deTector:
a Topology-aware Loss Localization System for Data Center Networks

Peng Yanghua

Losses have significant impact

- Significant latency increase and throughput drop
  - Violating SLA and drop revenue
- Takes operators up to tens of hours to find and fix the problem

cite http://netseminar.stanford.edu/seminars/05_23_16.pdf

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We want to know loss ASAP

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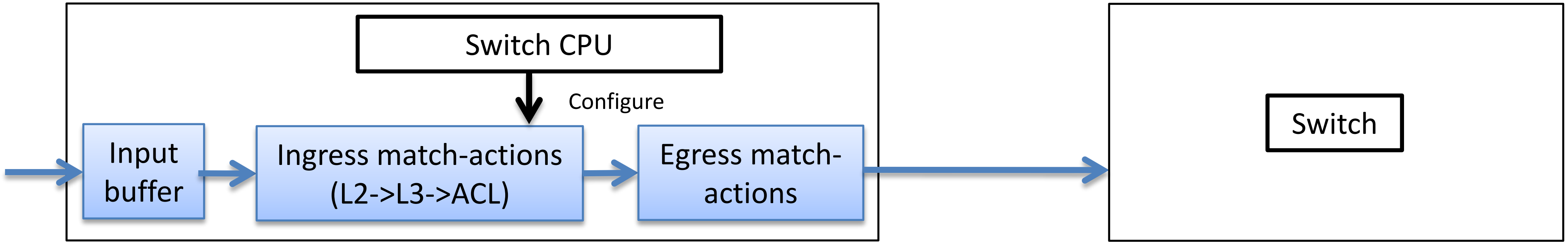
Challenge: many types of losses



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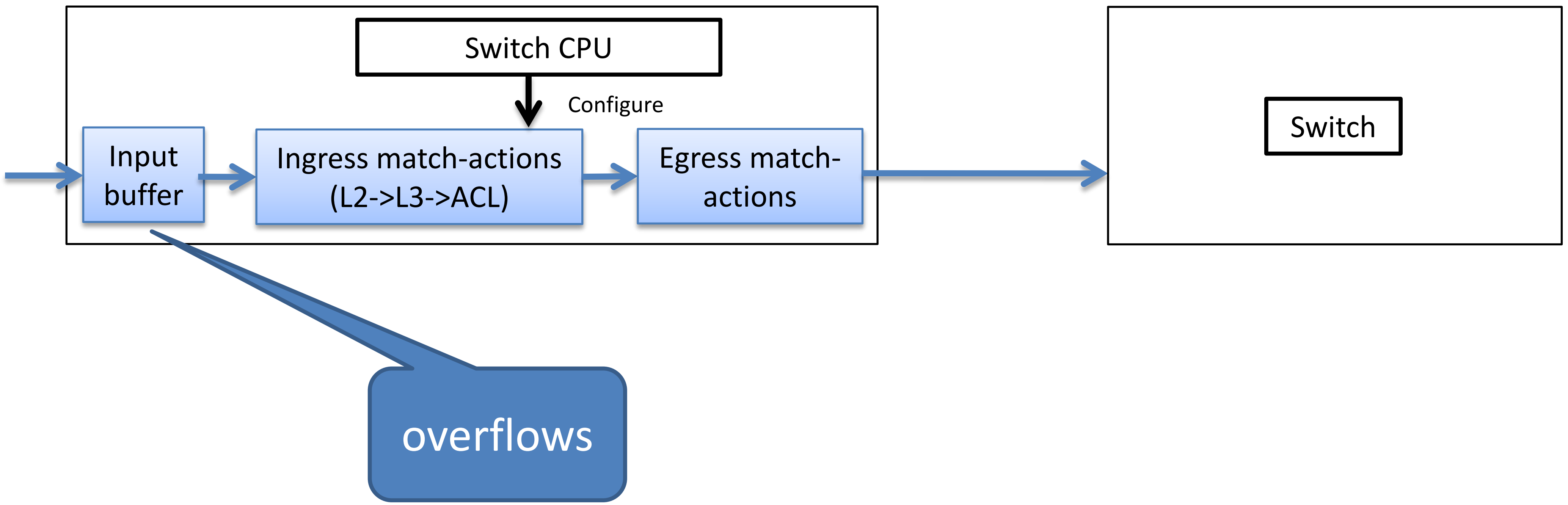

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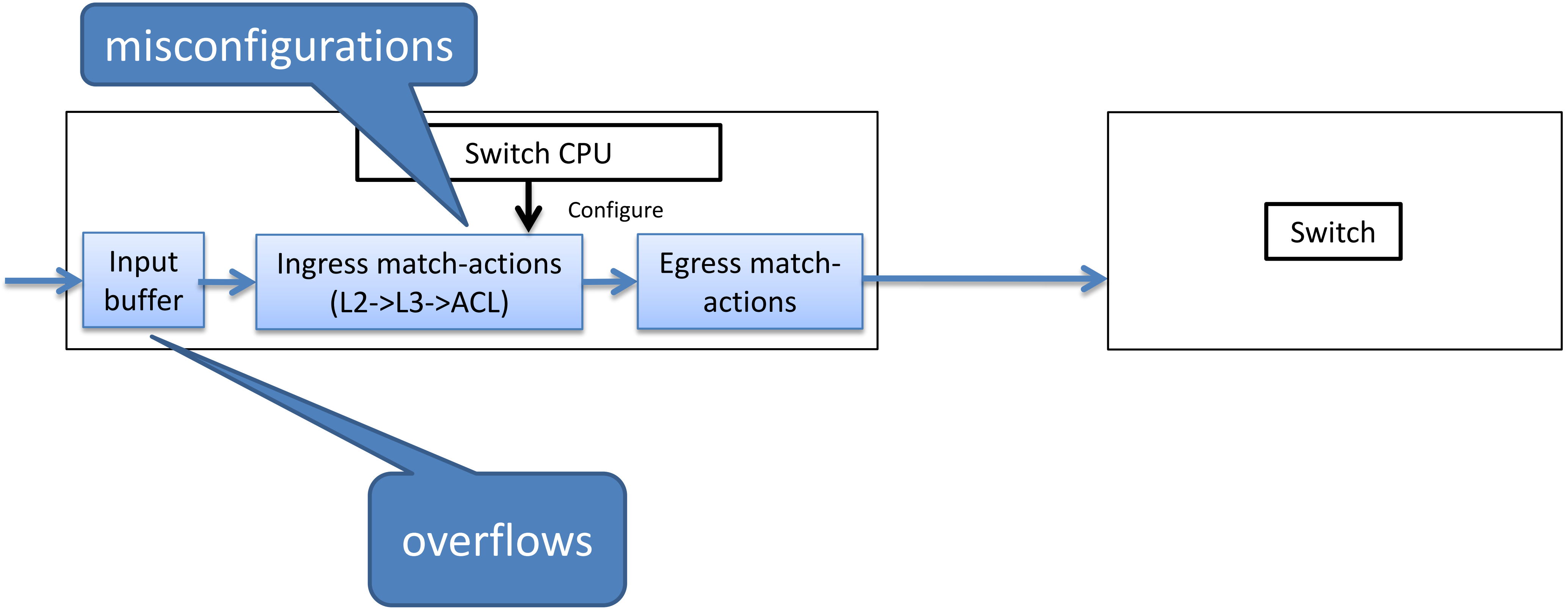

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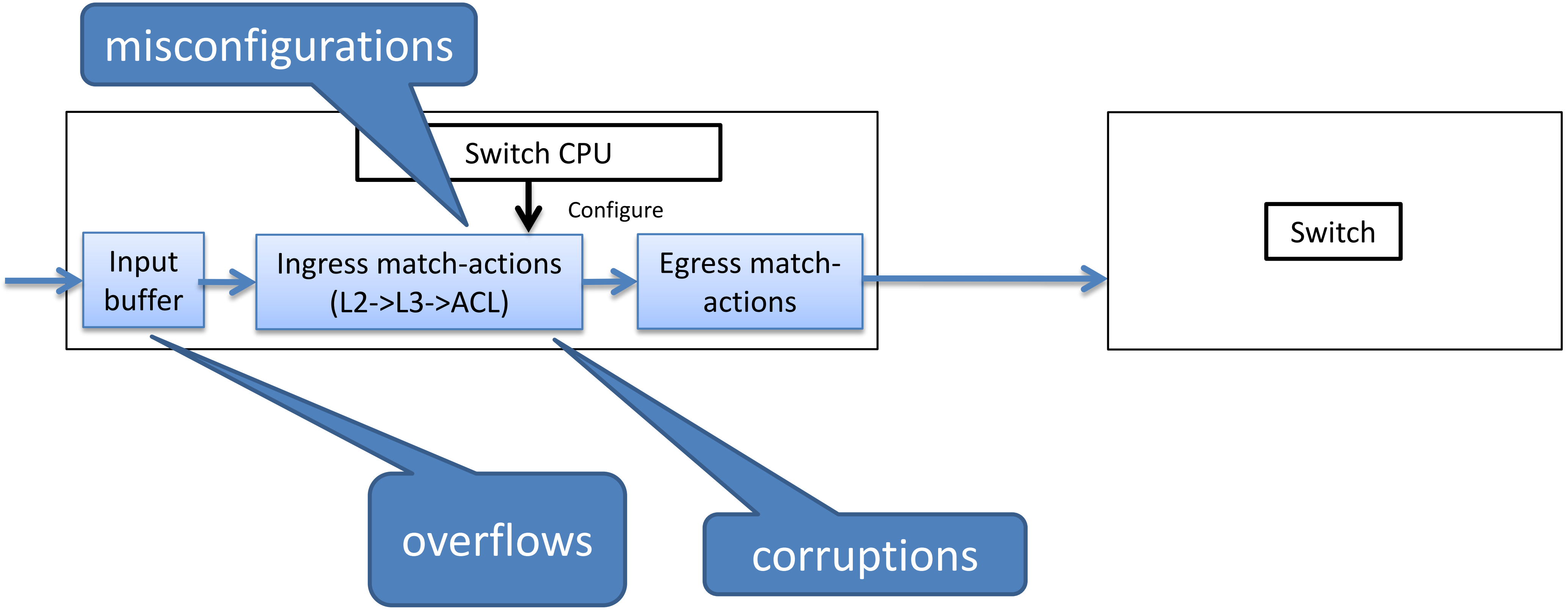

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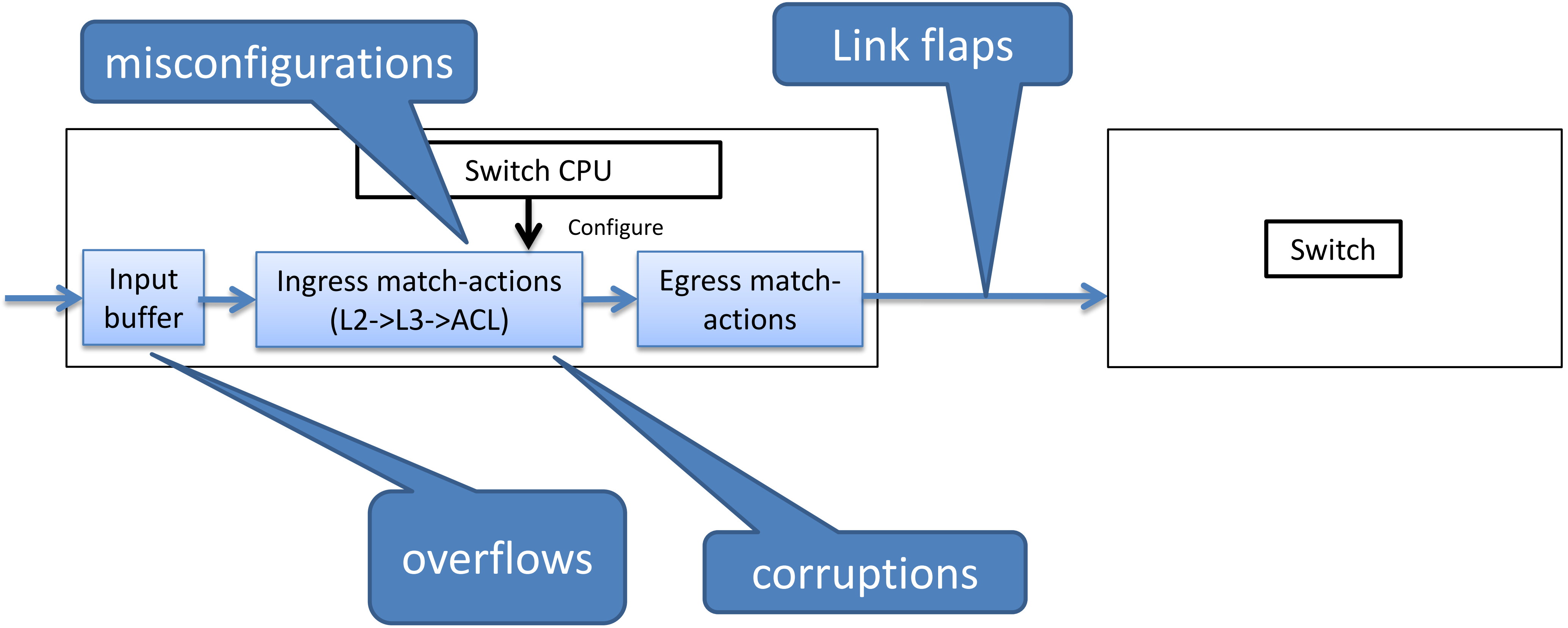

