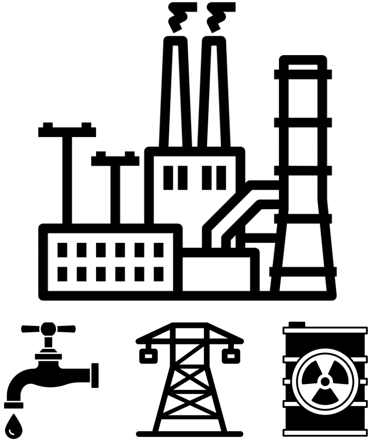
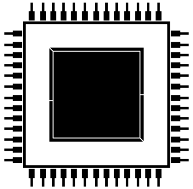
Attributions for ML-based ICS anomaly detection: From theory to practice

Clement Fung, Eric Zeng, Lujo Bauer
Carnegie Mellon University

What are industrial control systems?





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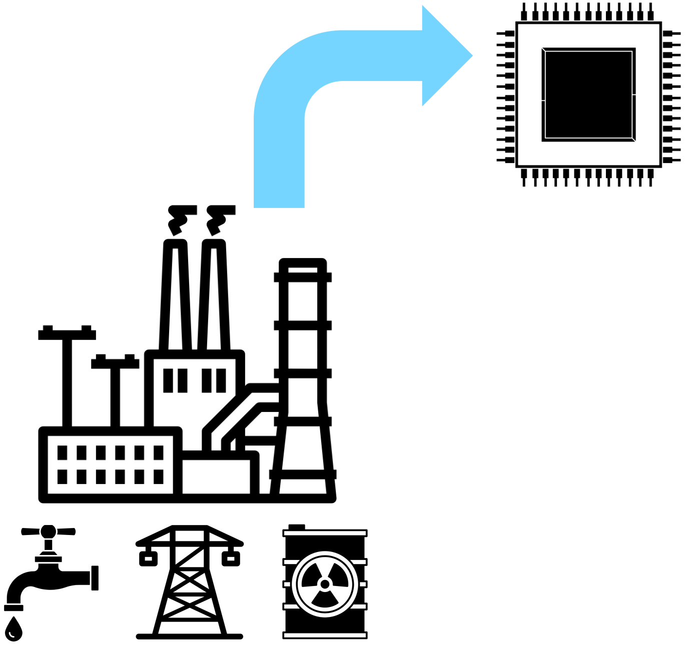

Read sensor values from physical process

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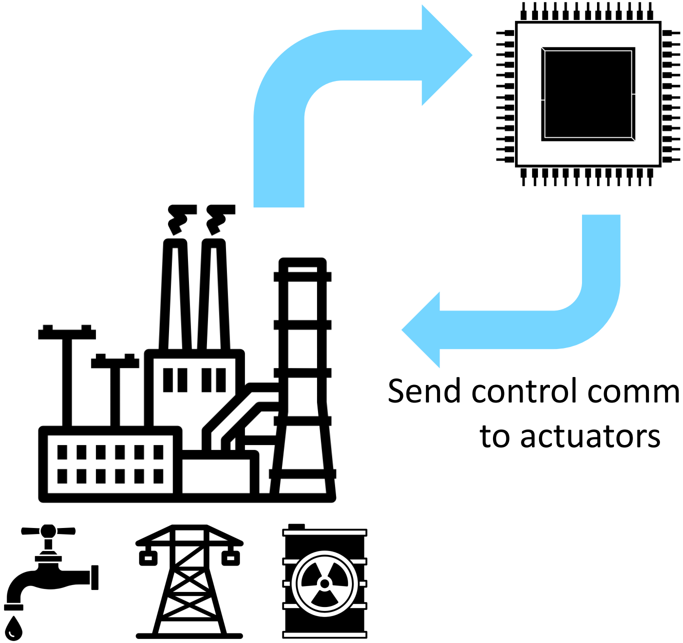

Read sensor values
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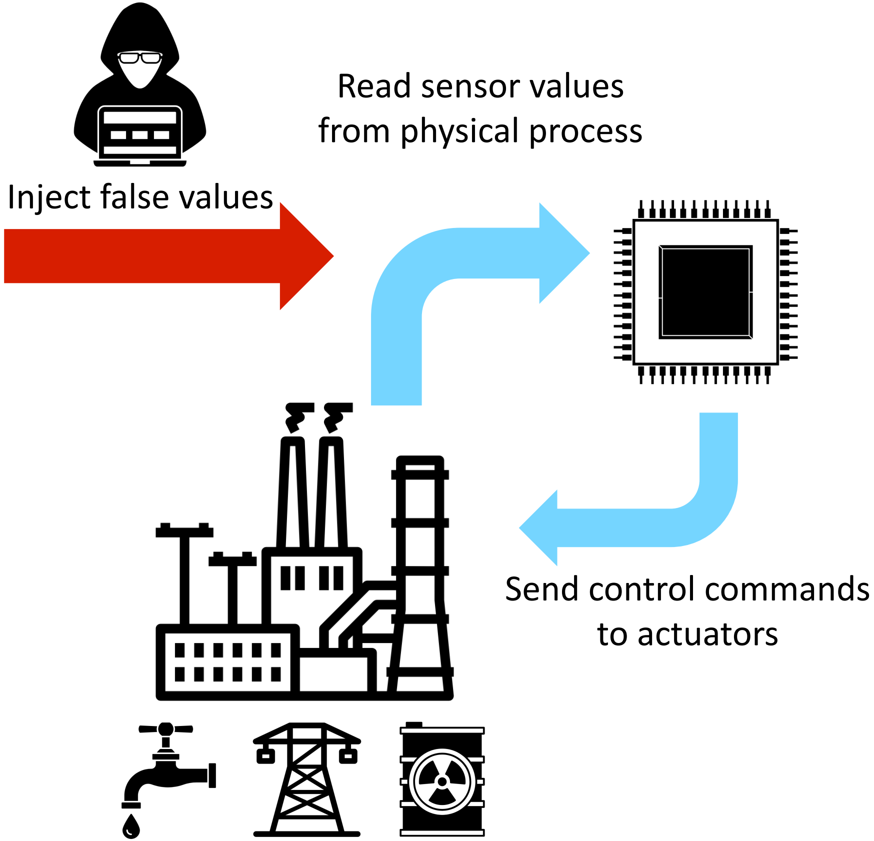
Send control commands
to actuators

Attacking industrial control systems



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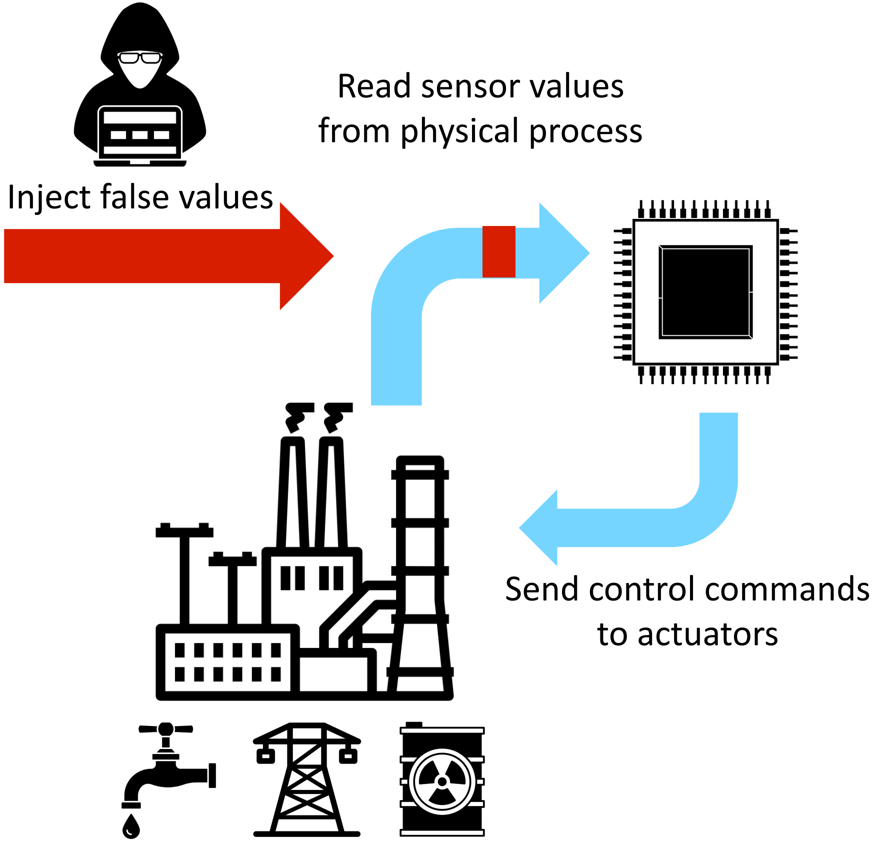

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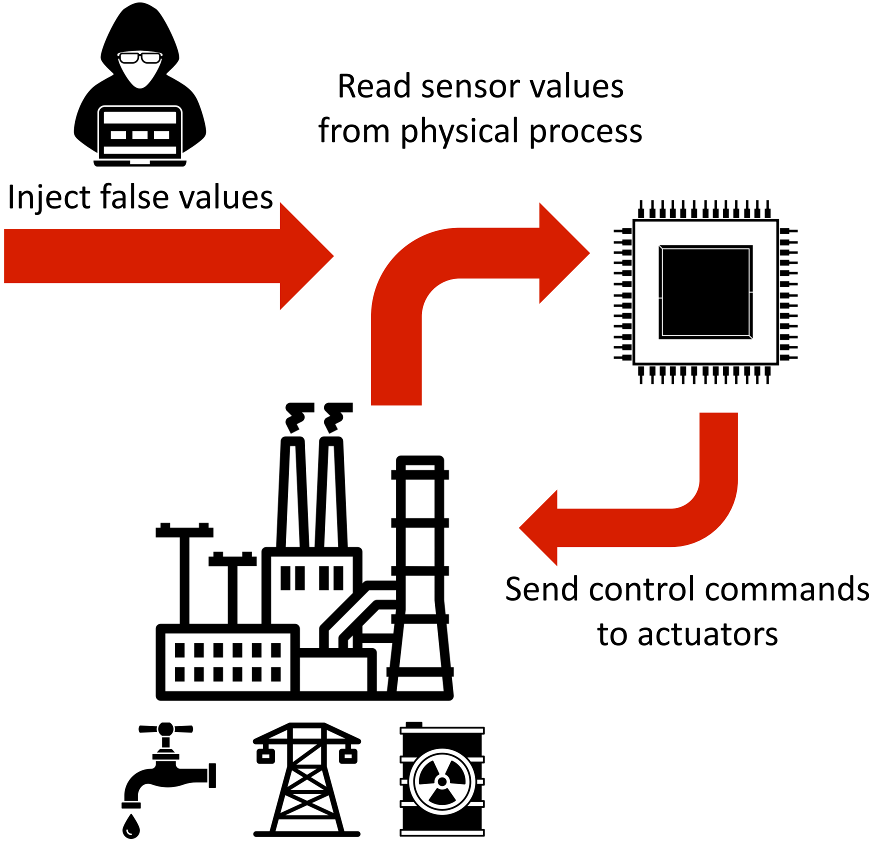

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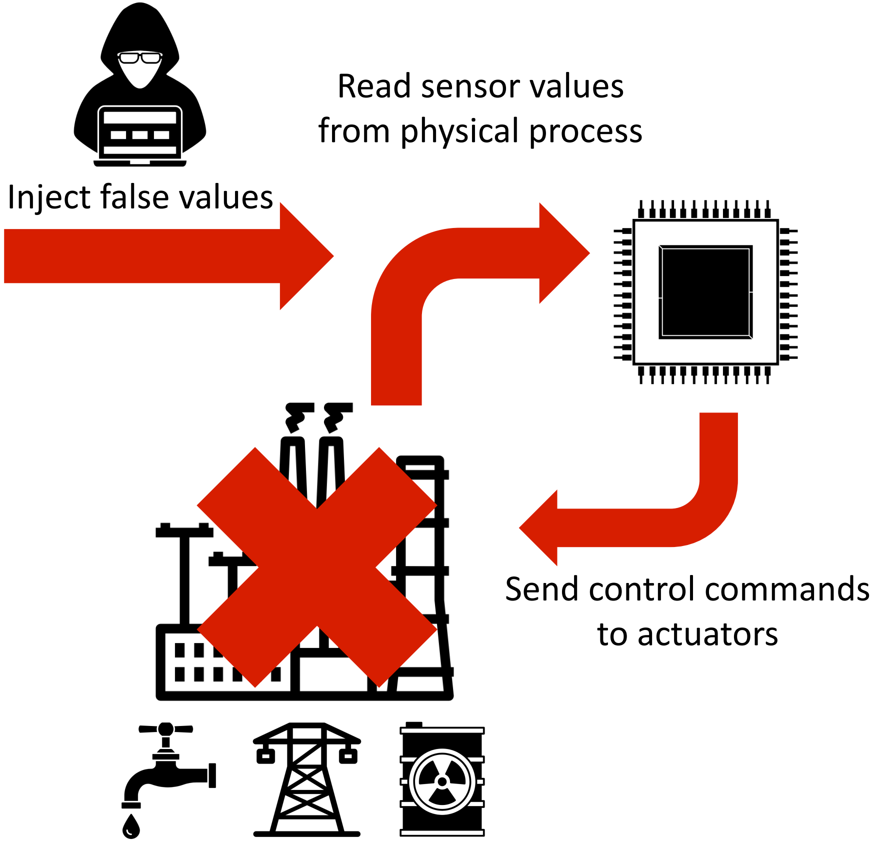

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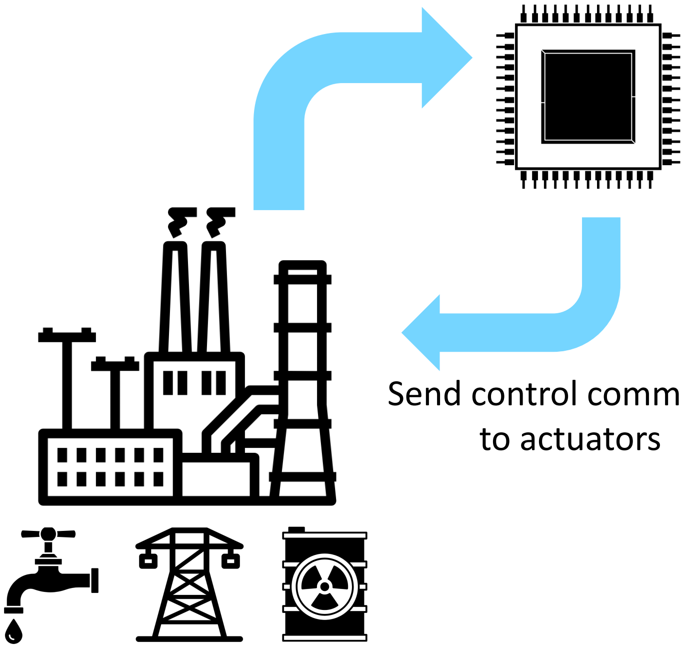
Defending industrial control systems



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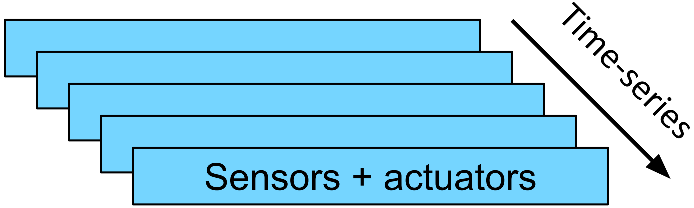

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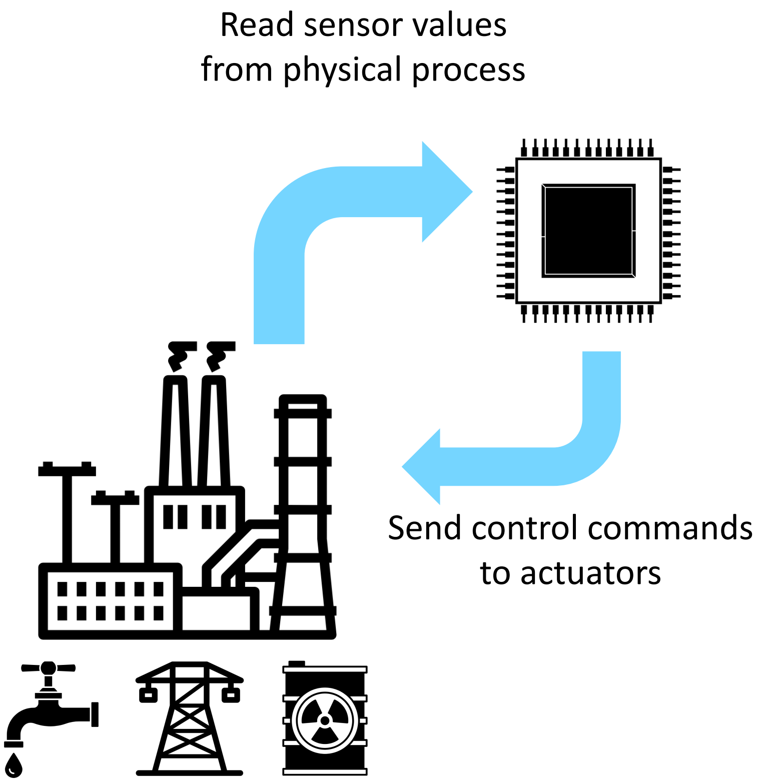

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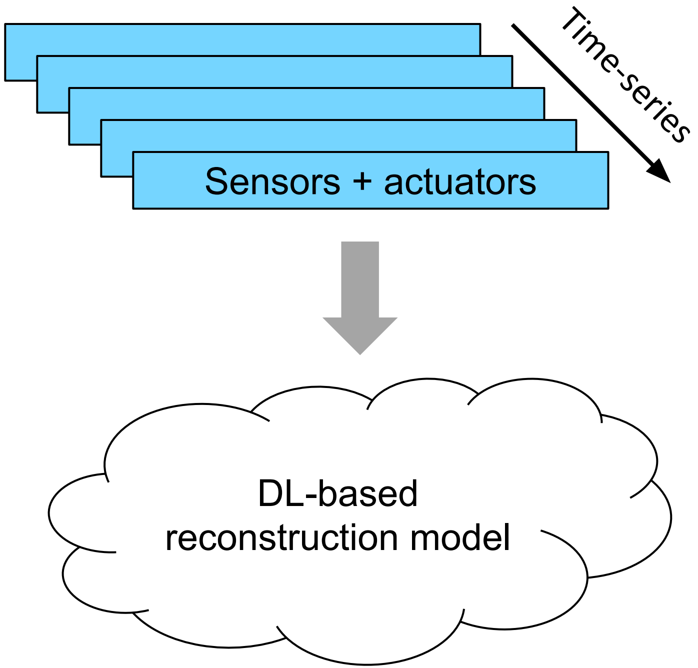

