The Power of Virtual Process Development

Faster solutions, lower cost, workforce development

Richard A. Gottscho, Ph.D.

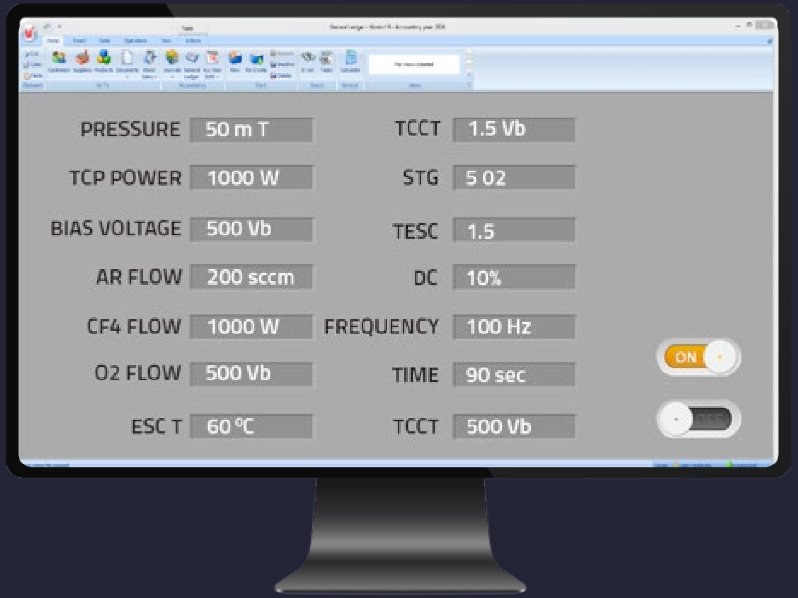
Executive Vice President, Strategic Advisor to the CEO, Innovation Ecosystem

Lam RESEARCH

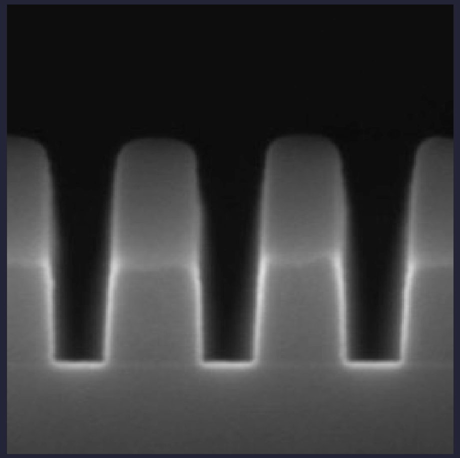
Why can’t we design a process like we design a chip?

