New method to simulate quantum interference using deterministic processes

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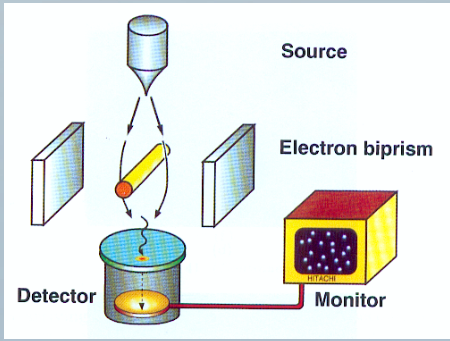
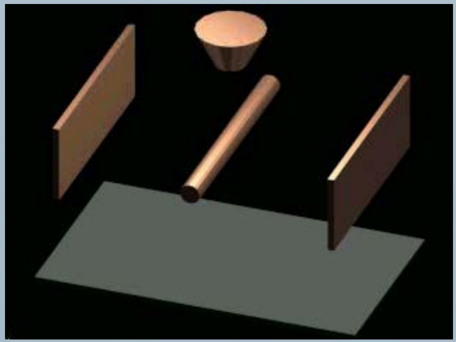
INTRODUCTION

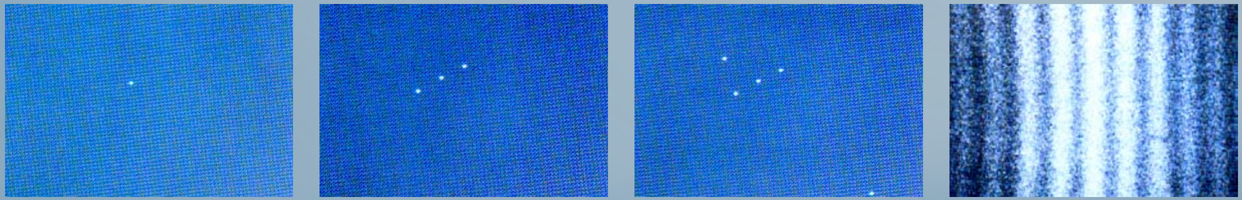
- Computer simulation is complementary to theory and experiment
  - D.P. Landau and K. Binder, *A guide to Monte Carlo Simulation in Statistical Physics*, Cambridge Univ. Press (2000)
- There are only a few physical phenomena that so far cannot be simulated on a computer, not even in principle
- This talk is NOT about interpretations of quantum theory but about deterministic dynamical systems that exhibit quantum mechanical behavior

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







1 | 3 | 5 | 50000

A. Tonomura, *The quantum world Unveiled by Electron Waves*, World Scientific (1998)

Introduction

- We can use quantum theory to compute the interference pattern but nobody seems to know how to simulate the individual events
- Quantum theory does not describe individual events, only 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)

Introduction

- If computer simulation is indeed a third scientific methodology to model physical phenomena it should be possible to simulate experiments on an event-by-event basis
  - To find such simulation methods we should step outside the framework that quantum theory provides.
    - Avoid the quantum measurement paradox
    - This talk is about a new simulation approach, NOT about interpretation(s) of quantum theory.

In this talk

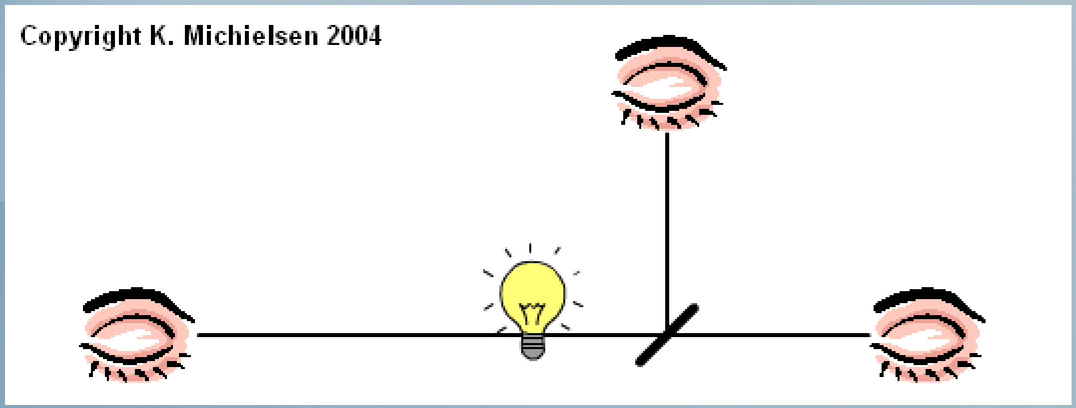
- We propose a new, general methodology to construct simulation algorithms that can simulate quantum phenomena using deterministic, local and causal event-based processes.
  - Main idea is to employ algorithms (processing units) that have primitive learning capabilities
- Networks of these units can simulate quantum interference and quantum computers
  - Simulation results are in excellent agreement with quantum theory

