Lancet: Better Network Resilience by Designing for Pruned Failure Sets

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This work was done when Yiyang Chang was at Purdue University

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Challenges in Network Design

- Failures are important in designing wide-area networks
  - Inevitable [1, 2] and costly
- Network users desire high service level objectives (SLOs)
  - 99.99% or even 99.999%

[1] Gill, et al, Understanding network failures in data centers: Measurement, analysis, and implications. Sigomm 2011.

[2] Potharaju and Jain, When the network crumbles: An empirical study of cloud network failures and their impact on services, SOCC 2013.

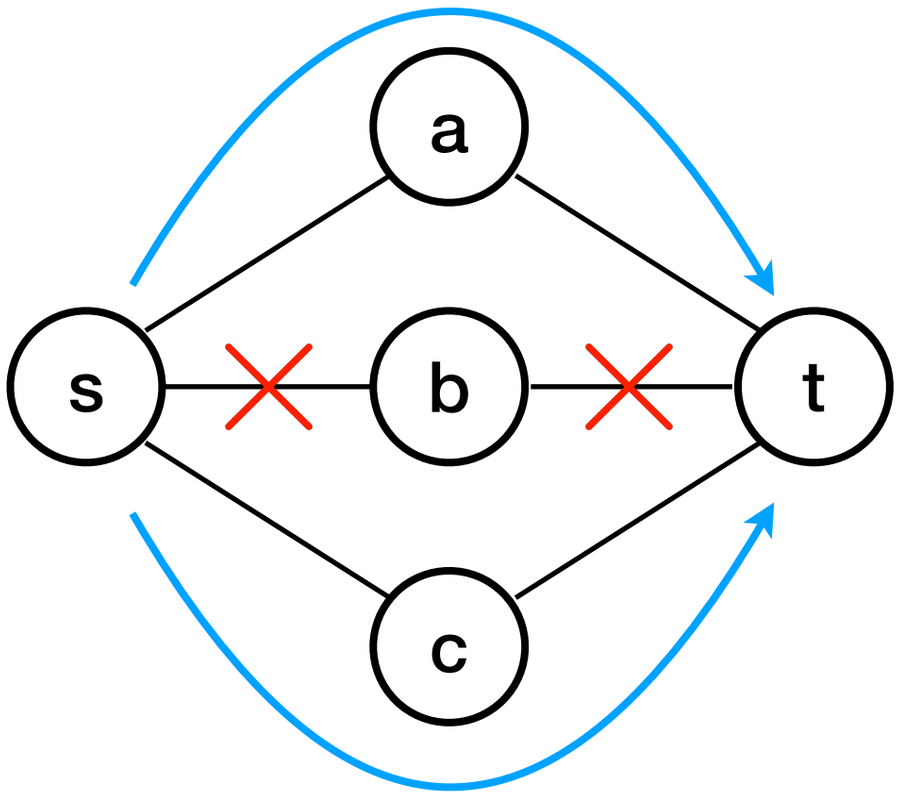
State-of-the-art in Network Design

- Key problem: how to design networks for such stringent requirements?

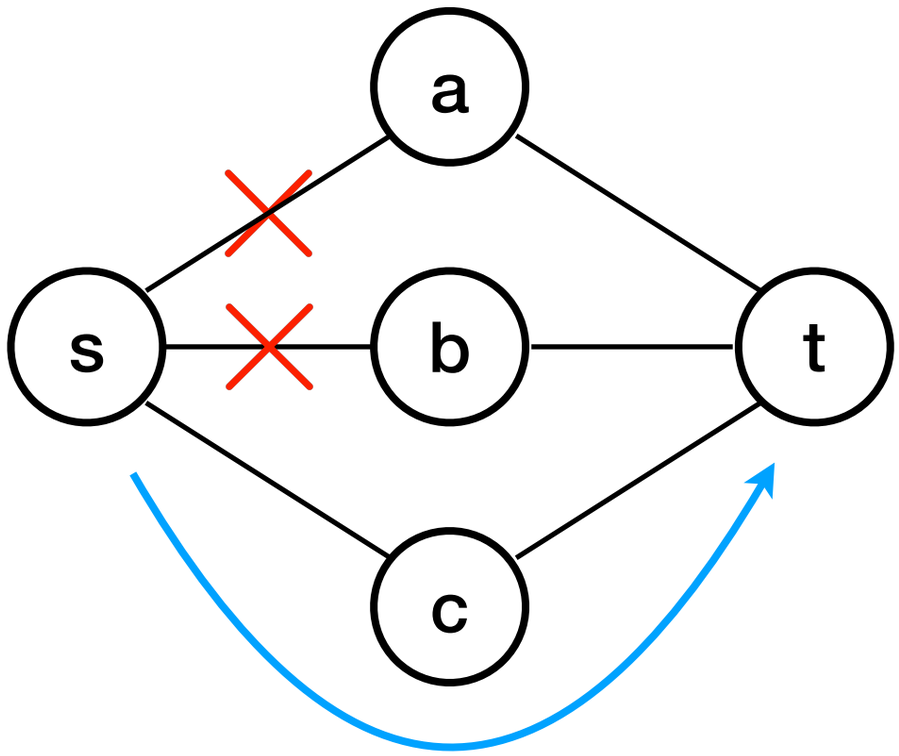
- State-of-the-art: Design for worst-case failure
  - Robust to all possible combinations of *f or fewer* failures
    - A weak point: If a single *f*-failure scenario cannot be tackled, forced to design for *f-1* failures only
- Examples: R3 (Wang, et al, Sigcomm 2010), FFC (Liu, et al, Sigcomm 2014)

Lancet - Beyond Worst-case

- Designing for worst-case may be conservative
- Can we design for most *f*-failure scenarios when designing for all is not possible?



Good 2-failure scenario



Bad 2-failure scenario

Link Capacity	1 unit
Demand from s to t	2 units

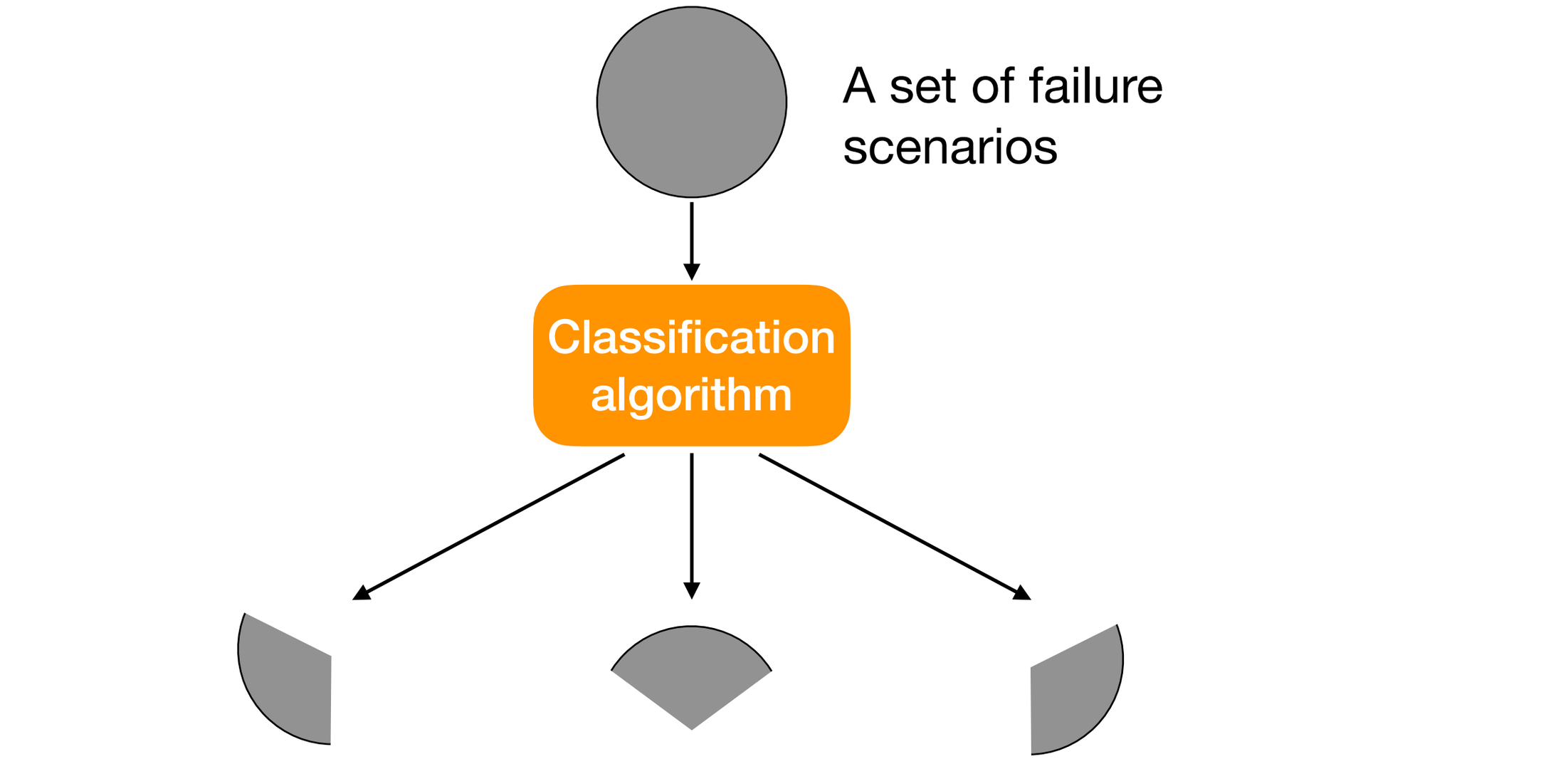
Lancet - Contributions

- New approach to designing protection routing
  - For most failure scenarios, when designing for all not possible
- Key components
  - Novel divide-and-conquer algorithm to efficiently identifies failure scenarios which a network can intrinsically handle
  - Provides a compact representation of these scenarios
  - Linear program (LP) approach to designing protection routing that exploits this compact representation
    - Cuts design time from > 18 hours to 10 seconds for a real-world topology
- Validations on real-world network topologies show Lancet's promise

Determine Which Scenarios to Design for

- How to determine which scenarios to design for?
  - Observation: Any routing scheme cannot perform better than an ideal scheme. An ideal scheme routes using multi-commodity flow
  - Exclude all bad scenarios with the ideal scheme
  - Design for the rest of the failure scenarios
- How to find which scenarios can be handled by the ideal scheme?
  - A divide-and-conquer algorithm to classify which failures can and cannot be handled

Lancet Classification Algorithm



Classification Algorithm in Operation

f = 0

Do all certify?