Sensors + actuators

Time-series

DL-based reconstruction model

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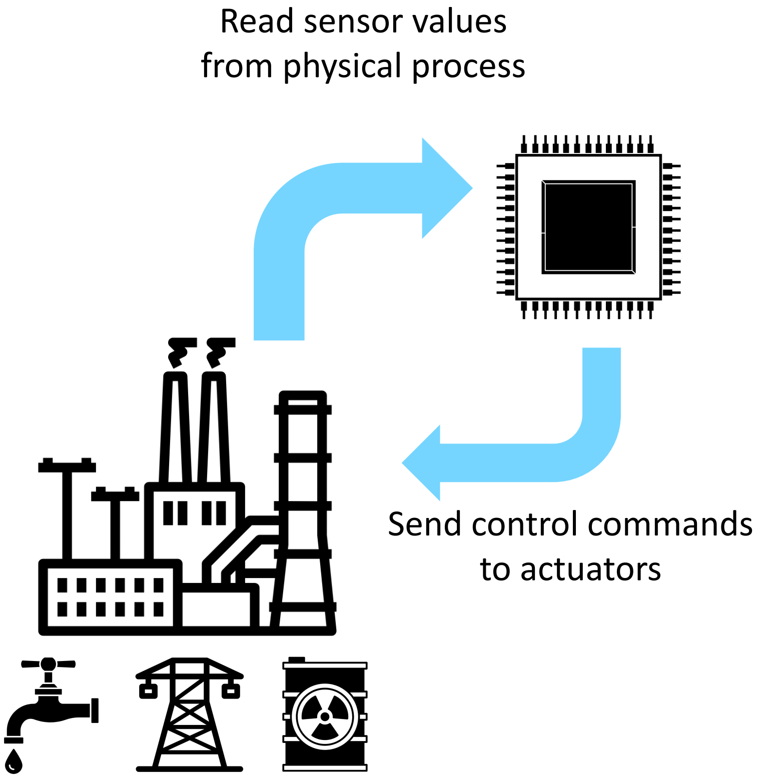

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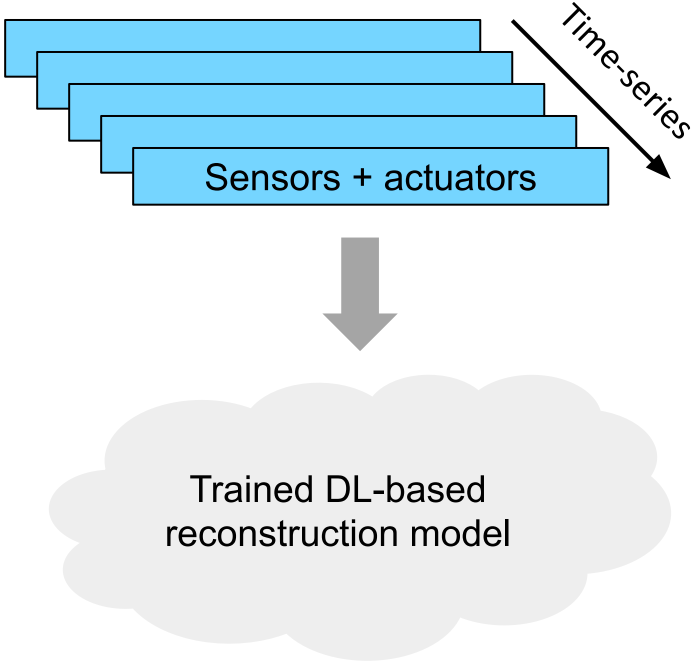

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Sensors + actuators

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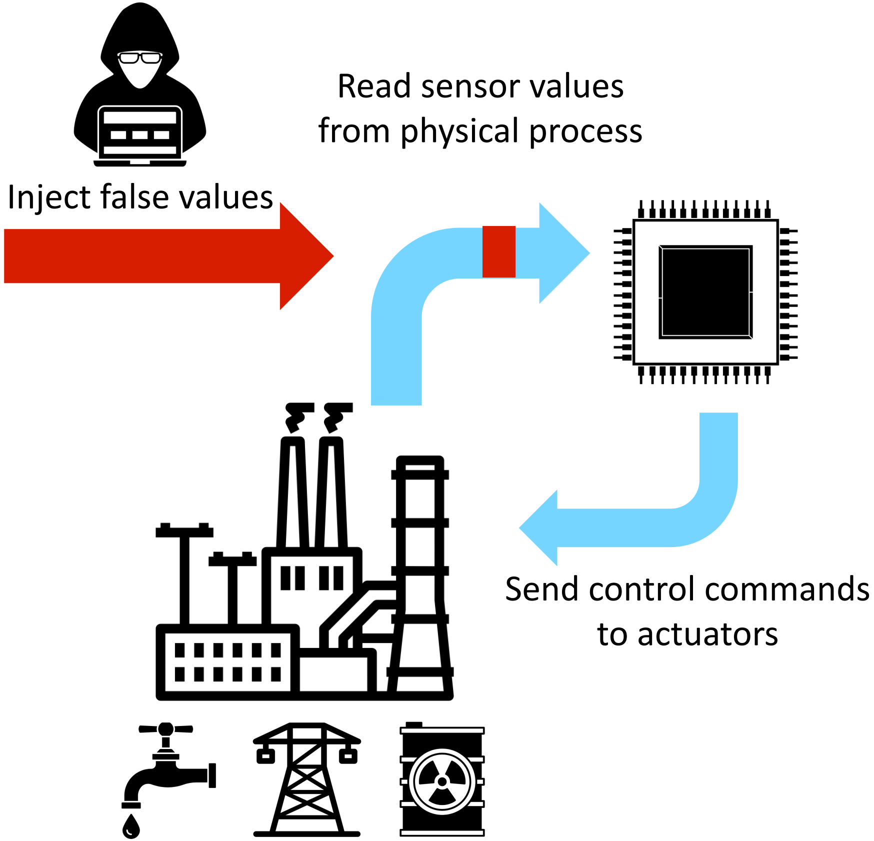

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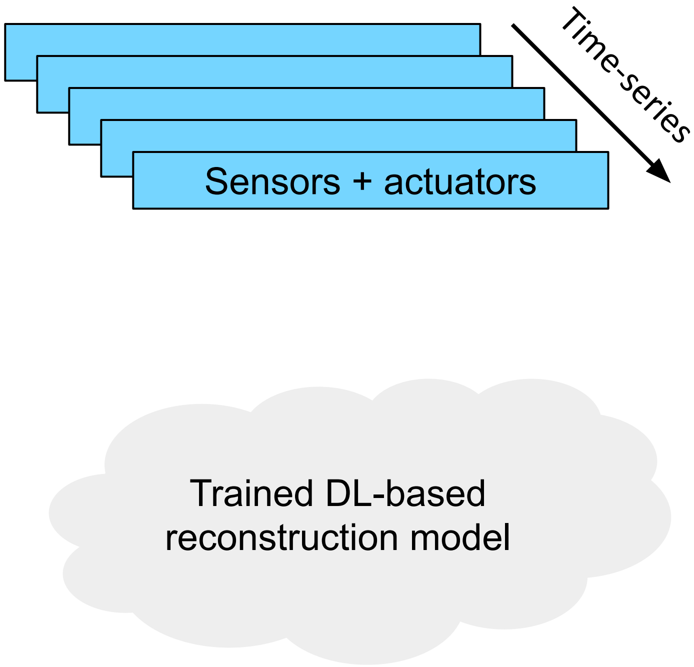

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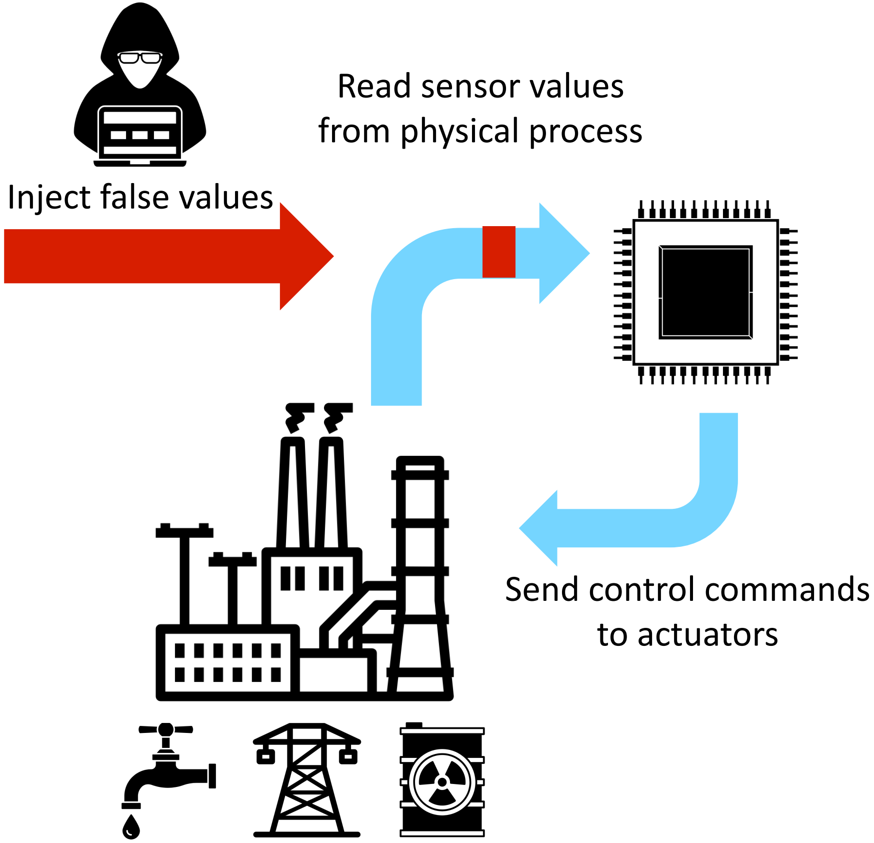

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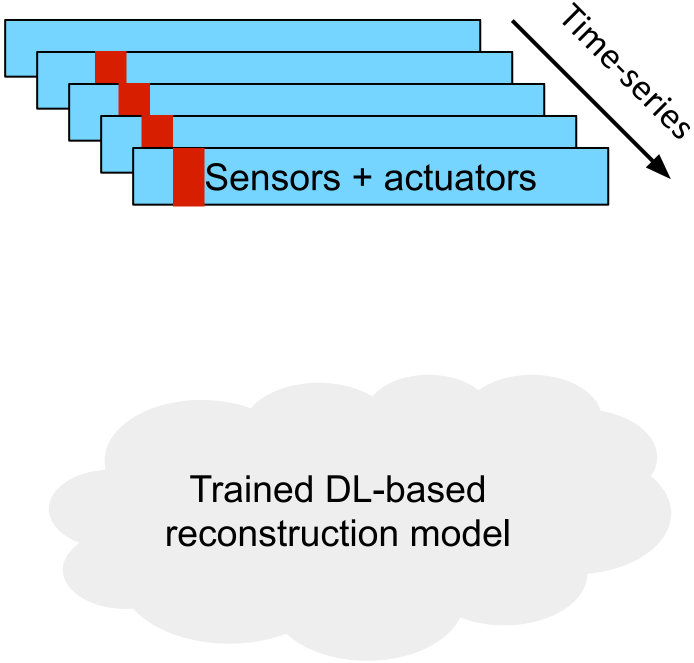

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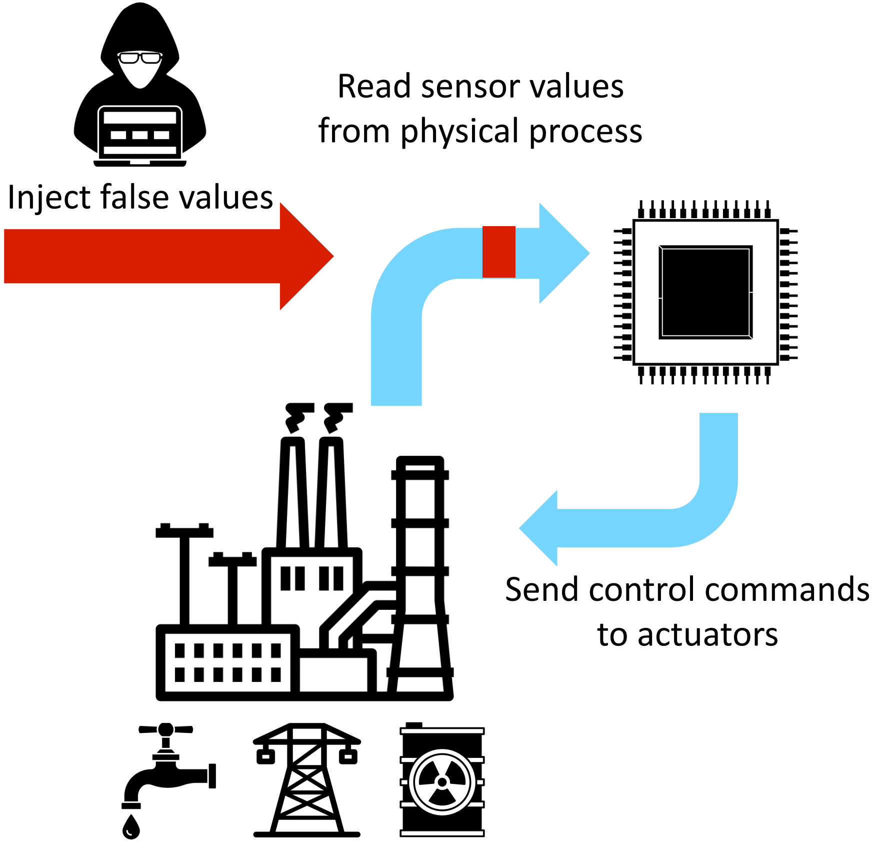

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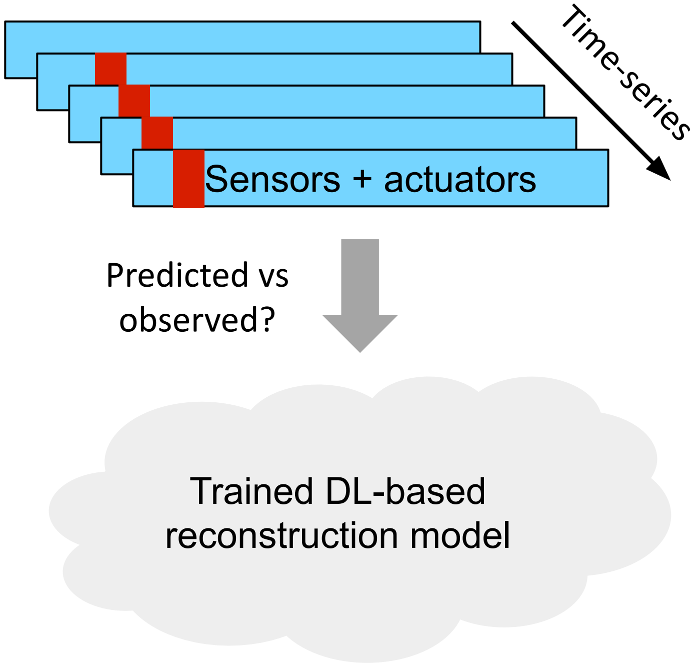

Sensors + actuators

Time-series

Predicted vs observed?

