Event-by-Event Simulation of Quantum Phenomena*

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http://www.compphys.net/dlm

*Based on work done in collaboration with:
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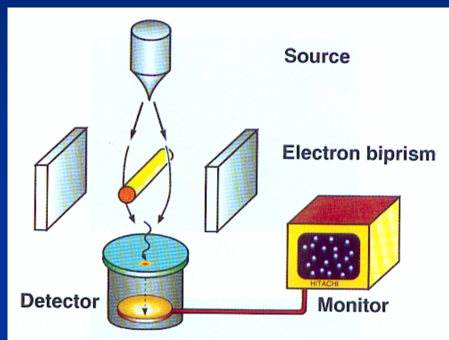
Introduction

- Recent advances in nanotechnology are paving the way to attain control over individual microscopic objects
  - The ability to prepare, manipulate, couple and measure single microscopic systems is essential for future applications of nanotechnology
- These technological developments facilitate the study of nanoscale systems at the level of individual events
  - We can directly address questions that are most fundamental to our current picture of the microscopic world

Single-Electron Two-Slit Experiment (Tonomura et al.)



- In this experiment, at any given time, only one electron travels from the source to the detector.
- Only after many (about 50000) electrons have been recorded an interference pattern emerges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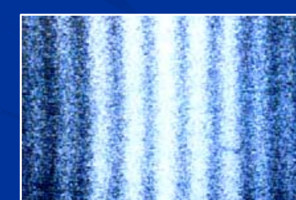

50000

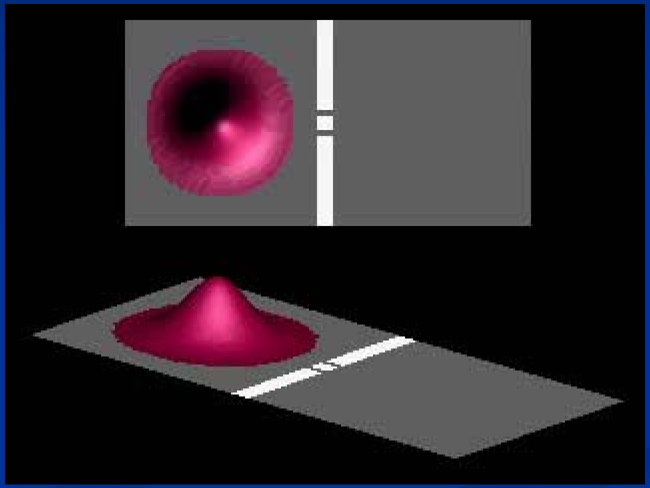
A. Tonomura, *The quantum world Unveiled by Electron Waves*, World Scientific (1998)
P.G. Merli, GF Missiroli, and G. Pozzi, Am. J. Phys. 44, 306 (1976)

Single-Electron Two-Slit Experiment

- Quantum theory can be used to assign a probability for an event to occur.
- We can use quantum theory to compute the interference pattern.
  - In Tonomura's experiment:

$$P(x, y \mid Conditions)$$

is the probability that we observe an electron at a position (*x*,*y*) on the screen (the event), assuming that the "Conditions" do not change during the experiment



- In many other instances, quantum theory describes the experimental data well.

Fundamental limitation of quantum theory

- We can use quantum theory to compute probability distributions (interference patterns) but quantum theory cannot model the process in terms of the individual events that we observe in a real experiment
  - Not a contradiction: Quantum theory does not describe individual events but the collective result of many events

- Reconciling the formalism of quantum theory with the experimental fact that each observation yields a definite outcome is called the quantum measurement paradox and is the central, most fundamental problem in the foundations of quantum theory
    - D. Home, *Conceptual Foundations of Quantum Physics*, Plenum Press, New York (1997)

Fundamental question

- Can we model the event-by-event processes observed in real experiments and reproduce the same statistical answers of experiments and quantum theory?

- After 100 years of hard work: All attempts to extend quantum theory have failed
  - Quantum measurement paradox
  - Prevailing logic in physics: Don't ask this question

- This talk is not about interpretations of quantum theory

What if we ask "the question"?

- Why limit ourselves to the framework that theoretical physics provides?
  - Quantum theory has nothing to say about individual events anyway

- Strategy: Stick to the data (= single events) that is provided by experiment and look for processes that generate these events such that the collective outcome agrees with quantum theory
    - N. Bohr: "There is no quantum world. There is only an abstract quantum mechanical description. It is wrong to think that the task of physics is to find out how Nature is. Physics concerns what we can say about Nature."
    - W. Heisenberg: "What we observe is not nature itself, but nature exposed to our method of questioning."

What can we do if there is no "theory"?

- Maybe later, we can make a theory for the simulation models
  - A. Einstein: "You can never solve a problem on the level on which it was created."

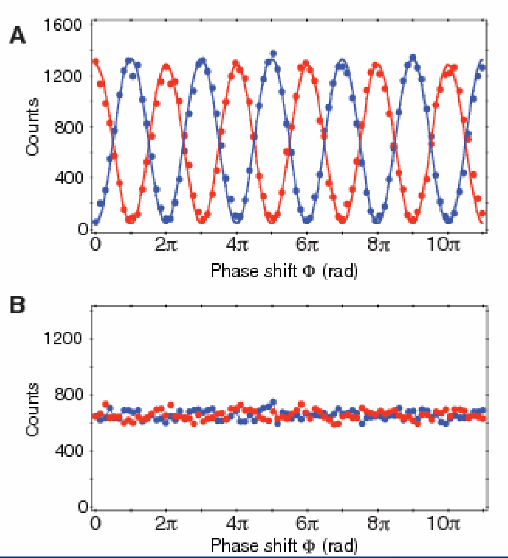
Event-by-event simulation of quantum phenomena

- Basic ideas:
  - Stick to what we know about the experiment
  - Try to invent a procedure (≠ a “theory”) that generates the same type of data as in experiment
  - Keep compatibility with our macroscopic picture
- Never use concepts of quantum physics
  - From events to quantum theory

Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment

Vincent Jacques,[1] E Wu,[1,2] Frédéric Grosshans,[1] François Treussart,[1] Philippe Grangier,[3] Alain Aspect,[3] Jean-François Roch[1]*

Wave-particle duality is strikingly illustrated by Wheeler's delayed-choice gedanken experiment, where the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: Either the interferometer is closed (that is, the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that gedanken experiment with single photons allowing unambiguous which-way measurements. The choice between open and closed configurations, made by a quantum random number generator, is relativistically separated from the entry of the photon into the interferometer.



