Optical Quantum Computing

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COSC 594
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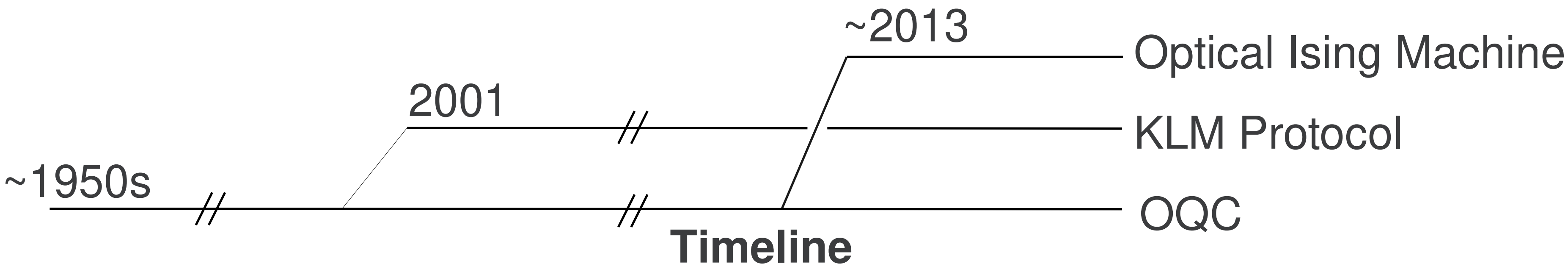
THE UNIVERSITY OF
TENNESSEE
KNOXVILLE

Overview

- Quantum light
- Optical components & effects
- Logic Circuits
- Past/Present/Future of OQC



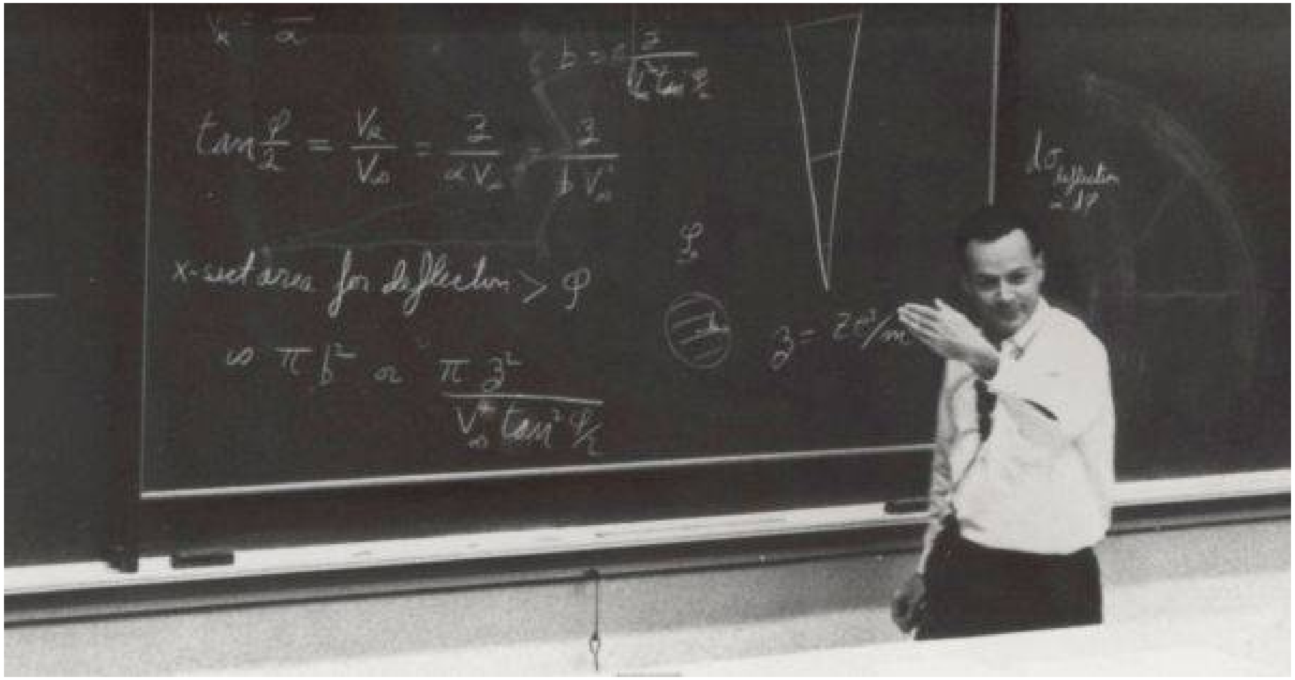
Timeline

What is Light?

Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave. So it really behaves like neither. Now we have given up. We say: "It is like neither."

Richard Feynman

Feynman Lecture, Vol. 1 Chap. 37



What is Light?

It behaves like a wave sometimes and a particle other times. Light energy is quantized in packets called **photons**.

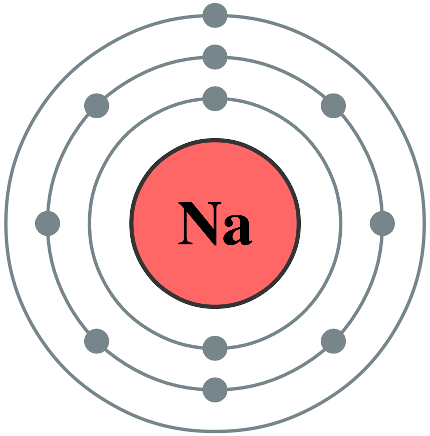
We'll be most interested in a particle perspective, but we can't focus on it too much.

Bosons vs. Fermions

Fermions

Must obey Pauli Exclusion Principle

- Particles in the same system *cannot* have the same quantum state.



Greg Robson, Wikipedia

Bosons

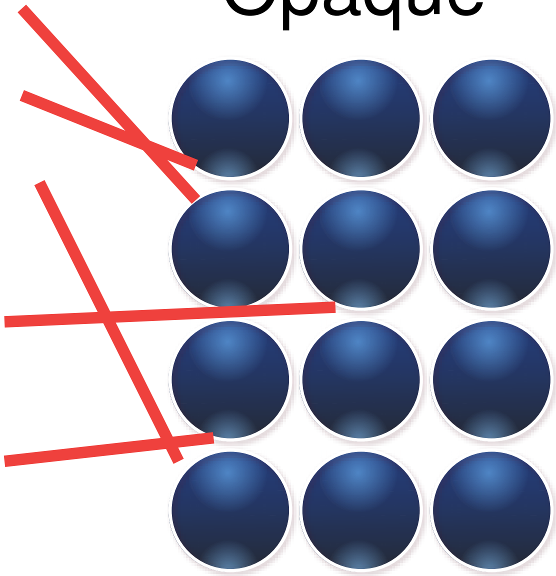
Don’t obey Pauli Exclusion Principle

- Particles in the same system *can* have the same quantum state

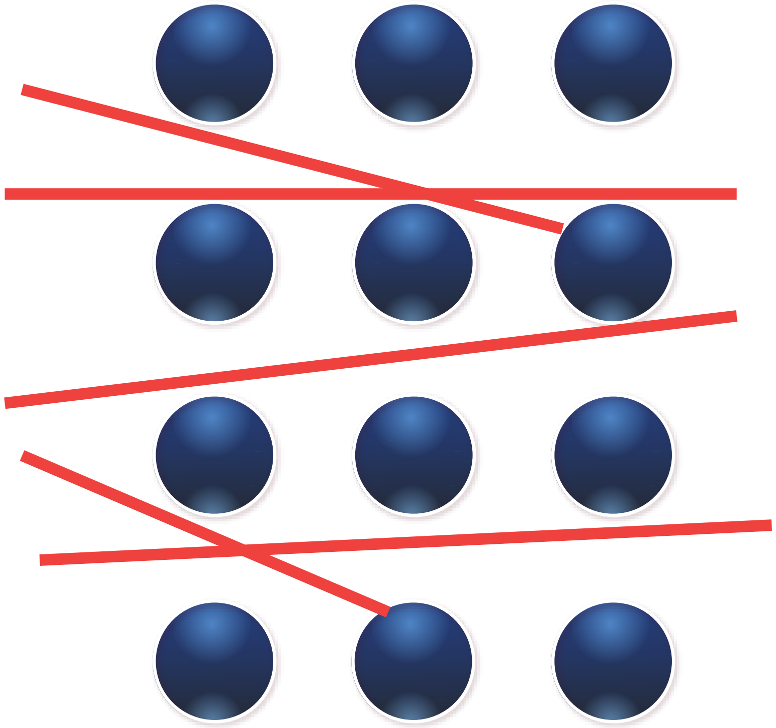
Photons are Bosons

So Then Why Are Some Materials Transparent?

Opaque



Transparent



So Then Why Are Some Materials Transparent?

