RESCUING QUANTUM MECHANICS FROM ATOMIC PHYSICS

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June 2002

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Thirty-one years ago [1949!], Dick Feynman told me about his "sum over histories" version of quantum mechanics. "The electron does anything it likes," he said. "It just goes in any direction at any speed, forward or backward in time, however it likes, and then you add up the amplitudes and it gives you the wave-function."

I said to him, "You're crazy."

But he wasn't.

-- Freeman Dyson, 1980

Using Feynman's path integral approach, based on the Principle of Least Action, there is no longer any difference between classical mechanics and quantum mechanics, except for a trivial adjustment to the mathematics. . .But . . . students are still taught classical mechanics the old-fashioned way, and then forced to train themselves into a new way of thinking in order to study quantum mechanics using the . . . Schrödinger equation. By the time most people learn about Feynman's approach (if they ever do), . . . it is hard to appreciate its simplicity, and galling to realize that they could have saved time and effort by learning quantum theory (and classical theory!) Feynman's way in the first place.

-- John and Mary Gribbin

Richard Feynman, A Life in Science

OUTLINE

1. Quantum mechanics, child of atomic physics, has outgrown its parent.

2. Sum over histories is a simple, fundamental, and powerful introduction to quantum mechanics.

3. Excerpts from incompletely realized story line on sum over histories.

4. Modern applications in context

5. Longer story line connecting general relativity, Newtonian mechanics, & quantum mechanics

6. Abbie Hoffman : "Steal this Book"

1. Quantum mechanics, child of atomic physics, has outgrown its parent.

Quantum mechanics grew out of the effort to decode the atom.

The "story line" of quantum mechanics has remained (pseudo!) historical – atomic physics.

Summary of first three chapters of French and Taylor QM text:

"Waves are particles and particles are waves. Here is a wave equation.

Let's go!"

Solving the Schrödinger equation is a professional specialty for those who manipulate the atom and its constructs But many current fields make different (more basic?) uses of quantum mechanics

NON-SCHRÖDINGER-APPLICATIONS

Photon quantum mechanics (Holbrow et al et al et al)

Quantum seeing in the dark

Delayed choice experiments

Entangled states

EPR experimentssssssss

Quantum information (qubit vs. bit)

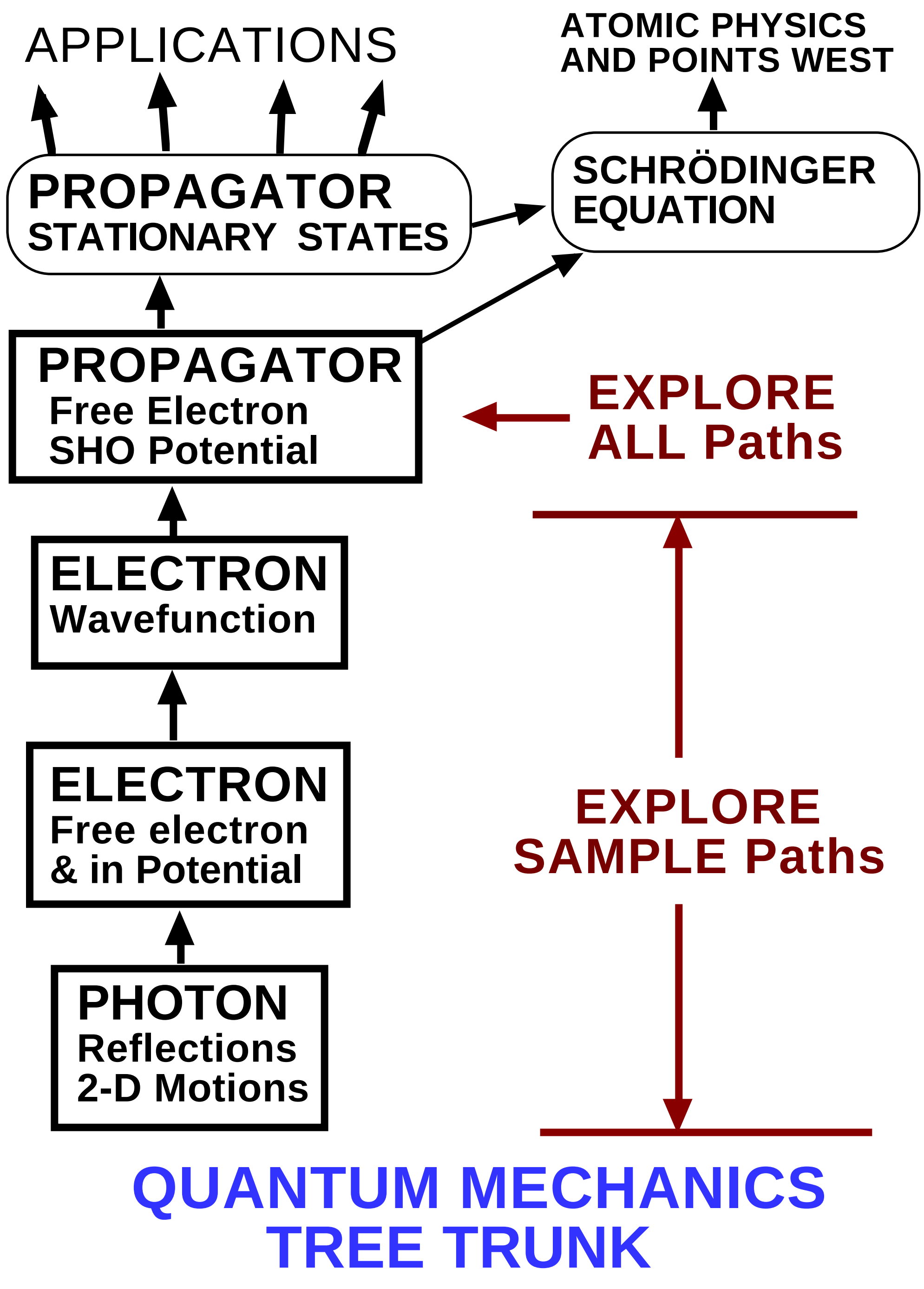
Quantum computing

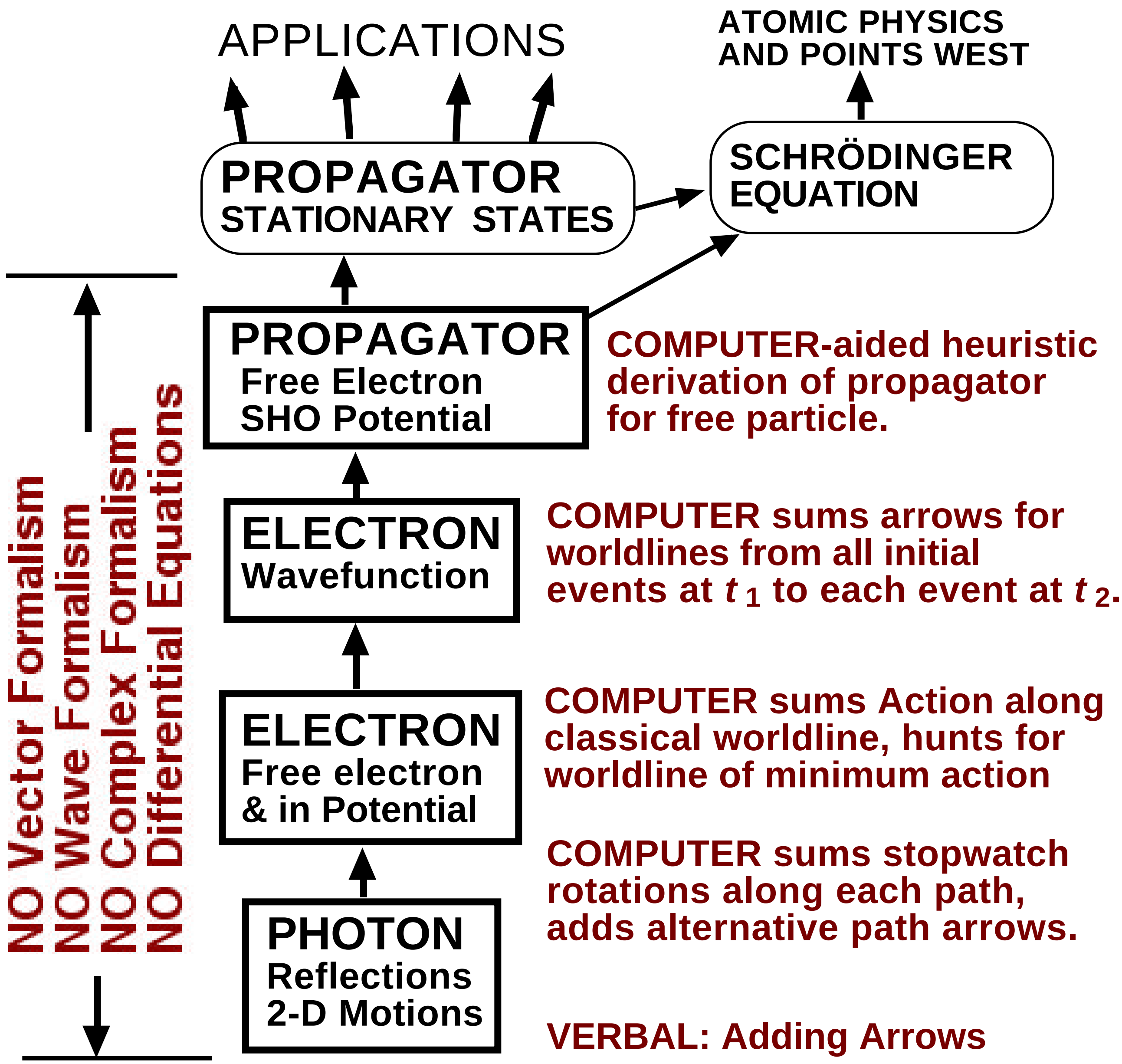
Quantum teleportation

Quantum cryptography

Feynman diagrams (Schroeder)

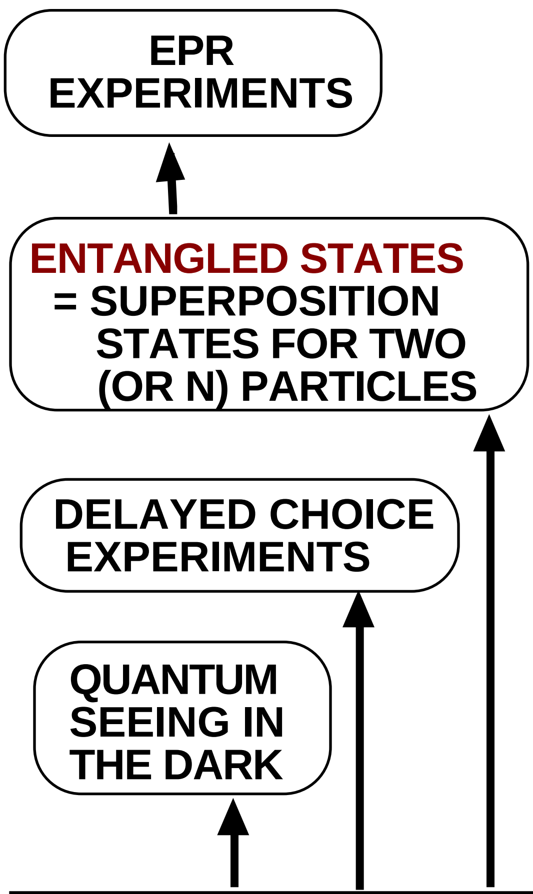
2. "Explore all paths!" is a simple, basic, and powerful introduction to quantum mechanics. Excerpts from an incompletely realized story line