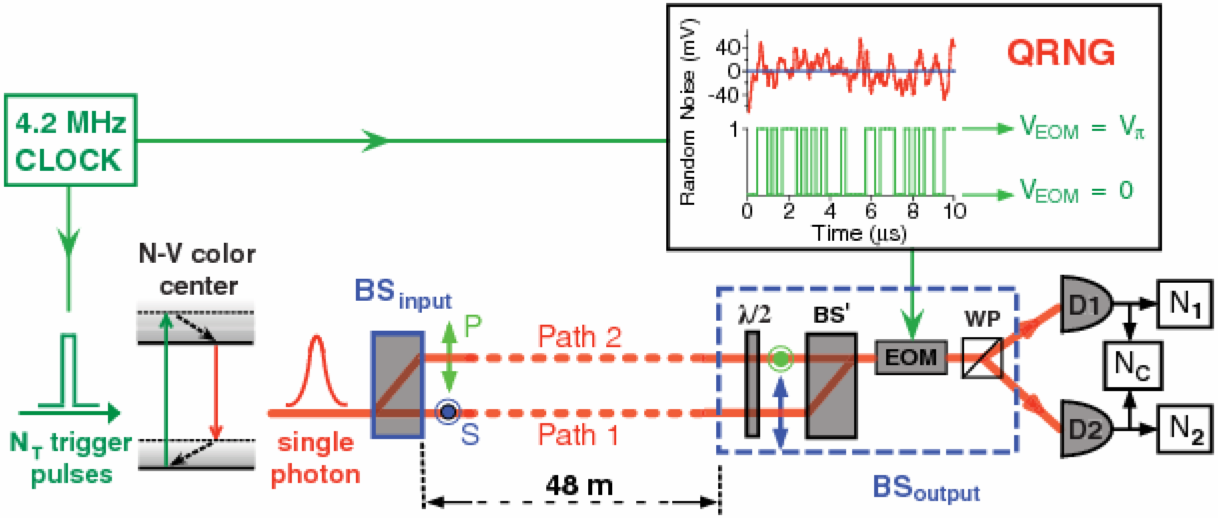


Fig. 2. Experimental realization of Wheeler's gedanken experiment. Single photons emitted by a single N-V color center are sent through a 48-m polarization interferometer, equivalent to a time of flight of about 160 ns. A binary random number 0 or 1, generated by the QRNG, drives the EOM voltage between $V = 0$ and $V = V_\pi$ within 40 ns, after an electronic delay of 80 ns. Two synchronized signals from the clock are used to trigger the single-photon emission and the QNRG. In the laboratory frame of reference, the random choice between the open and the closed configuration is made simultaneously with the entry of the photon into the interferometer. Taking advantage of the fact that the QNRG is located at the output of the interferometer, such timing ensures that the photon enters the future light cone of the random choice when it is at about the middle of the interferometer, long after passing BS_{input}.

Pictorial description: Conclusion

- BUT: The decision to apply $V \neq 0$ can be made during the time that the photon travels from BS_{input} to BS_{output}
- To explain the experimental facts, that is particle-like results if $V=0$ and interference if $V \neq 0$, we have to accept that we can influence the nature (particle/wave) of the photon in its PAST
  - Sounds like a mystery or (bad) science fiction
- Task of science should be to de-mystify our observations, not to cultivate mysteries

A way out ?

- Way out of this nonsensical conclusion: Quantum theory has nothing to say about individual events, it predicts averages only
- Einstein (1949): "The attempt to conceive the quantum mechanical description as the complete description of individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if one accepts the interpretation that the description refers to ensembles of systems and not to individual systems"

A way out? Not really …

- "Way out" prevents us from making nonsensical statements

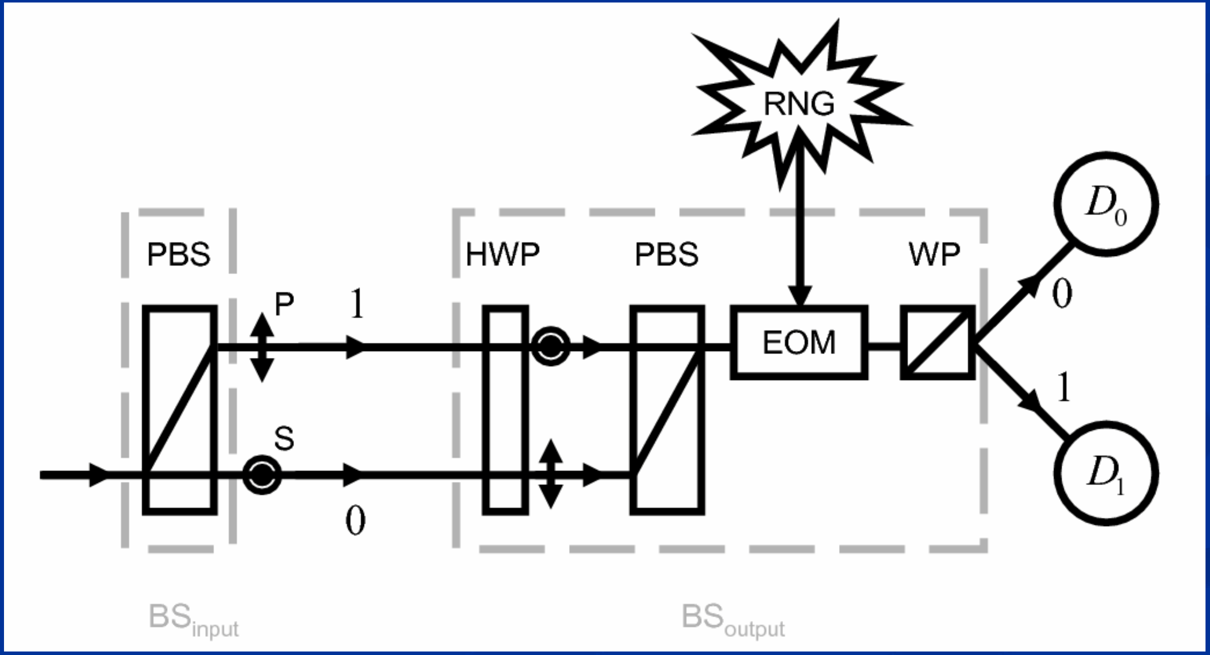
- Unfortunately, it does not give a single clue as how to explain the fact that individual events are observed and, when collected over a sufficiently long time, yield averages that agree with quantum theory.
  - Quantum measurement paradox

