Big data, little data, and virtual twins:

Accelerating process development for semiconductor device fabrication

FCMN 2024

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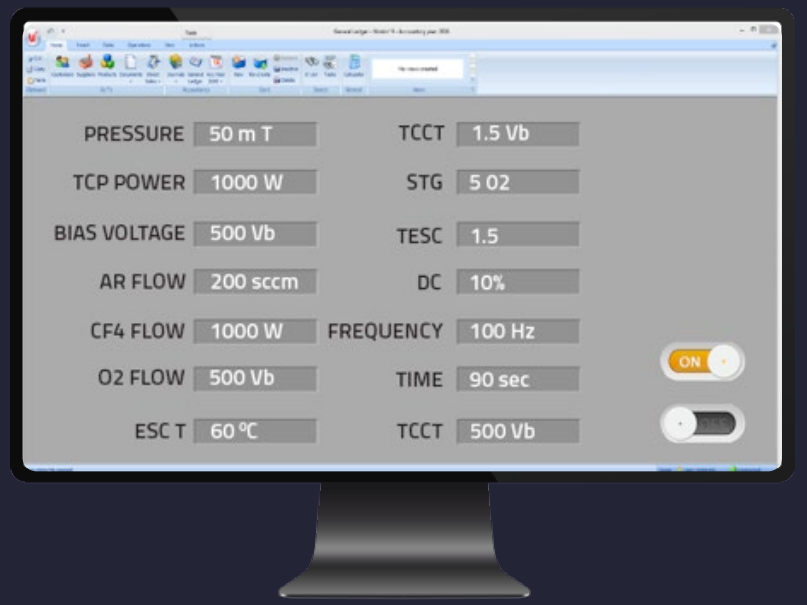
Lam RESEARCH

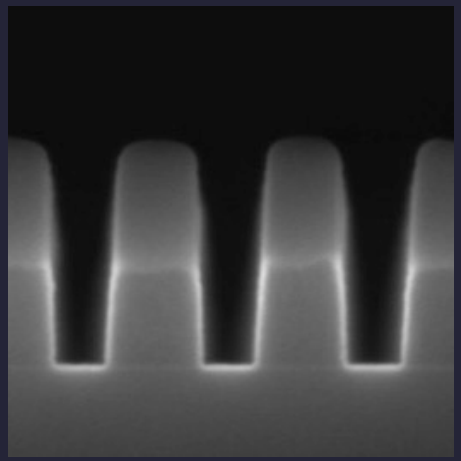
Why can’t we design a process like we design a chip?

SPEC

RECIPE



RESULT



Why not just use a *big data* approach?

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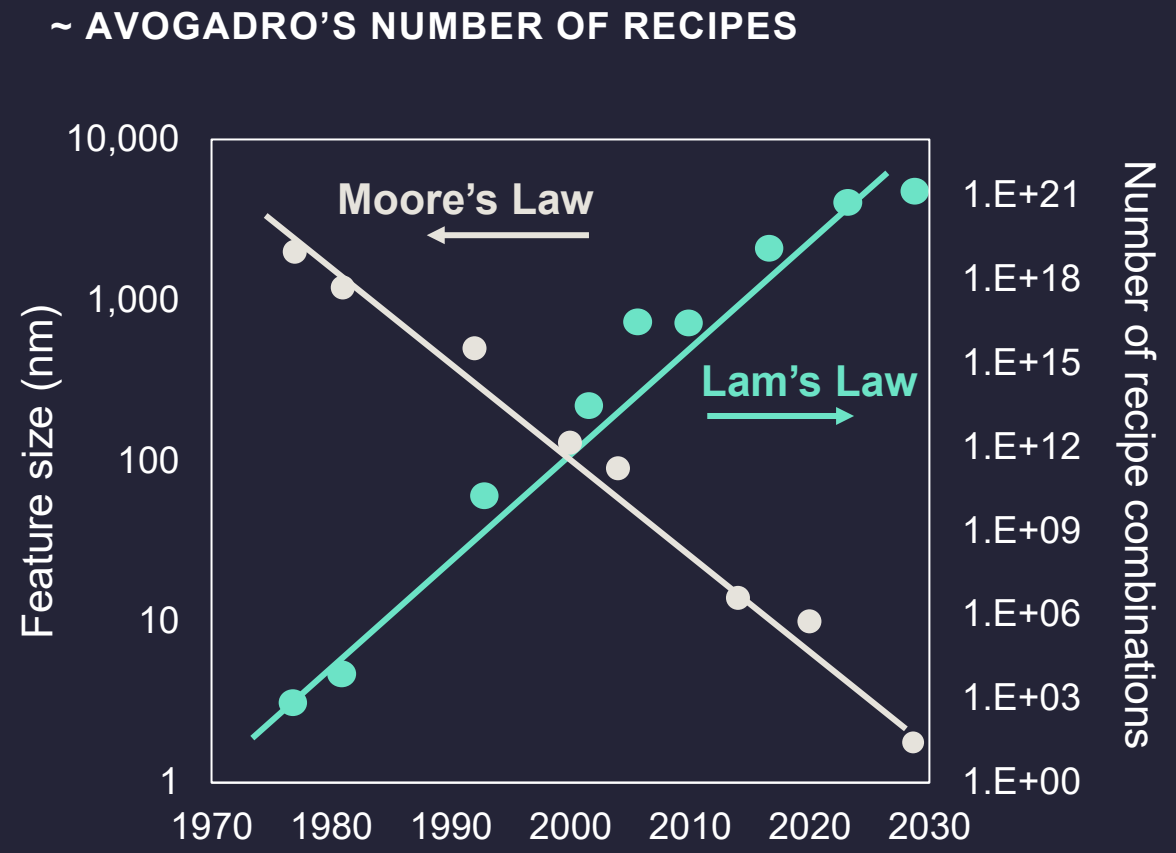
Simply put, it costs too much and takes too long

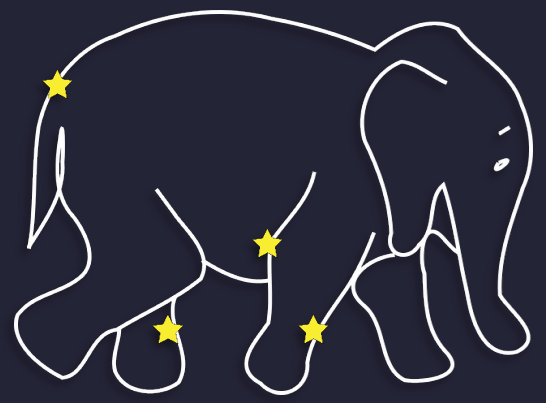
Little data world but *big* dimensional space



