Characterizing Deep Learning Neural Network Failures between Algorithmic Inaccuracy and Transient Hardware Fault

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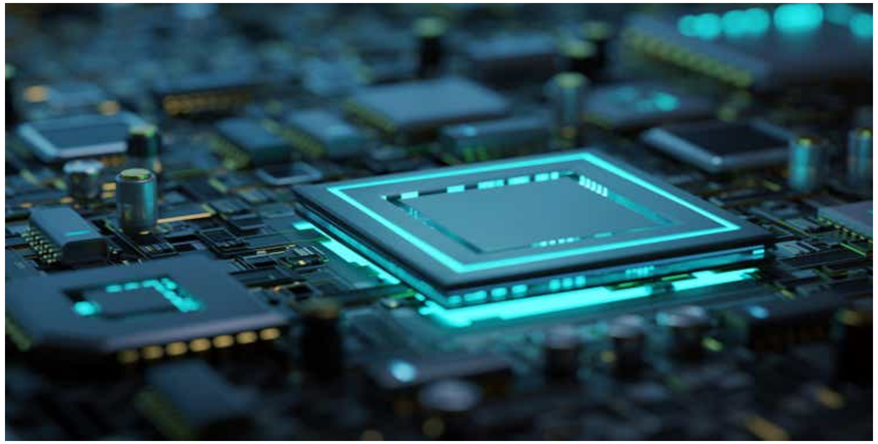
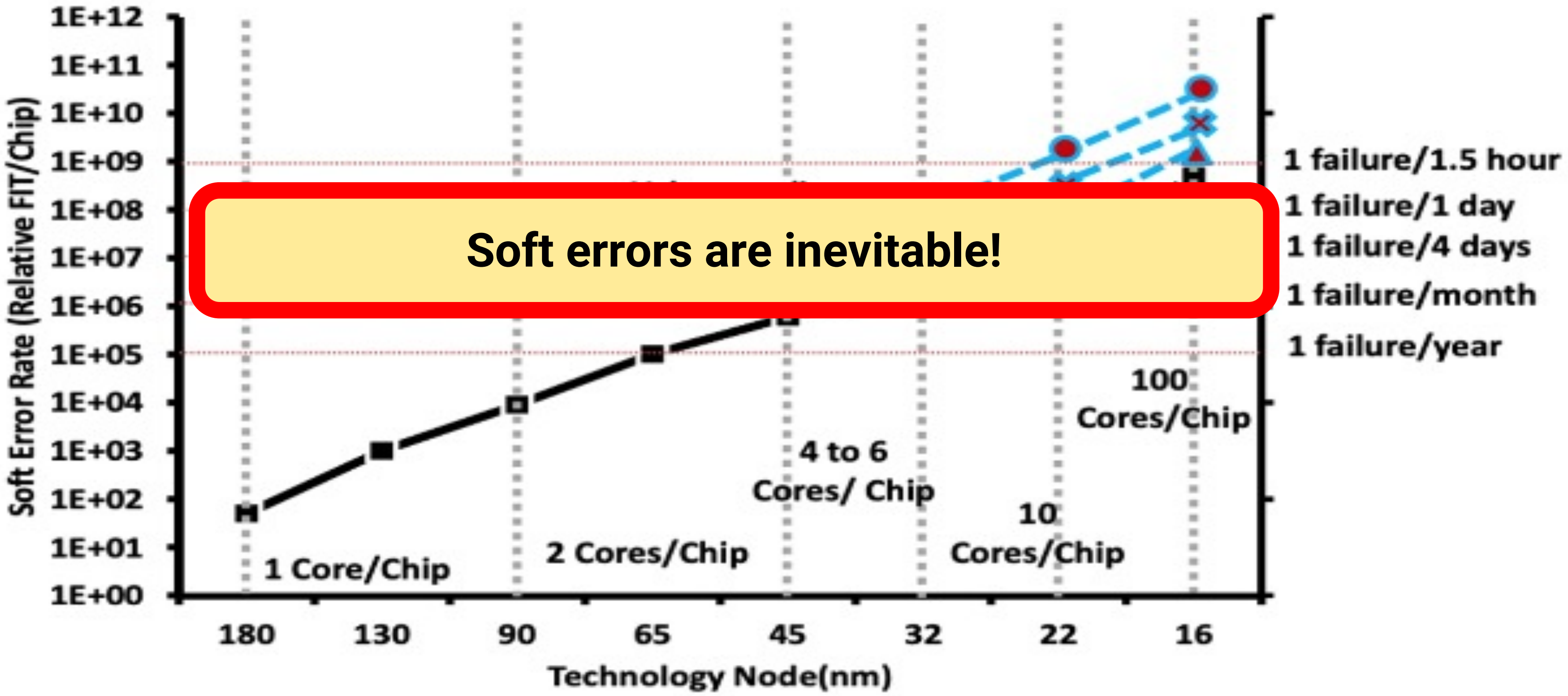
Motivation

- DNN has been increasingly deployed in many areas
  - Computer vision, NLP, autonomous vehicles (AVs)
- DNN reliability becomes important
  - ISO 26262 safety standard requires no more than 10 FIT (10 failures in every 10^9 hours)



Soft Error



Taken from [1]

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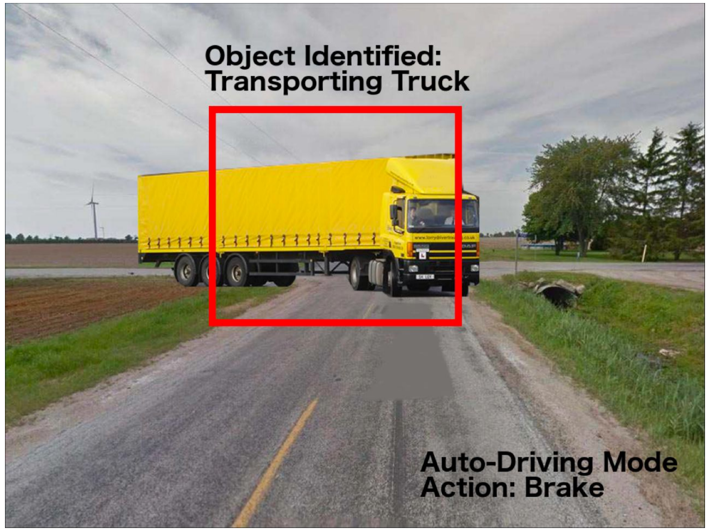
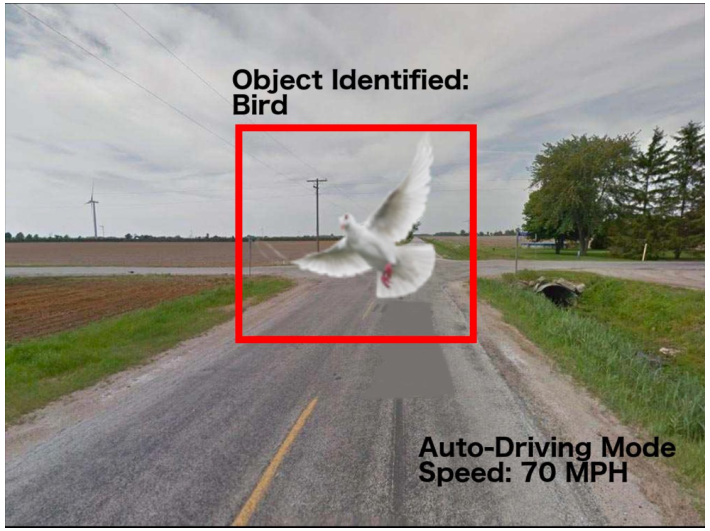
[1] Design of Low-Cost Reliable and Fault-Tolerant 32-Bit One Instruction Core for Multi-Core Systems

Consequences of Error Propagation in DNNs

- Single-bit fault[2] → Misclassification of image



Fault-free prediction label: Truck



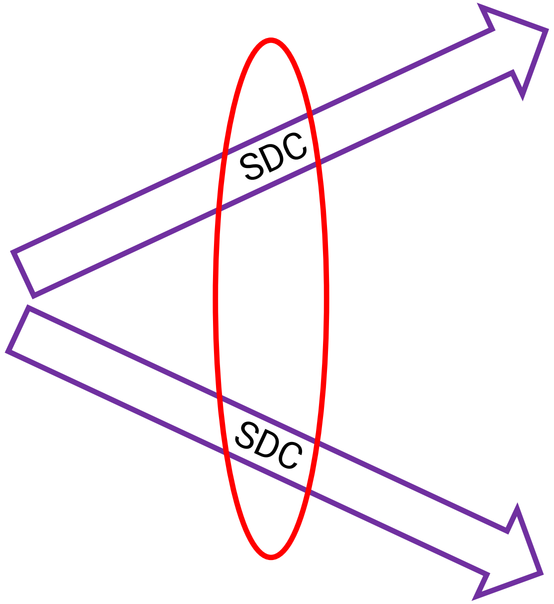
Faulty predicted label: Bird

- Reliability assessment: hardware vs software level
  - Software implemented fault injection (FI) simulation has lower cost

