Using machine learning in optical CD metrology

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25 YEARS

NOVA® PROCESS INSIGHT

Outline

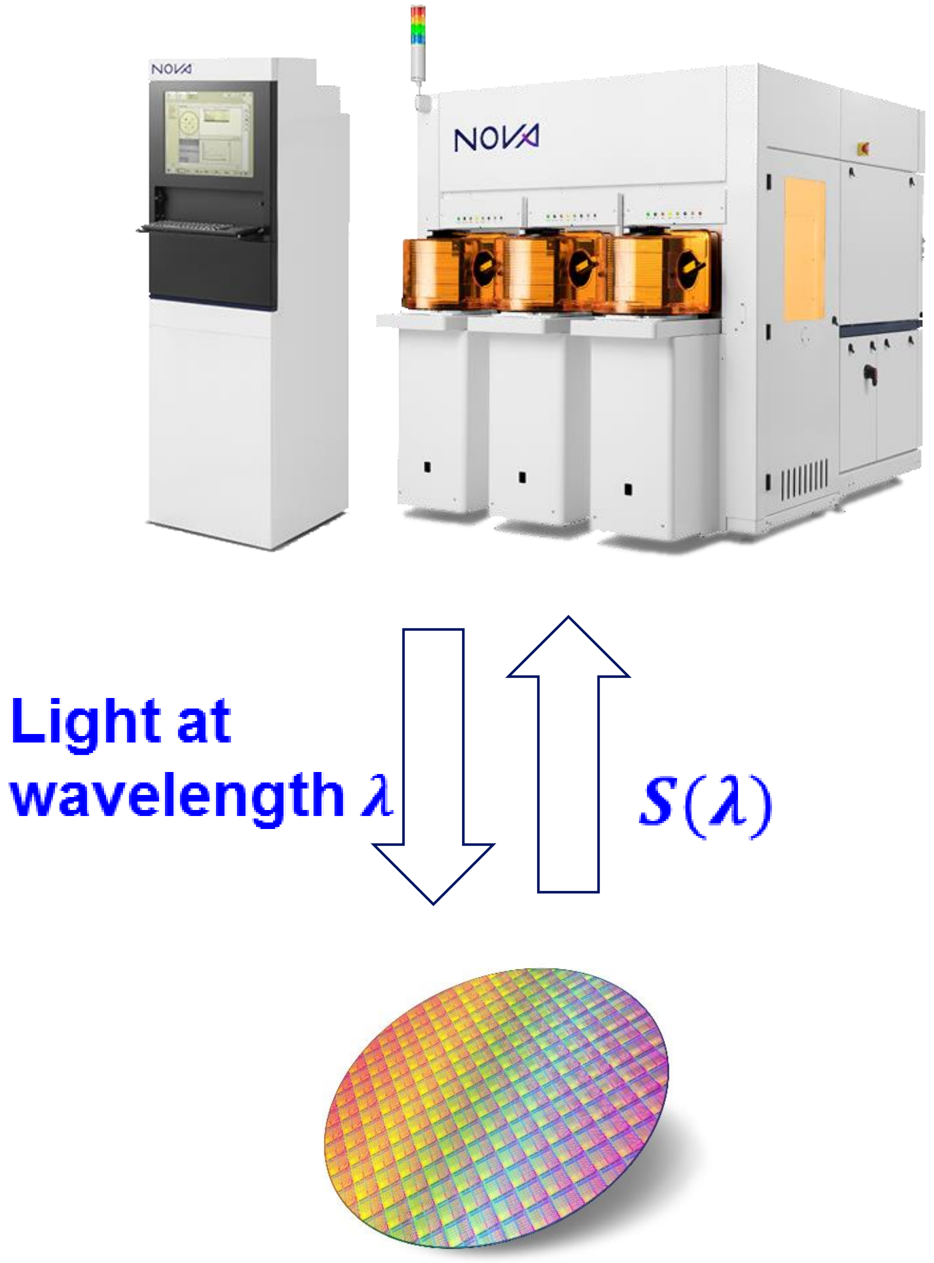
- Optical CD metrology and why machine learning in OCD.
- Nova's machine learning and big data solution.
- Performance:
  1. Basic accuracy performance.
  2. Budgeting accuracy and performance: spectral sensitivity, algorithm capacity, and data size and type.
- Summary

Why machine learning in OCD?

OCD:

Integrated metrology

- Less illumination and polarization modes.



Stand-alone or SA

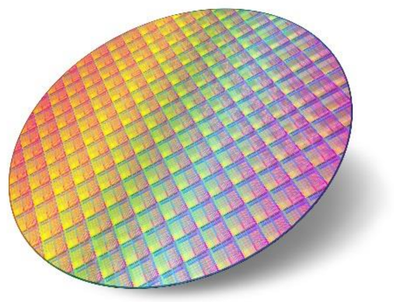
- Many illumination directions (azimuths and inclinations).
- Multiple polarization modes (full polarimetry).

Why machine learning in OCD?

OCD modeling:

Light at wavelength λ

$S(\lambda)$



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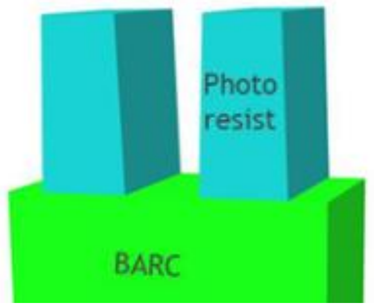
3D model:



Maxwell physical modeling:

$$\nabla \cdot \mathbf{E} = \frac{\rho_v}{\varepsilon} \quad \text{(Gauss' Law)}$$

$$\nabla \cdot \mathbf{H} = 0 \quad \text{(Gauss' Law for Magnetism)}$$

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \quad \text{(Faraday's Law)}$$

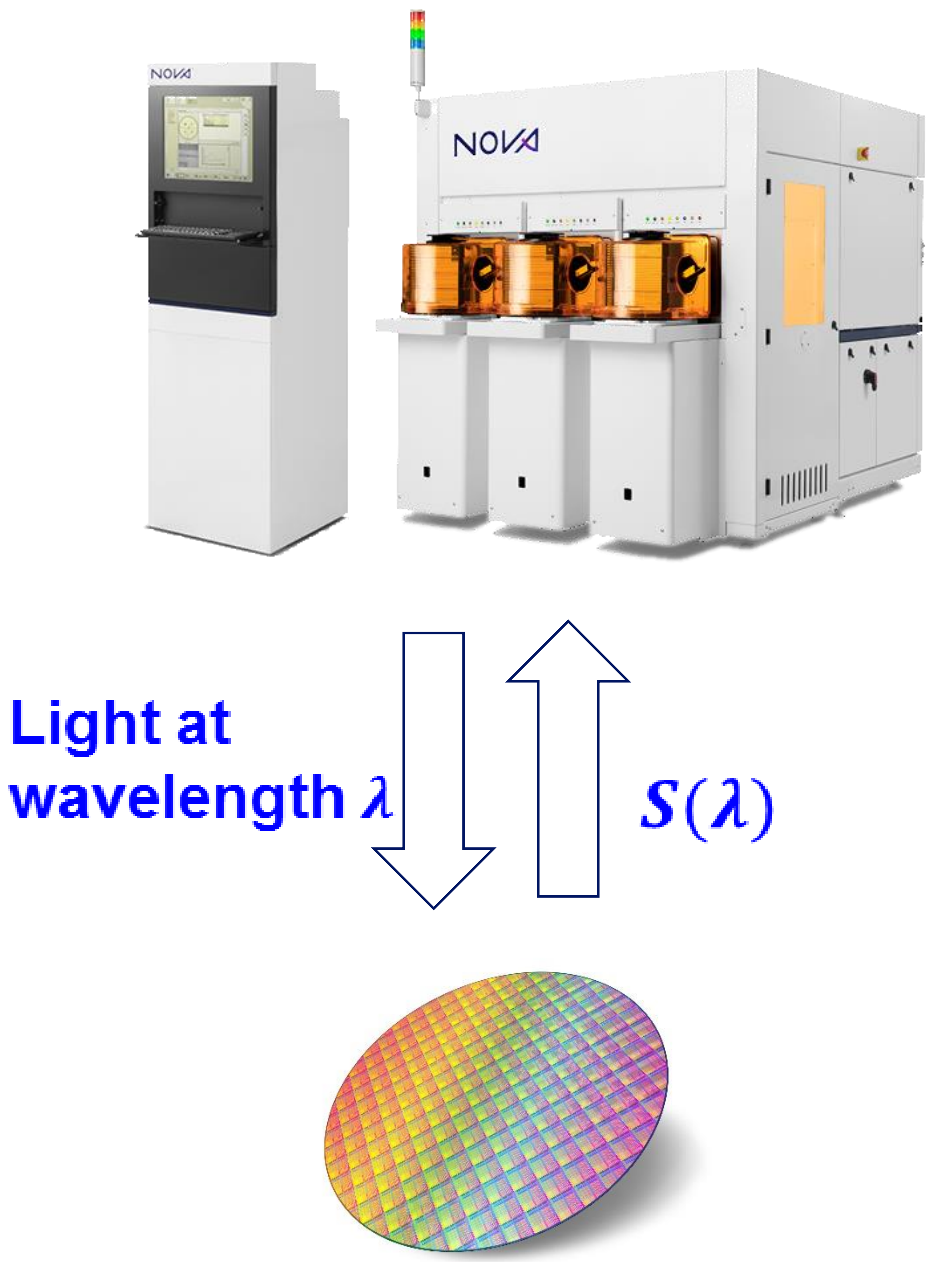
$$\nabla \times \mathbf{H} = \mathbf{J} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \quad \text{(Ampere's Law)}$$

HVM worthy model:

$S(\lambda) \rightarrow$ Model $\rightarrow CD$

Why machine learning in OCD?

OCD modeling with machine learning:



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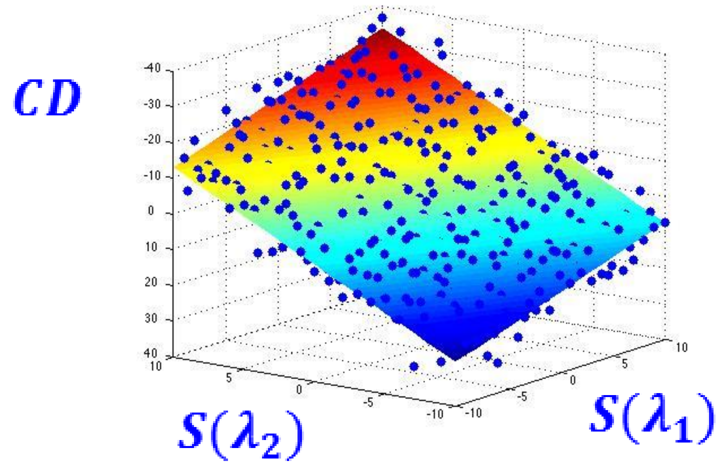
Data:

ID	$S(\lambda)$	CD
1	[0.54,0.43,...,0.32]	17.3A
2	[0.67,0.52,...,0.14]	16.3A
...	...	...
100	[0.33,0.15,...,0.28]	18.2A

Data science / modeling:



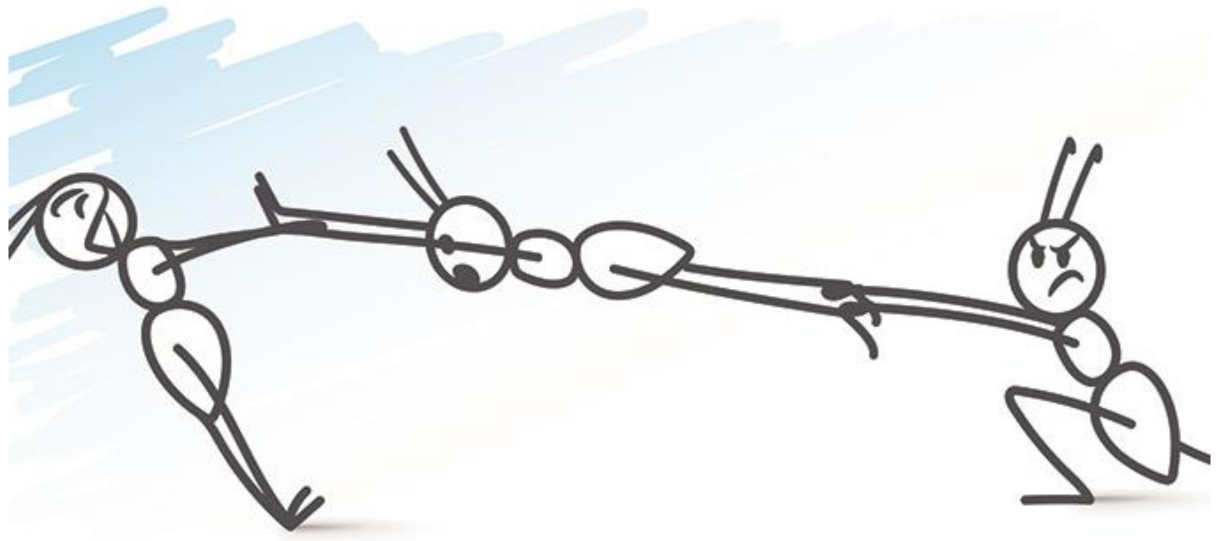
HVM worthy model:

$S(\lambda) \rightarrow$ Model $\rightarrow CD$

So … why machine learning in OCD?

Productive:

- FMP ~ sub-Angstrom
- TPT ~ measure every wafer and every die.



Accurate & robust:

- Spec ~ a few Angstroms
- Process splits and variations.

⇩

Integrated metrology tools

- *Measures every wafer.*
- *Less information in spectrum.*
- *Requires expert work.*

Automatic:

- Recipe creation time << operator shift.
- Reproducible, predictable.

