Chips Making Chips:

How Virtualization, Digital Twins and Machine Learning are Accelerating the Spiral of Innovation

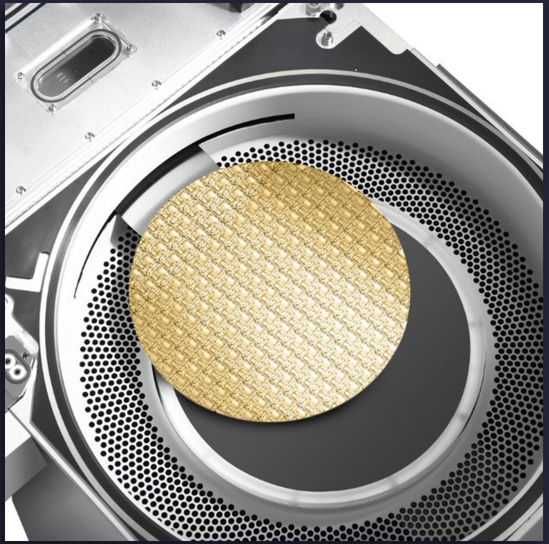
David M. Fried
Corporate Vice President – Semiverse™ Solutions

Presented at MES & Industry 4.0 Summit, September 7, 2023

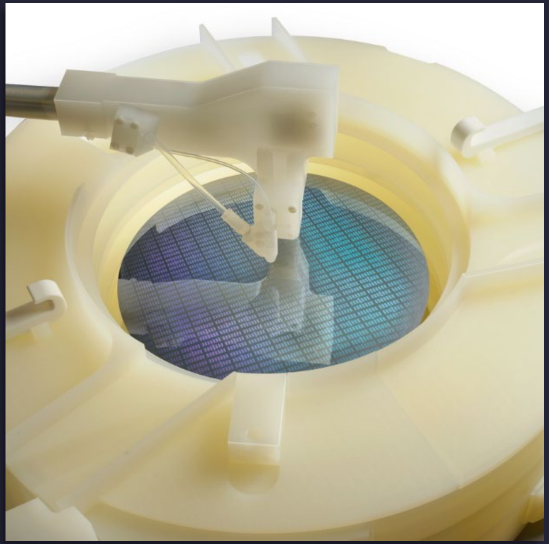
Lam Research at a glance

Etch & Strip

Deposition



Clean



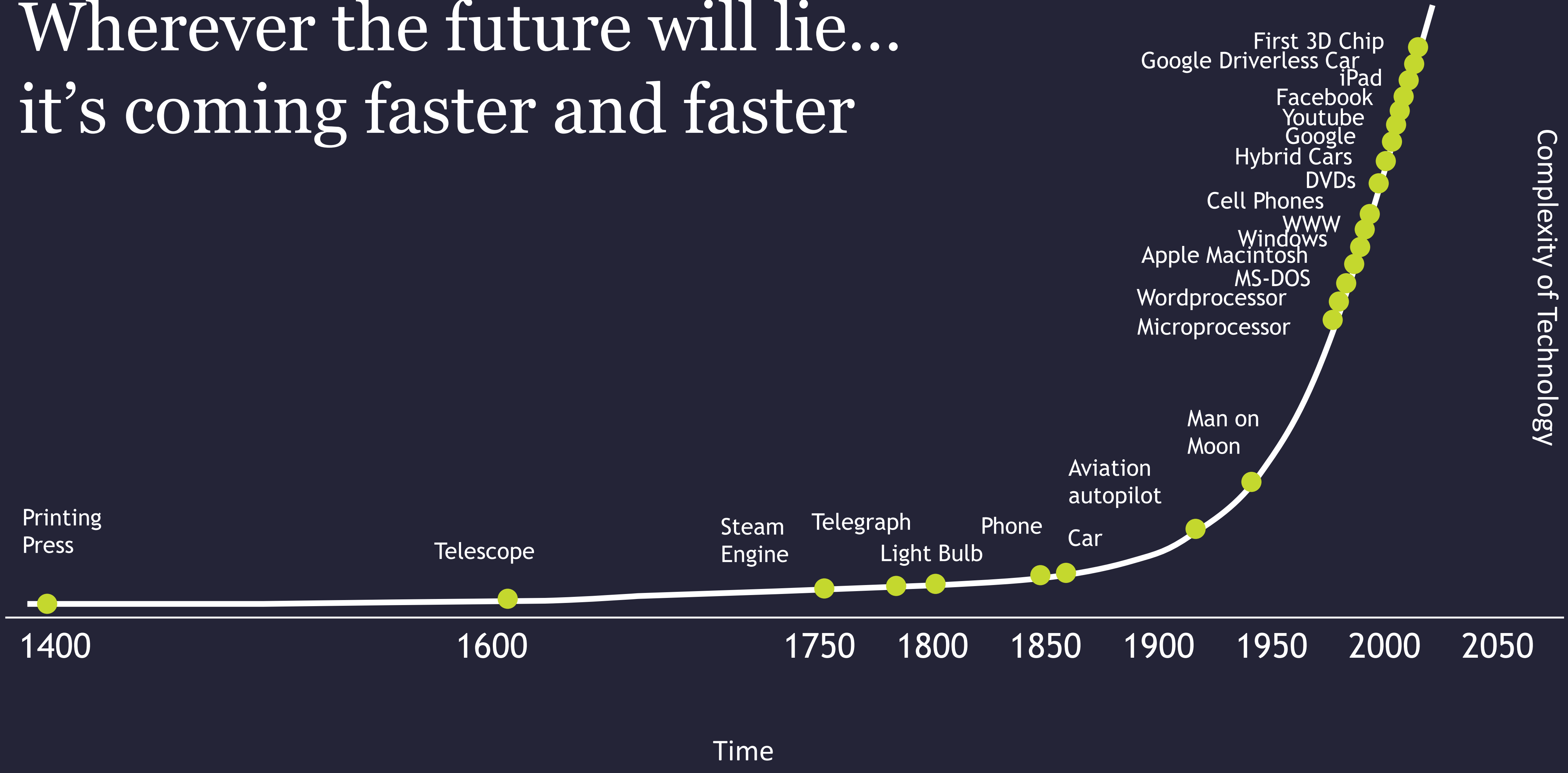
Service & Support

A leader in wafer fabrication equipment and services since 1980

Global R&D, engineering, manufacturing, customer support and supply chain

~18,700 employees

Wherever the future will lie...
it's coming faster and faster



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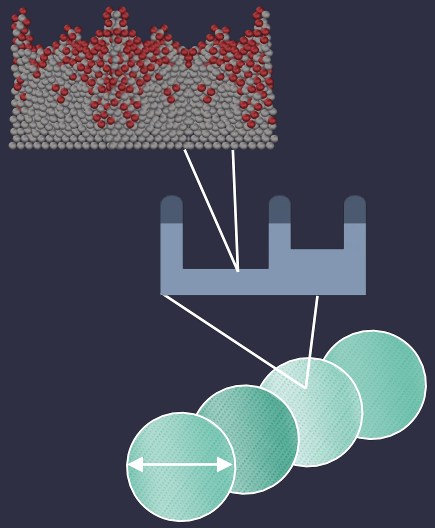
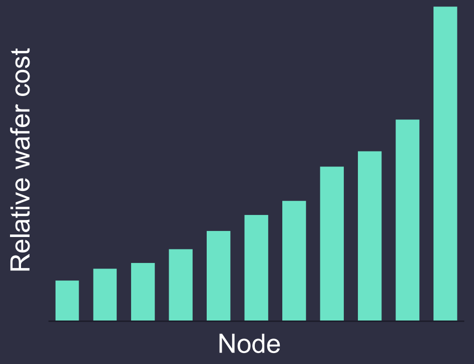
Grand Challenges: Let’s Create our own Future





Atomic-scale precision

Affordability

Sustainability

Speed to solution

Welcome to 2030 – The Era of Smart Tools and Smart Fabs

Smart tools are ubiquitous

Fab output has achieved unprecedented profitability

Equipment Intelligence® Platform

Transforming Production

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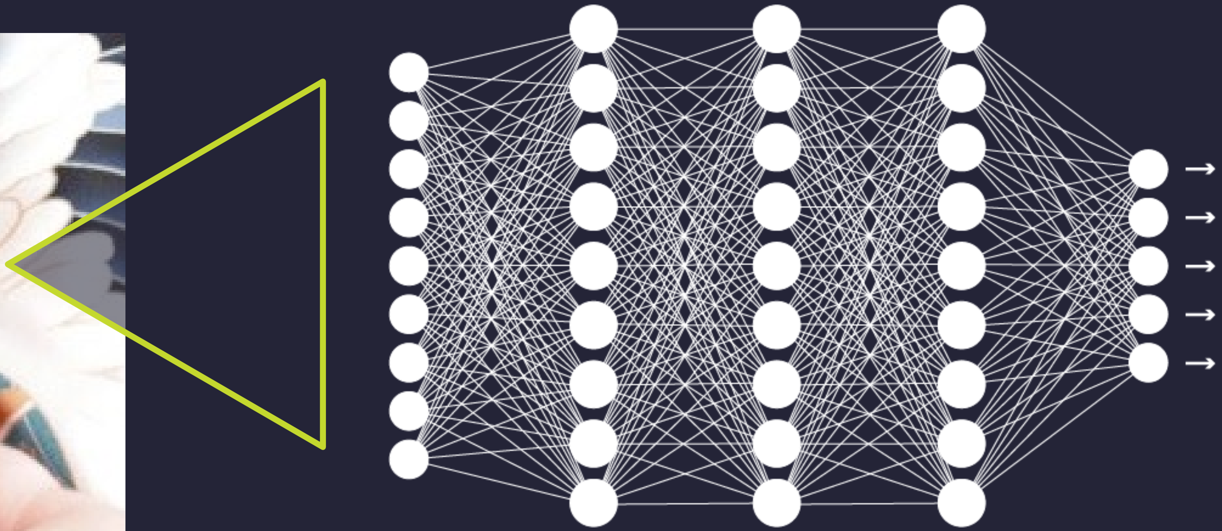
What is intelligence?



