On Polynomial-Time Congestion-Free Software-Defined Network Updates

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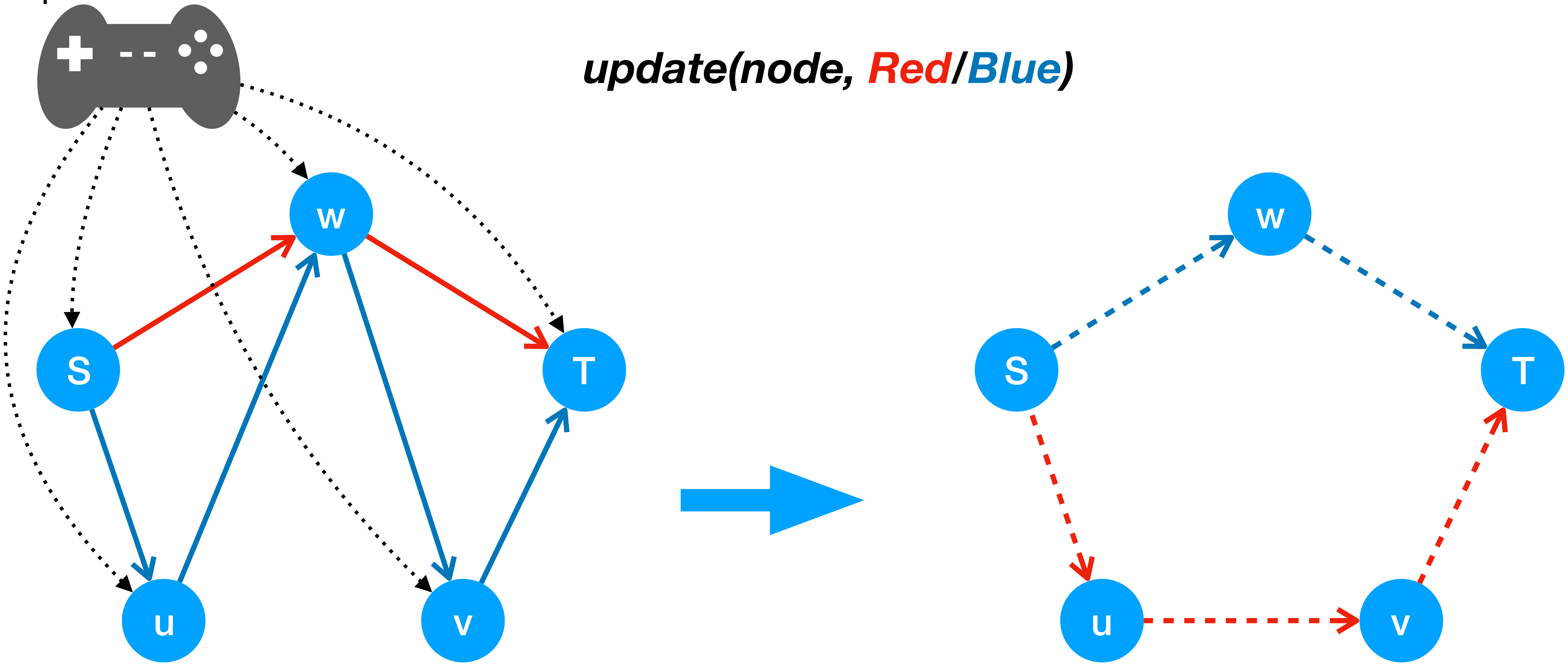
Why reroute?

- many reasons, including security and policy changes
- traffic engineering, optimizations, demand changes etc.
- rerouting involves distribution of new (forwarding) rules
- while maintaining certain consistency properties
- in a SDN, rules are distributed by a <u>controller</u>

SDN controller issues update commands



old routes

new routes

Task: reroute red and blue flows to their new route

Solid: old route

Dashed: new route

Let’s reroute!

update(u, Blue)

update(S, Blue)

update(w, Red)

update(S, Red)

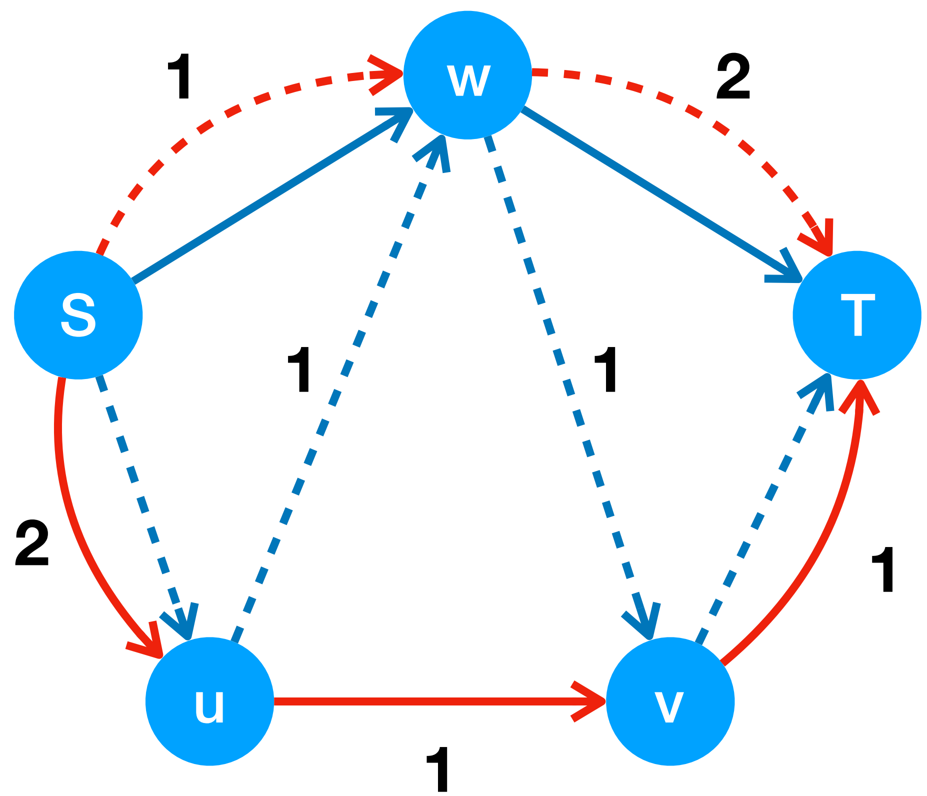
update(u, Red)

update(v, Red)

update(v, Blue)

update(w, Blue)

update(node, Red/Blue)



Task: reroute red and blue flows to their new route

Solid: old route

Dashed: new route

1-update(w, Red)

update(S, Blue)

update(w, Red)

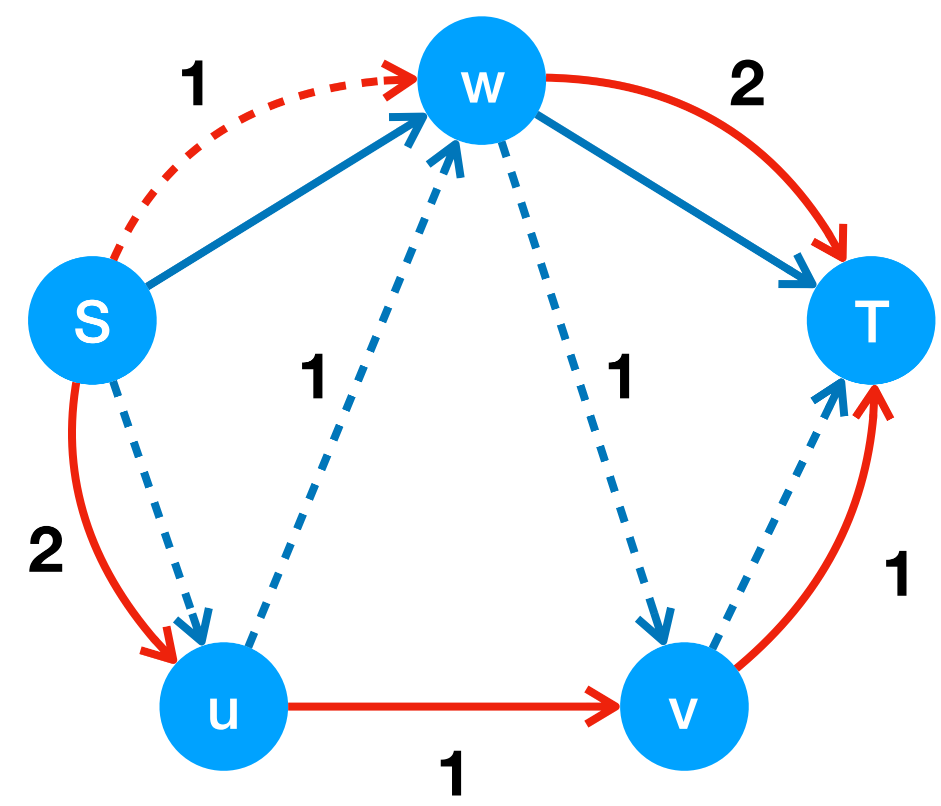
update(S, Red)

update(u, Red)

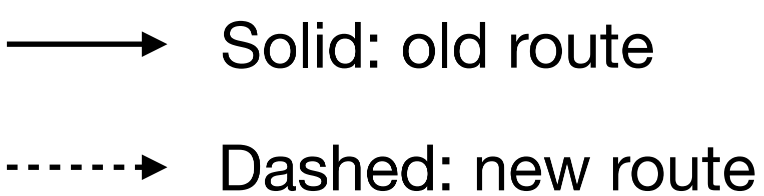
update(v, Red)

update(v, Blue)

update(w, Blue)



Rerouting red and blue flows to their new route, **congestion-free**!



1-update(w, Red)

2-update(S, Red)

update(w, Red)

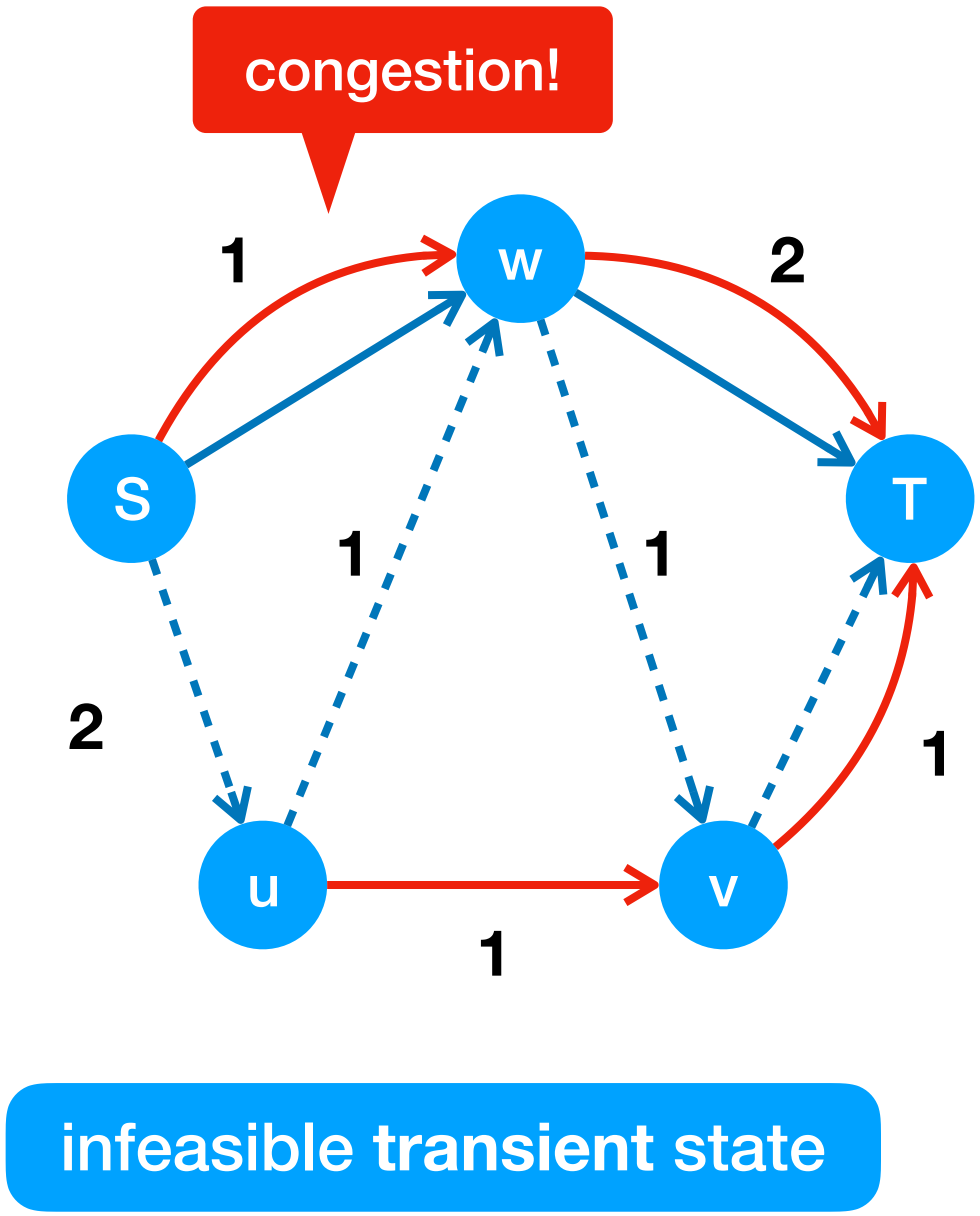
update(S, Red)

update(u, Red)

update(v, Red)

update(v, Blue)

update(w, Blue)



Rerouting red and blue flows to their new route, **congestion-free**!