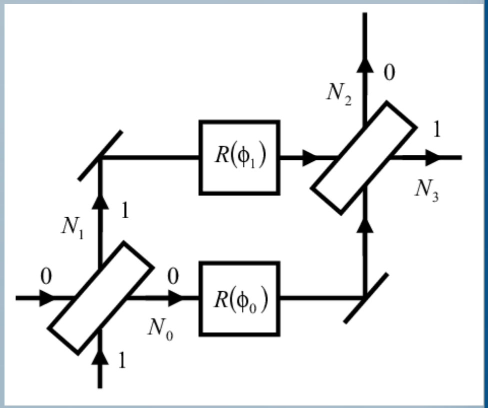
Central question

- What kind of algorithm(s) do we need to simulate quantum interference event-by-event?
  - Quantum theory gives us a set of rules (algorithms) to compute the probability for observing a particular event
    - N.G. Van Kampen, Physica A 153, 97 (1988)
  - Why not search for different kinds of algorithms?

Concrete example

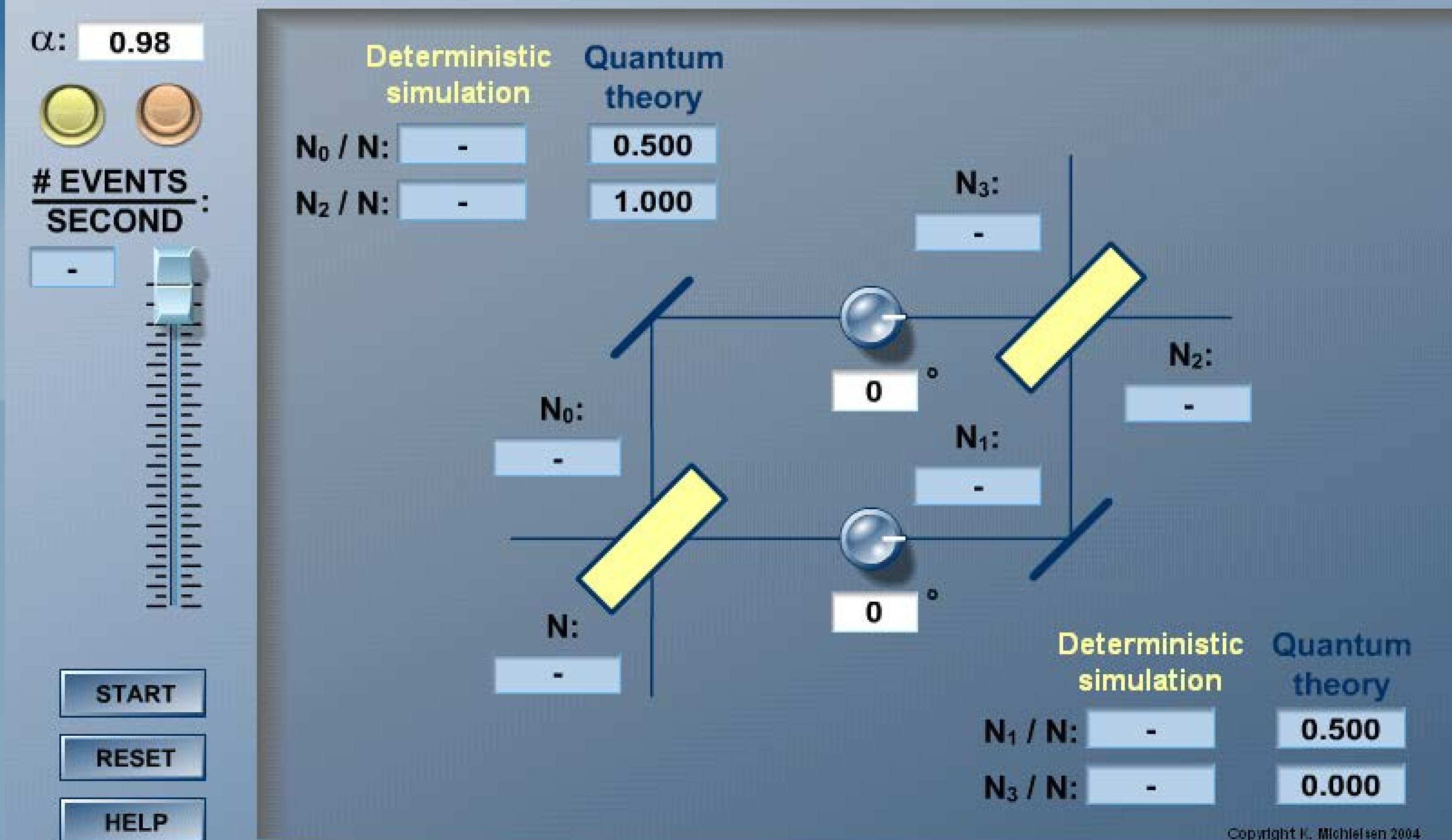
- Single-photon beam-splitter and Mach-Zehnder interferometer experiments
  - P. Grangier, R. Roger, and A. Aspect, Europhys. Lett. 1, 171 (1986)