- Self-aware
- Self-maintained
- Self-adaptive

What paces the development of self-awareness?

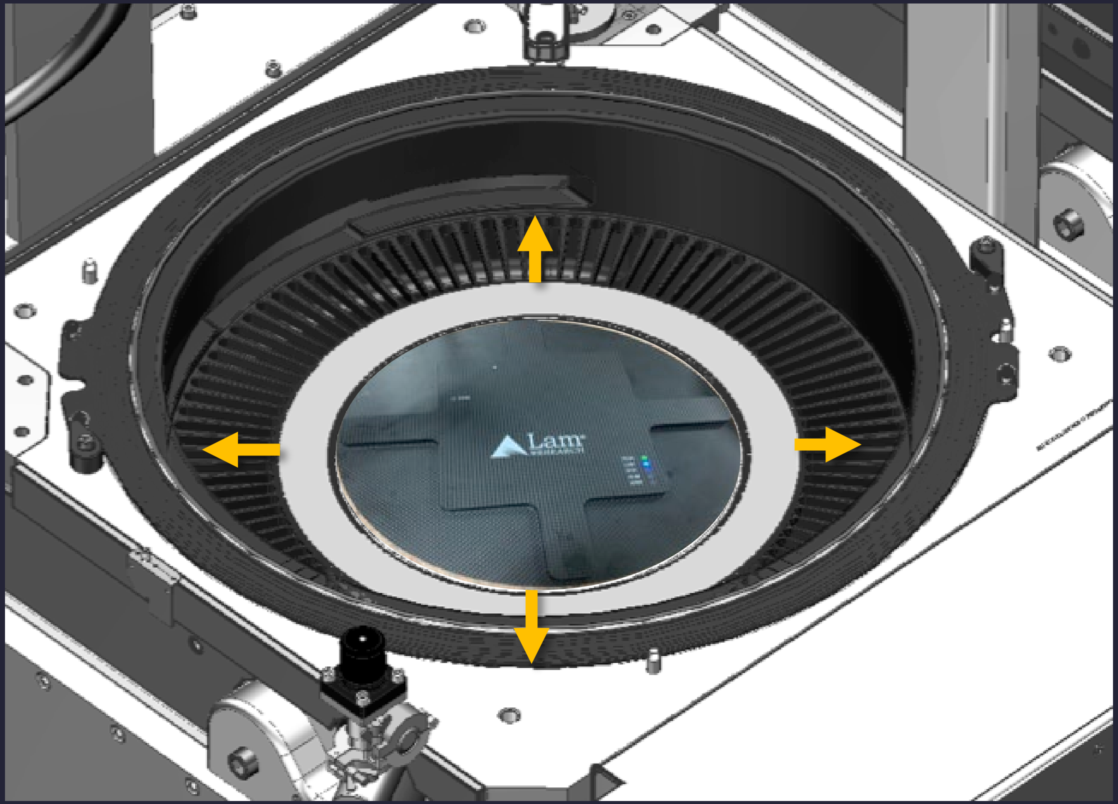
Self-Aware

Self-aware tools *know* what parts are inside and the properties of those parts past and present

Challenges:

- **All-digital supply chain**
- **End-to-end and point-to-point data transfers**
- **Standards**
- **IP**

Self-Aware, Self-Maintained...



Auto Positioning System

What Paces the Development of Self-Maintenance?

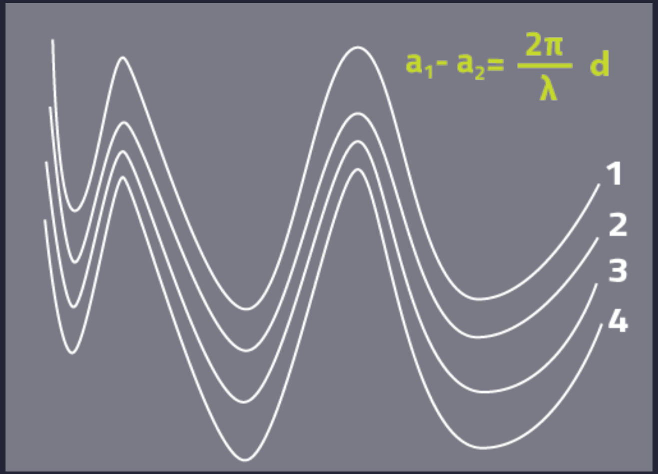
Self-Maintained

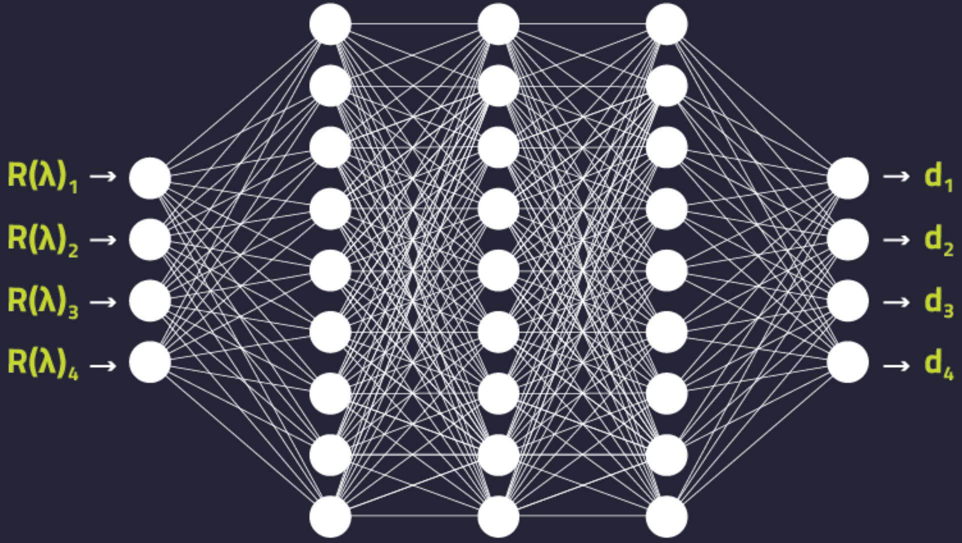
Self-maintained tools know when maintenance is required and *perform* maintenance automatically

Challenges:

- **Tool architectures**
- **Fab infrastructure**
- **Fab-tool co-design**
- **Standards**

Self-Aware, Self-Maintained, and Self-Adaptive





Machine learning on LSR-FM improved depth variability to ±1%

What Paces the Development of Adaptability?

Adaptive tools adjust themselves to compensate for unit process and incoming material variation to maintain consistent yield

Challenges:

- **Data flow across unit modules**
- **Algorithms**
- **Standards**
- **IP**

Adaptive

Equipment Intelligence® Solutions Are More Than Just a Smart Tool

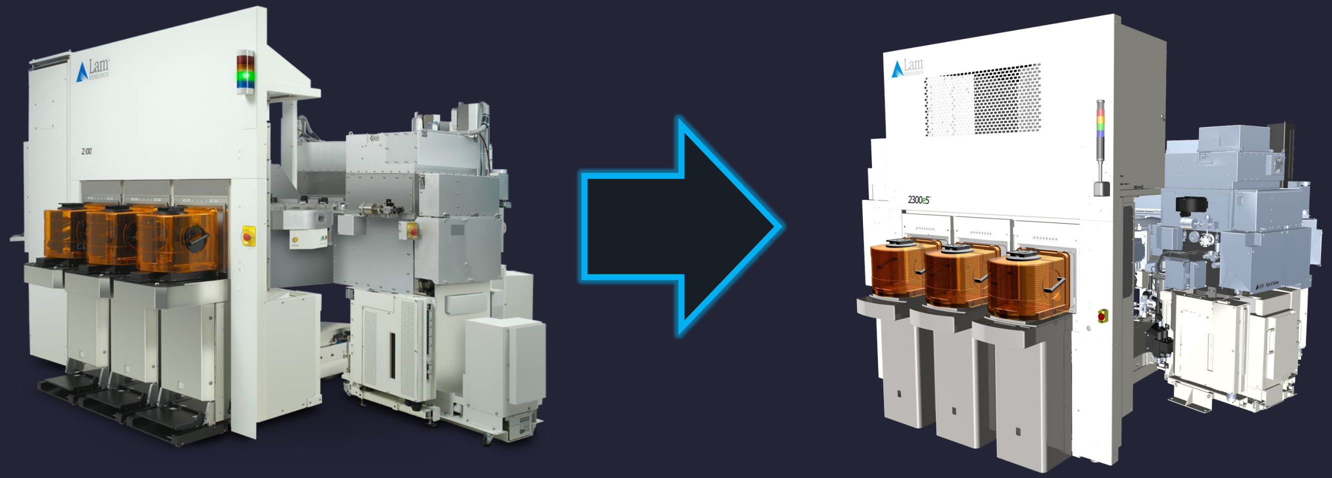
A new industry mindset is required

The semiconductor eco-system has to respond collaboratively

- All-digital supply chain
- End-to-end and point-to-point data transfer
- Co-design of fab and tool
- Big data and algorithms
- Standards and IP