⇩

SA optical or high-resolution non-optical:

- *Much information, highly accurate.*
- *Typically measures few wafers per lot.*
- *Requires expert work.*

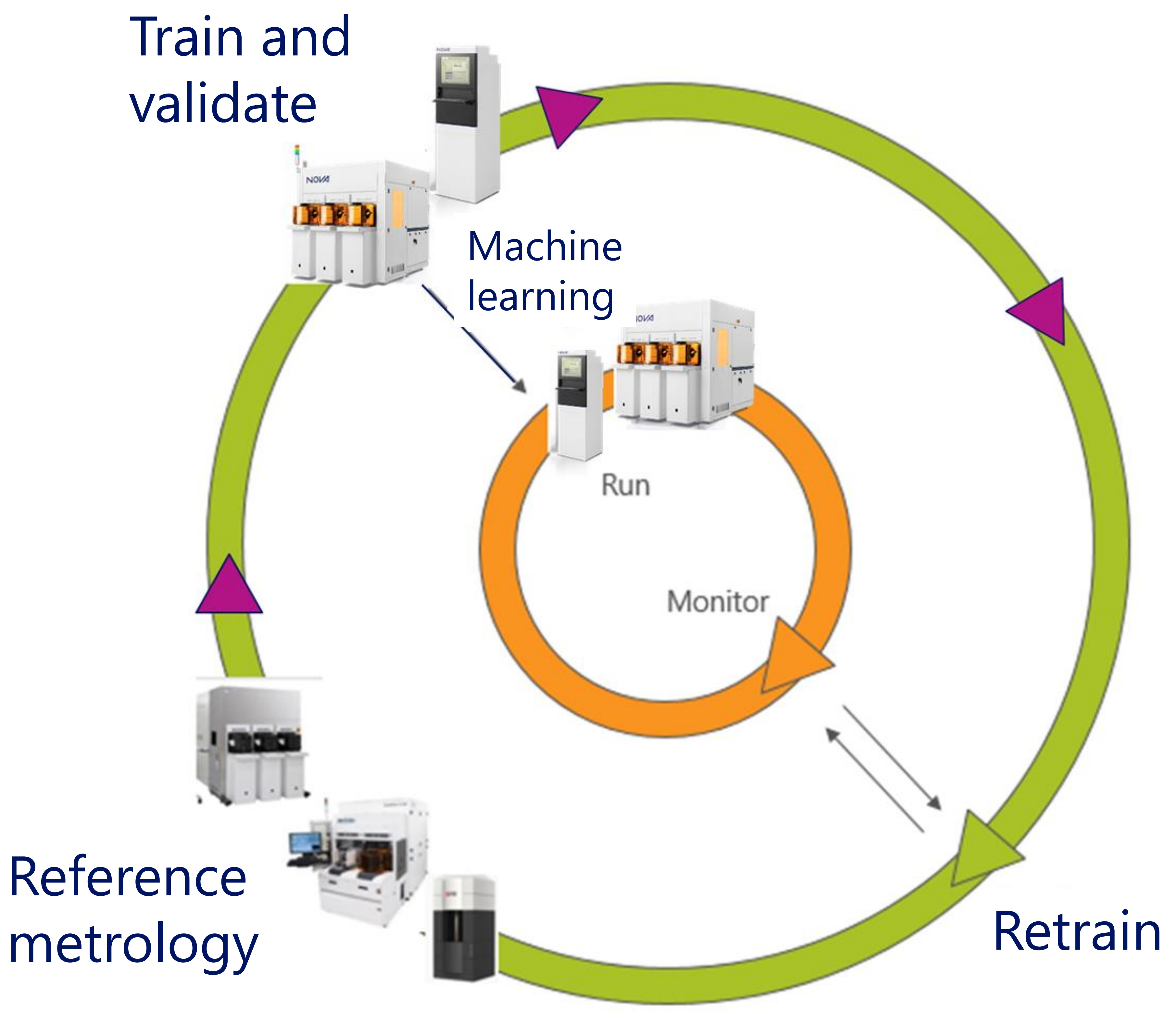
FMP = Fleet Measurement Precision
TPT = Throughput

A machine learning big data system solves this tension.

- Metrology solutions **built**, **tested**, **monitored** and **modified** **automatically**

⇩

Accuracy, speed, productivity, and predictability



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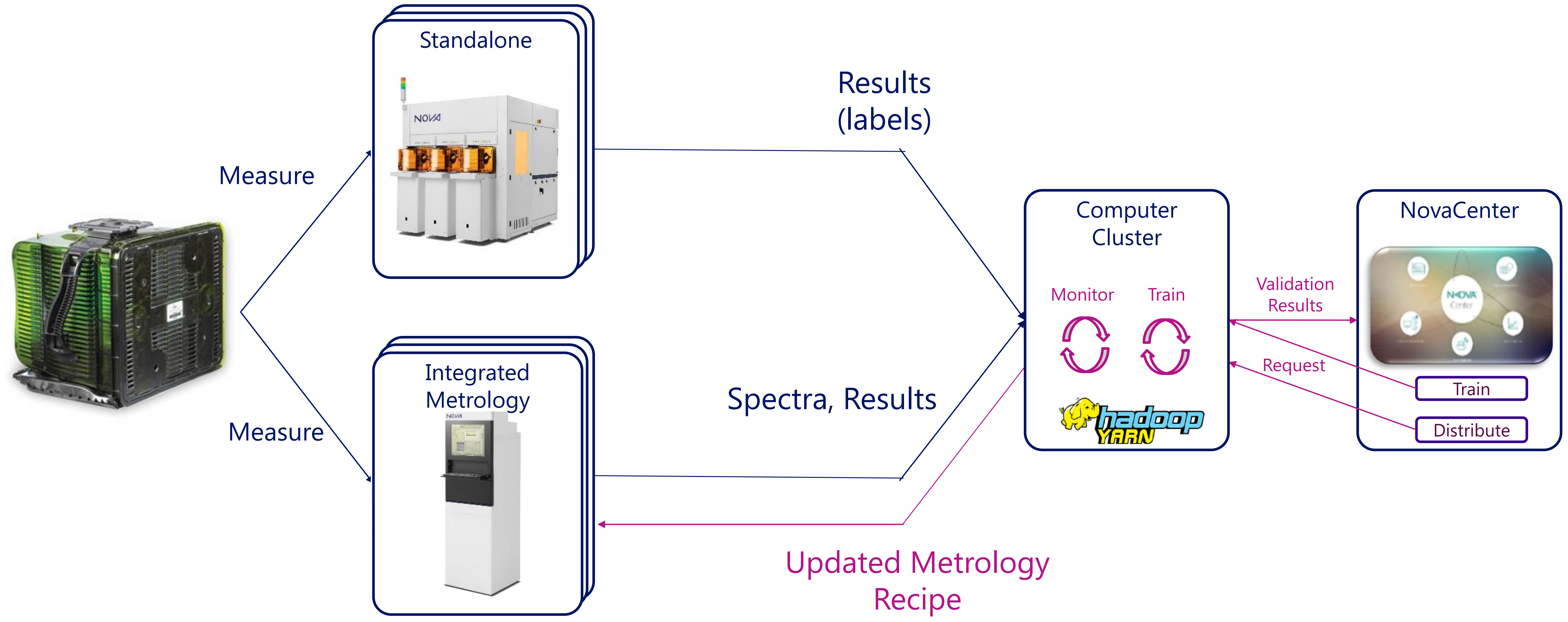
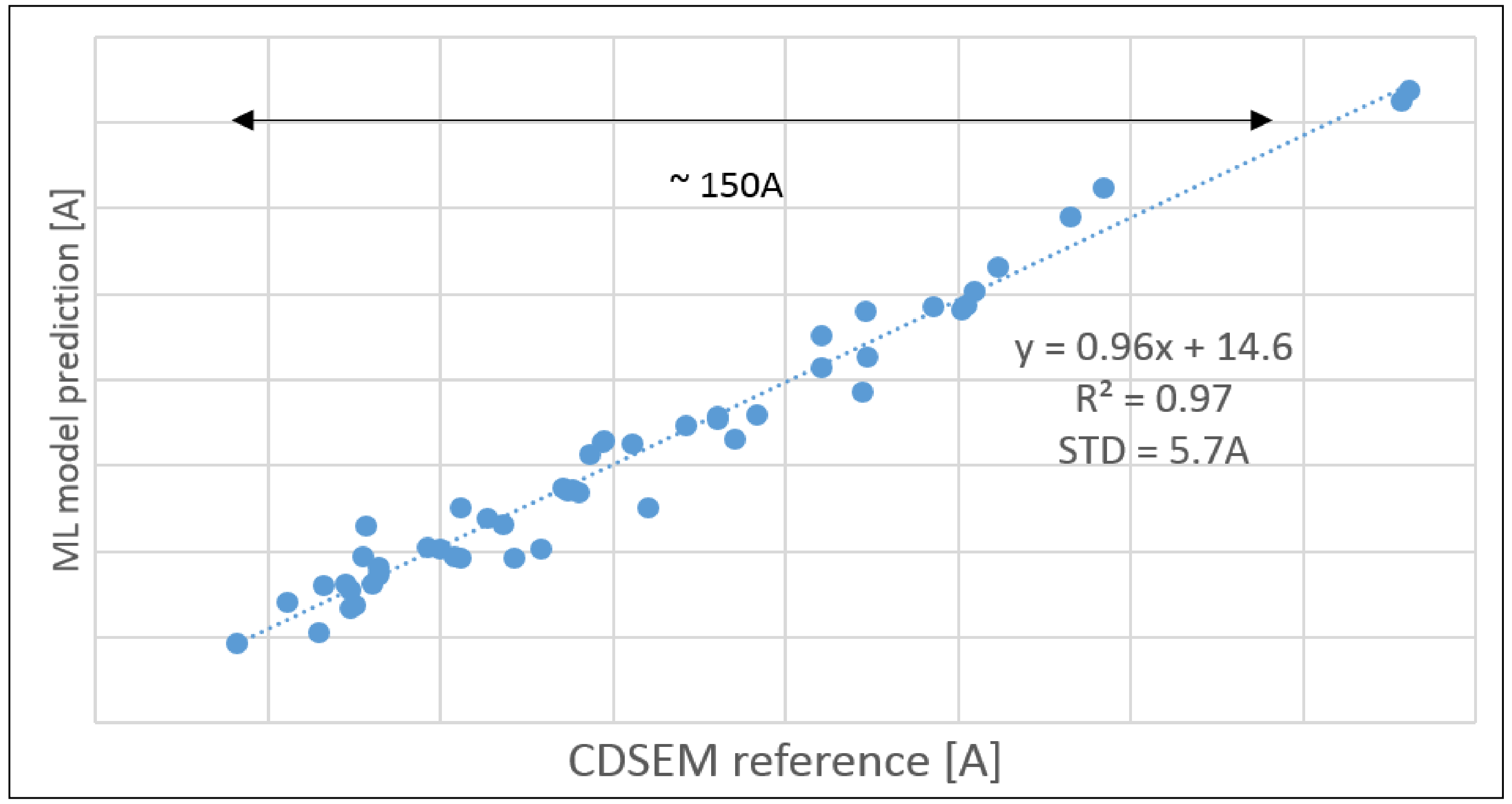
The Standalone (SA) to Integrated (IM) Data Flow