[2] *Understanding Error Propagation in Deep Learning Neural Network (DNN) Accelerators and Applications, SC'17*

Previous Works Only Consider SDC

Bus



Cab

Albatross

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[2] *Understanding Error Propagation in Deep Learning Neural Network (DNN) Accelerators and Applications, SC'17*

Not All Misclassifications Are Equal

Similar action for AVs

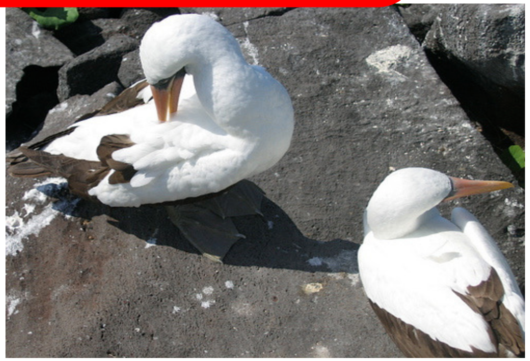
lassification

Bus

Need a different metric to differentiate safety critical misclassifications from non-safety critical ones

Misclassification

Different action for AVs



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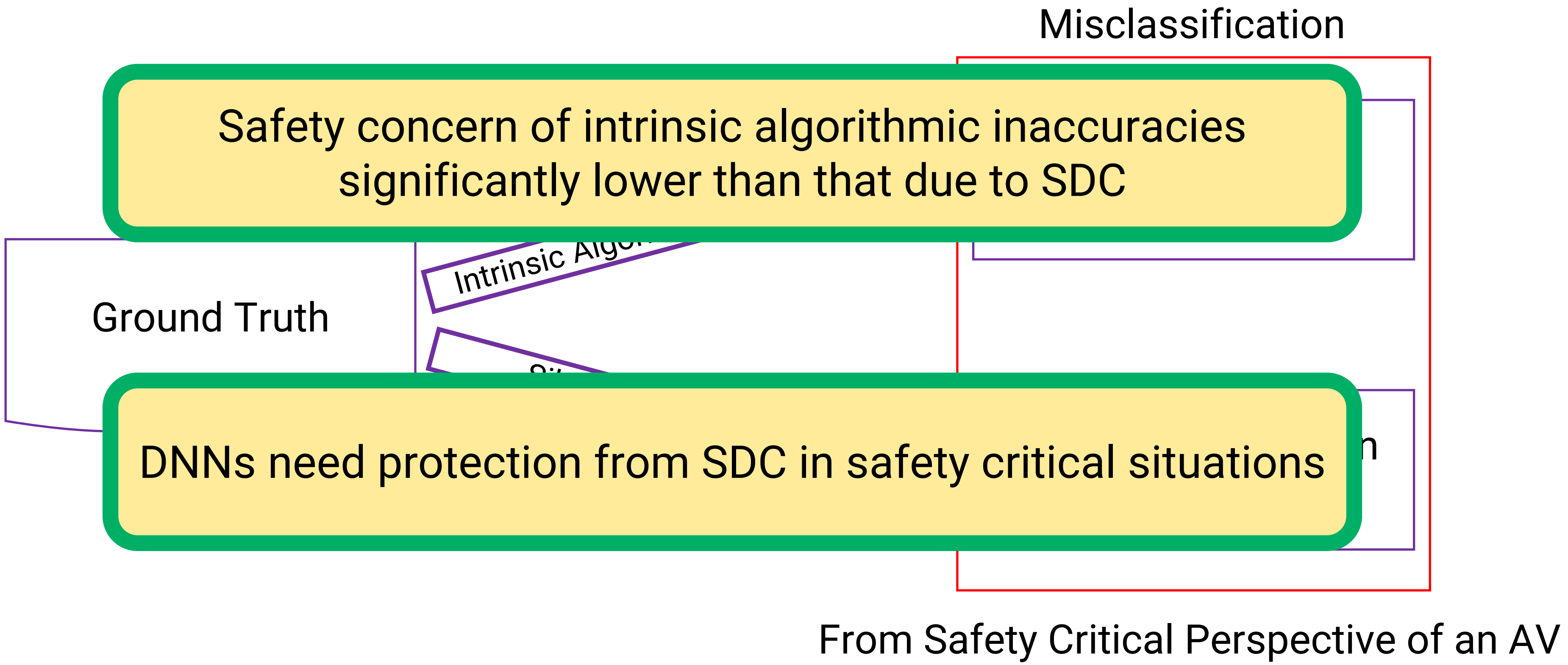
Our Hypothesis



Safety concern of intrinsic algorithmic inaccuracies significantly lower than that due to SDC

DNNs need protection from SDC in safety critical situations

Existing DNN Reliability Measurement Tools

TensorFI[3]

- A fault injector for TensorFlow applications
- Specifically, for TensorFlow 1 applications

TensorFI 2[4]

- A fault injector for
- This only supports sequential models

Need Support to inject faults in non-sequential DNN models with TensorFlow 2

Most DNN models are non-sequential

- Sequential: VGG16, VGG19
- Non-Sequential: ResNet50, ResNet101, GoogleNet, Xception, DenseNet121, DeseNet169, MobileNet

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[3] Tensorfi: A configurable fault injector for tensorflow applications, ISSREW'18
[4] https://github.com/DependableSystemsLab/TensorFI2

Our Contributions

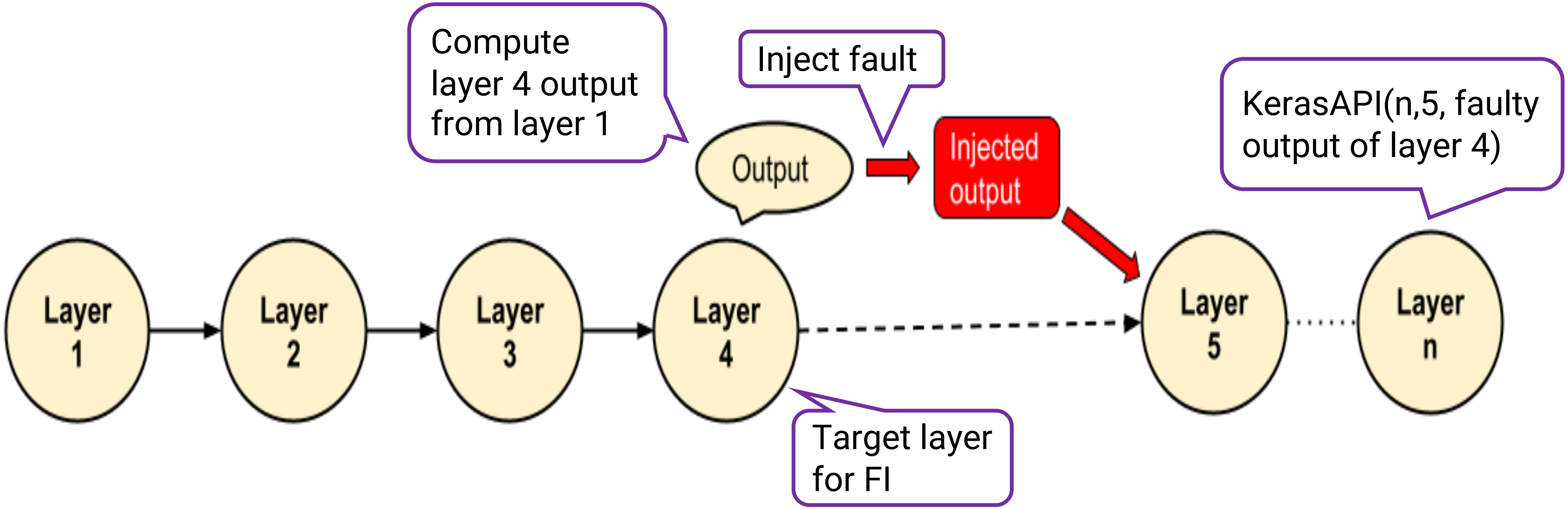
- Developed open-source tool, TensorFI+, to support FI in non-sequential DNN models
- Proposed new metrics to differentiate safety critical misclassifications from the perspective of AVs
- Analyzed why DNNs need protection from SDC in safety critical situations

