Introduction to entanglement

Making entanglement in the lab
Quantum teleportation

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Quantum states describing more than one system can be entangled

System A (a photon)
System B (another photon)

$|\Psi\rangle_{AB}$ = Two-photon state of A and B

- States that can be written $|\Psi\rangle_{AB} = |\varphi^1\rangle_A|\varphi^2\rangle_B$ are **separable**
  - **Example:** $|\Psi\rangle_{AB} = |H\rangle_A|V\rangle_B$

- States that <u>cannot</u> be written this way are **entangled**
  - **Example:** $|\Psi\rangle_{AB} = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + |V\rangle_A|H\rangle_B)$

Measurement outcomes are *random* and *correlated*

$$|\Psi\rangle_{\mathrm{AB}} = \frac{1}{\sqrt{2}}\left(|H\rangle_{\mathrm{A}}|V\rangle_{\mathrm{B}} + |V\rangle_{\mathrm{A}}|H\rangle_{\mathrm{B}}\right)$$

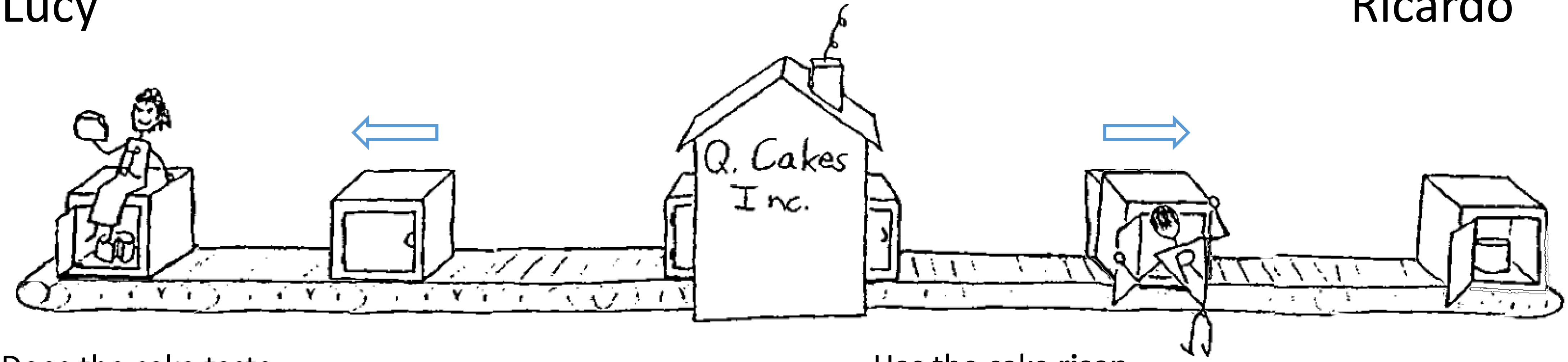
- 50% chance to measure H or V for either photon (random)
- But the photons always have orthogonal polarization (correlated)

But classical things can be random and correlated too… what’s special about entanglement?

Quantum cakes

Lucy

Ricardo



Does the cake taste **good** or **bad**?

Has the cake **risen** or **not risen** early?

Only one measurement can be made on any particular cake!

Lucy and Ricardo randomly decide which measurement to make on each cake, and record their results.

1. **They both check their ovens midway**
   - 9% of the time, both cakes **rise early** (the rest of the time, only one or neither does)
2. **One checks midway and the other waits**
   - Lucy's cake **rises early** → Ricardo's tastes **good**
   - Ricardo's cake **rises early** → Lucy's tastes **good**
3. **They both wait**
   - Do the cakes taste **good** or **bad**?

