Interventional Root Cause Analysis of Failures in Multi-Sensor Fusion Perception Systems

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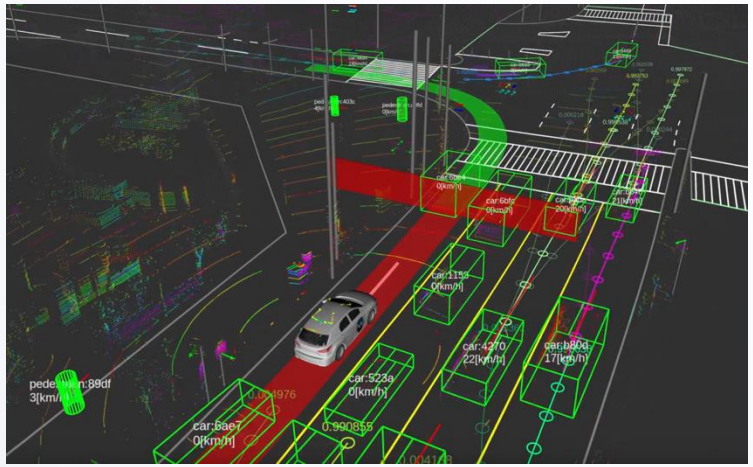
Outlines

- Background
- Existing Work
- Methodology
- Evaluation
- Summary

Background: Multi-Sensor Fusion Perception Systems



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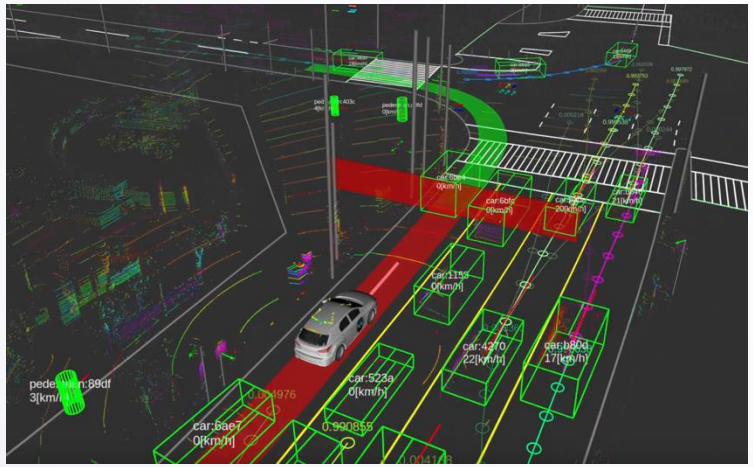

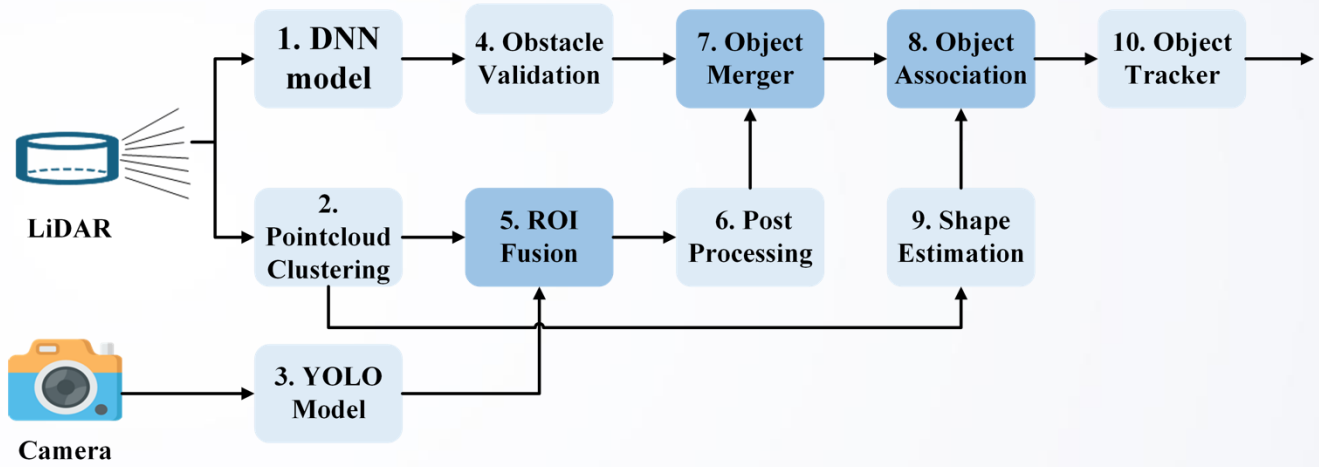

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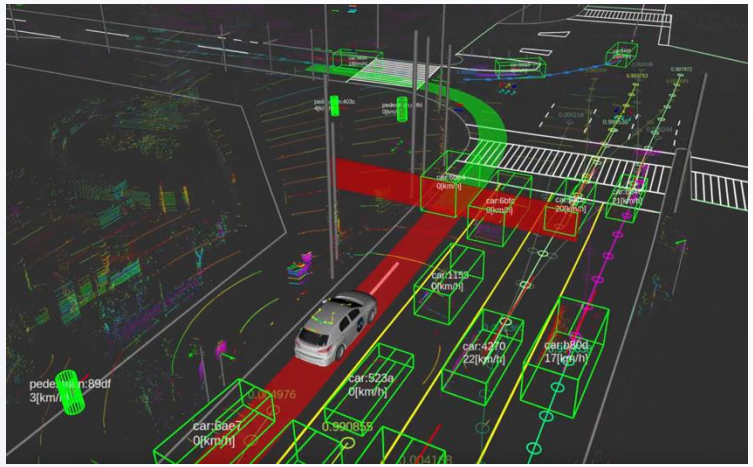

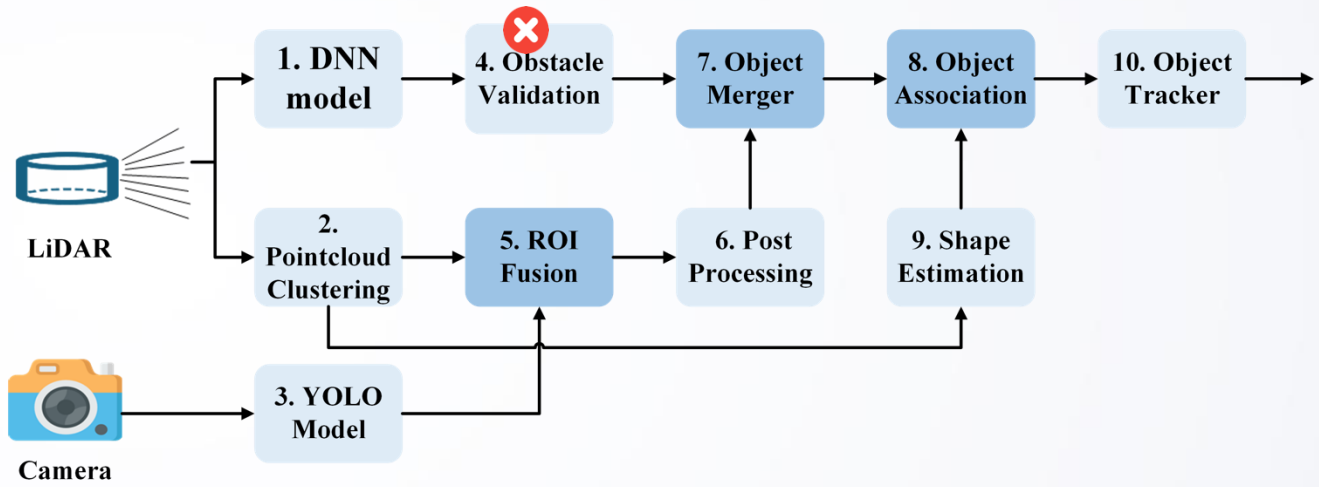

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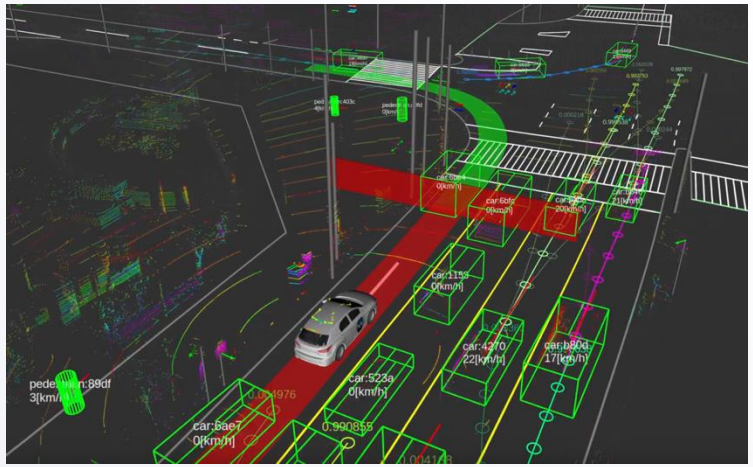

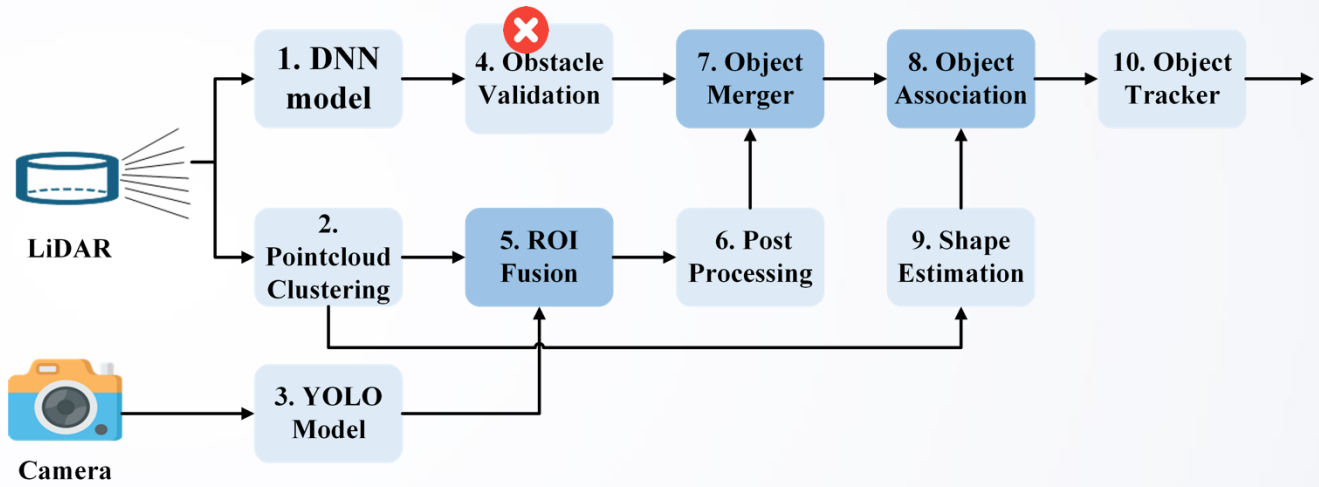

- **Perception Failures:** Missing obstacle, Ghost obstacle, …

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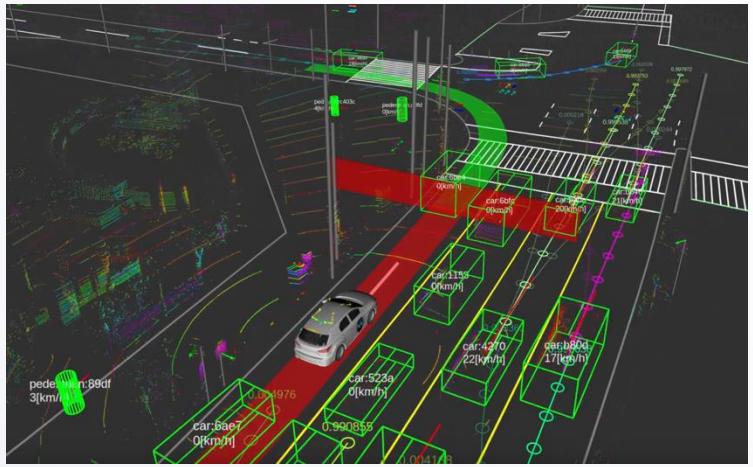

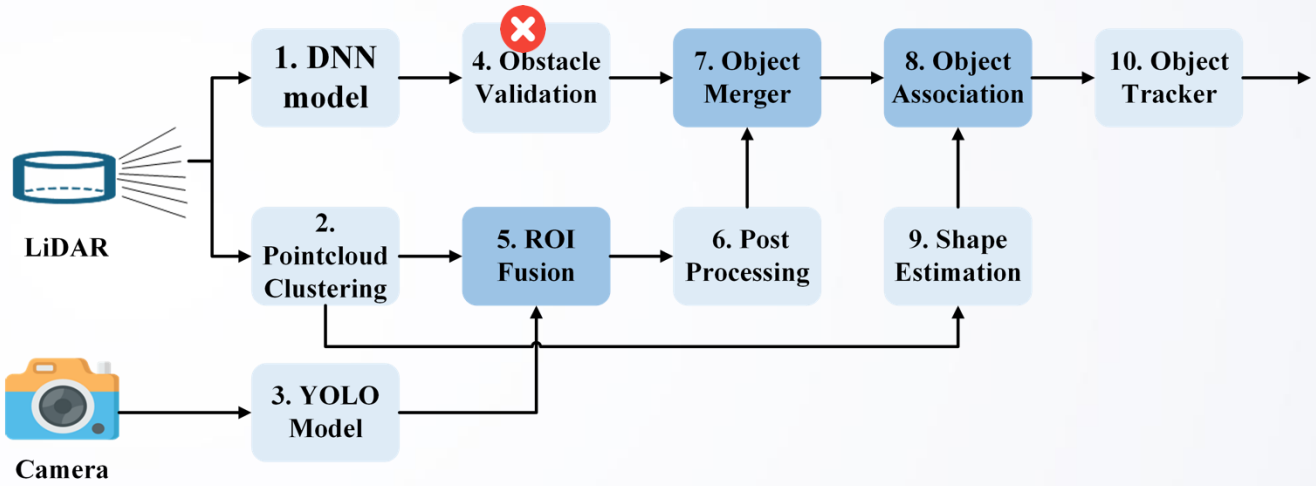

- **Perception Failures:** Missing obstacle, Ghost obstacle, …
- **Security Impact:** Risk of collision