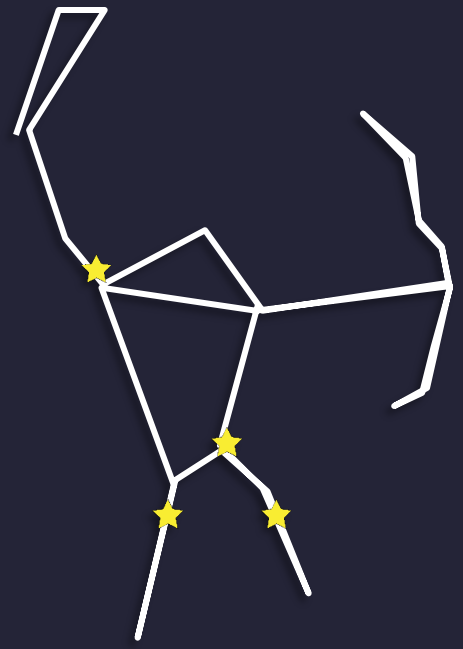
What about *physics?...*

Exploit little data with right (physics-based) model

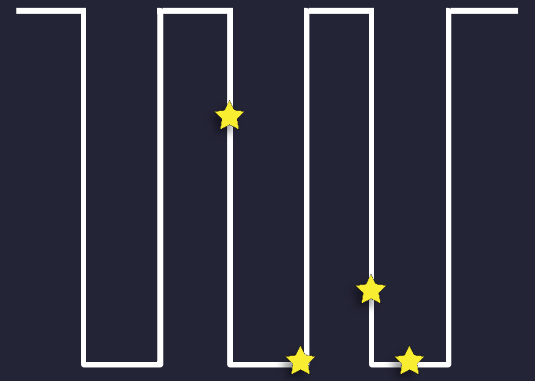
MODEL 1



MODEL 2



MODEL 3

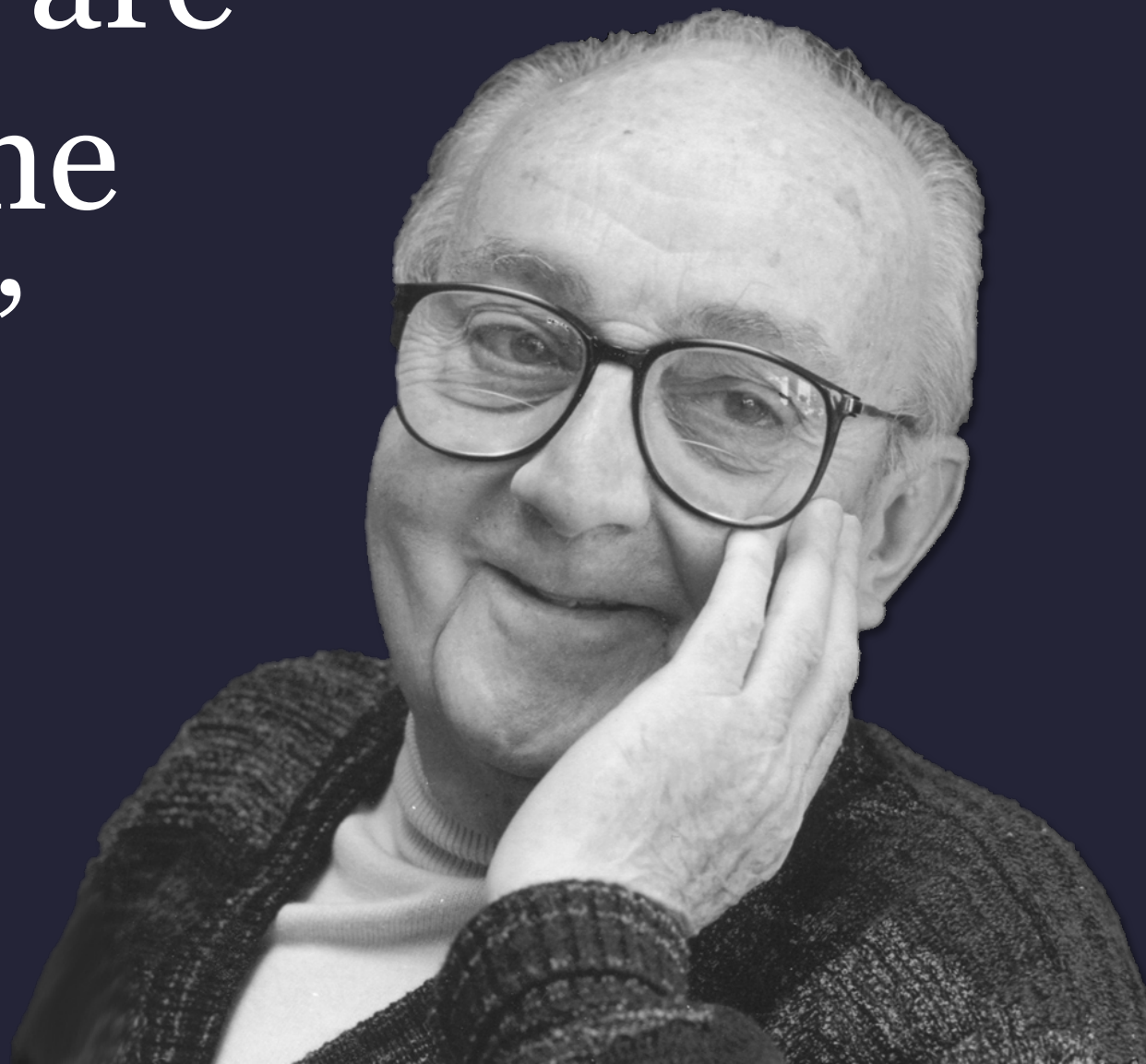


"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

John von Neumann, as related by Freeman Dyson (2004)
"A meeting with Enrico Fermi," Nature 427 (6972)

“All models are wrong, some are useful.”

George Box, 1976



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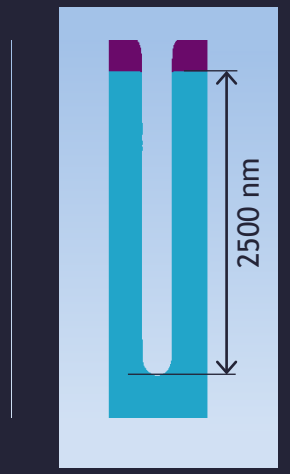
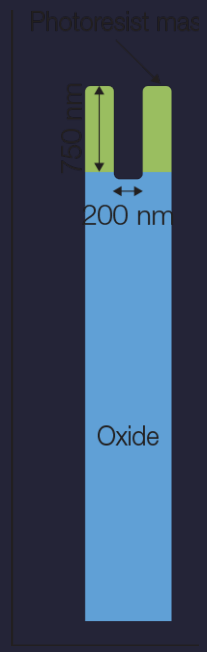
Let's play a "game" to find the useful models

