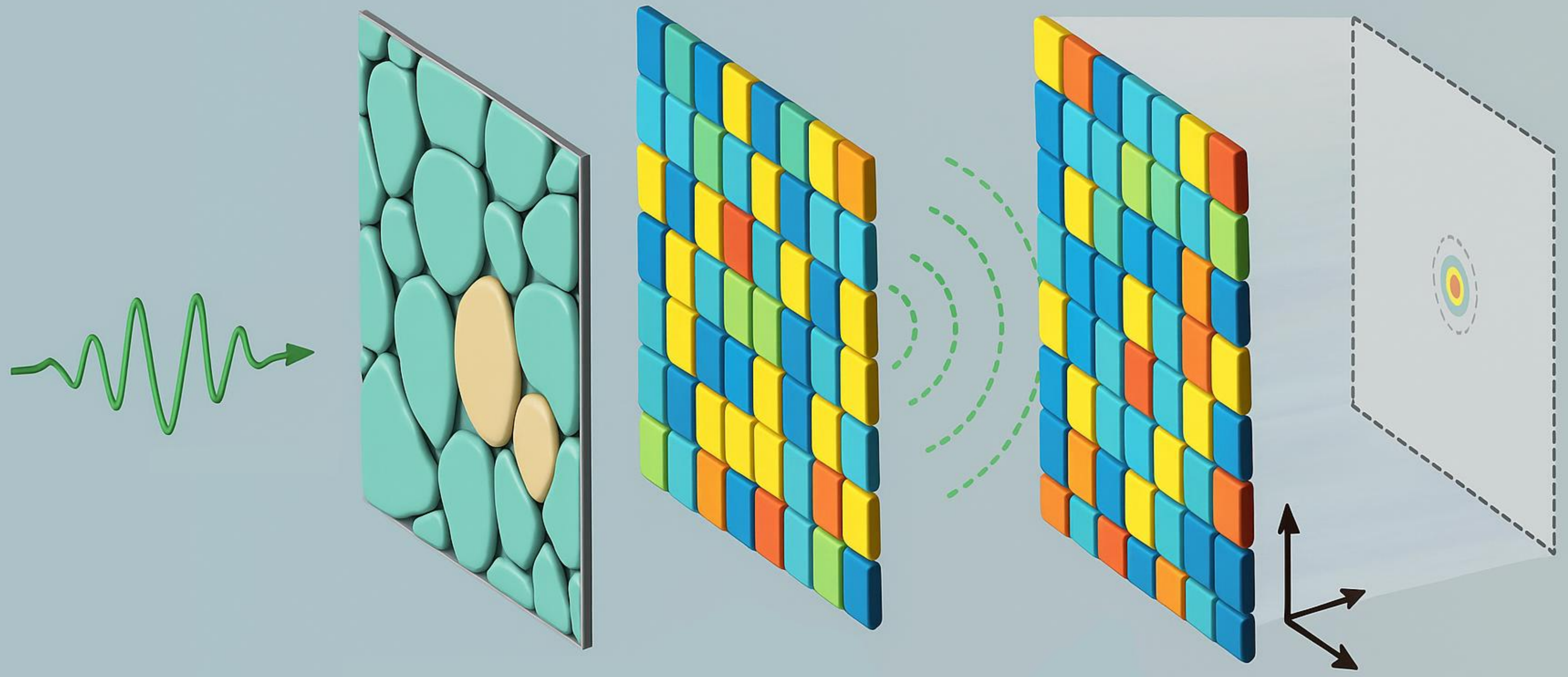
Optics that Learn



Marco Piccardo
Multimode Photonics Group

TÉCNICO LISBOA

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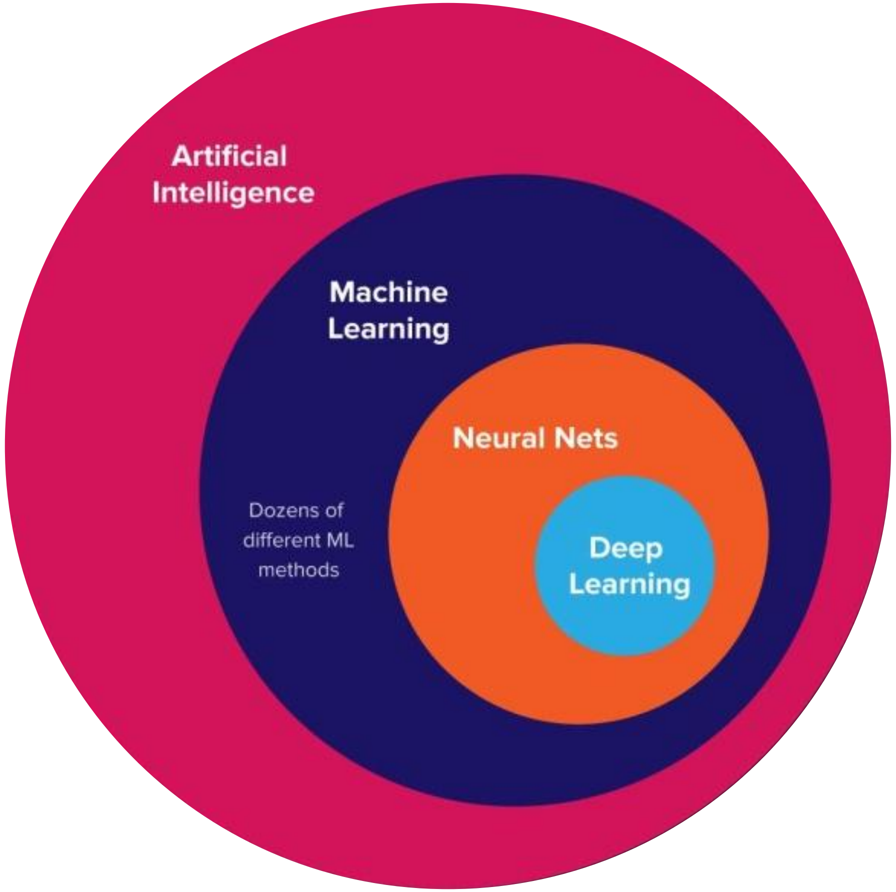
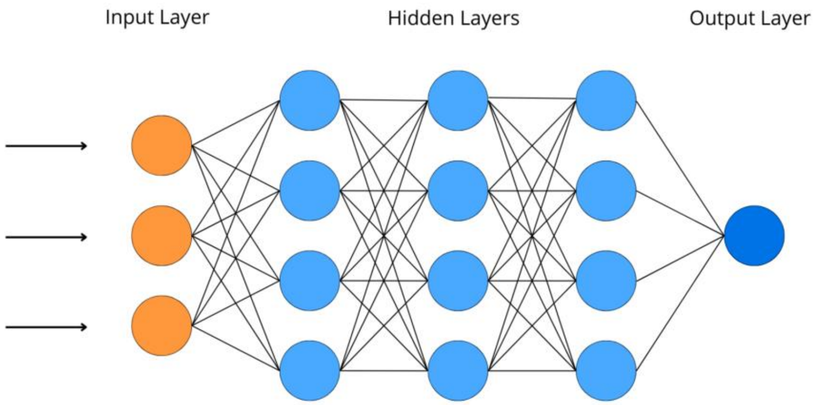
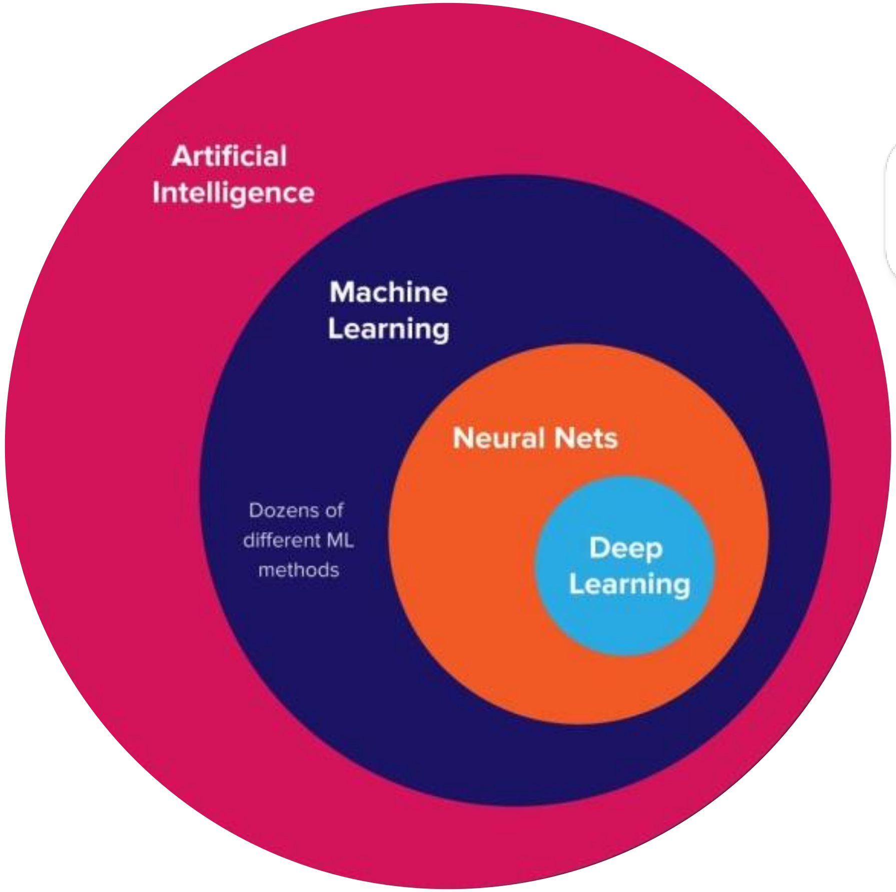
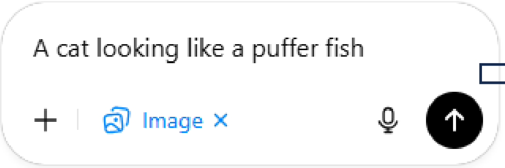
A key subset of Machine Learning: Artificial neural networks

