Photonics Research Group

Novel architectures for brain-inspired photonic computers

Nieuwe architecturen voor brein-geïnspireerde fotonische computers

Floris Laporte

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Prof. Dr. Ir. Wim Bogaerts	Universiteit Gent, INTEC
Prof. Dr. Ir. Serge Massar	Université Libre de Bruxelles, LIQ
Dr. Ir. Martin Fiers	Luceda Photonics

Overview

- **Background**
- Machine learning & Neuromorphic computing
- Reservoir computing with signal-mixing cavities
- Photontorch: optimizing photonic circuits
- Neuromorphic computing with photorefractive crystals

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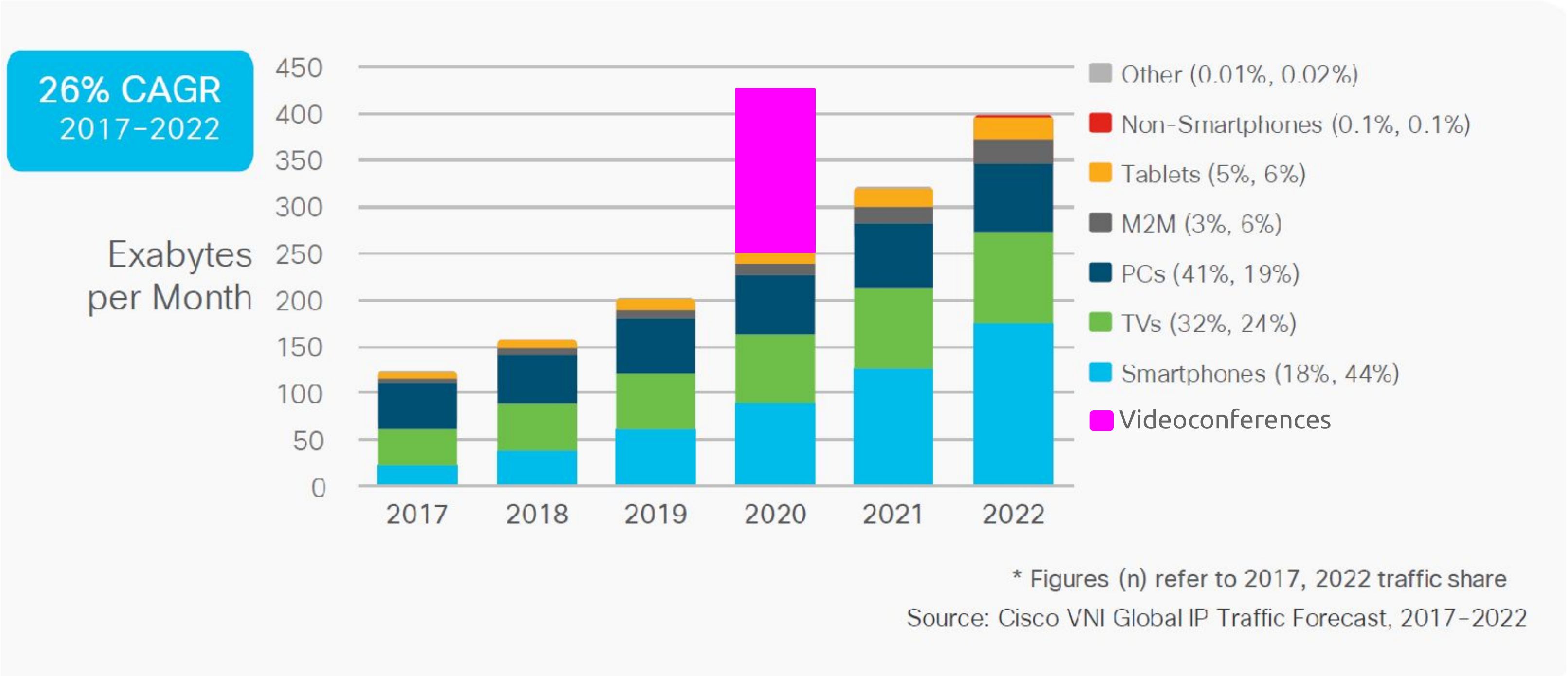
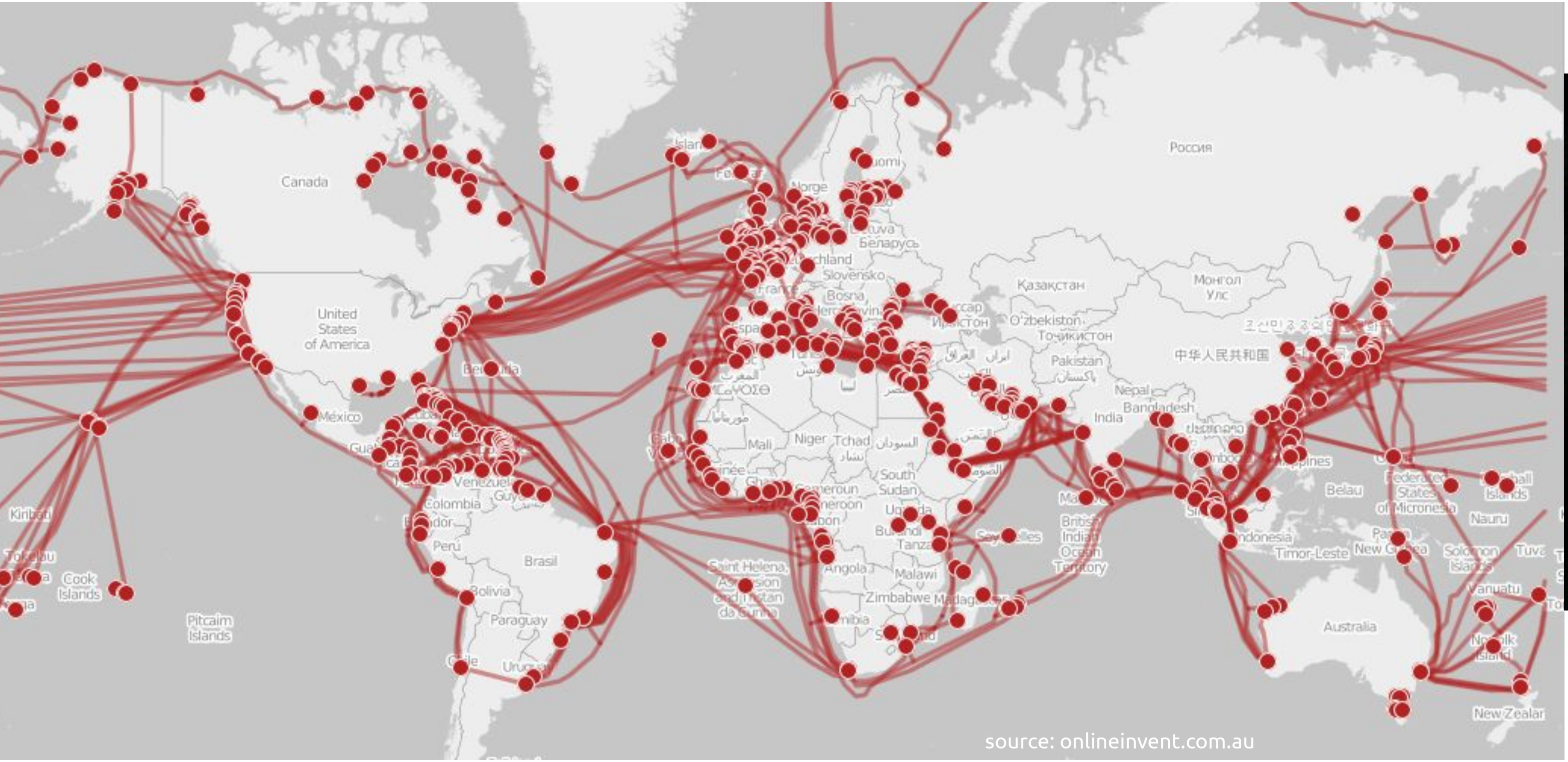
Internet usage

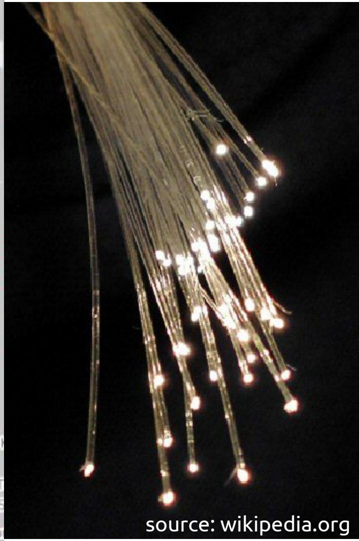


1 exabyte = 10^{18} bytes = 1 million terabytes

Data **transmission** is optical

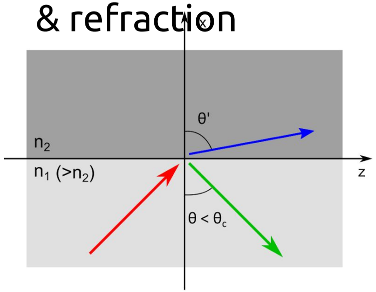


source: onlineinvent.com.au

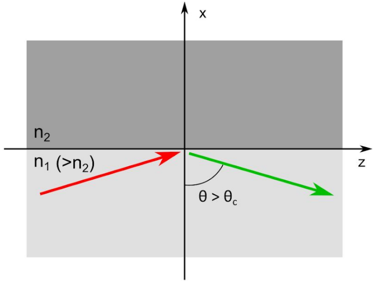

source: wikipedia.org

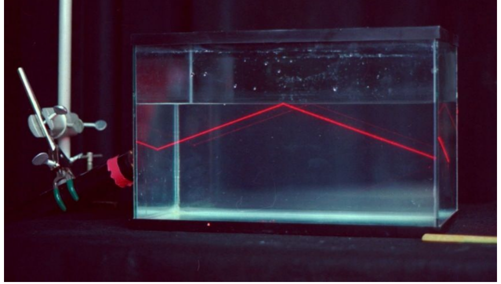
Data **transmission** is optical

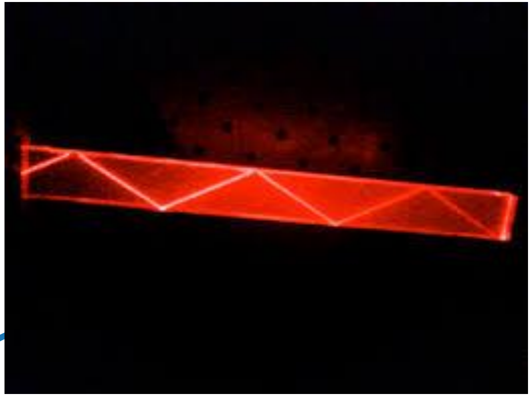
Partial reflection & refraction

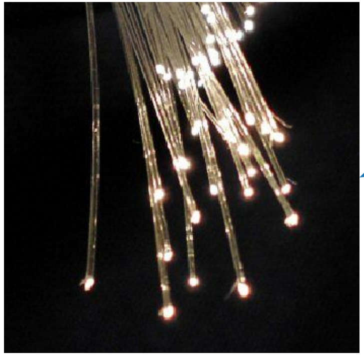


Total internal reflection









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Data **processing** is electrical

Digital Signal Processor (**DSP**):

Problem:

- Too costly
- Too power hungry

Main **challenge**:

- Increase bandwidth…
- … while decreasing power consumption

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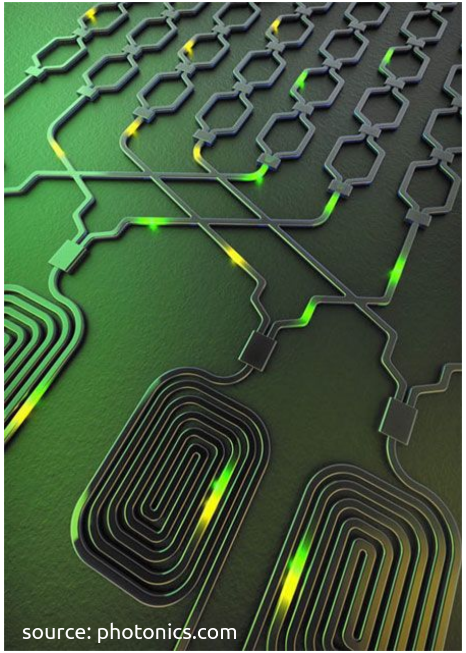
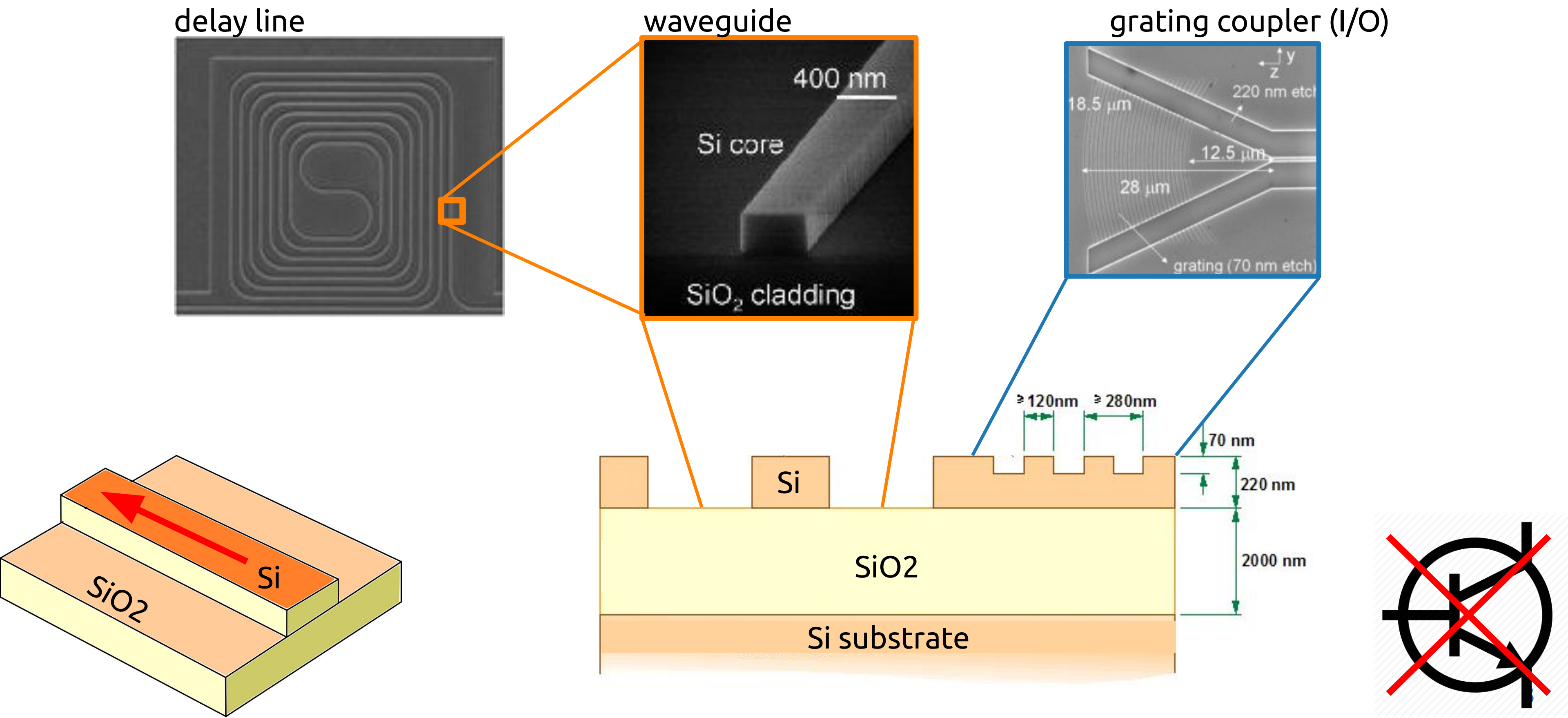
Optical signal processors?

- Very high bandwidth
- Low energy consumption
- Highly parallel execution

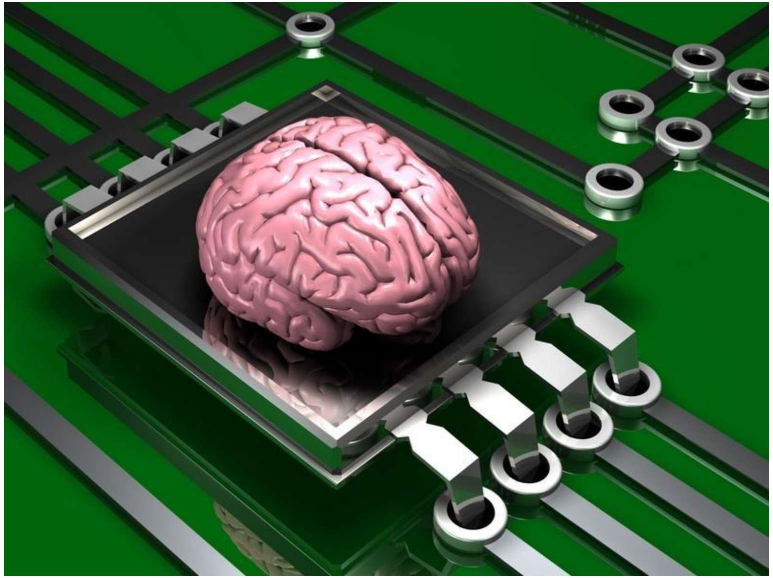


Silicon photonics



Neuromorphic computing

"brain-inspired"



Neuromorphic computing

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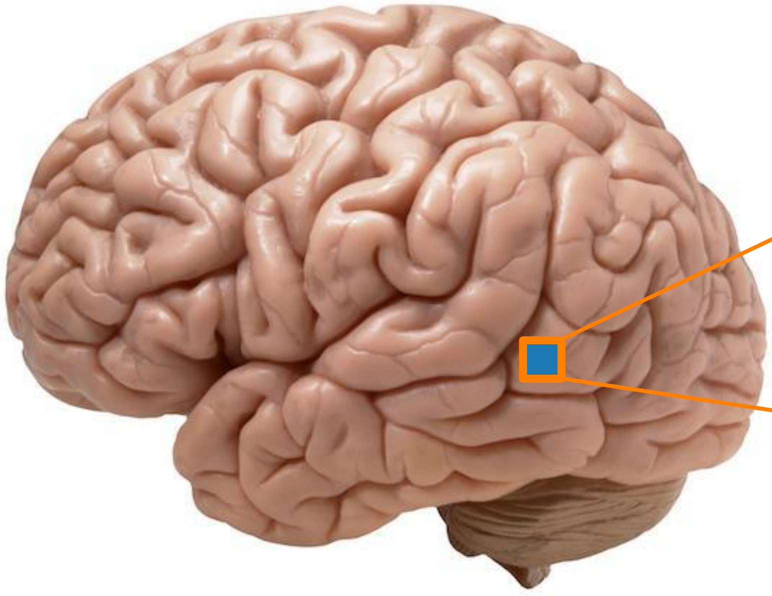
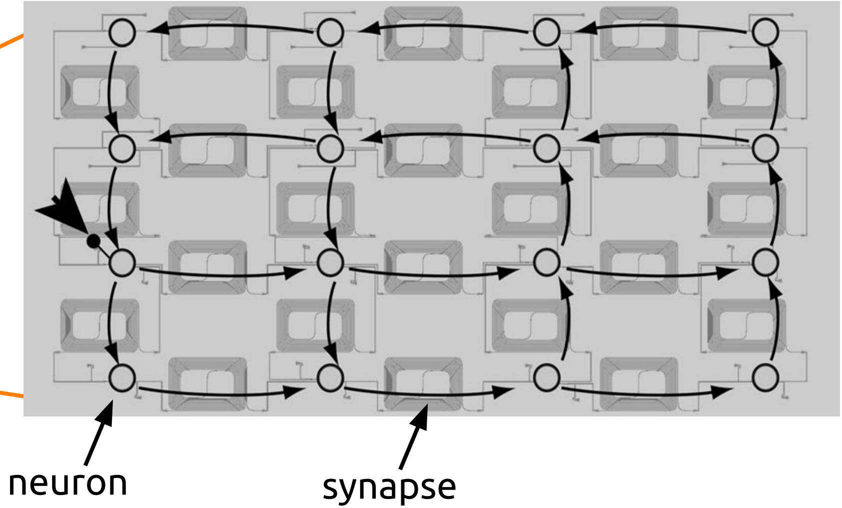
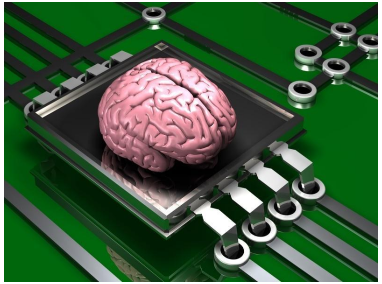




Goal

Solve **telecom** related tasks

- **Fast**
- **Efficiently**



By using smart **neuromorphic** photonic architectures

Overview

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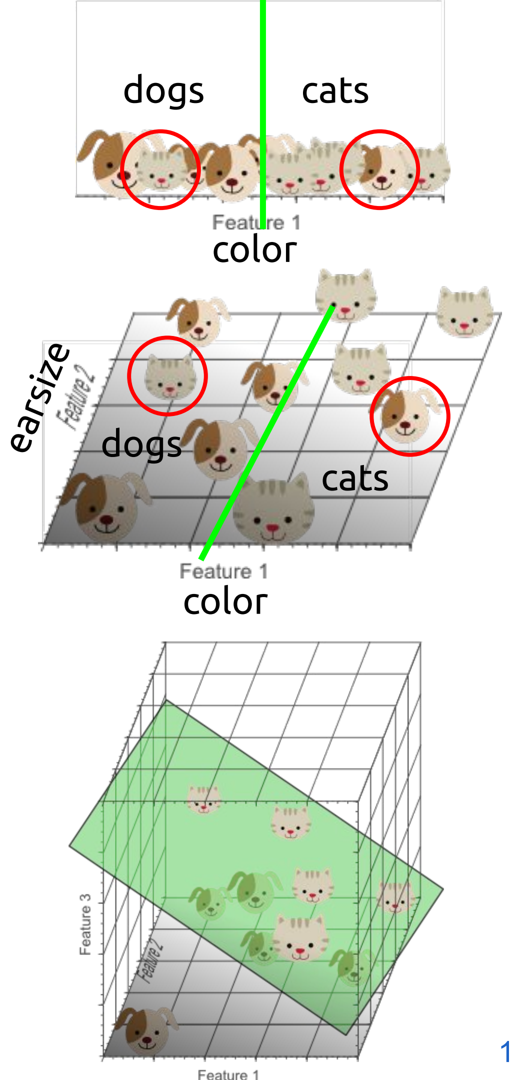
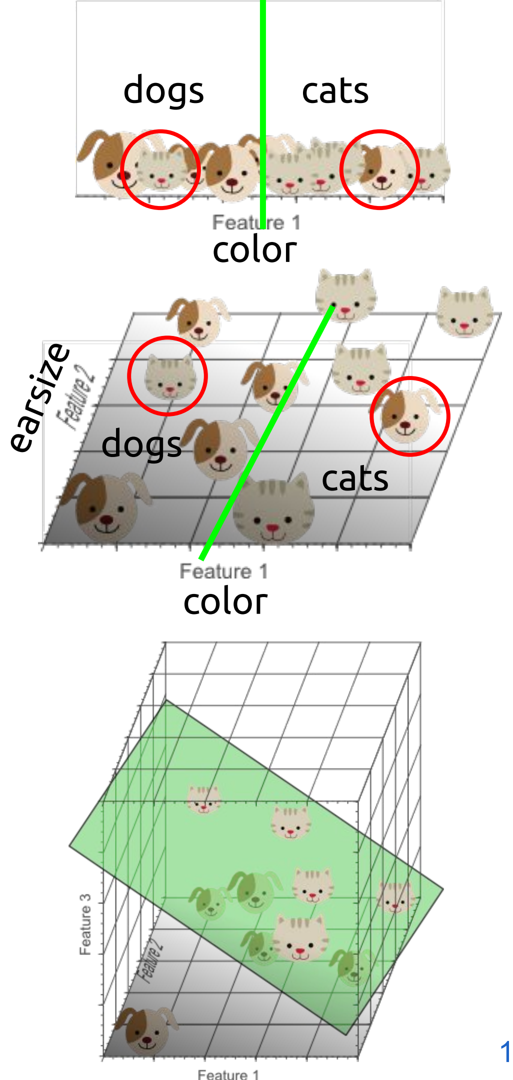
Learn from examples



source: https://www.visiondummy.com/2014/04/curse-dimensionality-affect-classification

