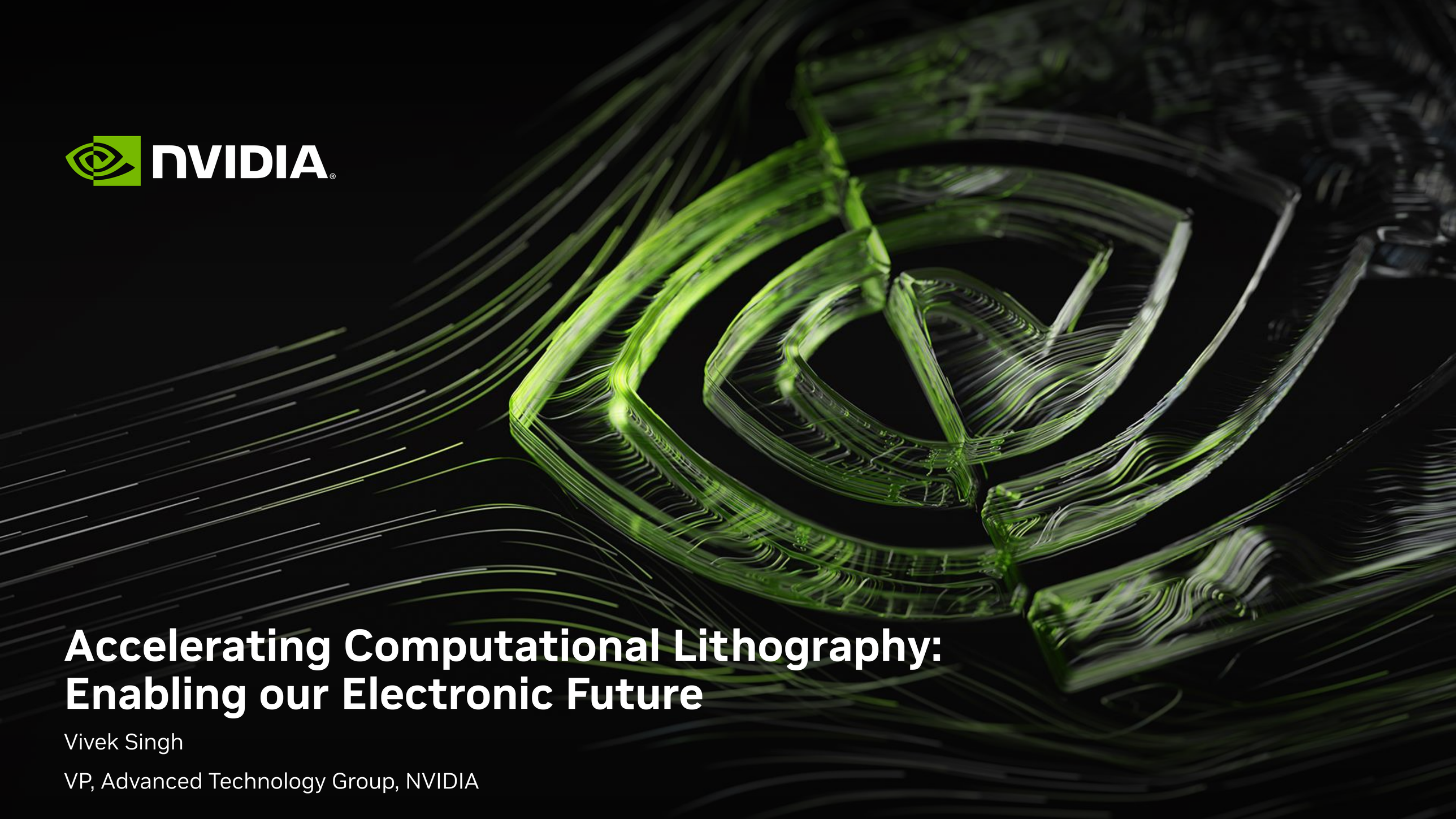

Accelerating Computational Lithography: Enabling our Electronic Future

Vivek Singh

VP, Advanced Technology Group, NVIDIA

Outline

- What is Computational Lithography?
- The Problem: Exploding Computation
- The Breakthrough!
- Enables Better Chip Technology, Faster
- Summary, and a quiz!

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Outline

- **What is Computational Lithography?**
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Warm up with photography

- Camera shopping tip: Buy largest aperture
  - Aperture shown as ratio
  - Need low denominator
  - 2.0 is good, 1.4 excellent, and expensive

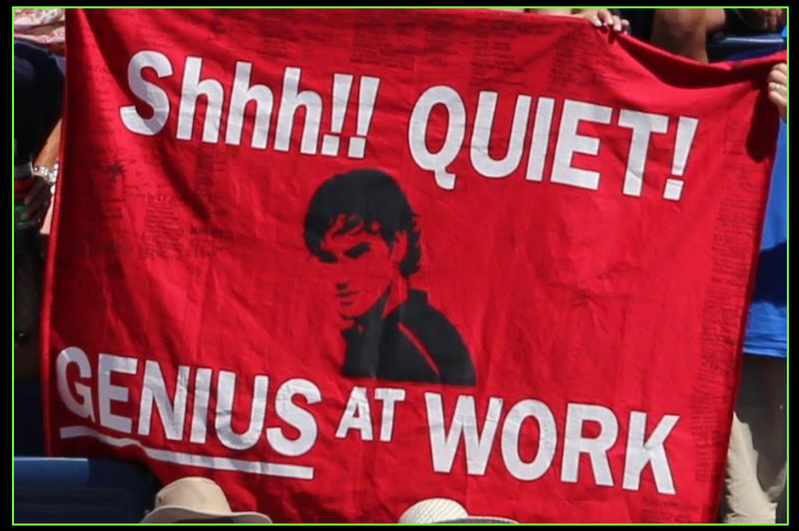
- Aperture also appears in Rayleigh Criterion in diffractive optics

$$resolution \propto \frac{wavelength}{aperture}$$

Aperture in daily life

Federer, Indian Wells 2015

Large aperture (f/2.0)
Low depth of field



Small aperture (f/7.1)
High depth of field

$$depth\ of\ field \propto \frac{1}{(aperture)^2}$$

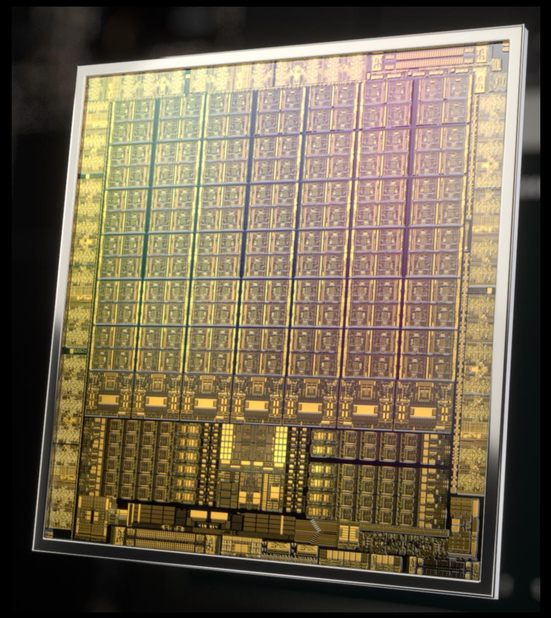
Low depth of field: good for pictures, bad for IC yield

NVIDIA

1X

Your laptop

15X



NVIDIA Ampere

NVIDIA

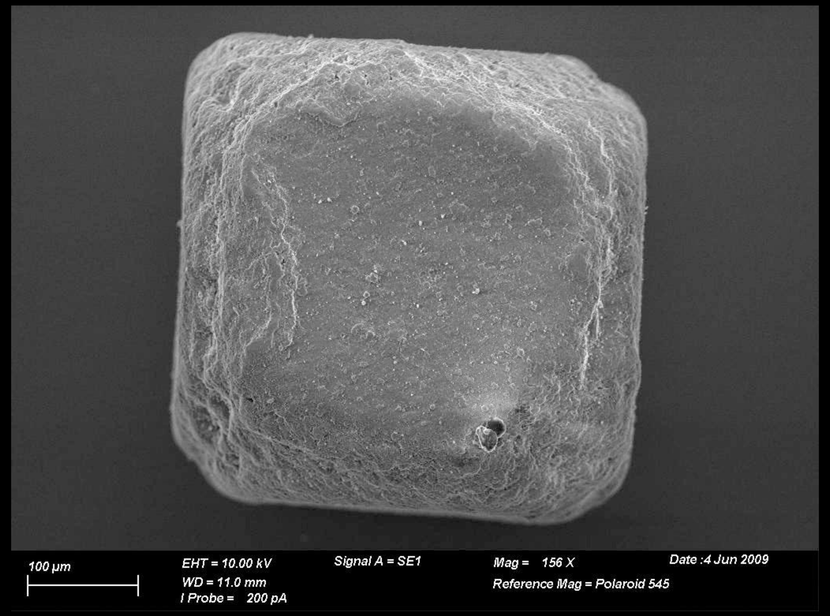
100X

Source: serious-science.org
https://serious-science.org/fire-ants-conquer-the-world-on-the-first-global-trade-network-2570

An Ant

NVIDIA.

1,000X



Source: Wikipedia
https://en.wikipedia.org/wiki/Salt#/media/File:Single_grain_of_table_salt_(electron_micrograph).jpg

Grain of salt

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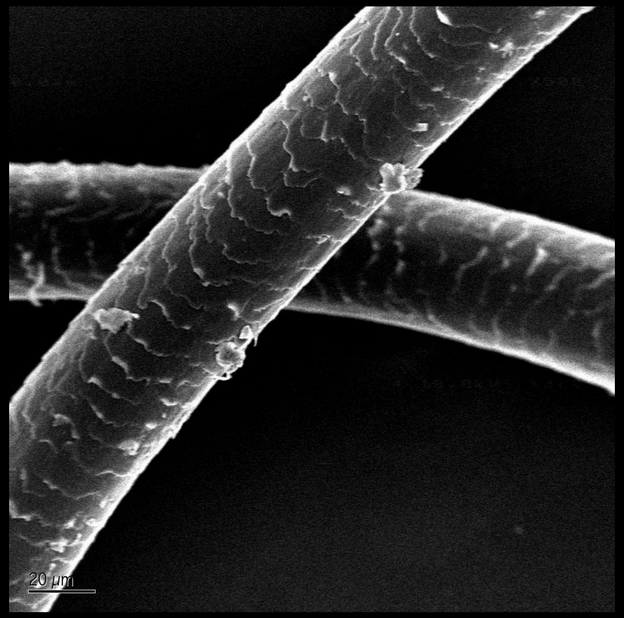
5,000X



Source: nisenet.org
https://www.nisenet.org/catalog/scientific-image-sem-image-human-hair

Human hair

50,000X

Red Blood Cell

Source: Guardian

https://www.theguardian.com/science/2022/nov/07/new-hope-for-sickle-cell-patients-as-uk-trial-of-lab-grown-red-blood-cells-begins

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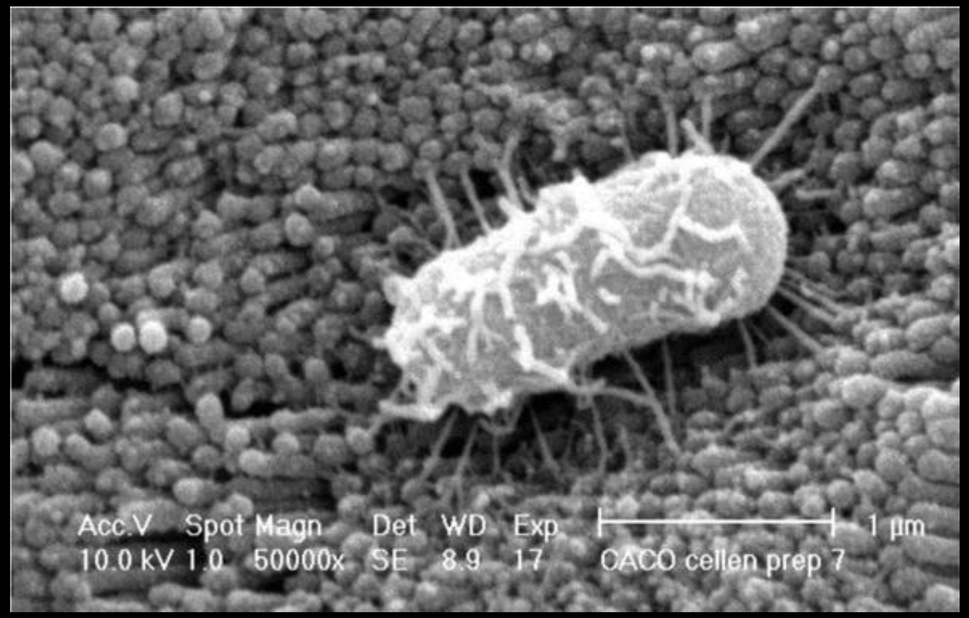
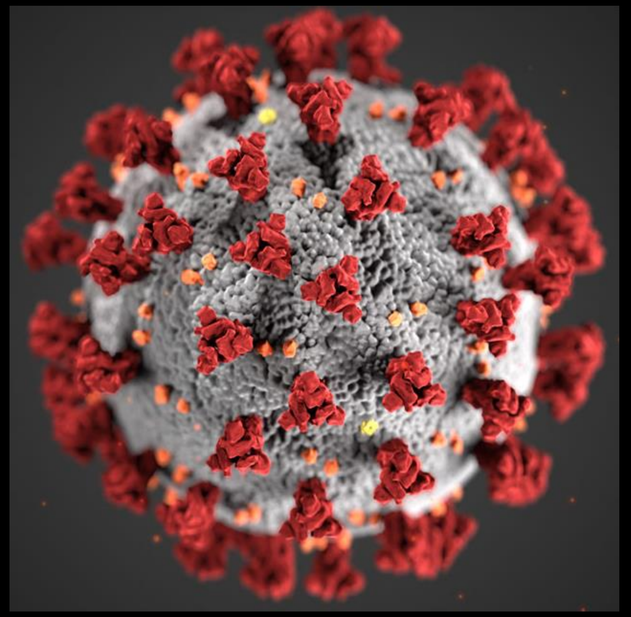
250,000X