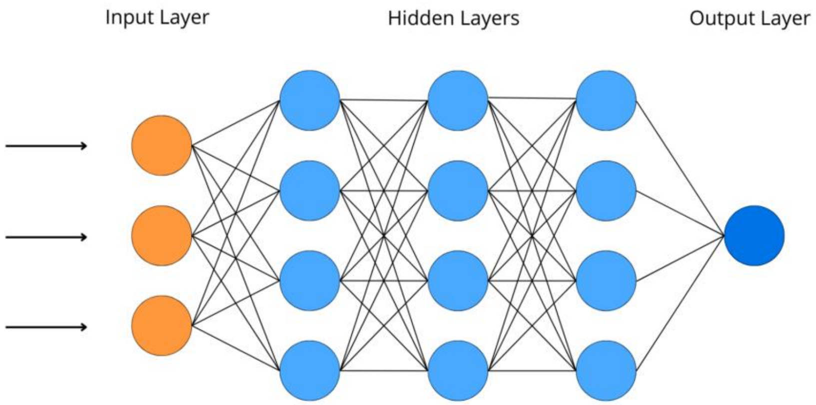




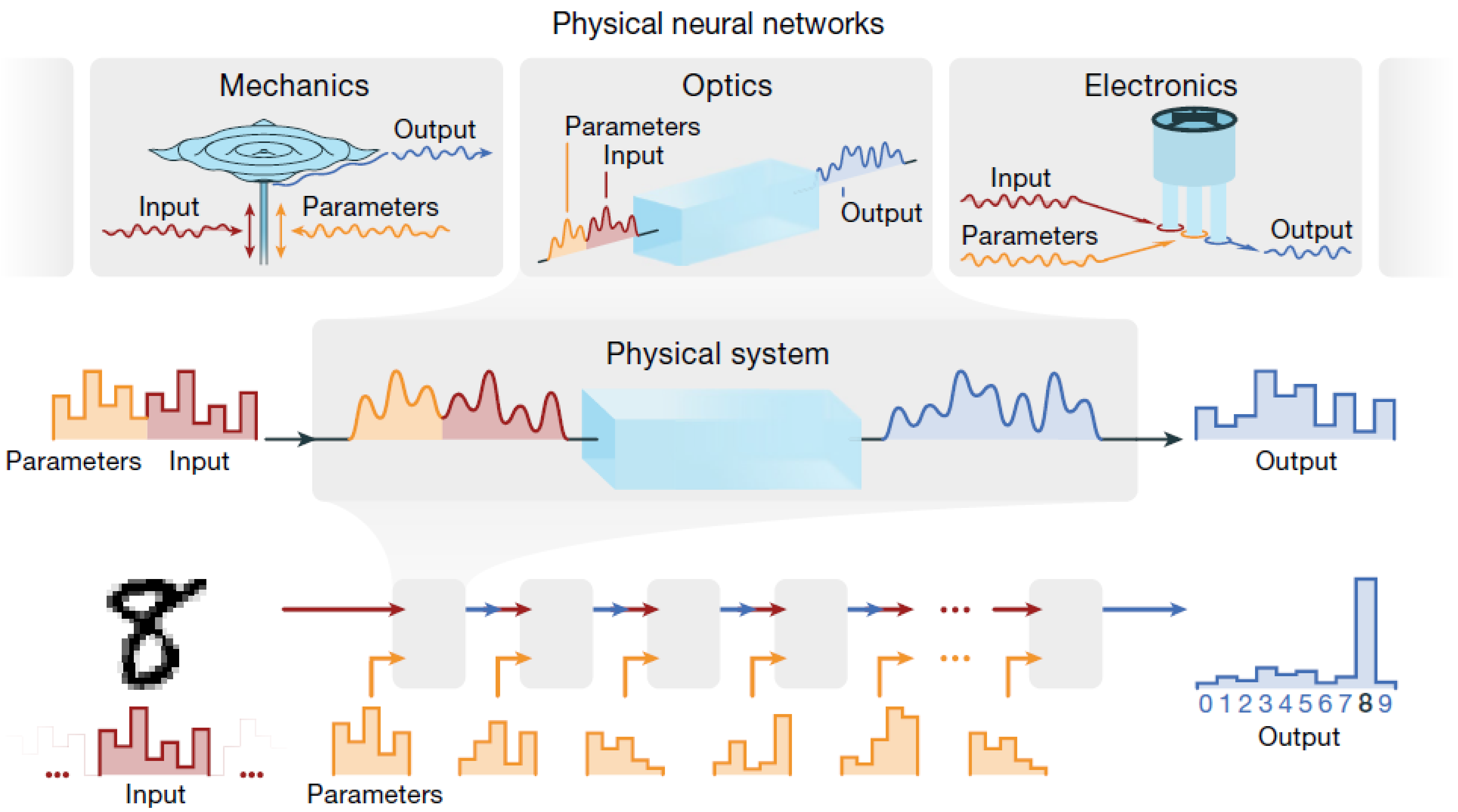
A key subset of Machine Learning: Artificial neural networks



