Weighted NetKAT

A Programming Language for Quantitative Network Verification

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Tiago Ferreira
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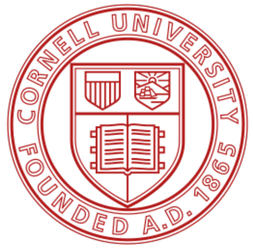
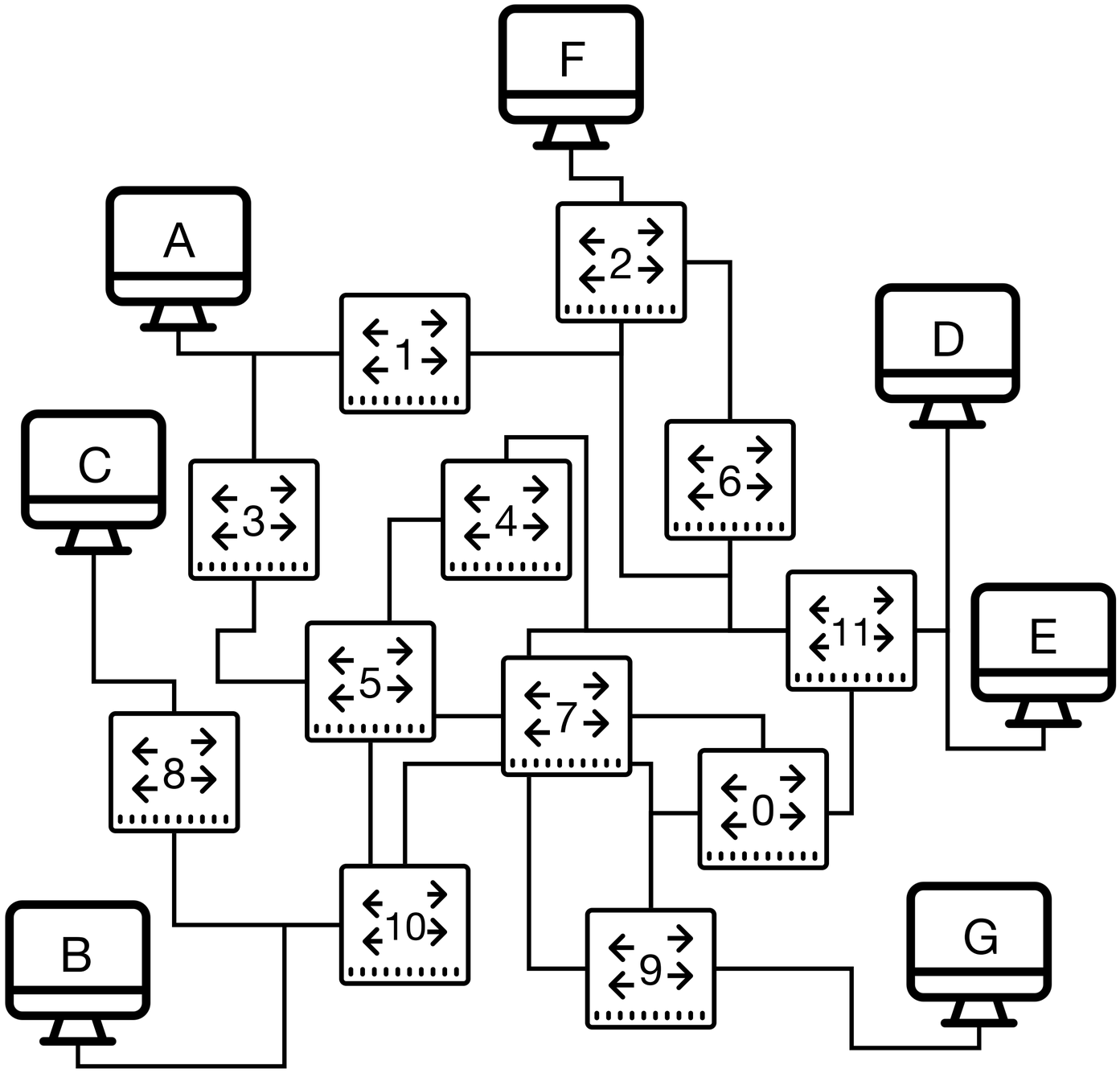
Oliver Bøving
Nate Foster
Alexandra Silva

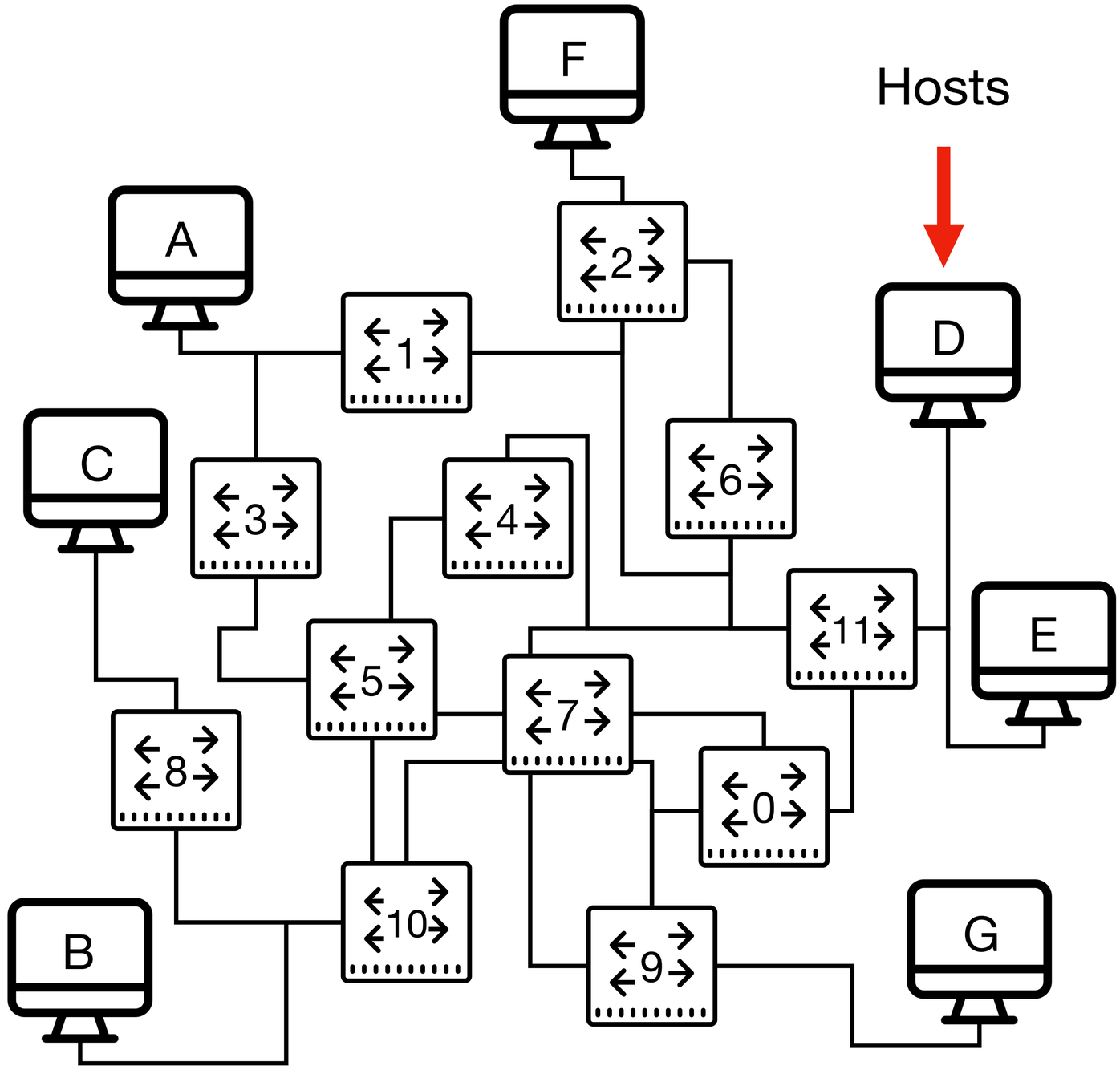


PLDI 2026

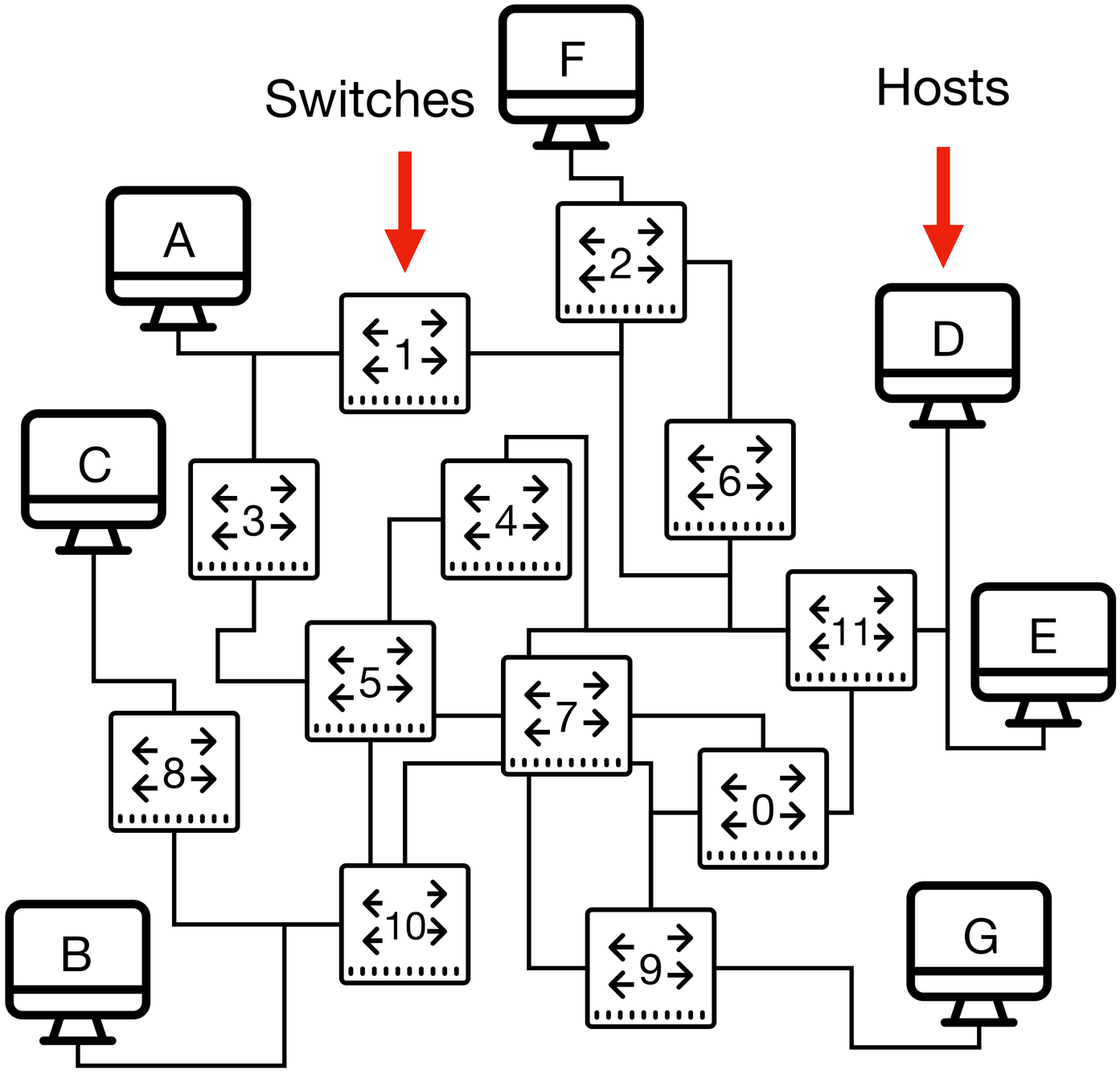
Network Verification



Network Verification



Network Verification



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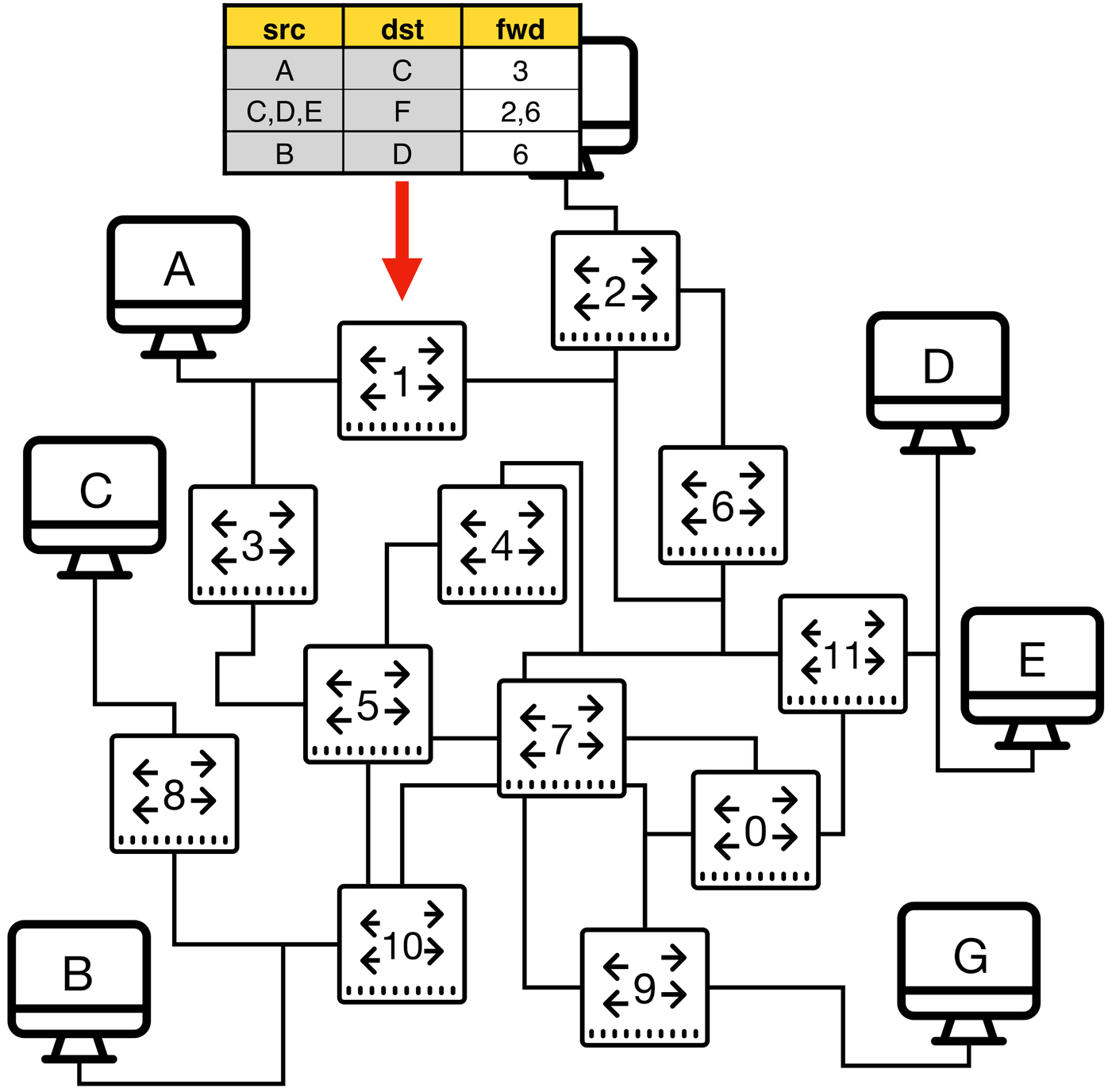
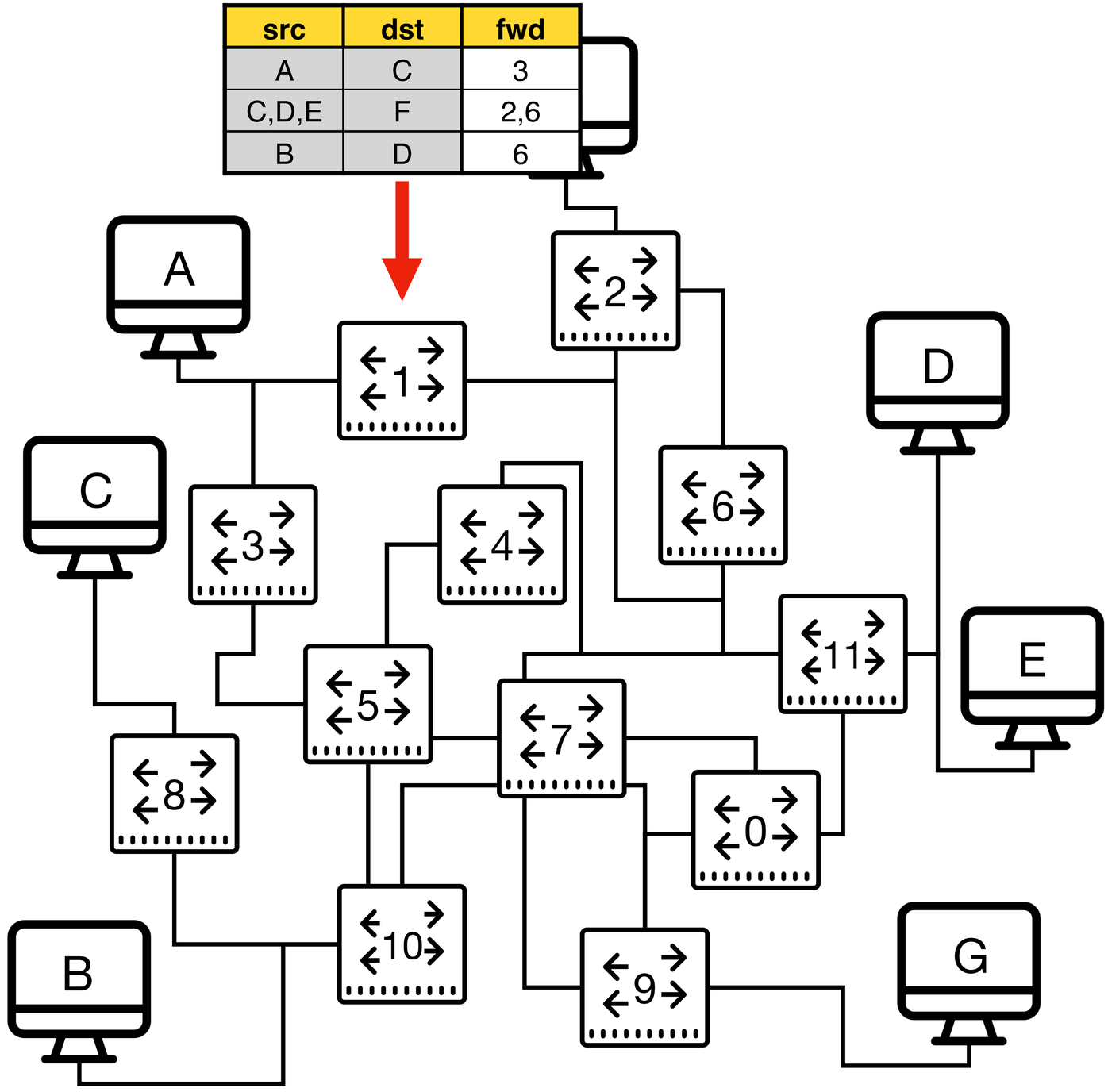


Network Verification

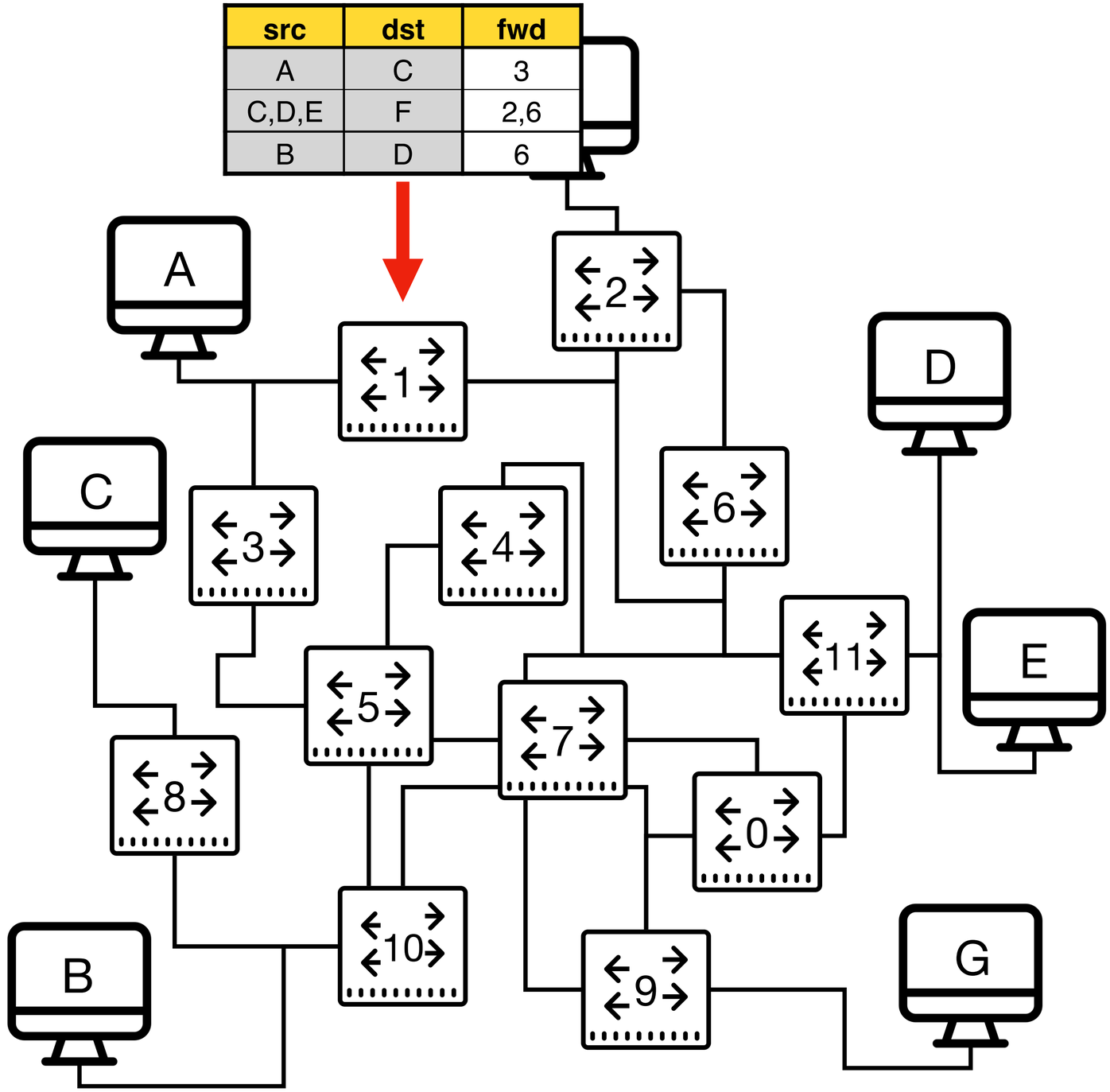
Automatically verify:



Network Verification

Automatically verify:

Can all hosts deliver packets to one another?