Event-by-event simulation of quantum phenomena

- Basic idea: “Particles” are messengers that carry messages (relative time, polarization…)
- Optical components are “processors” that interpret and manipulate messages
- Interference appears as a result of processing
  - No direct communication between two messengers
  - Satisfies intuitive (= Einstein’s) notion of local causality

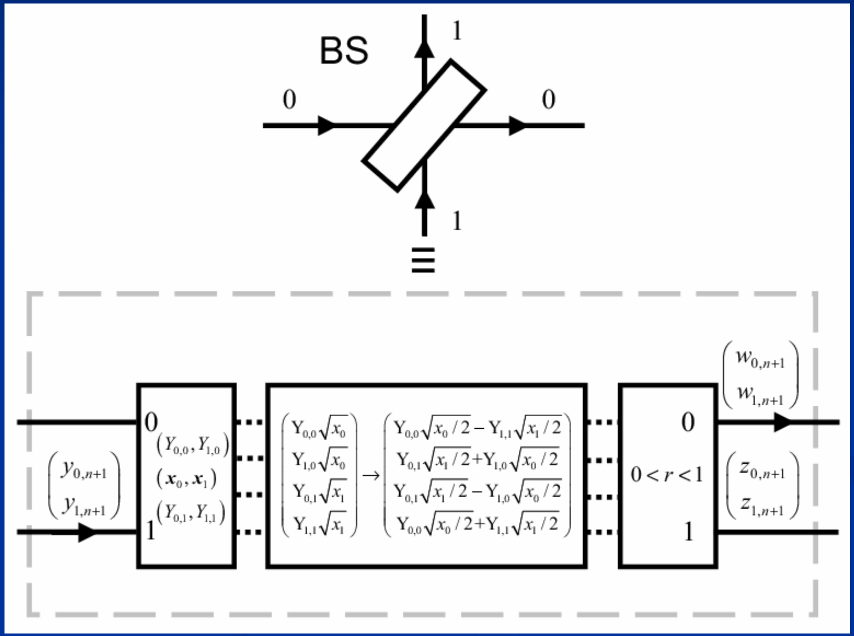
Basic idea

- Construct processors for each of the components in the experiment
  - Components should be “re-usable”



Deterministic Learning Machine (DLM)

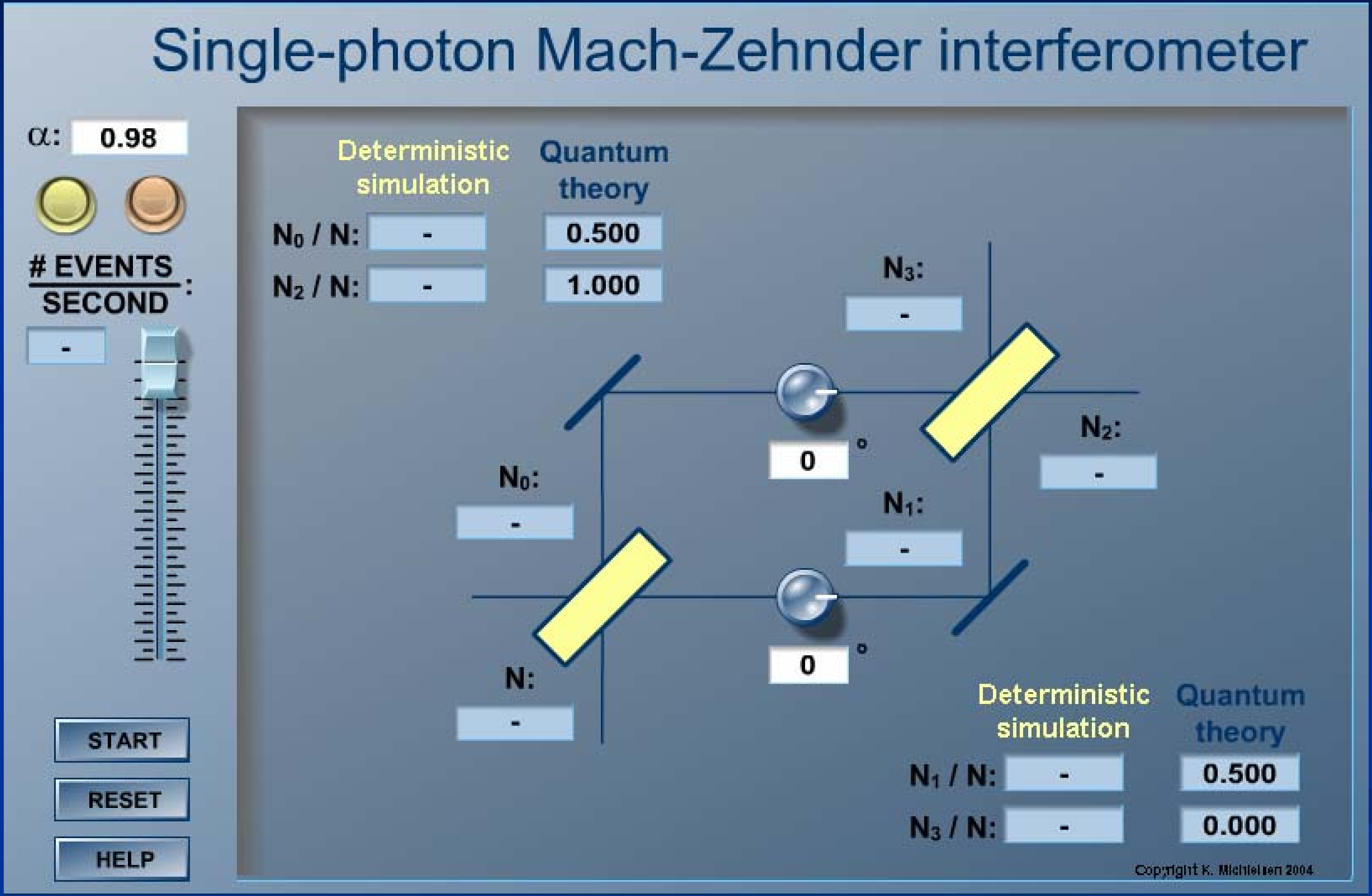
- Algorithm (example)
  - $(Y_{0,1}, Y_{1,1}) \leftarrow (y_0, y_1)$
  - $x_0 \leftarrow \alpha\, x_0$
  - $x_1 \leftarrow \alpha\, x_1 + 1 - \alpha$
    - "Learning" pace is controlled by α
    - $x_0 + x_1 = 1$
  - Apply transformation → (w_0, w_1, z_0, z_1)
  - If $(w_0)^2 + (w_1)^2 < r$ send "0" event, otherwise send "1" event