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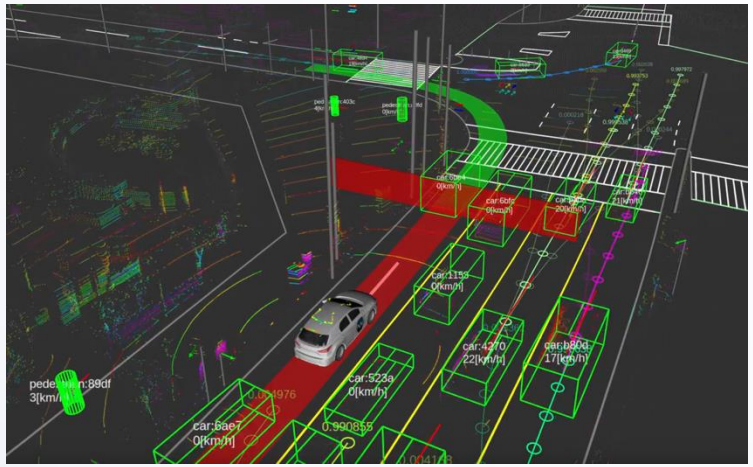

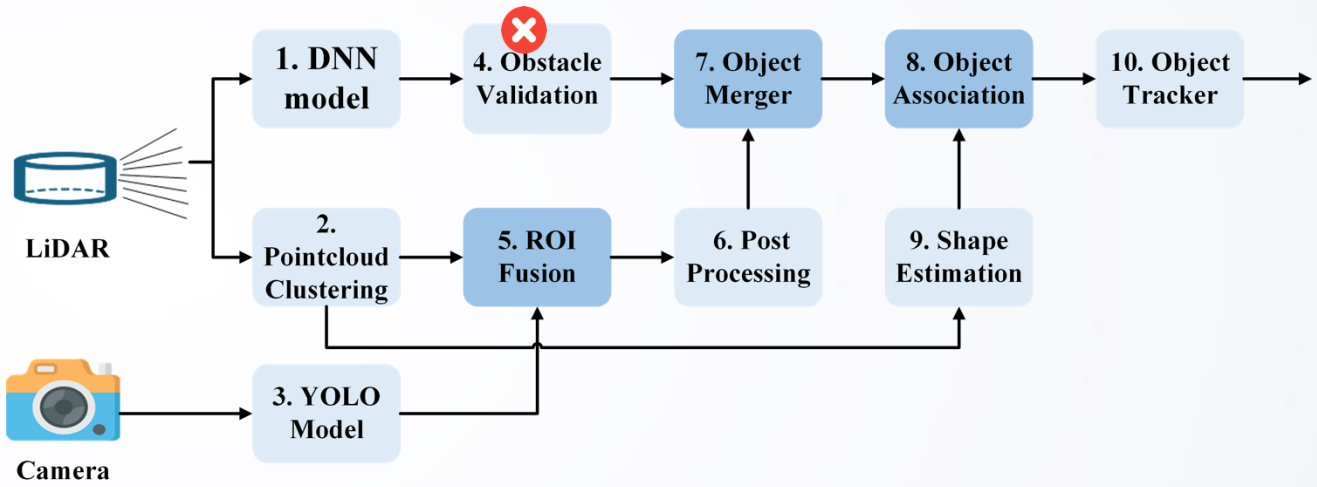

- **Perception Failures:** Missing obstacle, Ghost obstacle, …
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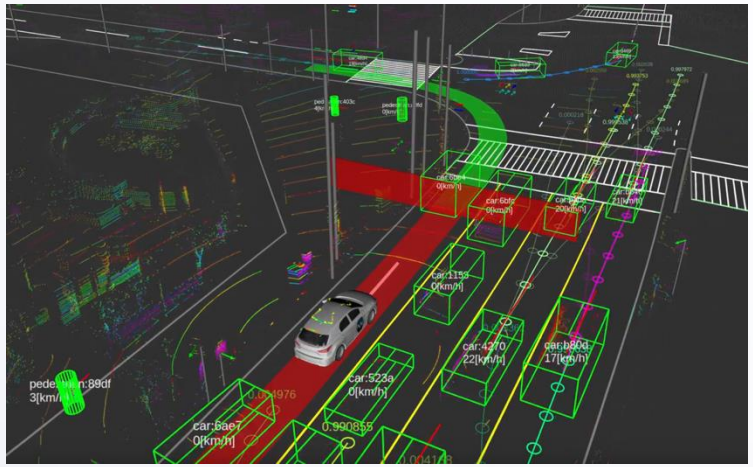

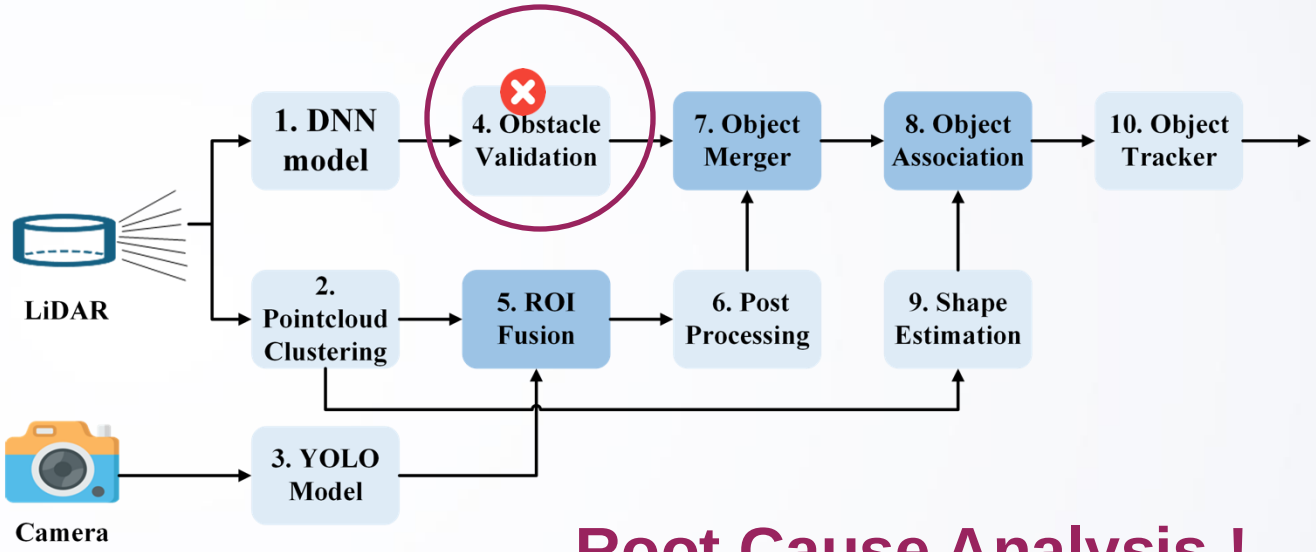

Root Cause Analysis !

- **Perception Failures:** Missing obstacle, Ghost obstacle, …
- **Security Impact:** Risk of collision, Improper driving decisions

Existing work and Limitation

Root Cause Analysis

Limitations

Existing work and Limitation

Root Cause Analysis	Limitations
Microservices RCD(NIPS' 22), CIRCA (KDD' 22)	

Existing work and Limitation

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Existing work and Limitation

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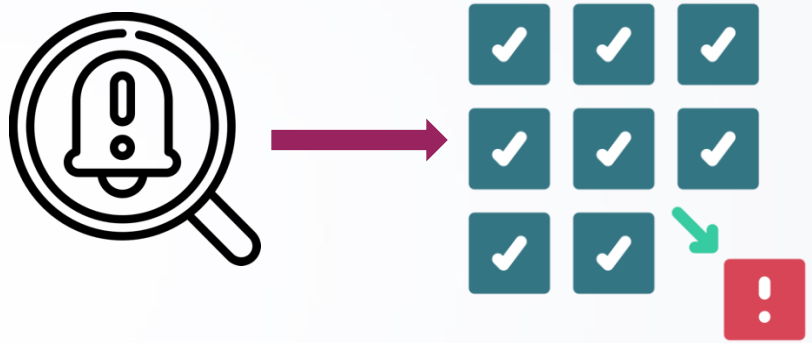
Causality Testing AID(SIGMOD' 20), CART(TOSEM'24)	→ Single Root Cause

Root Cause Analysis of Perception Failure

Our Goals:

1. **Locate Faulty Modules**
2. **Identify Fault Types**



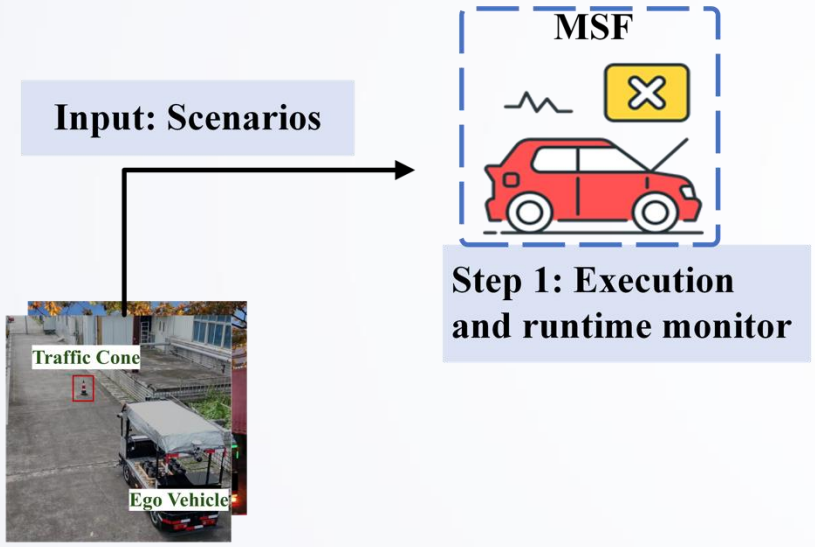
With the following features:

- **Multiple Concurrent Root Causes**
- **Highly Efficiency**
- **Fully Automated**
- **Generality**

IRCA: Interventional Root Cause Analysis

Input: Scenarios

IRCA: Interventional Root Cause Analysis



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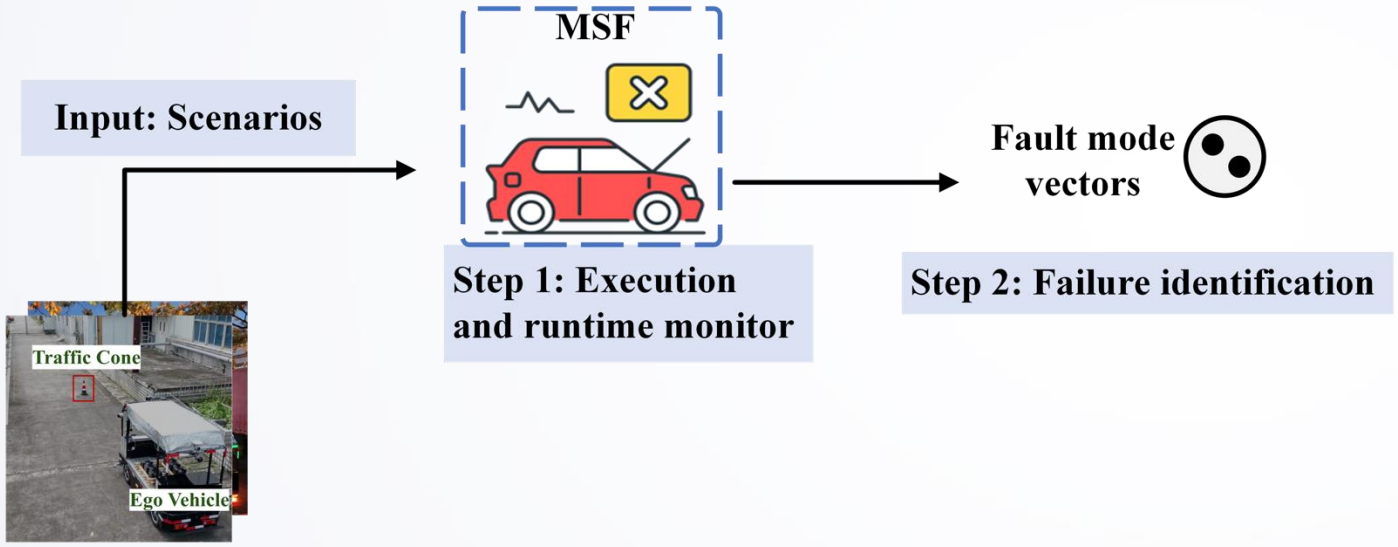

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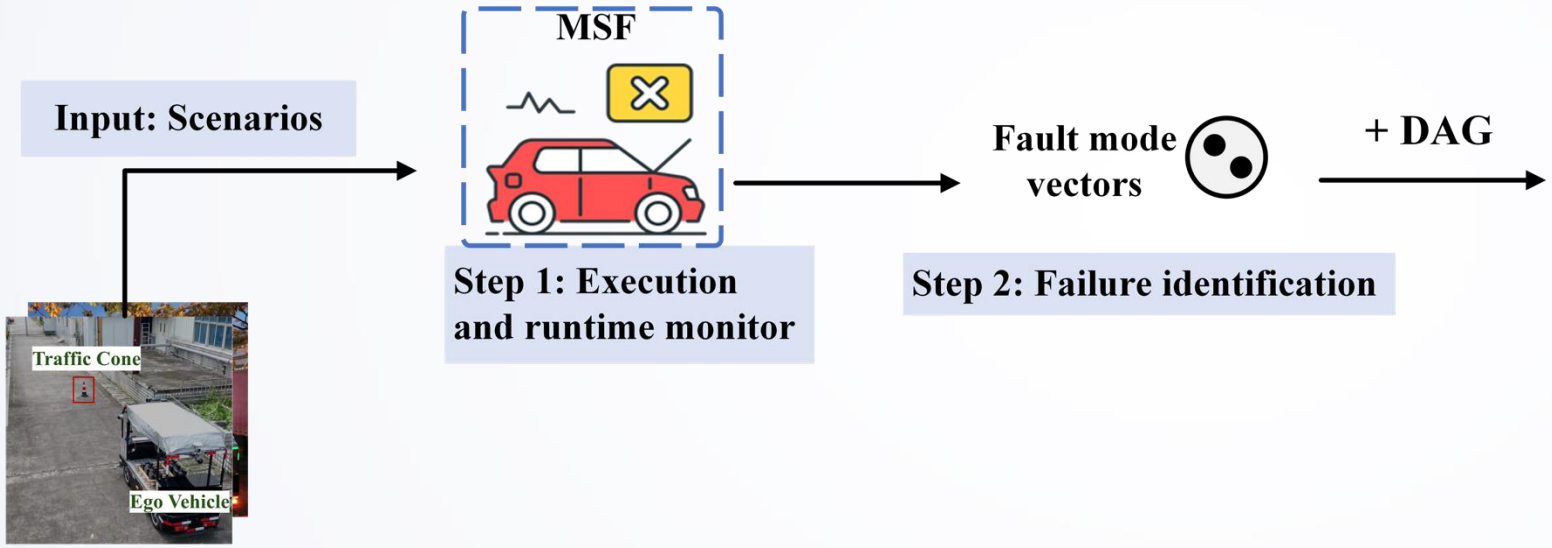