Yes.

Prune

Classification Algorithm in Operation

f = 0 f = 1

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Yes.

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Classification Algorithm in Operation

f = 0 f = 1 f = 2

Do all certify?

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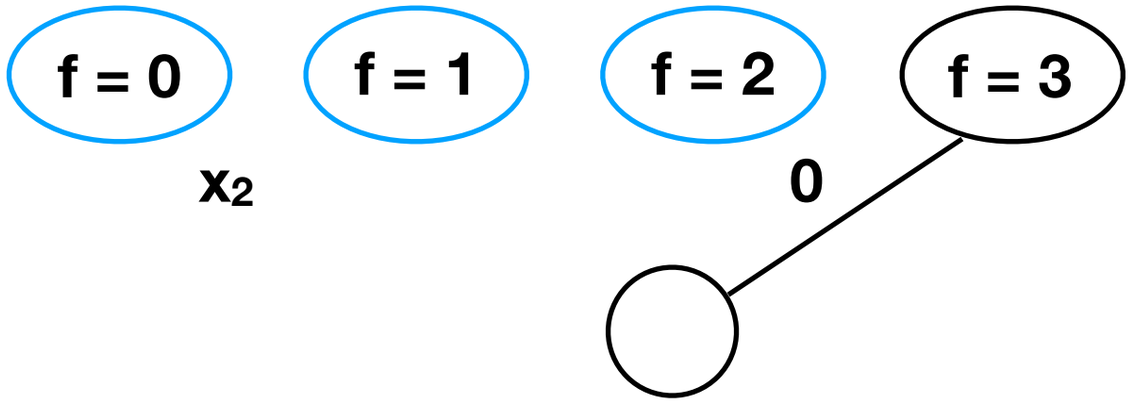
Prune

Classification Algorithm in Operation



Do all certify?

No.

Do all violate?

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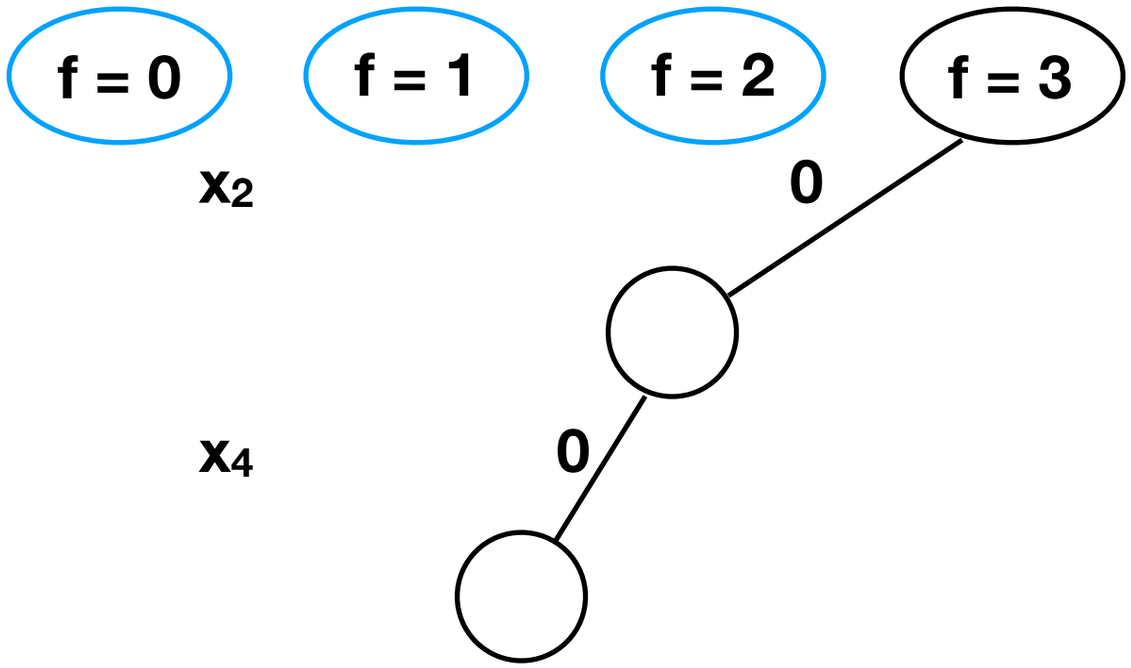
Partition scenarios

Classification Algorithm in Operation



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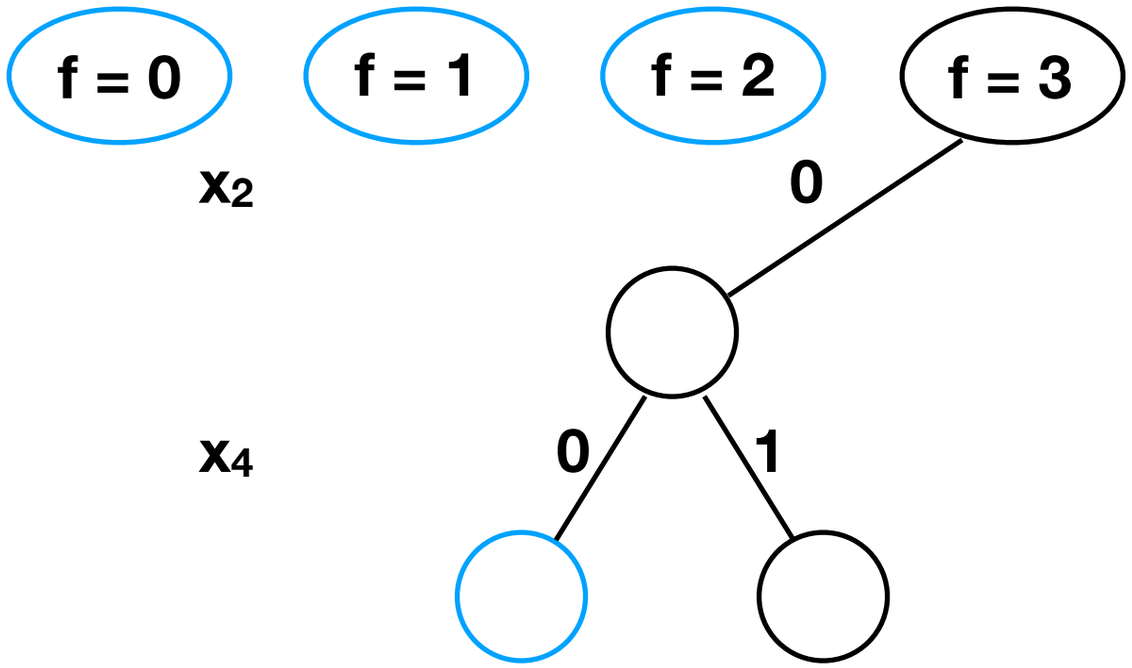

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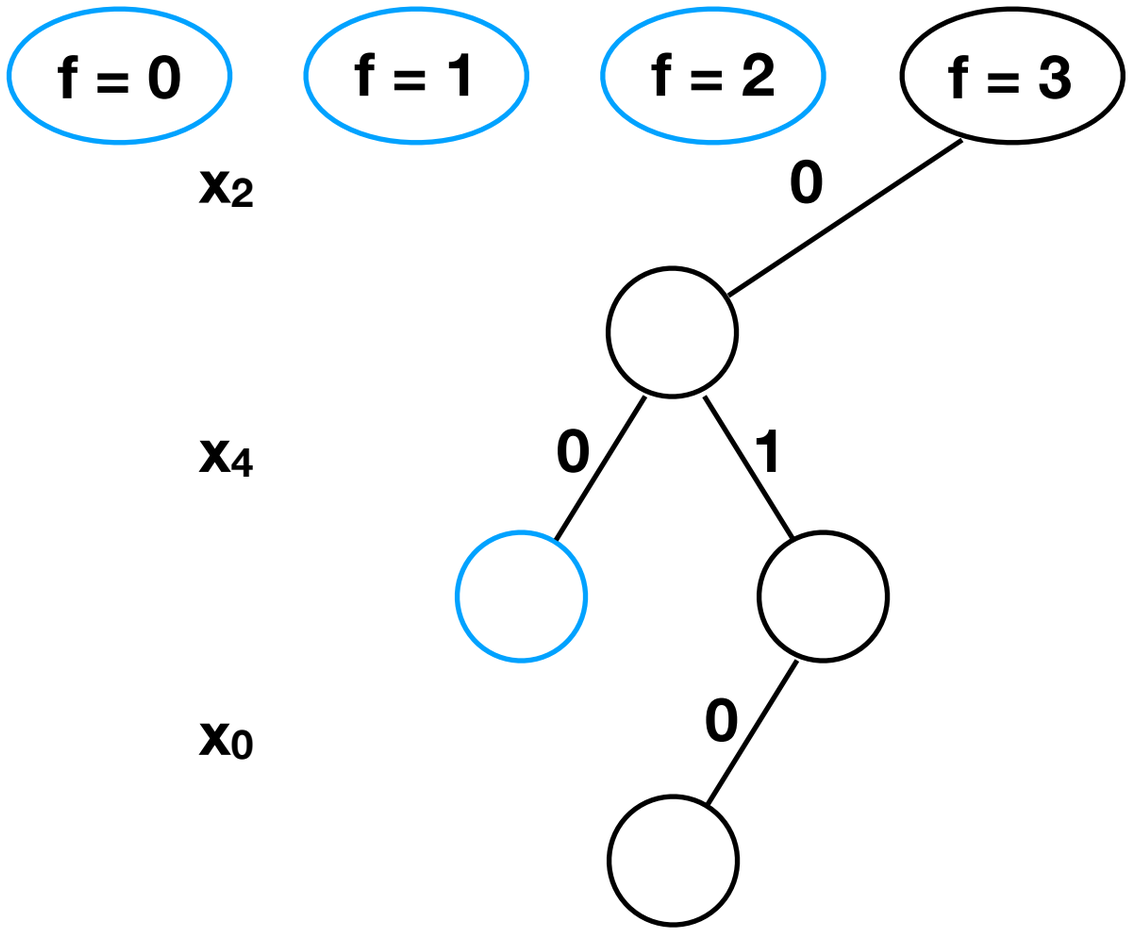