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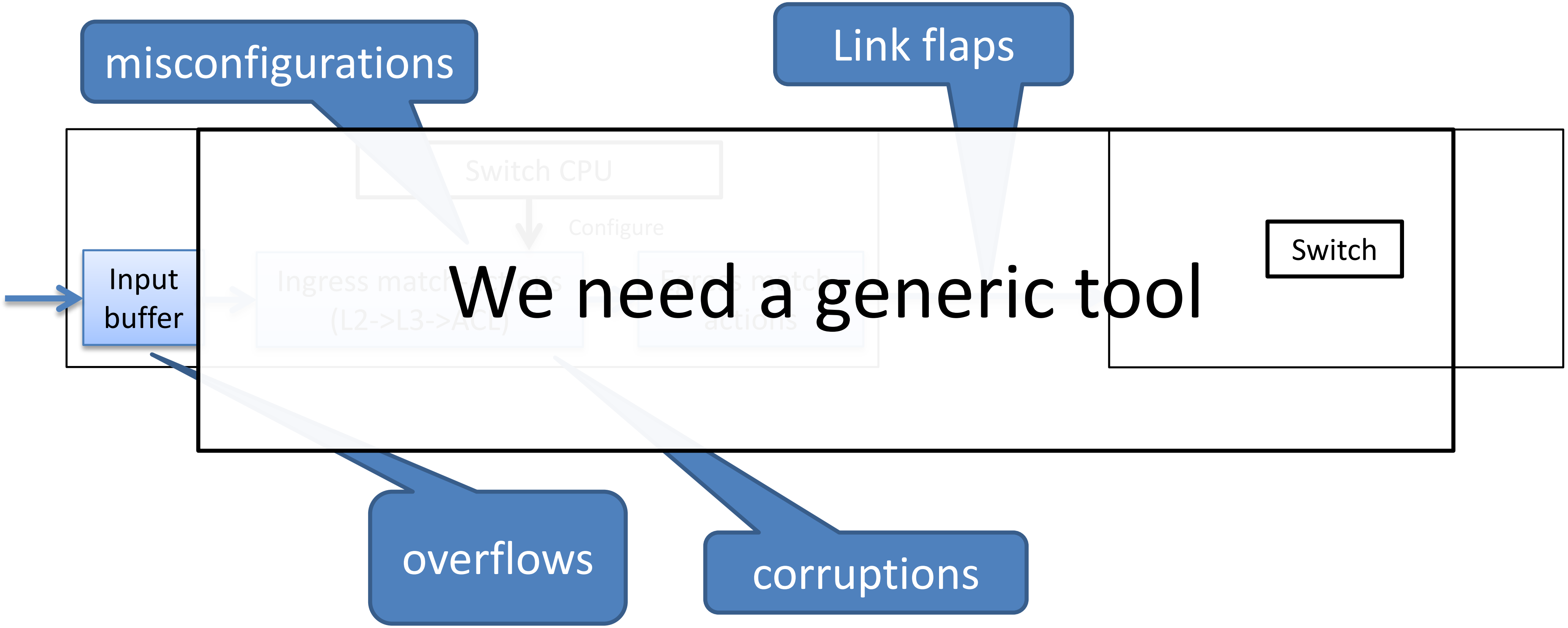

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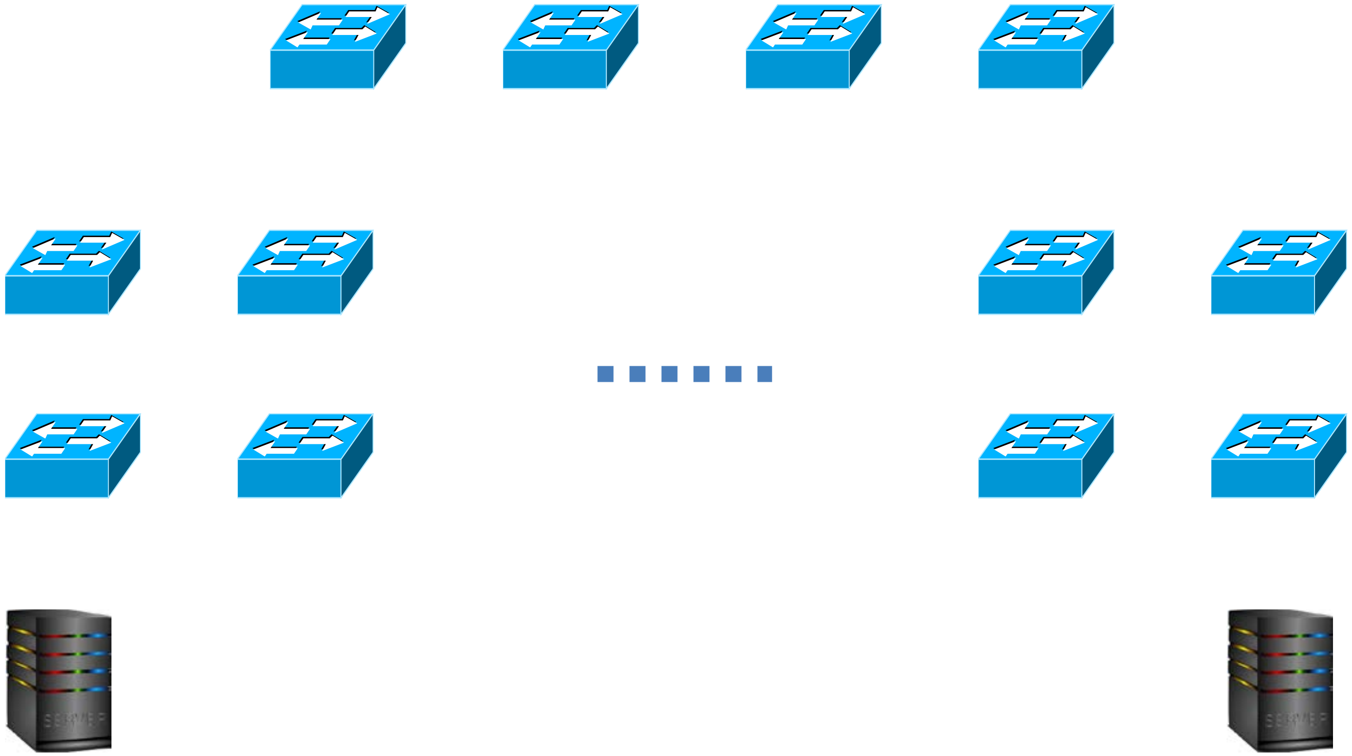

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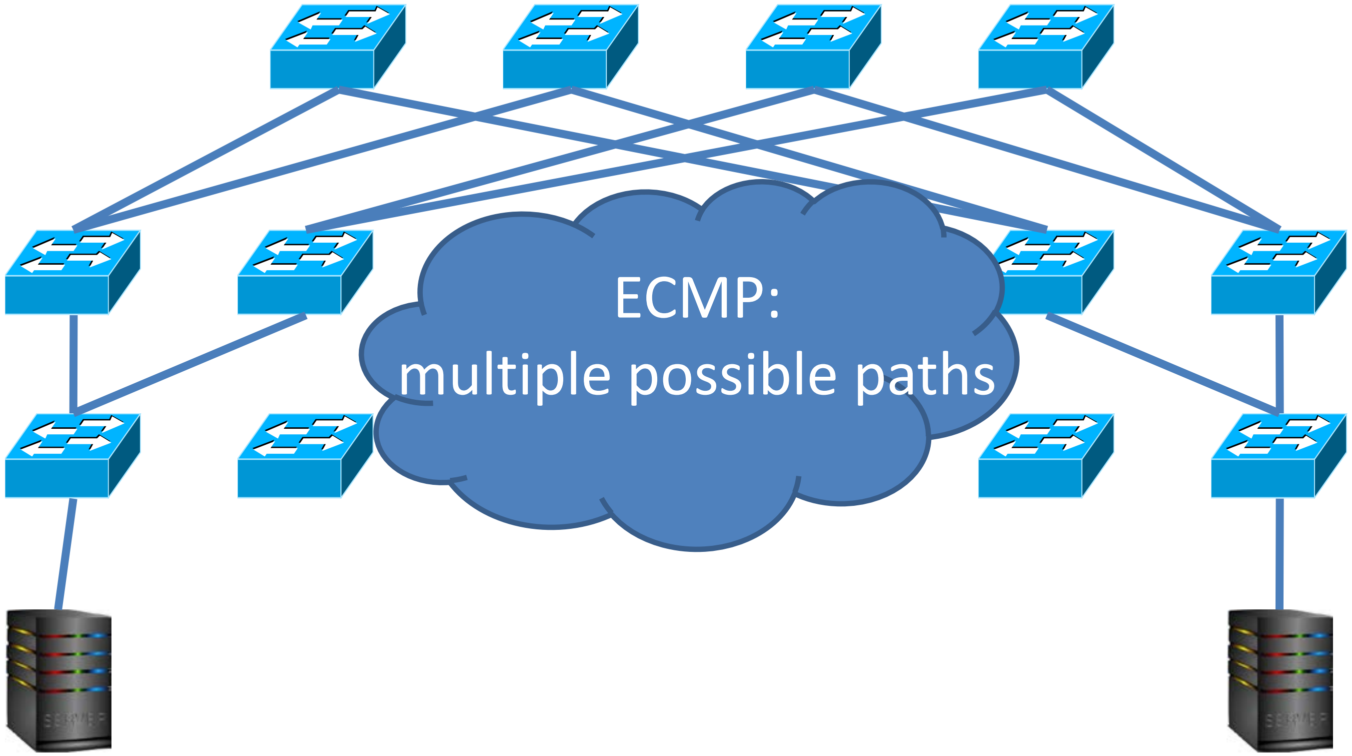

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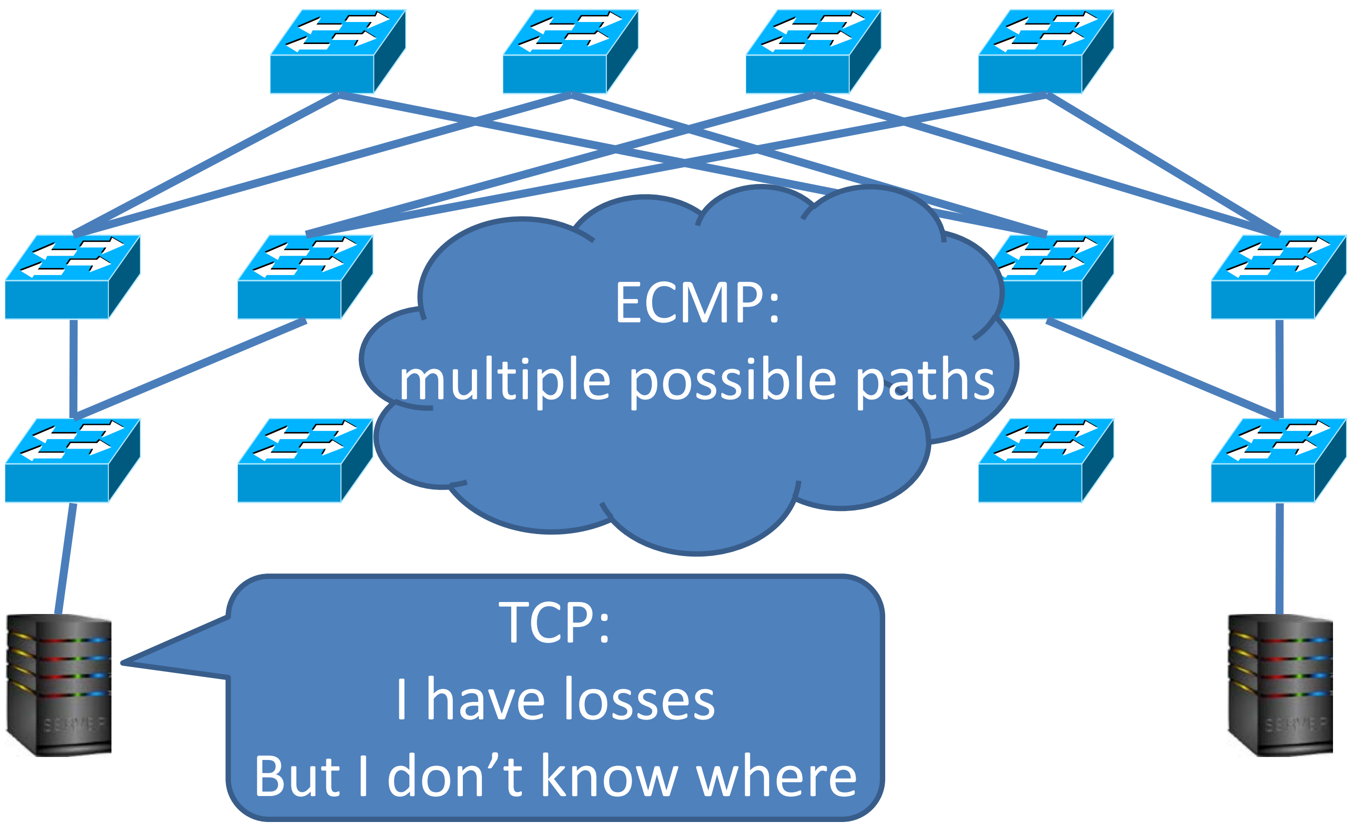