Solid: old route

Dashed: new route

Let's try again!

1-update(u, Blue)

2-update(S, Blue)

3-update(w, Red)

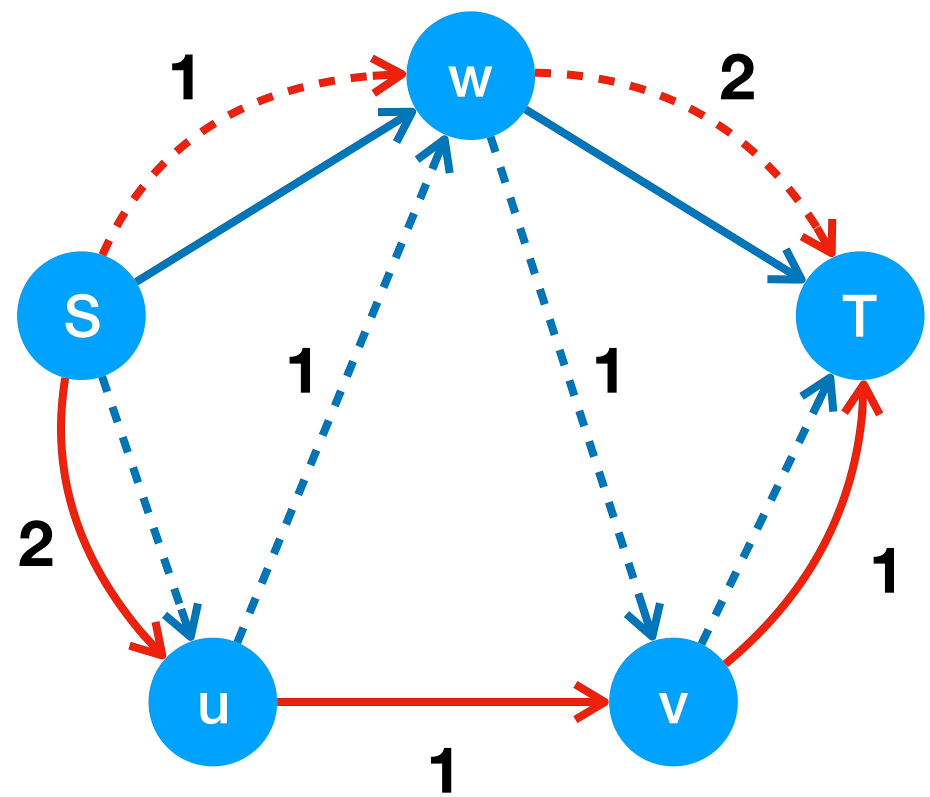
4-update(S, Red)

5-update(u, Red)

6-update(v, Red)

7-update(v, Blue)

8-update(w, Blue)



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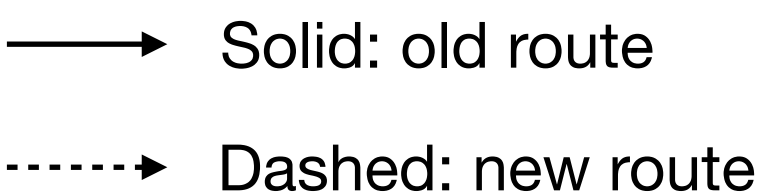


one update per round

1-update(u, Blue)

2-update(S, Blue)

3-update(w, Red)

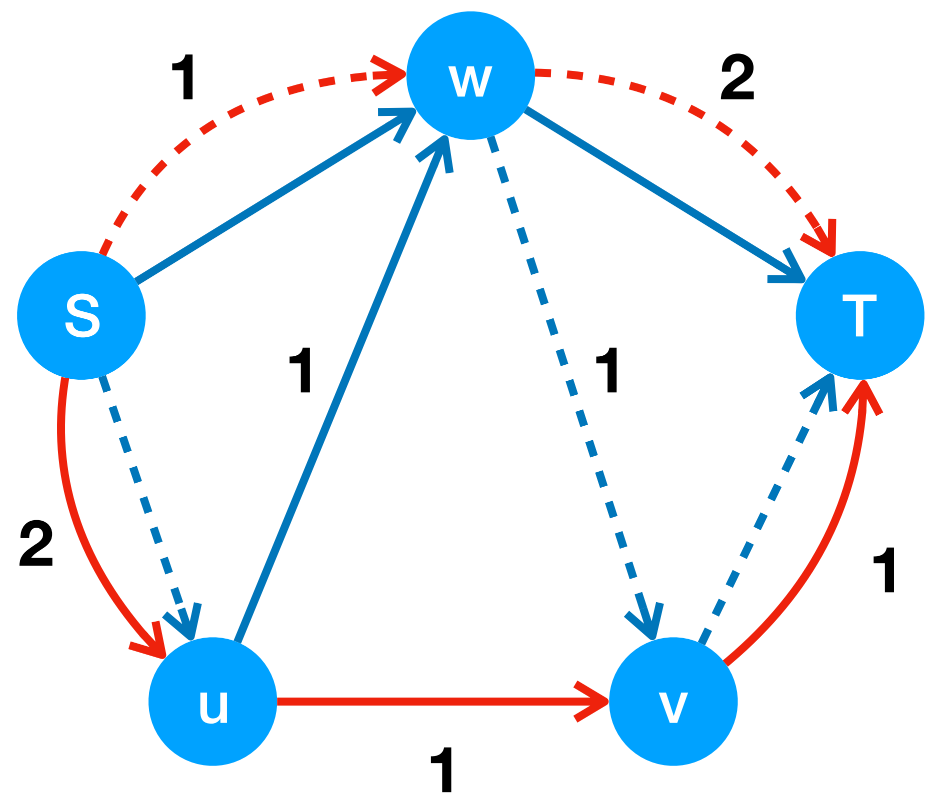
4-update(S, Red)

5-update(u, Red)

6-update(v, Red)

7-update(v, Blue)

8-update(w, Blue)



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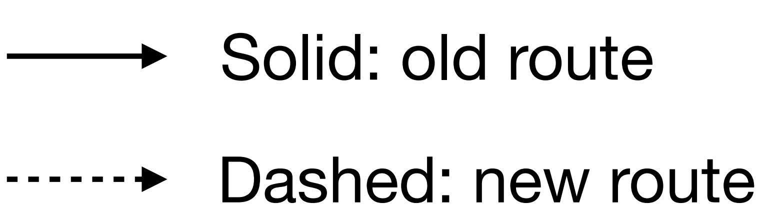


1-update(u, Blue)

2-update(S, Blue)

3-update(w, Red)

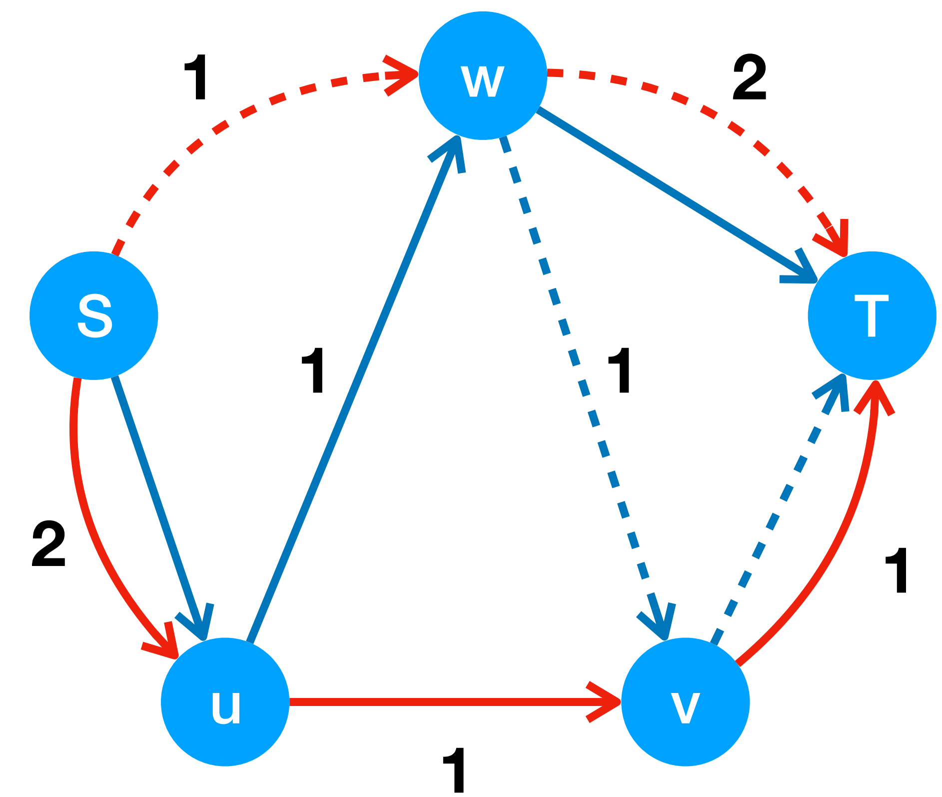
4-update(S, Red)

5-update(u, Red)

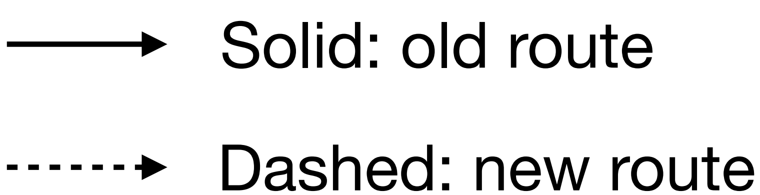
6-update(v, Red)

7-update(v, Blue)

8-update(w, Blue)



Rerouting red and blue flows to their new route, **congestion-free**!