Source: The Universe of E. Coli
https://www.intechopen.com/chapters/68841

E. Coli Bacteria

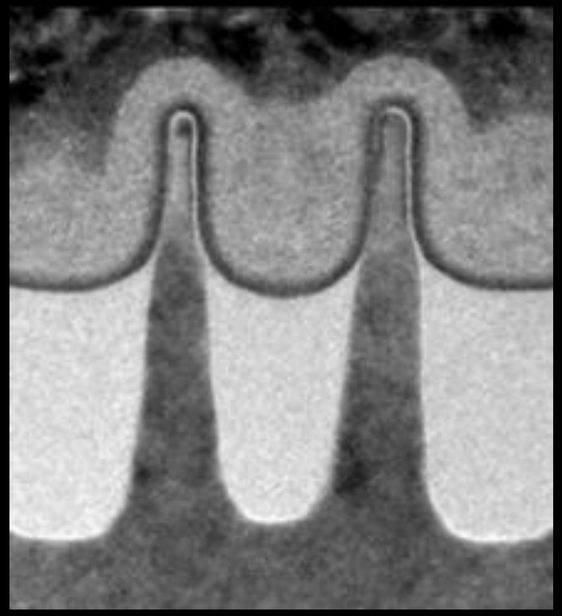
5,000,000X



Source: CDC
https://www.cdc.gov/dotw/covid-19/index.html

Coronavirus

50,000,000X



Source: Bhoir, et al (2019). IEEE J. Electron Devices Society.
http://dx.doi.org/10.1109/JEDS.2019.2934575

5nm Transistor

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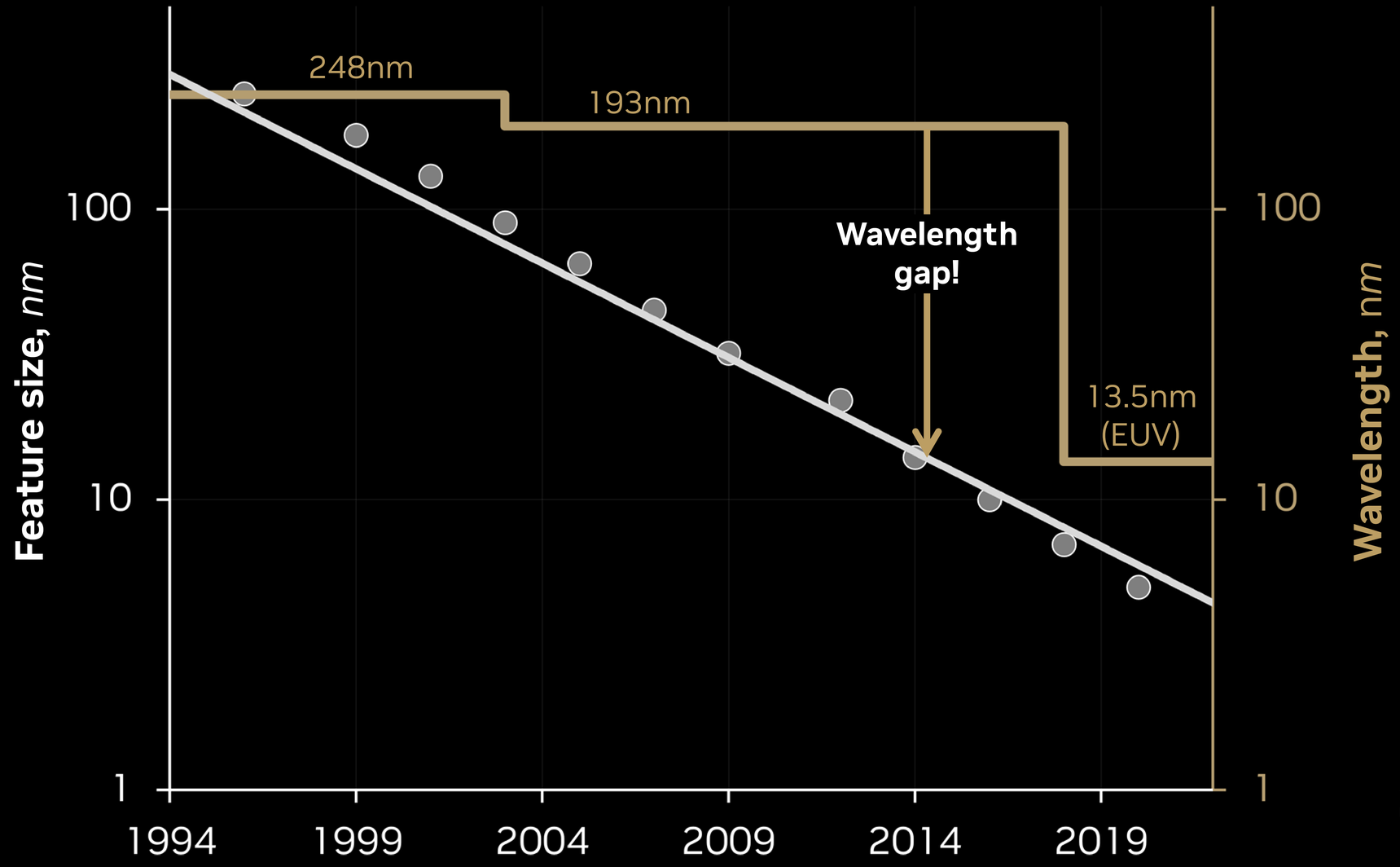
Too small for the light we use...

...have to find ways to bridge the gap



Source: Wikipedia

https://en.wikipedia.org/wiki/Moore%27s_law

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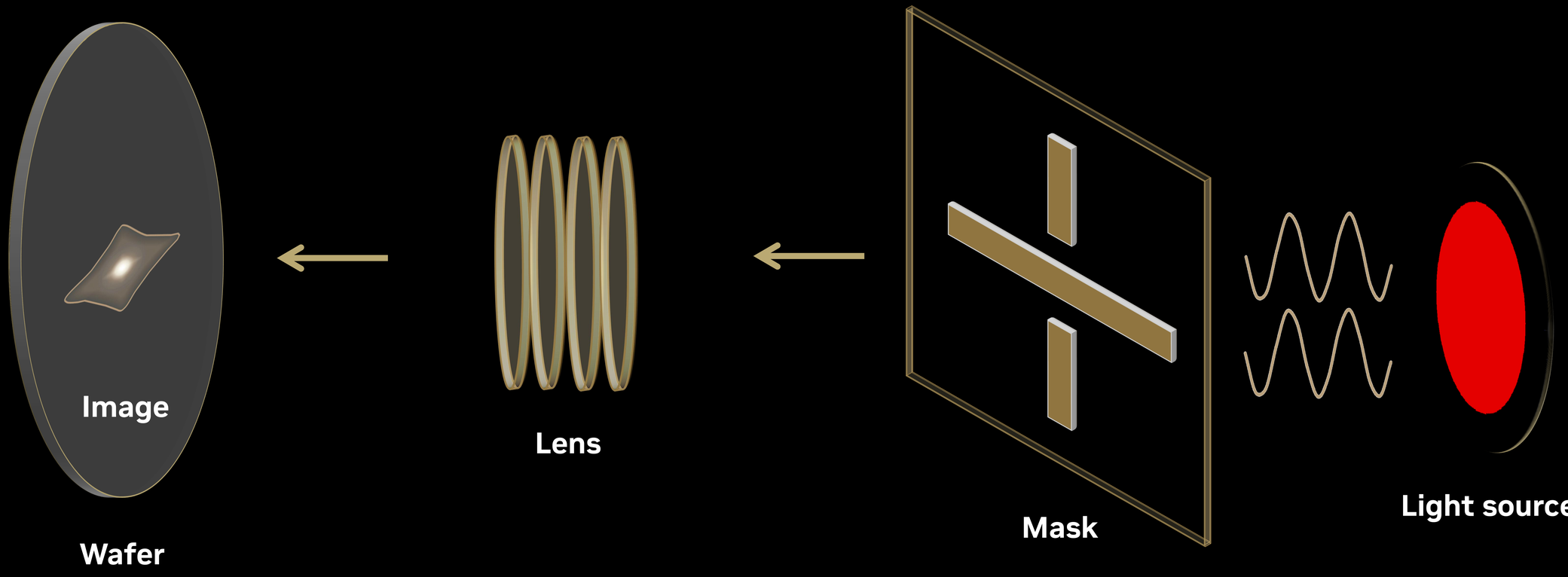
Lithography stepper, simplified



When feature is small, image is blurred

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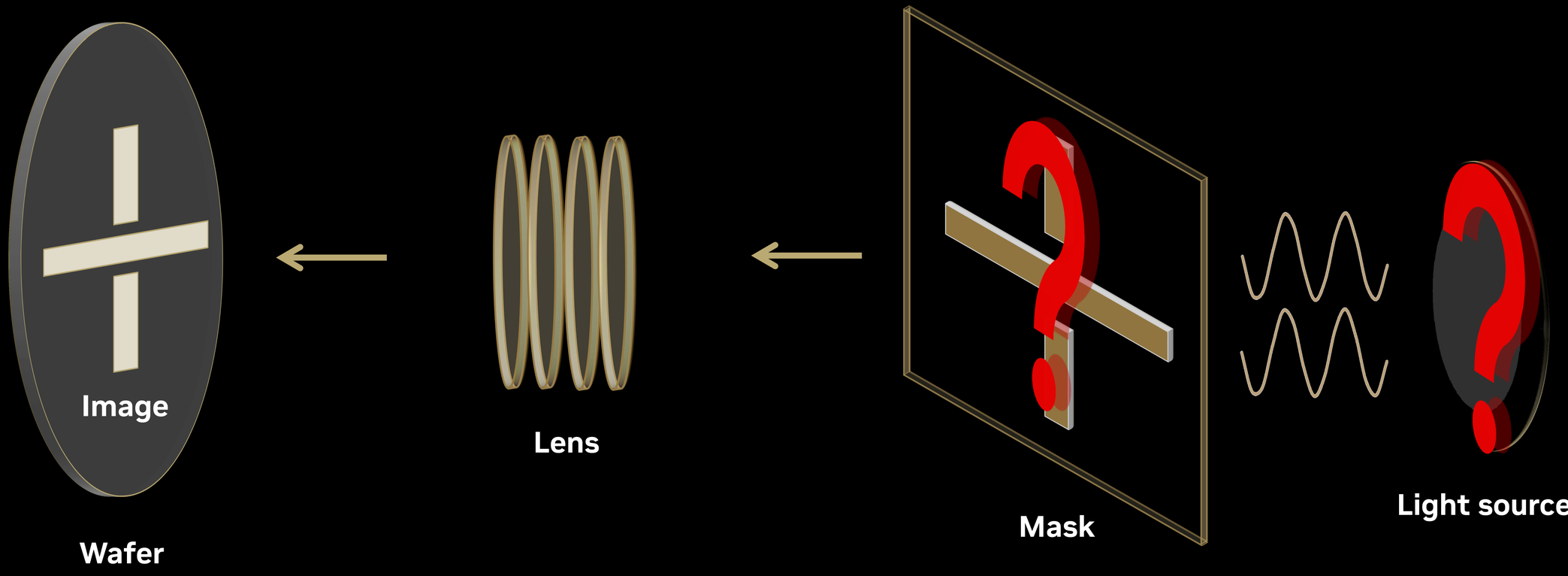
Can we “bend” light by inverting the problem?



Given an image, what mask and source do I need?

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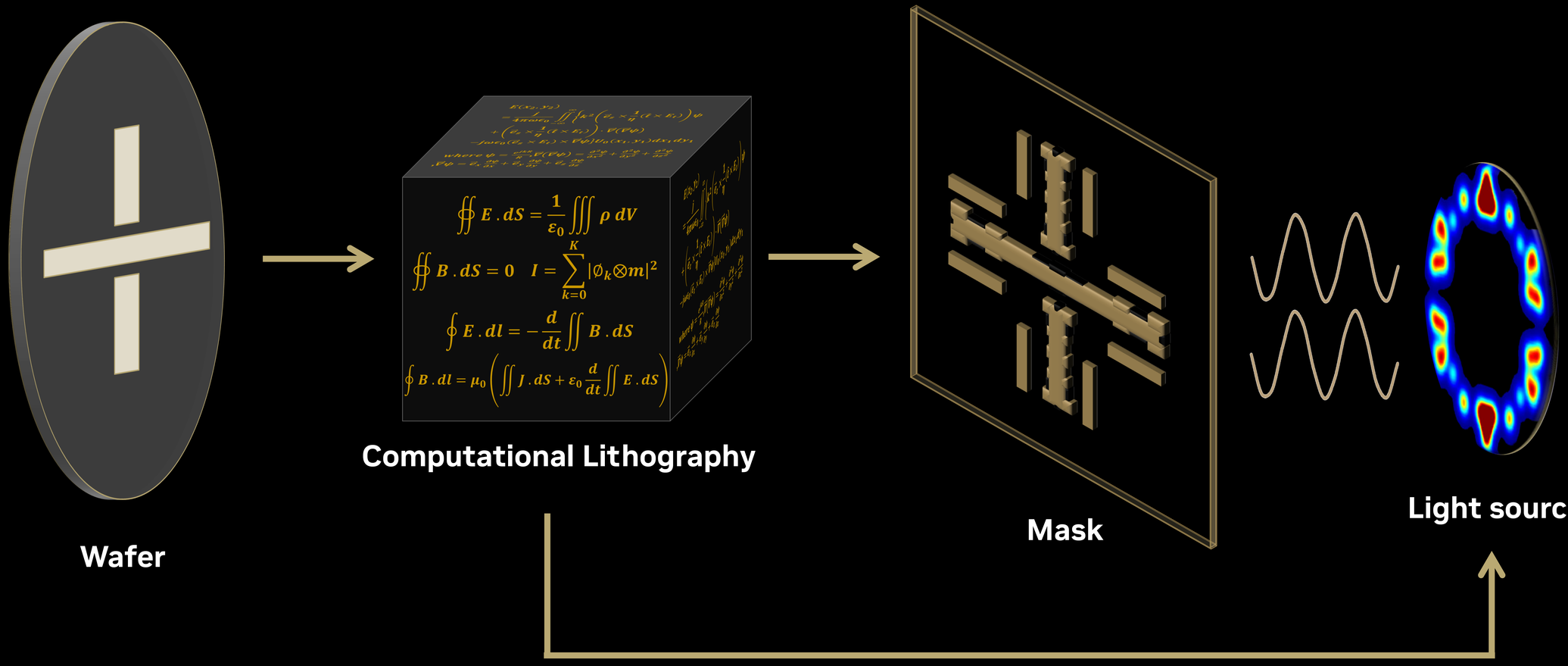
Answer: Computational Lithography