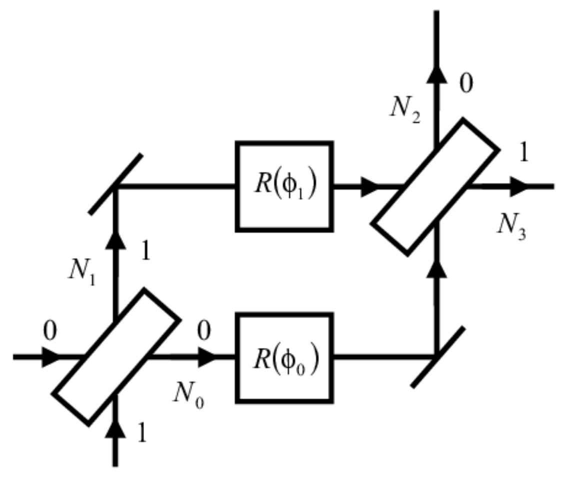


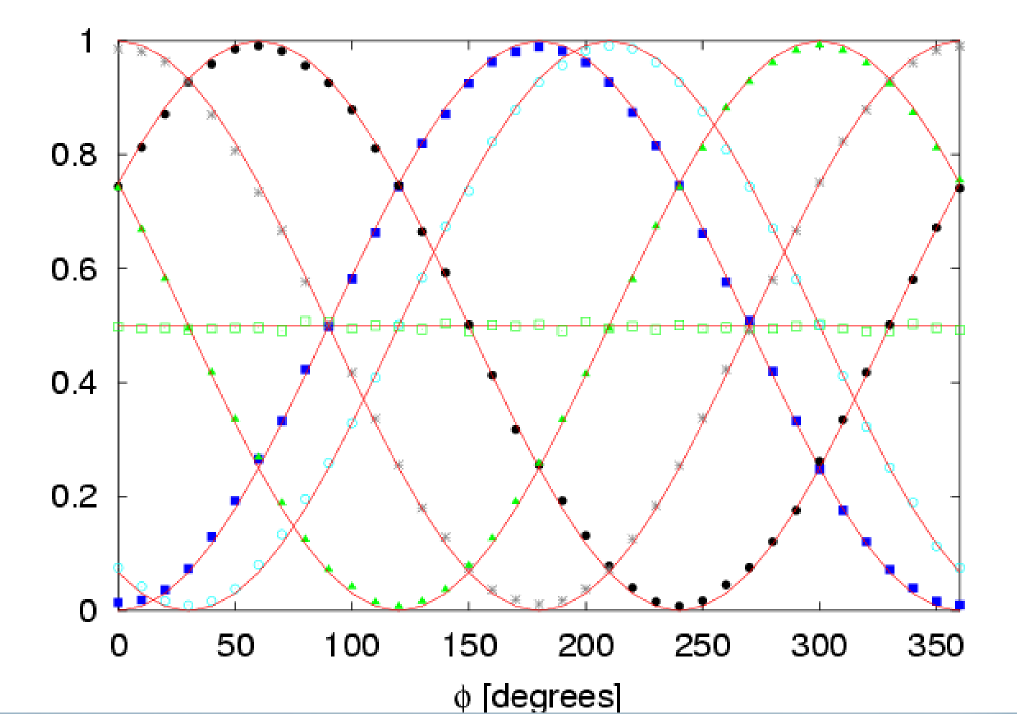
– Exhibit the same fundamental problems as the single-electron double-slit experiment of Tonomura et al. but are easier to describe in terms of algorithms

