Event-by-Event Simulation of Quantum Phenomena*

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Quantum Measurement Paradox

- We can use quantum theory to compute probability distributions but quantum theory cannot model processes in terms of the individual events that we observe in real experiments

- Not a contradiction: Quantum theory does not describe individual events but the collective result of many events
  - 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”
    - 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

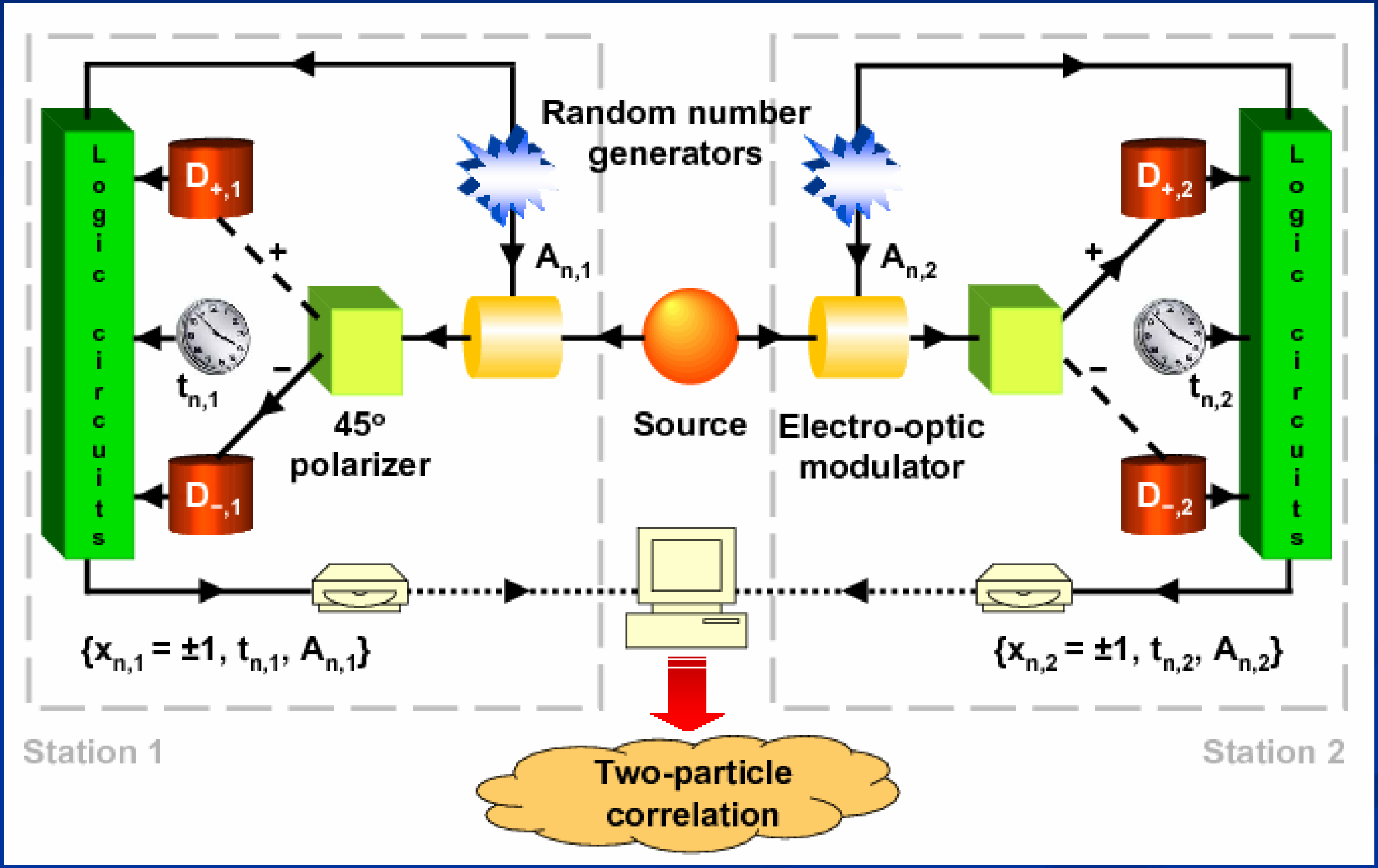
What if we ask “the question”?