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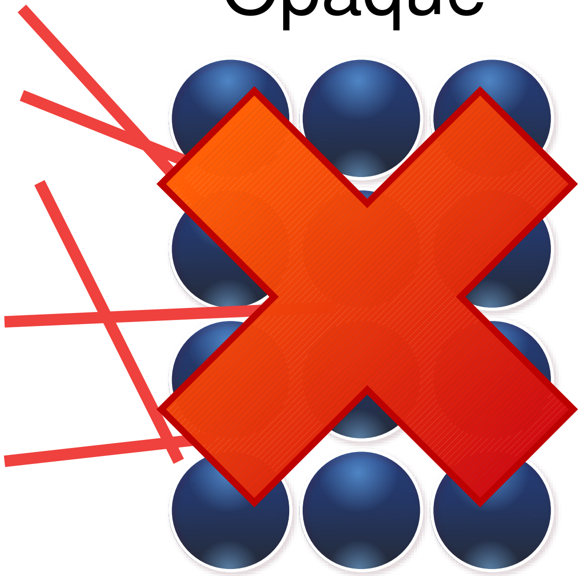
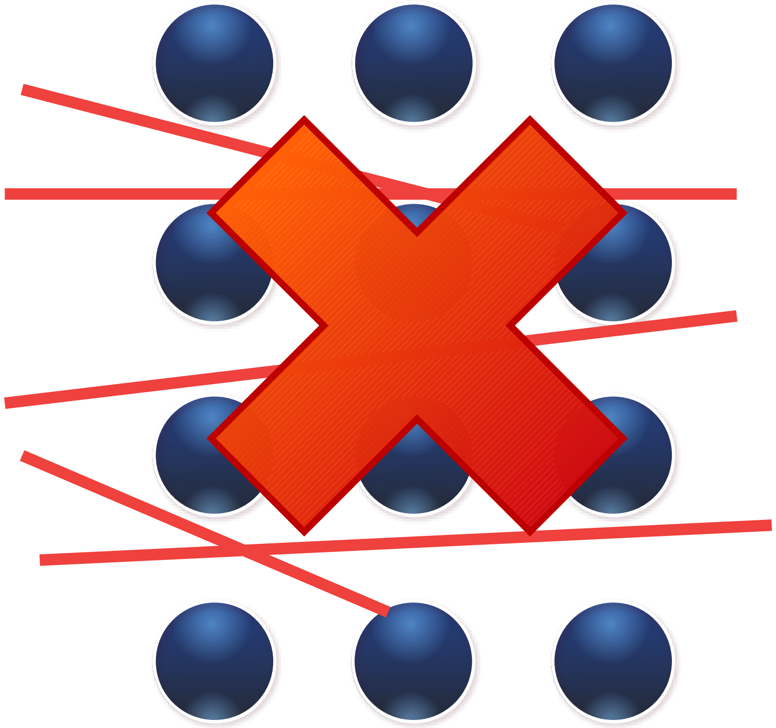
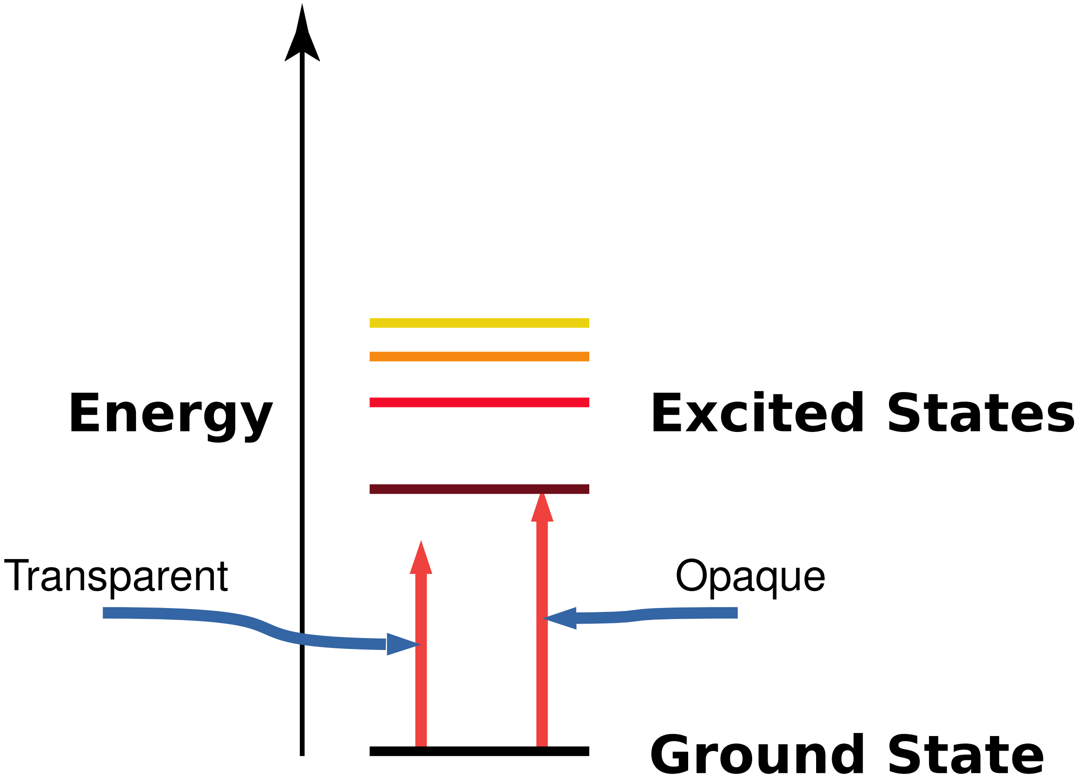


Transparent



It's Really Just Photons & Electrons



Energy

Excited States

Transparent

Opaque

Ground State

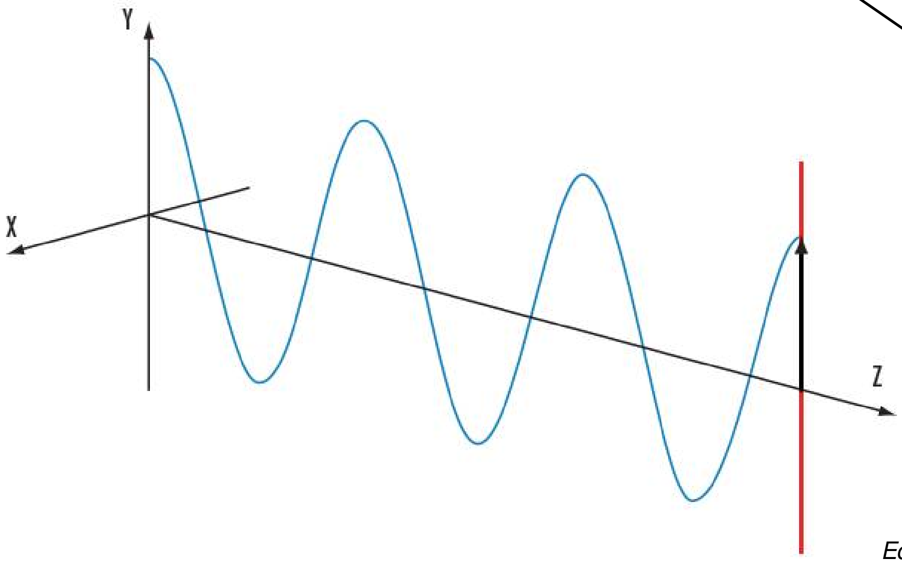
Rozzychan, Wikipedia

But photons also have another important property...

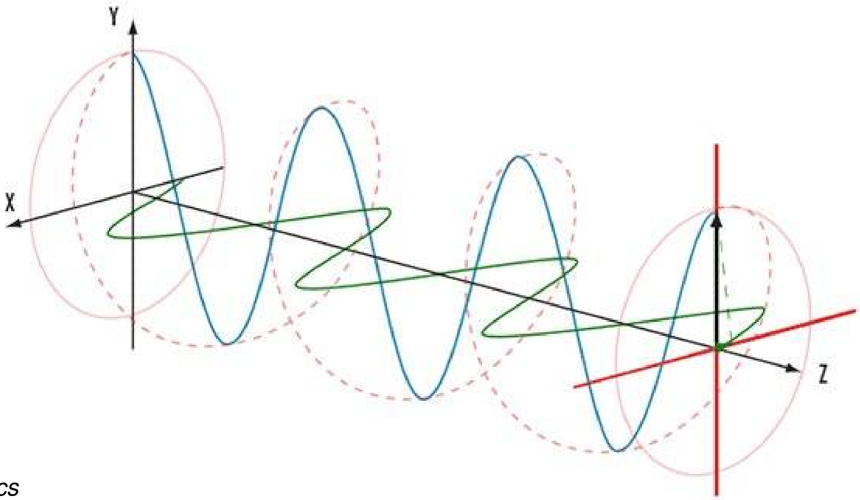
Polarization

Classically, a plane wave's orientation is called polarization.