When they both check midway…

9% of the time, both cakes **rise early**

Whenever Lucy’s cake **rises early**, Ricardo’s cake tastes **good**

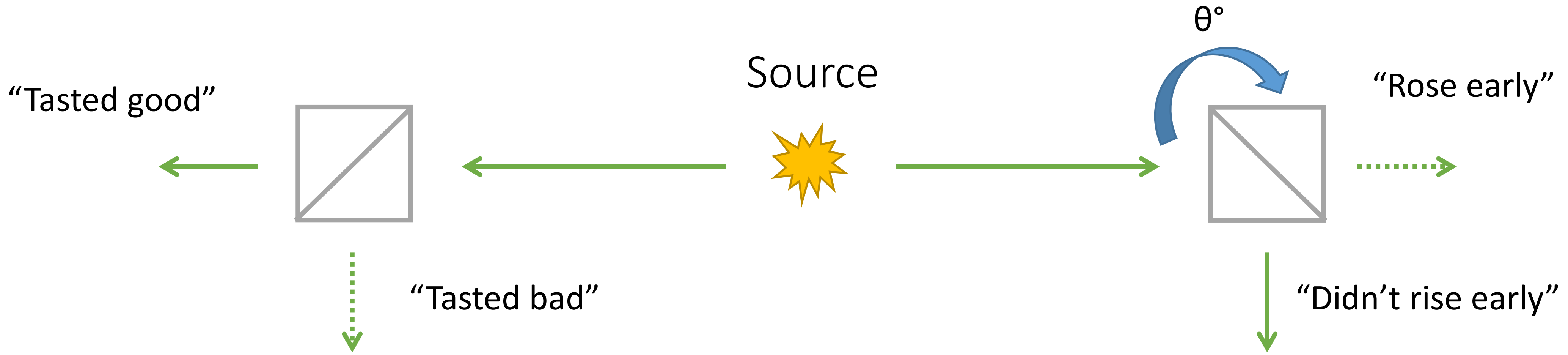
Whenever Ricardo’s cake **rises early**, Lucy’s cake tastes **good**

When they both wait…

How often do both cakes taste good?

Both cakes *never* taste good!

This experiment isn't really possible with cakes, but it is possible with photons



Tasted good = 0° (horizontal)
Tasted bad = 90° (vertical)

Rose early = -50.8°
Didn't rise early = 39.2°

Summary: quantum mechanics violates **local realism**, and we can prove it (with a Bell test or something like it)

Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres

B. Hensen, H. Bernien, A. E. Dréau, A. Reiserer, N. Kalb, M. S. Blok, J. Ruitenberg, R. F. L. Vermeulen, R. N. Schouten, C. Abellán, W. Amaya, V. Pruneri, M. W. Mitchell, M. Markham, D. J. Twitchen, D. Elkouss, S. Wehner, T. H. Taminiau & R. Hanson

A strong loophole-free test of local realism

Lynden K. Shalm,[1] Evan Meyer-Scott,[2] Bradley G. Christensen,[3] Peter Bierhorst,[1] Michael A. Wayne,[3,4] Martin J. Stevens,[1] Thomas Gerrits,[1] Scott Glancy,[1] Deny R. Hamel,[5] Michael S. Allman,[1] Kevin J. Coakley,[1] Shellee D. Dyer,[1] Carson Hodge,[1] Adriana E. Lita,[1] Varun B. Verma,[1] Camilla Lambrocco,[1] Edward Tortorici,[1] Alan L. Migdall,[4,6] Yanbao Zhang,[2] Daniel R. Kumor,[3] William H. Farr,[7] Francesco Marsili,[7] Matthew D. Shaw,[7] Jeffrey A. Stern,[7] Carlos Abellán,[8] Waldimar Amaya,[8] Valerio Pruneri,[8,9] Thomas Jennewein,[2,10] Morgan W. Mitchell,[8,9] Paul G. Kwiat,[3] Joshua C. Bienfang,[4,6] Richard P. Mirin,[1] Emanuel Knill,[1] and Sae Woo Nam[1]