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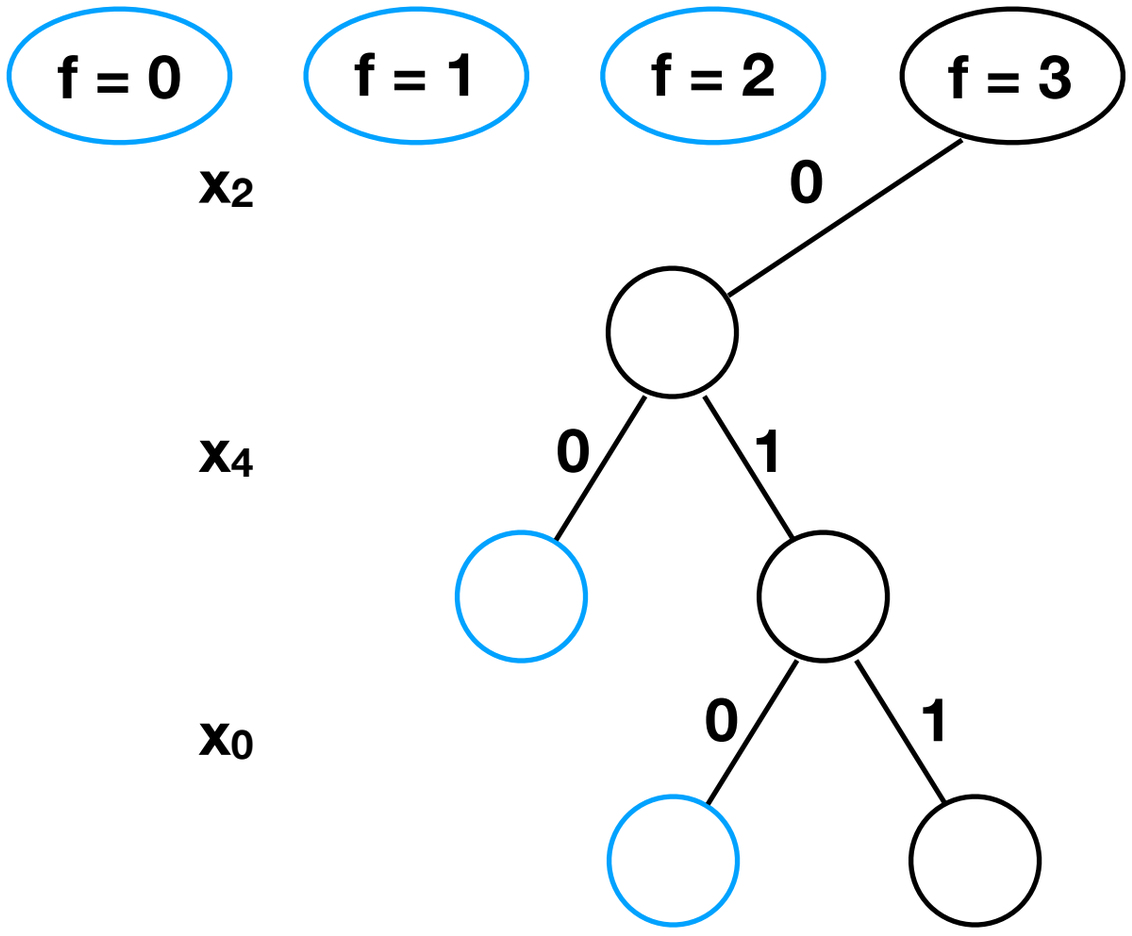

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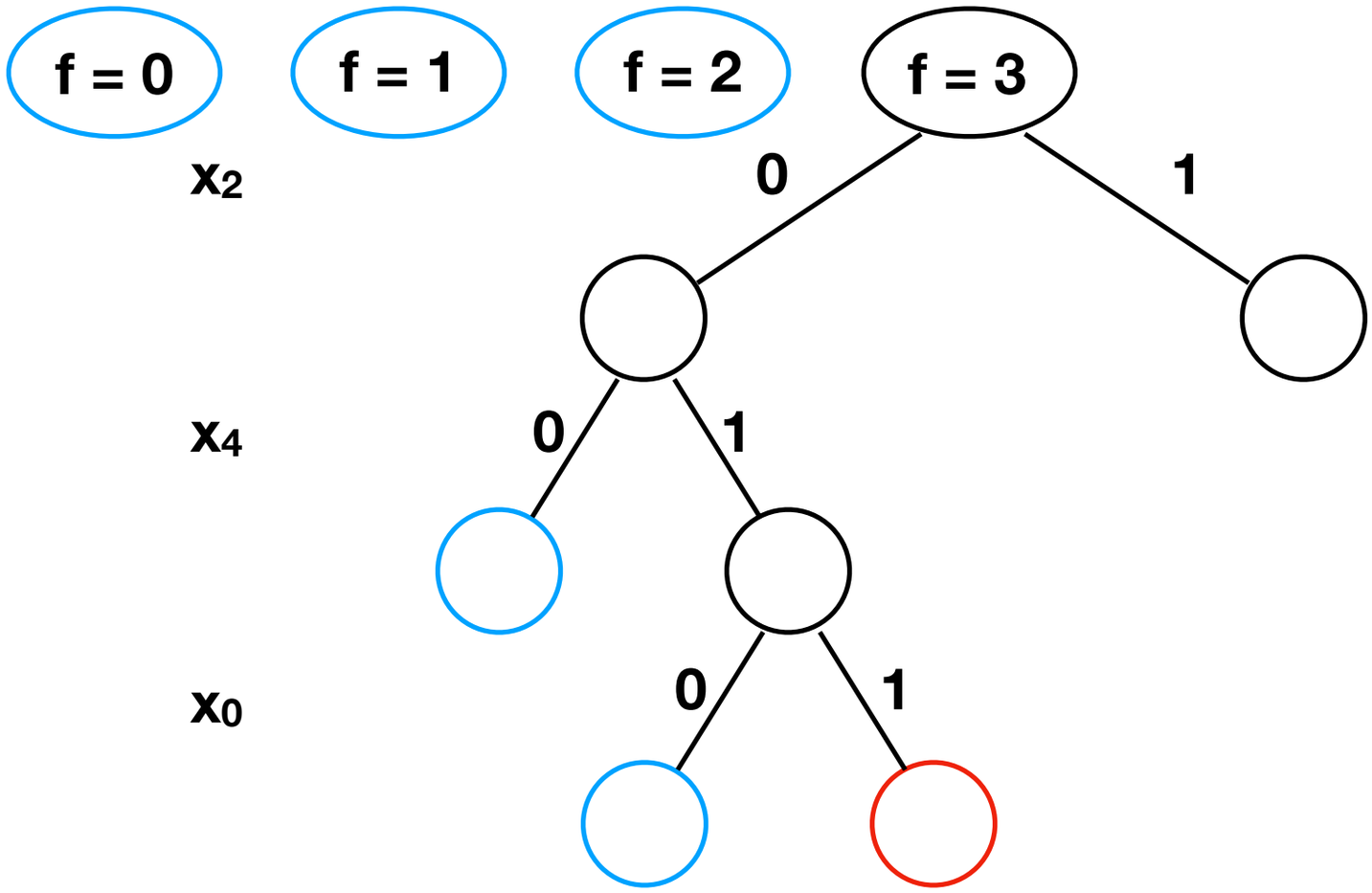

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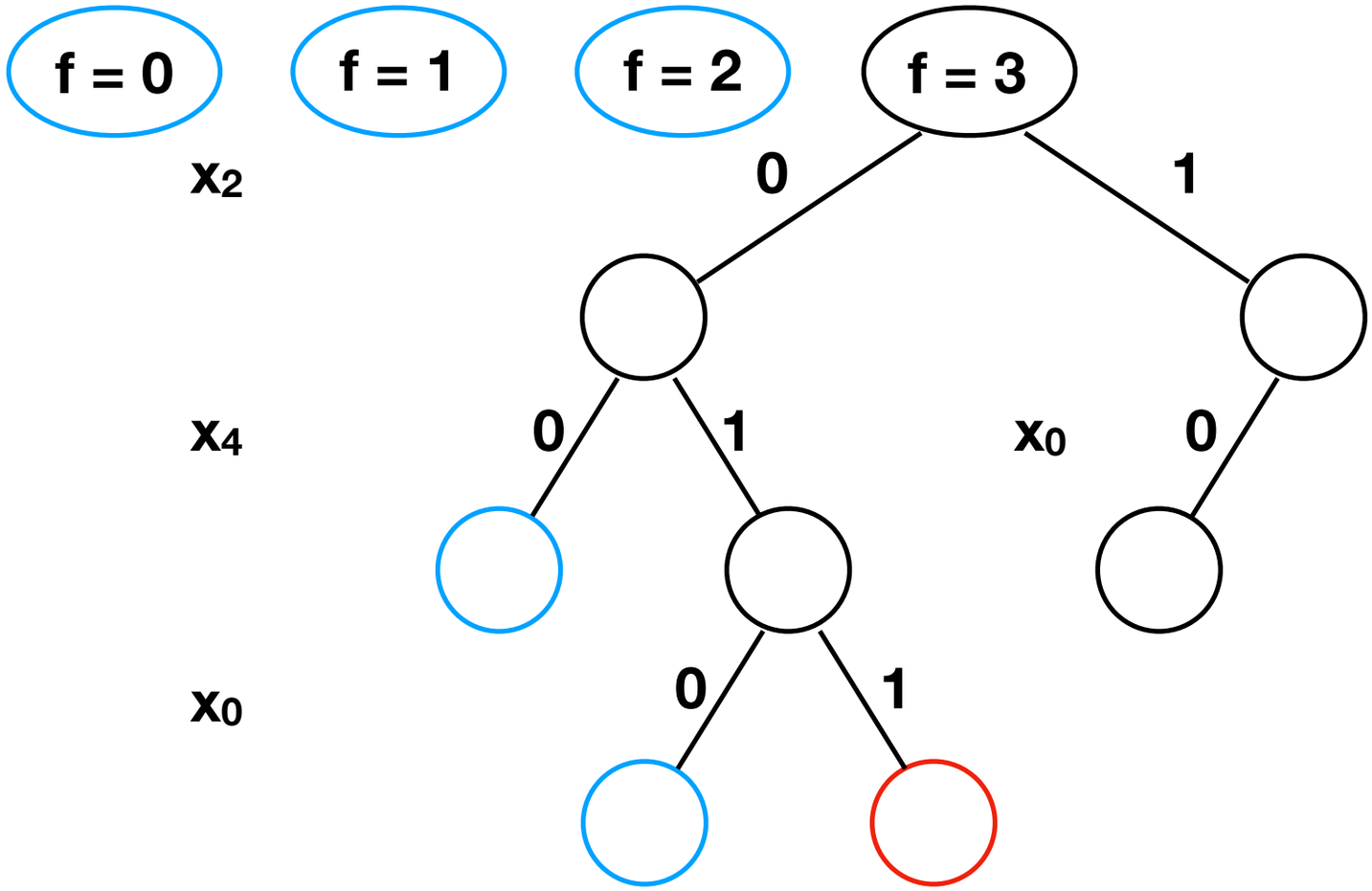