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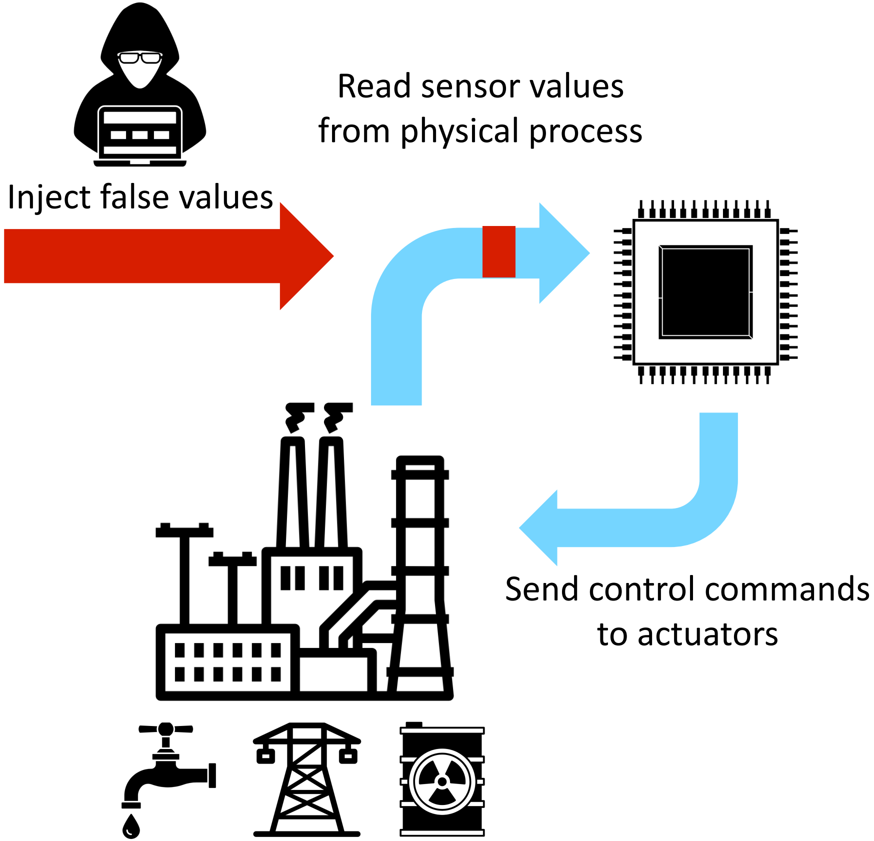

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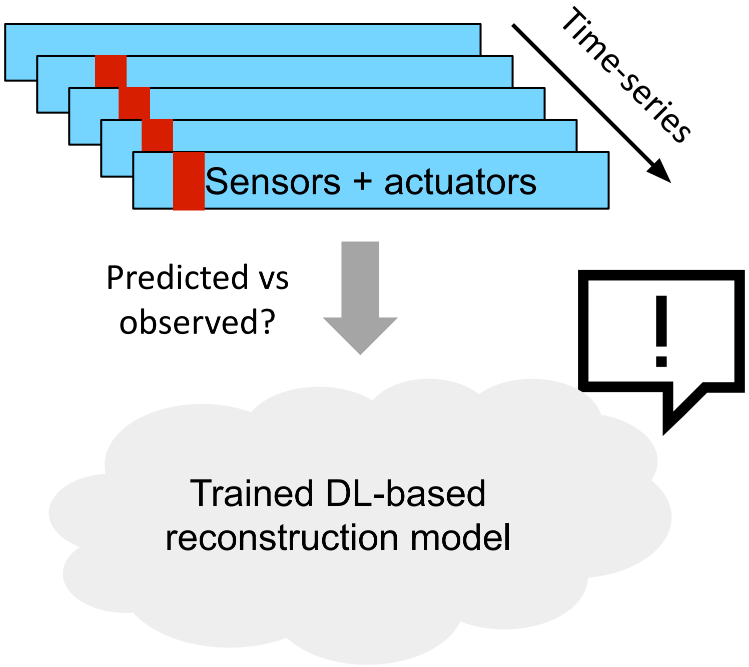

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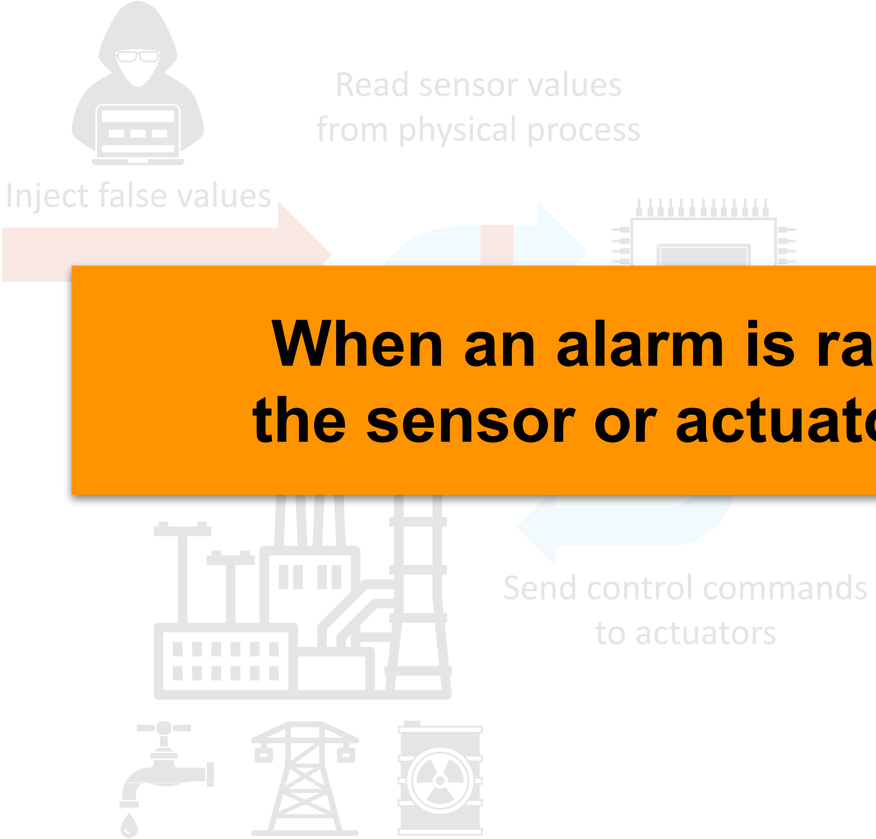

Time-series
Sensors + actuators
Trained DL-based
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When an alarm is raised, can we identify the sensor or actuator that was attacked?

Explainable AI (XAI) through attribution methods

- Attribution methods: explain what **input features** cause a model to **produce a specific output**

Sturmfels et al. "Visualizing the Impact of Feature Attribution Baselines". Distill 2020.

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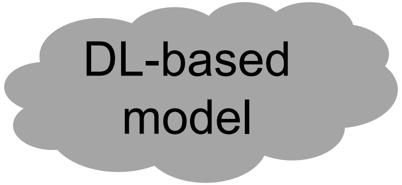

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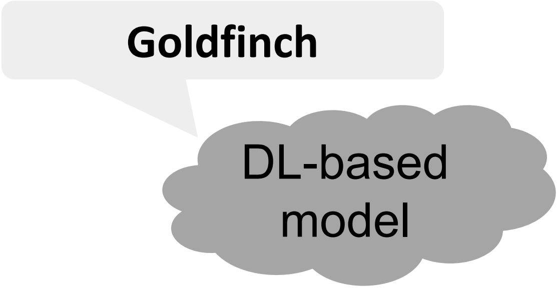

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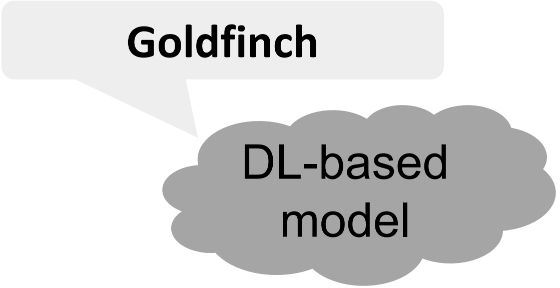

Goldfinch

DL-based model

Which **input pixels** caused the prediction?

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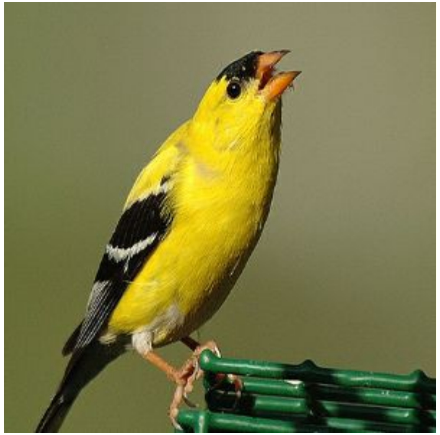

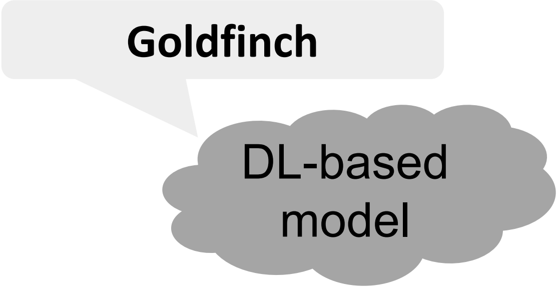

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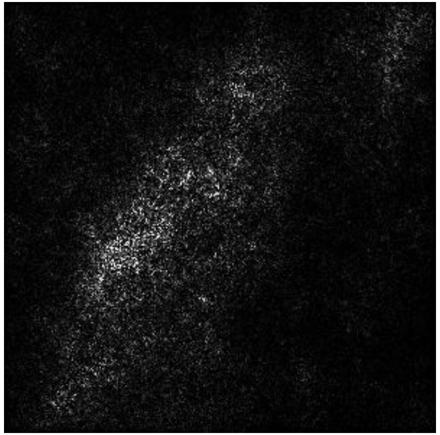

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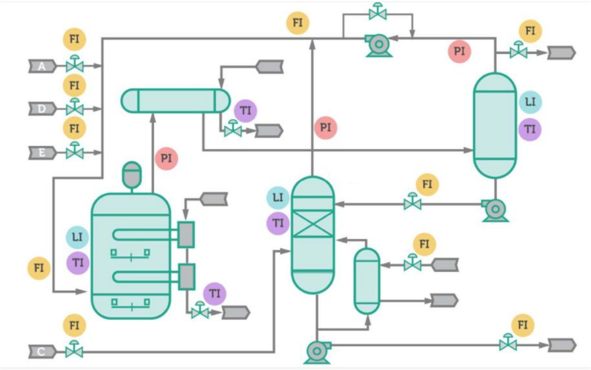

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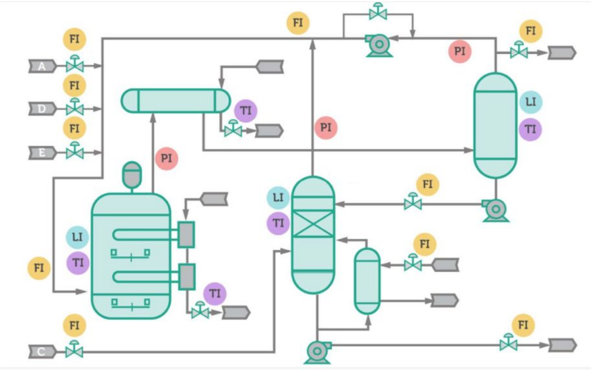

Anomaly!

DL-based model

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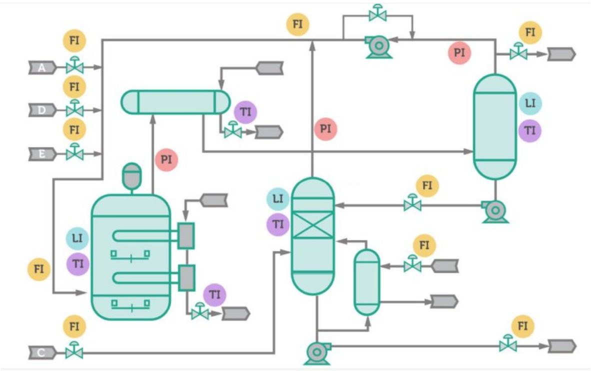

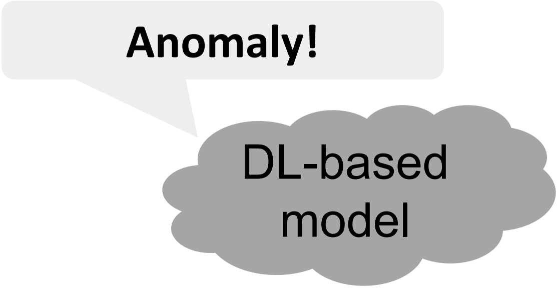

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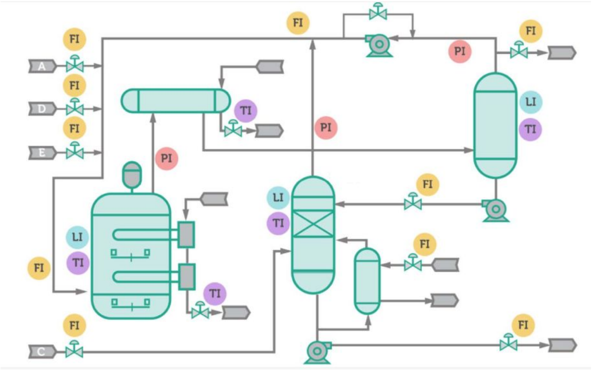

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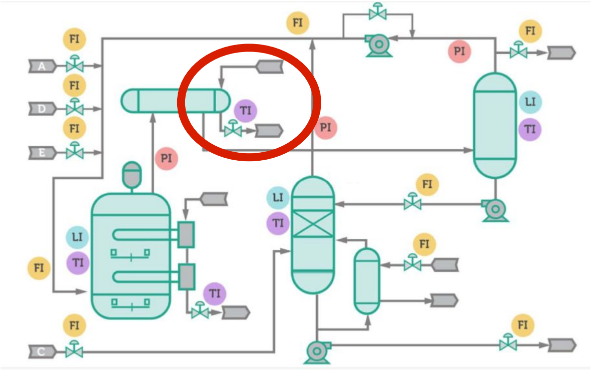

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In this work: exploring ICS anomaly attribution

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1. (How well) do prior, **off-the-shelf attribution strategies** work for ICS anomaly attribution?
2. How do **properties of ICS attacks** affect attribution accuracy?
3. **Can we do better** than prior attribution strategies?

RQ1: Do prior attribution strategies work well?

We evaluate attribution in diverse settings

- Compare a variety of anomaly-detection models [1]:
  - Linear models, CNNs, RNNs, LSTMs

[1] Fung et al. "Perspectives from a comprehensive evaluation of reconstruction-based anomaly detection in ICS." ESORICS 2022.
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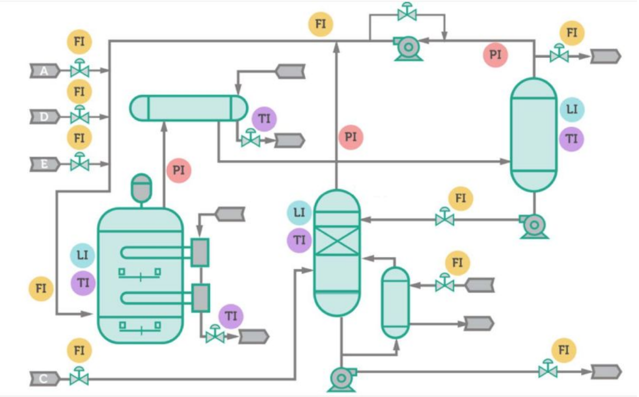

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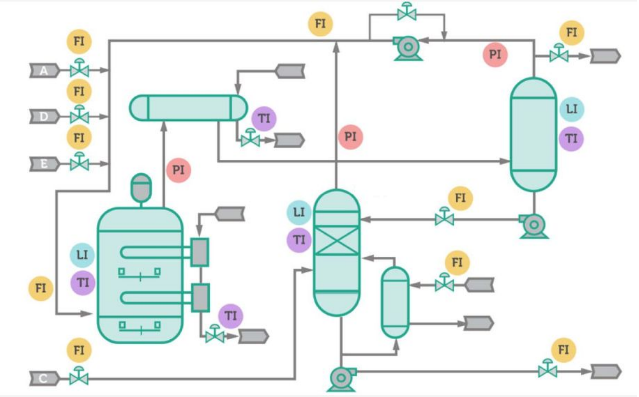
- Datasets [2,3]: SWaT, WADI, TEP
  - Water treatment (public datasets)
  - Chemical process (modified simulator)
- Attack scenarios:
  - 47 real attacks on water treatment
  - 100 synthetic attacks on chemical process
    - Made publicly available!



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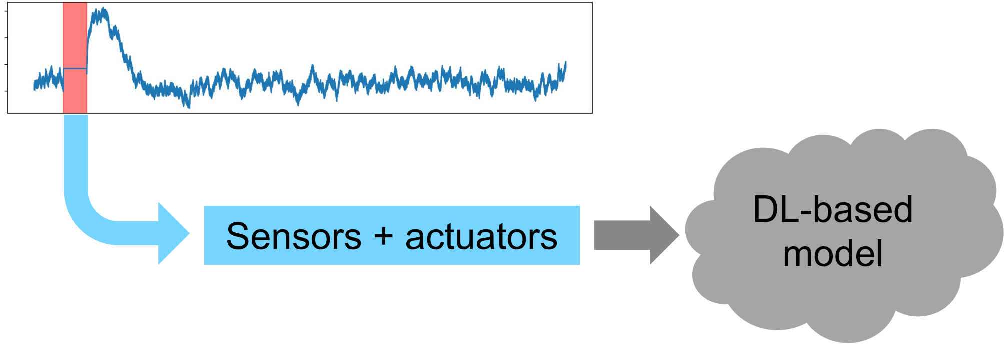

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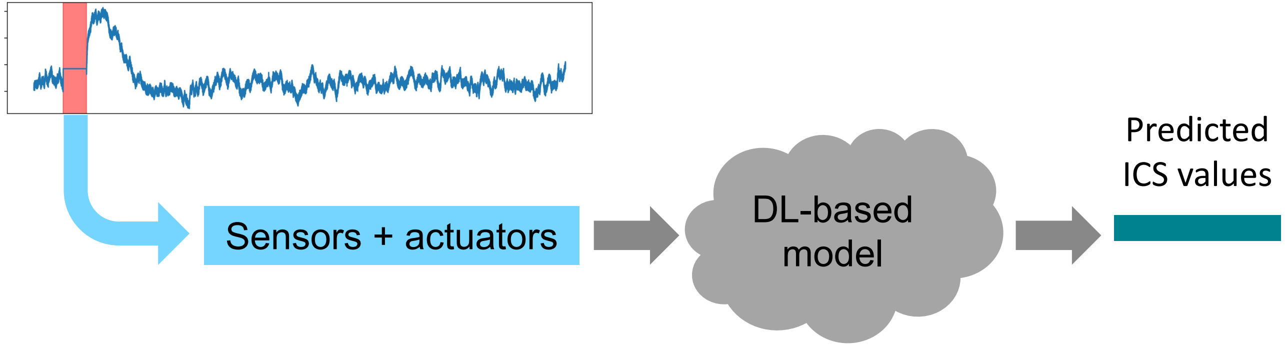

Sensors + actuators

DL-based model

Predicted ICS values

ICS anomaly attribution: previously

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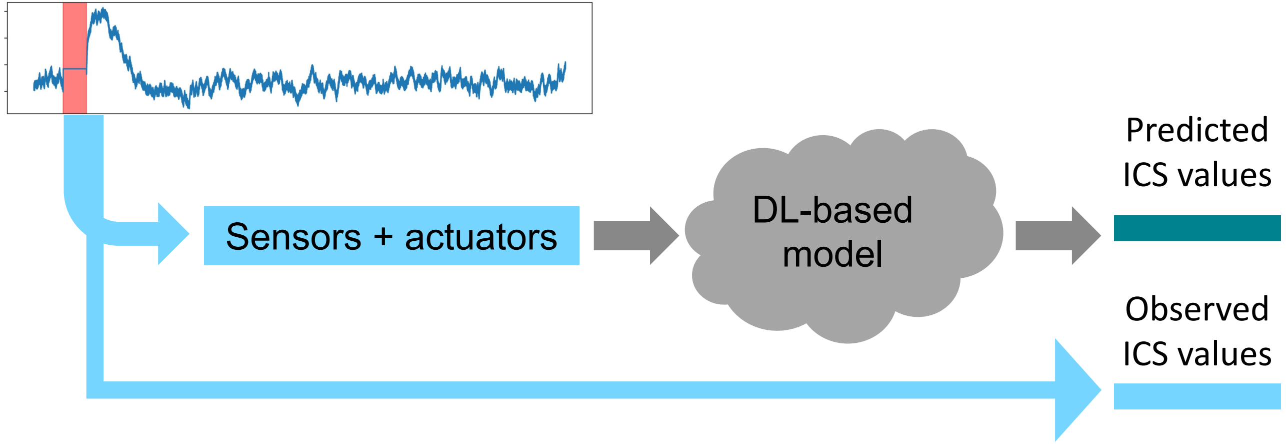