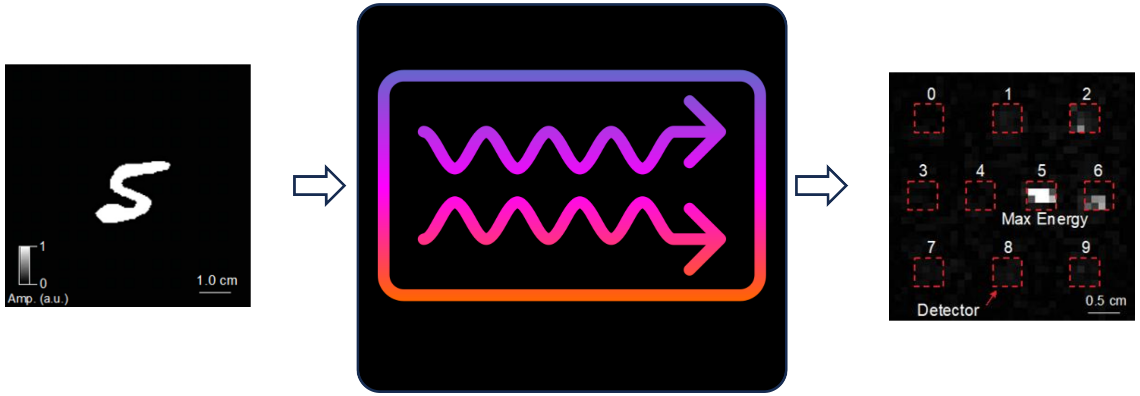


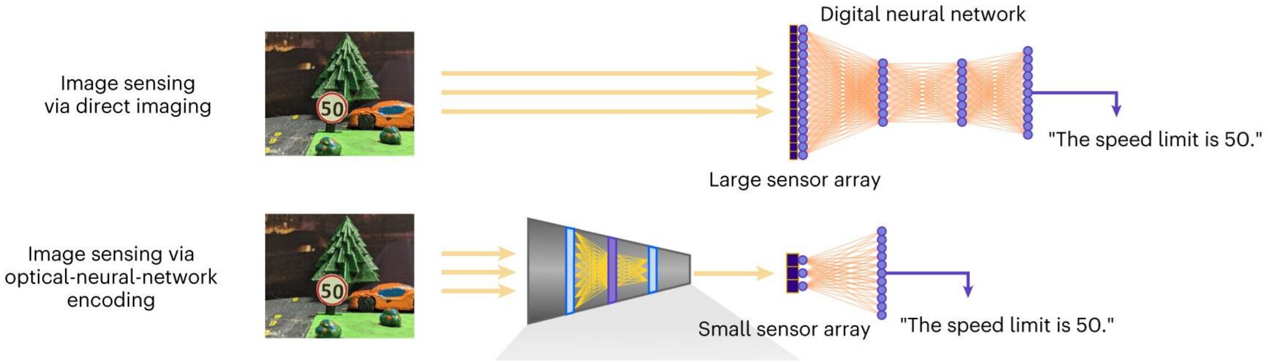


Physical neural networks

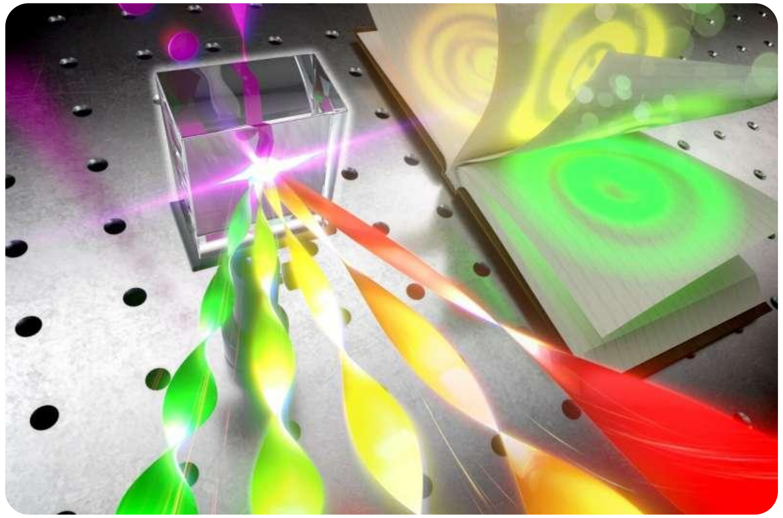


Optical neural networks

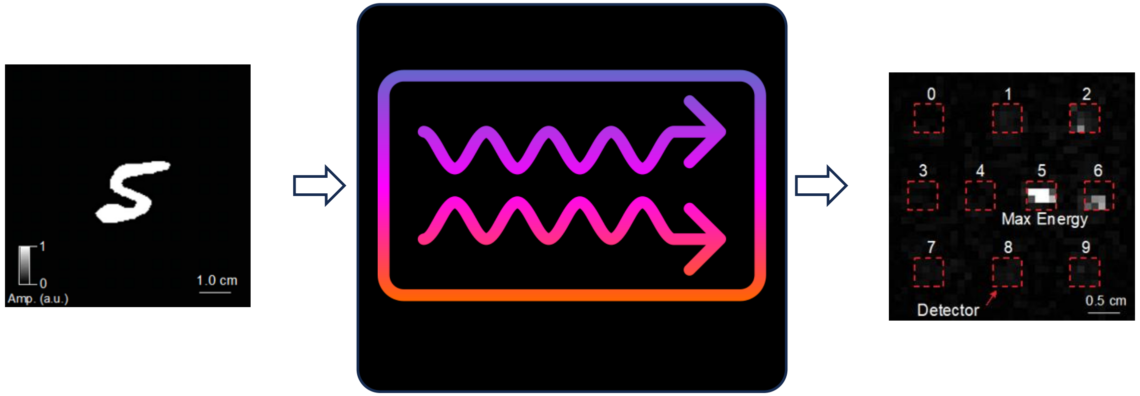


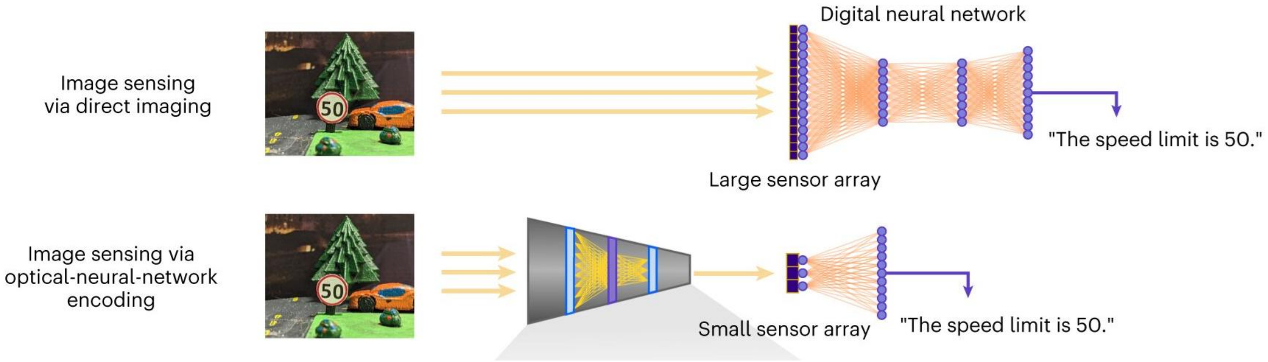


Complex structured light transformations



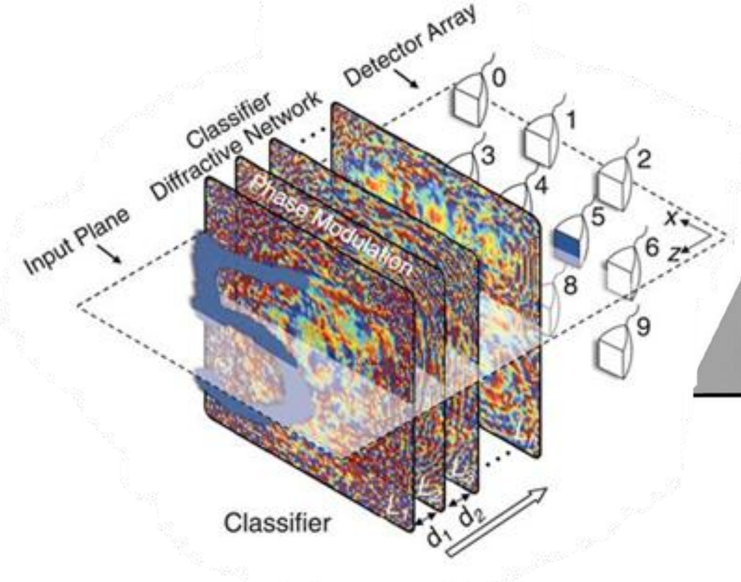
Optical neural networks



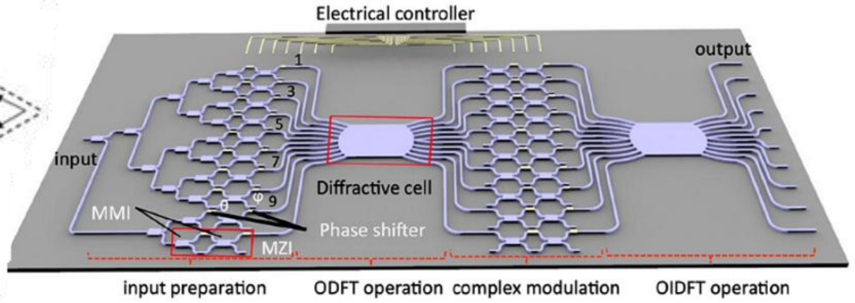


Architectures

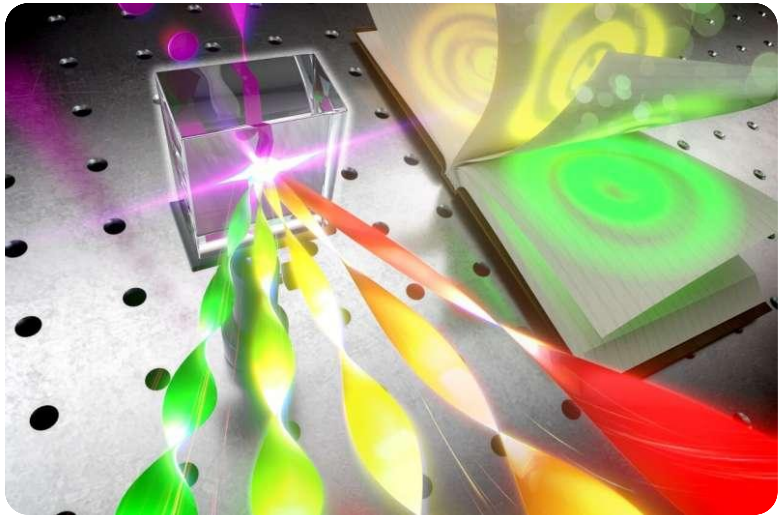
Free space and diffractive



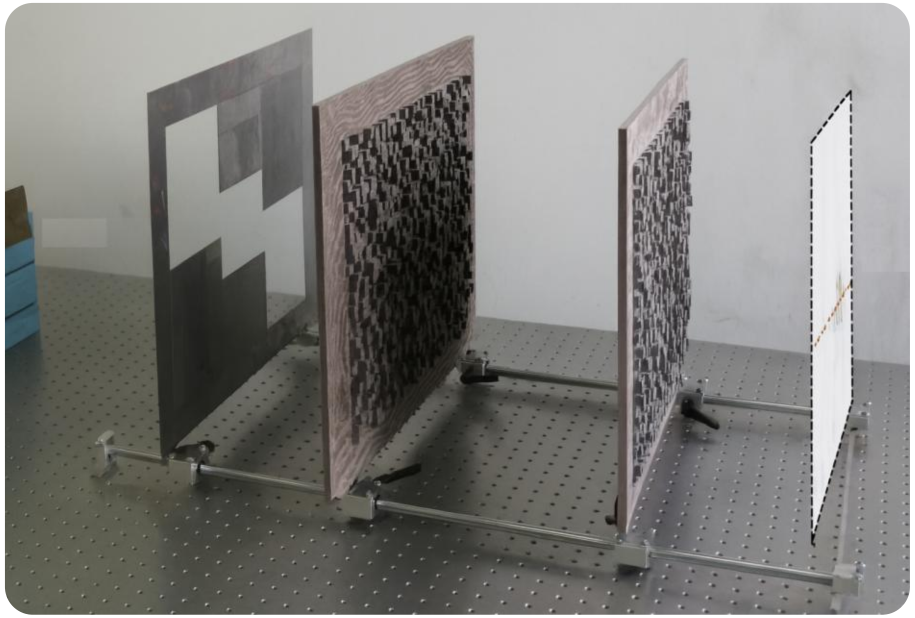
Integrated and interferometer-based

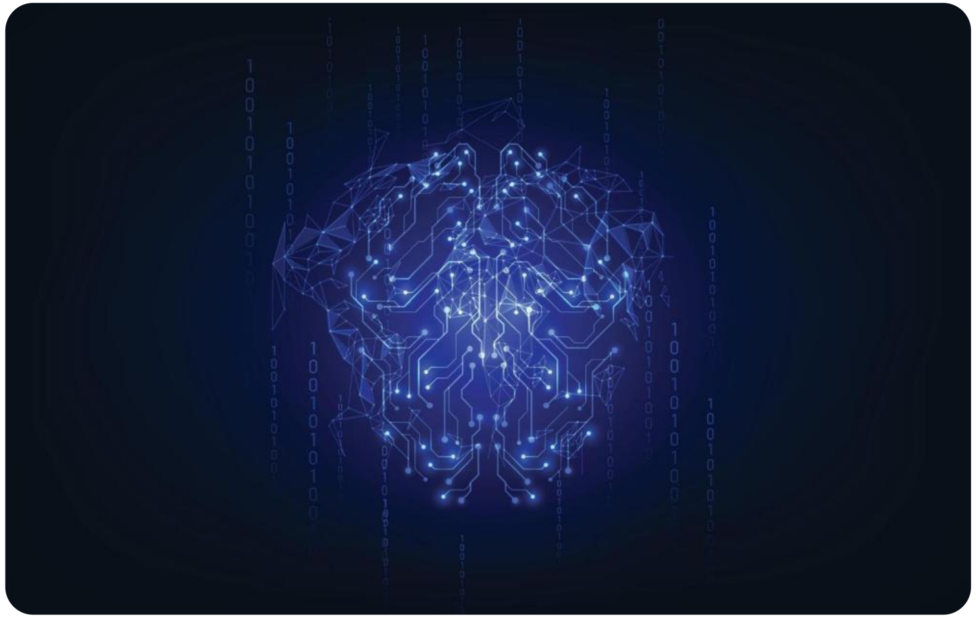


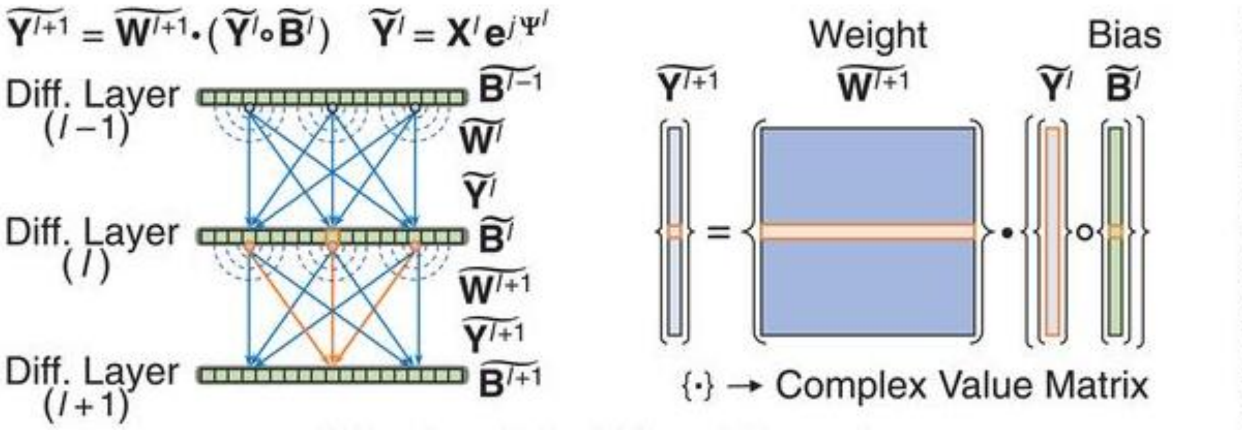
Complex structured light transformations