- $x_{i,n} = \alpha x_{i,n-1} + (1-\alpha)\delta_{i,k_n}$ mimics

$$\mathbf{P}(k,\omega) = \chi(k,\omega)\mathbf{E}(k,\omega)$$

Quantum theory: $\frac{N_0}{N} = \frac{N_1}{N} = \frac{1}{2}, \frac{N_2}{N} = \cos^2\frac{\varphi_1 - \varphi_0}{2}, \frac{N_2}{N} = \sin^2\frac{\varphi_1 - \varphi_0}{2}$



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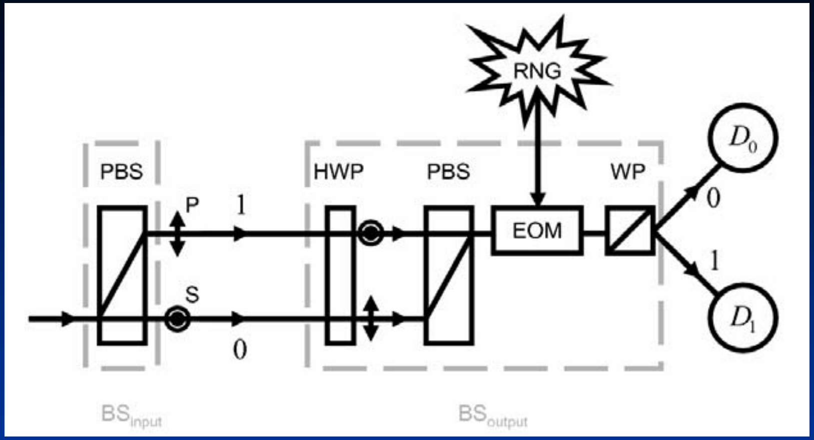
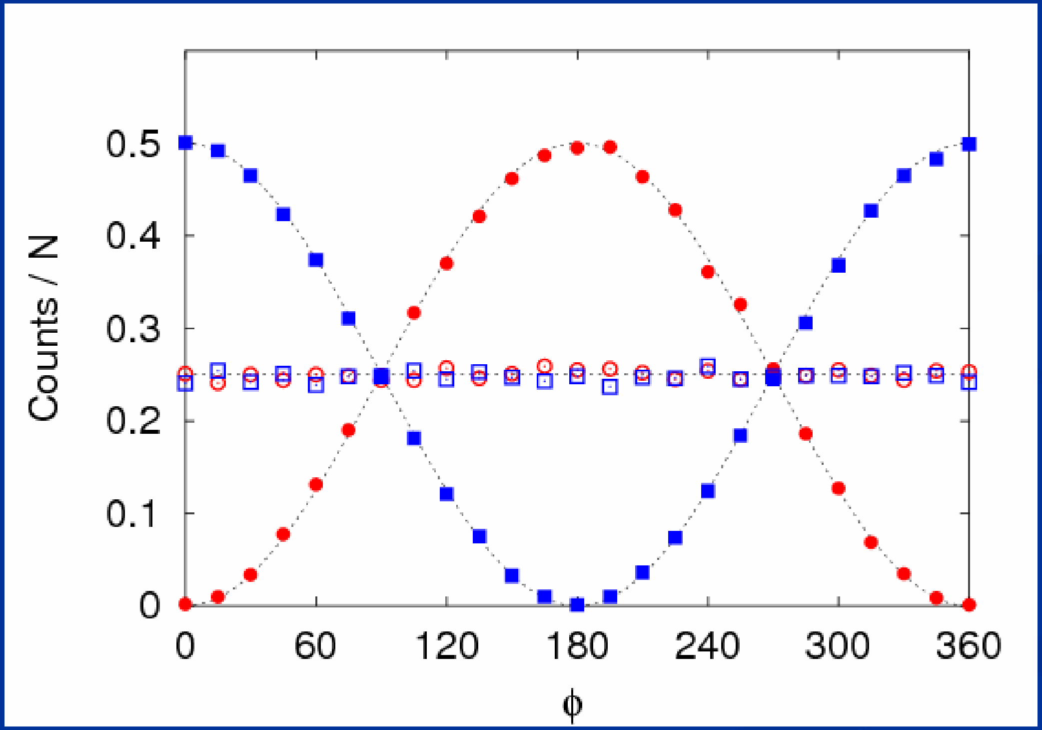
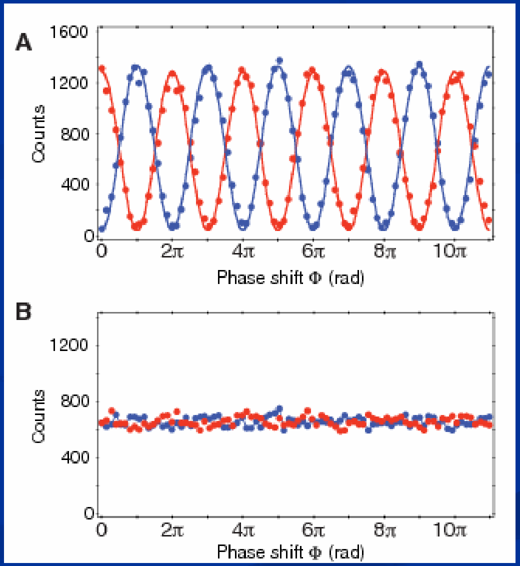