COMPUTER DOES THE HEAVY LIFTING

Introduce notation with modern applications



NOTATION: Photon Polarization States (with real equipment)

state: $|\psi\rangle$

amplitude = $\langle x|\psi\rangle$

probability = $|\langle x|\psi\rangle|^2$

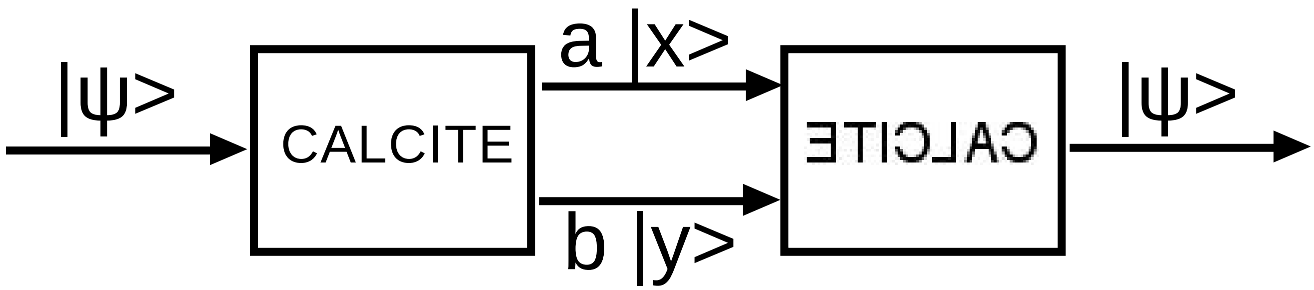
Alternative representations

$|\psi\rangle = a\,|x\rangle + b\,|y\rangle$

$= e\,|R\rangle + g\,|L\rangle$

SUM OVER PATHS IMPLIES SUPERPOSITION STATES

"xy ANALYZER LOOP" for photons

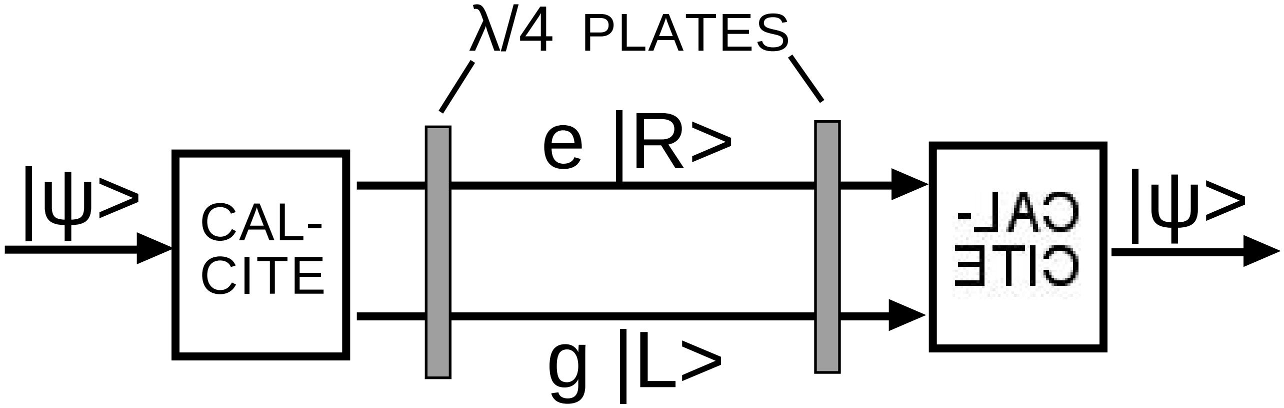


$$|\psi\rangle = a\,|x\rangle + b\,|y\rangle$$

ANY state |ψ> can be dismantled and reconstituted. This is the meaning of statement that |x> and |y> form a *complete set.*

Arbitrary orientation of xy axes implies there are an infinite number of alternative two-state complete sets.

Use quarter-wave plates to convert to "RL analyzer," yielding yet another complete set (& photon with spin one)



$$|\psi\rangle = e\,|R\rangle + g\,|L\rangle$$

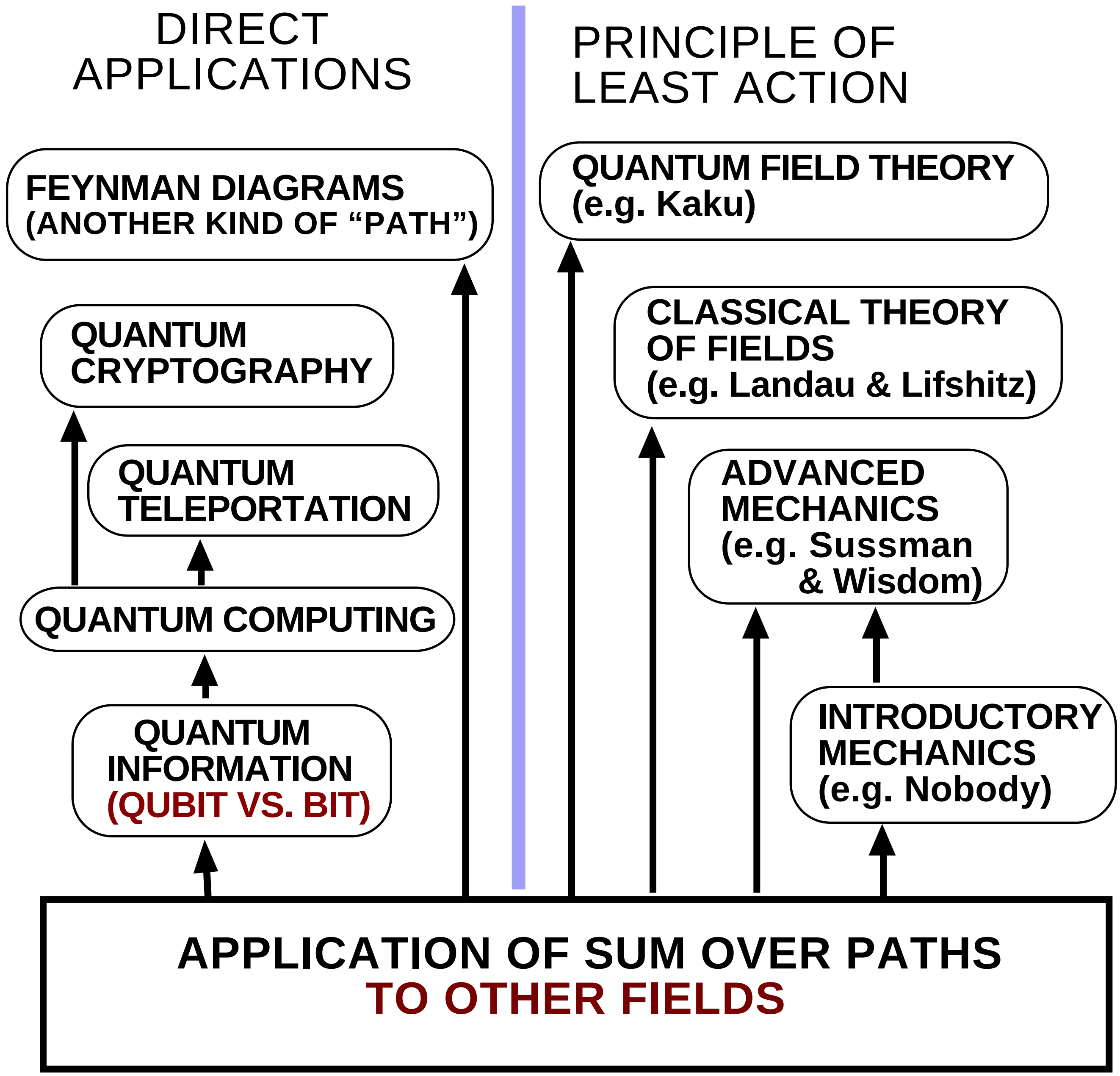
The states in ANY two-state complete set can be assigned the arbitrary indices 0 and 1.

The result is the QUBIT, the central actor in quantum information, computing, teleportation, cryptography

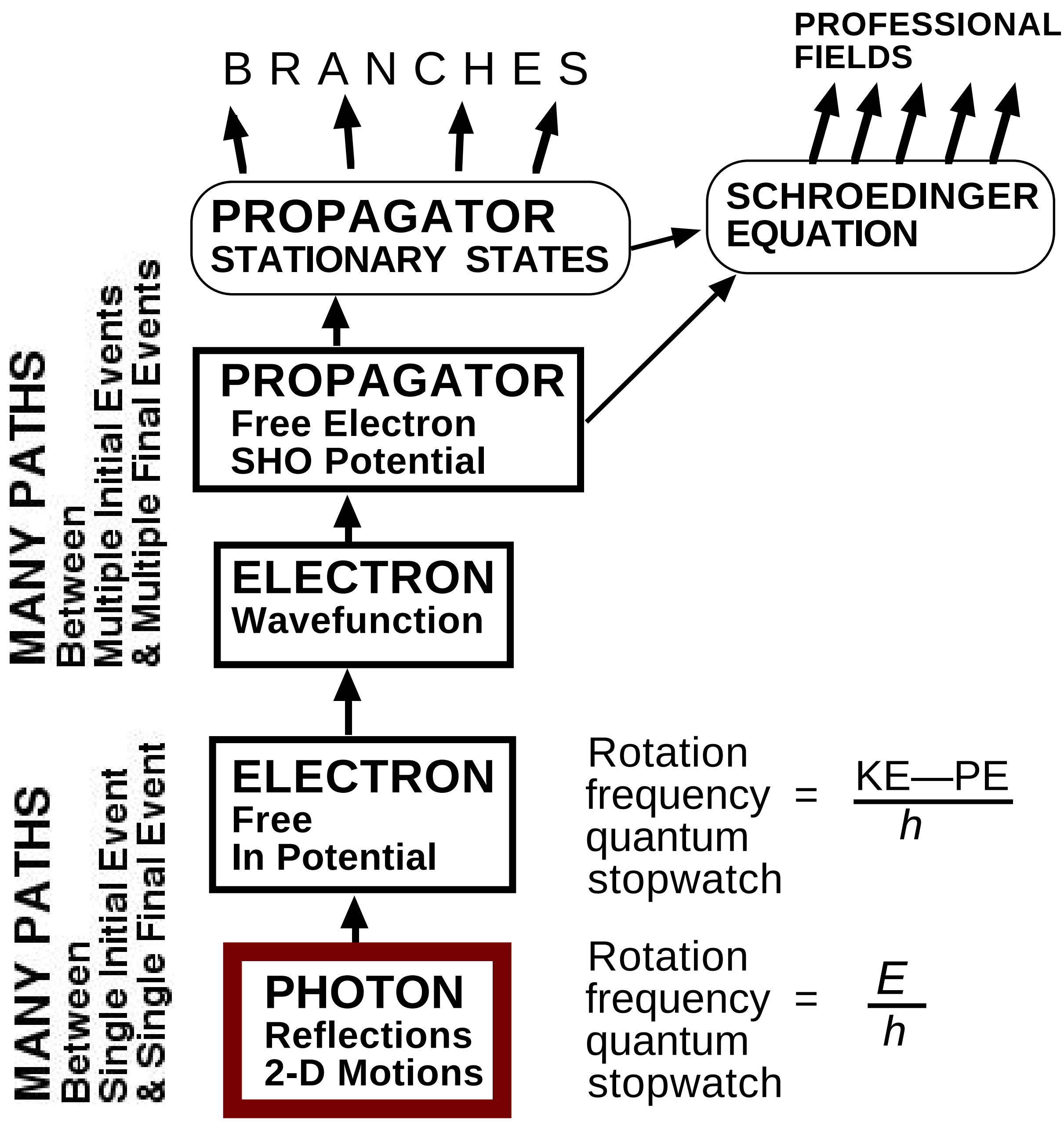
$$|Q\rangle = a\,|0\rangle + b\,|1\rangle$$