1-update(u, Blue)

2-update(S, Blue)

3-update(w, Red)

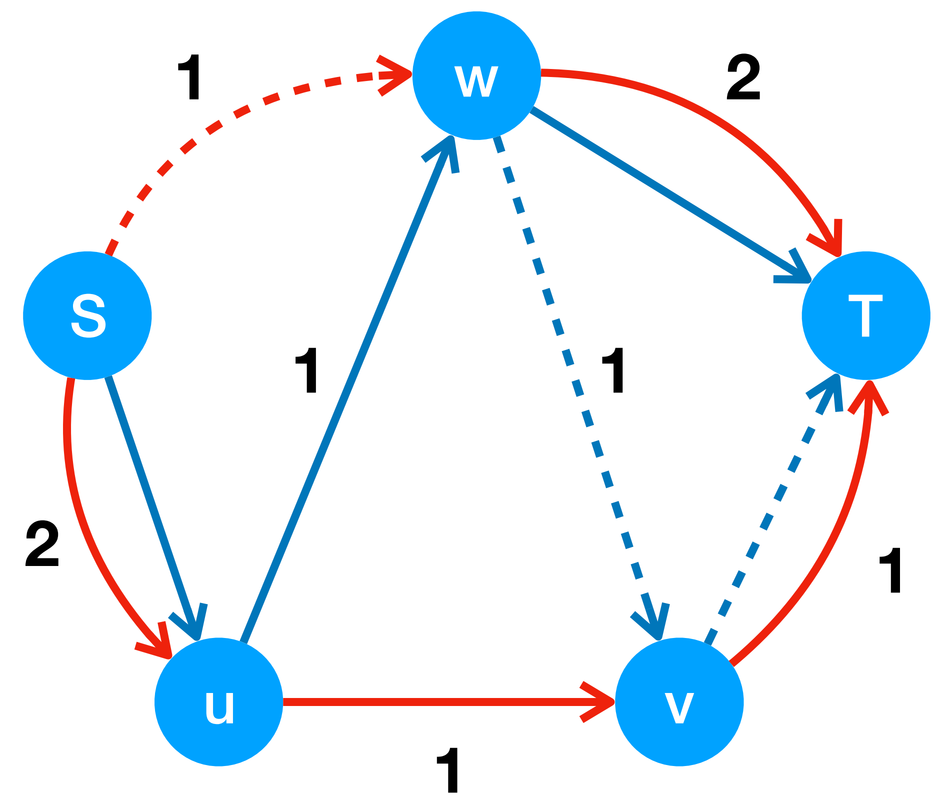
4-update(S, Red)

5-update(u, Red)

6-update(v, Red)

7-update(v, Blue)

8-update(w, Blue)



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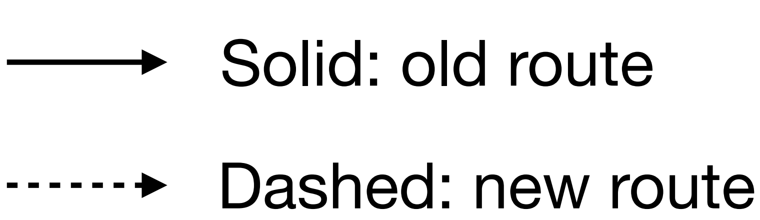


1-update(u, Blue)

2-update(S, Blue)

3-update(w, Red)

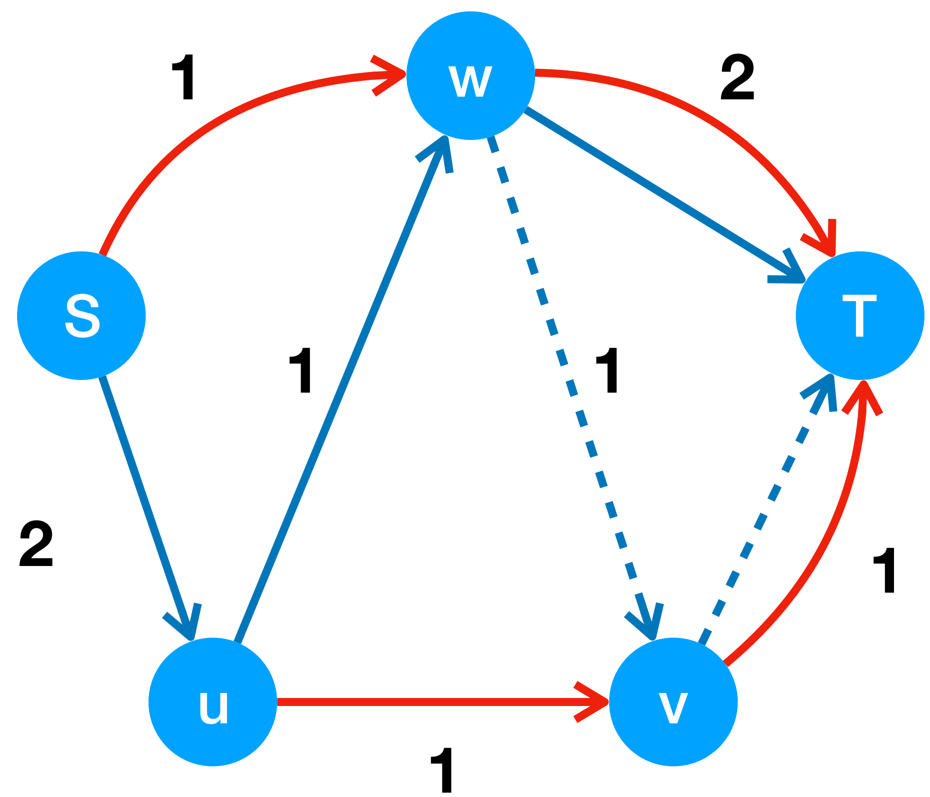
4-update(S, Red)

5-update(u, Red)

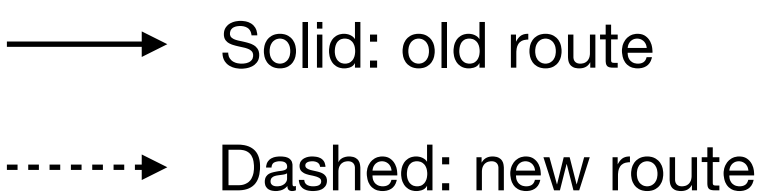
6-update(v, Red)

7-update(v, Blue)

8-update(w, Blue)



Rerouting red and blue flows to their new route, **congestion-free**!



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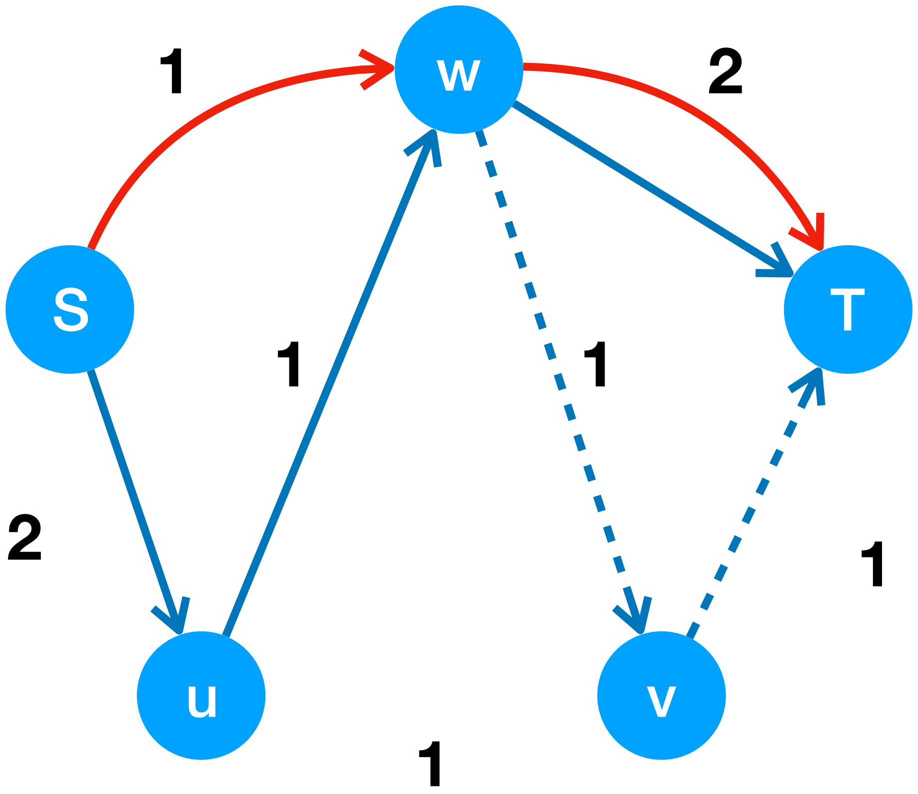

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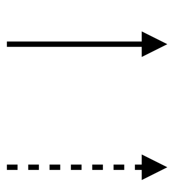

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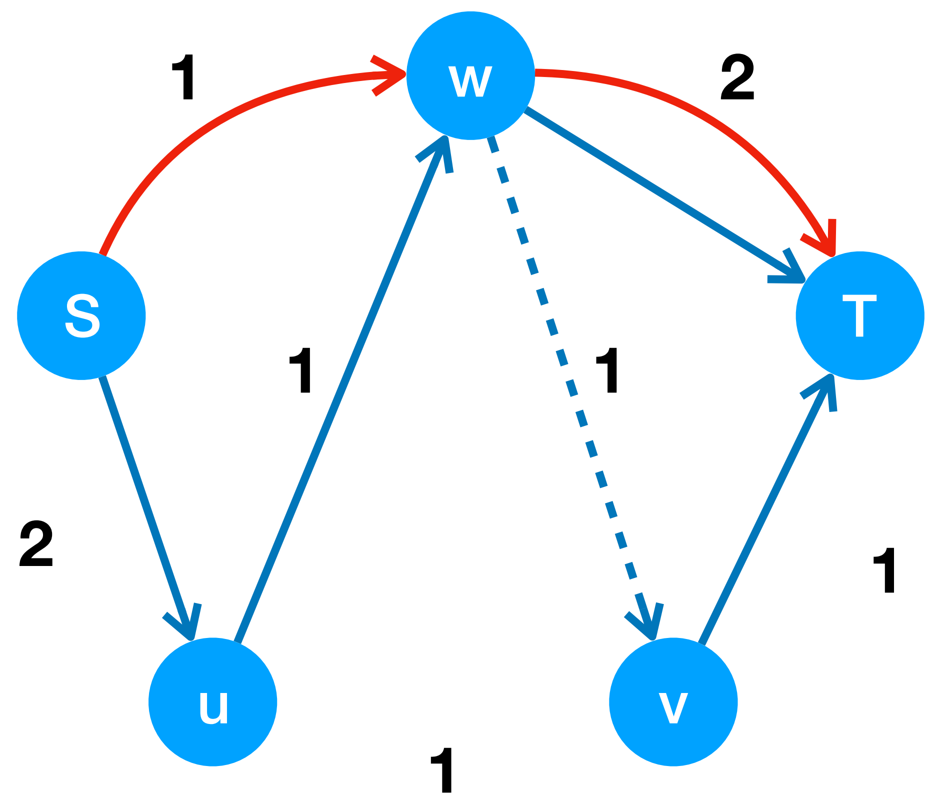

Rerouting red and blue flows to their new route, **congestion-free**!