Simulation results



Experimental results

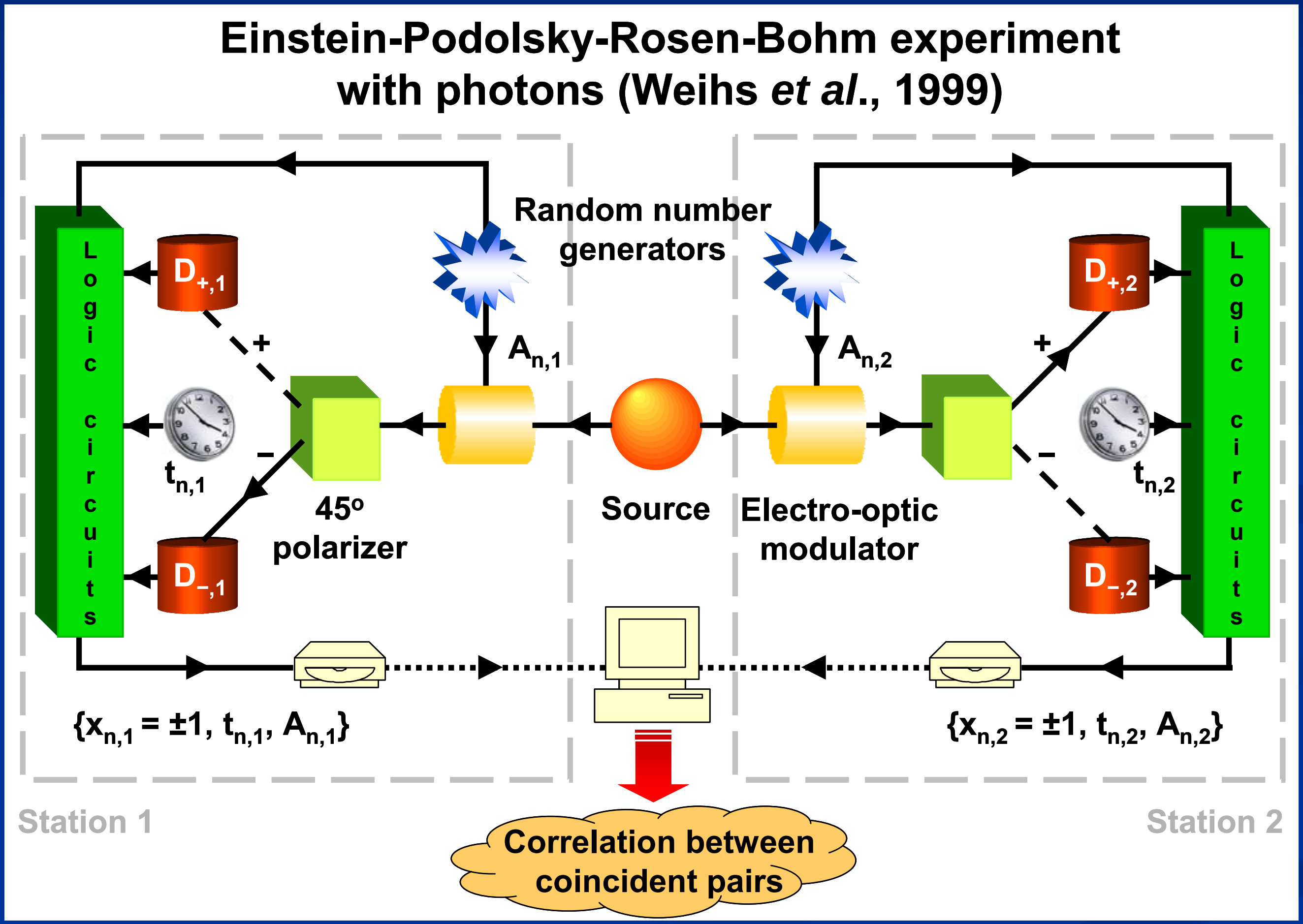


Excellent agreement with quantum theory!