Replaces BIT (0 or 1) in classical computing

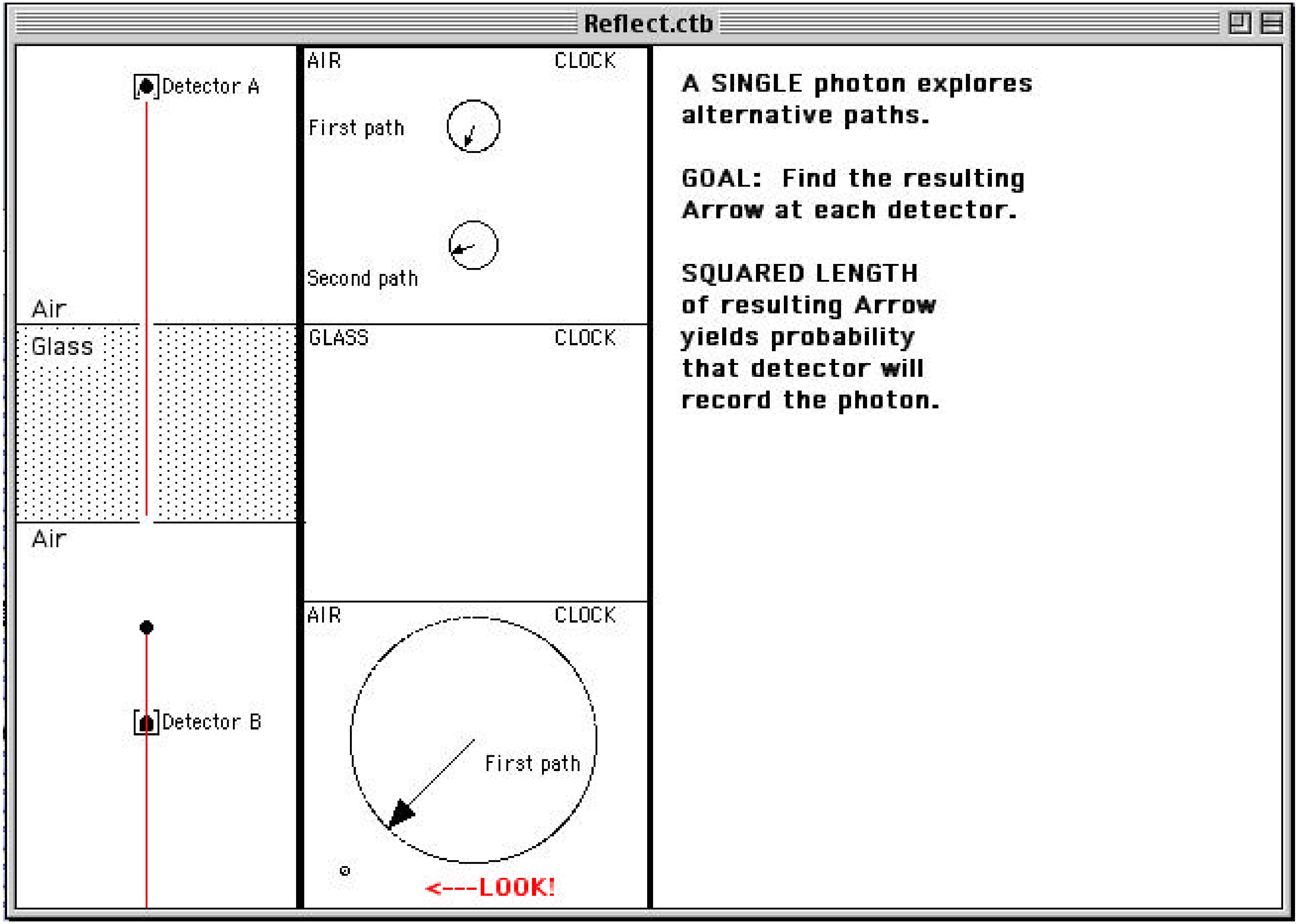
3. Additional modern applications



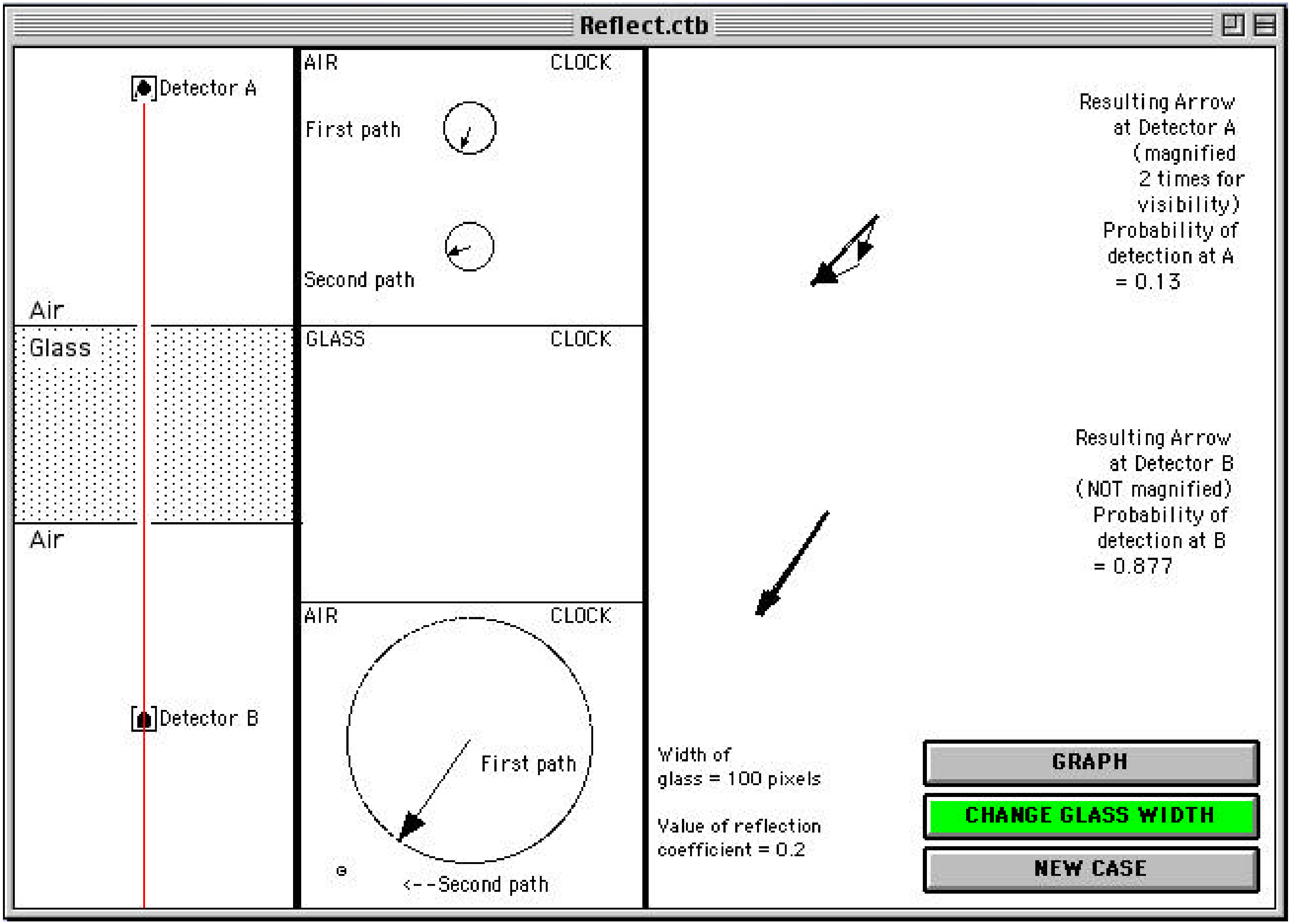
SOME DETAILS:
OF STORY LINE
START WITH PHOTONS