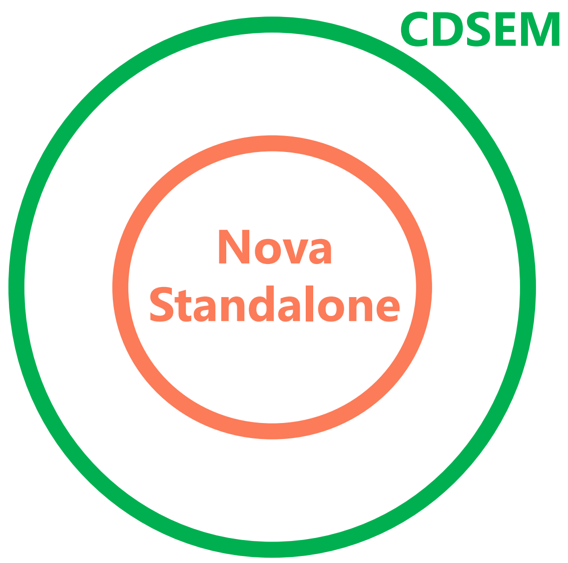


Accuracy performance of machine learning



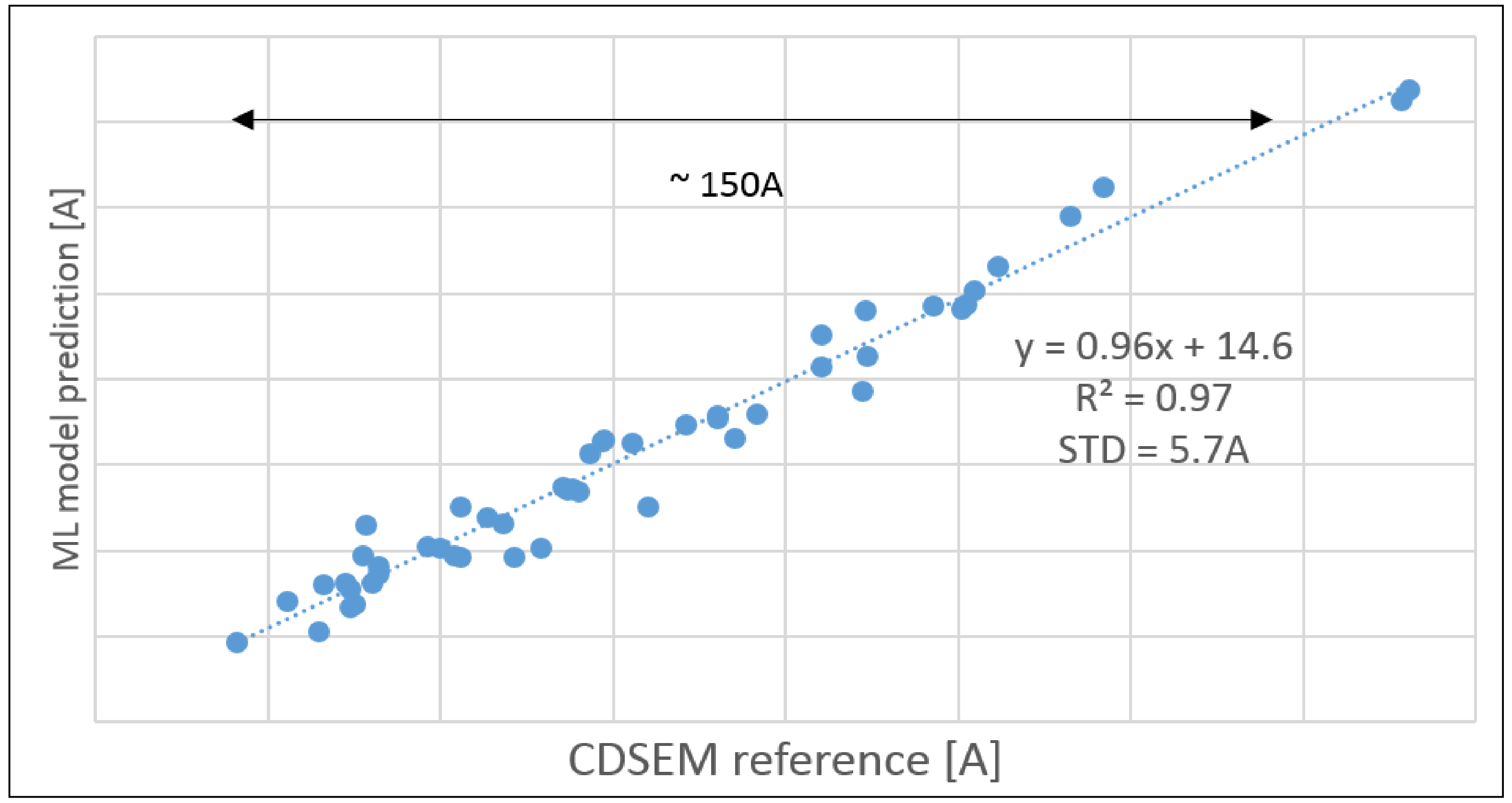
<u>Example A:</u>

Reference: CDSEM.
Inline tool: Nova Standalone.
Accuracy: $\mathbf{1\sigma \sim 5.7A}$
Train set: ~50dies DOE wafers.



Accuracy performance of machine learning

(also see SPIE 10585-32, 1014504, 97781W, JMM.15.4.044004)



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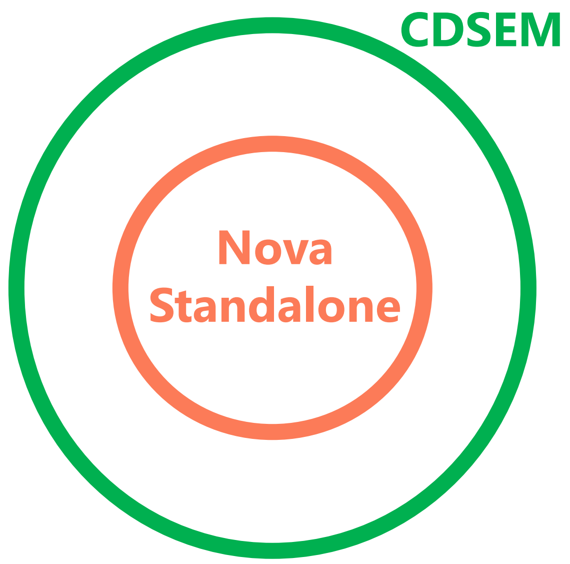
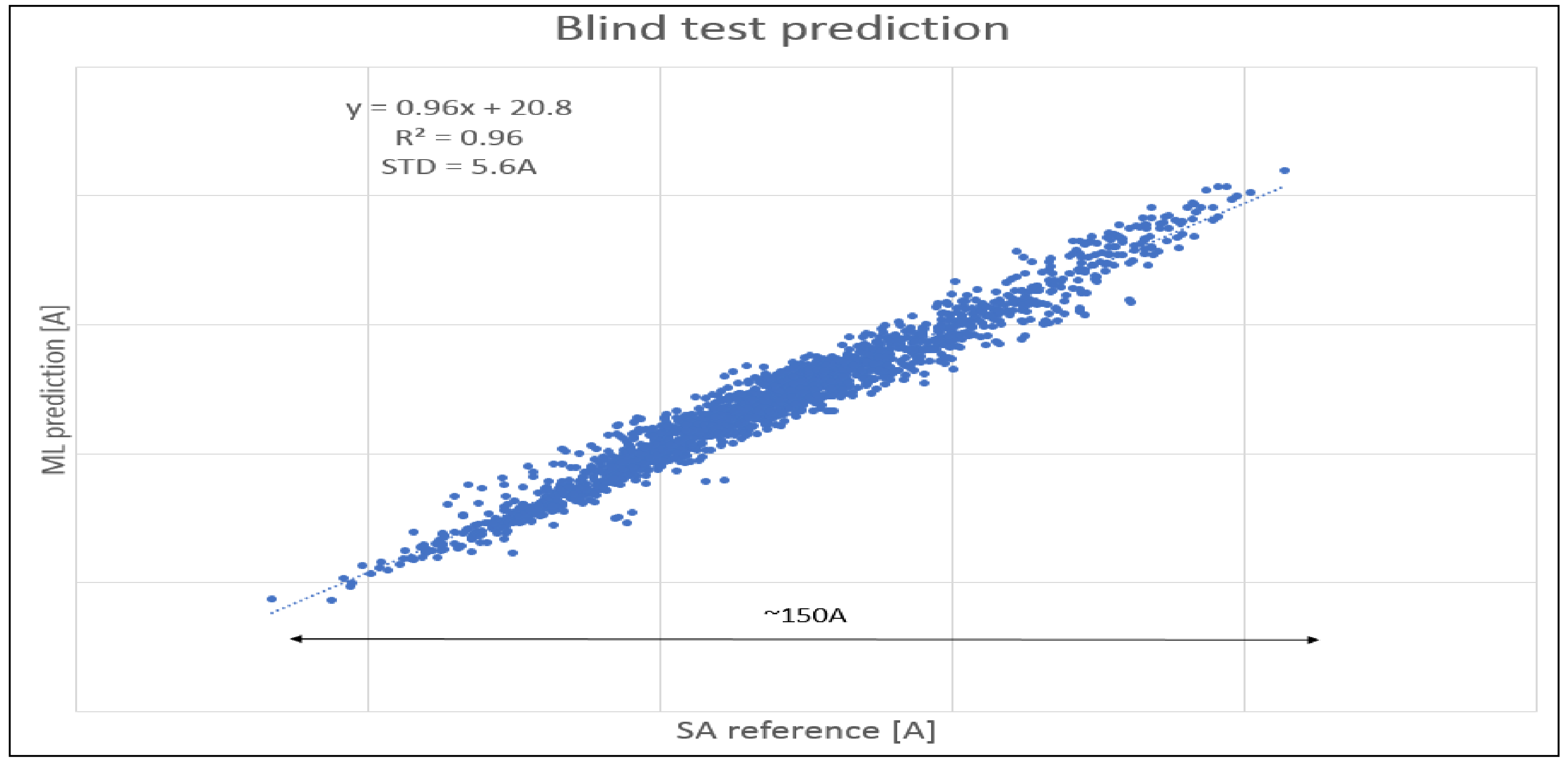
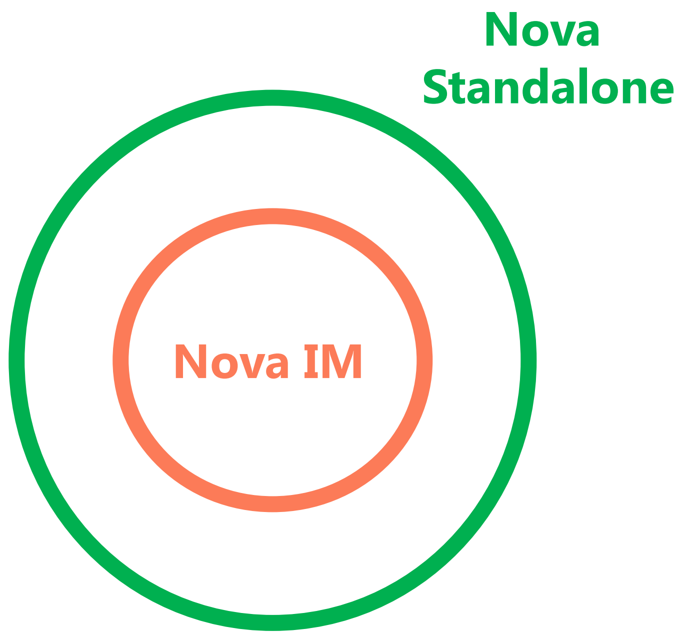




<u>Example B:</u>

Reference: Nova SA physical model.
Inline tool: Nova IM.
Accuracy: $1\sigma \sim 5.6A$
Train set: 6000dies from POR sampling.



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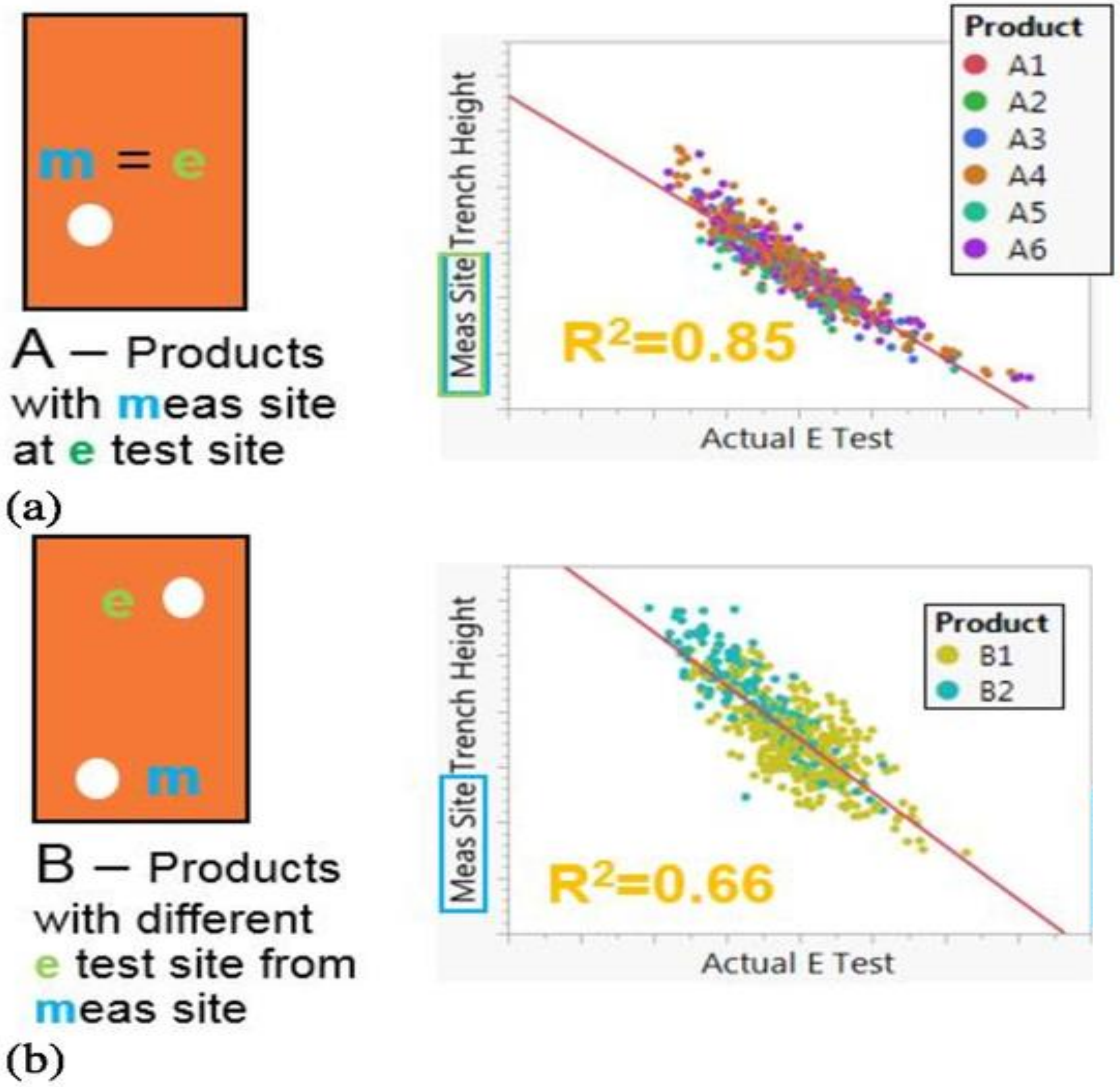
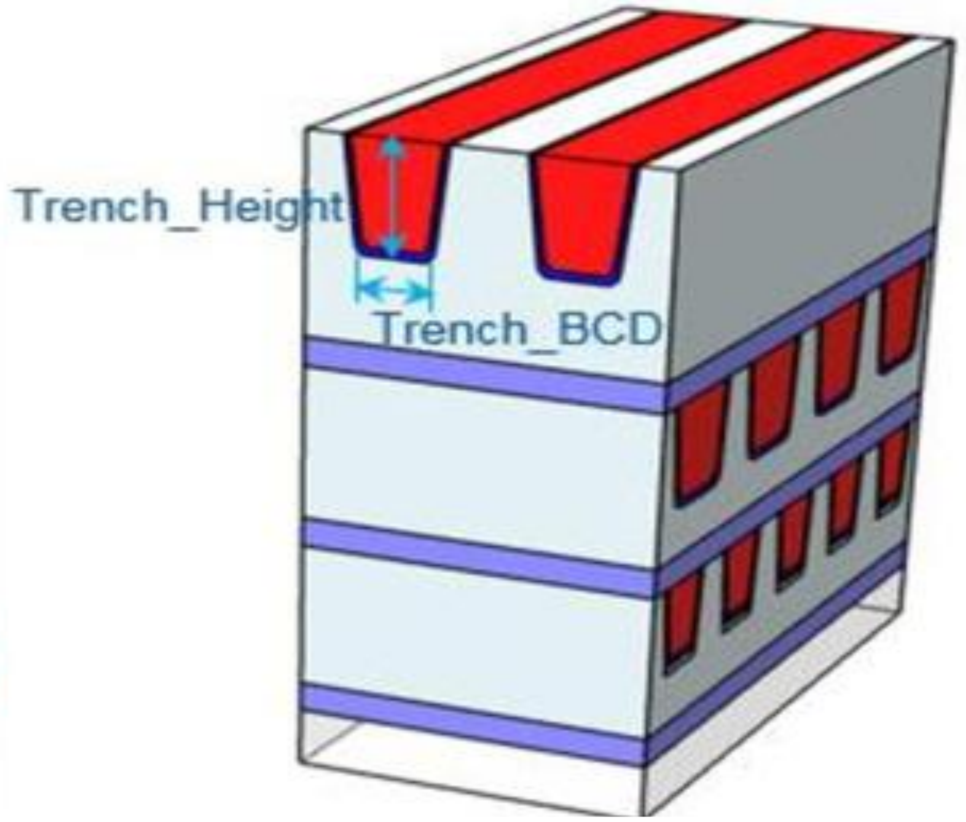
Accuracy performance of machine learning-from SPIE Advanced Lithography P. Timoney *et al.* 10585-32 (see also 1014504, 97781W, JMM.15.4.044004)