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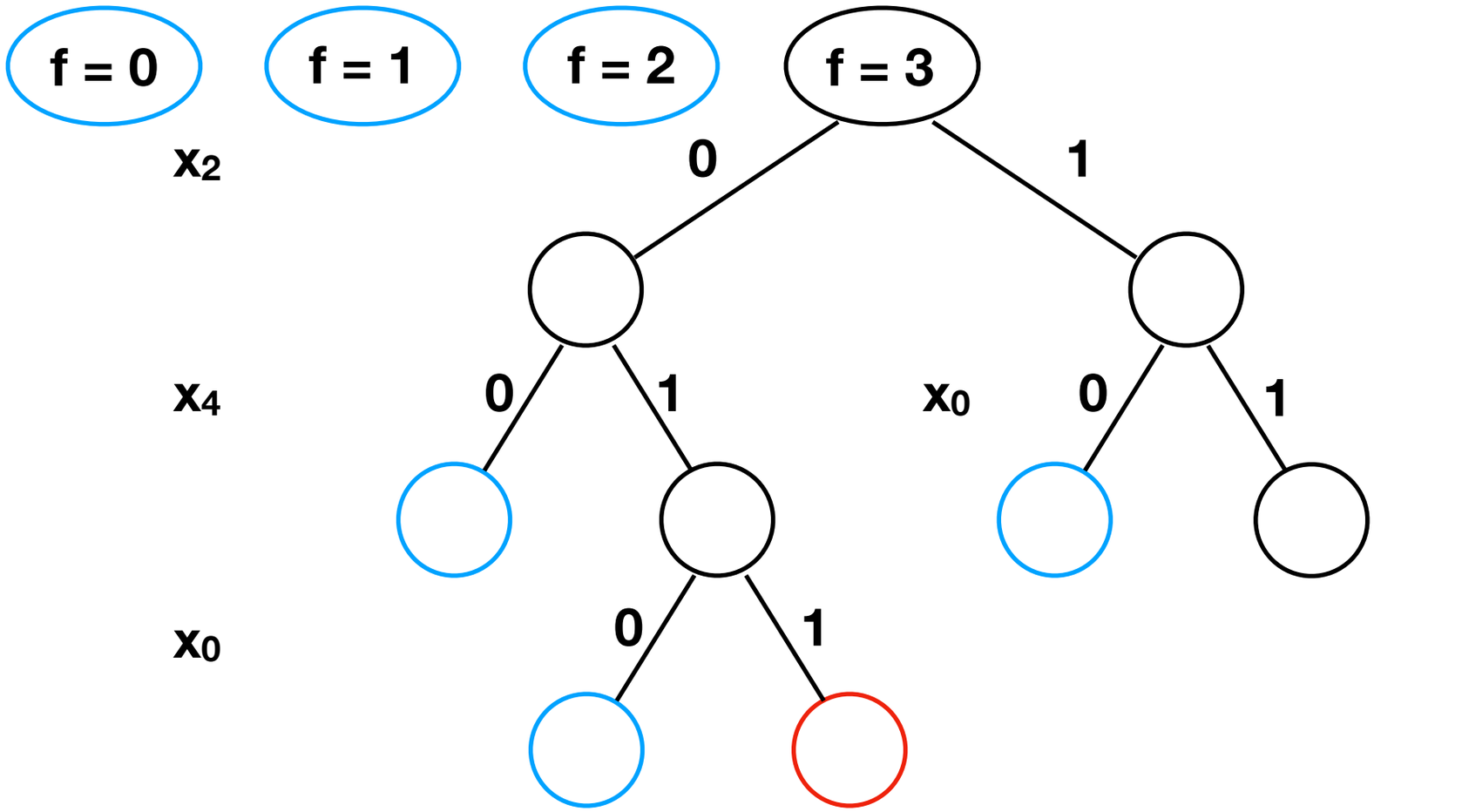

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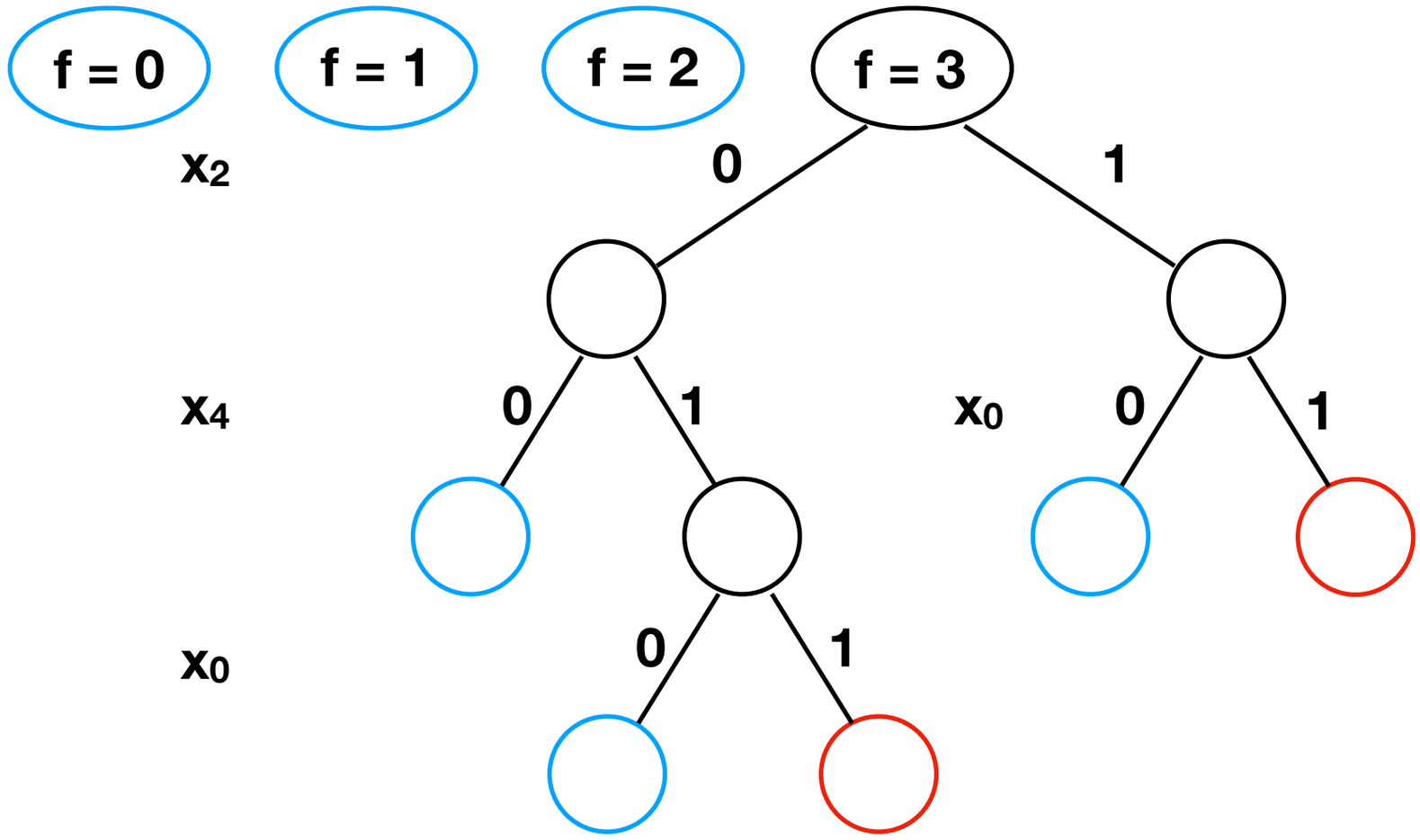


Done.