TensorFI+ Development

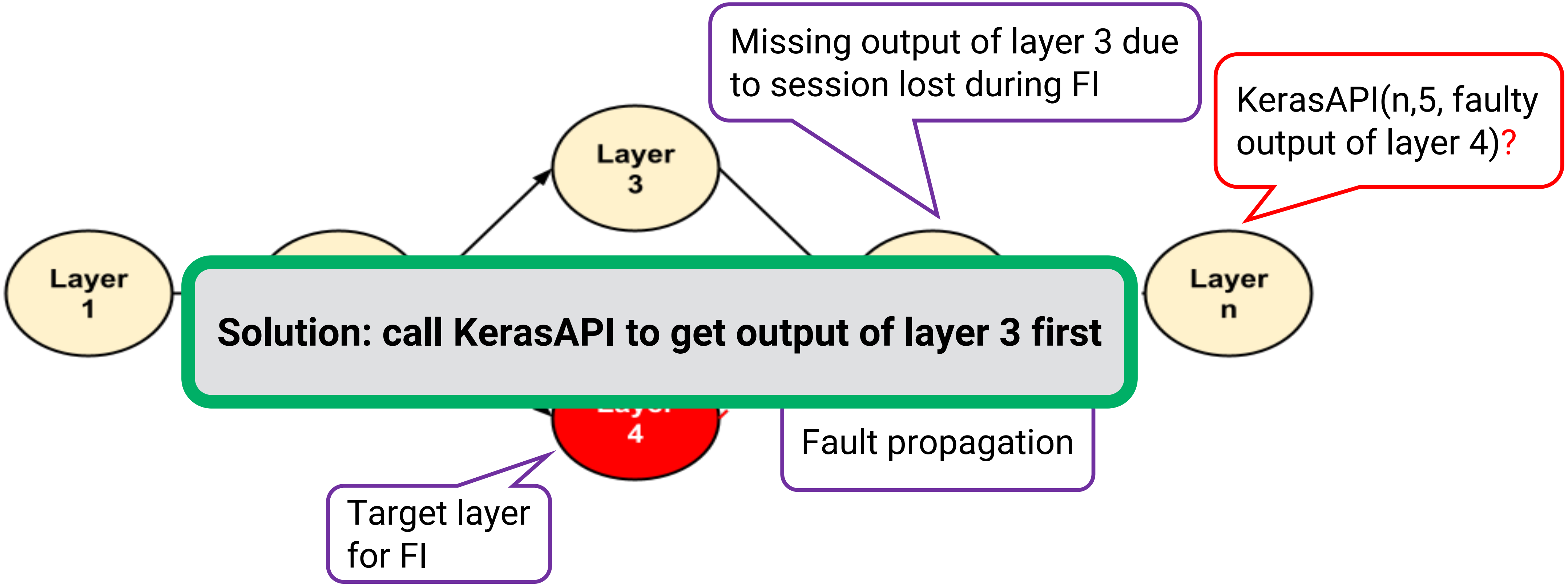
Keras Execution Flow Changes with TensorFI+

- Operators' structure changes in TensorFlow 2 are not allowed
- Need Keras API for fault injection and propagation
  - Output (layer D) = KerasAPI(Destination layer D, Source layer S, Input values of S)
  - KerasAPI call to get output of target layer t
  - Random bit fip of output of layer t
  - Previous session gone, need API calls to propagate faulty output to final layer

FI in a Sequential Model

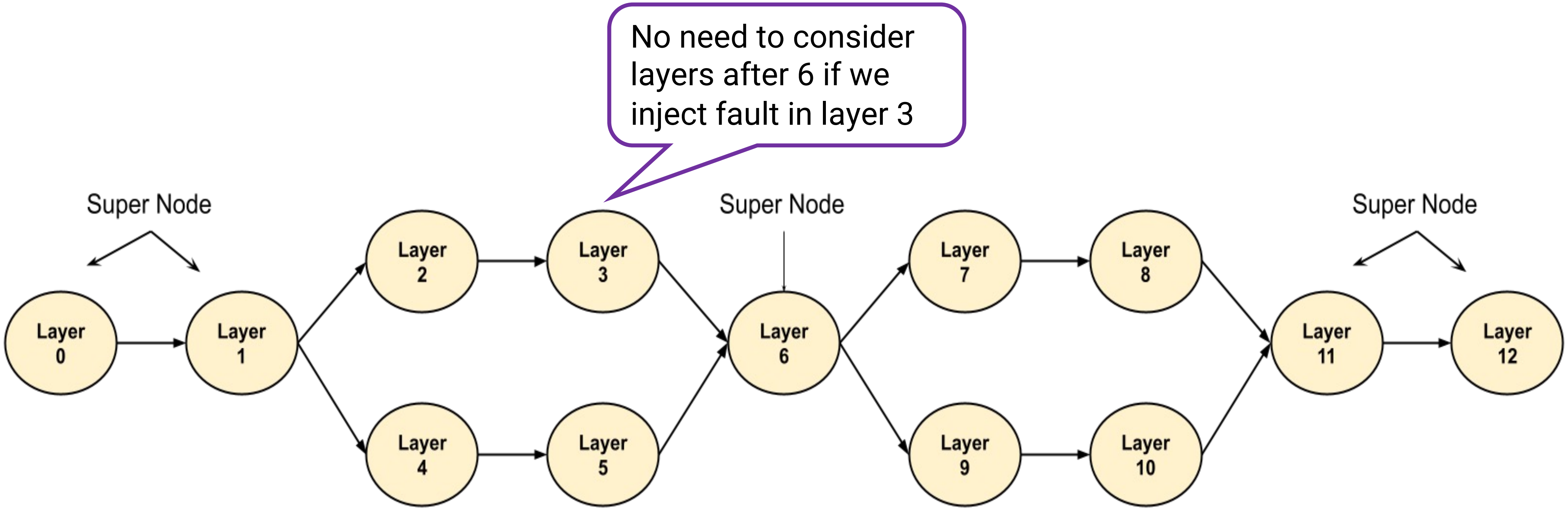


Issues in FI in Non-sequential Model



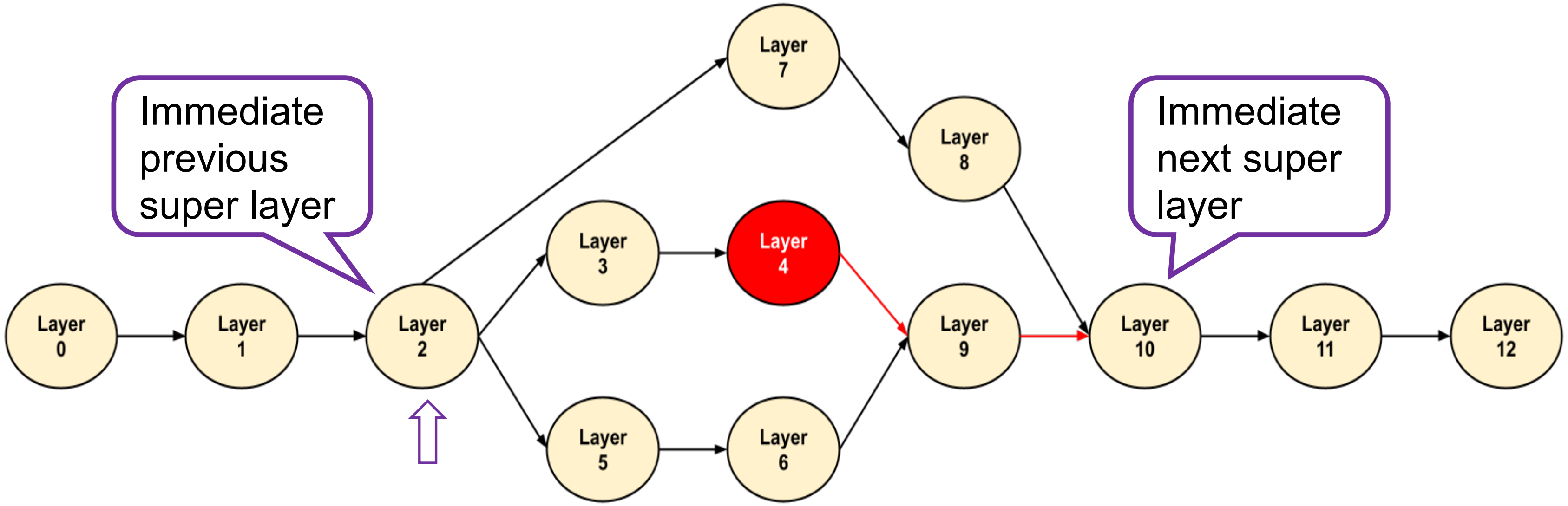
Solution: call KerasAPI to get output of layer 3 first