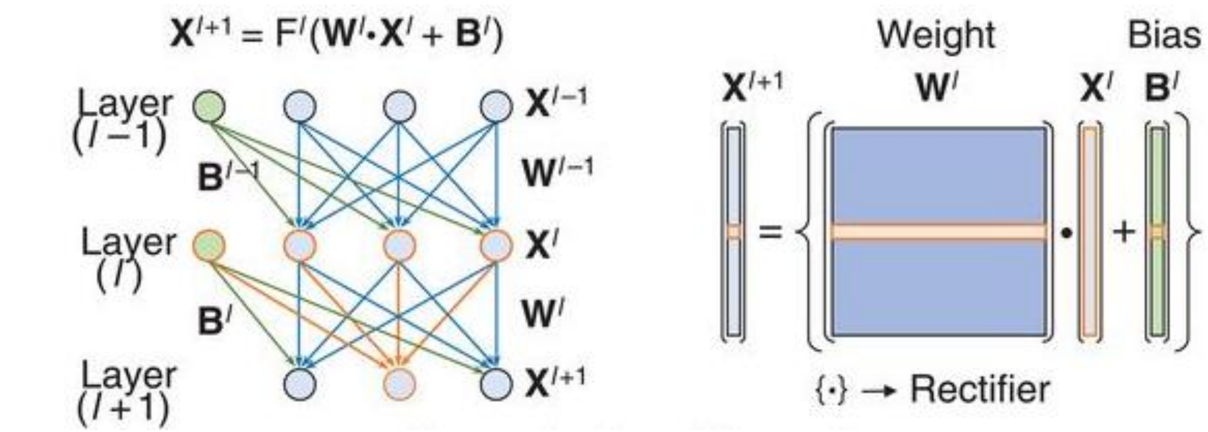


Optical vs. artificial neural networks



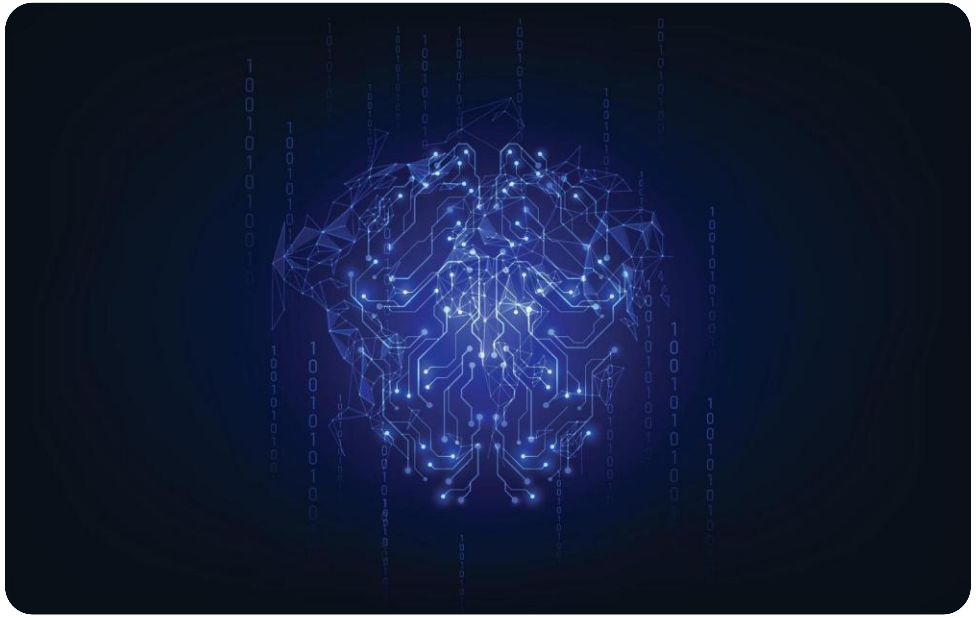


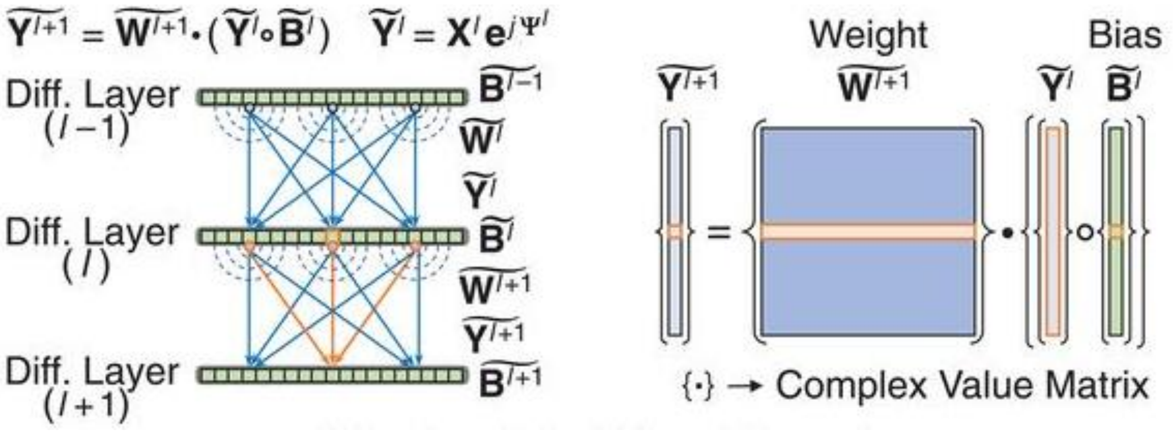


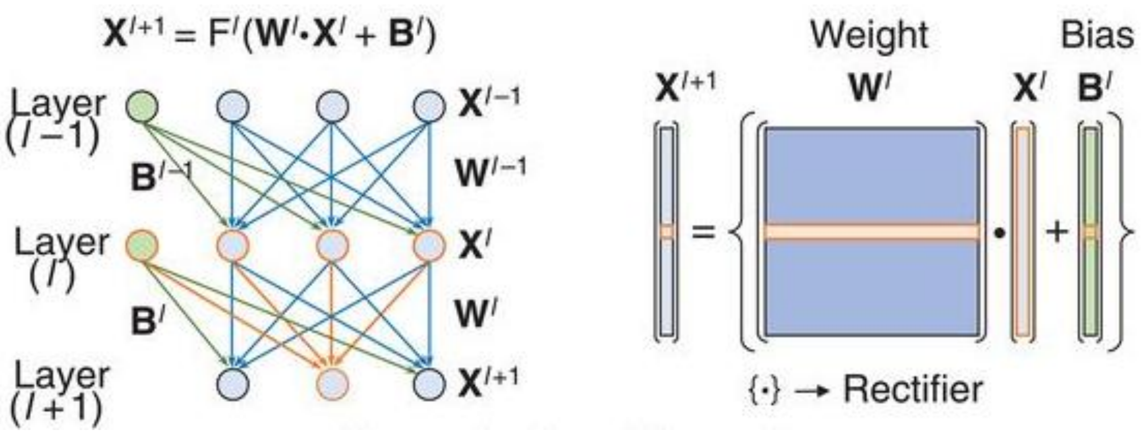


Optical vs. artificial neural networks

Nonlinearity + training are the bottleneck!



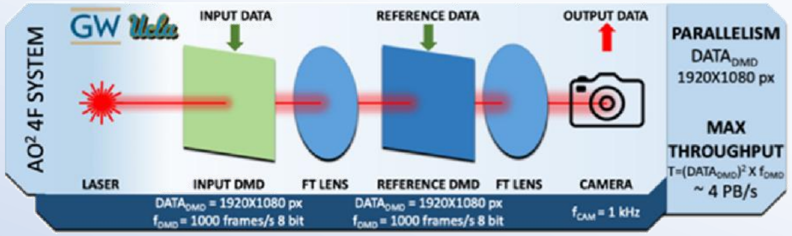




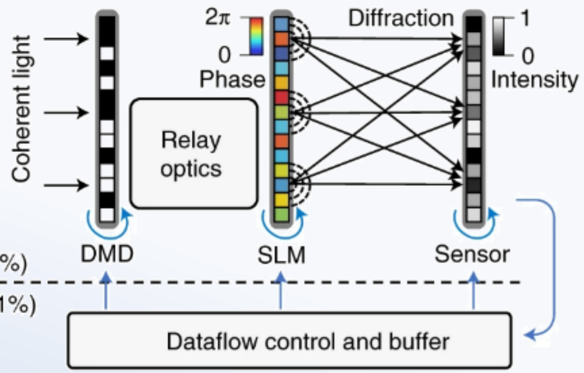
The issue of nonlinearity in optical neural nets

Optoelectronic hybrid NNs

Electronic detection



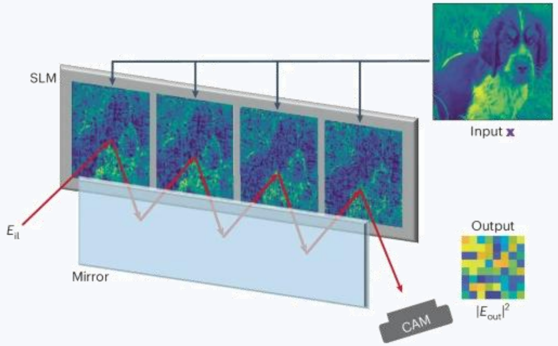
M. Miscuglio et al., Optica 7, 1812 (2020)



Optoelectronic implementation

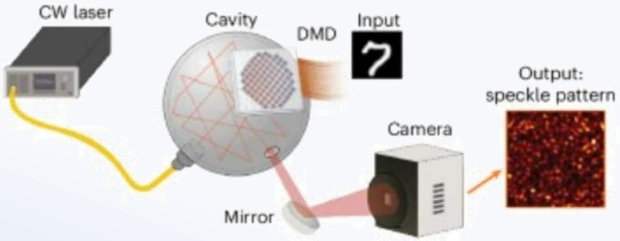
T. Zhou et al., Nature Photonics 15, 367 (2021)

Data repetition method



M. Yildirim et al., Nature Photonics 18, 1076 (2024)

Nonlinear mapping with a multiple-scattering cavity



F. Xia et al., Nature Photonics 18, 1067 (2024)

The issue of nonlinearity in optical neural nets

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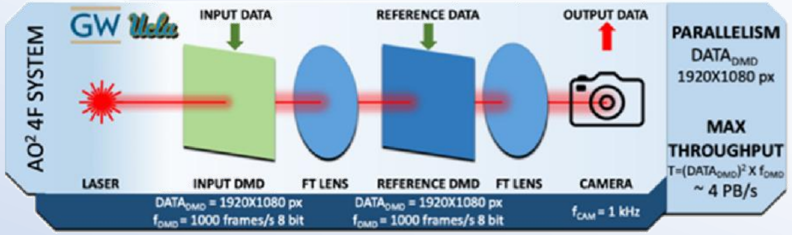
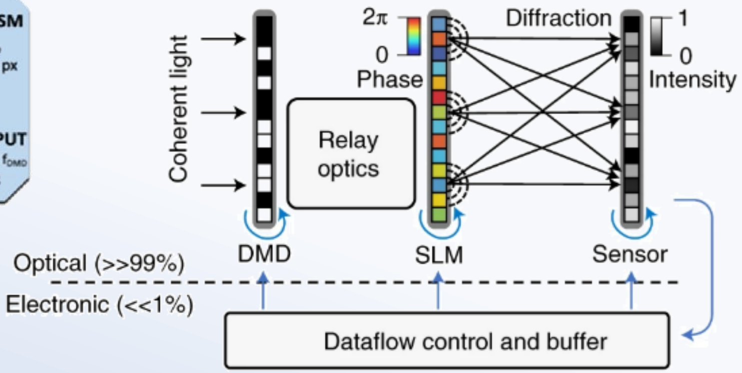


M. Miscuglio et al., Optica 7, 1812 (2020)



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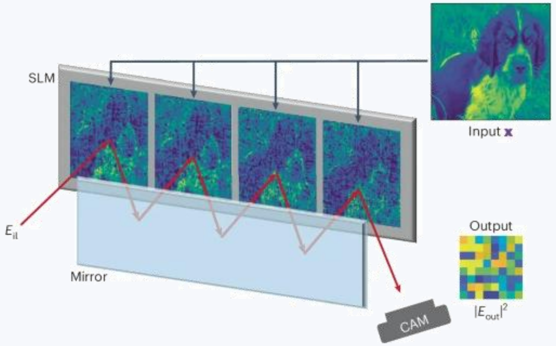
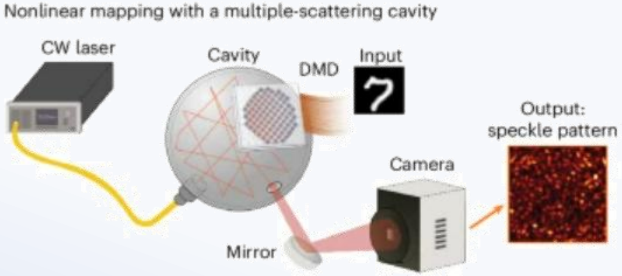