Illinois researchers help prove "spooky action at a distance" is really real

By Laura Ost, NIST
November 16, 2015

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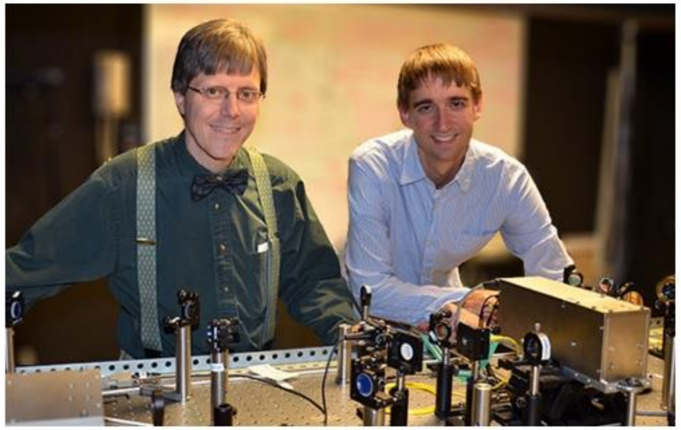
Long-sought proof of quantum theory closes all loop holes



Professor of Physics Paul Kwiat and graduate student Brad Christensen in the lab

Einstein was wrong about at least one thing: There are, in fact, "spooky actions at a distance," as now proven by researchers at the National Institute of Standards and Technology (NIST), including several members of physicist Paul Kwiat's research group at the University of Illinois at Urbana-Champaign.

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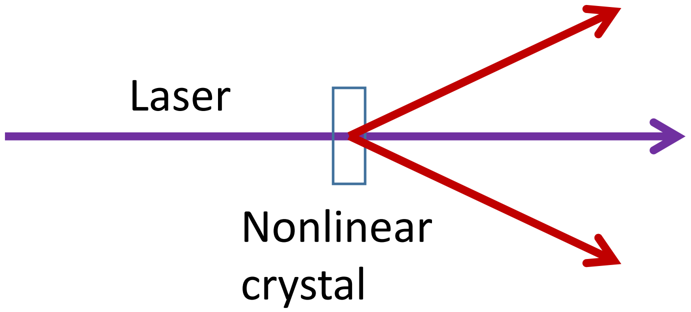
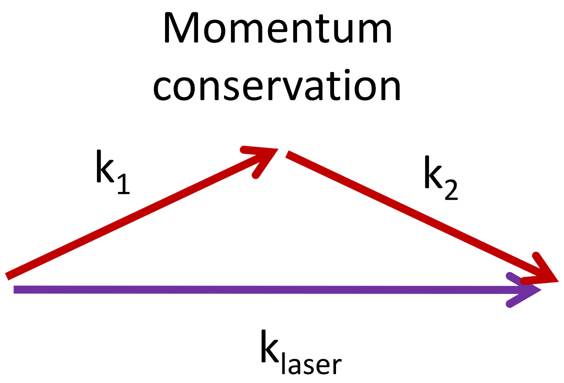
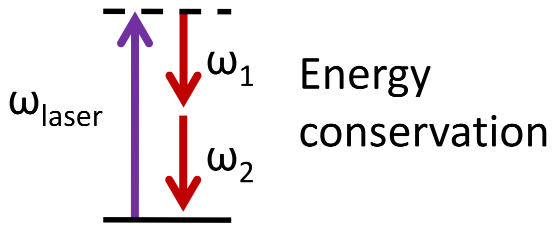
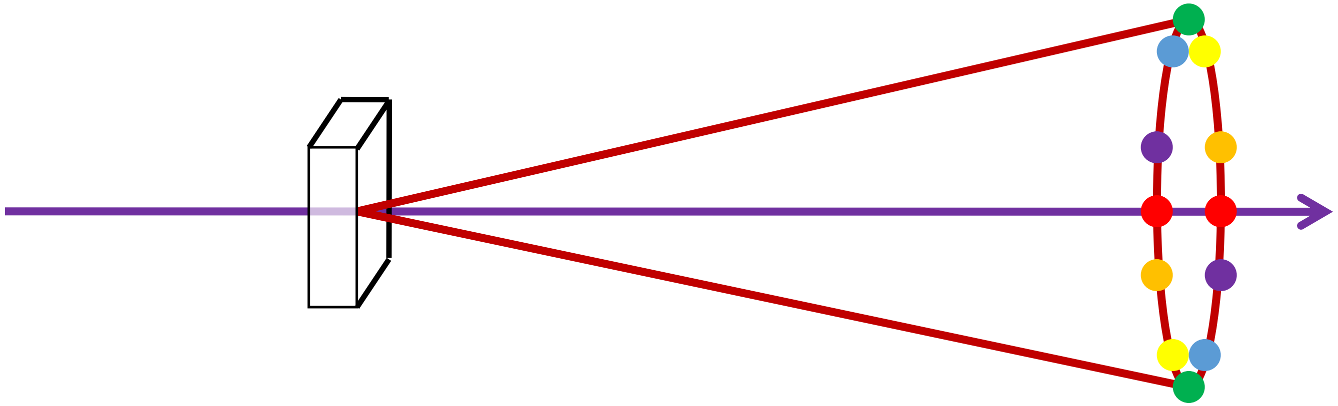
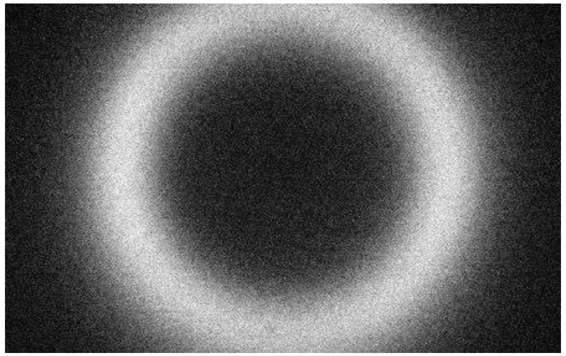
Downconversion produces pairs of photons