Linear Polarization



Circular Polarization



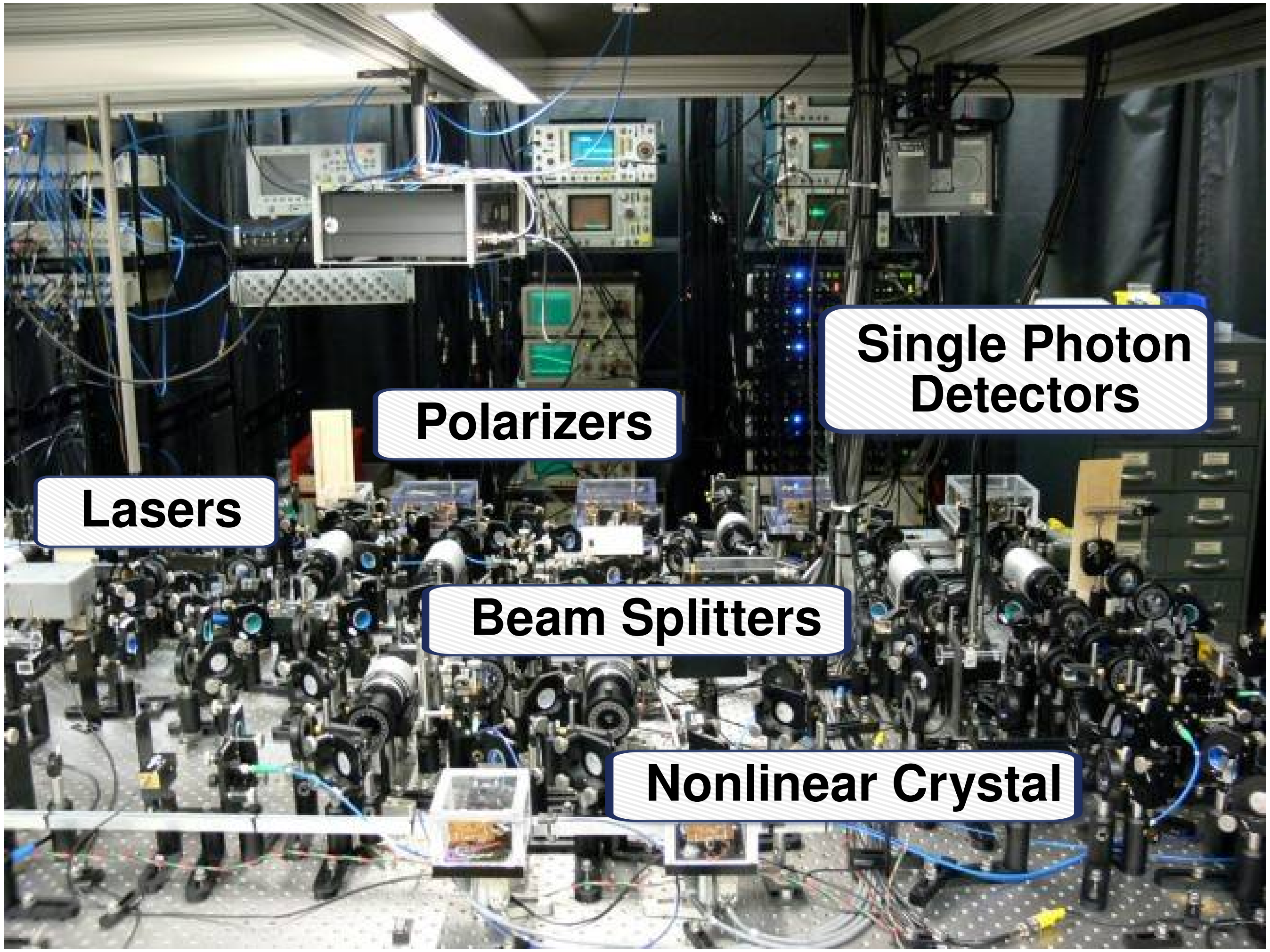
EdmundOptics

Information Encoding

Information is most commonly encoded in the polarization property, but spatial location can also encode information.

This leads to *dual-rail representation.*

Building Blocks of Optical Computing



UO Physics

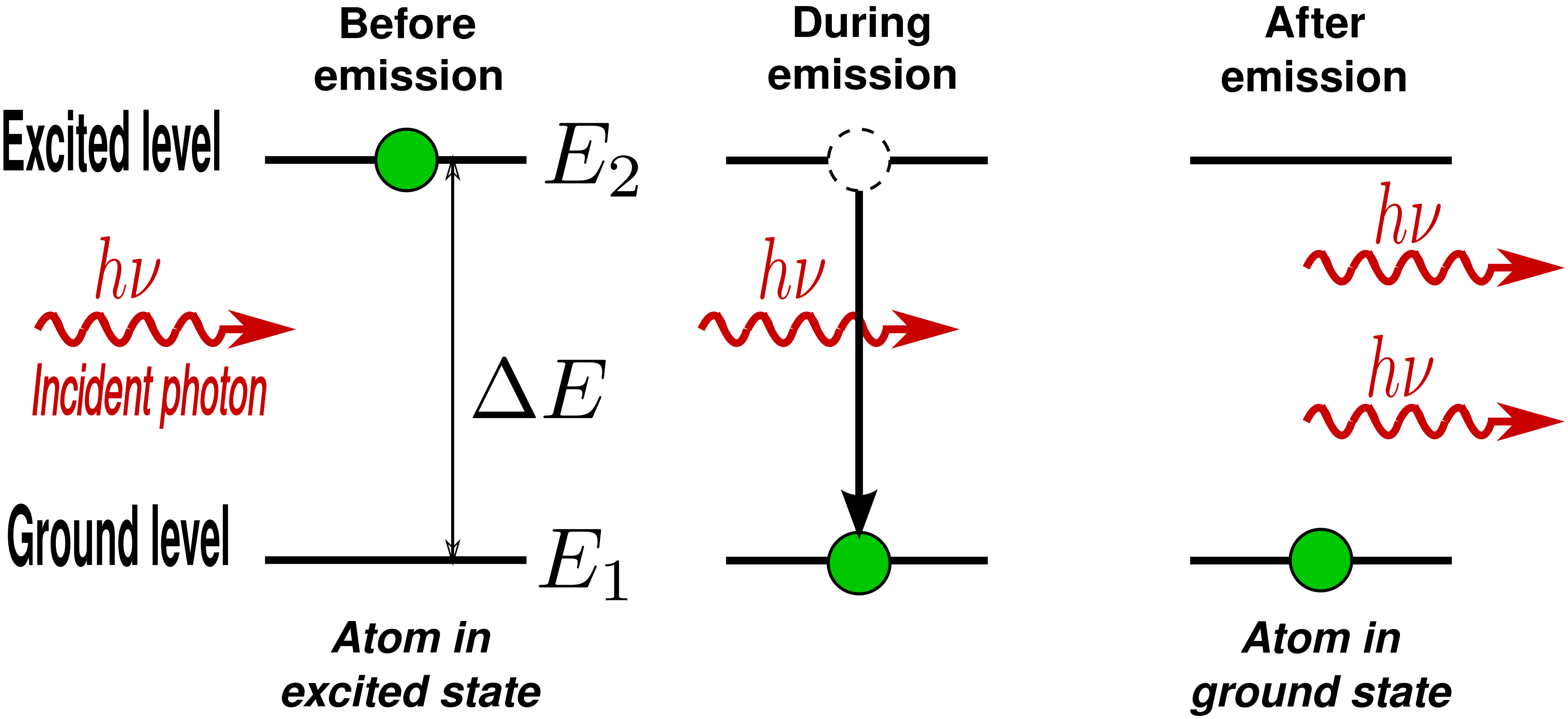
Polarizers

Changes the polarization of photons.

This can be exploited for many useful effects

Newport Corporation

Lasers – Where Photons Clone Themselves



$$E_2 - E_1 = \Delta E = h\nu$$

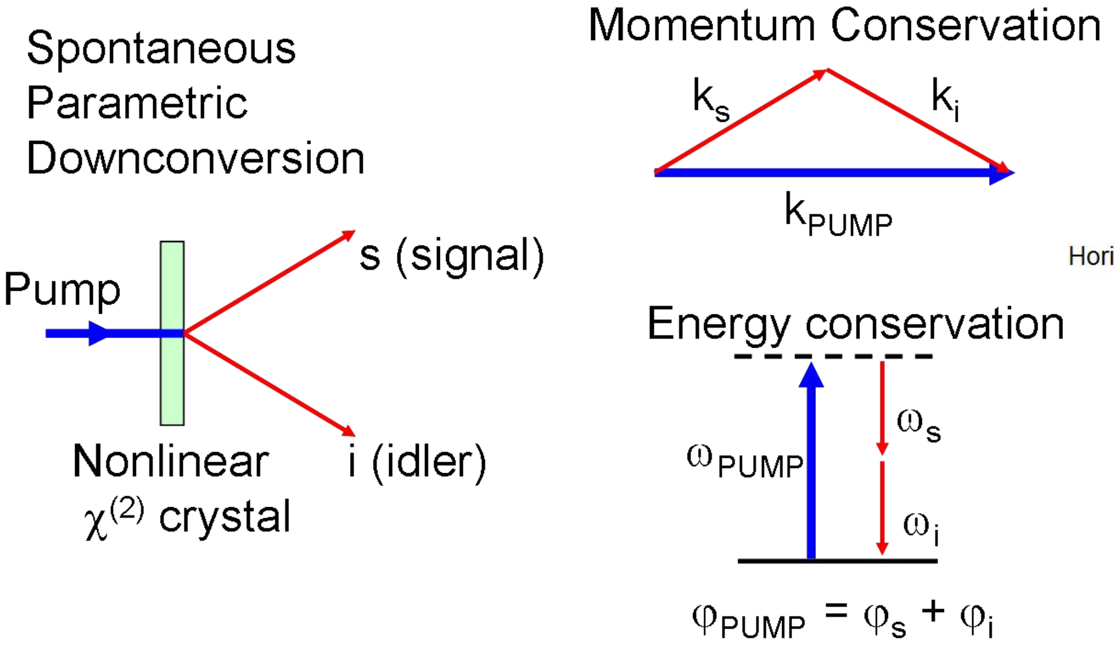
Lasers – Where Photons Clone Themselves

- Output: 1mW
- Wavelength: 630nm ●
- Photons per second: $$\frac{n}{s} = \frac{630nm}{hc} = 3.2 \times 10^{18}$$