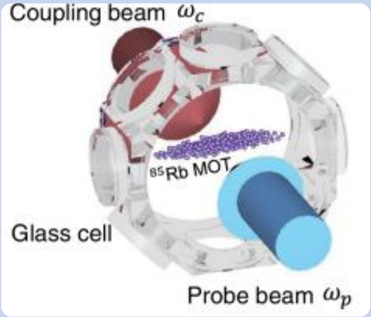
M. Yildirim et al., Nature Photonics 18, 1076 (2024)



F. Xia et al., Nature Photonics 18, 1067 (2024)

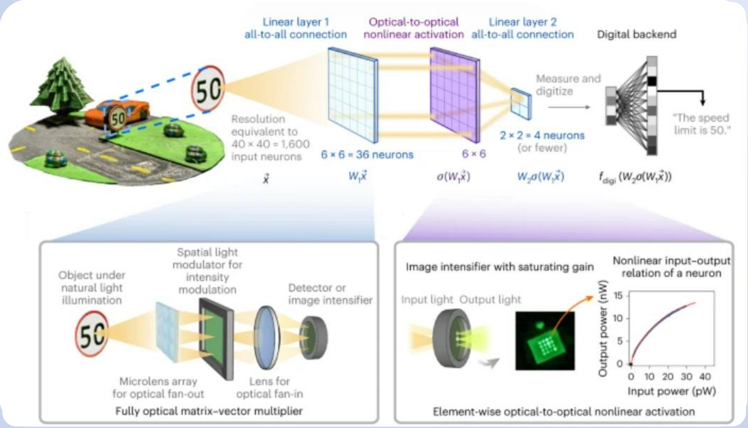
All-optical

Atomic nonlinearity



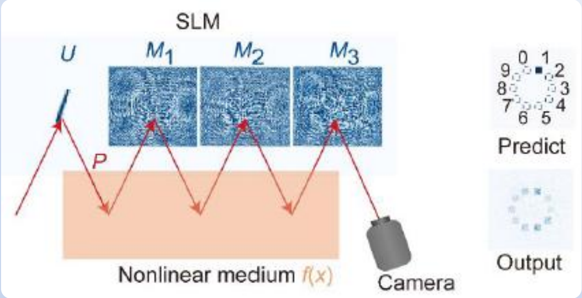
Y. Zuo et al., Optica 6, 1132 (2019)

Image intensifiers



T. Wang et al., Nature Photonics 17, 408 (2023)

Kerr nonlinearity

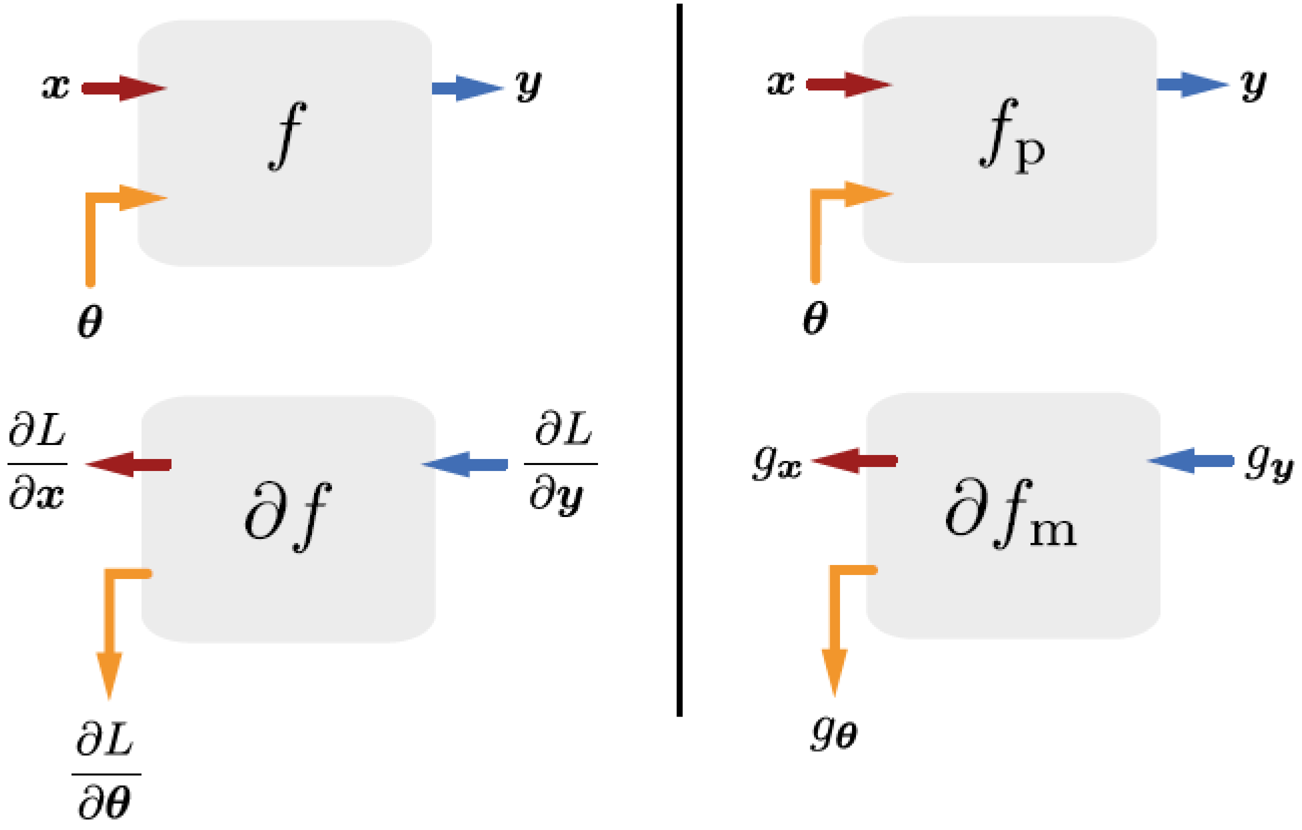


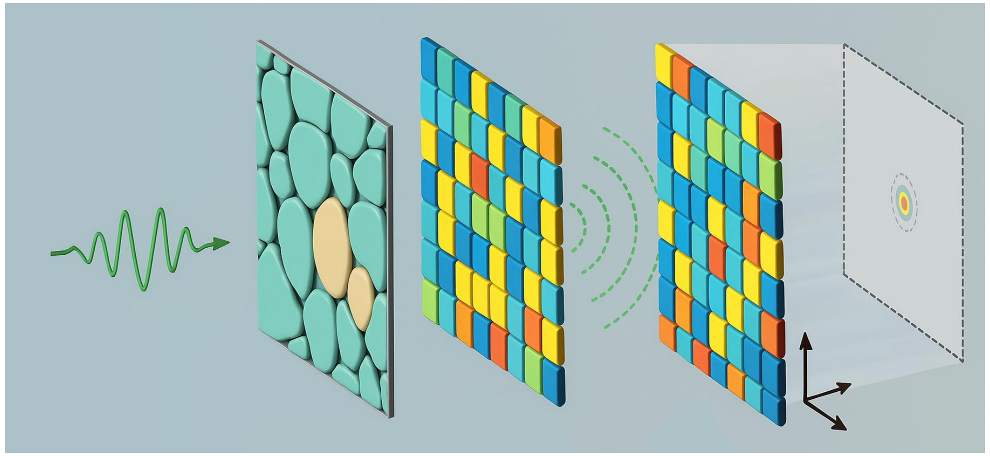
Y. Dong et al., arXiv:2504.13518 (2025)

How do optics learn?

Conventional back-propagation

Physics-aware training





Review

Training of physical neural networks

https://doi.org/10.1038/s41586-025-09384-2

Received: 25 January 2024

Accepted: 10 July 2025

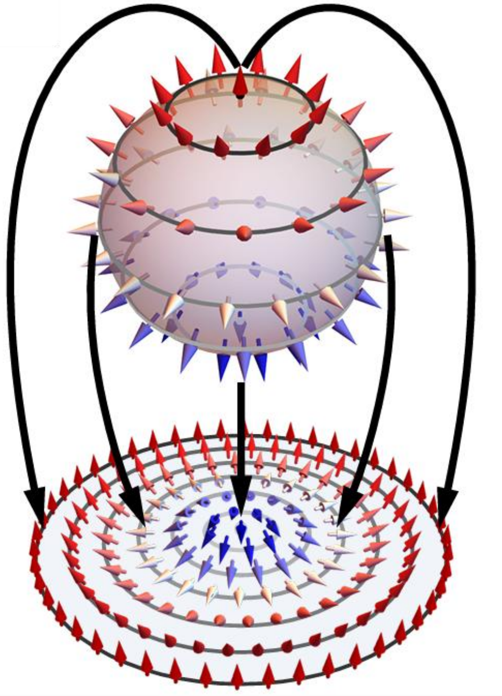
Published online: 3 September 2025

Check for updates

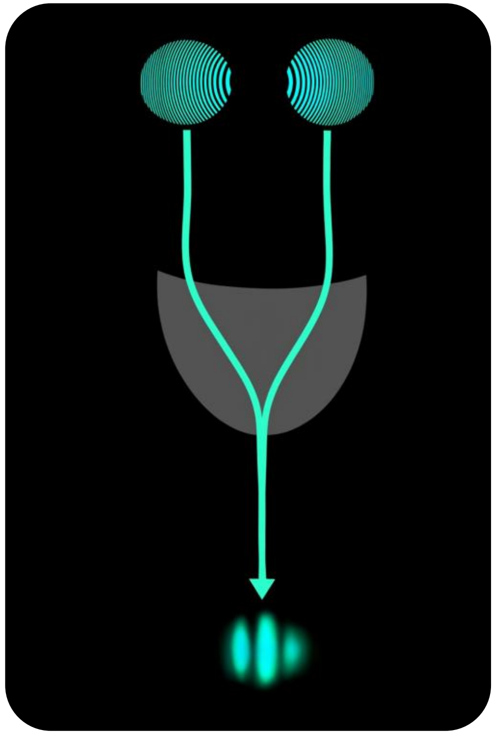
Ali Momeni[1], Babak Rahmani[2], Benjamin Scellier[3], Logan G. Wright[4], Peter L. McMahon[5], Clara C. Wanjura[6], Yuhang Li[7], Anas Skalli[8], Natalia G. Berloff[9], Tatsuhiro Onodera[5,10], Ilker Oguz[11], Francesco Morichetti[12], Philipp del Hougne[13], Manuel Le Gallo[14], Abu Sebastian[14], Azalia Mirhoseini[15,16], Cheng Zhang[2], Danijela Marković[17], Daniel Brunner[8], Christophe Moser[11], Sylvain Gigan[18], Florian Marquardt[6], Aydogan Ozcan[7], Julie Grollier[19], Andrea J. Liu[20], Demetri Psaltis[21], Andrea Alù[22,23] & Romain Fleury[1]✉

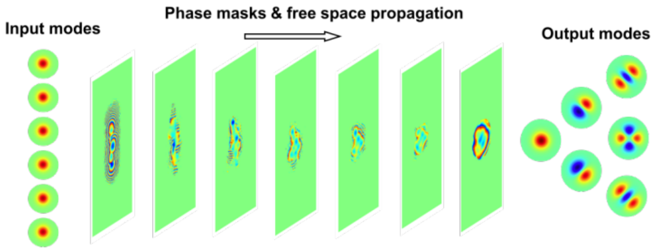
Two optical neural nets for two big challenges in structured light

Giving texture to light



Making an all-optical switch





"Easy"

Y. Zhang and N. K. Fontaine, arXiv:2304.11323 (2023)

Why Machine Learning?