Single-photon Mach-Zehnder interferometer



DLM simulation results





Input channel 0 receives photons with a phase ($\cos\psi_0$, $\sin\psi_0$). Input channel 1 does not receive photons. A uniform random number in the range [0,360] is used to choose the angle ψ_0. Each data point represents 10000 events ($N_0+N_1=N_2+N_3=10000$). Initially the rotation angle $\phi_0 = 0°$ and after each set of 10000 events, ϕ_0 is increased by 10°. Markers give the simulation results for the normalized intensities as a function of $\phi = \phi_0 - \phi_1$. Open squares: $N_0/(N_0+N_1)$; Solid squares: $N_2/(N_2+N_3)$ for $\phi_1=0°$; Open circles: $N_2/(N_2+N_3)$ for $\phi_1=30°$; Bullets: $N_2/(N_2+N_3)$ for $\phi_1=240°$; Asterisks: $N_3/(N_2+N_3)$ for $\phi_1=0°$; Solid triangles: $N_3/(N_2+N_3)$ for $\phi_1=300°$. Lines represent the results of quantum theory.

How and why does it work?

- Simplest (but generic) case: A machine that learns from input events (photons) that carry a message (the phase or polarization) in the form of a 2-dimensional vector
- Internal state of the machine after processing the *n*-th event is represented by a unit vector

$$\vec{x}_n = (x_{0,n}, x_{1,n}) \quad , \quad n = 0,1,\ldots$$

Deterministic learning machines (DLMs)

- Each input event carries a message represented by a unit vector

$$\vec{y}_{n+1} = (y_{0,n+1}, y_{1,n+1}) \quad , \quad n = 0,1,\ldots$$

- After receiving the (n+1)-th message the machine updates its internal state by deciding which of the update rules minimizes a cost function

Deterministic learning machines

- The candidate update rules are

$$\text{Rule 0: } x_0 \leftarrow \alpha x_0 \,,\; x_1 \leftarrow \pm\sqrt{1+\alpha^2(x_1^2-1)}$$

$$\text{Rule 1: } x_1 \leftarrow \pm\sqrt{1+\alpha^2(x_1^2-1)} \,,\; x_0 \leftarrow \alpha x_0$$