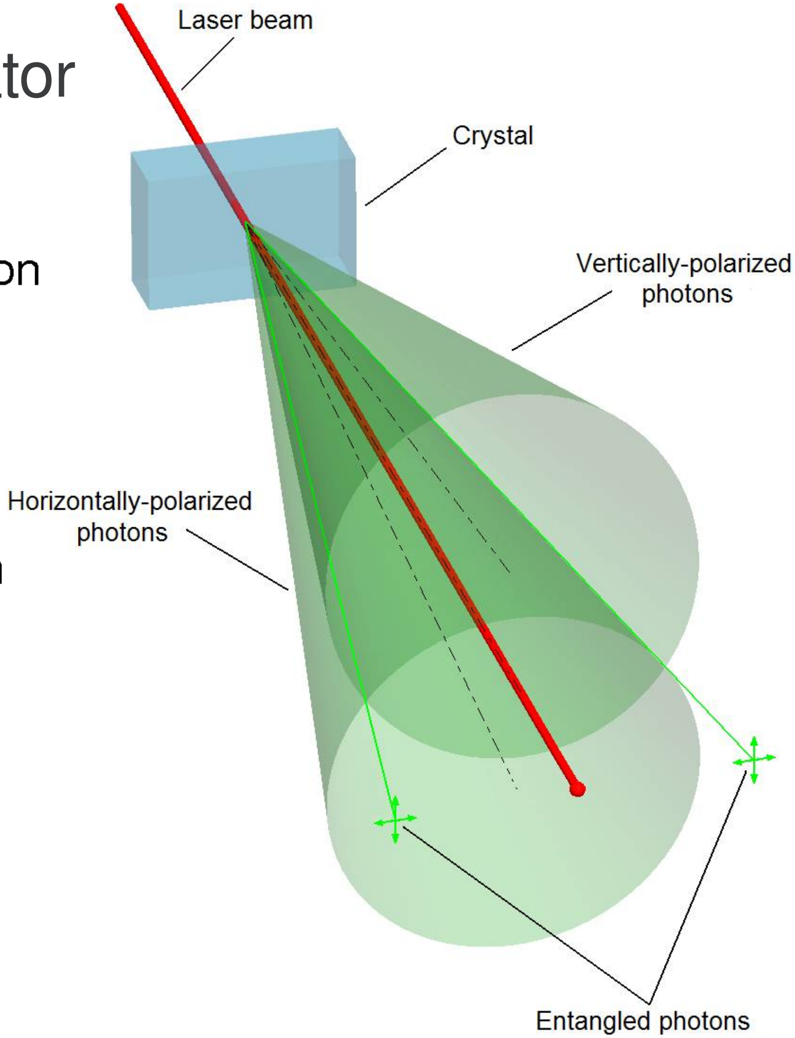
Output from a laser is coherent identical particles, although there is a small distribution of frequency and power.