Key procedures

- *DoAllCertify()*
- *DoAllViolate()*
- Partitioning strategy

Keys for Tractable Classification

- *DoAllCertify(A)*
  - We show it is NP-complete
  - Instead, get a conservative bound
  - Doesn't affect correctness
- *DoAllViolate(A)*
  - Simple feasibility LP to test if there is a good failure scenario
- Partitioning strategy
  - Heuristic to choose a link *l* that fails in many bad scenarios

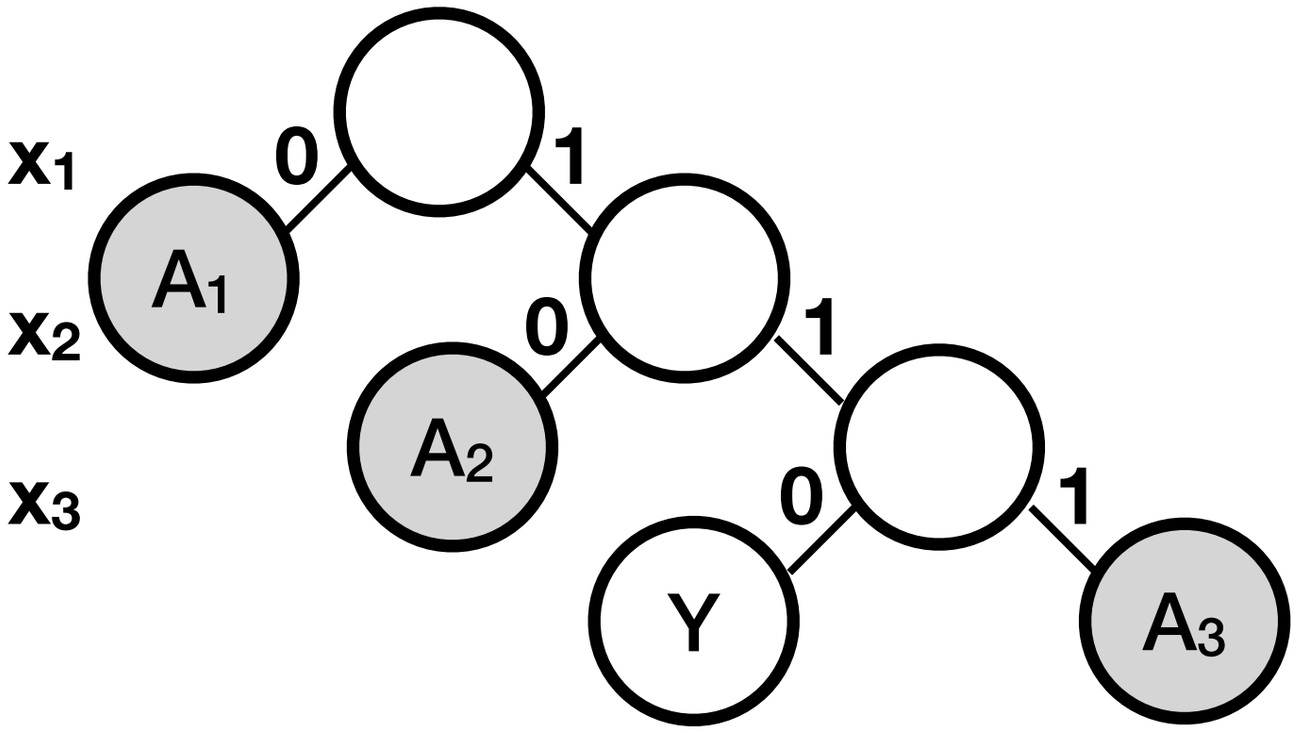
Algorithm 1: Lancet classification.

Function *Lancet()*
- SSets $\longleftarrow [F_f, F_{f-1}, \ldots, F_1, F_0]$
- pass_set, fail_set $\longleftarrow \emptyset, \emptyset$
- **while** SSets **do**
  - $A \longleftarrow$ SSets.*pop*()
  - *Classify*(*A*, pass_set, fail_set, SSets)

Function *Classify*(*A*, pass_set, fail_set, SSets)
- **if** *DoAllCerify(A)* **then**
  - pass_set.*add*(*A*)
- **else if** *DoAllViolate(A)* **then**
  - fail_set.*add*(*A*)
- **else**
  - $A_1, A_2, \ldots, A_n \longleftarrow$ *Partition*(*A*)
  - SSets.*extend*($[A_1, A_2, \ldots, A_n]$)

Compact Representation of Failure Sets

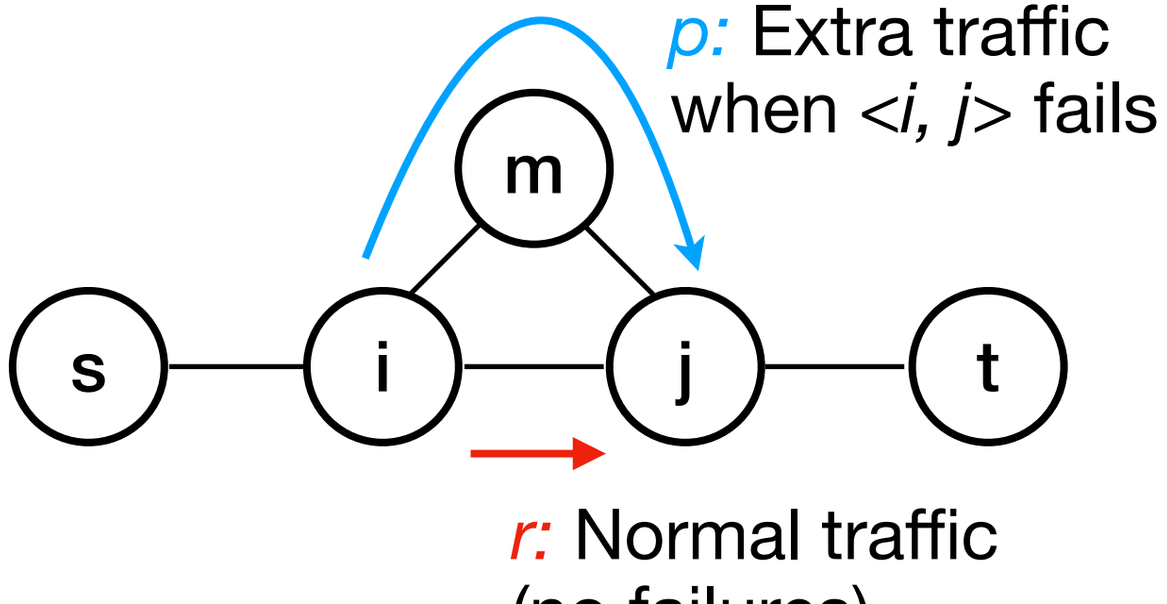
- Two ways to represent failure scenarios
  - A_1, A_2, and A_3 as 3 sets
  - 161k+ separate failure scenarios
- The classification algorithm naturally generates the first representation
- Next we will see why the first representation is better



- Sets of 3-failure scenarios of a 100-link network
- A_1, A_2, and A_3 certify
- *Y* is undecided

Protection Routing Design

- Link-based protection routing
  - Provisions bypass paths to protect against each failure scenarios
  - Achieved using (H), generalizing a state-of-the-art scheme [1]
- Issues with existing protection routing schemes
  - Only work if *X* is all f failures
  - If worst-case $U > 1$, we are forced to design for $f - 1$ failures
- What we want: Design for most *f* failures if not all



$$\text{(H)} \quad \min_{r,p,a,U} \quad U$$

$$\text{s.t. } r_{st} \text{ is a unit flow from } s \text{ to } t. \quad \forall s,t \in V$$

$$p_l \text{ is a flow of } a_l \text{ from } i \text{ to } j. \quad \forall l \in E, l = \langle i,j \rangle$$

$$\forall x \in X, e \in E,$$

$$\sum_{s,t} d_{st} r_{st}(e) + \sum_{l \in E} x_l p_l(e) \le U c_e (1 - x_e) + a_e x_e$$

$$a_e \ge 0 \quad \forall e \in E; \quad U \ge 0$$

[1] Wang, et al, R3: Resilient routing reconfiguration, Sigcomm 2010

Protection Routing Design with Excluded Scenarios

- Two ways to implement the capacity constraints (circled in red)
  1. Enumerate constraints, one for each failure scenario x
  2. Impose the constraint for a union of failure sets, each one represented using LP duality
- Our approach (2nd above) is more compact
  - Since number of sets can be exponentially smaller than the number of failure scenarios

(H) $\min_{r,p,a,U} \quad U$

s.t. r_{st} is a unit flow from s to t. $\quad \forall s,t \in V$

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Summarizing Design with Lancet

- Step 1: Reformulate (H) to an LP to handle arbitrary sets of failure scenarios
- Step 2: Determine which failure scenarios (represented in failure sets) to include with the classification algorithm
- Step 3: Leveraging the LP in Step 1, design a protection routing scheme for failure sets discovered in Step 2

Evaluations

- Real topologies

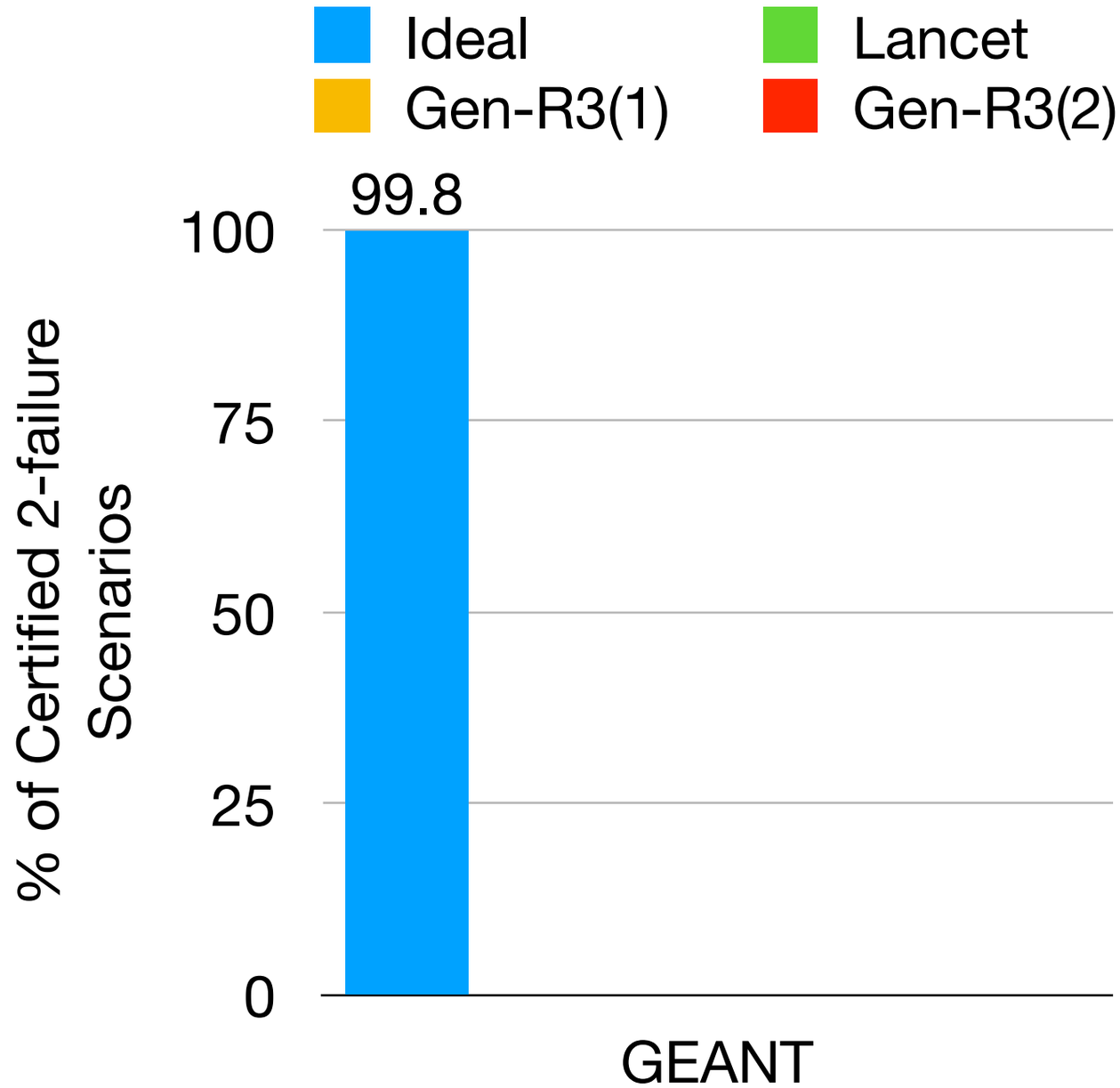
Network	# of Nodes	# of Edges	# of sub-links
Abilene	11	14	2
GEANT	32	50	2
Deltacom	103	151	2
ION	114	135	2