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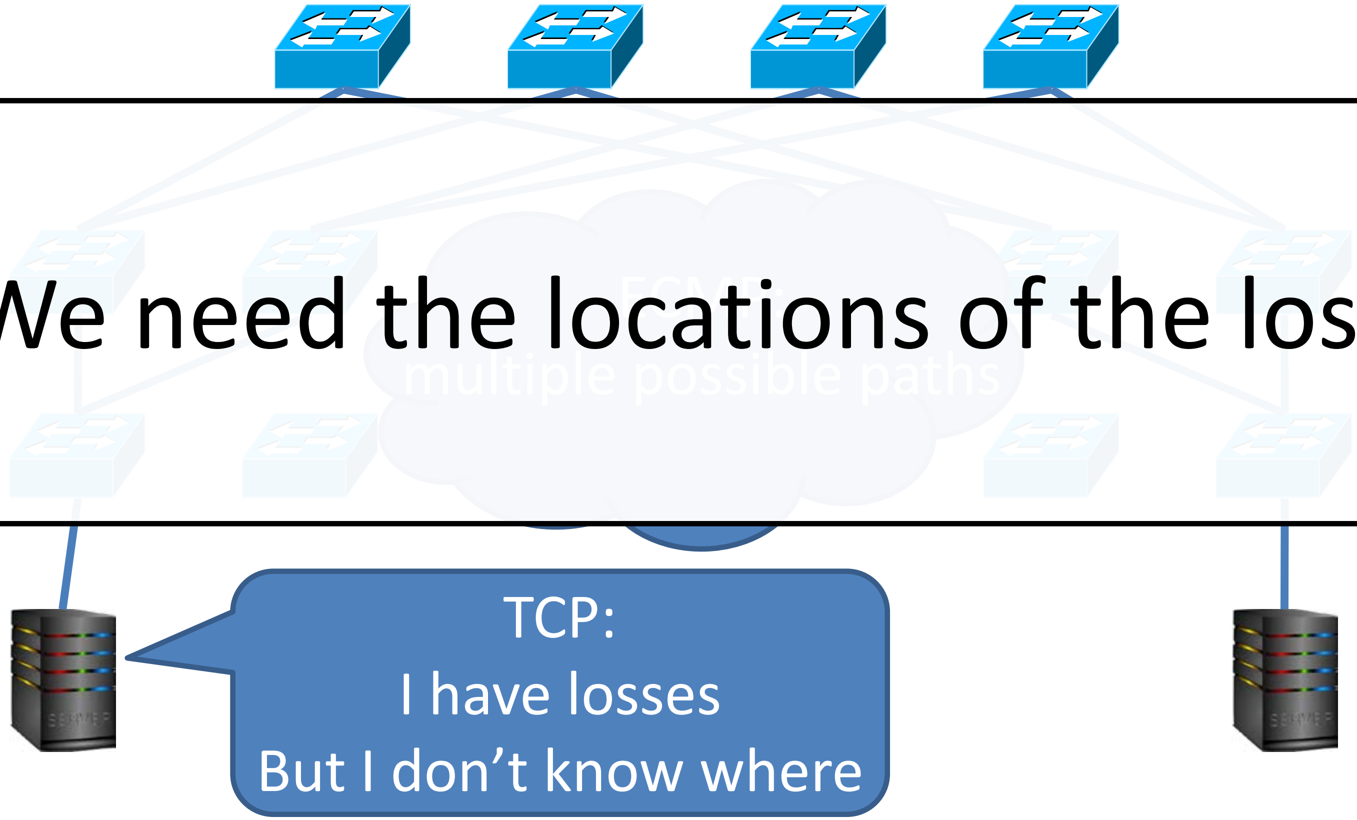
Challenge: losses could happen everywhere

We need the locations of the losses



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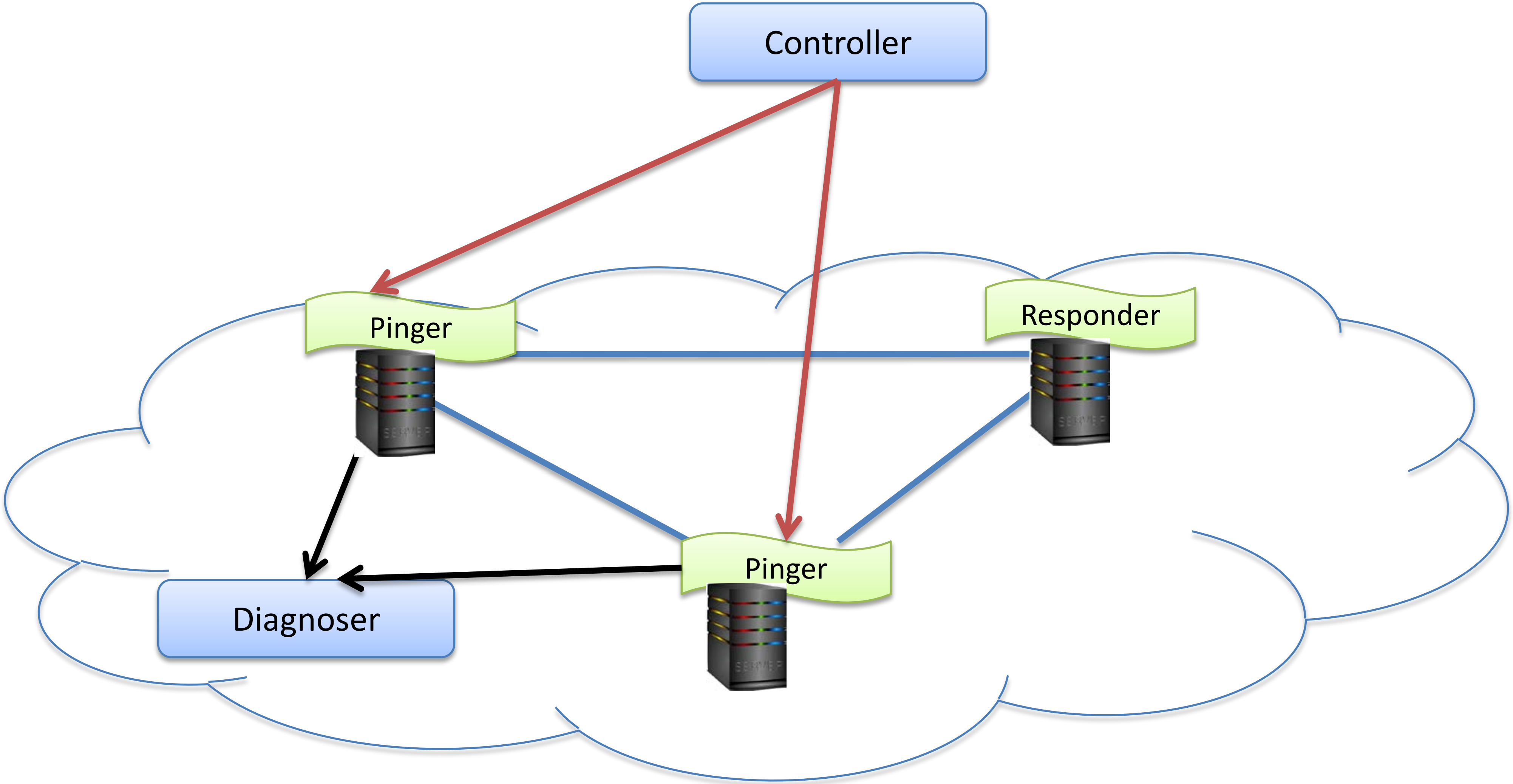
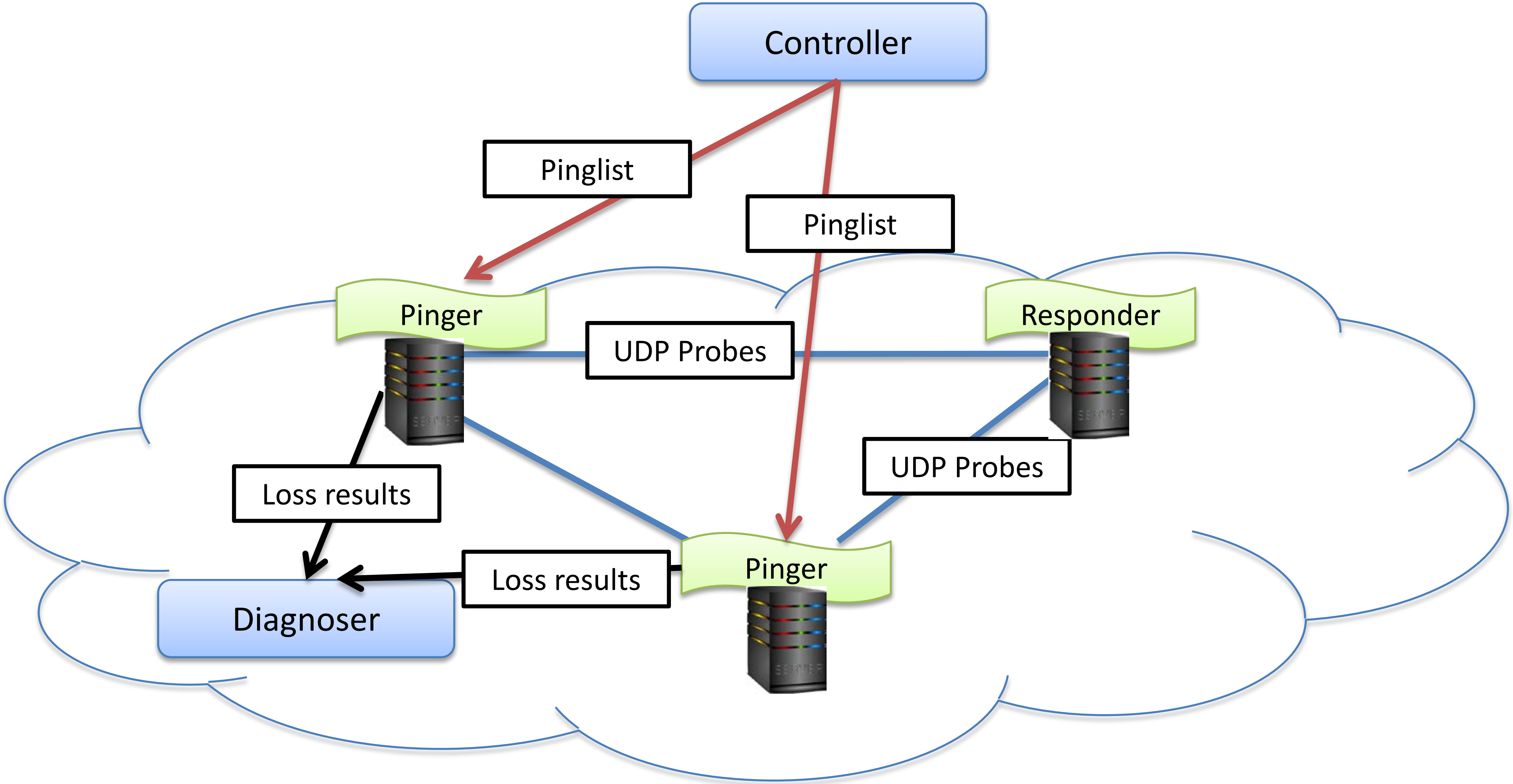
deTector

- deTector is a real-time, low-overhead and high-accuracy monitoring system for large-scale data center networks.