Machine learning

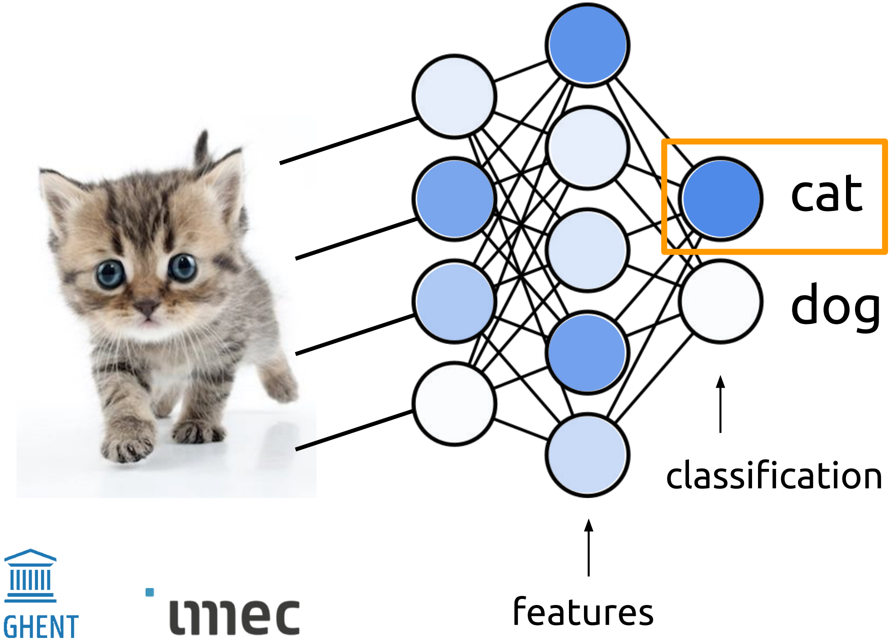
- Feature extraction
- Classification

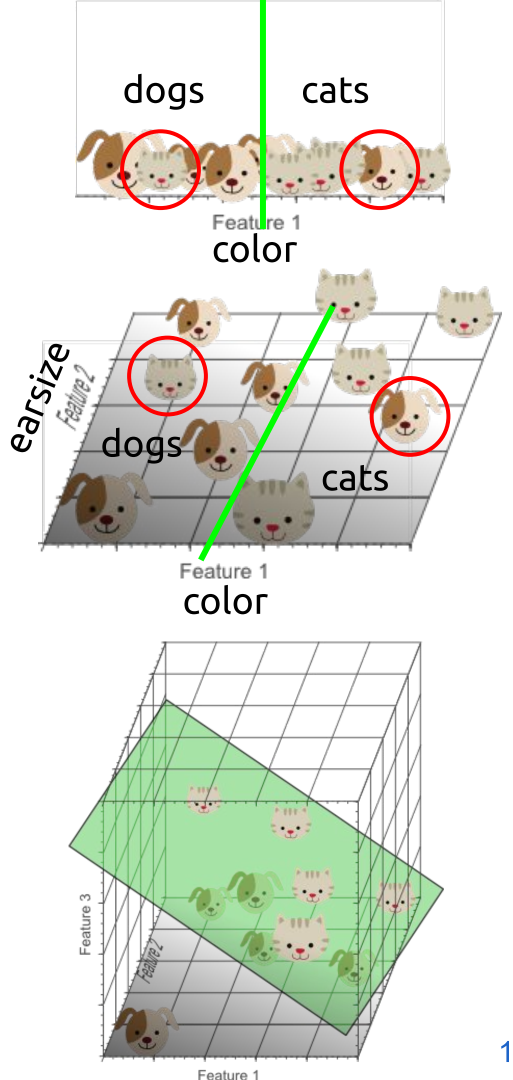


source: https://www.visiondummy.com/2014/04/curse-dimensionality-affect-classification

Neural networks

- Feature extraction
- Classification





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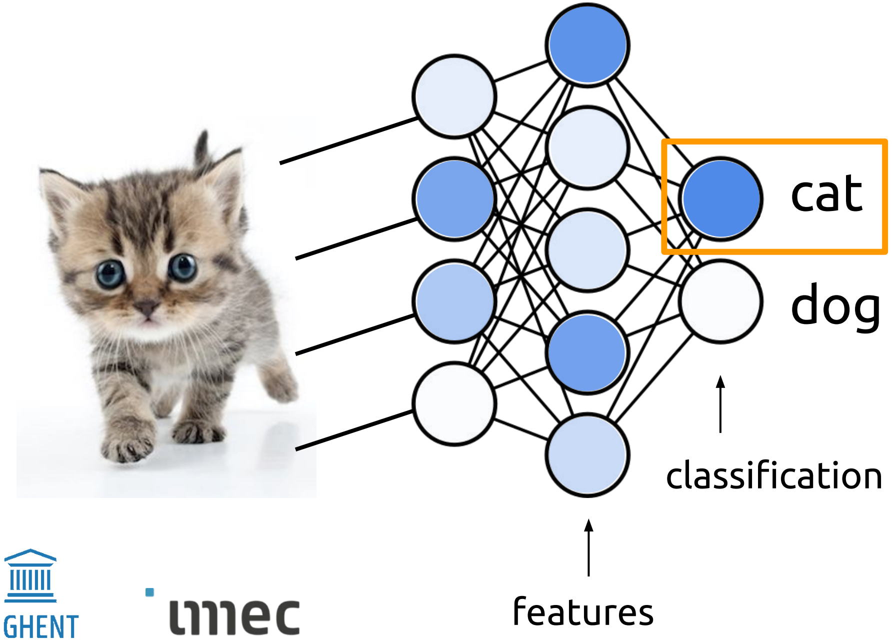
Neural networks

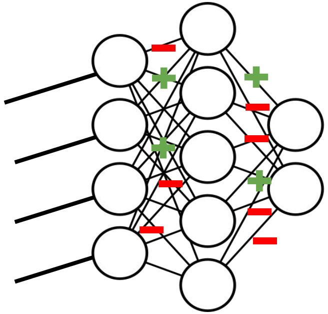
- Feature extraction
- Classification



- Image recognition
- Facial recognition
- ...

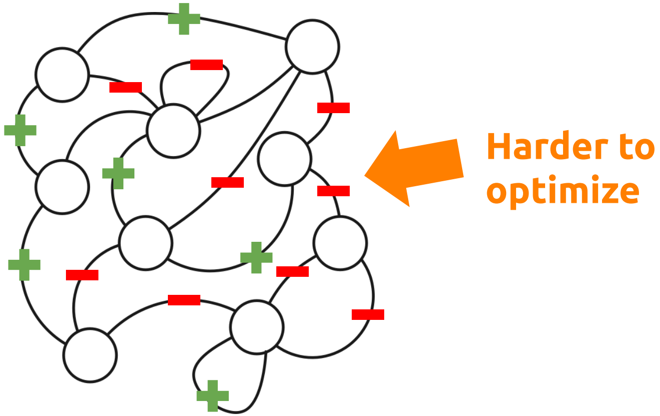
Neural networks

(Deep) Neural Network



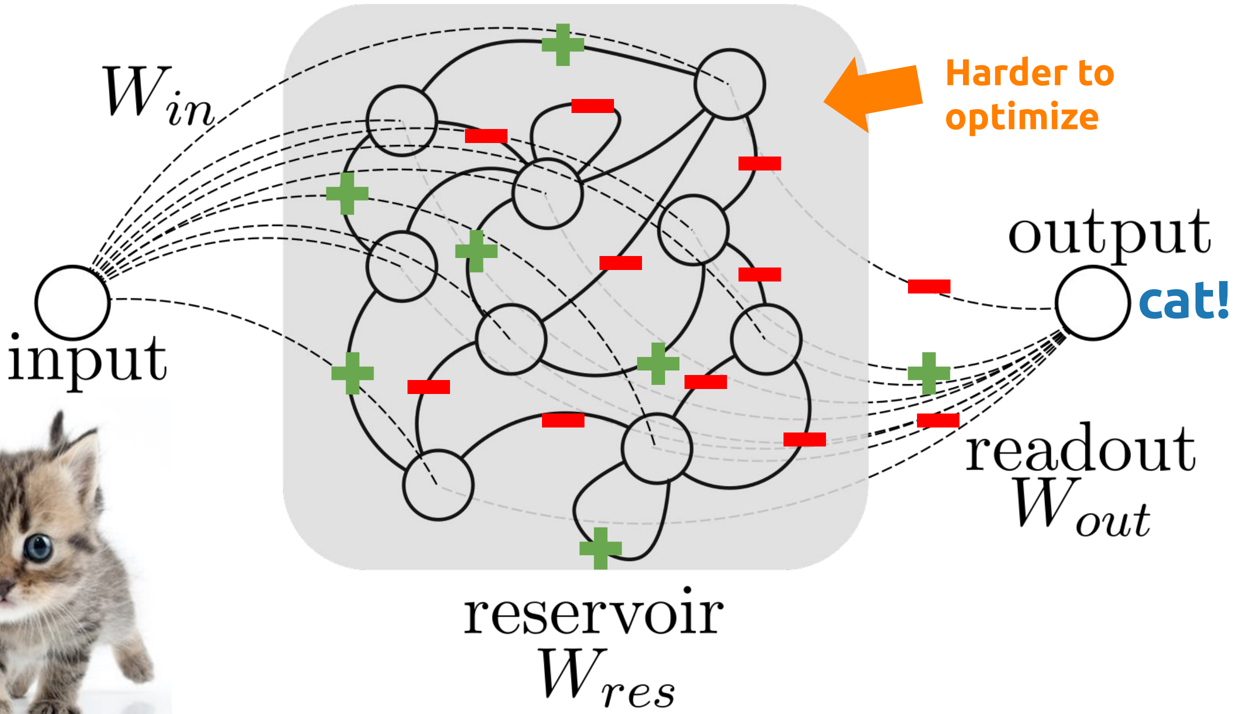
- Image recognition
- Facial recognition
- …

Recurrent Neural Network

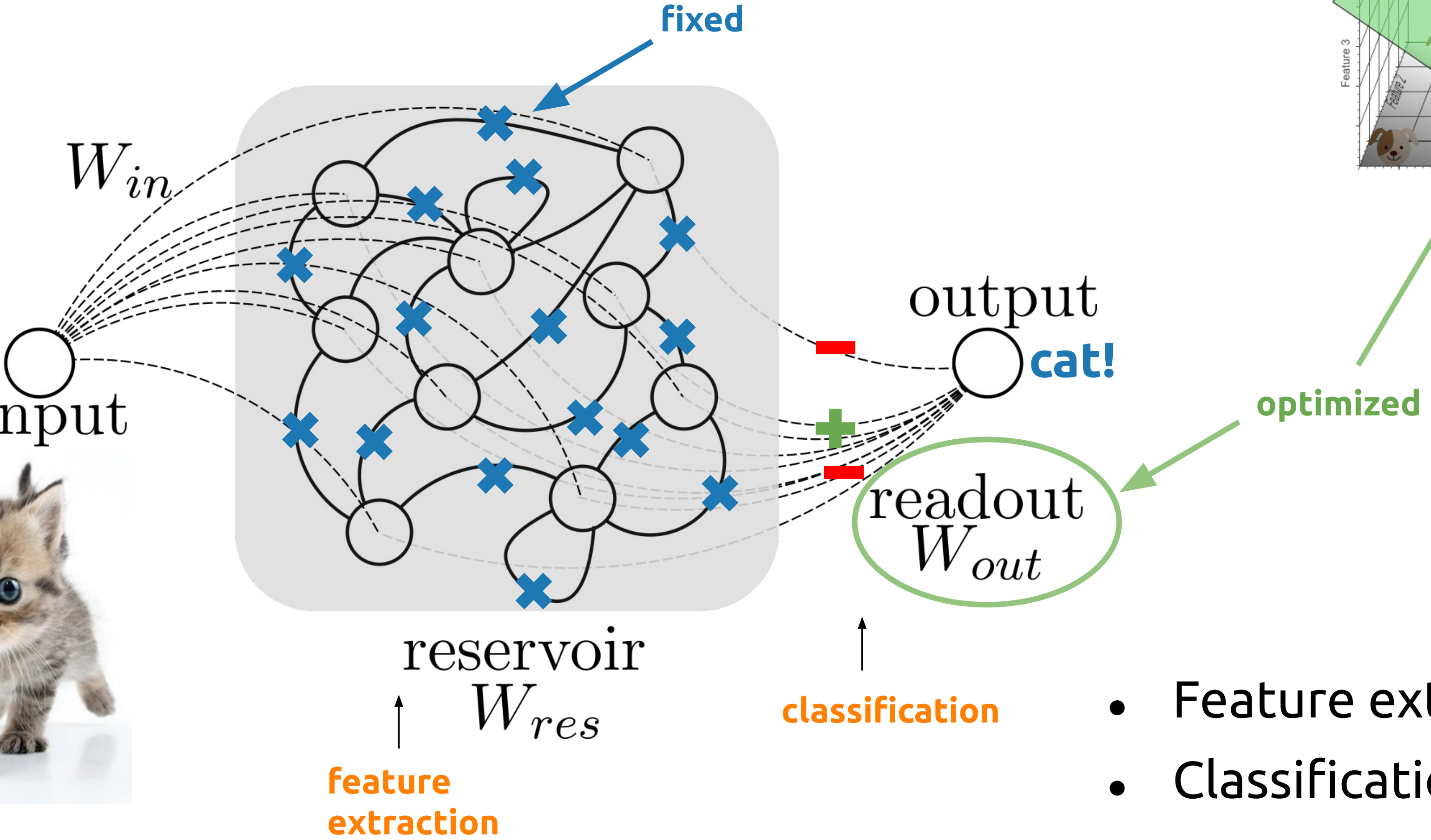


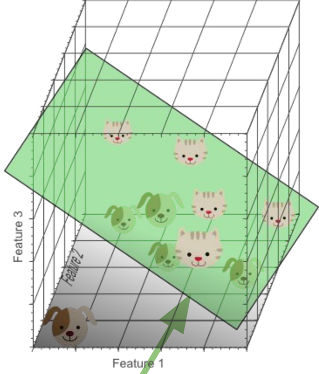
- Speech recognition
- Time series prediction
- Robot control
- …

Recurrent Neural Network



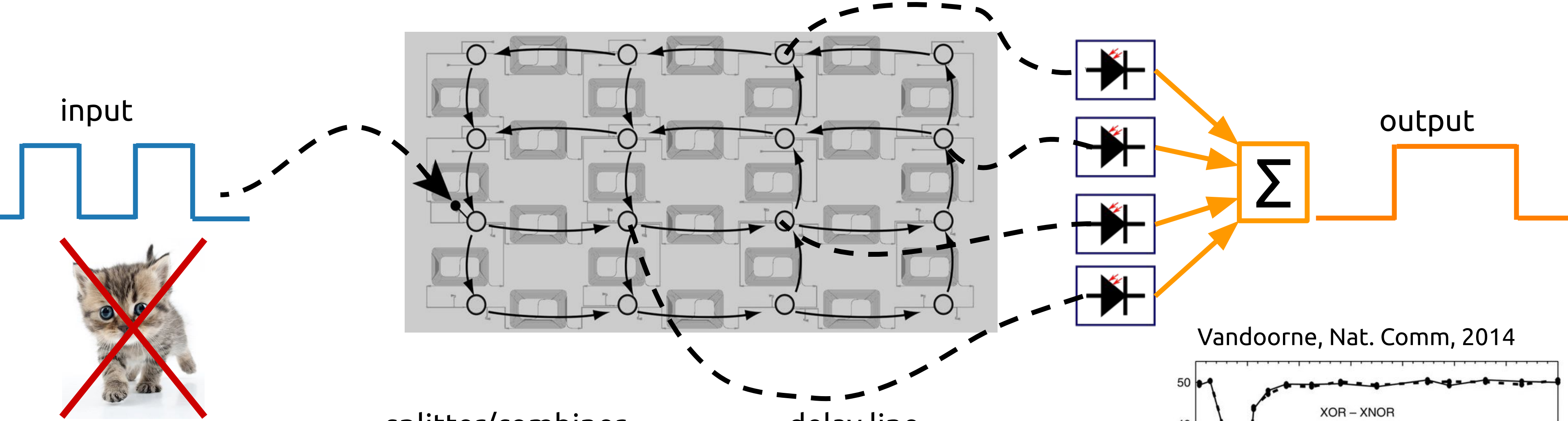
Reservoir computing



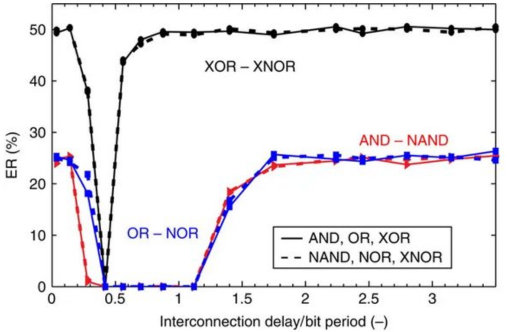


- Feature extraction
- Classification

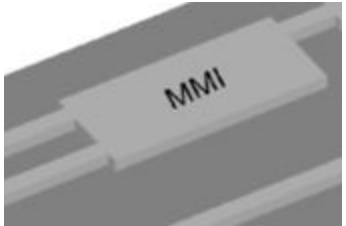
Photonic Reservoir Computing



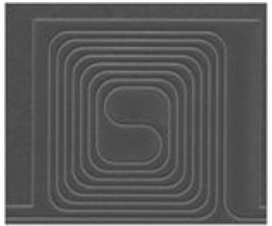
Vandoorne, Nat. Comm, 2014



splitter/combiner



delay line



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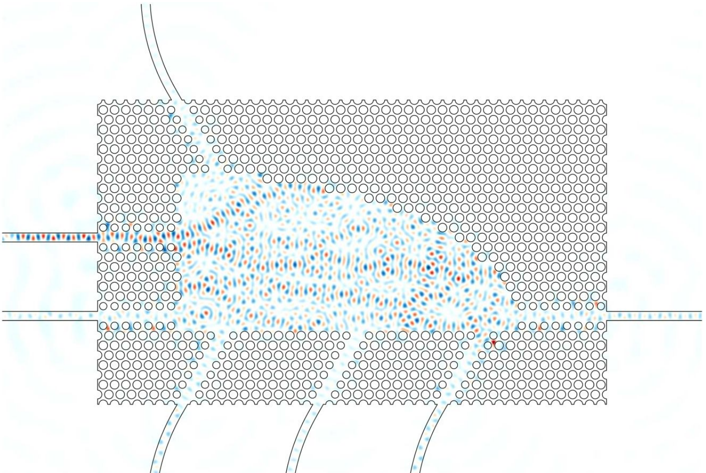
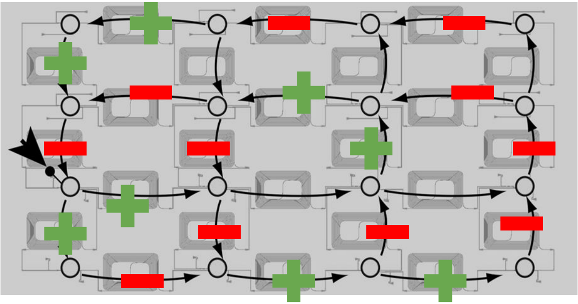
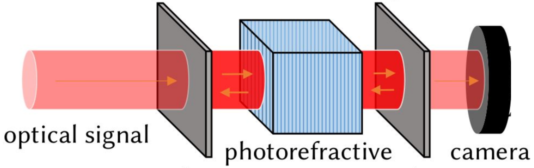
Novel architectures for brain-inspired photonic computers

- Reservoir Computing with **signal-mixing cavities**
- Transition to completely **optimizable photonic circuits**
- **Self-learning** with photorefractive crystals

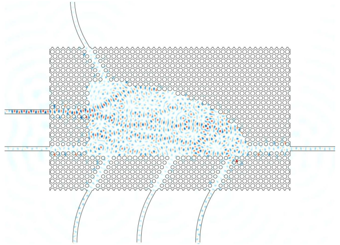






Overview

- Machine learning & Neuromorphic computing
- Towards photonic neuromorphic computing
- **Reservoir computing with signal-mixing cavities**
- Photontorch: optimizing photonic circuits
- Neuromorphic computing with photorefractive crystals



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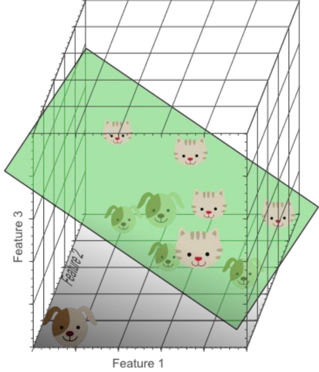
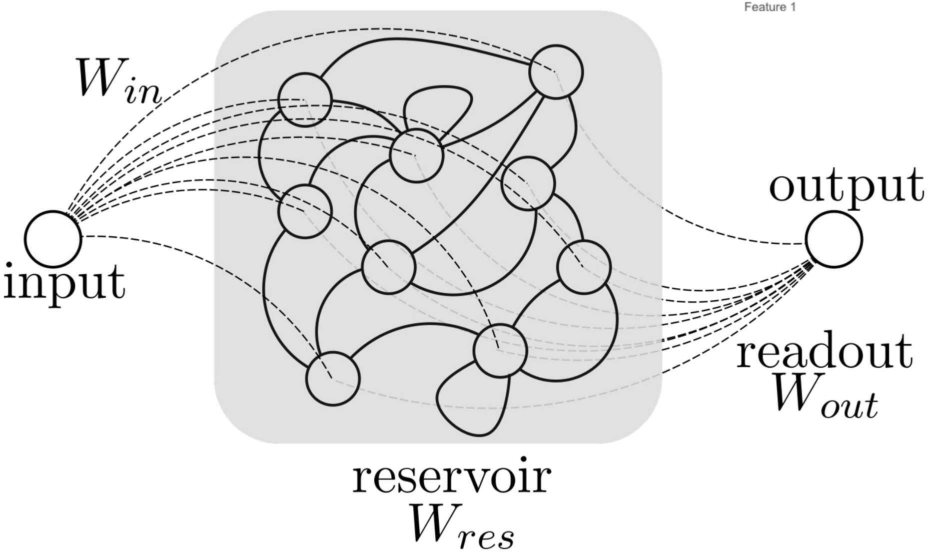
Reservoir Computing



- **preprocesses** the input to a **higher dimensional** space
- has **sufficient memory**



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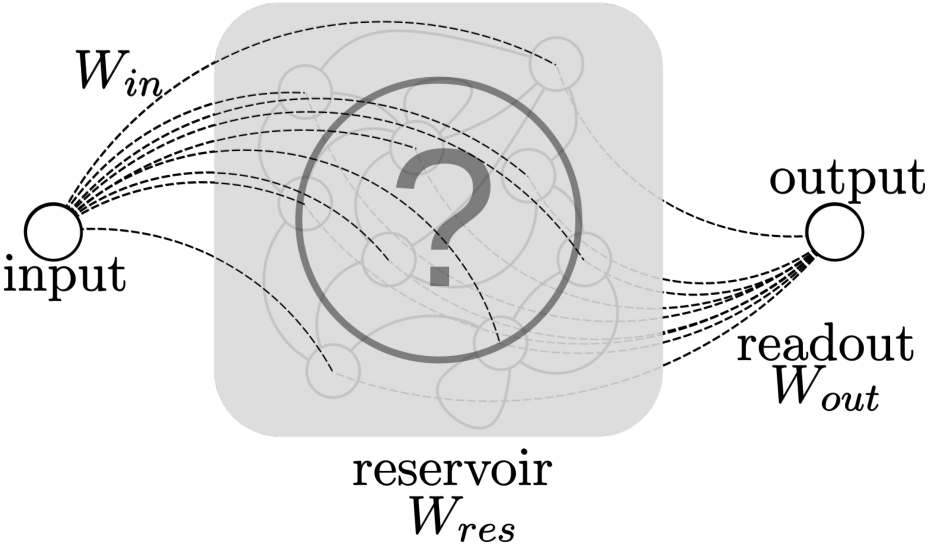
Anything can be used as a reservoir!