Quantitative Network Verification

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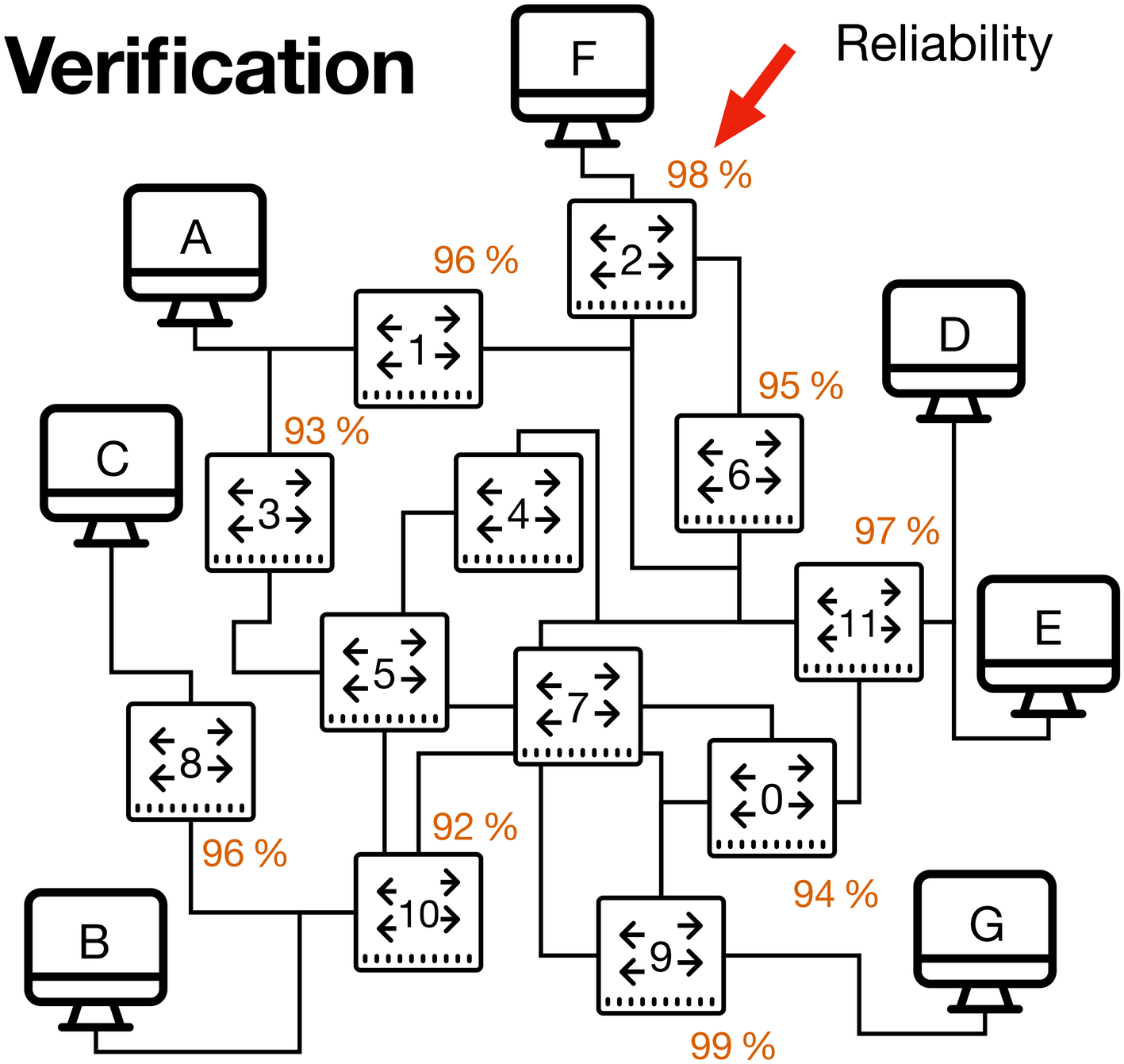
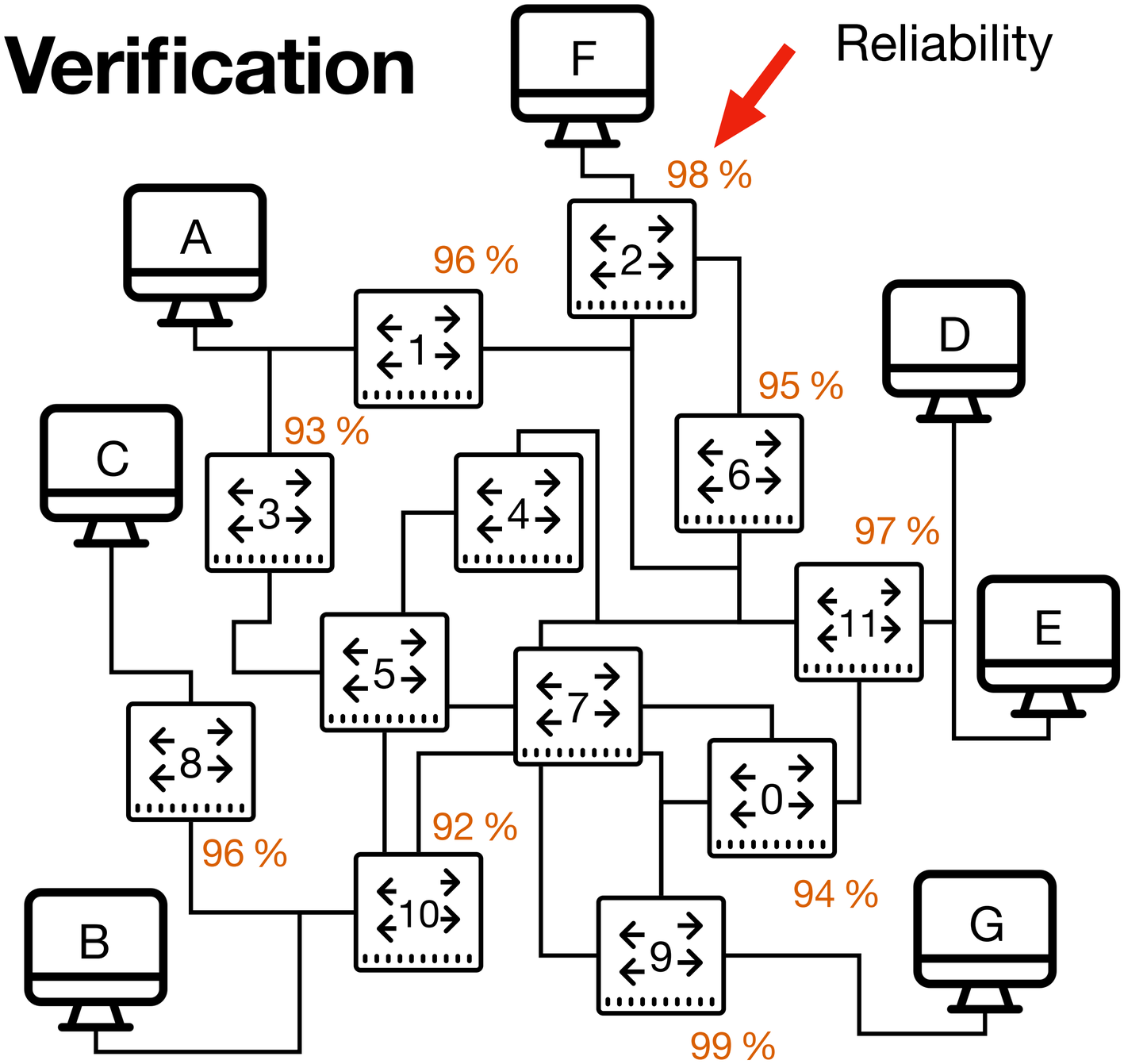


Quantitative Network Verification

Automatically verify:

Can all hosts deliver packets to one another?

Does all traffic get delivered with at least 90% reliability?



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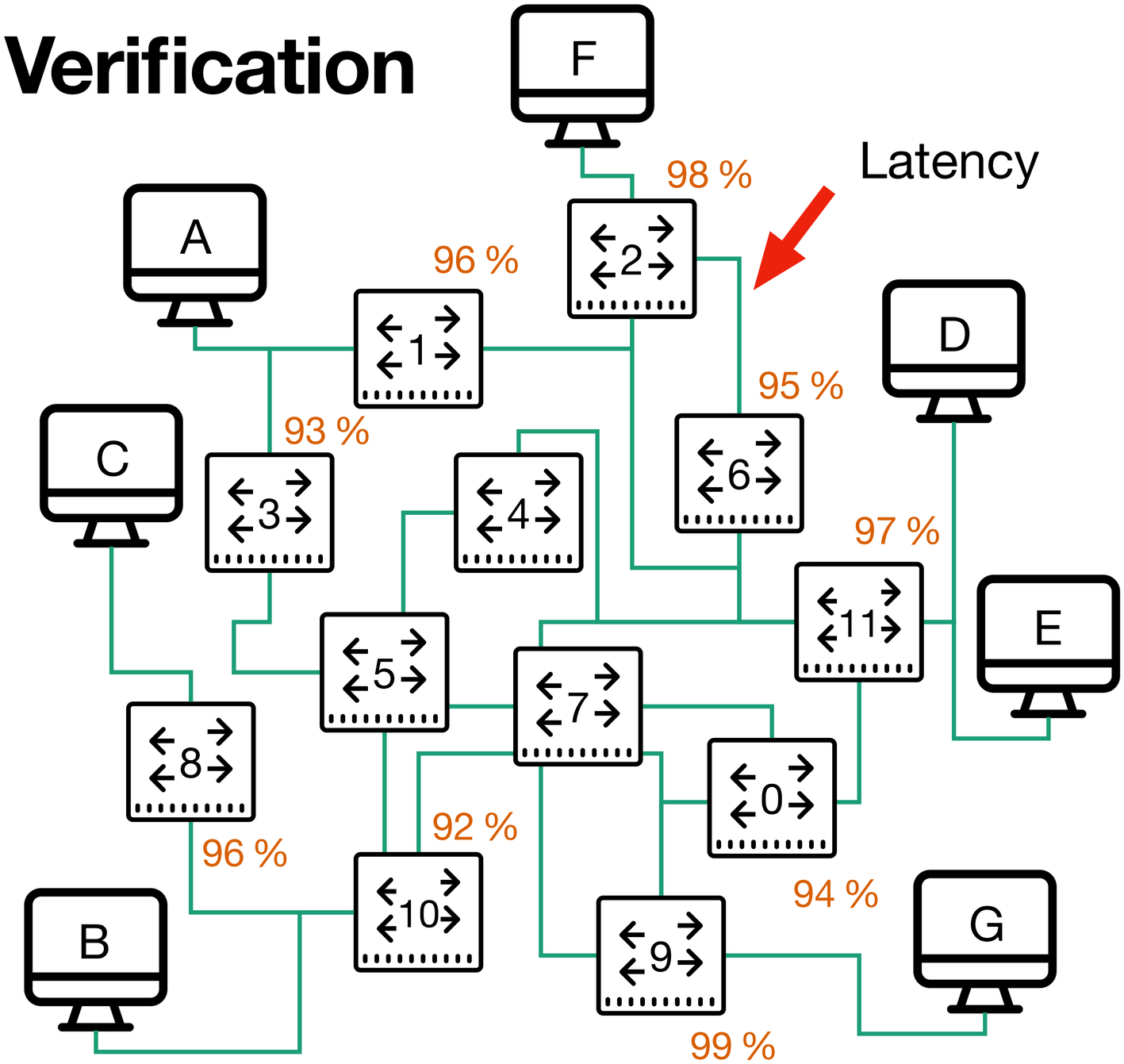


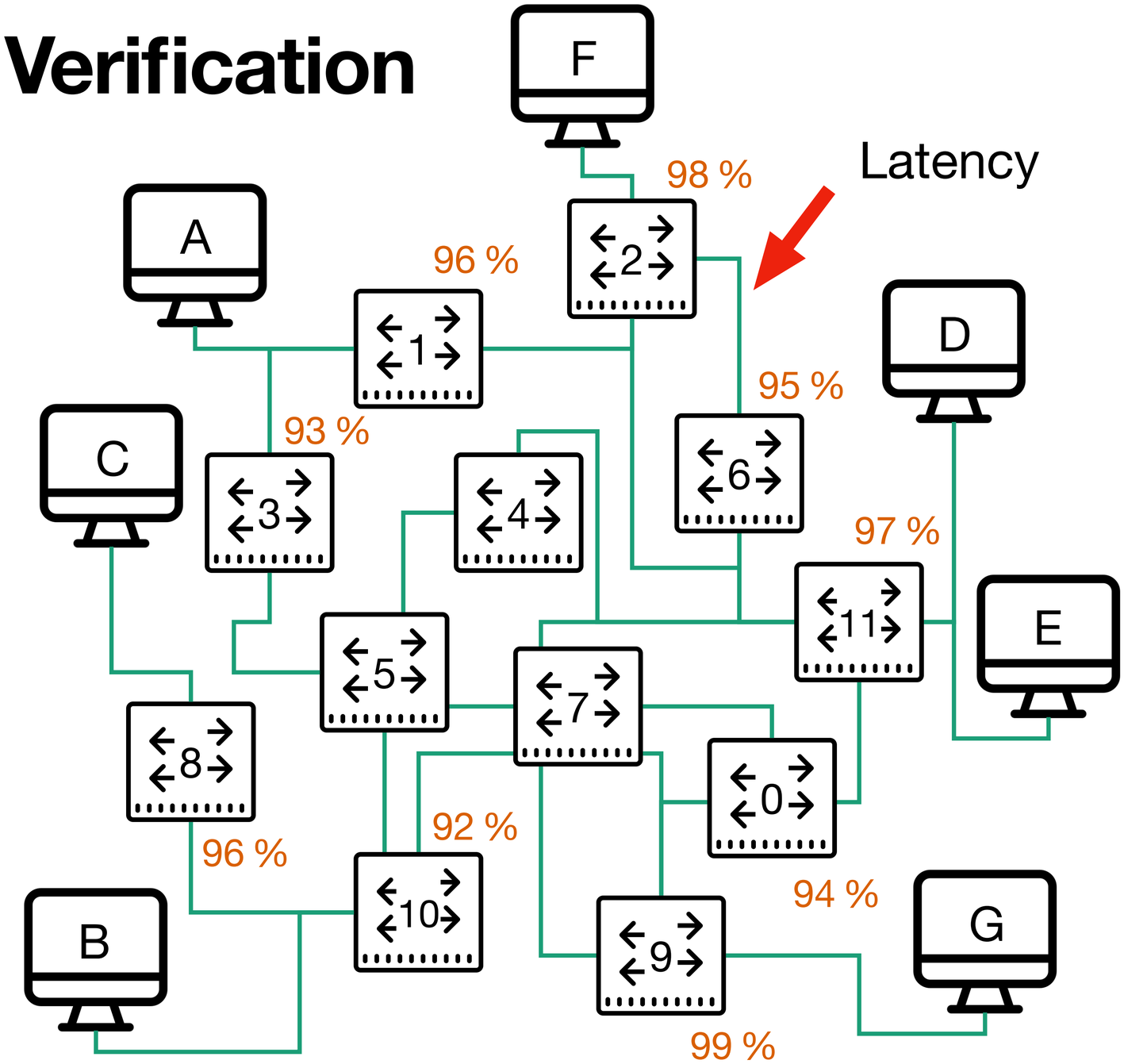
Quantitative Network Verification

Automatically verify:

Can all hosts deliver packets to one another?

Does all traffic get delivered with at least 90% reliability?

Can host A deliver packets to host B within 5ms?



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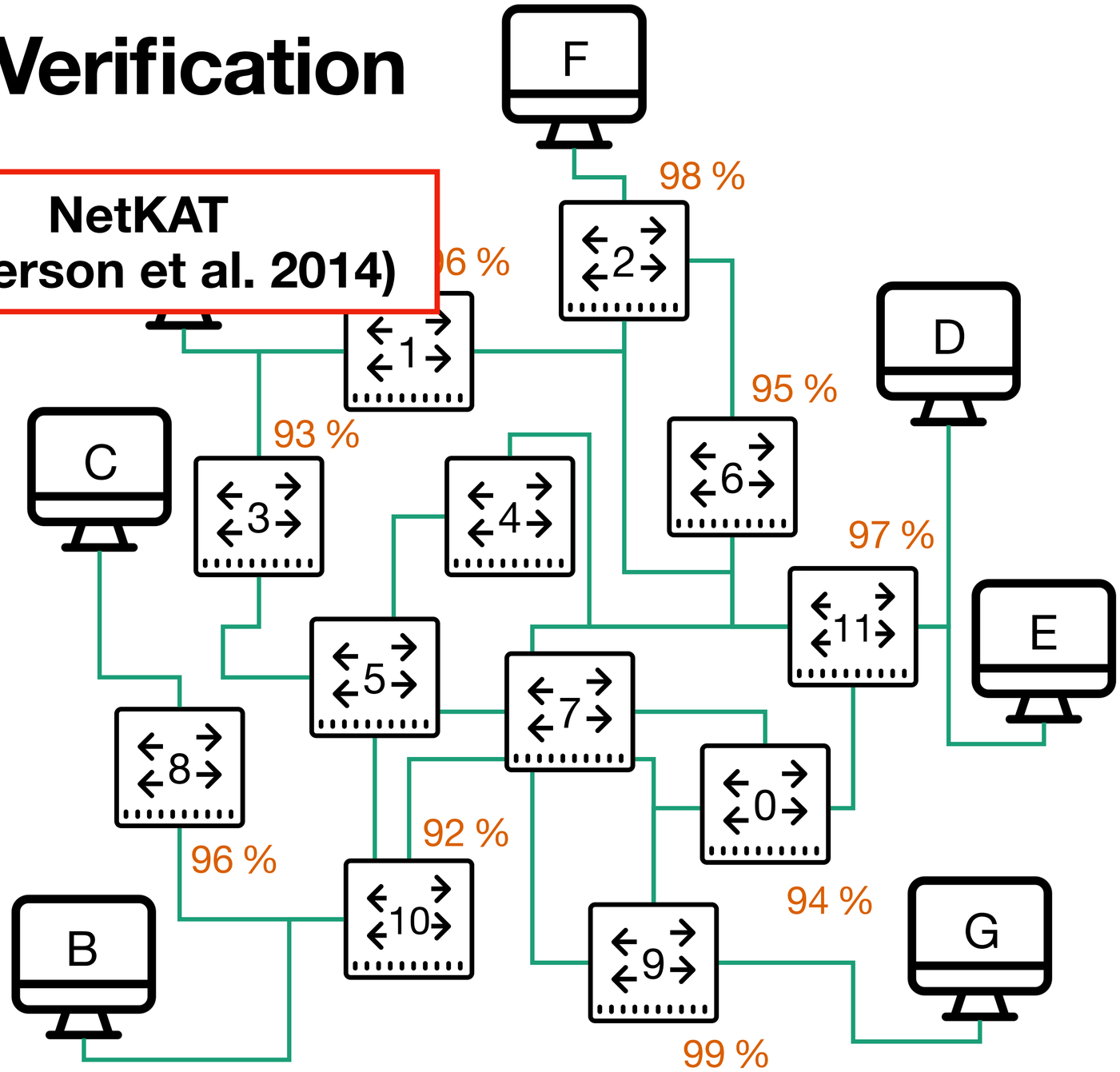
NetKAT (Anderson et al. 2014)



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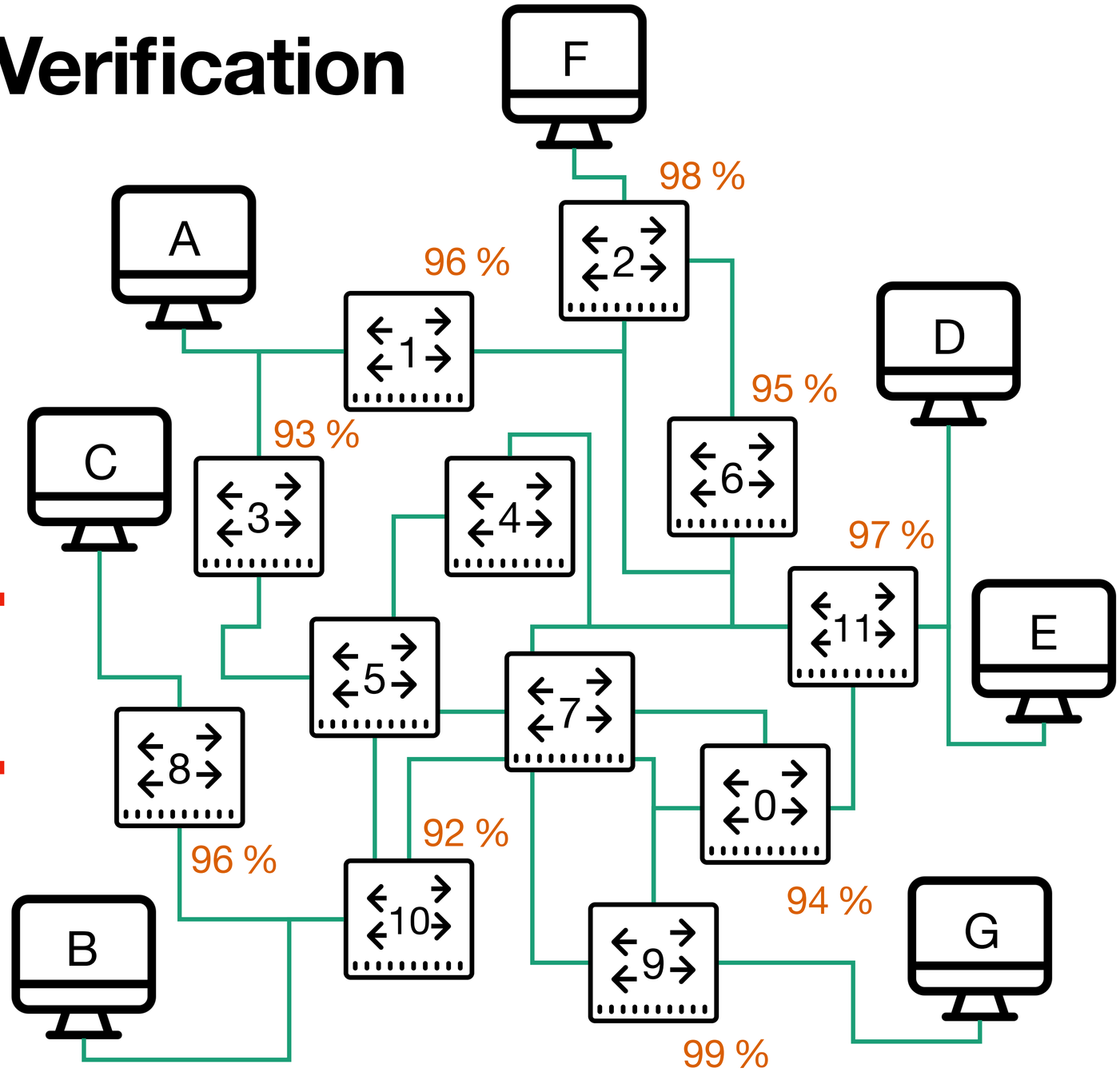
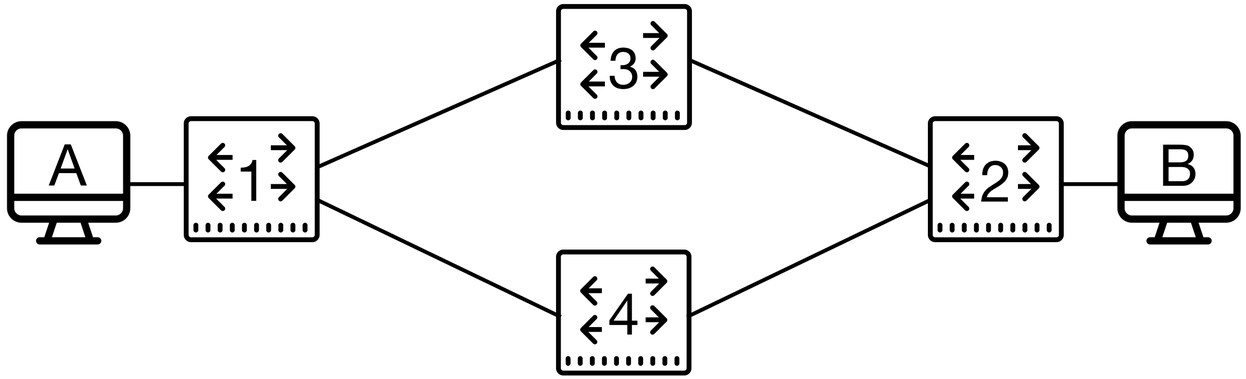