deTector architecture



deTector workflow



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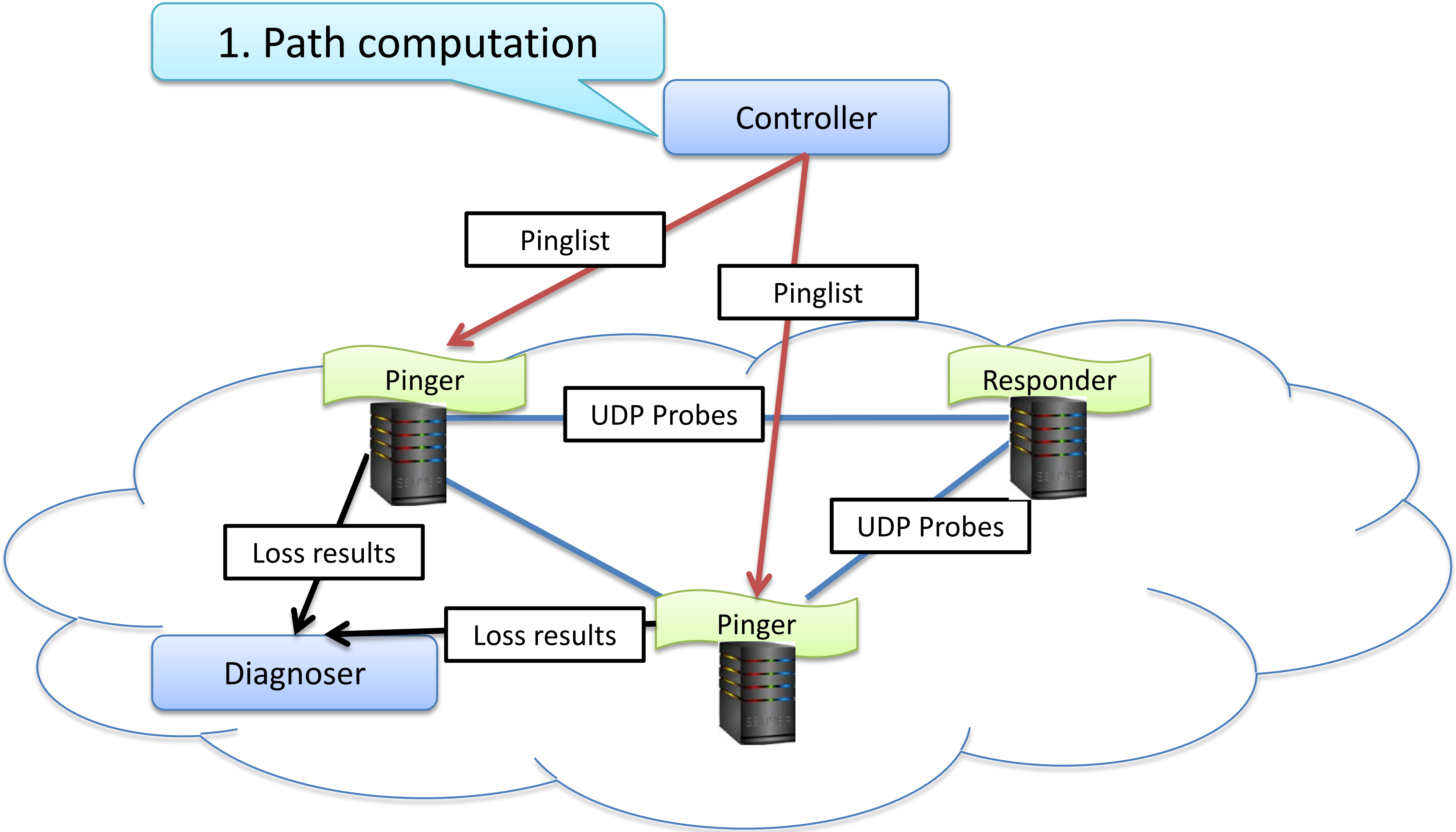

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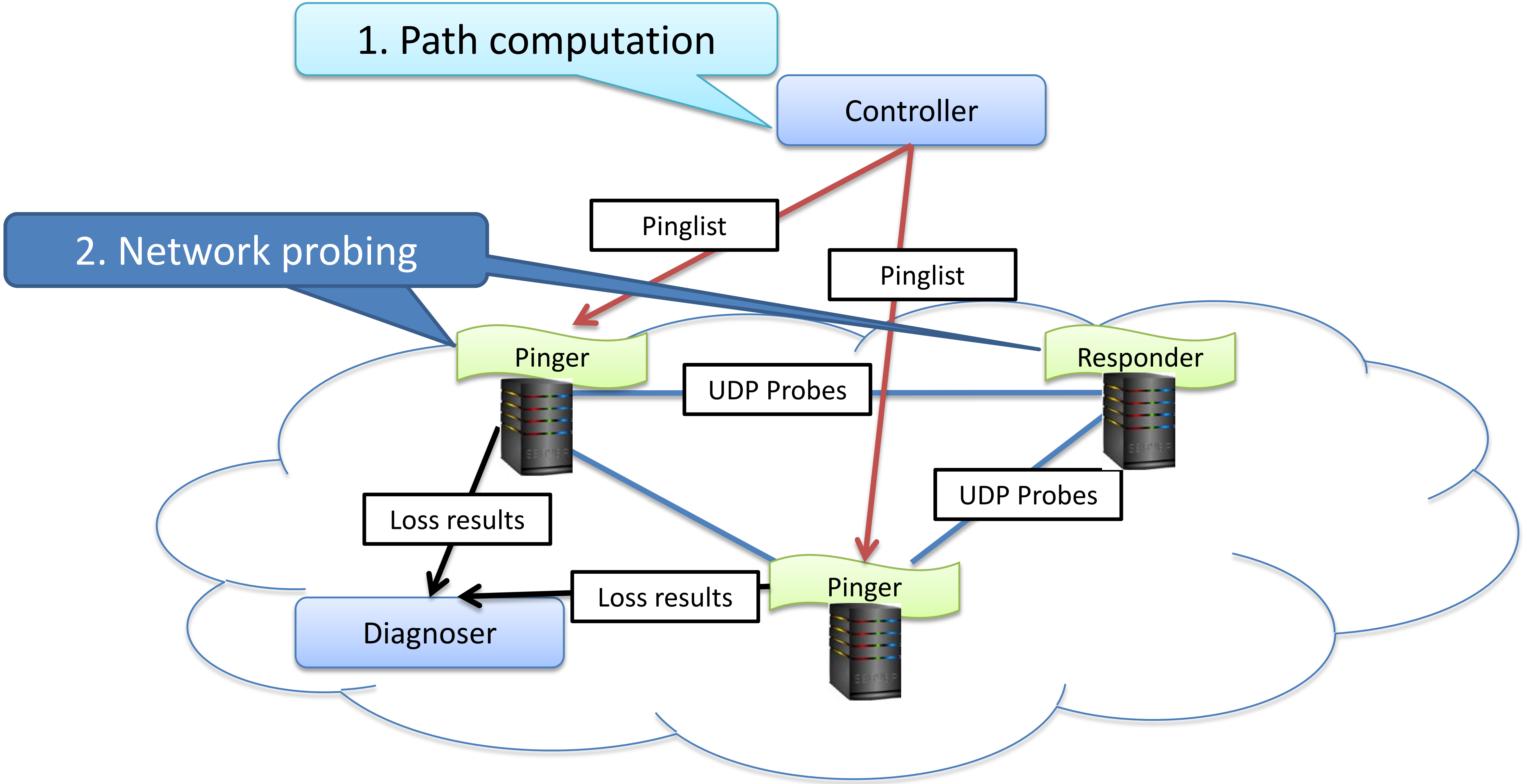

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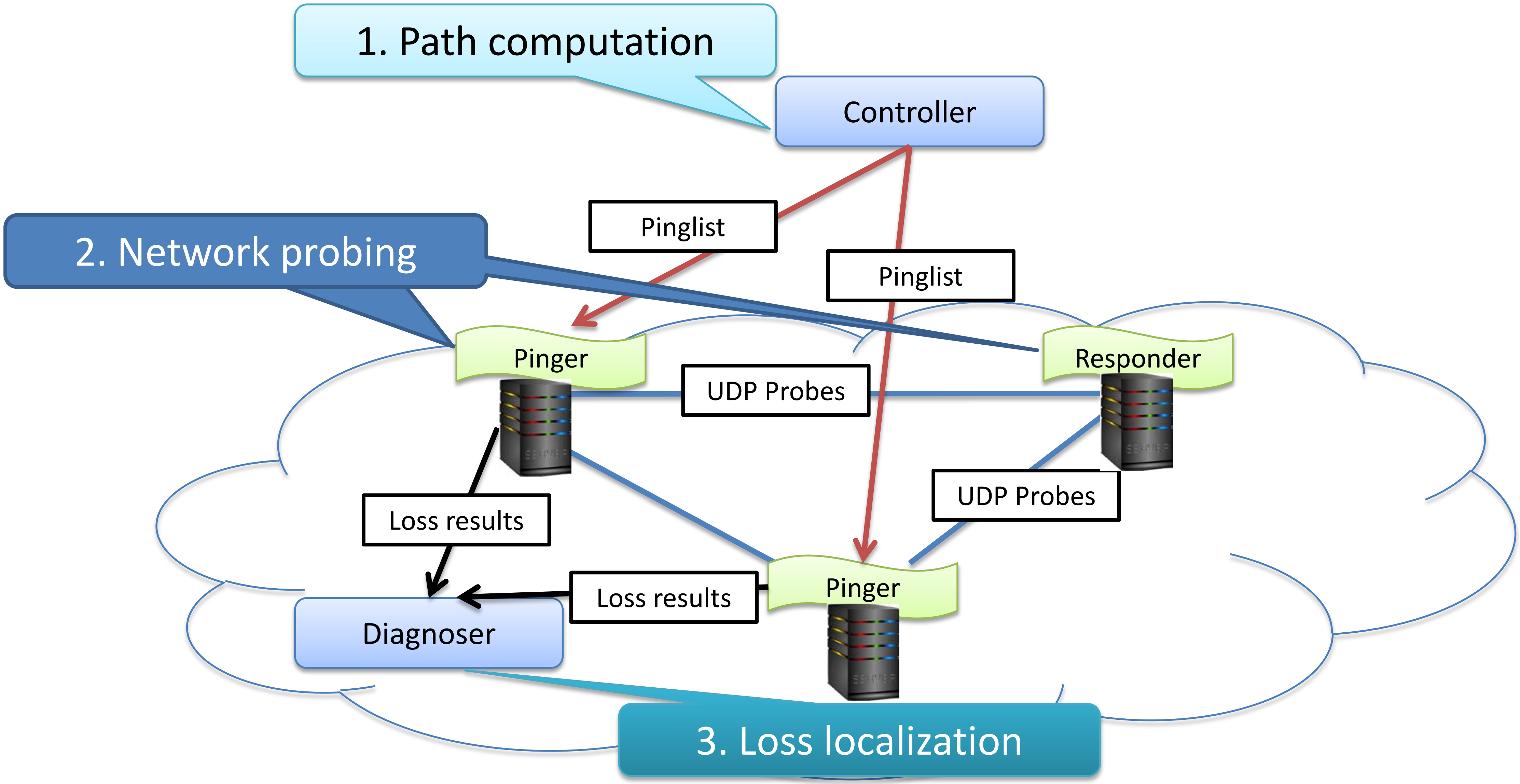
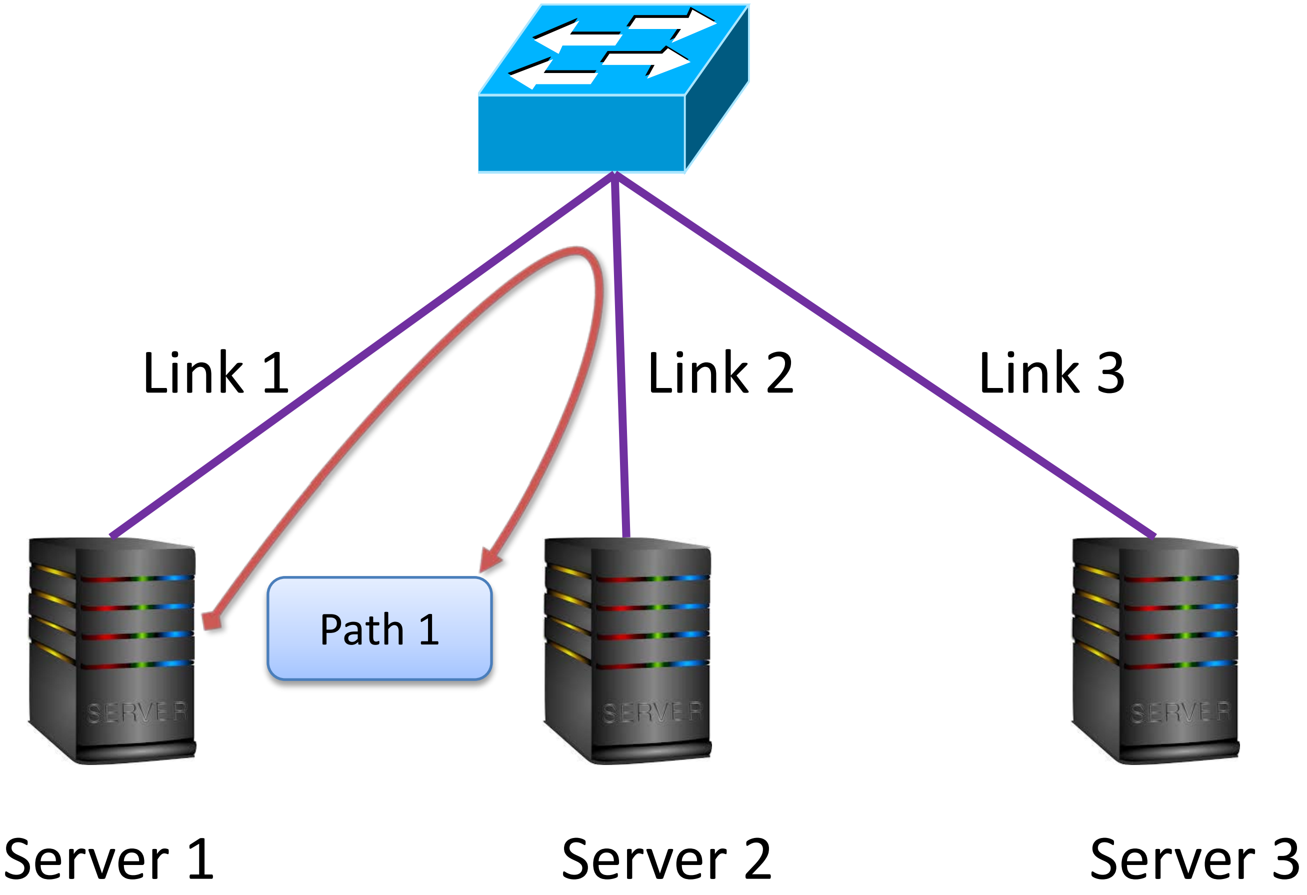