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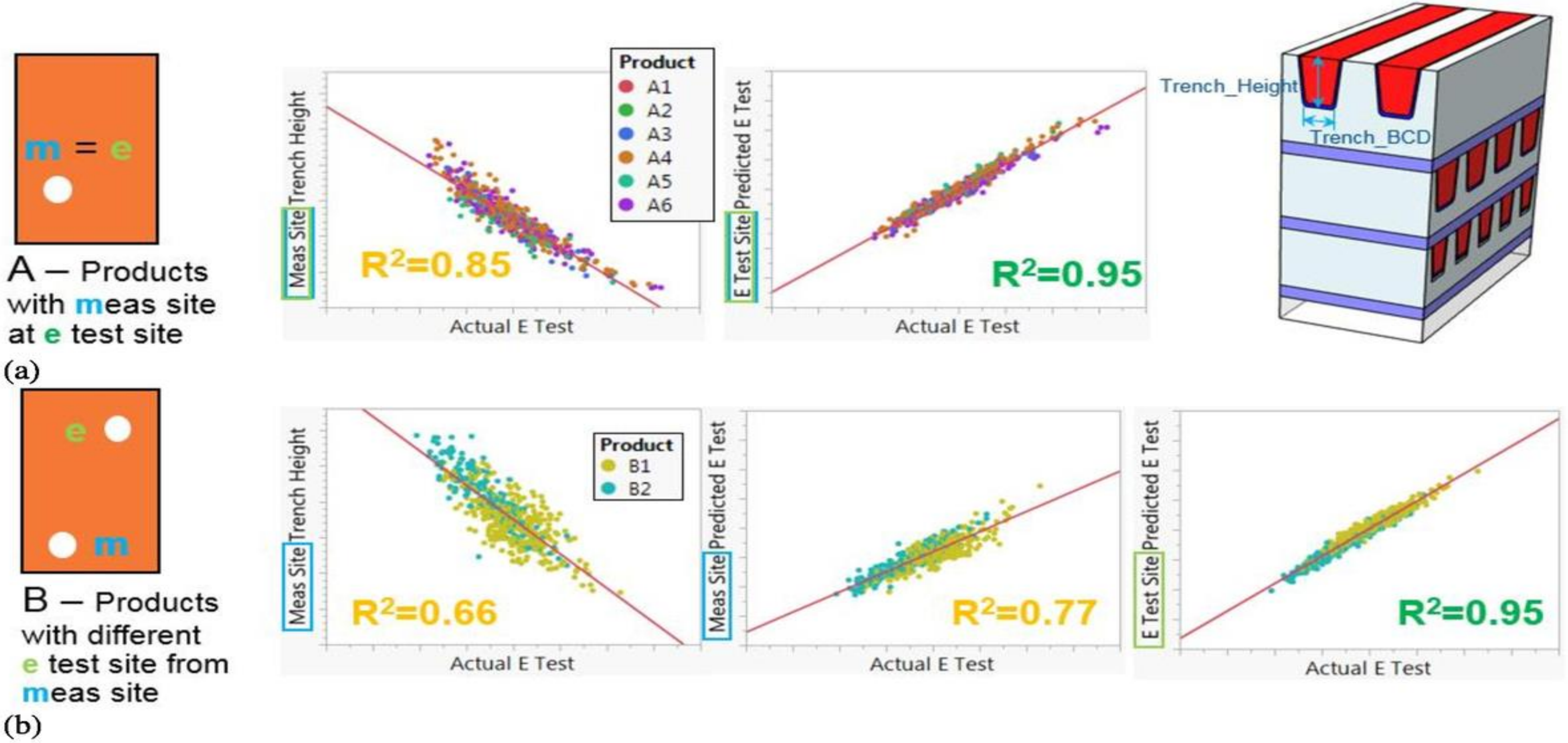

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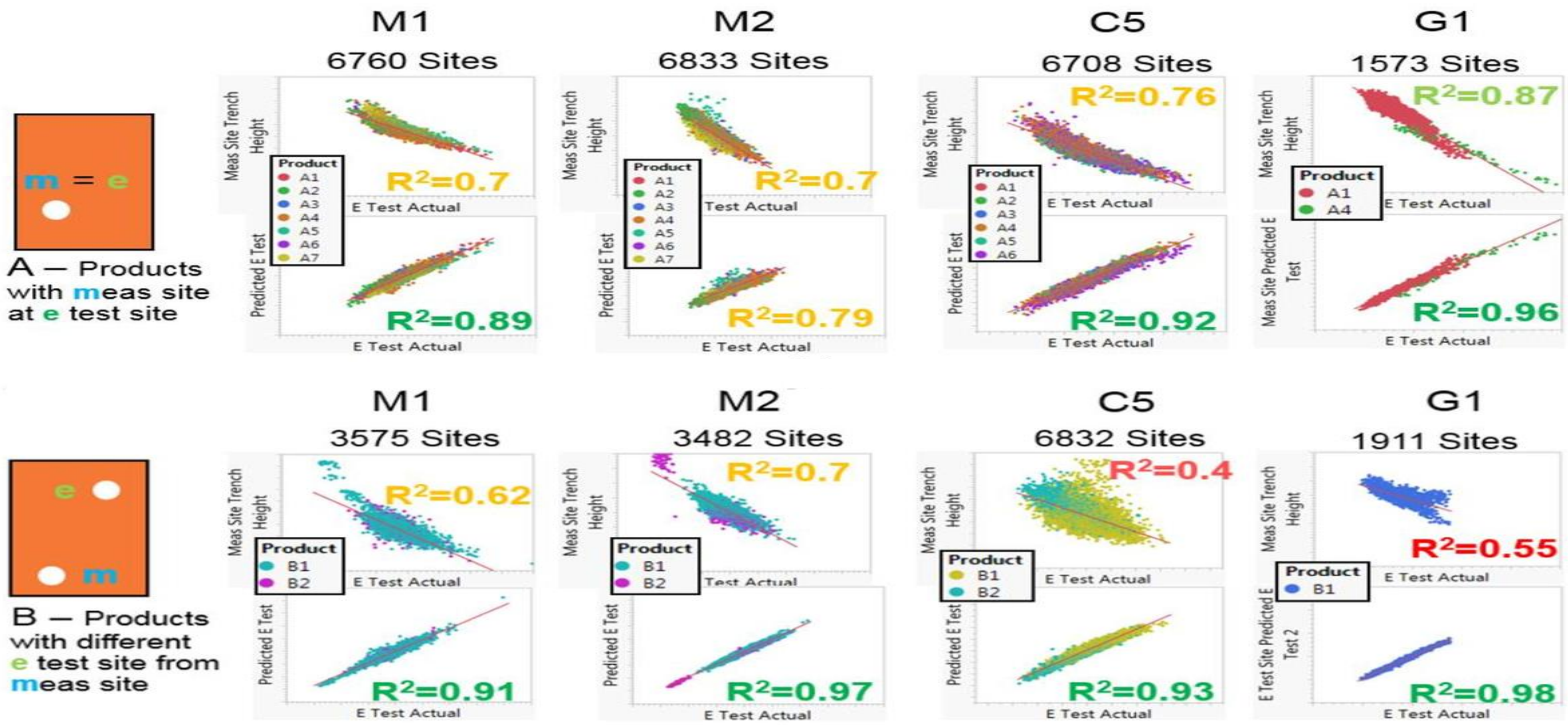

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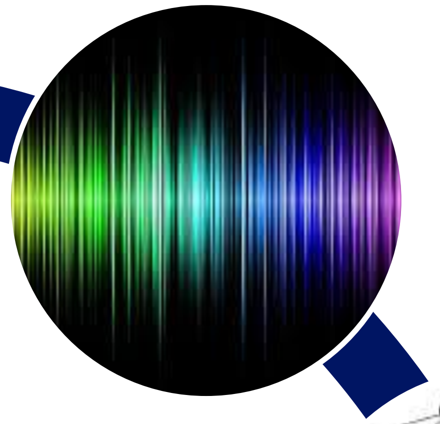
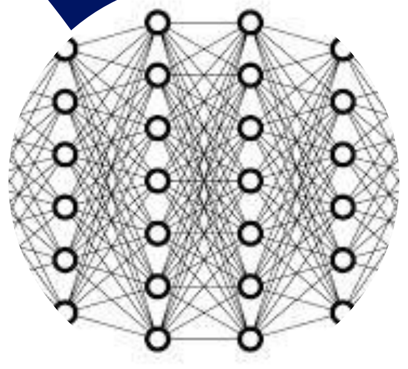
Error budgeting accuracy and robustness of machine learning

Robustness and Accuracy



Spectral sensitivity



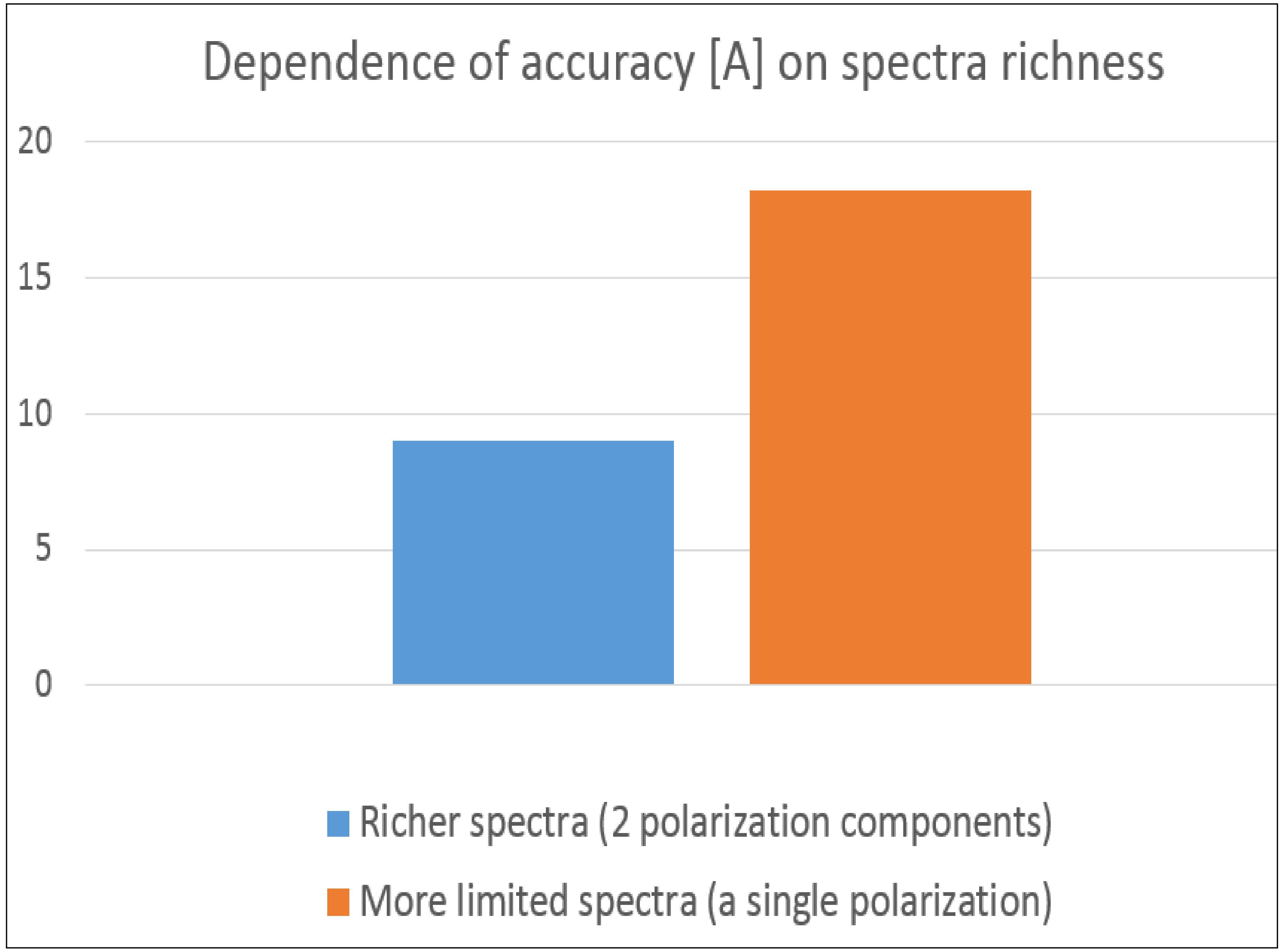
Algorithm capacity (simple models vs. DNN)