Solution: Super Layer



- Super layers are not part of any branch
- Any layer after a super layer is not dependent on any layer prior to super layer

Simulation of FI with TensorFI+



MDict

Layer 2

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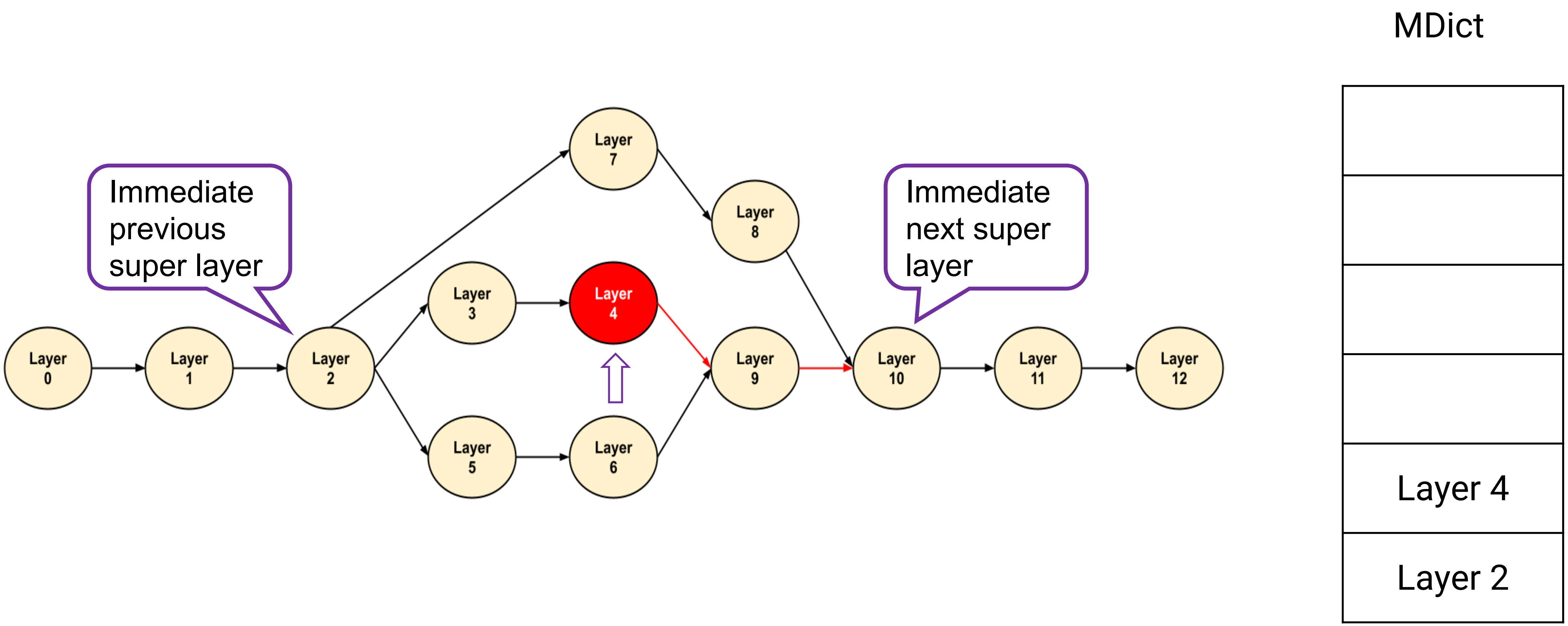
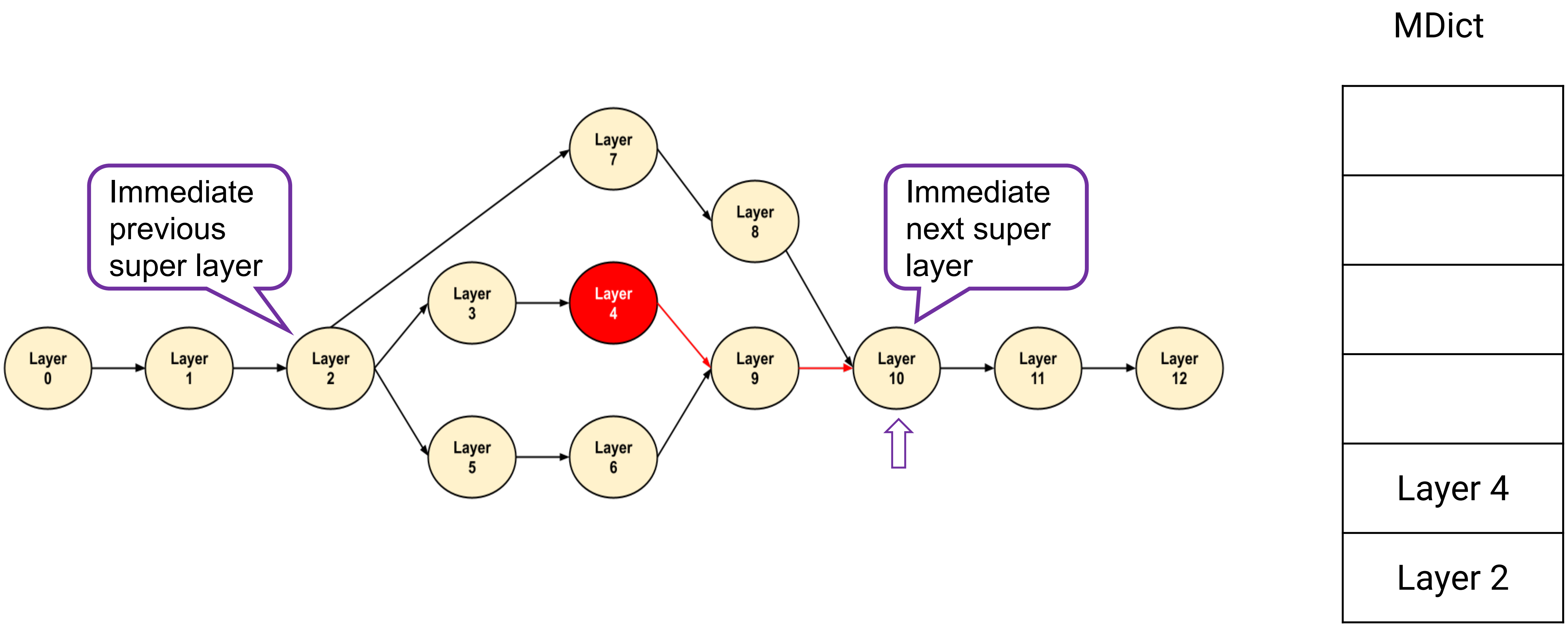
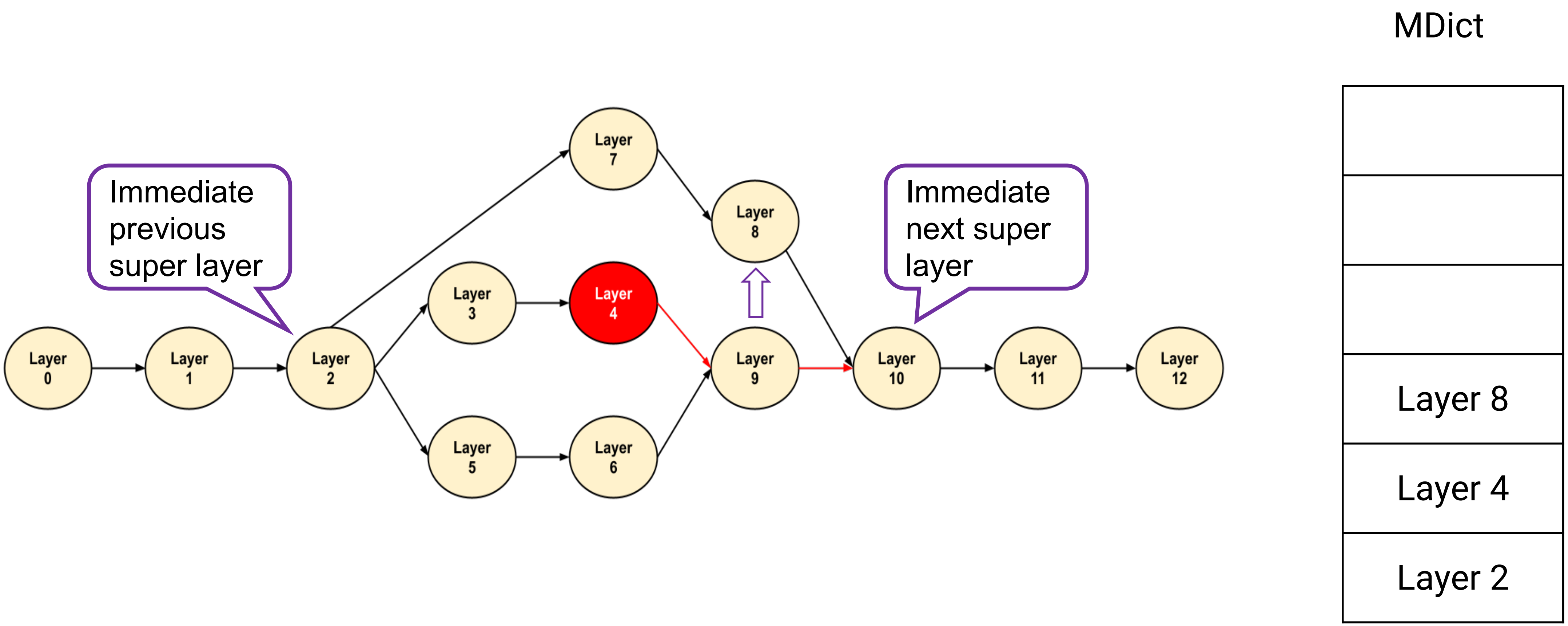
Simulation of FI with TensorFI+