As long as the system…

- **preprocesses** the input to a **higher dimensional** space
- has **sufficient memory**



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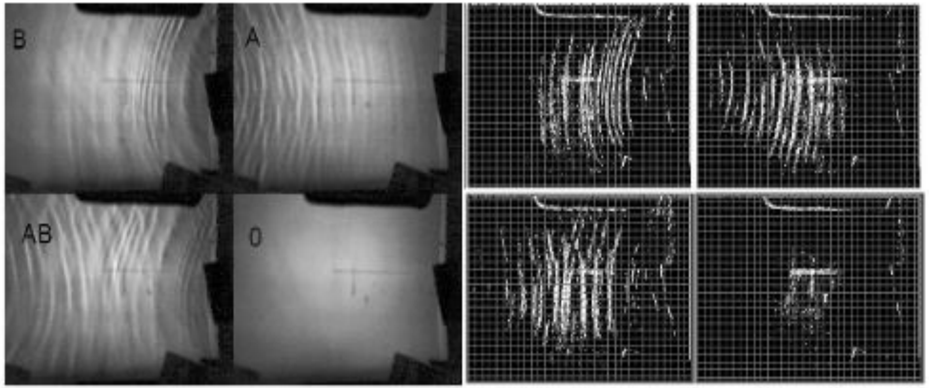
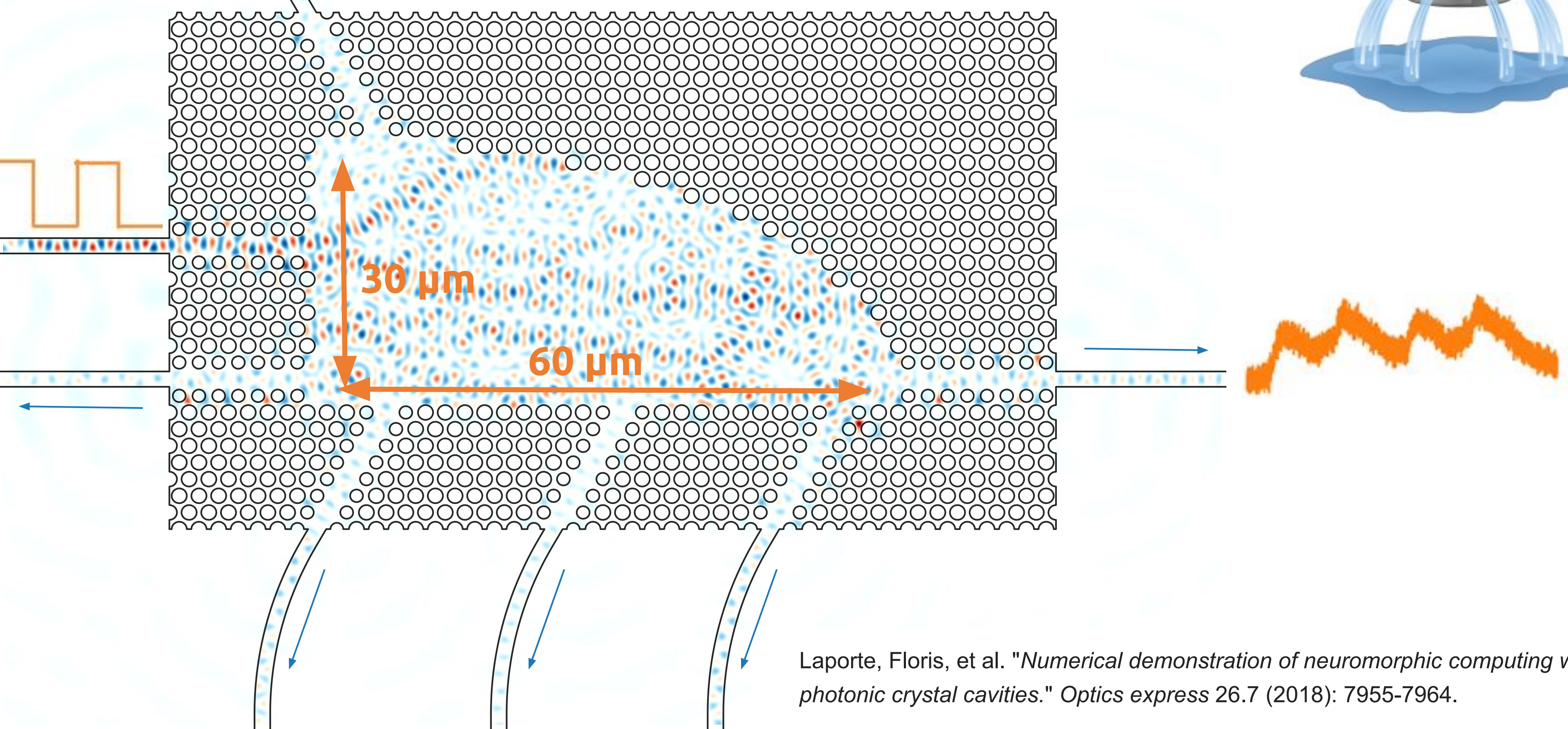


Fernando, C., & Sojakka, S. (2003, September). Pattern recognition in a bucket. In *European conference on artificial life* (pp. 588-597). Springer, Berlin, Heidelberg.

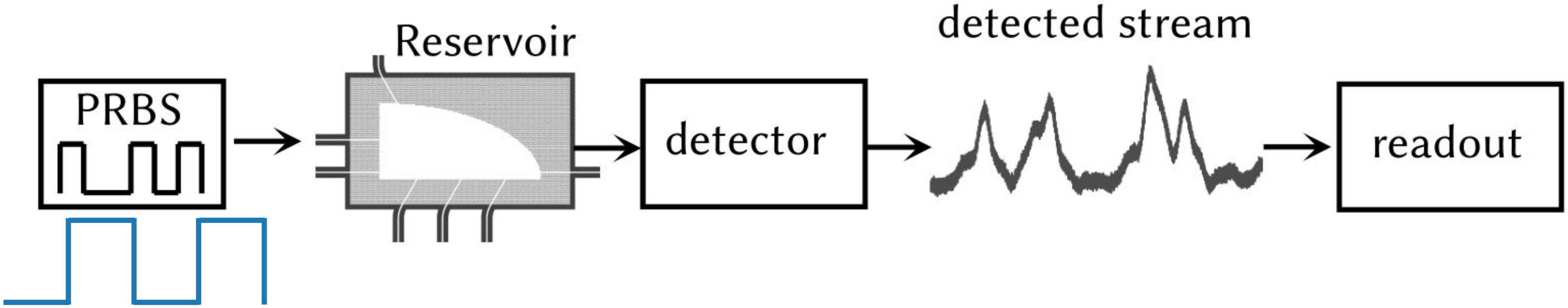
Anything can be used as a reservoir!



Laporte, Floris, et al. "*Numerical demonstration of neuromorphic computing with photonic crystal cavities.*" *Optics express* 26.7 (2018): 7955-7964.

Simulating Signal Mixing Cavity

Ideally:

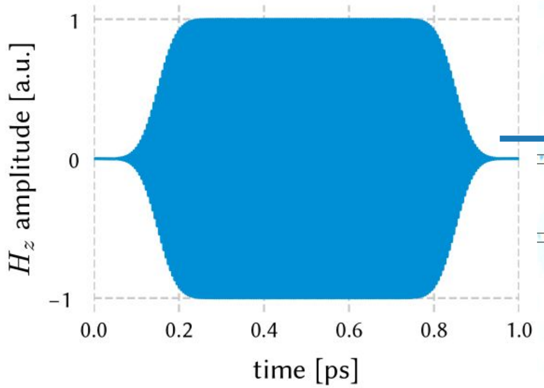


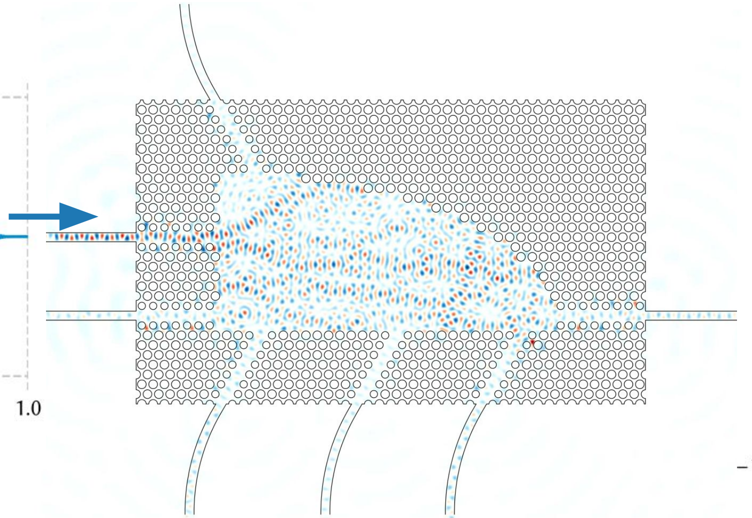
Problem: simulating a single bit takes about 24 hours.

Simulating Signal Mixing Cavity

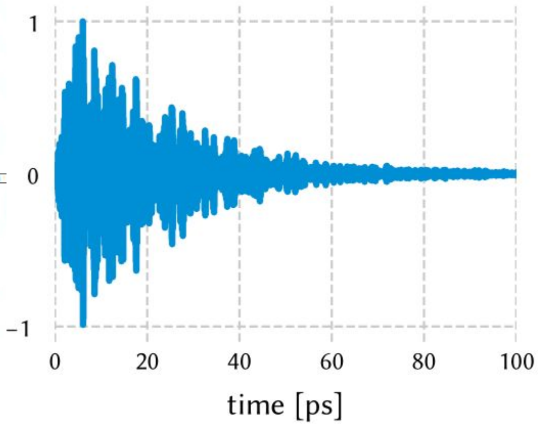
Problem: simulating a single bit takes about 24 hours.

pulse



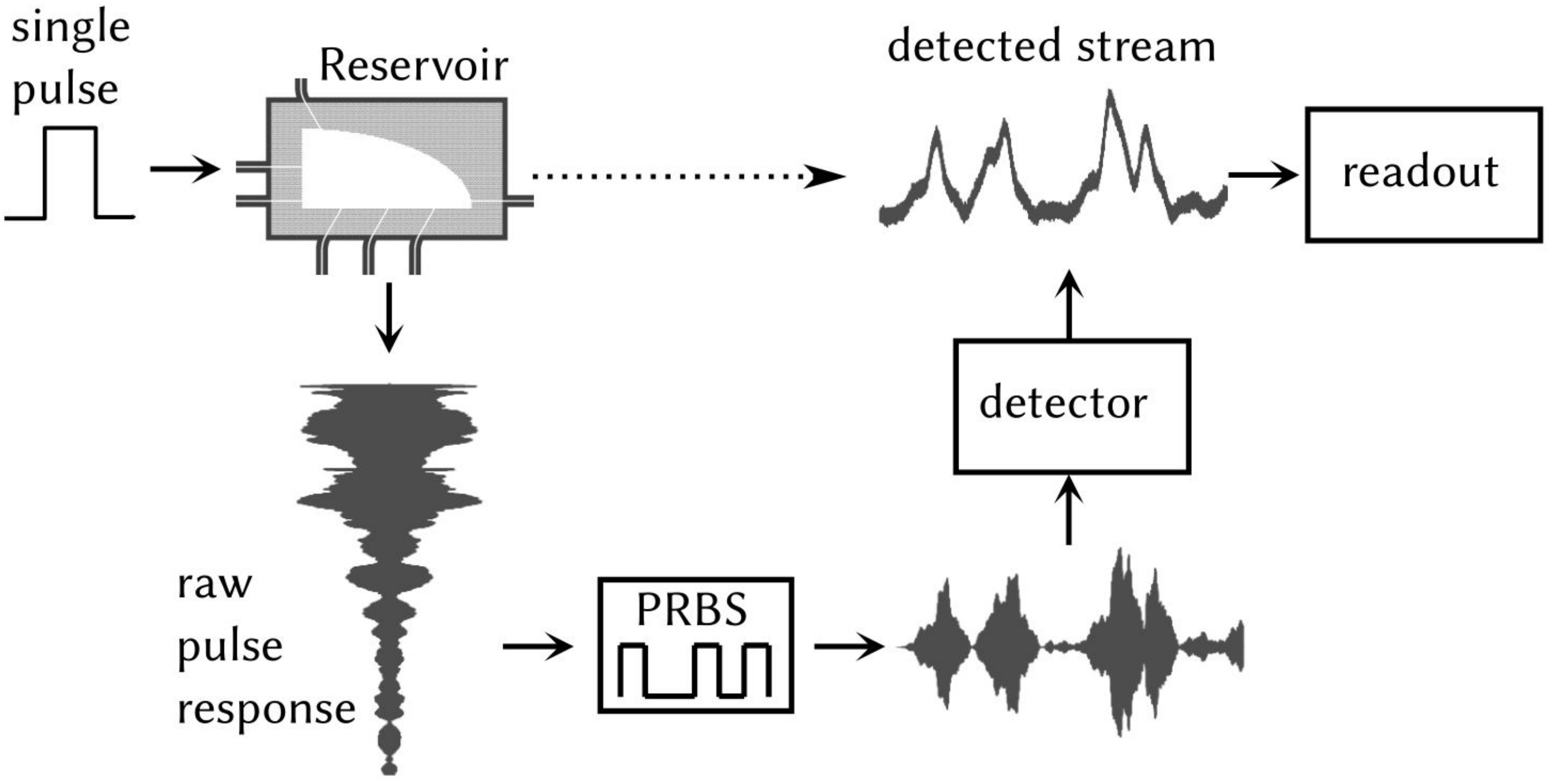


Pulse response



Simulating Signal Mixing Cavity

In stead:



Simulating Signal Mixing Cavity

Pulse:

$$\mathbf{u}(t) = \begin{pmatrix} \mathbf{E}_{\text{in}}(t) \\ \mathbf{H}_{\text{in}}(t) \end{pmatrix}$$

Response:

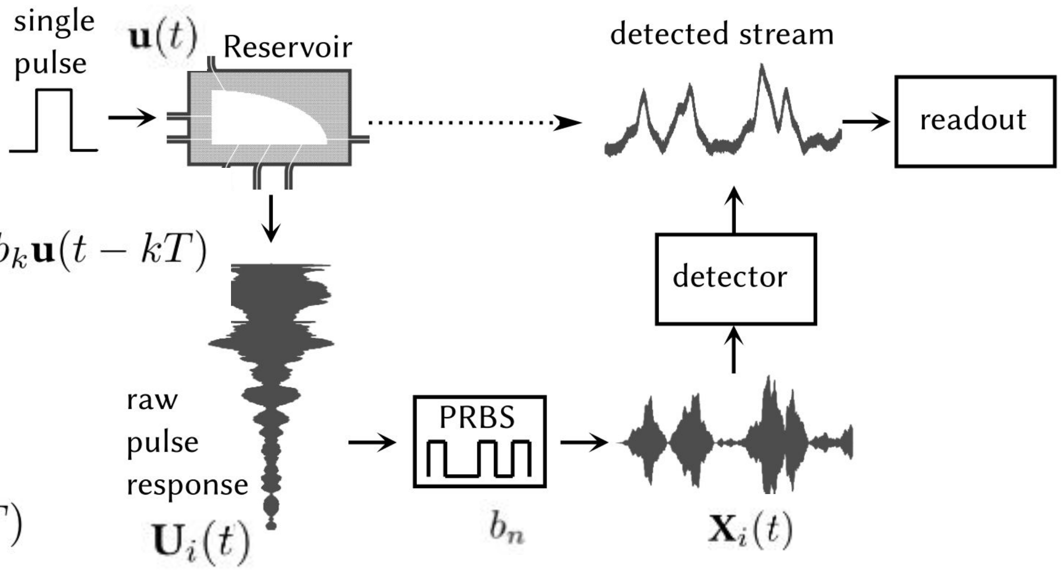
$$\mathbf{U}_i(t)$$

Input stream:

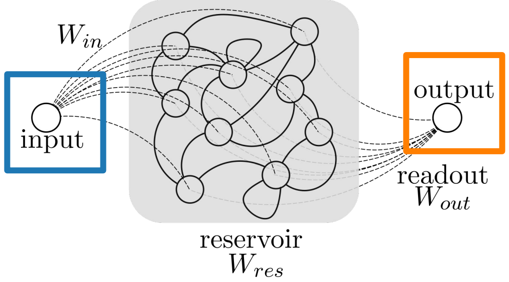
$$\mathbf{x}(t) = \begin{pmatrix} \mathbf{E}_{\text{in}}(t) \\ \mathbf{H}_{\text{in}}(t) \end{pmatrix} = \sum_{n=1}^{N} b_n \mathbf{u}(t - nT) = b_k \mathbf{u}(t - kT)$$

Output stream:

$$\mathbf{X}_i(t) = \begin{pmatrix} \mathbf{E}^i_{\text{out}}(t) \\ \mathbf{H}^i_{\text{out}}(t) \end{pmatrix} = \sum_{n=1}^{N} b_n \mathbf{U}_i(t - nT)$$



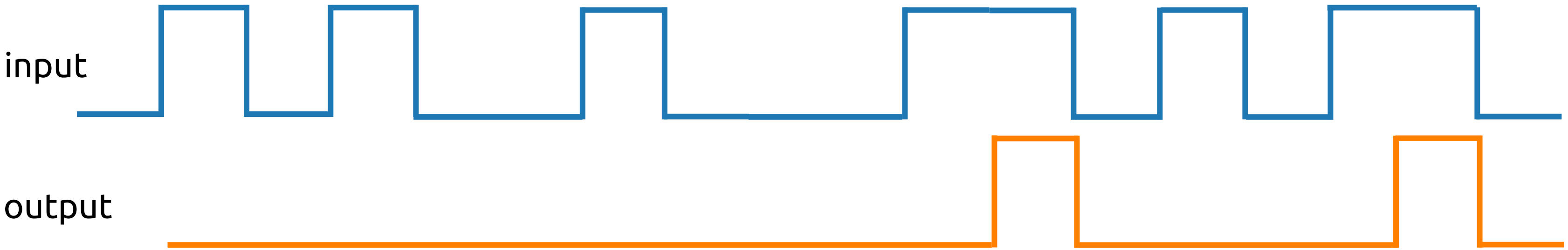
Telecom tasks: **AND**

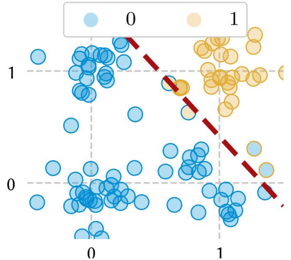


In telecom, we're working with bits:

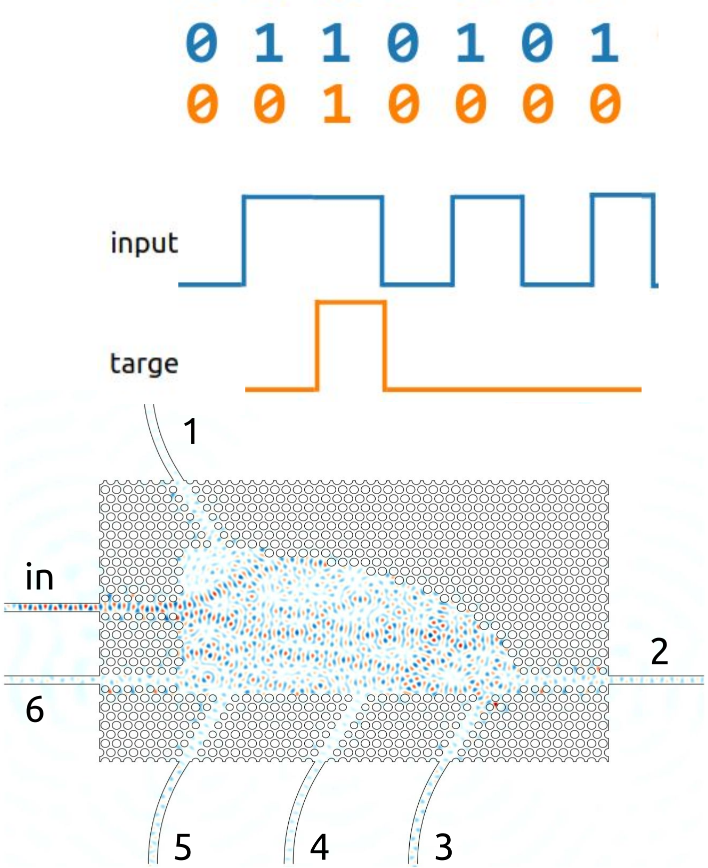
0 1 0 1 0 0 1 0 0 0 1 1 0 1 0 1 1 0

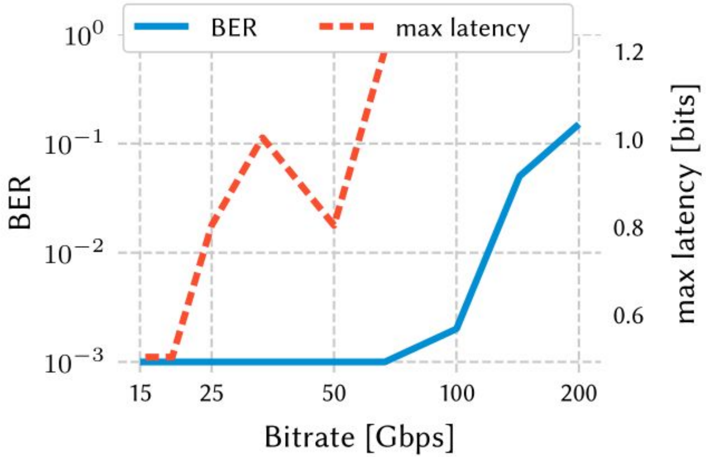
0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 1 0



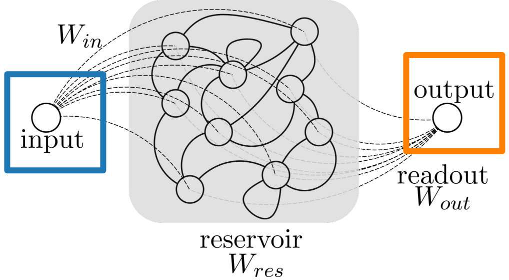


AND Task (simulation)





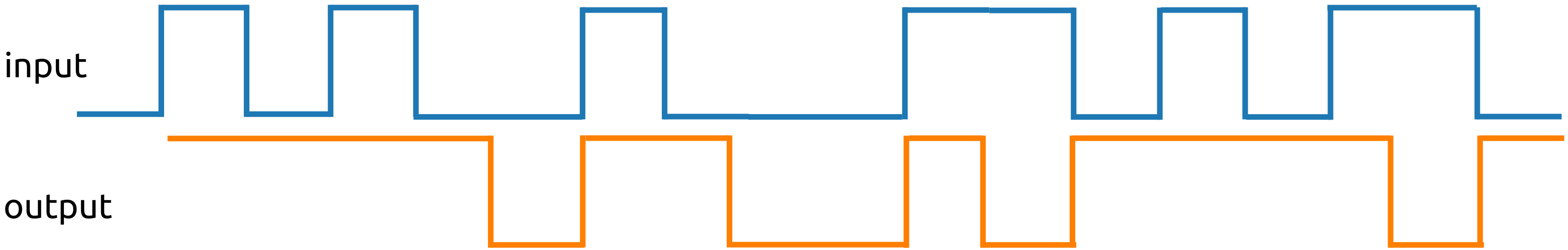
Telecom tasks: **XOR**

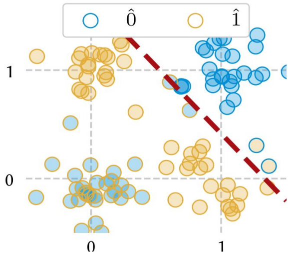


In telecom, we're working with bits:

0 1 0 1 0 0 1 0 0 0 1 1 0 1 0 1 1 0

1 1 1 1 0 1 1 0 0 1 0 1 1 1 1 0 1





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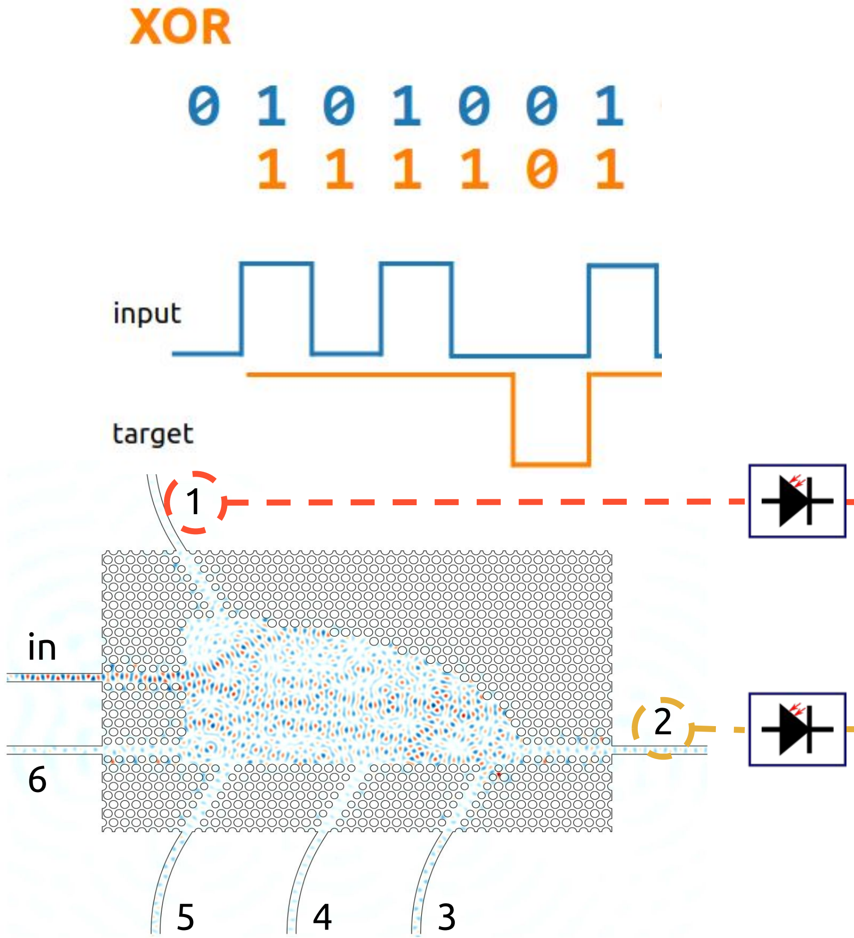
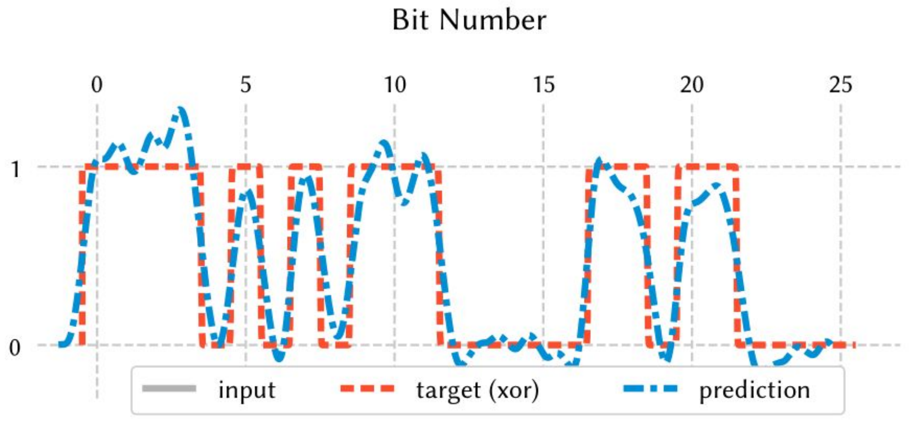
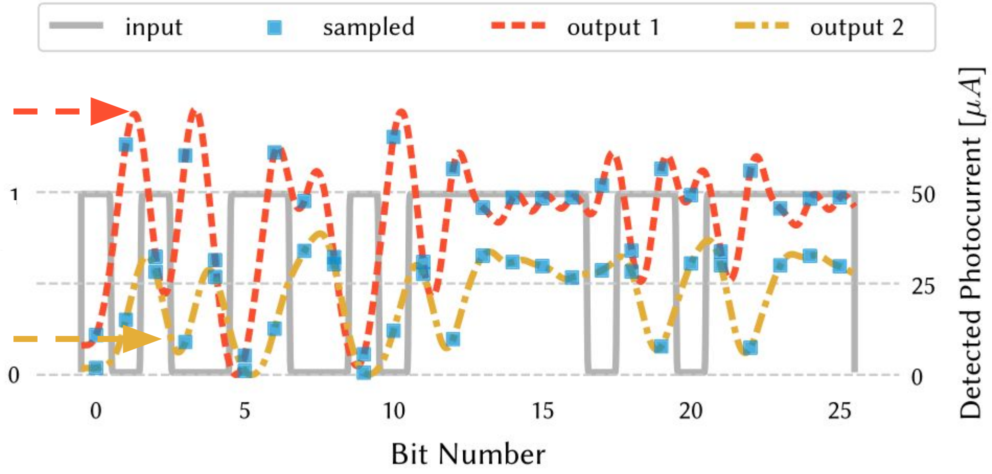
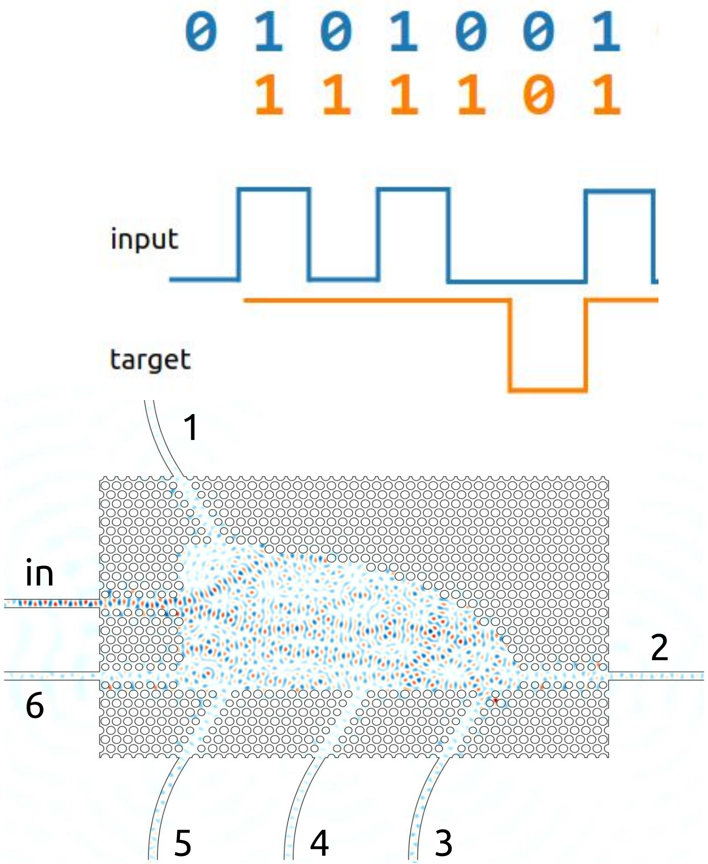
XOR Task (simulation)

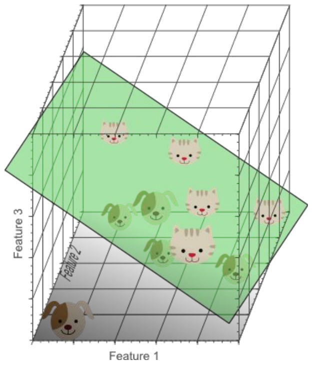


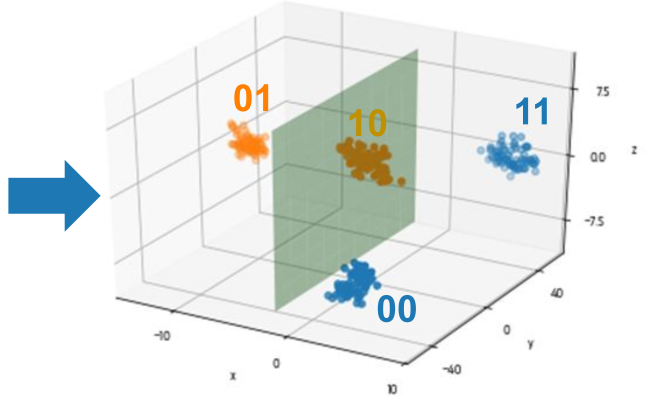


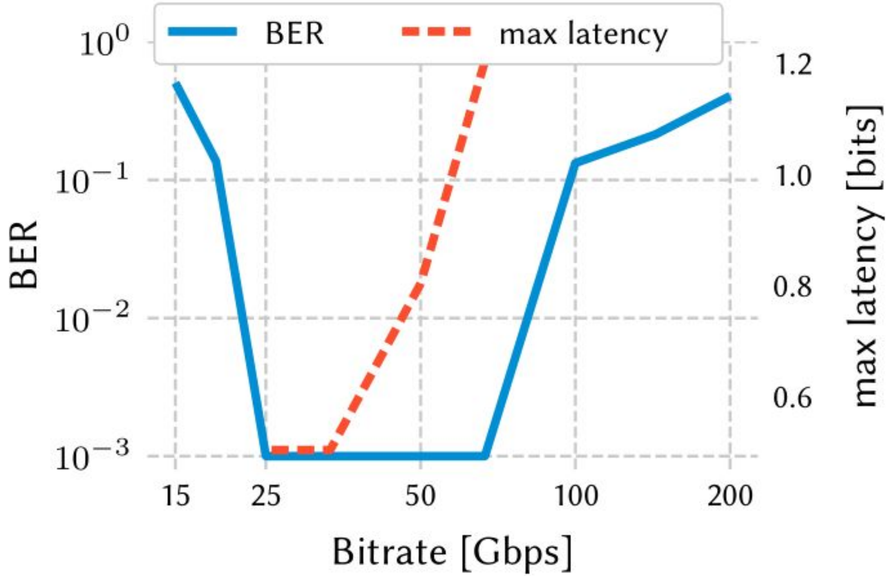


XOR Task (simulation)

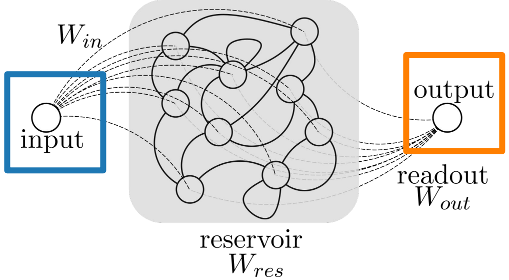








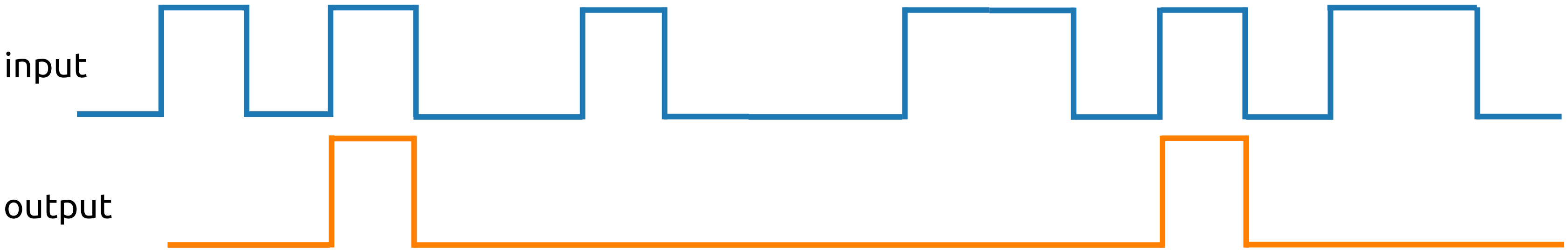
Telecom tasks: **Header Recognition**



In telecom, we're working with bits:

0 1 0 1 0 0 1 0 0 0 1 1 0 1 0 1 1 0

0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0



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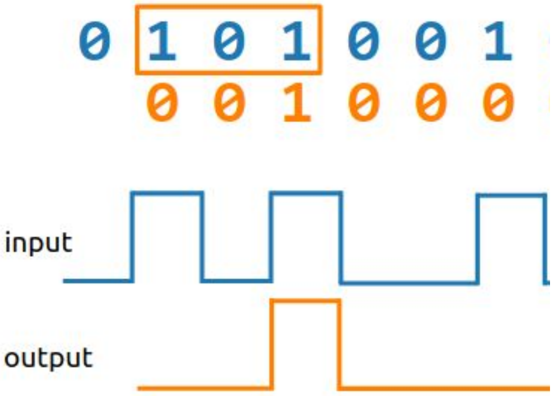
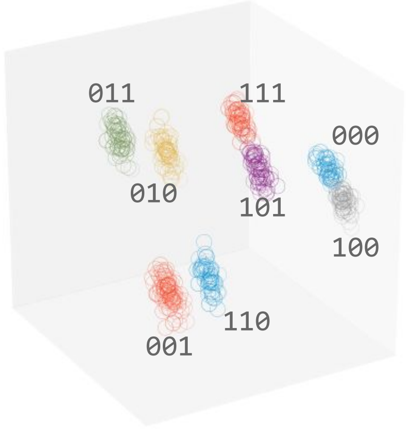
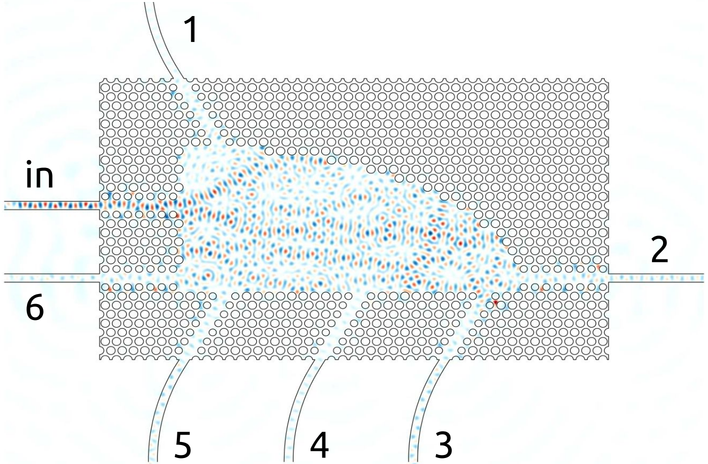
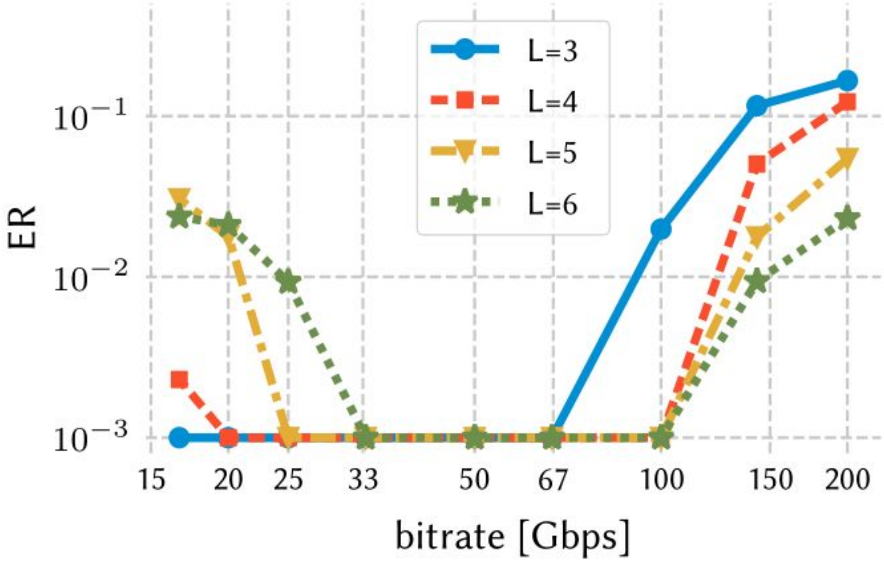
Header recognition (simulation)