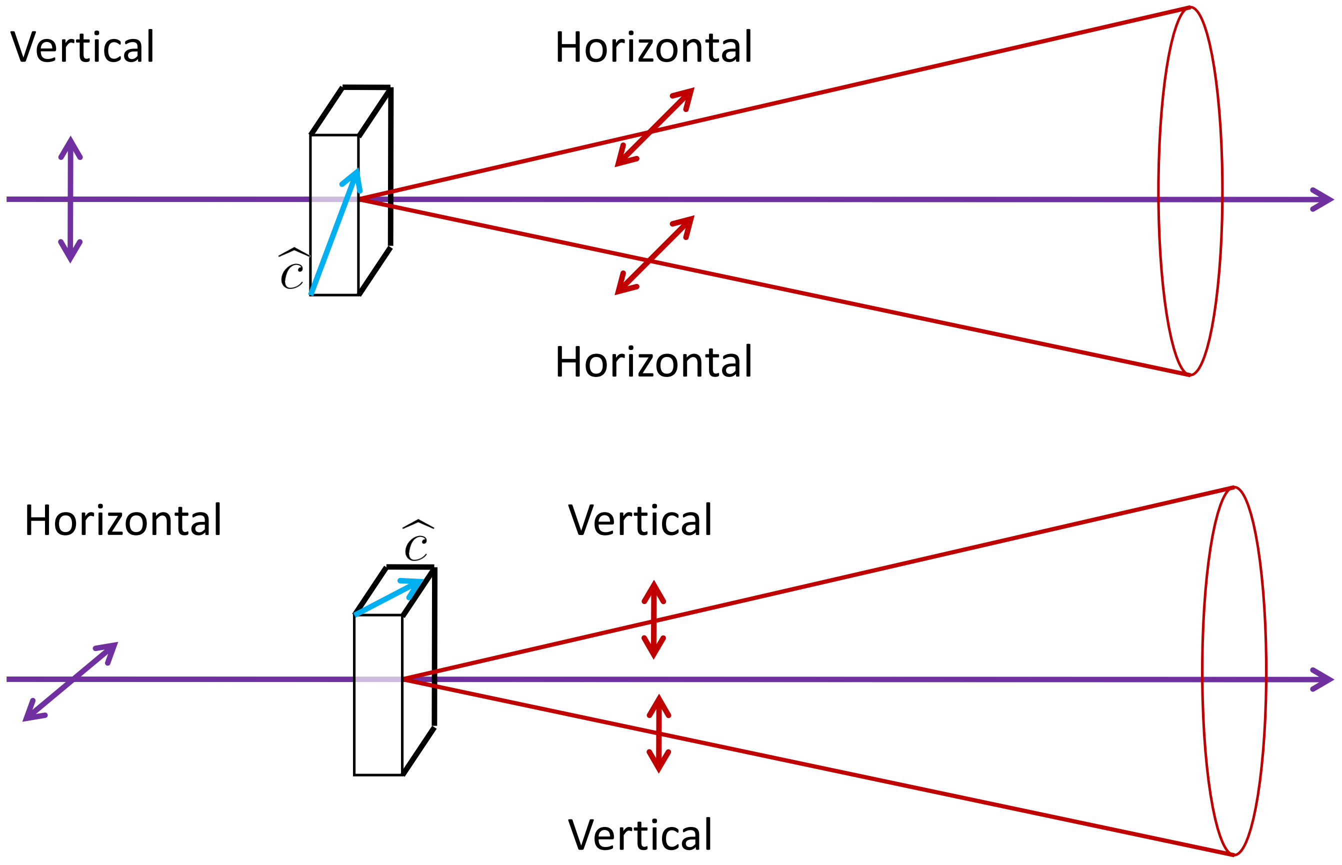




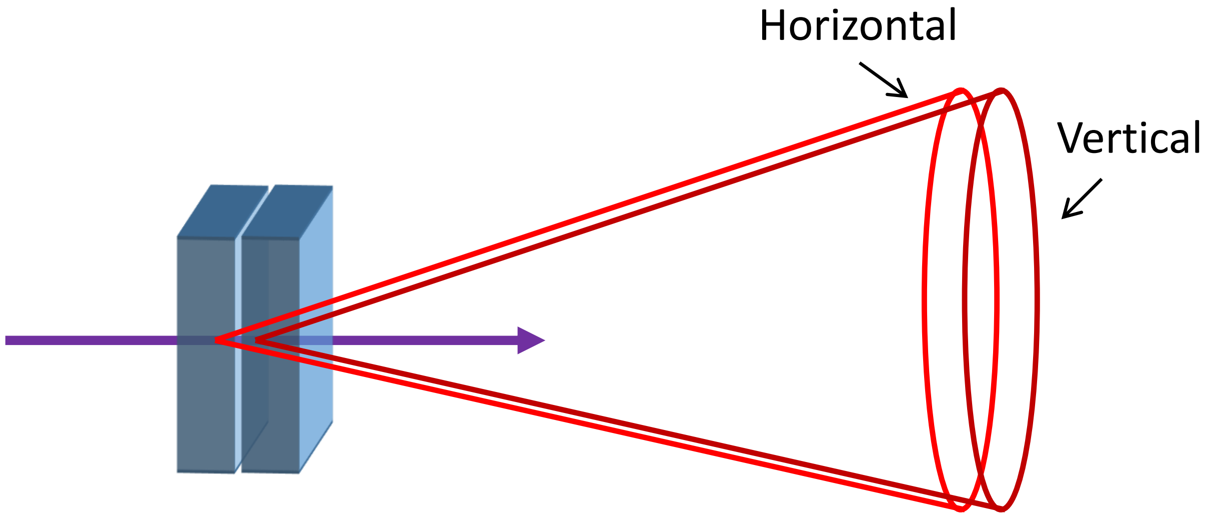


Source: David Guzman, Universidad de los Andes

Downconversion is polarization-dependent



Two crystals can create polarization entanglement



$|V\rangle \rightarrow |H\rangle|H\rangle$

$|H\rangle \rightarrow |V\rangle|V\rangle$

Superposition → Polarization entanglement

$|H\rangle + e^{i\varphi}|V\rangle \rightarrow |V\rangle|V\rangle + e^{i\varphi}|H\rangle|H\rangle$