SPEC

RECIPE



RESULT

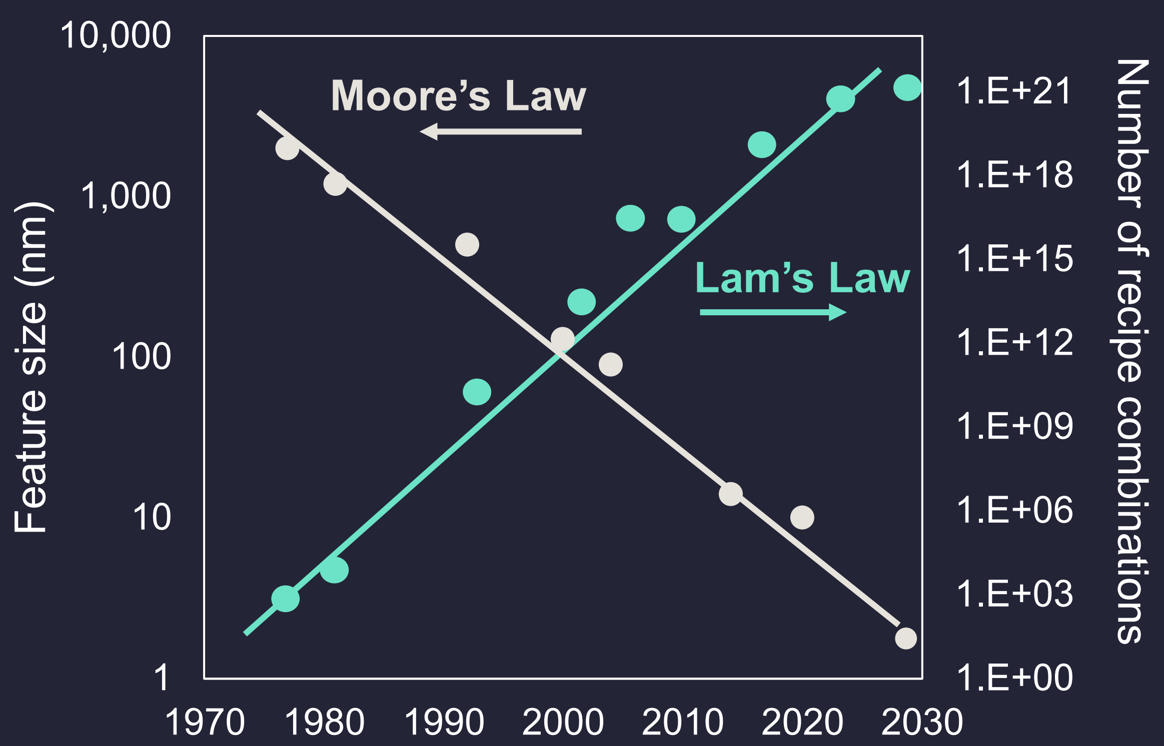


Why not just use a *big data* approach?

Simply put, it costs too much and takes too long

Little data world but *big* dimensional space

~ AVOGADRO'S NUMBER OF RECIPES



LAM RESEARCH

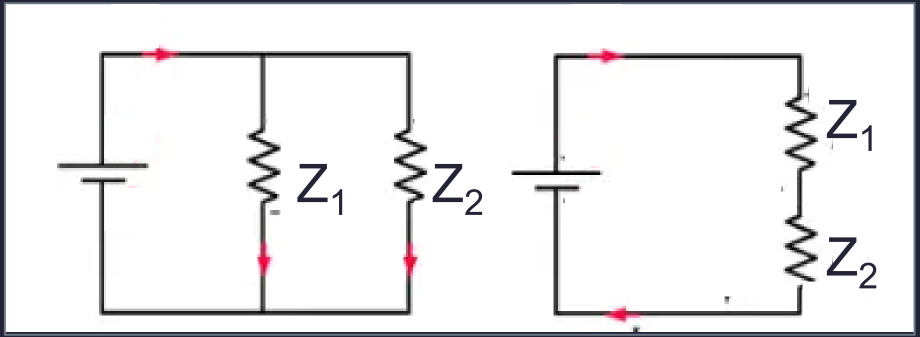
What about *physics?...*

Natural simplifications

TABLE I. Oxygen reaction set.

Reaction			Rate coefficients
$e+O_2$	$\longrightarrow$	$O_2^+ + 2e$	$k_1=9.0\times10^{-10}\ (T_e)^2 \exp(-12.6/T_e)\ cm^3\ s^{-1}$
$e+O_2$	$\longrightarrow$	$O(^3P)+O(^1D)+e$	$k_2=5.0\times10^{-8} \exp(-8.4/T_e)\ cm^3\ s^{-1}$
$e+O_2$	$\longrightarrow$	$O(^3P)+O^-$	$k_3=4.6\times10^{-11} \exp(2.91/T_e-1.26/T_e^2+6.92/T_e^3)\ cm^3\ s^{-1}$
$e+O(^3P)$	$\longrightarrow$	$O^+ + 2e$	$k_4=9.0\times10^{-9}\ (T_e)^{0.7} \exp(-13.6/T_e)\ cm^3\ s^{-1}$
$O^- + O_2^+$	$\longrightarrow$	$O(^3P)+O_2$	$k_5=1.4\times10^{-7}\ cm^3\ s^{-1}$
$O^- + O^+$	$\longrightarrow$	$O(^3P)+O(^3P)$	$k_6=2.7\times10^{-7}\ cm^3\ s^{-1}$
$e+O^-$	$\longrightarrow$	$O(^3P)+2e$	$k_7=1.73\times10^{-7} \exp(-5.67/T_e+7.3/T_e^2-3.48/T_e^3)\ cm^3\ s^{-1}$
$e+O_2$	$\longrightarrow$	$O(^3P)+O(^3P)+e$	$k_8=4.23\times10^{-9} \exp(-5.56/T_e)\ cm^3\ s^{-1}$
$e+O(^3P)$	$\longrightarrow$	$O(^1D)+e$	$k_9=4.47\times10^{-9} \exp(-2.286/T_e)\ cm^3\ s^{-1}$
$O(^1D)+O_2$	$\longrightarrow$	$O(^3P)+O_2$	$k_{10}=4.1\times10^{-11}\ cm^3\ s^{-1}$
$O(^1D)+O(^3P)$	$\longrightarrow$	$O(^3P)+O(^3P)$	$k_{11}=8.1\times10^{-12}\ cm^3\ s^{-1}$
$O(^1D)$	$\xrightarrow{\text{(wall)}}$	$O(^3P)$	$k_{12}=D_{eff}/\Lambda^2\ s^{-1}$
$e+O(^1D)$	$\longrightarrow$	$O^+ + 2e$	$k_{13}=9.0\times10^{-9}\ (T_e)^{0.7} \exp(-11.6/T_e)\ cm^3\ s^{-1}$
$O^+(g)$	$\xrightarrow{\text{(wall)}}$	$O(^3P)(g)$	$k_{14}=2u_{B,O^+}(R^2h_L+RLh_R)/R^2L\ s^{-1}$
$O_2^+(g)$	$\xrightarrow{\text{(wall)}}$	$O_2(g)$	$k_{15}=2u_{B,O_2^+}(R^2h_L+RLh_R)/R^2L\ s^{-1}$
$O(g)$	$\xrightarrow{\text{(wall)}}$	$\frac{1}{2}O_2(g)$	$k_{16}=\gamma_{rec}D_{eff}/\Lambda^2\ s^{-1}$