  – Update rules do not change the length of $\vec{x}$

- The cost function is

$$C = -\vec{x} \cdot \vec{y}_{n+1}$$

  – $\vec{x}$ denotes the result of one of the candidate update rules

Deterministic learning machines

- Simplest case: Fixed input messages

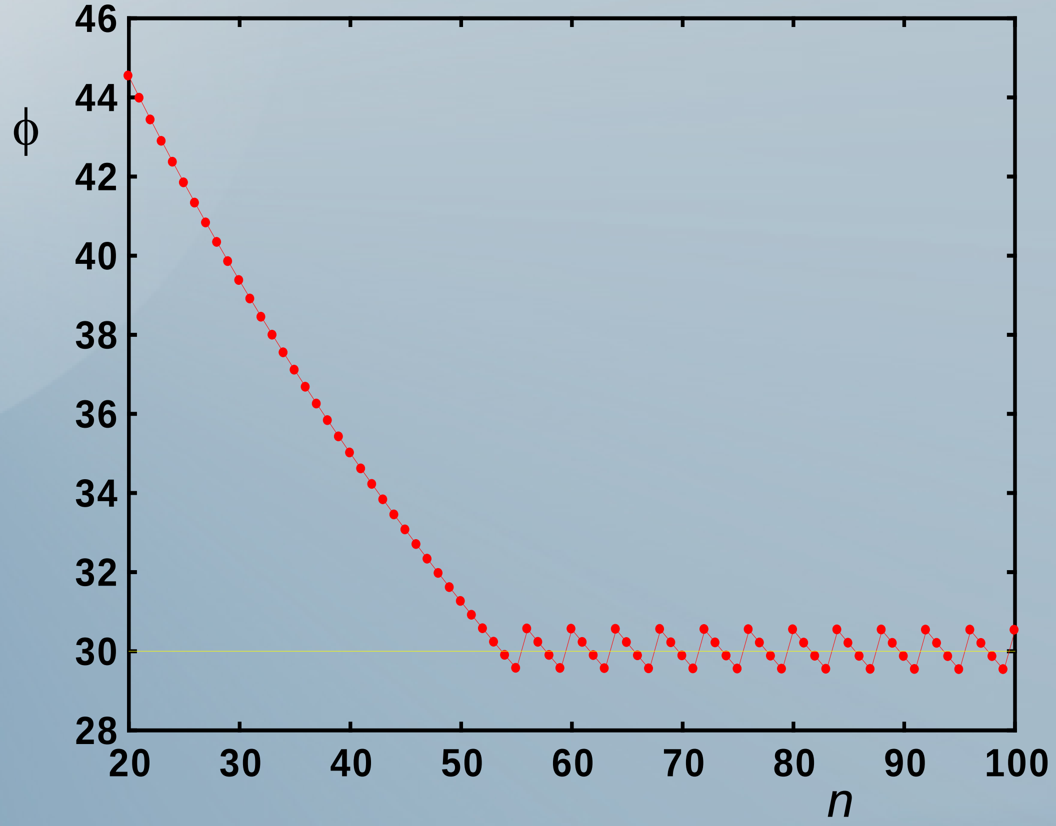
$$\vec{y}_{n+1} = (y_0, y_1) \quad , \quad n = 0,1,\ldots$$

- The machine will rotate the internal vector $\vec{x}_{n+1}$ towards $\vec{y}_{n+1}$ but after a number of steps $\vec{x}_{n+1}$ starts to oscillate about $\vec{y}_{n+1}$
- In this regime we have

$$\frac{\text{\# times rule 0 was selected}}{\text{total number of events}} \to \sin^2\phi = y_0^2$$


Deterministic Learning Machine (DLM)
ϕ
ϕ'
1
0
INPUT
INTERNAL
ϕ: 45 °
x: -
y: -
ϕ': 260 °
x': -0.174
y': -0.985
α: 0.99
INPUT
OUTPUT
EVENTS N: -
1: -
0: -
x²: -
y²: -
1 / N: -
0 / N: -
EVENTS / SECOND: -
START
RESET
HELP
90
60
30
0
330
300
270
240
210
180
150
120
Copyright K. Michielsen 2004

