworks.
Technical Report ISI/RR-87-180, University of Southern California, Information Sciences Institute, Los Angeles, CA, Mar. 1987.

[6] K. R. Gabriel and R. R. Sokal.
A new statistical approach to geographic variation analysis.
Systematic Zoology, 18(3):259–278, 1969.

[7] E. Kranakis, H. Singh, and J. Urrutia.
Compass routing on geometric networks.
In *Proceedings of the 11th Canadian Conference on Computational Geometry (CCCG'99)*, pages 51–54, Aug. 1999.

References II

[8] F. Kuhn, R. Wattenhofer, and A. Zollinger.
Asymptotically optimal geometric mobile ad-hoc routing.
In *Proceedings of the 6th International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIALM)*, pages 24–33. ACM Press, 2002.

[9] H. Liu, X. Chu, and Y. Wing Leung, editors.
Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols.
Bentham Science Publishers, 1 edition, 2009.

[10] S. Ruhrup.
Theory and practice of geographic routing.
In *Ad Hoc and Sensor Wireless Networks: Architectures, Algorithms and Protocols*, pages 69–88. Bentham Science Publishers, 2009.

[11] K. Seada, M. Zuniga, A. Helmy, and B. Krishnamachari.
Energy-efficient forwarding strategies for geographic routing in lossy wireless sensor networks.
In *Proceedings of the 2nd International Conference on Embedded Networked Sensor Systems (SenSys'04)*, pages 108–121. ACM, 2004.

[12] H. Takagi and L. Kleinrock.
Optimal transmission ranges for randomly distributed packet radio terminals.
IEEE Transactions on Communications, 32(3):246–257, Mar. 1984.

[13] M. Torrent-Moreno.
Inter-vehicle communications: Assessing information dissemination under safety constraints.
In *Proceedings of the 4th Annual IEEE/IFIP Conference on Wireless On-Demand Network Systems and Services (WONS)*, Jan. 2007.