Solid: old route

Dashed: new route

1-update(u, Blue)

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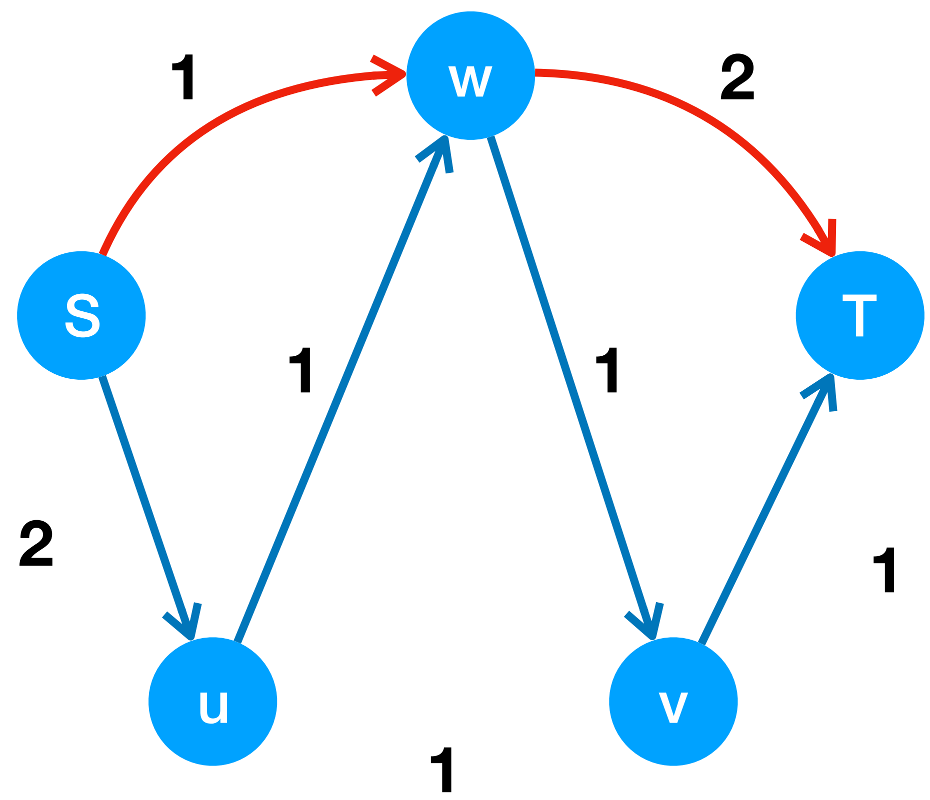
8-update(w, Blue)



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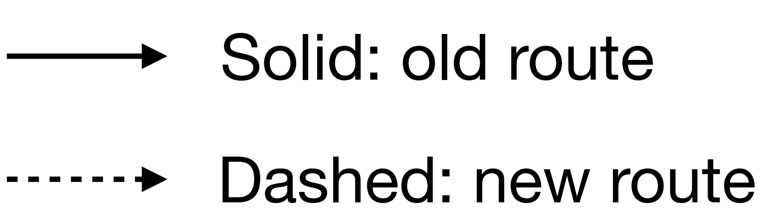


Observations

- 8 updates, 8 rounds in this example
- Multiple updates could be scheduled for a same round
- Updates in a same round finish in arbitrary order ⇒ **transient states**
- All transient states must respect capacity constraints
- The example admits a feasible schedule in only **4** rounds

Feasible Transient States

1-update(u, Blue)

2-update(S, Blue)

2-update(v, Blue)

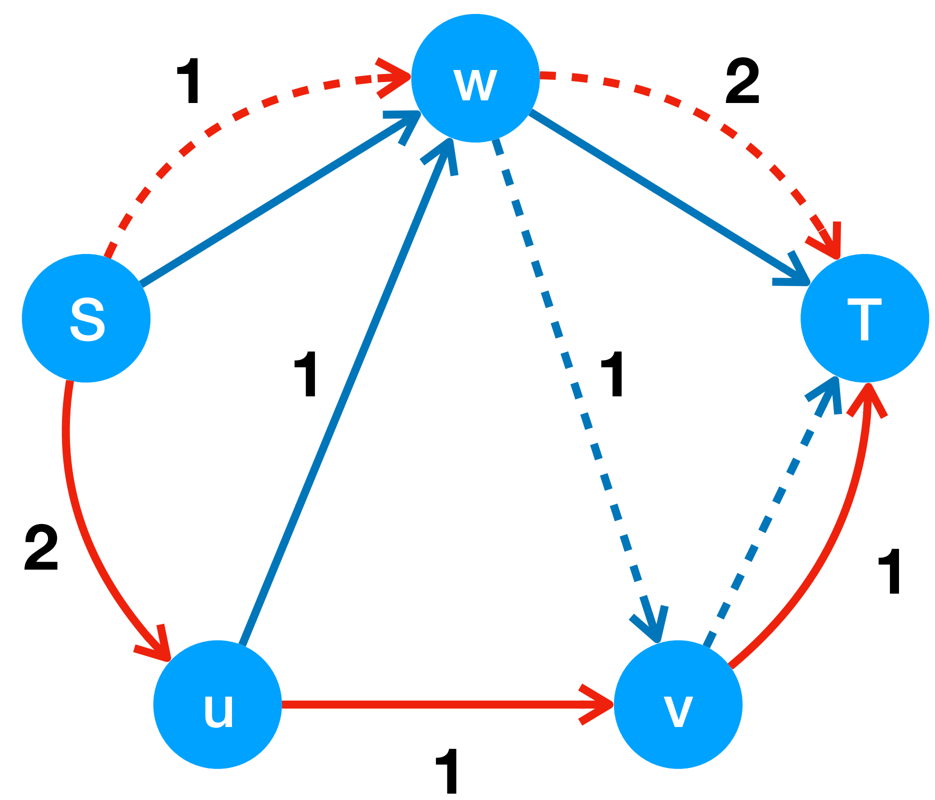
2-update(w, Red)

3-update(S, Red)

4-update(u, Red)

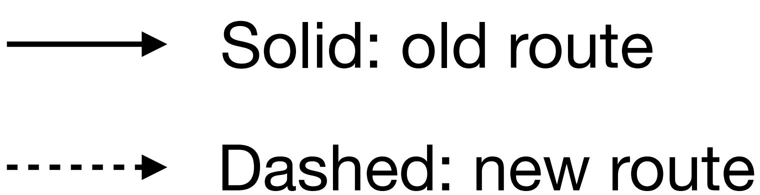
4-update(v, Red)

4-update(w, Blue)



2^3=8 possible transient states for round 2

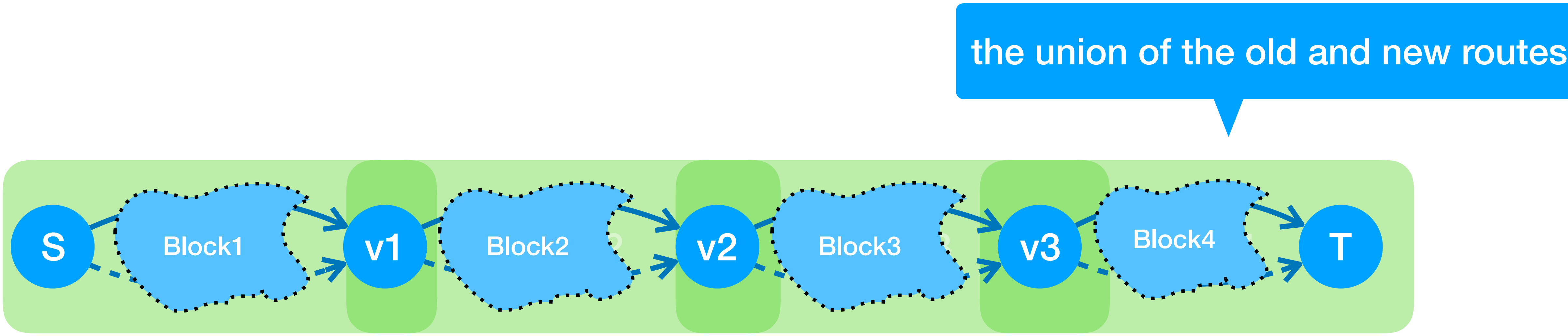
Rerouting red and blue flows to their new route, **congestion-free**!



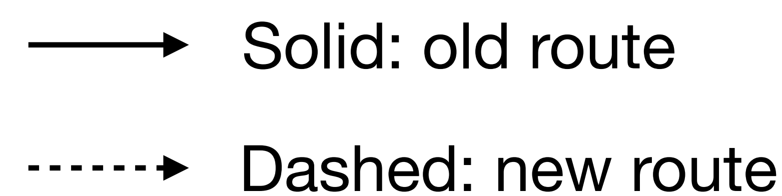
Problem Definition

- **Input**: two flow pairs *(old,new),* unit demands, unsplittable.
- **Task**: reroute each flow, from its **old** route to its **new** route, **consistently**.
- Consistent: Loop-free + Congestion-free.
- For every pair, *(old* ∪ *new)* is a **DAG** ⇒ Loop-freedom for free!
- **Feasibility**: is there a sequence of congestion-free updates?
- **Optimality**: how to minimize the number of rounds efficiently?

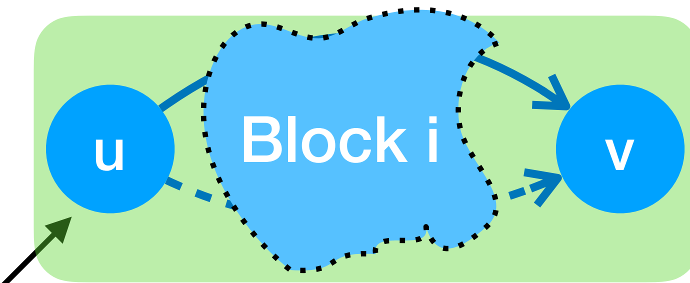
Block Decomposition



1) Take the union of old and new routes => a DAG
2) Obtain its nodes in a topologically sorted oder
3) Intersections consecutive in that order are **block**'s endpoints



Block Update



start of block

block update in 3 rounds

(1) activate all new route links not incident to **u**

(2) *update(**u**, **blue**)*

(3) deactivate links on the old route

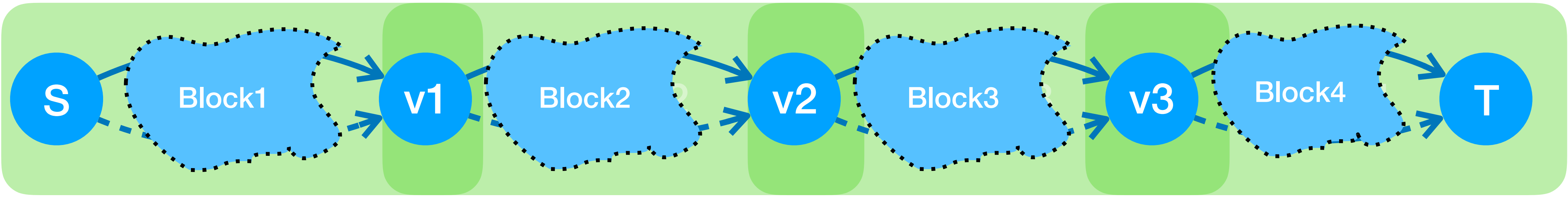
Lemma 2. *Given any feasible (not necessarily shortest) update sequence $\mathfrak{R}$, there is a feasible update sequence $\mathfrak{R}'$ which updates every block in at most 3 consecutive rounds.*

Solid: old route

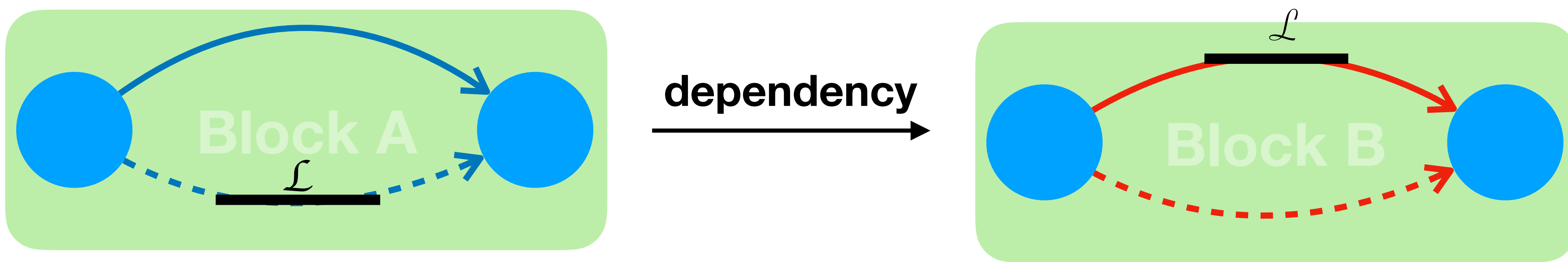
Dashed: new route

Towards an Efficient Algorithm

- Update the whole flow route block by block
- A block takes up to **3** rounds to update
- Blocks of the same flow can be updated independently
- Blocks of different flows may have dependencies



Towards an Efficient Algorithm for 2 Flows



- Link $\mathcal{L}$ has capacity 1
- Blue cannot reroute before Red reroutes away from $\mathcal{L}$
- Block A **depends** on Block B
- Any feasible schedule updates B before A

Lemma 3. *If there is a cycle in the dependency graph, then there is no feasible update sequence.*

Solid: old route

Dashed: new route

Overview of the Algorithm

1) Compute the block composition for the two flows.
2) Compute the dependency graph D of G.
3) If there is a cycle in D then terminate.
4) While D is not empty, repeat:
    1) Update all blocks that correspond to the **sink** vertices of D.
    2) Remove all the sink vertices from D.

of rounds

- All sink blocks are updated together, in 3 rounds.
- 3 rounds per iteration is not always necessary.
- Allocating the necessary rounds yields the optimal schedule

Theorem 1. *An optimal (feasible) update sequence on acyclic update flow networks with exactly 2 update flow pairs can be found in linear time.*

Hardness

Theorem 2. *Deciding whether a feasible network update schedule exists for a given update flow network in which each flow pair forms a DAG is* NP*-hard for six flows.*

The complexity for 3 to 5 flows remains open.