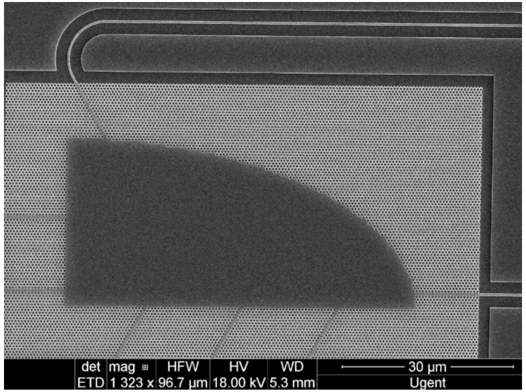


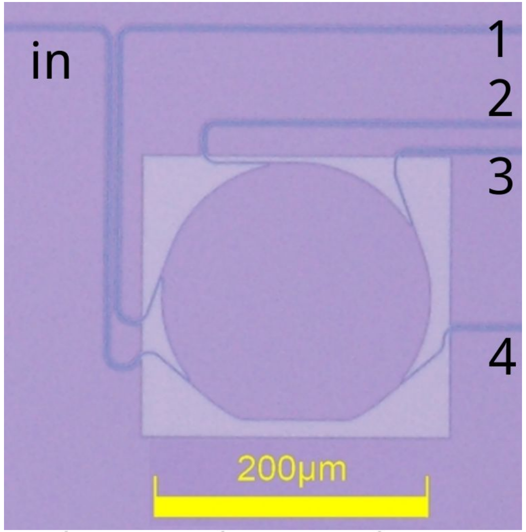


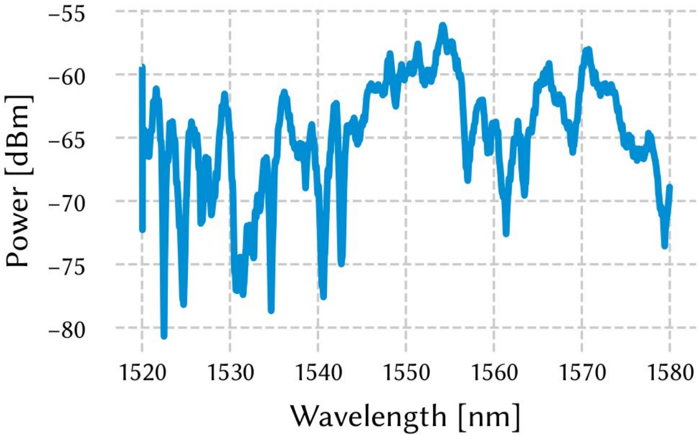


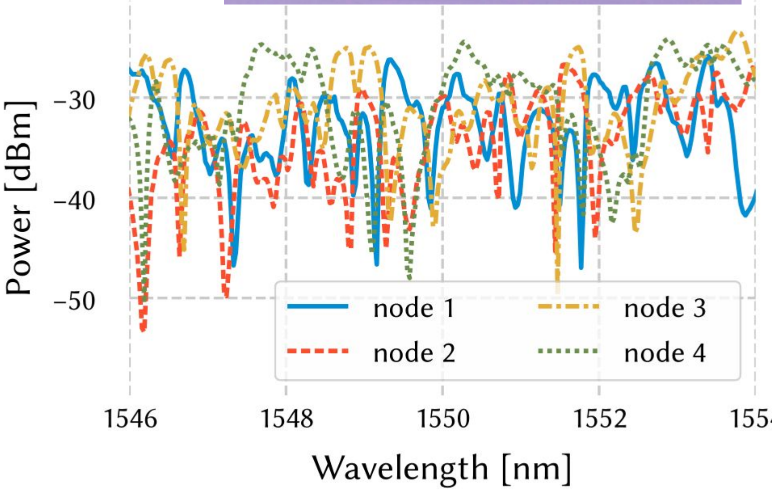


Fabricating Signal Mixing Cavity

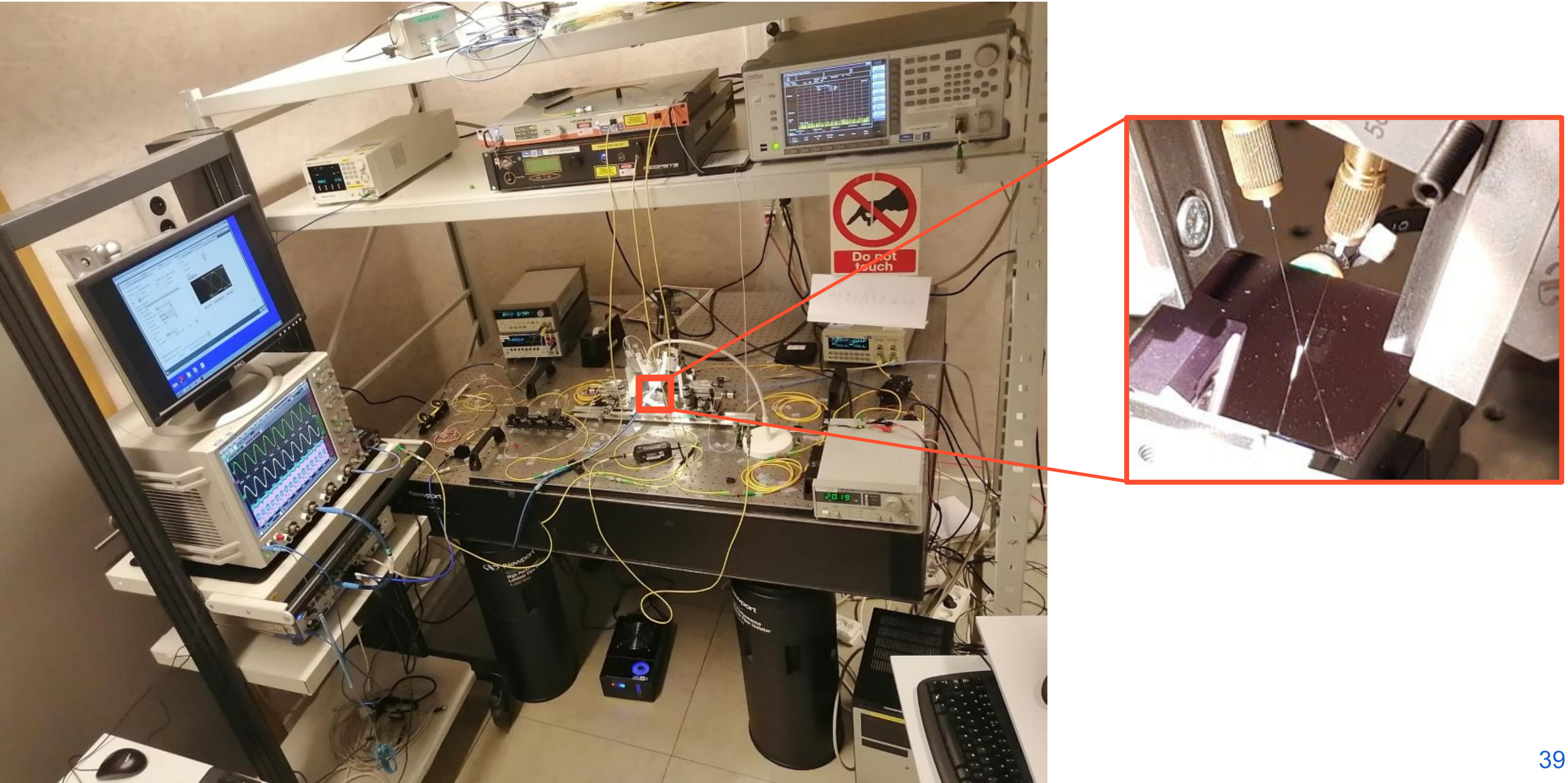




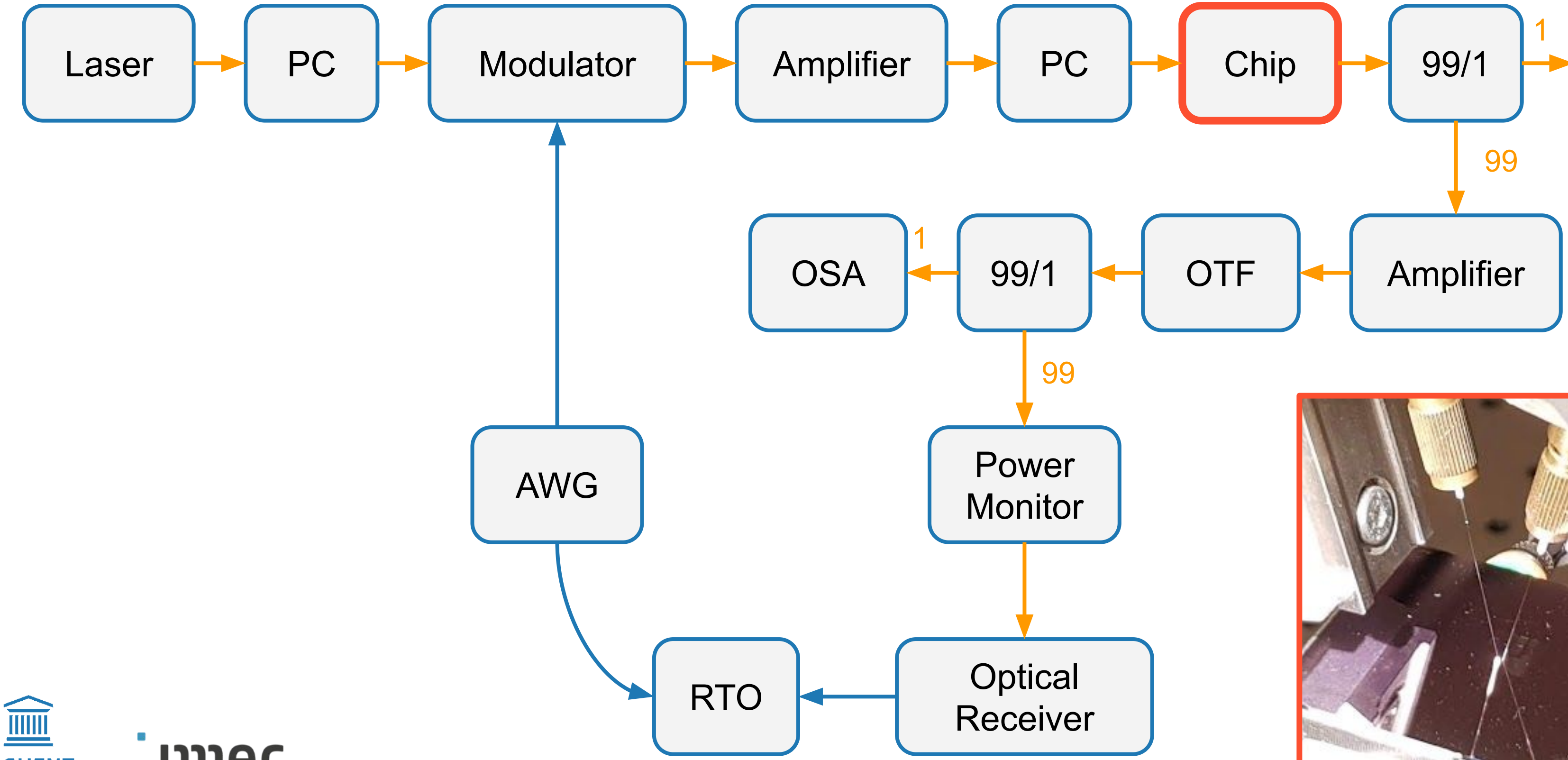




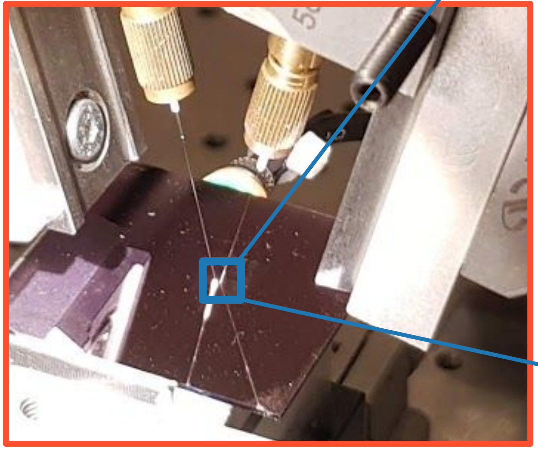
Measurement setup

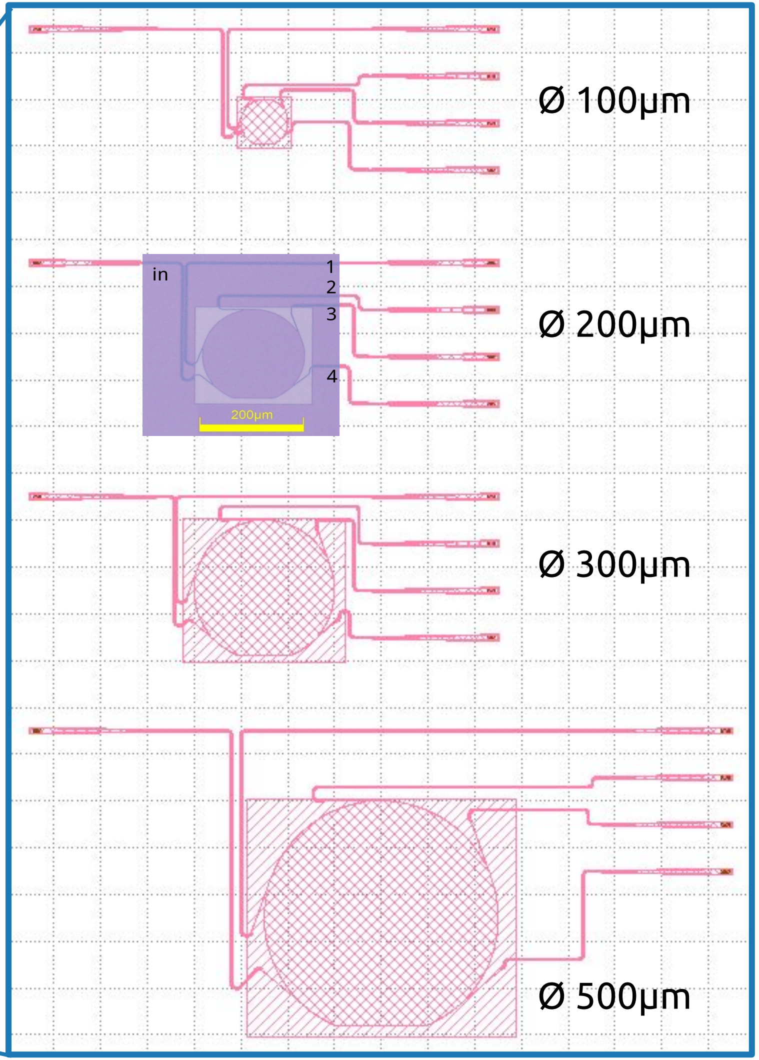


Measurement setup

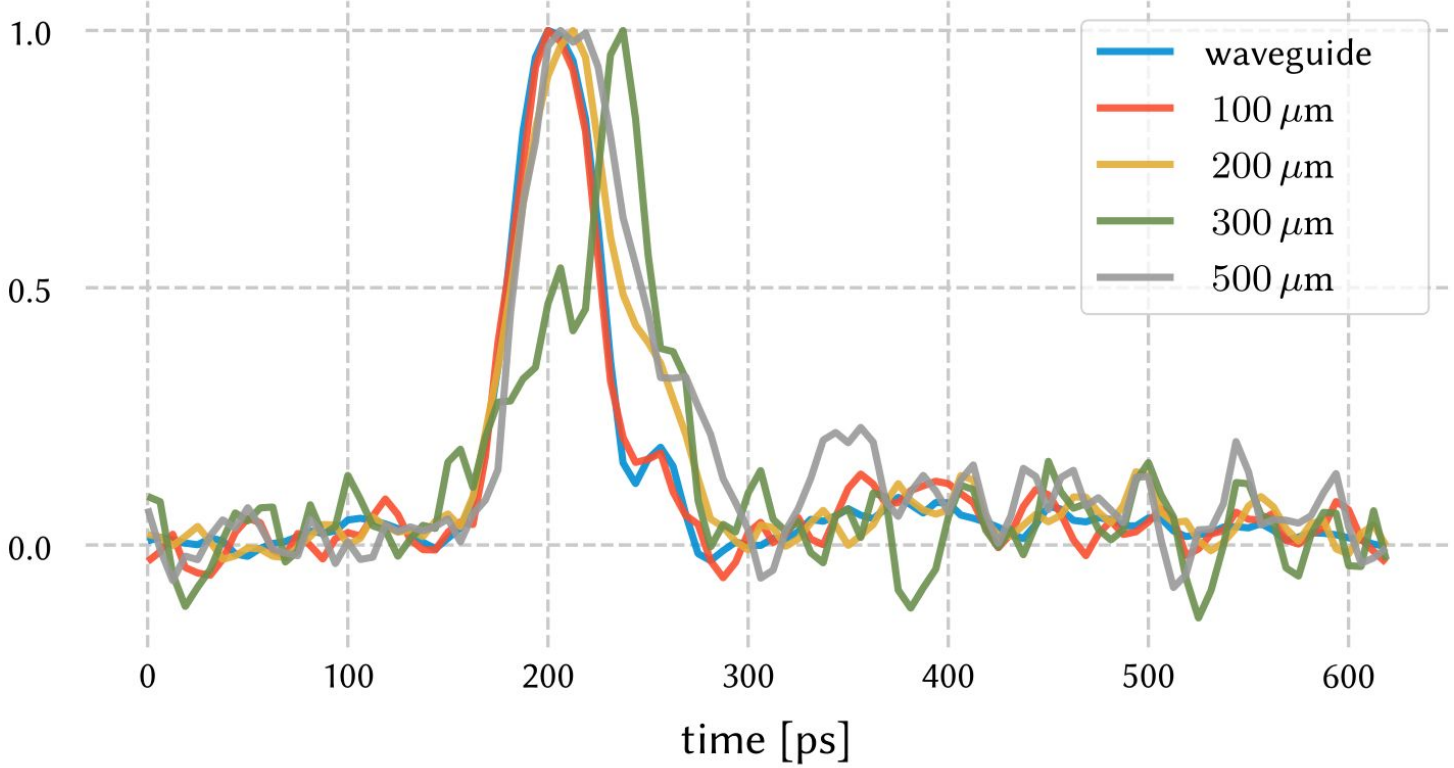


Measurement setup





Fabricated cavities: pulse response



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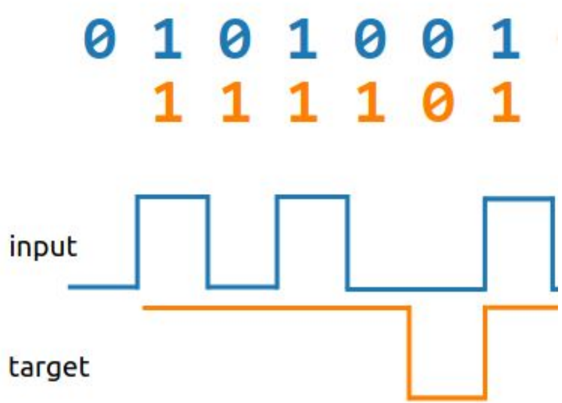
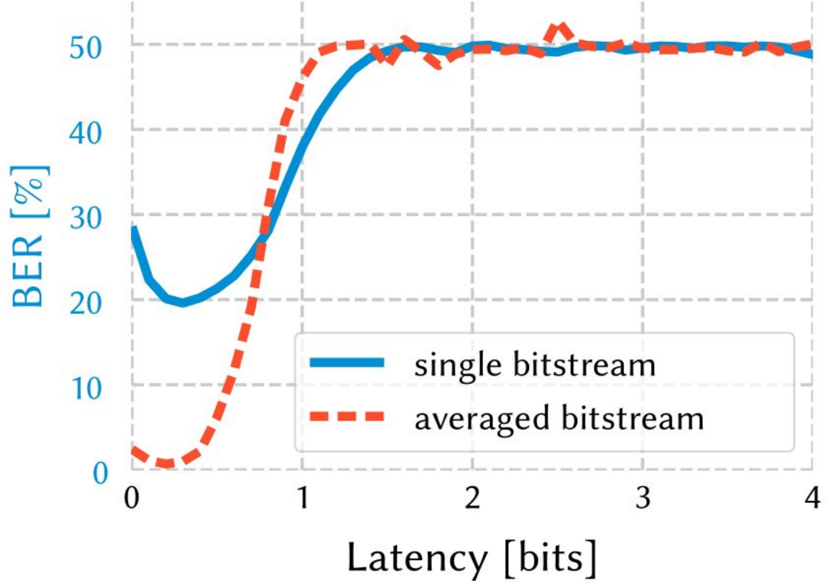
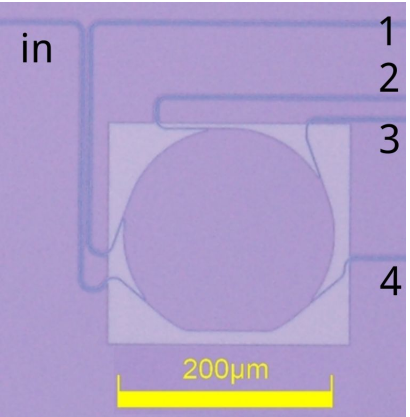
XOR Task **(measurement)**

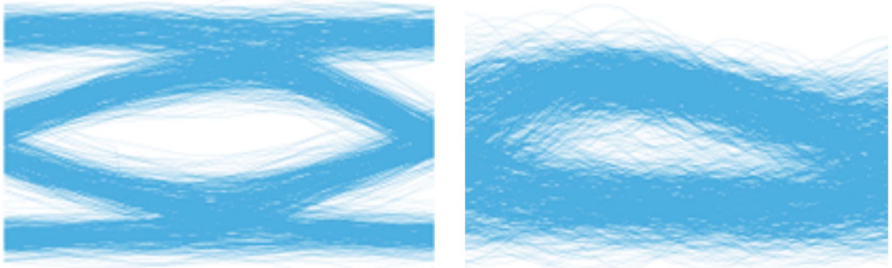




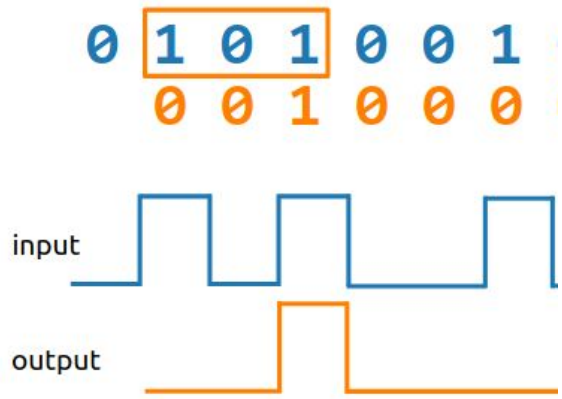


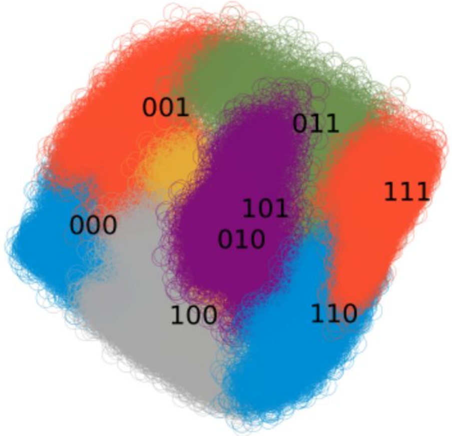
Before XOR:

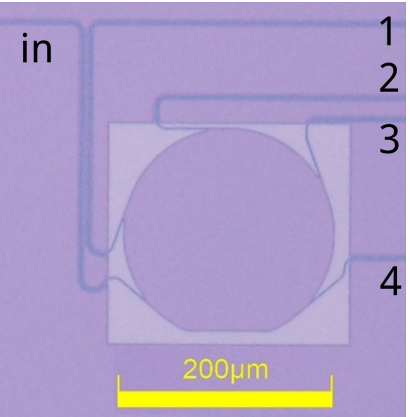
After XOR:



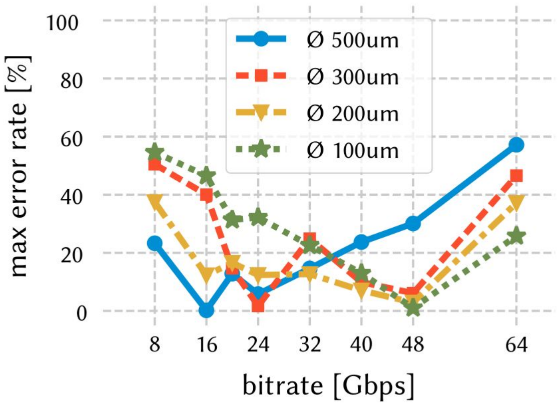
Header recognition **(measurement)**



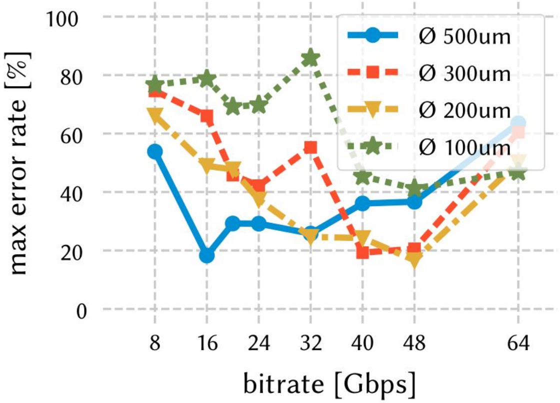




3 bit headers

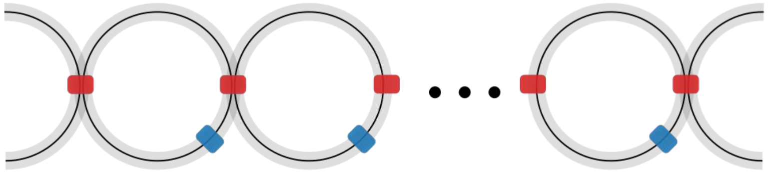


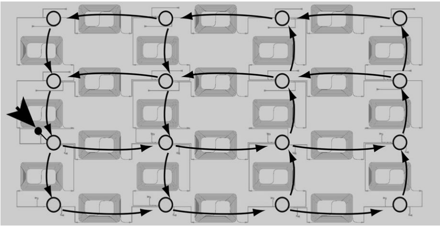
4 bit headers



Overview

- Machine learning & Neuromorphic computing
- Towards photonic neuromorphic computing
- Reservoir computing with signal-mixing cavities
- **Photontorch: optimizing photonic circuits**
- Neuromorphic computing with photorefractive crystals





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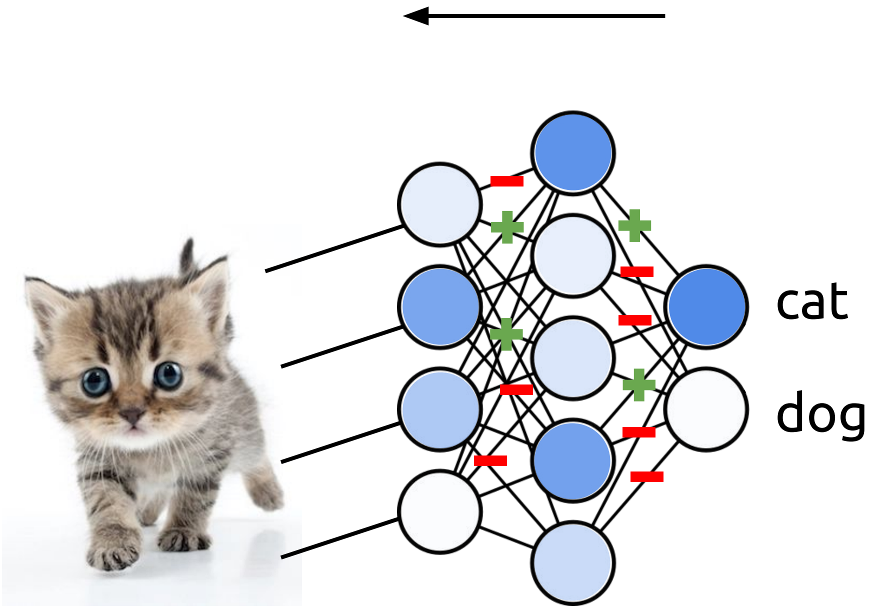
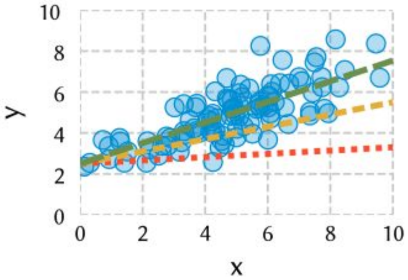
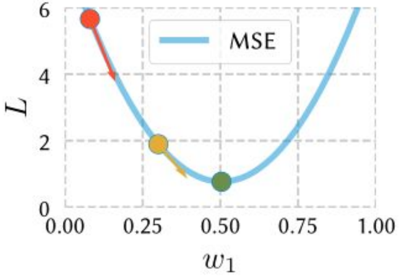
Training neural networks: **backpropagation**

Backpropagate error



To minimize loss function





$$L = \frac{1}{2m} |y - \hat{y}|^2$$

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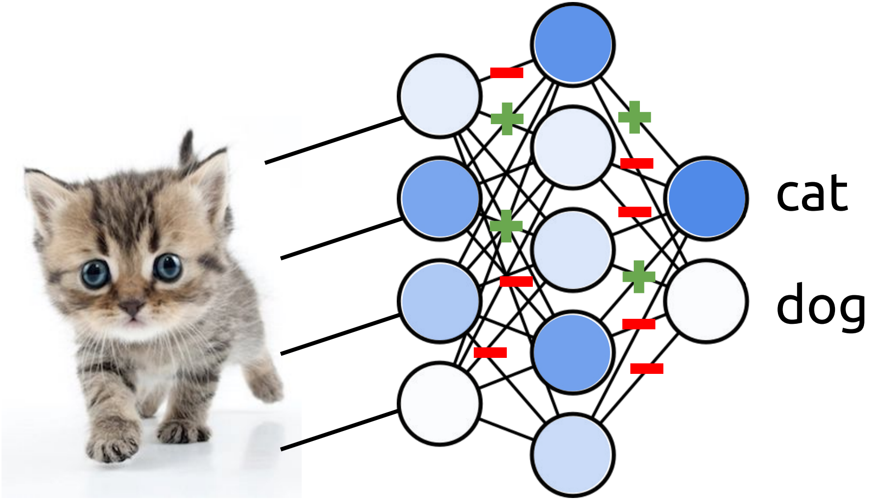
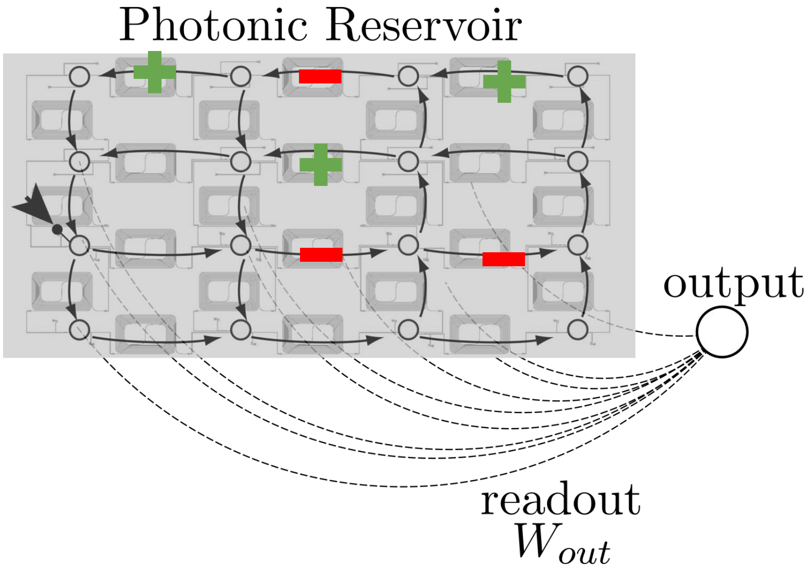
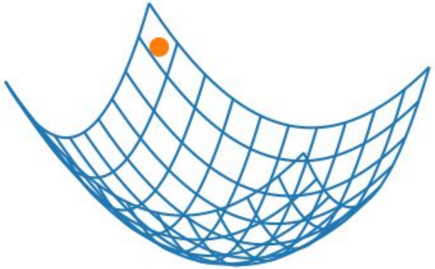
Training photonic circuits with backpropagation?





