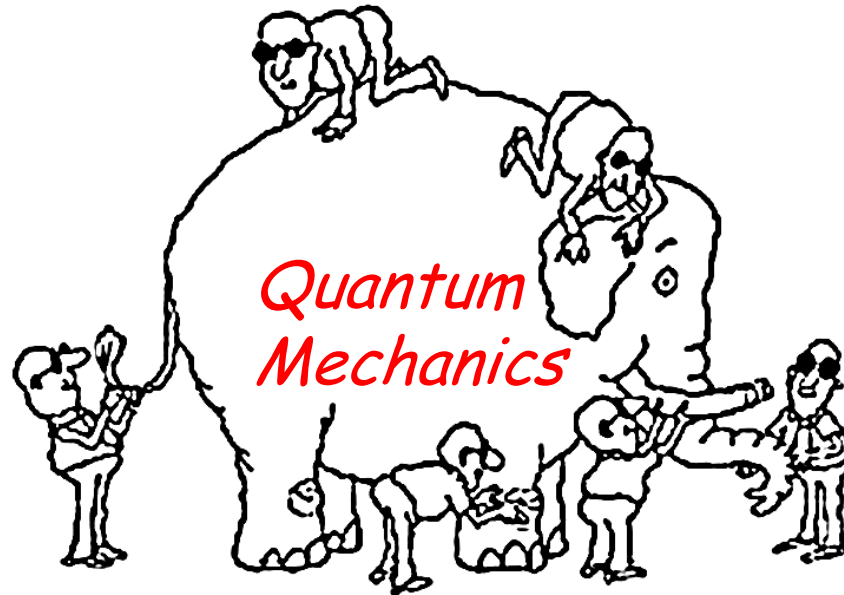# The Blind Men and the Quantum
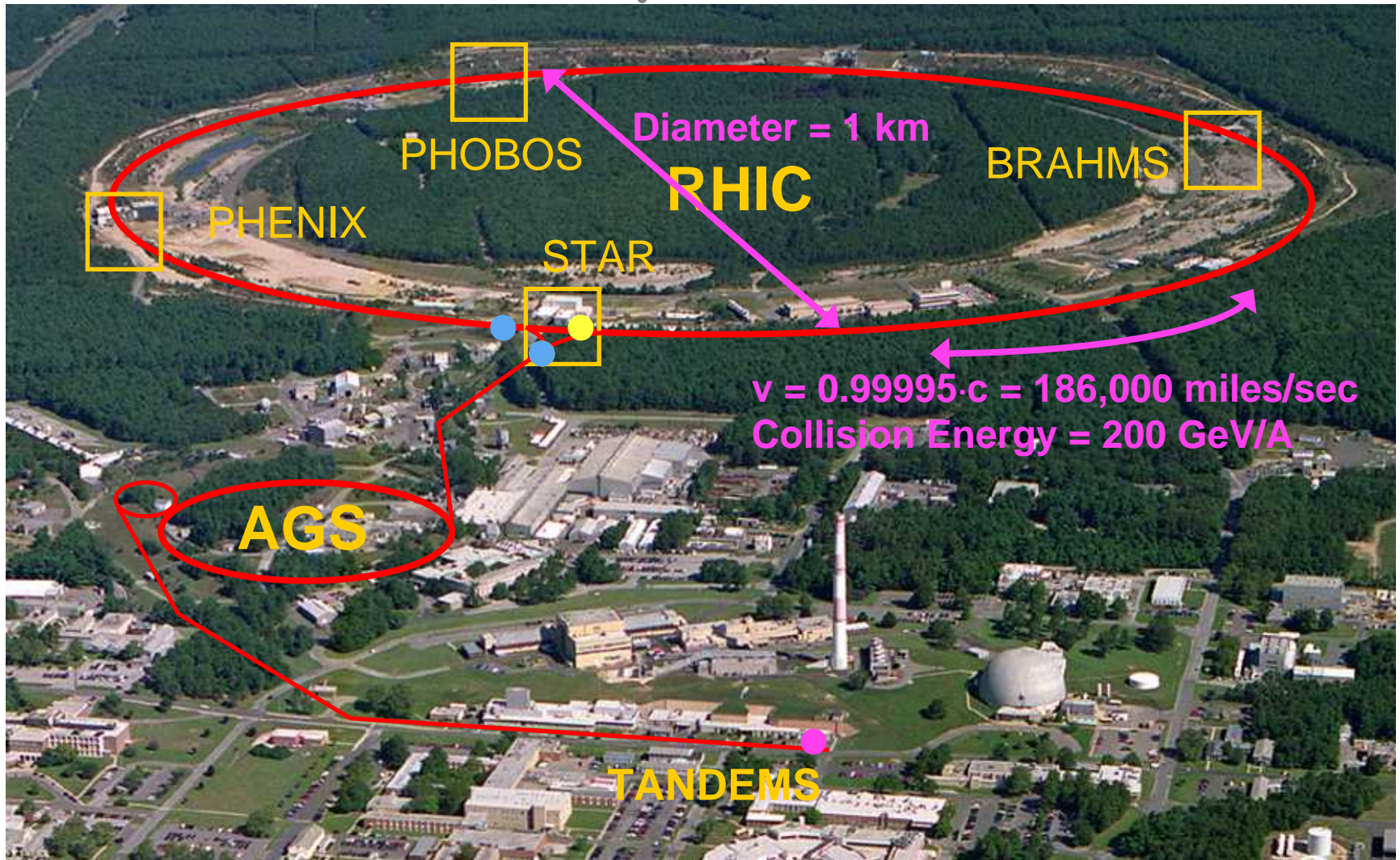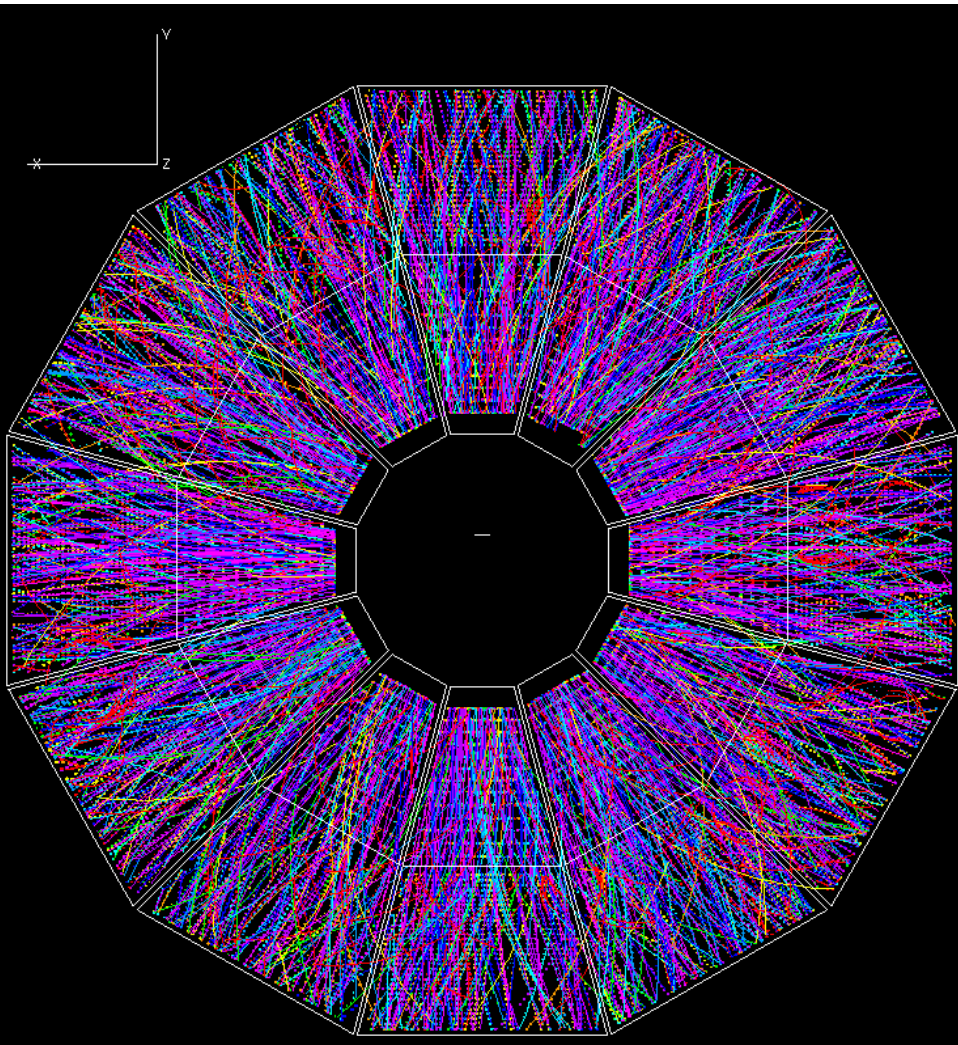