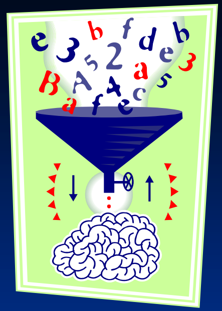
Wheeler's delayed-choice experiment: Summary

- We have proven that there exists a particle-only description of Wheeler's delayed-choice experiments that
  1. Reproduces the averages calculated from quantum theory
  2. Satisfies Einstein's criteria of realism and local causality
  3. Does not rely on any concept of quantum theory
  4. Is not in conflict with common sense

A Real Einstein-Podolsky-Rosen-Bohm experiments



* G. Weihs, T. Jennewein, C. Simon, H. Weinfurther, and A. Zeilinger, Phys. Rev. Lett. 81, 5039 (1998)



Data analysis (1)

- In any practical realization of (an EPR-Bohm) experiment, it is necessary to have a criterion that decides which particles form a pair and which particles do not

- In EPR-Bohm experiments, coincidence in time $|t_{n,1} - t_{n,2}| < W$ is used to define a pair*
  - W is a time window, chosen by the experimenter

C.A. Kocher and E.D. Commins, Phys. Rev. Lett. 18, 575 (1969)

* G. Weihs, T. Jennewein, C. Simon, H. Weinfurther, and A. Zeilinger, Phys. Rev. Lett. 81, 5039 (1998)

Data analysis (2)

- After all data has been collected, compute the two-particle coincidences*

$$C_{xy}(\alpha,\beta)=\sum_{n=1}^{N}\delta_{x,x_{n,1}}\delta_{y,x_{n,2}}\delta_{\alpha,A_{n,1}}\delta_{\beta,A_{n,2}}\Theta(W-|t_{n,1}(x,\alpha)-t_{n,2}(y,\beta)|)$$

  - x,y = ++,--,+-,-+ (+ ⇔ +1, - ⇔ -1)
  - α,β : rotation angles ⇔ setting of the electro-optic modulators 1 and 2
- Compute the two-particle correlation*

$$E(\alpha,\beta)=\frac{C_{++}(\alpha,\beta)+C_{--}(\alpha,\beta)-C_{+-}(\alpha,\beta)-C_{-+}(\alpha,\beta)}{C_{++}(\alpha,\beta)+C_{--}(\alpha,\beta)+C_{+-}(\alpha,\beta)+C_{-+}(\alpha,\beta)}$$

* G. Weihs, T. Jennewein, C. Simon, H. Weinfurther, and A. Zeilinger, Phys. Rev. Lett. 81, 5039 (1998)

Quantum theory for the EPRB experiment

- Single system of two *S*=1/2 particles
- The whole experiment is described by a singlet (total spin zero) state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2\right)$$

- A simple calculation shows that

$$\left.\begin{aligned} E_1(\mathbf{a},\mathbf{b}) &= E_1(\mathbf{a}) = \langle\Psi|\boldsymbol{\sigma}_1\cdot\mathbf{a}|\Psi\rangle = 0 \\ E_2(\mathbf{a},\mathbf{b}) &= E_2(\mathbf{b}) = \langle\Psi|\boldsymbol{\sigma}_2\cdot\mathbf{b}|\Psi\rangle = 0 \\ E(\mathbf{a},\mathbf{b}) &= \langle\Psi|\boldsymbol{\sigma}_1\cdot\mathbf{a}\;\boldsymbol{\sigma}_2\cdot\mathbf{b}|\Psi\rangle = -\mathbf{a}\cdot\mathbf{b} \end{aligned}\right\}$$

If QT is used to ``explain" data (= events) ⇒ EPR paradox

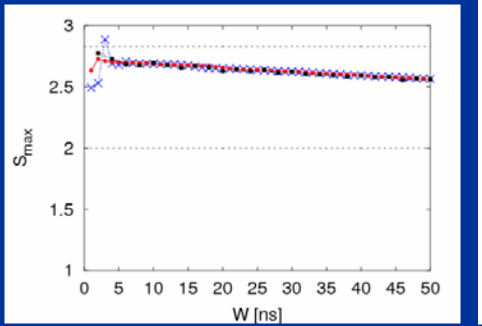
Real EPRB experiment

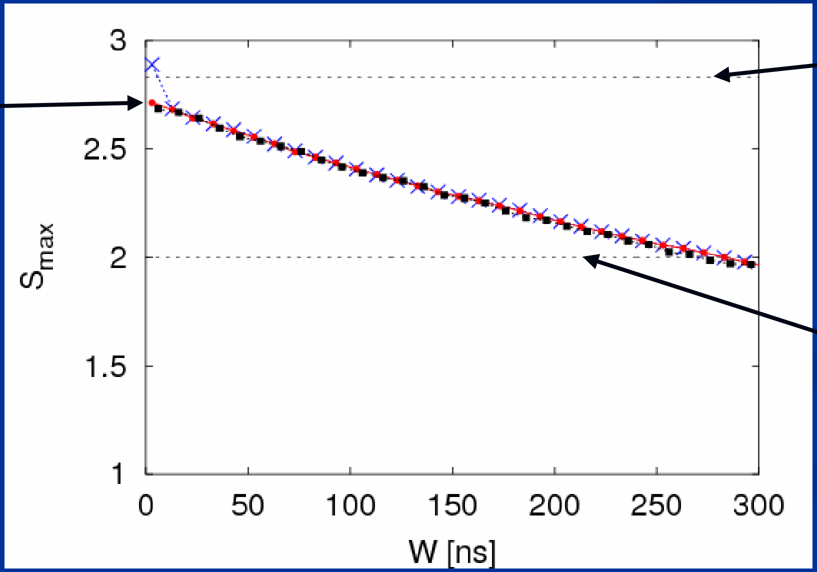
- Our analysis of experimental data of Weihs et al. using three different methods
  - http://www.quantum.at/research/photonentangle/bellexp/data.html

$S_{max} \equiv E(a,c) - E(a,d) + E(b,c) + E(b,d)$

Experiment: $a = 0, b = \pi/8, c = \pi/4, d = 3\pi/8$

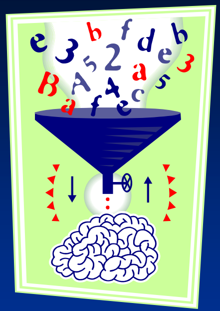
"Best" value cited in literature: 2.73 (Weihs et al.)