Input = design, output = mask + source



Outline

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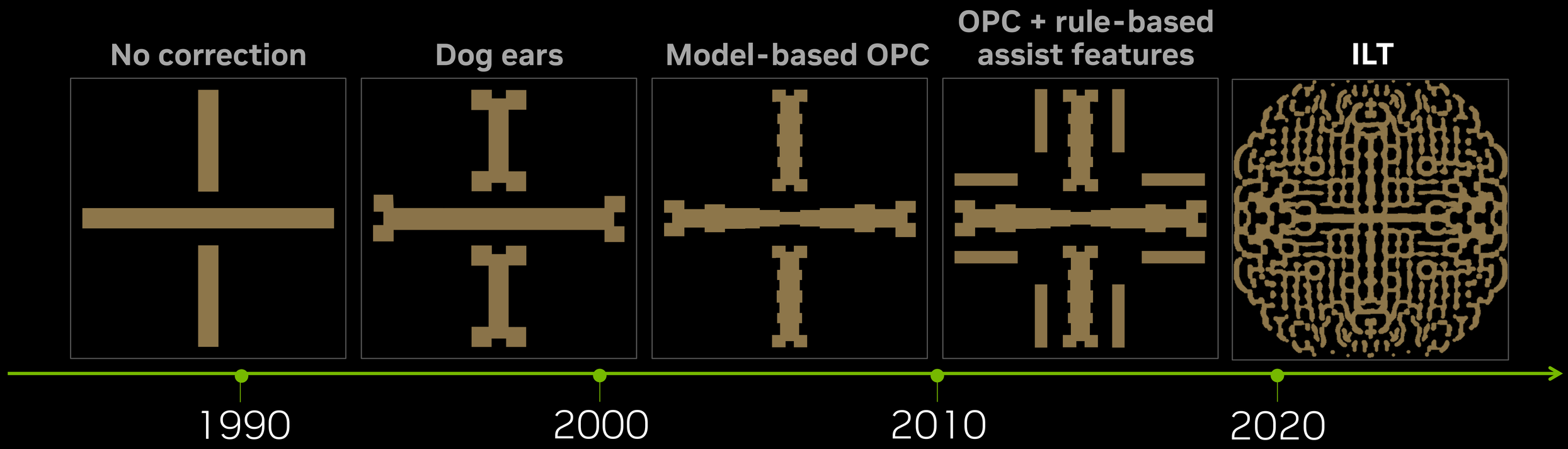
Increasing need for mask correction



- From simple decorations to complex “distortions”
- Intuition finally breaks down

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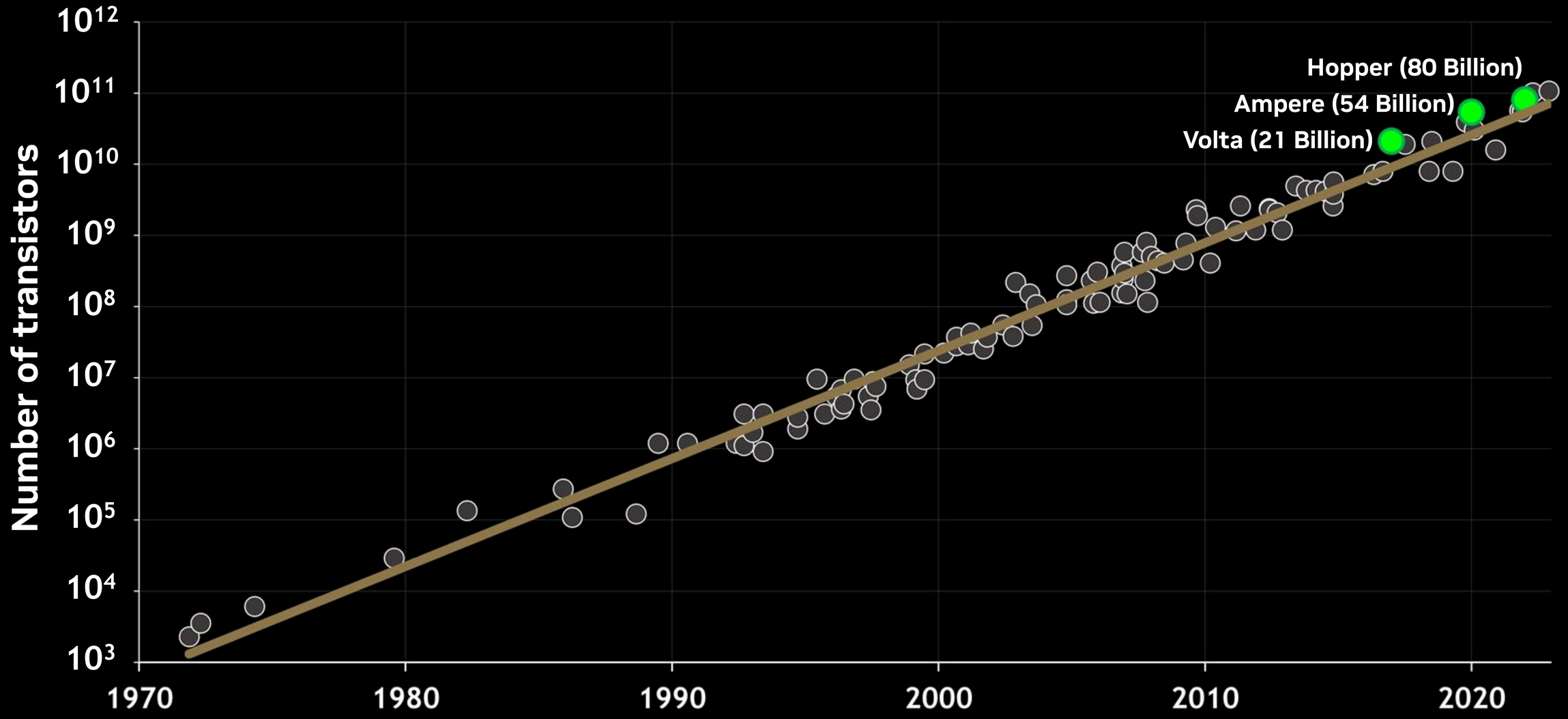
Billions of transistors on a chip



Sources:
https://github.com/karlrupp/microprocessor-trend-data
https://en.wikipedia.org/wiki/Transistor_count

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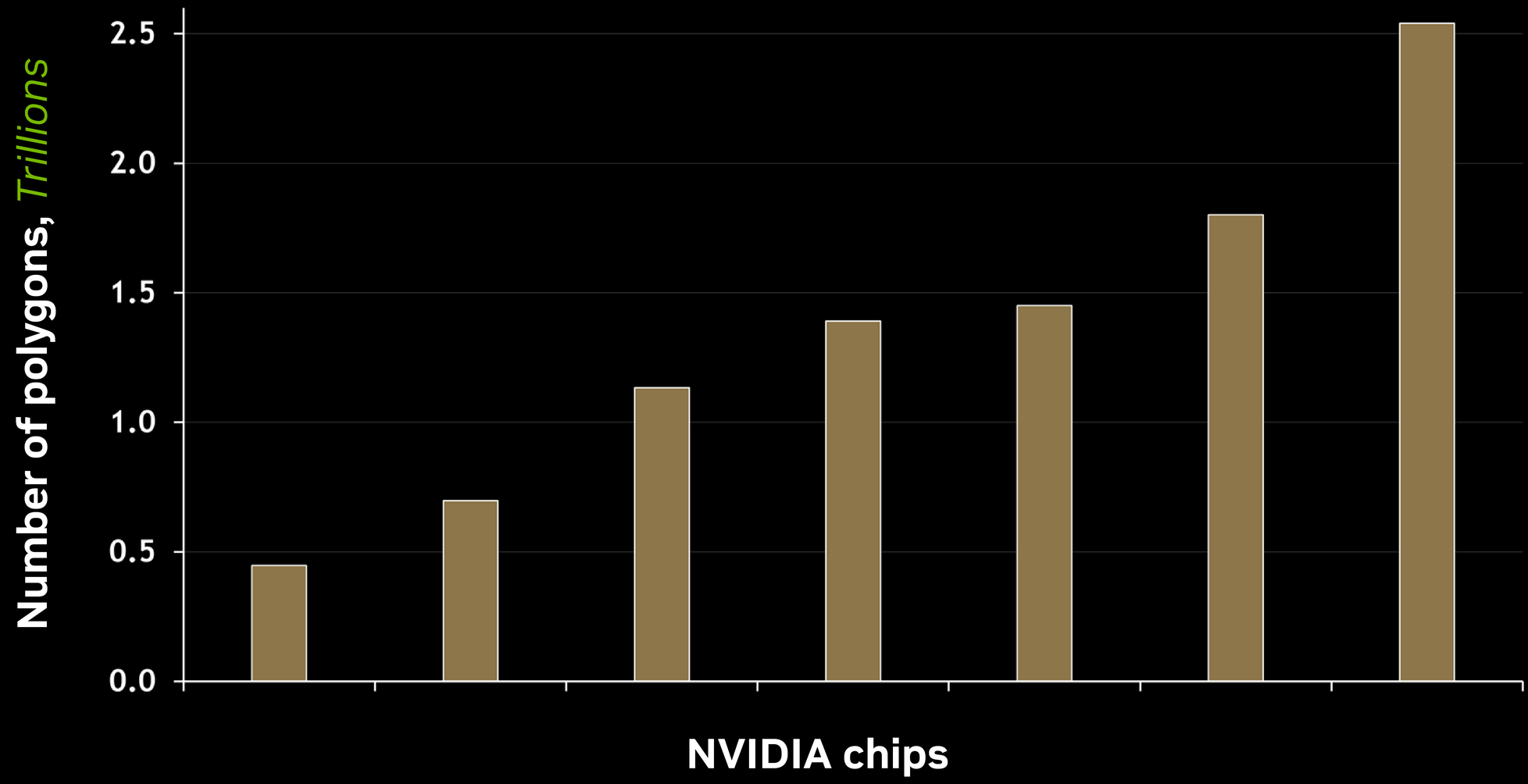
… trillions of polygons on a chip



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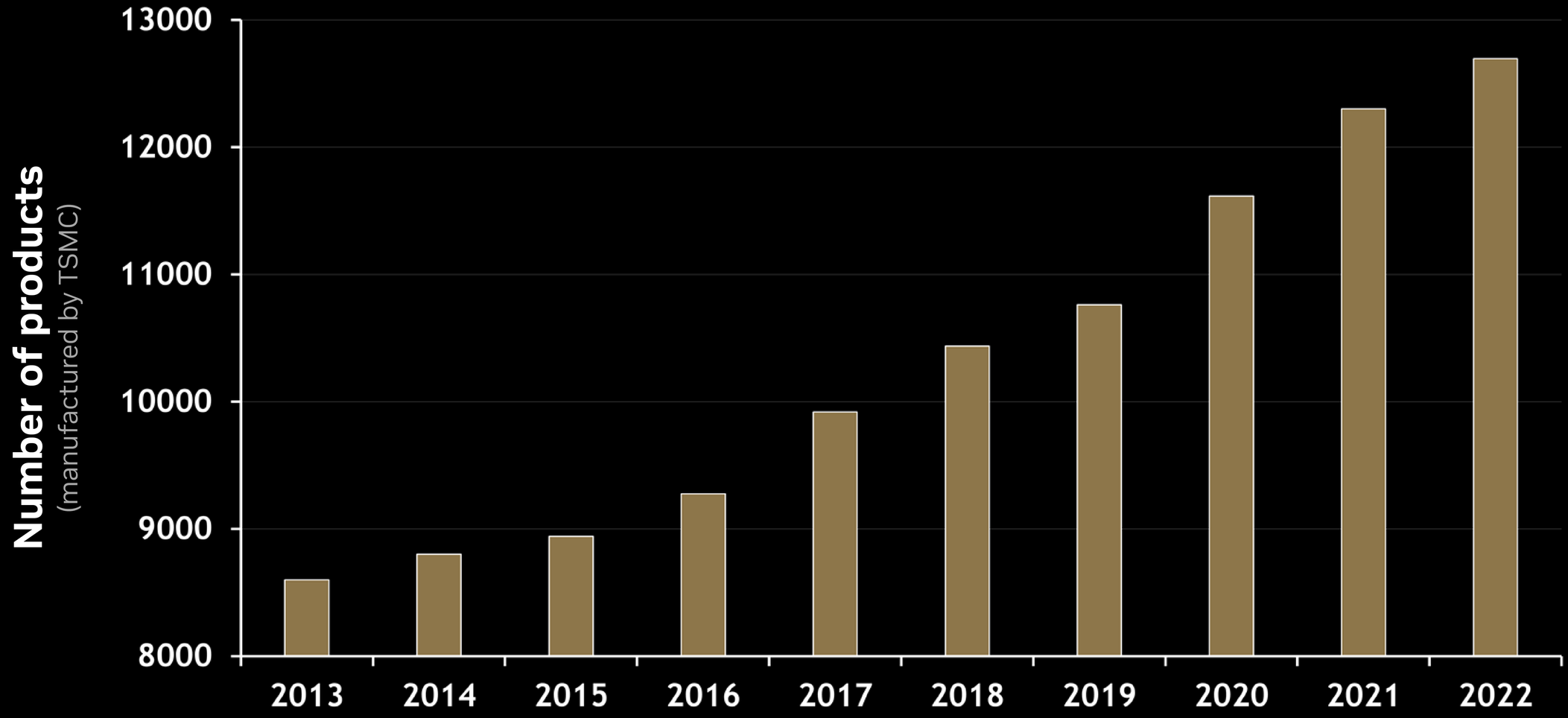
… and thousands of chips



Sources:
https://investor.tsmc.com/english/annual-reports
https://www.statista.com/statistics/1178174/taiwan-semiconductor-manufacturing-company-number-of-products/