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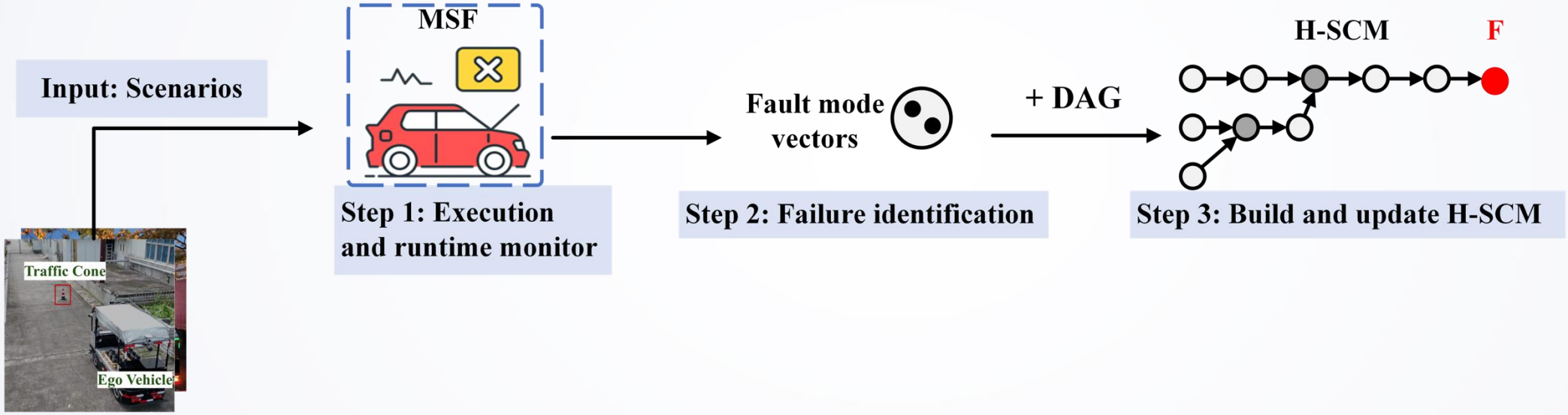

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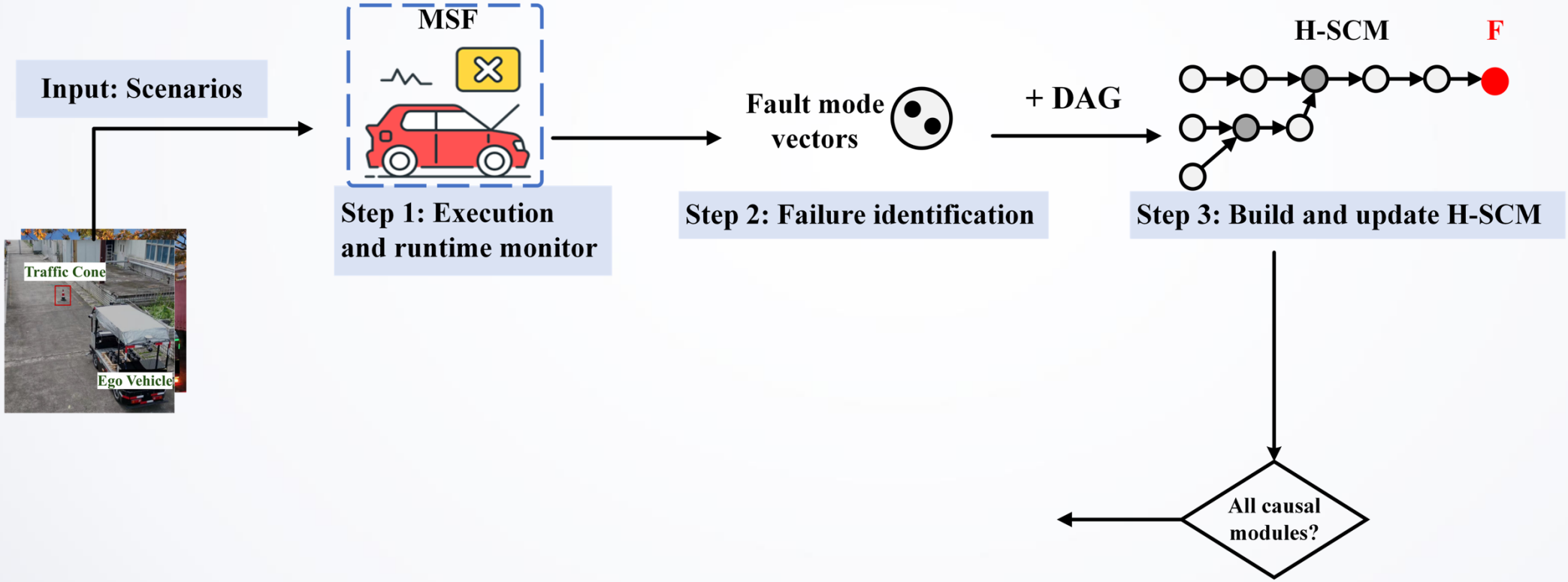

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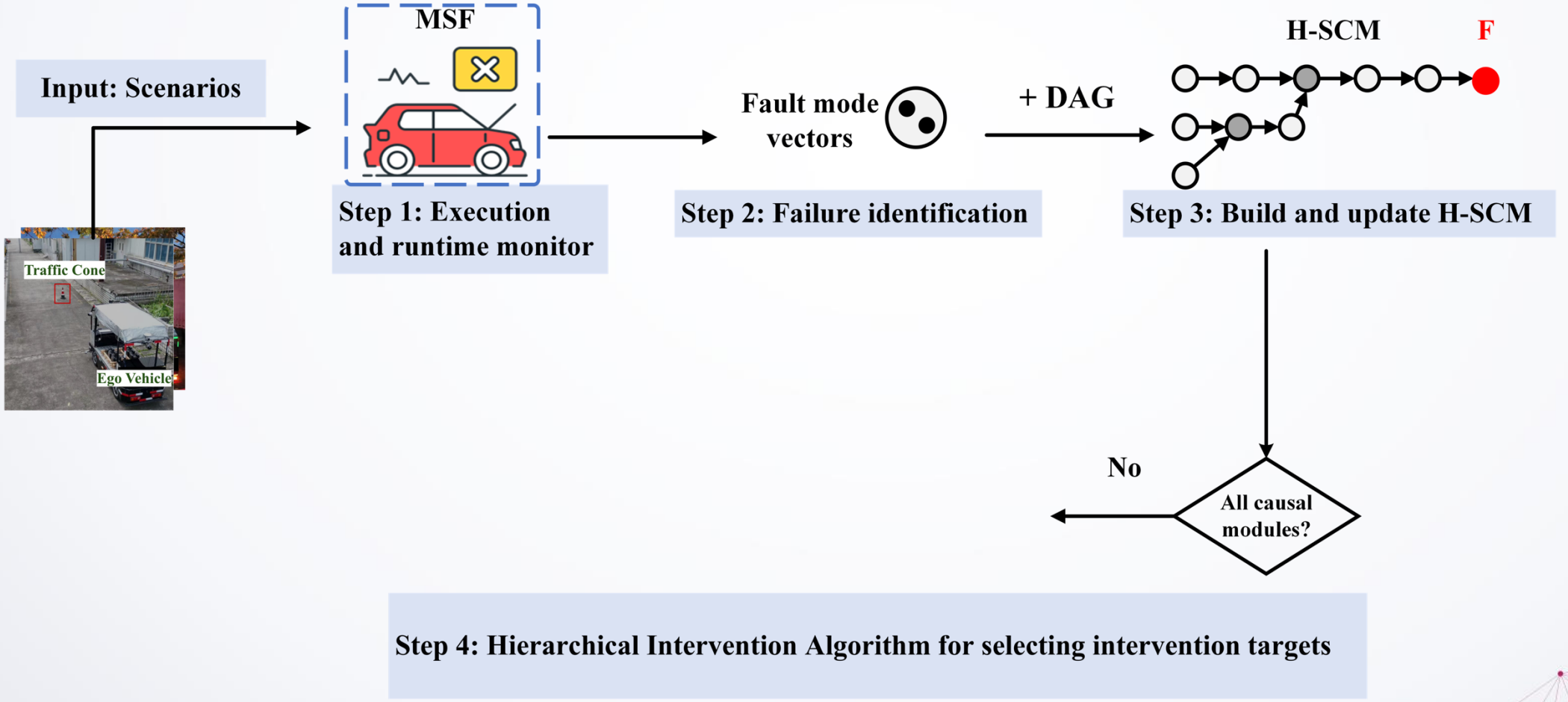

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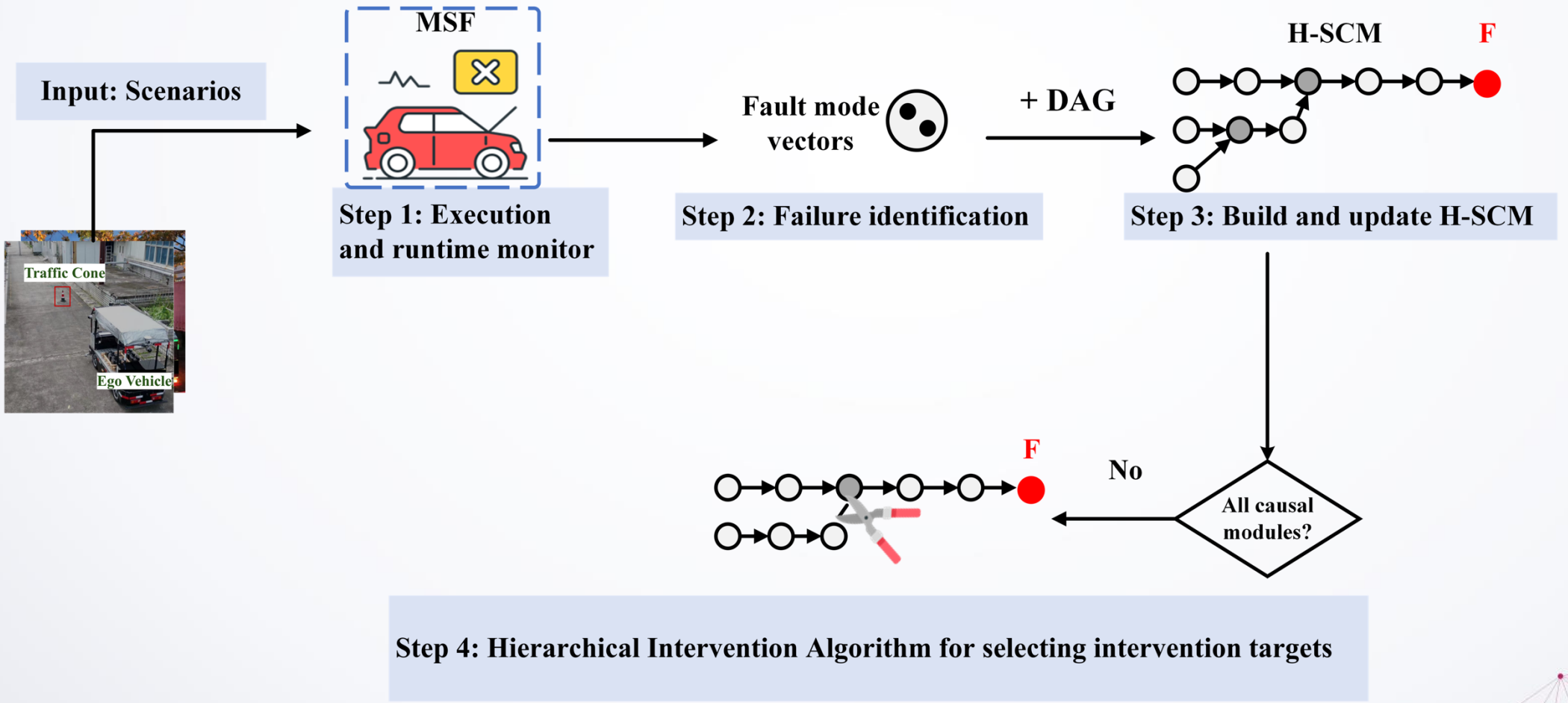

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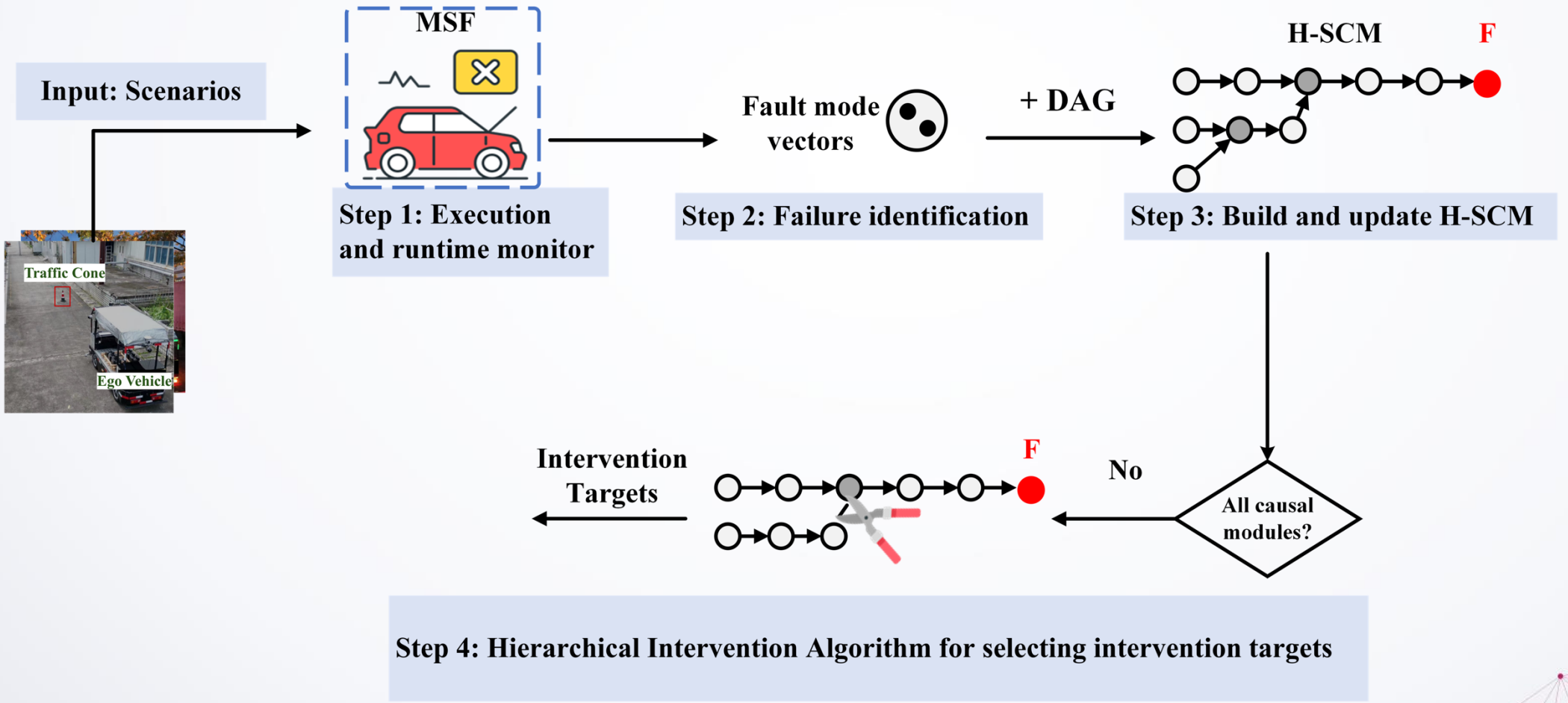