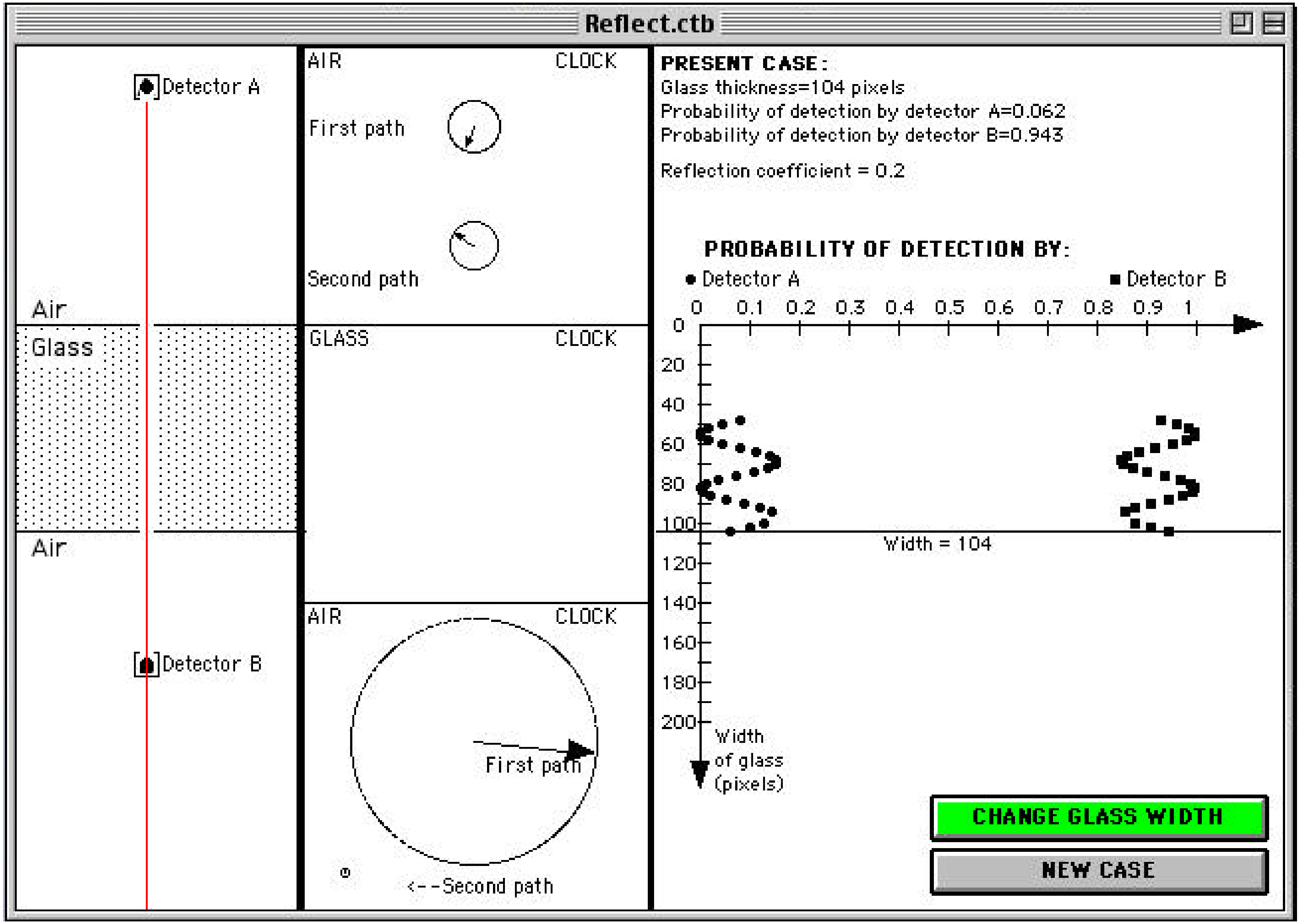
QUANTUM MECHANICS TREE TRUNK



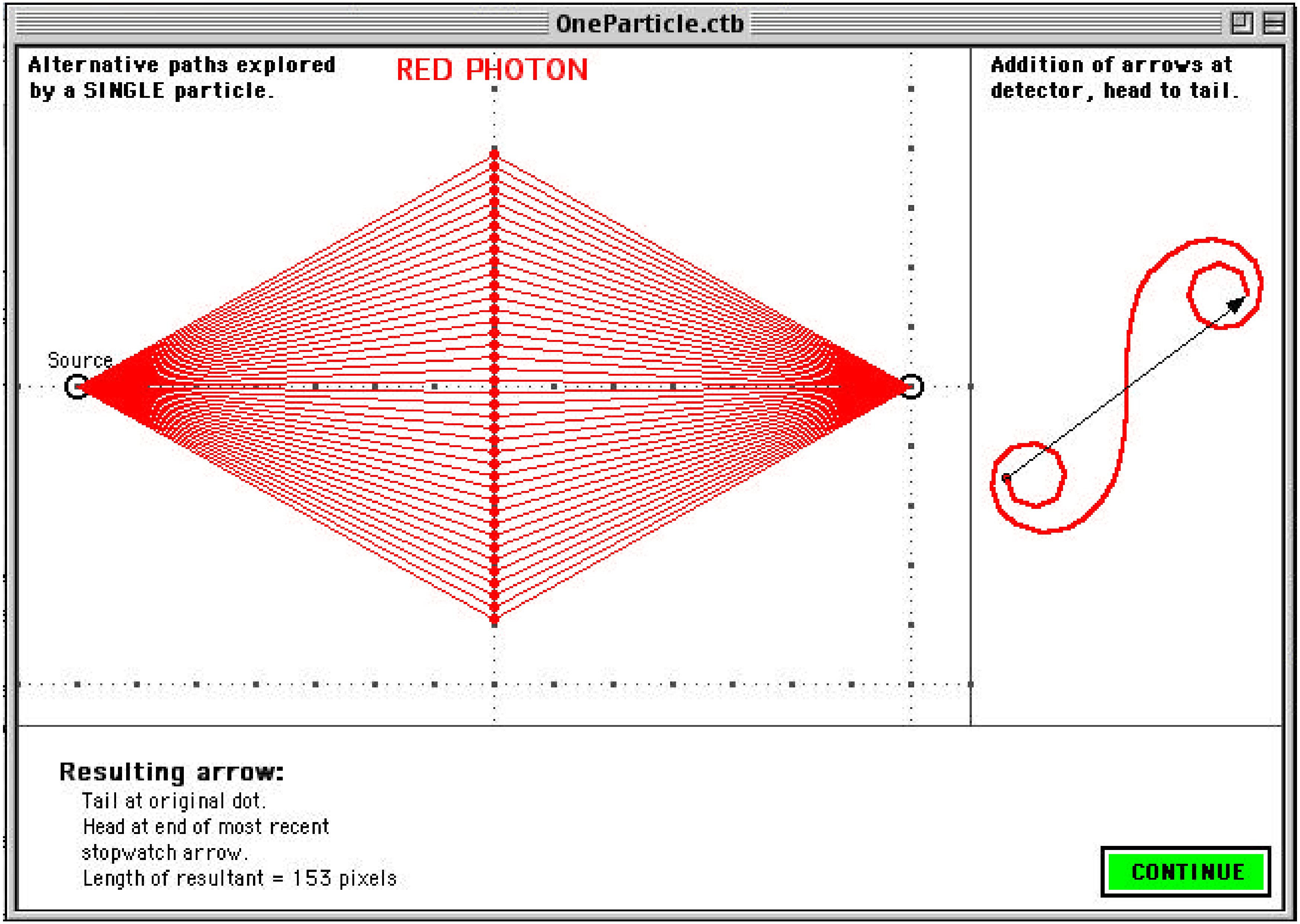
MULTIPLE REFLECTION PATHS FROM SOURCE TO DETECTORS



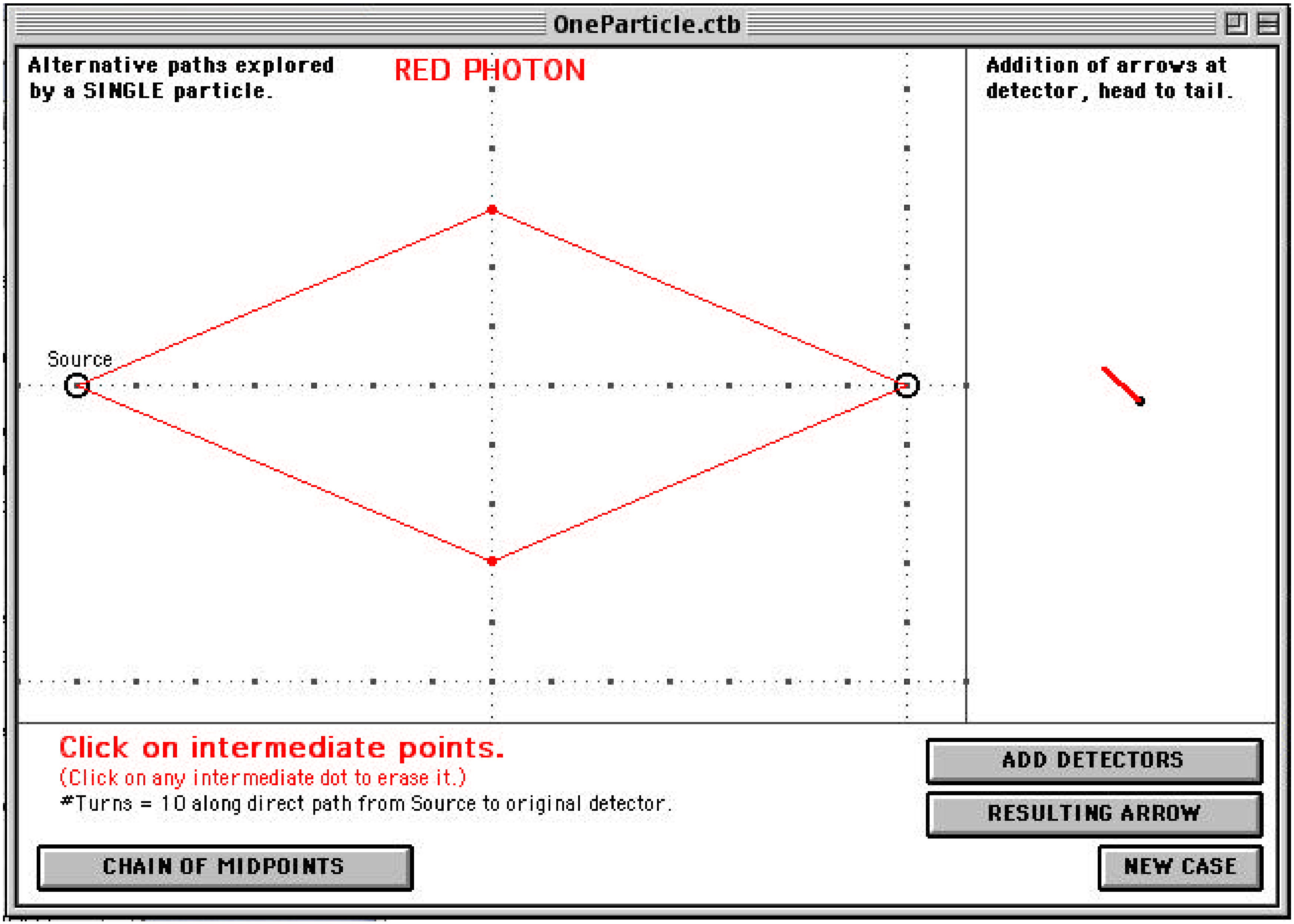
RESULTING QUANTUM AMPLITUDES AT DETECTORS A & B



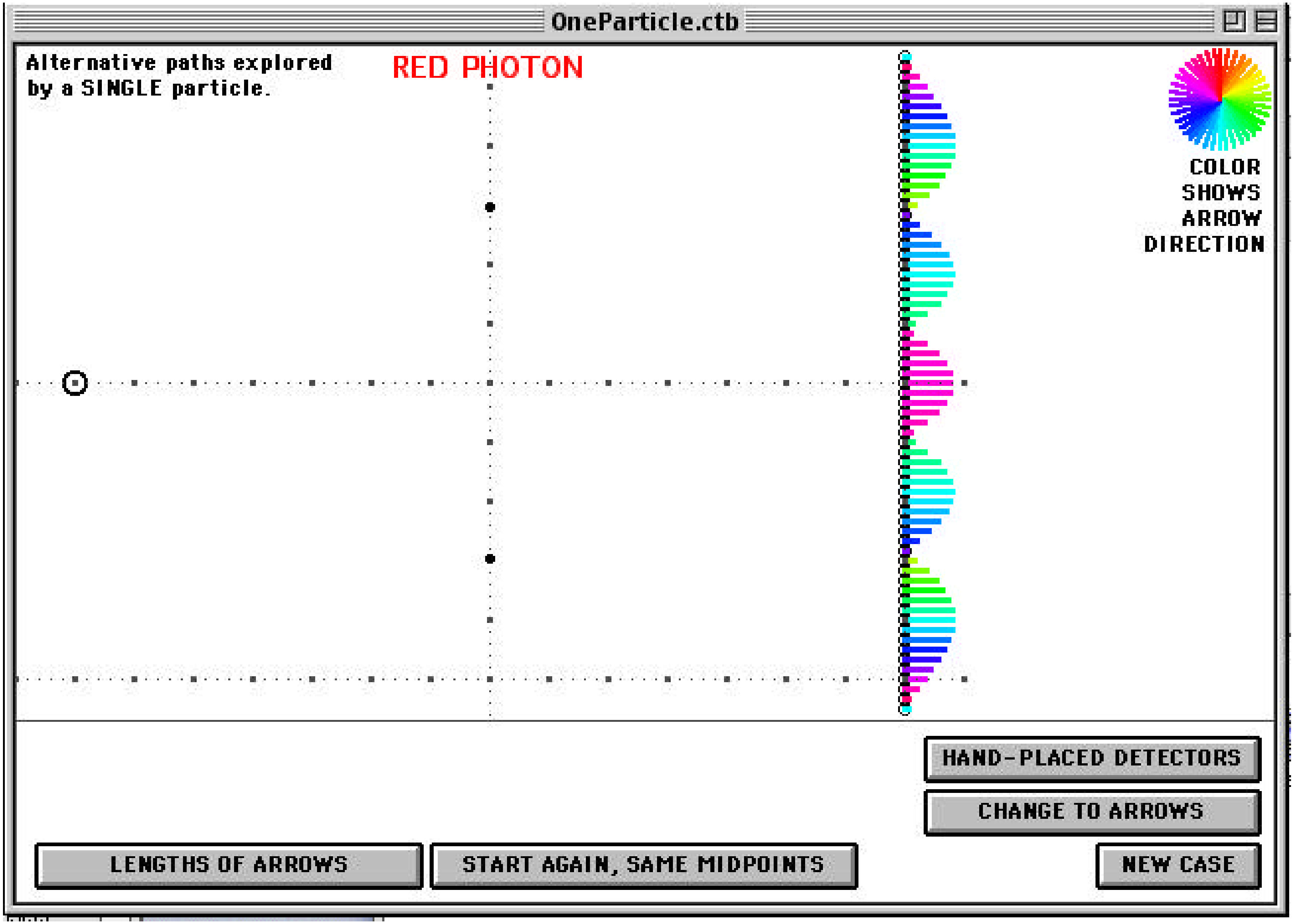
PROBABILITY = SQUARED MAG. OF RESULTANT AMPLITUDE