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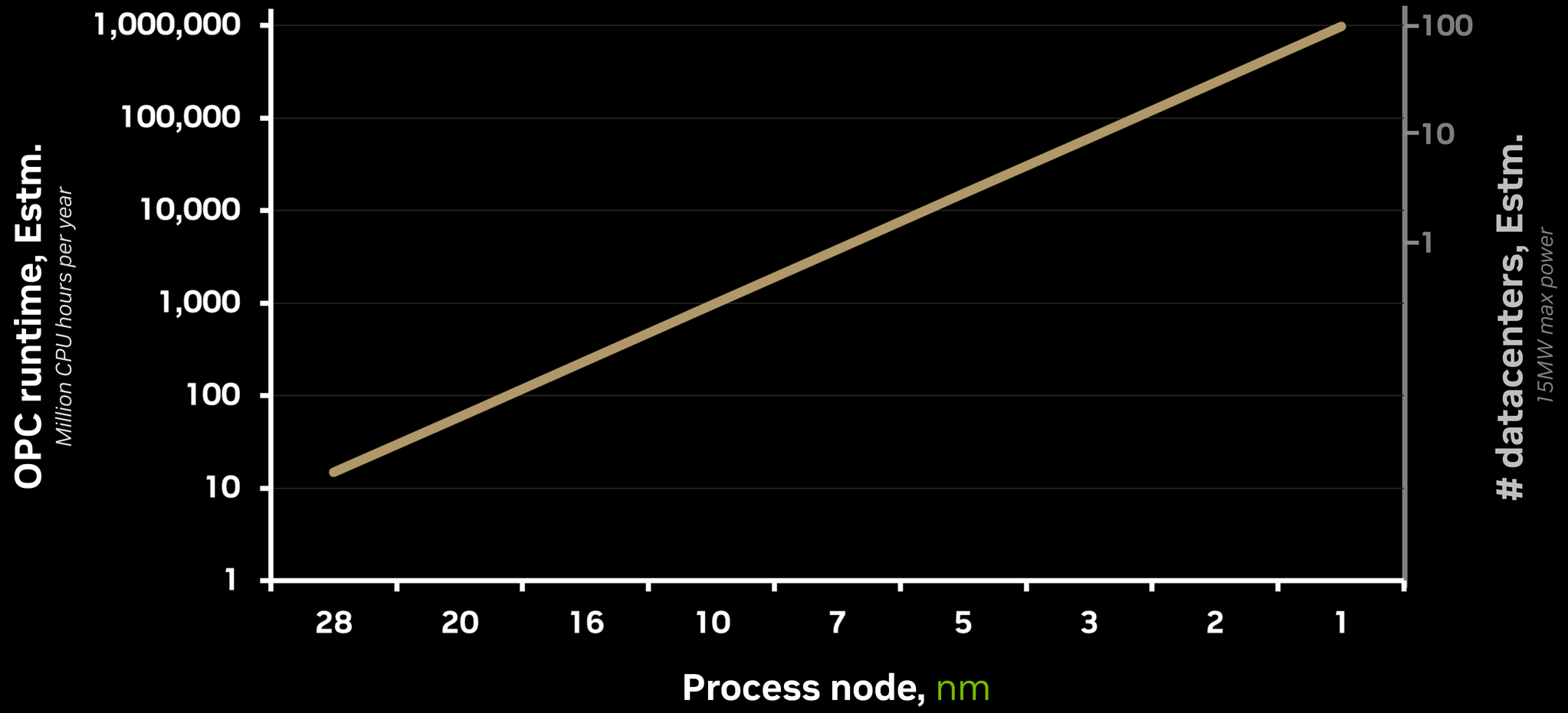
Can’t just keep adding datacenters



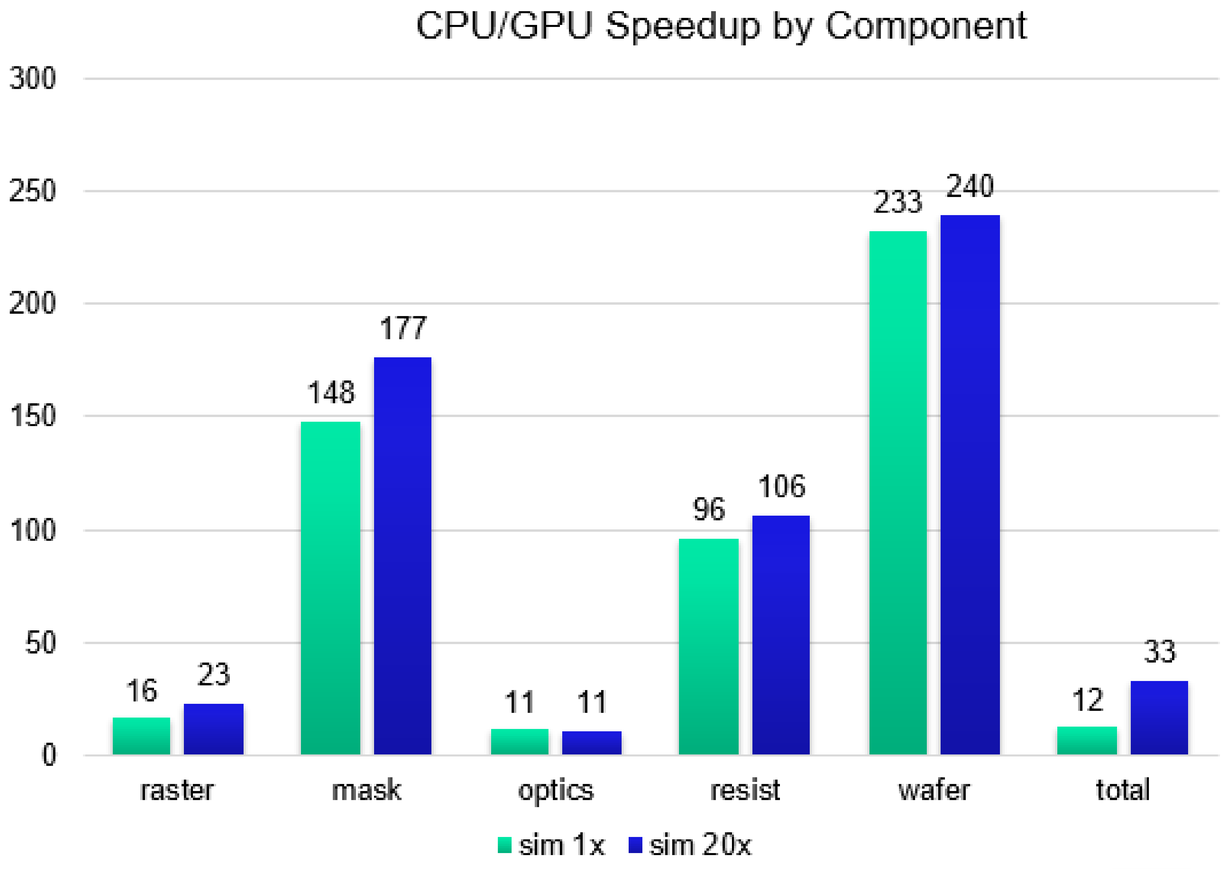
Sources:

S. Jones (2020), Nikon Lithovision

V. Singh (2022). SPIE Advanced Lithography Conference Keynote

ILT Performance Is Getting Faster

GPUs are reducing ILT simulation times > 10x



Test Conditions

- Run on single Tesla V100
- Forward sim 1x has one-time warmup overhead
- Forward sim 20x used to mimic OPC and amortize warmup time

Note: Real OPC also includes geometric processing beyond simulation; can itself be expensive

Can GPU libraries be used for polygon ops?

Source: Courtesy of K. Ho of TSMC, GTC 2020

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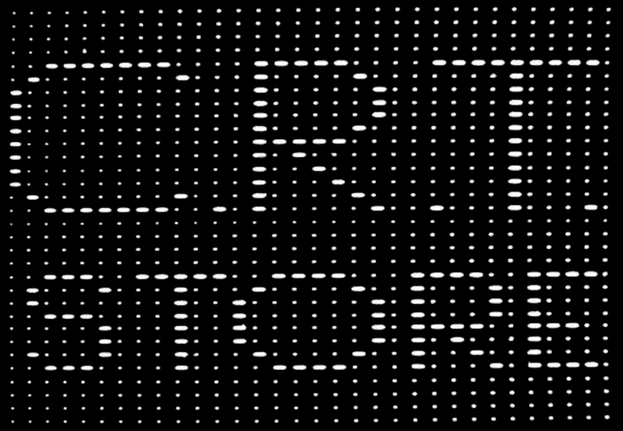
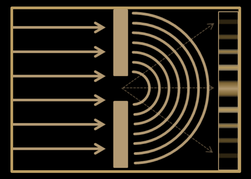


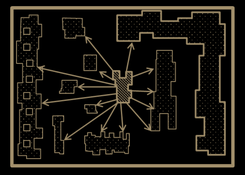
First Digital Picture
Tom Kilburn, University of Manchester, UK
1947

cuLITHO: accelerates computational lithography

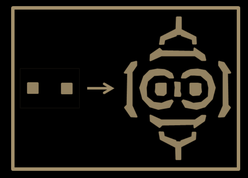
OPC Software



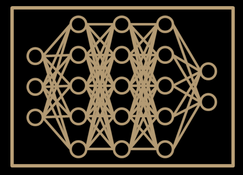
Diffraction



Geometry



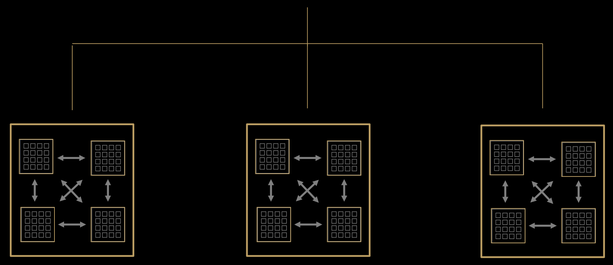
Optimization



AI

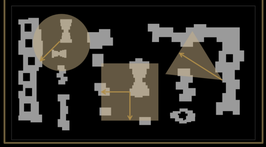
cuDOP | **cuCompGeo** | **cuOASIS** | **cuHierarchy**

CUDA, OptiX, cuFFT, cuBLAS, cuSolver, NPP, RAPIDS, NVComp, Thrust+CUB, ...



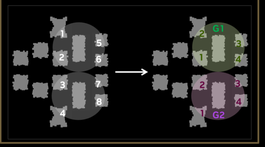
Parallel algorithms for primitive operations

Edge search



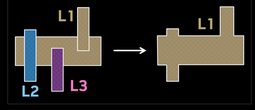
Edge Visibility

Edge sort & group



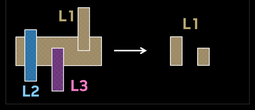
OR

L1 = L1 OR L2



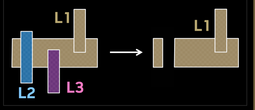
AND

L1 = L1 AND (L2 OR L3)



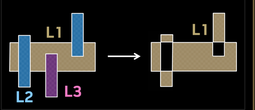
SUB

L1 = L1 SUB L2



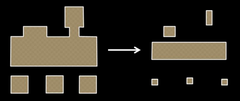
XOR

L1 = L1 XOR L2



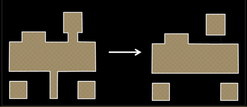
Grow/ Shrink

L1 = Shrink(L1,5)



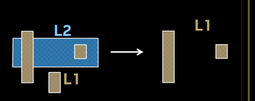
Under/ Over

L1 = UnderOver(L1,-5,5)



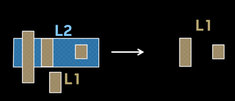
Interact

L1 = L1 Interact L2

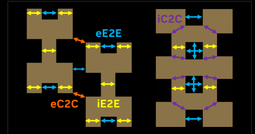


Inside/ Outside

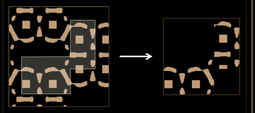
L1 = L1 Inside L2



E2E/C2C meas.

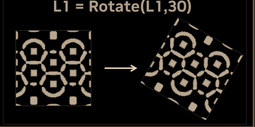


Clipping

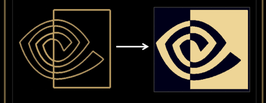


Rotation

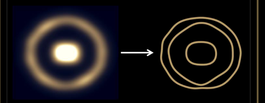
L1 = Rotate(L1,30)



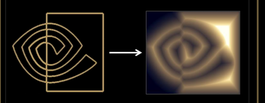
Rasterization



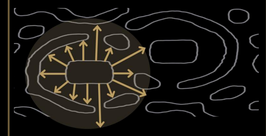
Contour extraction



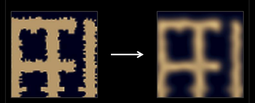
Contour dist. field



Contour visibility



Low-pass filters



TCC convolutions

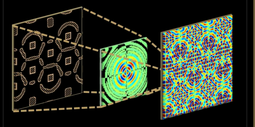


Image slope

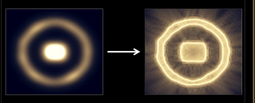


Image Laplacian

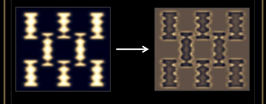


Image curvature

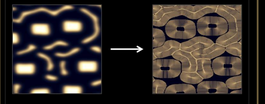
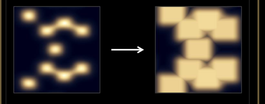
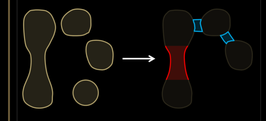


Image local min/max



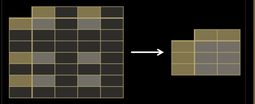
Bridge/Pinch meas.



CD/EPE meas.

EPE(L1,C1)

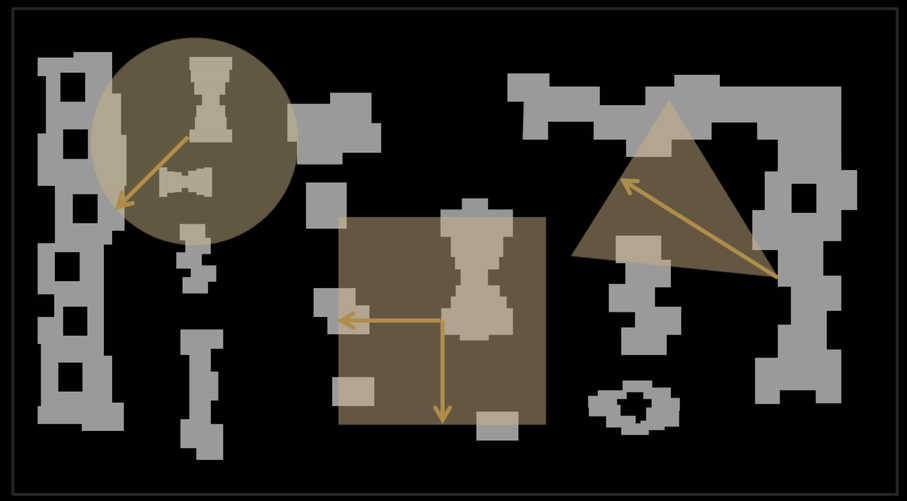
Data manipulation



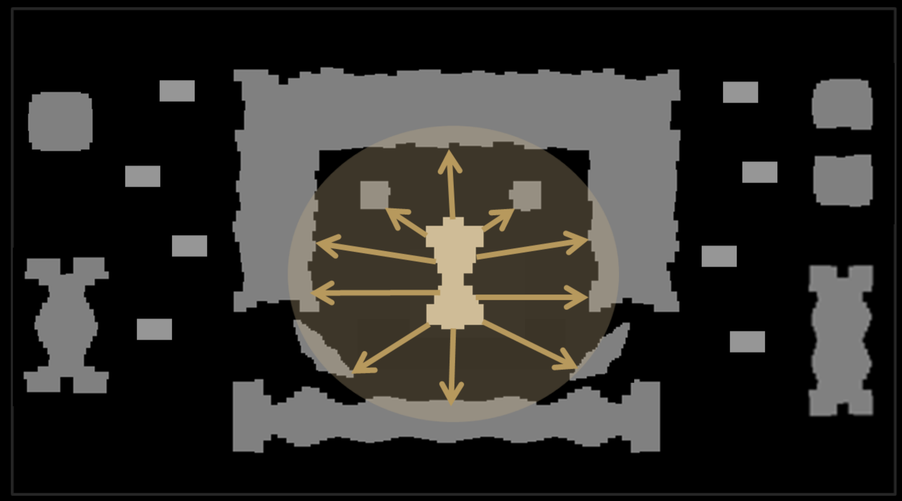
...