DLM dynamics

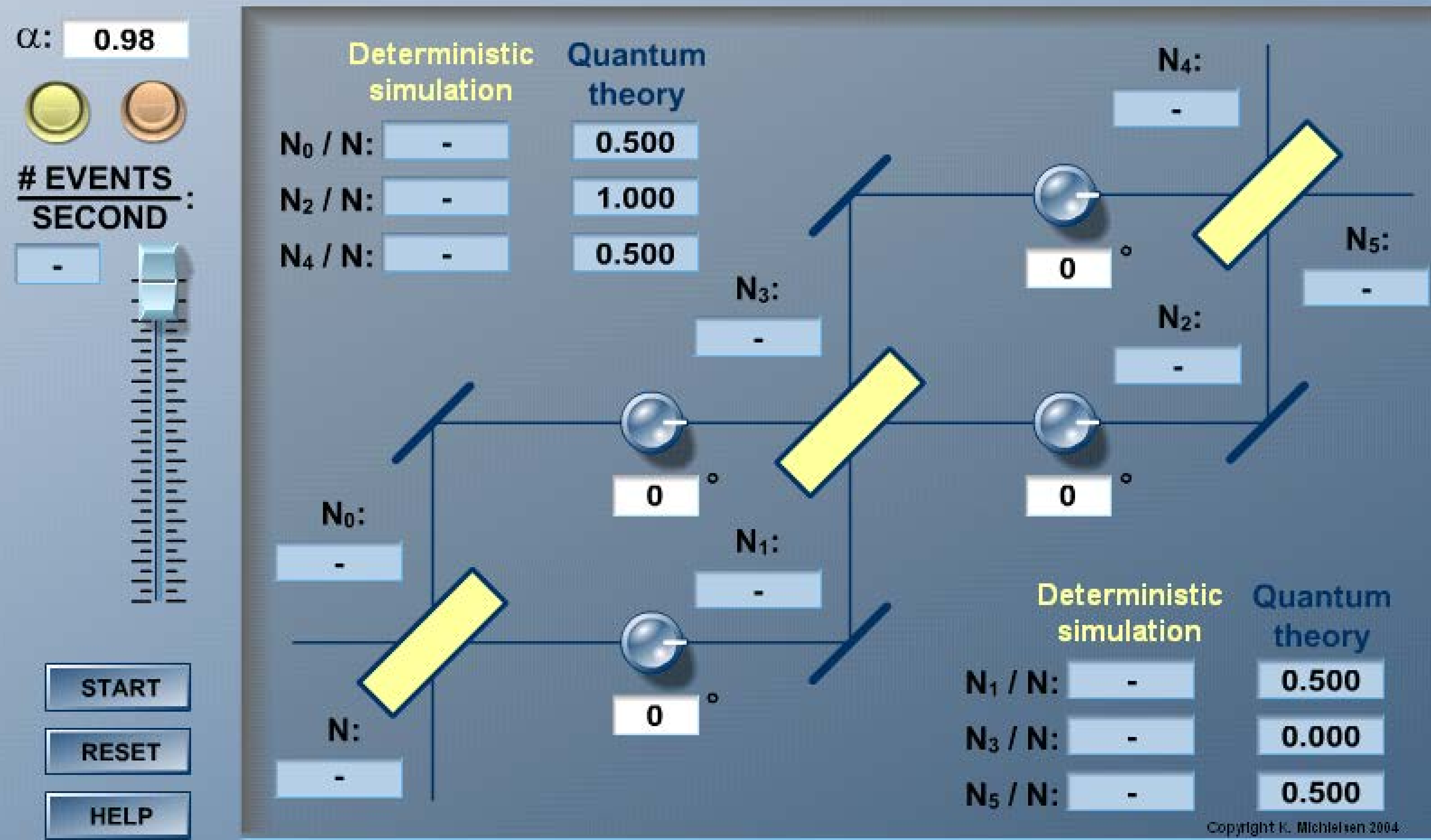


The angle of the hand ϕ as a function of the number of events. The handler is positioned at 30°. In this simulation α=0.99. For *n* > 60 the ratio of the number of 0 events to 1 events is 1/3, which is $(\sin 30° / \cos 30°)^2$. Data for *n* < 20 has been omitted to show the oscillating behavior more clearly. Lines are guides to the eyes.

Deterministic learning machines

- The combination of machine learning and decision taking generates output events of type 0 or 1 with frequencies that are identical to quantum mechanical probabilities
- This process is strictly deterministic
  - A marginal modification to the machine yields stochastic output, without changing the frequencies
    - This is necessary to account for the apparent random nature of experimental observations

Single-photon Mach-Zehnder interferometers



Conclusions

- We may have discovered a systematic procedure to construct algorithms that simulate quantum phenomena on an event-by-event basis using deterministic, causal and local processes
- These processes can generate events with frequencies that agree with the probability distributions of quantum theory
  - Exhibit “quantum interference”

Conclusions

- The same approach has been used to perform event-based simulations of the quantum gates that are necessary to build a universal quantum computer
  - See poster P19-14 by K. Michielsen
- A universal quantum computer can simulate the time evolution of quantum systems
    - C. Zalka, Proc. R. Soc. Lond. A454, 313 (1998)

Summary

- New approach for simulating quantum phenomena
- We have demonstrated that quantum interference can be simulated on an even-by-event basis using local, causal and deterministic processes, without using concepts such as wave fields or particle-wave duality
  - The simulation approach we have proposed satisfies Einstein's criteria of realism and causality