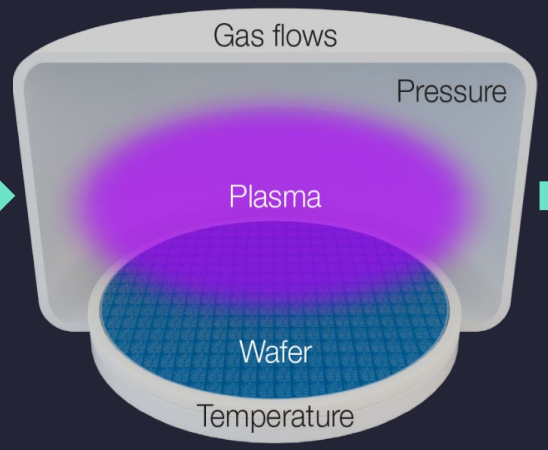


A virtual plasma etch process “cousin”

INCOMING	RECIPE → SIMULATOR → OUTPUT	TARGET	OTHER PROFILES

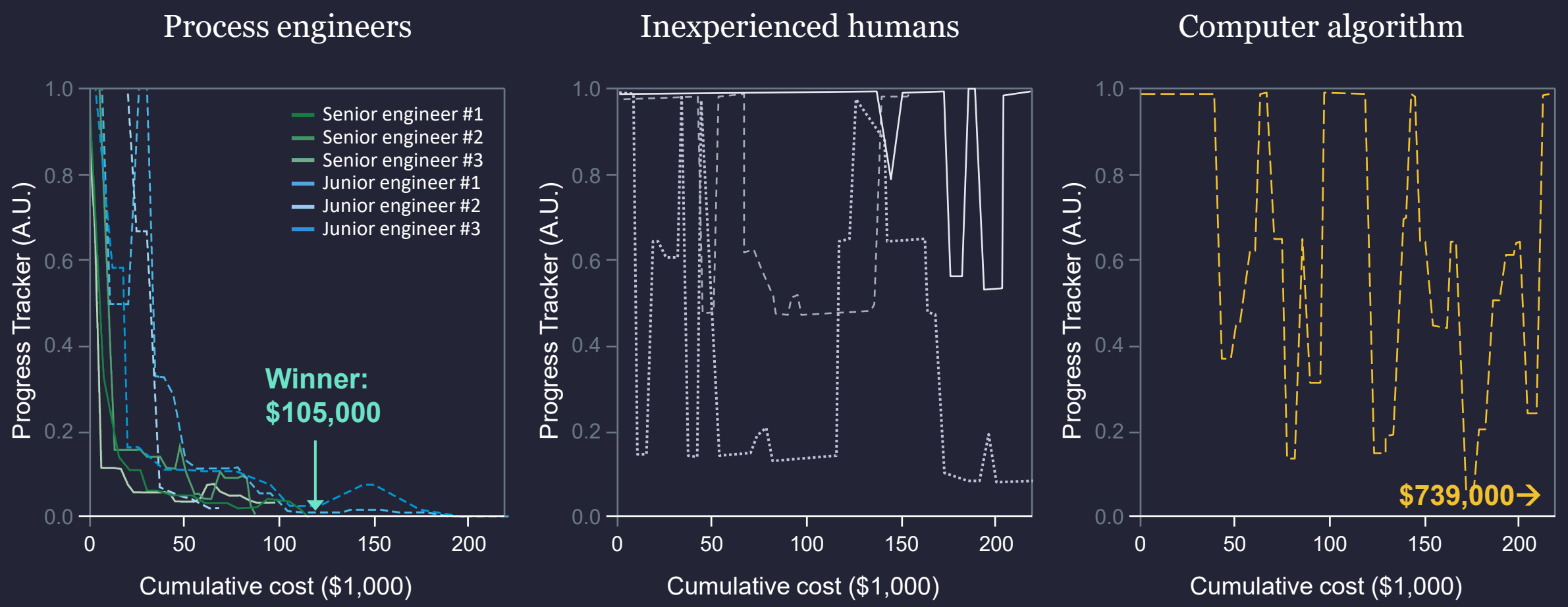


Pressure
Plasma power1
Plasma power2
Ar flow
Gas 1
Gas 2
Gas 3
Duty cycle
Pulse frequency
Temperature



Etch depth
Etch rate
Mask remain
Top CD
Delta CD
Bow CD

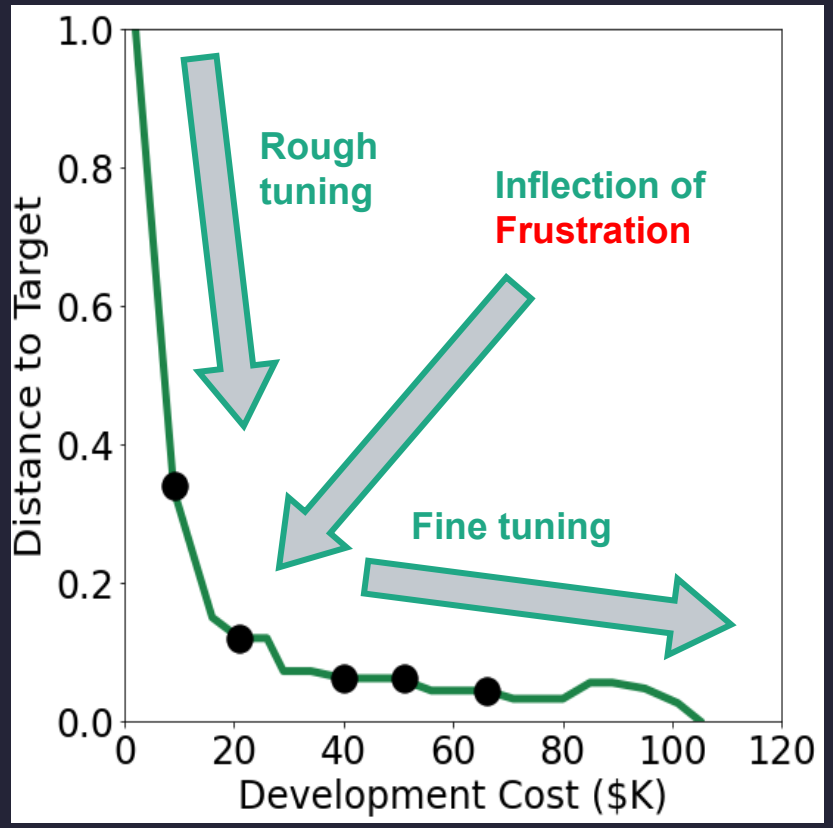
Machine alone was no match for expert engineer



Source: Kanarik et al, Nature, 2023

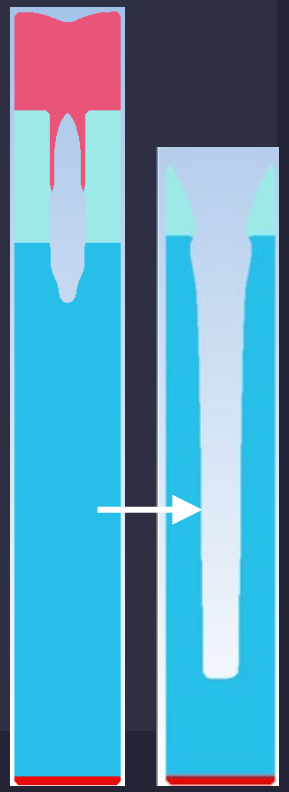
Human learning curve consists of rough and fine tuning