Search and visibility

Edge Search



Edge visibility



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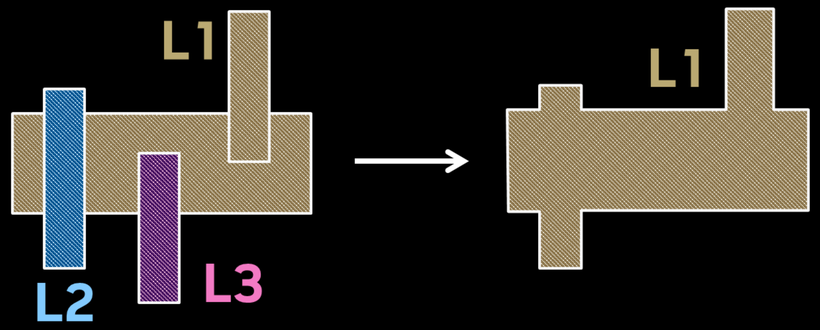
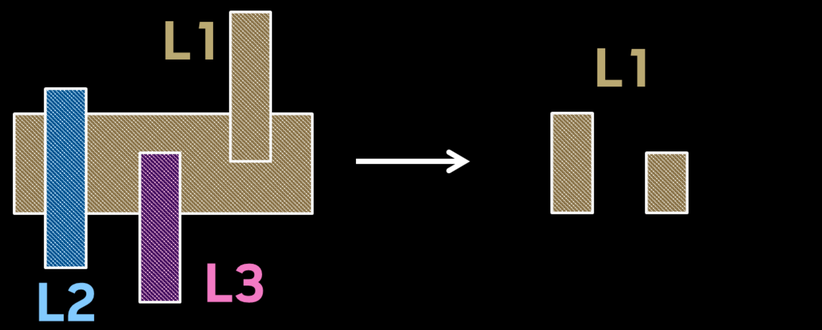
Polygon Booleans

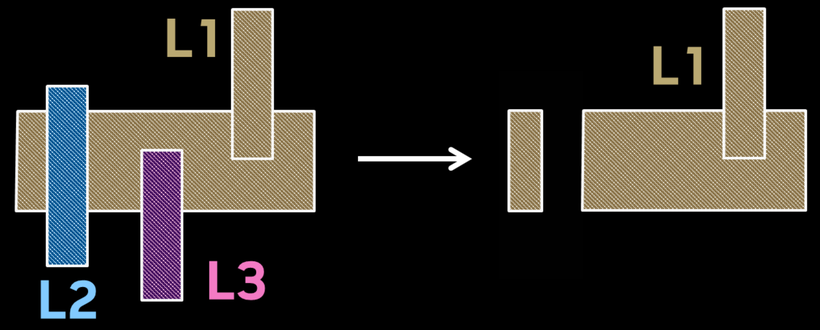
L1 = L1 OR L2



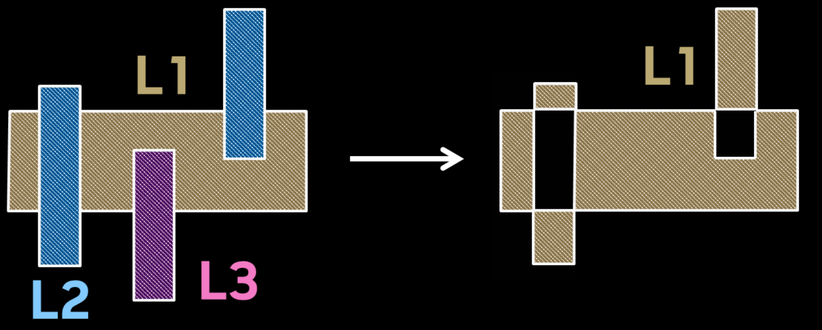
L1 = L1 AND (L2 OR L3)



L1 = L1 SUB L2



L1 = L1 XOR L2



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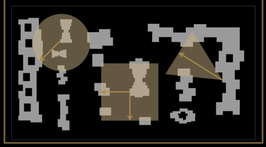
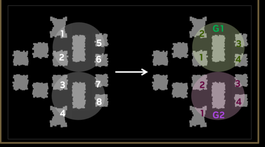
Parallel algorithms for primitive operations

Edge search

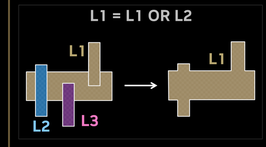


Edge Visibility

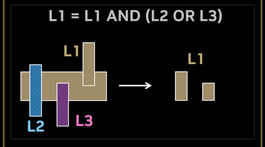
Edge sort & group



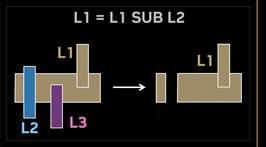
OR



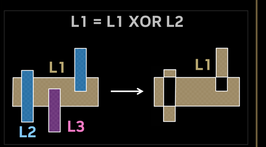
AND



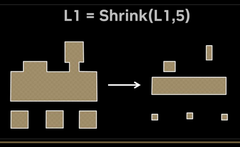
SUB



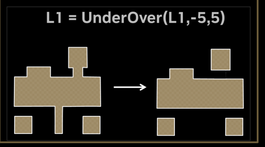
XOR



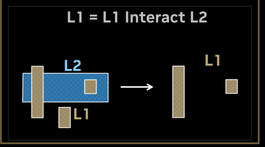
Grow/ Shrink



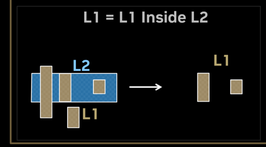
Under/ Over



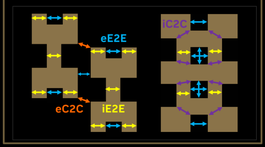
Interact



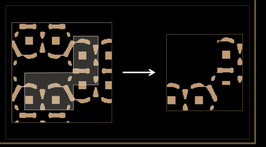
Inside/ Outside



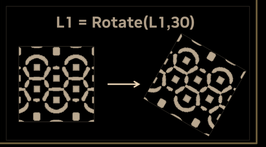
E2E/C2C meas.



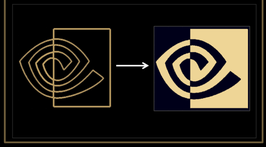
Clipping



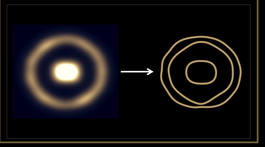
Rotation



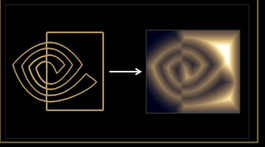
Rasterization



Contour extraction

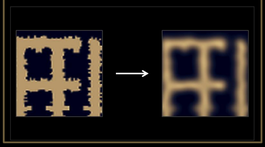


Contour dist. field



Contour visibility

Low-pass filters



TCC convolutions

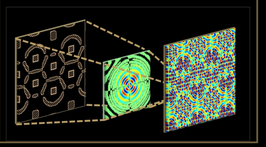


Image slope

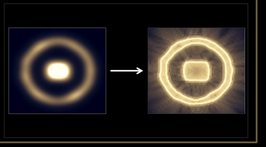


Image Laplacian

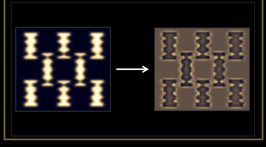


Image curvature

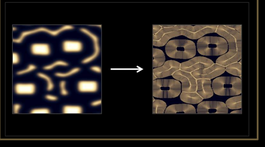
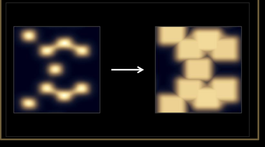
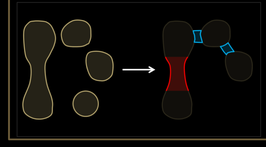


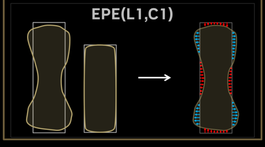
Image local min/max



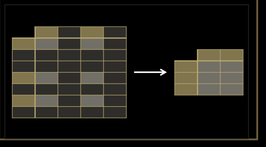
Bridge/Pinch meas.



CD/EPE meas.



Data manipulation



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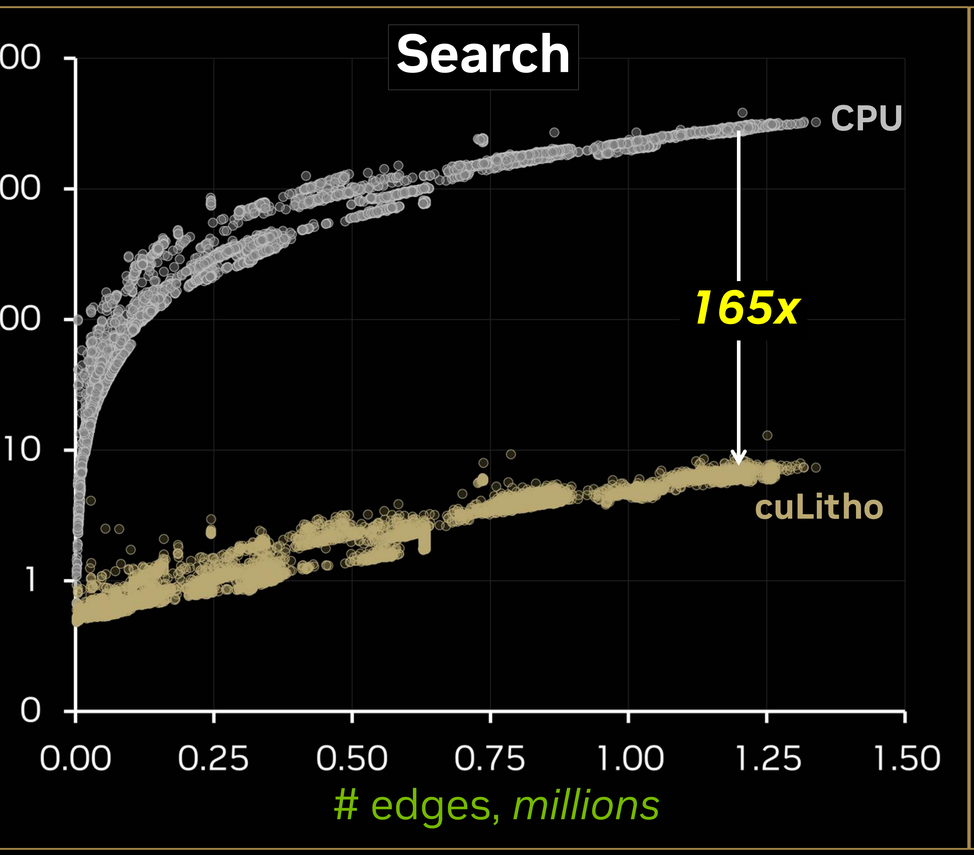
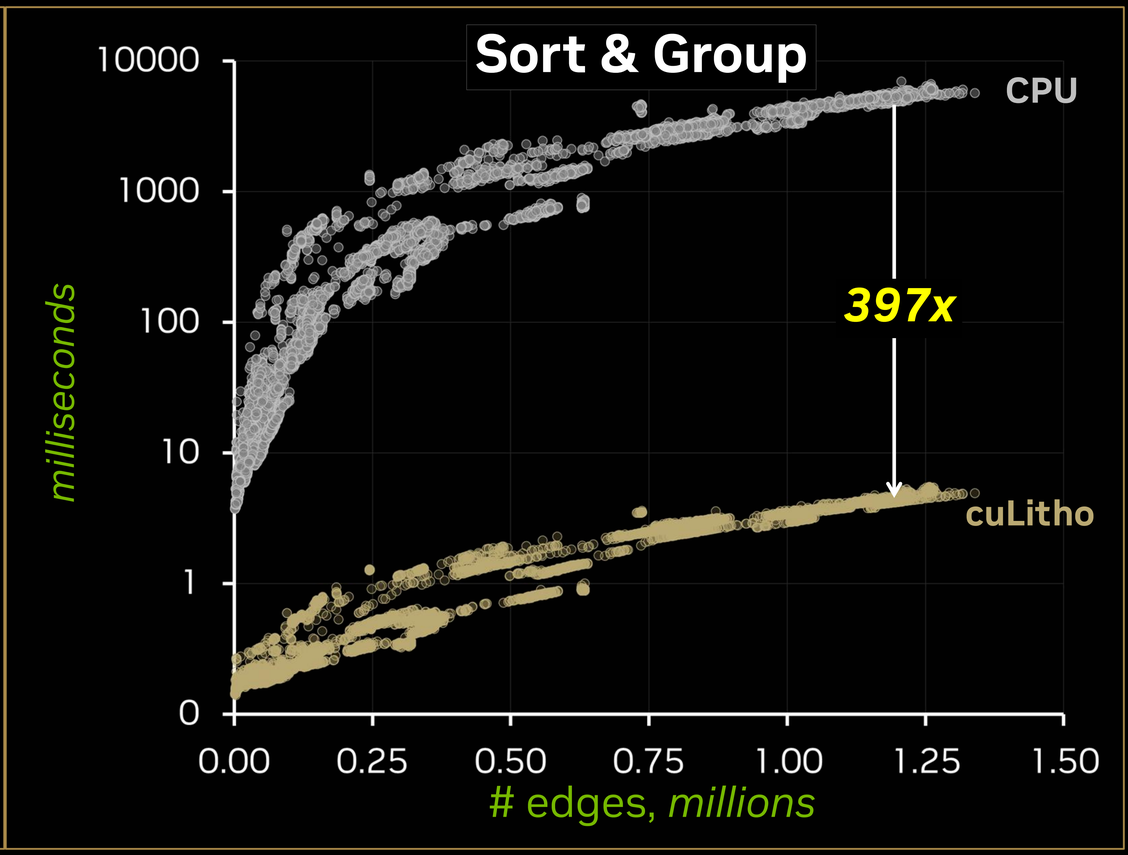
Parallel algorithms for primitive operations

Edge search | Edge Visibility | **Edge sort & group** | OR | AND | SUB | XOR





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Parallel algorithms for primitive operations