- Nonlinear optics
- Nonlinear loss

M. Ines Nunes

G. Vaz

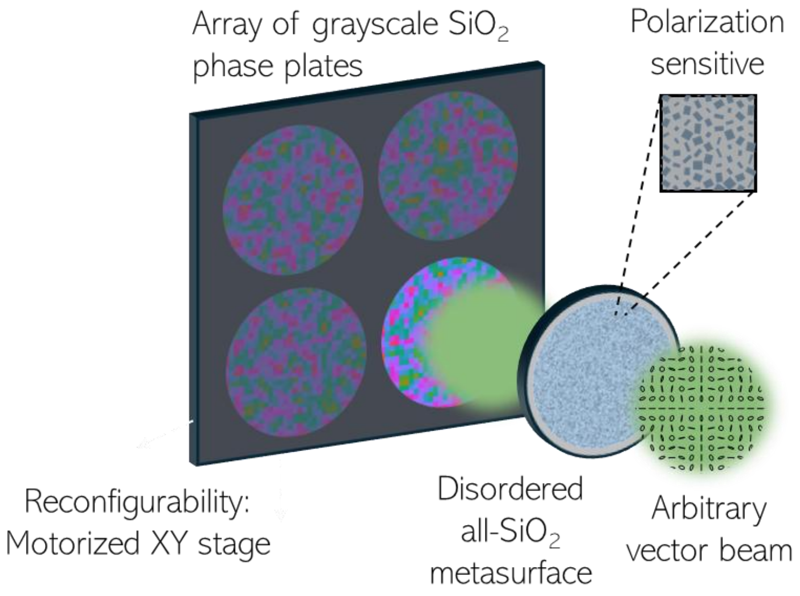
J. Bonito

J. Pimenta

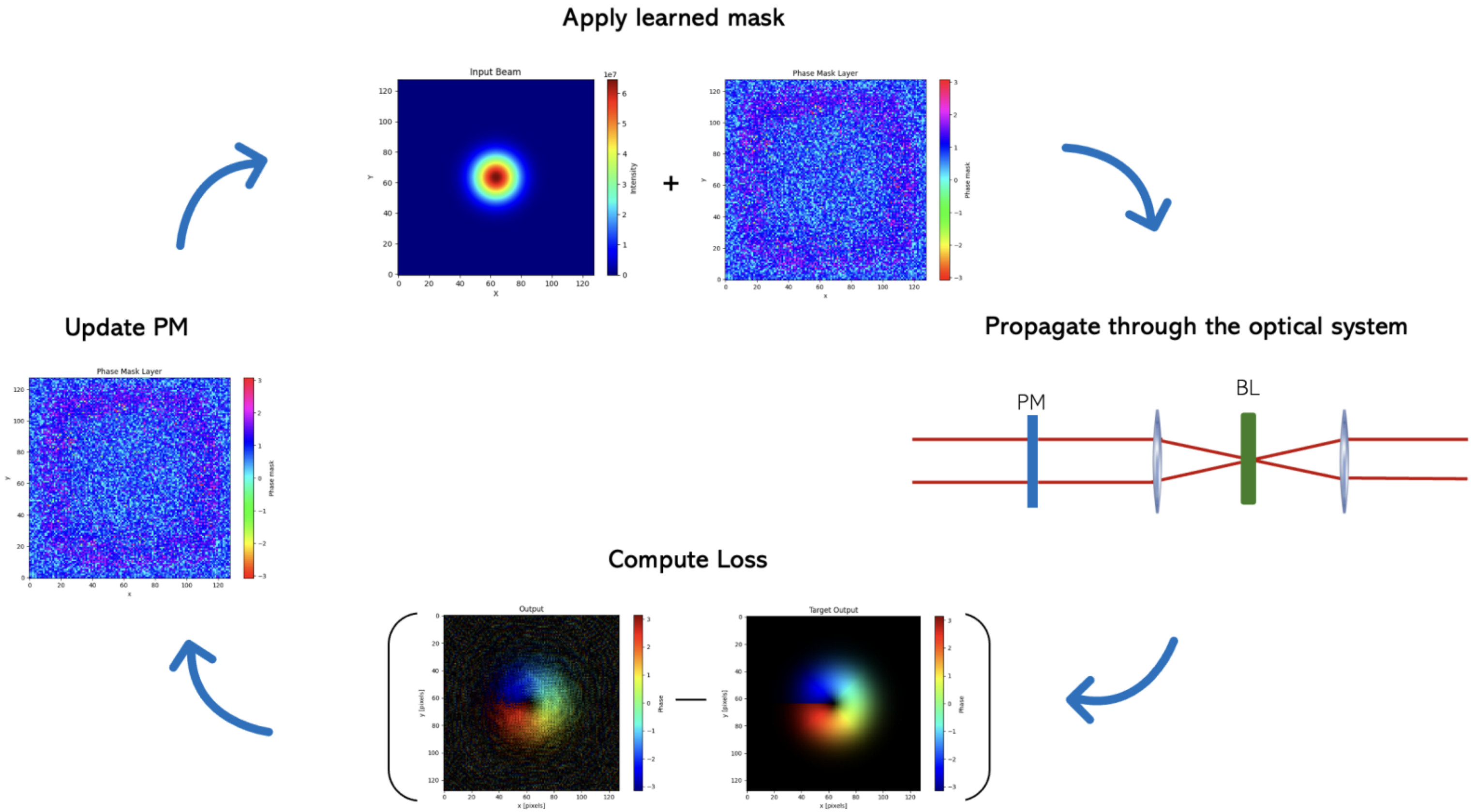
Multimode Photonics Group

Texturing light with a single metasurface

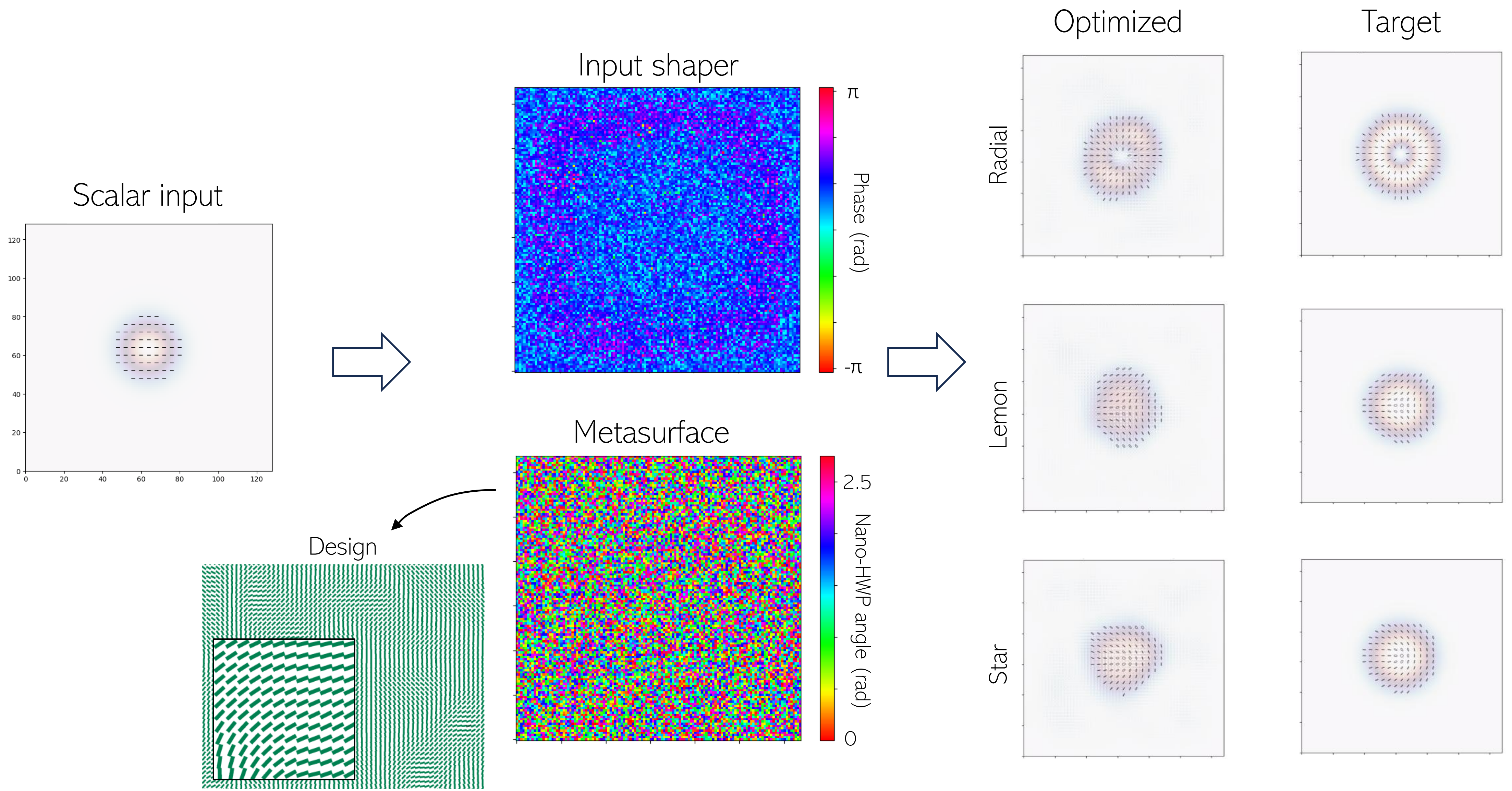
Our goal: Arbitrary vectorial outputs from a single disorder-engineered birefringent metasurface in combination with custom scalar phase plates



Machine Learning mask optimization:
our ML code designs an input mask for any arbitrary output vector beam