Modeling Network Behavior



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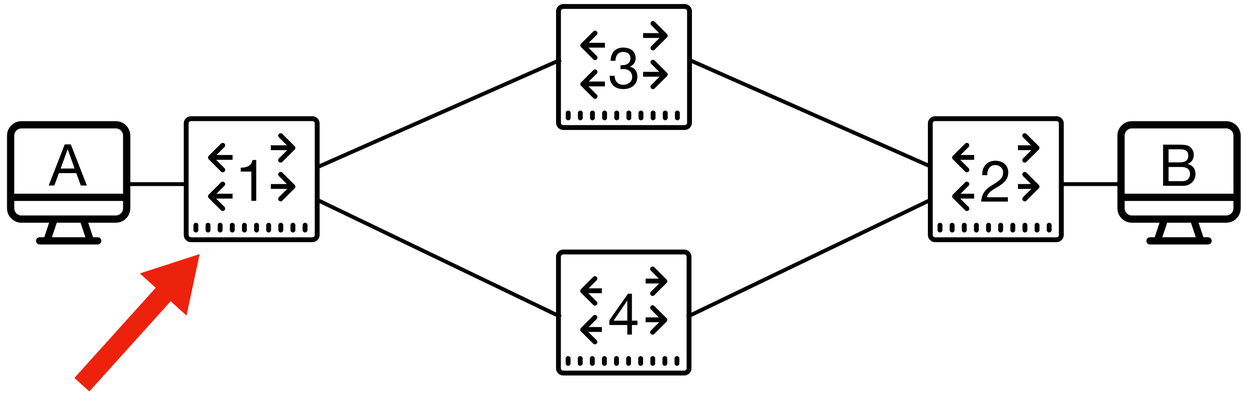
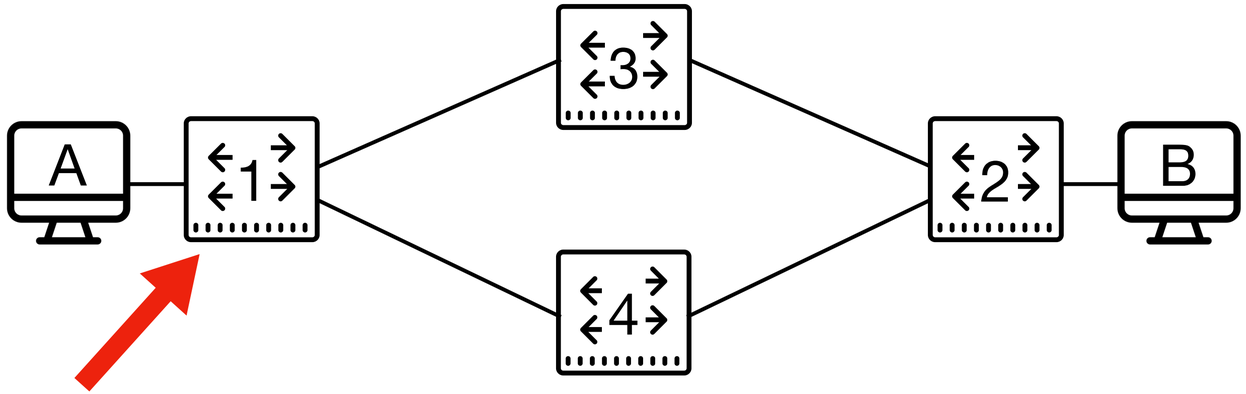
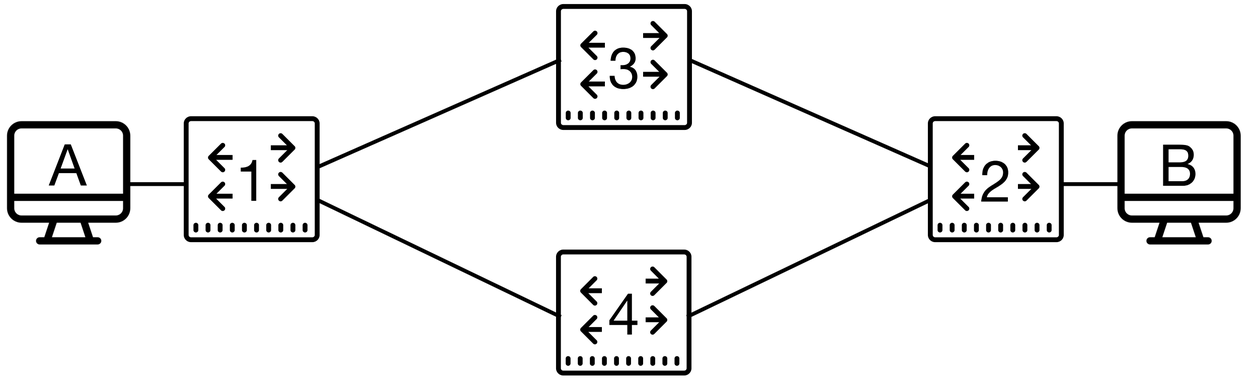


Modeling Network Behavior




```
p1 ≜
  if dst = B then
    sw <- 3 ⊕ sw <- 4
  else ...
```

Modeling Network Behavior



$p_1 \triangleq$

```
 if dst = B then
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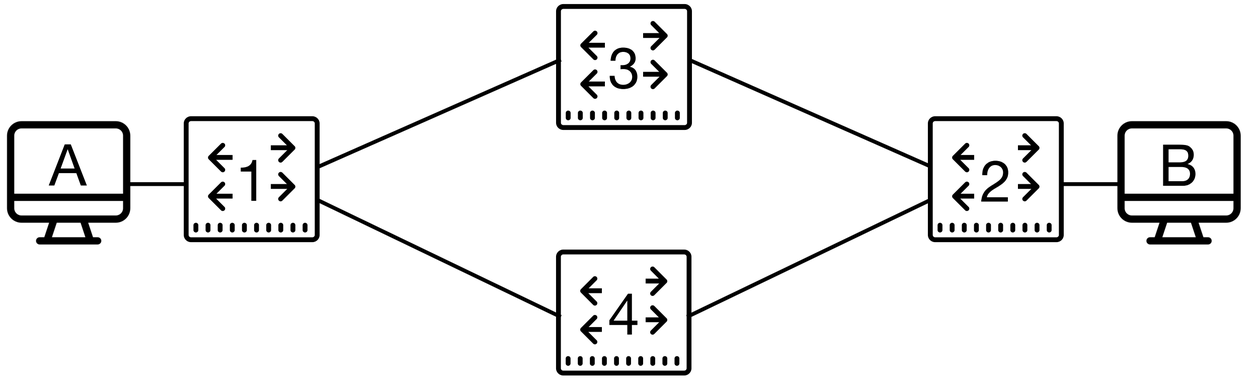
```

$p_2 \triangleq \ldots$ $p_3 \triangleq \ldots$ $p_4 \triangleq \ldots$

Modeling Network Behavior



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$p \triangleq$

```
if sw = 1 then p1
else if sw = 2 then p2
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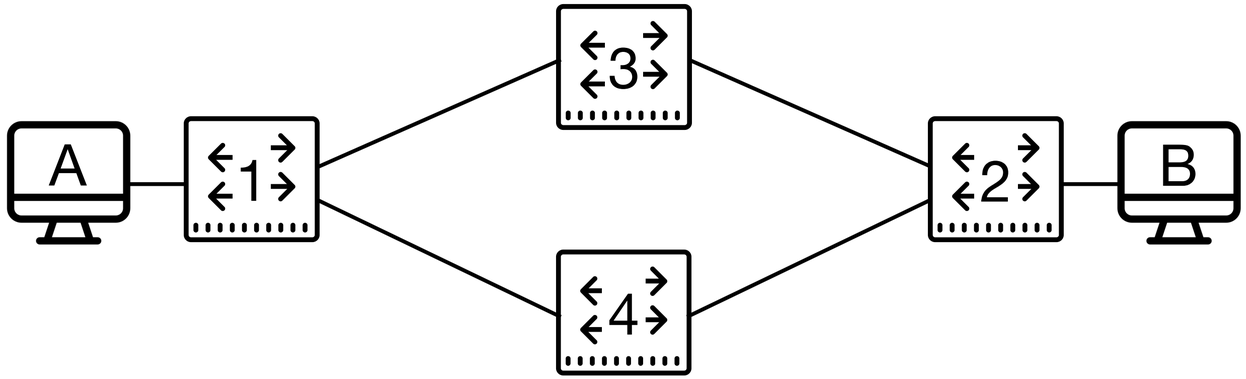
```

Modeling Network Behavior




```
p1 ≜
  if dst = B then
    sw <- 3 ⊕ sw <- 4
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```

```
p2 ≜ ...    p3 ≜ ...    p4 ≜ ...

p ≜       if sw = 1 then p1
      else if sw = 2 then p2
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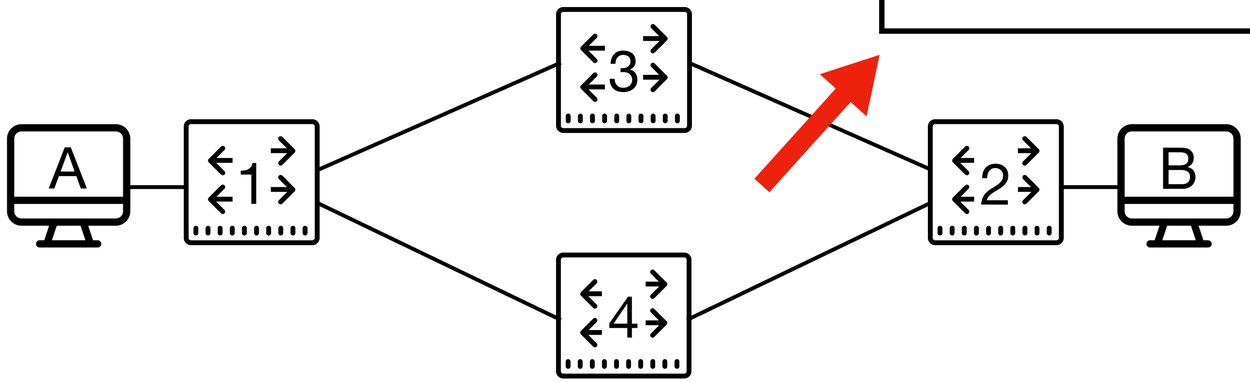
net ≜ ( p )*
```

Modeling Network Behavior

Can all hosts deliver packets to one another?



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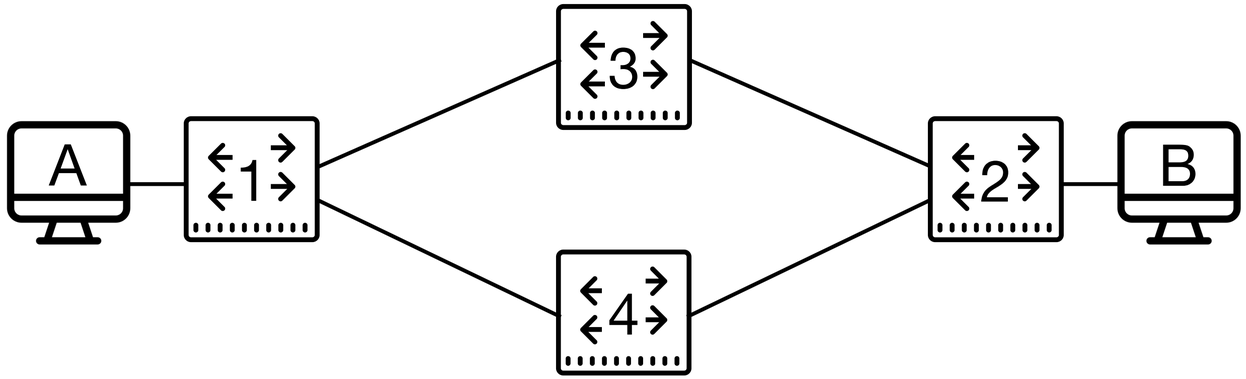
```

$net \triangleq (p)^*$

Modeling Quantitative Network Behavior



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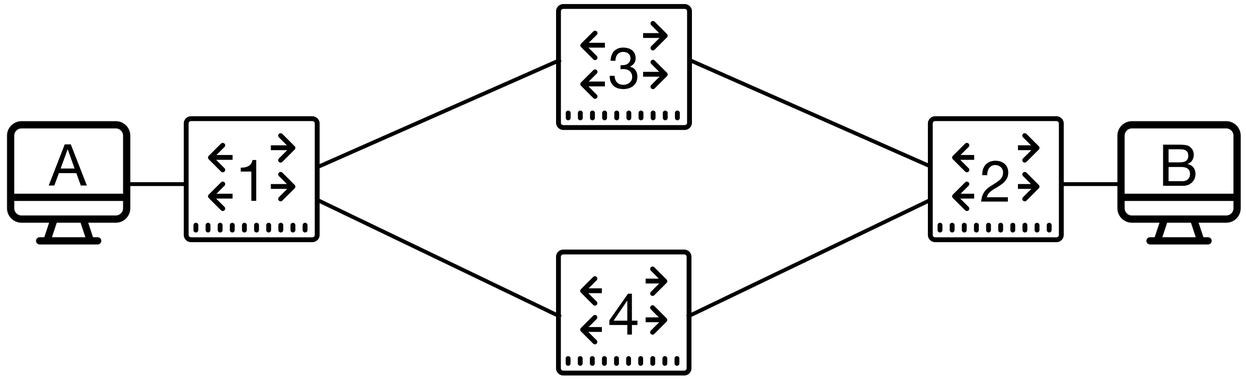
net ≜ ( p )*
```

Modeling Quantitative Network Behavior



$p_1 \triangleq$

```
if dst = B then
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else ...
```

$p_2 \triangleq$ ... $\triangleq$ ...

$p \triangleq$ p_1

2

3

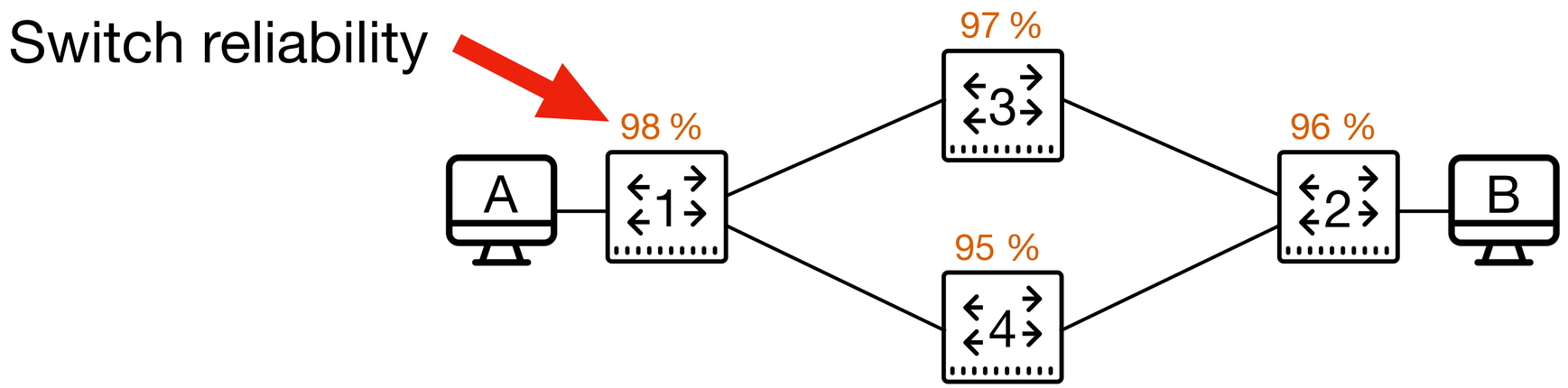
4

net

r ⊙ p

weighting:
“do p with weight r”

Modeling Quantitative Network Behavior



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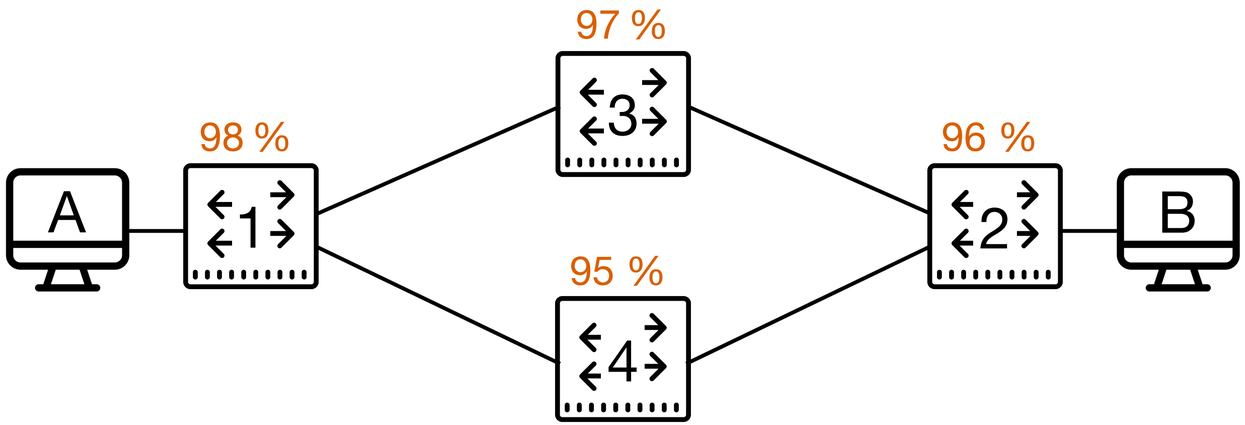
Modeling Quantitative Network Behavior



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if dst = B then
  sw <- 3 ⊕ sw <- 4
else ...
```

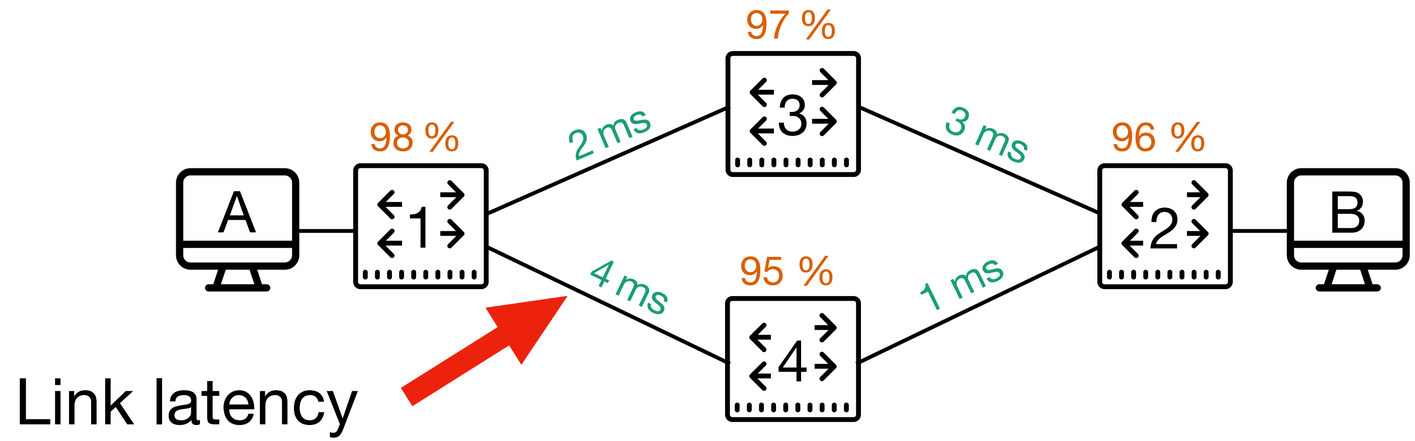
$p_2 \triangleq$ ... $p_3 \triangleq$ ... $p_4 \triangleq$ ...