Edge search

Edge Visibility

Edge sort & group

OR

L1 = L1 OR L2

AND

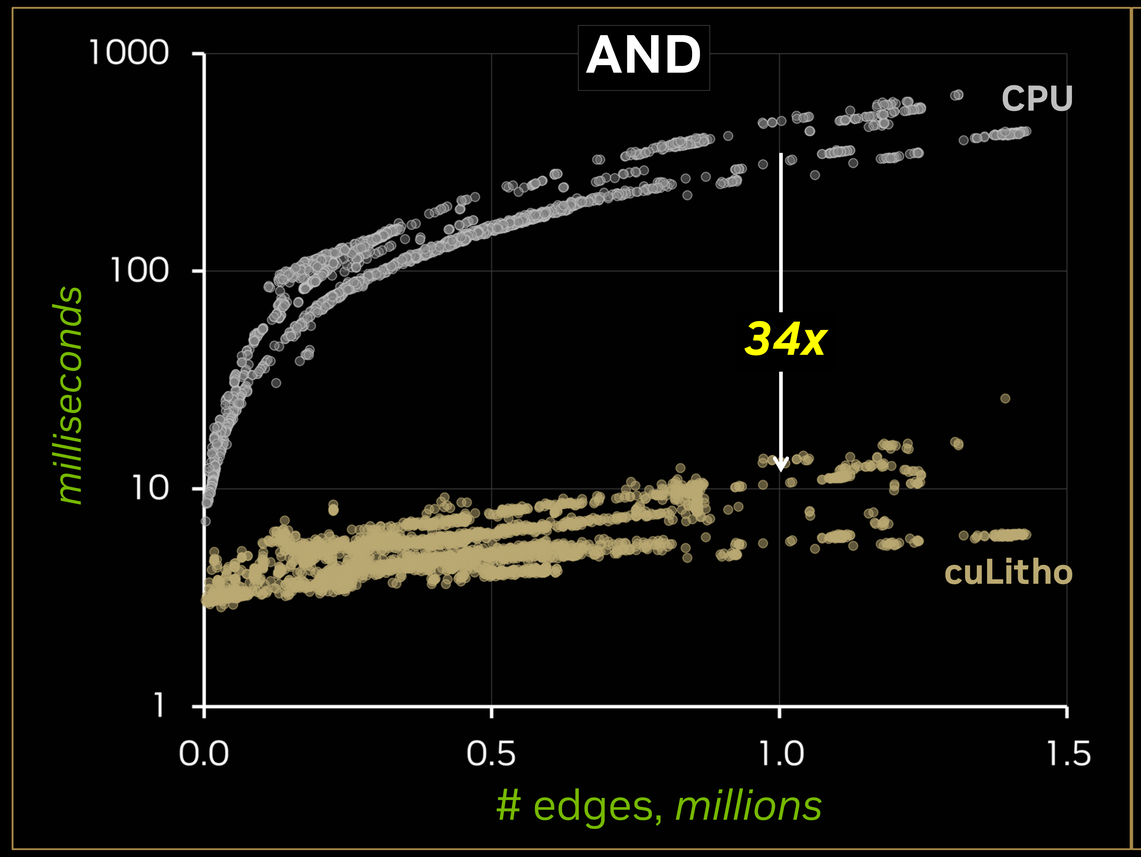
L1 = L1 AND (L2 OR L3)

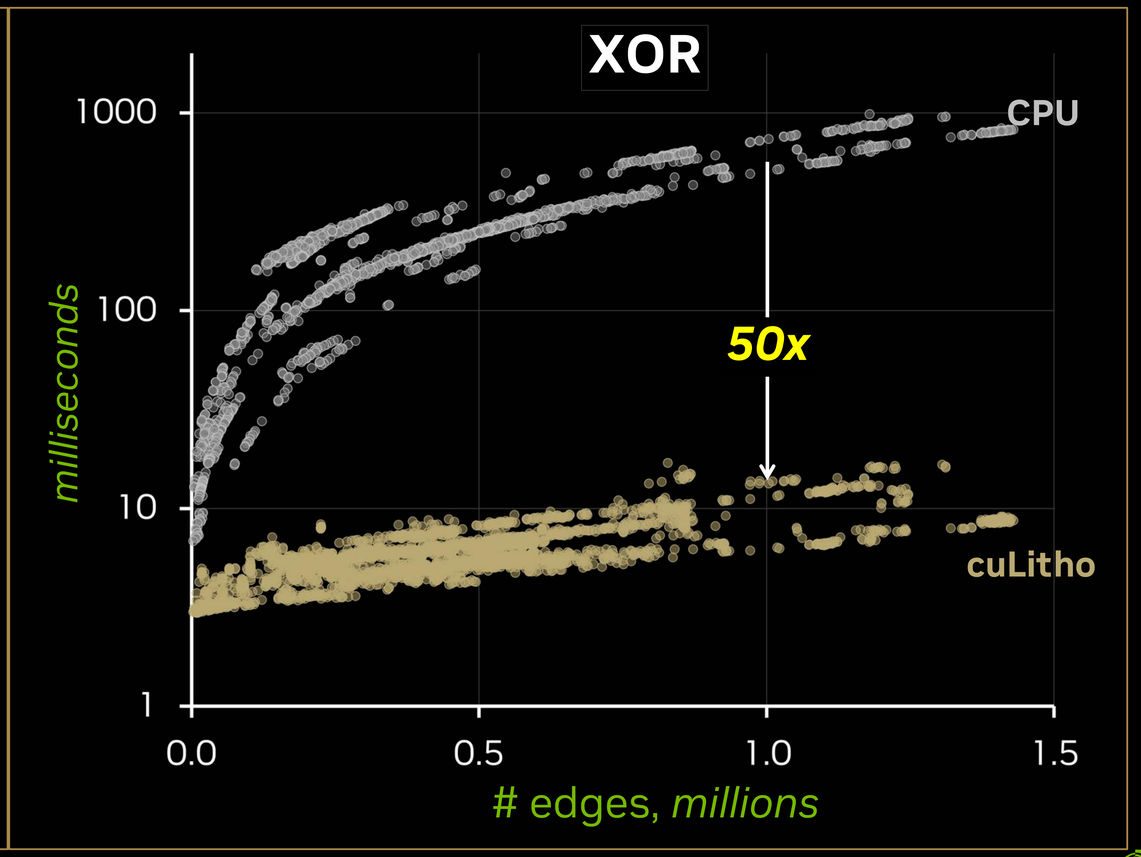
SUB

L1 = L1 SUB L2

XOR

L1 = L1 XOR L2





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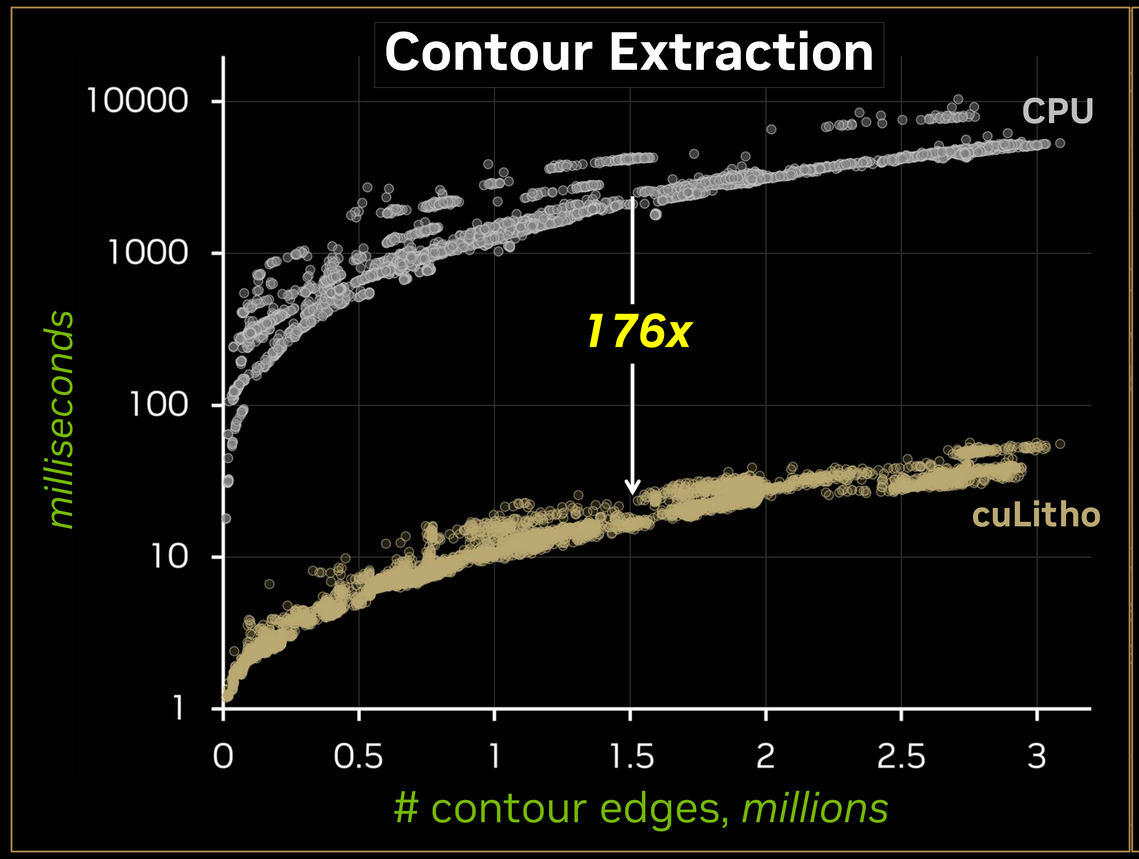
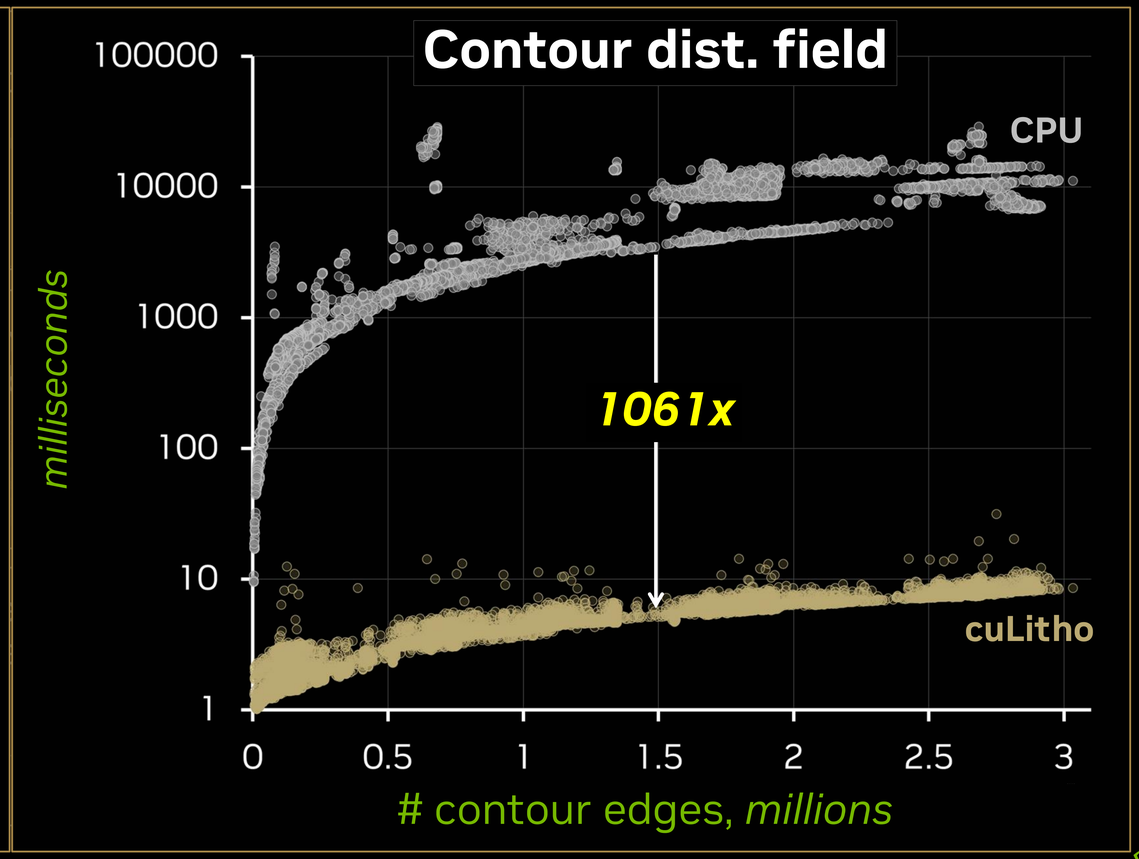
Parallel algorithms for primitive operations





Parallel algorithms for primitive operations

Edge search **165x**	Edge Visibility **165x**	Edge sort & group **397x**	OR **34x**	AND **34x**	SUB **26x**	XOR **50x**
Grow/ Shrink **38x**	Under/ Over **38x**	Interact **45x**	Inside/ Outside **40x**	E2E/C2C meas. **87x**	Clipping **33x**	Rotation **107x**
Rasterization **1650x**	Contour extraction **176x**	Contour dist. field **1061x**	Contour visibility **581x**	Low-pass filters **171x**	TCC convolutions **95x**	Image slope **504x**
Image Laplacian **77x**	Image curvature **406x**	Image local min/max **412x**	Bridge/Pinch meas. **46x**	CD/EPE meas. **179x**	Data manipulation **308x**	...