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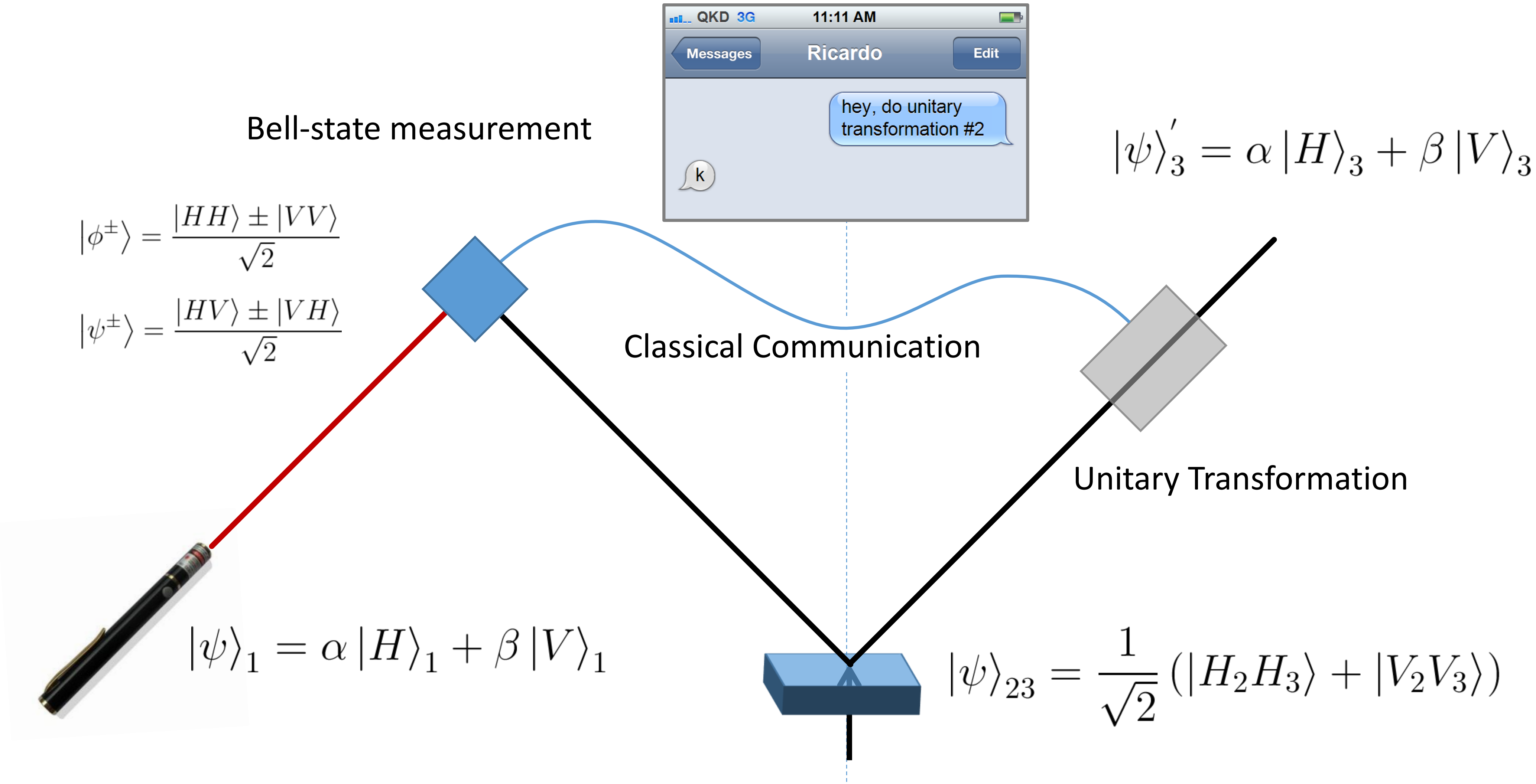
Lucy wants to communicate an unknown quantum state to Ricardo



Summary

- Entangled systems can't be completely described independently (not separable)
- Entanglement is a type of correlation between quantum systems that is stronger than any classical correlation, and violates local realism
- Entanglement is fairly easy to create in the lab
- Entanglement plays a central role in quantum information applications