Data size and type

Reference error

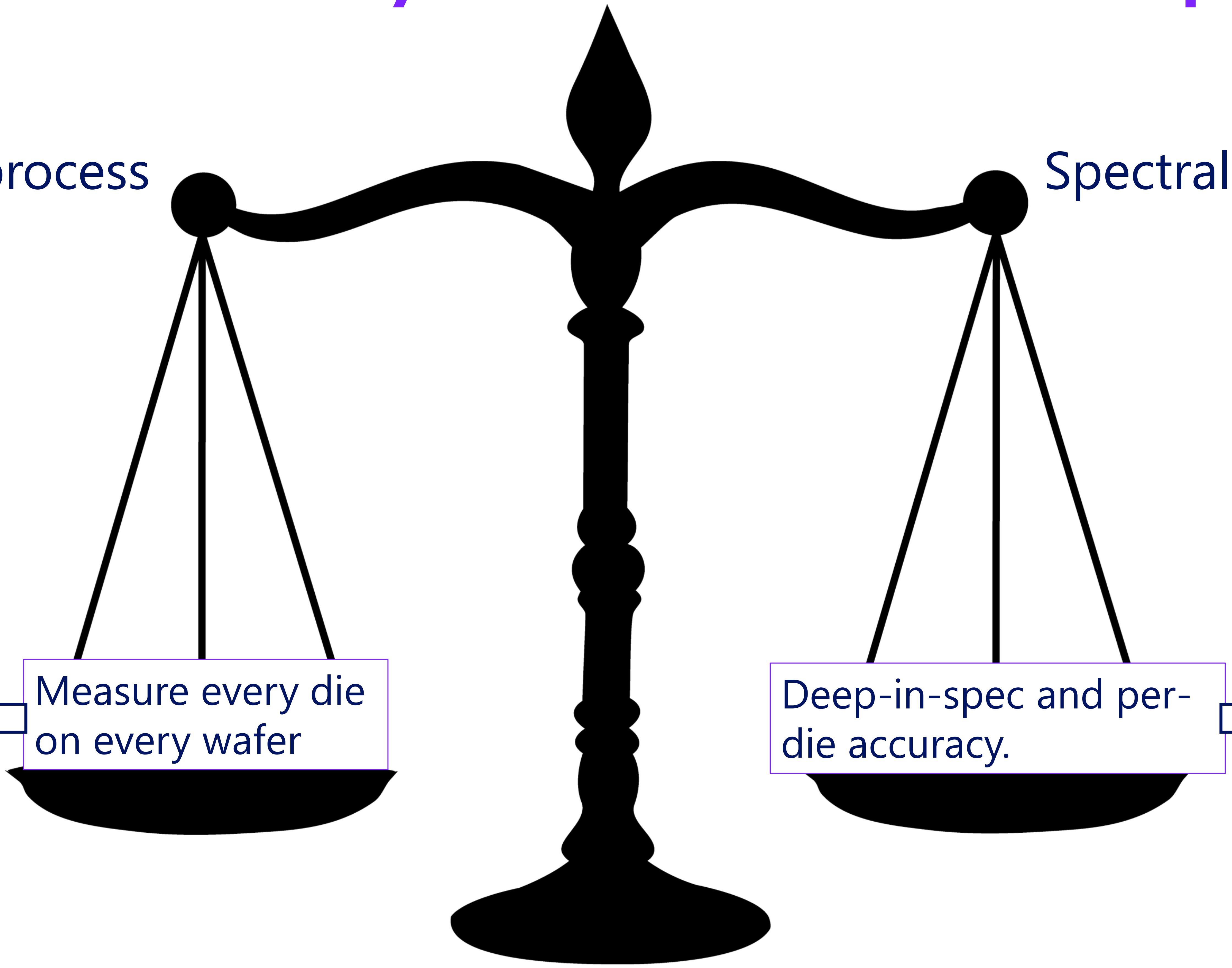
Today

Accuracy: spectral sensitivity

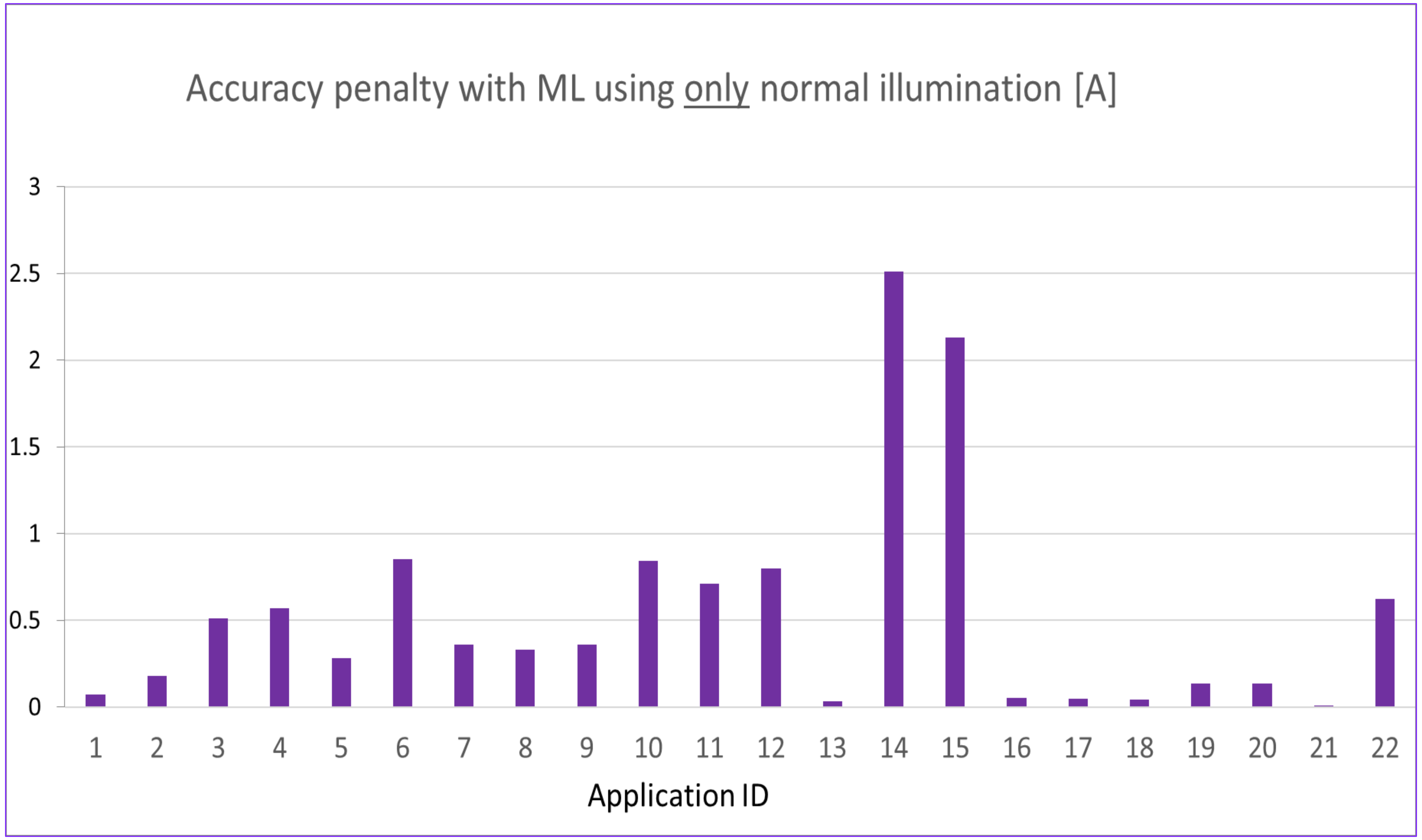


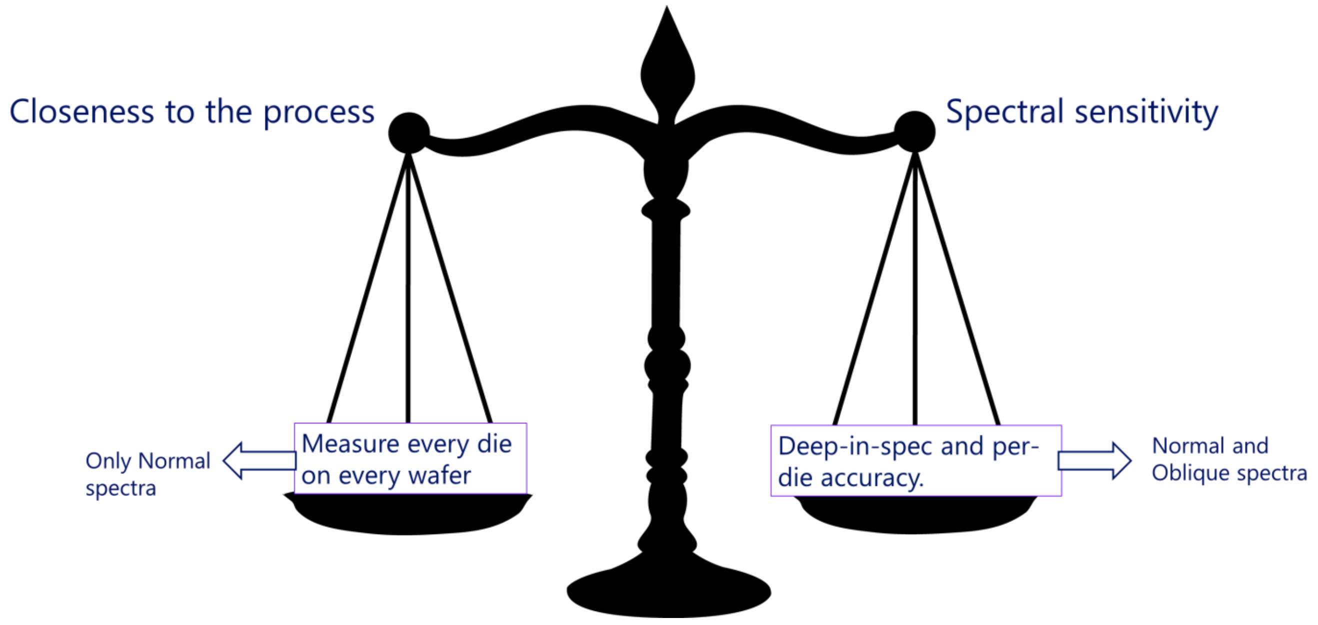
- Transfer of a physical model solution on Nova SA to a Nova IM.
- *Clearly ML is not `black magic':*
  - More spectral information improves accuracy by 2x: especially Normal channel vs Normal channel & Oblique.
  - Have other examples where we see how spectral information reflects the *underlying physics.*

Machine learning helps balance spectral sensitivity vs. closeness to the process



Balancing spectral sensitivity and closeness to the process

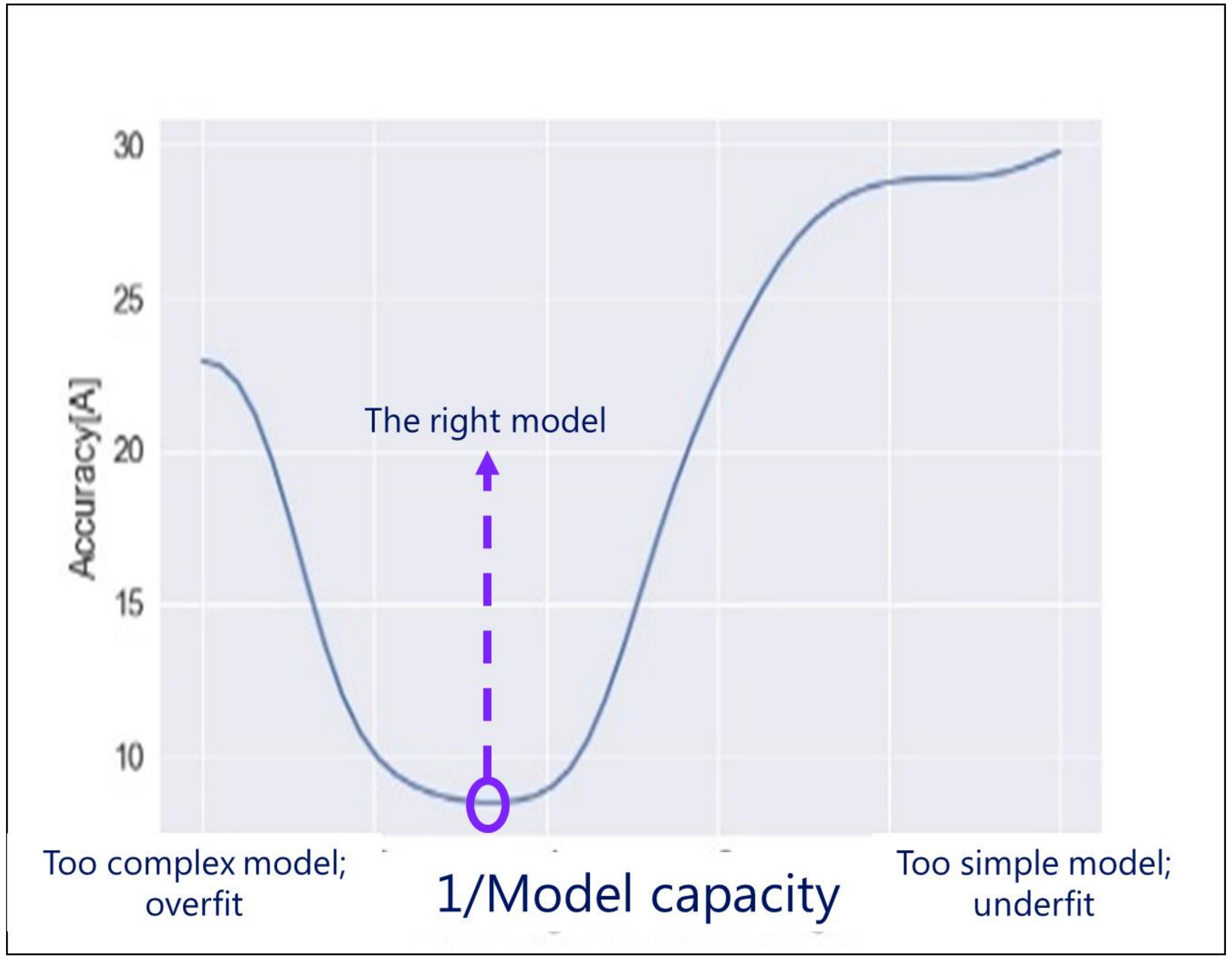




- Using machine learning we can balance spectral sensitivity and closeness-to-the-process.
- Customers are able to balance the two as per their specific needs.