- Partial failure model
  - All links comprises 2 sub-links
- Synthetic traffic matrix: Gravity model [1]
- Environment: single-threaded on a 3.00GHz Intel Xeon CPU
- Implemented in Python and Gurobi 8.0

[1] Yin Zhang, et al. Network anomography. IMC 2005.

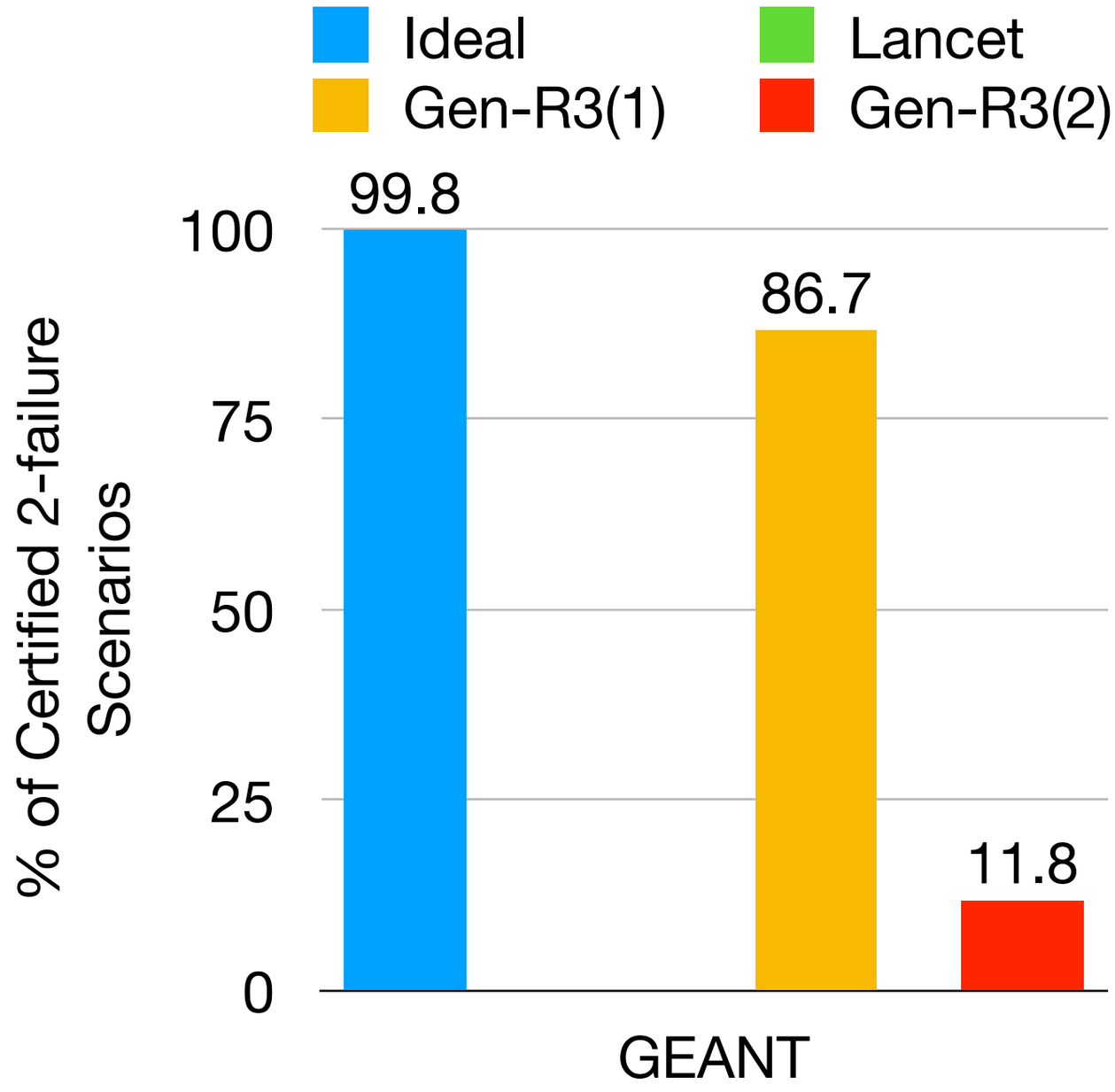
Design with Lancet

- The ideal scheme handles 99.8% of the 2-failure scenarios for GEANT



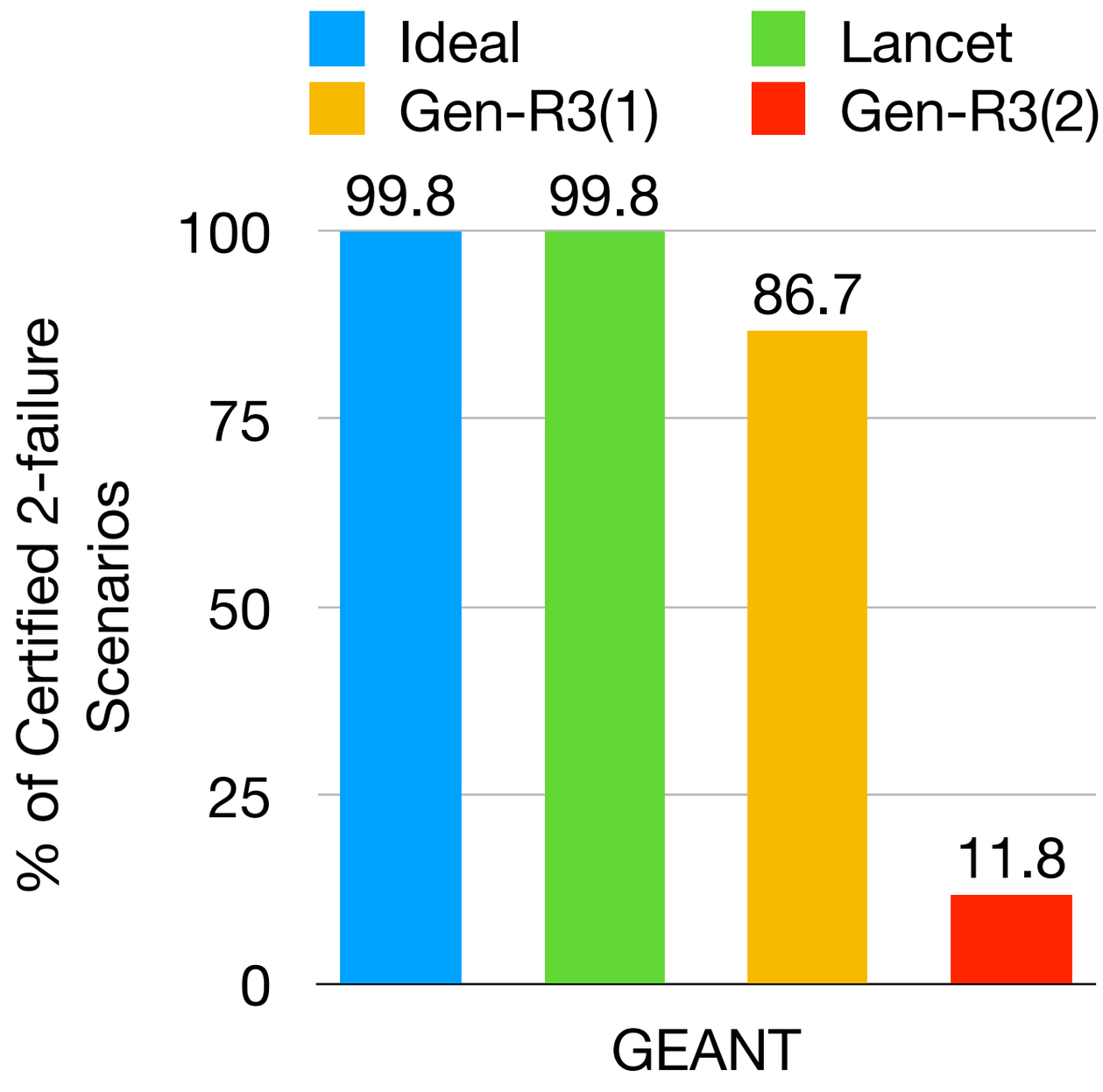
Design with Lancet

- Gen-R3 (f): the protection routing design obtained by optimizing worst-case *f*-failure scenarios
- Takeaway: Large performance gaps exist between Gen-R3 schemes and the ideal scheme