Spontaneous Parametric Down-Conversion

Most common entanglement generator



J S Lundeen, Wikipedia

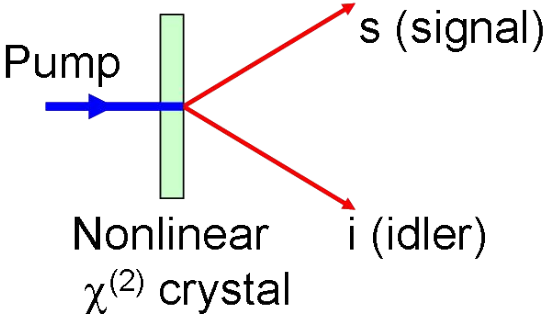


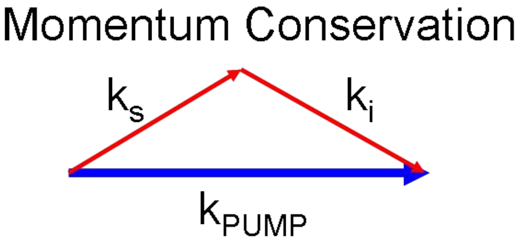
J-Wiki, Wikipedia

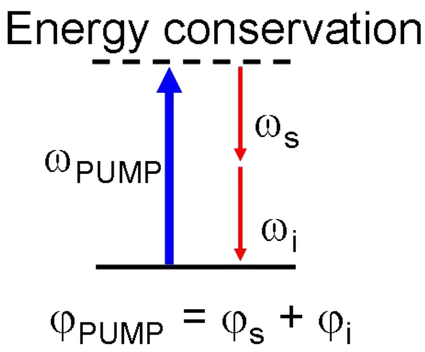
Spontaneous Parametric Down-Conversion

Most common entanglement generator

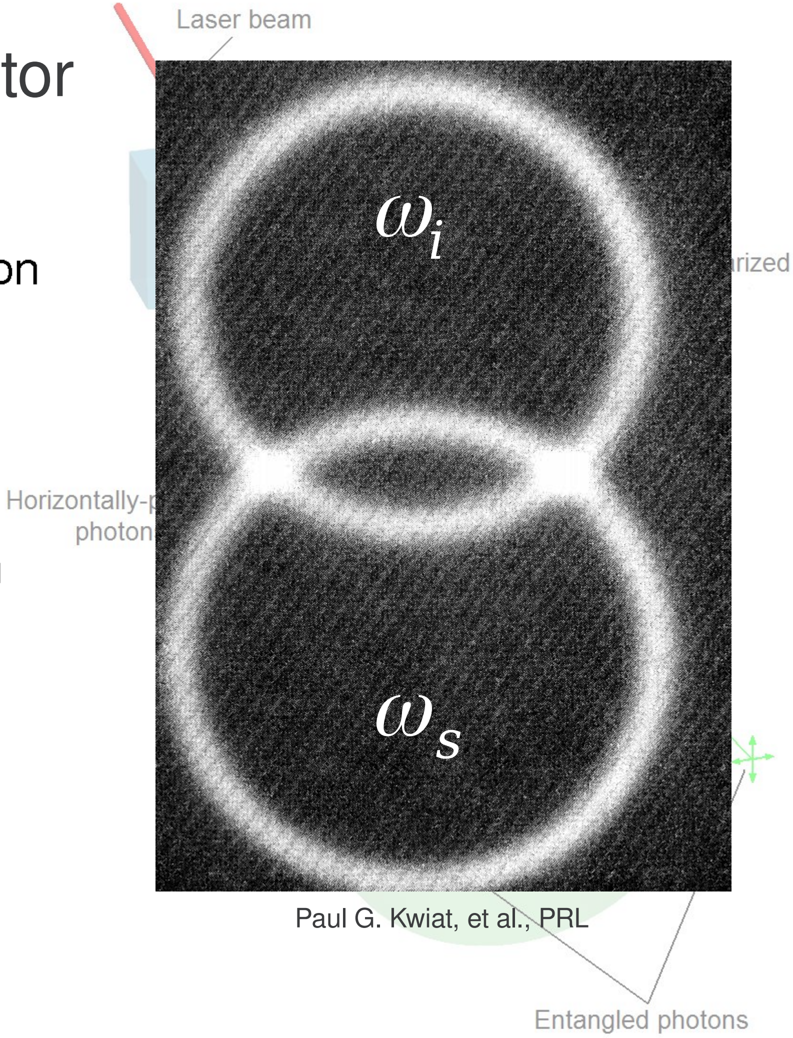
Spontaneous
Parametric
Downconversion







J S Lundeen, Wikipedia



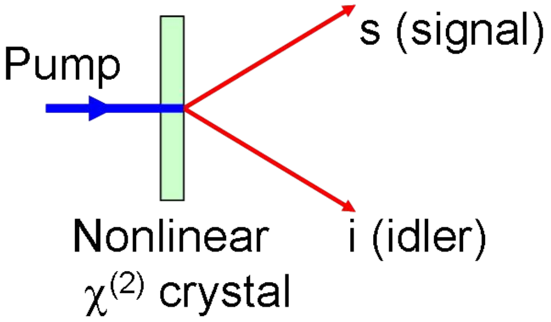
Paul G. Kwiat, et al., PRL

J-Wiki, Wikipedia

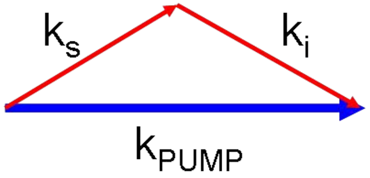
Spontaneous Parametric Down-Conversion

Most common entanglement generator

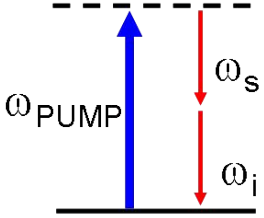
Spontaneous
Parametric
Downconversion



Momentum Conservation

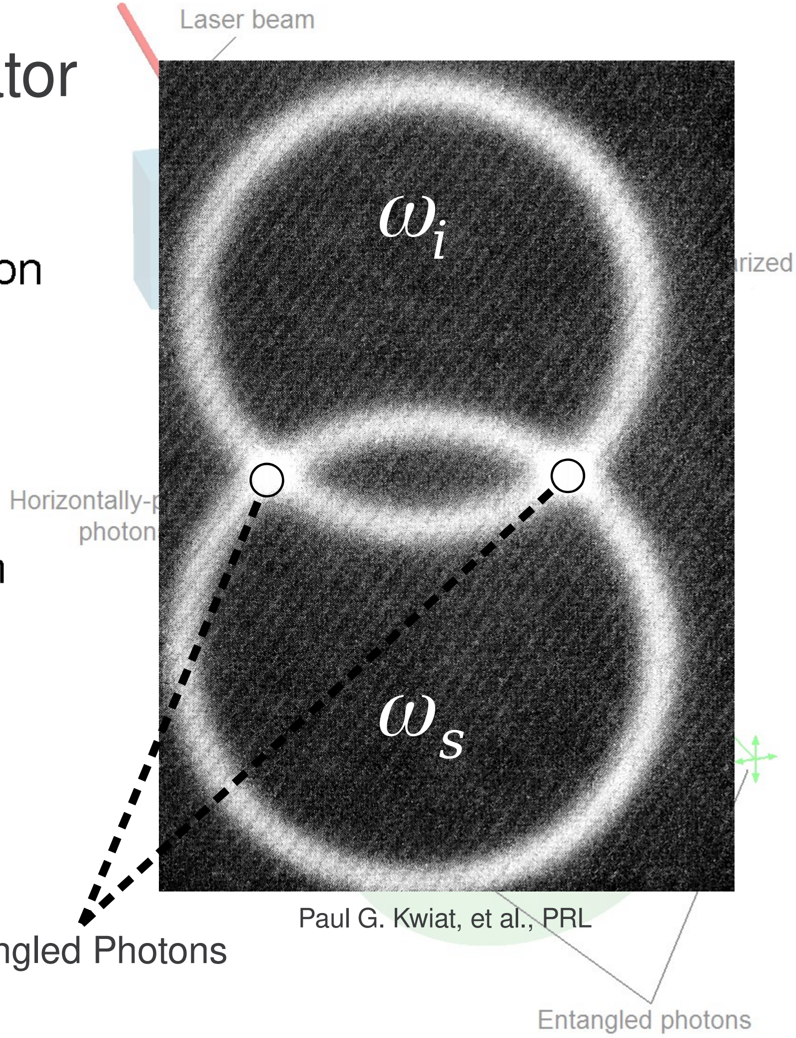


Energy conservation



$\varphi_{PUMP} = \varphi_s + \varphi_i$

J S Lundeen, Wikipedia



Paul G. Kwiat, et al., PRL

Entangled Photons

J-Wiki, Wikipedia

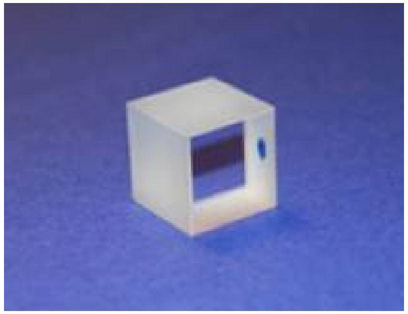
Spontaneous Parametric Down-Conversion

Requires a nonlinear crystal: index of refraction depends on pump intensity.

$$P(2) = I\chi^{(2)}$$

But in most materials, $\chi \sim 1 \times 10^{-15}$

Not unusual to see 1 pair generated from .05 to 10 billion pump photons.



Newlight Photonics Inc

Remember

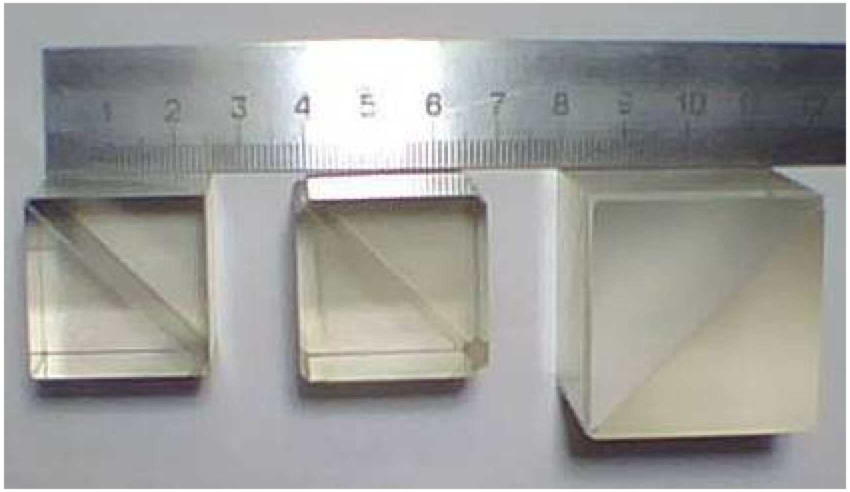
Inefficiencies are multiplicative.

Everything in an optical network needs to have high efficiencies.

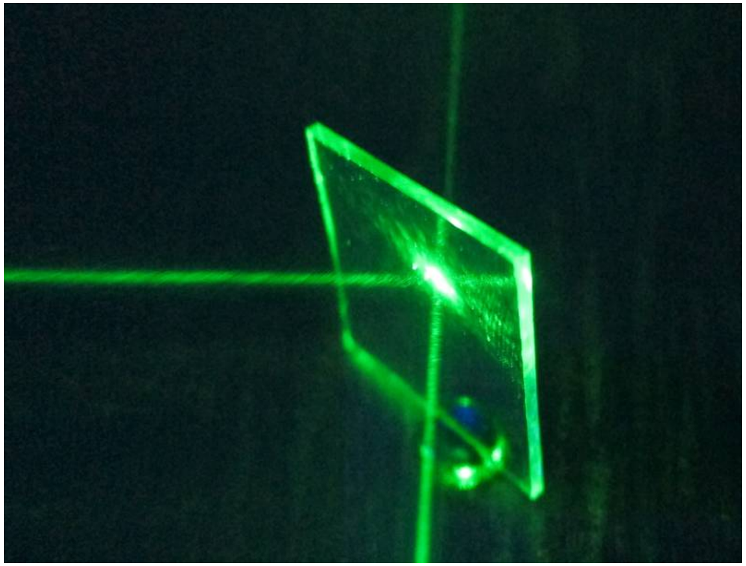
Bahmtec, Wikipedia

Beam Splitters

Ideally a Hadamard gate.