Part I: Path Computation

Routing matrix

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1



Problem formulation

	Link 1	Link 2	Link 3
Path 1	1	1	0
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Path 3	0	0	1

- Given a routing matrix, select probing paths to send probes:

(1) Minimize path number

(2) α-coverage

(3) β-identifiability

Problem formulation

Each link is covered by α paths

	Link 1	Link 2	Link 3
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Any β failed links can be identified correctly

An example of β-identifiability

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- Any β failed links can be identified correctly
- Probe matrix: path1 + path2

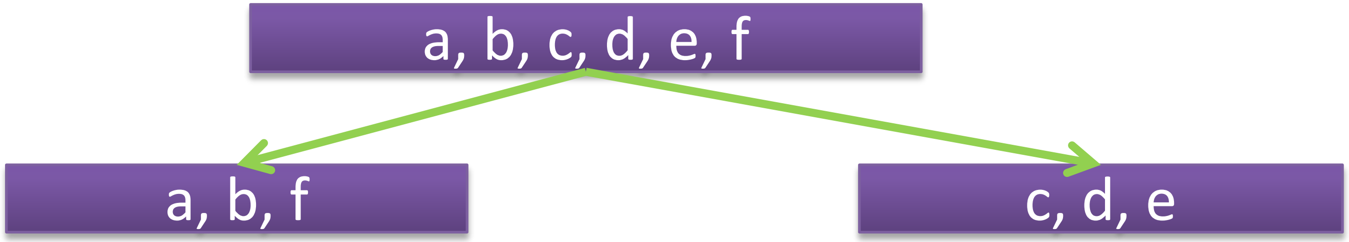
  1-identifiability but not 2-identifiability

Algorithm for 1-identifiability

a, b, c, d, e, f

Algorithm for 1-identifiability

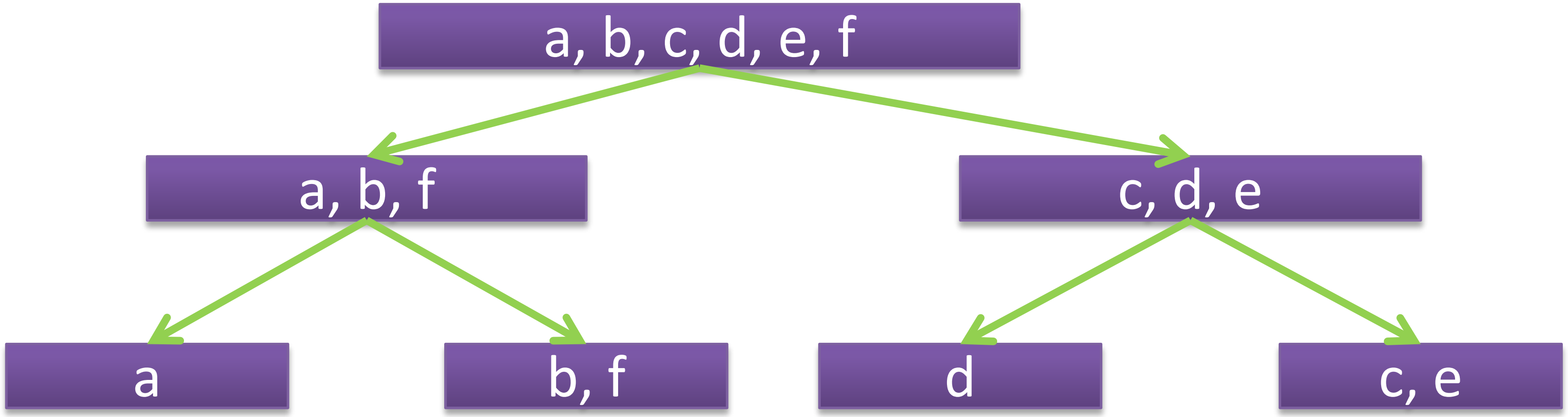
Path1: a->b->f



Algorithm for 1-identifiability

Path1: a->b->f

Path2: a->c->e

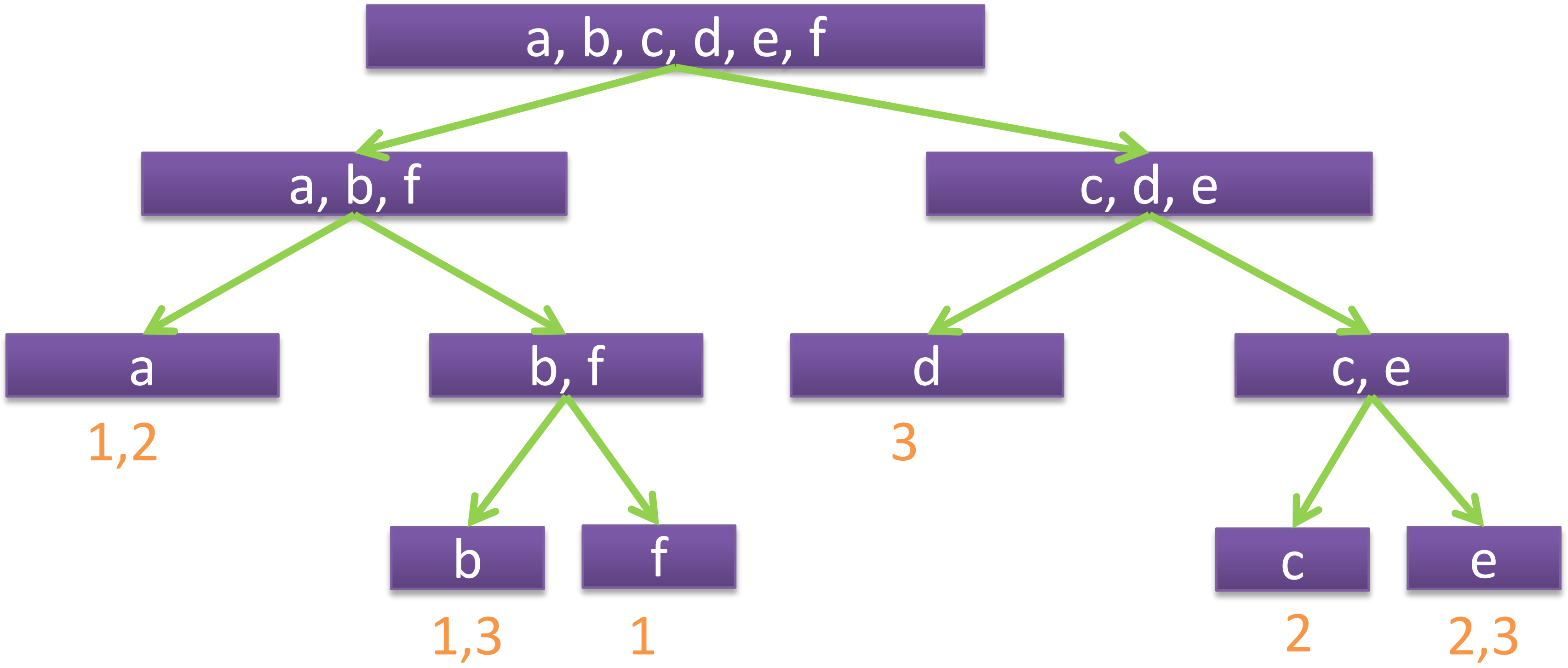


Algorithm for 1-identifiability

Path1: a->b->f

Path2: a->c->e

Path3: b->d->e



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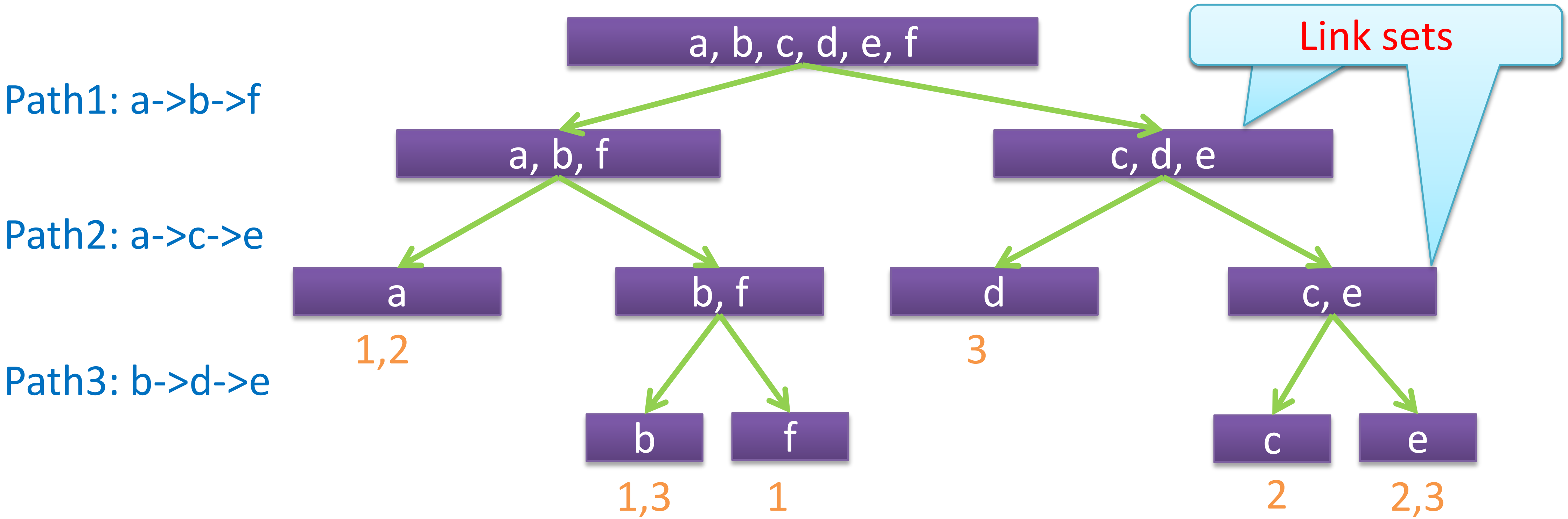
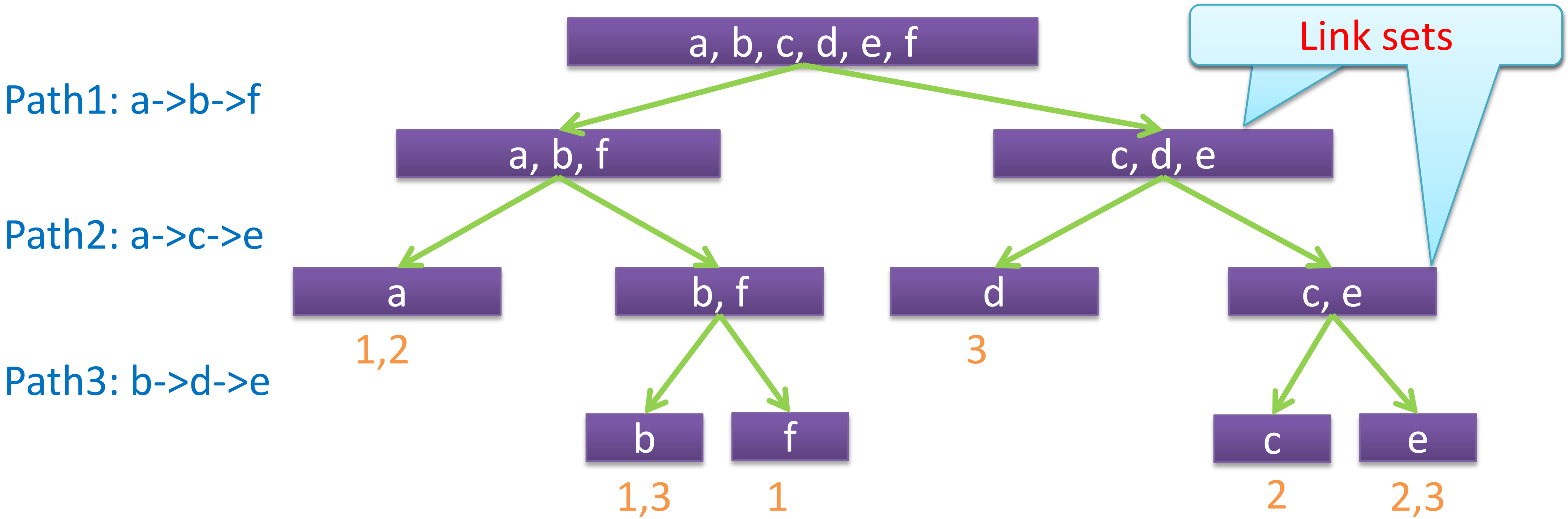


- Select the path that is present in the largest number of link sets to split link sets as much as possible.