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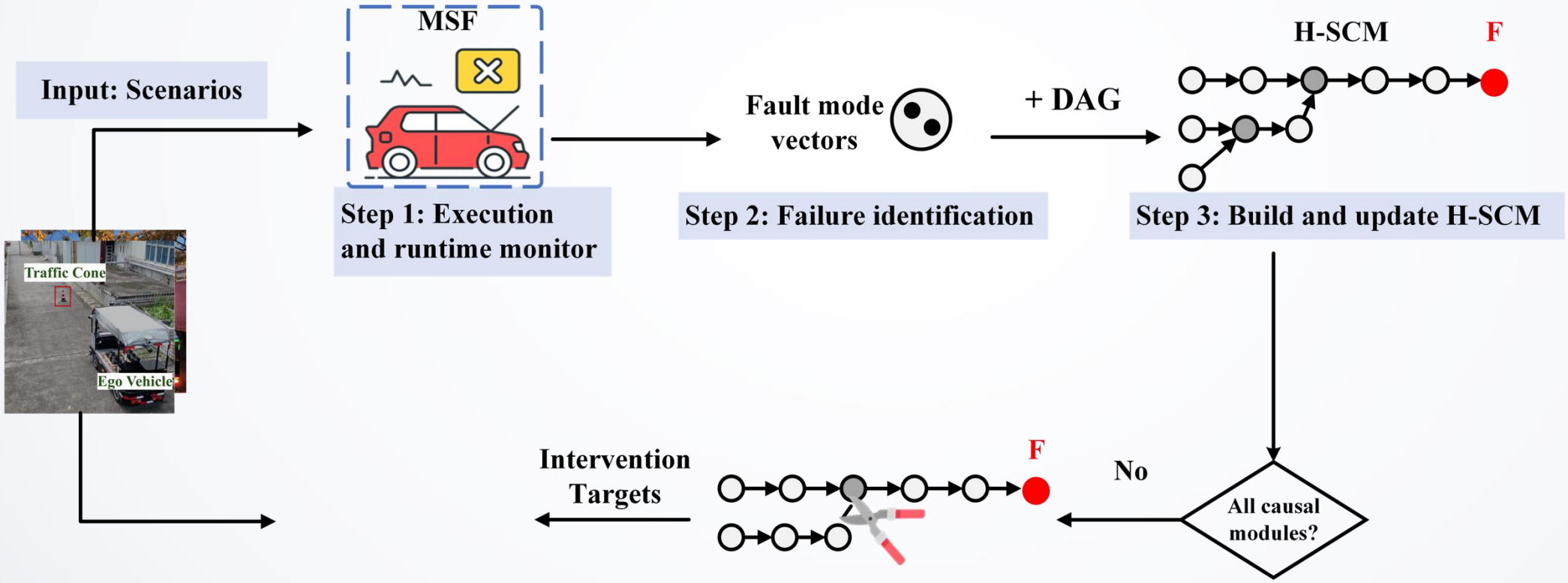

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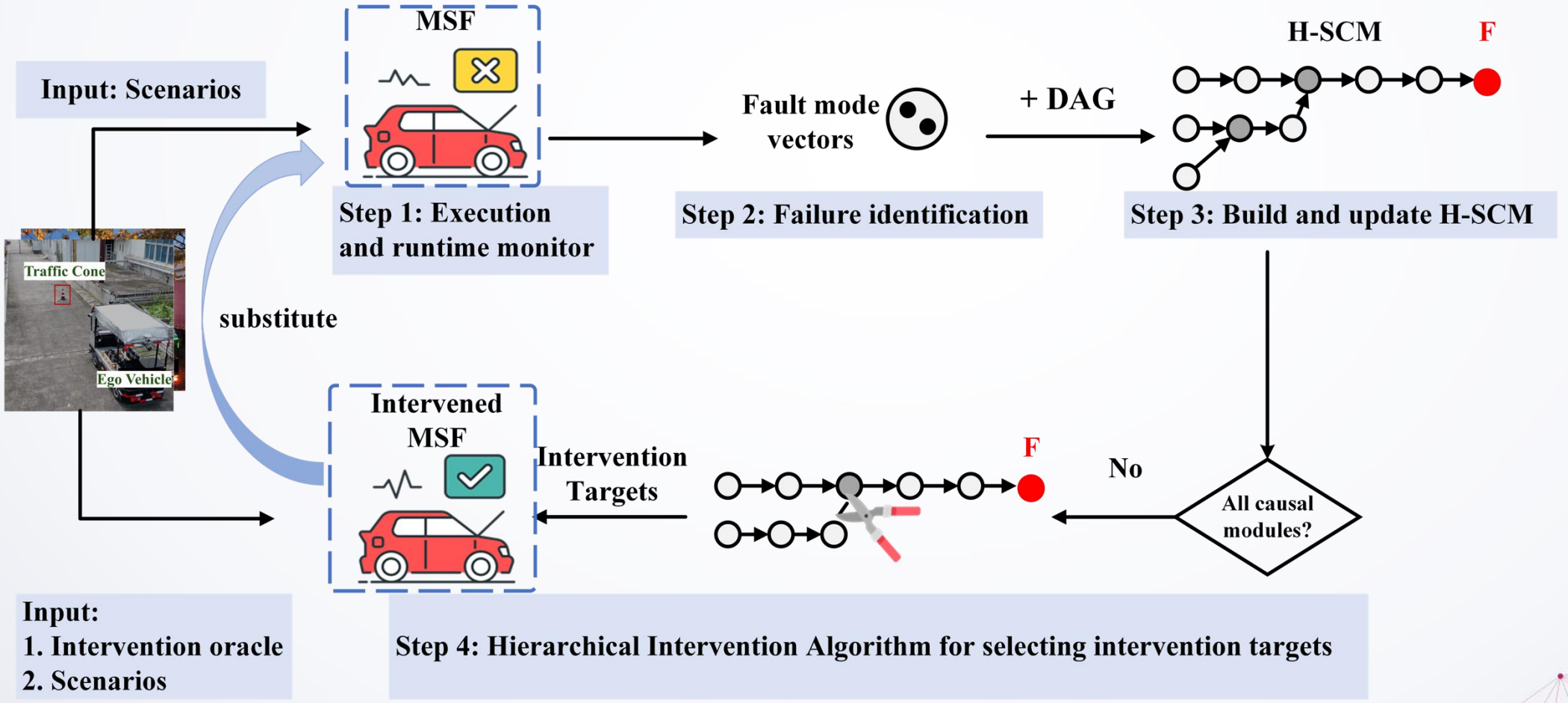

Generality: Cross-platform Compatible

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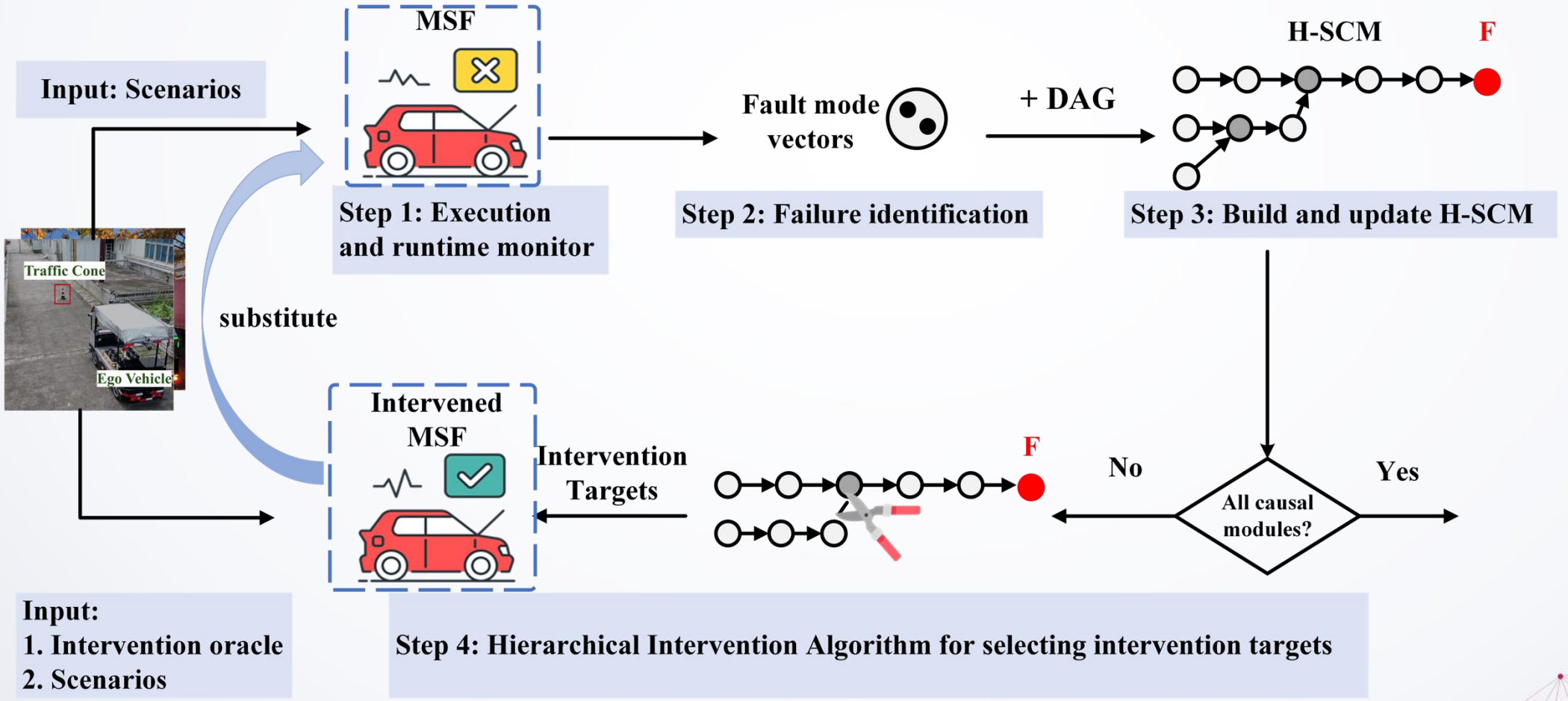

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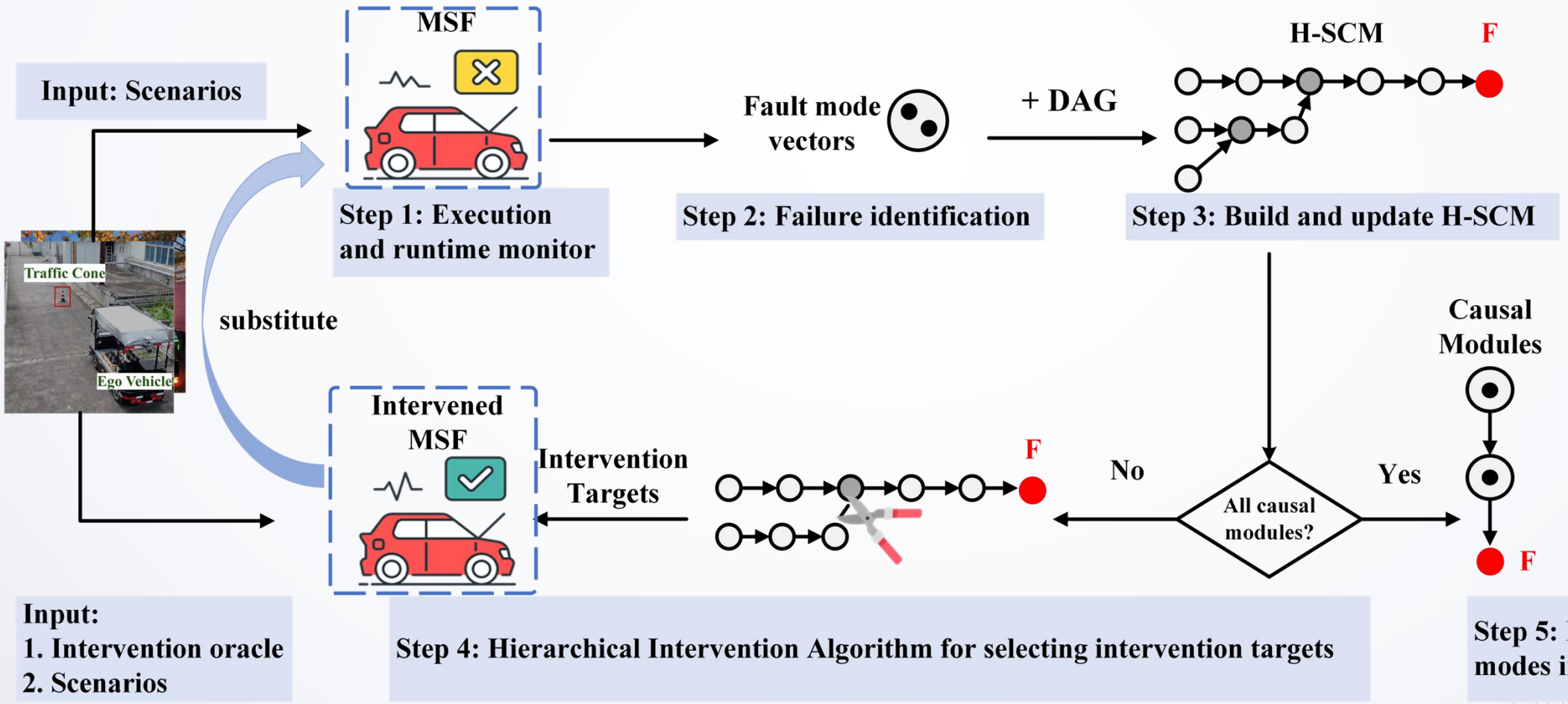