$p \triangleq$

```
if sw = 1 then 98% ⊙ p1
else if sw = 2 then 96% ⊙ p2
else if sw = 3 then 97% ⊙ p3
else if sw = 4 then 95% ⊙ p4
```

$net \triangleq (p)^*$

Modeling Quantitative Network Behavior



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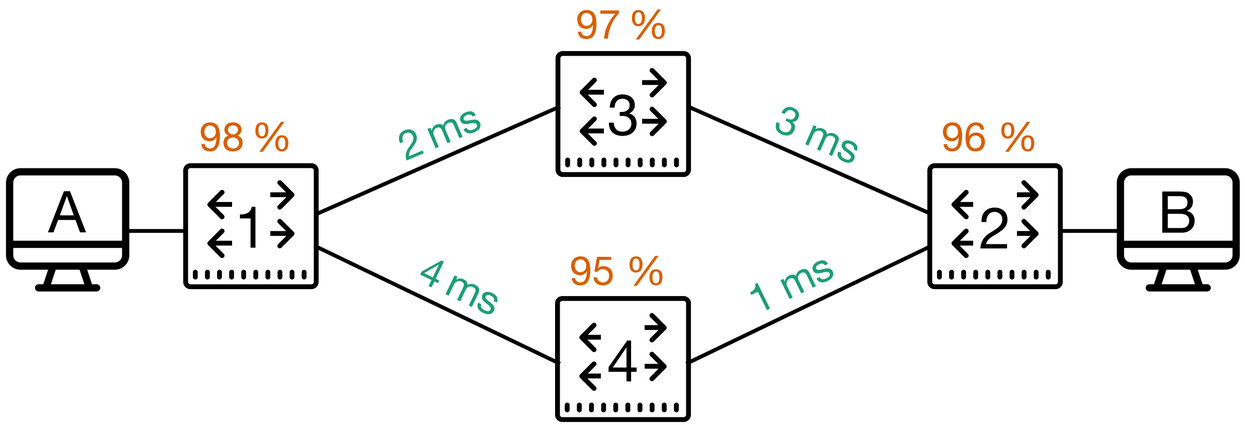

$p_1 \triangleq$

```
  if dst = B then

     (2ms ⊙ sw <- 3) ⊕
          (4ms ⊙ sw <- 4)

  else ...
```

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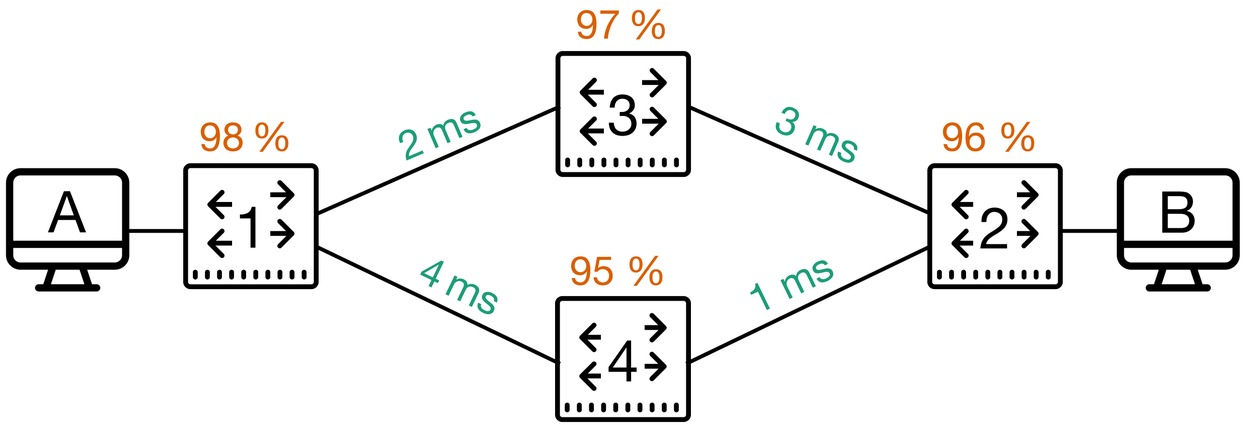

weighted choice

```
p1 ≜
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          (4ms ⊙ sw <- 4)
  else ...
```

```
p2 ≜ ...    p3 ≜ ...    p4 ≜ ...

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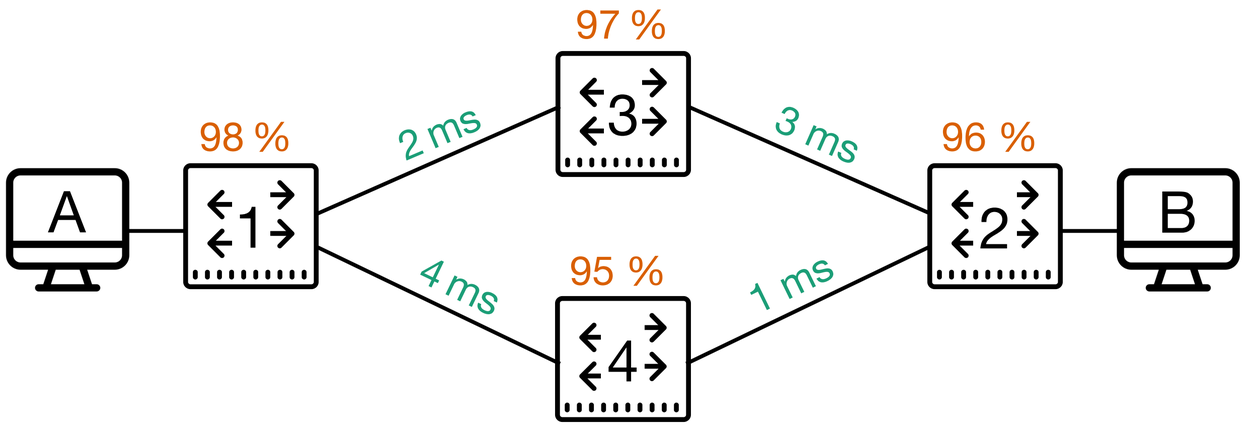
net ≜ ( p )*
```

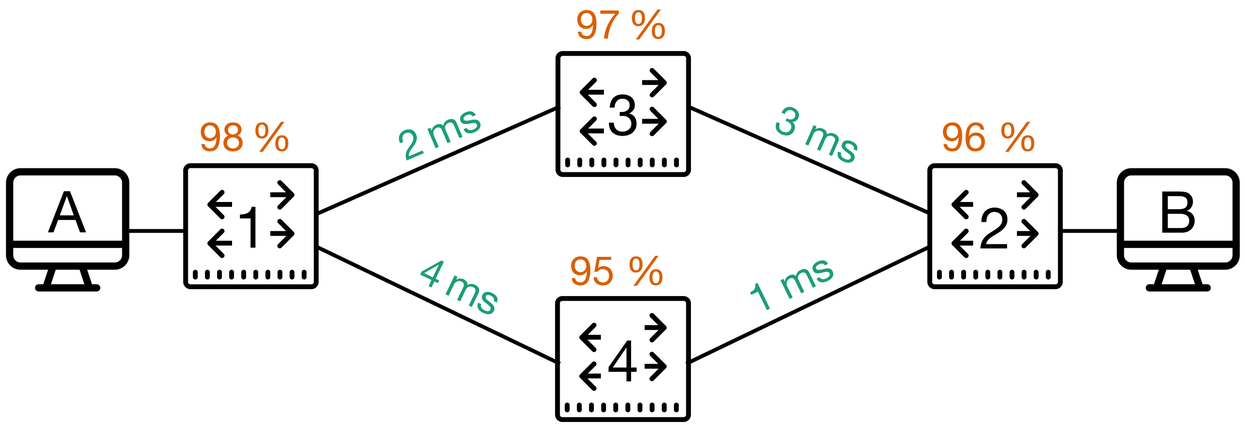
Modeling Quantitative Network Behavior



Weights of network (and operations $\odot$, $\oplus$) drawn from a **semiring**

$$\mathcal{S} \triangleq (S, +, \cdot, 0, 1)$$

Modeling Quantitative Network Behavior



Weights of network (and operations $\odot$, $\oplus$) drawn from a **semiring**

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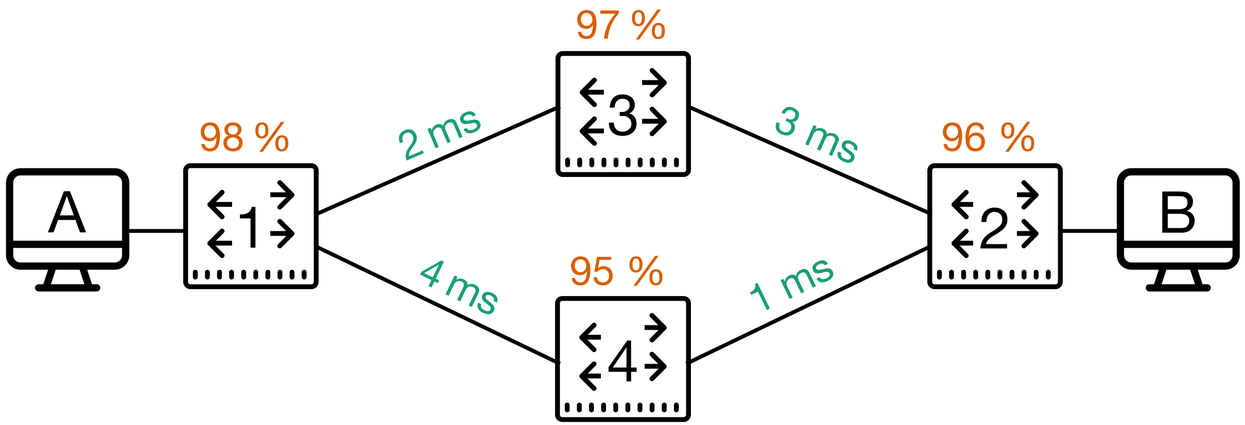
- Combining/accumulating weights along a path (multiplication)

Modeling Quantitative Network Behavior



Weights of network (and operations $\odot$, $\oplus$) drawn from a **semiring**

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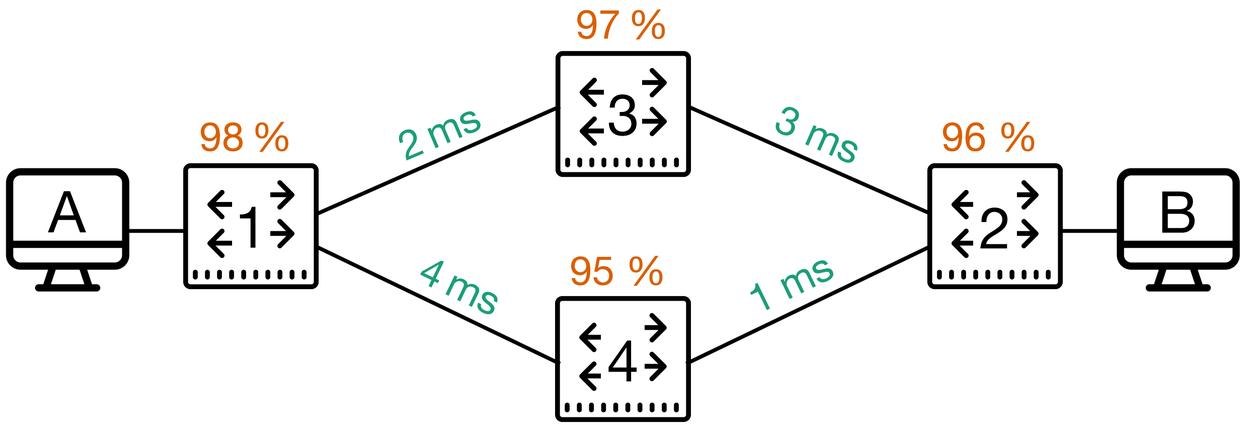
- Choosing between alternate paths (addition)

Modeling Quantitative Network Behavior

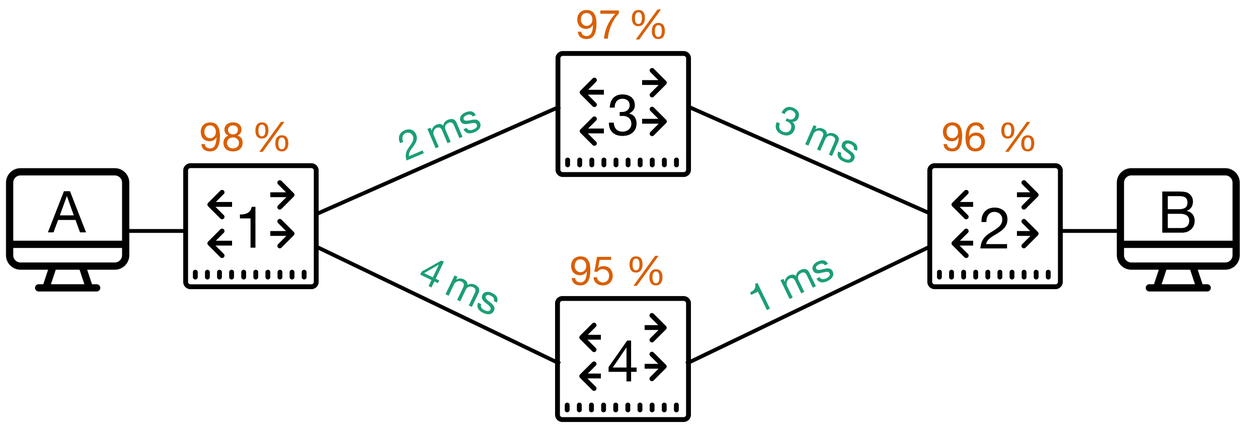


Weights of network (and operations $\odot$, $\oplus$) drawn from a **semiring**

$$\mathcal{S} \triangleq (S, +, \cdot, 0, 1)$$

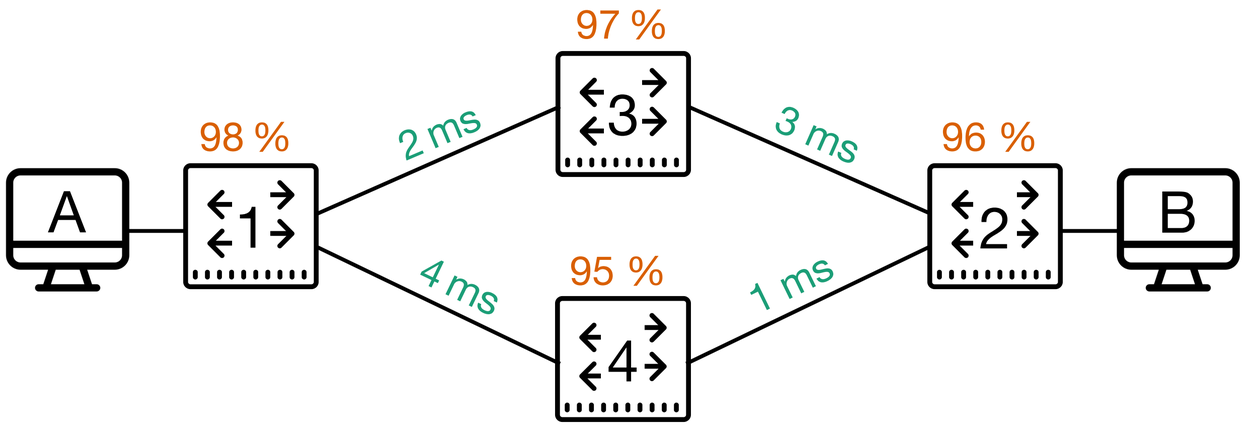
- Combining/accumulating weights along a path (multiplication)
- Choosing between alternate paths (addition)
- **Quantitative behavior we are modeling varies based on the choice of semiring**

Modeling Quantitative Network Behavior



Tropical Semiring
$(\mathbb{N}^{+\infty}, \texttt{min}, +, +\infty, 0)$
to model **Best-Case Latency**

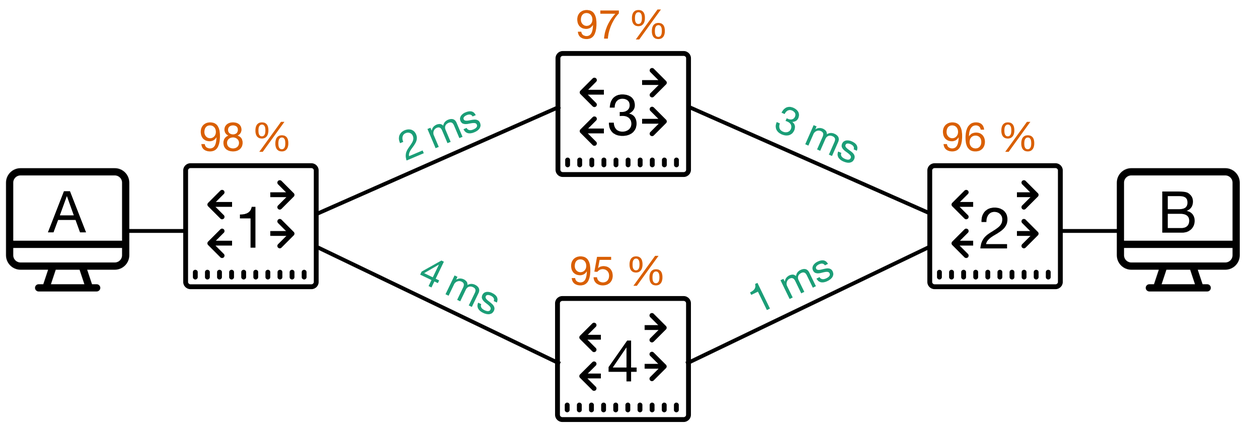
Modeling Quantitative Network Behavior



Tropical Semiring
$(\mathbb{N}^{+\infty}, \texttt{min}, +, +\infty, 0)$
to model **Best-Case Latency**

- weighted choice := `min` (choose better latency)

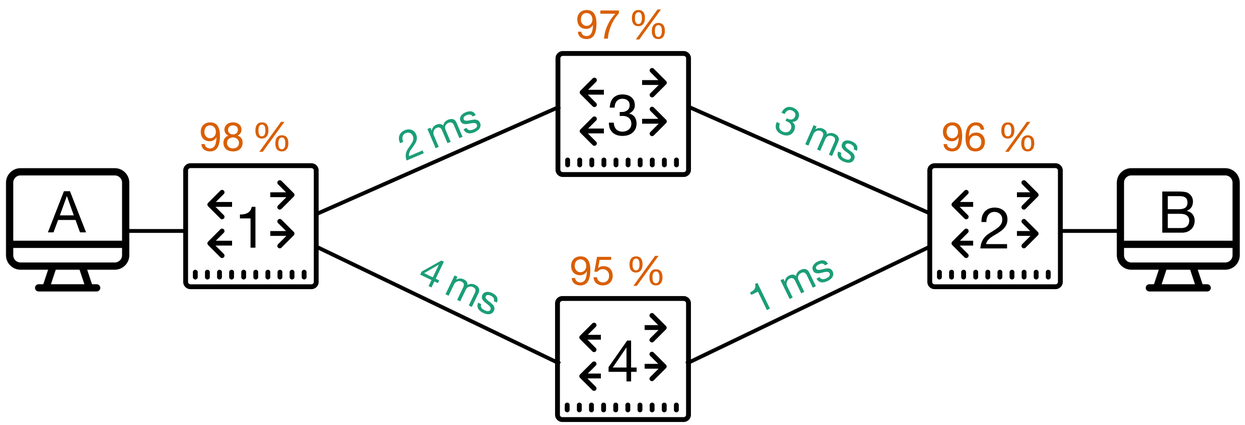
Modeling Quantitative Network Behavior



Tropical Semiring
$(\mathbb{N}^{+\infty}, \texttt{min}, +, +\infty, 0)$
to model **Best-Case Latency**

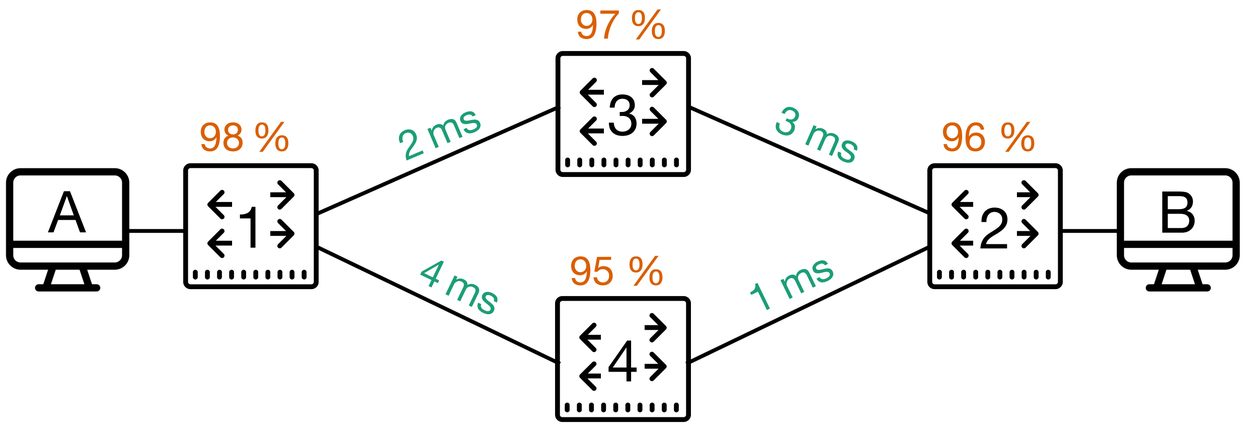
- weighted choice := `min` (choose better latency)
- path accumulation := + (add latencies together)

Modeling Quantitative Network Behavior



Viterbi Semiring
`([0,1], max, ·, 0, 1)`
to model **Best-Case Reliability**

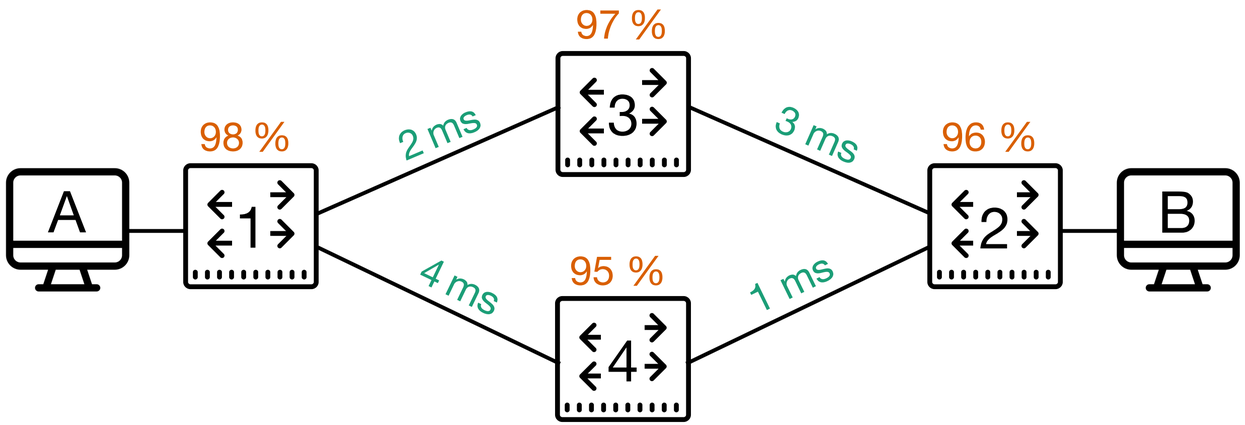
Modeling Quantitative Network Behavior



Viterbi Semiring
`([0,1], max, ·, 0, 1)`
to model **Best-Case Reliability**

- weighted choice := `max` (choose better reliability)