RESULTANT ARROW SUM OF ARROWS FOR ALTERNATIVE PATHS

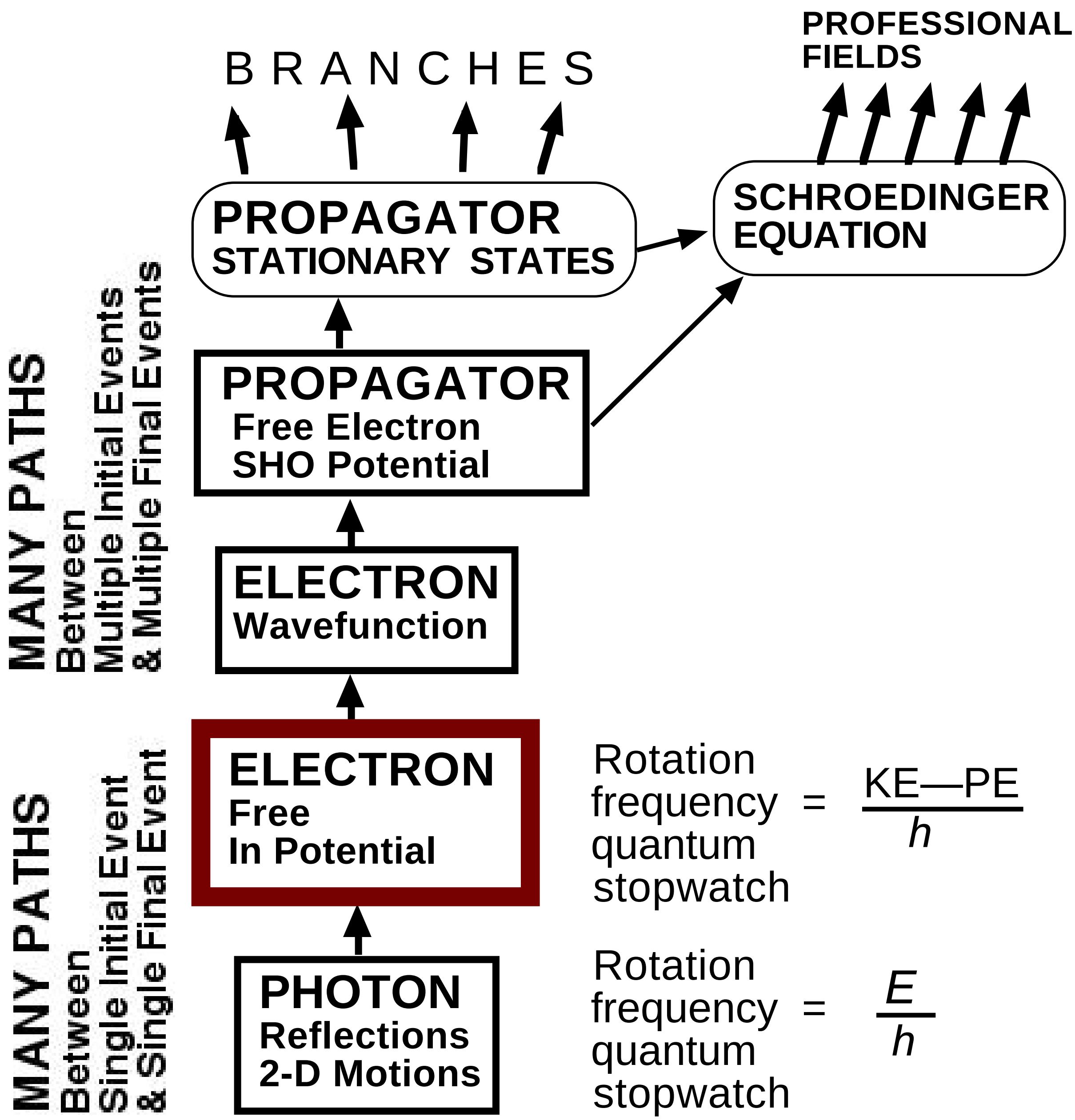


TWO-SLIT INTERFERENCE

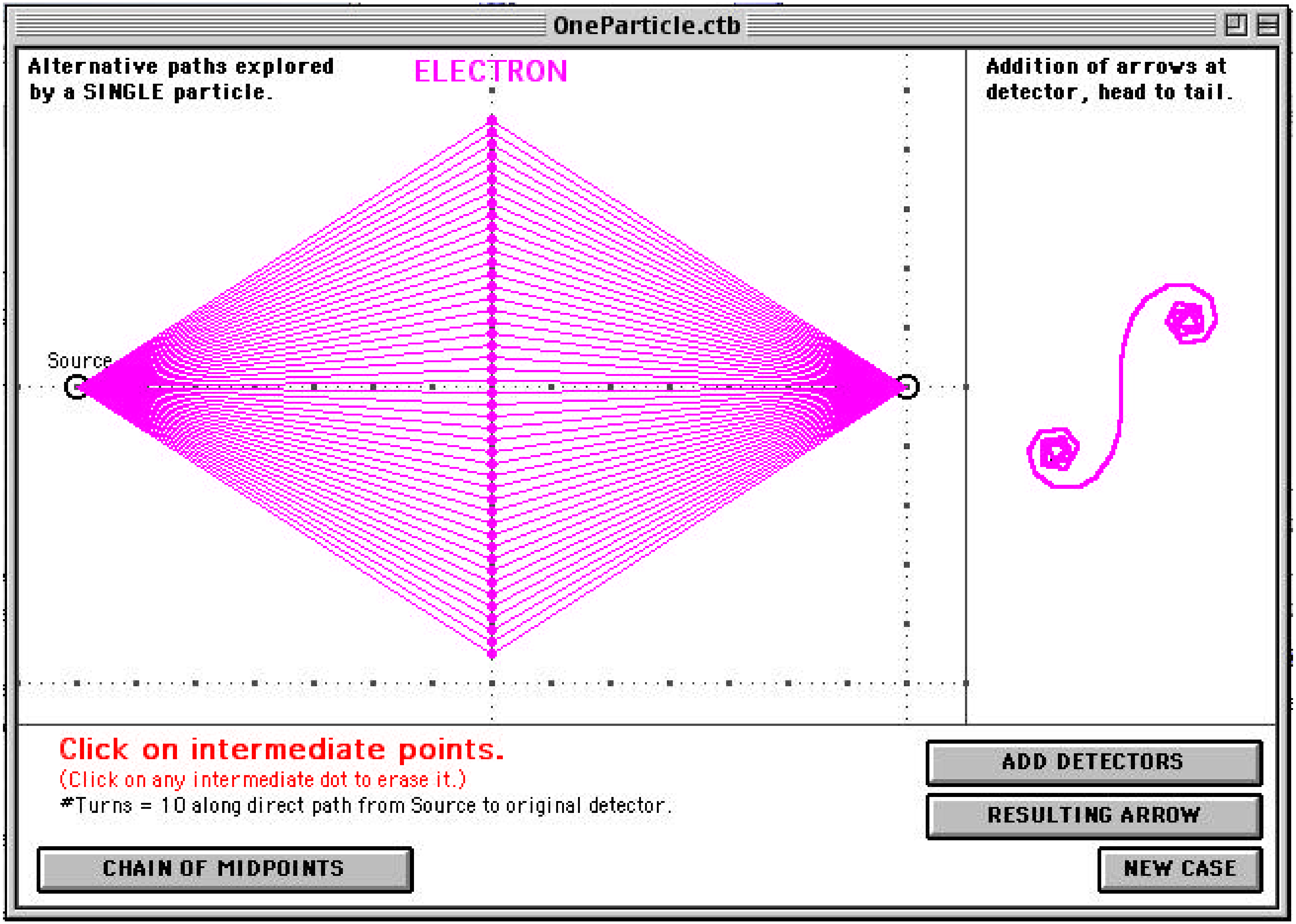


STYER REPRESENTATION OF ARROW DIRECTION

CONTINUE STORY LINE
MOVE ON TO ELECTRONS



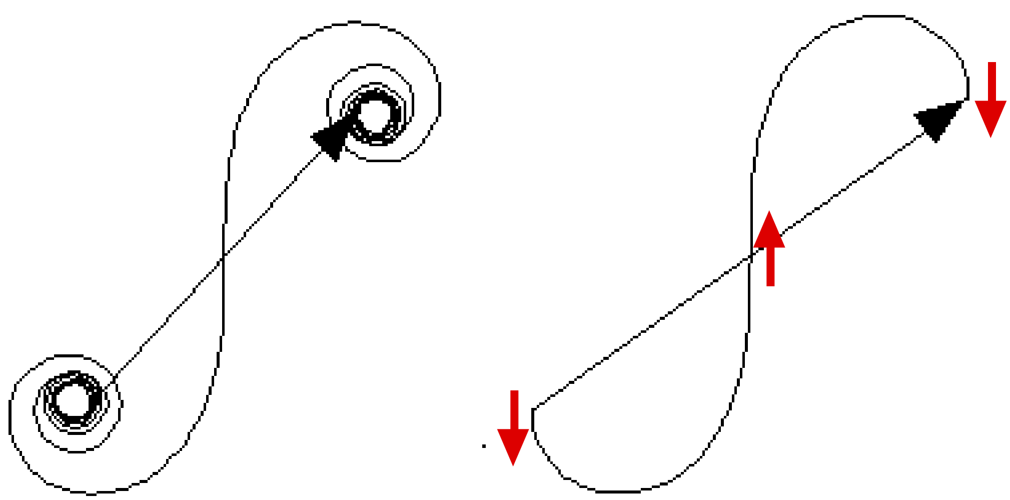
QUANTUM MECHANICS TREE TRUNK



FREE ELECTRON ARROW ROTATION RATE: KE/ h

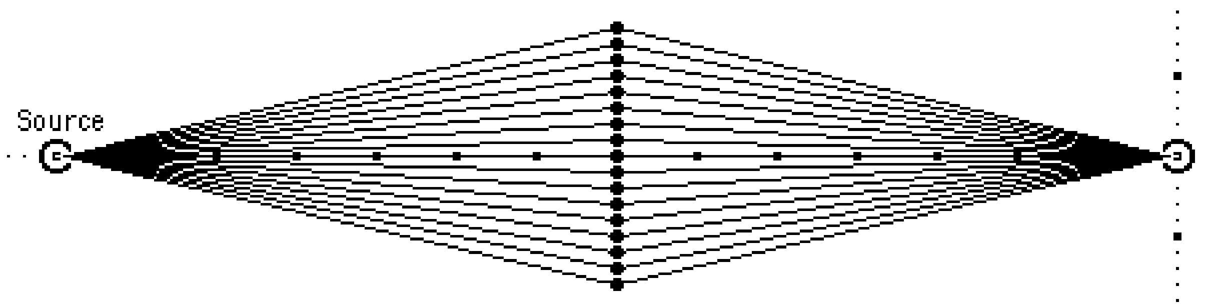
SEAMLESS TRANSITION TO CLASSICAL MECHANICS

In principle, the electron takes an infinite range of alternative paths, but there is a "pencil" of paths that make the major contributions to the resulting vector

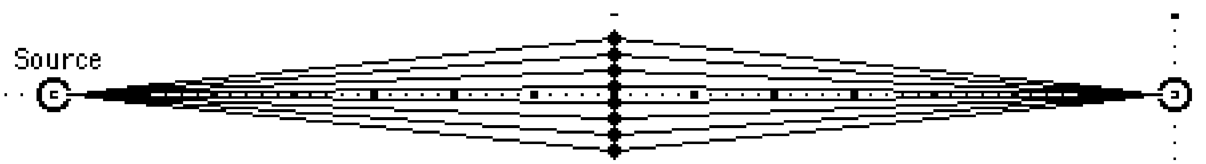


The “pencil” of paths making major contribution to final arrow shrinks as the mass increases.

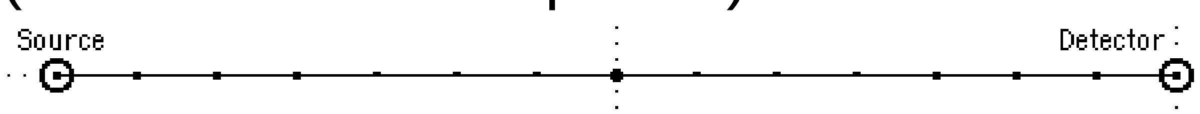
For mass = mass of electron:



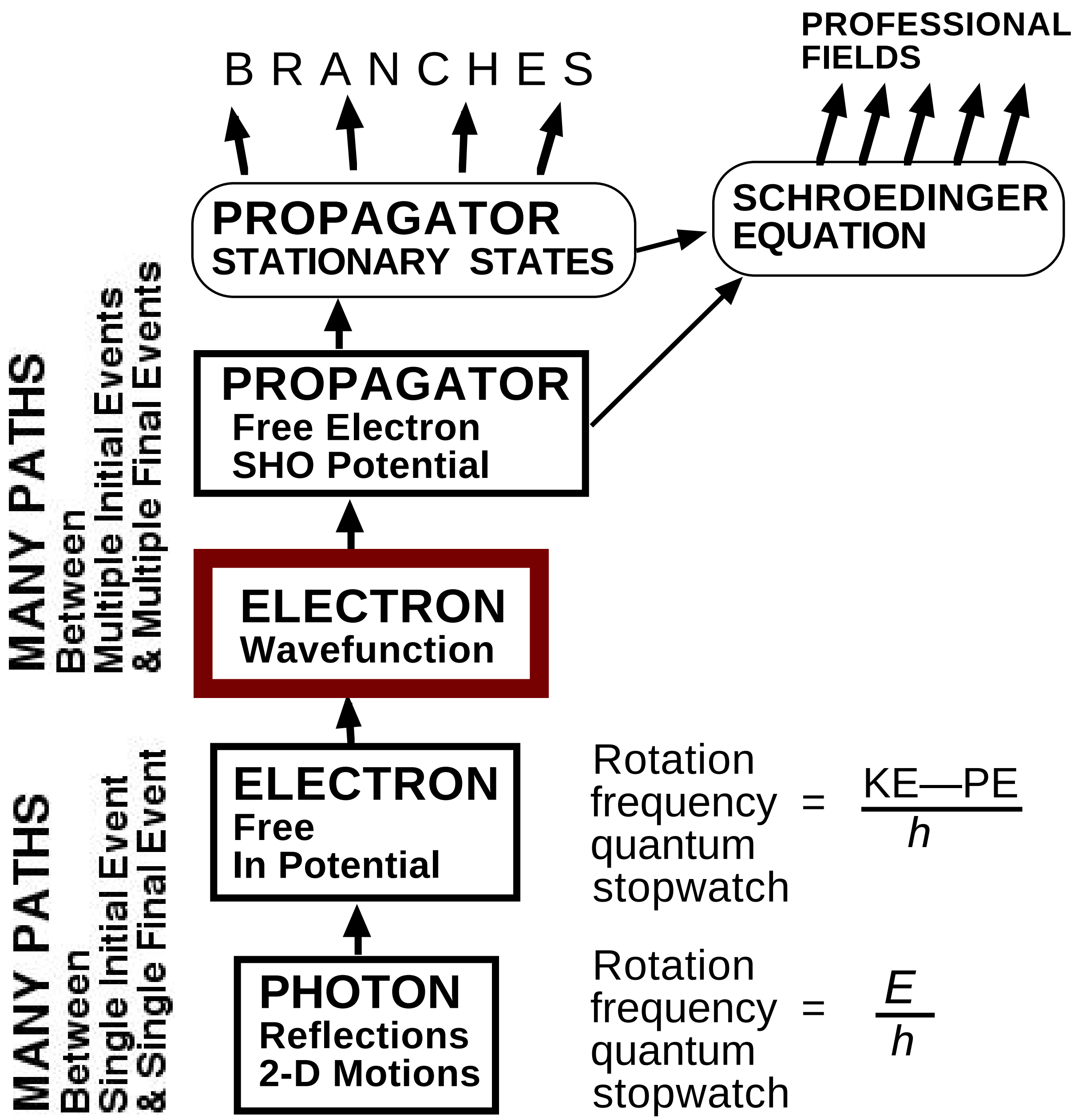
For mass = 4 times mass of electron



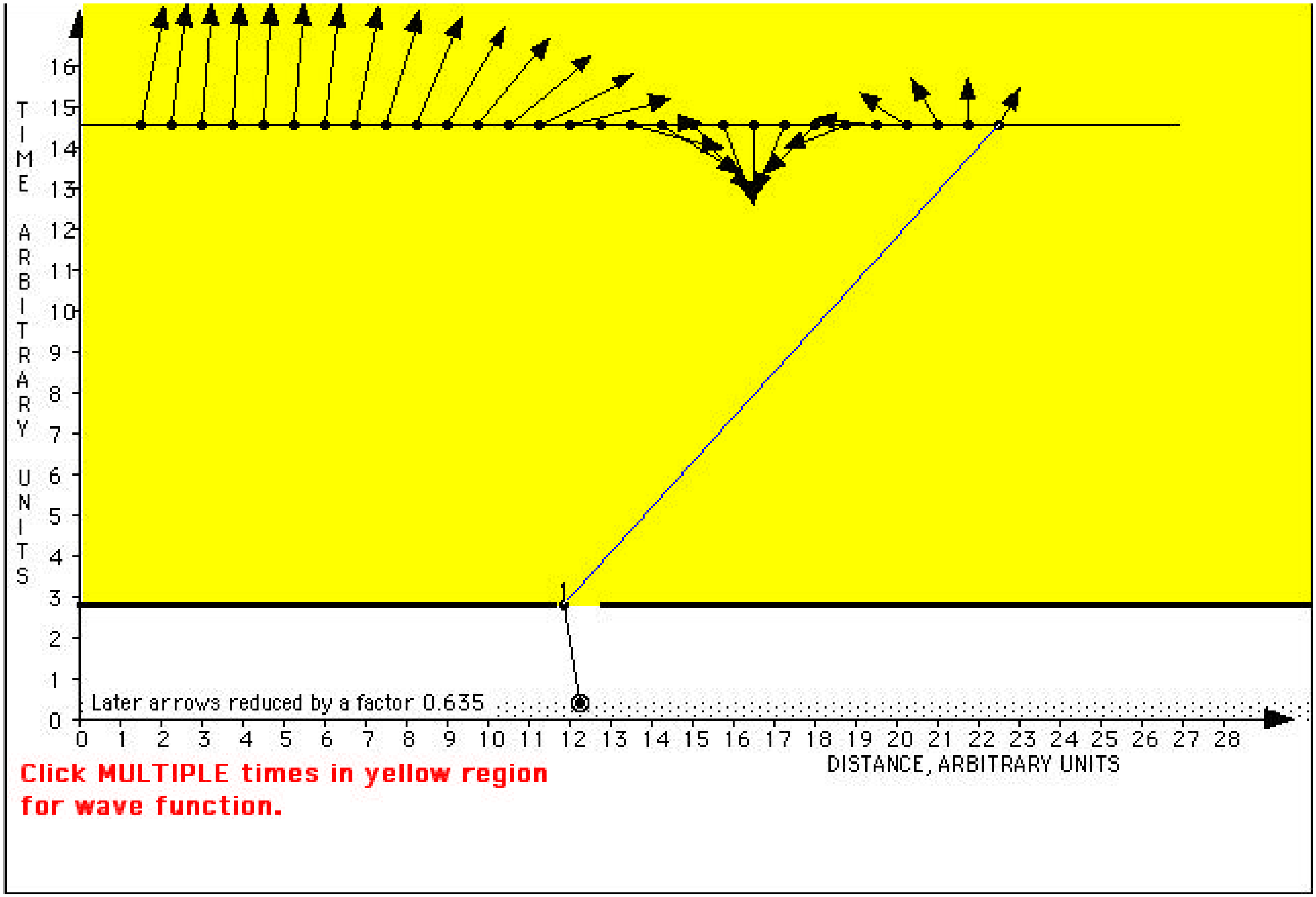
For mass = 1000 times mass of electron (half the mass of a proton)