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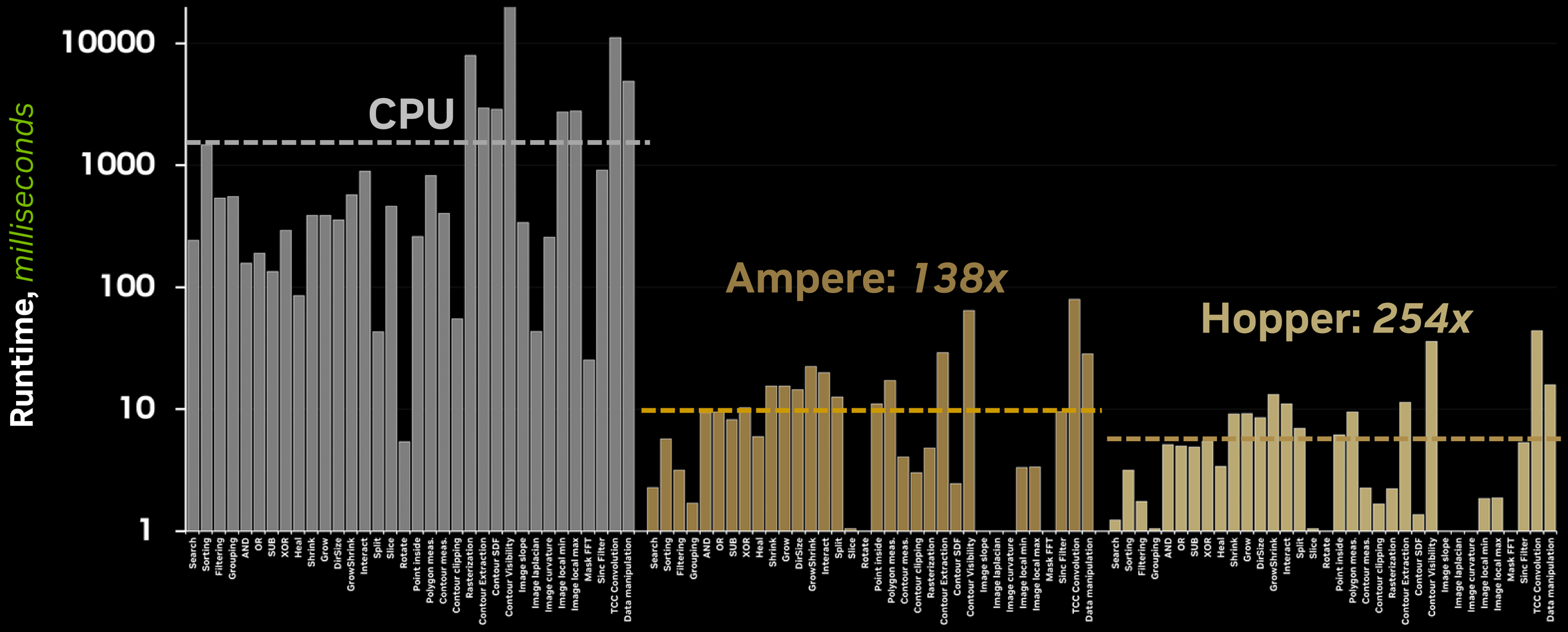
Component Speedup



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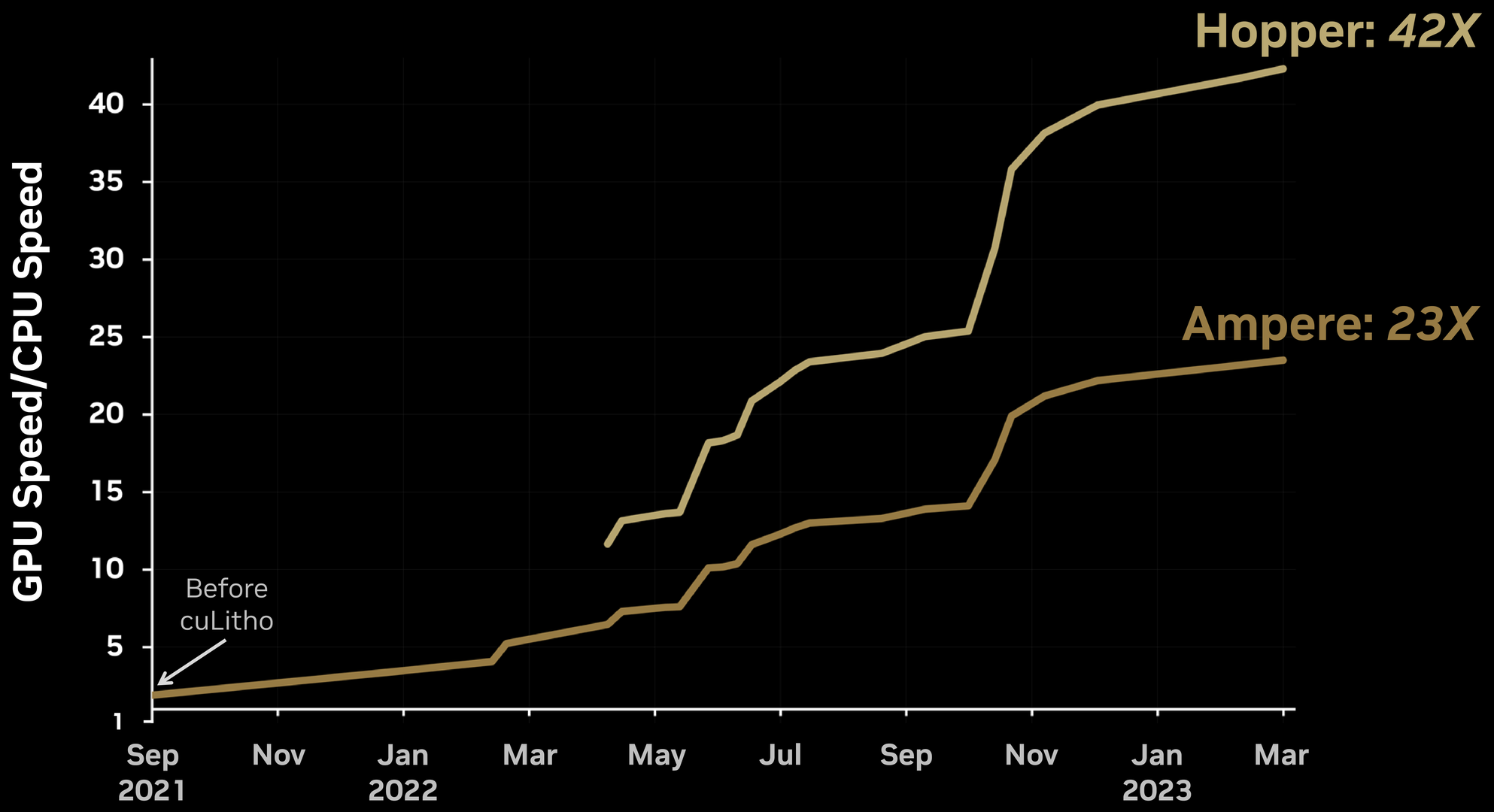
End-to-End OPC Speedup

Mask processing overnight, instead of 2 weeks

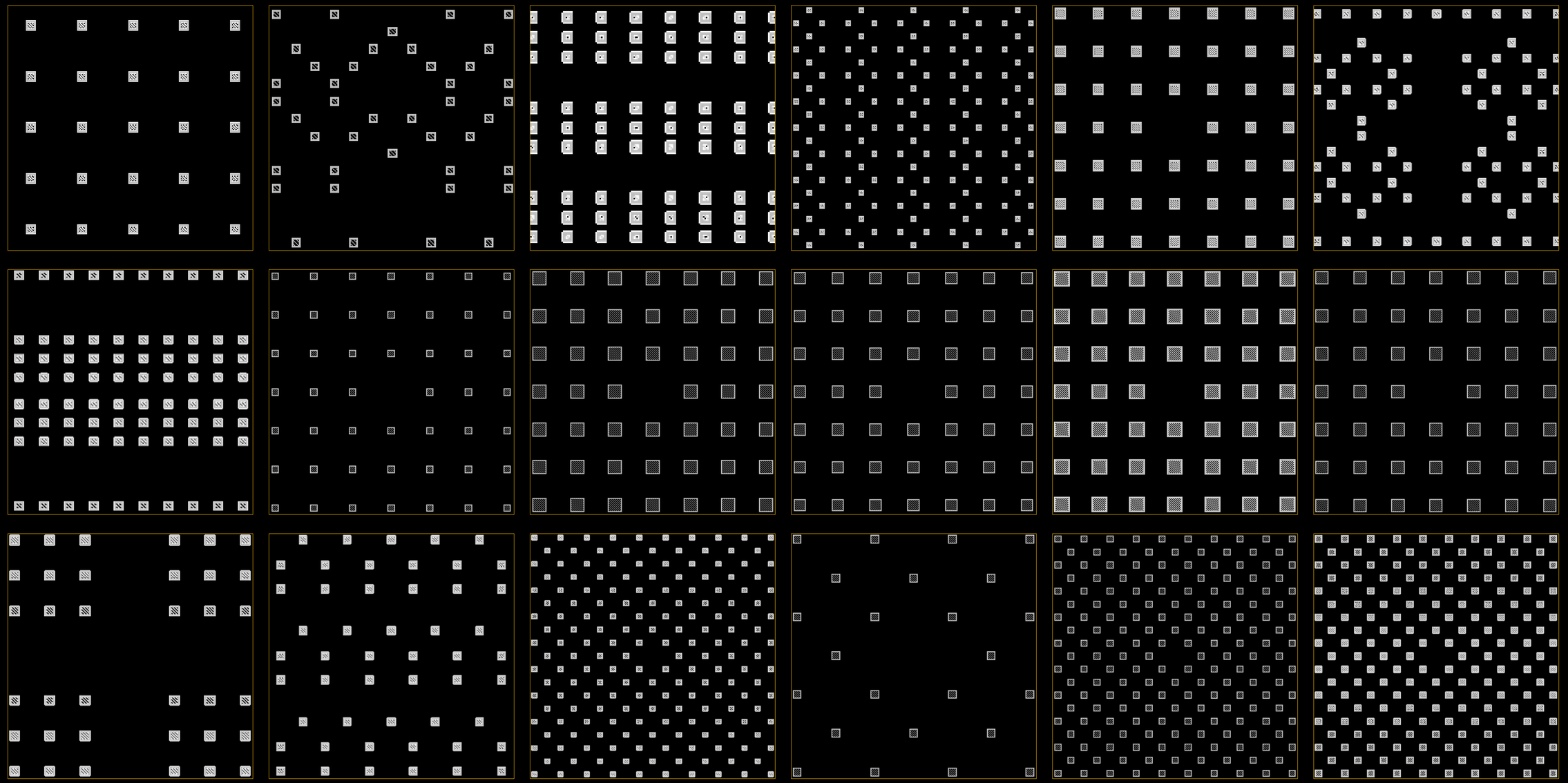


NVIDIA.

Outline

- What is Computational Lithography?
- The Problem: Exploding Computation
- The Breakthrough!
- **Enables Better Chip Technology, Faster**
- Summary, and a quiz!

Chip Design



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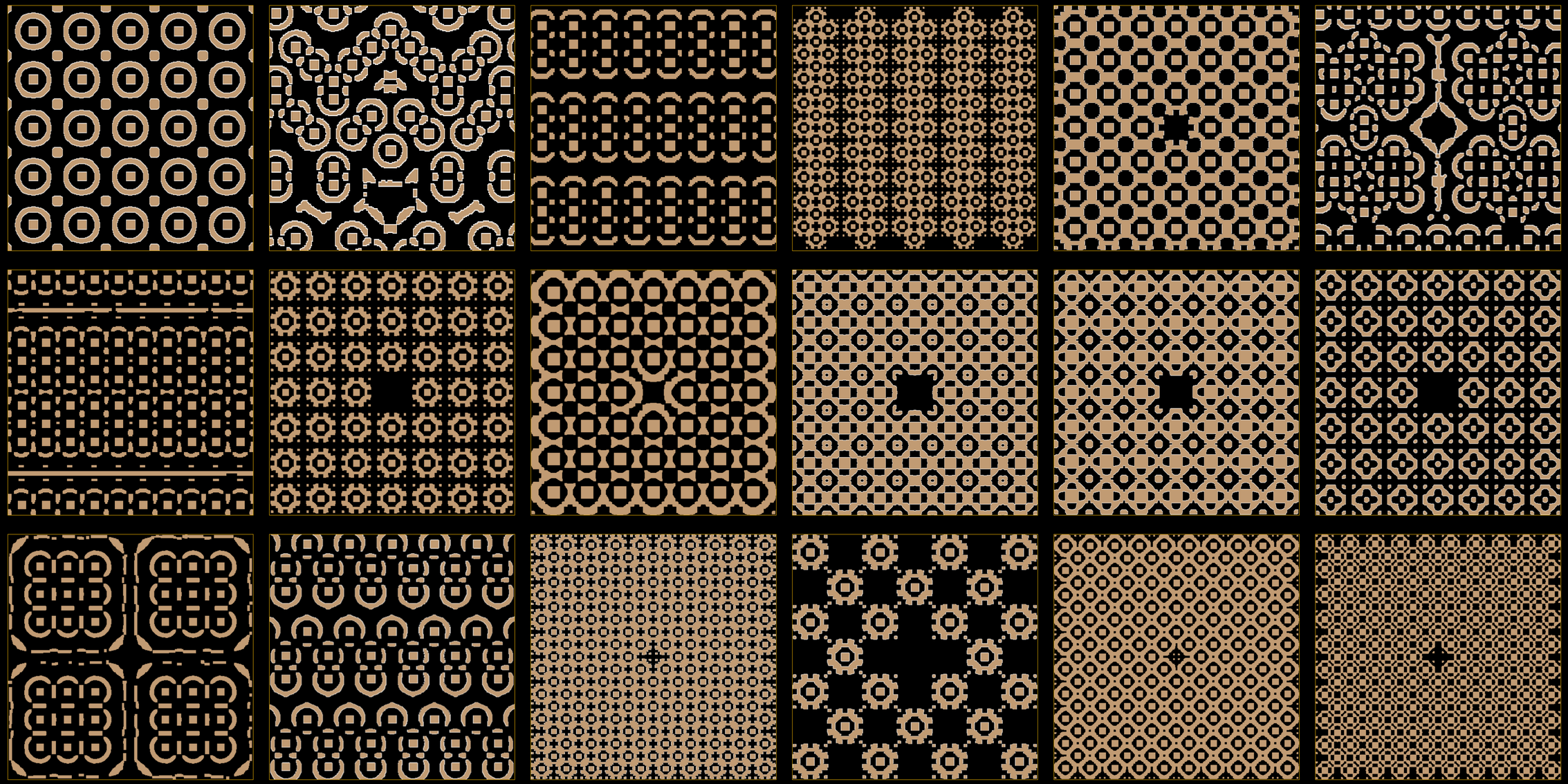
Inverse Mask



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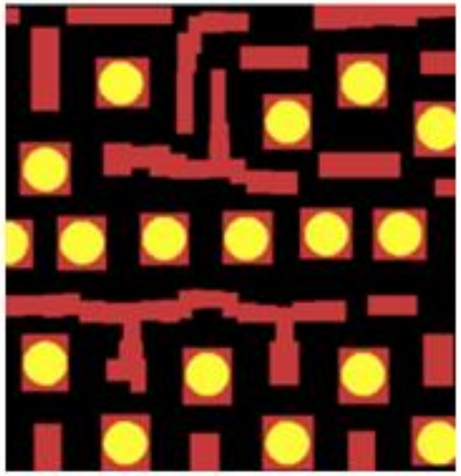
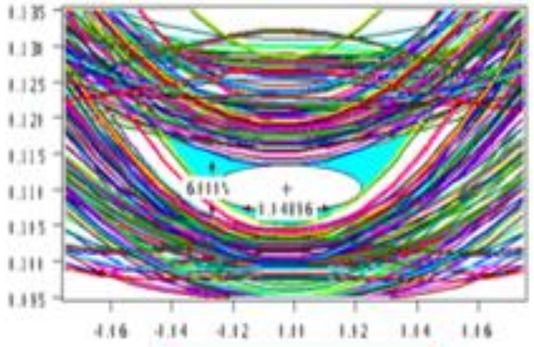
Confidential
Security C