Quantum Mechanics

John G. Cramer

Dept. of Physics, Univ. of Washington

Seattle, Washington 98195, USA

NIAC Keynote Talk

Atlanta, GA, March 7, 2006

The Brookhaven National Laboratory
Relativistic Heavy Ion Collider (RHIC)
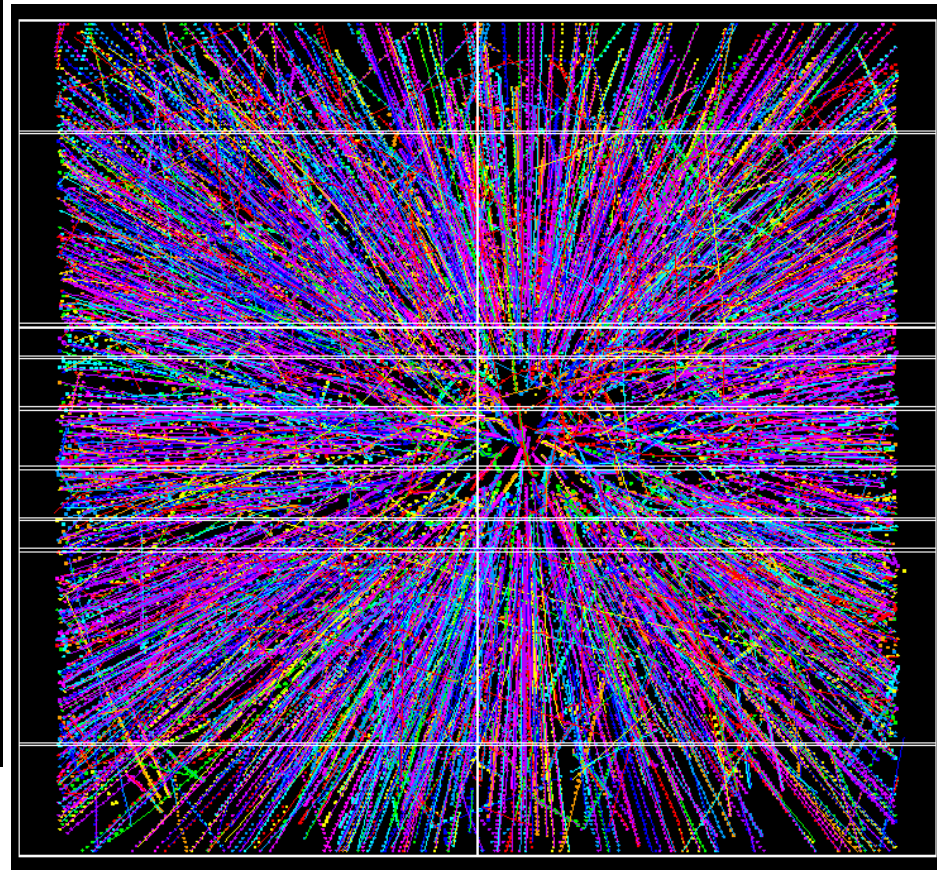