PARALLEL **SERIES**



$$\frac{1}{Z_{eff}} = \frac{1}{Z_1} + \frac{1}{Z_2}$$

$$Z_{eff} = Z_1 + Z_2$$

$Z_{eff} \sim Z_1$ When $Z_2 >> Z_1$

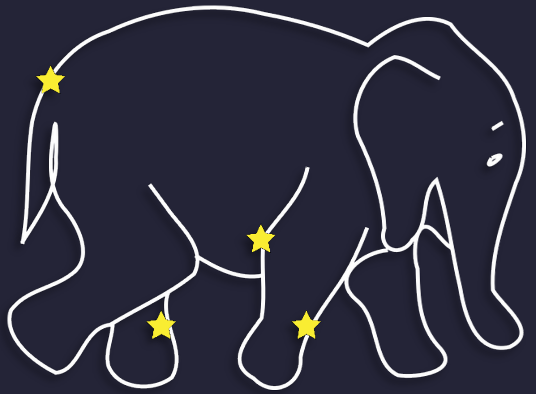
$Z_{eff} \sim Z_2$ When $Z_2 >> Z_1$

Where Z ≡ chemical impedance ~1/keff

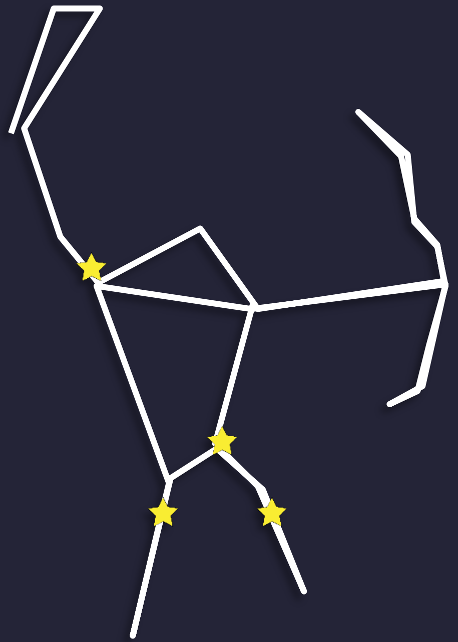
Source: Lee and Lieberman, global model, 1994