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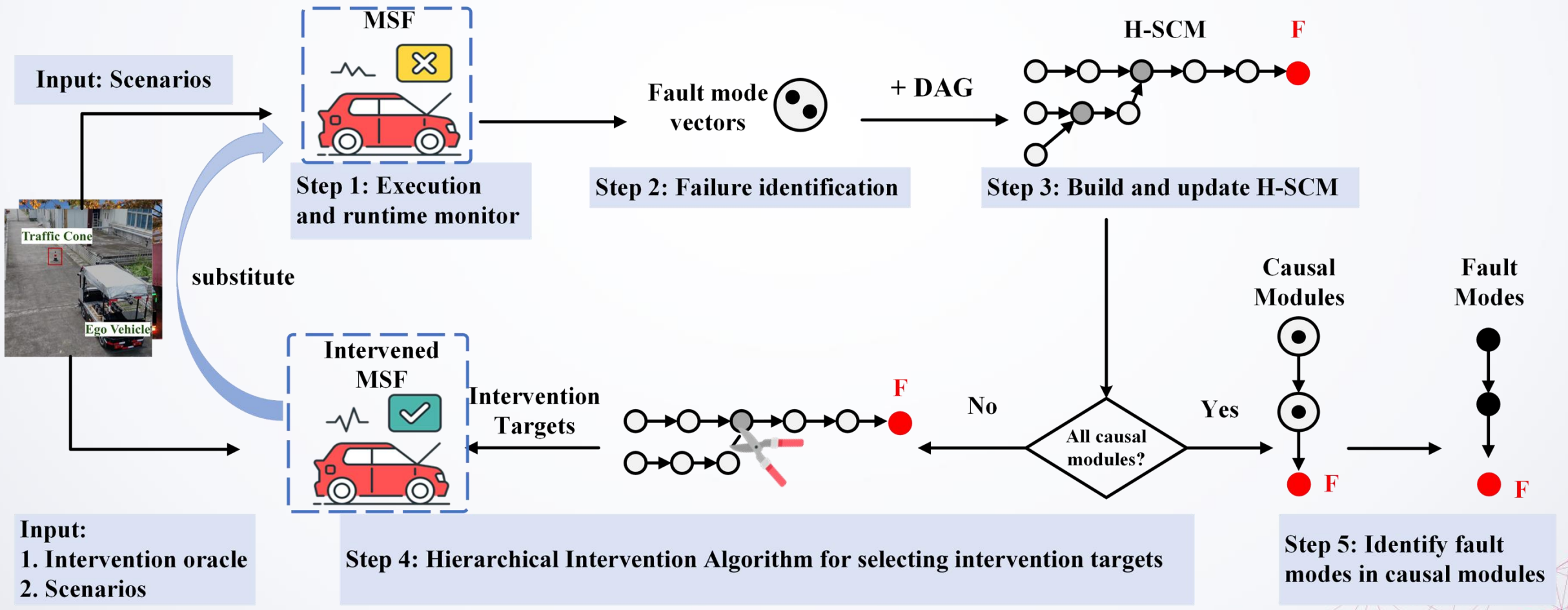

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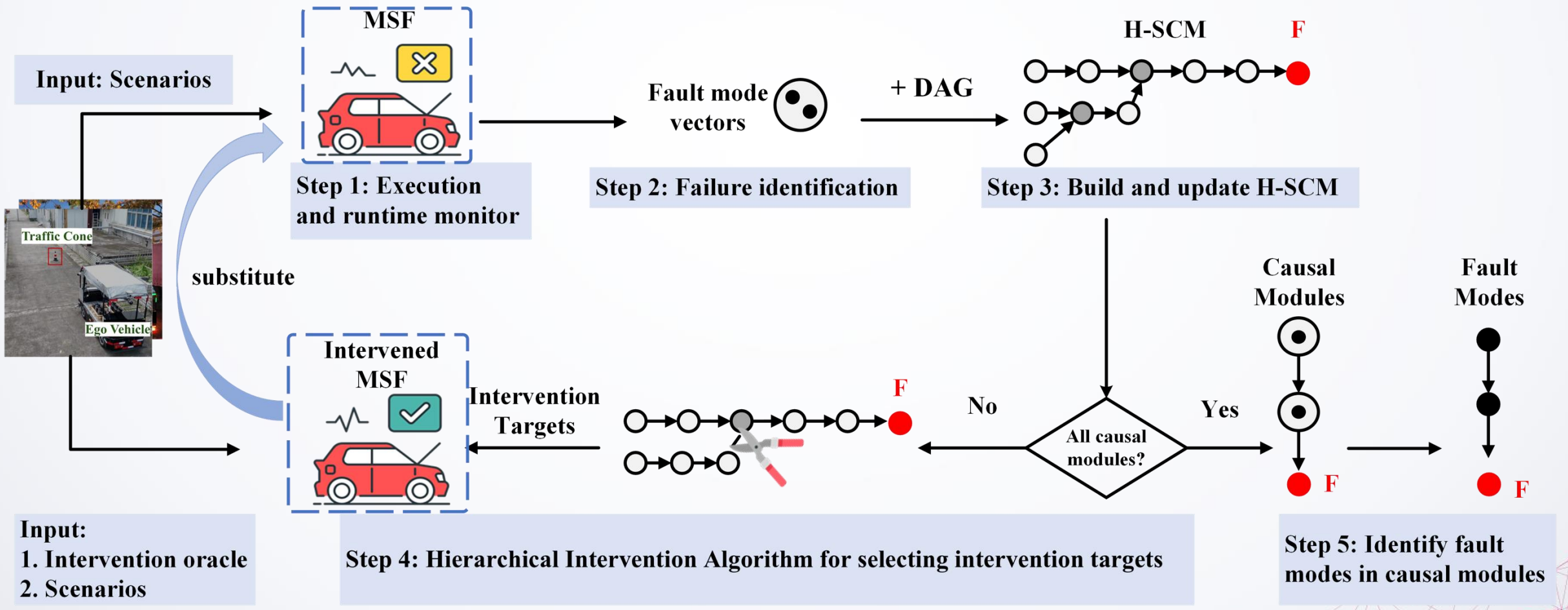
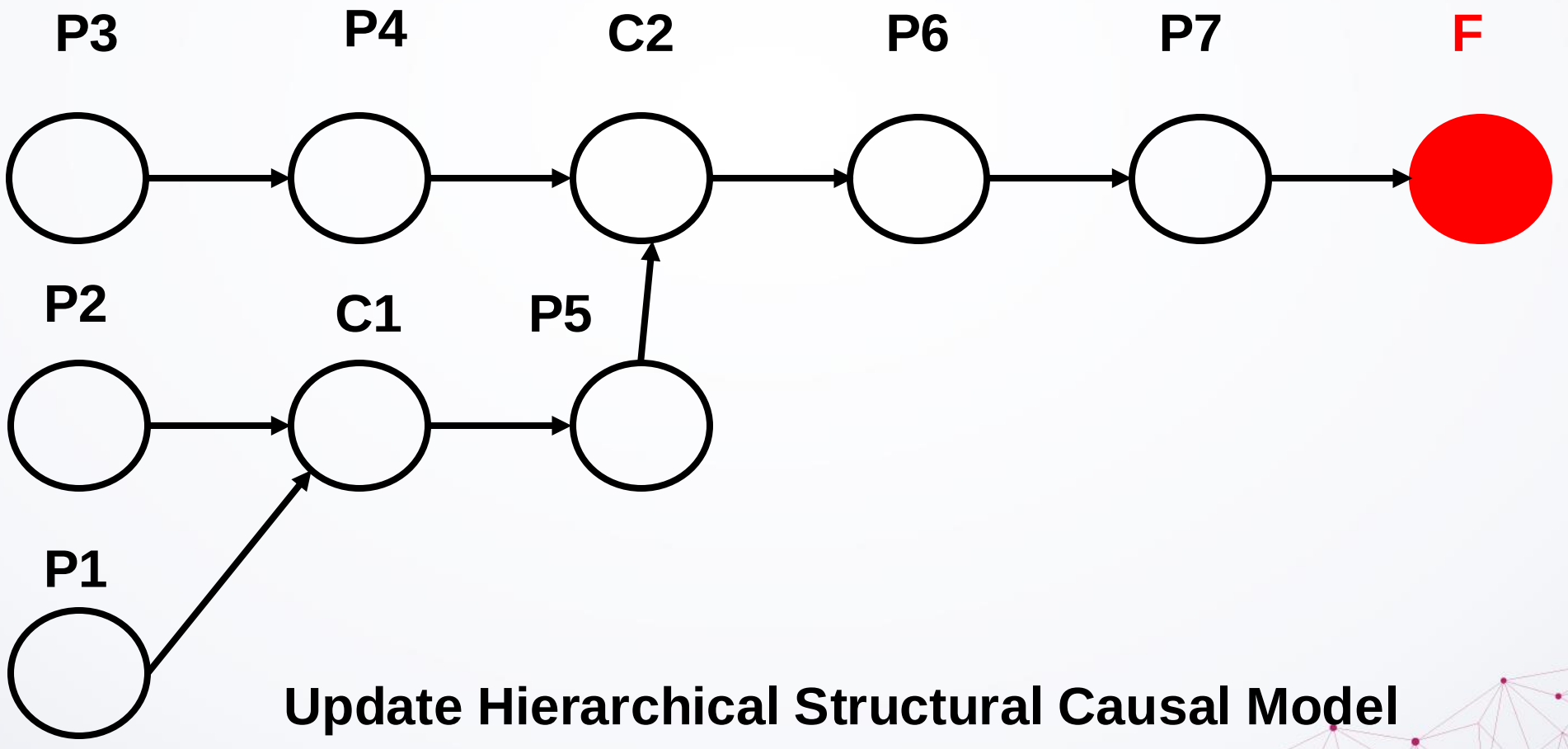