Upper bound for a system of two S=1/2 particles

Upper bound for a system of two uncorrelated S=1/2 particles



A Solution (1)

Listen to what the data has to say,
not what people say about the data

- Start from the observation that experiment generates data sets[#]

$$\Upsilon_{N,i} = \left\{ x_{n,i} = \pm 1, t_{n,i}, A_{n,i} \mid n = 1, \ldots, N \right\} \quad , \quad i = 1, 2$$

  - Main rule of the game: Einstein's criterion of local causality* (≠ Bell's notion of locality)
    - "But on one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former"

[#] G. Weihs, T. Jennewein, C. Simon, H. Weinfurther, and A. Zeilinger, Phys. Rev. Lett. 81, 5039 (1998)

* P.A. Schilpp, Ed., "Albert Einstein, Philospher-Scientist, Tudor, NY (1949)

A Solution (2)

- Simulation model:
  - Particle *i* =1,2 carries a vector $\mathbf{S}_{n,i} = (-1)^{i+1}(\cos\xi_n, \sin\xi_n)$
  - The electro-optic modulator *i* rotates this vector by α_i
  - The polarizer *i* directs the particle to the detector

    $$x_{n,i} = \mathrm{sign}(\cos 2(\xi_n - \alpha_i))$$

  - The modulator+polarizer causes a time delay

    $$0 \le t_{n,i} - t_0 \le T\,|\sin 2(\xi_n - \alpha_i)|^d$$

  - Correlations are calculated in exactly the same manner as in experiment

Satisfies Einstein’s criteria of local causality and realism

Simulation results

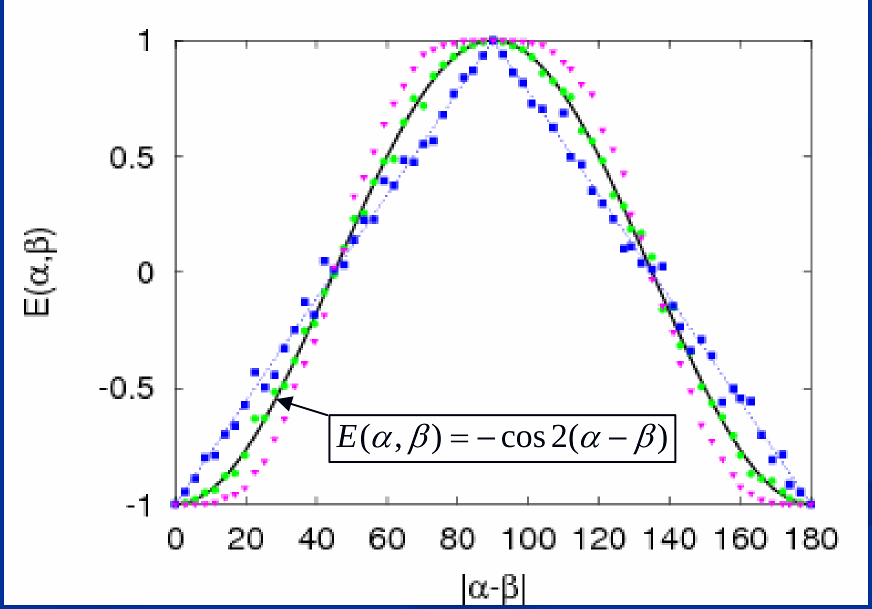
- Free parameters of the simulation model
  - Window *W* / τ
  - Maximum delay T/τ
  - Time-delay exponent *d*
  - Number of events *N*

$N = 10^6$, $W = \tau = 0.000125\,T$

■: $d = 0$ Text book "Bell" model

● $d = 2$ Quantum theory

▼ : $d = 4$ "Beyond" quantum



Results (1)

- Event-by-event simulation models* for the EPR-Bohm experiments reproduce the results of quantum theory for a system of two S=1/2 particles
  - Our models strictly satisfy Einstein's conditions of local causality
  - Rigorous proof for 2 (3)-component spins and *d* = 2,4 (*d* = 3)

*De Raedt, Keimpema, De Raedt, Michielsen, Miyashita, Eur. Phys. J. B 53, 139 (2006)
(De Raedt)^2, Michielsen, Comp. Phys. Comm. 176, 642 (2007)
H. De Raedt, K. Michielsen, S. Miyashita, and K. Keimpema, Euro. Phys. J. B 58, 55 (2007)
(De Raedt)^2 , Michielsen, Keimpema, Miyashita, J. Comp. Theor. Nanosci. 4, 957(2007)
S. Zhao, H. De Raedt, and K. Michielsen, Found. of Phys. (in press)

Results (2)

- For $d = 0$ or $W \rightarrow \infty$ ($\Leftrightarrow$ removing the time-tag data), we recover the results of a model considered by Bell
  - Textbook "EPR paradox" is the result of analyzing experiments in terms of (Bell-type) models that do not account for all essential experimental data

Summary

- The same “components” have been used to simulate
  - Single-photon beam-splitter and Mach-Zehnder interferometer experiments
  - Quantum cryptography
  - Universal quantum computation
  - Wheeler’s delayed choice experiment
  - Quantum eraser, single-photon quantum optics in general
  - Einstein-Podolsky-Rosen-Bohm experiments with photons
  - Optical properties of layered materials,…

Conclusion

- We have invented a systematic, modular procedure to construct causal, Einstein-local, classical (non-Hamiltonian) dynamical systems that can be used for a deterministic or pseudo-random (unpredictable) event-by-event simulation of real-time quantum phenomena
  - Event-by-event simulation of universal quantum computation and hence of all quantum systems (in principle)
    - Michielsen and (De Raedt)^2, J. Comp. Theor. Nanosci. 2, 227 (2005)
- Real-time quantum dynamics: $\Psi(t) = U_N \ldots U_1 \Psi(t=0)$
  - For any set of unitary matrices U_i, there is a (non-unique) procedure to build a network of DLMs such that this network generates, event-by-event, the distribution of numbers $p_n(t) = |\langle n | \Psi(t) \rangle|^2$
- Published papers, demo's and additional information can be found on www.compphys.net/dlm