Exploit little data with right (physics-based) model

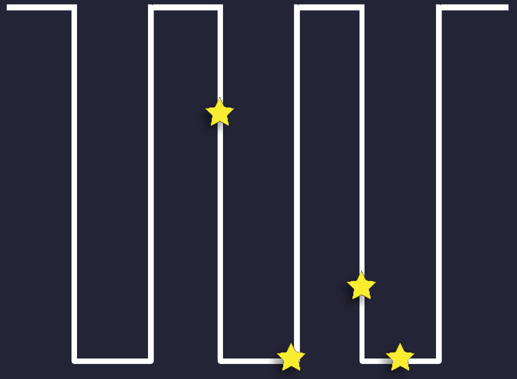
MODEL 1



MODEL 2



MODEL 3

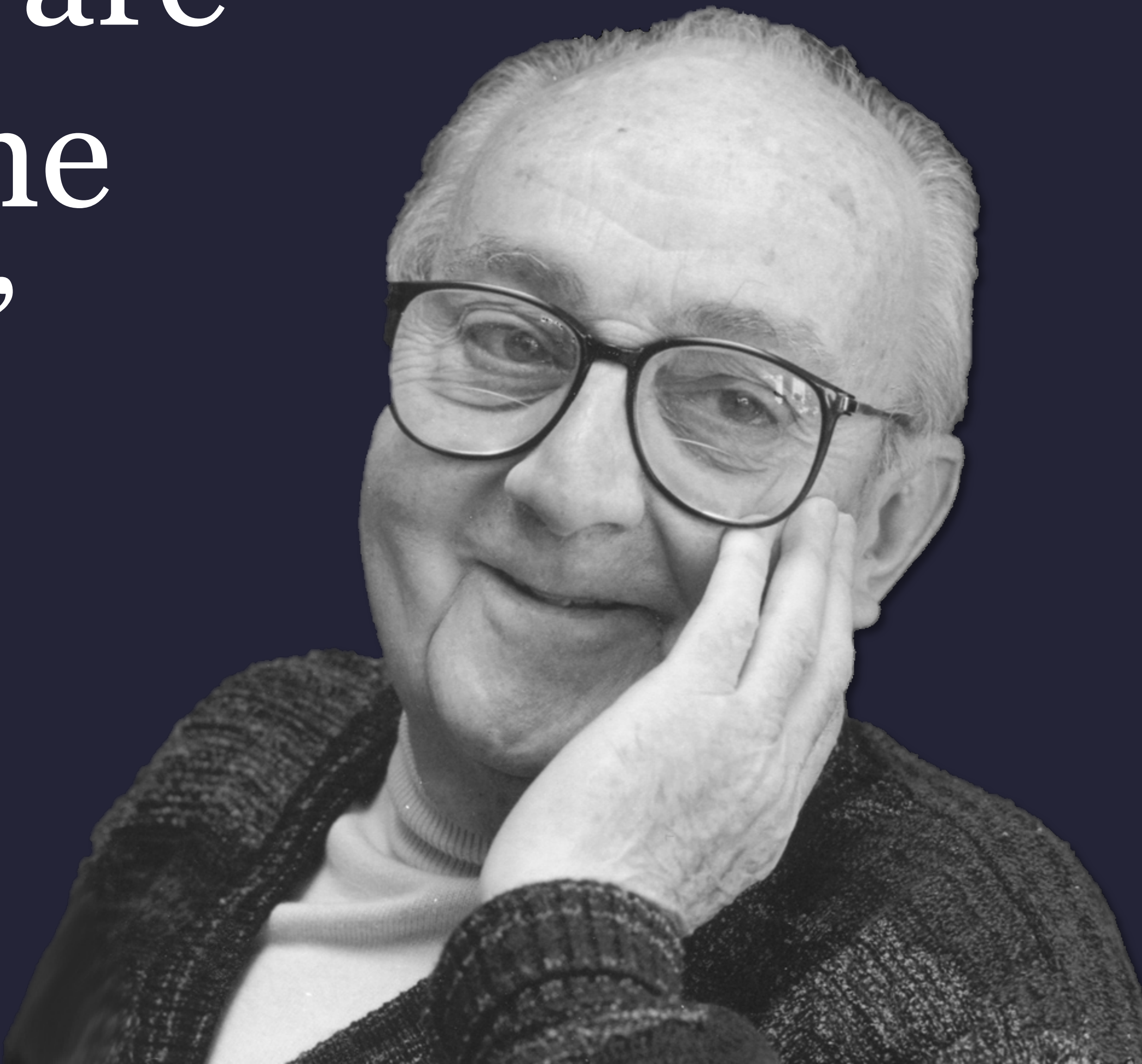


"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk."