Summary

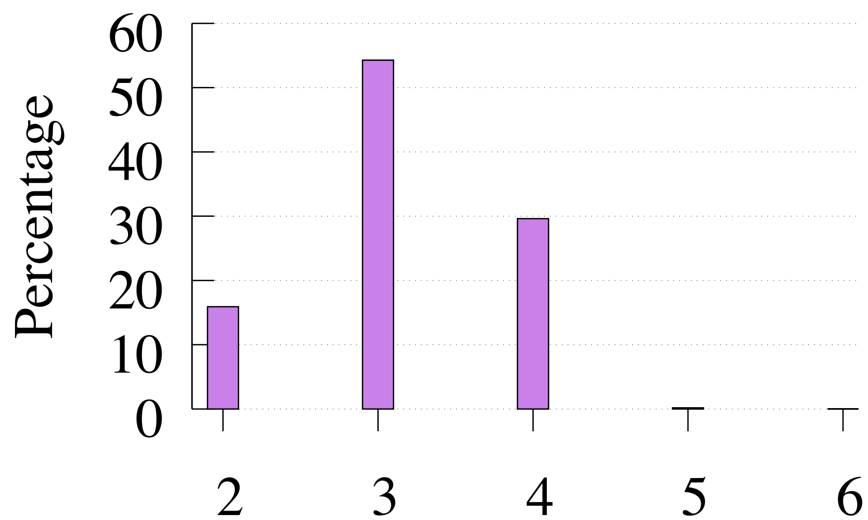
- NP-hard from 6 flows
- special case: 2 flows, every route pair forms a **DAG**
- optimal schedule for **2 flows**, given **acyclic** pairs
- congestion-free schedule for $3 \leq k \leq 5$ flows? **open**

Summary

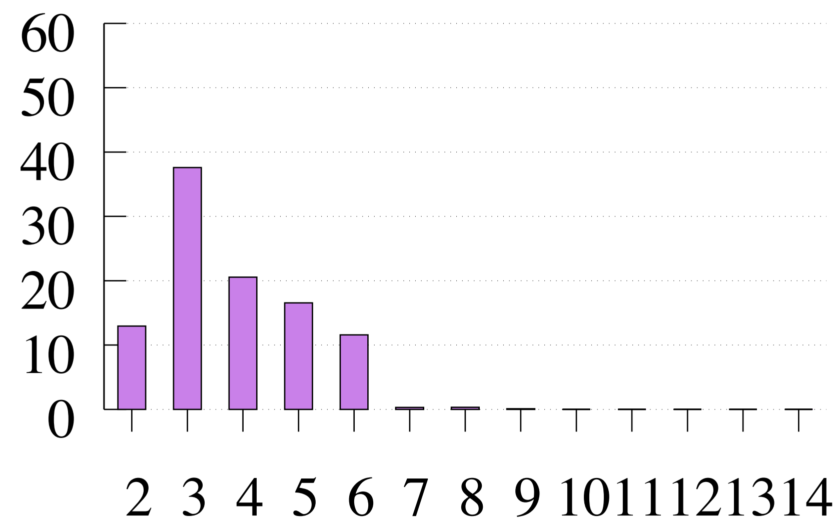
- NP-hard from 6 flows
- special case: 2 flows, every route pair forms a **DAG**
- optimal schedule for **2 flows**, given **acyclic** pairs
- congestion-free schedule for $3 \leq k \leq 5$ flows? **open**

Thank you!

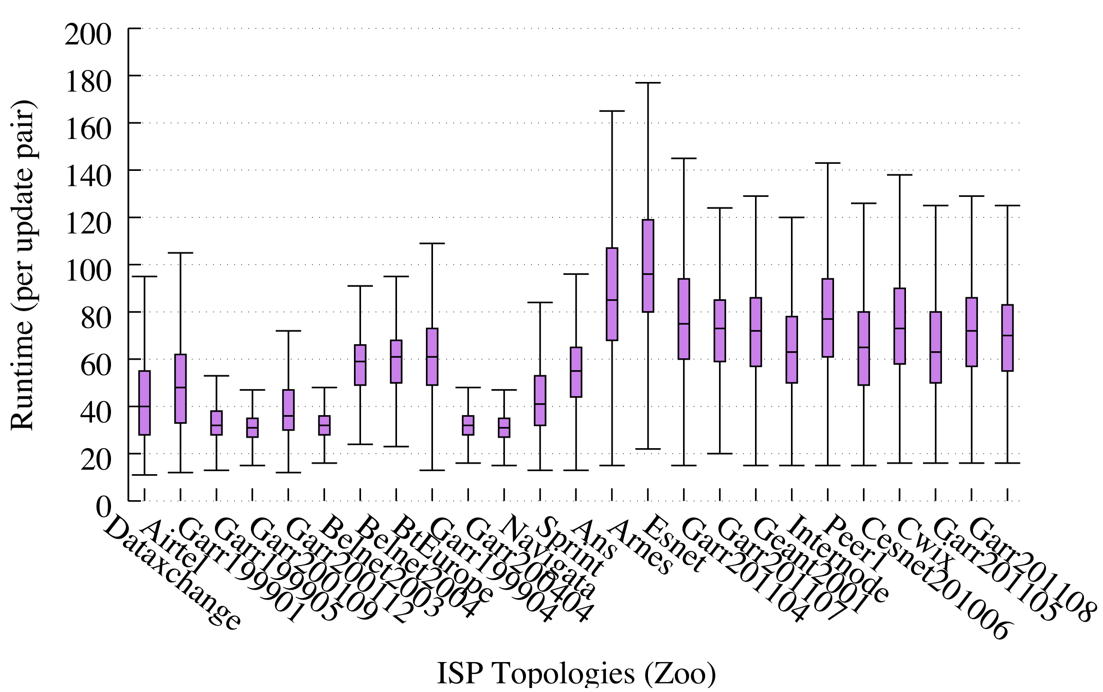
Backup slides



The frequency of each possible number of rounds (in %) in optimal schedules from Algorithm 2

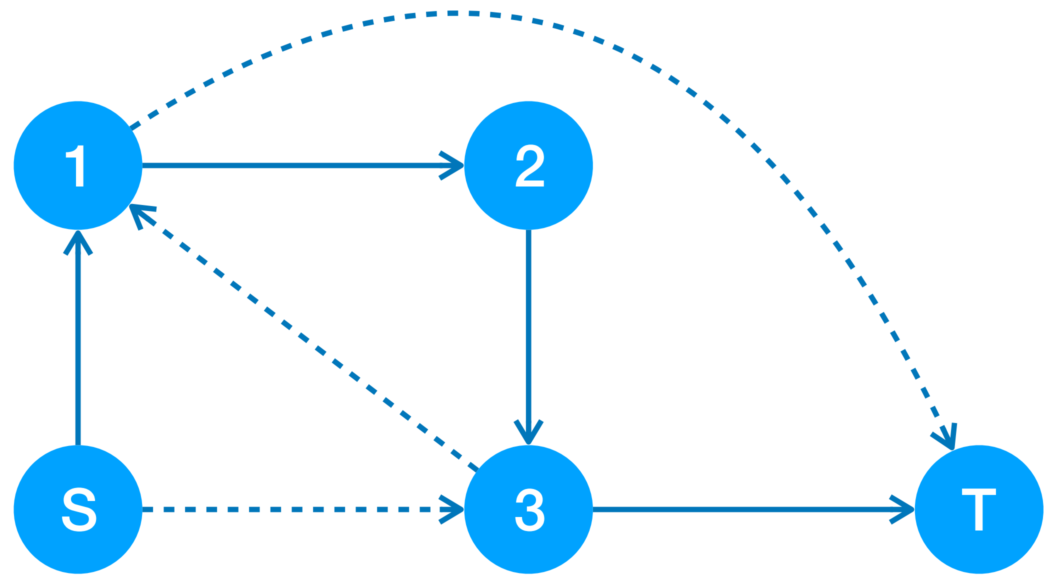


arbitrary feasible schedules from Algorithm 1



Distribution of runtime (in microsecond) over all the problem instances from some of the evaluated graphs

Loop-free Rerouting



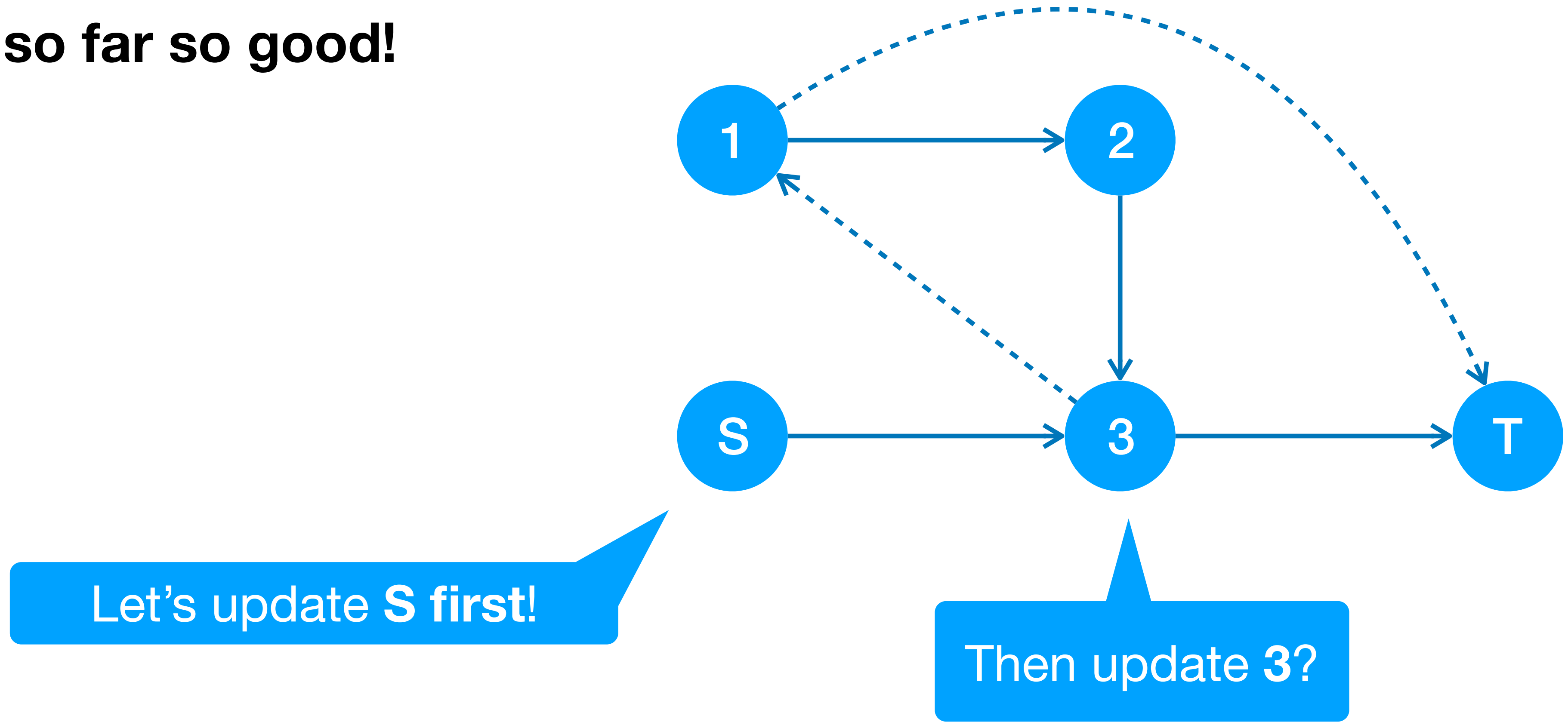
Let’s update **S first**!