Expert trajectory



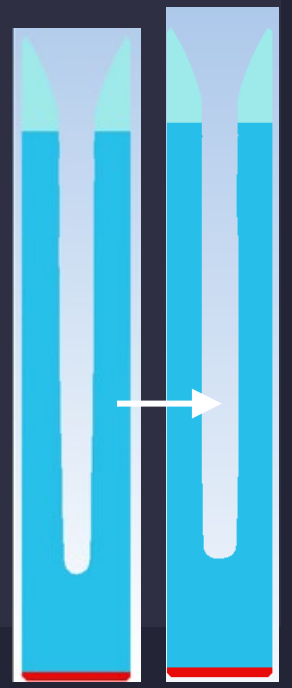
Rough-tuning stage

- Baseline from experience
- Domain knowledge and physical intuition are valuable
- Fulfilling, rapid progress *toward* solution



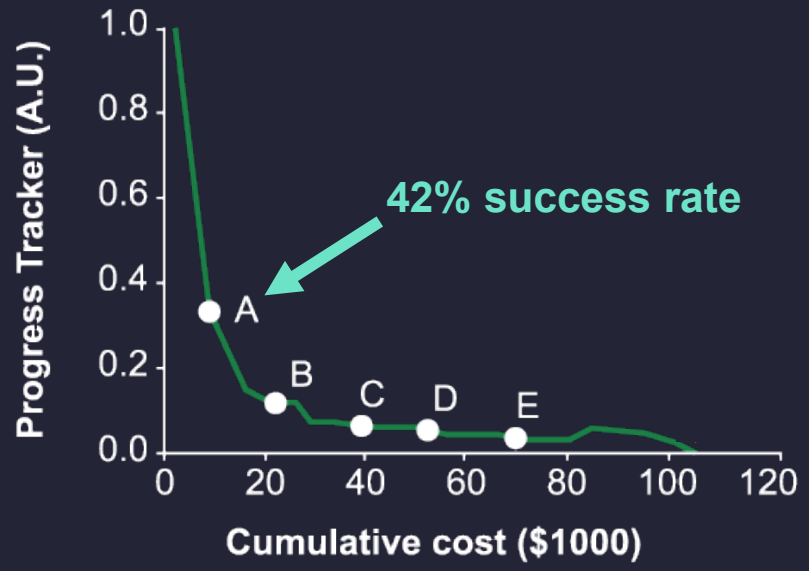
Fine-tuning stage

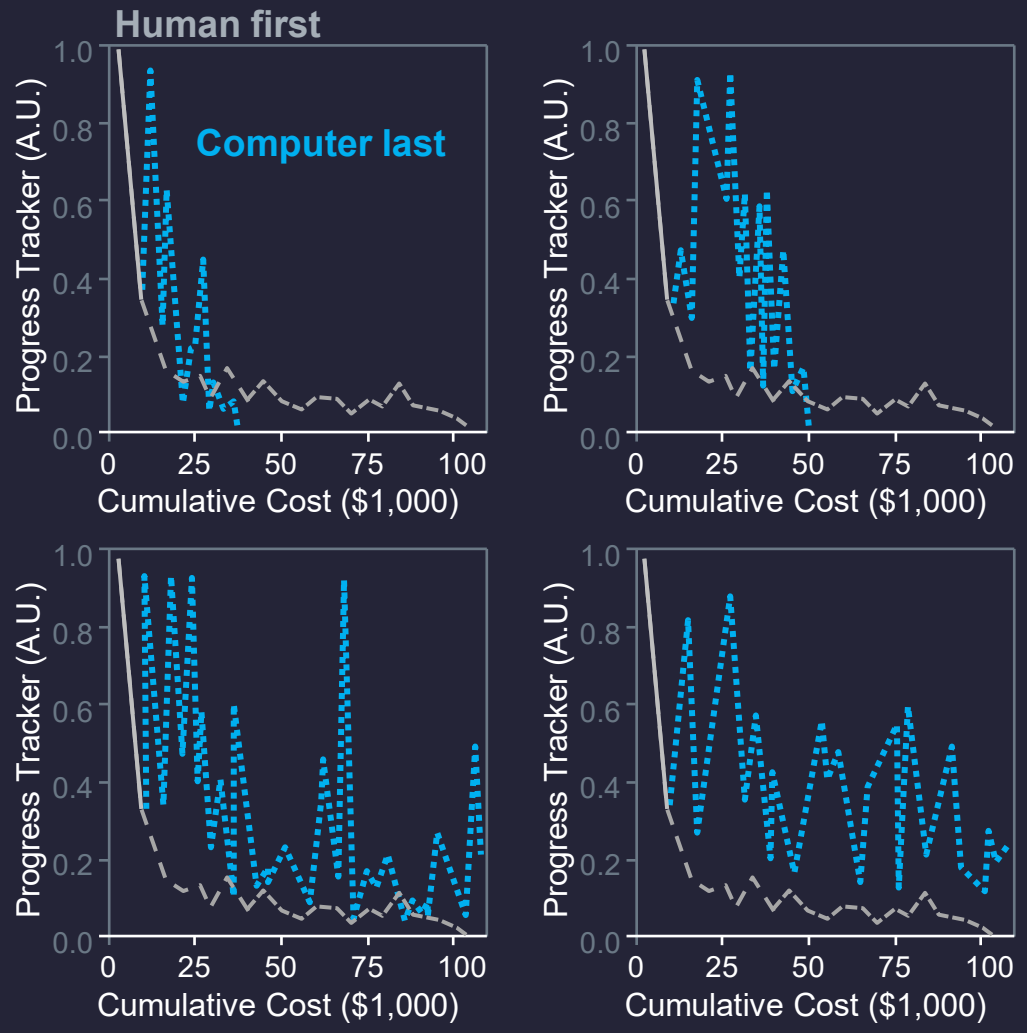
- Close to spec
- Physical intuition and domain knowledge less useful
- Frustrating, low-productivity path to solution



Human-Machine Collaboration: Transfer point “A”