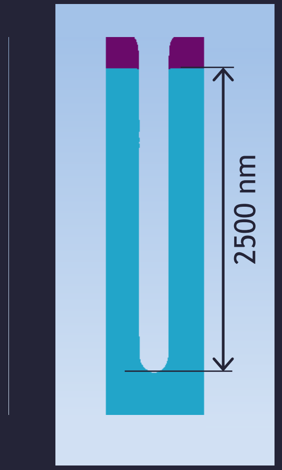
John von Neumann, as related by Freeman Dyson (2004)
"A meeting with Enrico Fermi," Nature 427 (6972)

“All models are wrong, some are useful.”

George Box, 1976

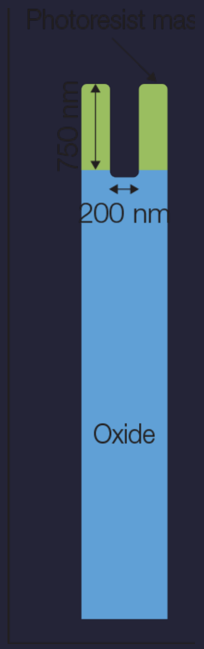


Let's play a "game" to benchmark different AI (and human) approaches

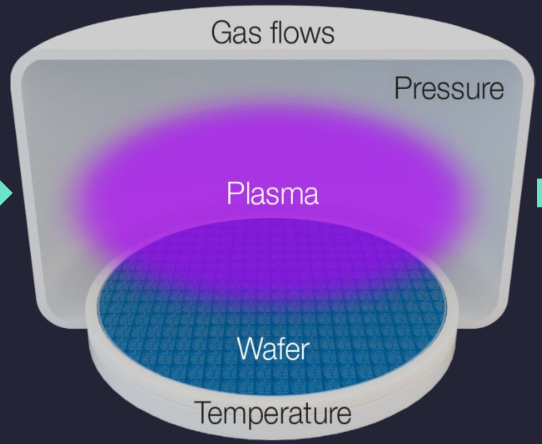


A virtual plasma etch process “cousin”