Simulation of FI technique of TensorFI+



Simulation of FI technique of TensorFI+



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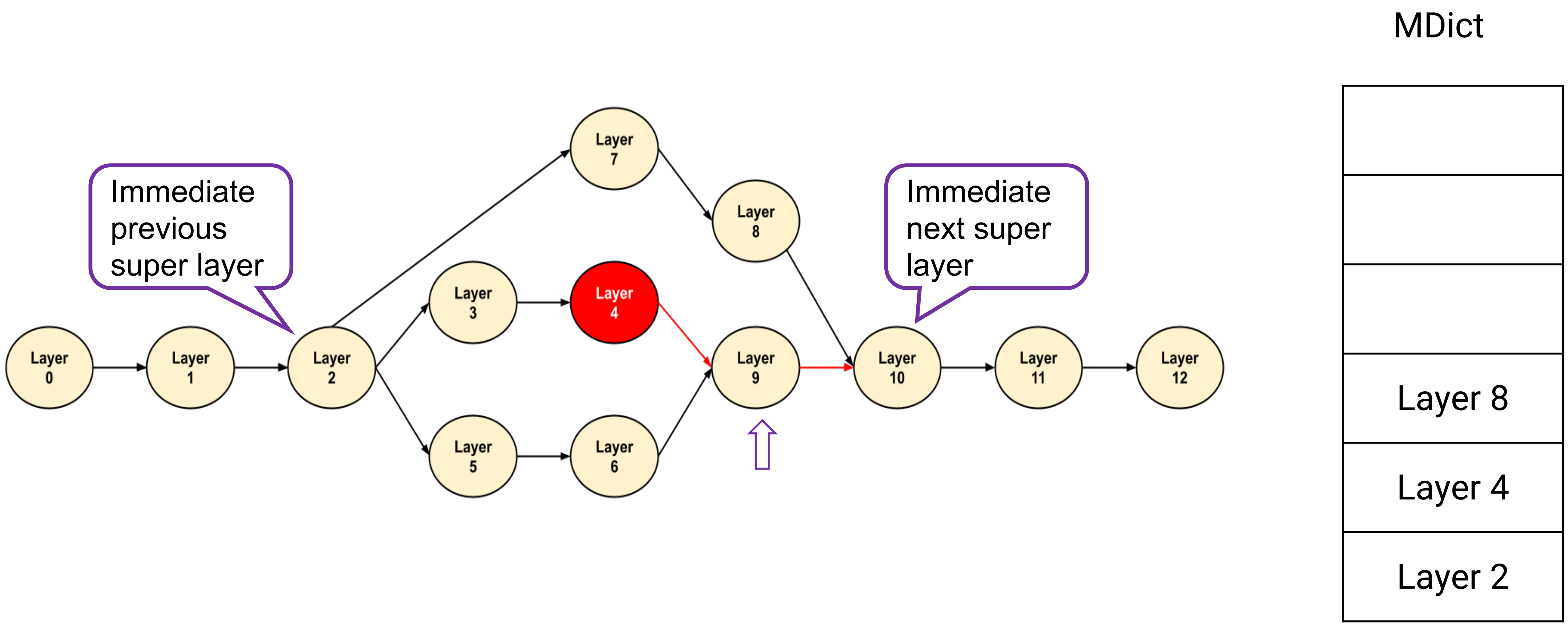

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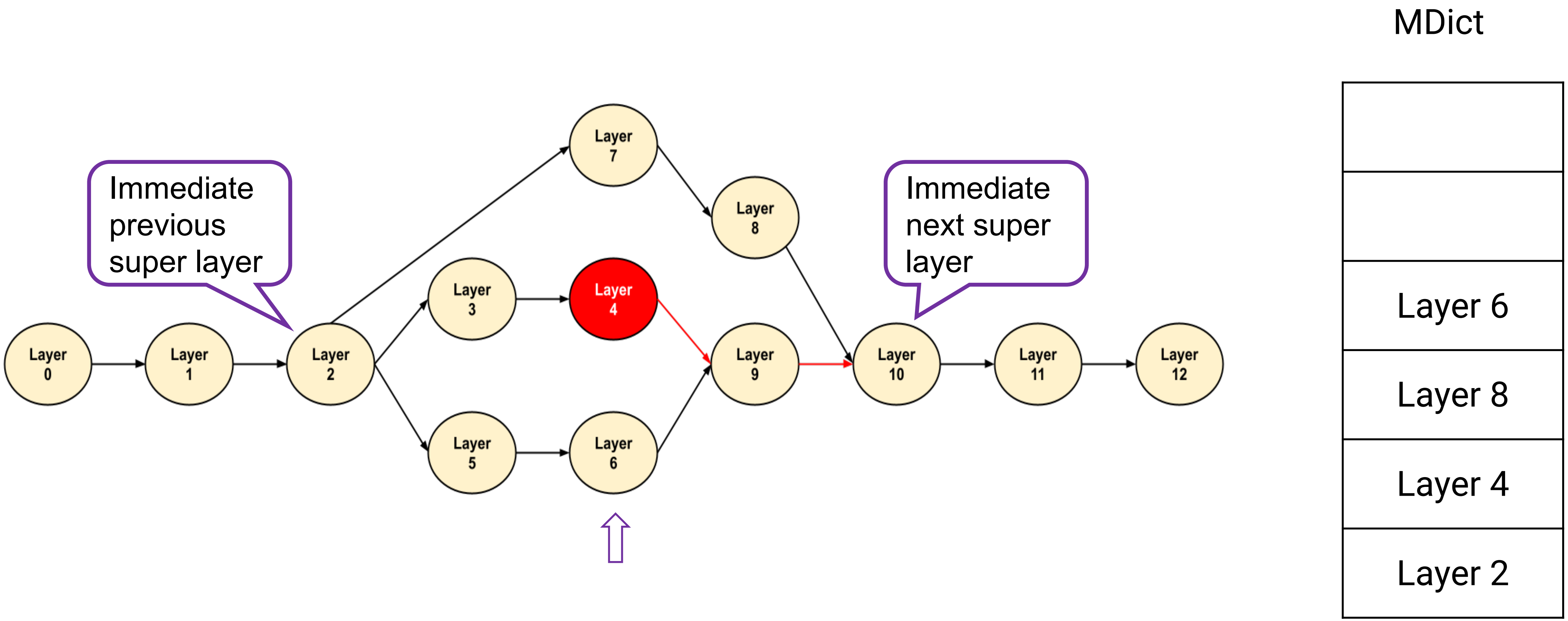