Collaborative response must deliver equitable returns

Semiverse™ Solutions



Digital Twin and Thread:

Virtual representation of real asset including associated data and processes of record for all parts in the system

Digital twin and thread enables:

Virtual Build:

Digital design for manufacturability and serviceability

Digital twin and thread enables:

VR/AR-Led Training and Installation:

Step-by-step instructions for system installs and post- installation service

Virtual Process Development

Transforming R&D

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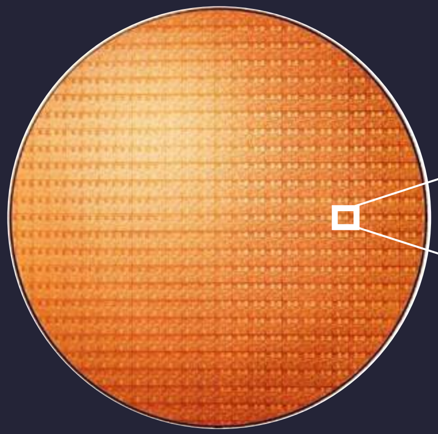
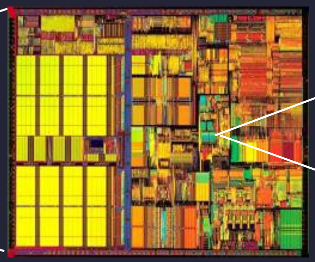
We develop the processes that make the chips

300 mm Wafer

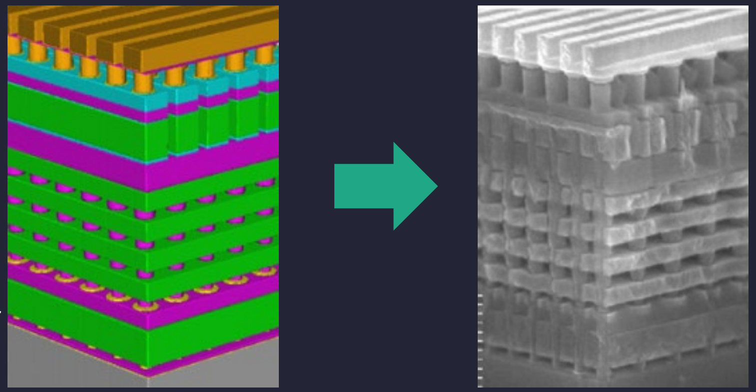


Chip



Source: Intel Museum

Just because you can design a chip, doesn't mean you can make it



Source: Chipworks

How much data from a semiconductor fab?

Example: Fleet running at high capacity

Fleet Size	200 chambers
Sensors	100 / chamber
Frequency	5 Hz

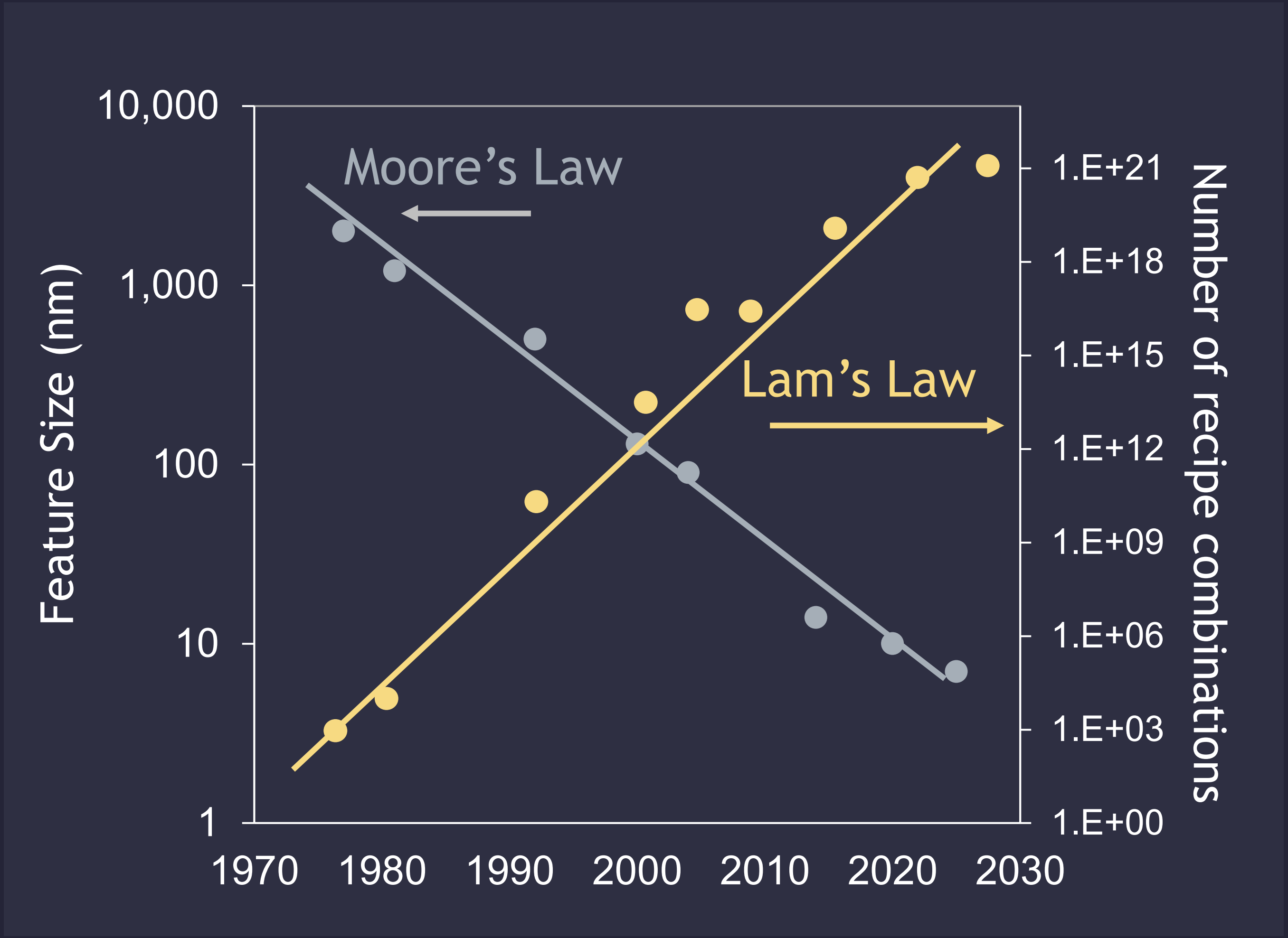
5 to 10 billion raw data points per day

Depending on the nature and complexity of the process

100 million feature data points per day

For each single wafer process run, there could be as many as 5,000 features extracted

Moore's Law and "Lam's Law"



Engineers must choose from many recipe combinations with little data available. The number of recipe combinations expected by 2030 will approach the number of silicon atoms in a computer chip

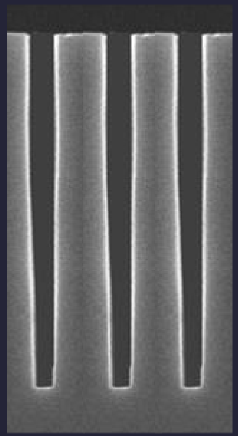
Yet we still do process engineering the “old” way...