Algorithm for 1-identifiability



- Select the path that is present in the largest number of link sets to split link sets as much as possible.
- Stops when the total number of link sets equals to the number of links

1-identifiability => β-identifiability

	Link 1	Link 2	Link 3	Link 12	Link 13	Link 23
Path 1	1	1	0	1	1	1
Path 2	1	0	1	1	1	1
Path 3	0	0	1	0	1	1

Physical links OR Virtual links

- Extend routing matrix with virtual links.
- If virtual link 12 is bad, we say both link 1 and link 2 have been failed.

α-coverage

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- Assign a counter w[link] to each link to track the number of paths through it.
- If w[link] > α, then the link has enough paths through it.

PMC algorithm

- Define a score for each path

$$score(path) = \sum_{link \in path} w[link] - \#\text{ of link sets on } path$$

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- Stop when achieving α-coverage and β-identifiability

PMC algorithm

Algorithm 1 PMC: Probe Matrix Construction Algorithm

Require: $\mathbf{R}$, α, β

Initialize w, $score$ to $\mathbf{0}$, $setnum$ to 1, $selpaths$ to $\emptyset$
$\mathbf{R'} \leftarrow LINKOR(\mathbf{R}, \beta)$
$paths \leftarrow$ all paths in $\mathbf{R'}$, $physlinks \leftarrow E$
while $(setnum \neq |E| \;\|\; physlinks \neq \emptyset)$ && $paths \neq \emptyset$ **do**
    for $path \in paths$ **do**
        update $score[path]$ according to (1)
    $path \leftarrow \text{argmin}_{path' \in paths}\, score[path']$
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    update $setnum$ as the total number of link subsets after split by $path$
return probe matrix constructed by paths in $selpaths$ (retaining only physical links on the paths)

Extend routing matrix with virtual links

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Select the path with minimal score

PMC algorithm

Extend routing matrix with virtual links

Update path score

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Update w[link] and remove links that achieve α-coverage

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Update the total number of link sets

PMC algorithm

- Achieves 63% approximation ratio.
- Time complexity $O(n^2)$ where n is the number of paths.
- A Fattree(64) DCN has more than 2^{32} paths, running time > 24 hours

Four optimizations for speedup

- Routing matrix decomposition
- Partial score update
- Lazy update
- Symmetry reduction

Routing matrix decomposition

1	1	0	0	0
1	0	1	0	0
0	1	1	0	0
0	0	0	1	0
0	0	0	1	1

1	1	0
1	0	1
0	1	1

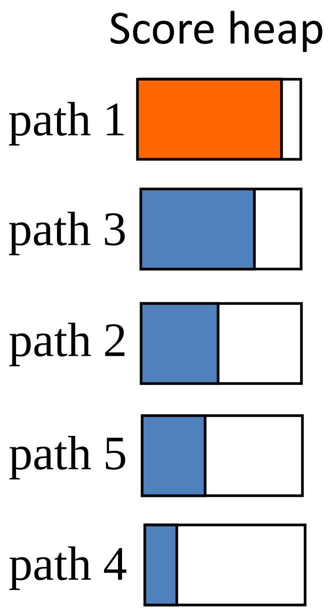
1	0
1	1

Partial update

	Link 1	Link 2	Link 3
Path 1	1	1	0
Path 2	1	0	1
Path 3	0	0	1

- After selecting path1, we only need to update the score of path2 since path3 shares no links with path1.

Lazy update



- Defer the score update of a path as much as possible until we have to.

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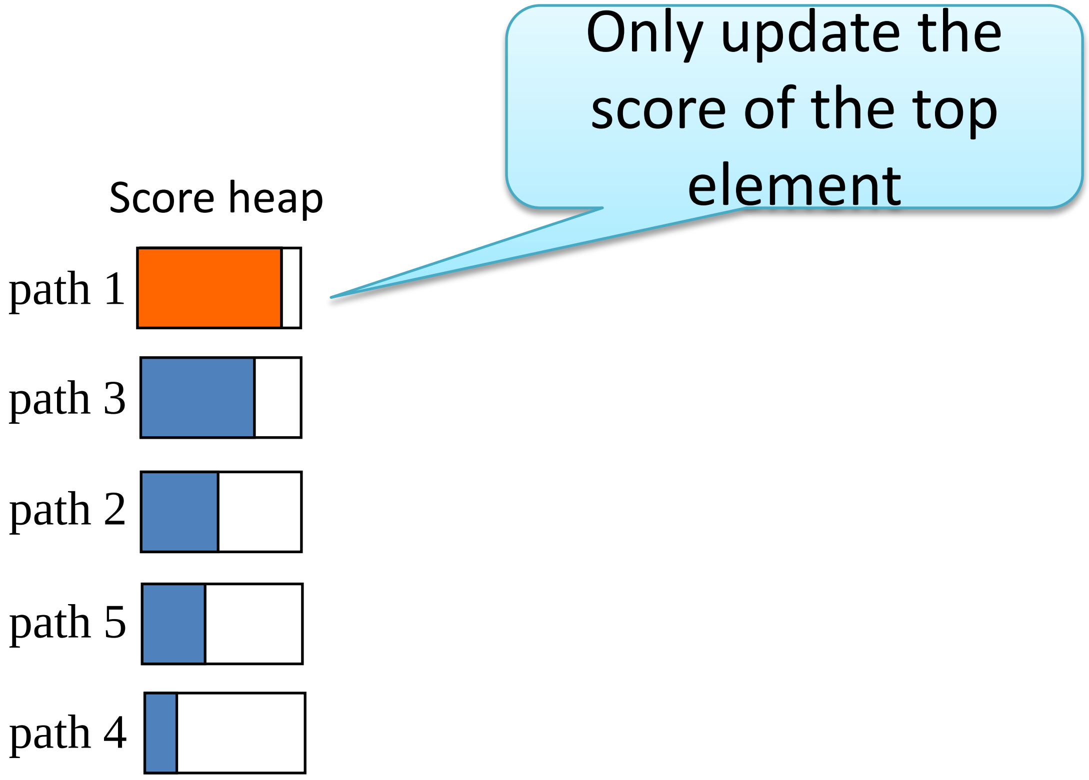

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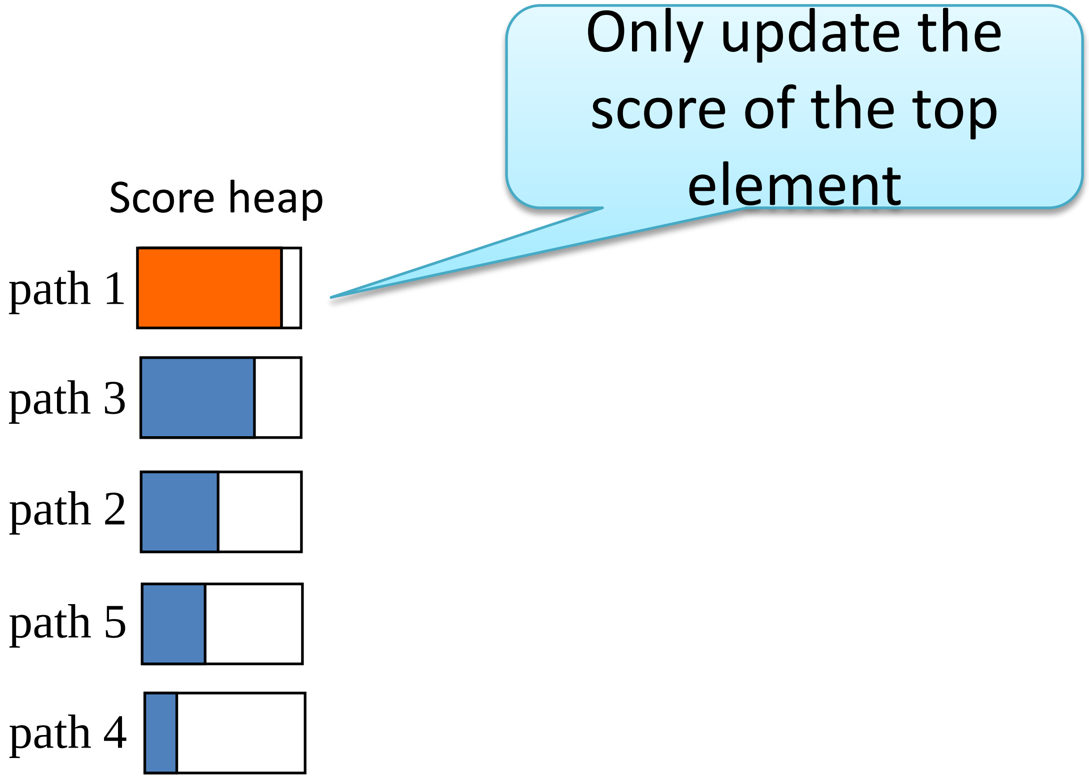
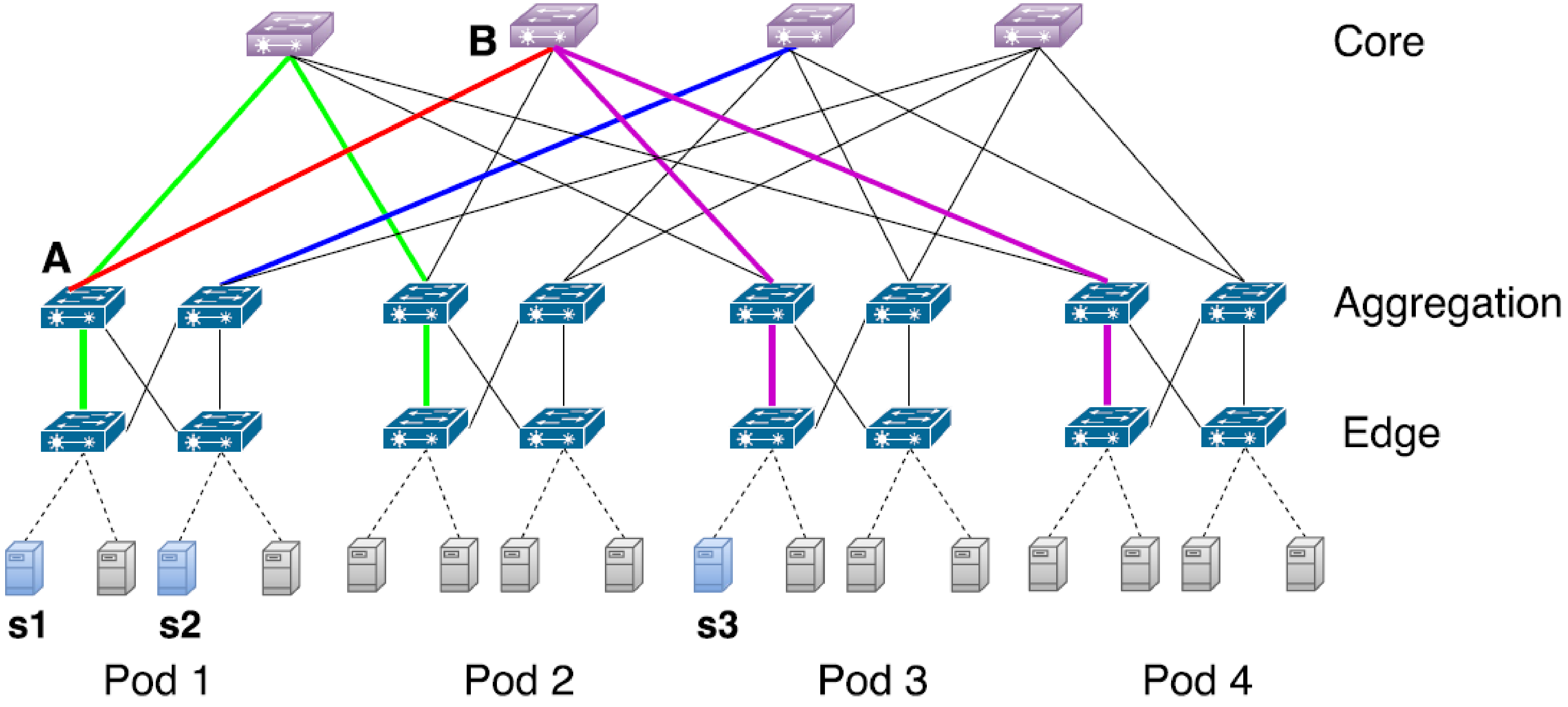


- Defer the score update of a path as much as possible until we have to.
- Correctness guaranteed by the submodularity of the objective function.