Generality: Cross-platform Compatible

Fully Automated

Hierarchical Intervention Algorithm

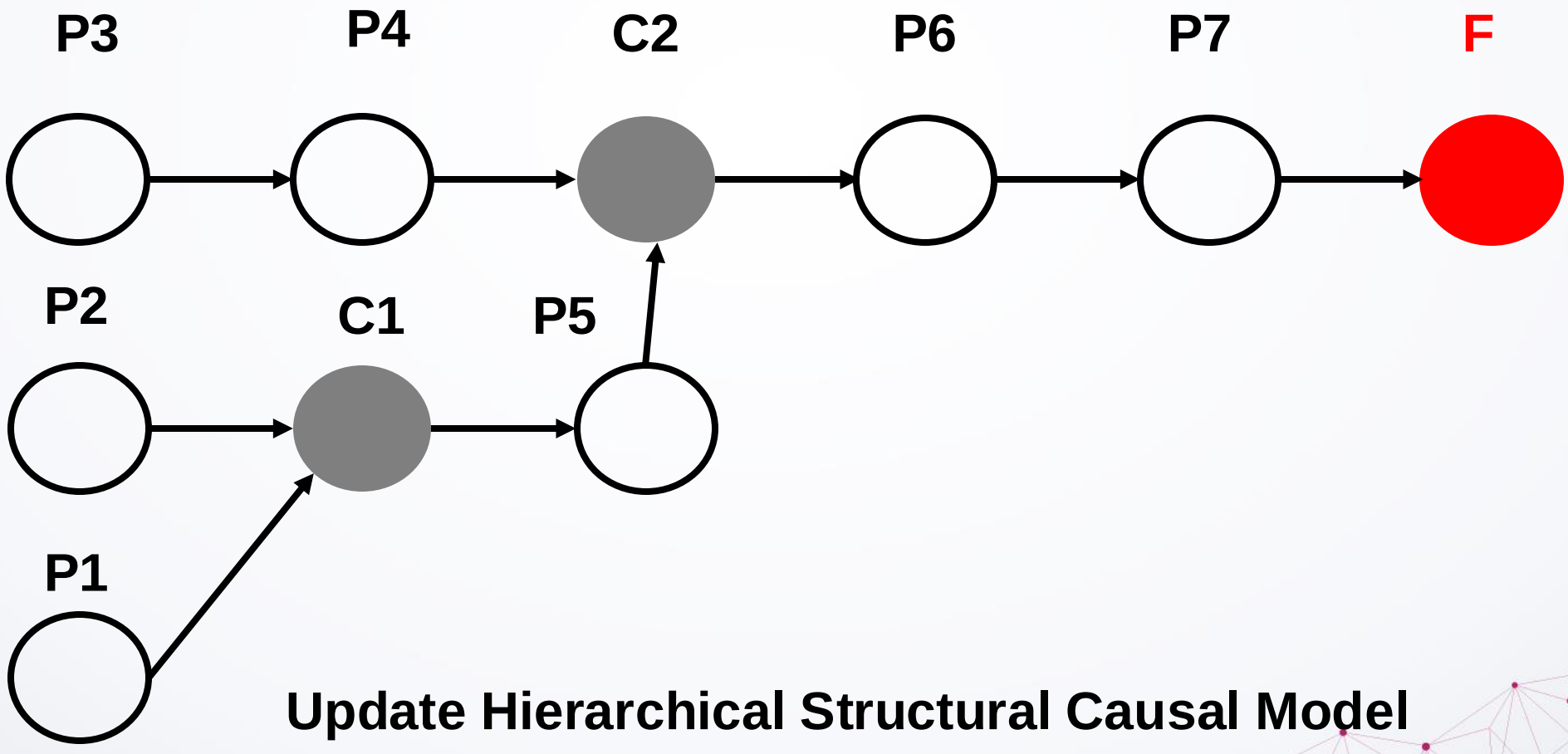
- Stage 1- Branch Pruning



Update Hierarchical Structural Causal Model

Hierarchical Intervention Algorithm

- Stage 1- Branch Pruning



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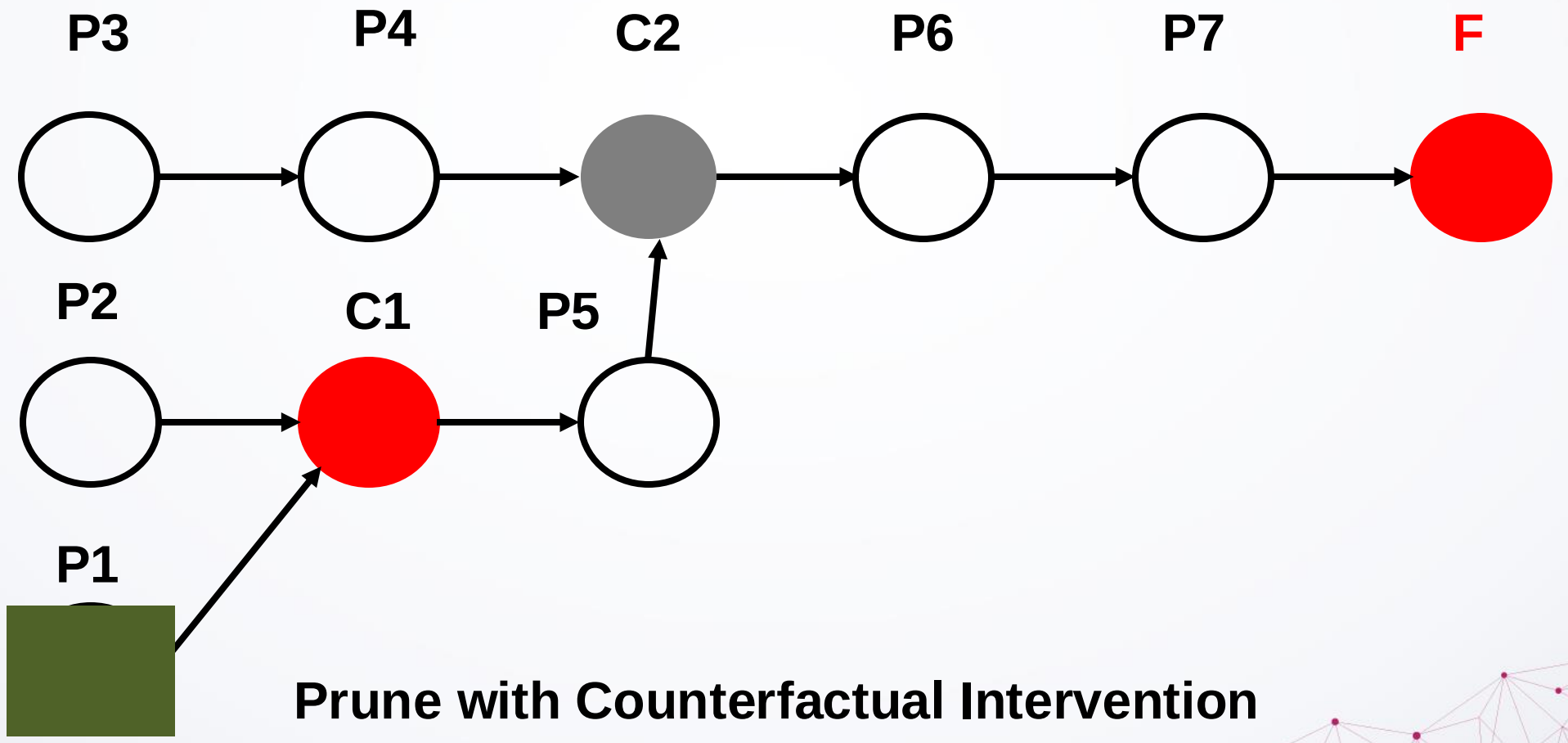

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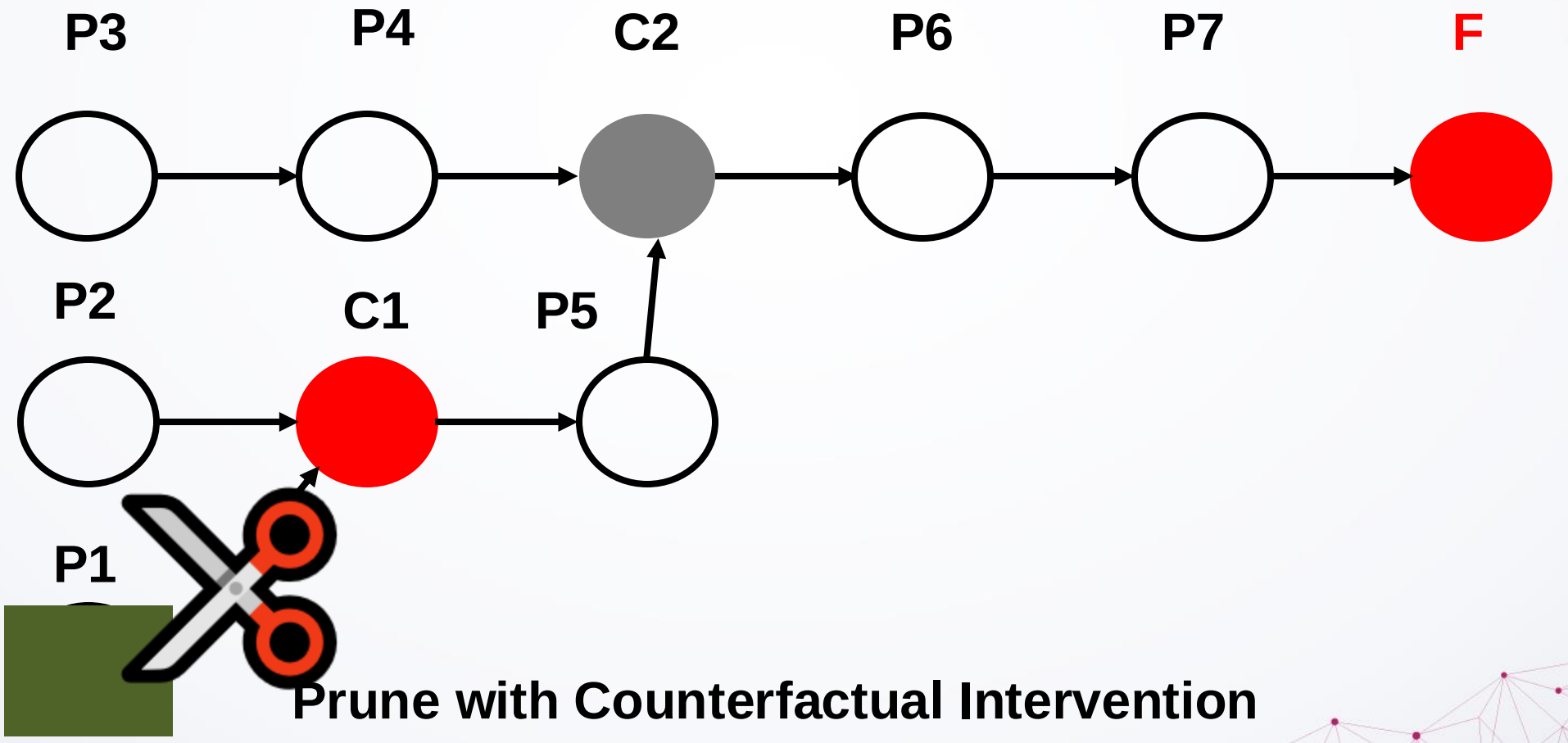

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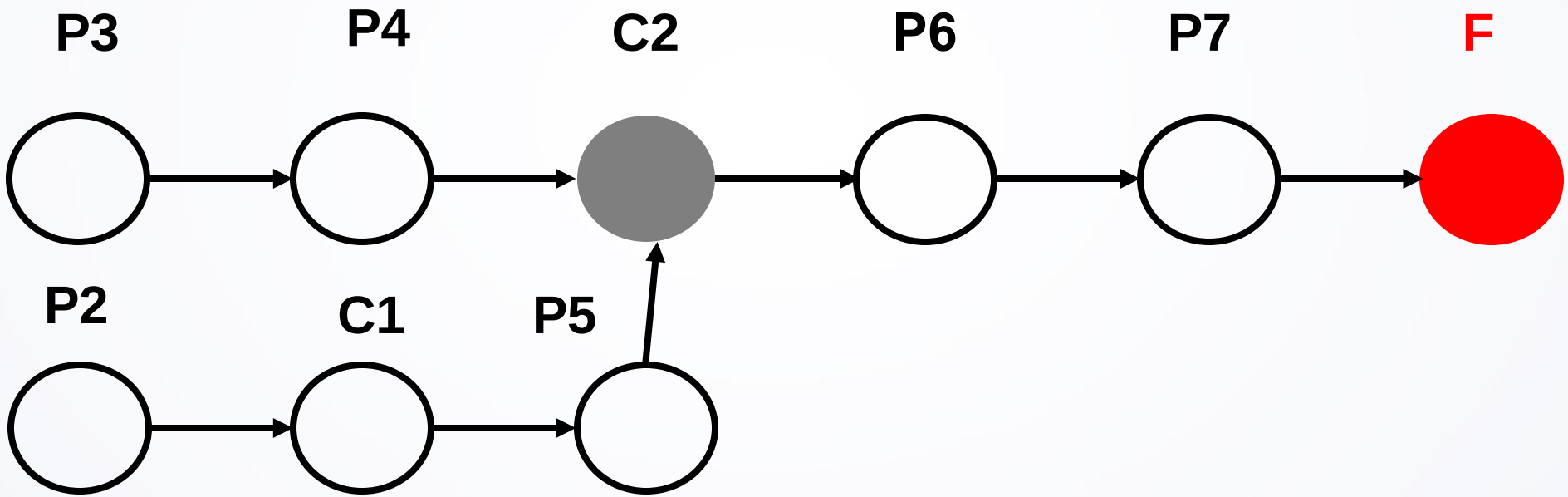
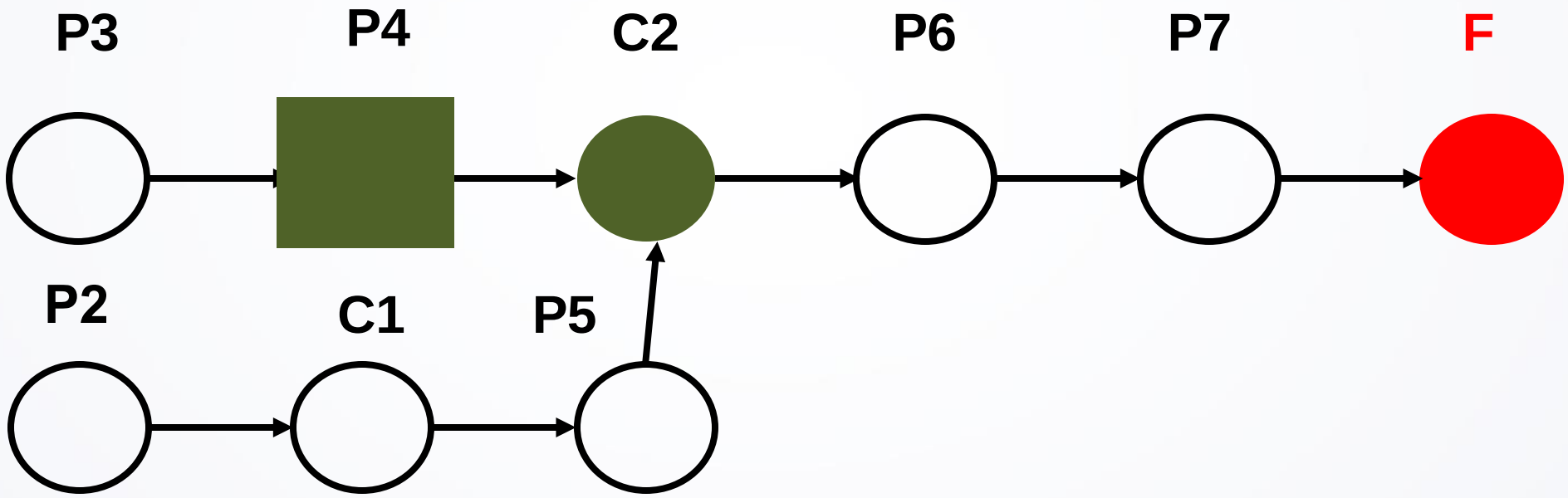


Prune with Counterfactual Intervention

Hierarchical Intervention Algorithm

- Stage 1- Branch Pruning



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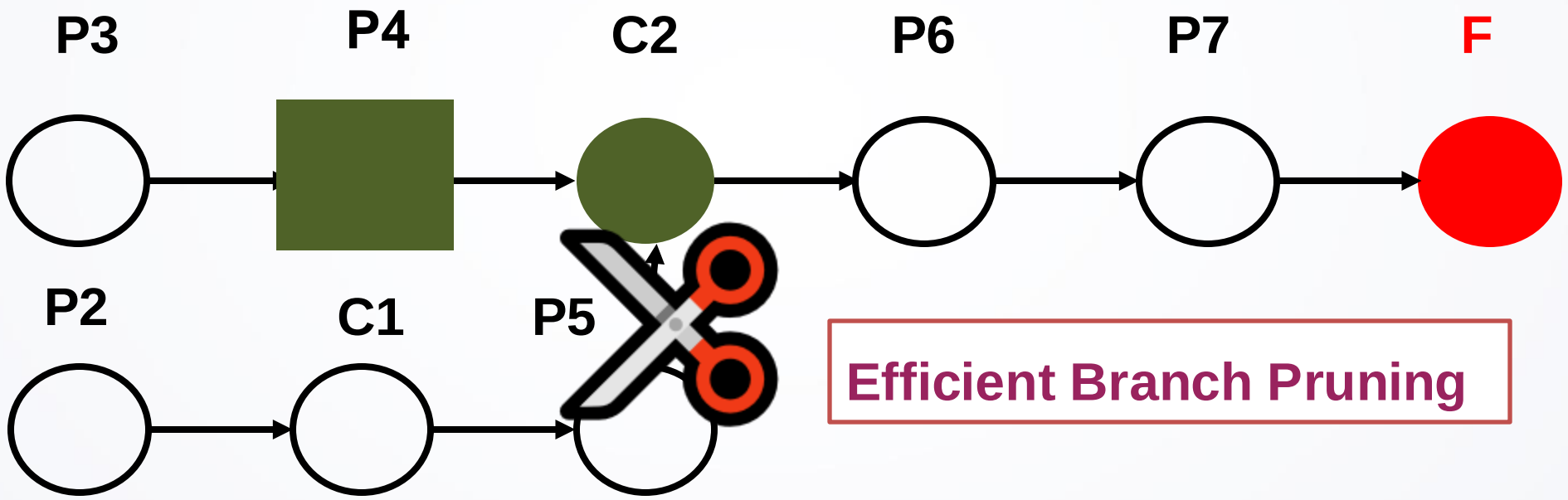