Diameter = 1 km

RHIC

PHOBOS

PHENIX

STAR

BRAHMS

AGS

v = 0.99995·c = 186,000 miles/sec
Collision Energy = 200 GeV/A

TANDEMS

One STAR Au+Au Collision
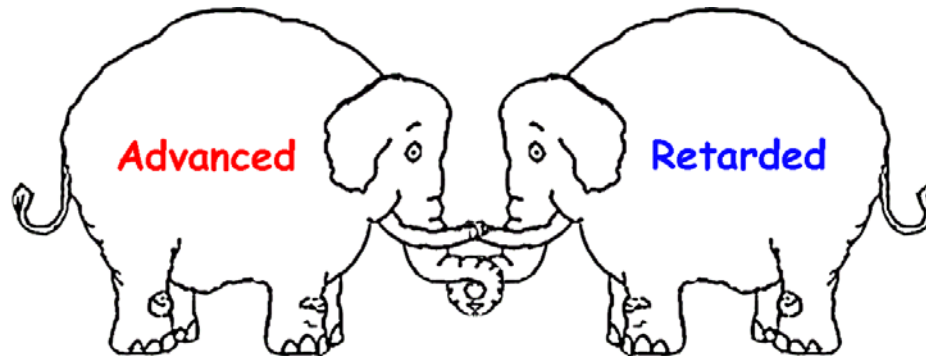

Run: 1186017,   Event: 32, central

colors ~ momentum: low - - - high

Outline

- 🔴 **A Quantum Metaphor**
- 🟠 **Quantum Theory and Interpretations**
- 🟢 **The Transactional Interpretation of QM**
- 🔵 **The TI and Quantum Paradoxes**
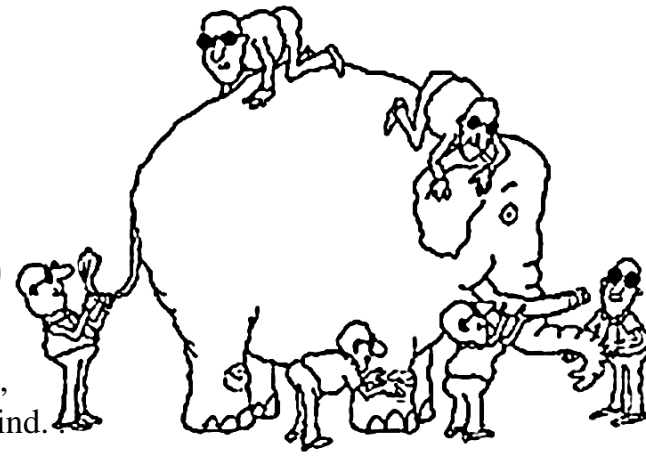- 🟣 **Time, Pseudo-Time, and Causal Loops**
- 🔴 **Last Words**

A Quantum Metaphor

(With apologies to Indostanis with Disabilities)

The Blind Men and the Elephant
by John Godfrey Saxe (1816-1887)

It was six men of Indostan, To learning much inclined, Who went to see the Elephant, (Though all of them were blind), That each by observation, Might satisfy his mind.

The First approached the Elephant, And happening to fall, Against his broad and sturdy side, At once began to bawl: "God bless me! but the Elephant, Is very like a *wall!*"

The Second, Cried, "Ho! what have we here, So very round and smooth and sharp? To me 'tis mighty clear, This w t, Is very like a *spear!*"

The Third approached the animal g to take, The squirming trunk within his hands, Thus boldly up and spake: "I see," quoth he, "the Eleph e a *snake*!"

The Fourth reached out an eager nee. "What most this wondrous beast is like, Is mighty plain," quoth he; " 'Tis clear enough the Elep
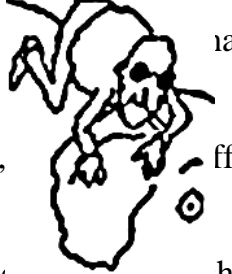
The Fifth, who chanced to touch the ear, Said: " inde what this resembles most; Deny the fact who can, This marvel of an Elephant, Is very like a *f*

The Sixth no sooner had begun, About the beast Than at fell within his scope, I see," quoth he, "the Elephant, Is very like a *rope!*"

And so these men of Indostan, Disputed loud and long, Each in his own opinion, ff
Though each was partly in the right, And <u>all</u> were in the wrong!
quantum interpretational discussions
Moral: So oft in ~~theologic wars,~~ The disputants, I ween, Rail on in utter ignorance, Of what each
And prate about ~~an Elephant,~~ Not one of them has seen!
a quantum process

Quantum Theory and Interpretations

What is Quantum Mechanics?

Quantum mechanics is a *theory*. It is our current "standard model" for describing the behavior of matter and energy at the smallest scales (photons, atoms, nuclei, quarks, gluons, leptons, ...).

Quantum Mechanics

Like all theories, it consists of a mathematical *formalism*, plus an *interpretation* of that formalism.
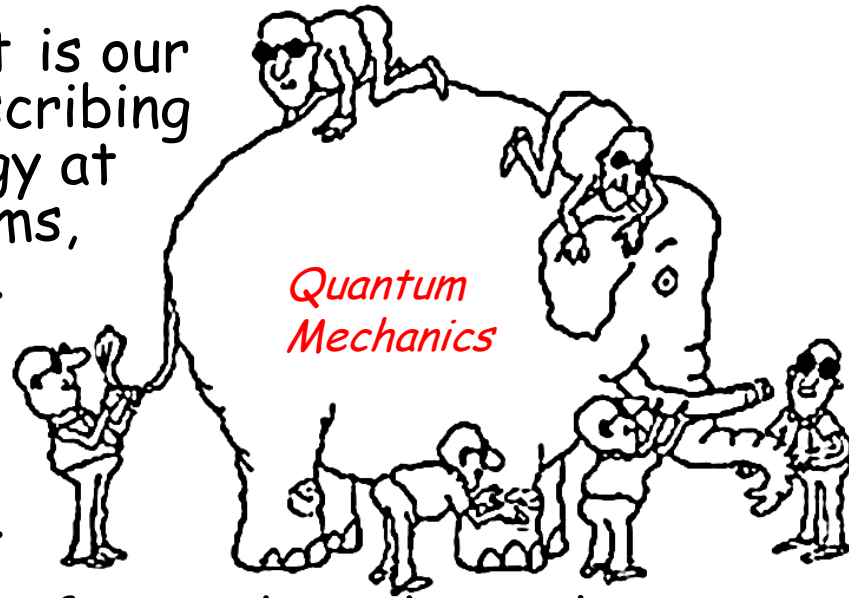
However, quantum mechanics differs from other physical theories because, while its *formalism* of has been accepted and used for 80 years, its *interpretation* remains a matter of controversy and debate. Like the opinions of the 6 blind men, there are many rival QM interpretations on the market (Copenhagen, Many-Worlds, ...).