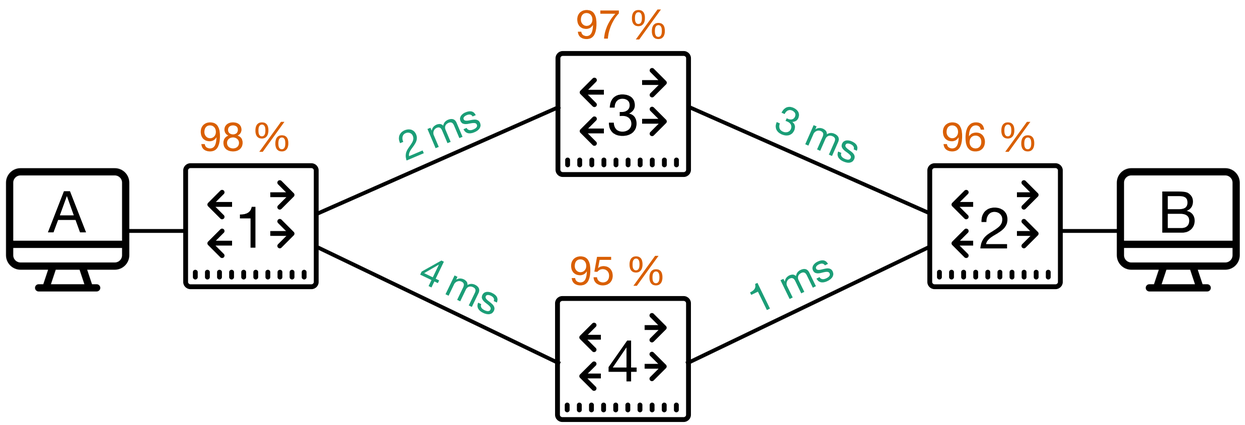
Modeling Quantitative Network Behavior



Viterbi Semiring
`([0,1], max, ·, 0, 1)`
to model **Best-Case Reliability**

- weighted choice := `max` (choose better reliability)
- path accumulation := · (multiply probabilities together)

Modeling Quantitative Network Behavior



Worst

Viterbi Semiring
`([0,1], max, ·, 0, 1)`
to model ~~**Best**~~**-Case Reliability**

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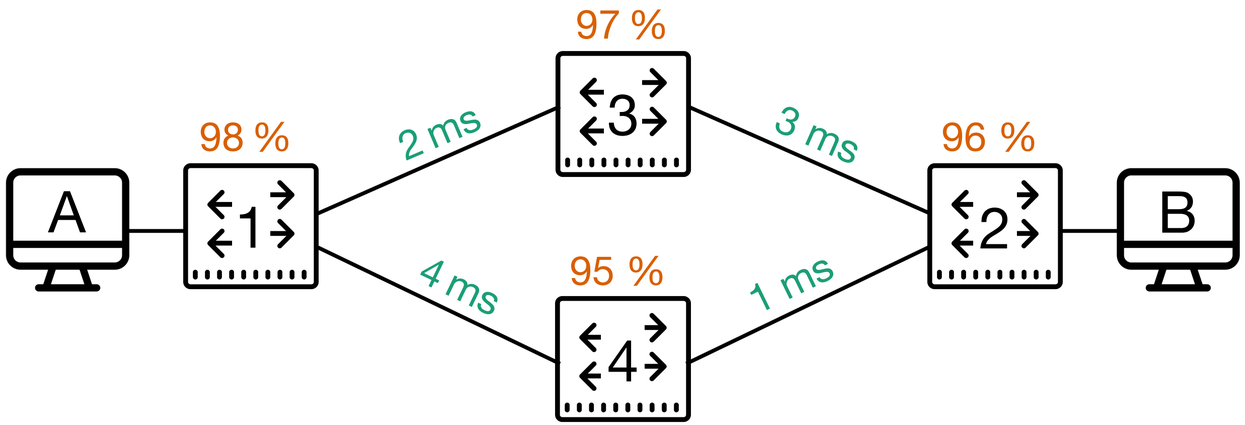
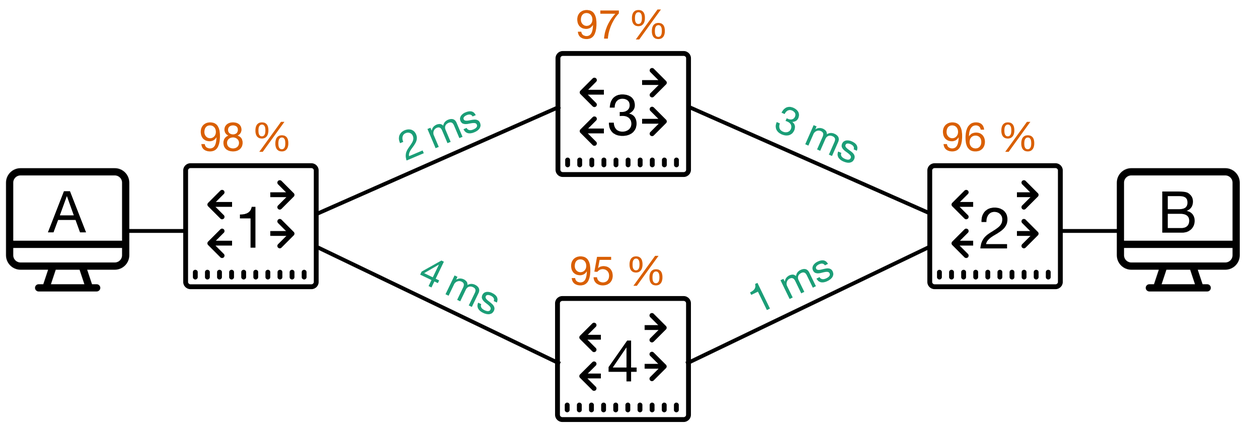
- path accumulation := · (multiply probabilities together)

Modeling Quantitative Network Behavior



Probabilistic-union Semiring
$([0,1] \cup \{-\infty\}, \max, \uplus, -\infty, 0)$
to model **Worst-Case Reliability**

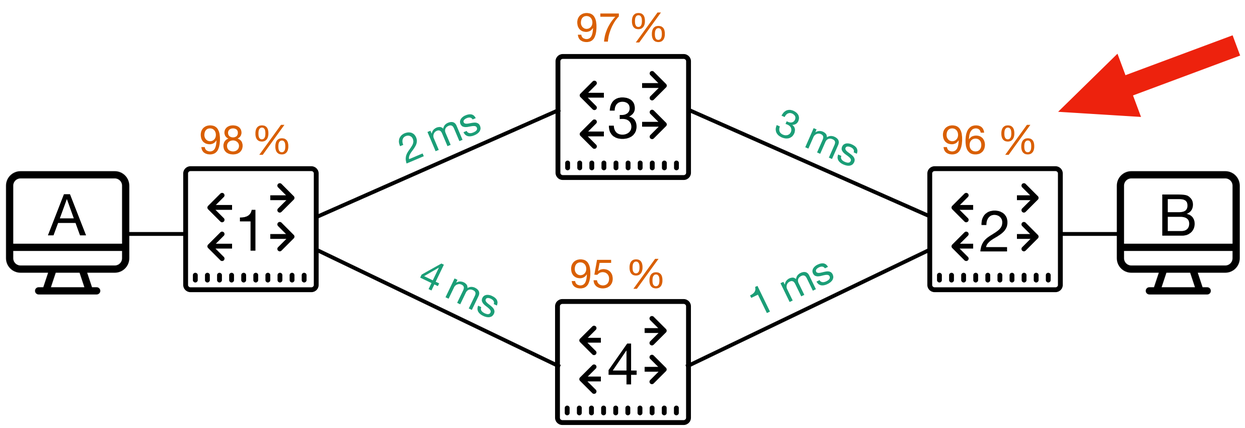
Modeling Quantitative Network Behavior



Probabilistic-union Semiring
$([0,1] \cup \{-\infty\}, \max, \uplus, -\infty, 0)$
to model **Worst-Case Reliability**

- weighted choice := $\max$ (choose worse failure rate)

Modeling Quantitative Network Behavior



96% success rate
=
4% failure rate

Probabilistic-union Semiring
$([0,1] \cup \{-\infty\}, \max, \uplus, -\infty, 0)$
to model **Worst-Case Reliability**

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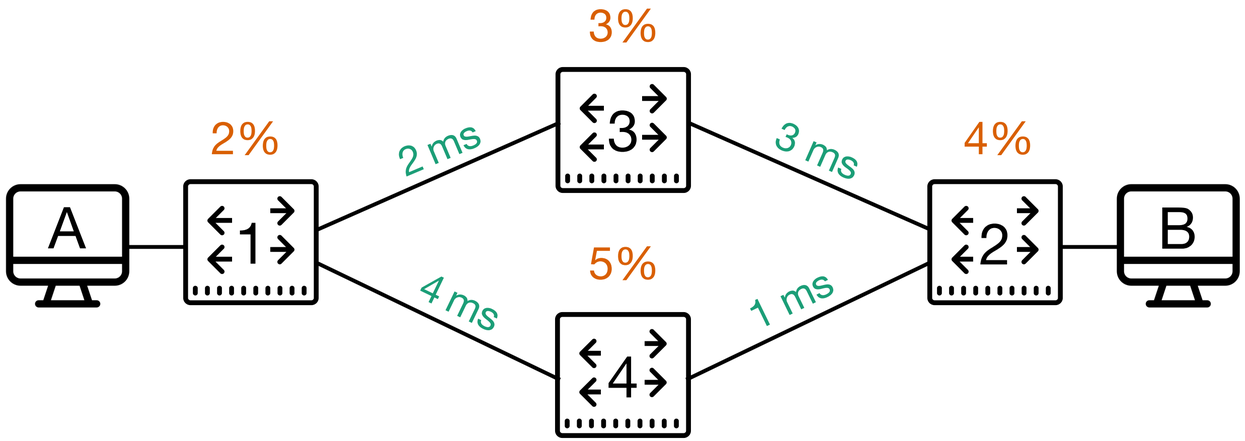

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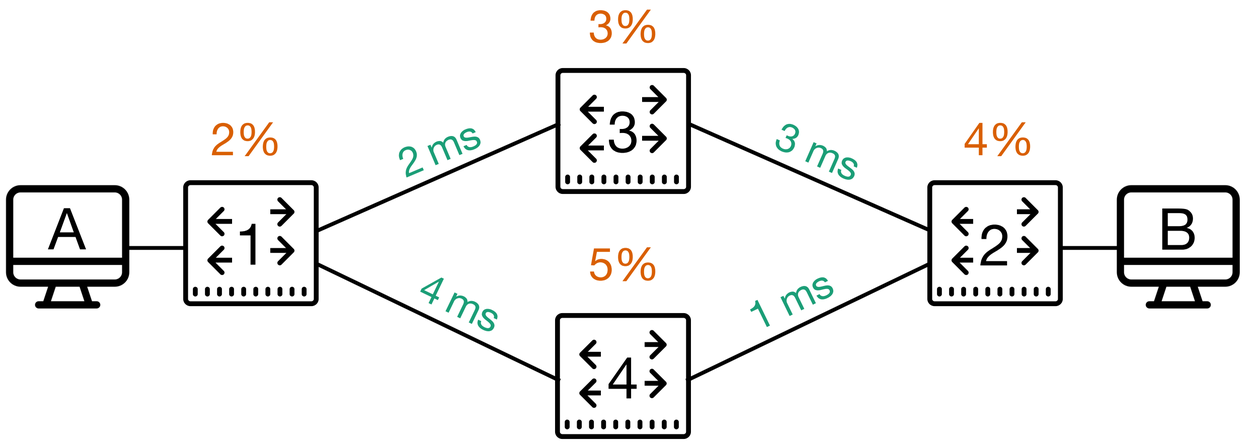

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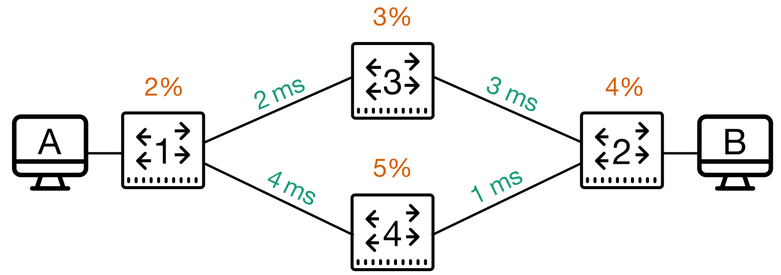
to model **Worst-Case Reliability**

- weighted choice := $\max$ (choose worse failure rate)
- path accumulation := $\uplus$ (probability of union of 2 events: p + q - pq)

From Modeling to Verification



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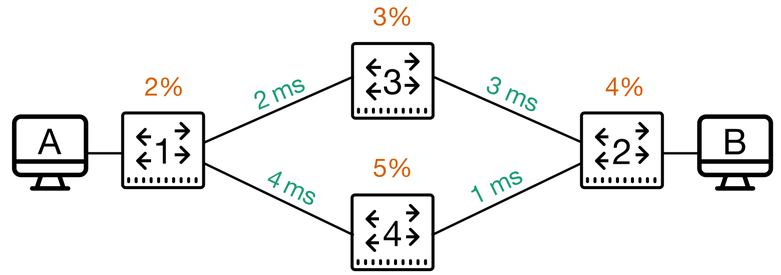

Program `p` takes input packet `π` and assigns a *weight* to every output trace `h`

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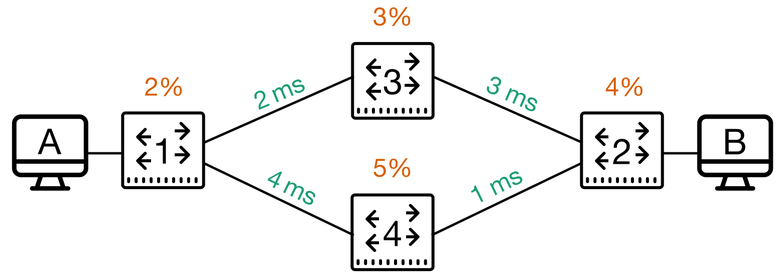

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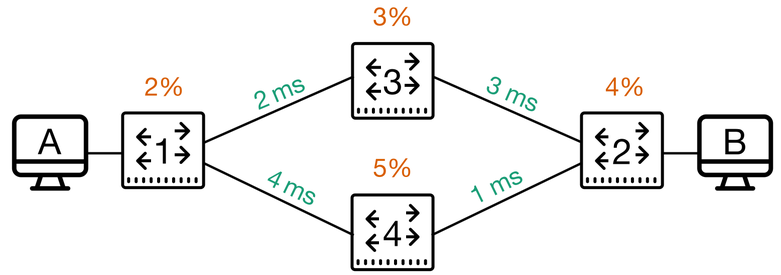

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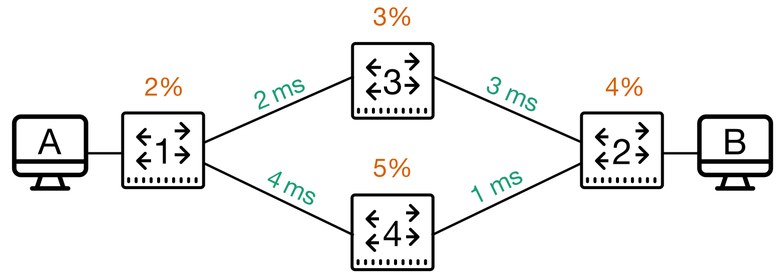
Note:

From Modeling to Verification



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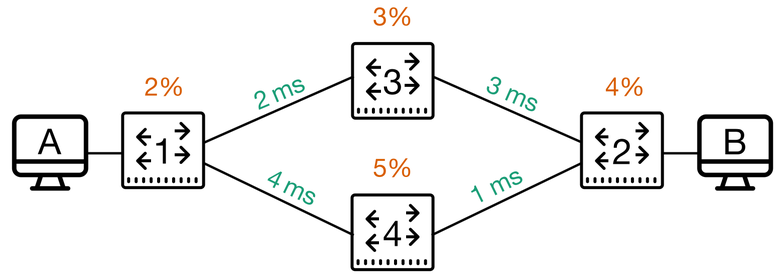

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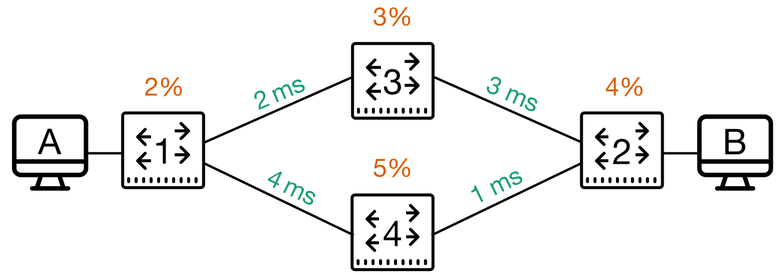

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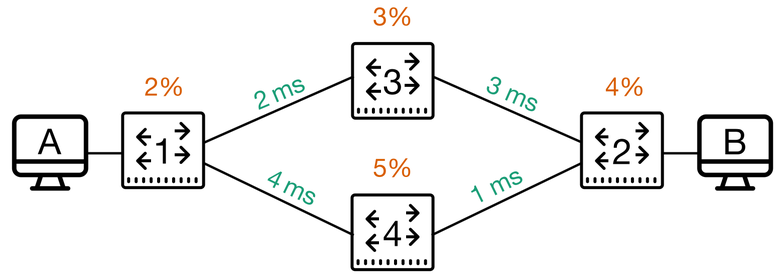

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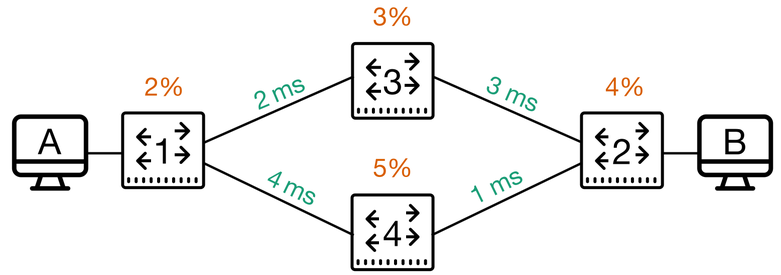

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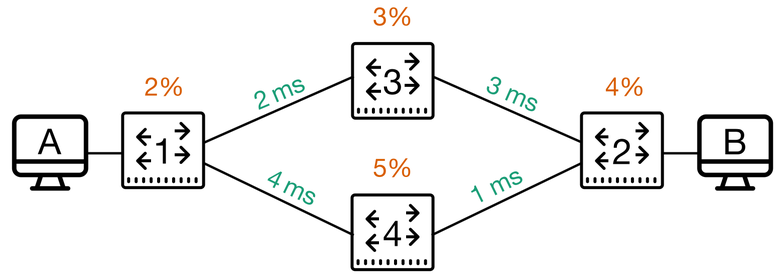
- Still suitable for many **Quantitative Verification Questions**
  - modern network hardware has made packet-level interactions less important
  - many quantities are independent of congestion (e.g., reliability, security)

From Modeling to Verification



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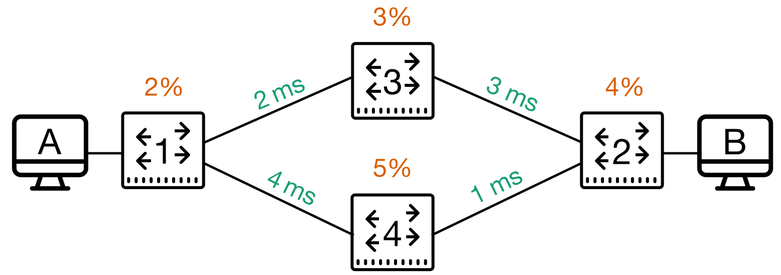

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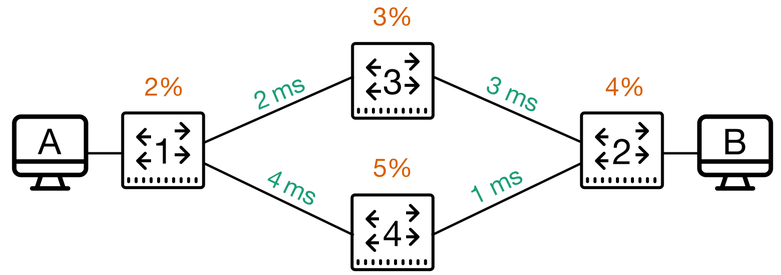
Quantitative Verification Questions

$\mathtt{r}$**-safety**
(Does all network traffic have weight *at most* $\mathtt{r}$)?

From Modeling to Verification



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Does all traffic get delivered with at least 90% reliability?

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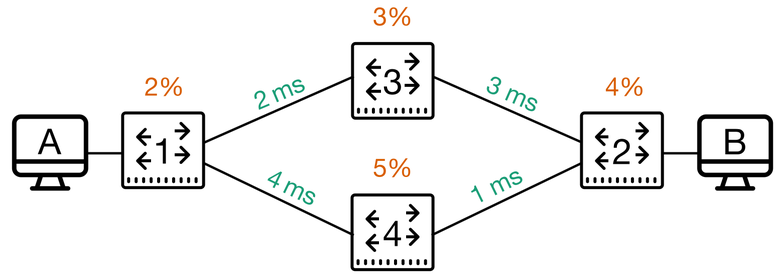

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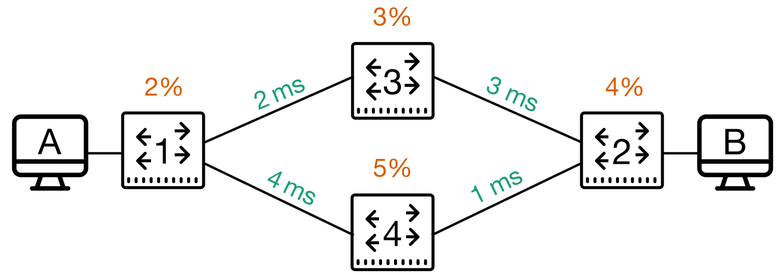

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(Does there exist network traffic with weight *at least* $\mathtt{r}$)?