Solid: old route

Dashed: new route

Loop-free Rerouting

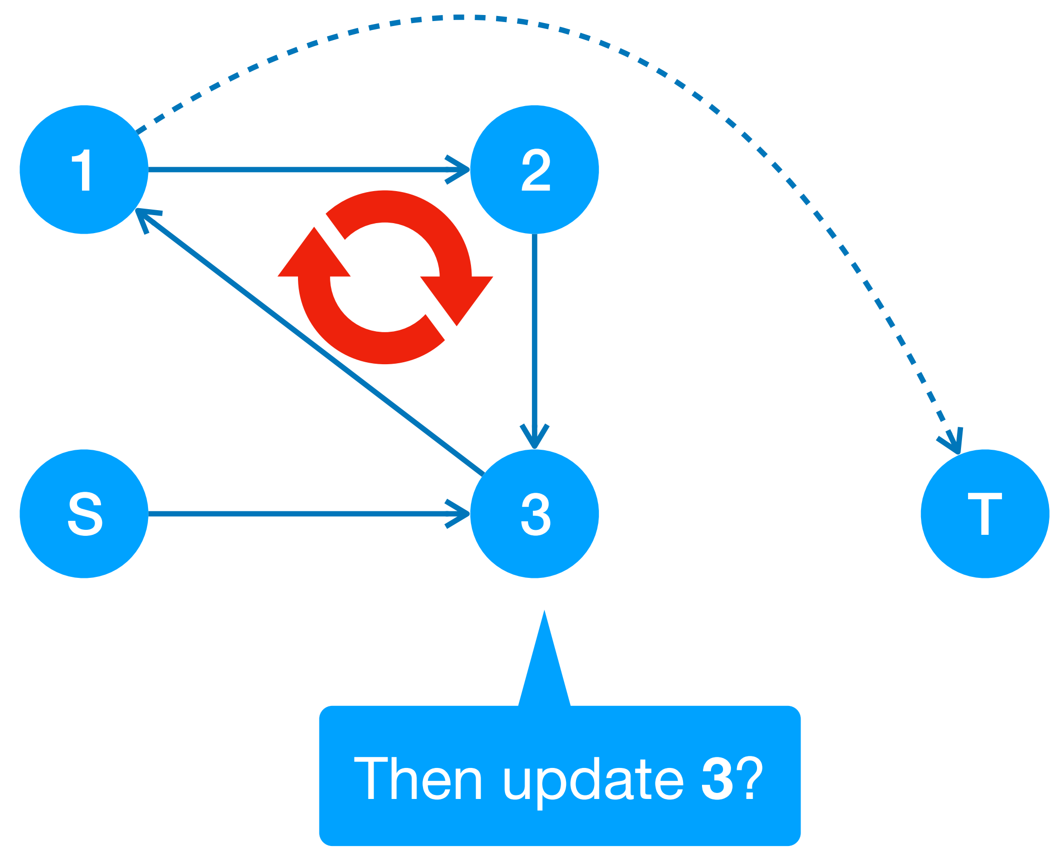
so far so good!



Solid: old route

Dashed: new route

Loop-free Rerouting

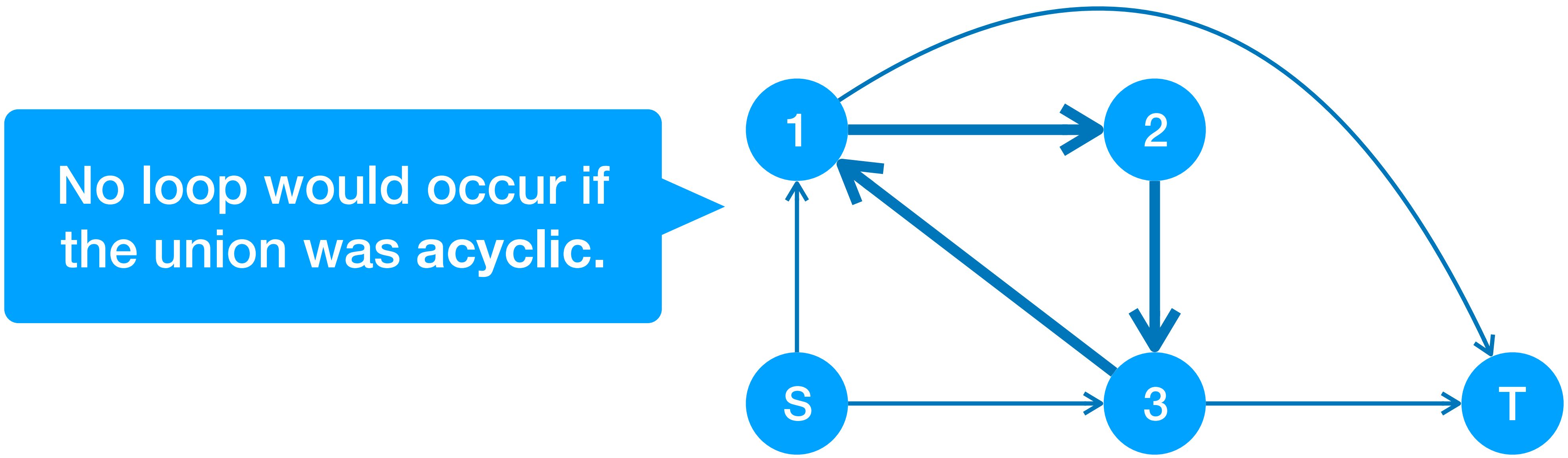


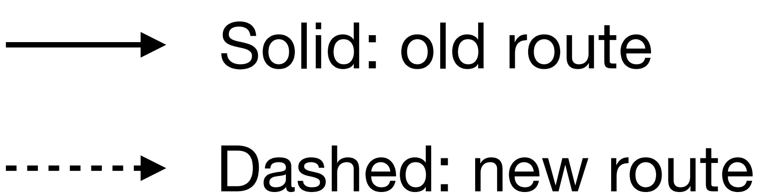
Not consistent!

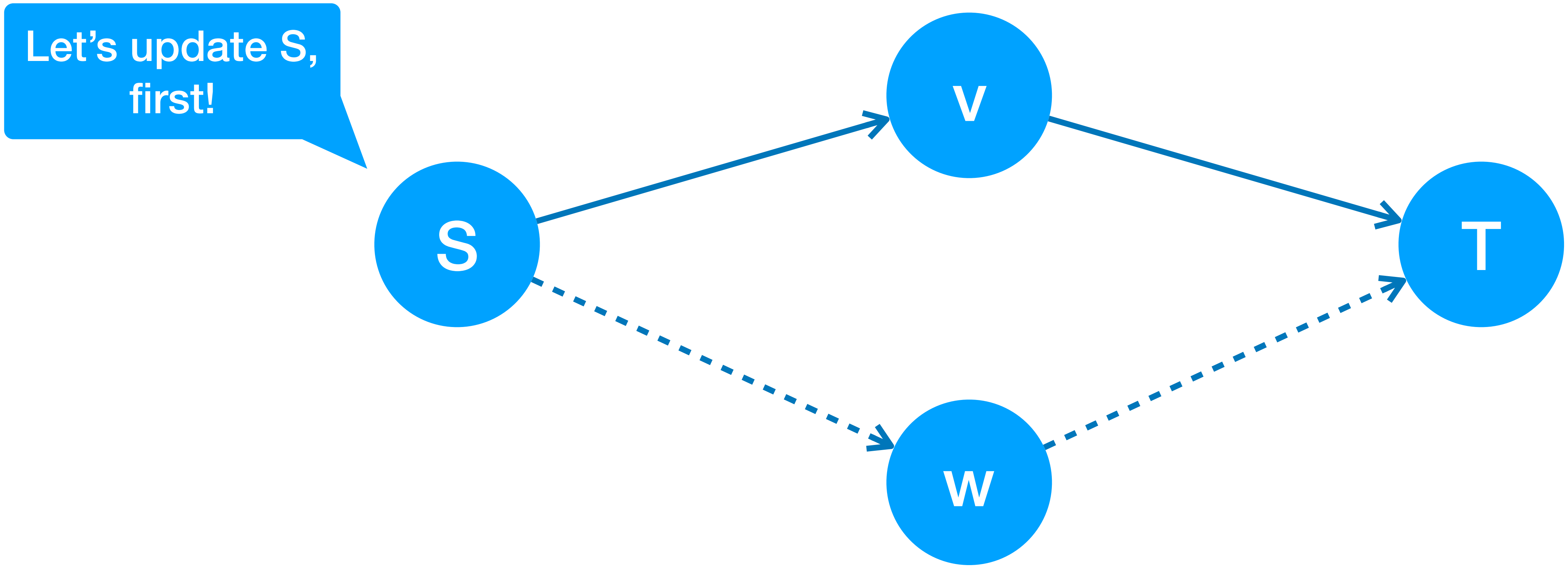
Solid: old route

Dashed: new route

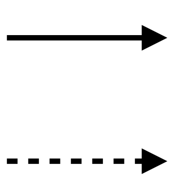
Loop-free Rerouting

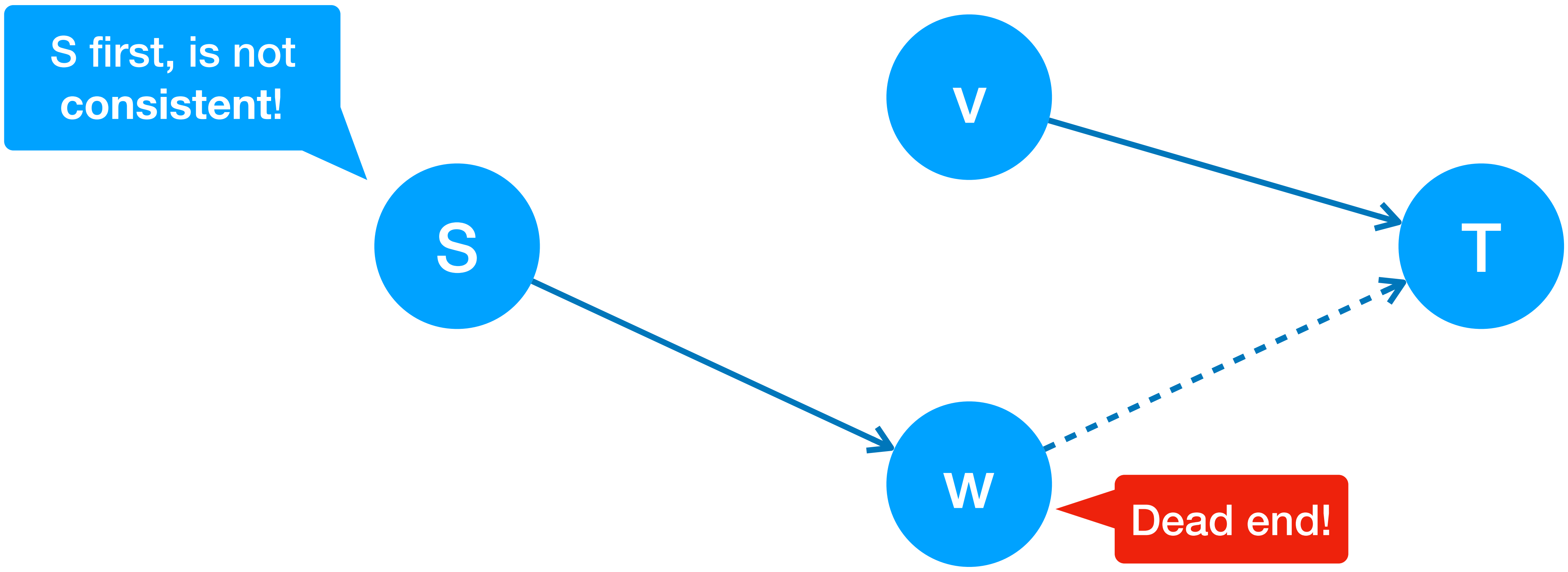






rerouting the old route to the new route





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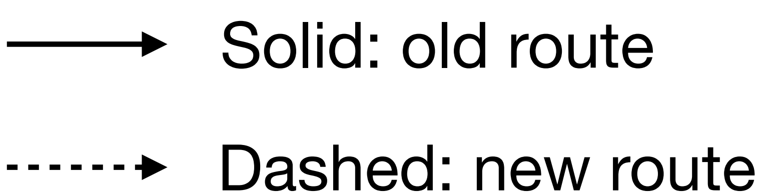