Customer asks for Spec

Human process engineering

- Make hypothesis
- Choose recipes
- Run experiments
- Prep for metrology
- Image collection
- Data analysis

Spec is met



REPEAT

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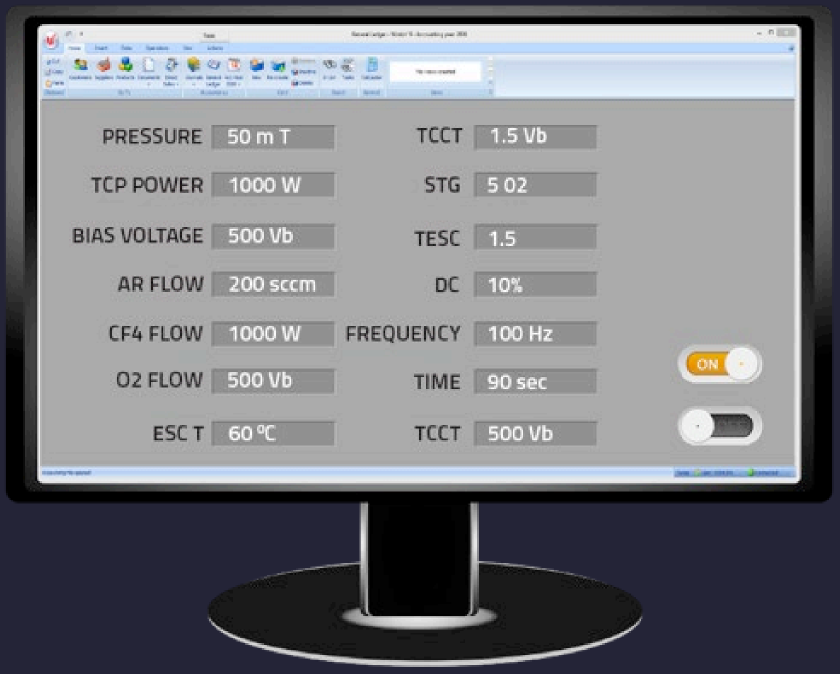
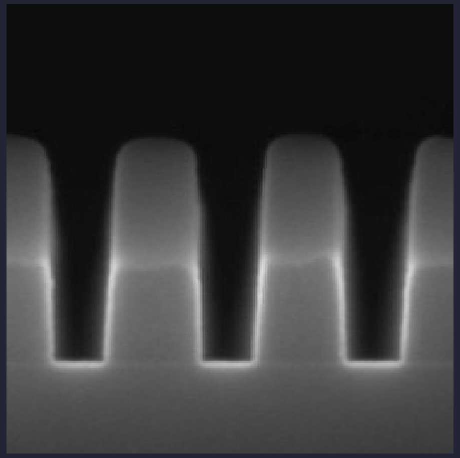
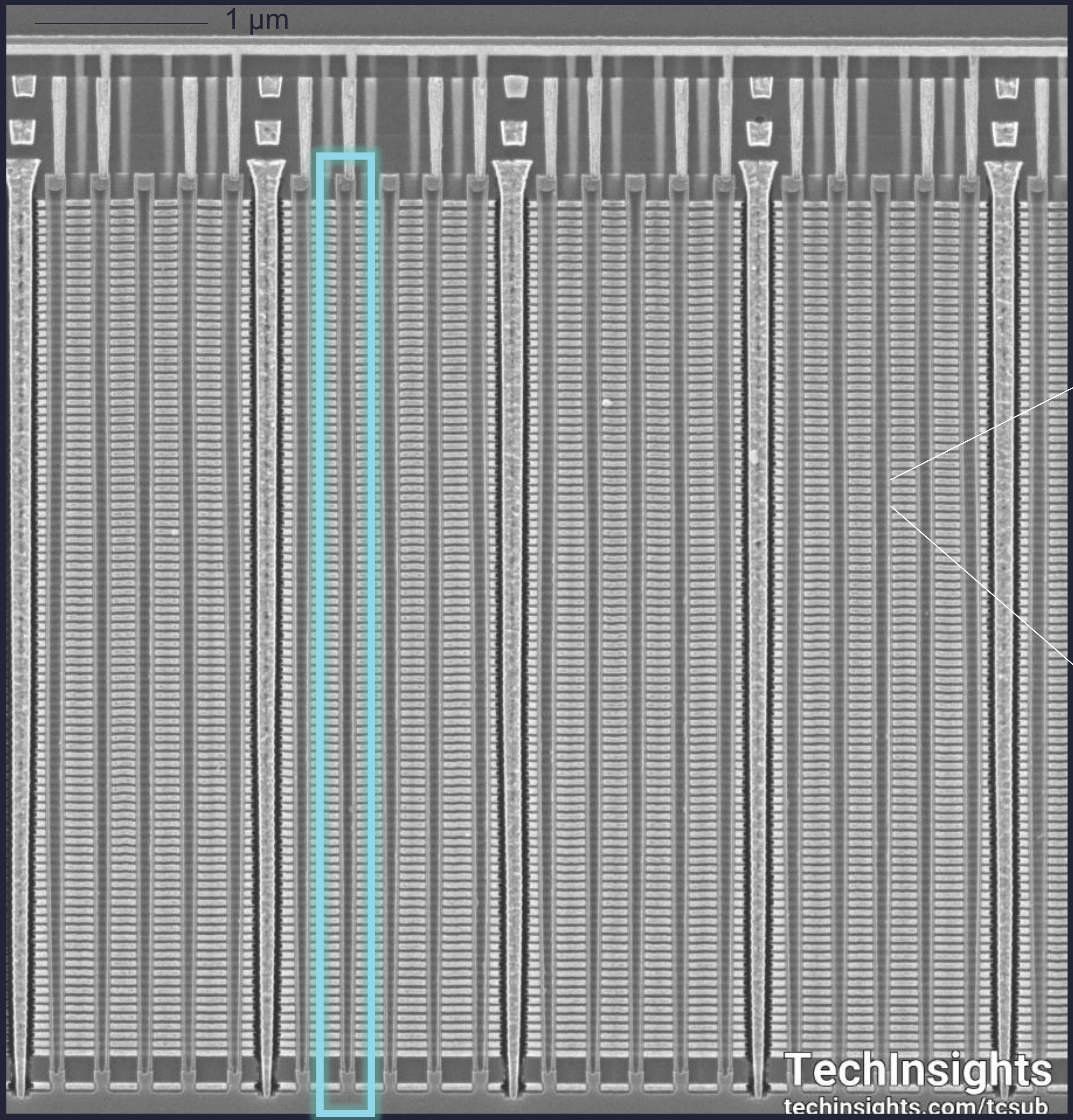
Why can’t we design a process like we design a chip?



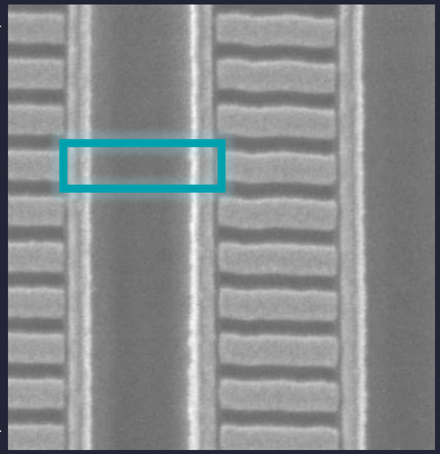


Consider memory hole etch in 3D NAND

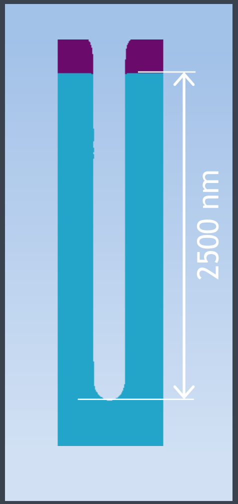
SEM of 3D NAND Samsung 92L, 256Gb, TLC, Tech Insights



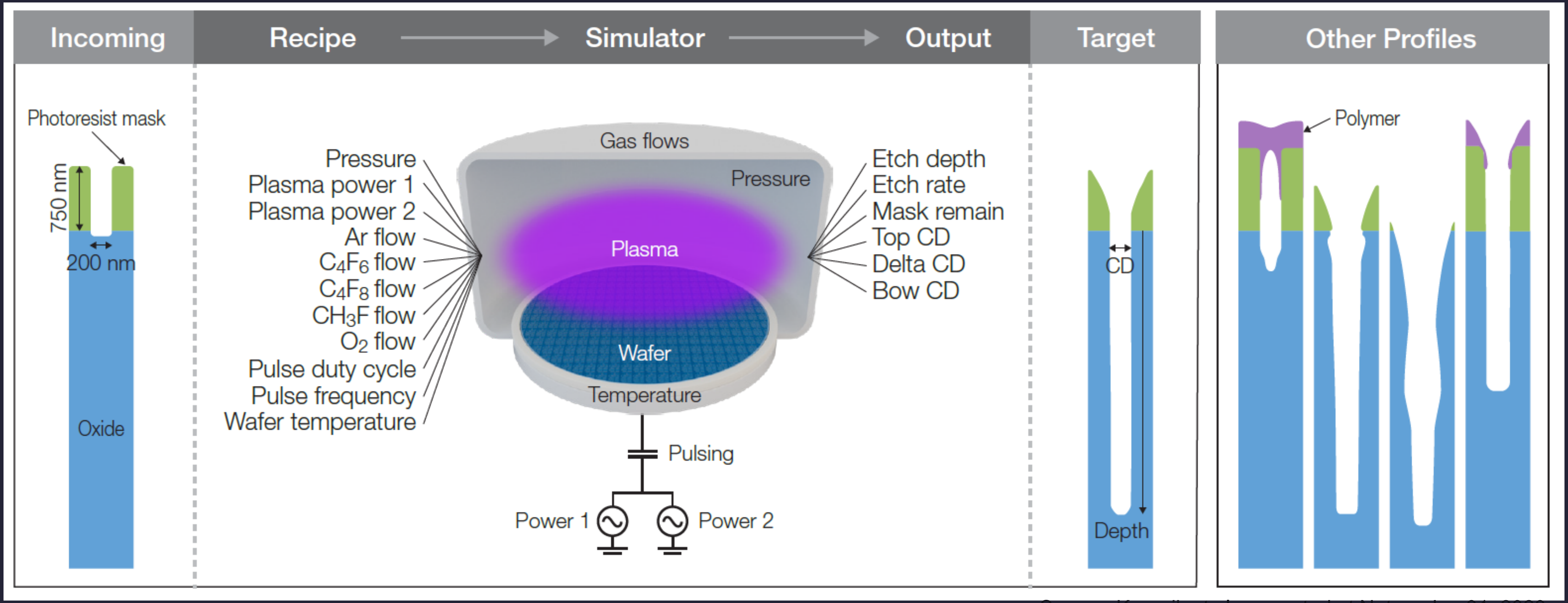
Memory cell



Let’s play a “game” to benchmark different AI (and human) approaches to developing an Etch Process Recipe