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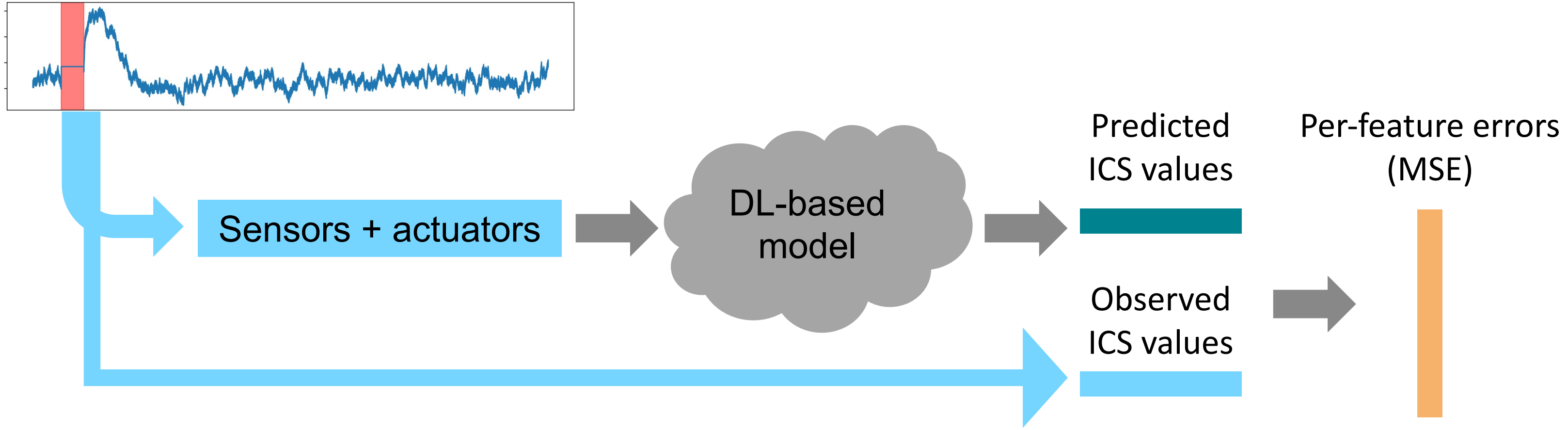
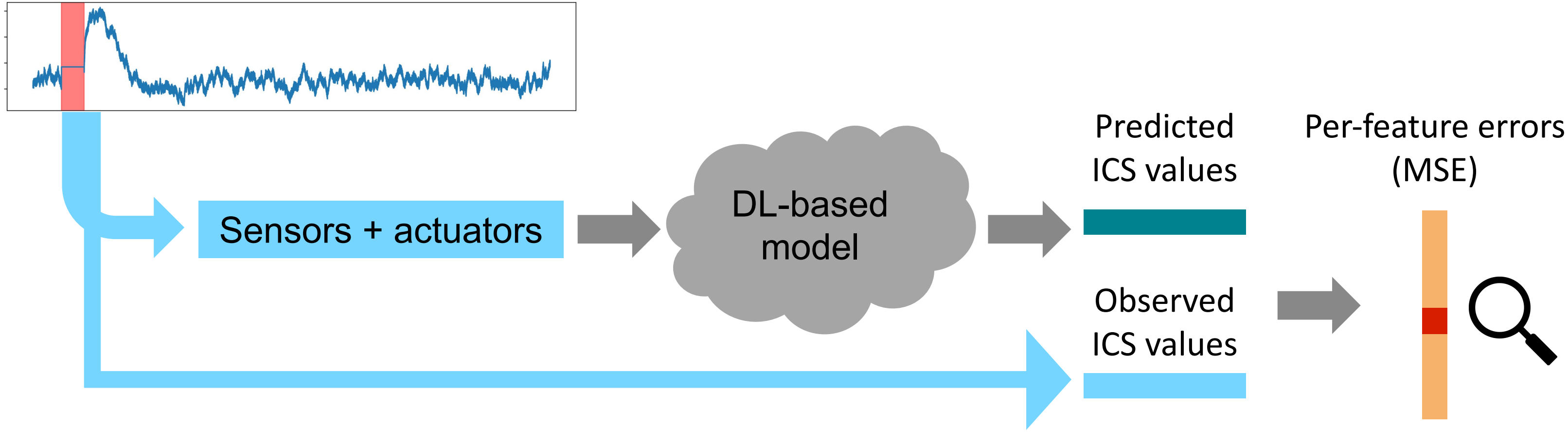


ICS anomaly attribution: previously

- Compare model prediction to observed ICS values
- Attribute alarm to feature with **highest error (MSE)**



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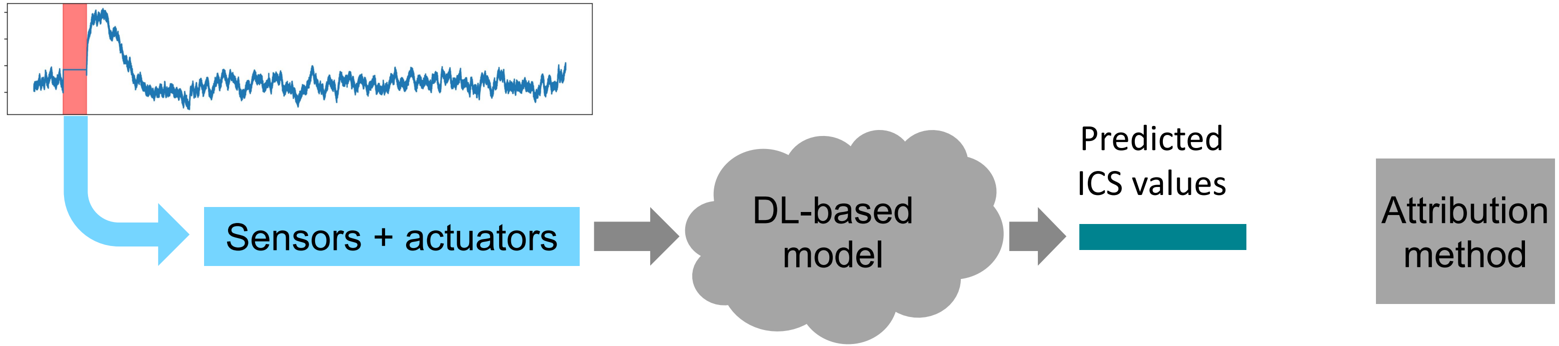

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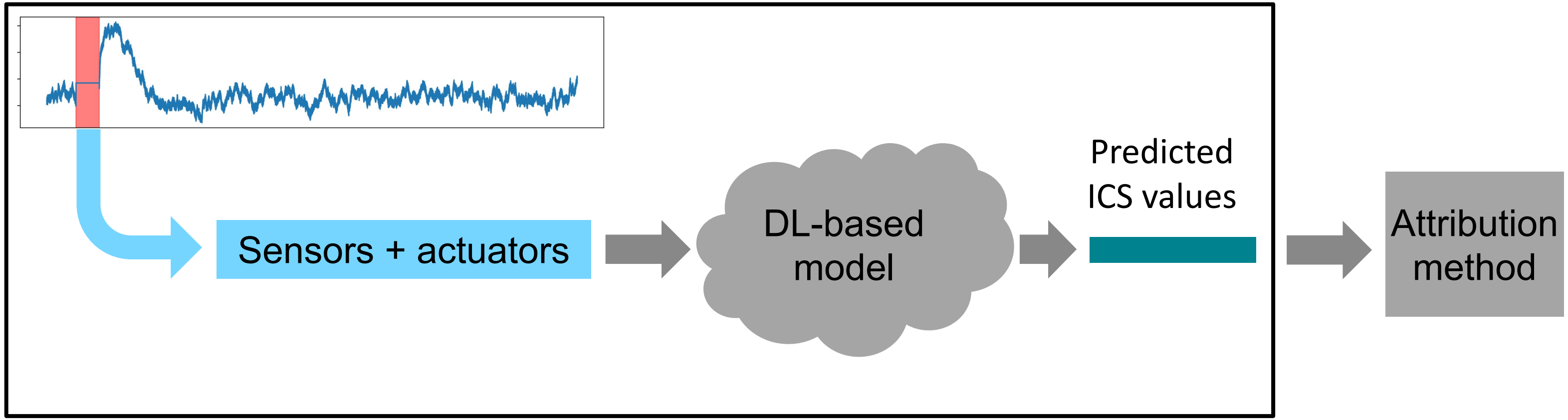

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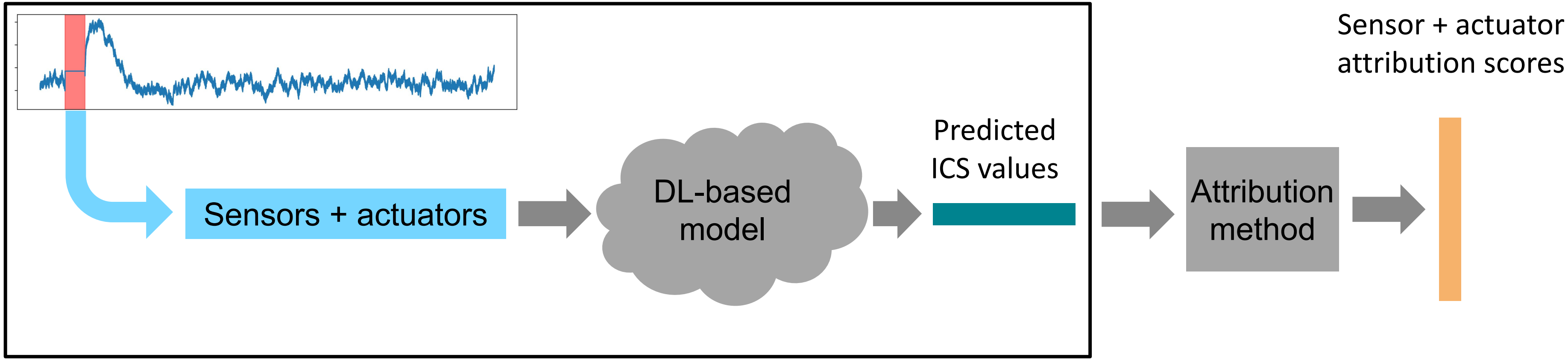

We evaluate attribution for practical workflows

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  - Not how attribution scores would be used in practice
- Preliminary survey of ICS operators (n=7)
  - Operators prefer to see multiple features, but not necessarily all
  - Trade-off between number of features seen and accuracy

“A balanced trade-off is needed. Often having [a] list of max 10 [sensors] with minimal error rate is more useful than having less with high error rate.” –P4

We propose AvgRank to evaluate attribution

Sensor + actuator
attribution scores

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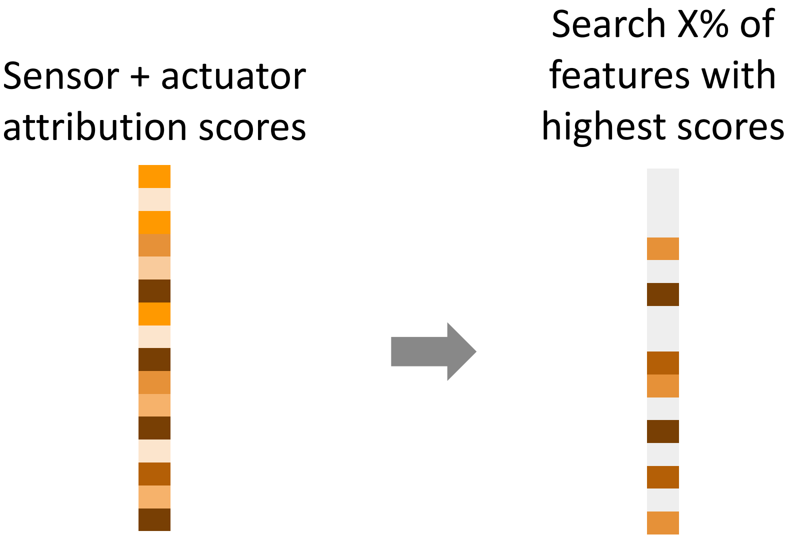
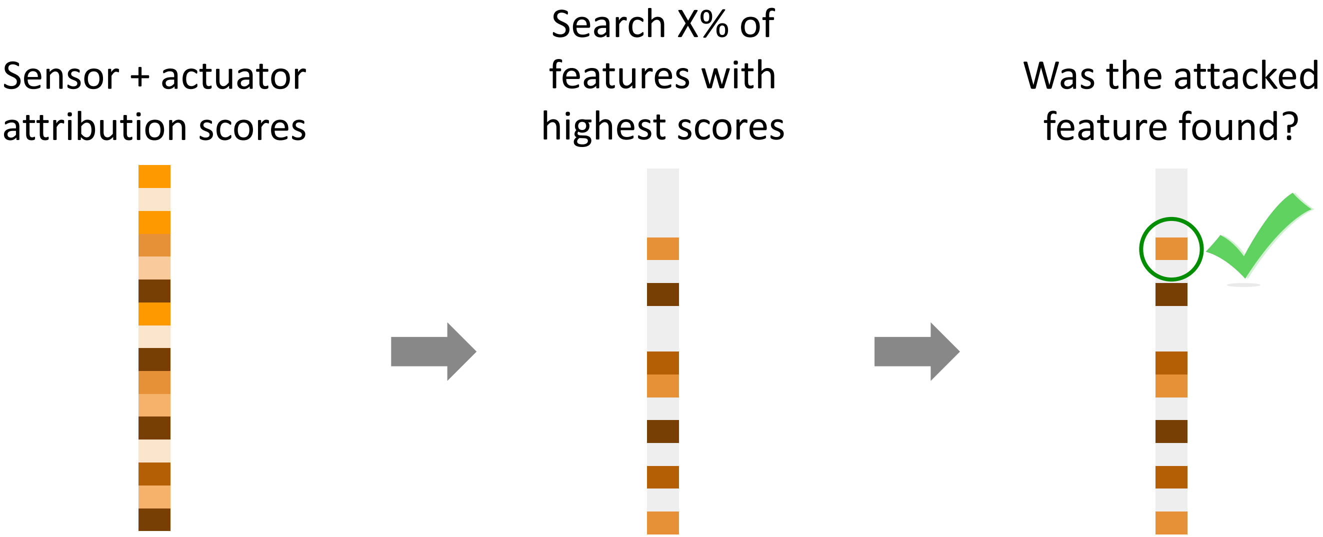


Sensor + actuator attribution scores

Search X% of features with highest scores

We propose AvgRank to evaluate attribution



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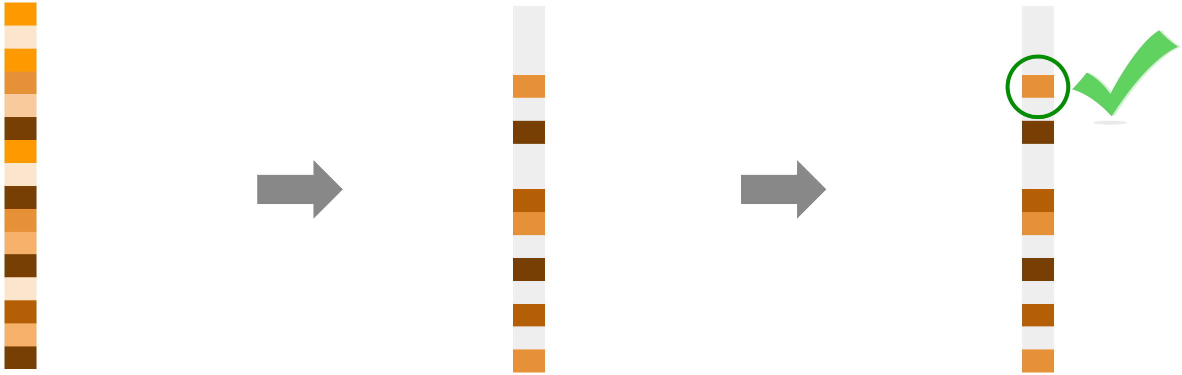

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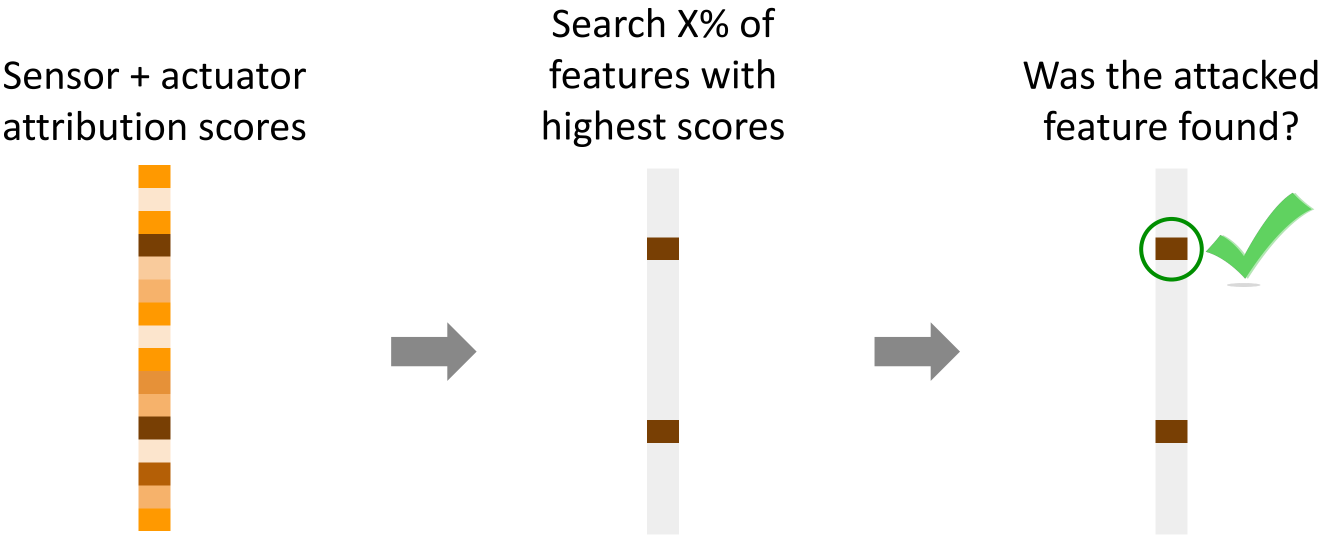
  - Lower AvgRank is better: operators consider fewer features, save time



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Using MSE ranking for attribution performs worse than previously reported

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[2] M. Kravchik and A. Shabtai, “Efficient cyber attack detection in industrial control systems using lightweight neural networks and PCA,” IEEE Transactions on Dependable and Secure Computing, vol. 19, no. 4, 2022.