Today, however, we'll consider only one QM interpretation, the *Transactional Interpretation of quantum mechanics.*

The Role of an Interpretation

An **interpretation of a formalism** should:

- Provide links between the mathematical symbols of the formalism and elements of the physical world;

- Neutralize the paradoxes; **_all_** of them; addressing only **_a few_** of the formalism's interpretational problems is undesirable;

- Provide tools for visualization, for speculation, and for extension.

- An interpretation should not have its own sub-formalism!

- It should not make its own testable predictions, (but it _may_ be falsifiable, if it is found to be inconsistent with the formalism and/or with experiment)!

Example: Newton's 2ⁿᵈ Law

● **Formalism:**

$$\vec{F} = m\vec{a}$$

● **Interpretation:** "The vector force $\vec{F}$ on a body is proportional to the product of its scalar mass m, which is positive, and the 2ⁿᵈ time derivative $\vec{a}$ of its vector position."

● **What this interpretation does:**

  ■ It relates the formalism to physical observables.
  ■ It avoids the paradoxes that would arise if $m < 0$.
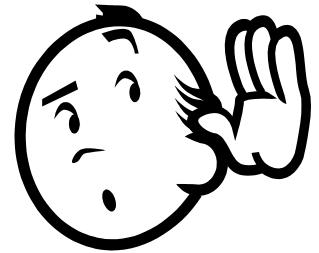 ■ It insures that $\vec{F} \| \vec{a}$.

The Transactional Interpretation of Quantum Mechanics

"Listening" to the Quantum Mechanical Formalism

Consider a quantum matrix element:

$$\langle S \rangle = \int_V \psi^* \, S \, \psi \, dr^3 = \langle f \,|\, S \,|\, i \rangle$$

... a ψ^* - ψ "sandwich". What does this suggest?

Hint: The complex conjugation in ψ^* is the Wigner operator for time reversal. If ψ is a *retarded* wave, then ψ^* is an *advanced* wave.

If $\psi = A \, e^{i(kr - \omega t)}$ then $\psi^* = A \, e^{i(-kr + \omega t)}$

(retarded)   *(advanced)*

A *retarded* wave carries positive energy to the future.
An *advanced* wave carries negative energy to the past.

Maxwell's Electromagnetic Wave Equation (Classical)

$$\nabla^2 \mathbf{F}_i = 1/\mathbf{c}^2 \ \partial^2 \mathbf{F}_i /\partial \mathbf{t}^2$$
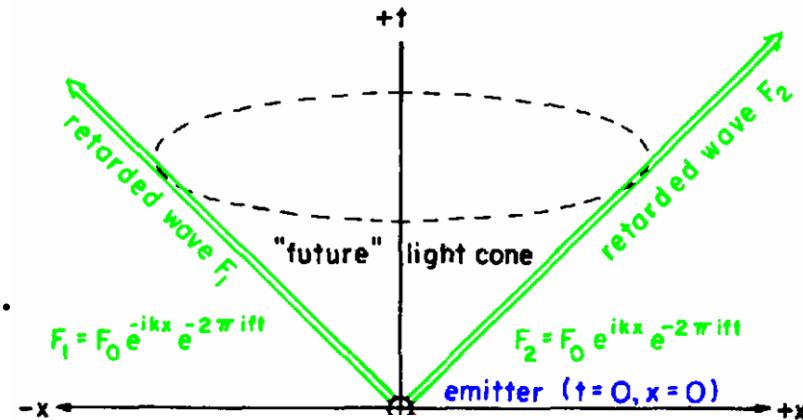
This is a 2<u>nd</u> <u>order</u> differential equation, which has <u>two</u> time solutions, retarded and advanced.

Conventional Approach:
Choose only the retarded solution (a "causality" boundary condition).

Wheeler-Feynman Approach:
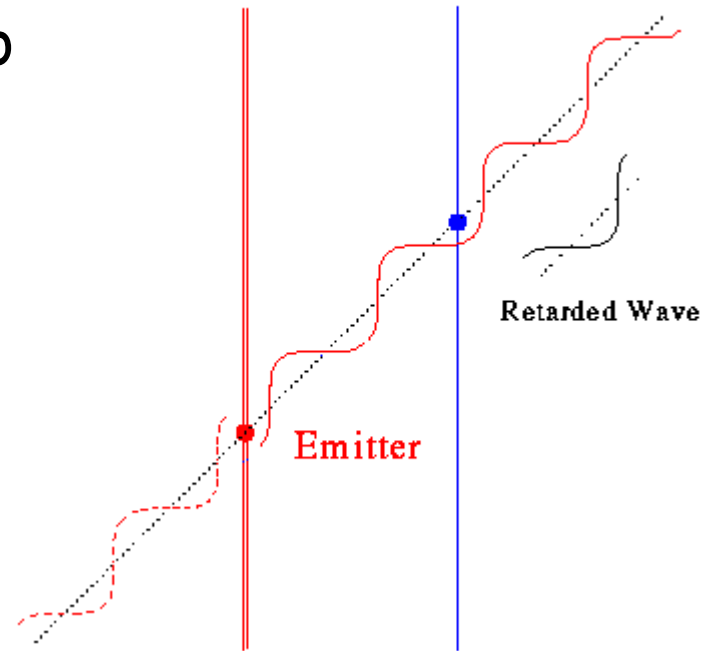Use ½ retarded and ½ advanced (time symmetry).