Virtual Environment for High Aspect Ratio Etch



Source: Kanarik et al., accepted at Nature Jan 31, 2023

Cost structure: \$1,000/recipe + \$1,000/batch of recipes
Added variability: none

Goal of game: Lowest cost-to-target recipe

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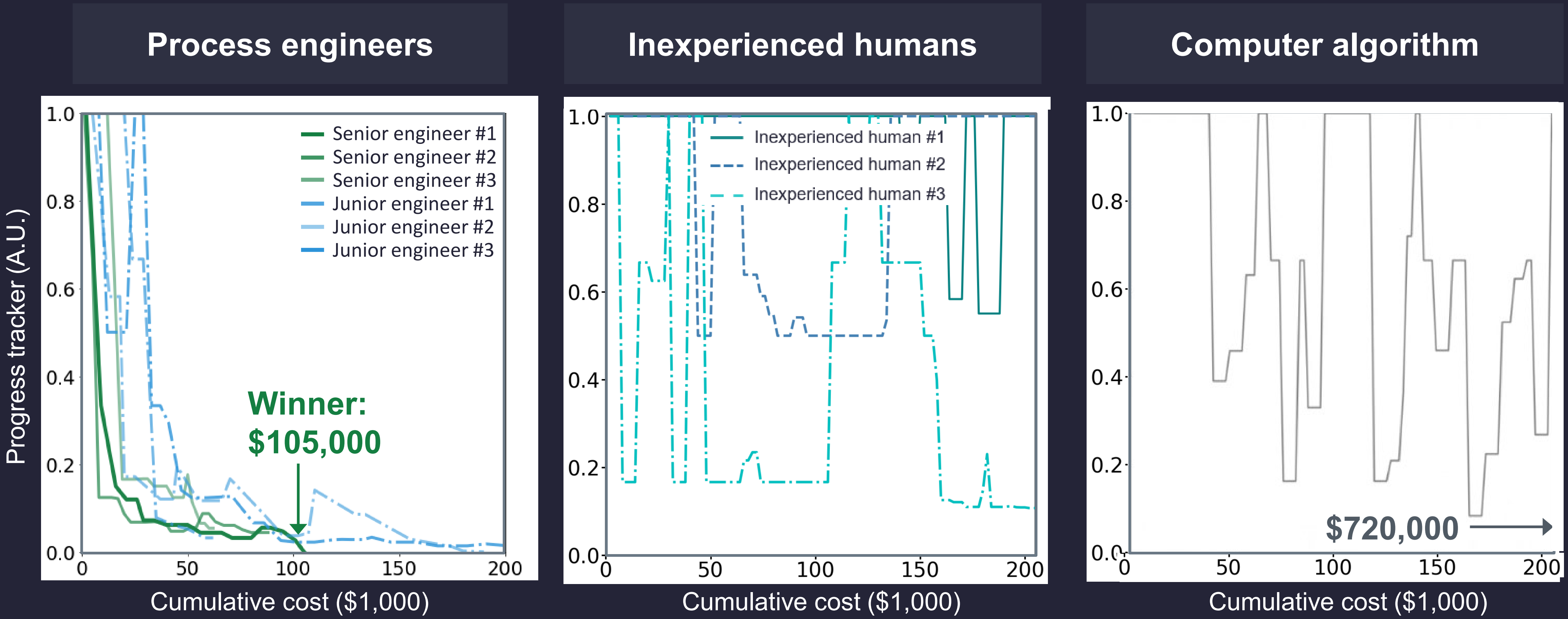
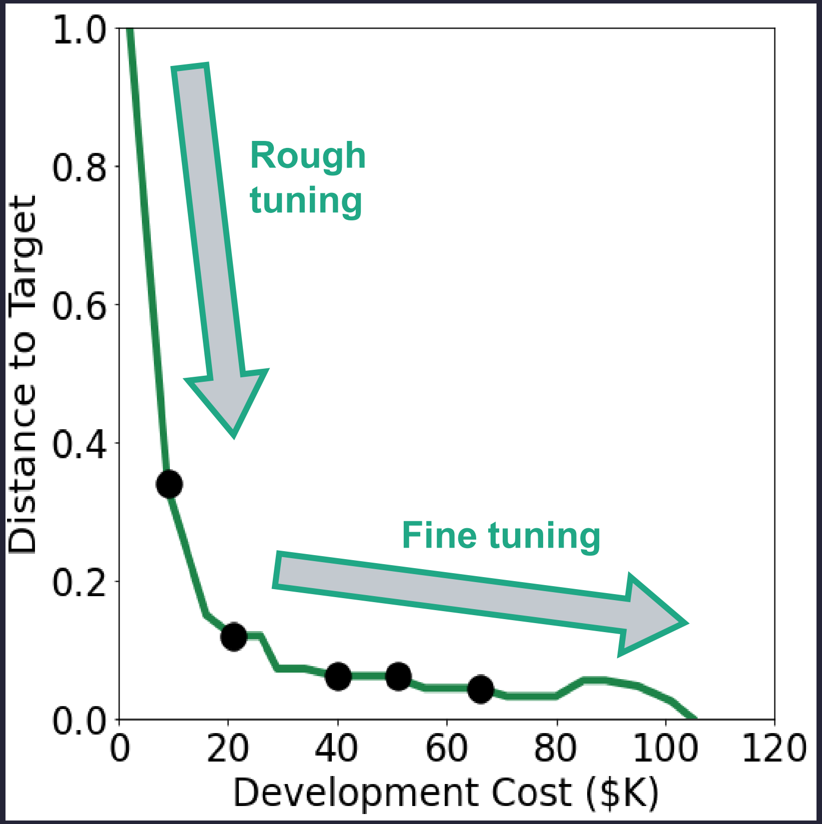
Undirected Machines are No Match for Expert Process Engineers



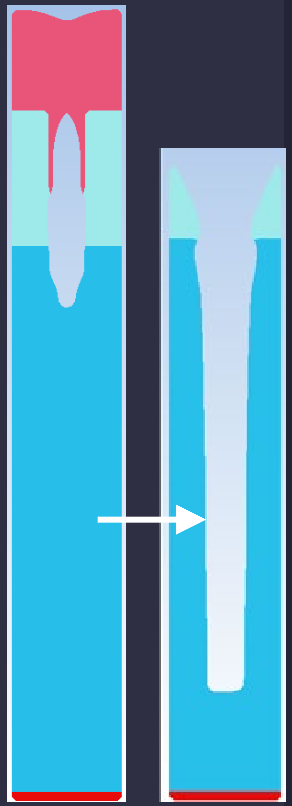
Human expert advantage occurs early in development

Expert trajectory



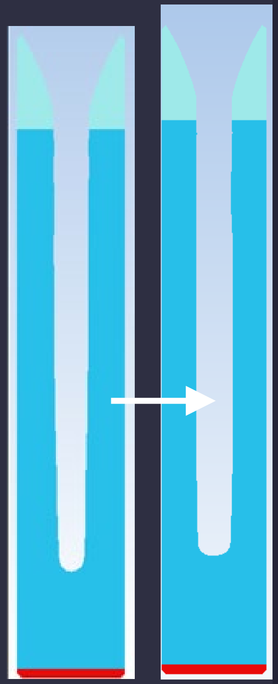
Rough-tuning stage

- Baseline from experience
- Move rapidly towards spec
- Domain knowledge: macro trends, physics principles and models, tribal knowledge, previous trends