INCOMING | **RECIPE** → **SIMULATOR** → **OUTPUT** | **TARGET** | **OTHER PROFILES**

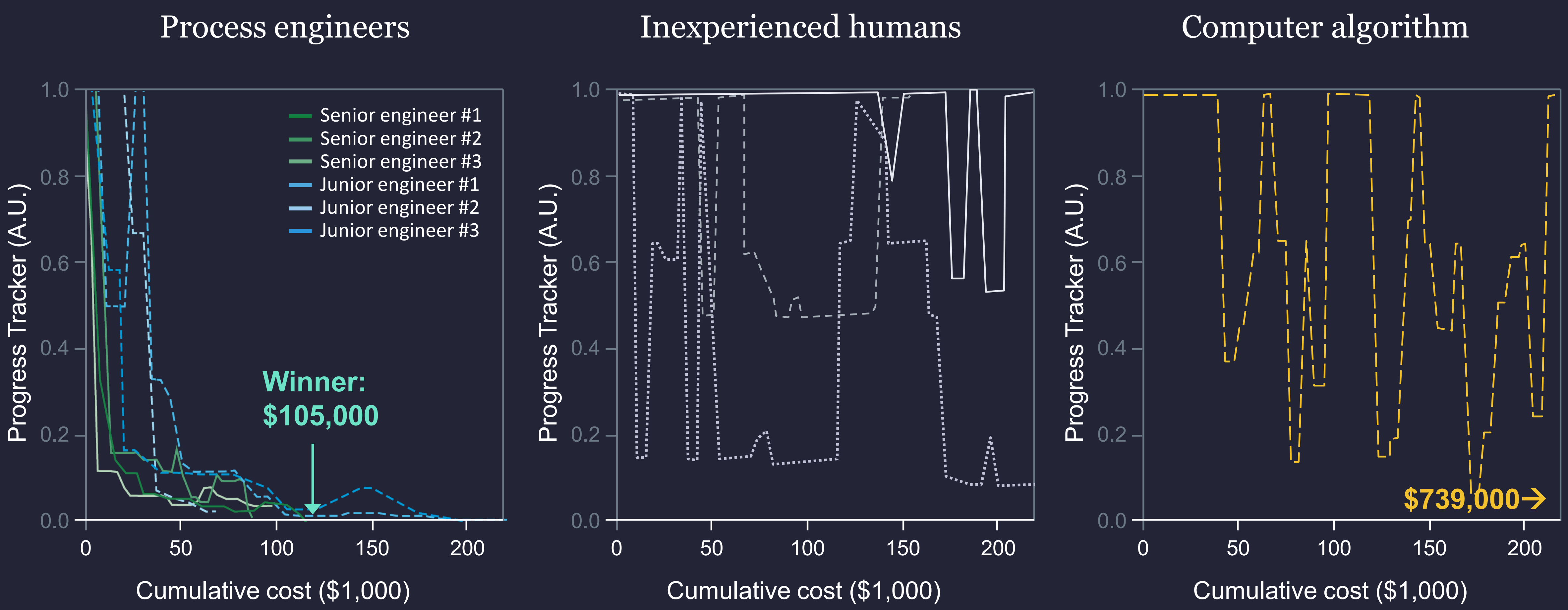


Pressure
Plasma power1
Plasma power2
Ar flow
Gas 1
Gas 2
Gas 3
Duty cycle
Pulse frequency
Temperature



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

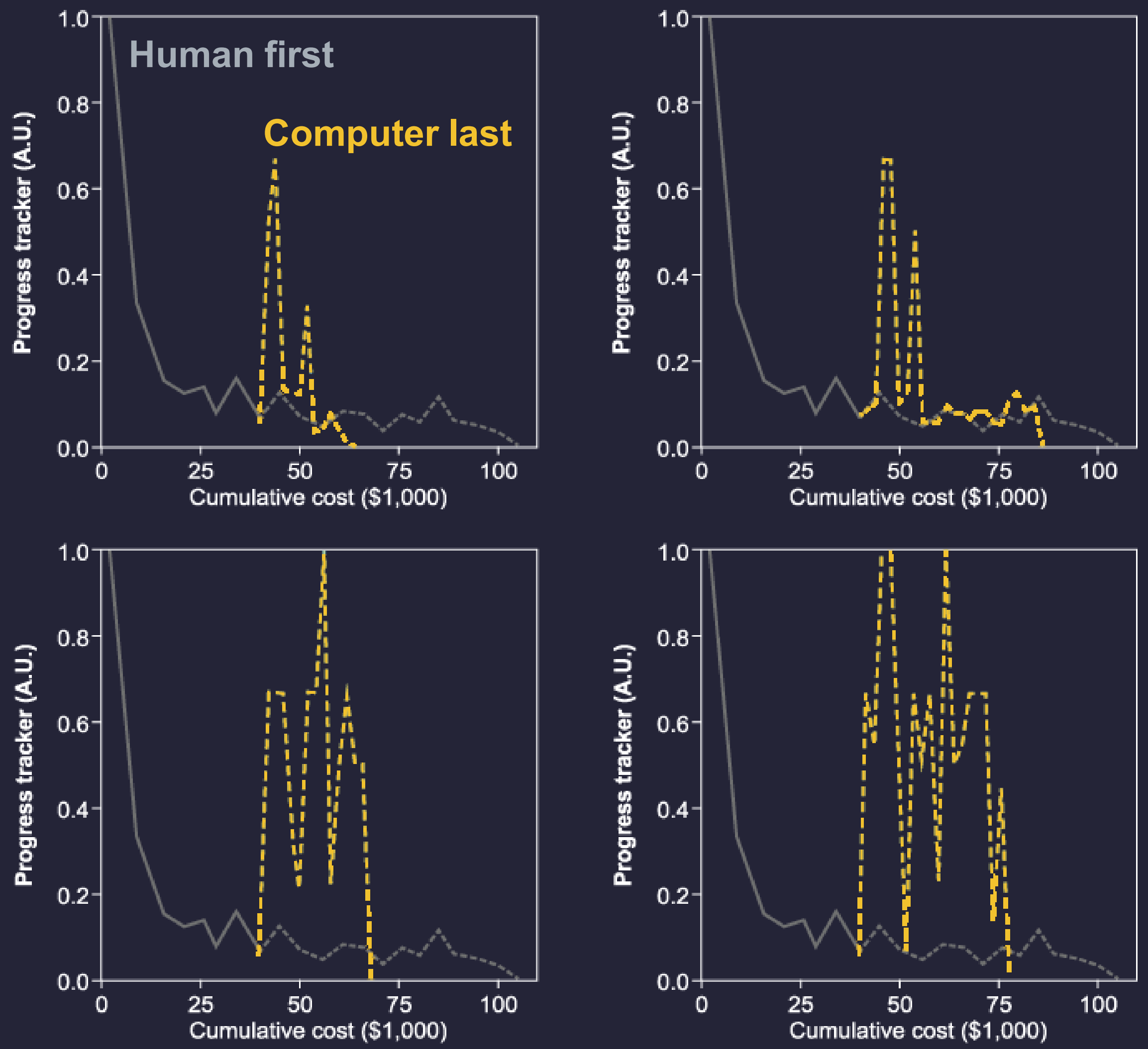
Machine alone was no match for expert engineer