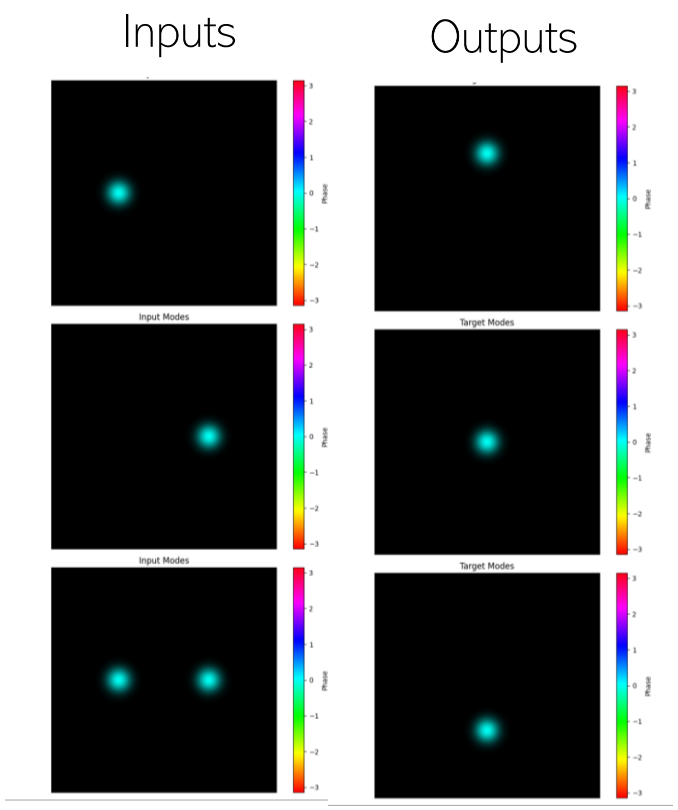


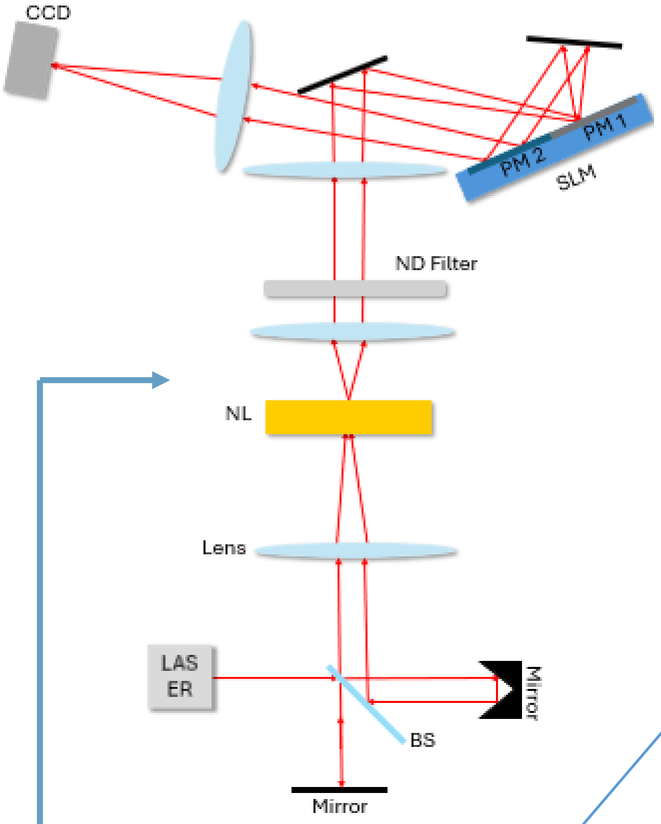
Scalar to vectorial mapping

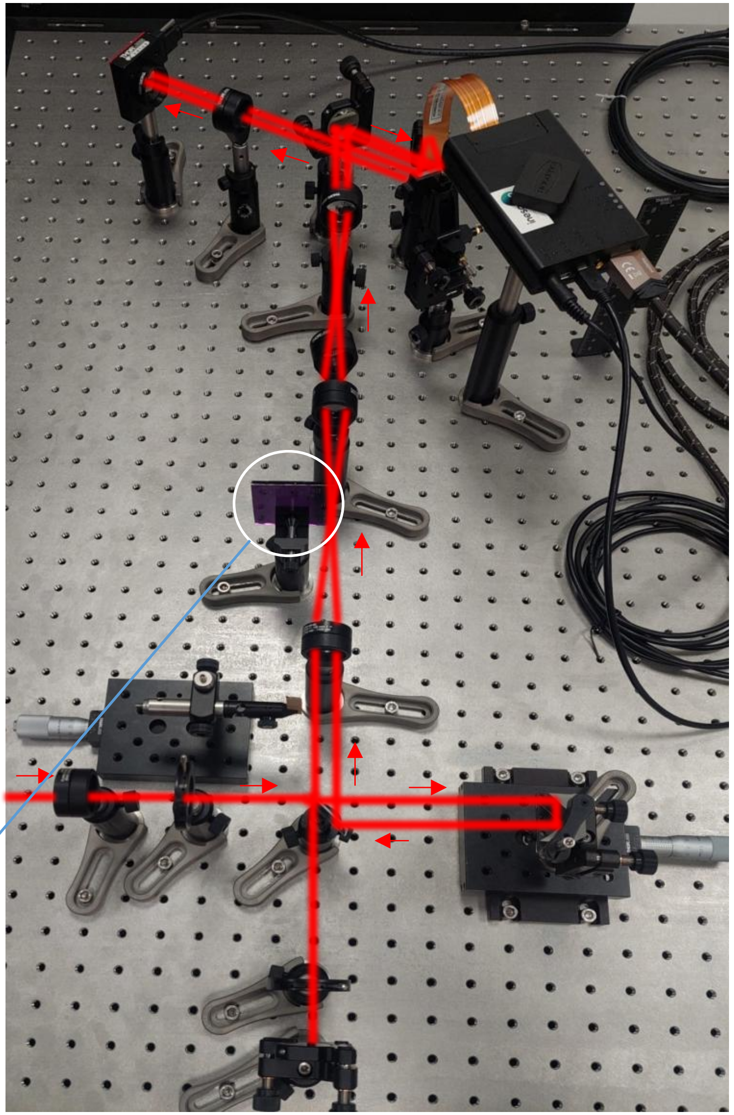


Chasing 3 dots: Analog logic gates of structured light

What if we had a Decoder but for light?







But how?

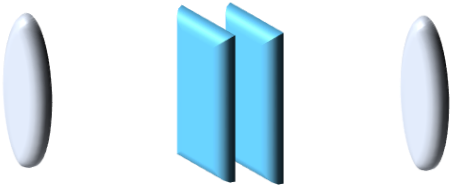
Using a Physical Neural Network!

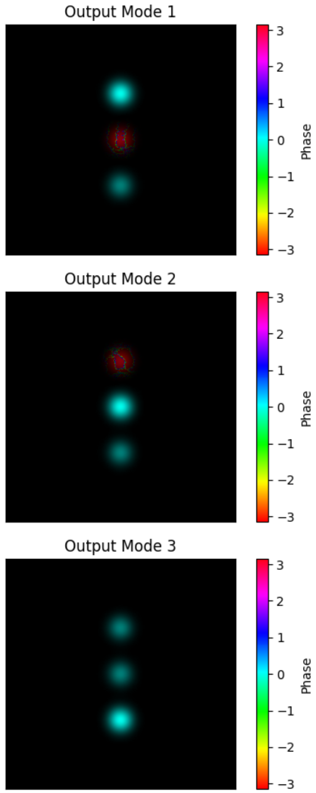
Nonlinear Layer!

Why a Nonlinear Layer?

Without Nonlinear Layer

Phase Masks

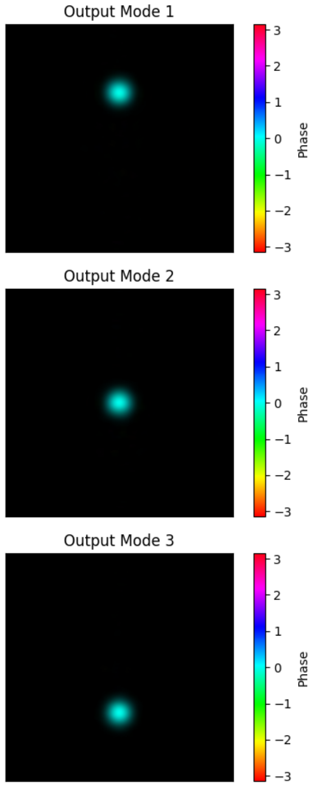




With Nonlinear Layer

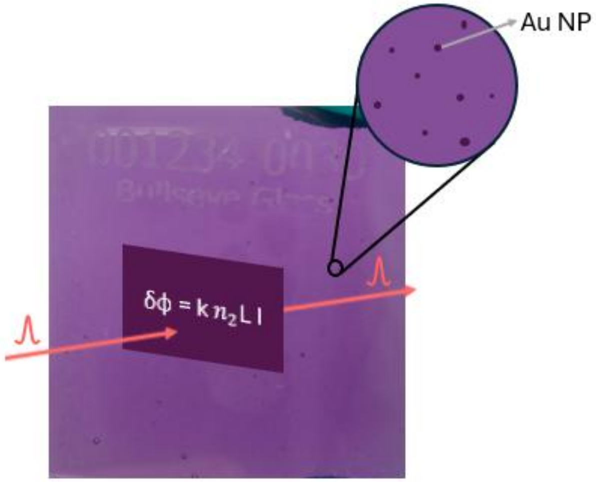
Nonlinear Layer

Phase Masks



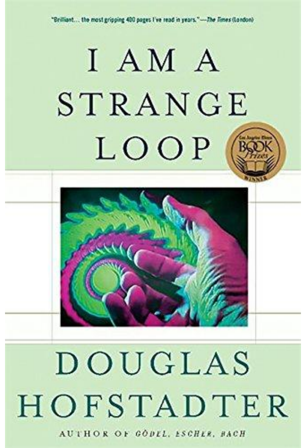
Nonlinearity enables the switch!