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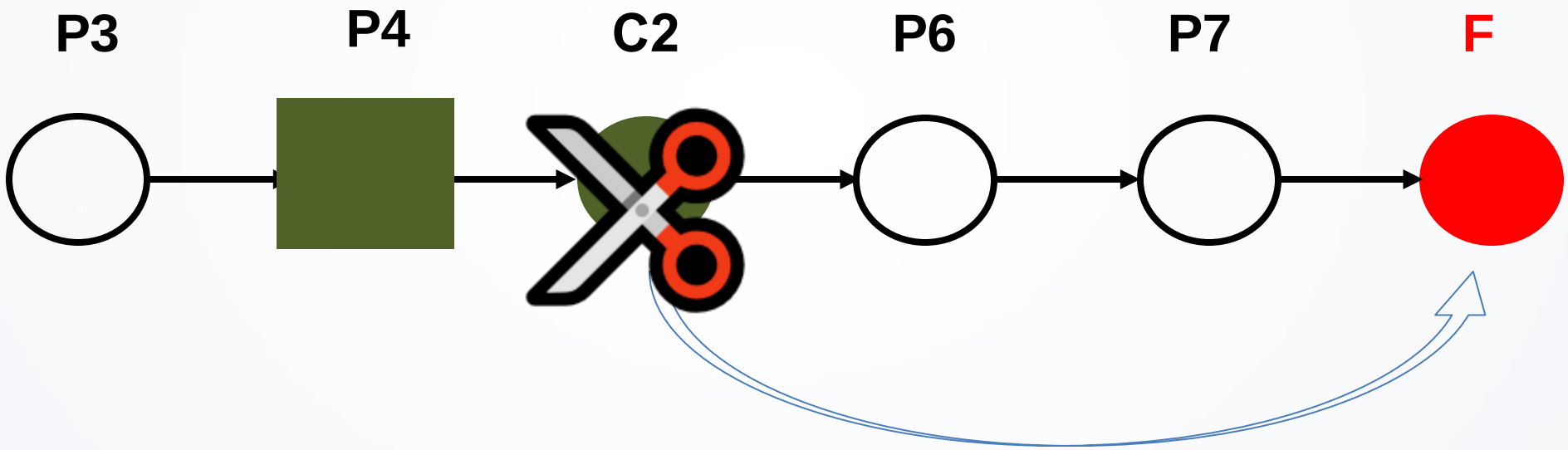
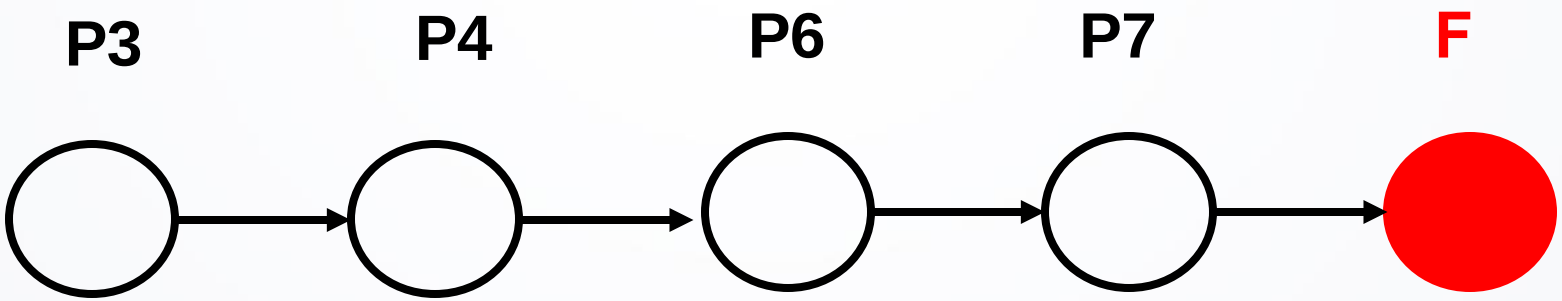


Conflict! -> Non-causal

Prune with Counterfactual Intervention

Hierarchical Intervention Algorithm

- Stage 2- Node Pruning



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Hierarchical Intervention Algorithm

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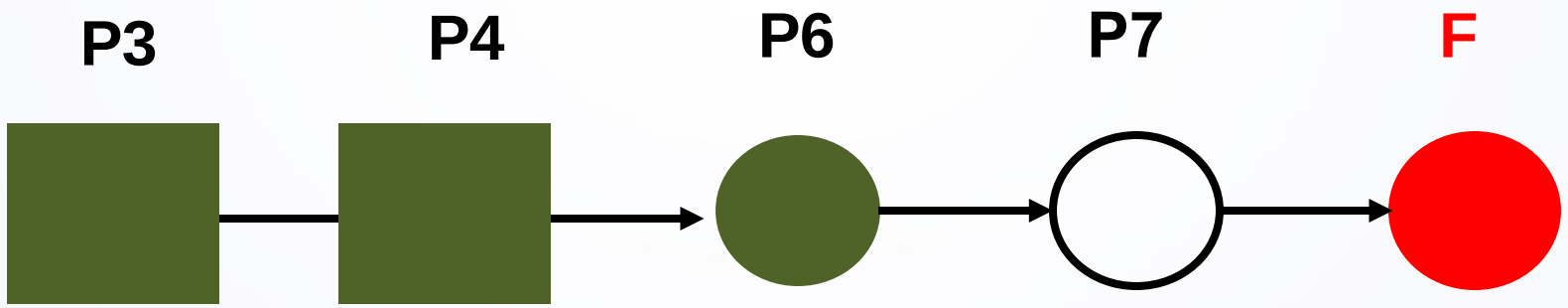

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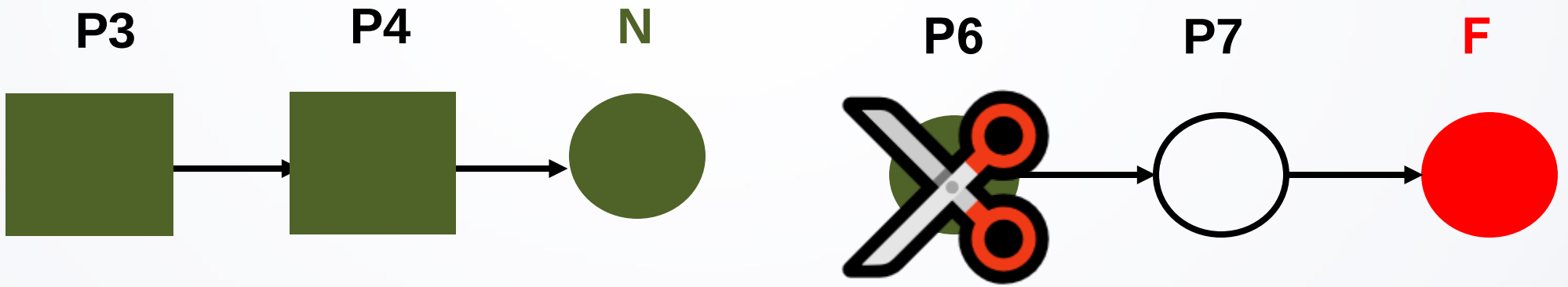

Track Multiple Concurrent Root Causes

Hierarchical Intervention Algorithm

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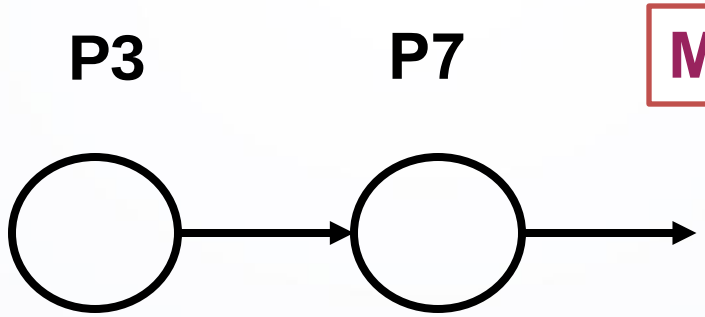
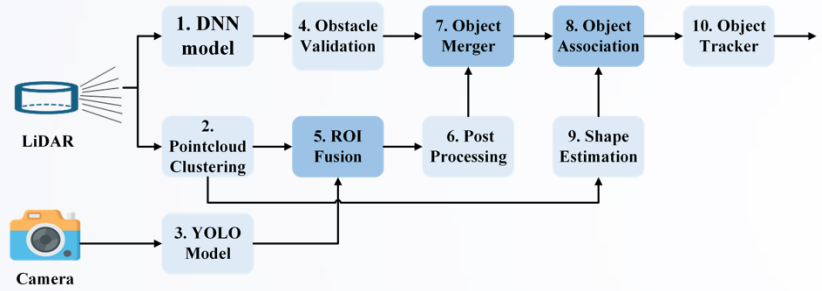


Multiple Causal Modules

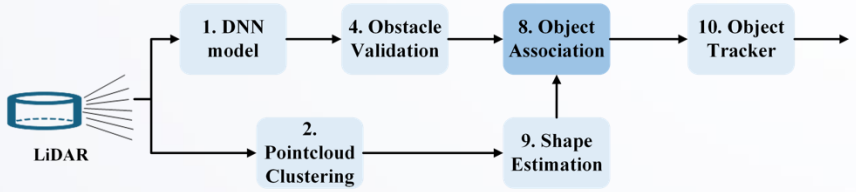
Track Multiple Concurrent Root Causes

Evaluation Experiments

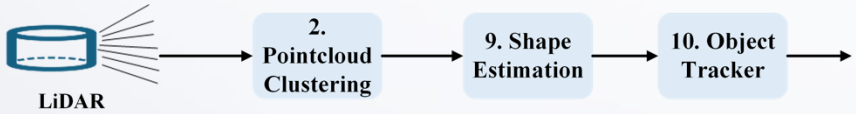
MSF Configurations



Camera-LiDAR-fusion pipeline



LiDAR-fusion pipeline



Cluster pipeline

Datasets

1. Real Fault Scenarios

- Github issues

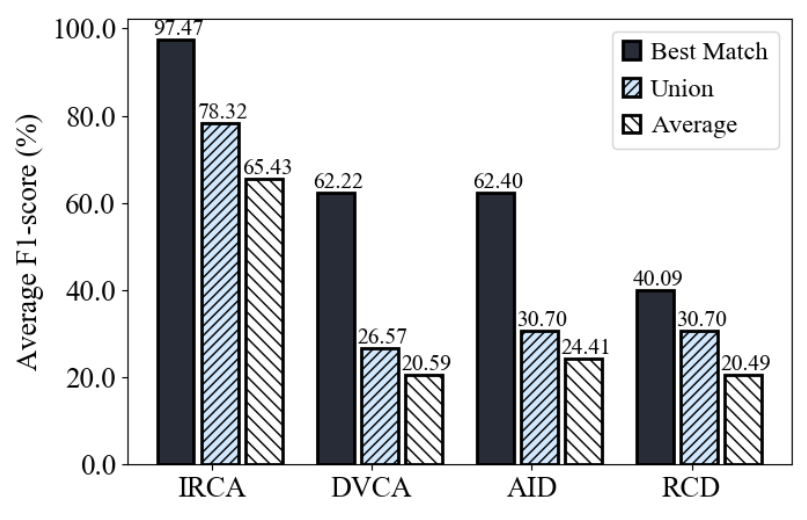
2. Synthetic Fault Scenarios

- Single fault
- Multiple faults

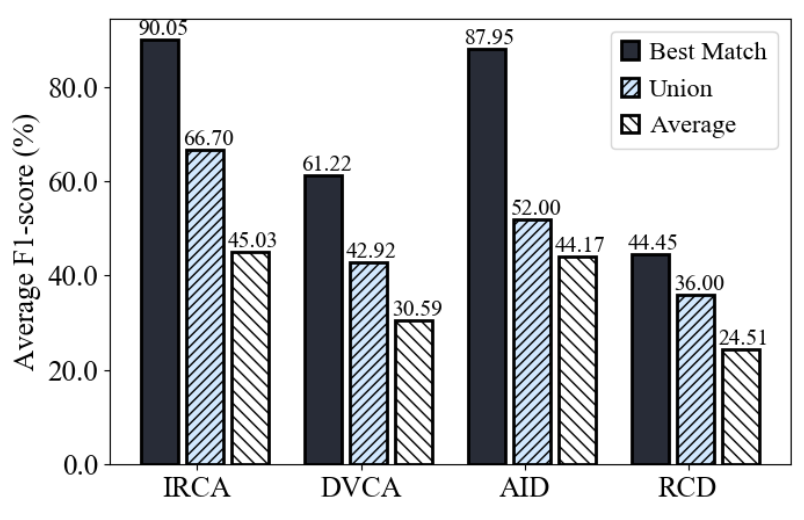
Baselines

- Driving Violation Cause Analysis (DVCA)
- Adaptive Interventional Debugging (AID)
- Root Cause Discovery (RCD)

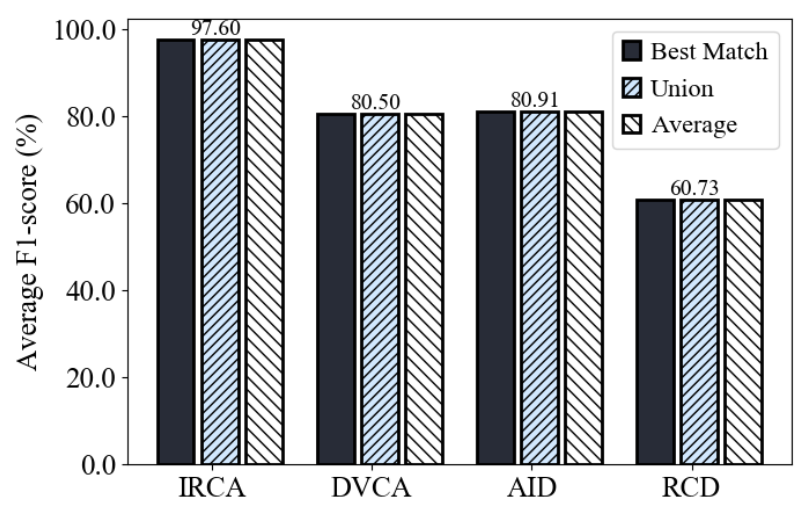
Effectiveness on Real Fault Scenarios



Camera-LiDAR-fusion configuration



LiDAR-fusion configuration



Cluster configuration

- Leading Performance: Achieved the highest average F1-score
- Robust: Consistently effective across configuration

➢ Excels in handling diverse and realistic fault scenarios

Effectiveness on Synthetic Fault Scenarios

- Single fault

TABLE IV: Evaluation results on the synthetic fault scenarios (single fault).