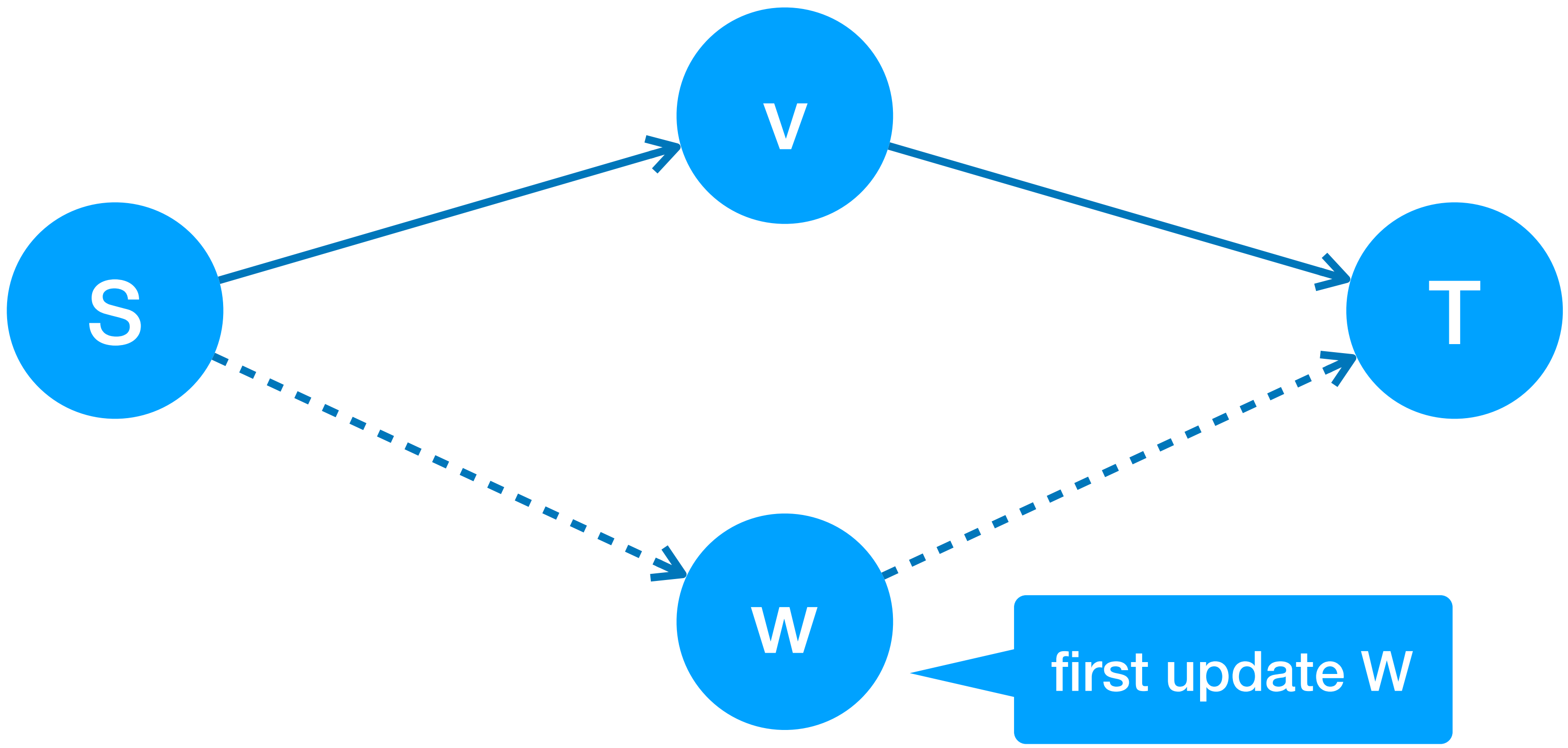

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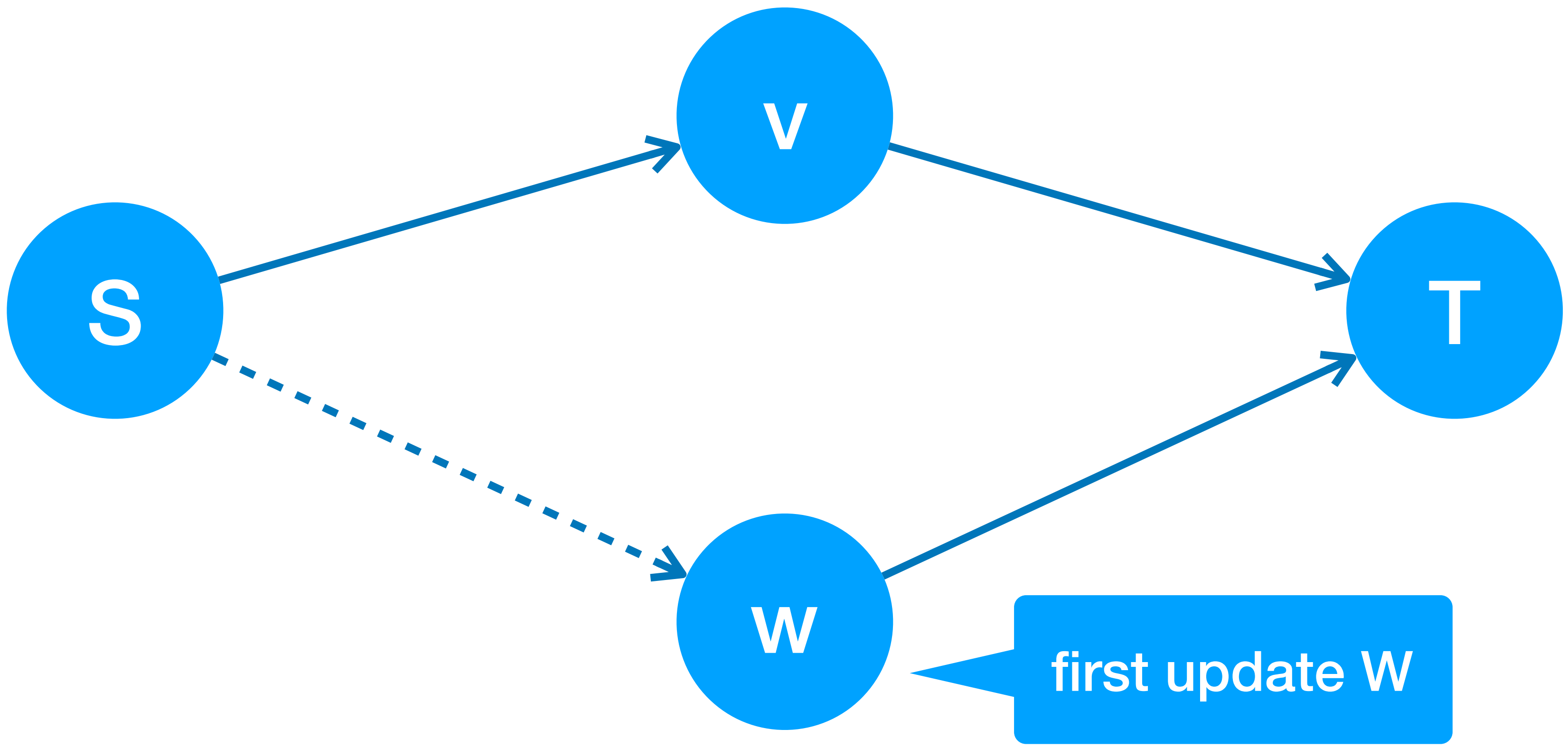

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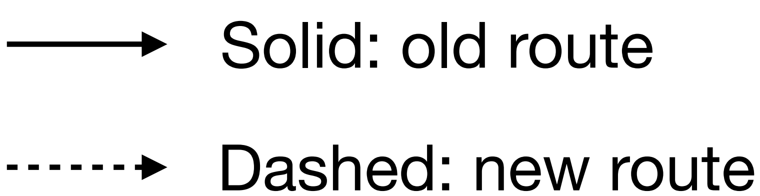

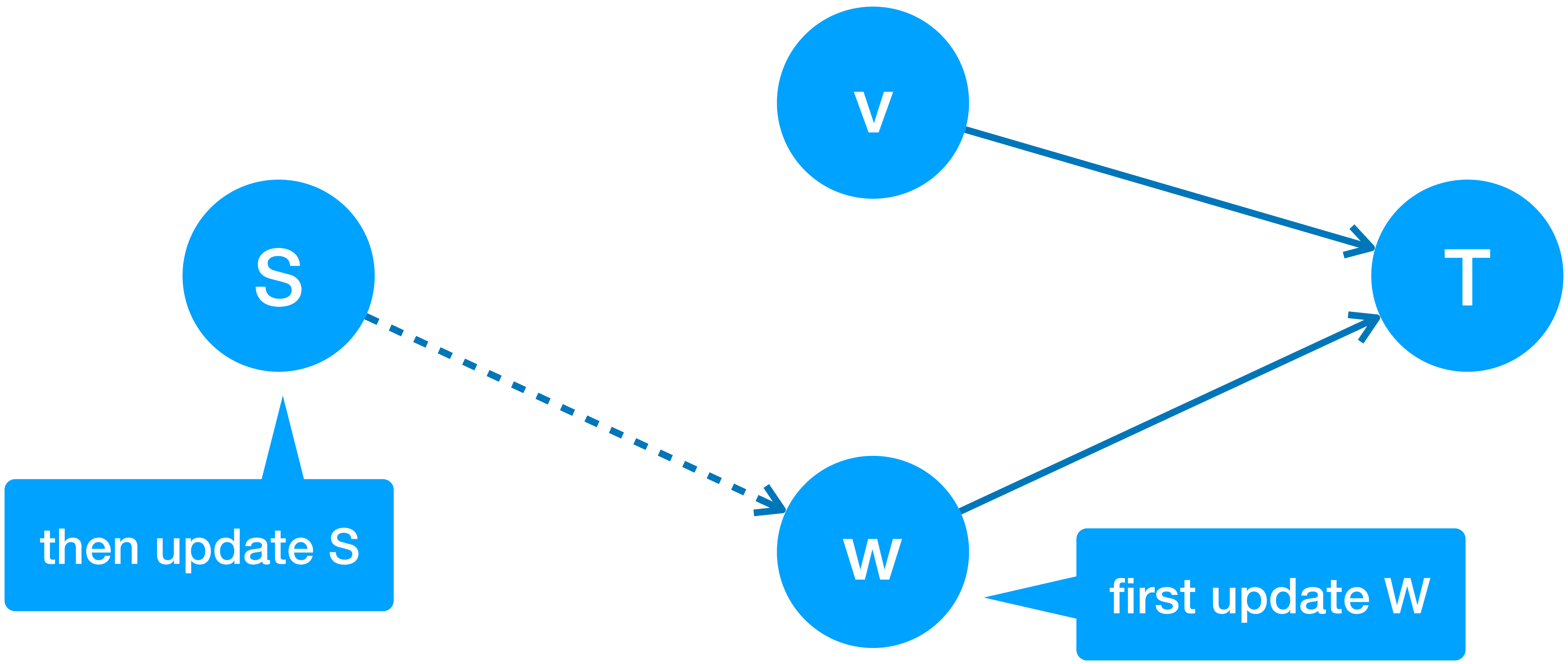

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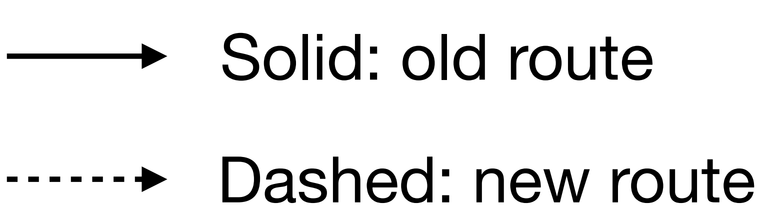