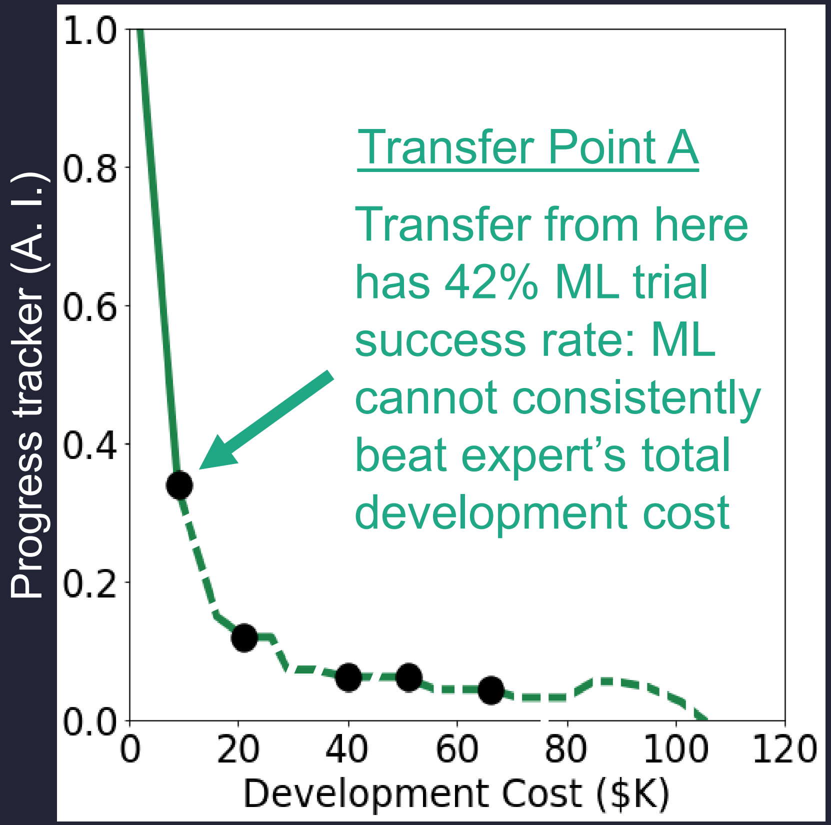
Fine-tuning stage

- Very close to spec
- Hyper-sensitive, physics *seems* to break down
- Smaller changes, smaller dynamic range
- Can take >50% of demo for engineer

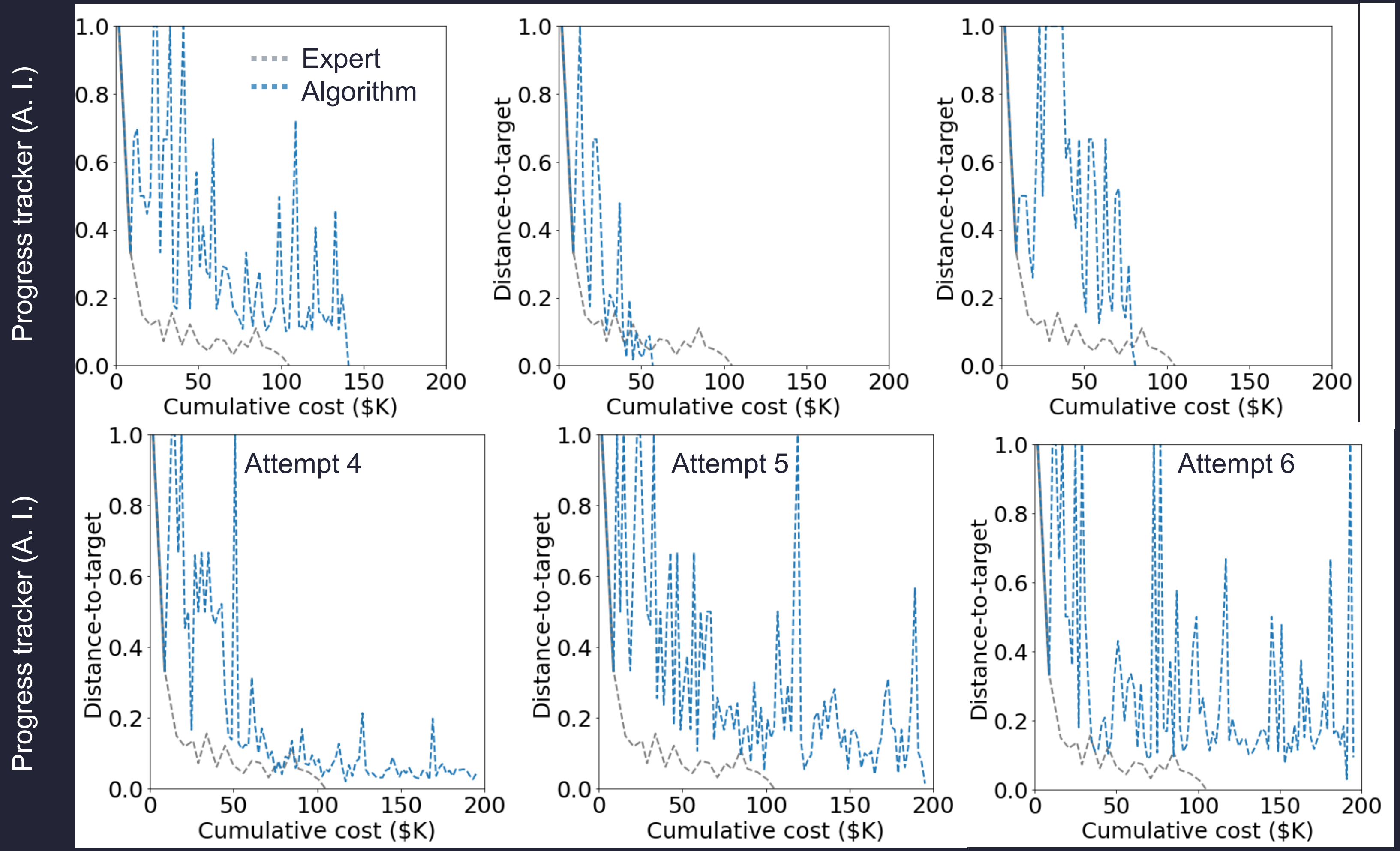


Transfer point "A": Computer improves but not enough

Expert Results – Without ML

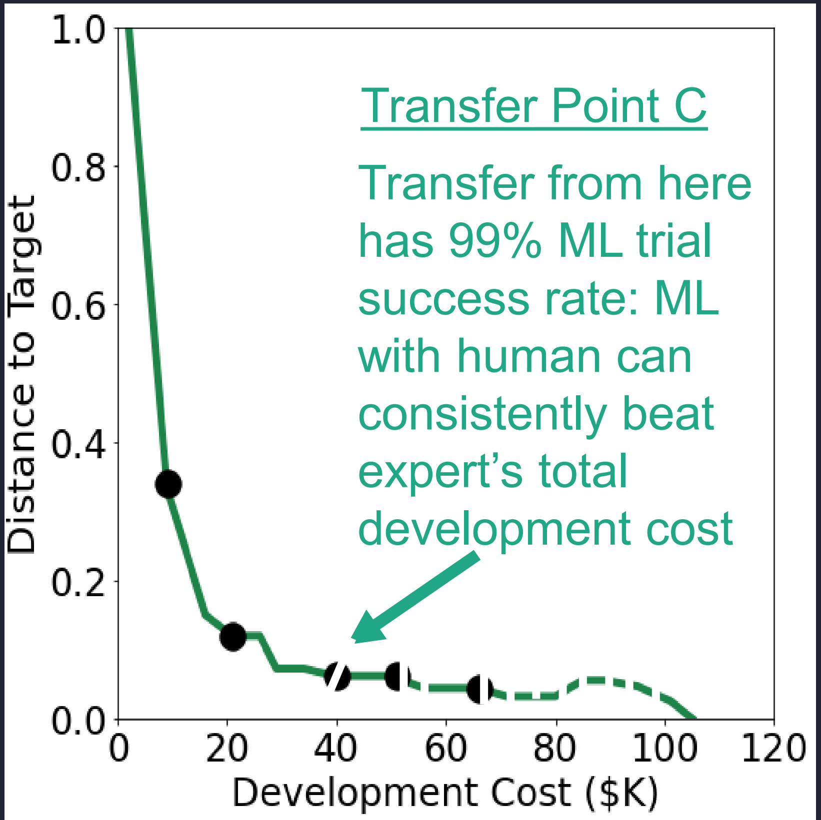


Machine Learning Trials – Cost to Target (6 attempts shown)