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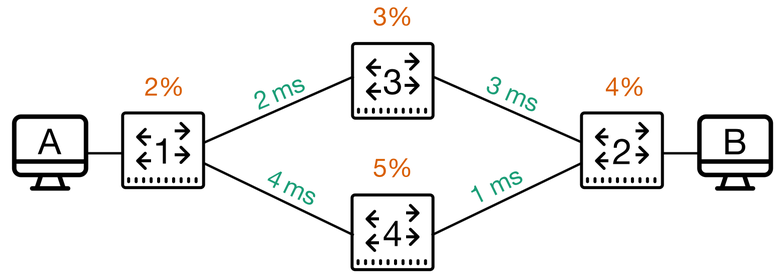

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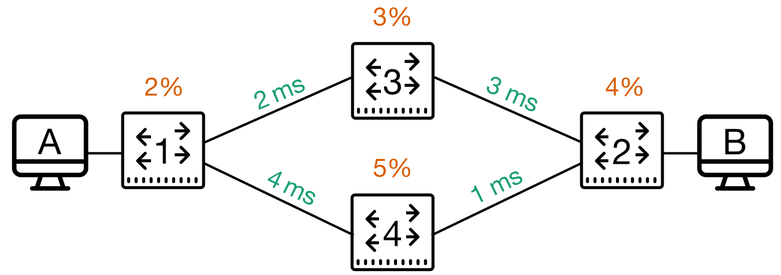
Can host A deliver packets to host B within 5ms?

From Modeling to Verification



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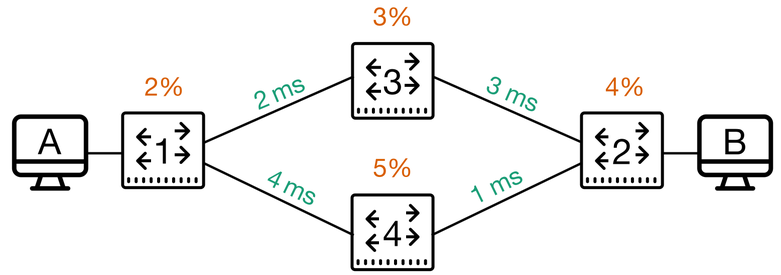

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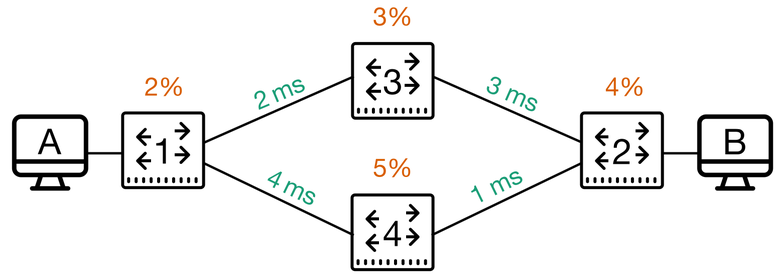

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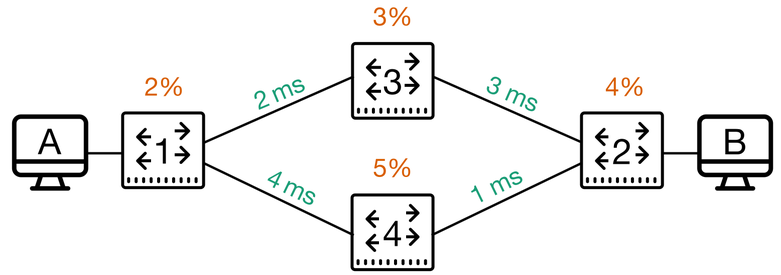
Automatic Verification
Need to compute semantics for:

From Modeling to Verification



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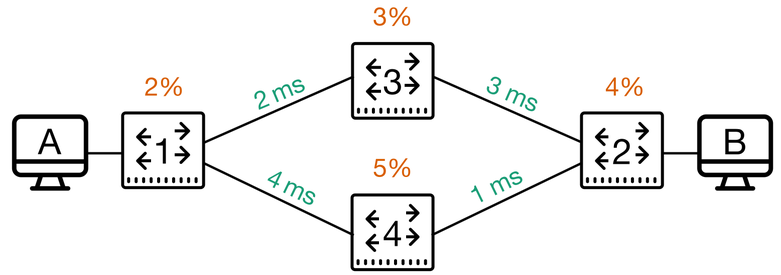

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Need to compute semantics for:

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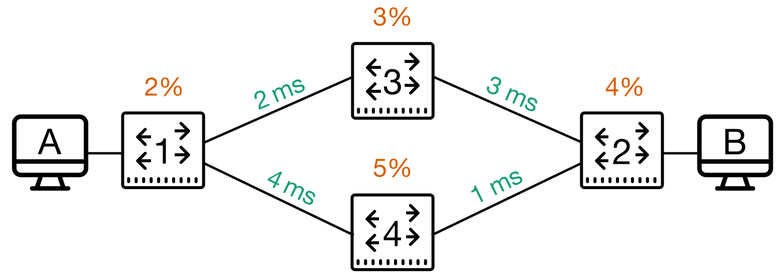
From Modeling to Verification



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Approach
Automata-based model checking

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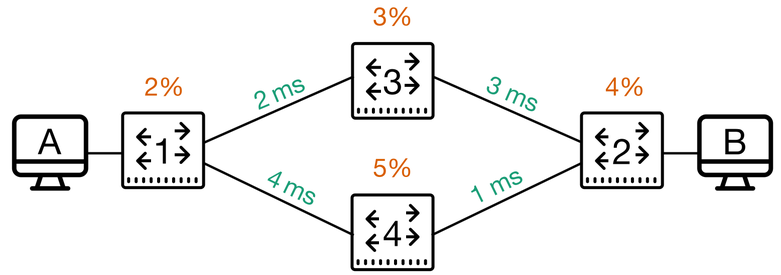

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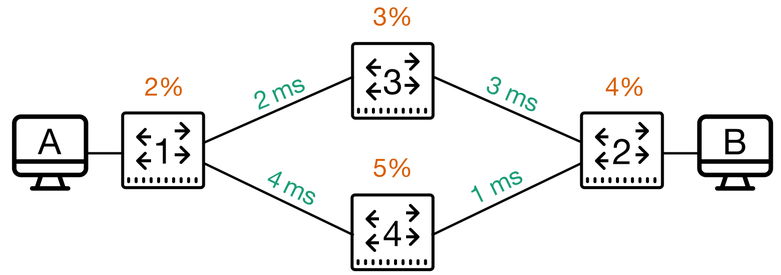

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- wNetKAT has *stateful packet transitions*

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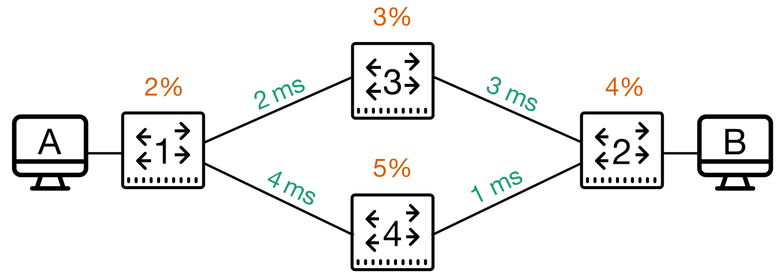

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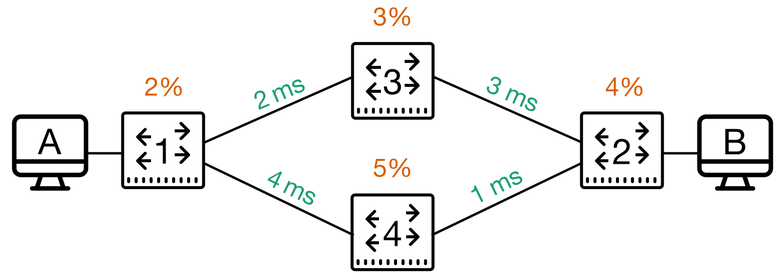

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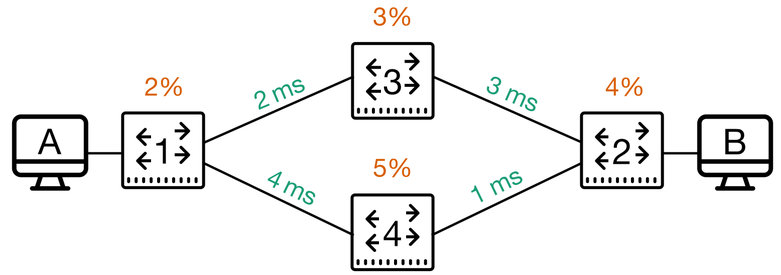

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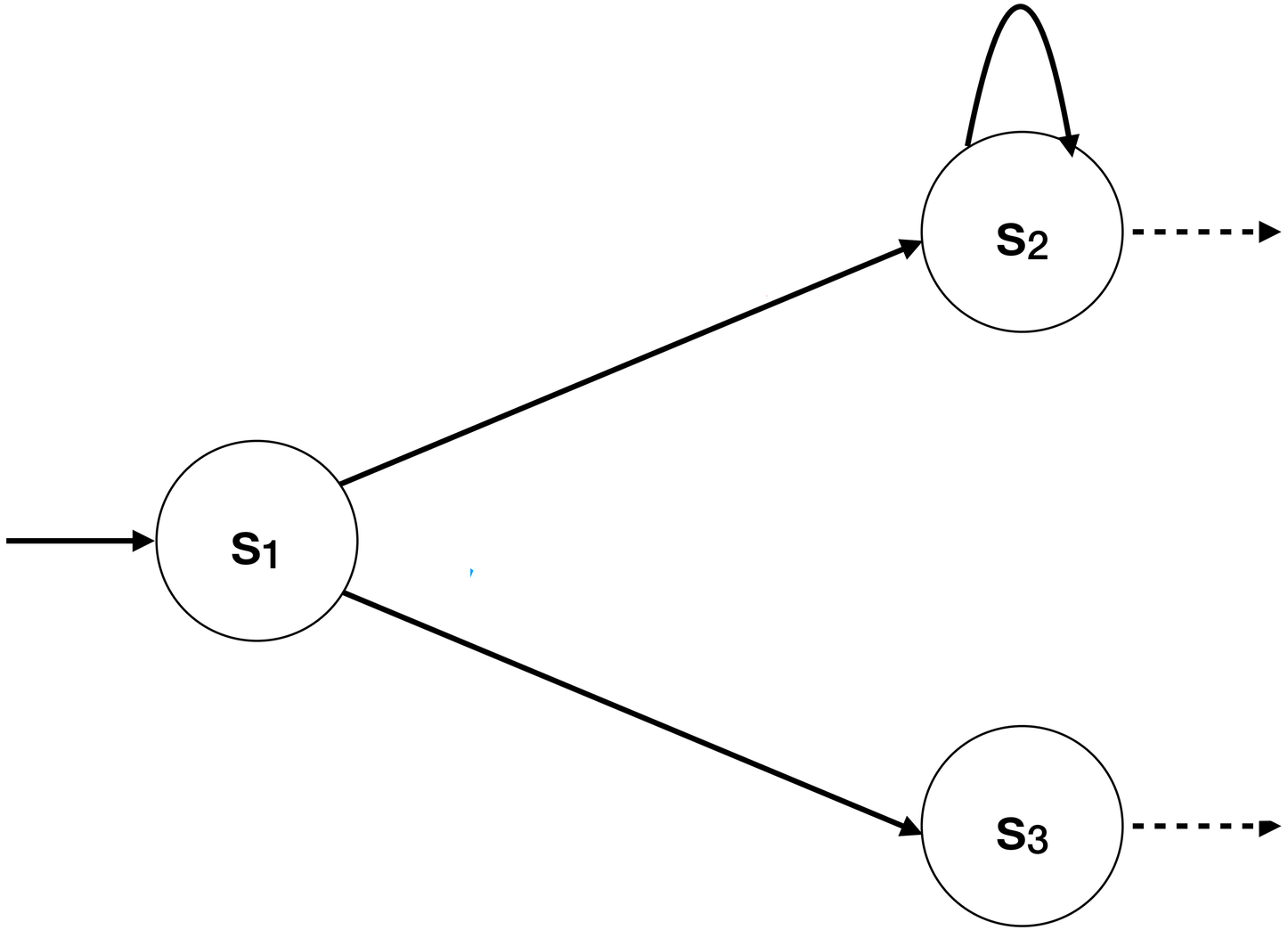
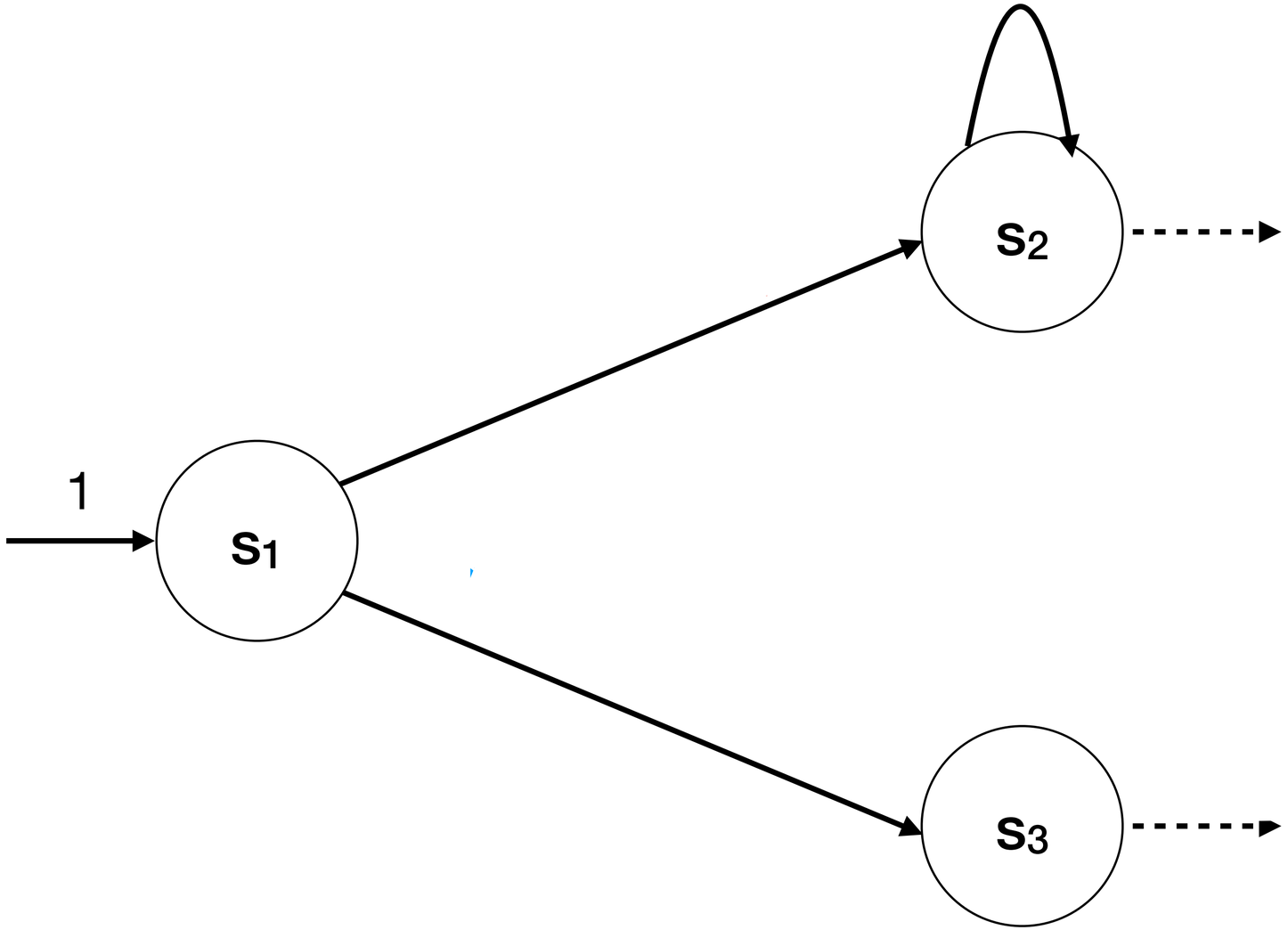
- Regular automata are not suitable

wNetKAT Automata



Tropical Semiring
$(\mathbb{N}^{+\infty}, \min, +, +\infty, 0)$

wNetKAT Automata



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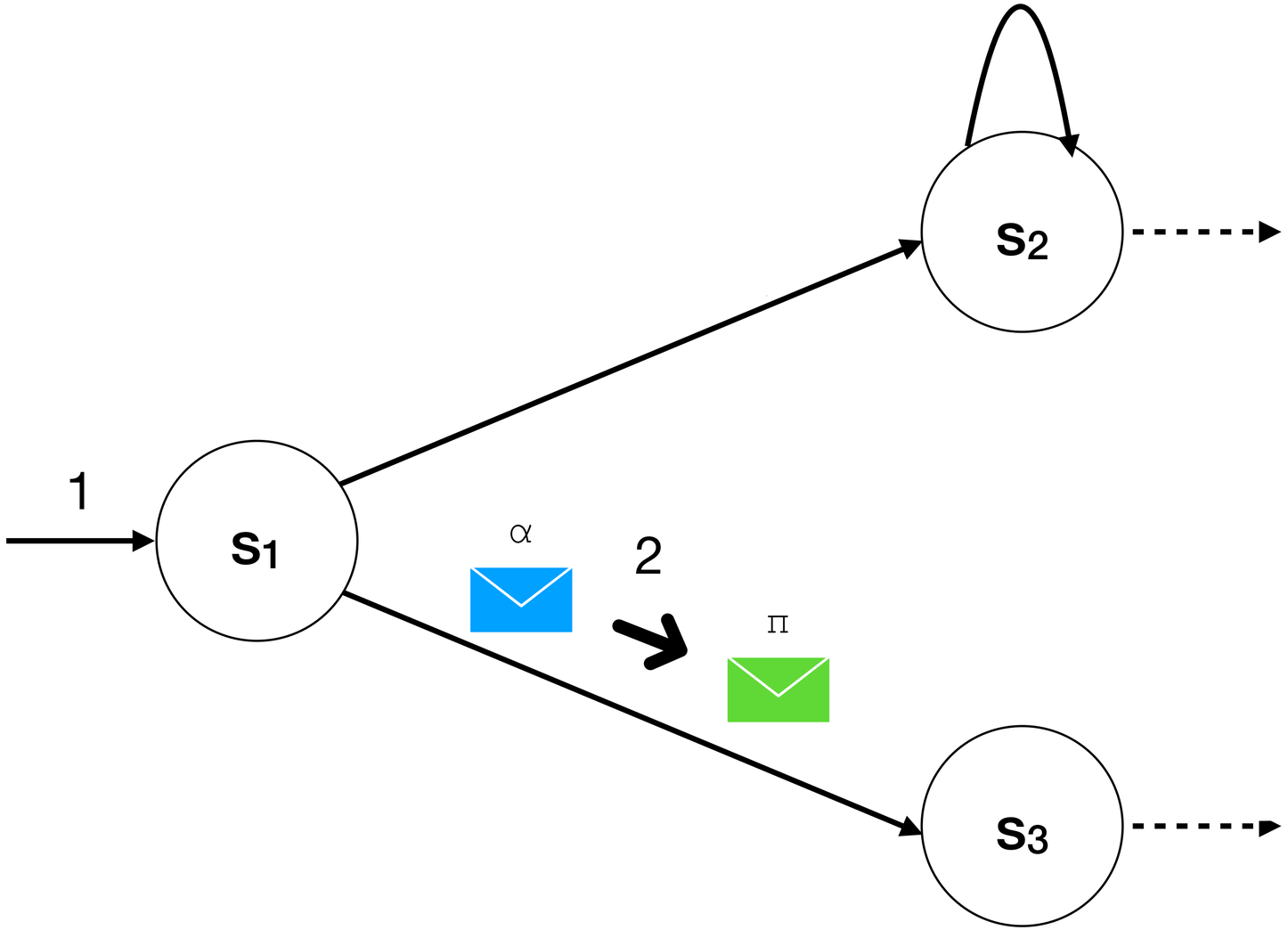

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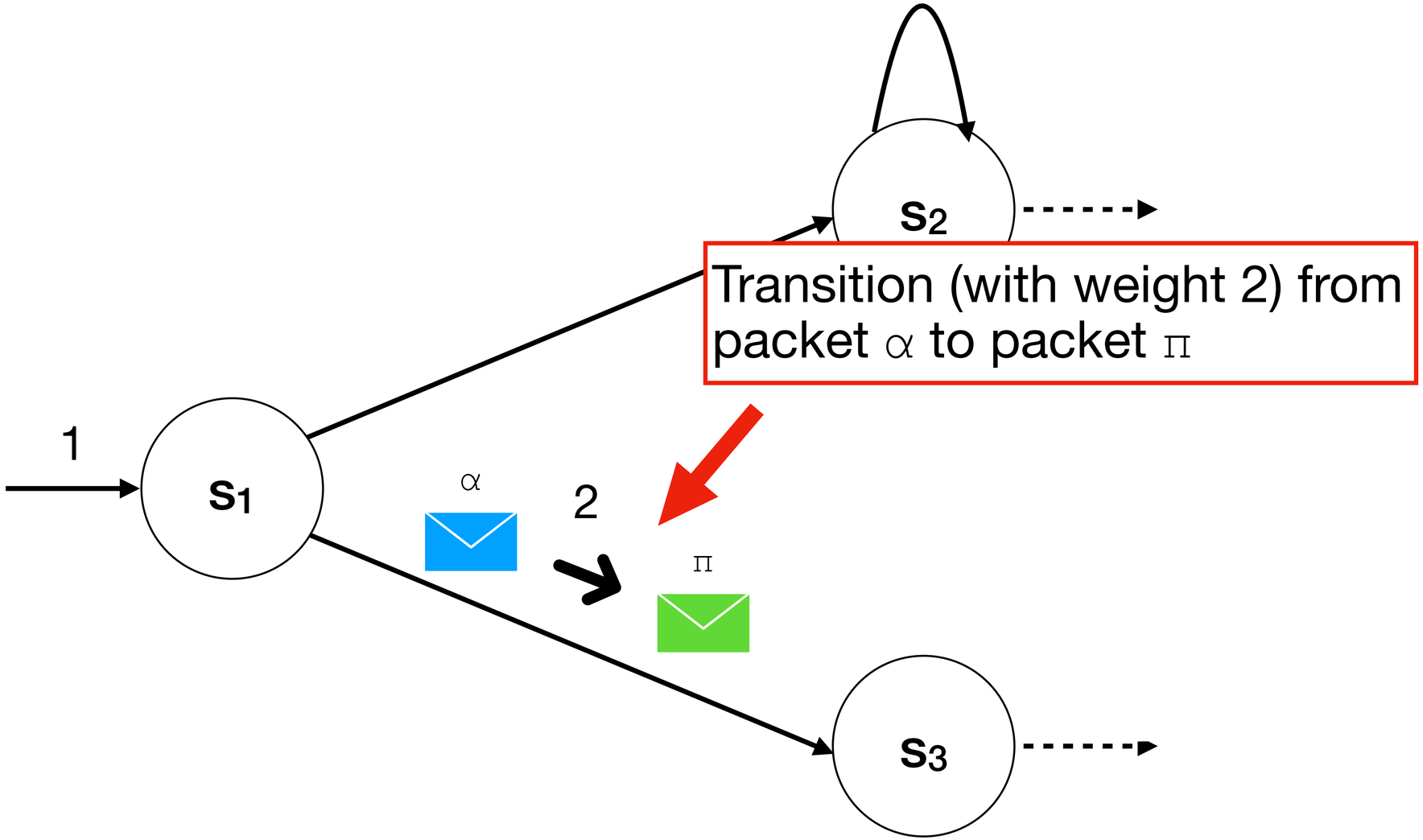