Tamasflex, Wikipedia



Zaereth, Wikipedia

Single Photon:

$$[\hat{B}_s] = \frac{1}{\sqrt{2}} \begin{bmatrix} T' & R \\ R' & T' \end{bmatrix}$$

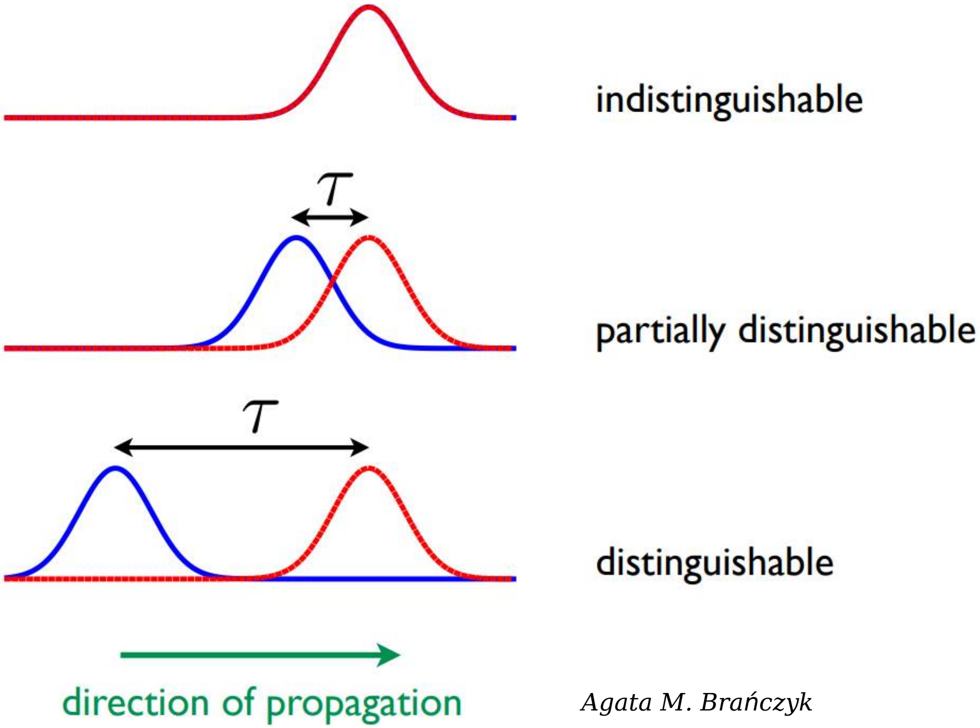
$$50\colon 50BS \downarrow$$

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 \\ i \end{bmatrix} = [\hat{B}_s] \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

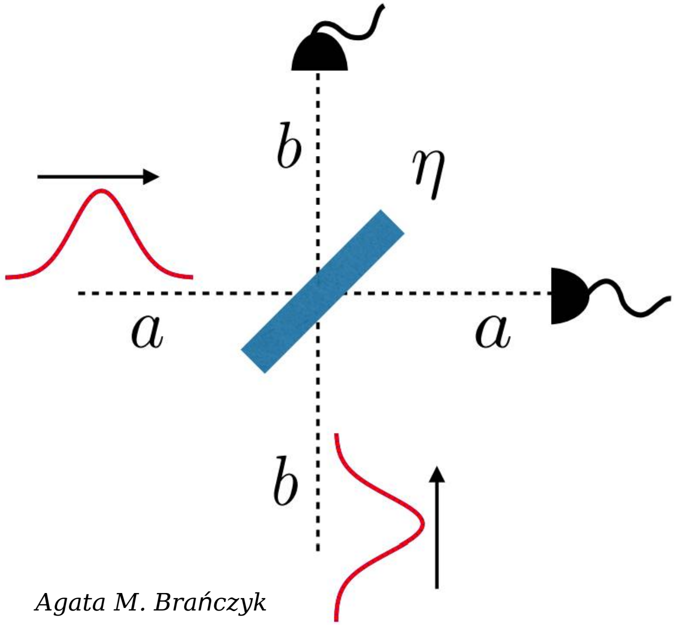
Can we use one with two photons?

Beam Splitters

Indistinguishable photons interfere when travelling through a beamsplitter.



Agata M. Brańczyk



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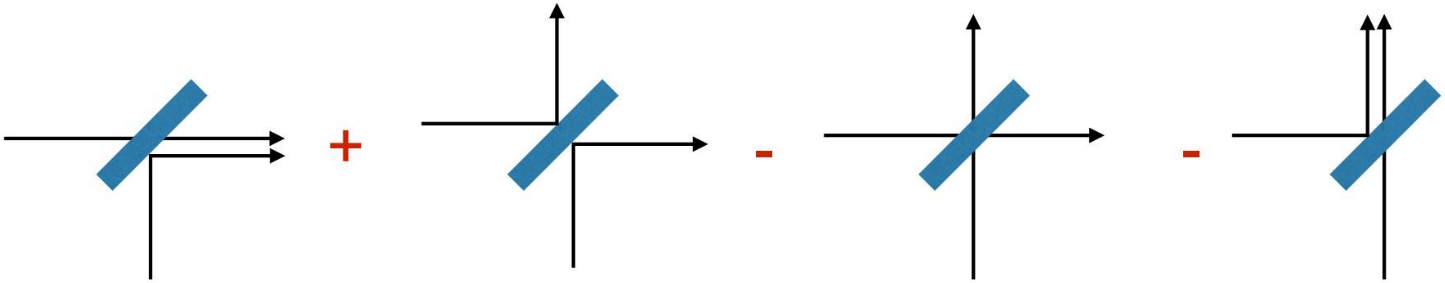
Hong-Ou-Mandel Interference

Indistinguishable photons interfere when travelling through a beamsplitter.



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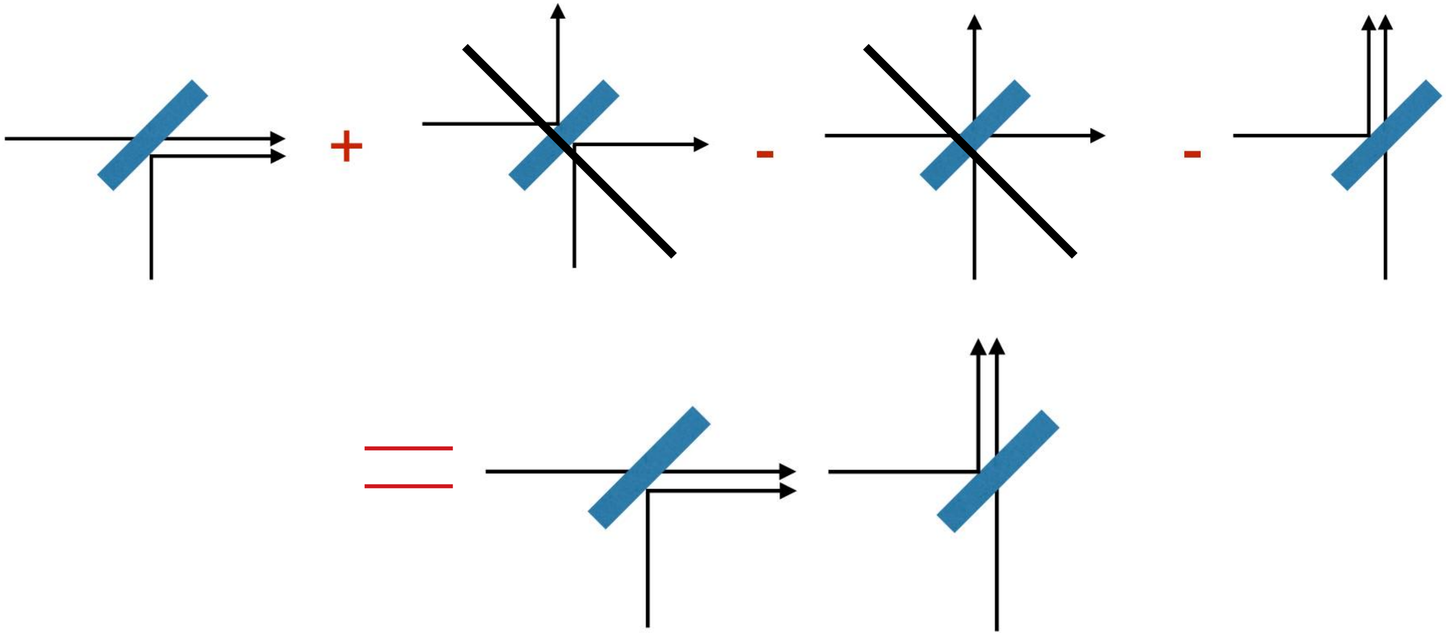

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Hong-Ou-Mandel Interference

$$|\Psi\rangle_{ab} = (\hat{a}_i^\dagger \hat{b}_j^\dagger) |0\rangle_{ab} = |1; i\rangle_a |1; j\rangle_b$$

$$\hat{a}^\dagger \xrightarrow{\hat{U}} \sqrt{1-\eta}\hat{a}^\dagger + \sqrt{\eta}\hat{b}^\dagger$$

$$\hat{b}^\dagger \xrightarrow{\hat{U}} \sqrt{\eta}\hat{a}^\dagger + \sqrt{1-\eta}\hat{b}^\dagger$$

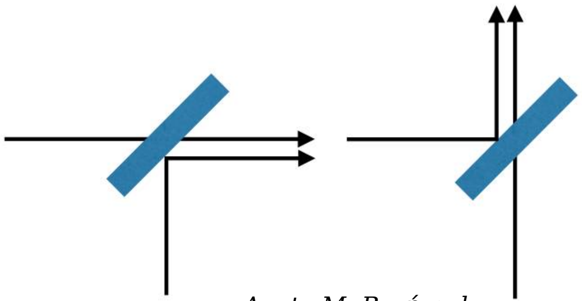
$$\begin{aligned} |\Psi'\rangle_{ab} &= \hat{U} |\Psi\rangle_{ab} \\ &= \hat{U}(\hat{a}_i^\dagger \hat{b}_j^\dagger |0\rangle_{ab}) \\ &= (\sqrt{1-\eta}\hat{a}_i^\dagger + \sqrt{\eta}\hat{b}_i^\dagger)(\sqrt{\eta}\hat{a}_j^\dagger - \sqrt{1-\eta}\hat{b}_j^\dagger) |0\rangle_{ab} \\ &= (\sqrt{\eta(1-\eta)}\hat{a}_i^\dagger \hat{a}_j^\dagger + \eta \hat{a}_j^\dagger \hat{b}_i^\dagger - (1-\eta)\hat{a}_i^\dagger \hat{b}_j^\dagger + \sqrt{\eta(1-\eta}\hat{b}_i^\dagger \hat{b}_j^\dagger) |0\rangle_{ab} \end{aligned}$$