Accuracy: model capacity

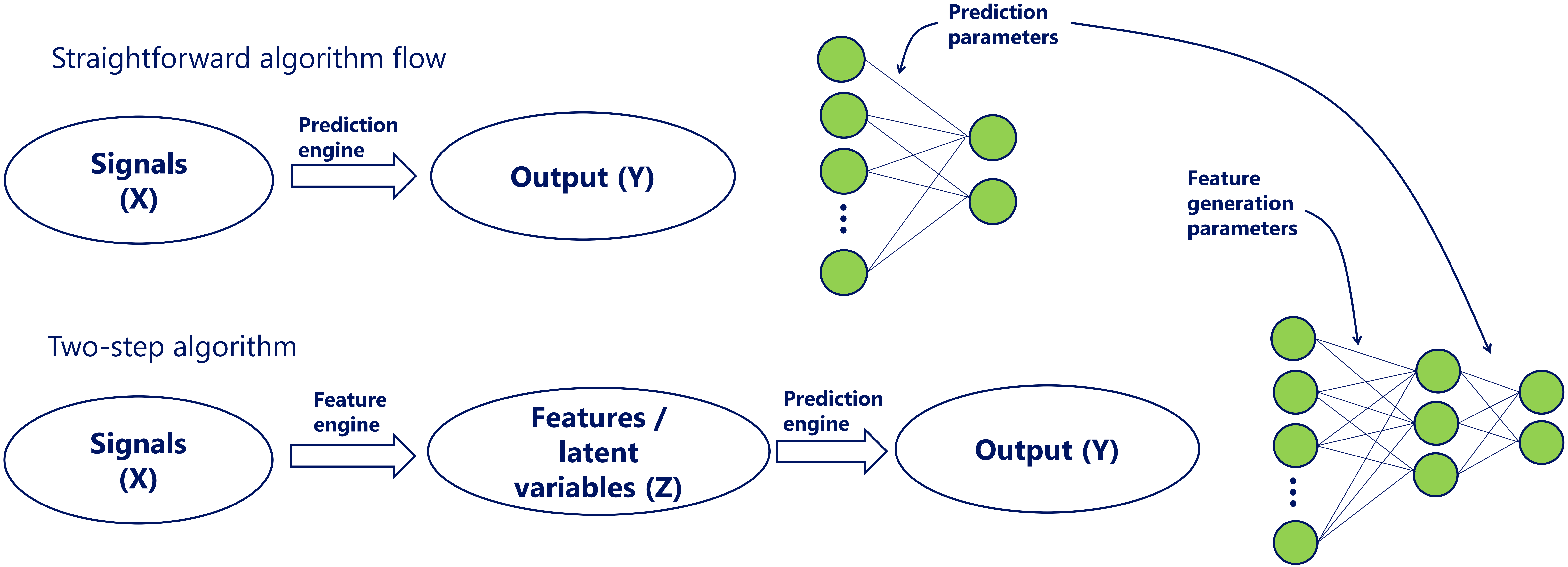
<u>Example A: changing model capacity with a single hyper-parameter</u>



- Transfer of a physical model solution on Nova SA to a Nova IM.
- Here, model capacity was modified by regularization on a fixed data size.
- Simplicity of model setup makes it easy to *<u>automate.</u>*

Accuracy: model capacity

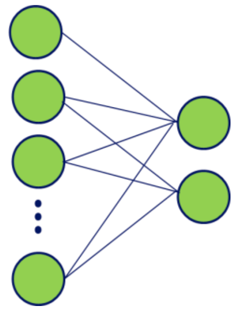
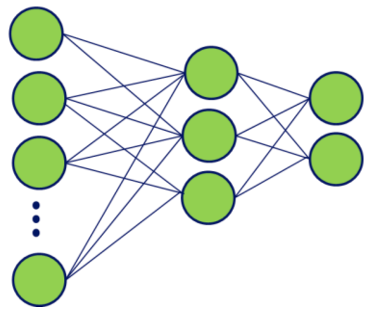
Example B: changing model capacity by changing the number of hyper-parameters



Accuracy: model capacity

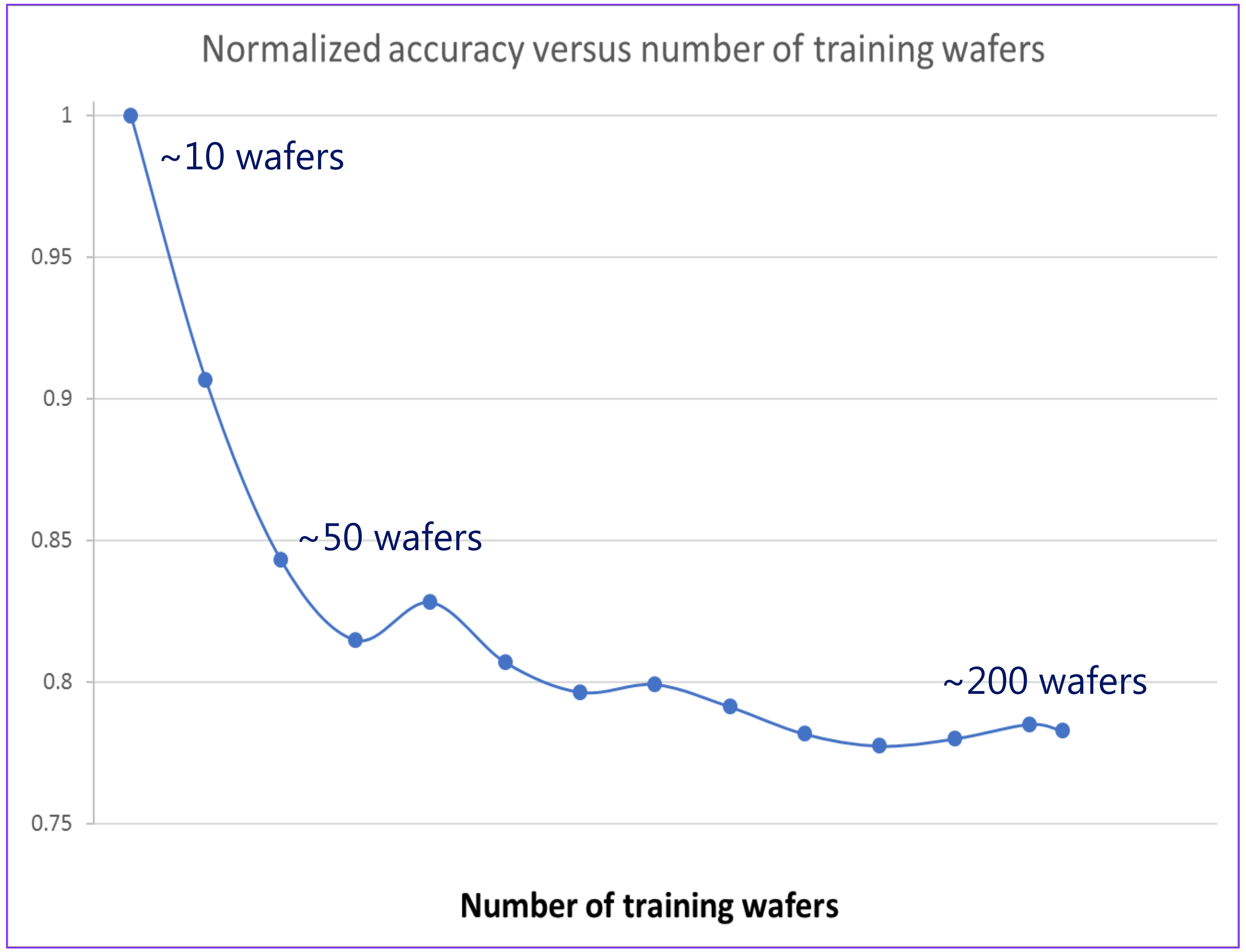
Example B: changing model capacity by changing
the number of hyper-parameters

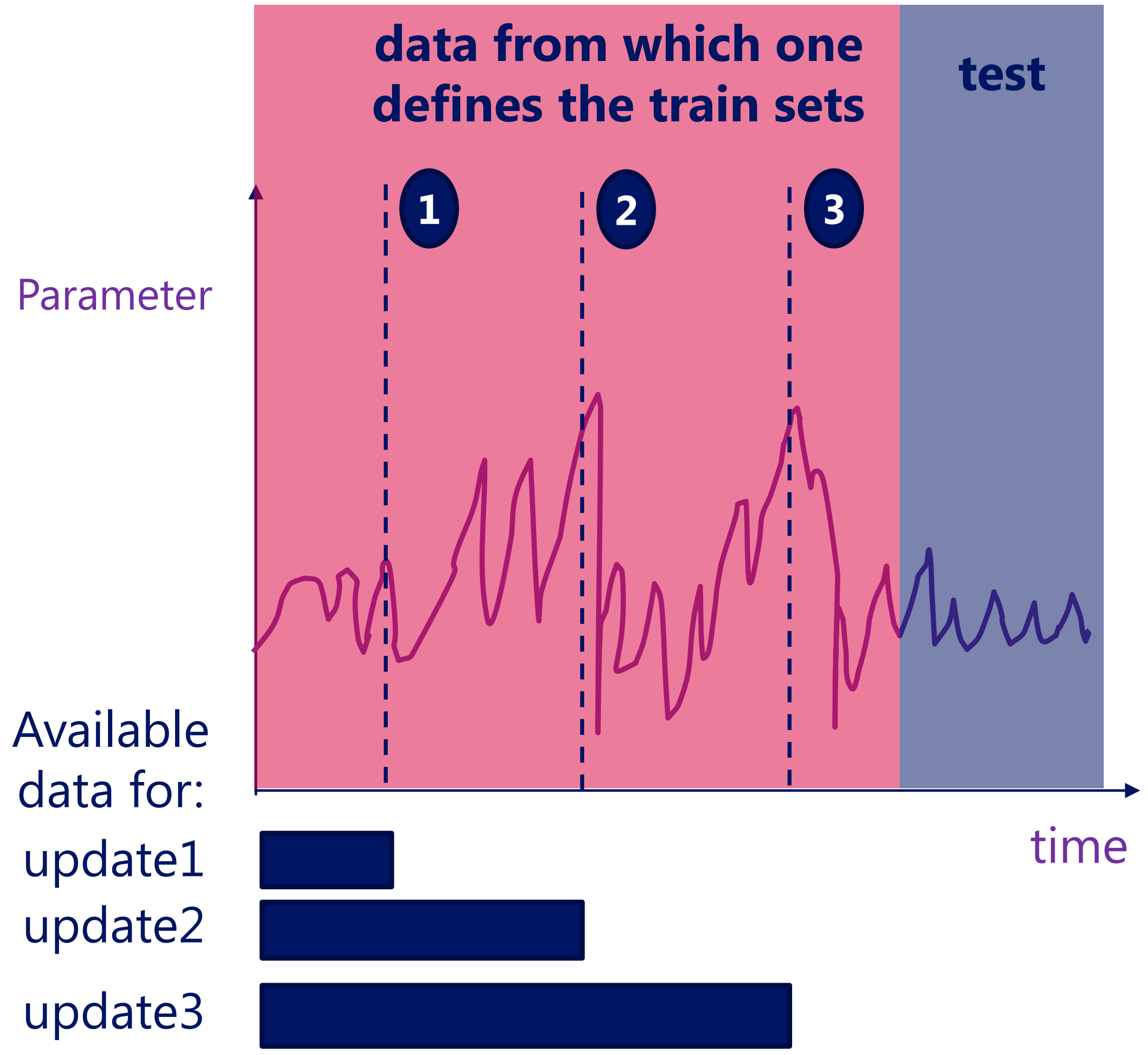
<u>CMP thickness case, from Standalone to Nova IM (train and test sets each comprised of production data of ~75 wafers)</u>

Attribute		
STD in Angstrom	23	16
R2	0.96	0.98
Slope	0.92	0.97

Accuracy: data size

Example below: transfer of a physical model solution on SA to Nova IM.

