How to Train Your Dragon

How to Train Your Photon

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Saturday Physics for Everyone, December 5, 2015
Today’s Program

10:15 Talk and demos

10:40 Raffle

10:45 Tour 1

11:05 Tour 2

During the tours, I will give another presentation
I'm beginning to see the light
Properties and Applications of Our Friendly Photons

Speaker: Professor Paul Kwiat
Date: Saturday, November 7, 2015
Time: 10:15 a.m.
Place: 141 Loomis Laboratory

The year 2015 is officially designated as the International Year of Light, and Light-based Technologies. In fact, light has long been a motivator for much of our scientific understanding of the world, and a key tool -- arguably the most important one -- for making further discoveries.

In this talk we will illuminate (!) the properties of light, with LOTS of dazzling demos, and discuss some of its application in science, technology, commerce, medicine, entertainment, life, etc.

Saturday Physics for Everyone 2015
Physics Illinois
University of Illinois at Urbana-Champaign
Light is a wave

Thus, like water waves, light can interfere.

http://abyss.uoregon.edu/~js/21st_century_science/lectures/lec13.html
Light is made of particles!

Einstein realized that light is made of particles in 1905

...for which he received the 1921 Nobel Prize
“for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect.”

The particles of light are called photons
Photons

- Photons are powerful tools
  - Photons carry information at the *speed of light*
  - Photons are quantum objects
    - Quantum computers
    - Simulators of quantum systems
    - Precision measurement
    - Secure communication

- Photons are hard to train!
  - Photons travel at the speed of light
    - Don’t stick around very long
  - Photons are quantum objects
    - Fragile
    - Affected by environment
    - Require special technologies
Counting photons

Electron
Excited

Photon

Avalanche!

Photon detected!

Audible “clicks” occur every 10,000 photons
We are surrounded!

• Billions of photons in a fully lit room

• But the photons are wild
  – Unruly colors
  – Going in all directions
  – Not working as a team

• We need the photons to be trained
  – We want a certain number of photons (1, 2,...)
  – In colors that are easy to use (detectable, good over long distances)
  – Going in one direction, from point A to point B
  – Working together, so changing one changes another
  – Arriving at the right time

http://www.lactamme.polytechnique.fr/Mosaic/descripteurs/Galerie_QuantumMechanics.FV.html
How do you get photons with the right properties?

First, create the right environment.
Choose materials that enable photons to interact

Materials that allow up to three or four photons to exchange energies at once

E.g. crystals (three photons), glass (four photons)
Lasers are unidirectional, coherent and bright.
Their properties (color, duration) influence the properties of the photons we create.
But be gentle

You can use a laser to create photons, but you don’t want too many, so you keep the laser intensity low.
You must give to receive

Energy is conserved

To get photons of a certain energy (color), photons with the same total energy are sacrificed.

Example: two orange photons $\rightarrow$ a green and a red photon

Same for momentum.
Example: generating photons in optical fiber

- The fiber guides low-intensity laser light
- The light interacts with the glass of the fiber
- Two orange photons are sacrificed in exchange for a green and red photon

- The photons now
  - Come in pairs
  - Have controlled colors
  - Have a controlled direction and shape

- But they don’t work together yet
Even a single photon can interfere with itself!

Path 1  Path 2
Atomic, Molecular & Optical Physics & Quantum Information

Kwiat
DeMarco
Gadway
Lorenz

4 experimental research groups
2 postdoctoral researchers
23 graduate students
11 undergraduate researchers

http://physics.illinois.edu/research/qi.asp
Kwiat Group

Paul Kwiat (2001-present)
Bardeen Professor of Physics

http://research.physics.illinois.edu/QI/Photonics/

• Develop resources for optical quantum information processing
  – single- and entangled-photon sources
  – high efficiency detectors
  – quantum memories

• For applications including
  – quantum cryptography
  – quantum teleportation
  – Fundamental science
    • trying to understand quantum 'nonlocality'
    • the ultimate limits of quantum measurements
The coldest substances in the universe are gases cooled using lasers and magnets to temperatures just billionths of a degree above absolute zero.

Creates ultracold gases and traps them in crystals formed from light.

Uses these “optical lattices” to explore one of the frontiers of science: understanding how many interacting, quantum particles form exotic phases of matter like superconductors.
Use ultracold atomic gases -- samples of atoms trapped in vacuum and cooled by lasers to temperatures and densities about a billion times lower than those found in air.

Use ultracold atomic gases as quantum simulators of other physical systems that are poorly understood and/or difficult to experiment on directly.

Study emergent behavior in collections of interacting particles, and we currently investigate topological systems that feature robust transport properties.
Lorenz Group

- Engineer the properties of single photons and entangled photon-pairs.
- Build **quantum memories** to store and retrieve photons.
- Use photons’ **interaction with matter** to study:
  - How energy moves from one form to another in materials and
  - How thin films of ferromagnets can be magnetized by electric currents.
Raffle time!
Tours

- One tour per person
- CAUTION! Do not touch the training equipment. Never look directly at a laser beam.
- When the tour is over, come back here for 2nd half of presentation
- Second tour is at 11:05

Have fun!
Even a single photon can interfere with itself!

The two pathways can correspond to two polarizations

Path 1: photons are vertically polarized
Path 2: photons are horizontally polarized
Superposition

• A photon can be vertically *and* horizontally polarized
• If we check, it will be in only one of the states

• If we have two photons, we can *entangle* the states such that knowing about one photon tells us about the other
If I check one photon, it will end up in just one state, causing the other photon to also be in just one state.

But how do you get them to be entangled?
Generation of polarization entanglement

Twisted by 90°

Fiber loop

PBS

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Generation of polarization entanglement
Trained Photons

What we’ve achieved so far:

- We want a certain number of photons (1, 2,...)
- In colors that are easy to use (detectable, good over long distances)
- Going in one direction, from point A to point B
- Working together, so changing one changes another
Hi Virginia,

- There is no indication of eavesdropping
- Security relies on computational difficulty of determining the key
Quantum Key Distribution

$\left[ \begin{pmatrix} \uparrow & \uparrow \end{pmatrix} + \begin{pmatrix} \rightarrow & \rightarrow \end{pmatrix} \right]$}

Security is guaranteed by the laws of quantum physics!

- Eavesdropping without being detected is impossible because measurement changes the correlations.
Entangled photon source
Quantum memory
Entanglement swapping

Long-Distance QKD

Entanglement is subject to dissipation
- Loss is exponential over distance
  → Use repeater stations
Quantum Memory

Like computer memory
Store and retrieve 0 or 1
...and superpositions
Thank you!

- Inga Karliner
- Toni Pitts
- Peter Adshead
- Paul Kwiat
- Brian DeMarco
- Bryce Gadway
- Erika Smith
- Postdocs
- Graduate students
- Undergraduates

- Thank You!