Photontorch: backpropagation through photonic circuits

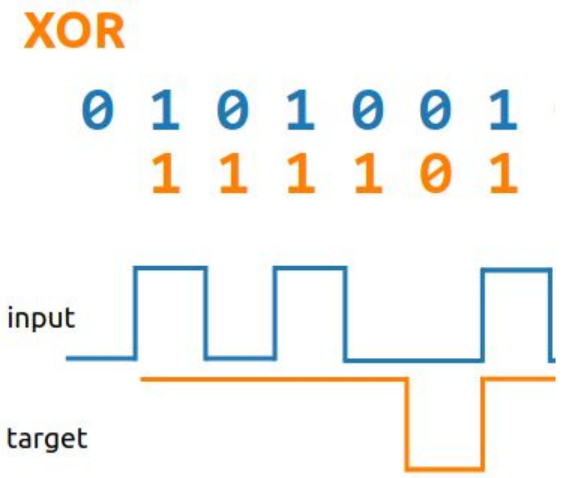


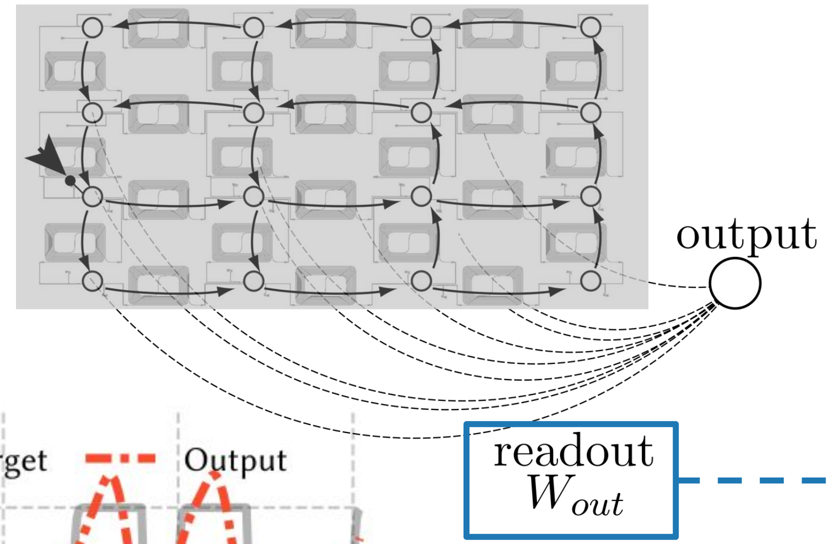
- The simulator needs to **keep track** of the order of operations, i.e. the **computation graph** for the backward pass

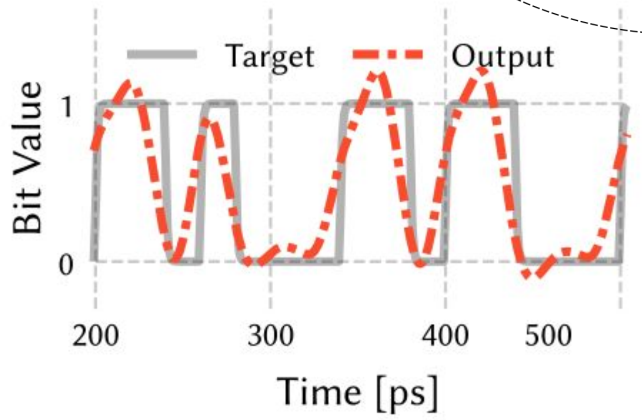
This requires a whole **new photonic simulator**

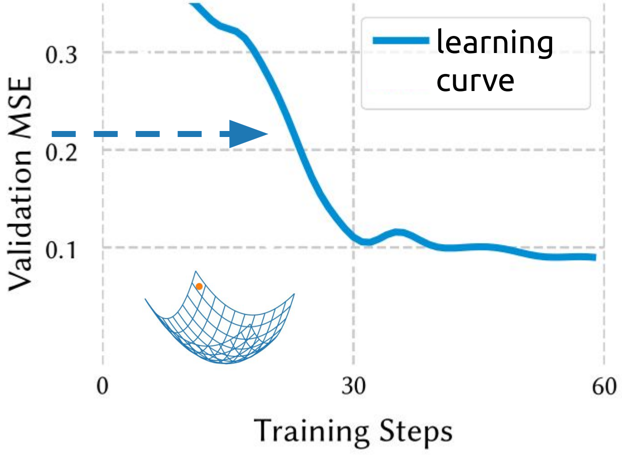
Optimization: Reservoir

Starting point:



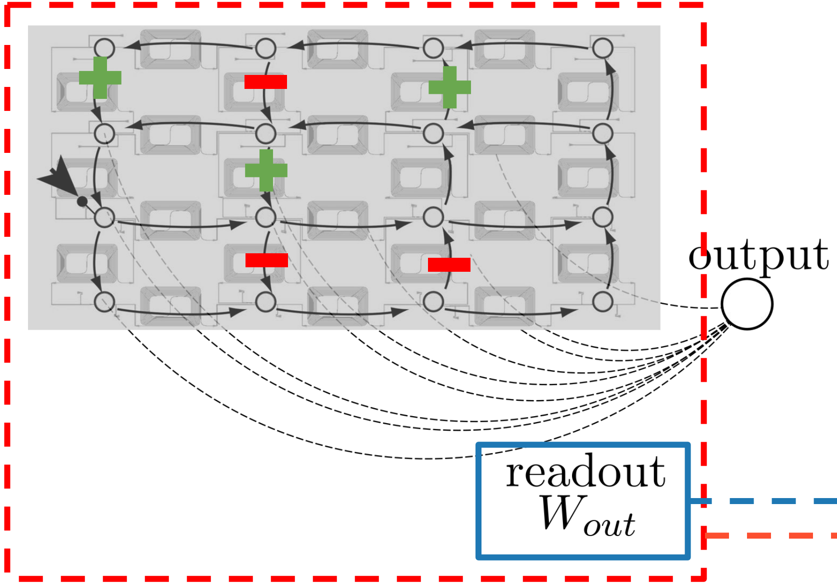


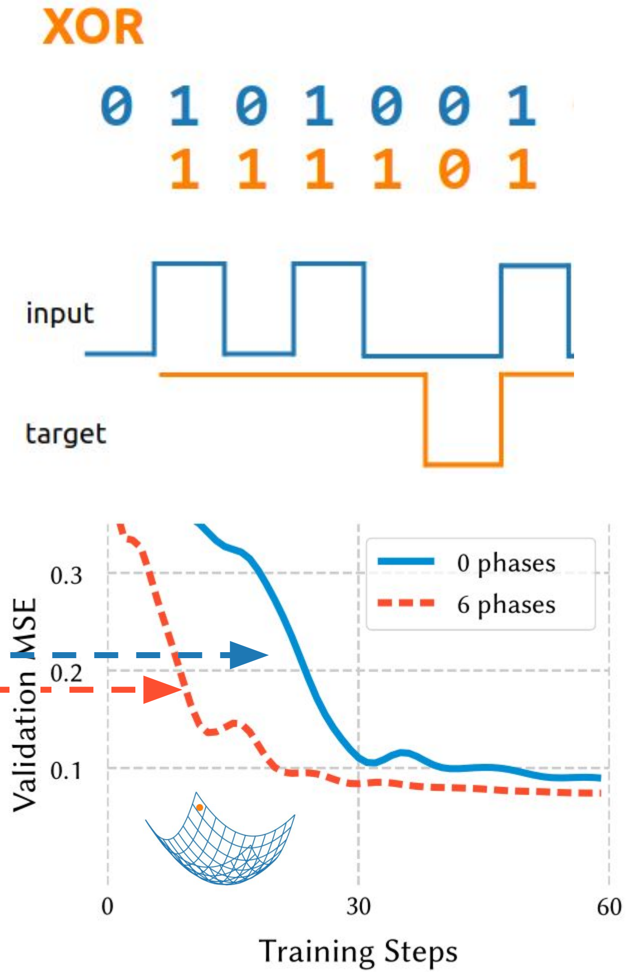




Optimization: Reservoir

Allow to **optimize some phases:**





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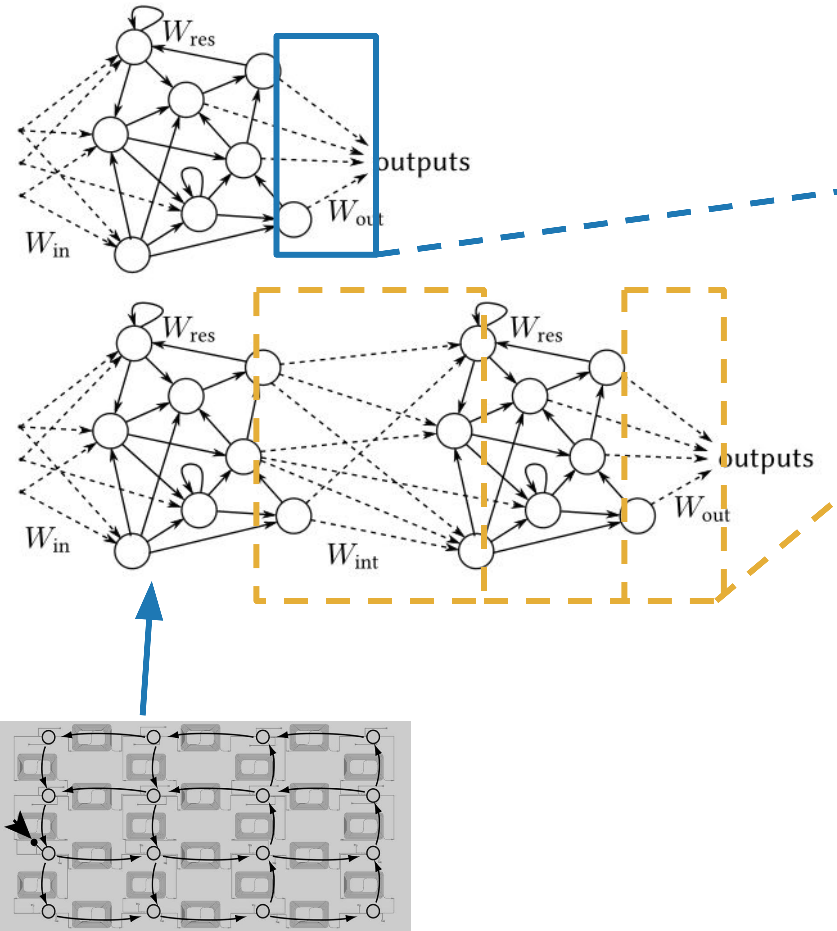
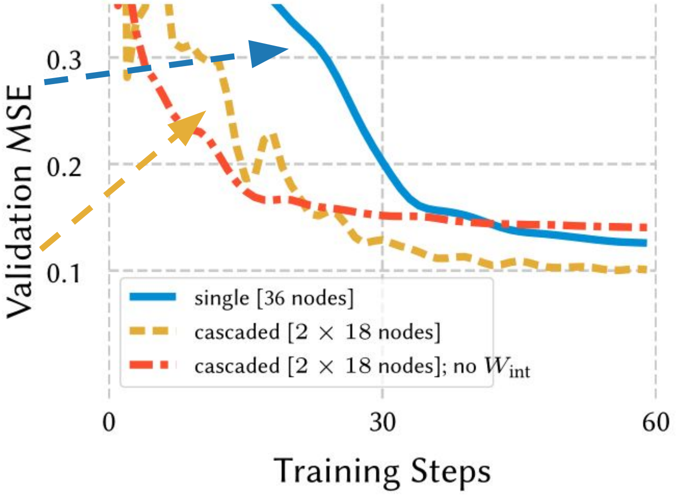
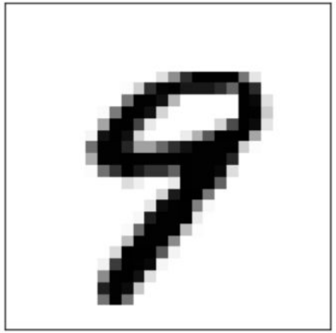
Optimization: **Cascaded Reservoir**

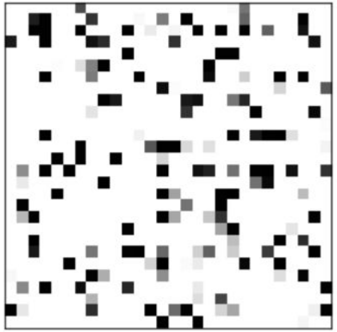


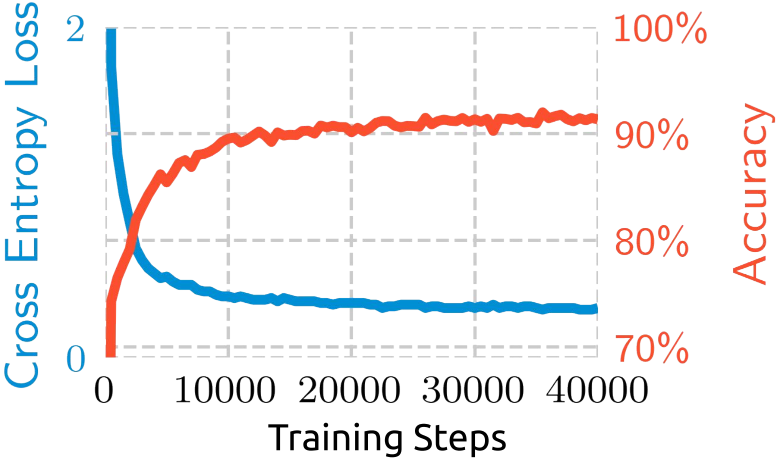


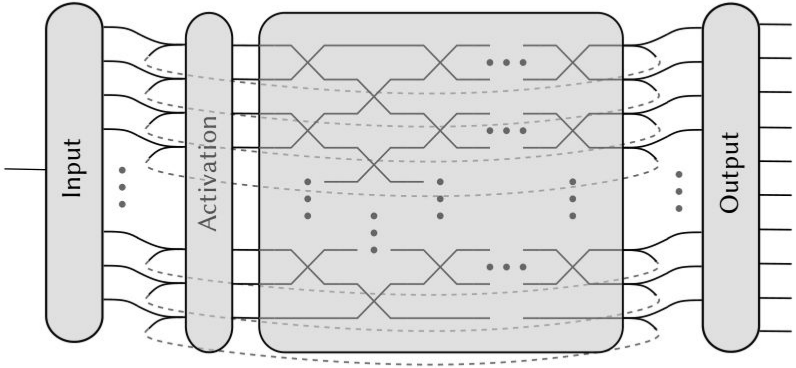
XOR of two bits with one intermediate bit

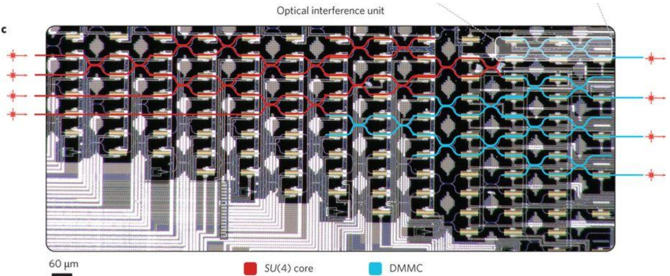
Optimization: **MNIST**





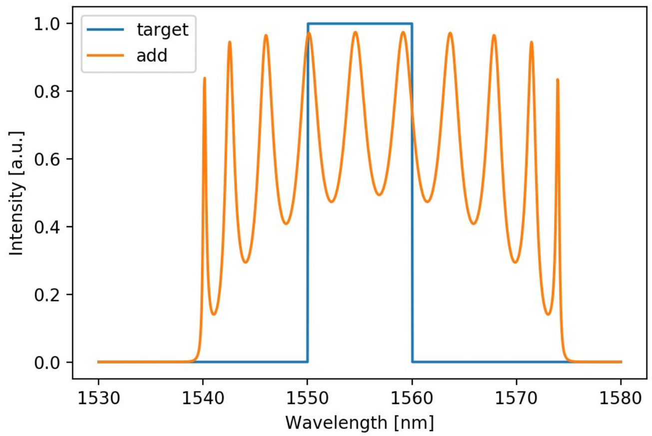


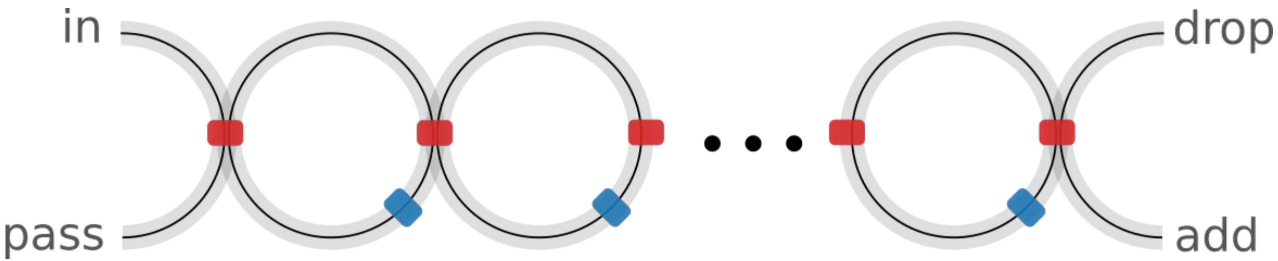




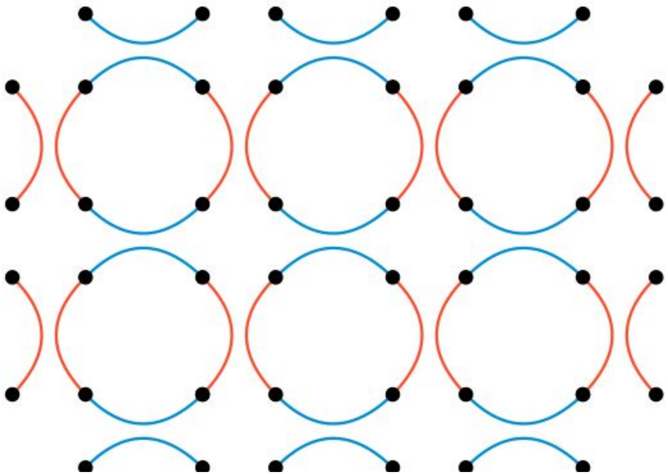
Shen, Nature, 2017

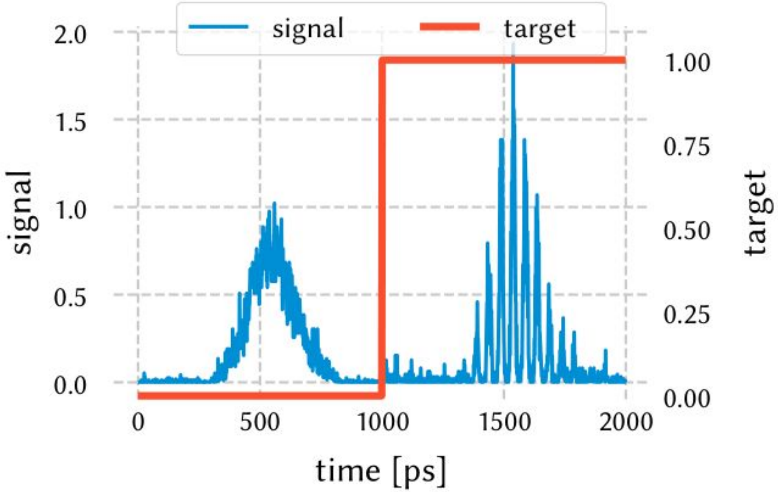
Optimization: CROW

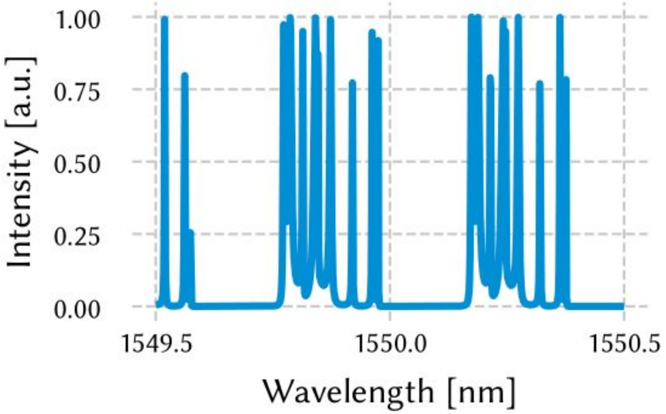


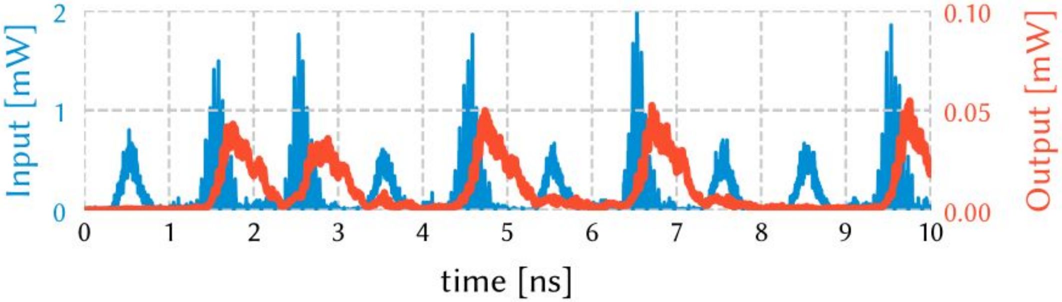


Optimization: **ring network**

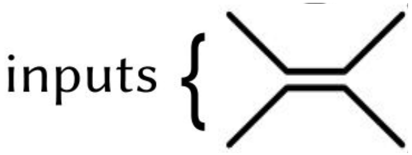


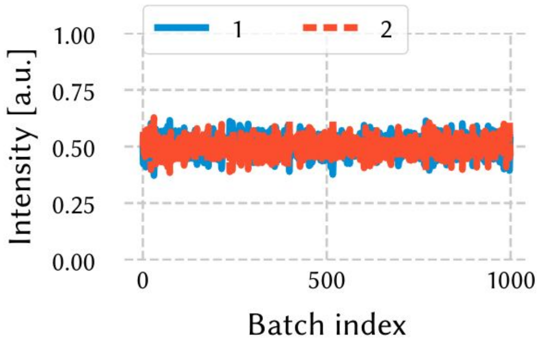




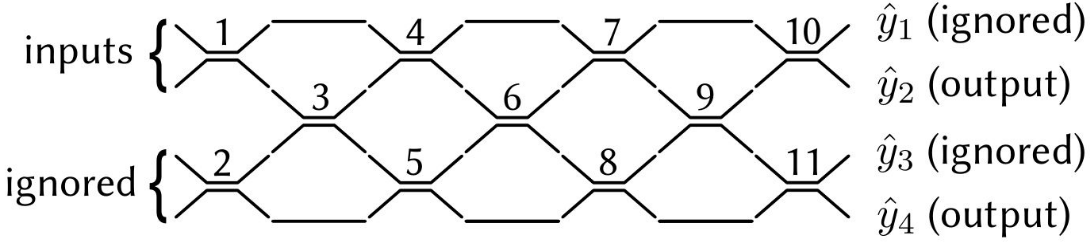


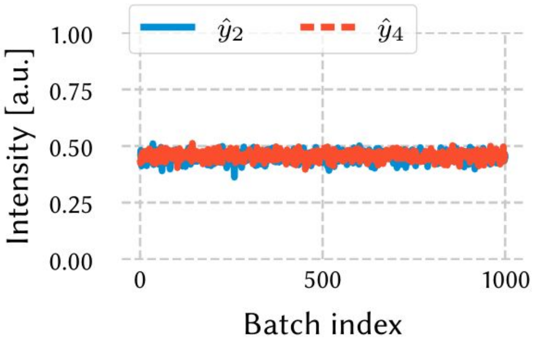
Optimization: **built-in tolerance**





σ=0.05





σ=0.016

$$L = \alpha\left(\frac{1}{B}\sum_{b=1}^{B}\sum_{i=1}^{4}\left(\hat{y}_{bi}-y_i\right)^2\right)$$
$$+\beta\left(\frac{1}{B}\sum_{b=1}^{B}\left(\hat{y}_{b2}-\frac{1}{B}\sum_{n=1}^{B}\hat{y}_{n2}\right)^2+\left(\hat{y}_{b4}-\frac{1}{B}\sum_{n=1}^{B}\hat{y}_{n4}\right)^2\right)$$

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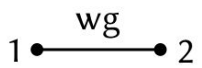
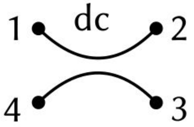
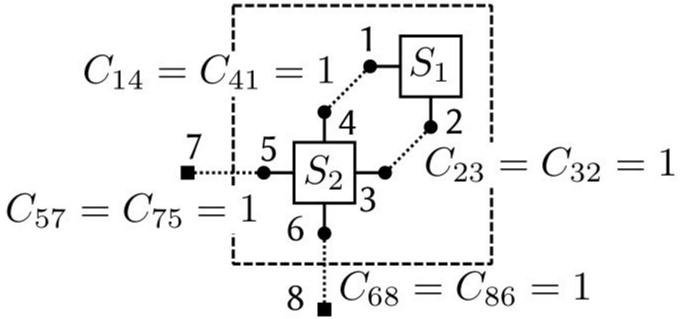
Photontorch



$$S^{\text{wg}} = \begin{pmatrix} 0 & \exp(\frac{2\pi i}{\lambda} n_{\text{eff}} L) \\ \exp(\frac{2\pi i}{\lambda} n_{\text{eff}} L) & 0 \end{pmatrix}$$



$$S^{\text{dc}} = \begin{pmatrix} 0 & \tau & i\kappa & 0 \\ \tau & 0 & 0 & i\kappa \\ i\kappa & 0 & 0 & \tau \\ 0 & i\kappa & \tau & 0 \end{pmatrix}$$



$$S = \begin{pmatrix} S_1 & & & \\ & S_2 & & \\ & & \ddots & \\ & & & S_N \end{pmatrix}$$

C_{int} C_{ext}

$$C = \left(\begin{array}{cccccc|cc} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{array}\right)$$

Frequency domain:

$$S_{\text{circuit}} = C_{\text{ext}}^T S (I - C_{\text{int}} S)^{-1} C_{\text{ext}}$$

Photontorch: very parallelizable

Frequency domain:

$$S_{\text{circuit}} = C_{\text{ext}}^T S (I - C_{\text{int}} S)^{-1} C_{\text{ext}}$$

Time domain:

- Ideally: **FT(S_{circuit})** → VF, IIR, FIR, ...
- Approximation:

$$\begin{pmatrix} x^{\text{ML}} \\ x^{\text{MC}} \end{pmatrix} = \begin{pmatrix} C^{\text{MLML}} & C^{\text{MLMC}} \\ C^{\text{MCML}} & C^{\text{MCMC}} \end{pmatrix} \begin{pmatrix} S^{\text{MLML}} & 0 \\ 0 & S^{\text{MCMC}} \end{pmatrix} \star \begin{pmatrix} x^{\text{ML}} \\ x^{\text{MC}} \end{pmatrix}$$
$$= \begin{pmatrix} C^{\text{MLML}} & C^{\text{MLMC}} \\ C^{\text{MCML}} & C^{\text{MCMC}} \end{pmatrix} \begin{pmatrix} S^{\text{MLML}} x^{\text{ML}} \\ S^{\text{MCMC}} \star x^{\text{MC}} \end{pmatrix}$$

$$\tilde{C} = \left(C^{\text{MCMC}} + C^{\text{MCML}} \cdot S^{\text{MLML}} \cdot (1 - C^{\text{MLML}} S^{\text{MLML}})^{-1} C^{\text{MLMC}} \right)$$

$$x^{\text{MC}} = \tilde{C} S^{\text{MCMC}} \begin{pmatrix} x_1^{\text{MC}}(t - dt_1) \\ x_2^{\text{MC}}(t - dt_2) \\ \vdots \\ x_P^{\text{MC}}(t - dt_P) \end{pmatrix}$$