- 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 and experiment
    - 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.”
- This talk is not about interpretations of quantum theory

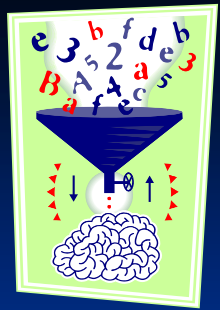
Event-by-event simulation of quantum phenomena

- Basic ideas:
  - Focus on the data produced by the experiment
  - Invent a procedure (≠ a "theory") that generates the same type of data as in experiment and reproduces the averages
  - Keep compatibility with our macroscopic picture
- Never use concepts of quantum physics
  - From events to quantum theory, not vice versa!

Example: 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 by which we decide 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 but made as small as possible

[#] 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),(-1,-1),(+1,-1),(-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)

Real EPR-Bohm experiment

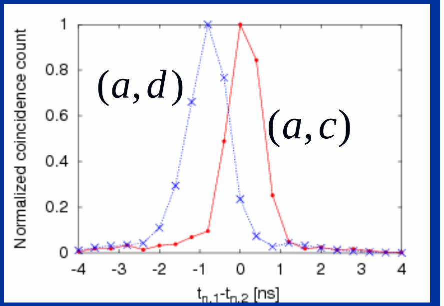
- Our analysis of experimental data of Weihs et al. using three different methods
  - http://www.quantum.at/research/photonentangle/bellexp/data.html

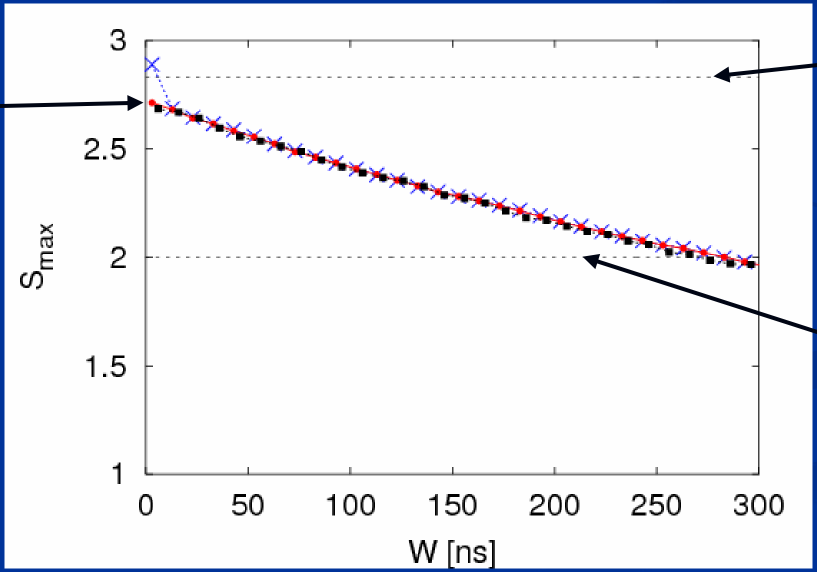
Average time between events ~ 30 000 ns

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

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

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

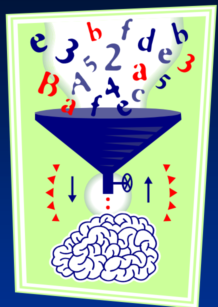




Upper bound for a system of two S=1/2 particles

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

$c \approx 30$ cm/ns



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: Einstein’s criterion of local causality* (≠ Bell’s notion of local causality)
    - “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 $x_{n,i} = \pm 1$

$$p(x_{n,i} \mid \xi_n - \alpha_i) = \cos^2(\xi_n - \alpha_i) \quad \Longrightarrow \quad \text{Malus law}$$

  - The modulator + polarizer causes a time delay

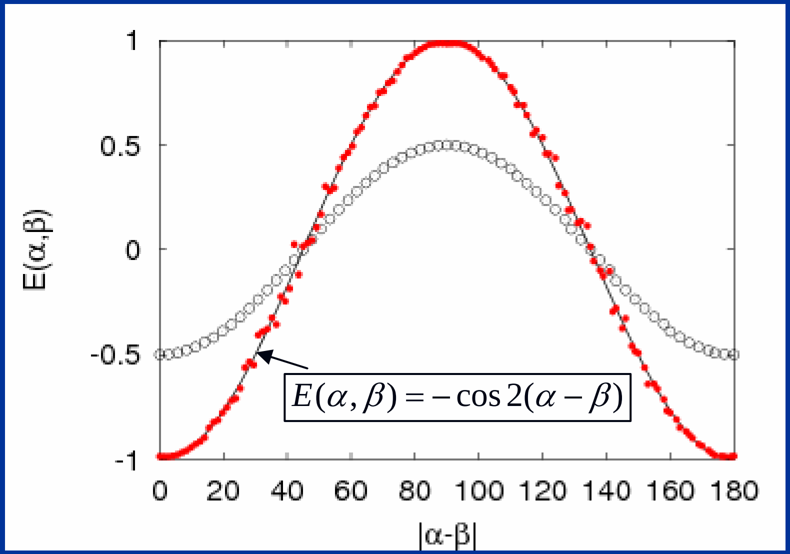
$$0 \le t_{n,i} - t_0 \le T \,|\sin 2(\xi_n - \alpha_i)|^d$$