Group ID	IRCA (Ours)			DVCA			AID			RCD		
	P	R	F1	P	R	F1	P	R	F1	P	R	F1
8	**97.09**	**100.00**	**98.52**	92.00	92.00	92.00	92.00	92.00	92.00	67.35	66.00	66.67
9	96.70	88.00	**92.15**	77.00	77.00	77.00	**97.33**	73.00	83.43	90.14	**90.14**	90.14
10	99.01	**100.00**	**99.50**	95.00	95.00	95.00	**100.00**	97.00	98.48	92.13	82.00	86.77
11	95.10	**97.00**	96.04	95.00	95.00	95.00	**97.00**	**97.00**	**97.00**	92.93	92.00	92.46
12	95.24	**100.00**	97.56	98.00	98.00	98.00	**100.00**	96.00	**97.96**	91.92	91.00	91.46
13	93.46	**100.00**	**96.62**	90.00	90.00	90.00	**100.00**	93.00	96.37	**100.00**	91.00	95.29
Avg.	96.10	**97.50**	**96.73**	91.17	91.17	91.17	**97.72**	91.33	94.21	89.08	85.36	87.13

All methods effectively identify single faults

- Multiple faults

TABLE V: Evaluation results on the synthetic fault scenarios (multiple faults).

Group ID	IRCA (Ours)			DVCA			AID			RCD		
	P	R	F1	P	R	F1	P	R	F1	P	R	F1
14	88.53	**96.50**	**92.34**	91.00	45.50	60.67	**100.00**	50.00	66.67	98.04	50.00	66.23
15	69.66	**81.50**	**75.12**	97.00	48.50	64.67	**100.00**	50.00	66.67	83.87	65.00	73.24
16	96.04	**97.00**	**96.52**	**100.00**	50.00	66.67	76.00	38.00	50.67	50.52	48.50	49.49
17	98.34	**89.00**	**93.44**	90.00	45.00	60.00	**100.00**	50.00	66.67	46.51	30.00	36.47
18	94.29	**99.00**	**96.59**	71.00	35.50	47.33	**98.00**	49.00	65.33	78.67	59.00	67.43
19	79.17	**76.00**	**77.55**	67.00	33.50	44.67	**98.00**	49.00	65.33	96.08	49.00	64.90
Avg.	87.67	**89.83**	**88.59**	86.00	43.00	57.34	**95.33**	47.67	63.56	75.62	50.25	59.63

Our IRCA achieves the best recall and F1-score

➢ Highly effective in complex fault scenarios

Efficiency Analysis

Method	Real Faults		Single Fault		Multiple Faults	
	Intervention	Time	Intervention	Time	Intervention	Time
IRCA	2.99	4.67	**0.96**	**1.58**	2.51	3.91
DVCA	**2.29**	**3.60**	1.03	1.62	**1.79**	**2.72**
AID	3.34	5.07	1.03	1.62	1.84	2.79
RCD	3.03	4.82	1.04	1.64	2.55	3.97

- Real Faults: Marginally longer execution time, but provides more comprehensive diagnostics
- Single Fault: Requires the fewest interventions
- Multiple Faults: Modest increase in execution time

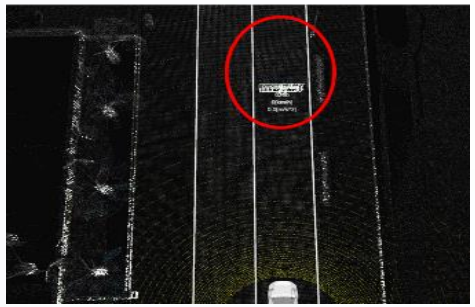
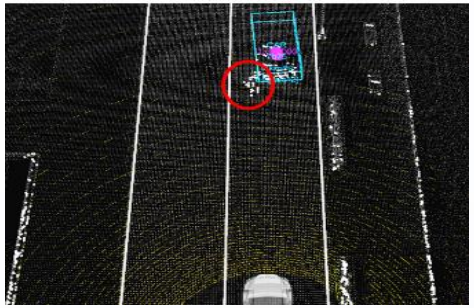
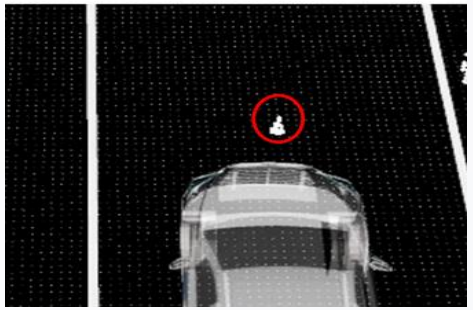
➢ Swift in identifying causal modules

Case Study: GitHub Issues

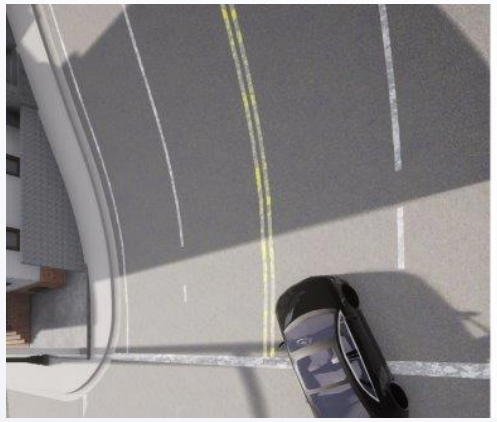
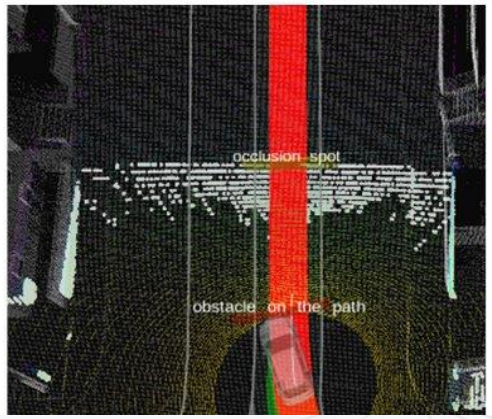
Simulation view

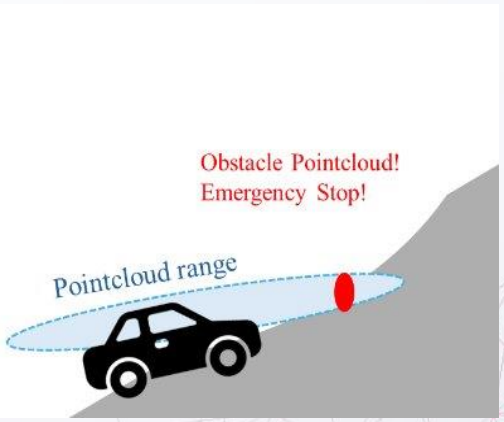
ADS view



Issue #7106 Issue #7563 Issue #6938

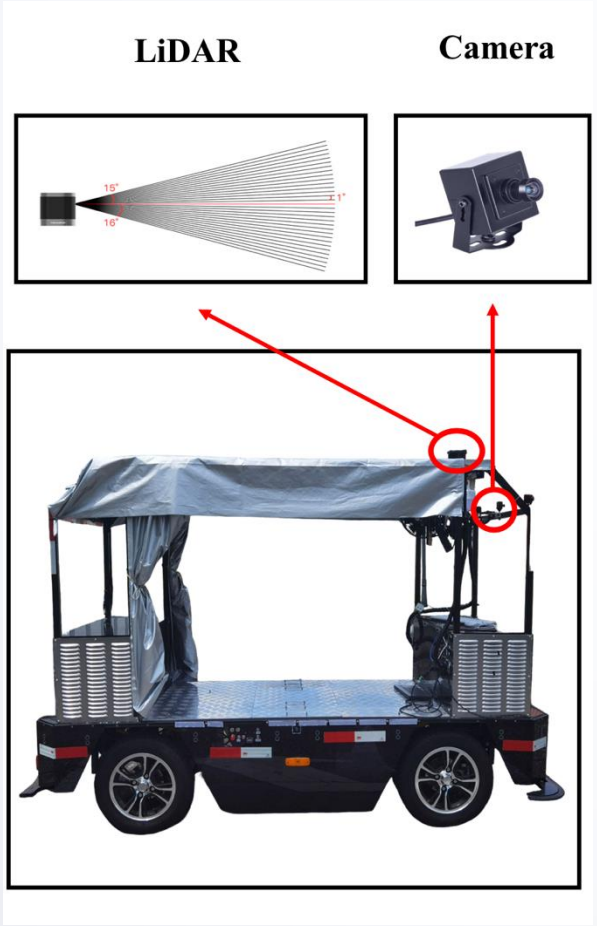





Issue #6936: Unfiltered point cloud introduces ghost obstacles

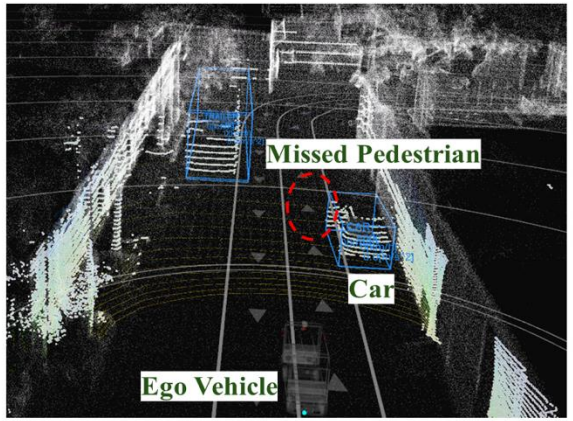
Real-World Evaluation

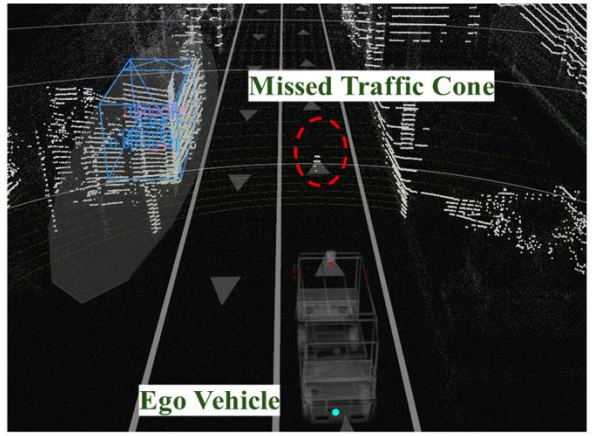
Testbed car



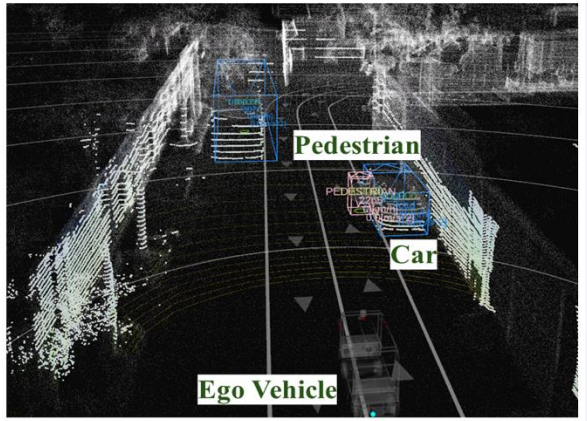
Physical scenario

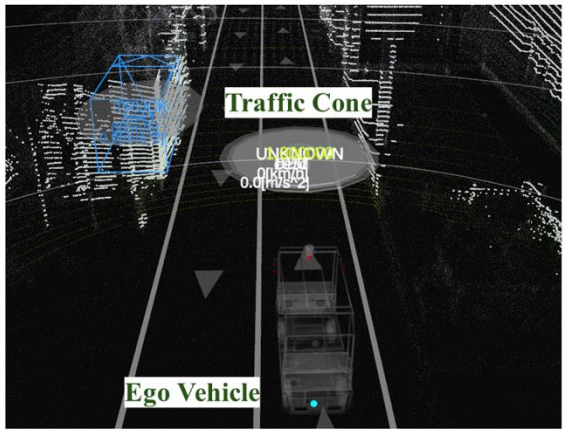
ADS view





Counterfactual effect





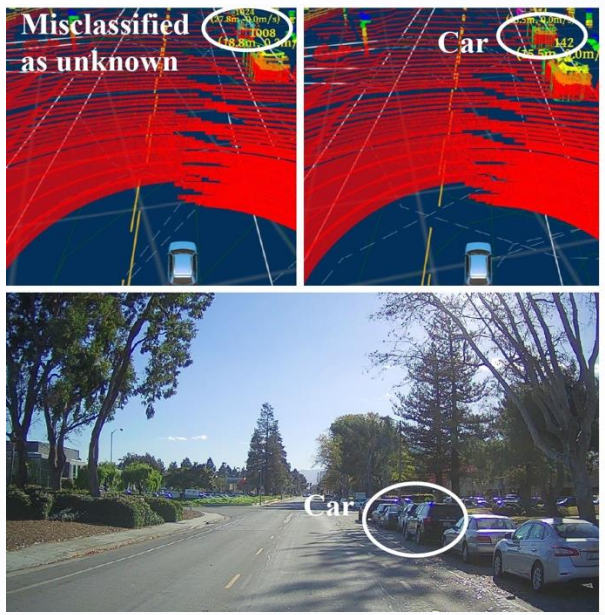
- Prove the practical effectiveness

Cross-Platform Validation

- Scenarios from **Apollo's** sensor data

Missed pedestrian

Missed shopping cart



Misclassified car

Ghost object

- **Left:** Failure scenarios **Right:** Counterfactual effects
- **Bottom:** Corresponding camera images

➢ Validate the generality

Summary

Our IRCA method achieves

1. Multicausality

Capable of tracking **multiple concurrent** root causes

2. Fully Automated

Implemented and evaluated on **Autoware**

3. Generality

Cross-platform evaluation on **Apollo**

4. Real-World Applicability

Successfully tested in **real-world scenarios**

香港城市大學
City University of Hong Kong

Thanks

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