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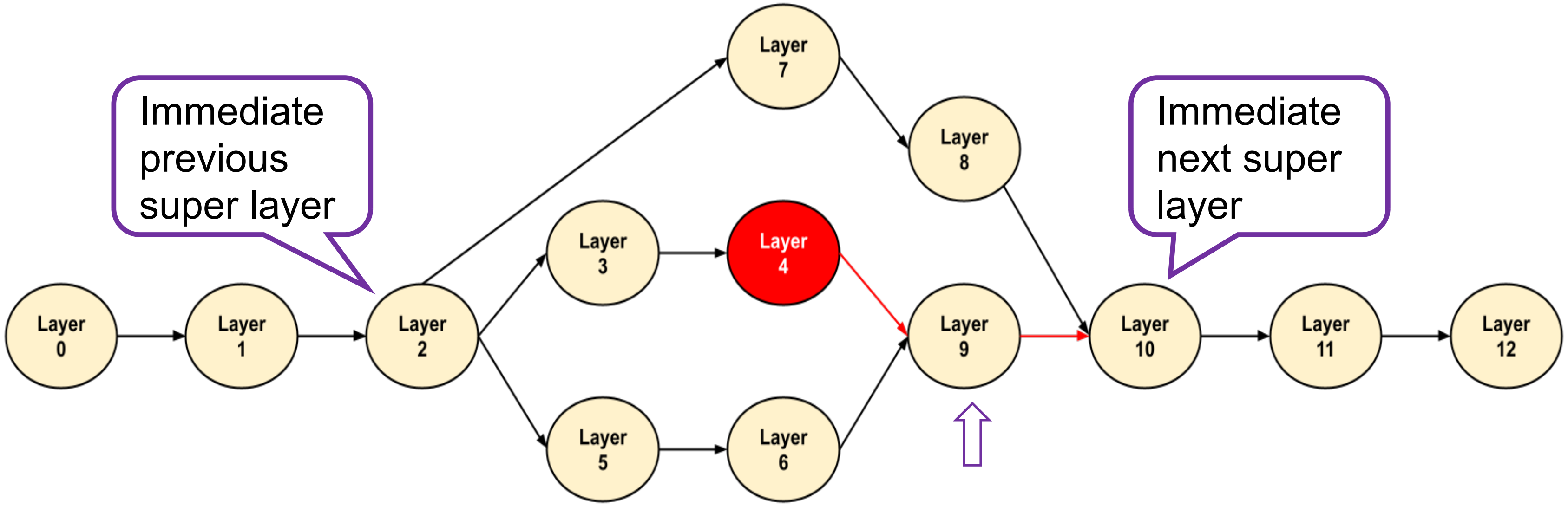
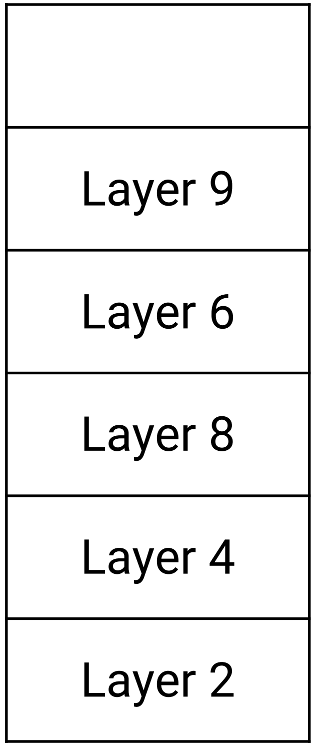


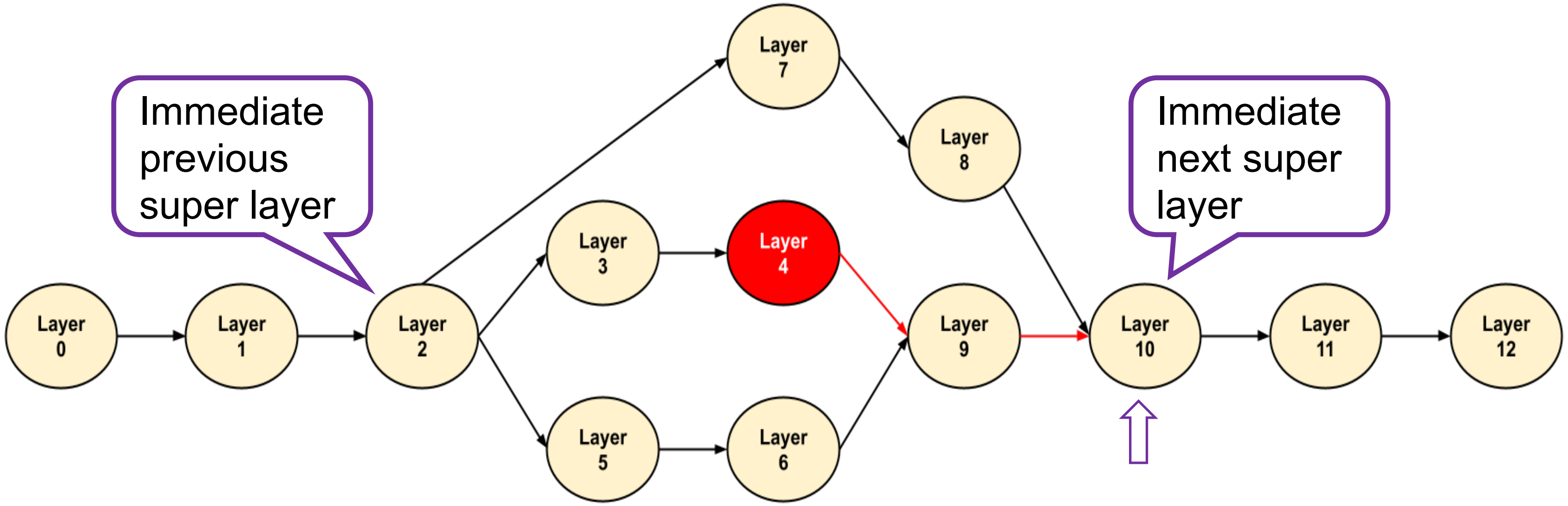
MDict



Simulation of TensorFI+

MDict

Layer 10
Layer 9
Layer 6
Layer 8
Layer 4
Layer 2



👉 Finally Compute the output of layer 12 using only one KerasAPI(12, 10, inputs(10)) call

Metrics to Differentiate Safety Critical Misclassification

Overview: Steps to Define Our Metrics

- Create several groups based on similarity of objects
- Organize all the groups into two supergroups based on safety concern
- Define two metrics to measure whether a misclassification is safety critical or not.

Group Formation

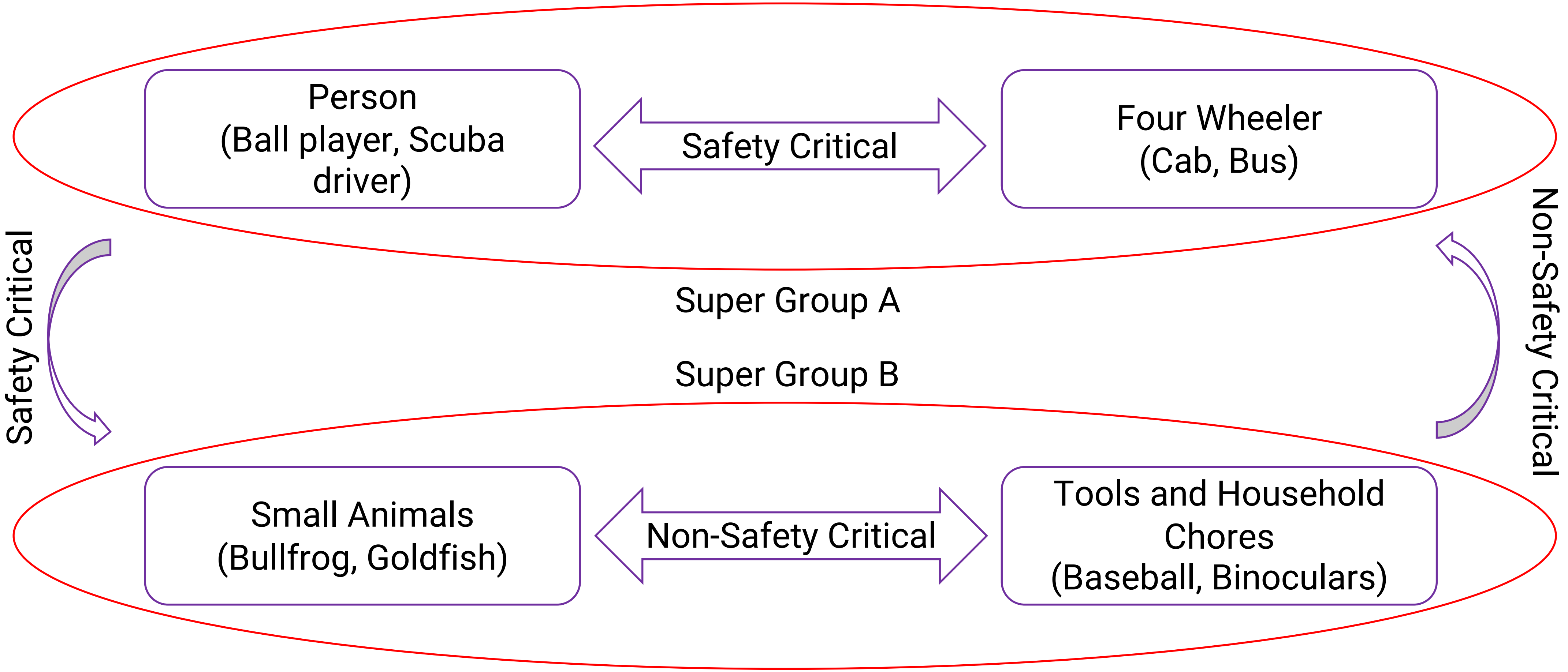
Objects:

- Ball player
- Scuba driver
- Cab
- Bus
- Bullfrog
- Goldfish
- Baseball
- Binoculars

Groups:

- Person
- Four Wheeler
- Small Animals
- Tools and Household Chores

Organize Groups into Two Supergroups



Metrics: SCM and Non-SCM Probability

- Safety Critical Misclassification(SCM) Probability
  - Original label is in Supergroup A and the predicted label is in Supergroup B
  - They are from different groups within Supergroup A
- Non-Safety Critical Misclassification(Non-SCM) Probability
  - Non-SCM probability complements to SCM probability
  - They add up to 100%.