Expert trajectory

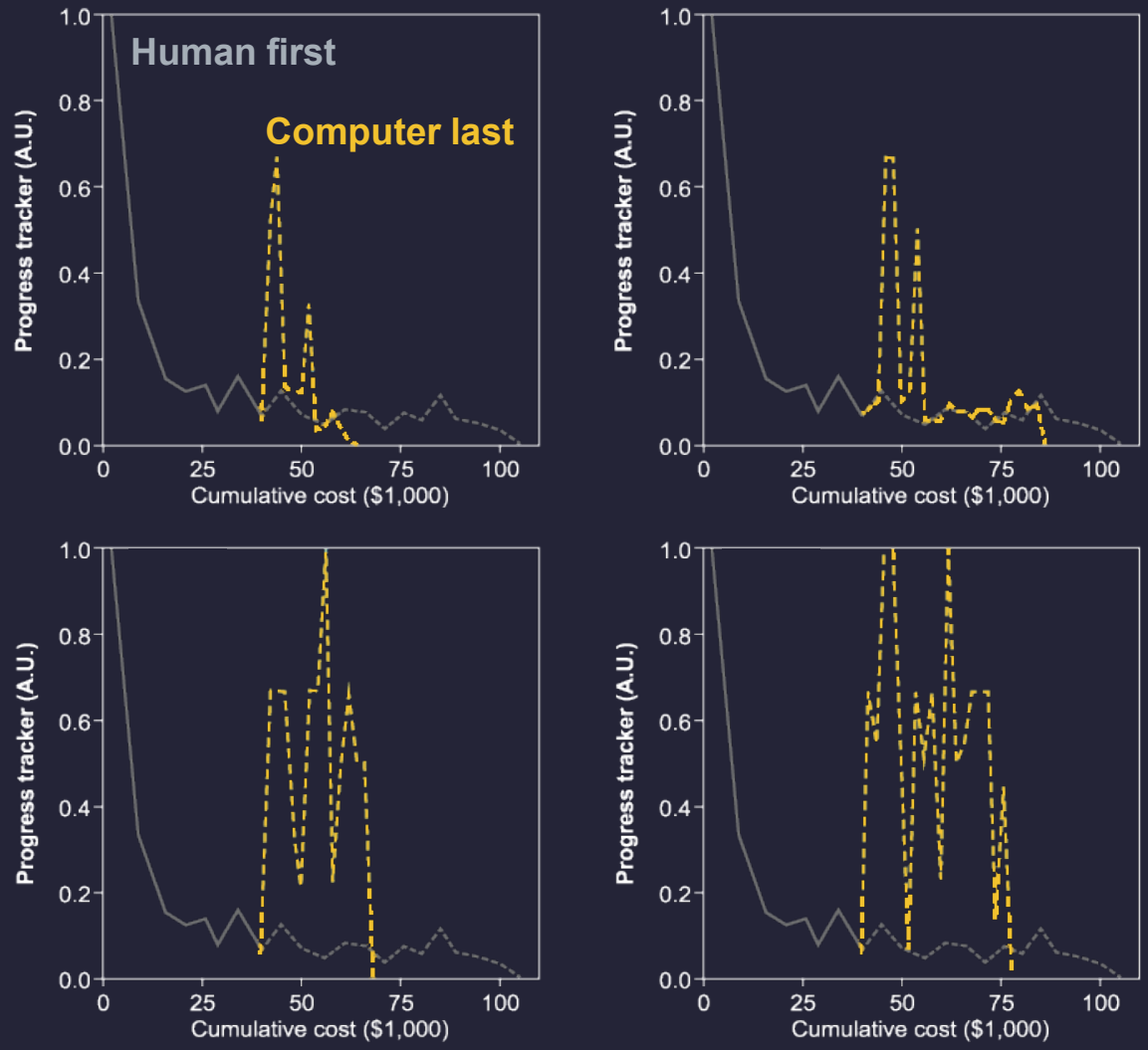




Source: Kanarik et al, Nature, 2023

Human-machine collaboration yields cost and time savings

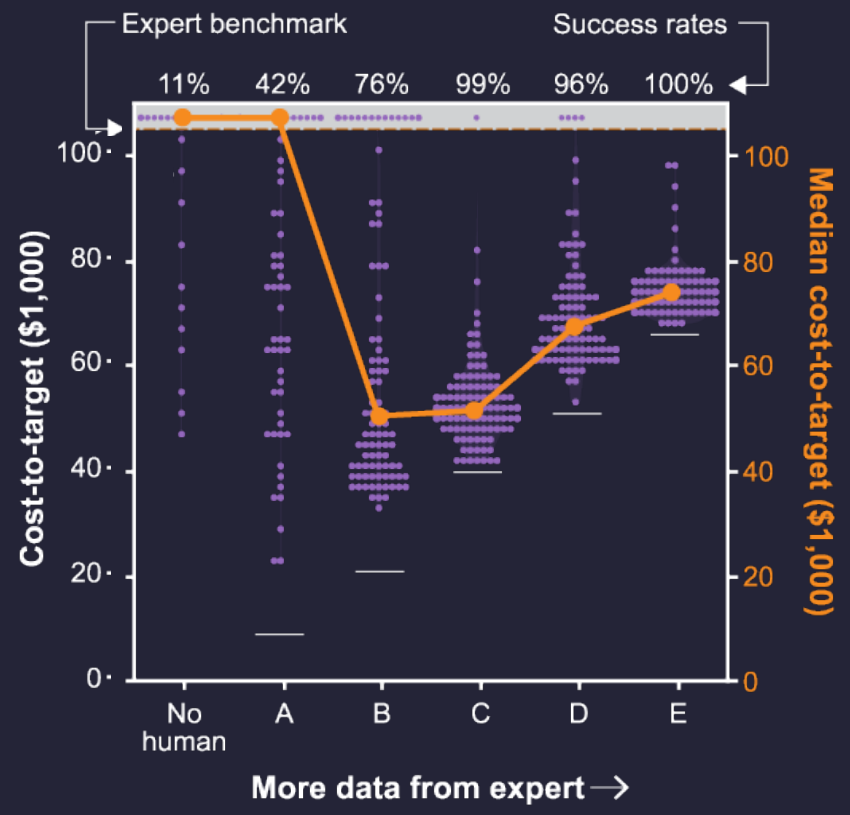
Expert trajectory



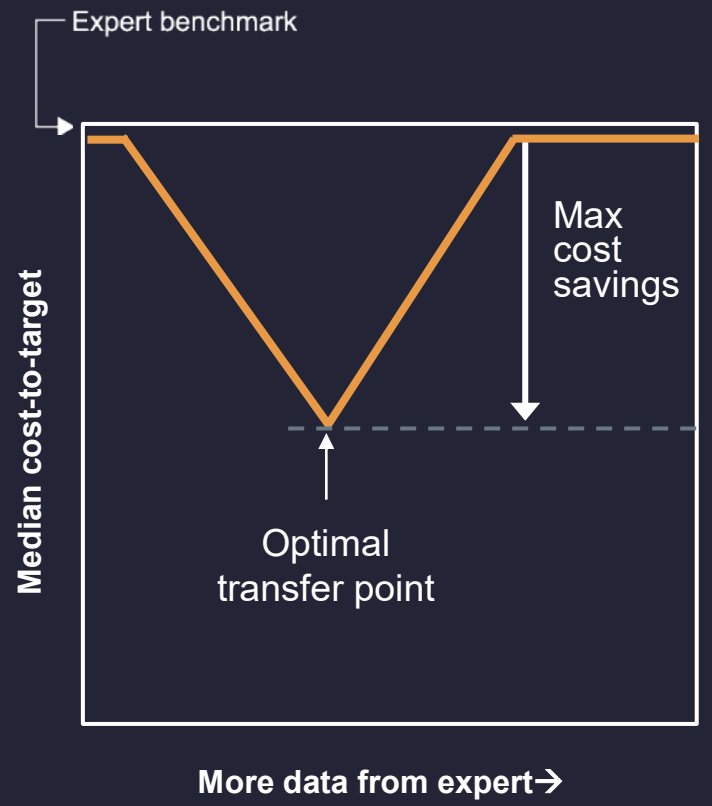
Success rate: % meeting target at lower cost than expert
Source: Kanarik et al, Nature, 2023