Symmetry reduction



- DCN topology is symmetric and thus we only need to compute paths for a small symmetry component.

PMC results

- Running time

DCNs	# of nodes	# of links	# of original paths	Strawman	Decomposition	Partial update	Lazy update	Symmetry
Fattree(12)	612	1296	184,032	231.458	5.216	1.509	0.506	0.126
Fattree(24)	4,176	10,368	11,902,464	> 24h	1381.226	99.778	23.254	0.280
Fattree(72)	99,792	279,936	8,703,770,112	> 24h	> 24h	> 24h	> 24h	17.054

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Fattree(72)	99,792	279,936	8,703,770,112	> 24h	> 24h	> 24h	> 24h	17.054

- The number of selected paths

DCNs	# of original paths	# of selected paths with (α, β)		
		(1, 0)	(1, 1)	(3, 2)
Fattree(32)	66,977,792	4,096	7,680	12,288
Fattree(64)	4,292,870,144	32768	61,440	98,304

Part II: Network Probing

Network probing

- How to route probes: source routing to control paths
- How pingers send probes: frequency, QoS, source port
- How responders reply probes: timestamp

Part III: Loss Localization

Problem formulation

	Link 1	Link 2	Link 3	Loss measurements
Path 1	1	1	0	4
Path 2	1	0	1	1
Path 3	0	0	1	3

Problem formulation

4 probes are lost on path1

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- Given the probe matrix and loss measurements, select the least number of links to explain the observation.
- NP-hard

PLL algorithm

	Link 1	Link 2	Link 3	Loss measurements
Path 1	1	1	0	4
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- In each iteration we select a link that can explain the largest number of probe losses until all are explained

PLL algorithm

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- Link1 is bad.

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- Link1 is bad.

PLL algorithm

	~~Link 1~~	Link 2	Link 3	Loss measurements
~~Path 1~~	~~1~~	~~1~~	~~0~~	~~4~~
~~Path 2~~	~~1~~	~~0~~	~~1~~	~~1~~
Path 3	0	0	1	2
	-	0	2	

- In each iteration we select a link that can explain the largest number of probe losses until all are explained.

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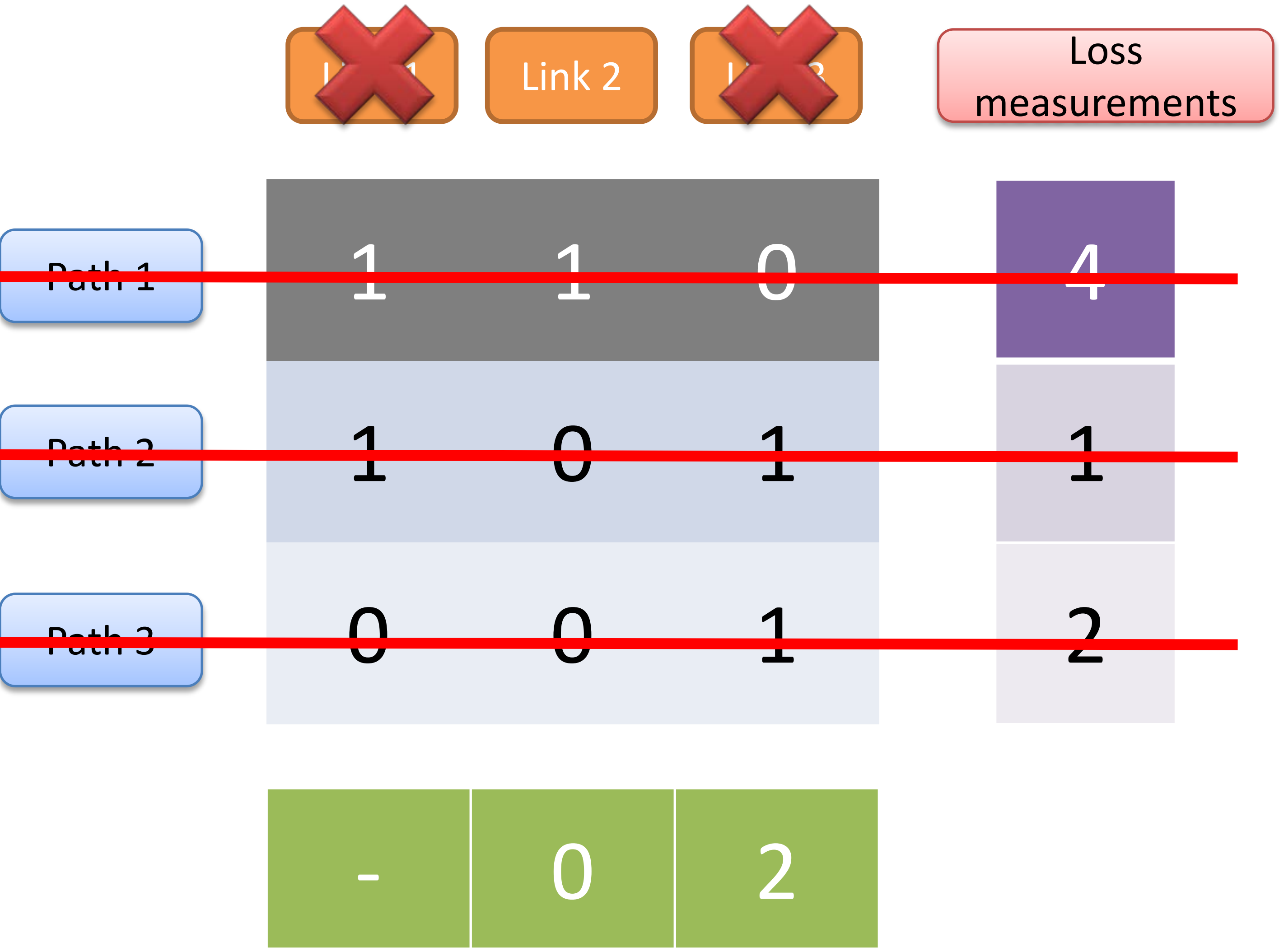
- Link3 is also bad.

PLL algorithm

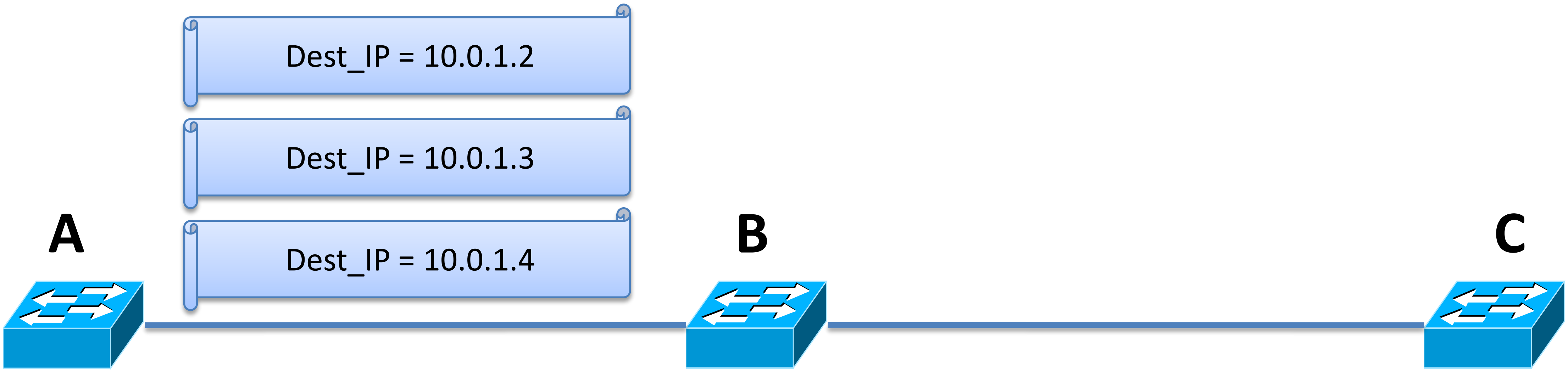


- In each iteration we select a link that can explain the largest number of probe losses until all are explained.

- Link3 is also bad.

Losses are more complicated in reality

- Partial link loss: if a link is bad, not all probing paths through it will observe probe losses.
  - Packet blackhole



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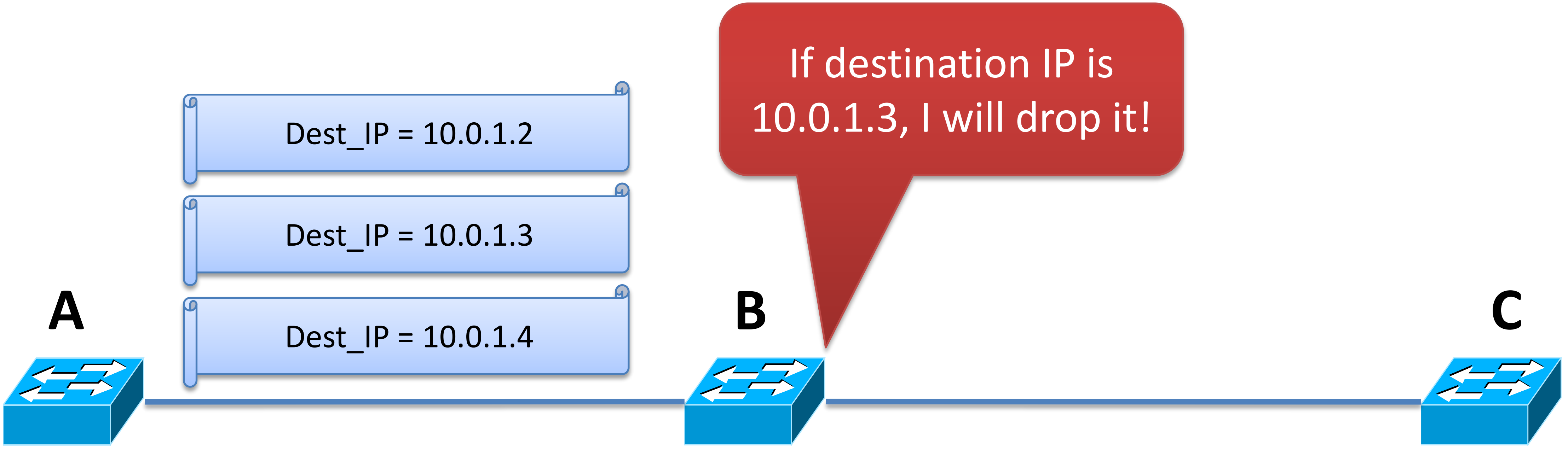