$\boxed{\eta=0.5}$

$$|\Psi'\rangle_{ab} = \frac{1}{2}(\hat{a}_i^\dagger \hat{a}_j^\dagger + \hat{a}_j^\dagger \hat{b}_i^\dagger - \hat{a}_i^\dagger \hat{b}_j^\dagger - \hat{b}_i^\dagger \hat{b}_j^\dagger) |0\rangle_{ab}$$

$\boxed{\{i, j\} \rightarrow \{H, V\}}$

$$\begin{aligned} |\Psi'\rangle_{ab} &= \frac{1}{2}(\hat{a}_H^\dagger \hat{a}_H^\dagger + \hat{a}_H^\dagger \hat{b}_H^\dagger - \hat{a}_H^\dagger \hat{b}_H^\dagger - \hat{b}_H^\dagger \hat{b}_H^\dagger) |0\rangle_{ab} \\ &= (\hat{a}_H^\dagger \hat{a}_H^\dagger - \hat{b}_H^\dagger \hat{b}_H^\dagger) |0\rangle_{ab} \\ &= \frac{1}{\sqrt{2}}(|2; H\rangle_a - |2; H\rangle_b) \end{aligned}$$



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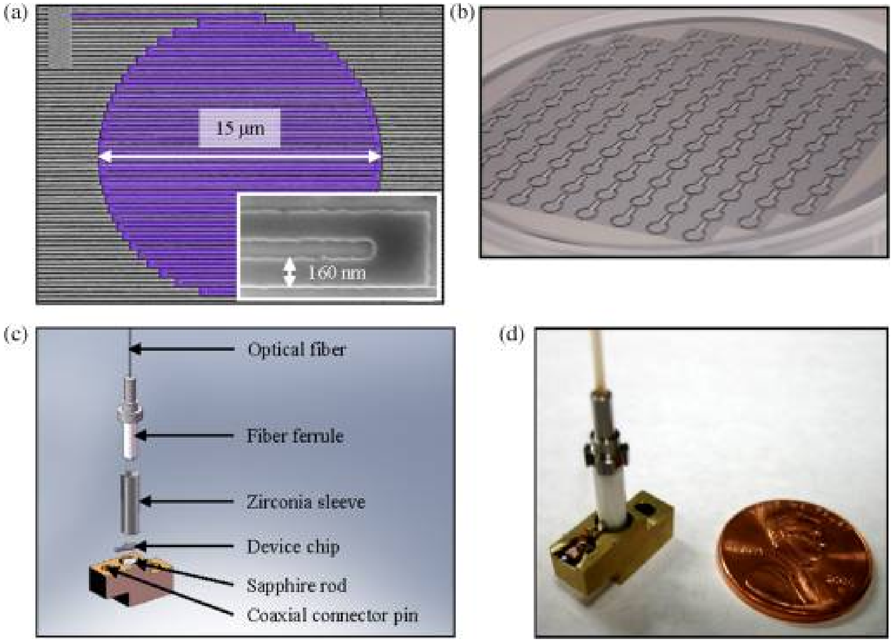
Single Photon Detectors

Nanowire

- Uncommon
- Expensive!
- Efficient ~ 90+%



Eric A. Dauler, et al. OE 5(3)

Excelitas Technology Corp.

Avalanche

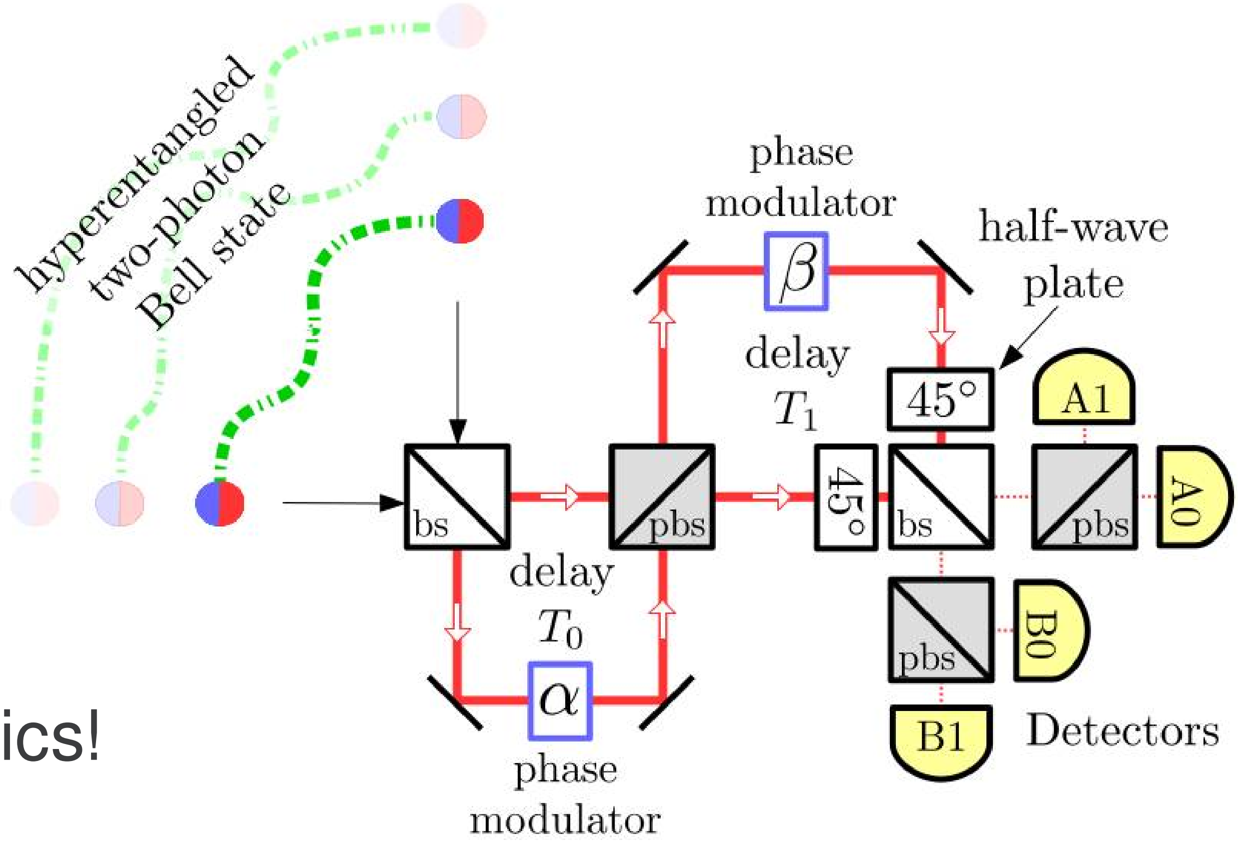
- Common
- Cheap (~$5k)
- Inefficient ~40+%

Deterministic Complete Bell-State Measurement

Combines

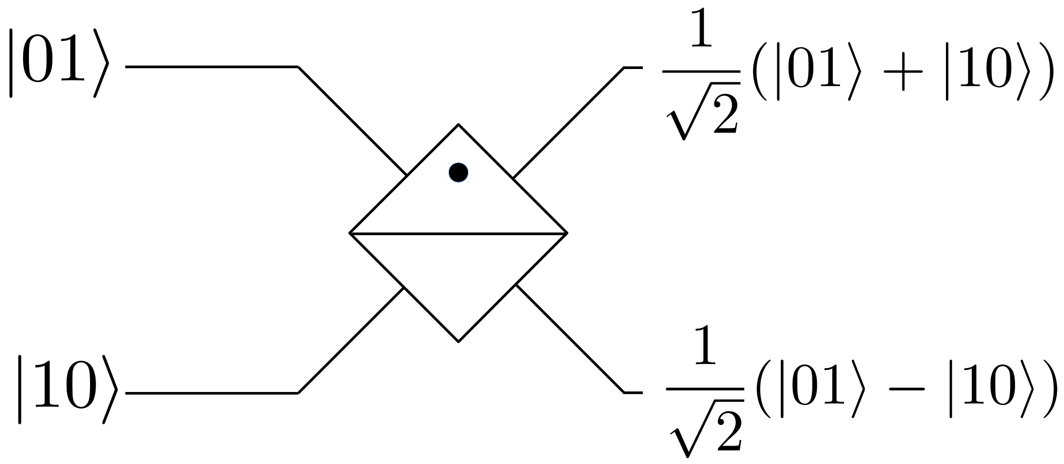
- Beam Splitters
- Polarizers
- HOM Effect
- SPDs

No nonlinear optics!