In our case, the nonlinearity comes from the **Kerr Effect**, a third order nonlinear effect



Vision: A path towards artificial photonic life

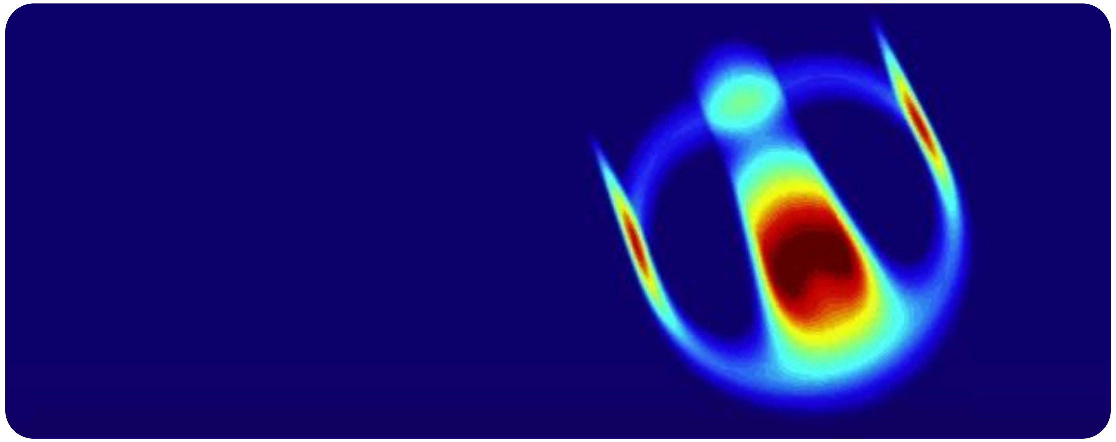
Loops are essential to move from useful processors to truly intelligent and aware systems



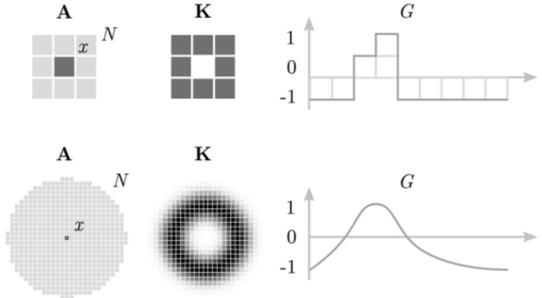
14 open problems in Artificial Life:

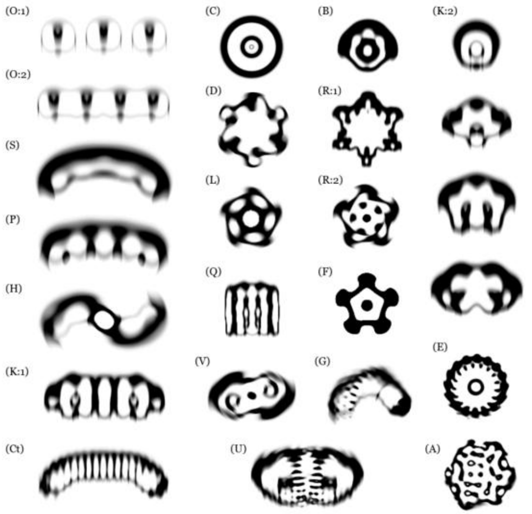
#3 Determine whether fundamentally novel living organizations can exist

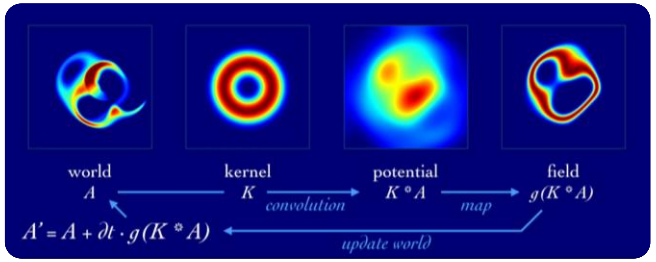
Lenia project @Google Brain

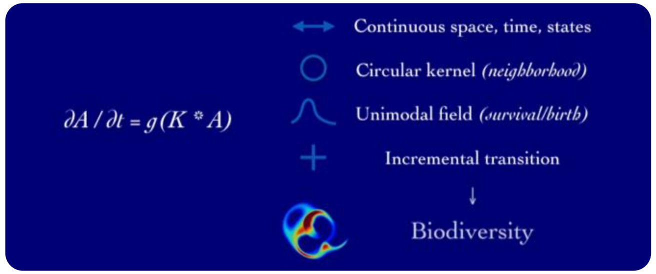


- Mathematical project based on continuous cellular automata
- Lifelike features like: self-organization, self-repair, bilateral and radial symmetries, locomotive dynamics, and sometimes chaotic nature
- From a smooth continuous version of Conway's Game of Life

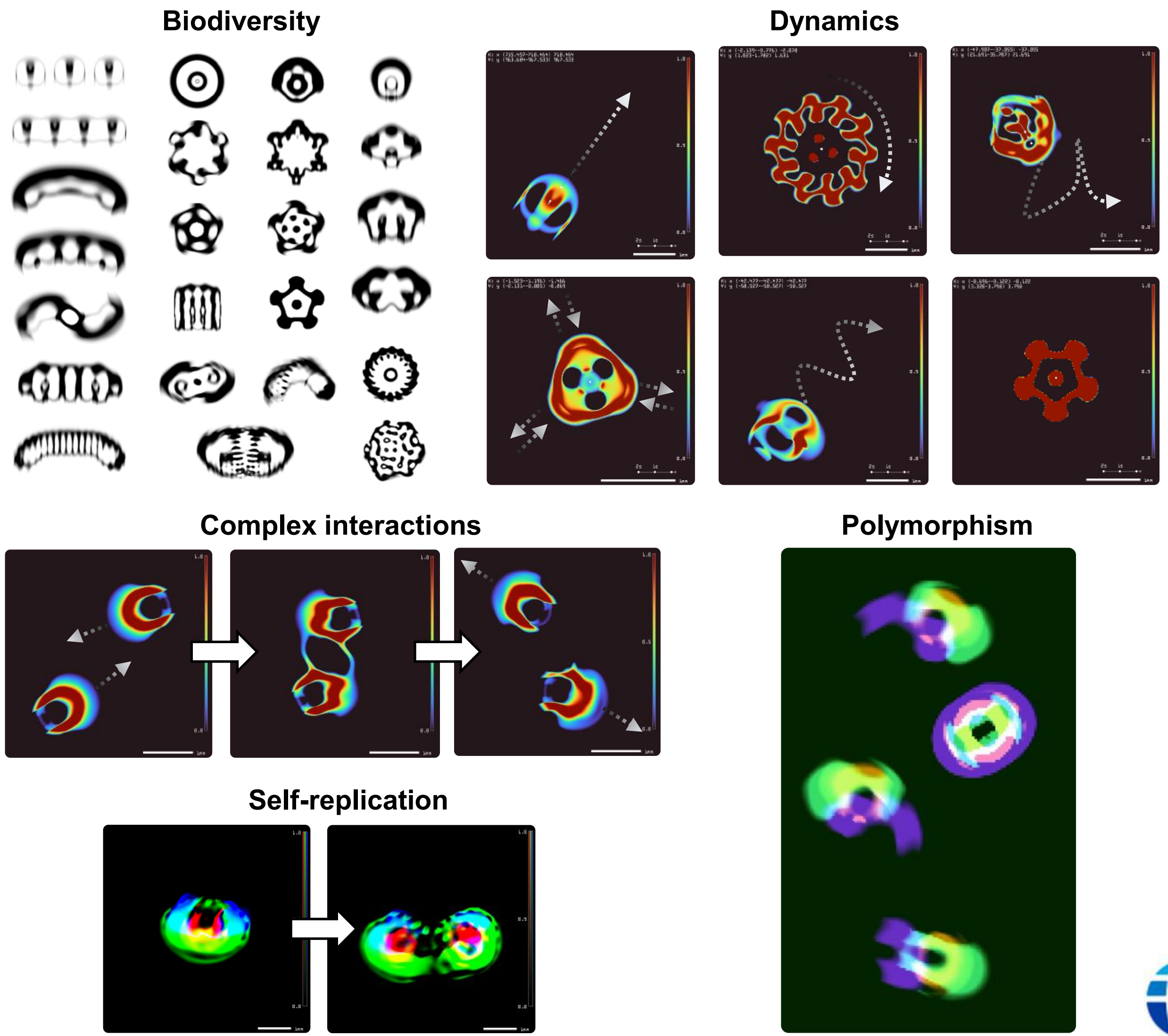


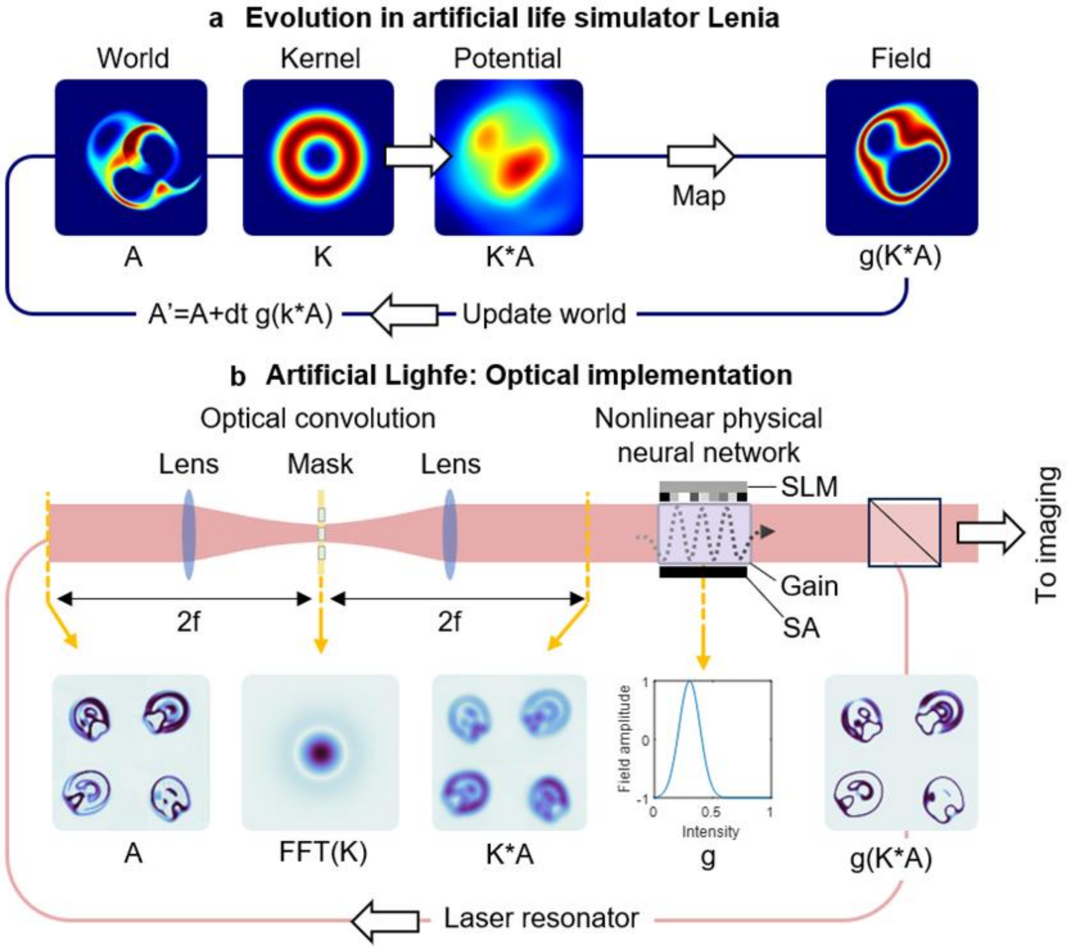






Optical Lenia





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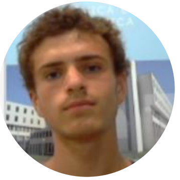
Vitthal Mishra

Ines Silva
(with J.P. Conde)



Adrian Cabral
(with G. De Tomasi)

MSc

Bruno Semiao

Ines Nunes

Joana Bonito

Joaquim Pereira

Joana Pimenta

Sofia Simenta

Carlos Reis
(with D. Caetano)

Filipe Baptista

Miguel Martins