Optimal transfer leverages human investment

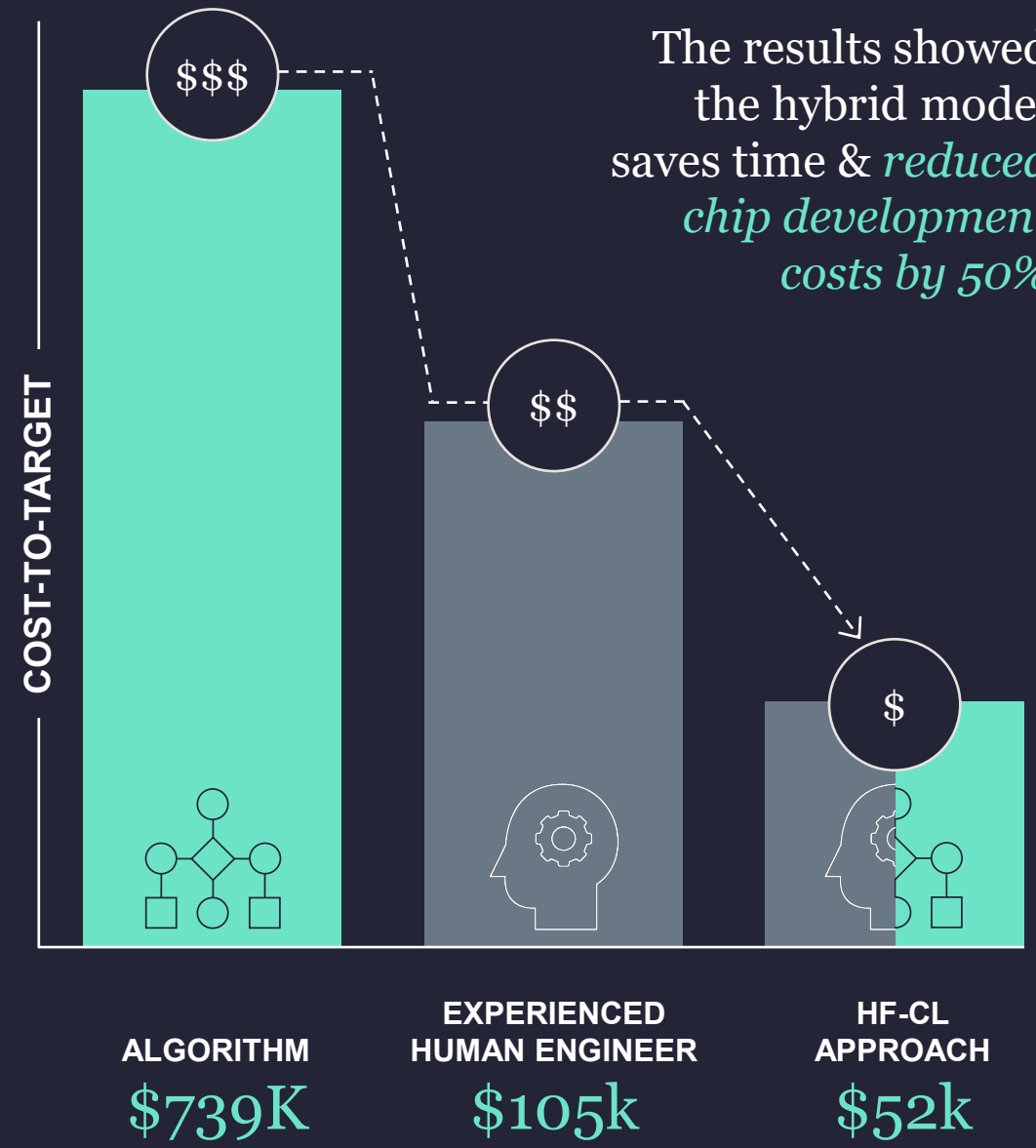
Experimental V-curve



Schematic



Source: Kanarik et al, Nature, 2023

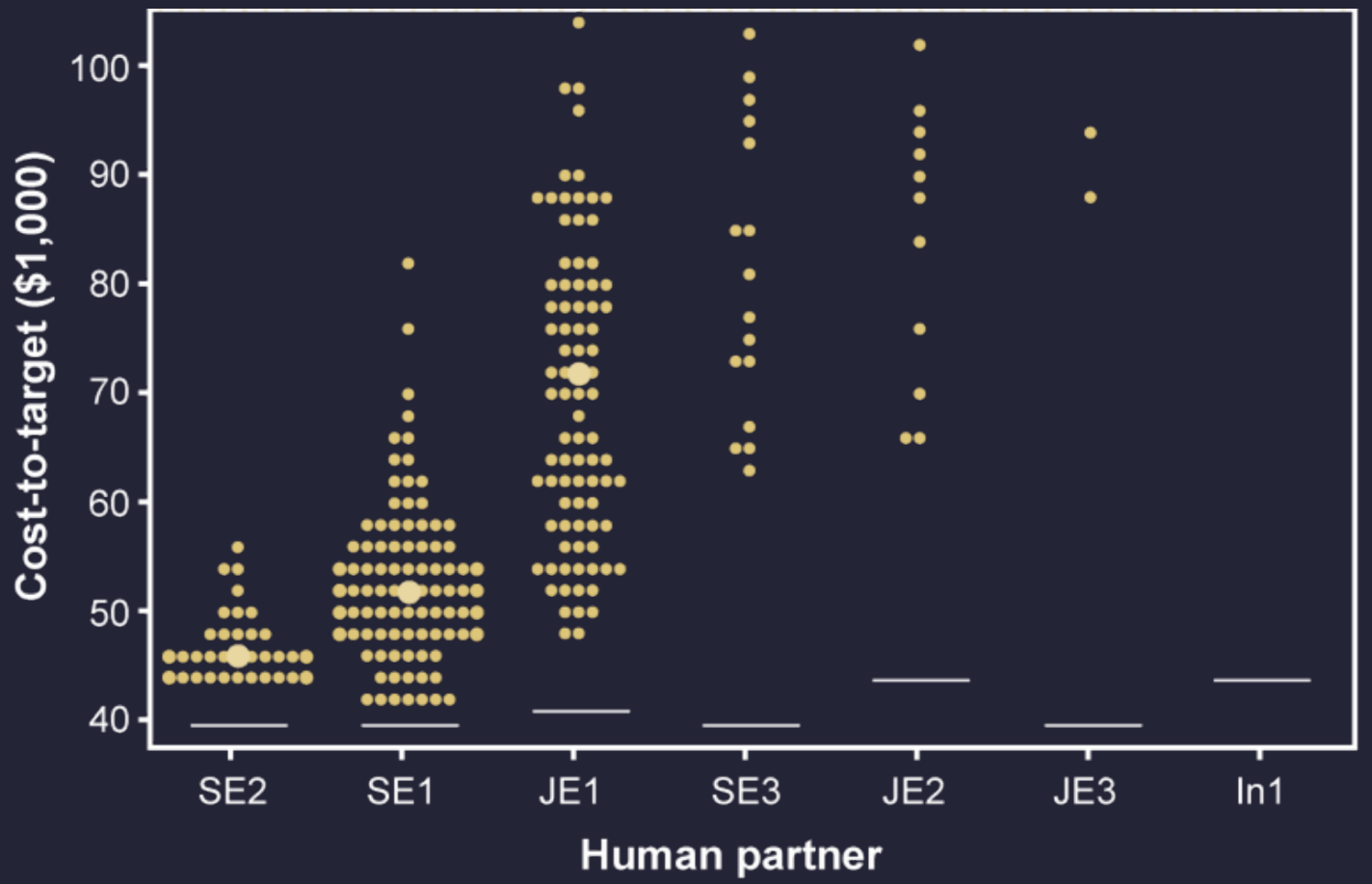


The results showed the hybrid model saves time & *reduced chip development costs by 50%*

Hybrid approach wins

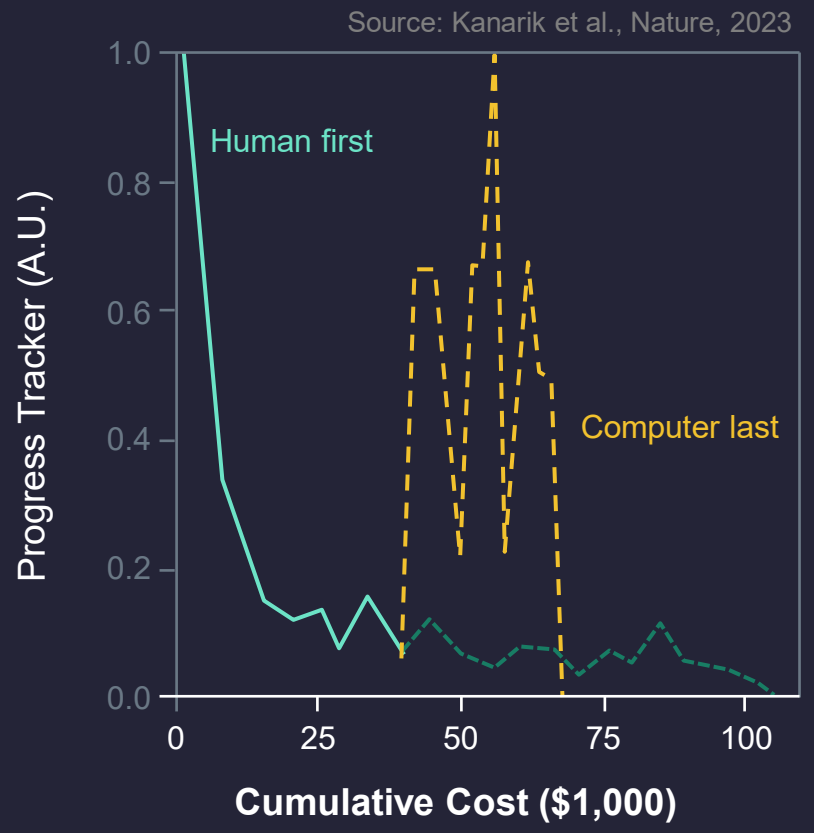
Human-first, machine-last saves countless hours and millions of dollars

Computer should partner with an experienced engineer



Source: Kanarik et al, Nature, 2023

Algorithm behaves differently than process engineer



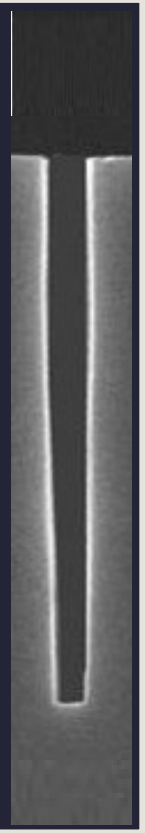
Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5	Parameter 6	Parameter 7	Parameter 8
1148.6	68.5	4026	90.7	33.9	20.9	220.0	50.9
1165.2	66.5	3594	198.7	33.3	22.3	231.0	58.4
1166.8	67.1	3480	167.6	32.6	21.3	226.1	58.2
1149.3	68.3	3842	109.2	30.7	17.9	252.7	58.3