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

Satisfies Einstein’s criteria of local causality and realism

Simulation results

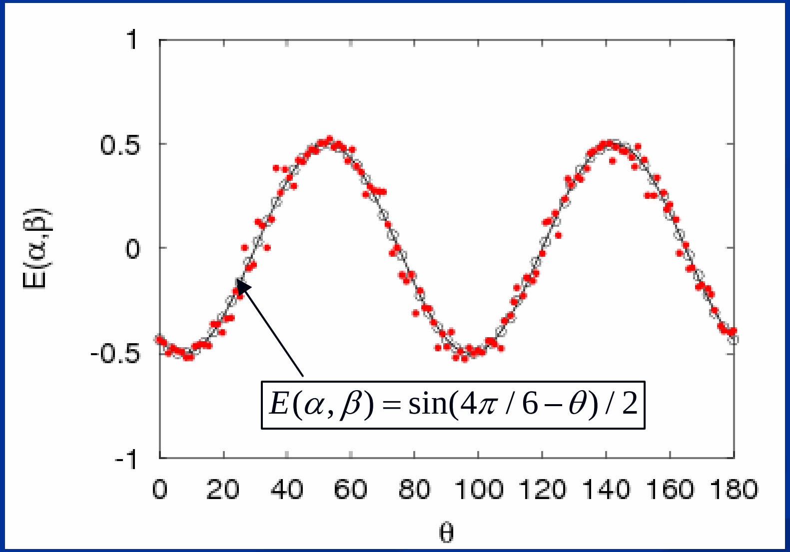
- $\xi_{n,2} = \xi_{n,1} + \pi / 2$
  - uniform distribution
  - $N = 10^6$, $W = \tau = 0.00025T$



○ $d = 0$ → Text book "Bell" model

● $d = 4$ → Quantum theory: singlet state

- $\xi_{n,2} = \xi_{n,1} + \pi / 2$
  - $\xi_{n,1} = \pi / 6$, $\alpha = \theta$, $\beta = \theta + \pi / 4$
  - $N = 10^6$, $W = \tau = 0.00025T$



○ $d = 0$ → Quantum theory: product state

● $d = 4$ → Quantum theory: product state

EPR-B: Summary of results

- Our 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*
  - Models strictly satisfy Einstein's conditions of local causality
  - Rigorous proofs for some integer *d*
  - For $d = 0$ or $W \to \infty$ (⇔ 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 models that do not account for all essential experimental data

*De Raedt, Keimpema, De Raedt, Michielsen, Miyashita, Eur. Phys. J. B 53, 139 (2006)
(De Raedt)^2, Michielsen, Comp. Phys. Comm. 176, 642 (2007)
(De Raedt)^2, Michielsen, Keimpema, Miyashita, J. Phys. Soc. Jpn. 76, 104005 (2007)
De Raedt, Michielsen, Miyashita, Keimpema, Euro. Phys. J. B 58, 55 (2007)
(De Raedt)^2 , Michielsen, Keimpema, Miyashita, J. Comp. Theor. Nanosci. 4, 957(2007)
Zhao, De Raedt, Michielsen, Found. of Phys. 38, 322 (2008)

Summary

- We have invented a systematic, modular procedure to construct Einstein-local, causal, 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 without invoking concepts of quantum theory
- Our event-by-event simulation approach works for:
  - Single-photon Mach-Zehnder interferometers
  - Universal quantum computation
  - Quantum cryptography
  - Wheeler's delayed choice experiment
  - Quantum eraser
  - EPR-Bohm experiments, including non-orthogonal detection planes
  - Double-slit/Fresnel bi-prism experiment with single photons
- For more information visit http://www.compphys.net

Thank you

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

Local causality according to J.S. Bell

- According to 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 a vase 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 the result of the first draw ⟶ $P(b|AZ) = 0$
    - Experiment 2: Do not show the 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)

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

$P(A \mid BabC) = P(A \mid aC)$

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
  - A vase with a red and a white ball is "nonlocal"?
- Bell's "theorem" is irrelevant for (quantum) physics