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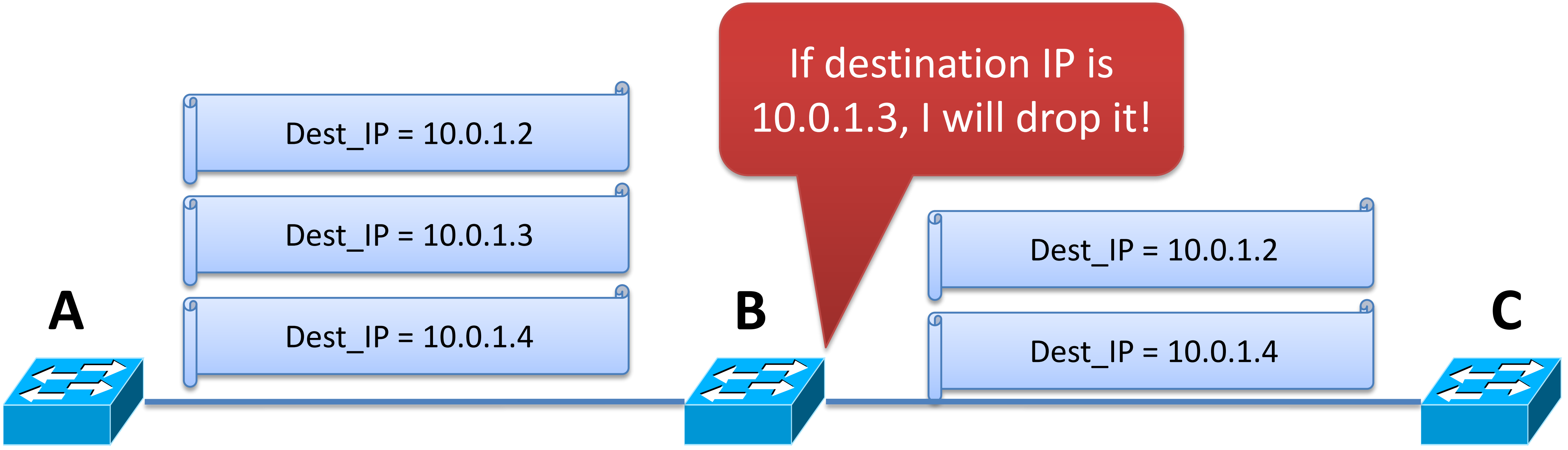
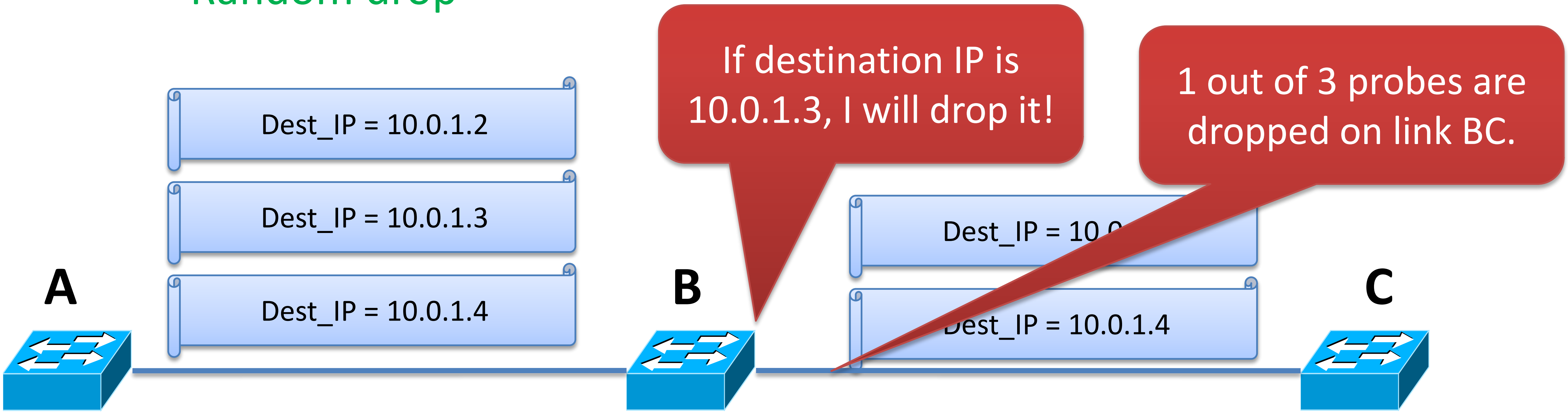


Losses are more complicated in reality

- Partial link loss: if a link is bad, not all probing paths through it will observe probe losses.
  - Packet blackhole
  - Random drop



Hit ratio

	Link 1	Link 2	Link 3	Loss measurements
Path 1	1	1	0	0
Path 2	1	0	1	2
Path 3	0	0	1	2

- Hit ratio of a link: the number of lossy paths divided by all paths through the link

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	Link 1	Link 2	Link 3	Loss measurements
Path 1	1	1	0	0
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Hit ratio	0.5	0	1	

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Hit ratio	0.5	0	1	

- Hit ratio of a link: the number of lossy paths divided by all paths through the link
- Only if the hit ratio of a link is larger than a threshold do we think the link is bad.

The tradeoff of hit ratio

- Larger hit ratio: more paths of a link experience loss and we have higher confidence that the link is faulty.

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- Larger hit ratio: more paths of a link experience loss and we have higher confidence that the link is faulty.

- But some failures only incur packet loss on one or two specified paths.
  - Our algorithm may miss them.

Conclusion

- deTector is a real-time, low-overhead and high-accuracy monitoring system for large-scale data center networks.
  - Real-time → without help of other diagnosis tools
  - Low overhead → PMC algorithm minimizes the probing cost
  - High accuracy → carefully design probe matrix + PLL algorithm
  - Large scale → optimizations to speed up the computation of PMC and PLL

Thanks

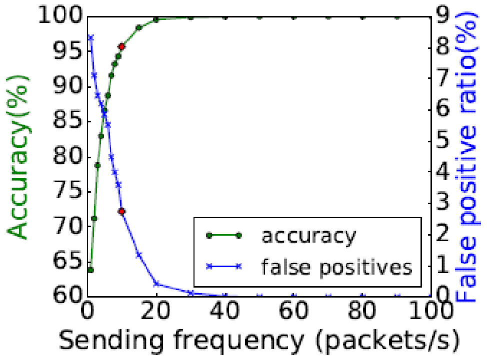
Evaluation

- Fault localization accuracy and running time in a 48-radix Fattree

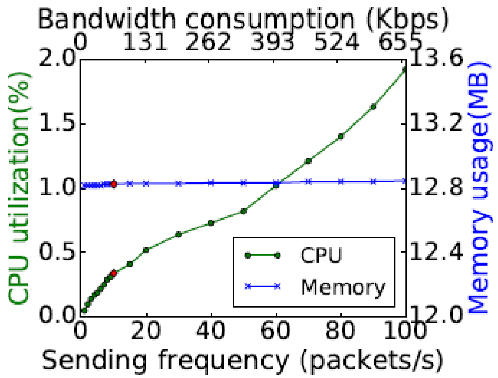
# of failed links / Algorithms	Accuracy (%)				False positive ratio (%)				Running time (seconds)	
	1	5	20	50	1	5	20	50	5	50
Sherlock [2]	33.90	5.57	1.45	1.24	10.26	14.43	34.58	56.10	79.200	225.600
SCORE [27]	93.86	90.27	90.02	88.77	3.68	4.37	4.42	5.19	0.720	9.600
OMP [35]	89.74	91.38	49.43	19.37	6.82	11.61	23.22	44.62	14.400	16.320
Tomo [9]	94.48	90.45	89.88	88.87	3.74	4.61	4.51	5.31	0.672	9.360
PLL	96.00	91.87	91.24	89.87	1.73	2.95	3.18	3.84	0.486	0.772

Evaluation

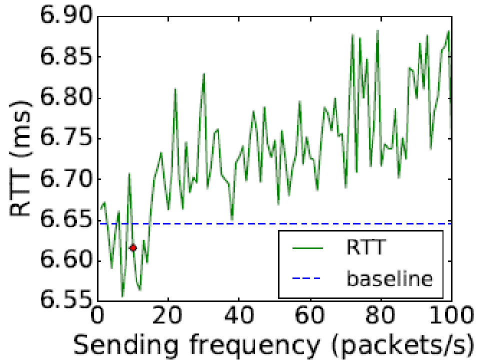
- Sensitivity test of sending frequency



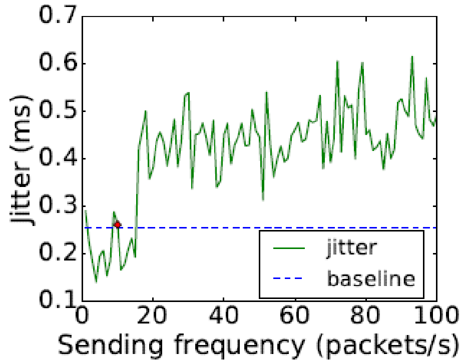
(a) PLL performance with one failure



(b) CPU, memory and bandwidth overhead on pingers



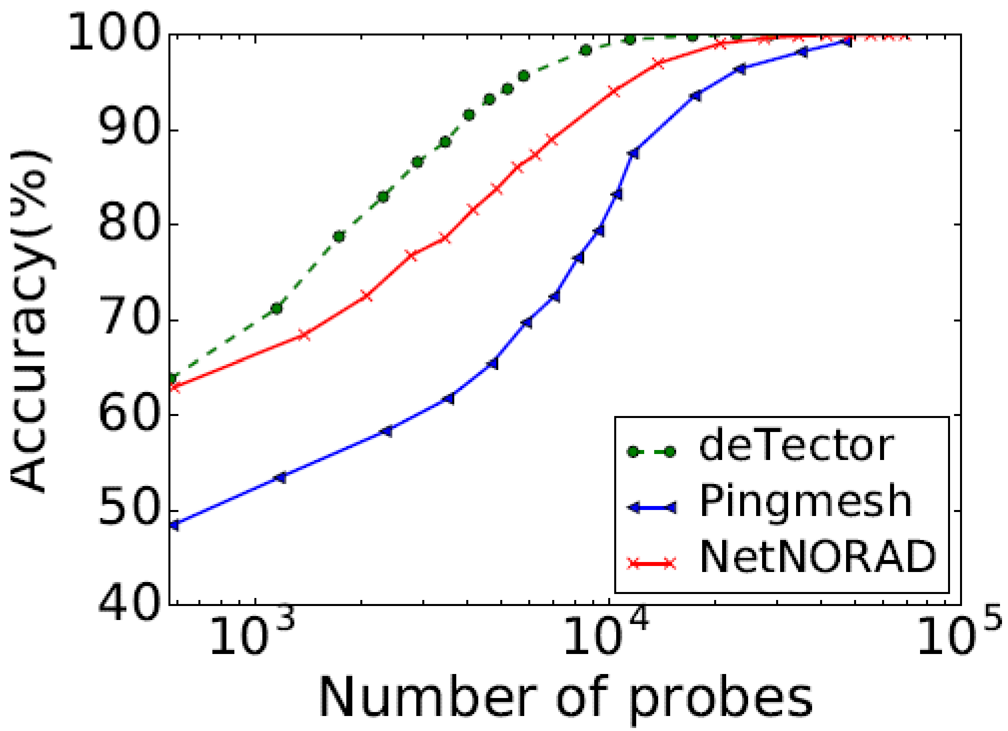
(c) RTT of background traffic

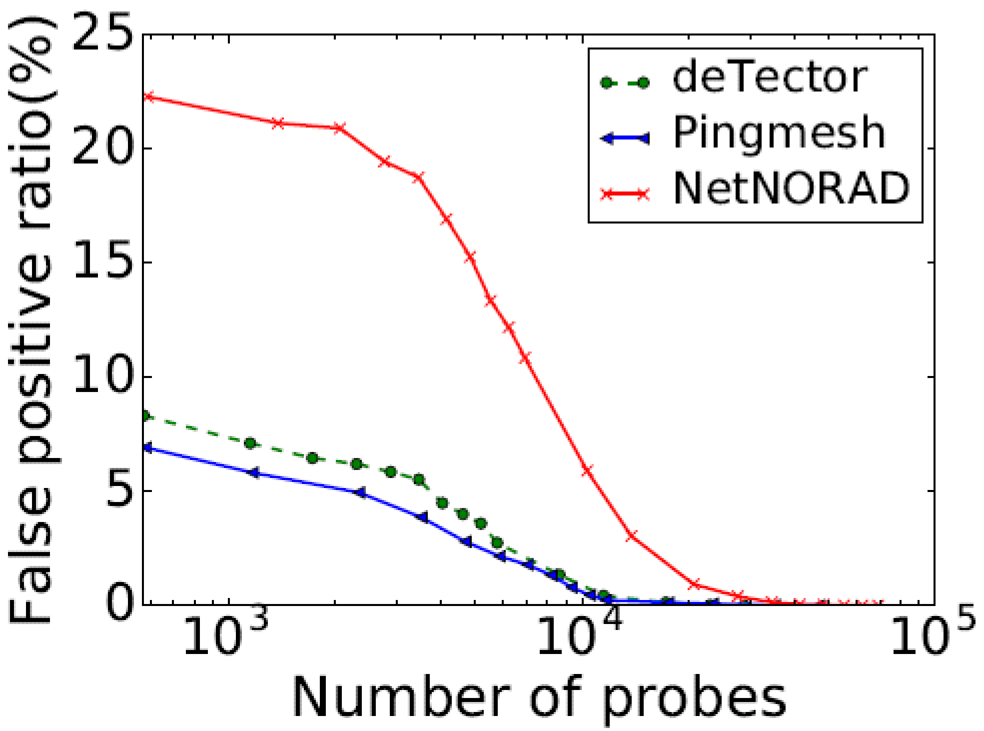


(d) Jitter of background traffic

Evaluation

- Accuracy and false positives of three monitoring systems with different number of probes





Evaluation

- Fault localization performance with probe matrix of 2-identifiability in a 48-ary Fattree

# of failed links	1	5	10	20	50
Accuracy (%)	98.95	98.99	98.98	98.93	98.87
False positive (%)	0.01	0.02	0.02	0.02	0.02
False negative (%)	1.05	1.01	1.02	1.07	1.13

Thanks