Source: Kanarik et al, Nature, 2023

Human-machine collaboration yields cost and time savings

Expert trajectory

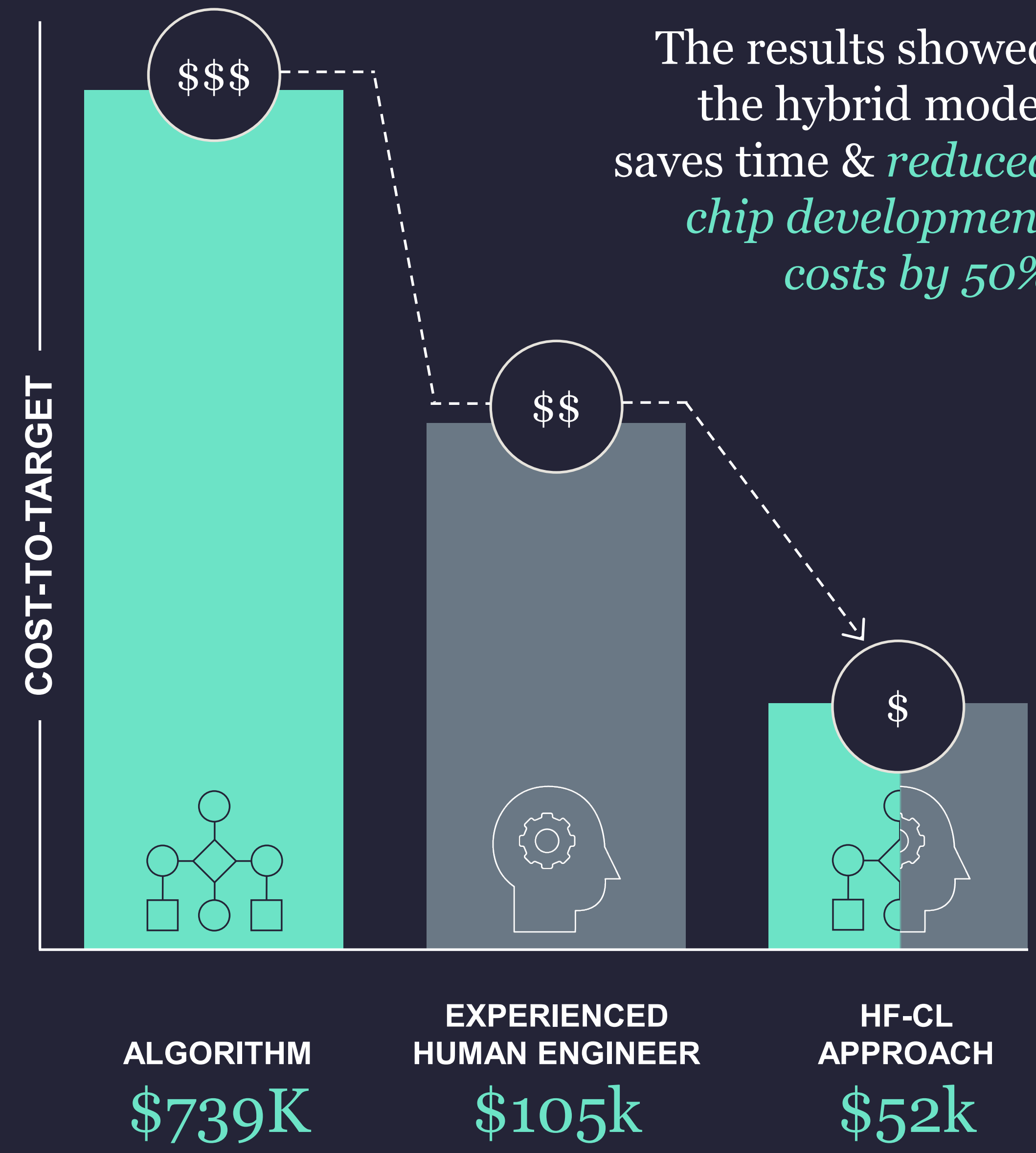


Success rate: % meeting target at lower cost than expert
Source: Kanarik et al, Nature, 2023