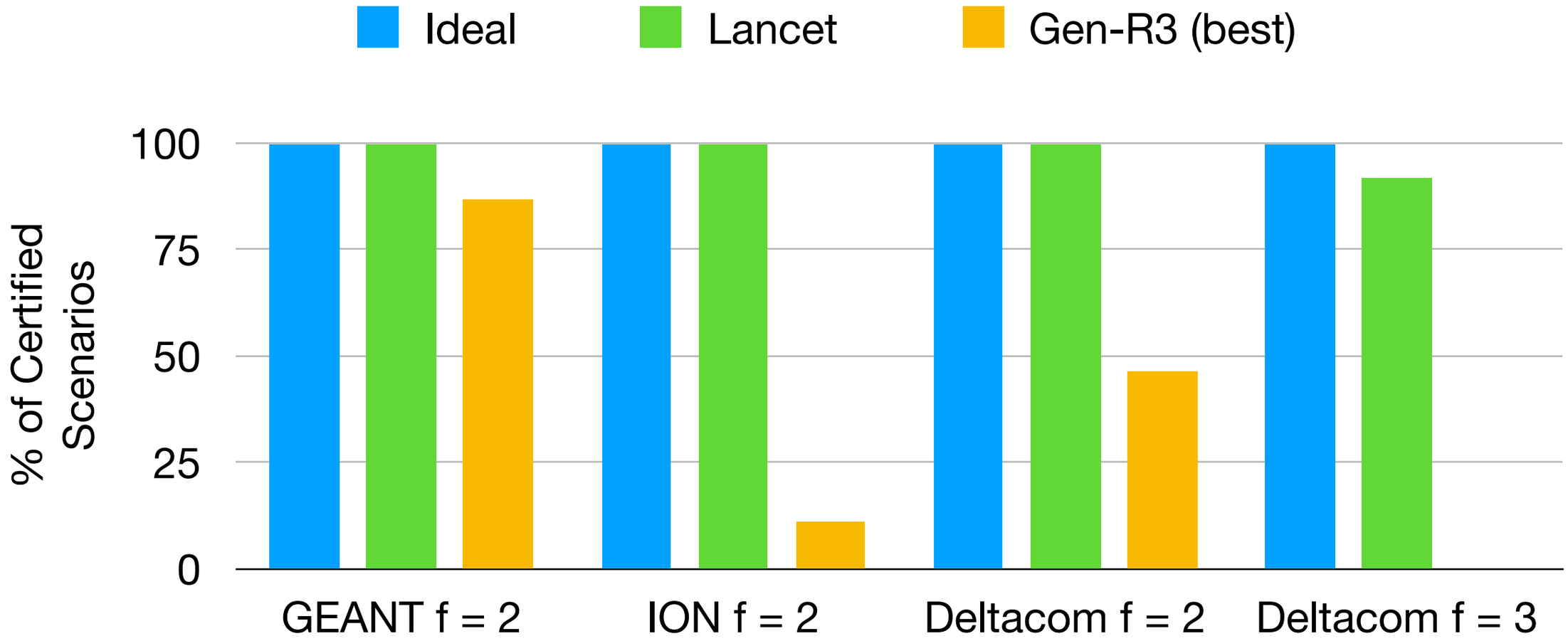


Design with Lancet

- Lancet: protection routing designed with Lancet by excluding bad failure scenarios
- Takeaway: Lancet bridges the performance gap, reaching optimal for GEANT



Design with Lancet on Larger Networks

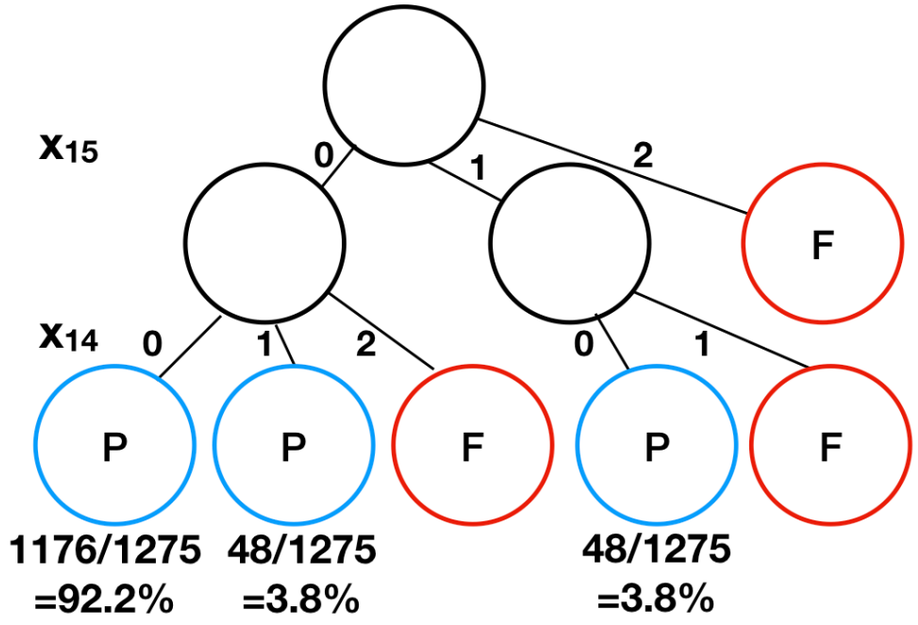


- Gen-R3 (best): the Gen-R3 (f) that gives the best result
- Takeaway: Lancet achieves much better performance than Gen-R3 (best) and is close to optimal

Compactness of Failure Set Representation

- Lancet represents a large number of failure scenarios in a small number of failure sets
- Enables tractable designs of protection routing

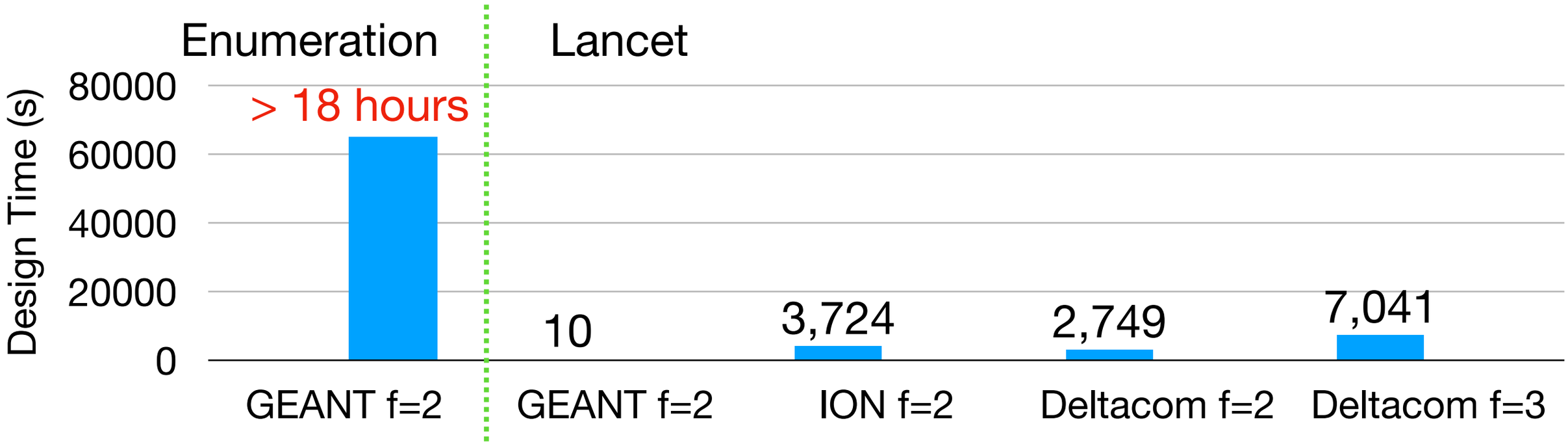
Topology (# of failures)	# of sets	# of scenarios
GEANT (2)	3	1272
ION (2)	5	9172
Deltacom (2)	6	11,465
Deltacom (3)	3	466,486



GEANT

Design Time with Lancet and Enumeration

- For a moderate-sized network GEANT
  - Lancet reduces design time from > 18 hours to 10 seconds
- Makes it possible to handle large topologies in less than 2 hours



Extensions and Other Results

- Generalizations and extensions
  - Richer failure models
    - E.g., Shared-risk link group (SRLG)
    - Design to meet probability requirements
    - Multiple traffic demands
- Other results
  - Design with multiple traffic classes
  - Validations on SDN testbed

Conclusions

- Network design for worst-case failure is conservative
- Lancet, an algorithm that efficiently identifies failure scenarios the network can handle
- Lancet yields a compact representation of good failure sets
- Design using the compact representation performs close to ideal, while reducing the design time form > 18 hours to 10 seconds
- Evaluations and validations on real-world topologies show the promise of Lancet

Thanks!