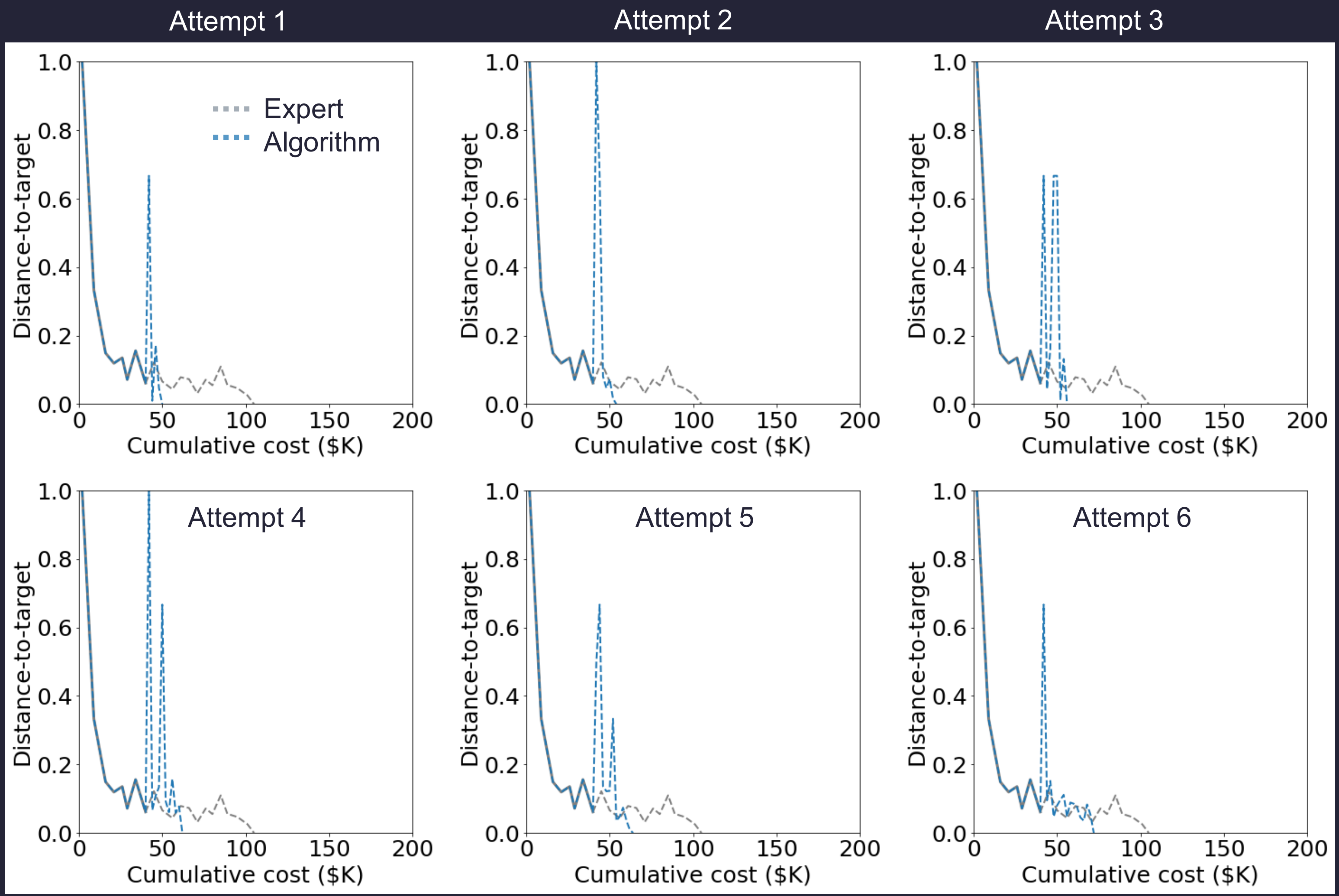


Transfer point "C": Human First, Computer Last Lowers Cost

Expert Results – Without ML

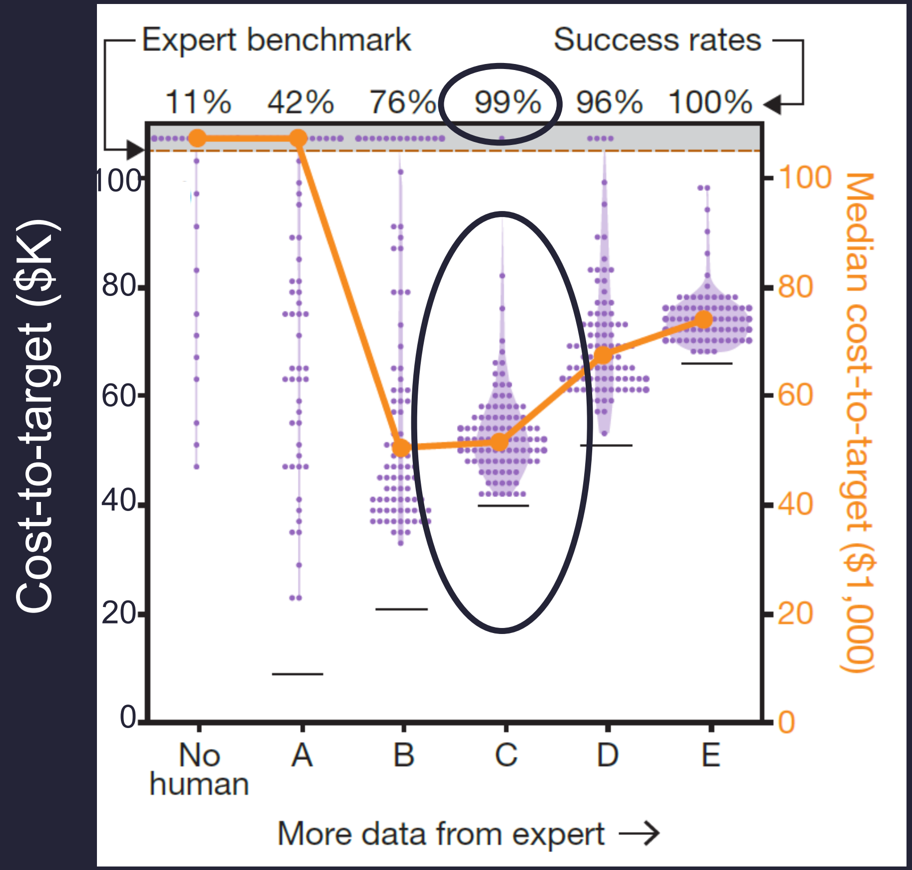


Machine Learning Trials – Cost to Target (6 attempts shown)

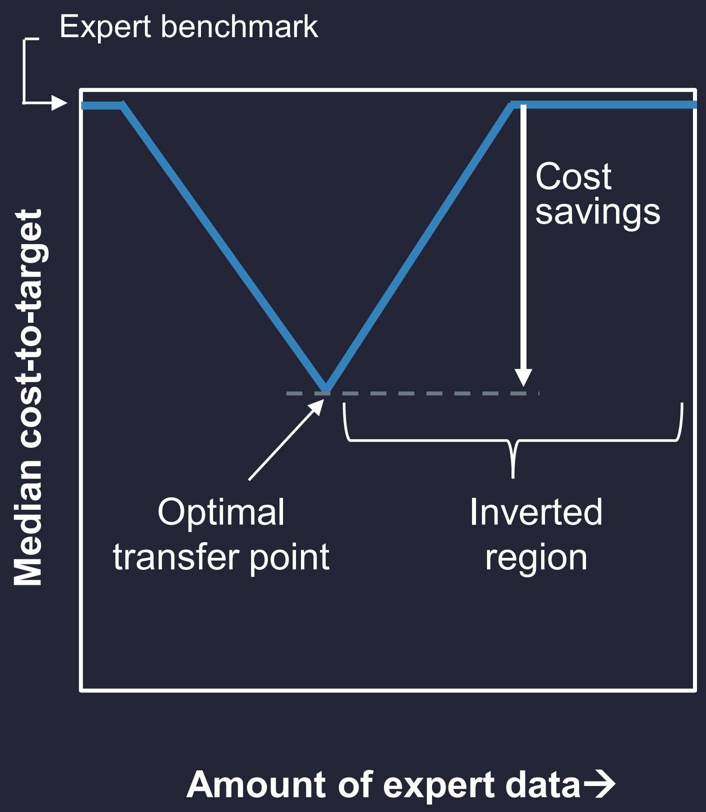


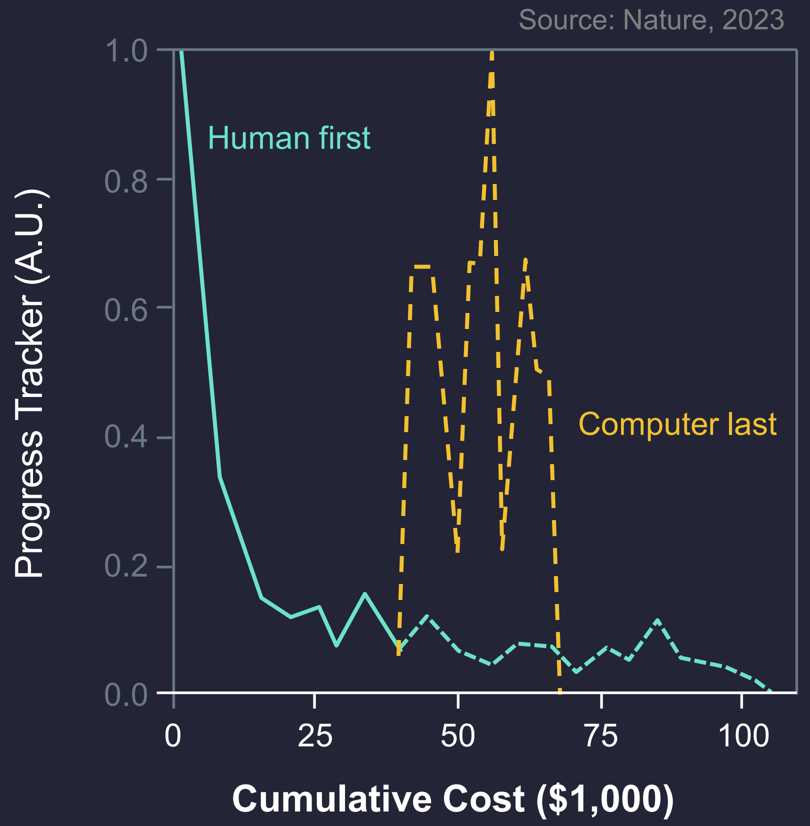
Optimal transfer point not too soon or too late (circled area)