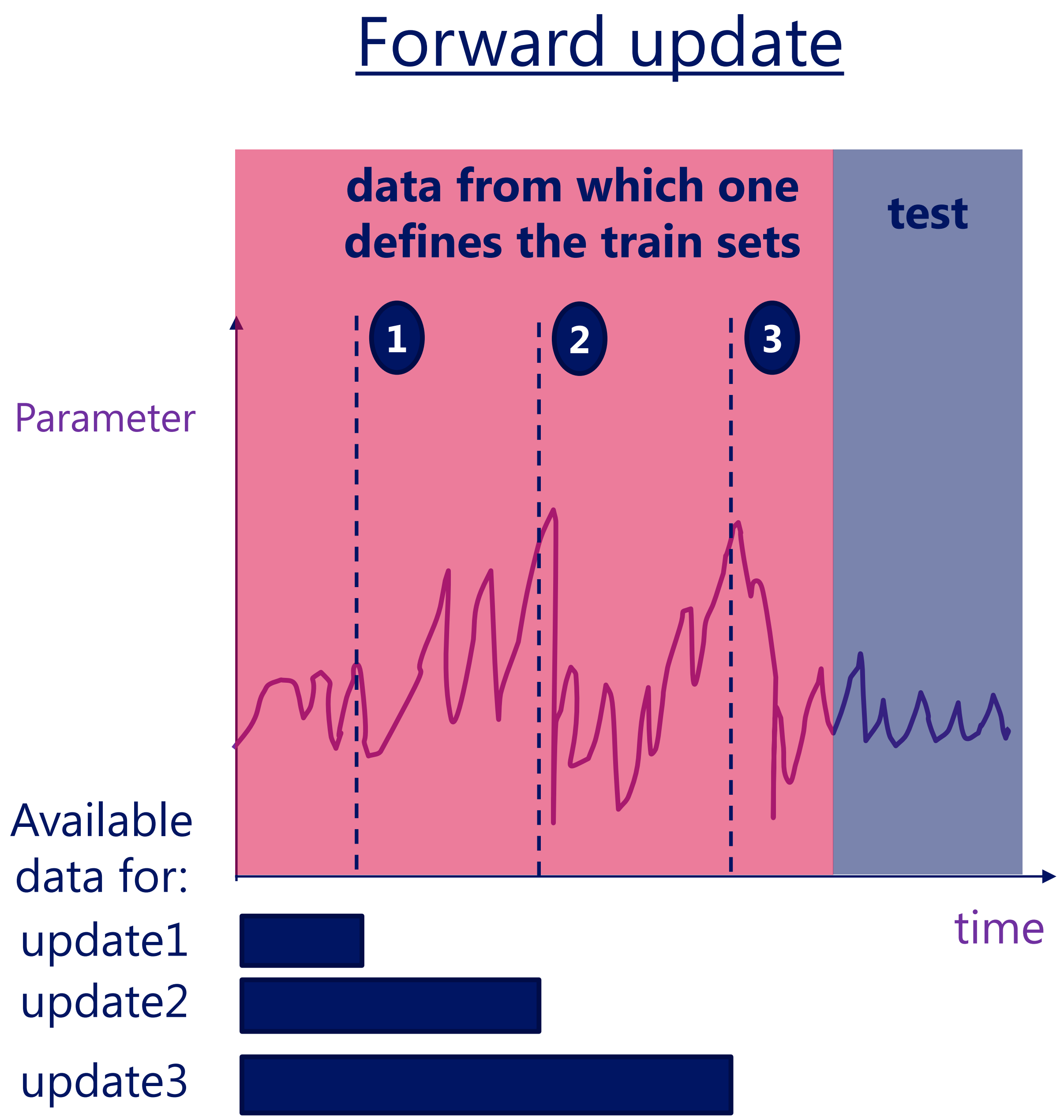


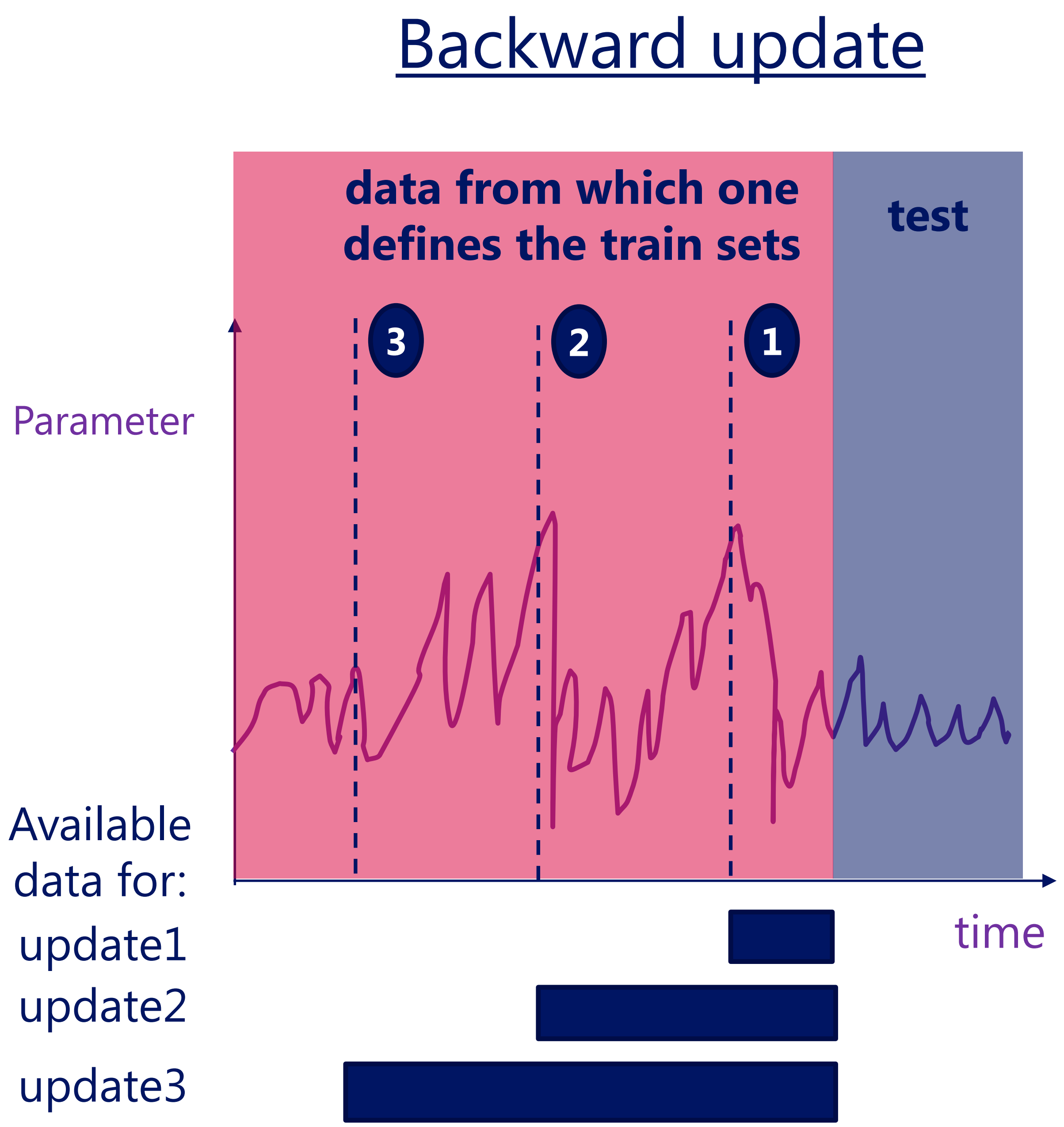


- An extreme case: can gain 15% accuracy by increasing train set from 10 to 50 wafers.
- Model retrain, enabled by a big data system, is important here.

Accuracy: data size and type

We find it is important to test how the blind test accuracy differs between two different update methods

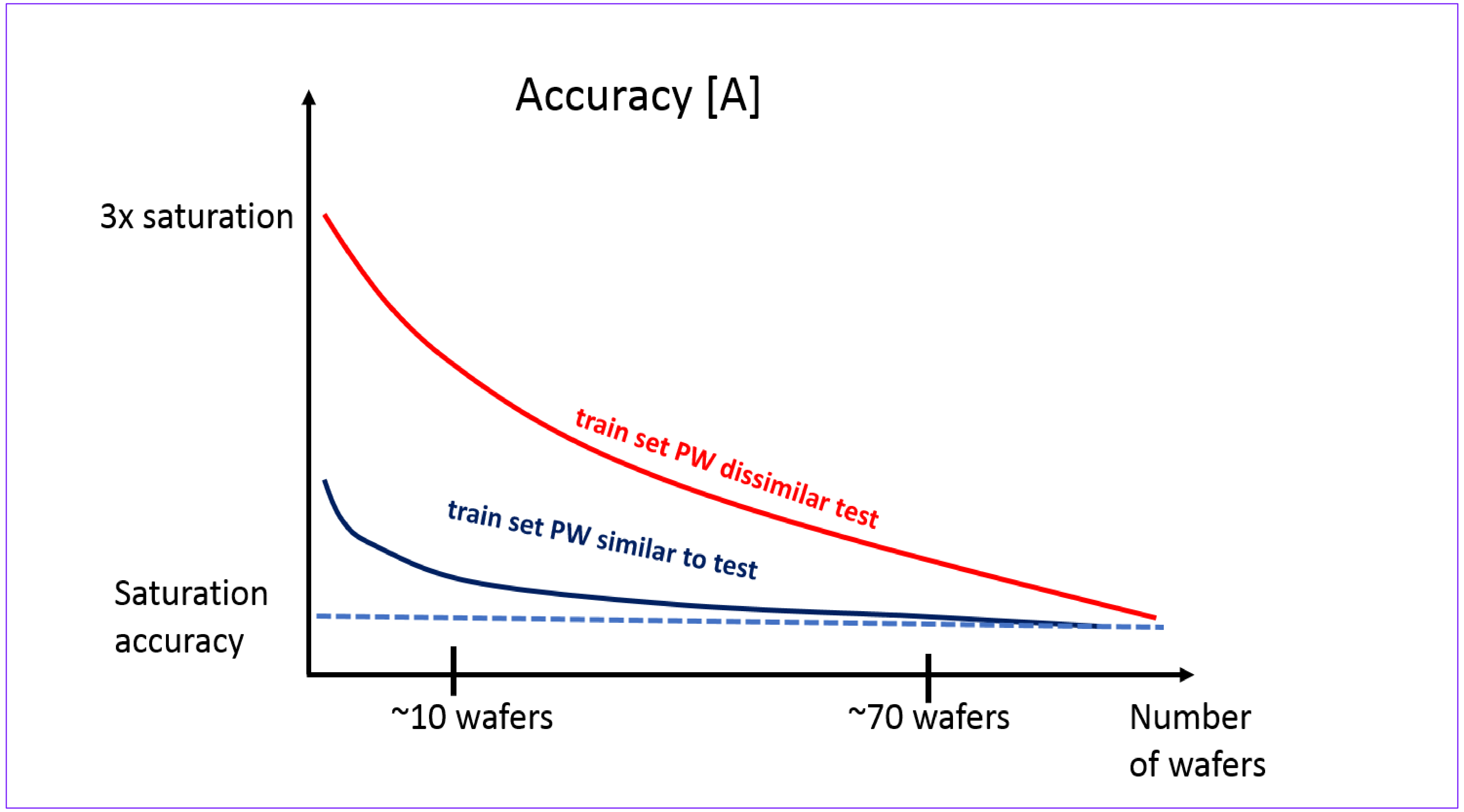




→ Any sizeable difference between forward and backward indicates process instability and the need for a dynamic update and control system.

Accuracy: data size and type

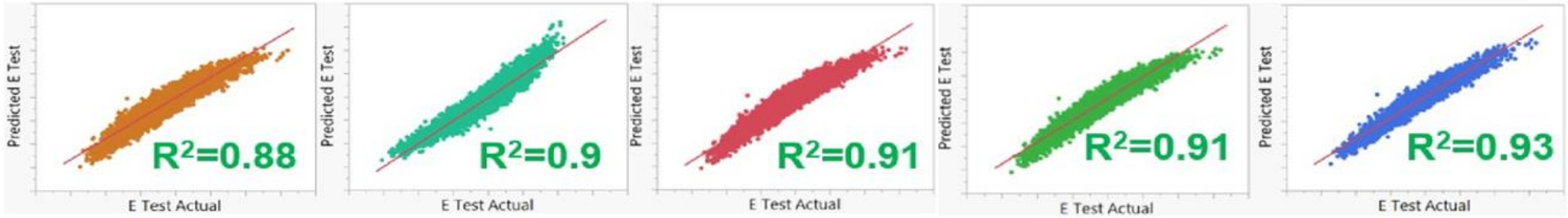
Example below: transfer of a physical model solution on SA to Nova IM.

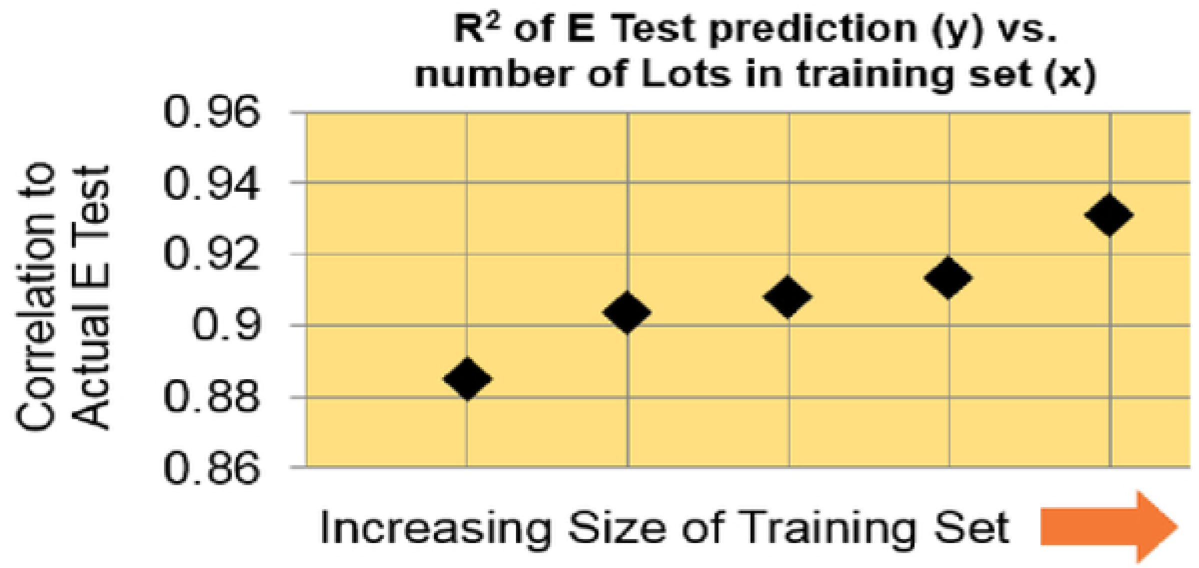


- Process Window (PW) is important. Plot is a sketch of what happens when the PW drifted with time.
- Clearly if PW(train) ~ PW(test), accuracy is better.
- Model retrain, enabled by a big data system, is important here.