+t

retarded wave F_1

"future" light cone

retarded wave F_2

$F_1 = F_0 \, e^{-ikx} \, e^{-2\pi ift}$

$F_2 = F_0 \, e^{ikx} \, e^{-2\pi ift}$
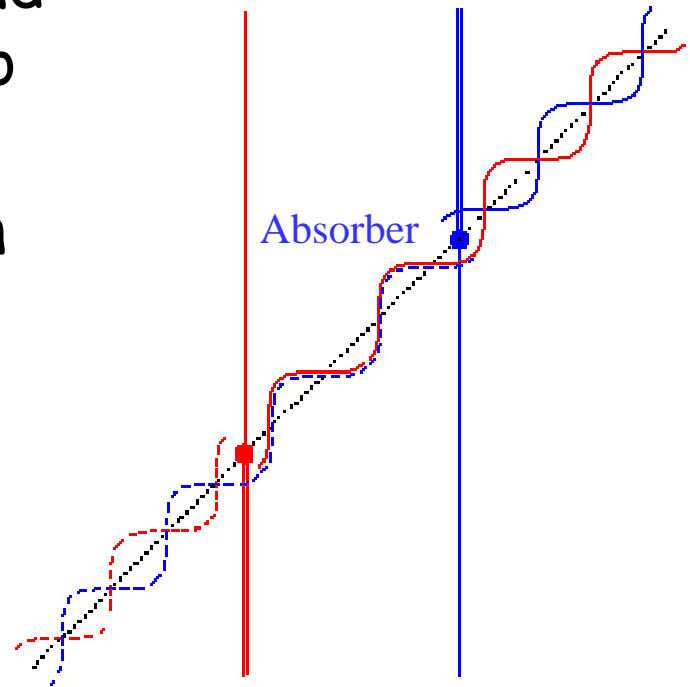
emitter $(t=0, x=0)$

-x   +x

A Wheeler-Feynman Electromagnetic "Transaction"

- The emitter sends retarded and advanced waves. It "offers" to transfer energy.

A Wheeler-Feynman Electromagnetic "Transaction"

- The emitter sends retarded and advanced waves. It "offers" to transfer energy.

- The absorber responds with an advanced wave that "confirms" the transaction.

Absorber

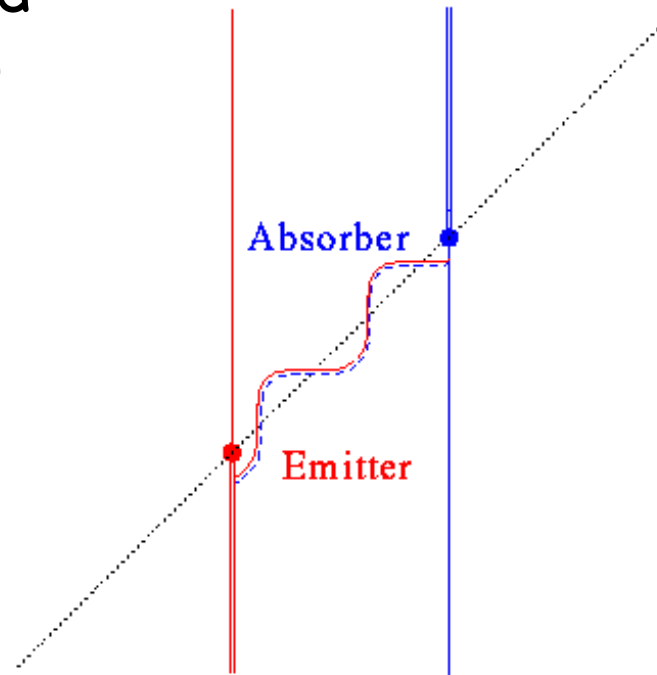# A Wheeler-Feynman Electromagnetic "Transaction"

- The emitter sends retarded and advanced waves. It "offers" to transfer energy.

- The absorber responds with an advanced wave that "confirms" the transaction.

- The loose ends cancel and disappear, and energy is transferred.

Absorber

Emitter

Overview of the Transactional Interpretation

Offer Wave:

The initial wave function ψ is interpreted as a retarded-wave offer to form a quantum event.
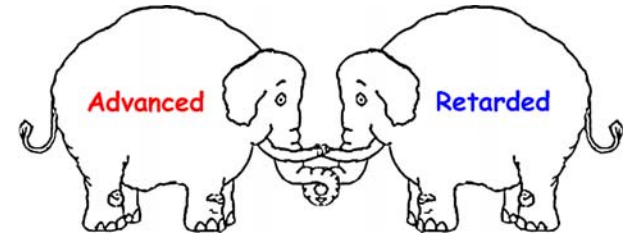
Confirmation wave:

The conjugate wave function ψ^* is interpreted as an advanced-wave confirmation to proceed with the quantum event.

Transaction – the Quantum Handshake:

The many $\psi\,\psi^*$ combinations present in the QM formalism are interpreted as indicating the formation of a forward/back-in-time standing wave that transfers energy, momentum, and other conserved quantities.

No Observers:

Transactions involving observers are no different from other transactions; Observers and their knowledge play no special roles.

No Paradoxes:

Transactions are intrinsically nonlocal, and paradoxes are resolved.

Few Postulates (Economical):

Heisenberg's uncertainty principle and *Born's statistical interpretation* can be derived from the Transactional Interpretation.

The Quantum Transactional Model

We apply the same logic to QM:

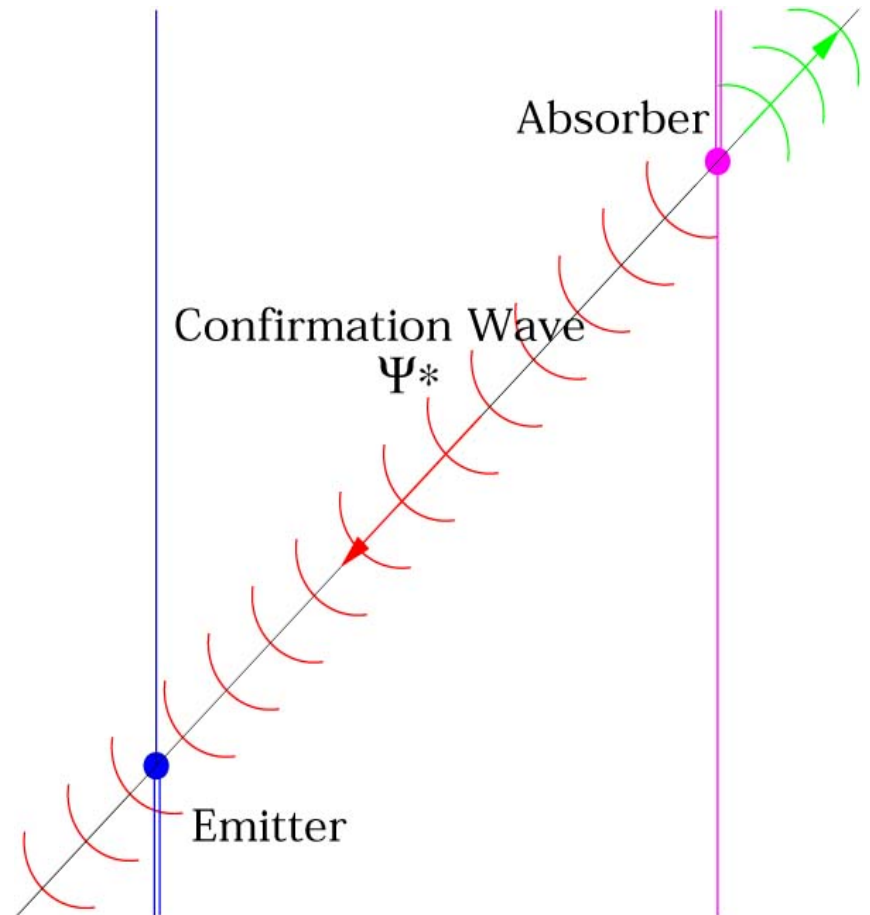**Step 1:** The emitter sends out an "offer wave" Ψ.

Absorber

Offer Wave
Ψ

Emitter

The Quantum Transactional Model
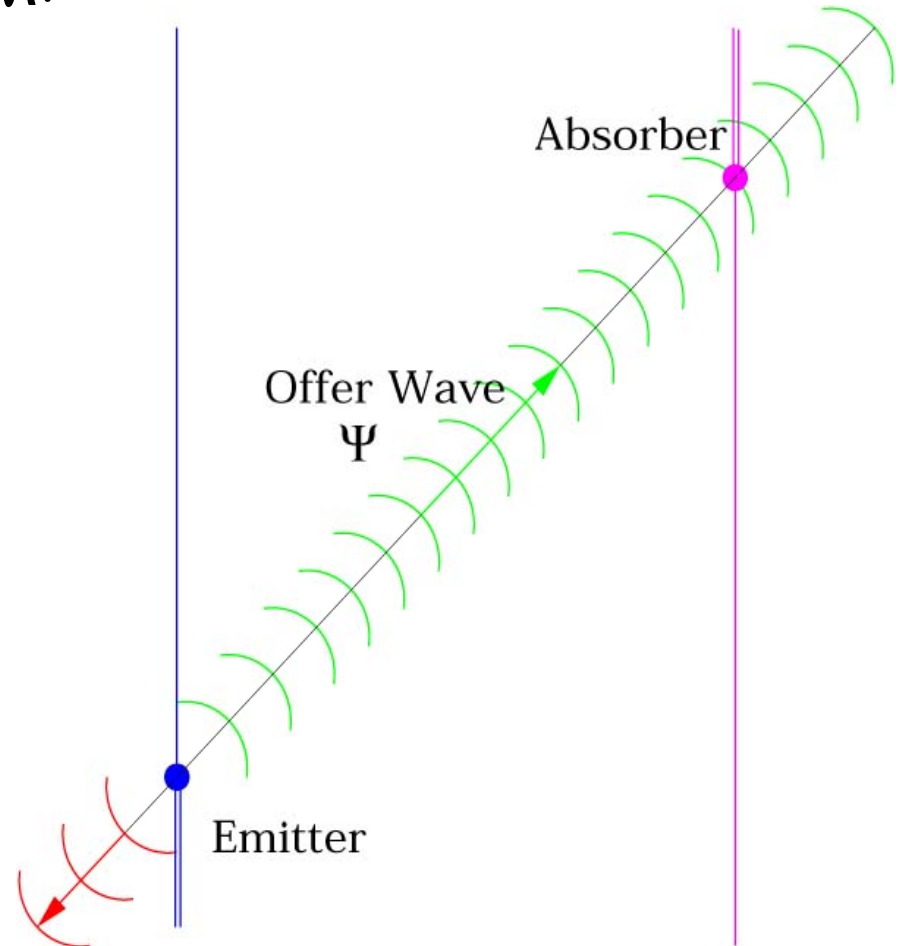
We apply the same logic to QM:

Step 1: The emitter sends out an "offer wave" Ψ.

Step 2: The absorber responds with a "confirmation wave" $\Psi*$.