Experimental V-curve



Schematic of V-curve





Embrace human machine collaboration: Humans for creative work and machines for repetition and tedious work

Human–Machine Collaboration for Improving Semiconductor Process Development

Nature 616, 707 (2023)

Scan with your phone for link to paper:

Keren J. Kanarik, Wojciech T. Osowiecki, Yu (Joe) Lu, Dipongkar Talukder,

Niklas Roschewsky, Sae Na Park, Mattan Kamon, David M. Fried, Richard A. Gottscho

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Semiverse™ Solutions for *10,000x lower cost*

Virtualization *leverages* (not replaces!) investment in physical assets and real experiments

Virtual experimentation saves time, money, and resources (per recipe)

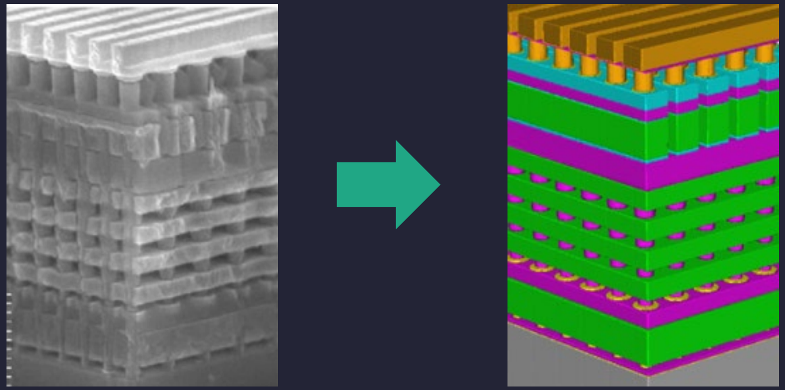
- Real experiments - $1,000, 0.5 days
- Simulated experiments - $0.11, 8 minutes
- Emulated simulations - $3e-07, 0.0013 seconds

Virtual experimentation can be ubiquitous and an effective workforce training tool

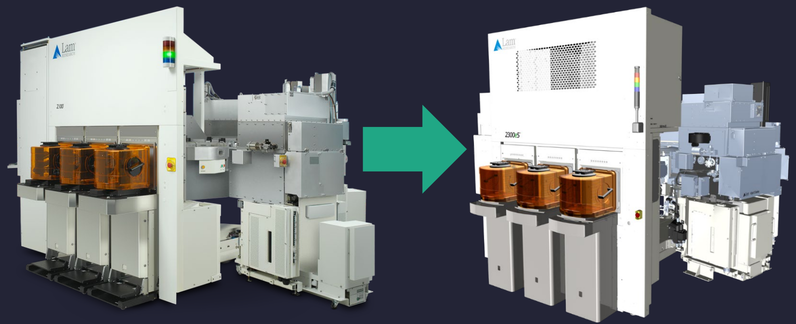
Barriers

- ***Business model***
- ***Some invention required***
- ***Data sharing/ownership concerns***

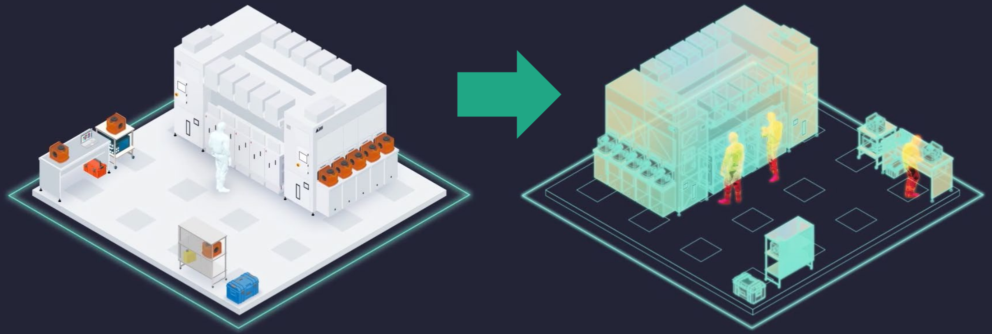
Virtual process:



Virtual tool:



Virtual fab:



Conclusions

The R&D little data problem requires maximum leveraging of information from real experiments

Models don't have to be accurate to be useful. They do need to be *realistic.*

The virtual environment can be used in workforce development

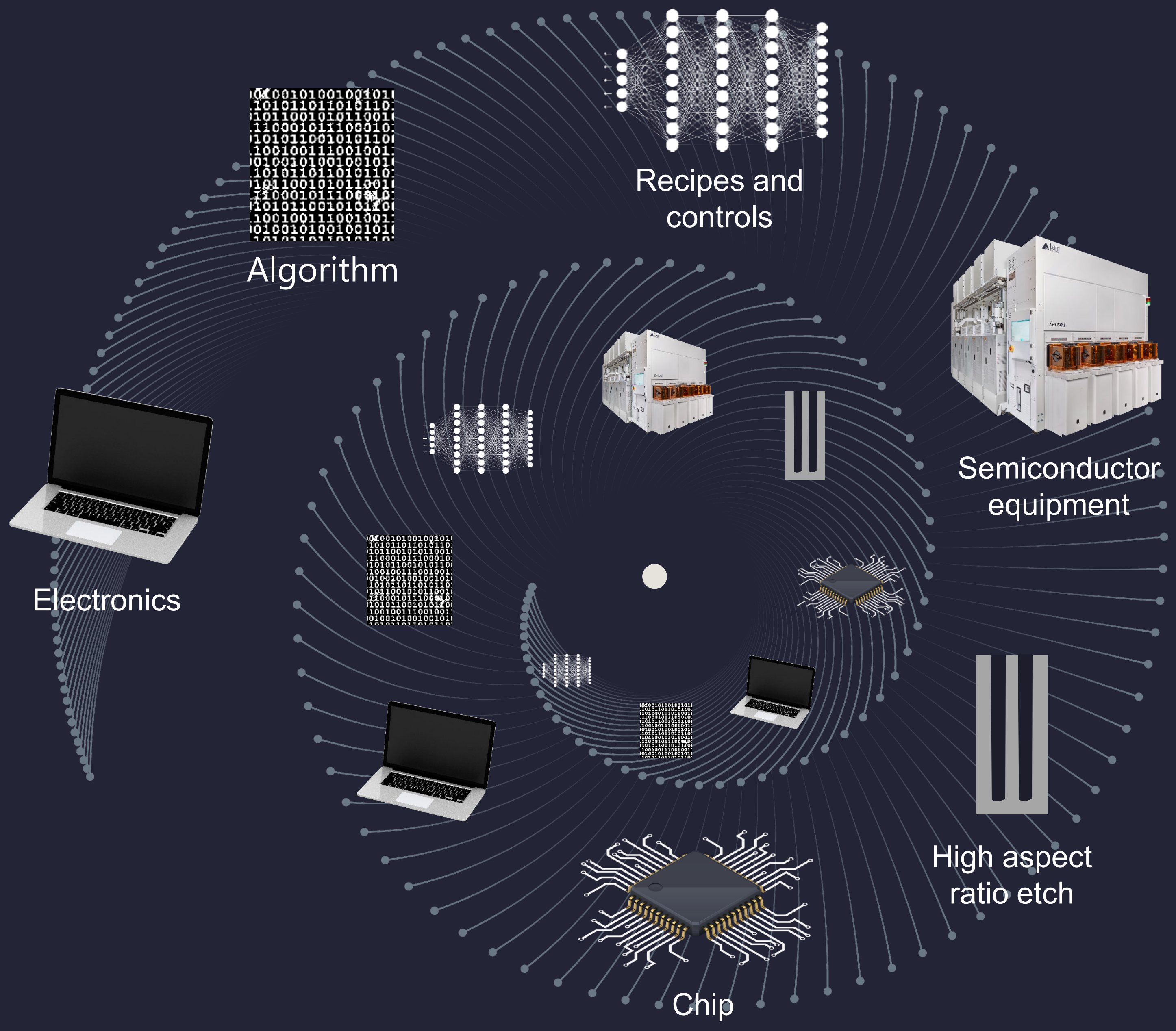
- Challenge problems
- Built-in analytics

The virtual environment enables speed to solution

The virtual environment reduces costs

Virtual process development – no panacea, but close!

We see ourselves in a virtuous, accelerating spiral of innovation



Q&A

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