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  - On average, operators would have to consider **>14% of features** before finding attacked feature

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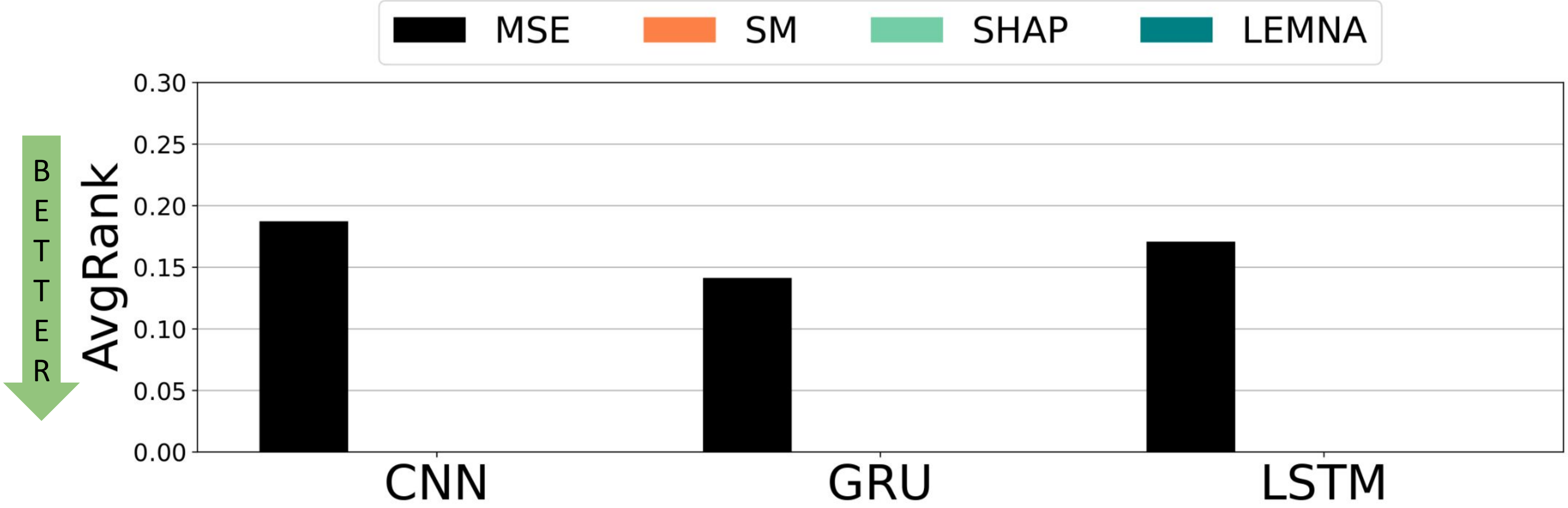
Do attribution methods perform better?

- Three best-performing attribution methods (SM, SHAP, LEMNA)



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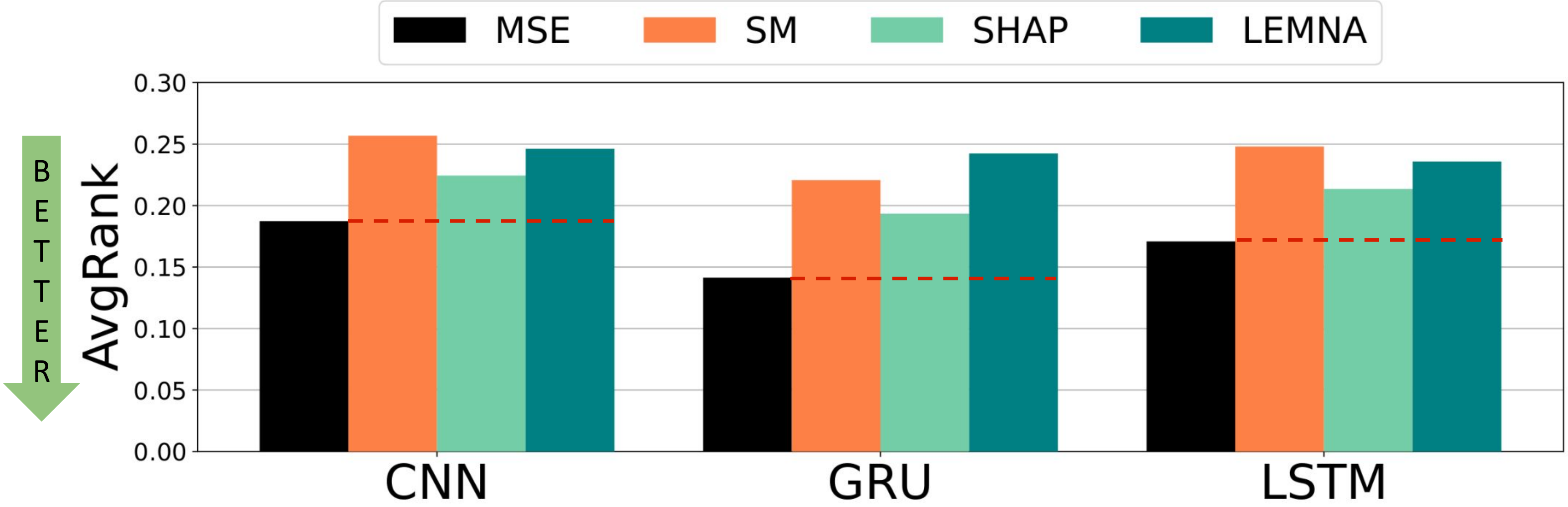

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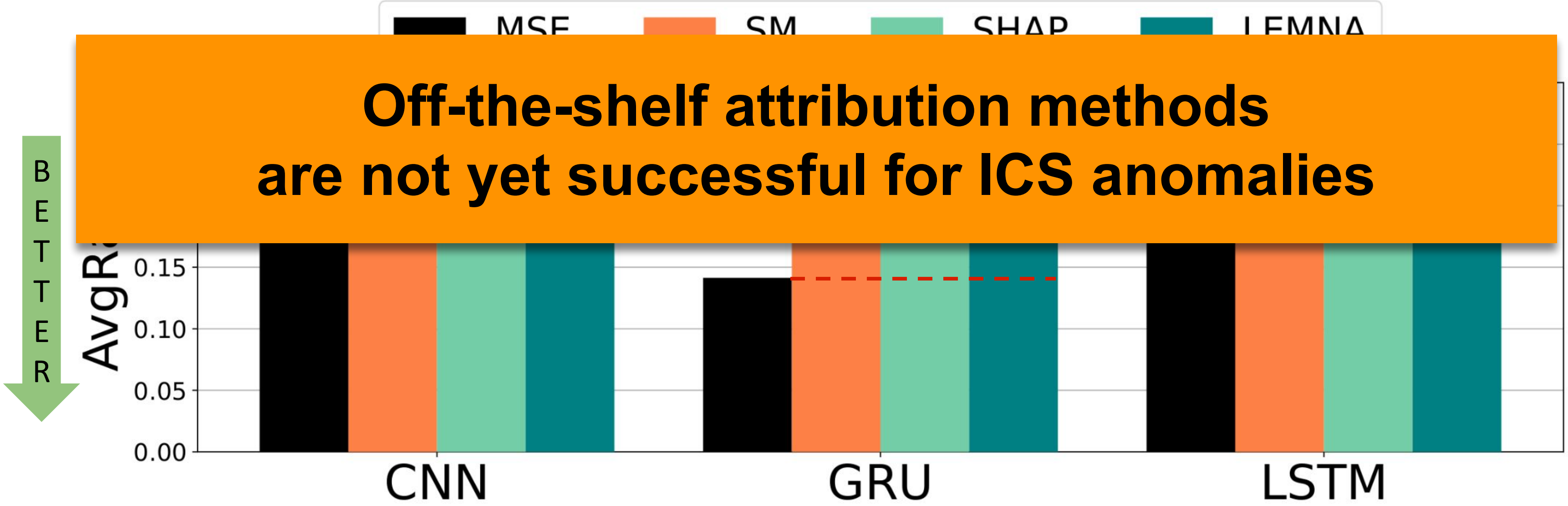

Off-the-shelf attribution methods are not yet successful for ICS anomalies

RQ2: How do ICS attack properties affect attribution?

Why are attributions worse than expected?

- Broad differences among our 147 ICS attacks:
  - Detection outcomes
    - Latency, if detected, etc.
  - Input manipulation
    - Magnitude, location, pattern

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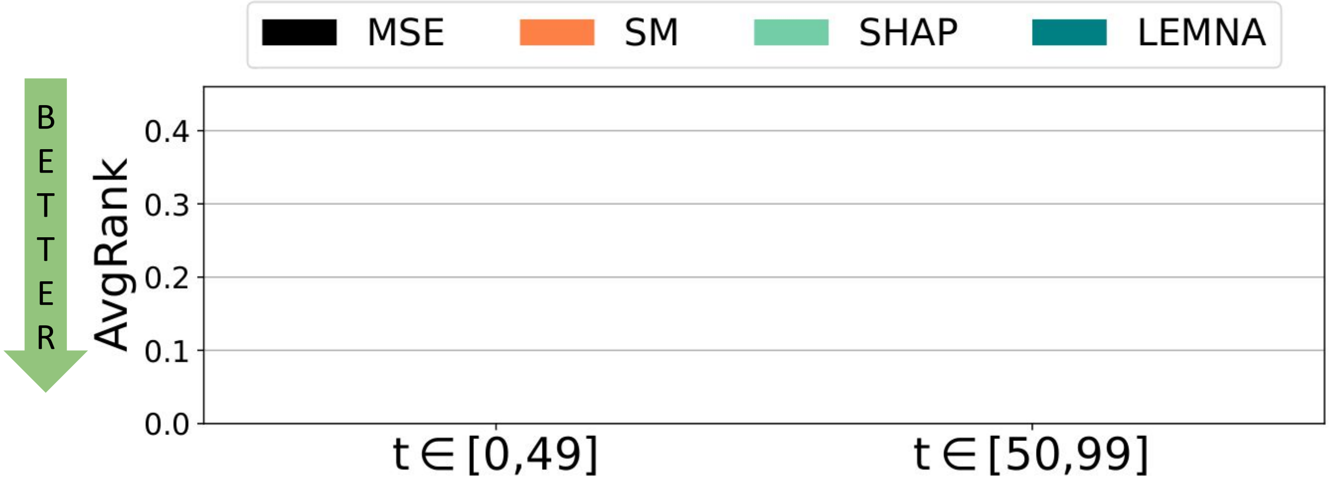
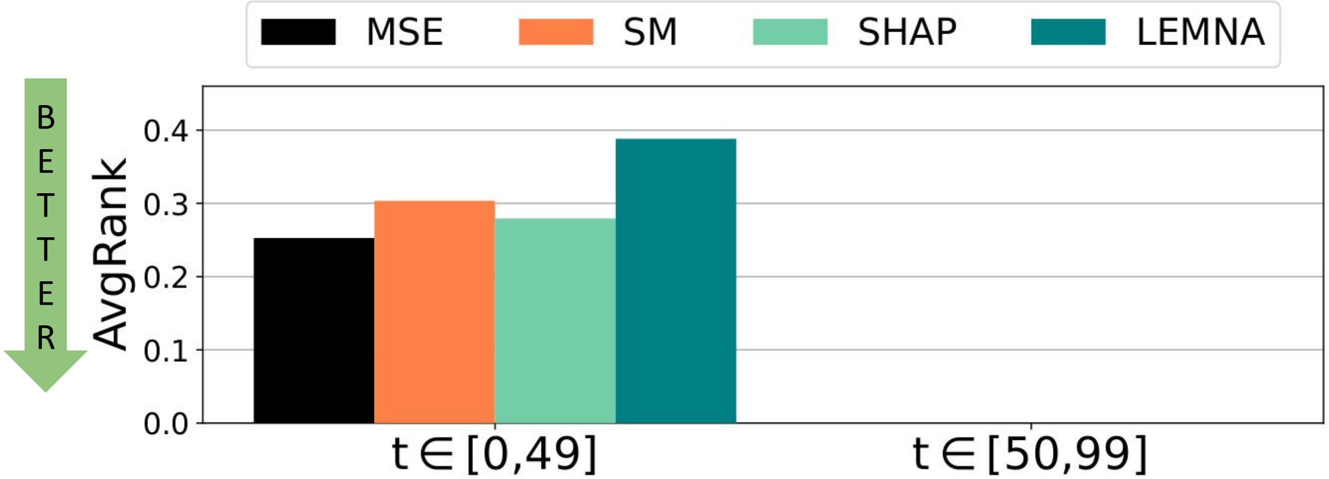
Attribution accuracy varies by detection latency



Attribution accuracy varies by detection latency

- Attributions are inaccurate within first 50 seconds



CyLab Carnegie Mellon University Security and Privacy Institute

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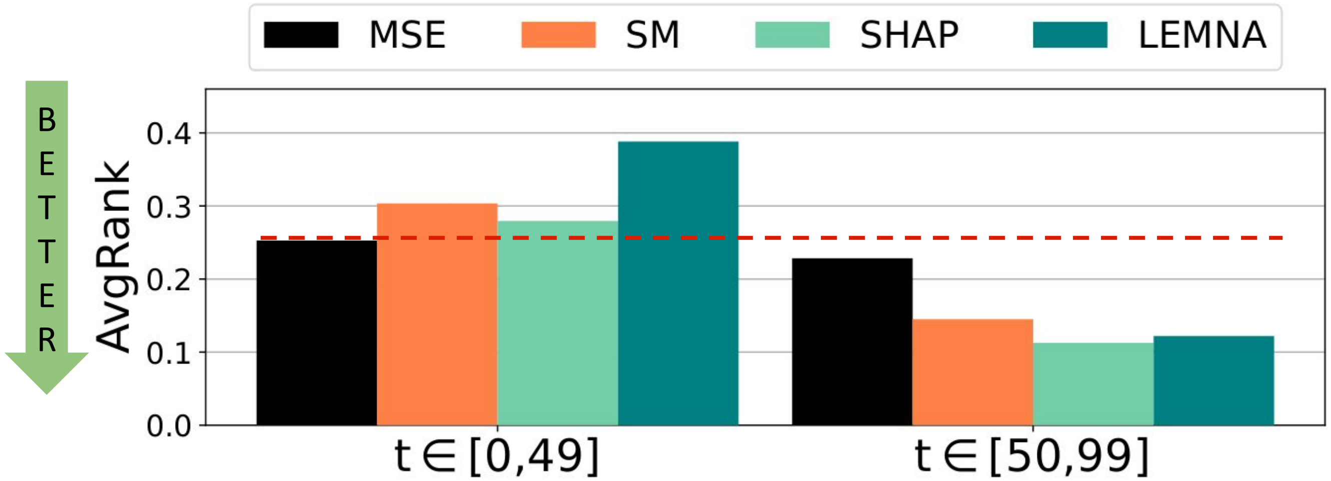
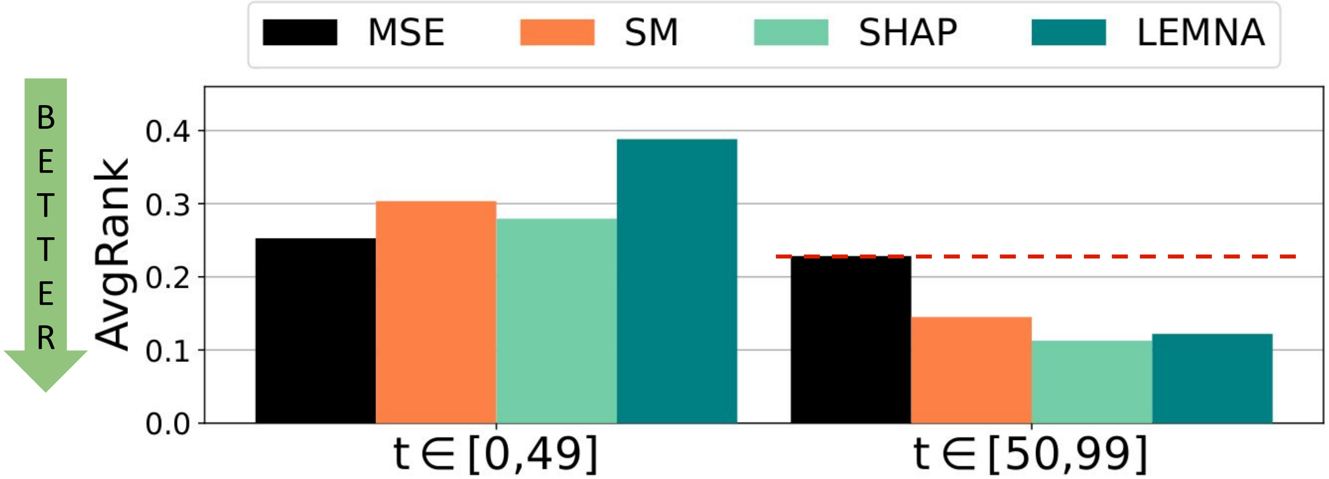


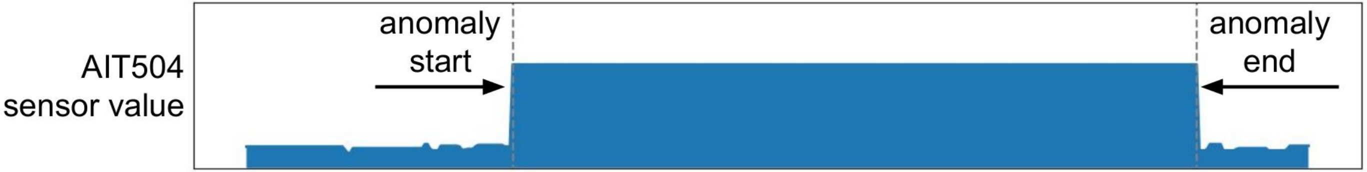
Attribution accuracy varies by detection latency

- Attributions are inaccurate within first 50 seconds
  - But improve when computed within 50-100 seconds
  - SM, SHAP, LEMNA now outperform MSE



How can timing affect attribution?