Absorber
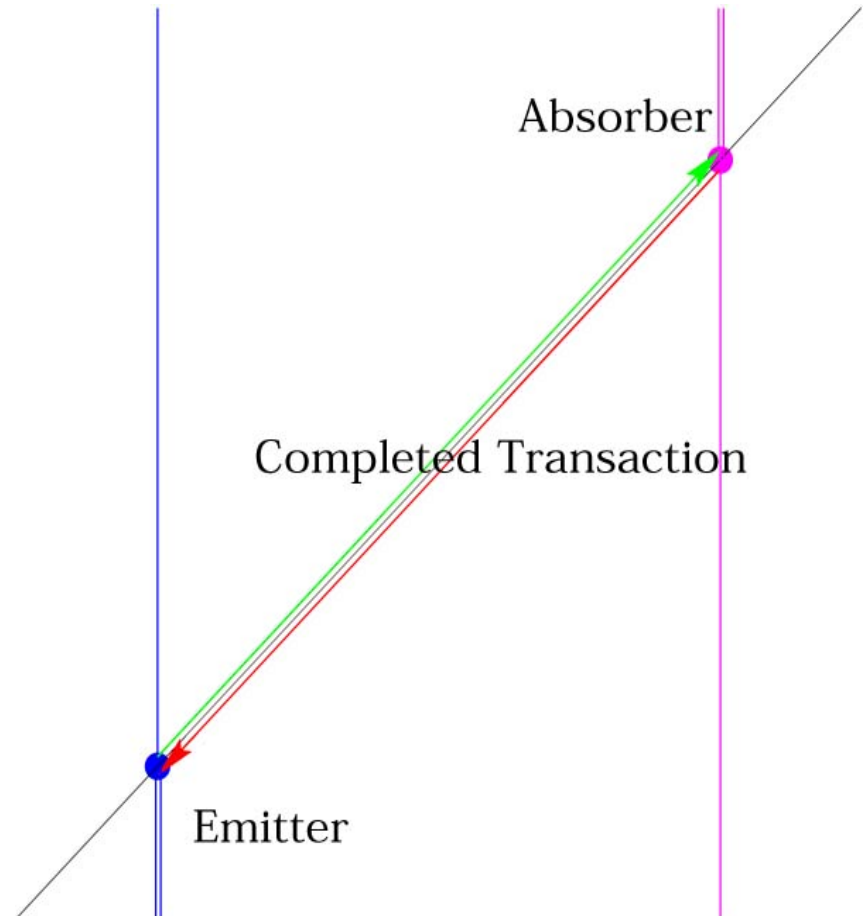
Confirmation Wave
$\Psi*$

Emitter

The Quantum Transactional Model

We apply the same logic to QM:

**Step 1:** The emitter sends out an "offer wave" Ψ.

Step 2: The absorber responds with a "confirmation wave" $\Psi*$.

Step 3: The process repeats until energy and momentum is transferred and the transaction is completed (wave function collapse).

Absorber

Completed Transaction

Emitter

The TI and the Uncertainty Principle

- The completed transaction projects out *only* that part of the offer wave ψ that had been reinforced by the confirmation wave ψ* (=> measurement).

- Consequently, the transaction can project out only one of two complementary variables.

- This accounts for Heisenberg's Uncertainty Principle.

Absorber

Completed Transaction
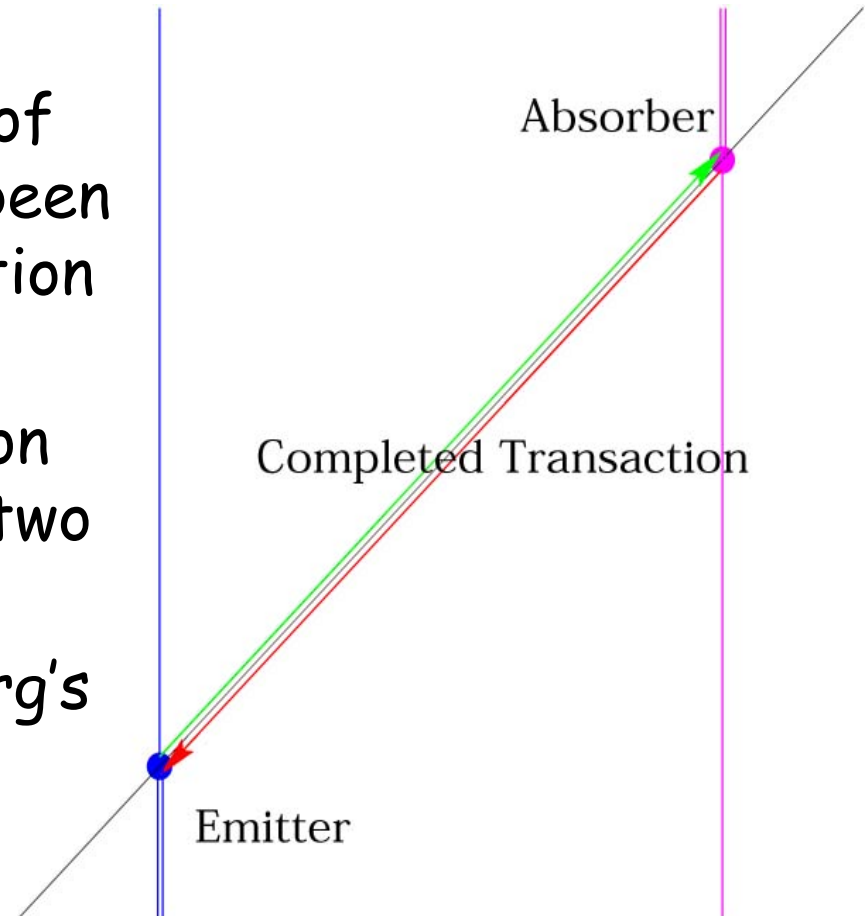
Emitter

The TI and the Born Probability Law

- Starting from E&M and the Wheeler-Feynman approach, the E-field "echo" that the emitter receives from the absorber is the product of the retarded-wave E-field at the absorber and the advanced-wave E-field at the emitter.

- Translating this to quantum mechanical terms, the "echo" that the emitter receives from each potential absorber is $\psi_i \, \psi_i^*$, leading to the Born Probability Law.