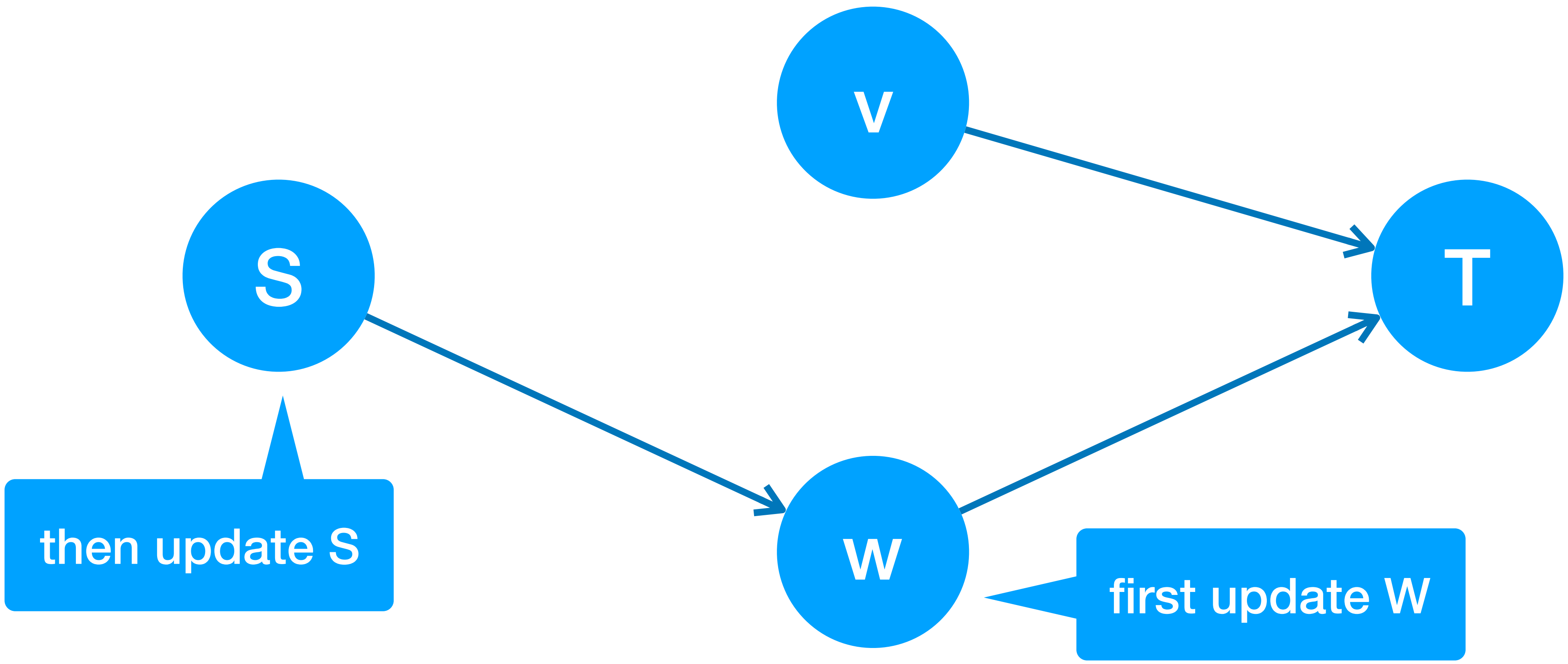

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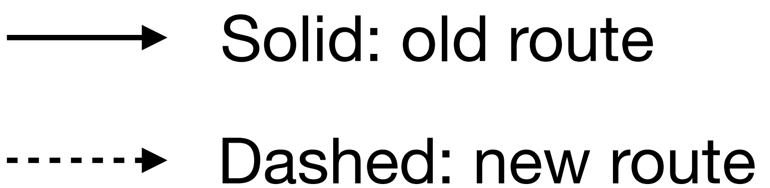

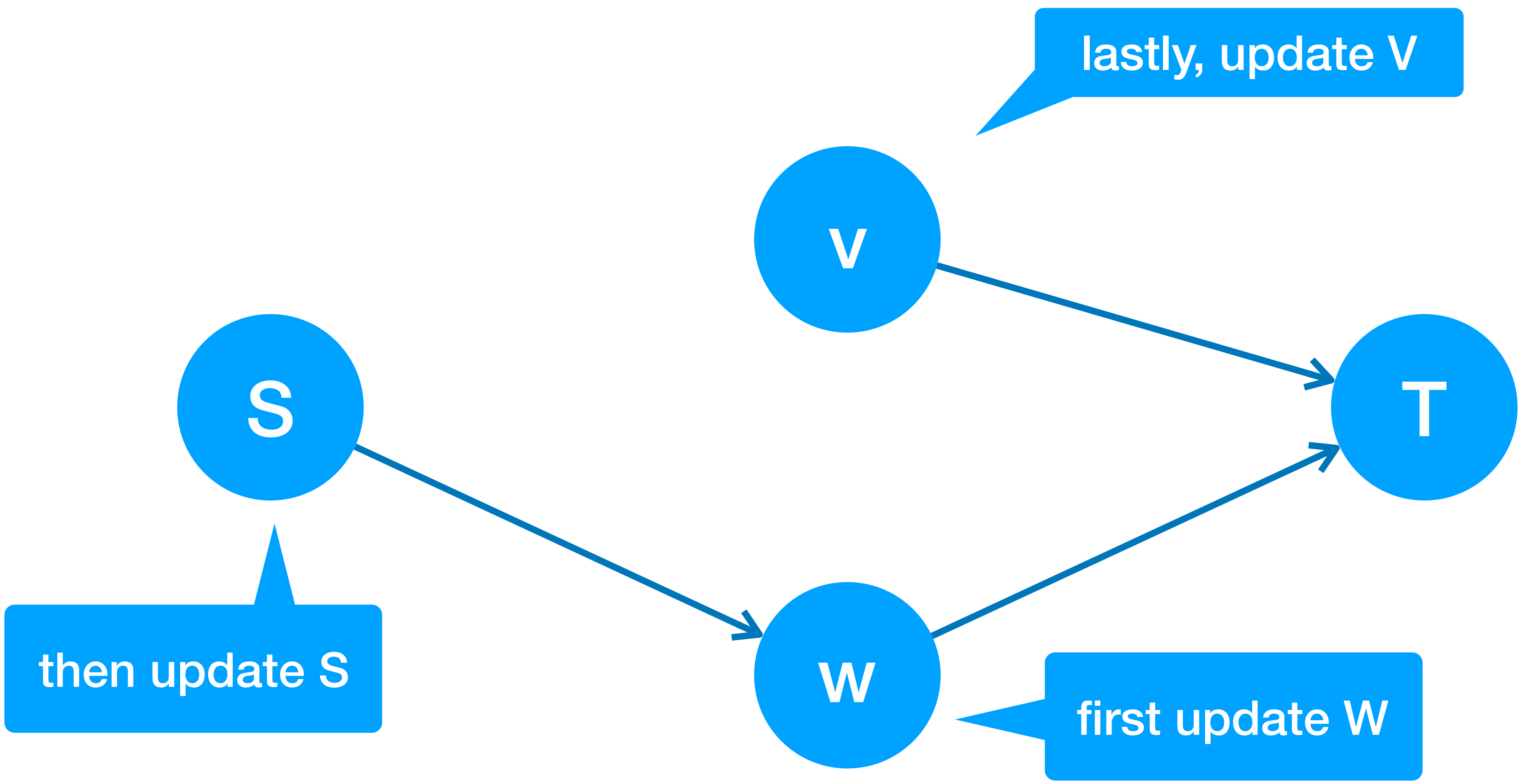

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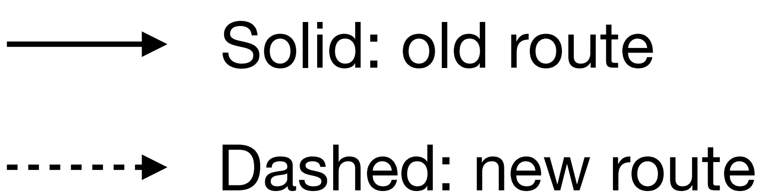

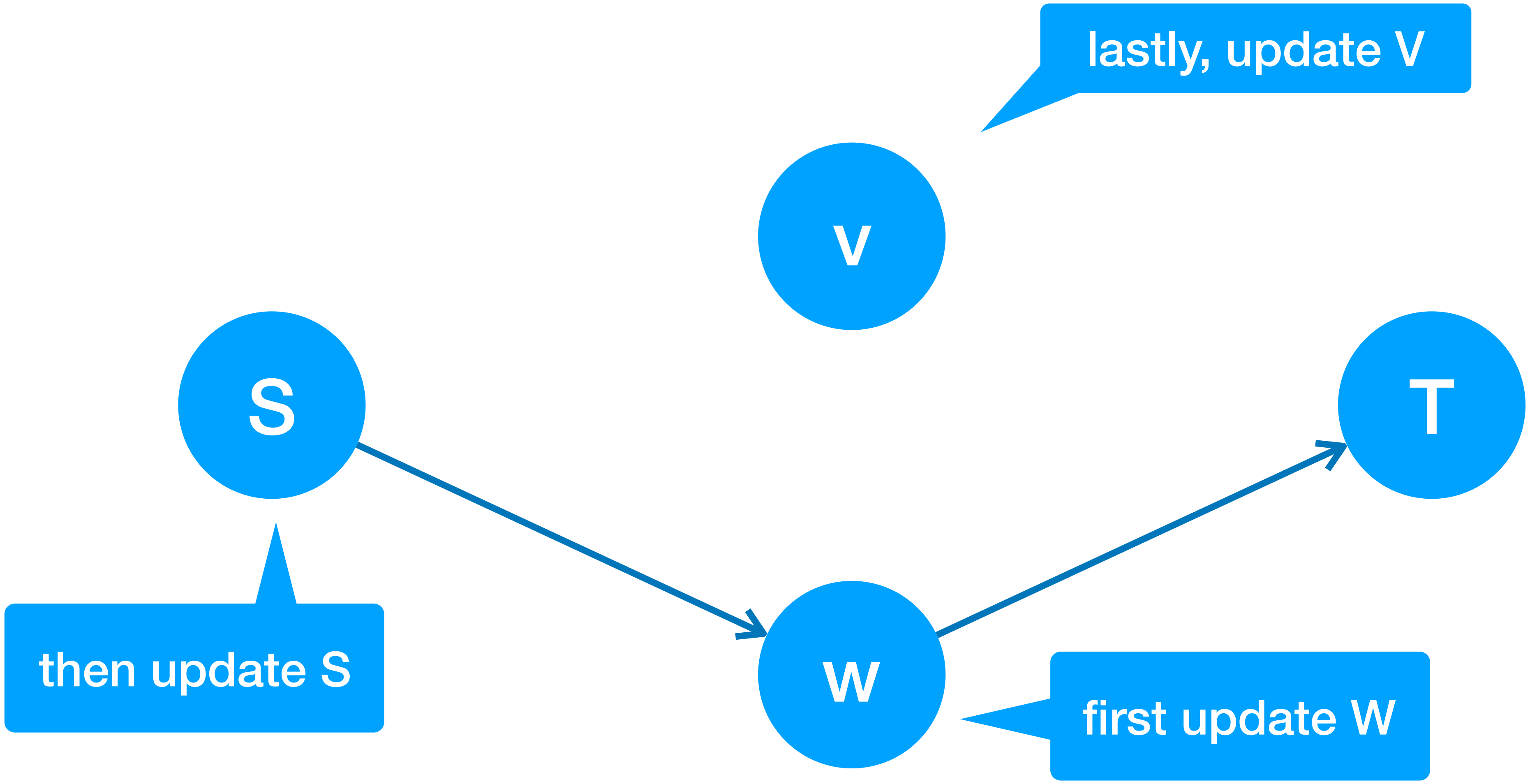

rerouting the old route to the new route

Solid: old route

Dashed: new route