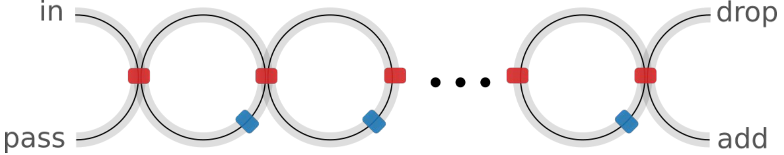
No dispersion taken into account

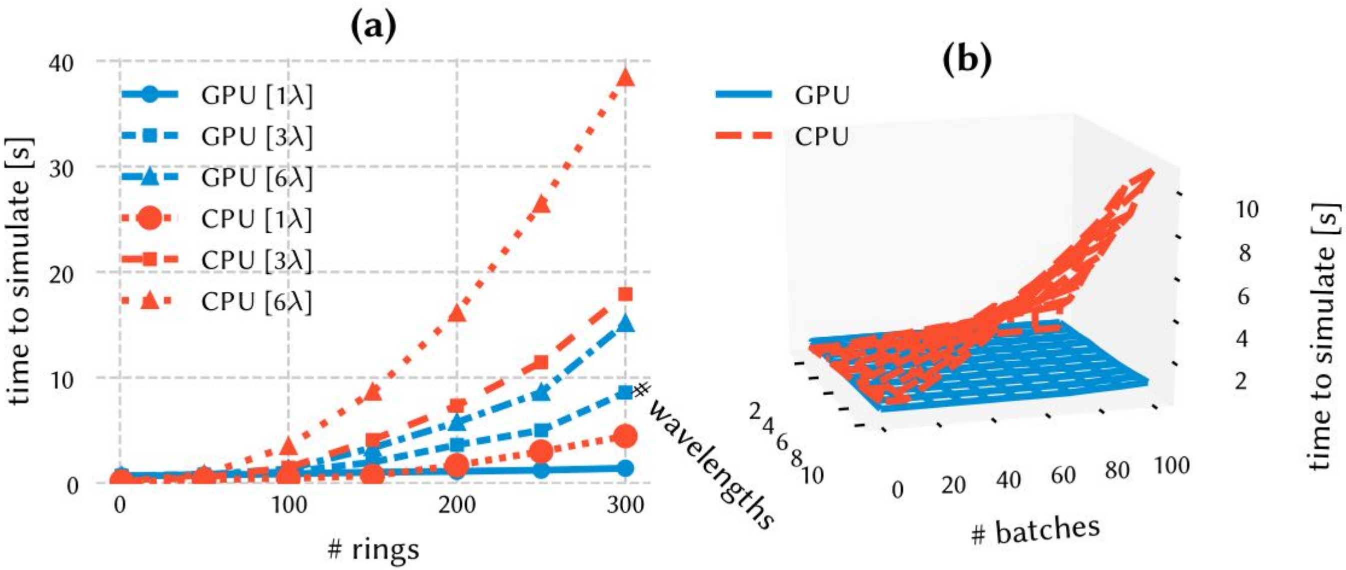
$$\boxed{x_{(q+1)mnb} = \sum_i^N \sum_j^N \tilde{C}_{mni} S_{mij} \star x_{qmjb}}$$

If GVD is important

$$\frac{\partial u}{\partial t}(t) = f(t, u, x)$$

Performance





$$x_{(q+1)mnb} = \sum_{i}^{N} \sum_{j}^{N} \tilde{C}_{mni} S_{mij} \star x_{qmjb}$$

Overview

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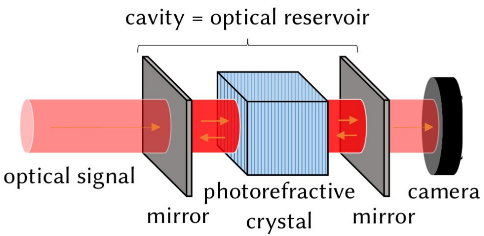
- Reservoir computing with signal-mixing cavities
- **Neuromorphic computing with photorefractive crystals**



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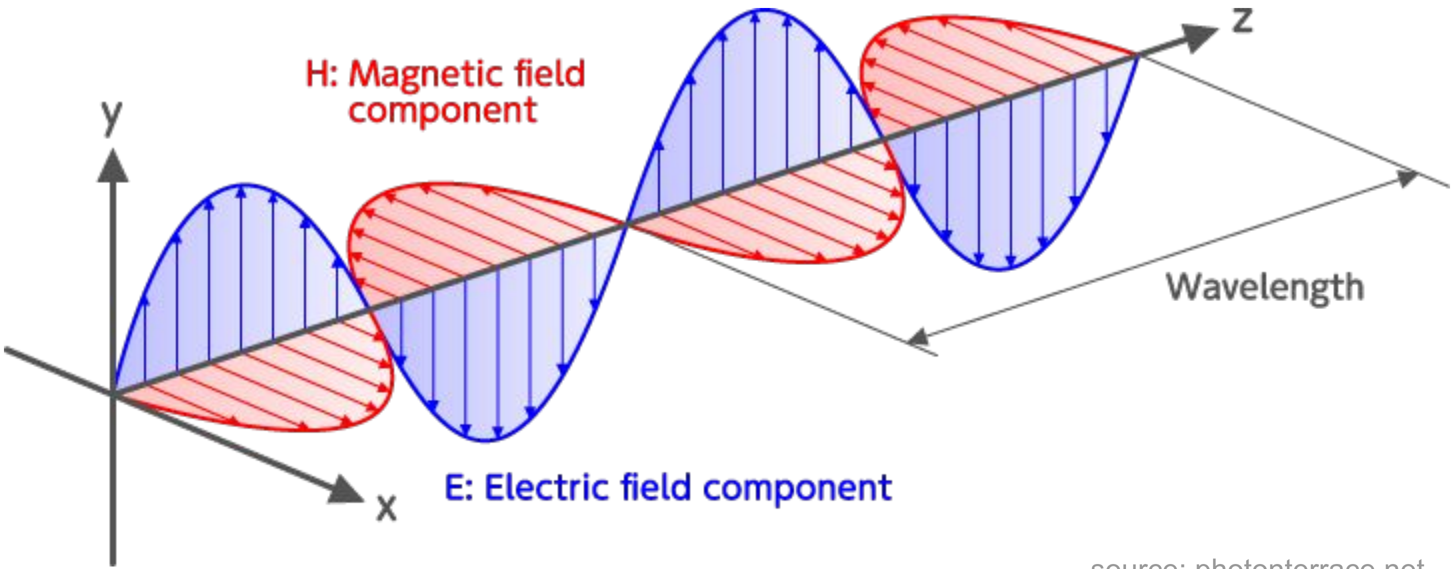
Light is an electromagnetic wave



source: photonterrace.net

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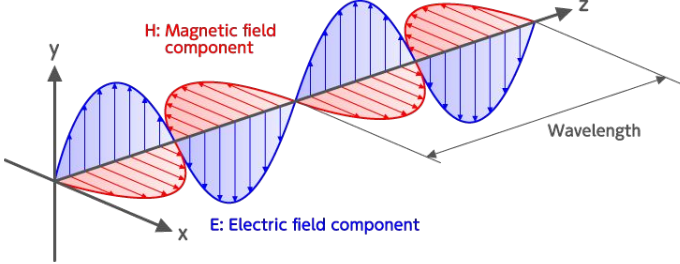
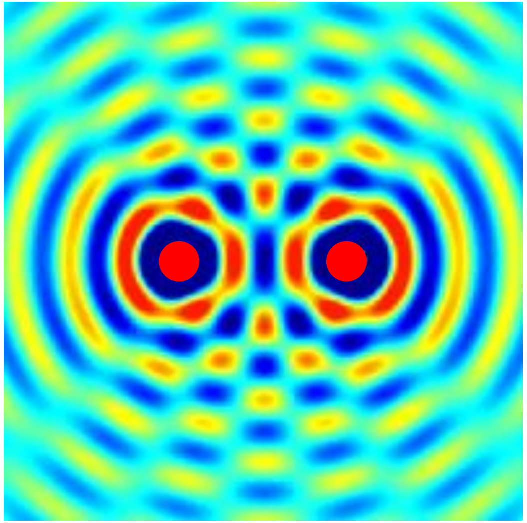
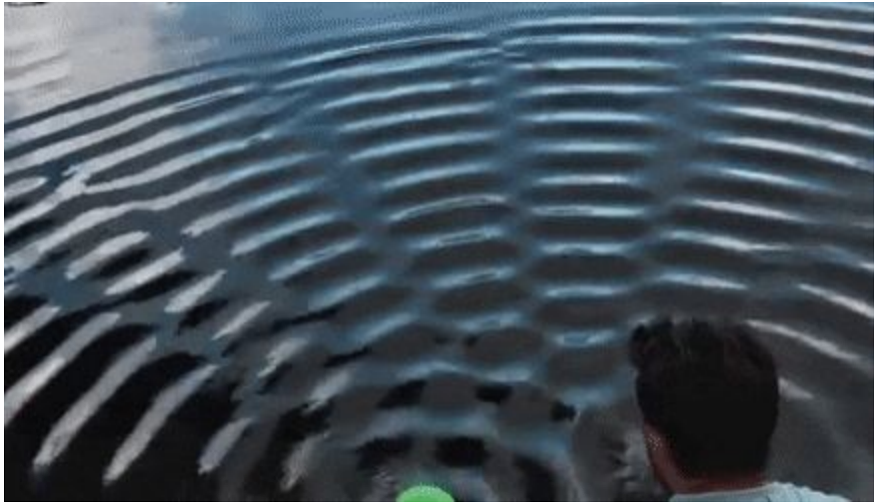
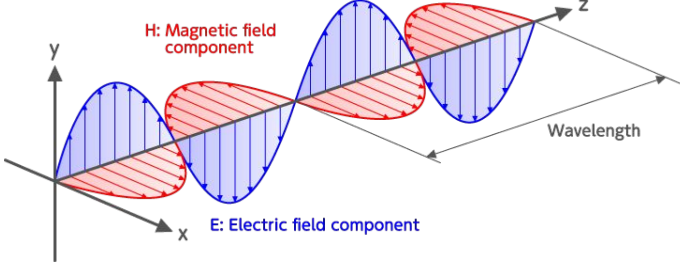
Interference

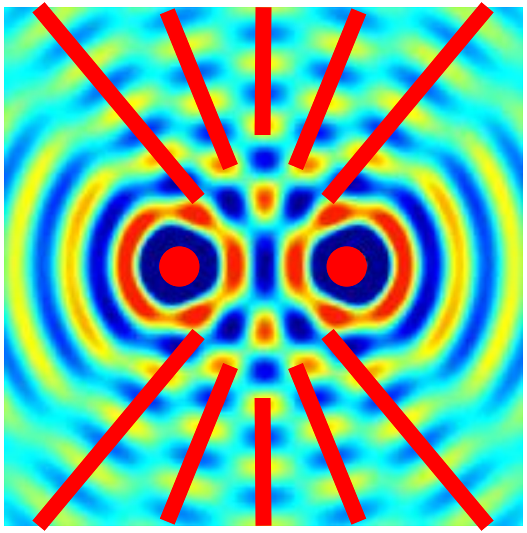


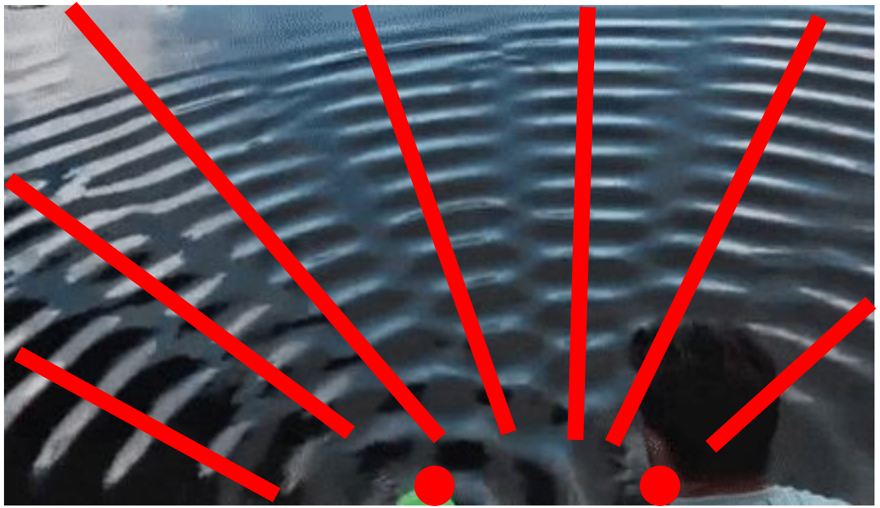




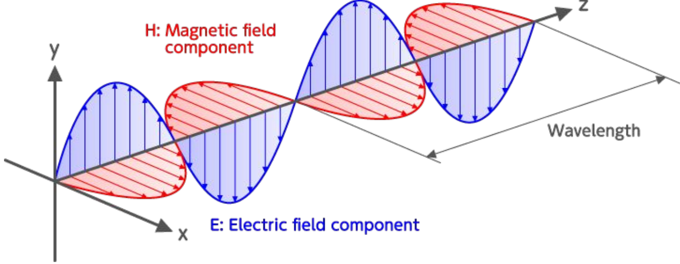
Interference

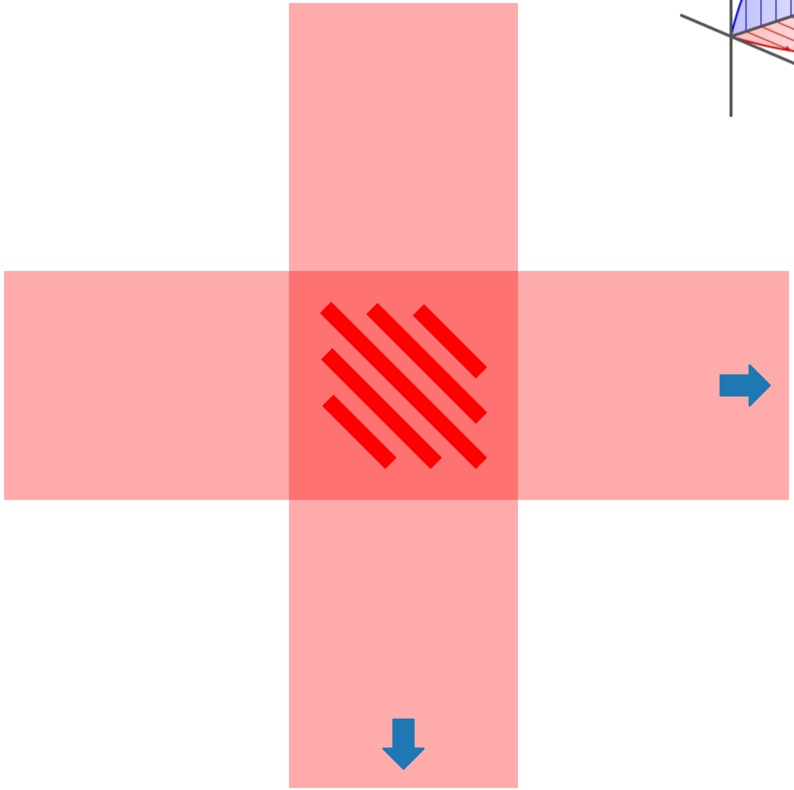




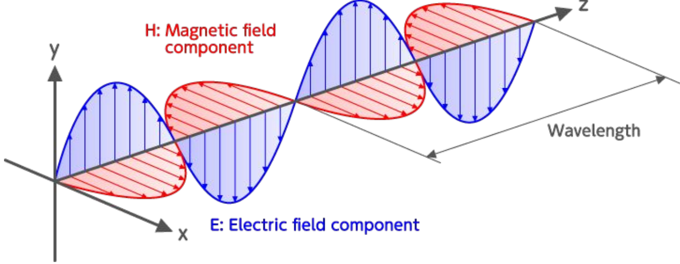


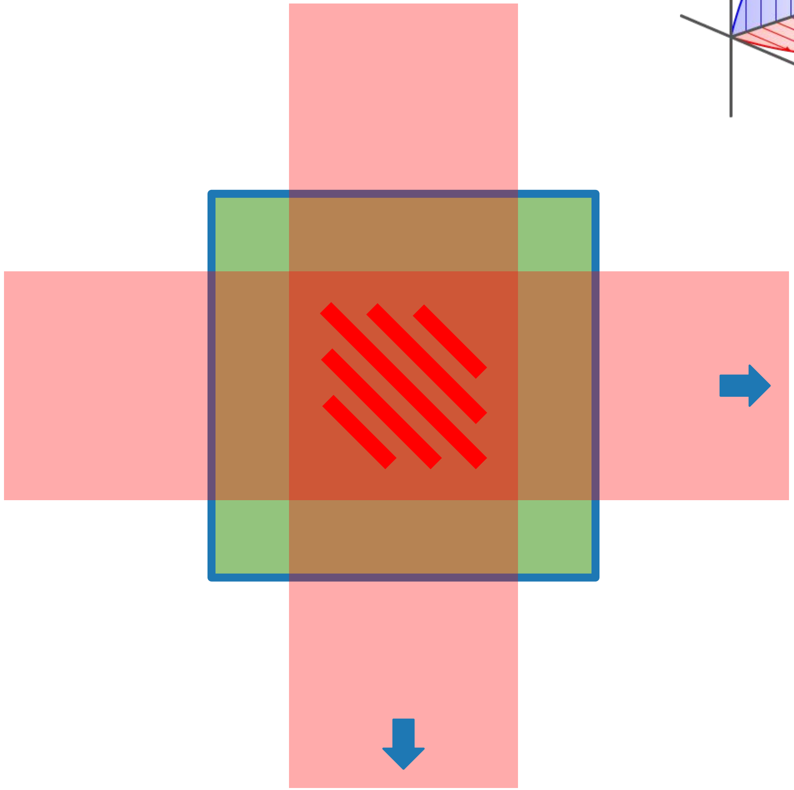
Interference



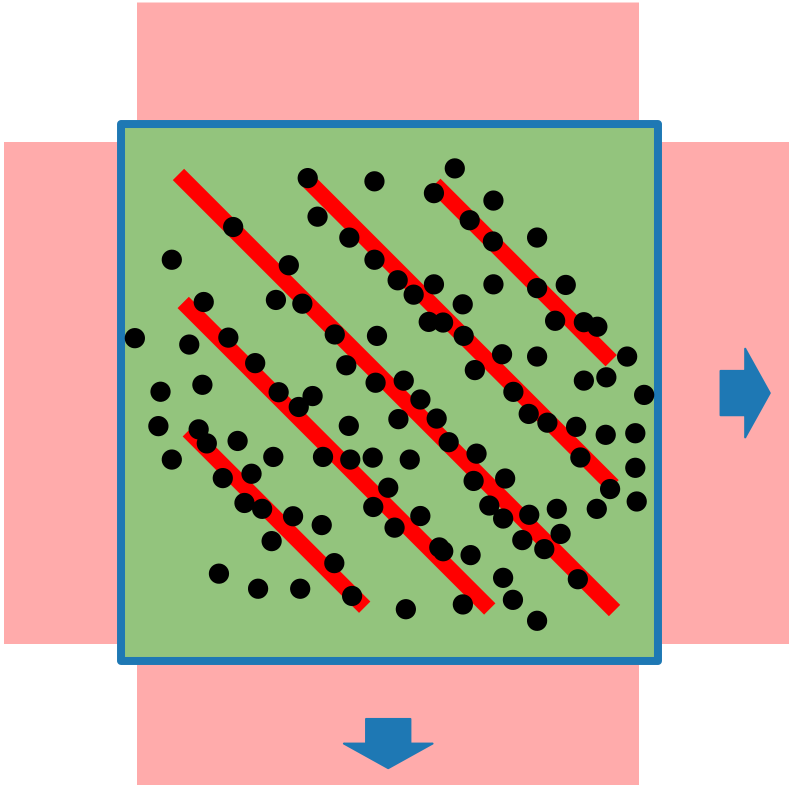


Photorefractive effect



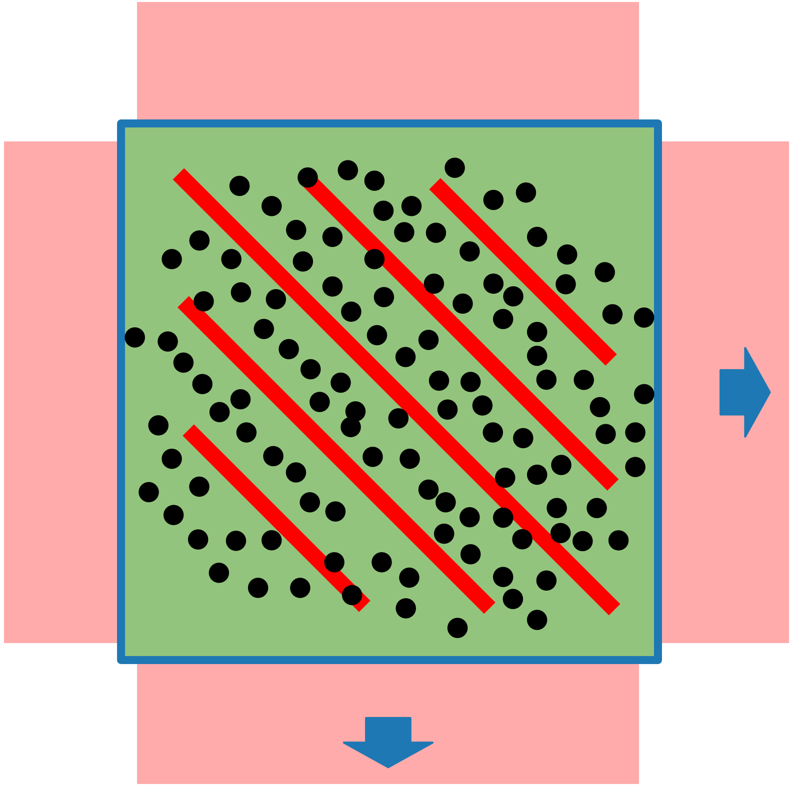


Photorefractive effect



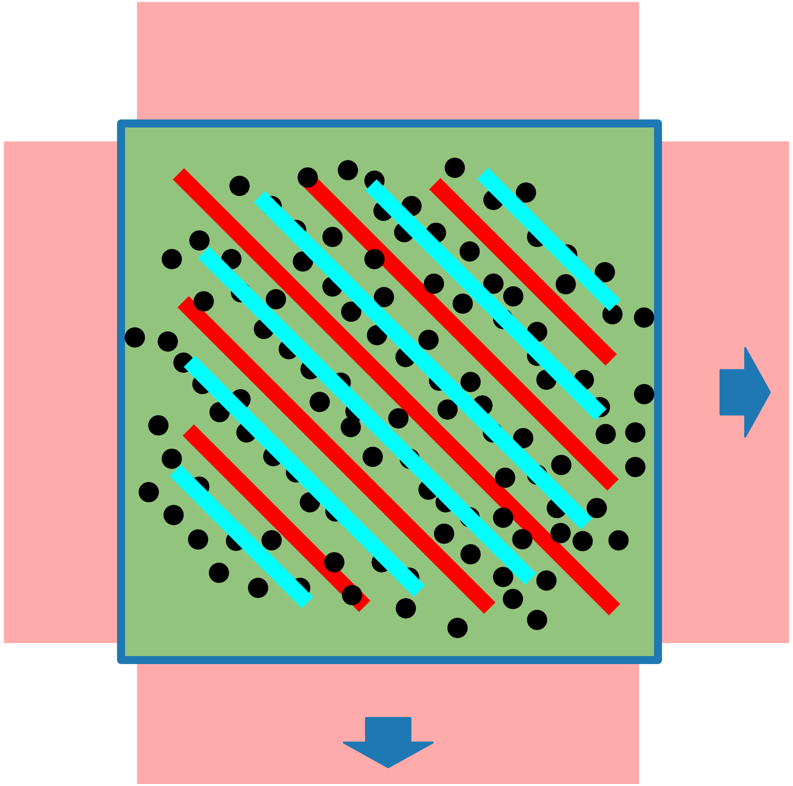
$$\frac{dn}{dt} = \boxed{(sI+\beta)(N_D - N_D^+)} - \gamma n N_D^+ + \frac{\mu k T}{e}\nabla n - \mu n \mathbf{S}$$

Photorefractive effect



$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) - \gamma n N_D^+ + \boxed{\frac{\mu k T}{e}\nabla n - \mu n \mathbf{S}}$$

Photorefractive effect



$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) \boxed{- \gamma n N_D^+} + \frac{\mu k T}{e}\nabla n - \mu n \mathbf{S}$$