Benchmark & Experimental Setup

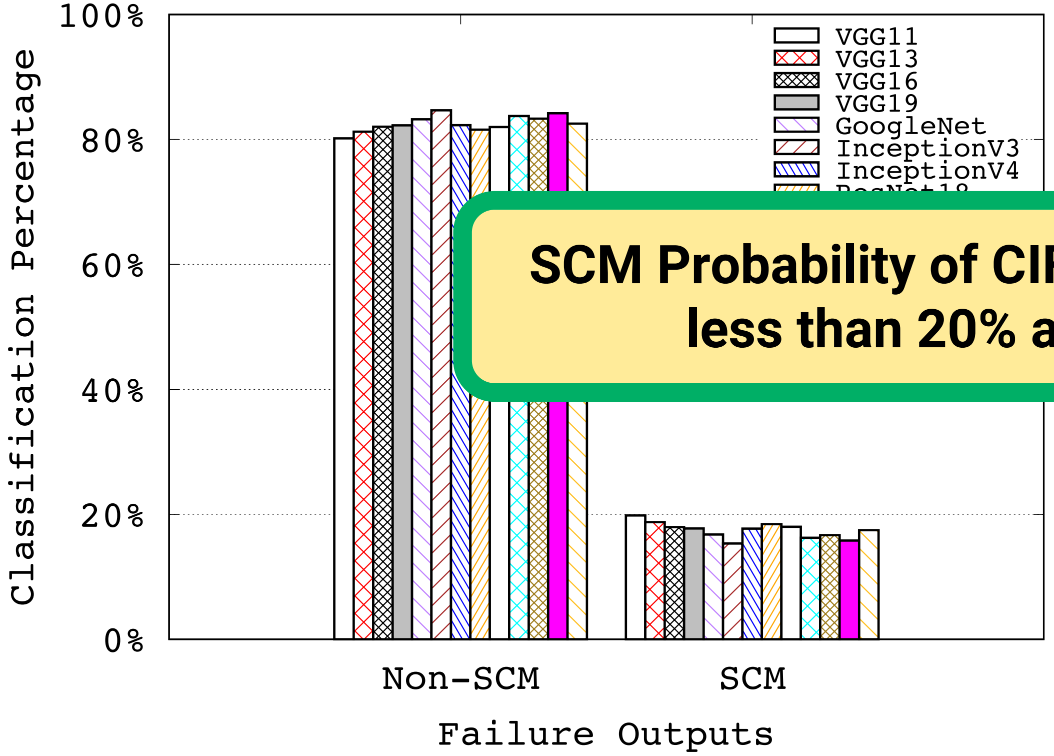
- Demonstrated on 30 popular DNN models
  - VGGNets, ResNets, DenseNets
- 2 open-source widely used datasets
  - CIFAR-100, ImageNet
- 3000 random fault injections per DNN model
- Measured SDC, SCM and Non-SCM probability in the evaluation

Results: SDC rates

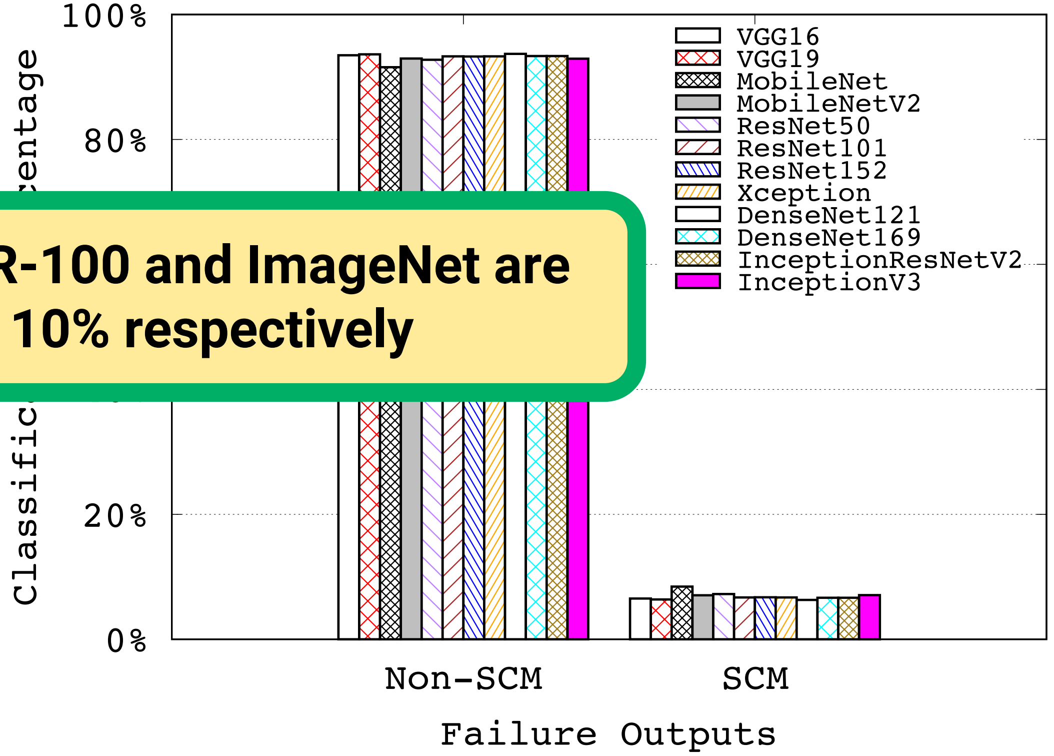
Dataset	Model	Top-1 Accuracy	SDC Rate
ImageNet	VG16(Sequential)	71.18%	3.53%
	ResNet50(Non-sequential)	74.76%	1.43%
	DenseNet121(Non-sequential)	75.04%	1.20%
CIFAR-100	VGG19(Sequential)	71.53%	1.23%
	GoogleNet(Non-sequential)	76.70%	1.57%
	Xception(Non-sequential)	77.96%	2.00%

SDC rates range from 0.53% to 2.07% (error bars range from 0.10% to 2.95%) across different non-sequential DNN models