Accuracy: data size-from SPIE Advanced Lithography P. Timoney *et al.* 10585-32

- E Test results from one of the GlobalFoundries products



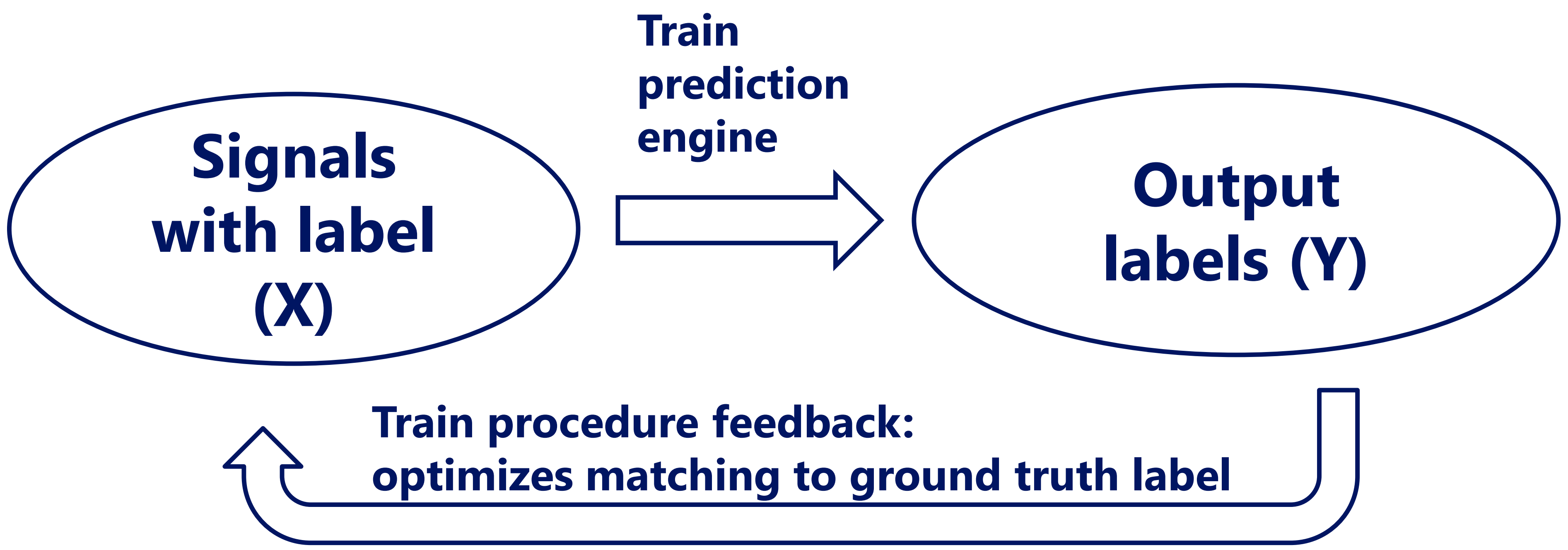


Change with increasing training data size is moderate.

Algorithm performance: repeatability

- Modify model setup to balance accuracy with repeatability.

<u>Typically in machine learning</u>



Algorithm performance: repeatability

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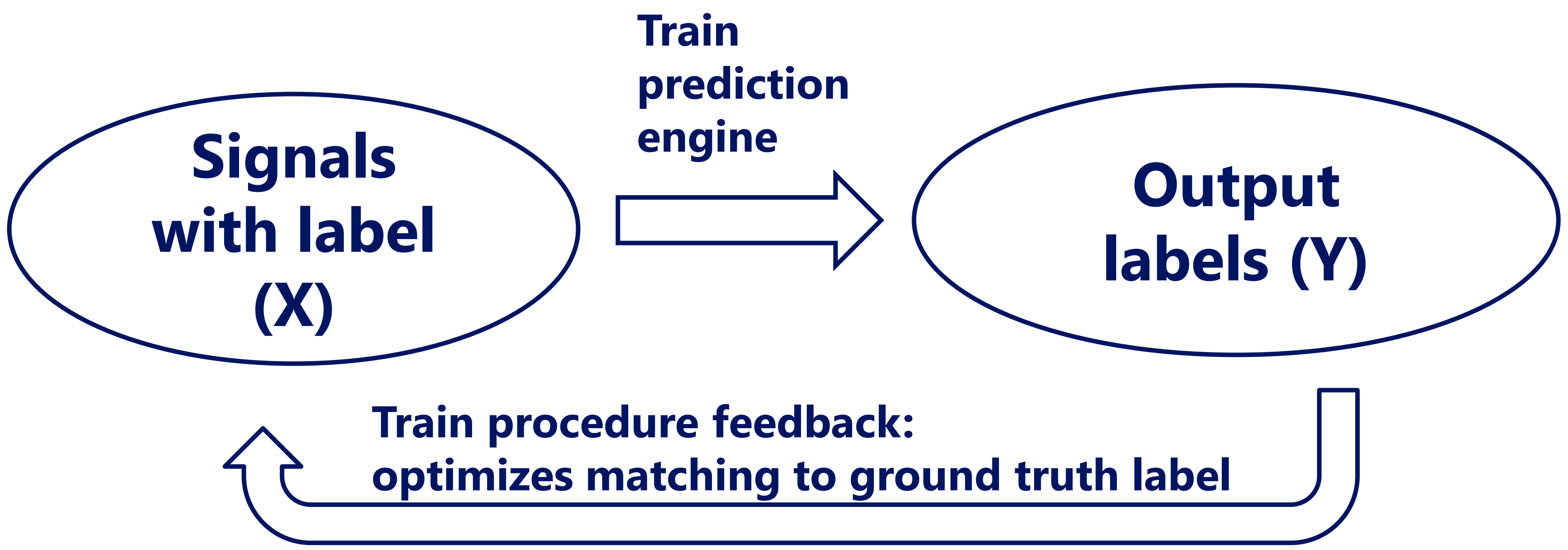
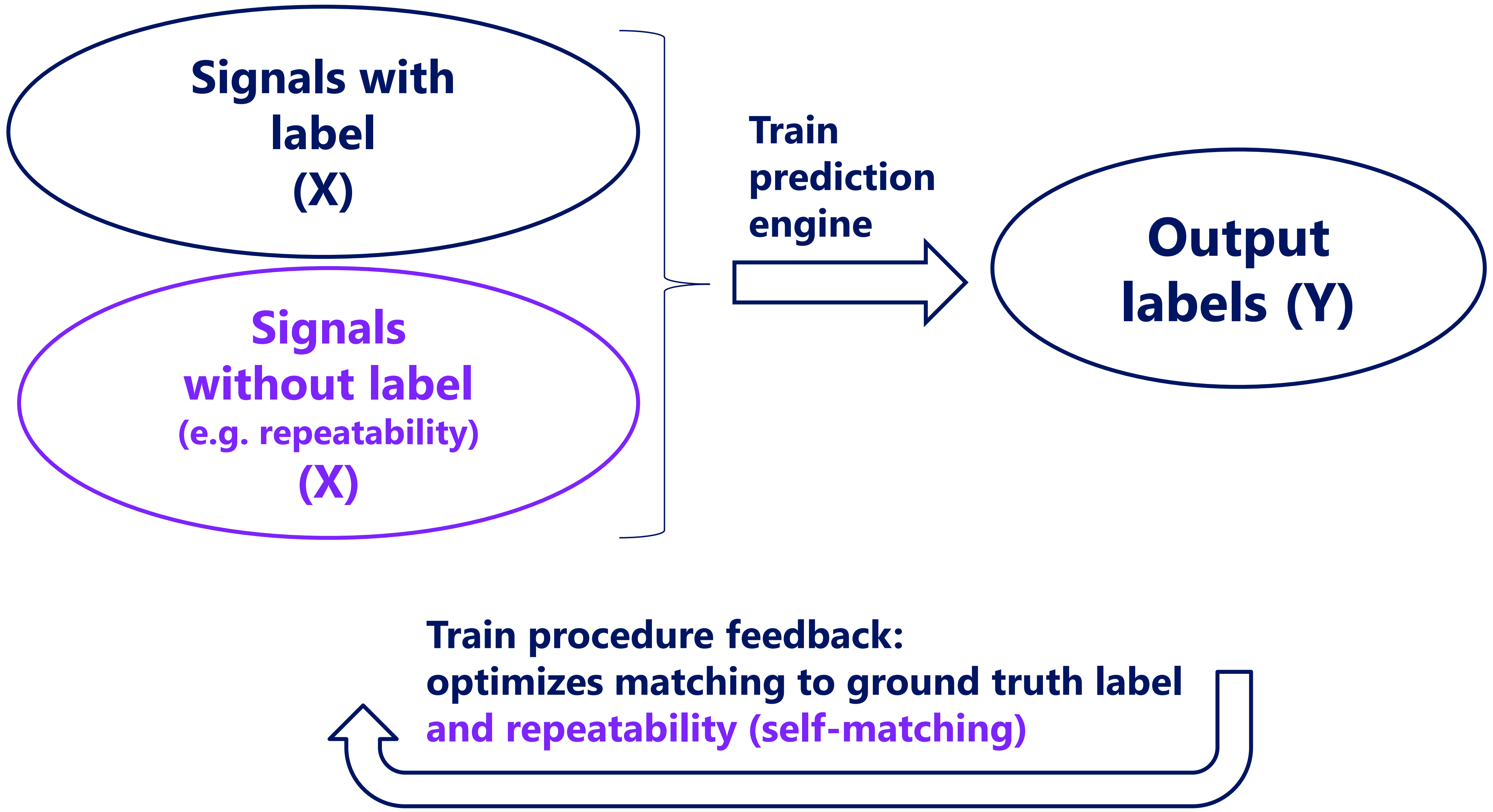
Typically in machine learning



Machine learning in OCD metrology



Repeatability optimization

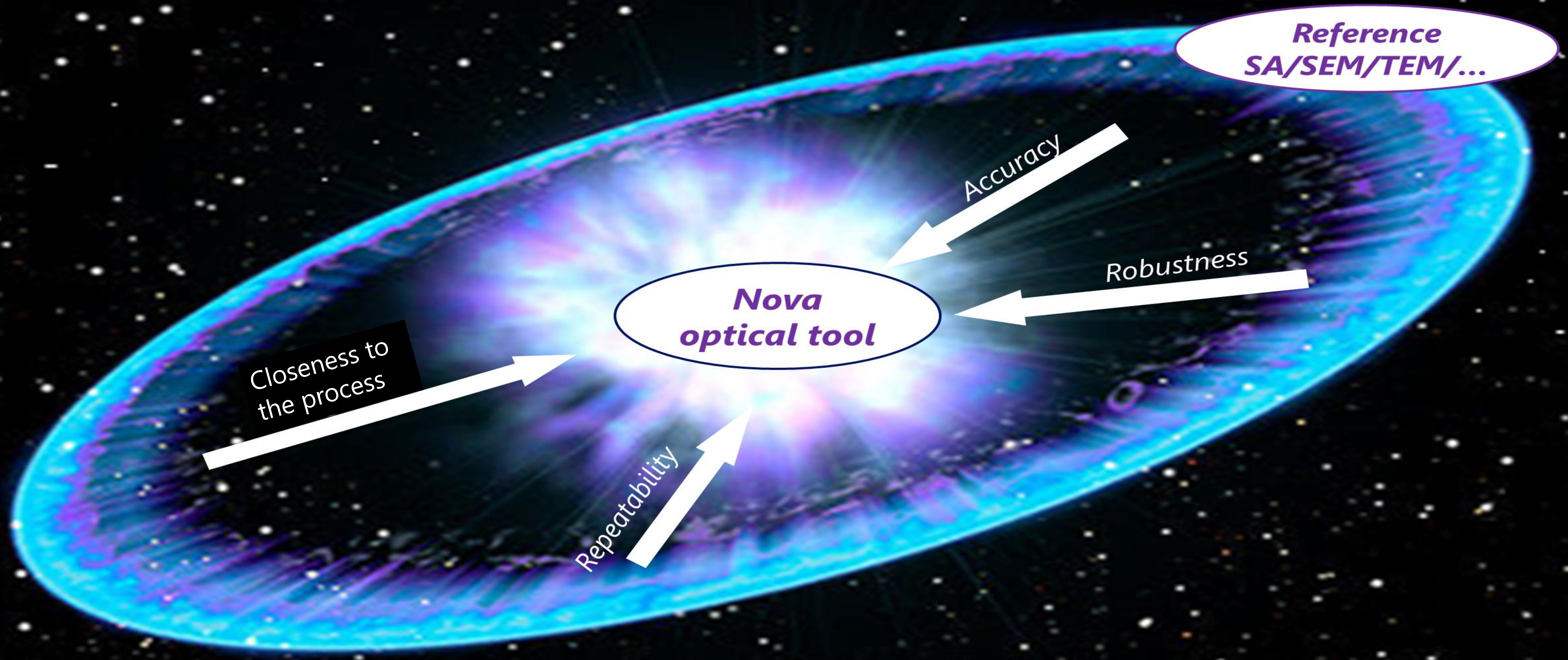
- Modify model setup to balance accuracy with repeatability.

Layer	Accuracy change [relative in percent]	Repeatability improvement [relative in percent]
Logic	-21	+136
	-17	+133
	0	+40
	-18	+123
	-17	+155
Memory	-13	+123
	-7	+11

Accuracy penalties are all less than 10% of customer spec

Improvement are significant, can be 50%-100% of customer spec

In summary: machine learning is valuable for OCD



But ….

There are still unsolved problems, mainly:

- Interpretability: the `black box' issue.
- Reference cost.

⇨

Different approaches:

- Combining physical modeling and machine learning.
- Another alternative: see talk by Noam Tal at APC2018.

Thanks to all my co-authors at Nova: the machine learning and big data group at Nova

Eitan, Ilya, YongHa, Noam, Oded, Shay, Ariel, Eylon, and Tal

And to the GLOBALFOUNDRIES and Nova authors of

SPIE Advanced Lithography – Metrology, Inspection, and Process Control for Microlithography – P. Timoney *et al*. 10585-32

P. Timoney, T. Kagalwala, E. Reis, H. Lazkani, J. Hurley, H. Liu, B. Kang, P. Isbester, N. Yellai, M. Shifrin, Y. Etzioni