1160.1	60.5	3110	181.0	27.2	17.8	204.5	58.1
1158.0	60.0	3103	156.8	27.0	17.8	202.9	58.0
1143.9	68.6	3550	90.1	33.4	16.1	180.0	59.5
1137.1	67.3	3715	96.7	34.1	17.4	180.6	59.5
1160.5	67.7	3830	169.9	30.2	18.0	199.4	57.0
1170.7	67.0	3728	196.3	29.2	17.5	195.7	56.3
1161.6	67.2	3687	181.9	30.2	17.7	194.5	56.0

There is high value learning from virtual worlds that *are* *not* precisely predictive

Real vs. virtual processes : Cost and time comparison

Real process in lab

- Build cost: >**$1,000,000** to purchase reactor for the laboratory

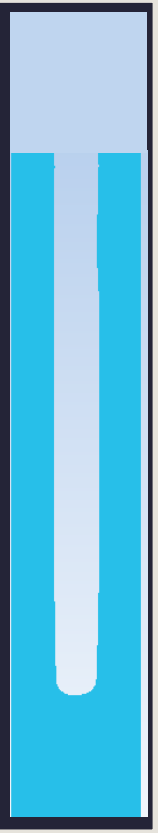


Per recipe:

- Cost per recipe: **$1000**
- Time per recipe: **half day**

Simulation of process

- Build cost: **$100,000** person-hours to program HARC application into SEM3D



Per recipe:

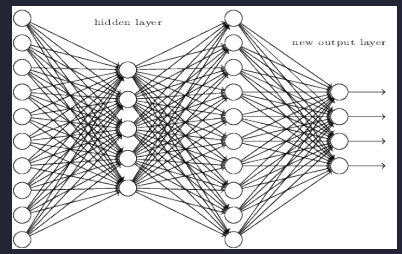
- Cost per recipe*: **$0.11**
- Time per recipe: **8 min**