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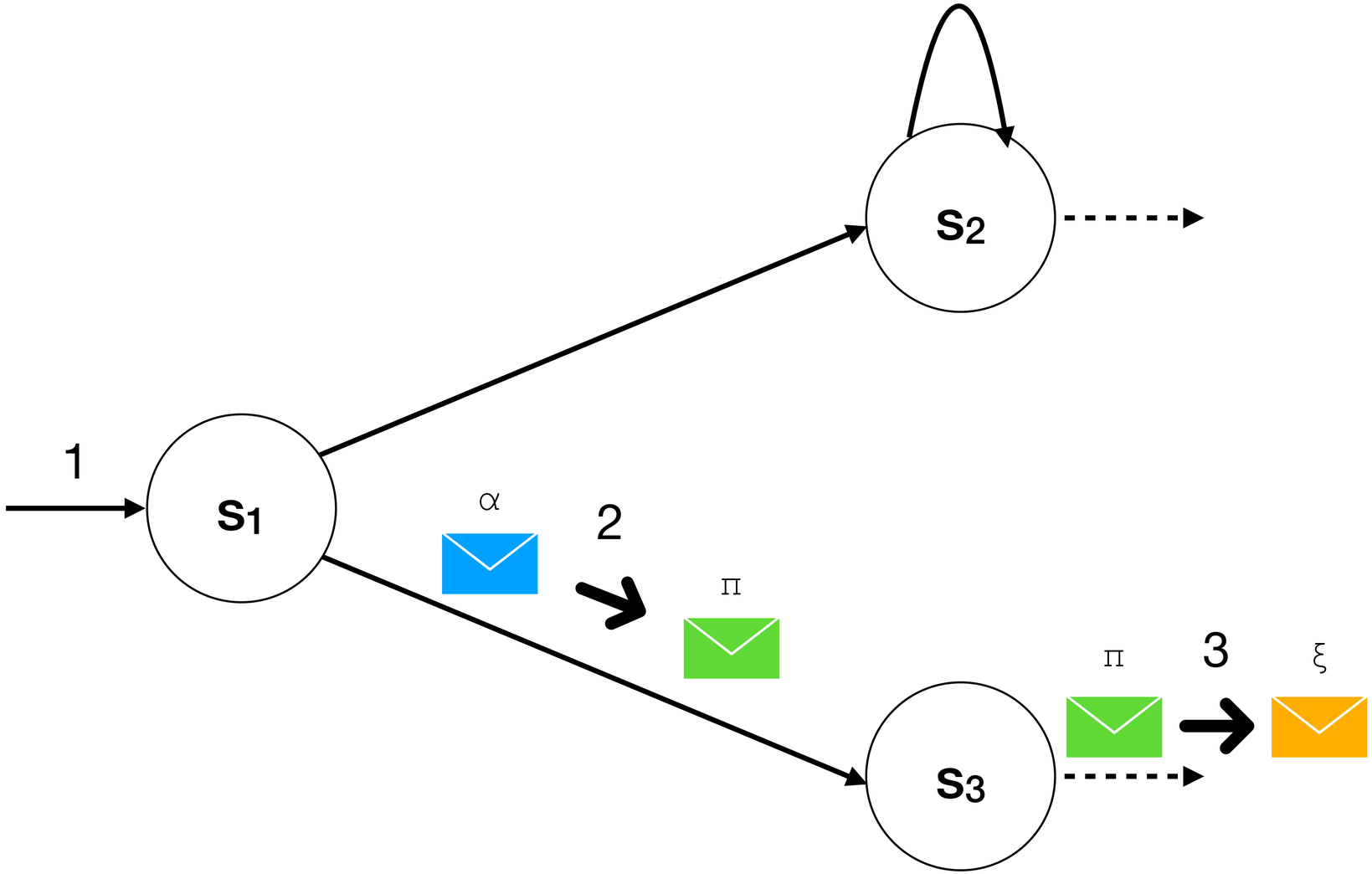

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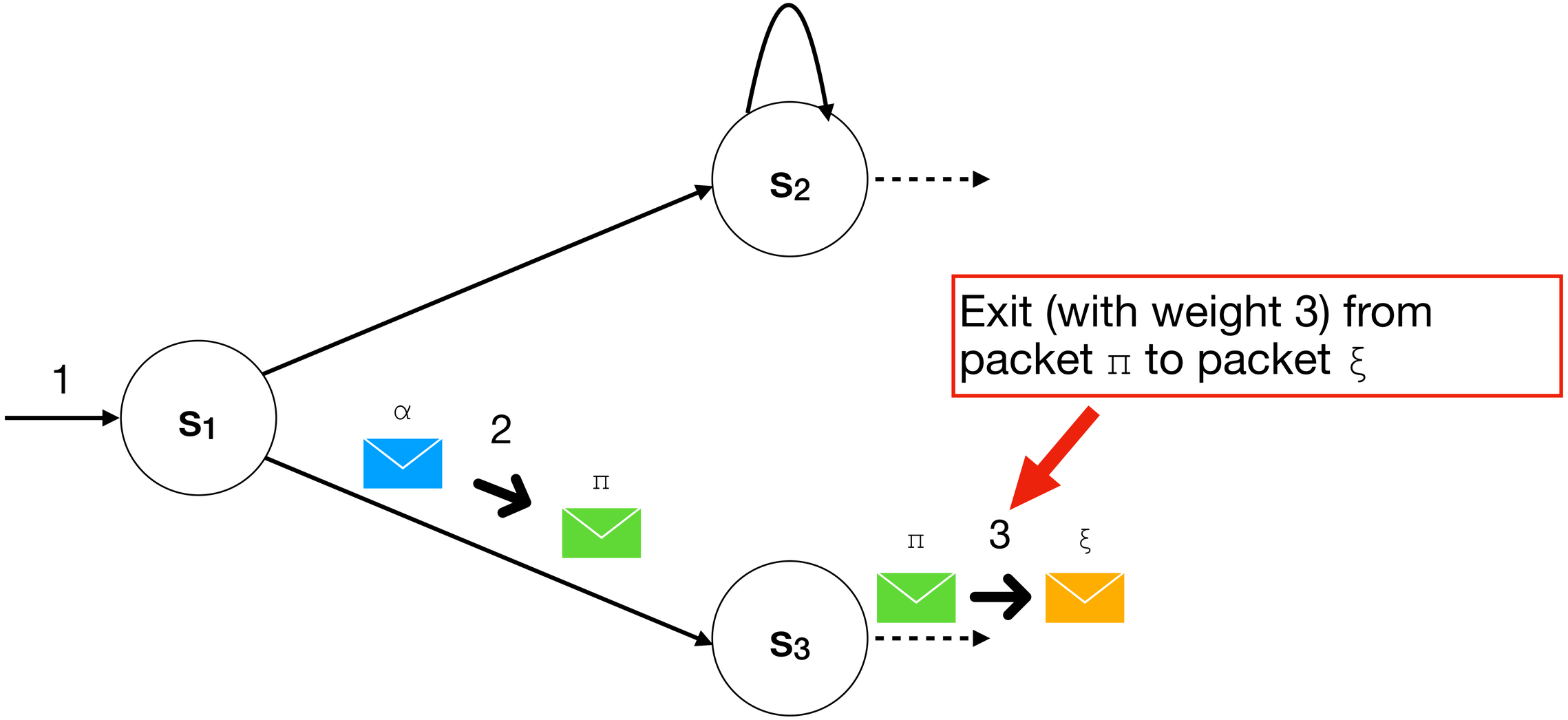
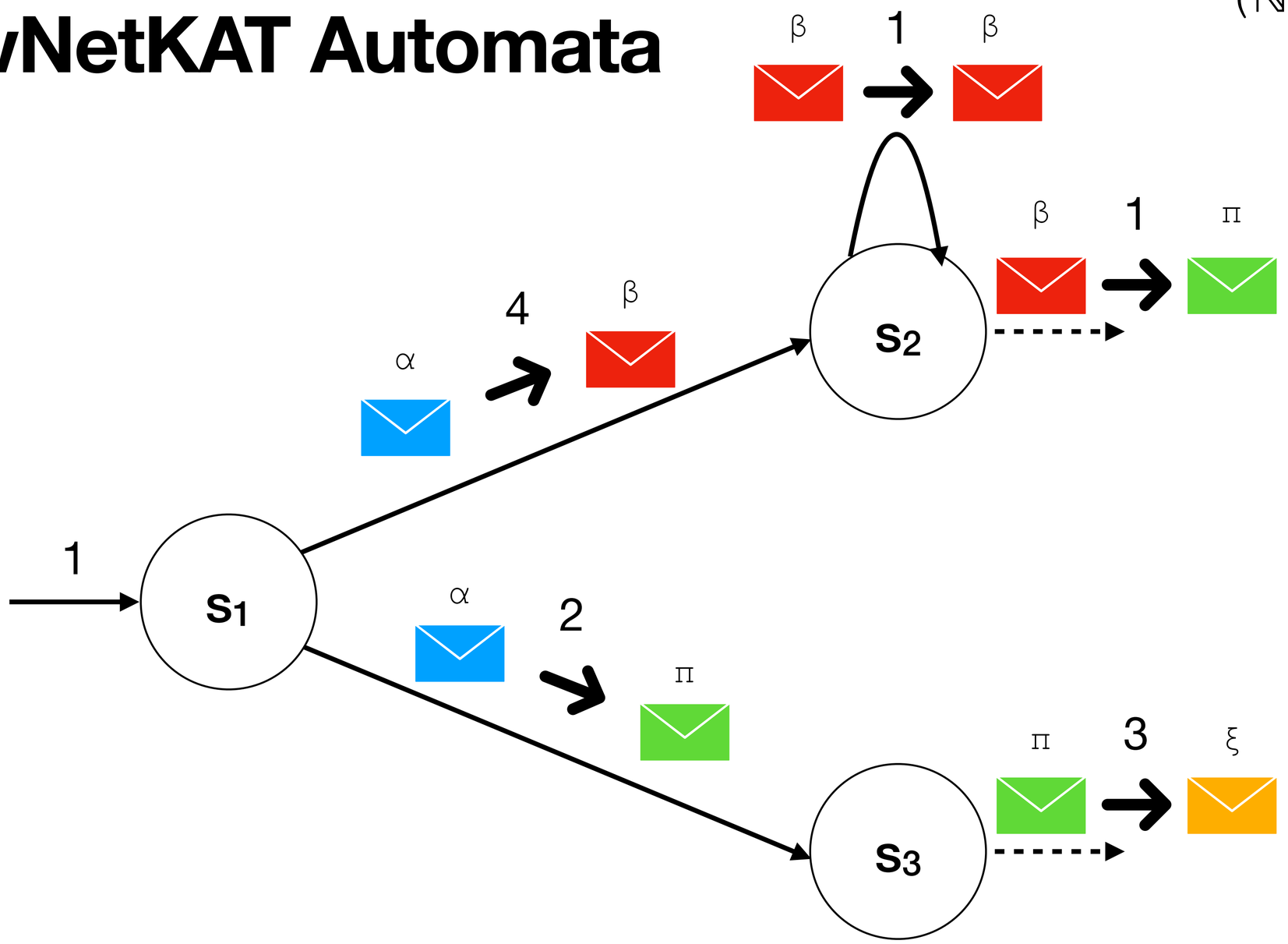
wNetKAT Automata



wNetKAT Automata

Tropical Semiring
$(\mathbb{N}^{+\infty}, \min, +, +\infty, 0)$



wNetKAT Automata

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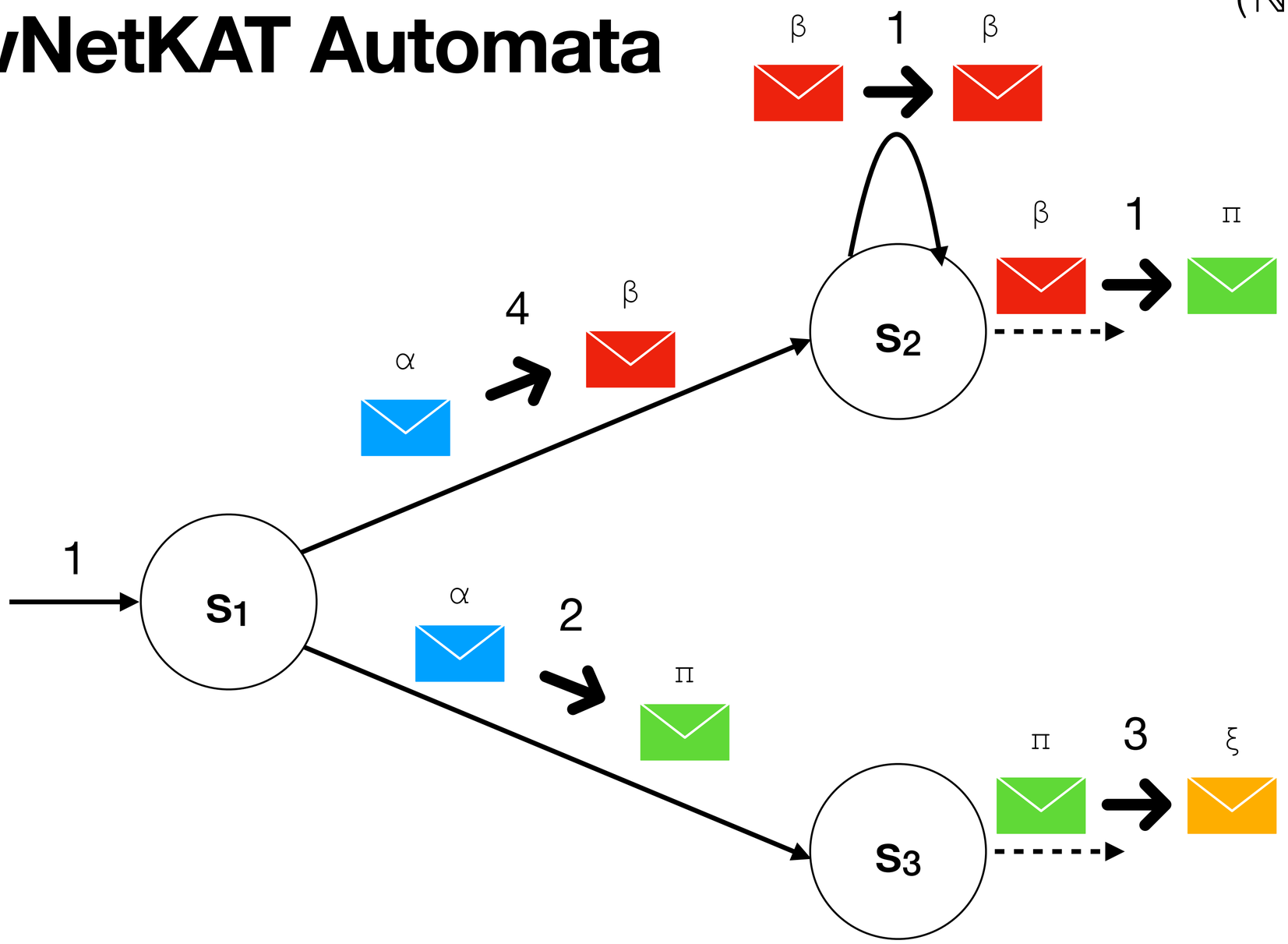

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wNetKAT Automata

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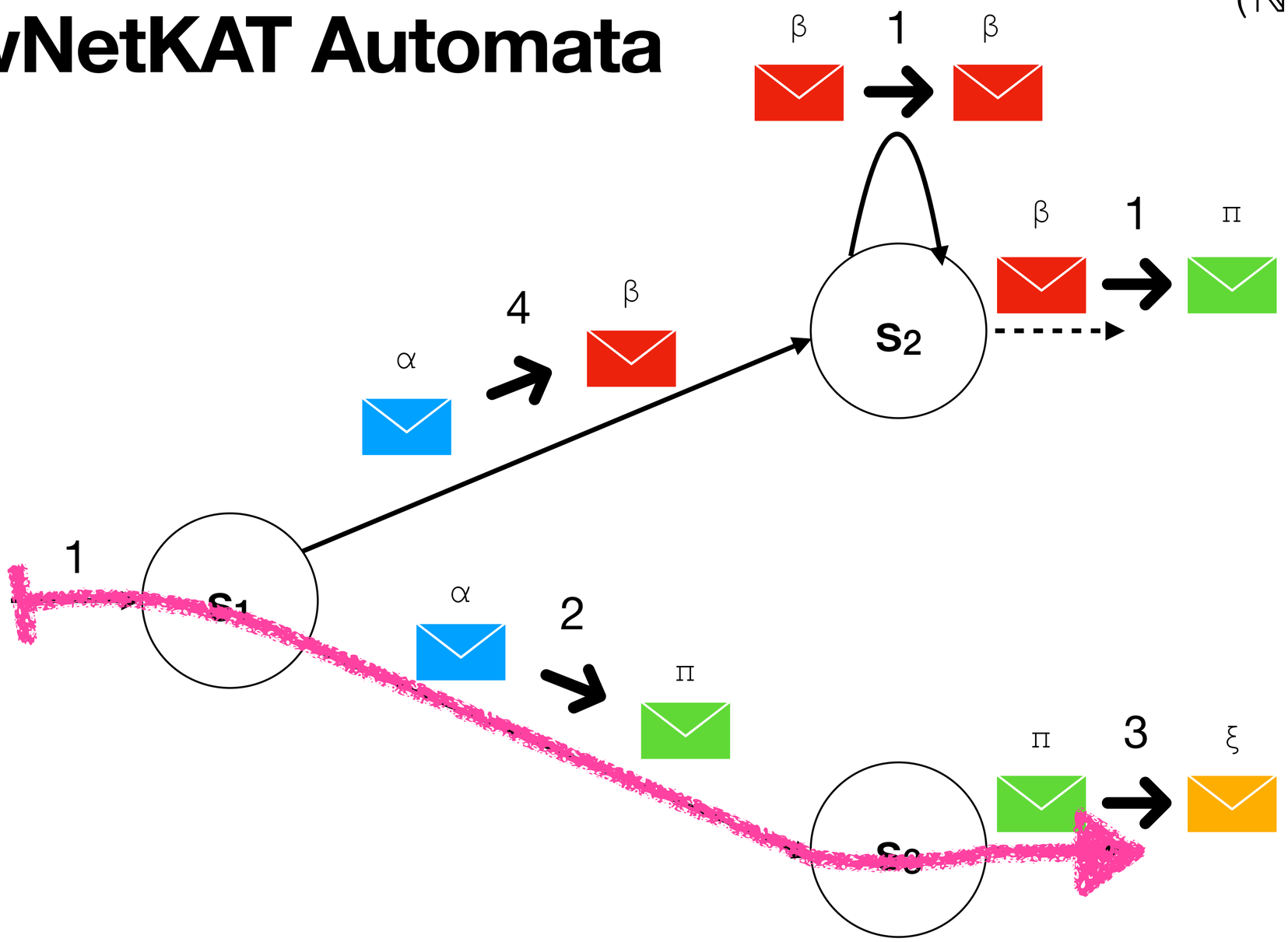
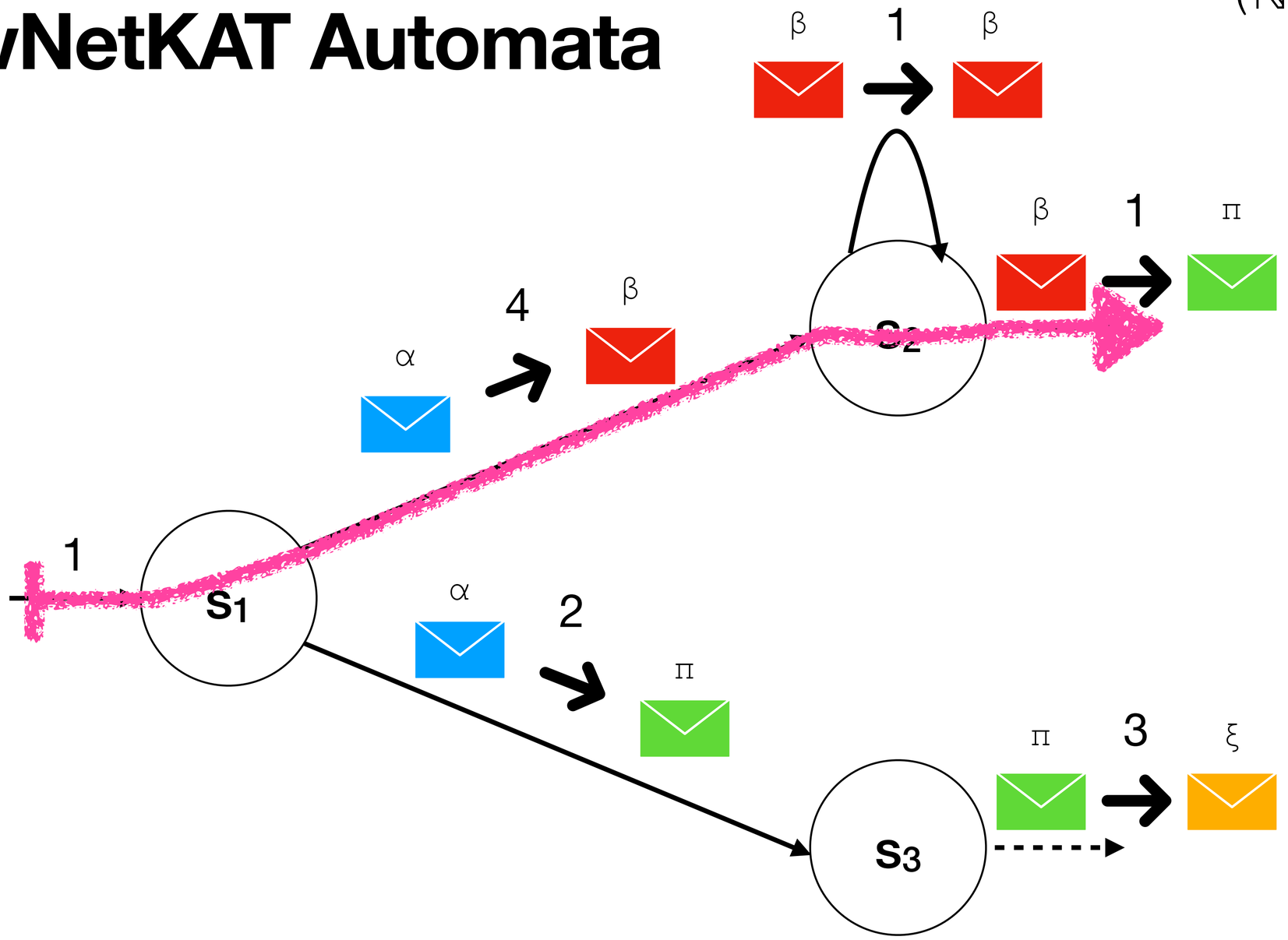