Example: SWaT attack #10



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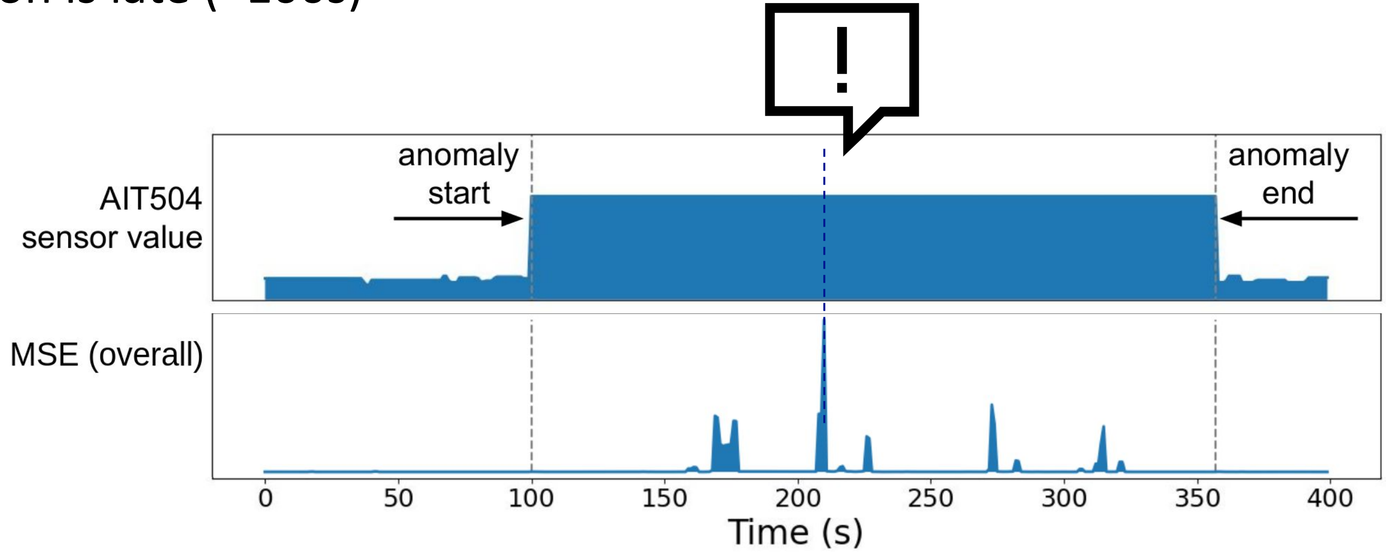
Example: SWaT attack #10

Detection is late (~100s)



How can timing affect attribution?

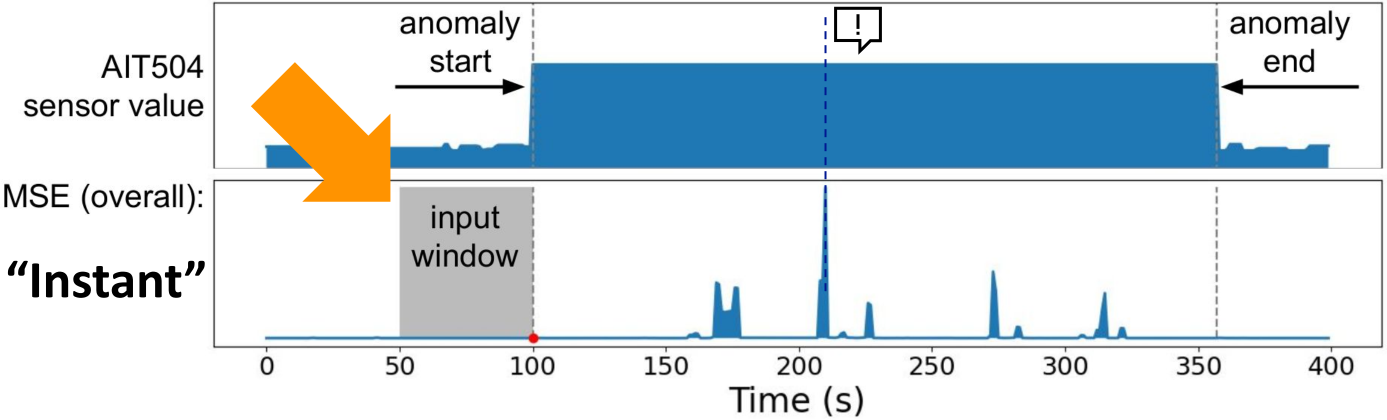
Example: SWaT attack #10

Detection is late (~100s)

Option 1: "Instant"

Input window preceding anomaly start

Input is mostly benign data



How can timing affect attribution?

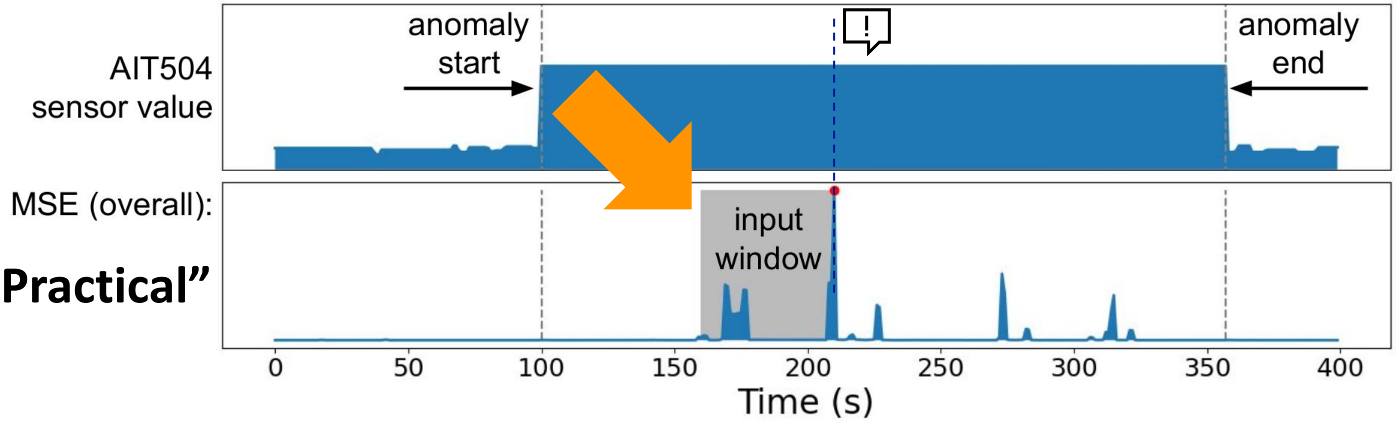
Example: SWaT attack #10

Detection is late (~100s)

Option 2: "Practical"

Input window preceding detection

Realistic, but late



How can timing affect attribution?

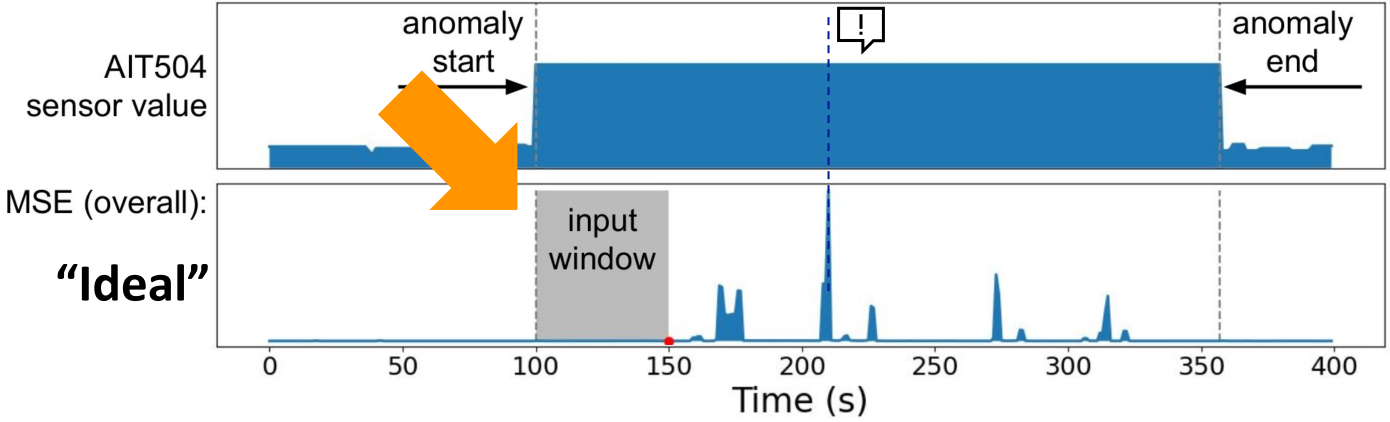
Example: SWaT attack #10

Detection is late (~100s)

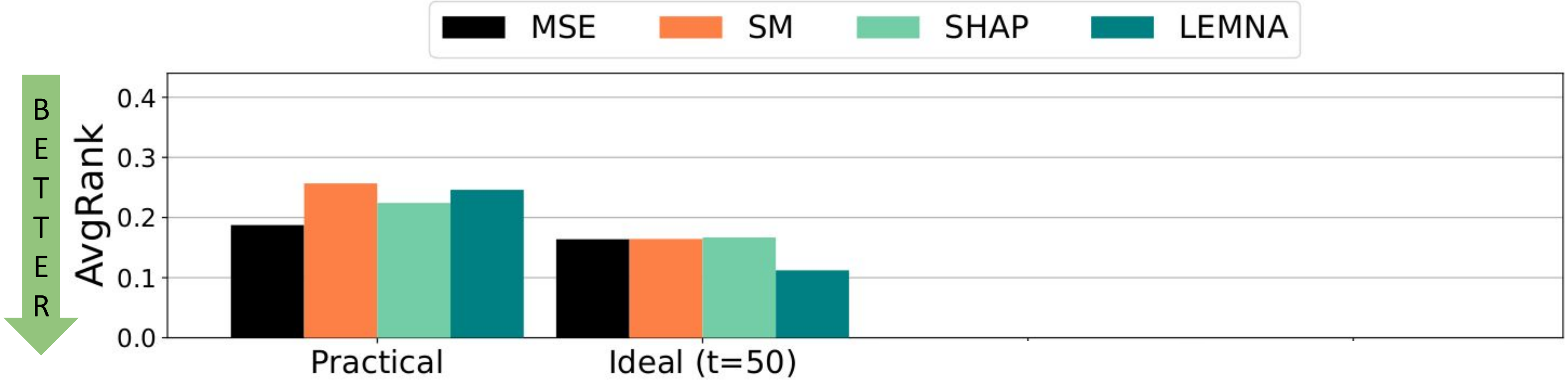
Option 3: “Ideal”

Input window begins with anomaly start

Ideal, but unknown in real time

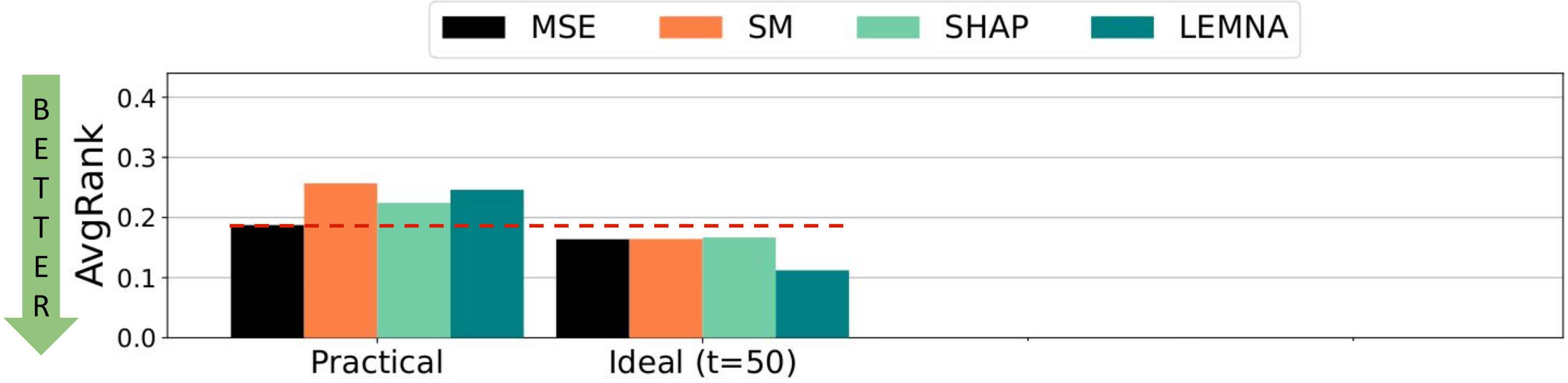


Attribution accuracy varies by timing strategy



Attribution accuracy varies by timing strategy

- Ideal timing outperforms practical outcomes



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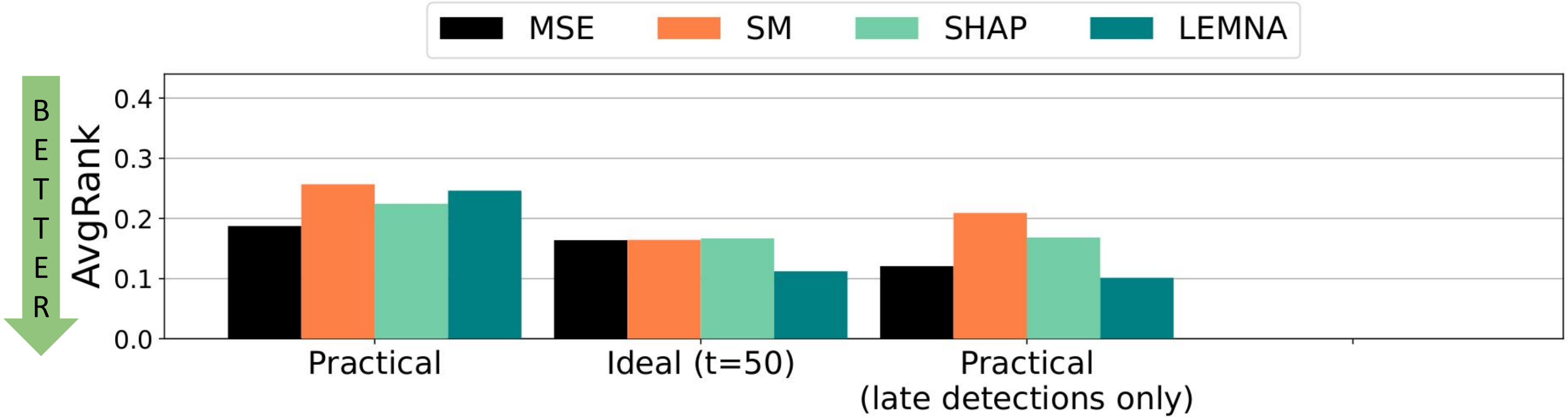

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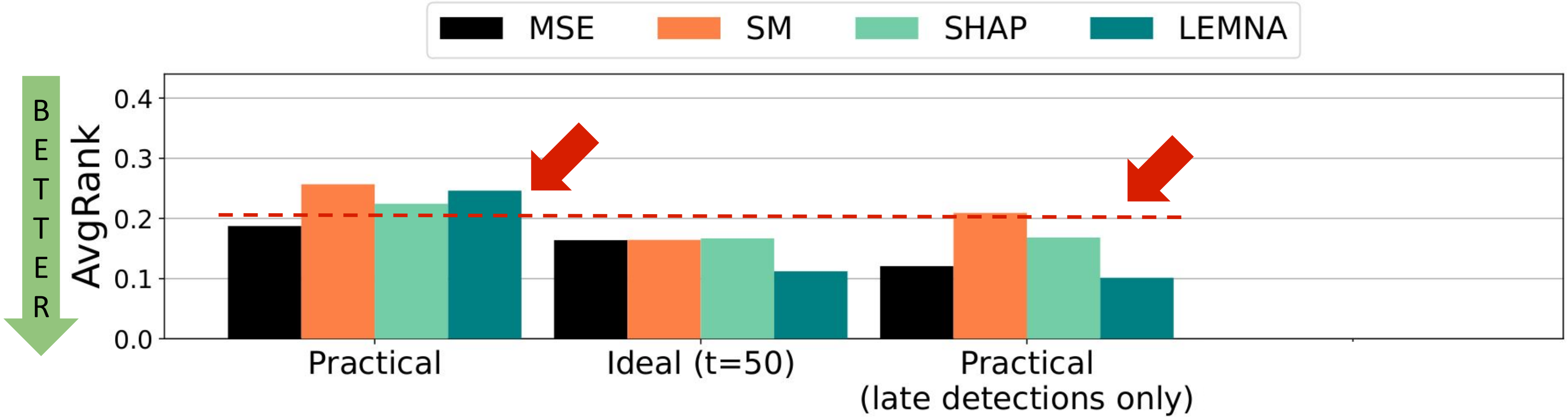
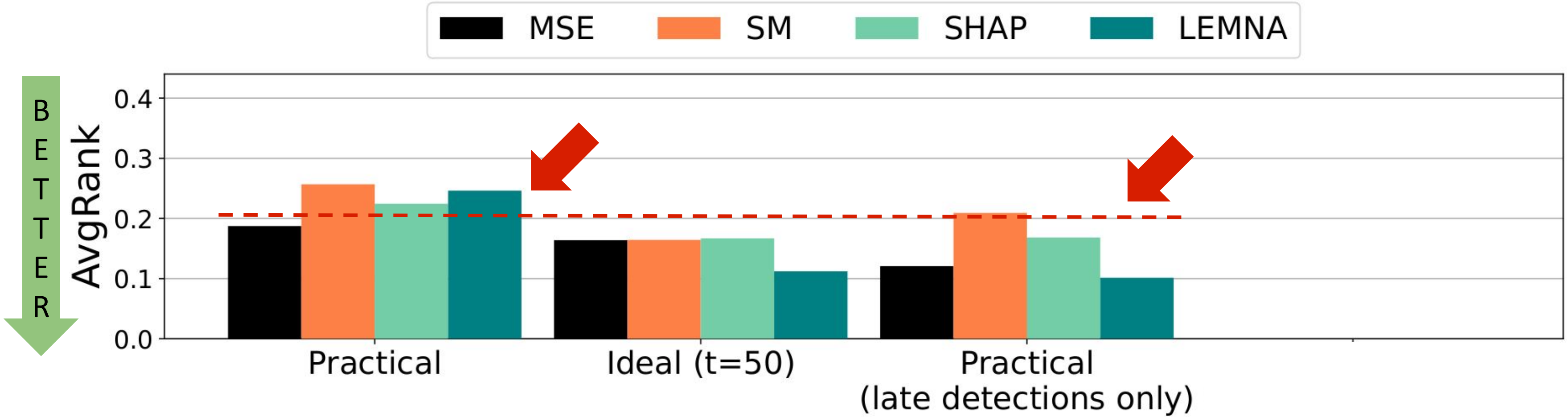