ILT Curvilinear Mask Delivers Superior Process Window

Curvilinear ILT vs. Standard OPC

Standard OPC

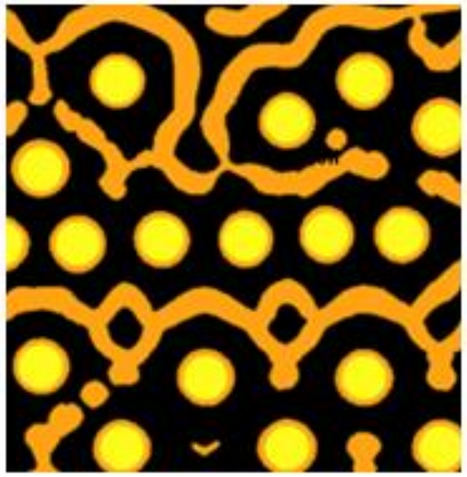


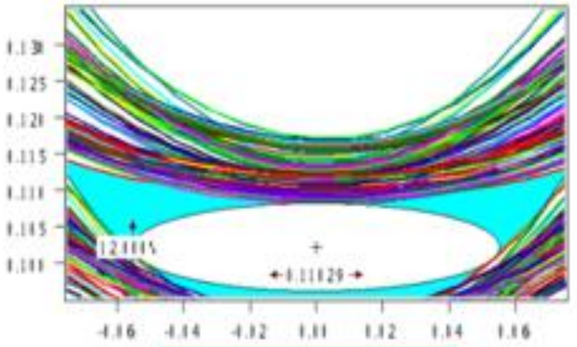


49nm DoF @ 12%EL

>2x increase in DoF

Curvilinear ILT

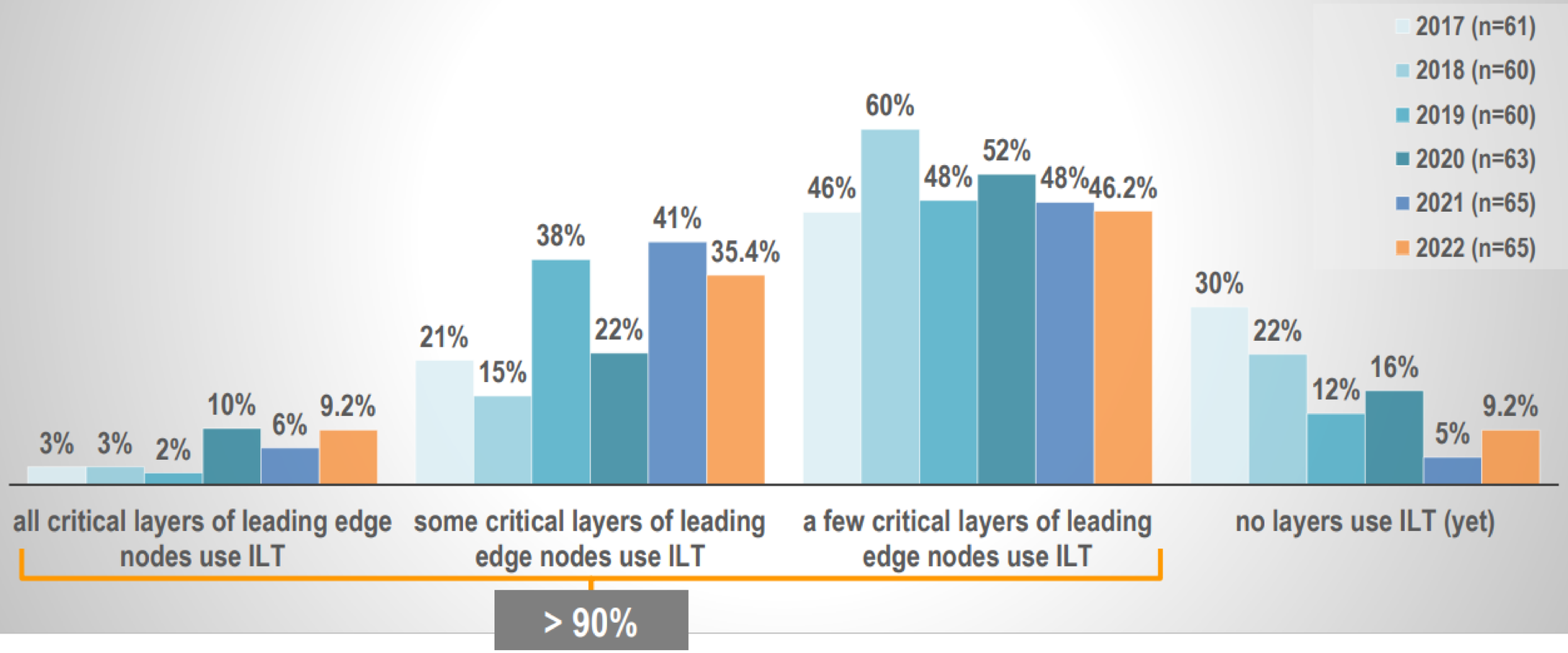




110nm DoF @ 12%EL

How broadly is inverse lithography (ILT) used for production chips today (2022)?

(use includes for hot spots only; ILT refers to both Manhattanized ILT & Curvilinear ILT)



eBeam Initiative luminaries survey results, 2022. https://www.ebeam.org/docs/2022-ebeam-luminaries-survey-final-1.pdf

If OPC, ILT are 40X faster…

How much does that speed up

- Each experiment in the Fab?
- Each product stepping?
- A technology node’s time-to-yield?
- A product’s time-to-market?

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Partnership with TSMC

“The cuLitho team has made admirable progress on speeding up computational lithography by moving expensive operations to GPU. This development opens up new possibilities for TSMC to deploy lithography solutions like Inverse Lithography Technology (ILT) and Deep-Learning more broadly in chip manufacturing, making important contributions to the continuation of semiconductor scaling”

– Dr. C.C. Wei, CEO, TSMC

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Partnership with ASML

“We are planning to integrate support for GPUs into all of our computational lithography software products. Our collaboration with NVIDIA on GPUs and cuLitho should result in tremendous benefit to computational lithography, and therefore to semiconductor scaling. This will be especially true in the era of High NA EUV Lithography.”

– Peter Wennink, CEO, ASML

Partnership with Synopsys

“Computation lithography, specifically Optical Proximity Correction (OPC) is pushing the boundaries of compute workloads for the most advanced chips. By collaborating with our partner, NVIDIA, to run Synopsys OPC software on the CULitho Platform, we massively accelerated the performance from weeks to days! The team-up of our two leading companies continues to force amazing advances in the industry.”

– Aart de Geus, Chair and CEO, Synopsys

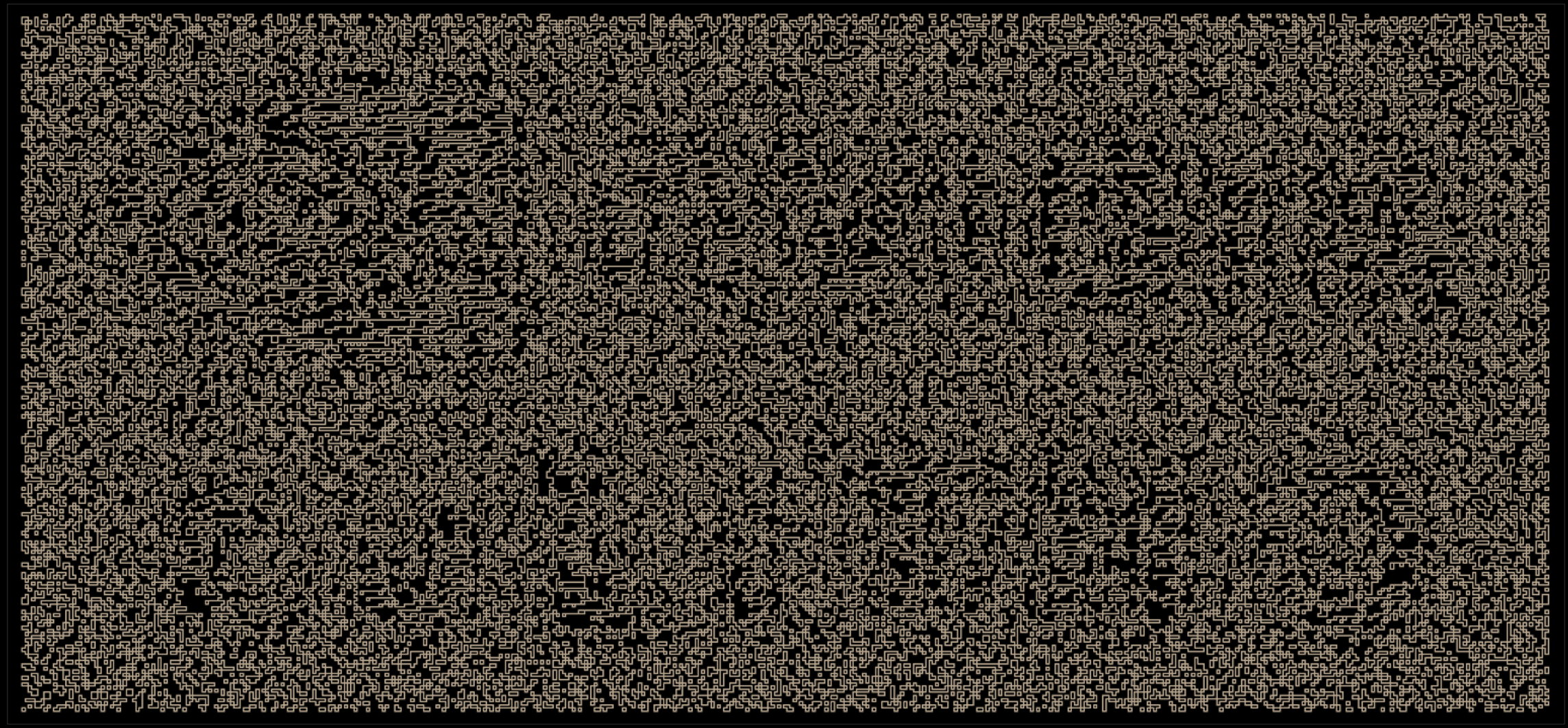
Outline

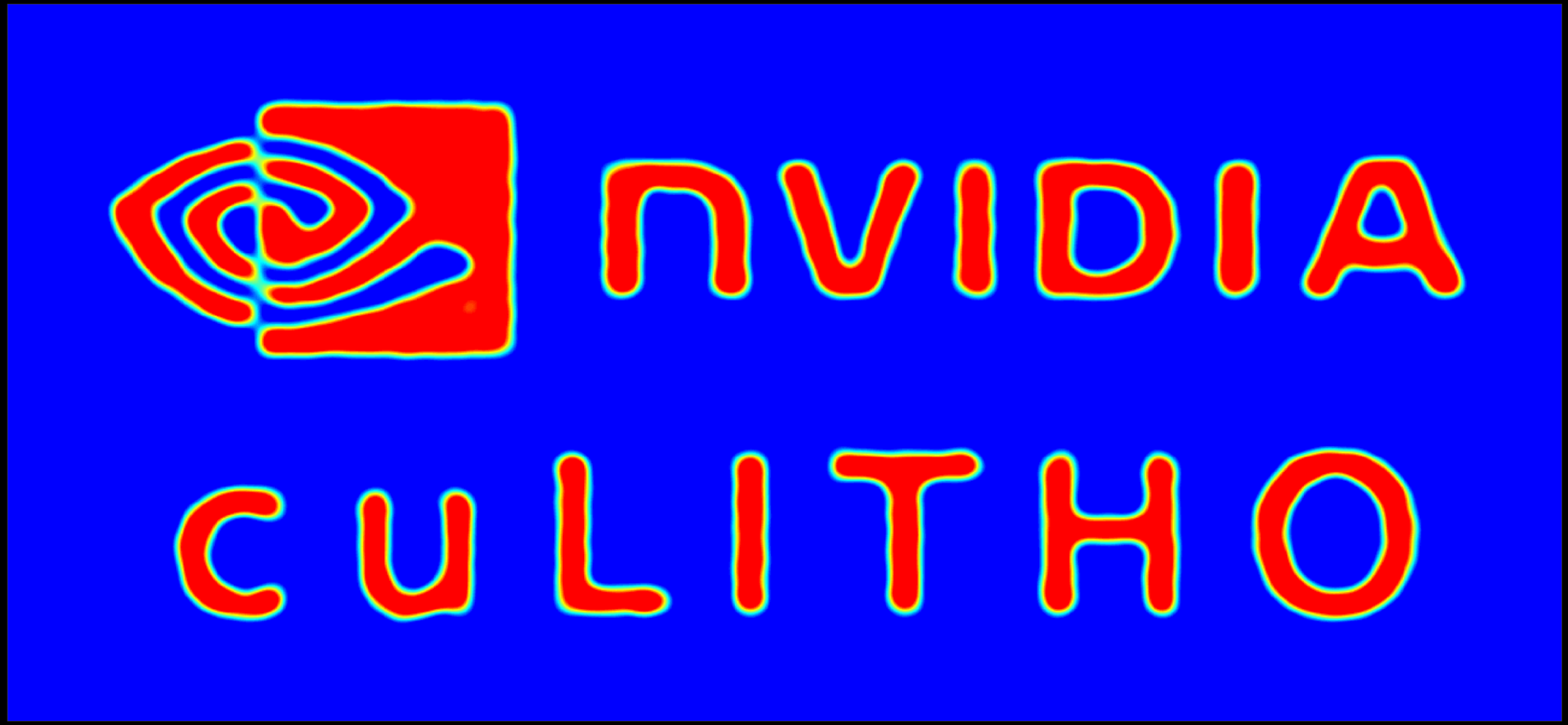
- What is Computational Lithography?
- The Problem: Exploding Computation
- The Breakthrough!
- Enables Better Chip Technology, Faster
- **Summary, and a quiz!**

“The semiconductor industry is essential in driving every other industry in the world and advancing its capabilities is key to the future of innovation. As current technology nears the limits of physics, NVIDIA’s introduction of cuLitho is helping to unlock this potential. Working with our partners TSMC, ASML and Synopsys, we can increase their throughput, decrease cycle time and accelerate speed to market, opening the door to innovations in a wide range of fields.”

– Jensen Huang, Founder and CEO, NVIDIA

How will this mask print?

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CULITHO


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