Results: Fault Free Inference



CIFAR-100



ImageNet

SCM Probability of CIFAR-100 and ImageNet are less than 20% and 10% respectively

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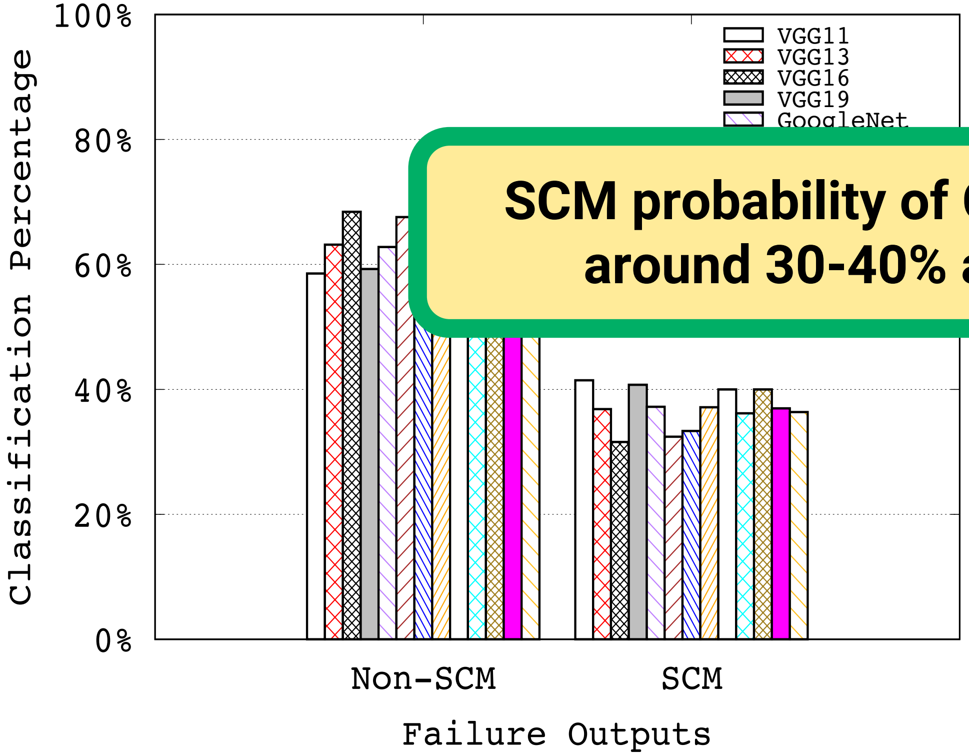
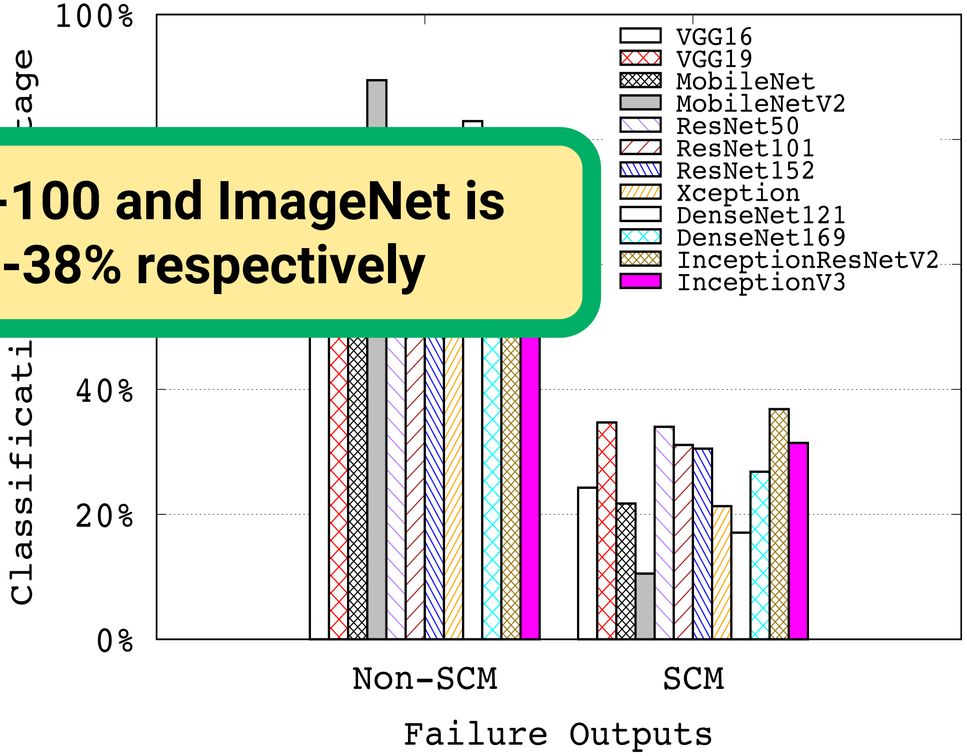
Results: FI in Correctly Classified Images



CIFAR-100



ImageNet

SCM probability of CIFAR-100 and ImageNet is around 30-40% and 10-38% respectively

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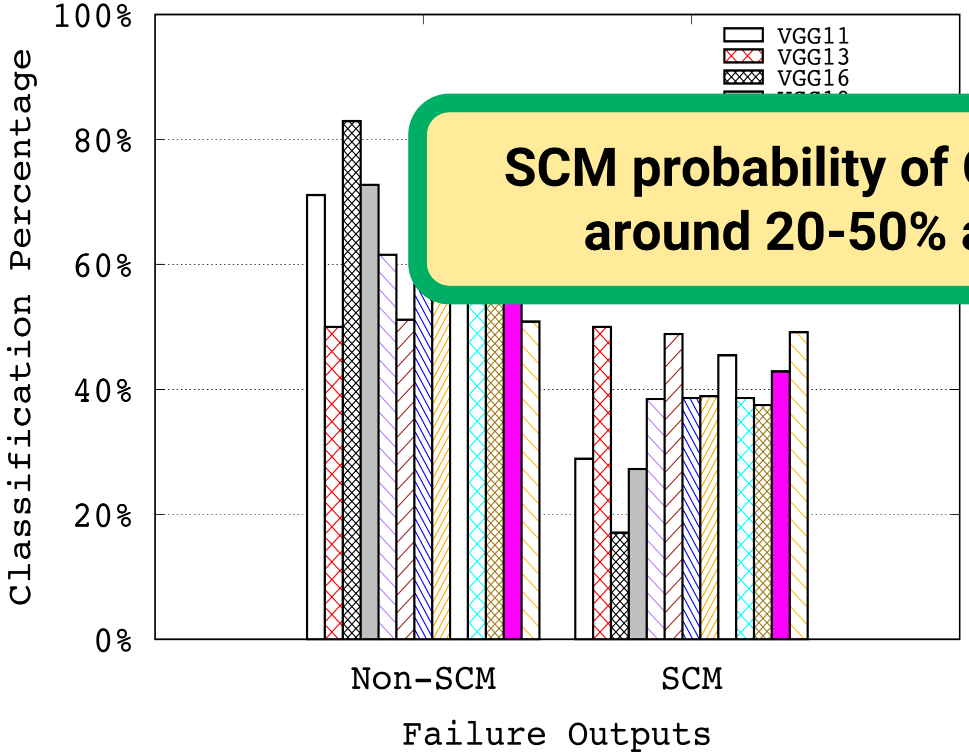
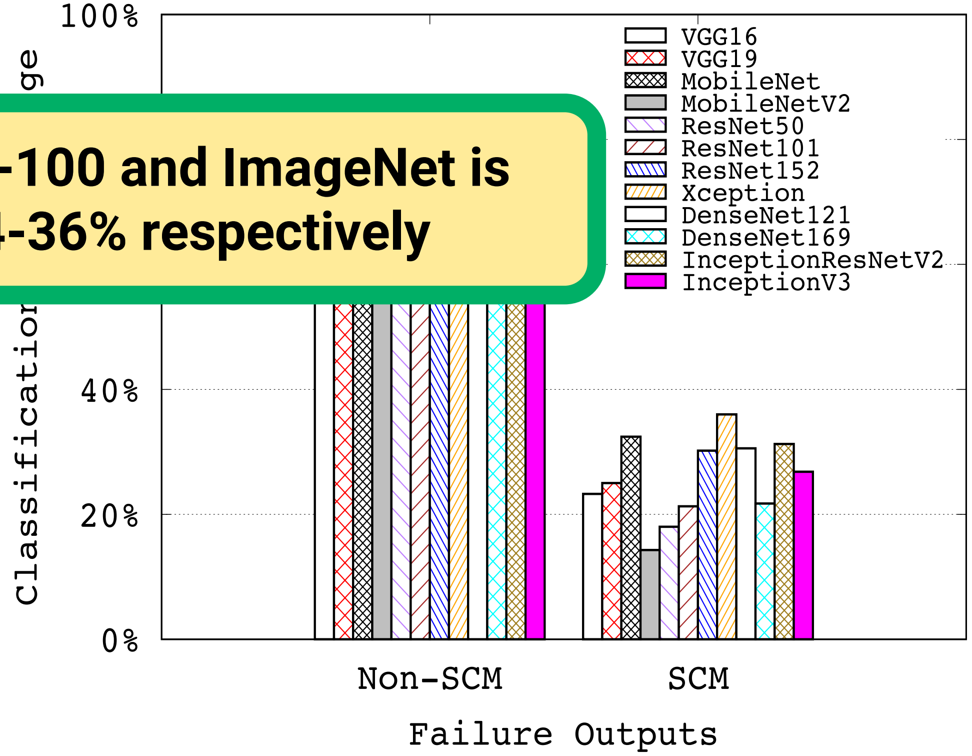
Results: FI in Misclassified Images



CIFAR-100



ImageNet

SCM probability of CIFAR-100 and ImageNet is around 20-50% and 14-36% respectively

Conclusion

- Built a FI tool, TensorFI+, for both sequential and non-sequential DNN resilience evaluation
- We introduce two new metrics to differentiate safety critical misclassifications.
- SCM probability is much higher with FI compared to fault free inference
  - Shows the necessity of protecting DNN models from SDC.
- Our code is open source at https://github.com/sabuj7177/characterizing_DNN_failures

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