Emulator (model of simulator)

- Build cost: Used **$30,000** of data (240,533 simulations) to train the neutral network

Per recipe:

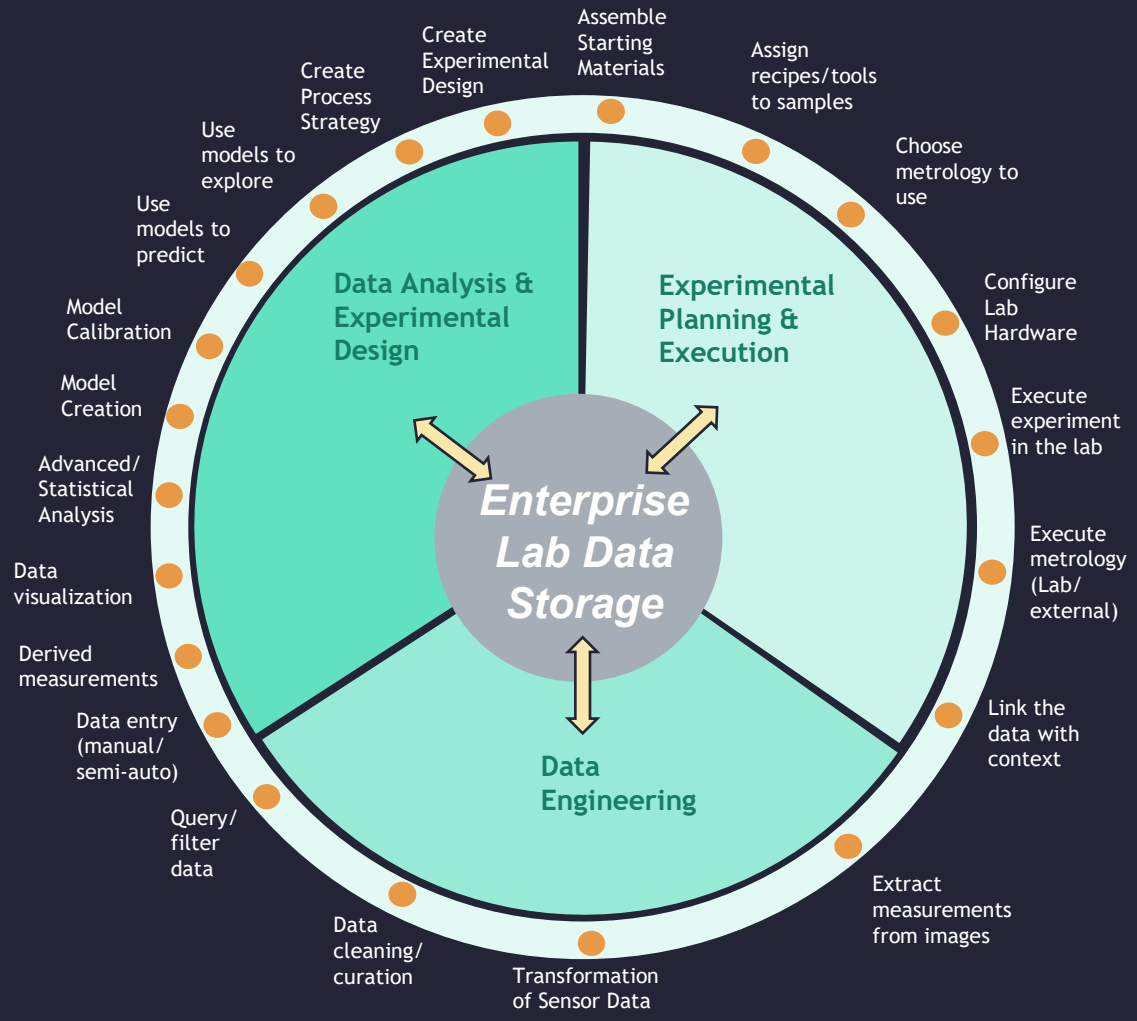
- Cost*: **$3e-07**
- Time: **0.0013 s**



*Computation cost: $0.8/hr for one f16 instance on HPC.

Virtual Process Development

Transform process development through digitalization, automation, simulation & data analysis

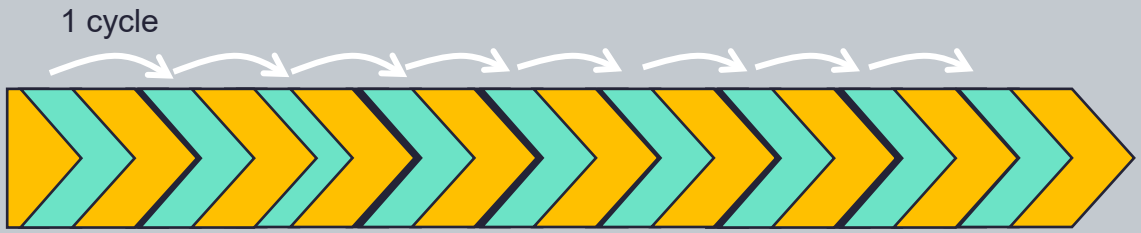


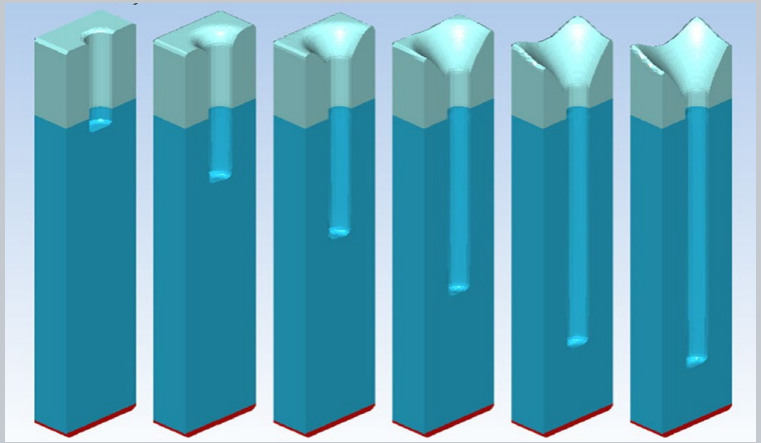
- Process Development is not one monolithic workflow. It is many different paths through a variety of different activities. Catering to these varied workflows requires a holistic strategy.
- The activities largely reside in three disciplines, with specific requirements, and must be connected through enterprise-scale storage of experimental process data.
- Modernizing and automating physical experimental activities in the lab is key to delivering the contextual data to the data store
- Image analysis and flexible platforms for data science, machine learning and advanced analytics are critical for data engineering.
- Connecting platforms and systems to create efficient, friction-free workflows = Virtual Process Development

Real-time profile metrology for *100x* cycle time reduction

Metrology for high aspect ratio solution development costly, time-consuming, and destructive

Real-time metrology offers 100x cycle time reduction





Meet the authors

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