Hybrid approach wins

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

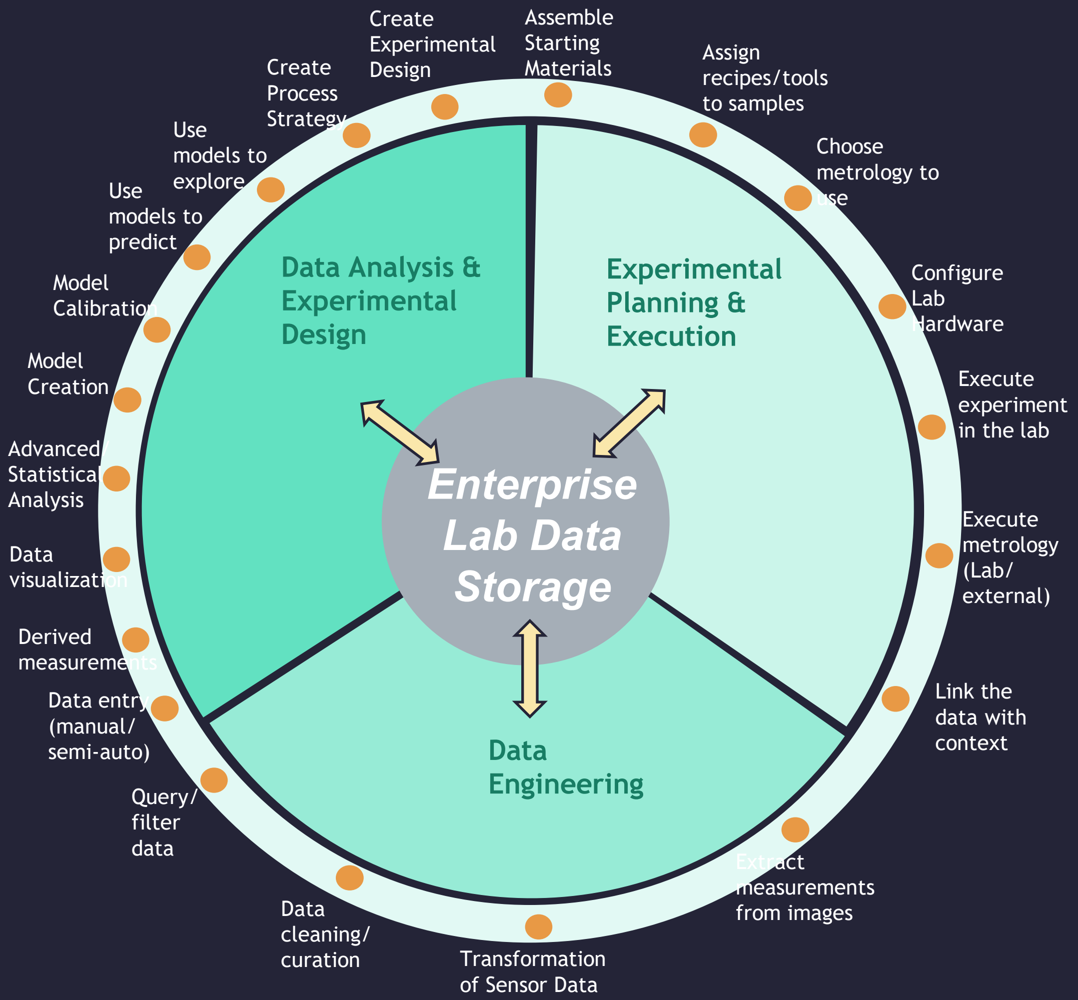
The results showed the hybrid model saves time & *reduced chip development costs by 50%*



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

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

LAM RESEARCH

Lam®
RESEARCH