Language Accepted:

$\alpha\ \pi\ \xi \mapsto 6$

wNetKAT Automata



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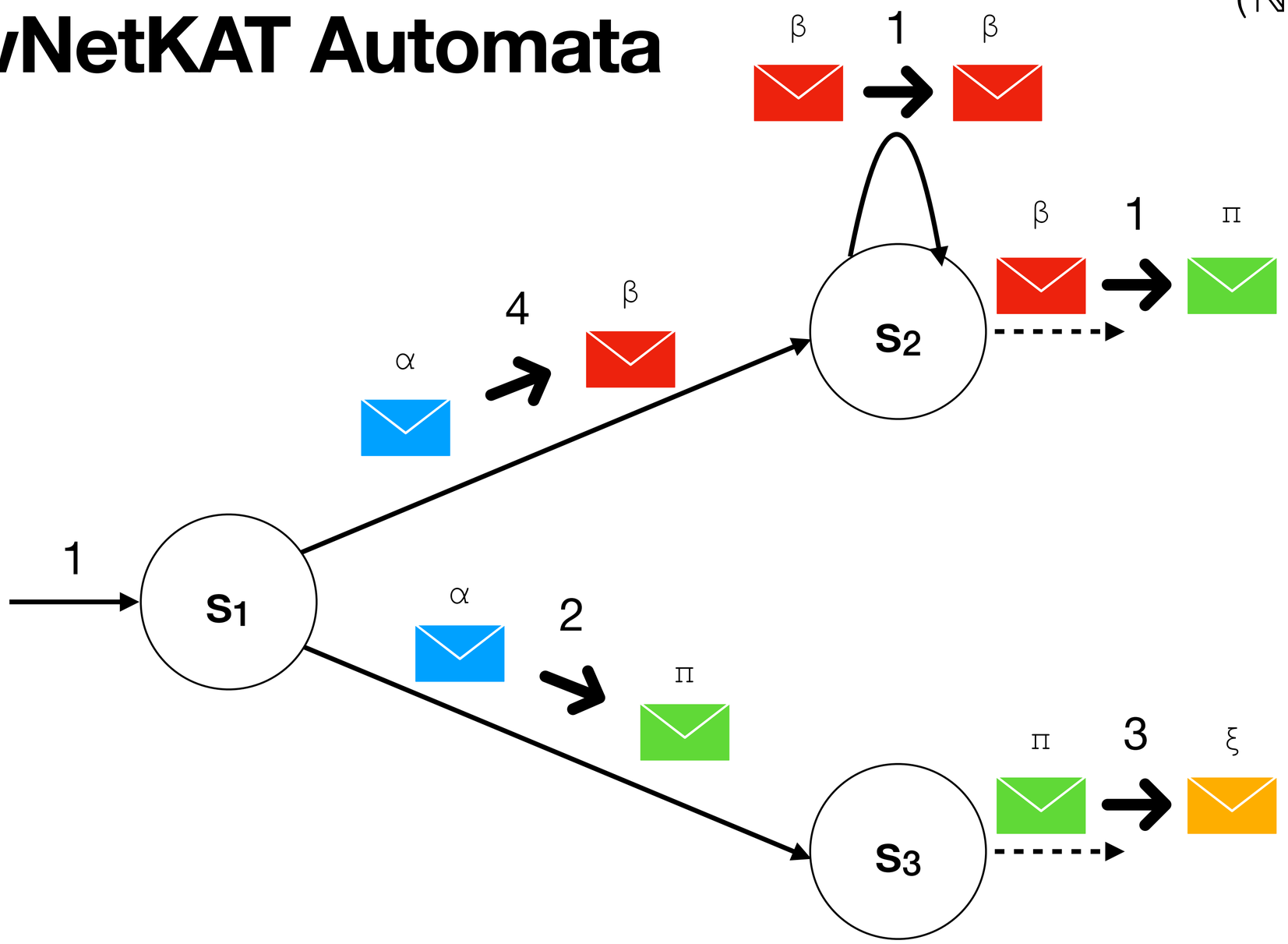

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...

wNetKAT Automata

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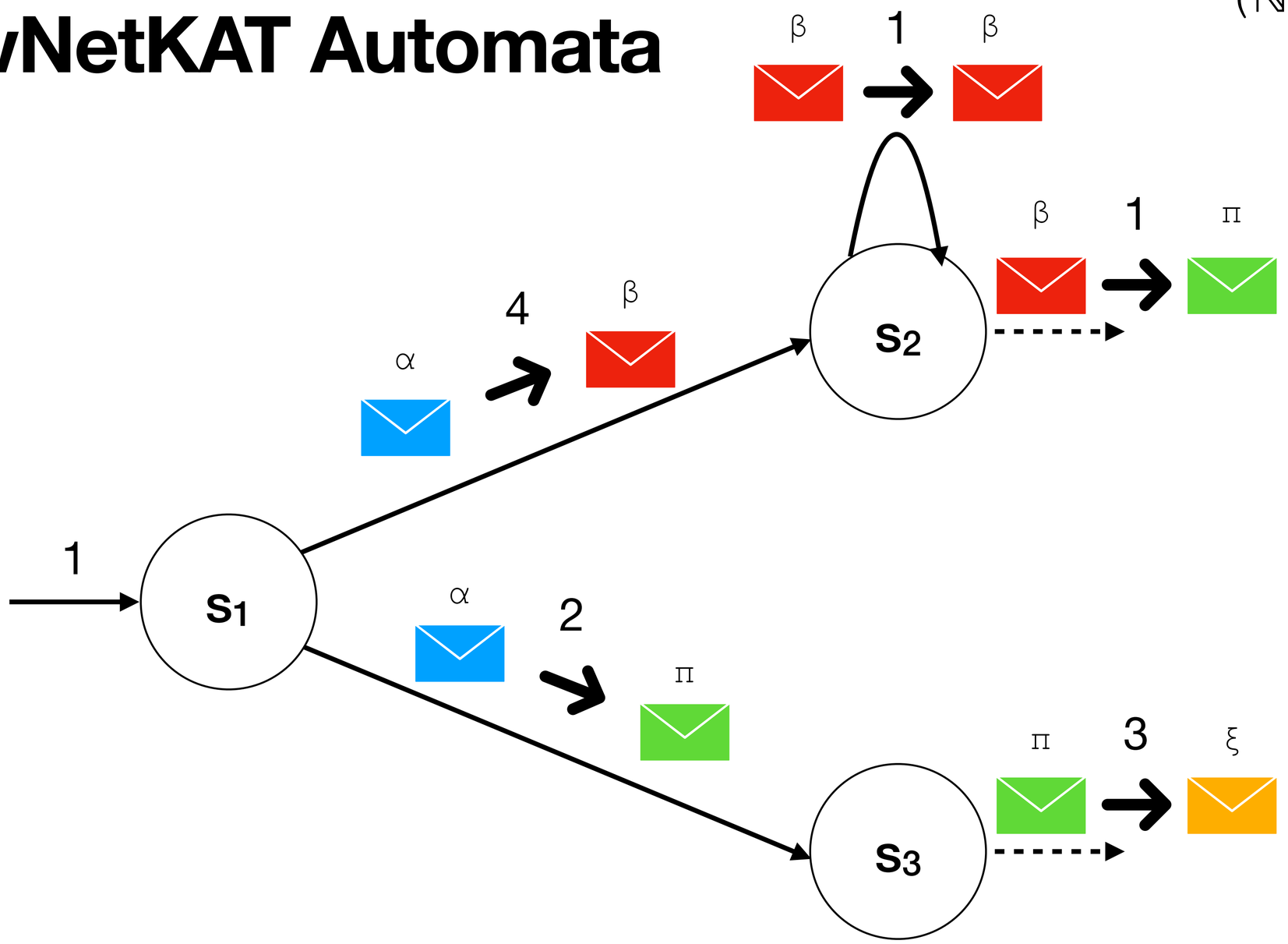

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Complete network traces

wNetKAT Automata

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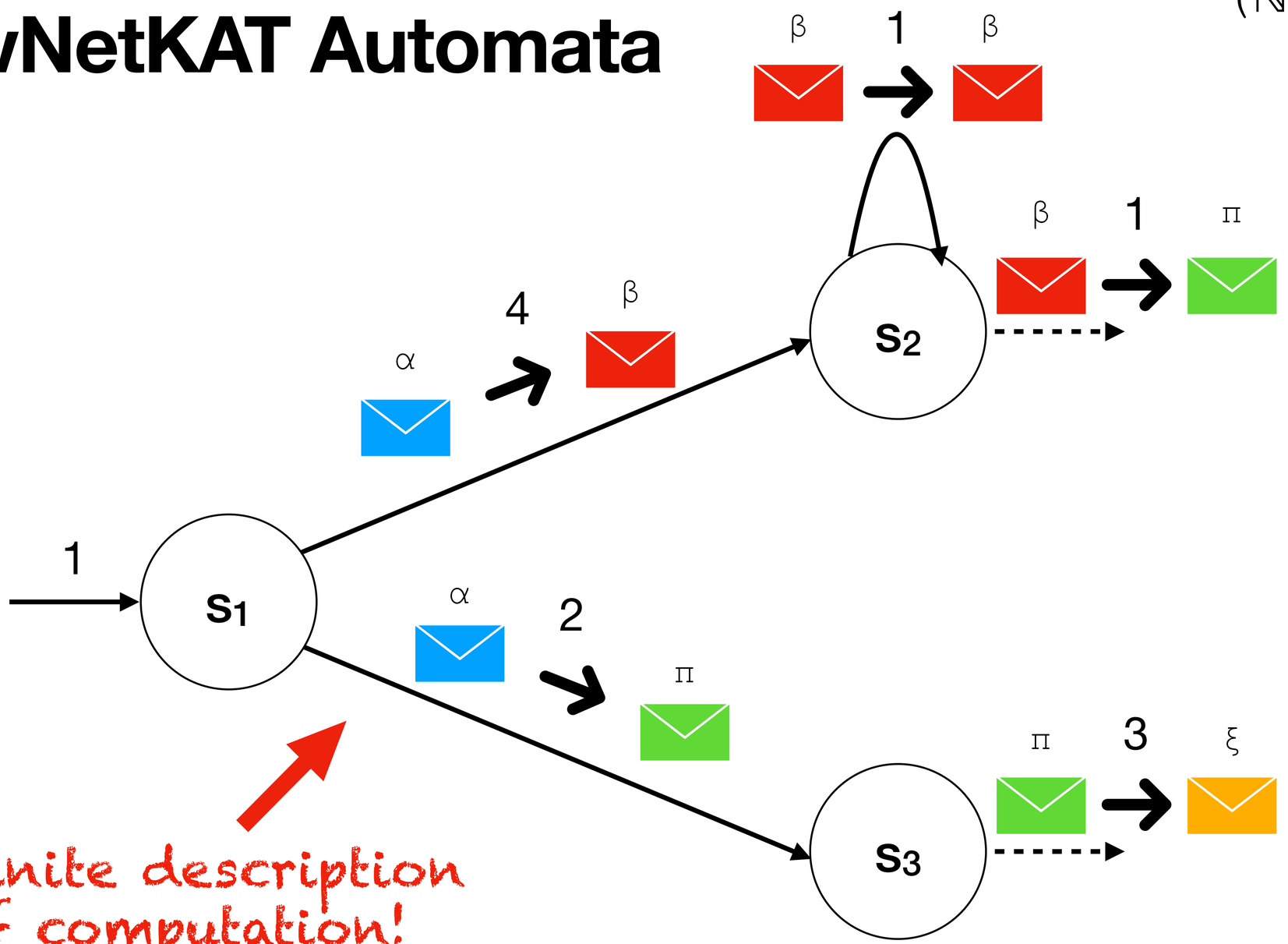

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Finite description of computation!

Complete network traces

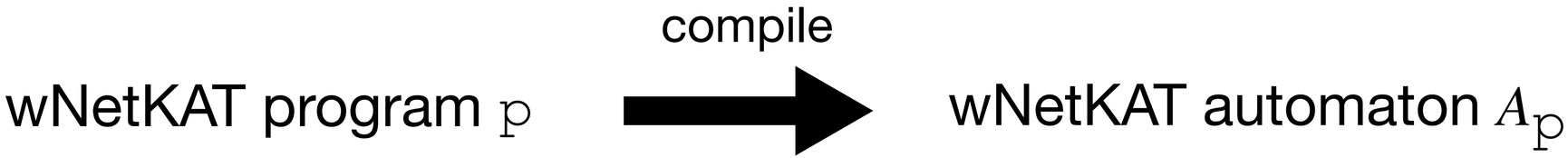
Automatic Verification

wNetKAT program $\mathtt{p}$

Automatic Verification

wNetKAT program `p` 

Automatic Verification



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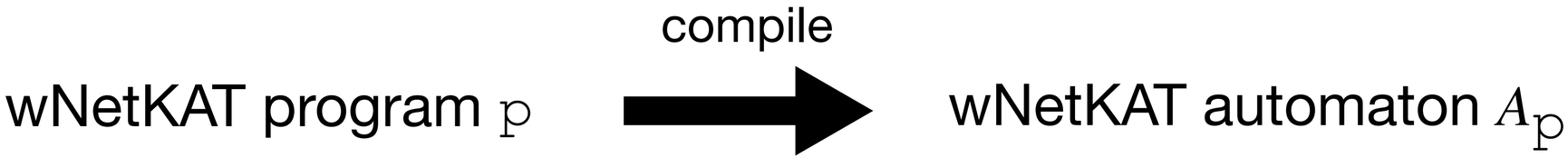
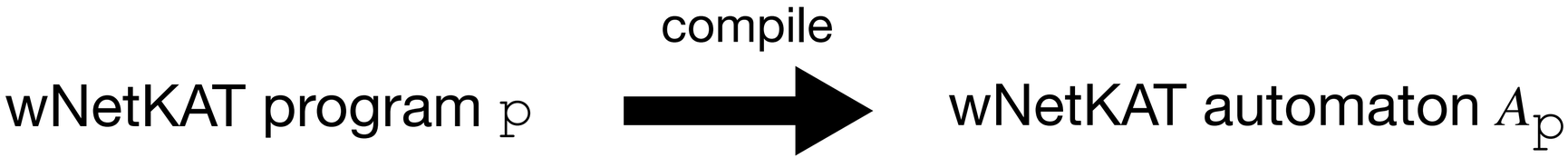


We show:

Automatic Verification



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$$[\![\mathrm{p}]\!] \;=\; [\![A_{\mathrm{p}}]\!]$$

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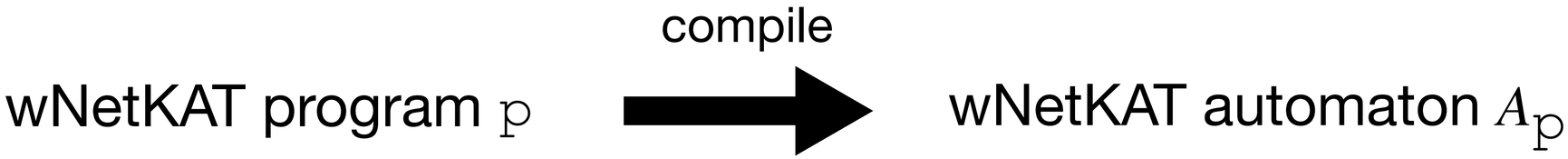

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Theorem:
Semantics of any wNetKAT program can be computed by compiling to wNetKAT automata.

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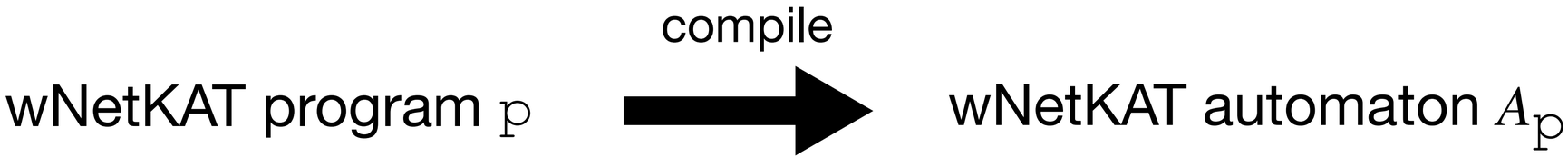

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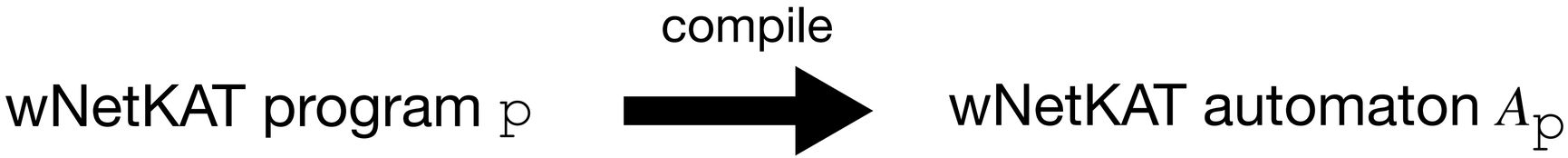

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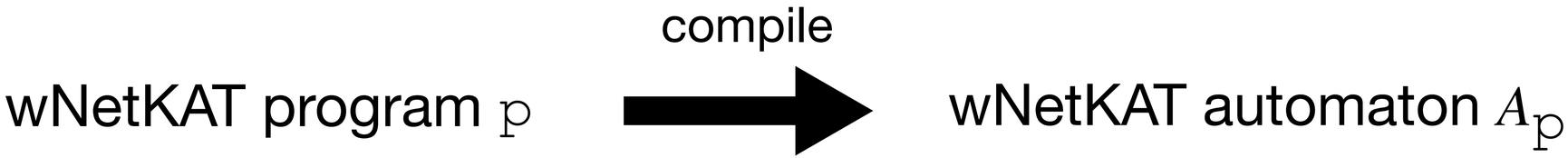
⇒ Automatic verification of r-safety / r-reachability can be done at the level of wNetKAT automata

Automatic Verification



Theorem:
Semantics of any wNetKAT program can be computed by compiling to wNetKAT automata.

⇒ Automatic verification of $\mathtt{r}$-safety / $\mathtt{r}$-reachability can be done at the level of wNetKAT automata

Several properties of automata generally become undecidable in the presence of weights!

Automatic Verification

We develop decision procedures over wNetKAT automata to establish decidability of:

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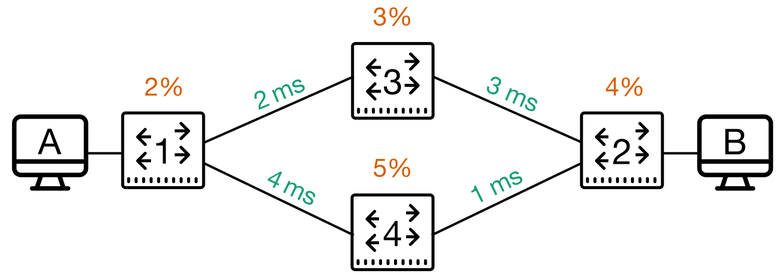
`r`**-safety**
(Does all network traffic have weight *at most* `r`)?

$$\forall \pi, h: \ [\![p]\!](\pi)(h) \leq r$$

`r`**-reachability**
(Does there exist network traffic with weight *at least* `r`)?

$$\exists \pi, h: \ [\![p]\!](\pi)(h) \geq r$$

Automatic Verification



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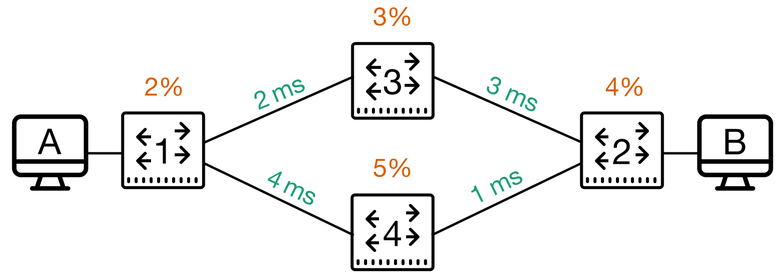

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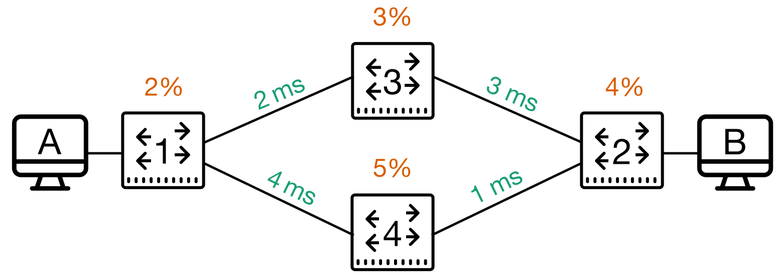

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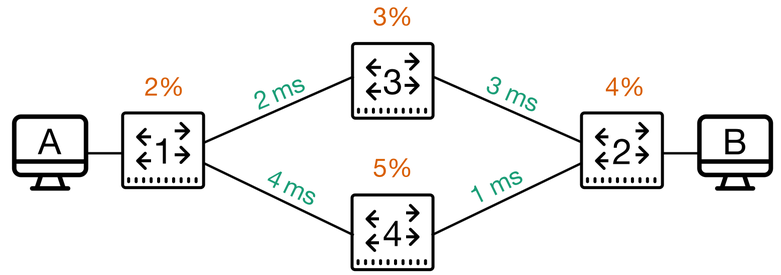
Can host A deliver packets to host B within 5ms?

Automatic Verification



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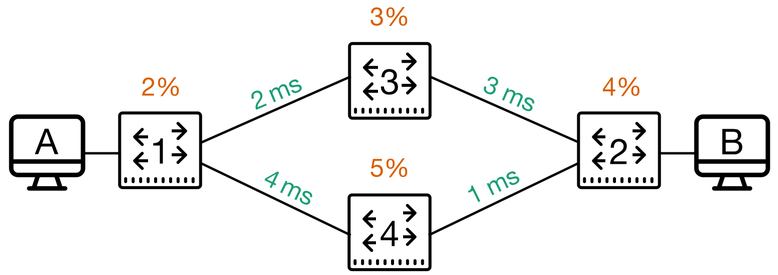

Generic over a broad class of semirings

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Thank You!

See Paper For:

- Semantics of wNetKAT
- Compilation to automata
- Decision procedures
- Case study

Current/Future Work:

- Lean mechanization
- Symbolic representations of automata
- Efficient implementations of procedures