Brian Williams, et al. APS

Optical Hadamard Gate



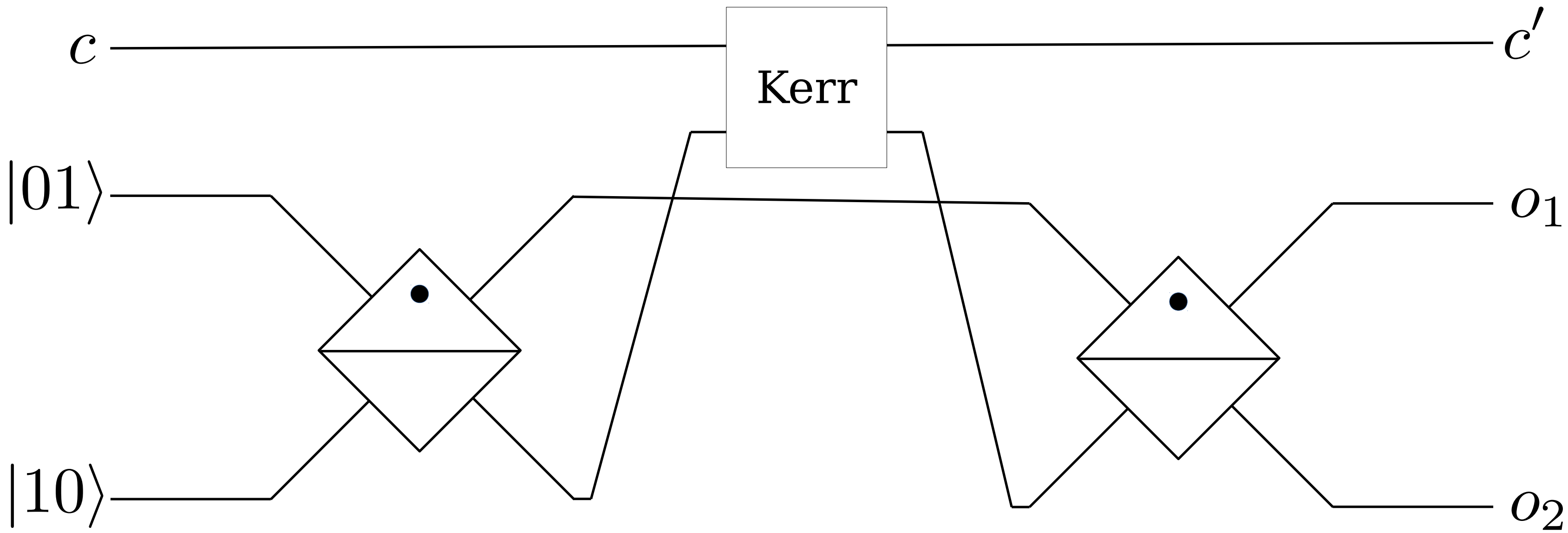
$|01\rangle$

$|10\rangle$

$\frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$

$\frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$

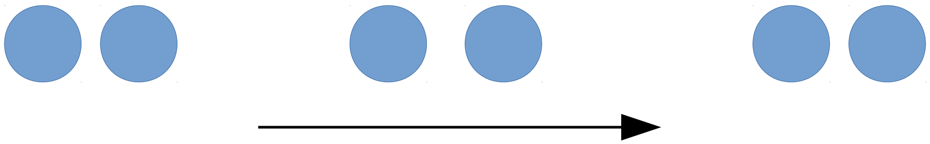
Nonlinear Optical Fredkin Gate



But Didn’t We Say That Kerr Media Are Inefficient???

Before 2001, poeple thought nonlinear components were required. But Knill, Laflamme and Milburn published their “KLM Protocol” stating a universal QC can be built with only linear optical components, single photon sources, and single photon detectors.

But it turns out this seems to be more complicated than before. Sometimes requires *photon bunching.*



History of Optical Computing

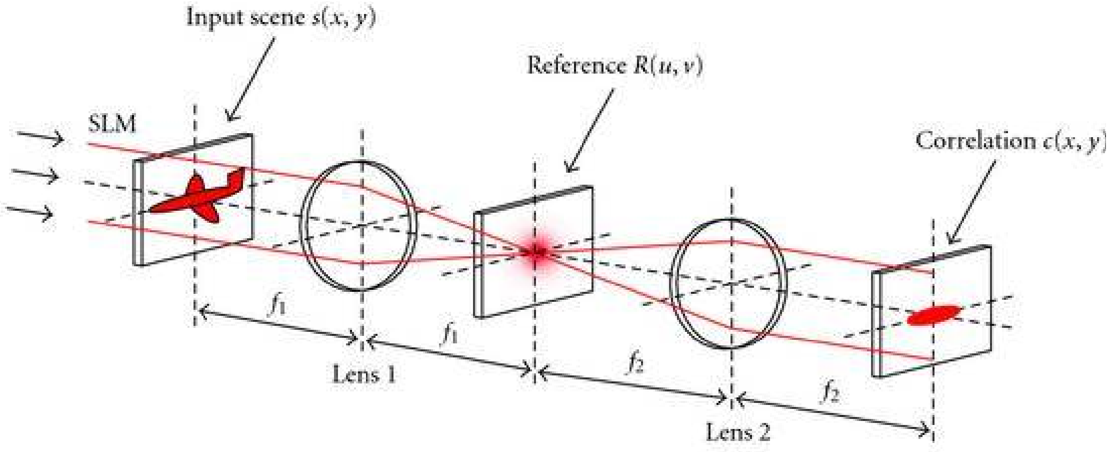
People previously thought nonlinear components were required, and an optical computer would be built out of optical logic gates (some of which we discussed).

Real time pattern recognition was thought to be most promising (1950s)

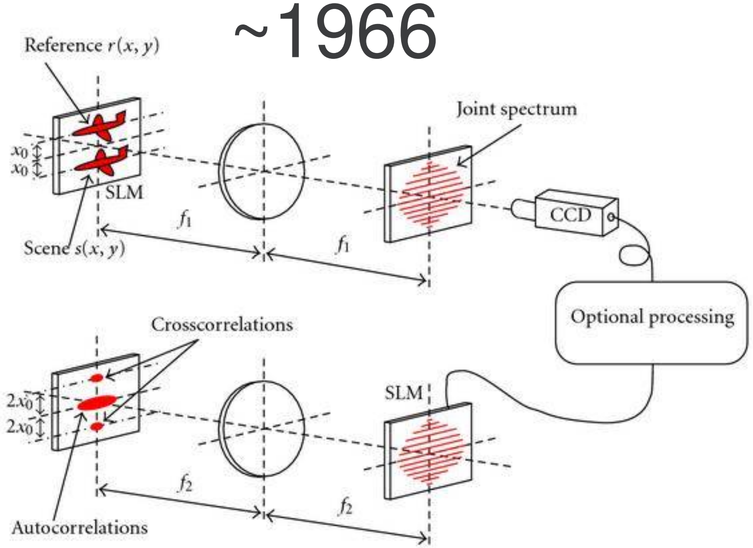
History of Optical Computing

Information carried by complex wave probabilities.

1953



~1966



Pierre Ambs, Advc. In Op. Tech. 2010

History of Optical Computing

As silicon control technology and manufacturing techniques evolved, they were integrated with optical computing.

The first successful coherent optical processor was for processing synthetic aperture radar data (1960).

Around this time an effort began to construct a general purpose universal optical computer.

Optical memory was researched, compared to core memory it seems *much* better.

History of Optical Computing

Golden age ran 20 years from 1984-2004.

Previous research machines were analog optical computers, but ~1995 digital OC was introduced in response to the growth of traditional computers.

Current Status of Optical Computing

Interest in optical computing has faded, no more major conferences or journals dedicated to the field.

Some work on optical correlators persists, some of the original pattern recognition algorithms are now implemented on conventional computers.

Nanotechnology and nanofabrication has renewed interest, even with talk about *biophotonics*.

Future of Optical Computing

Biophotonics and nanophotonics are somewhat popular, still waiting on a demonstration of a “killer app”

Seems unlikely traditional general purpose OC will replace conventional computers any time soon: too inefficient.

Special application accelerators for conventional computers may become the next GPGPUs.

Quantum Optical Coherent Ising Machine

- Ising Hamiltonion:

$$\mathcal{H}(\sigma) = -\sum_{\langle ij \rangle} J_{ij}\sigma_i\sigma_j - \mu \sum_j h_j \sigma_j$$

- An Ising machine solves an Ising problem:
  - Hamilton Cycles
  - Partitioning
  - Covering
  - Packing
  - Satisfiability
- This is similar to the types of problems the D-Wave machine solves

Conclusions

- Nonlinear components create interesting effects but are inefficient.
- Alternative optical computing frameworks eliminated the need for nonlinear components.
- But these frameworks seem to increase the number of components and overall complexity.
- Single photon computing won’t be here soon.
- But optical ising machines may be on the horizon, will act as an accelerator much like GPGPUs now.

End

Thanks!