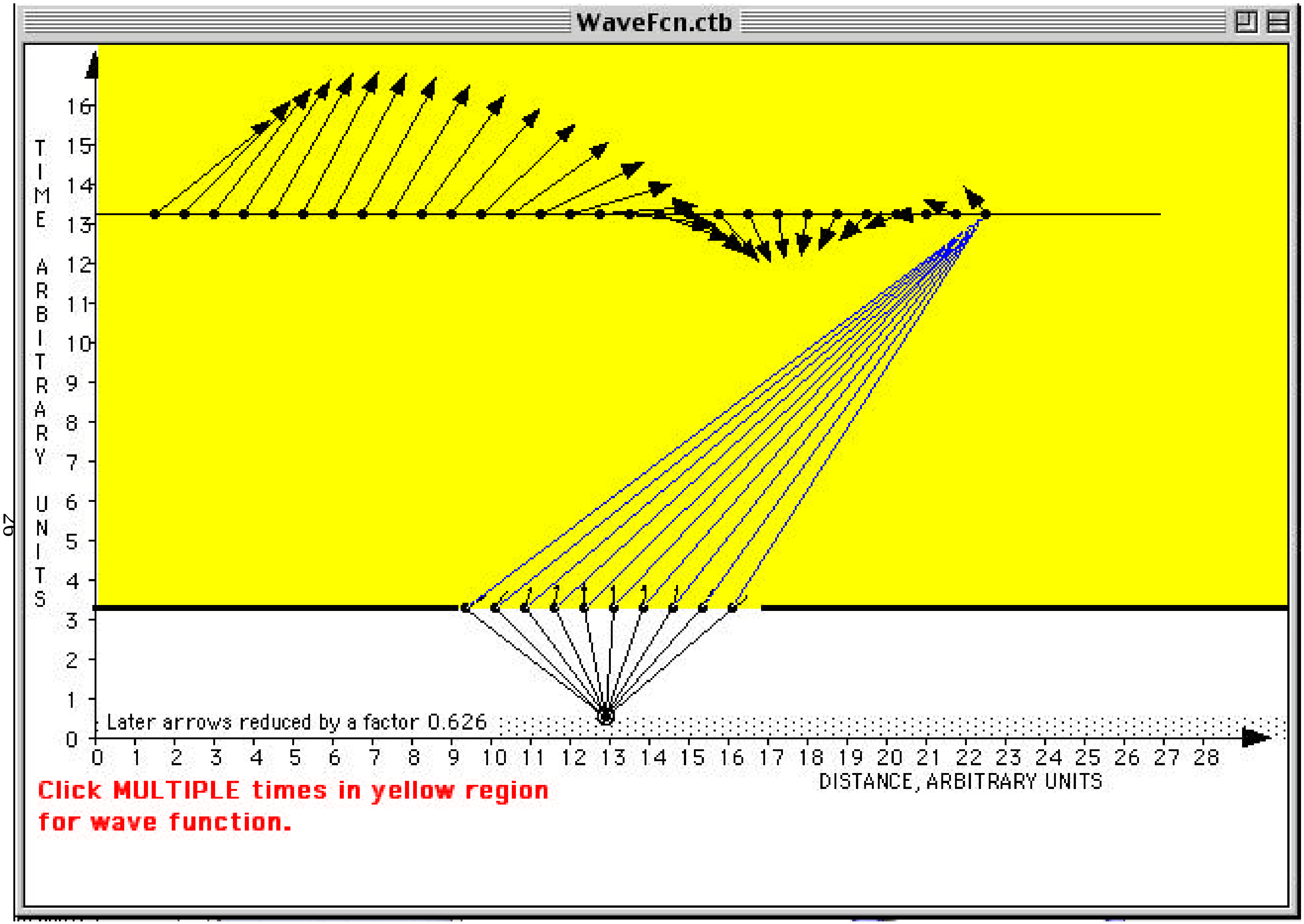
INTRODUCE THE WAVEFUNCTION



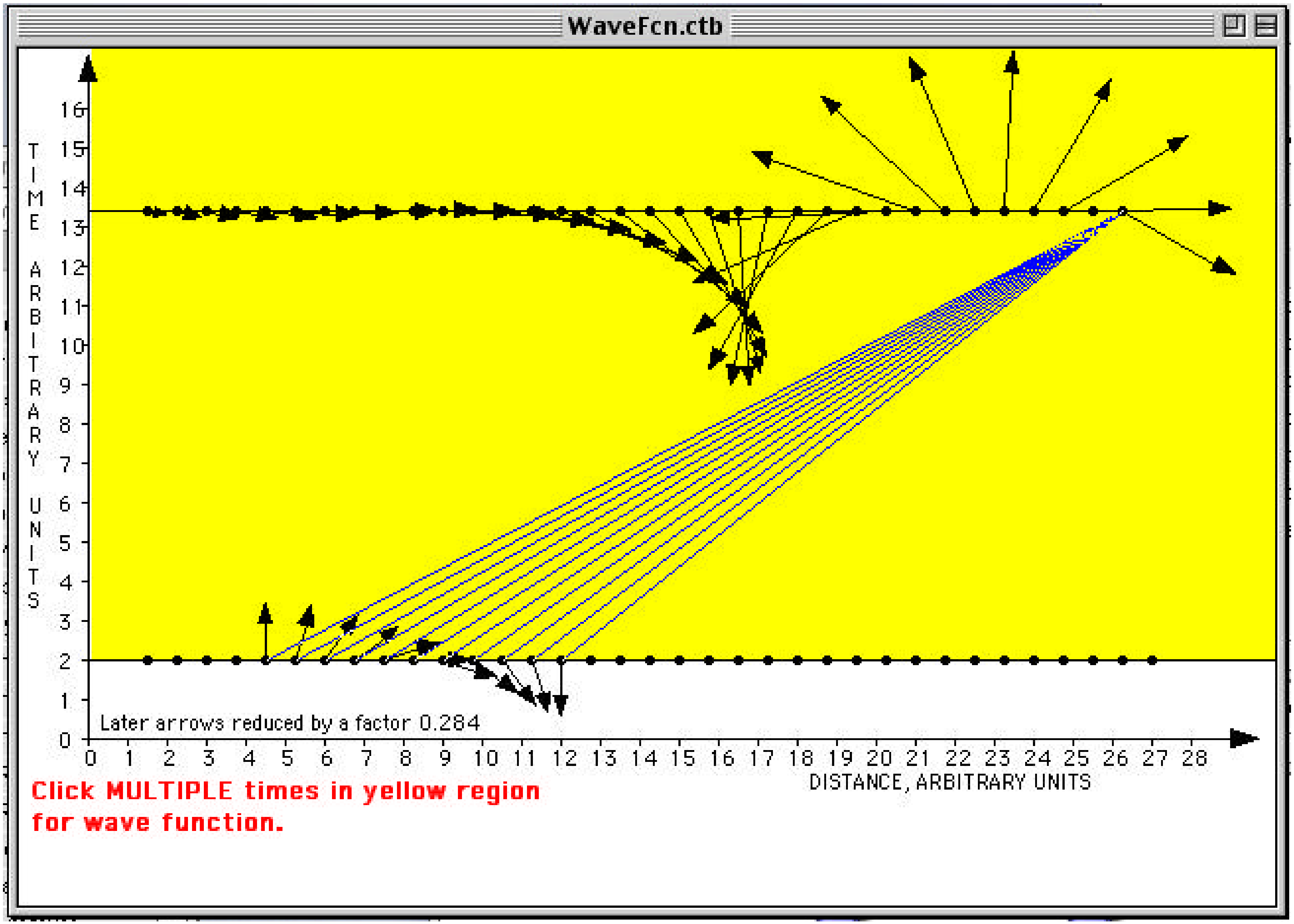
QUANTUM MECHANICS TREE TRUNK



ONE INITIAL SOURCE, MULTIPLE POSSIBLE DETECTIONS

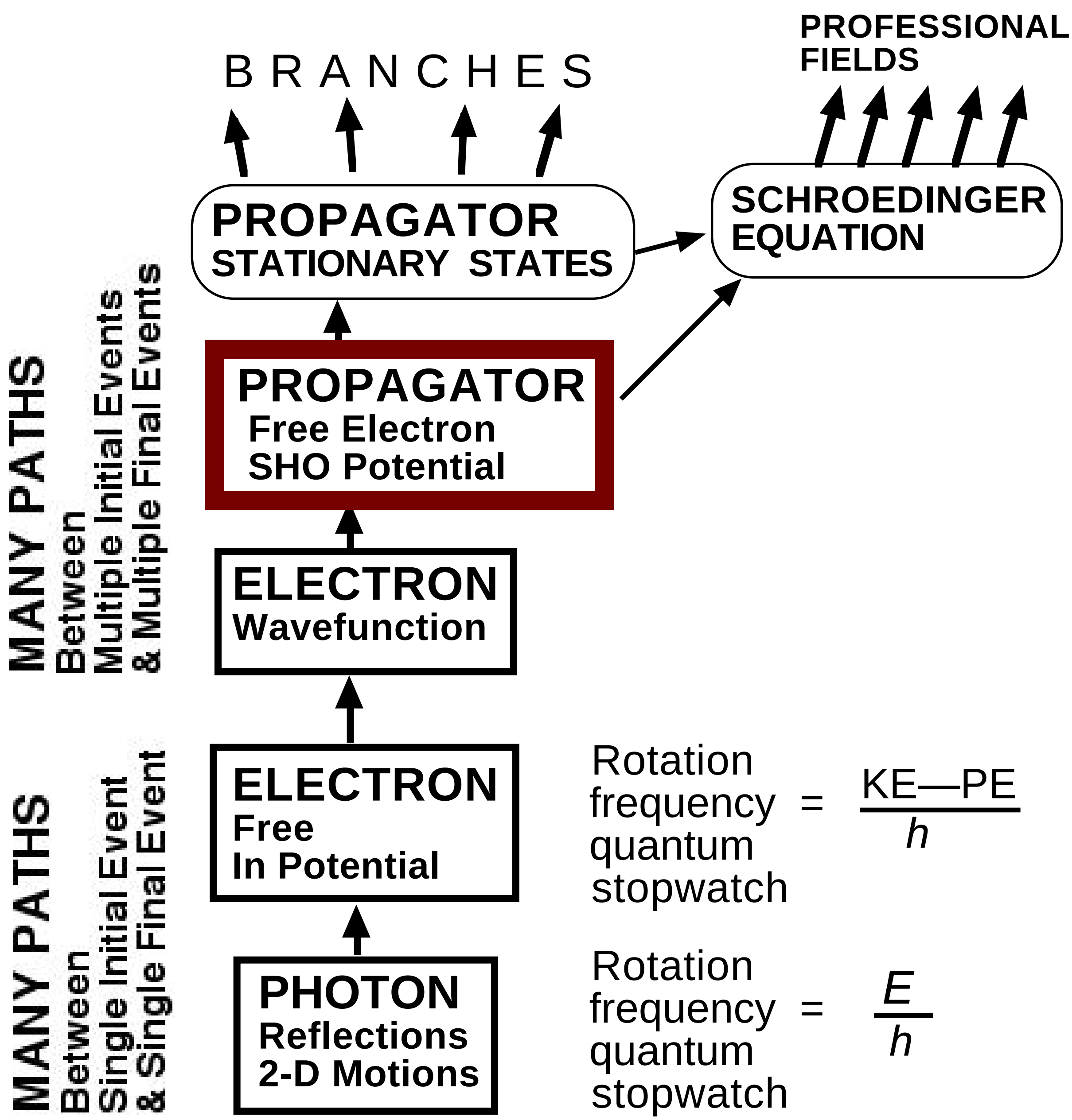


COHERENT INITIAL SOURCES, MULTIPLE POSSIBLE DETECTIONS



ARBITRARY INITIAL **WAVEFUNCTION** PROPOGATES IN TIME

PROPAGATOR CONVERTS SAMPLING OF PATHS TO ALL PATHS



QUANTUM MECHANICS TREE TRUNK

PROPAGATOR summarizes result of ALL paths from one initial event *a* to one final event *b*. (Feynman calls it the KERNEL, hence symbol K)

$$\begin{pmatrix}\text{arrow at}\\ \text{event } b\end{pmatrix} = K(b,a)\begin{pmatrix}\text{arrow at}\\ \text{event } a\end{pmatrix}$$

***K(b,a)* simply rotates arrow *a*, changes its length to contribute to arrow *b*.**

Final arrow at *b* is sum of propagated arrows from initial events.

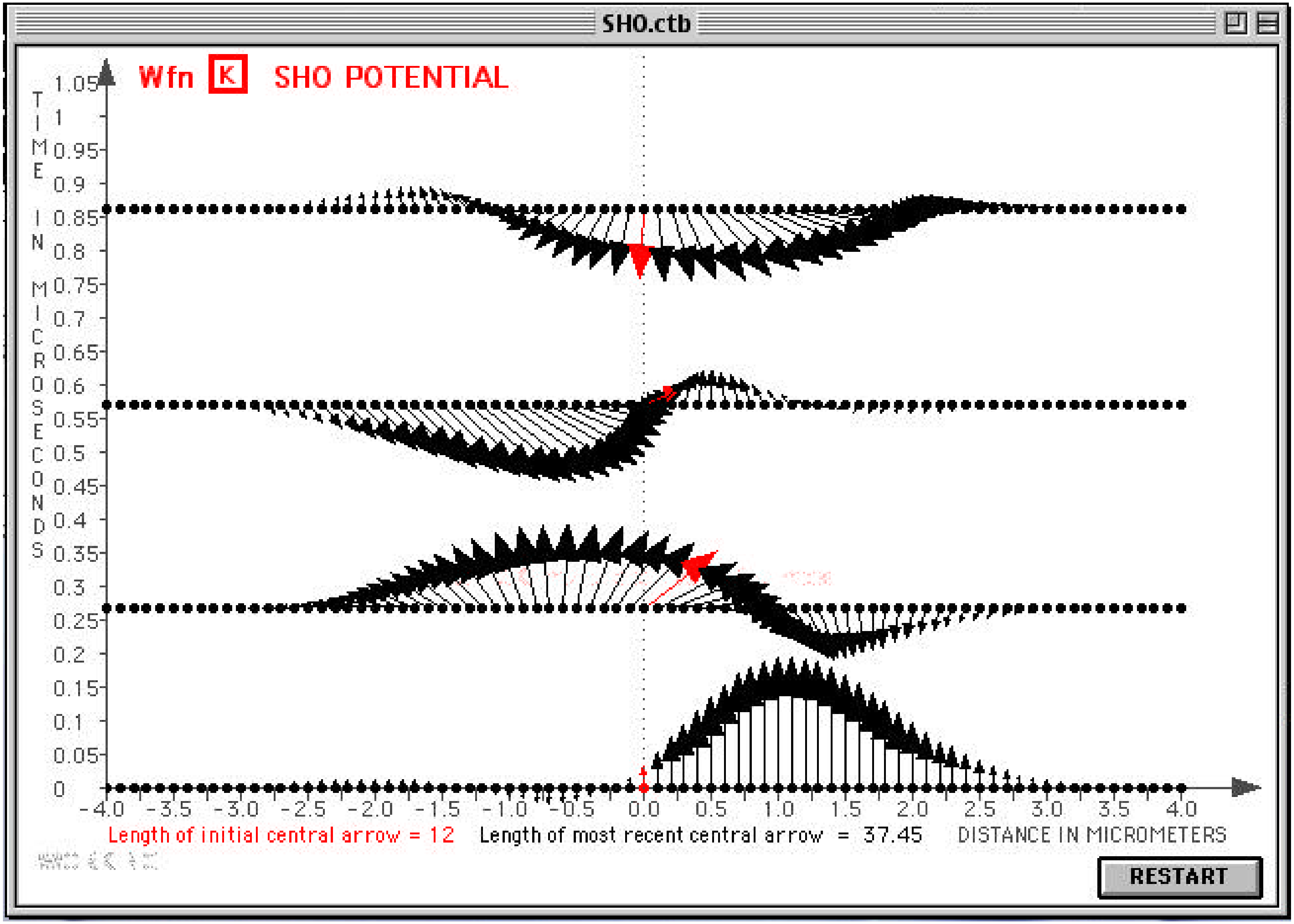
Sum over initial arrows goes to integral over initial wavefunction:

$$\psi(x_b, t_b) = \int_{-\infty}^{+\infty} K(b,a)\,\psi(x_a, t_a)\,dx_a$$

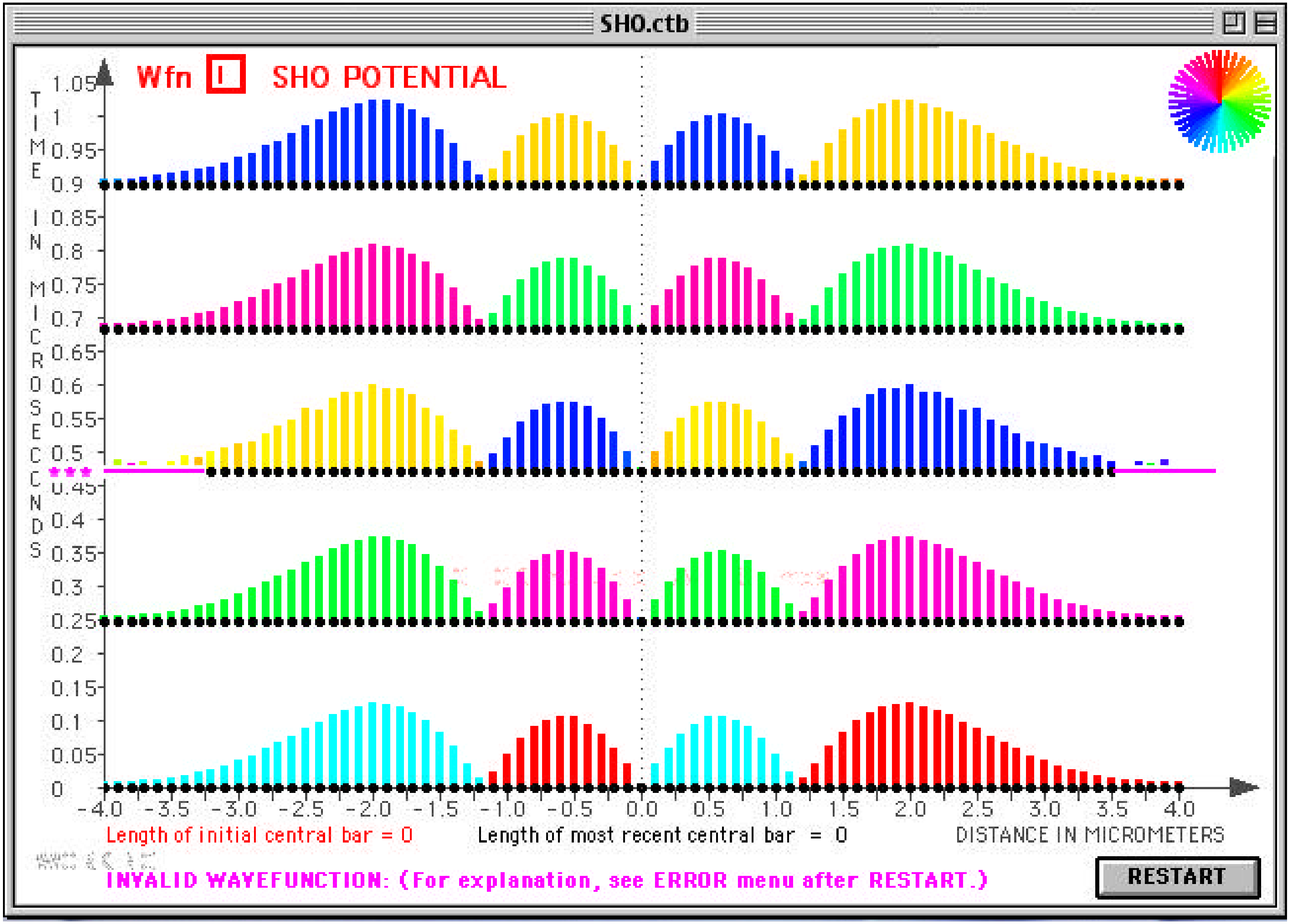
(Until now just words, no equations.)

Heuristic derivation of propagator for free particle, using computer and trial and error.

GIVEN propagator for simple harmonic oscillator in computer program, can discover stationary states as special case of "sloshing" probabilities for arbitrary initial wavefunction.



SUPERPOSITION OF FIRST THREE SHO ENERGY STATES



TIME DEVELOPMENT OF FOURTH SHO STATIONARY STATE

SUMMARY OF A STORY LINE

SPECIAL RELATIVITY
GENERAL RELATIVITY

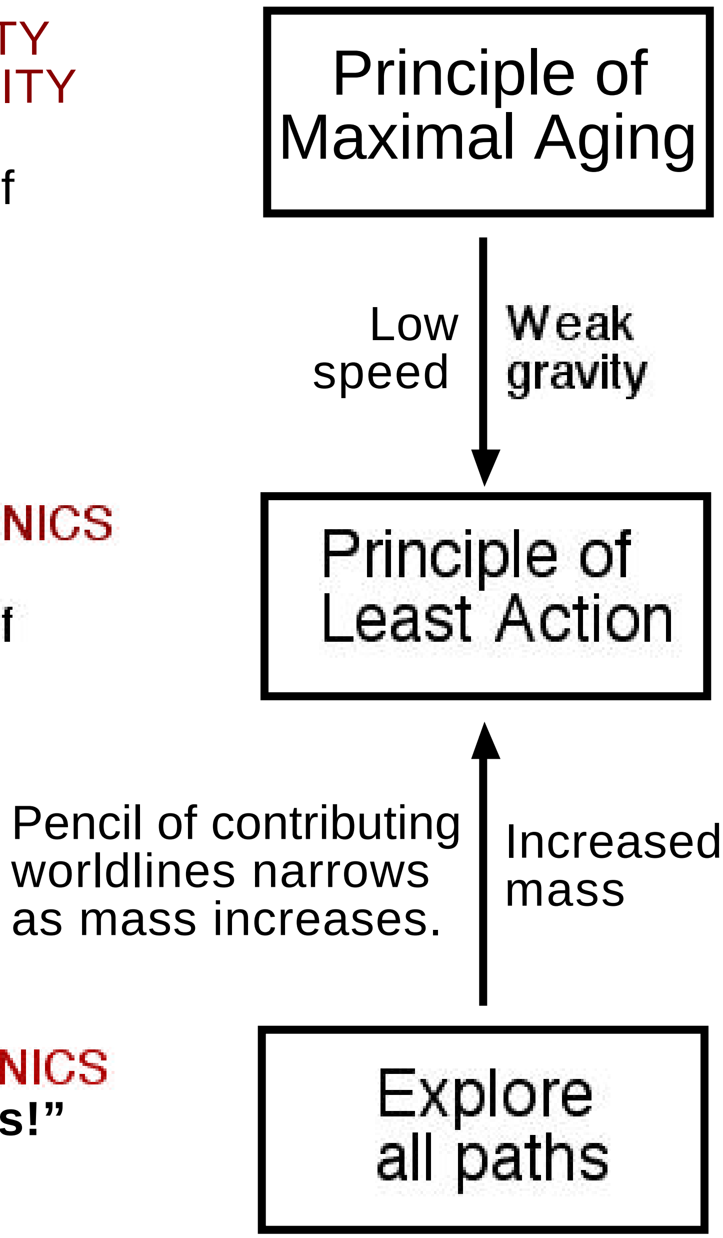
"Go straight!"
(Follow worldline of maximal aging.)

CLASSICAL MECHANICS

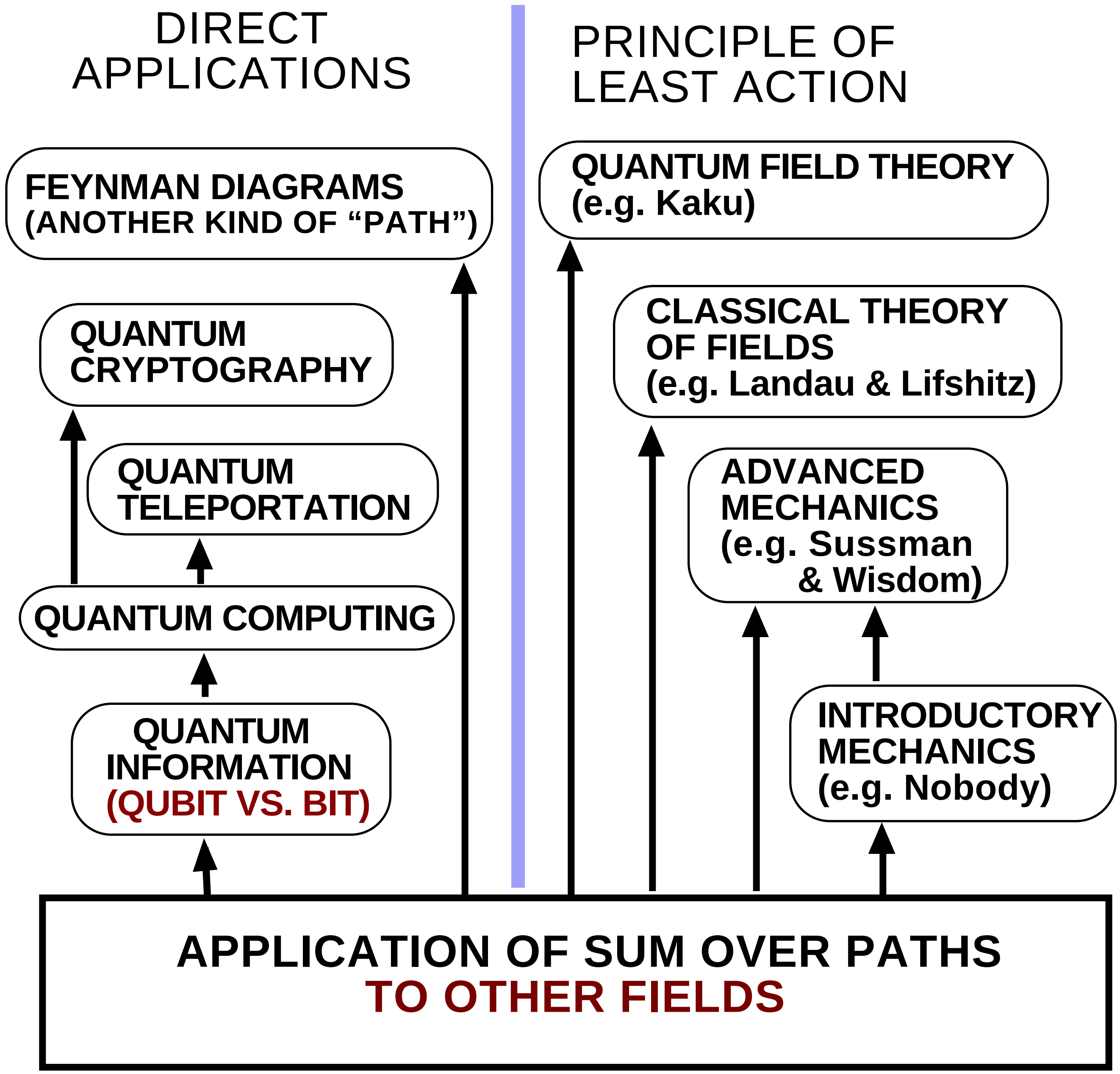
"Go straight!"
(Follow worldline of Least Action.)

QUANTUM MECHANICS

"Explore all paths!"



("Maximal" and "least" generalize to "extremal.")


DIRECT
APPLICATIONS
PRINCIPLE OF
LEAST ACTION
FEYNMAN DIAGRAMS
(ANOTHER KIND OF "PATH")
QUANTUM FIELD THEORY
(e.g. Kaku)
QUANTUM
CRYPTOGRAPHY
CLASSICAL THEORY
OF FIELDS
(e.g. Landau & Lifshitz)
QUANTUM
TELEPORTATION
ADVANCED
MECHANICS
(e.g. Sussman
& Wisdom)
QUANTUM COMPUTING
INTRODUCTORY
MECHANICS
(e.g. Nobody)
QUANTUM
INFORMATION
(QUBIT VS. BIT)
APPLICATION OF SUM OVER PATHS
TO OTHER FIELDS

Not only does the least-action principle offer a means of formulating classical mechanics that is more flexible and powerful than Newtonian mechanics, [but also] variations on the least-action principle have proved useful in general relativity theory, quantum field theory, and particle physics.
As a result, this principle lies at the core of much of contemporary physics.

Thomas A. Moore
Macmillan Encyclopedia of Physics

HISTORY OF SUM OVER HISTORIES:

Online classes on National Teachers Enhancement Network, Montana State

One semester class at MIT

NEXT STEPS

Abbie Hoffman: *Steal this Book*

HANDOUT

Rescuing Quantum Mechanics from Atomic Physics

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Initial steps in story line based on
Richard P. Feynman, *QED: The Strange Theory of Light and Matter*
1985, Princeton University Press, ISBN 0 691 02417 0

Advanced treatment of path integral approach to quantum mechanics:
R. P. Feynman and A. R. Hibbs, *Quantum Mechanics and Path Integrals*
McGraw-Hill, 1965, Library of Congress 64-25171 (Before ISBNs!)
FULL of typos and errors. For list of corrections, see:
http://www.oberlin.edu/physics/dstyer/TeachQM/Hibbs.pdf

WEBSITE: www.eftaylor.com/

Available from quantum mechanics page of this website:

1. Transparencies for this talk

2. All computer programs (Mac and Windows) illustrated in this talk, and more.

3. Student workbook to accompany computer programs.

4. Link to following article:
"Teaching Feynman's sum-over-paths quantum theory"
Edwin F. Taylor, Stamatis Vokos, and John M. O'Meara, and Nora S. Thornber
Computers in Physics, Vol. 12, No 2, Mar/Apr 1998, pages 190 –198