Attribution accuracy varies by timing strategy

- Ideal timing outperforms practical outcomes
- Avoiding “early” timings improves practical attribution results



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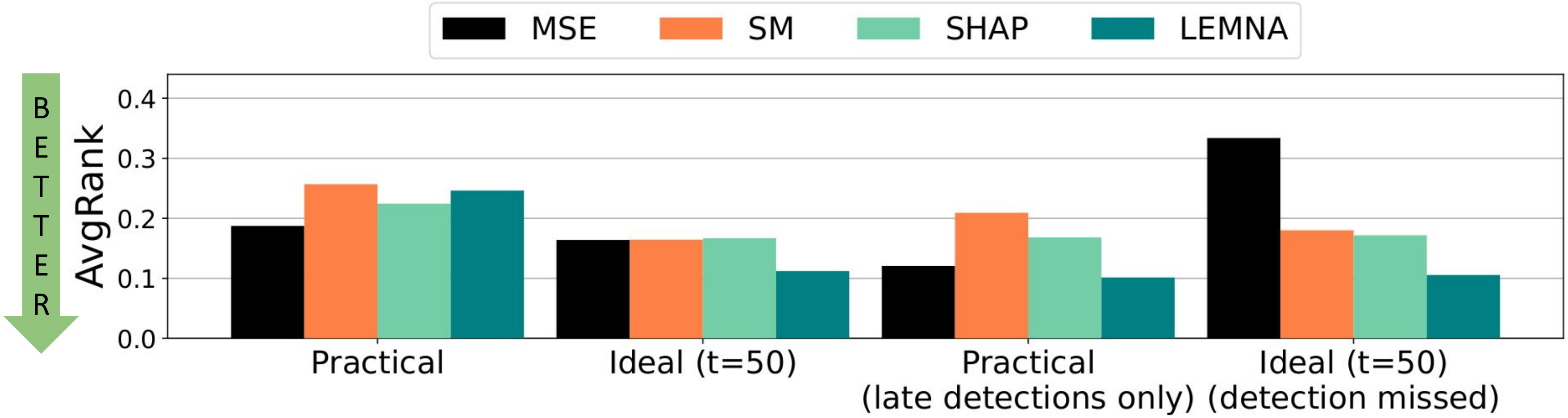

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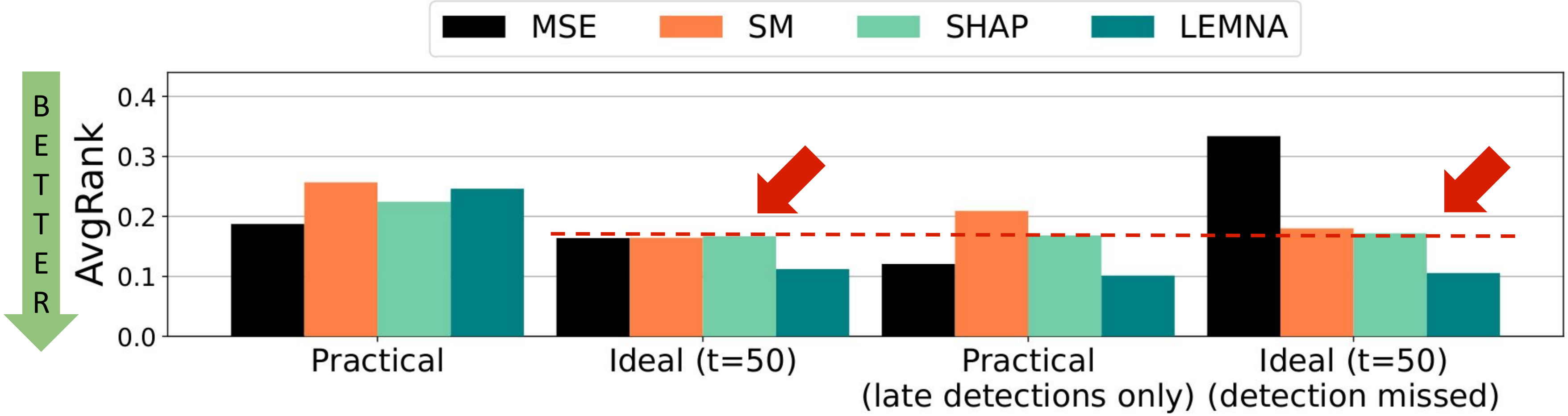

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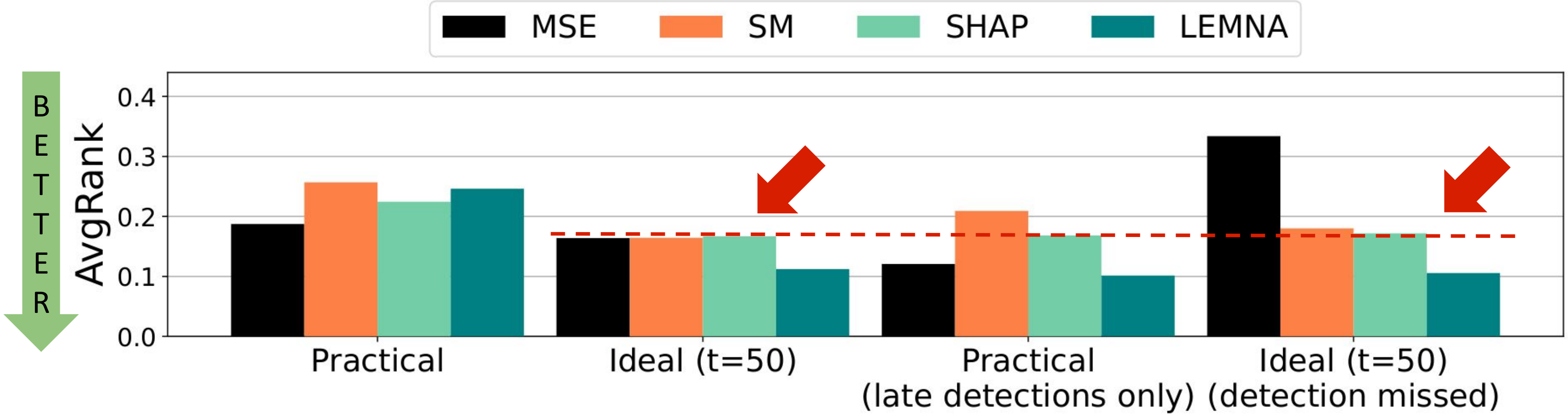

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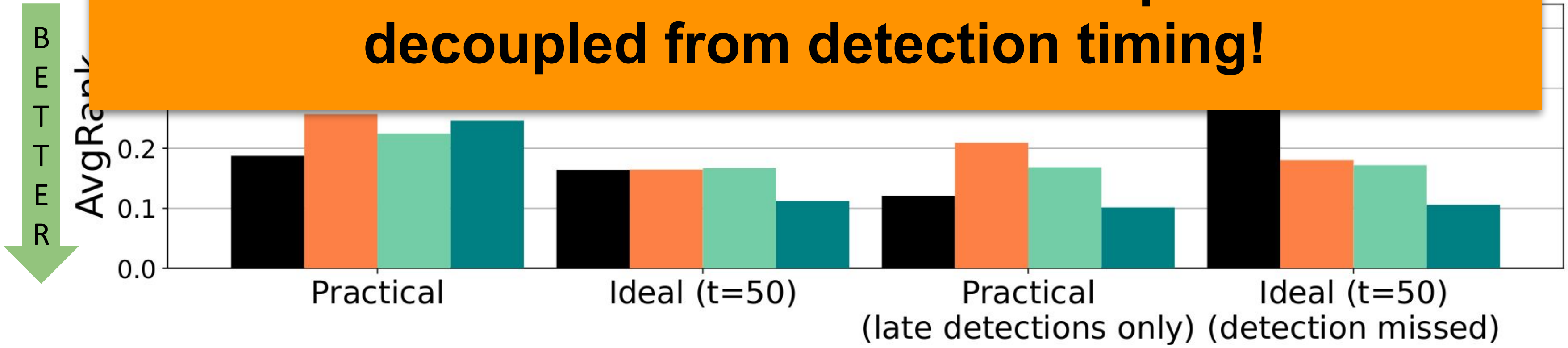

Attribution of ICS anomalies can improve when decoupled from detection timing!

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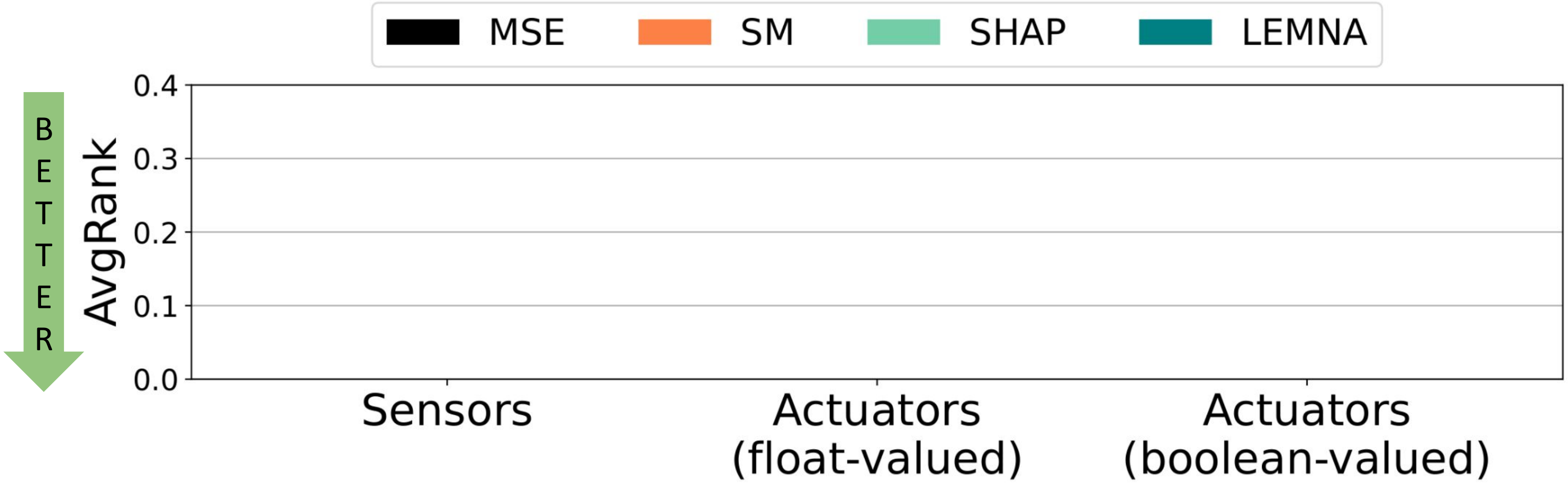
Attribution accuracy varies <u>by component type</u>



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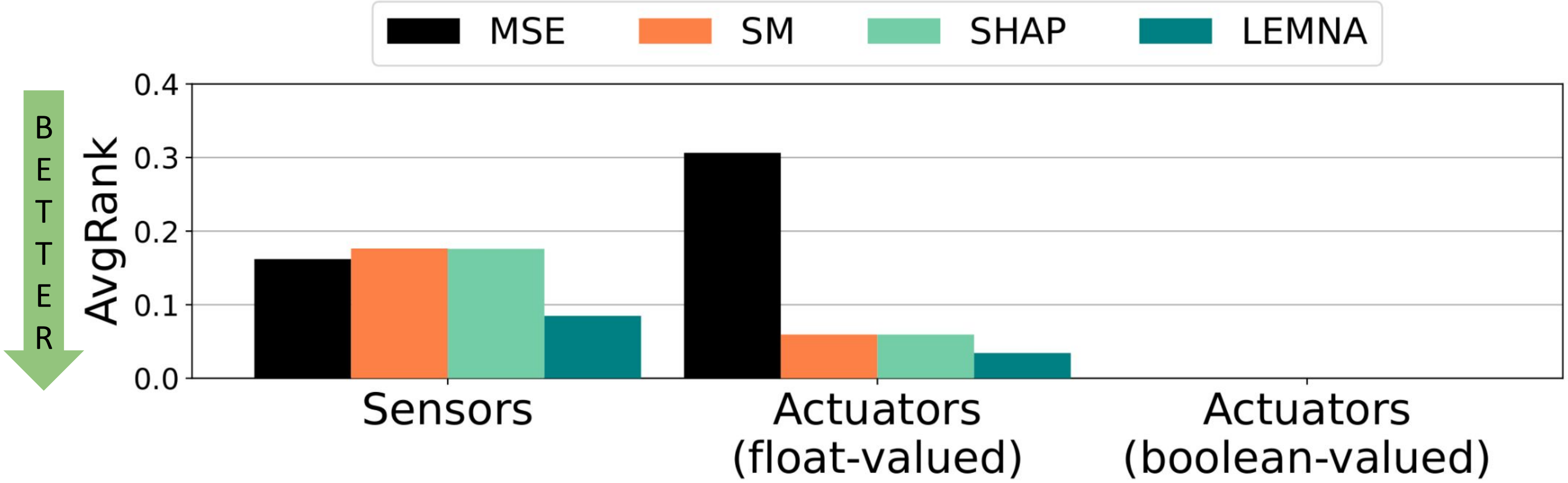
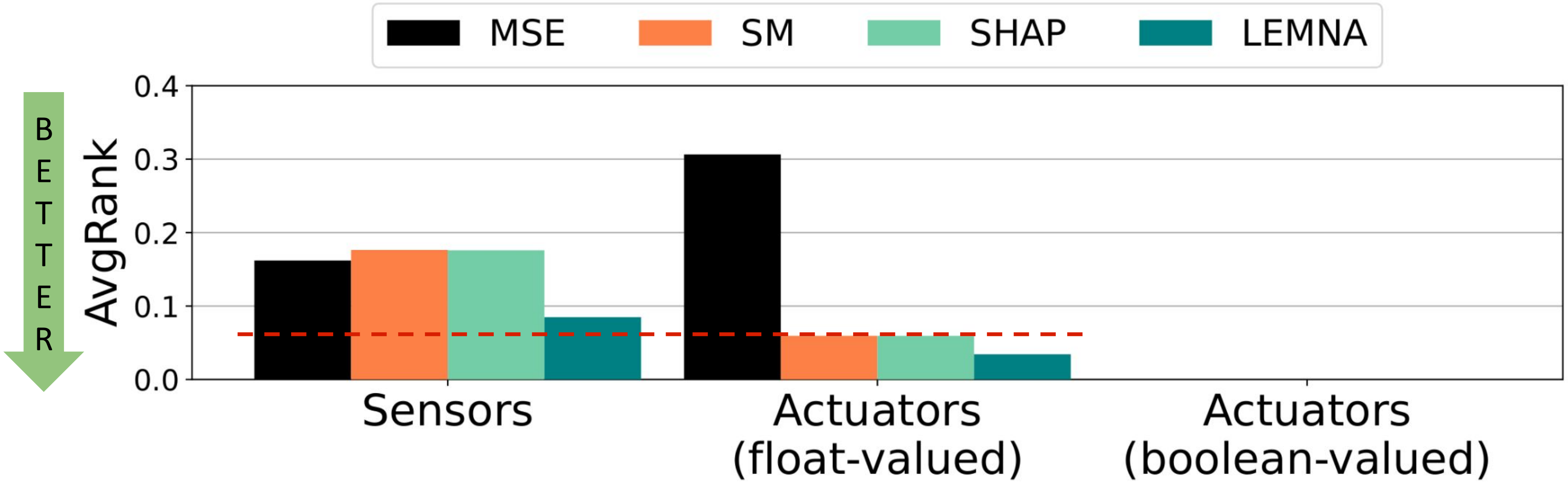


Attribution accuracy varies by component type

- Attribution methods: more accurate for float-valued actuators



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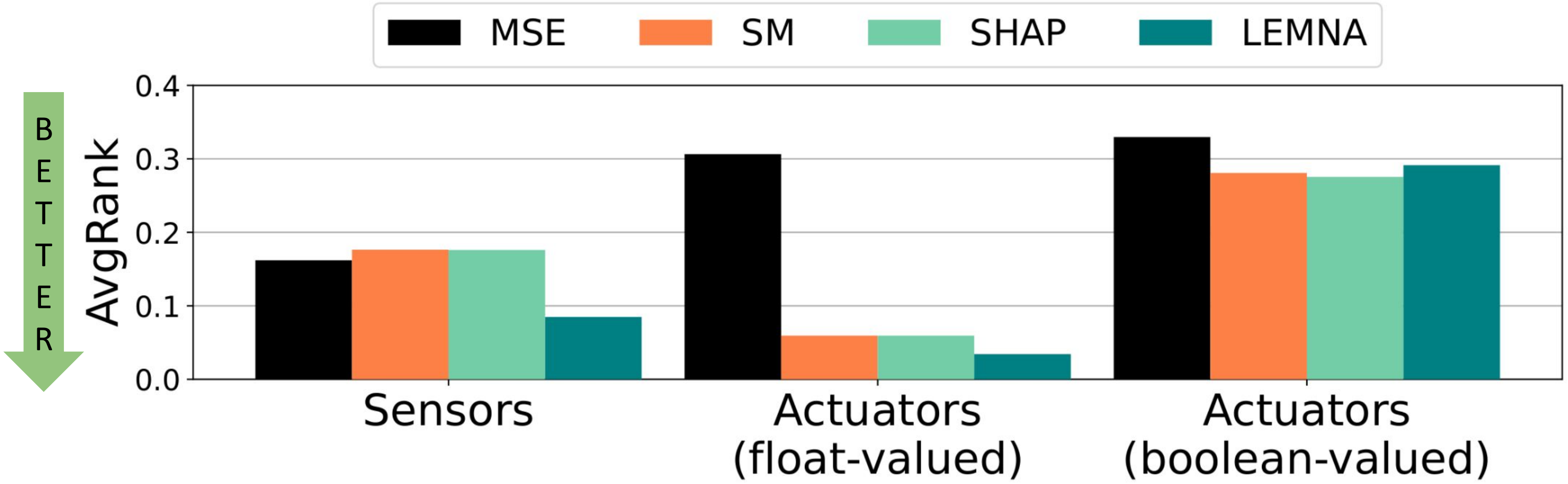