Email your questions to

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Sanjay Rao: sanjay@ecn.purdue.edu

Backup slides

Protection routing design with excluded scenarios

- Why do we want to design with excluded scenarios?
  - Hard to find a good design with existing approaches, if the worst-case failure scenario is infeasible to tolerate
  - Incentive to design for most rather than all *f*-failure scenarios

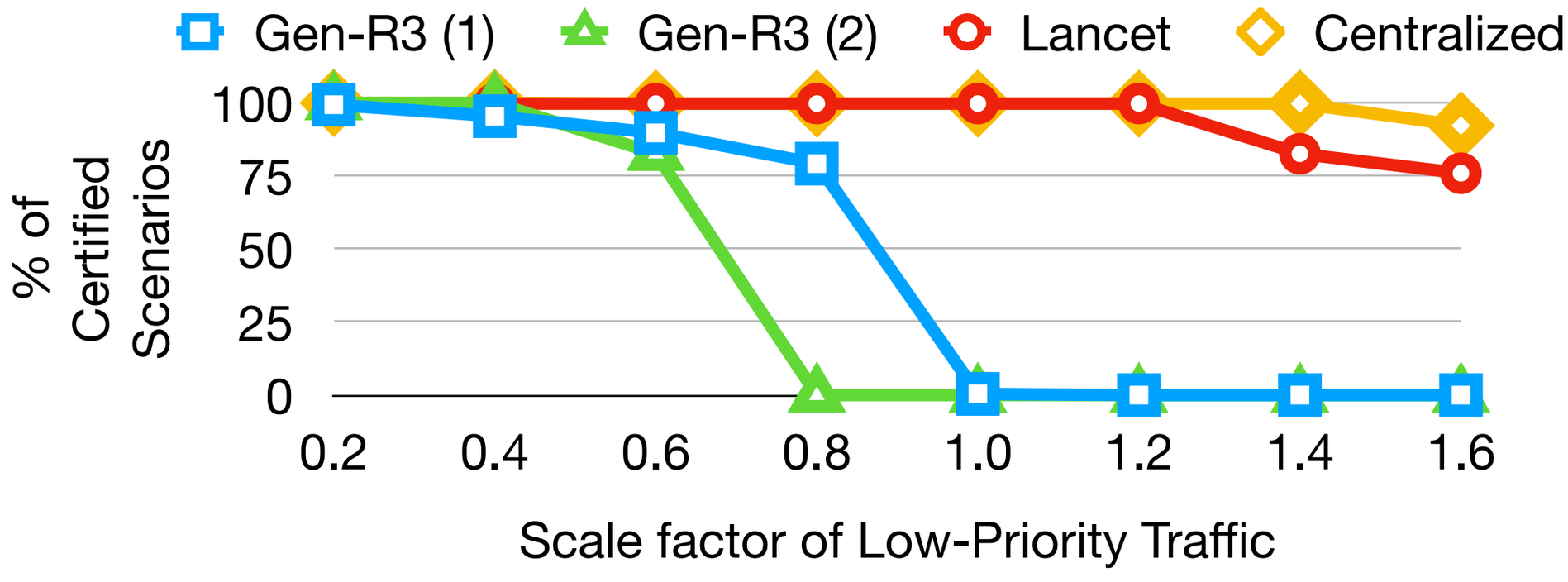
- Directly using formulation (H) is not scalable
  - O(*NE*) constraints, where *E* is the number of links, and *N* is the number of failure scenarios, which are often large (e.g., $N = \binom{E}{f}$ for all *f*-failure scenarios)
  - O(*NE*) dense constraints (i.e., constraints with large number of variables), largely impacting on computation time

Protection routing design with excluded scenarios

- The key is to reformulate (H) with compactly represented scenarios in the form of a union of *M* sets, where *M* is small compared to the number of failure scenarios
  - Reformulated (H) now has O(ME^2) constraints (*O(ME)* if each set has exactly one failure scenario)
  - Only *O(ME)* dense constraints
- Applies to partial link failure model
- Refer to the paper for the proofs and details on how the compact representation *exactly* reformulate (H)

Design with Multiple Traffic Classes

- Lancet applies to multiple traffic classes
  - Meet all high-priority, and as much low-priority traffic as possible.
  - Scale factor: after satisfying high-priority traffic, how much low-priority traffic is handled
- Split the original GEANT traffic matrix randomly into high- and low-priority
- **Takeaway**: Lancet performs nearly as well as Centralized (ideal). While it degrades moderately for the most stringent performance thresholds 1.4 and 1.6

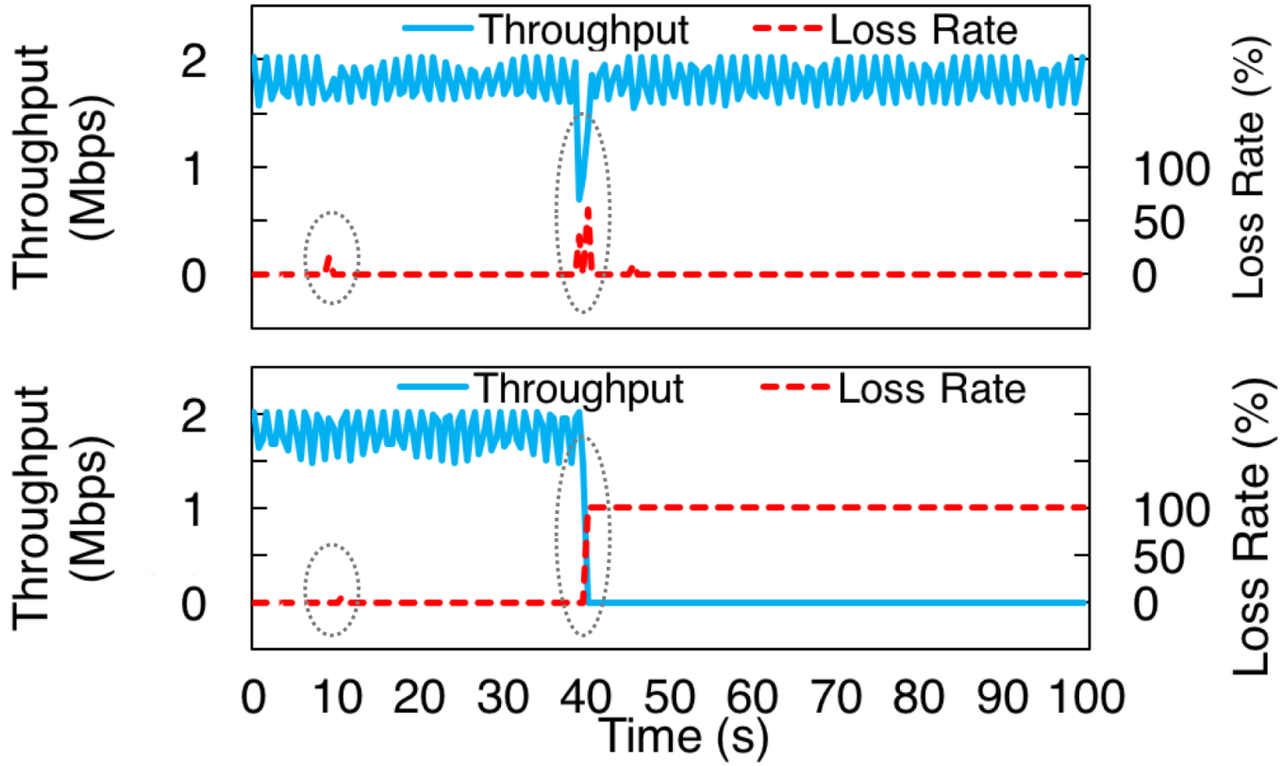


Validation on Testbed

- Emulation setup
  - Mininet 2.2 + OpenVSwitch 2.10 + OpenFlow 1.5
  - Abilene network, k = 1
    - MLU < 1 for single failures; MLU > 1 for two failures
- Protection routing implementation
  - Initial flow rules installed by a central controller
  - Failure information propagated by MPLS-label switching
  - Central controller updates protection routing on detecting failures

Validation on Testbed

- Experiment setup
  - Gen-R3: designed for *f = 1*
  - Lancet: designed for all *f <= 2* scenarios, excluding bad ones
  - 30 UDP flows with the same demands between source and destination
- **Takeaway**
  - Lancet tolerates the second link failure, but Gen-R3 fails to react
  - Reasoning: Gen-R3 resulted in two failed links mutually using each other to protect against their respective failures



Lancet (top) vs. Gen-R3 (bottom)

on Abilene k = 1

Protection Routing Design

- Link-based protection routing
  - Provision by-pass paths to protect against each link failure
  - Achieved using (H), generalizing a state-of-the-art scheme [1]
- Issues with existing protection routing schemes
  - Only work if *X* is all f failures
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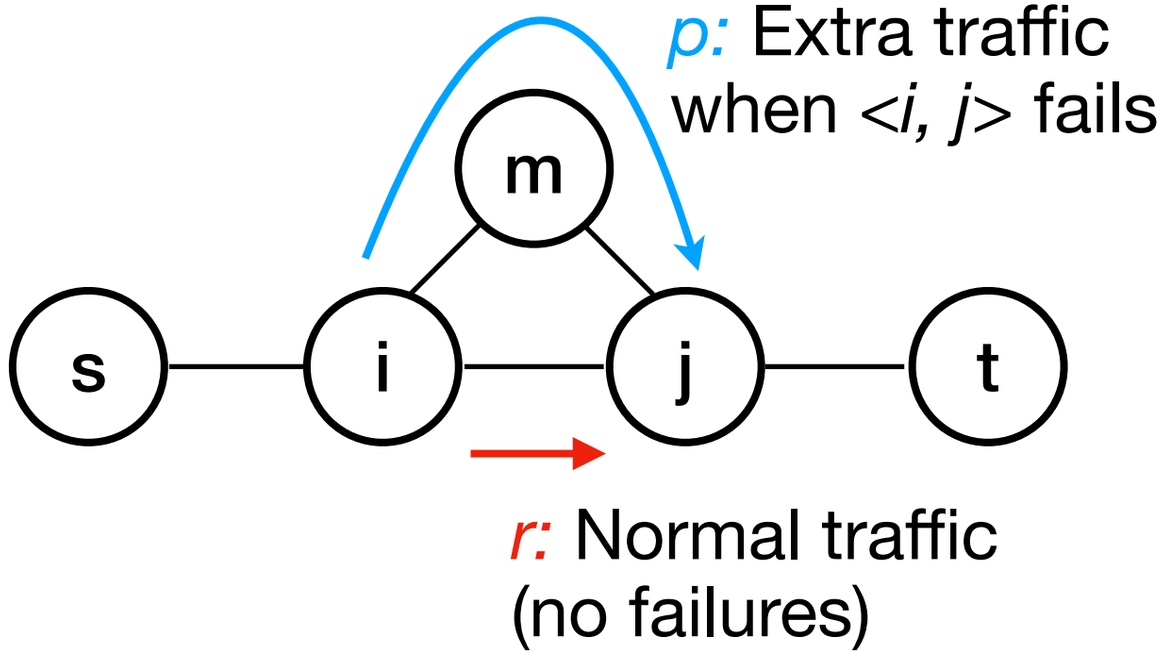
- What we want: Design for most *f* failures if not all



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