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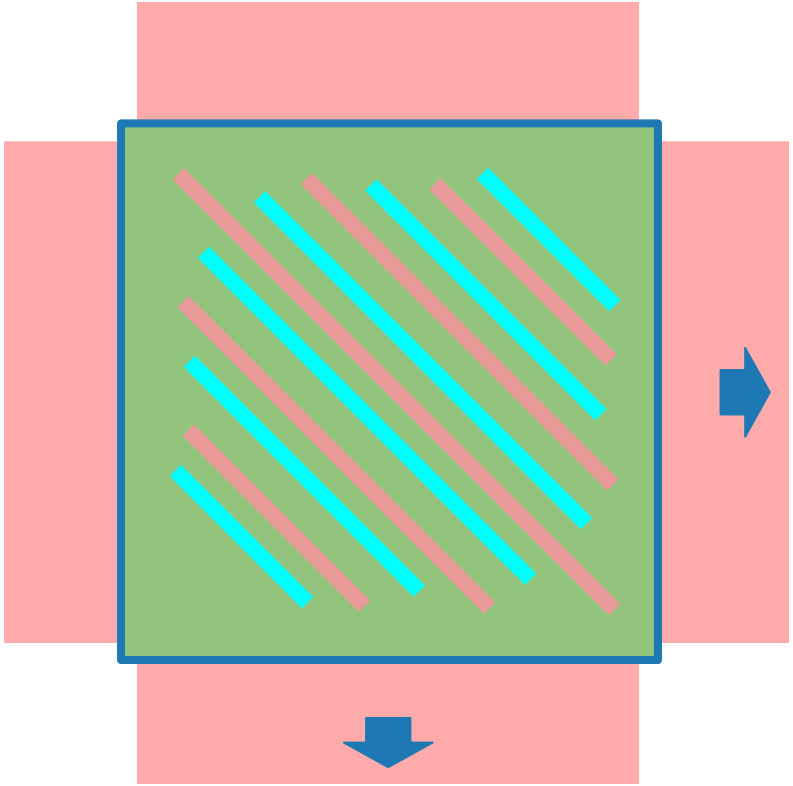
Photorefractive effect



$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) \boxed{- \gamma n N_D^+} + \frac{\mu k T}{e} \nabla n - \mu n \mathbf{S}$$

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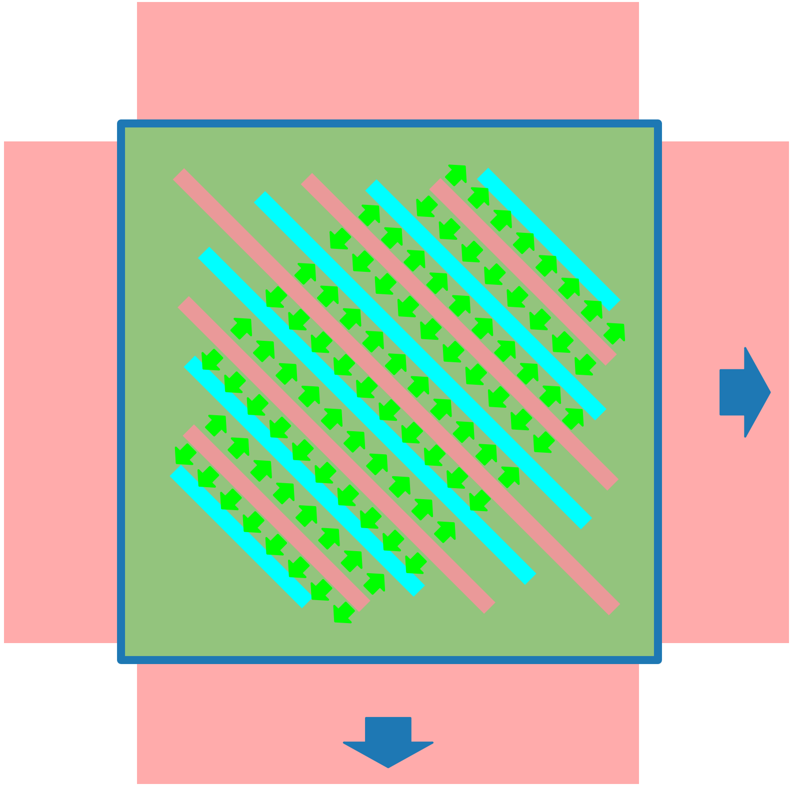
Photorefractive effect



$$\nabla \cdot \mathbf{S} = \frac{\rho}{\epsilon_s}$$

$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) - \gamma n N_D^+ + \frac{\mu k T}{e}\nabla n - \mu n \mathbf{S}$$

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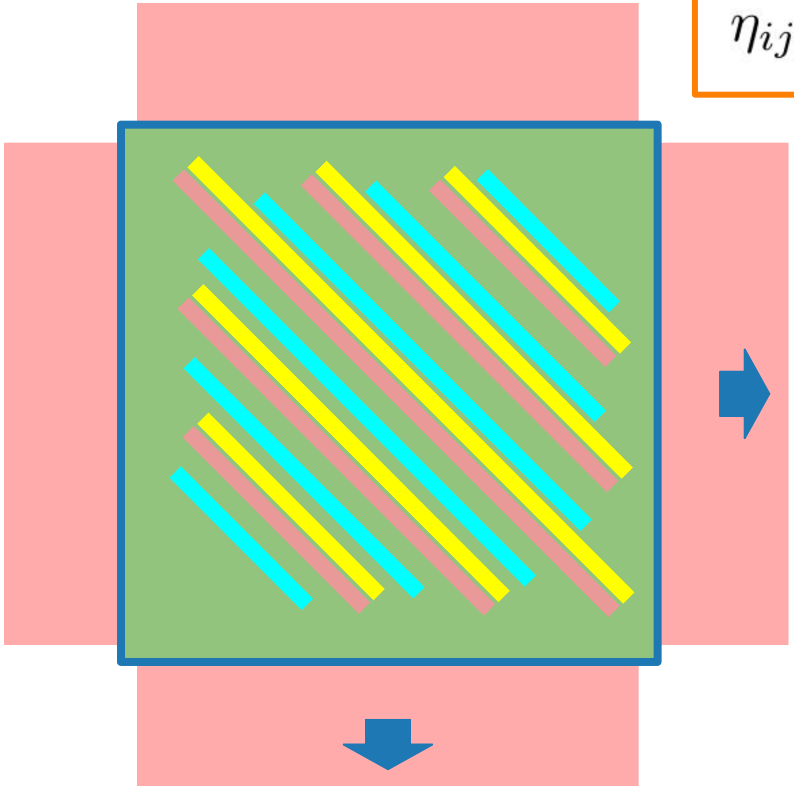
Photorefractive effect

$$\eta_{ij}(\mathbf{S}) = \eta_{ij}(0) + r_{ijk} S_k$$

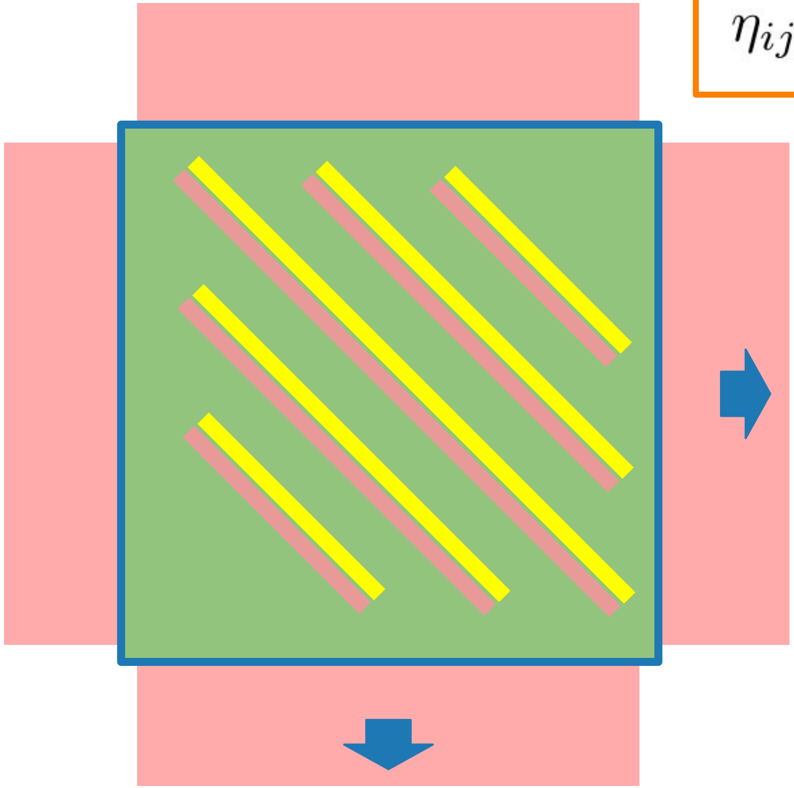


$$\nabla \cdot \mathbf{S} = \frac{\rho}{\epsilon_s}$$

$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) - \gamma n N_D^+ + \frac{\mu k T}{e} \nabla n - \mu n \mathbf{S}$$

Photorefractive effect

$$\boxed{\eta_{ij}(\mathbf{S}) = \eta_{ij}(0) + r_{ijk} S_k}$$



$$\nabla \cdot \mathbf{S} = \frac{\rho}{\epsilon_s}$$

$$\frac{dn}{dt} = (sI + \beta)(N_D - N_D^+) - \gamma n N_D^+ + \frac{\mu k T}{e} \nabla n - \mu n \mathbf{S}$$

Bringing it all together

Kukhtarev equations:

$$\frac{dn}{dt} = \frac{dN_D^+}{dt} + \nabla \cdot \mathbf{J}$$

$$\frac{dN_D^+}{dt} = (sI + \beta)(N_D - N_D^+) - \gamma n N_D^+$$

$$\mathbf{J} = \frac{\mu k T}{e}\nabla n - \mu n \mathbf{S}$$

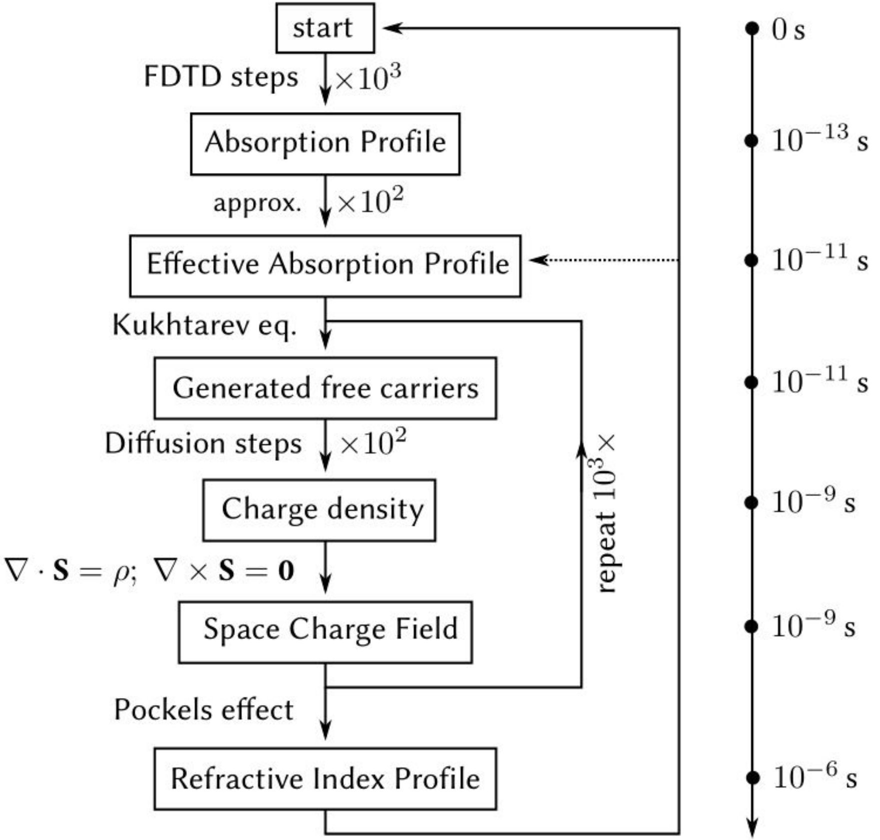
Diffusion Equation:

$$\frac{\partial n}{\partial t} = \left.\frac{\partial n}{\partial t}\right|_{\text{diff}} + \left.\frac{\partial n}{\partial t}\right|_{\text{drift}} = D\nabla^2 n - \nabla \cdot \mathbf{F}$$

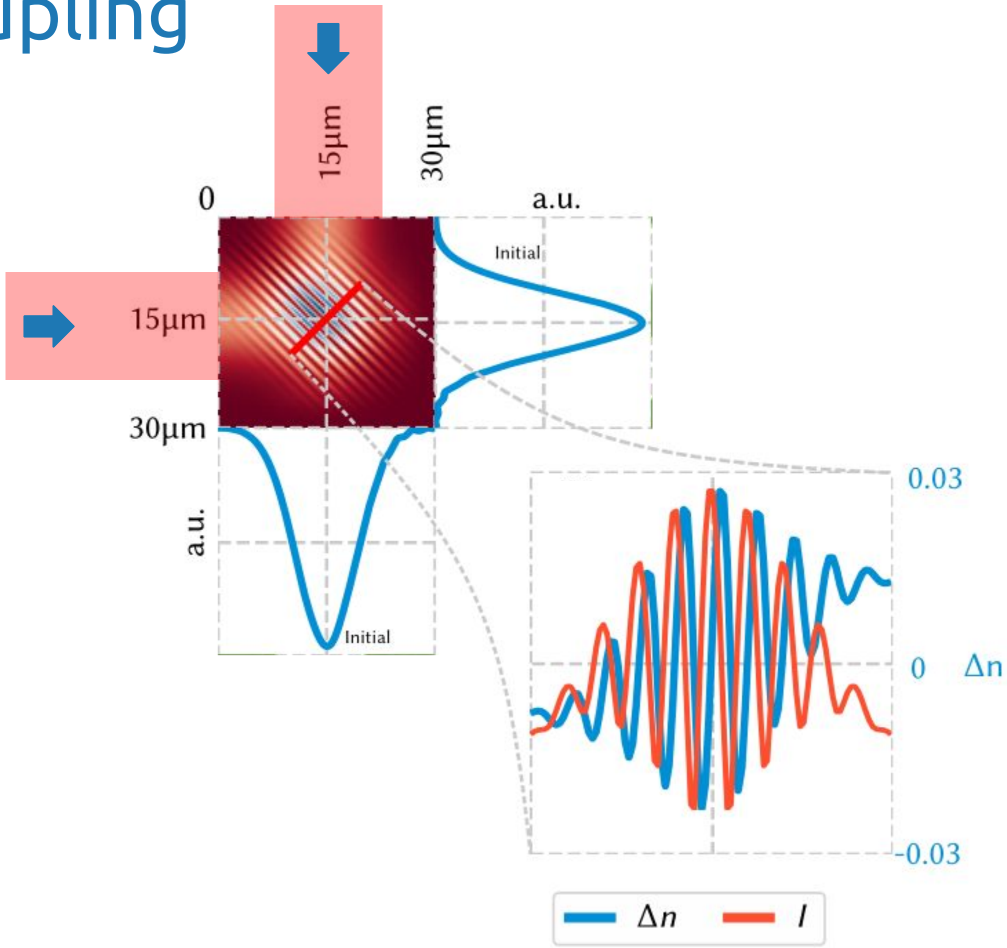
Maxwell equations:

$$\nabla \cdot \mathbf{S} = \frac{\rho}{\epsilon_s}$$

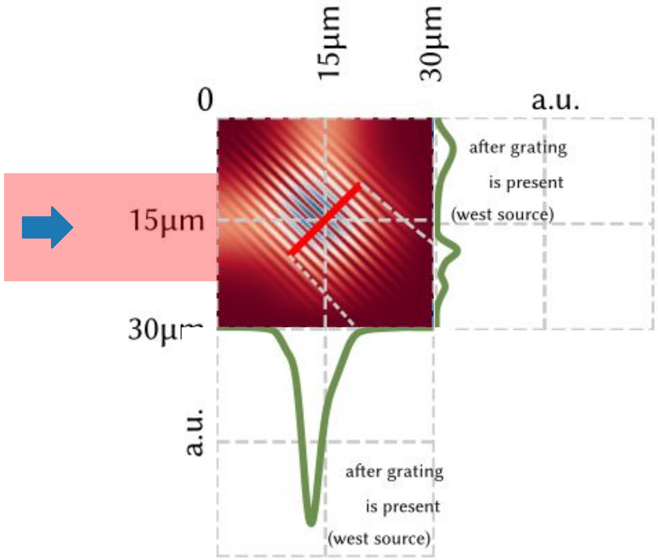
$$\nabla \times \mathbf{S} = \mathbf{0}$$



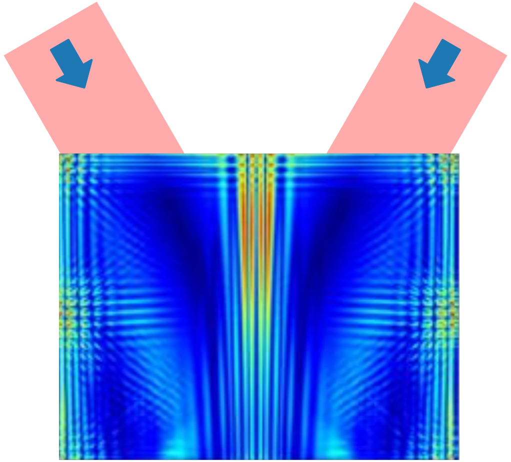
Beam Coupling



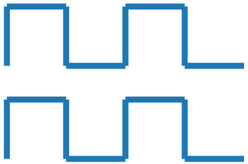
Beam Coupling

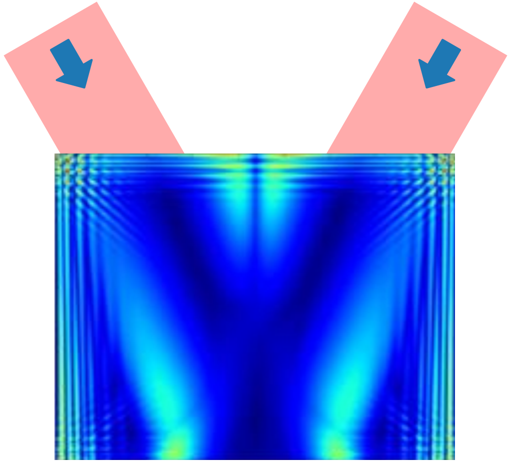


Self learning with photorefractive crystals

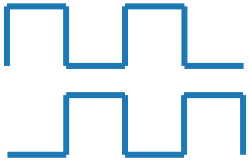


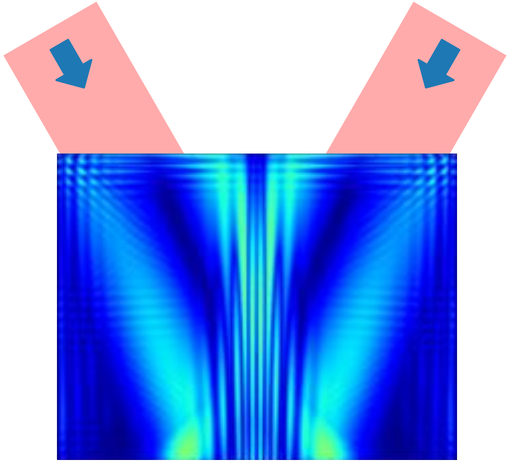
Purely Interfering
(same bits arrive at the same time)



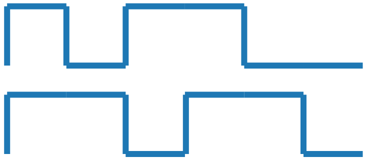


Alternating
(opposite bits arrive at the Alternating times)

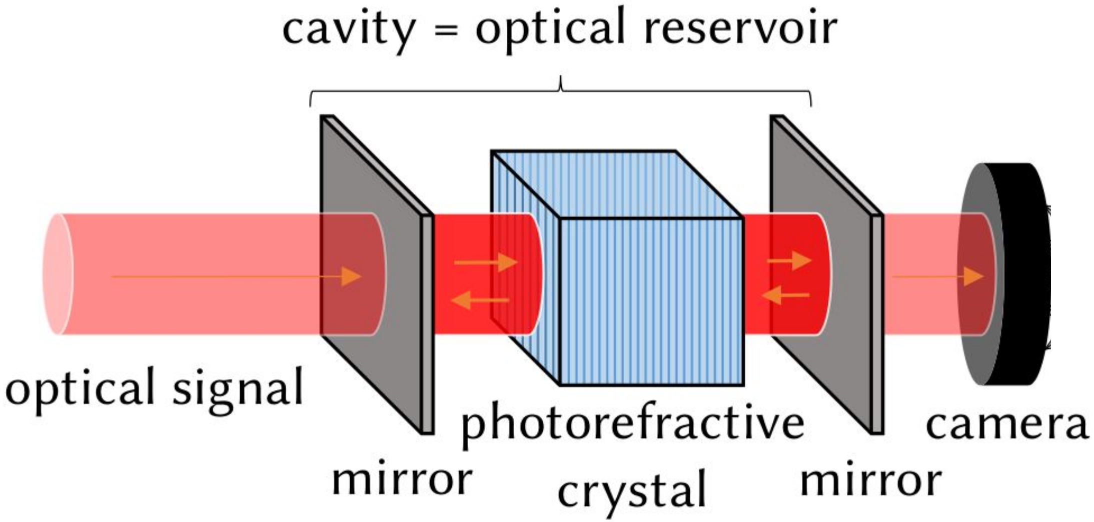




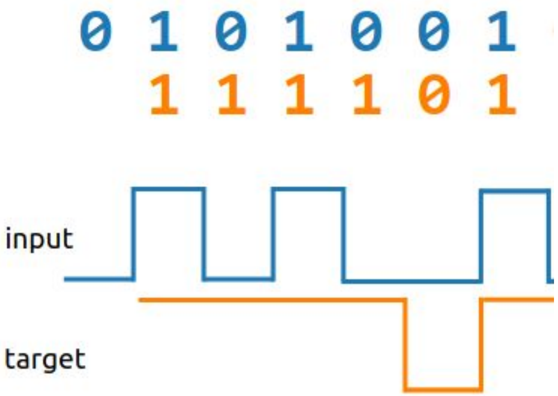
Random
(two random bitstream, Sometimes interfering, Sometimes alternating)

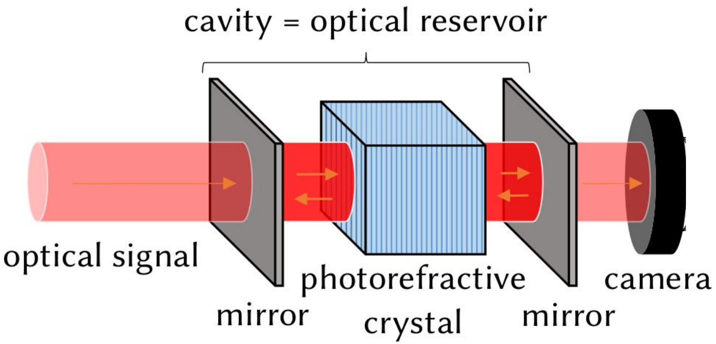


Self learning with photorefractive crystals

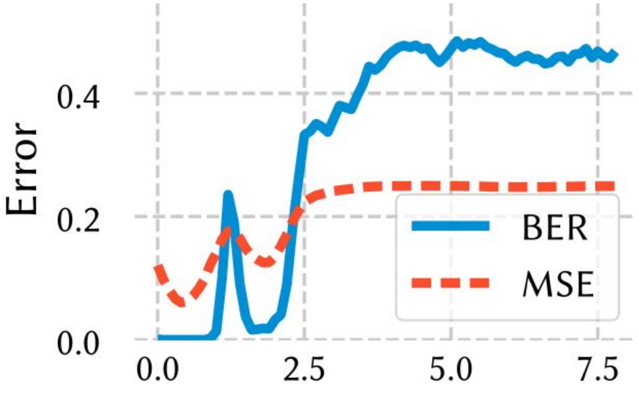


XOR Task

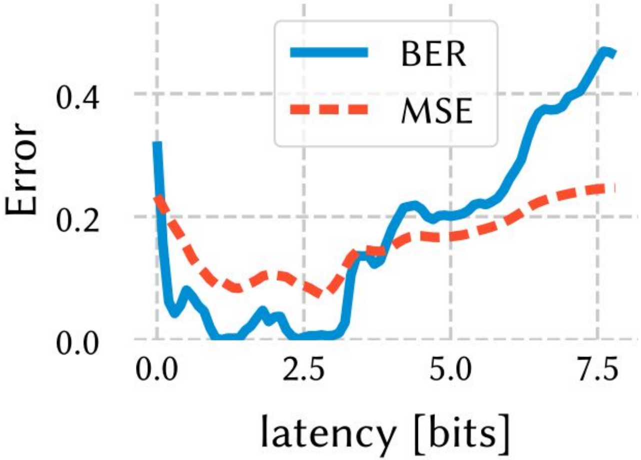




Before “priming”:



After “priming”:



Conclusions

Conclusions

- Reservoir computing with **on-chip cavities** seems to be a promising alternative to traditional node-based designs:
  - Benchmark tasks like **HREC and XOR show promising results**, both in simulation and experiments.
- **Photontorch** shows the viability of optimizing photonic circuits through **backpropagation**
  - Completely **new way of optimizing** photonic circuits
  - Very **parallelizable** (➡️ Fast)
    - wavelength multiplexing
    - waveform multiplexing (batched execution)
- Self-reorganization in photorefractive crystals, such as **priming** the crystal might help for neuromorphic computing schemes **beyond reservoir computing** such as self-learning