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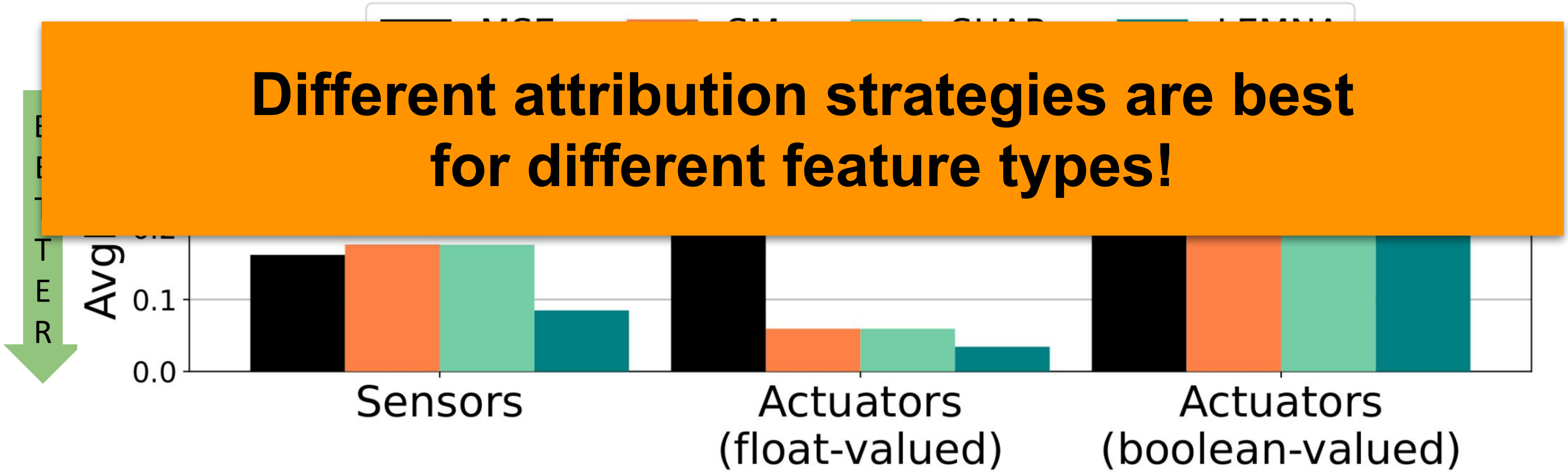
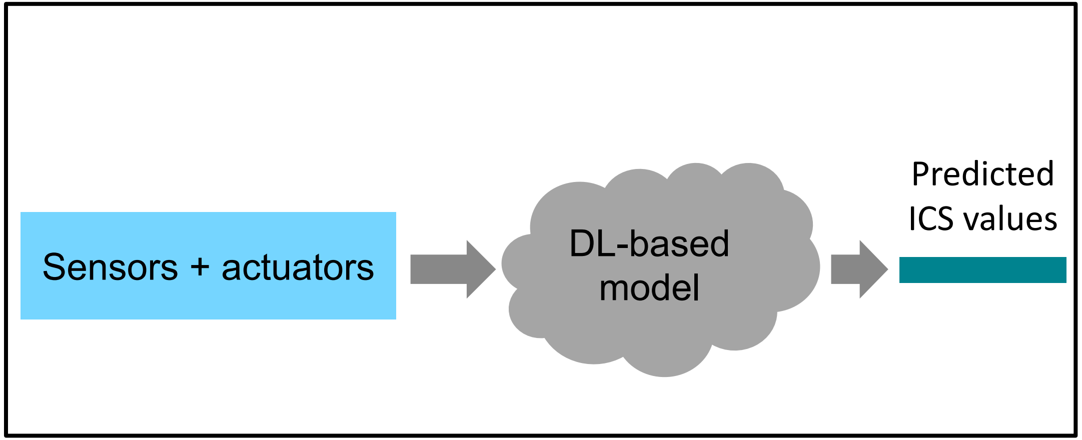


Different attribution strategies are best for different feature types!

RQ3: Can we do better than prior attribution strategies?

Better attributions via ensembles?

- Without knowing what attack or timing is used, can one strategy be best?



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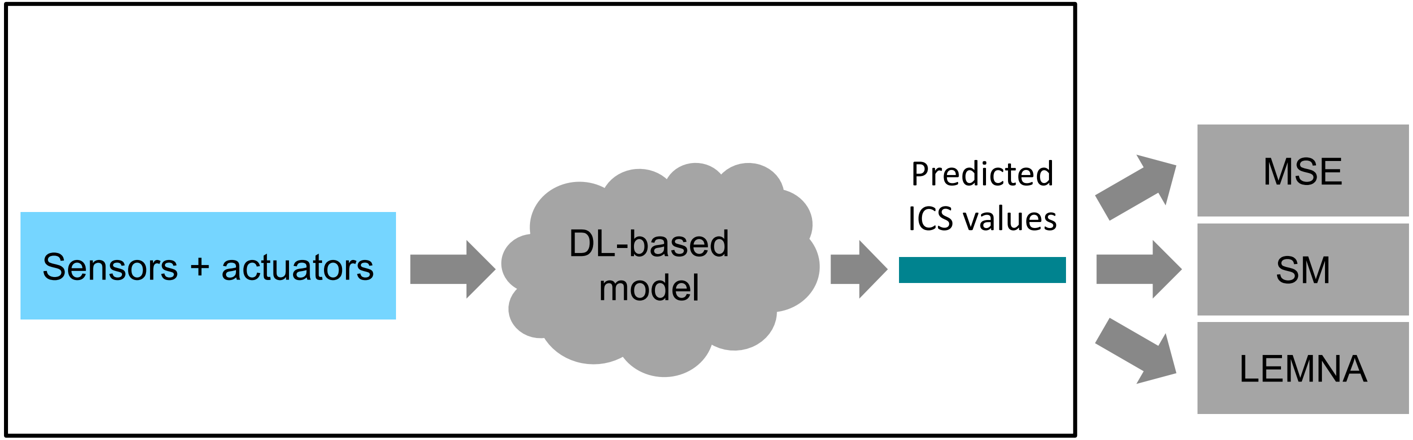
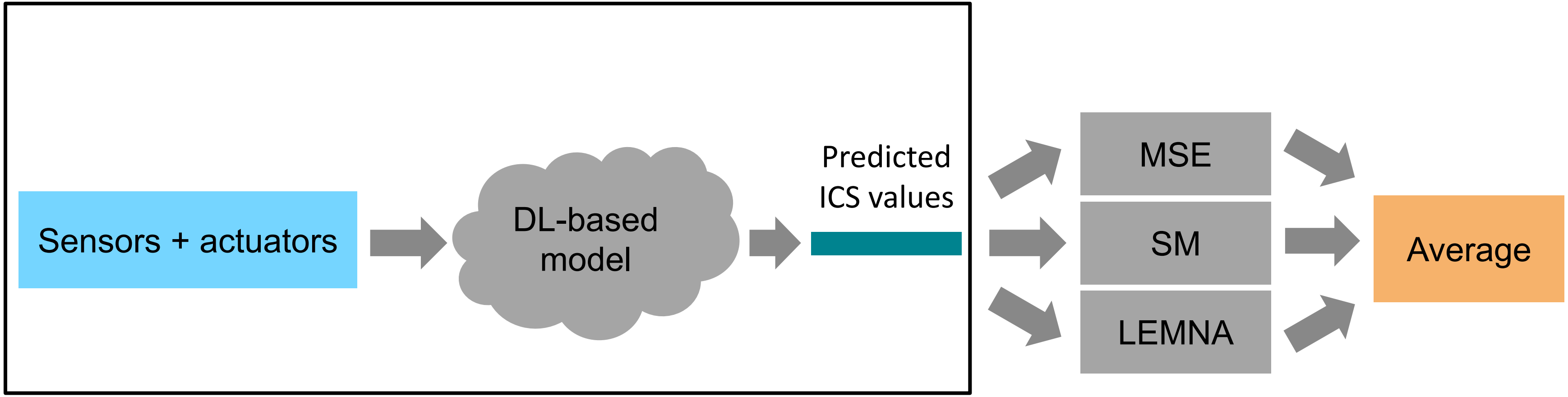
- We propose an ensemble attribution method:



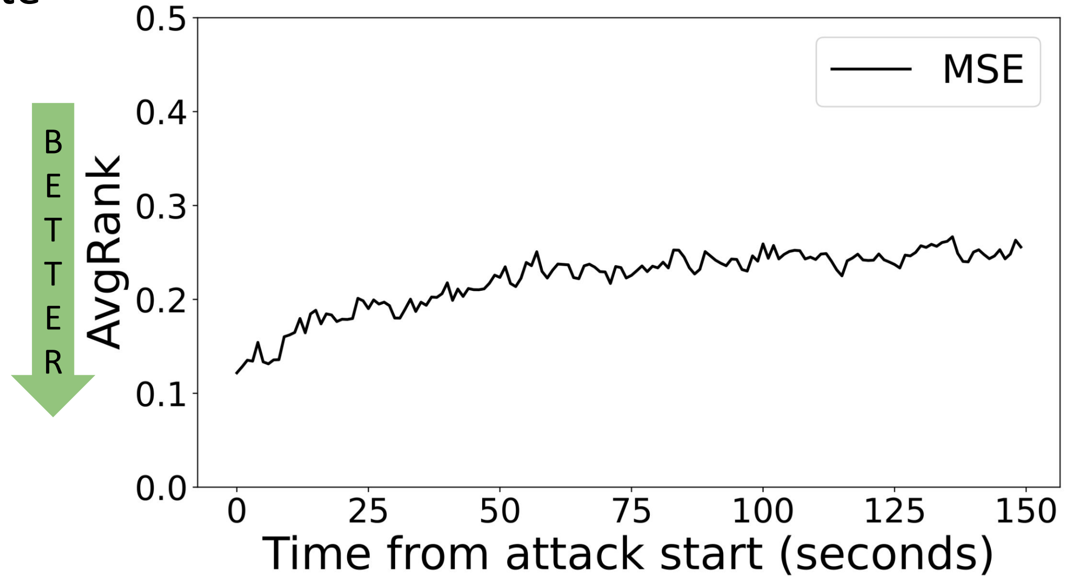
Better attributions via ensembles?

- Without knowing what attack or timing is used, can one strategy be best?
- We propose an ensemble attribution method:
  - Take the average of attribution scores (MSE, SM, LEMNA) for each feature



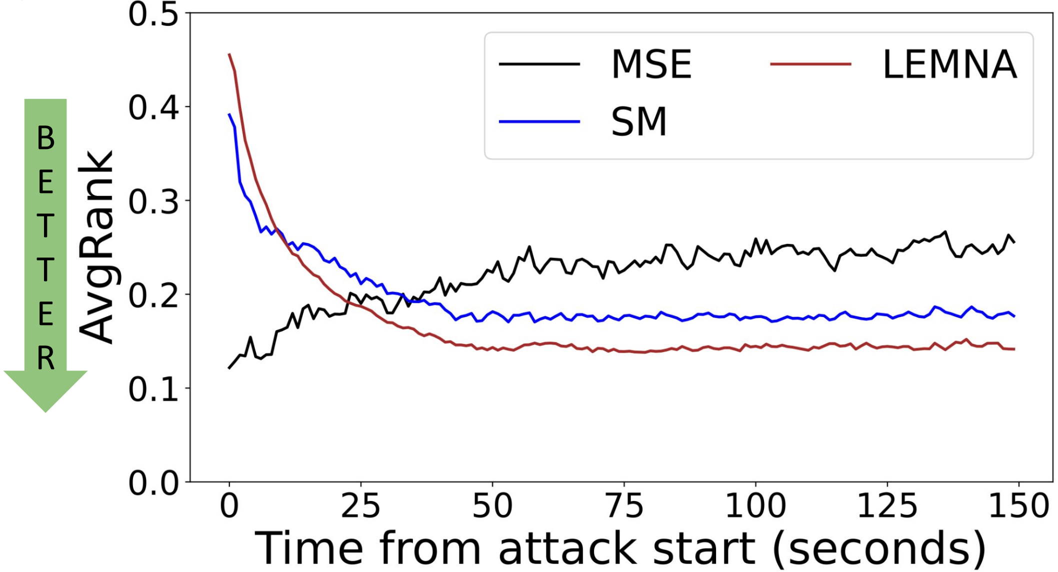
Better attributions via ensembles?

- MSE performs worst when late



Better attributions via ensembles?

- MSE performs worst when late
- SM and LEMNA perform worst when early
  - Time-series history needed for attribution



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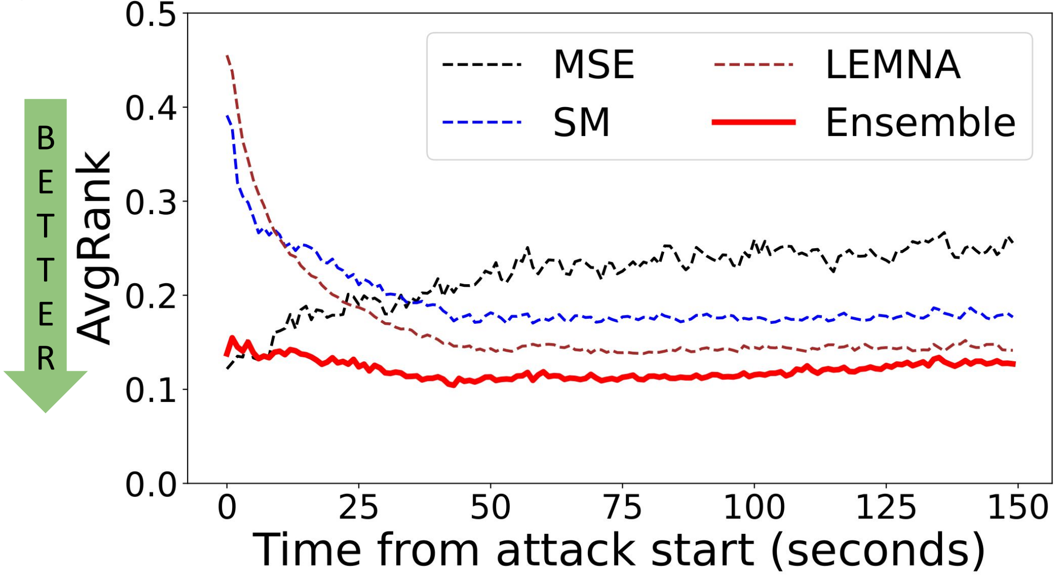

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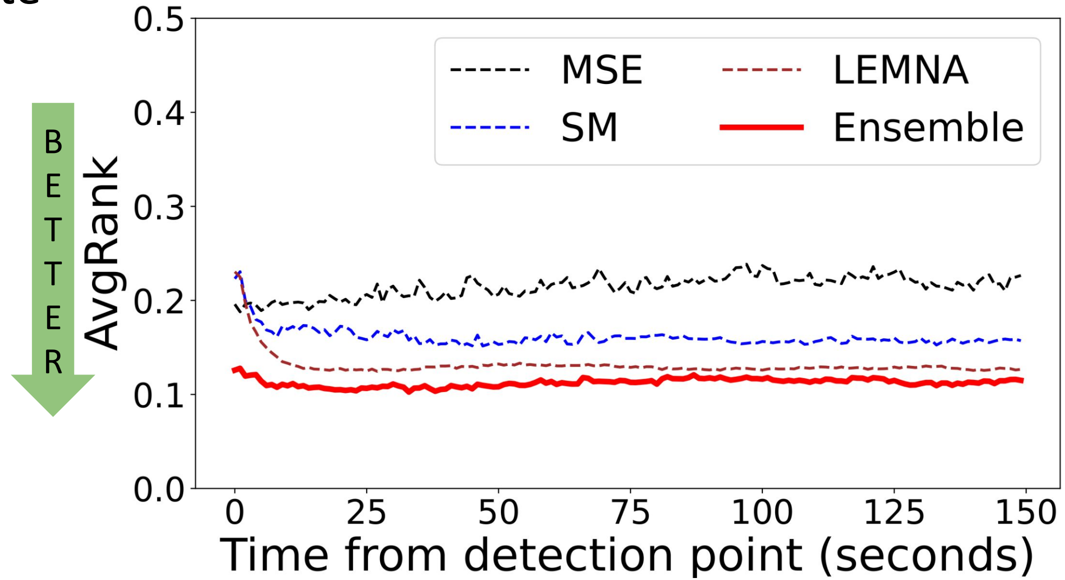
- **Ensembles outperform all individual methods**
  - At practical timings too!



Attribution methods for ICS anomaly detection

Prior performance is worse than reported ☹

Attribution methods for ICS anomaly detection

Prior performance is worse than reported

ICS anomaly attribution is complex

Timing and feature types affect which methods work best

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An ensemble approach balances tradeoffs

Though imperfect, attributions can help ICS operators

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Though imperfect, attributions can help ICS operators

Clement Fung, Eric Zeng, Lujo Bauer
Carnegie Mellon University
clementf@cs.cmu.edu

Artifact Evaluated
NDSS SYMPOSIUM
Available
Functional

Synthetic attacks: https://doi.org/10.1184/R1/23805552
Modified simulator: https://github.com/pwwl/tep-attack-simulator
Attribution code: https://github.com/pwwl/ics-anomaly-attribution

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