Thank you

$P(A|BabC) = P(A|aC)$

Local causality according to J.S. Bell

- In a locally causal theory, if *b* has no causal effect on *A* then $P(A|bZ) = P(A|Z)$
  - J.S. Bell, “Speakable and unspeakable in quantum mechanics”, p.54
- Example (E.T. Jaynes, 1989): Consider an urn with one red and 1 white ball. A blind monkey draws the balls.
  - *A*: First draw yields a red ball, *b*: Second draw yields a red ball
  - Experiment 1: Show result of the first draw ⟶ $P(b|AZ) = 0$
  - Experiment 2: Do no show result of the first draw
    - As the second draw cannot have a causal effect on the first draw, according to Bell, in a locally causal theory, we must have
      - Experiment 2: $P(A|bZ) = P(A|Z) = 1/2$?
    - Correct application of probability theory (= common sense)

      $P(Ab|Z) = P(A|bZ)P(b|Z) = P(b|AZ)P(A|Z) \longrightarrow P(b|AZ) = P(A|bZ)$
      - Experiment 2: $P(A|bZ) = 0$

$P(\frown{A} | \breve{B}\frown{a}\breve{b}C) = P(\frown{A} | \frown{a}C)$

Local causality according to J.S. Bell

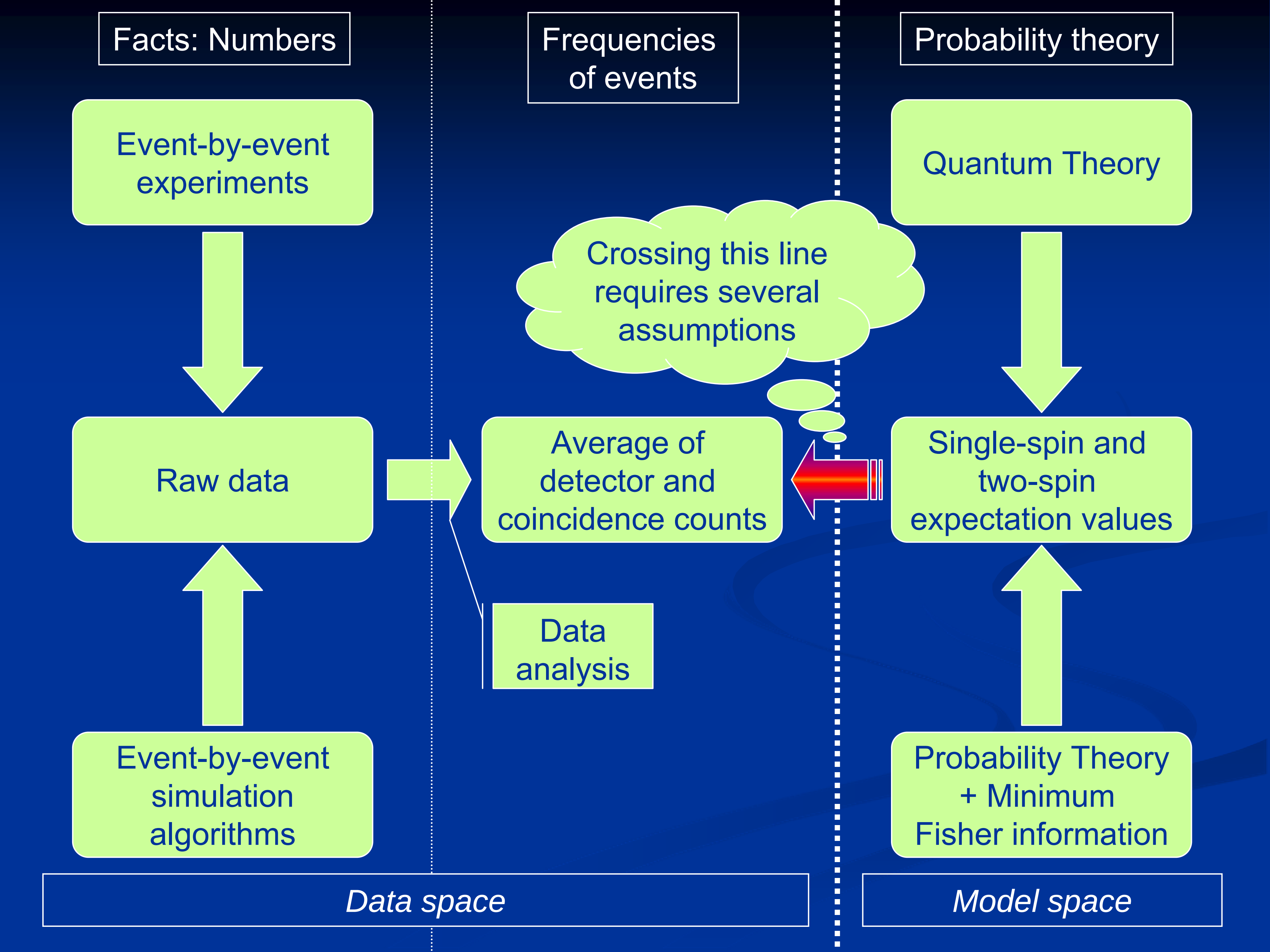
- Bell did not seem to have realized that the absence of causal influence does not imply logical independence

Logical independence

$\neq$

Physical independence

  - First logic then physics
- Bell's extension of Einstein's event-based notion of locality to probabilistic theories leads to logical inconsistencies
  - Is a vase with a red and a white ball "nonlocal"?
- Bell's "theorem" is irrelevant to science



Facts: Numbers
Frequencies of events
Probability theory
Event-by-event experiments
Quantum Theory
Crossing this line requires several assumptions
Raw data
Average of detector and coincidence counts
Single-spin and two-spin expectation values
Data analysis
Event-by-event simulation algorithms
Probability Theory + Minimum Fisher information
Data space
Model space