Absorber

Confirmation Wave
Ψ_*

Wave amplitude here is $\psi\psi^*$

Emitter
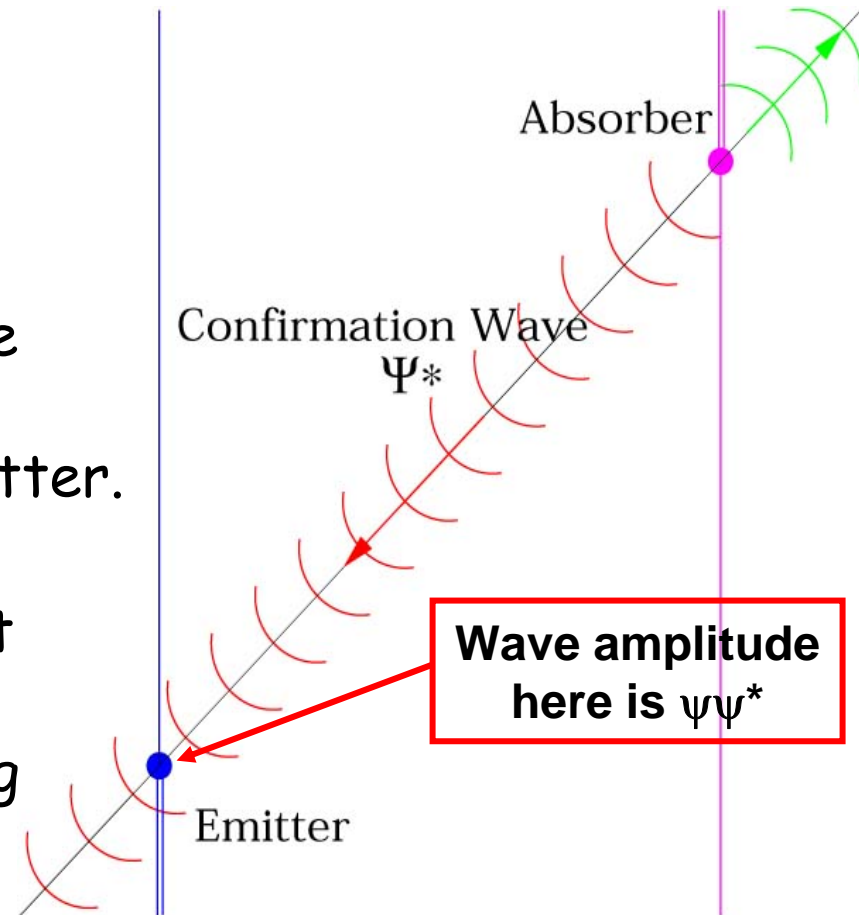
Role of the Observer
in the TI
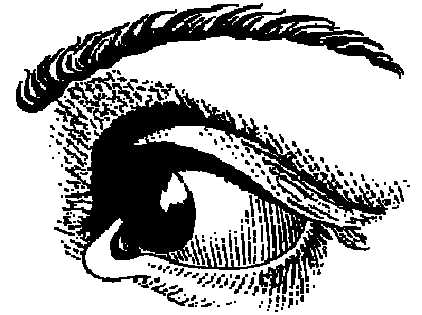
- In the Copenhagen Interpretation, observers are given the special role as "Collapsers of Wave Functions". This leads to problems, e.g., in quantum cosmology where no observers are present.

- In the Transactional Interpretation, transactions involving an observer are the same as any other transactions.

- Thus, the observer-centric aspects of the Copenhagen Interpretation are avoided.

Can the TI be Tested?

- The simple answer is *"No!"*. It is the *formalism* of quantum mechanics that makes all of the testable predictions.

- As long as an interpretation like the TI is consistent with the formalism, it will make the *same* predictions as any other valid interpretation, and no experimental tests are possible.

- However, an interpretations may be inconsistent with the quantum mechanical formalism and its predictions.

- If this is true, then the interpretation can be *falsified*.

- The Transactional Interpretation follows the quantum formalism very closely and does not appear to have problems in this area.
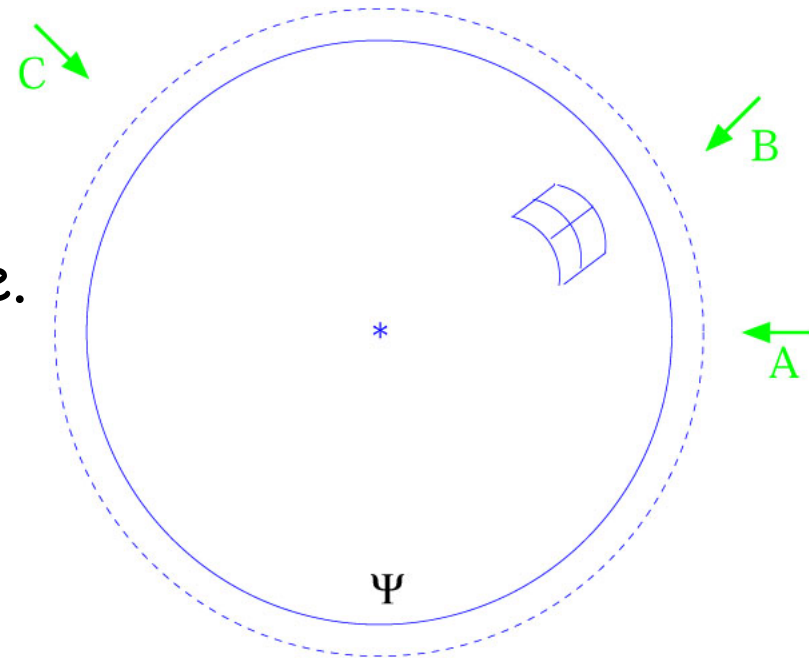
The TI and Quantum Paradoxes

Paradox 1 (non-locality):
Einstein's Bubble

Situation: A photon is emitted
from a source having no
directional preference.

C

B

A

*

Ψ

Paradox 1 (non-locality): Einstein's Bubble

Situation: A photon is emitted from a source having no directional preference.

Its spherical wave function Ψ expands like an inflating bubble.

C

B

A

*

Ψ
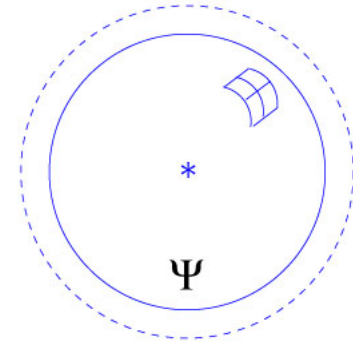
Paradox 1 (non-locality):
Einstein's Bubble

Situation: A photon is emitted from a source having no directional preference.
Its spherical wave function Ψ expands like an inflating bubble.
It reaches Detector **A**, and the Ψ bubble "pops" and disappears.

C ↘

↙ B

∗

Ψ
∗ ←
A

Question: *(originally asked by Albert Einstein)*

If a photon is detected at Detector **A**, how does the photon's wave function Ψ at the locations of Detectors **B** & **C** "know" that it should vanish?

Paradox 1 (non-locality):
Einstein's Bubble

It is as if one throws a beer bottle into Boston Harbor. It disappears, and its quantum ripples spread all over the Atlantic.

Then in Copenhagen, the beer bottle suddenly jumps onto the dock, and the ripples disappear everywhere else.

That's what quantum mechanics says happens to electrons and photons when they move from place to place.

Paradox 1 (non-locality): Einstein's Bubble

TI Explanation:

- A transaction develops between the source and detector **A**, transferring the energy there and blocking any similar transfer to the other potential detectors, due to the 1-photon boundary condition.

- The transactional handshakes acts *nonlocally* to answer Einstein's question.

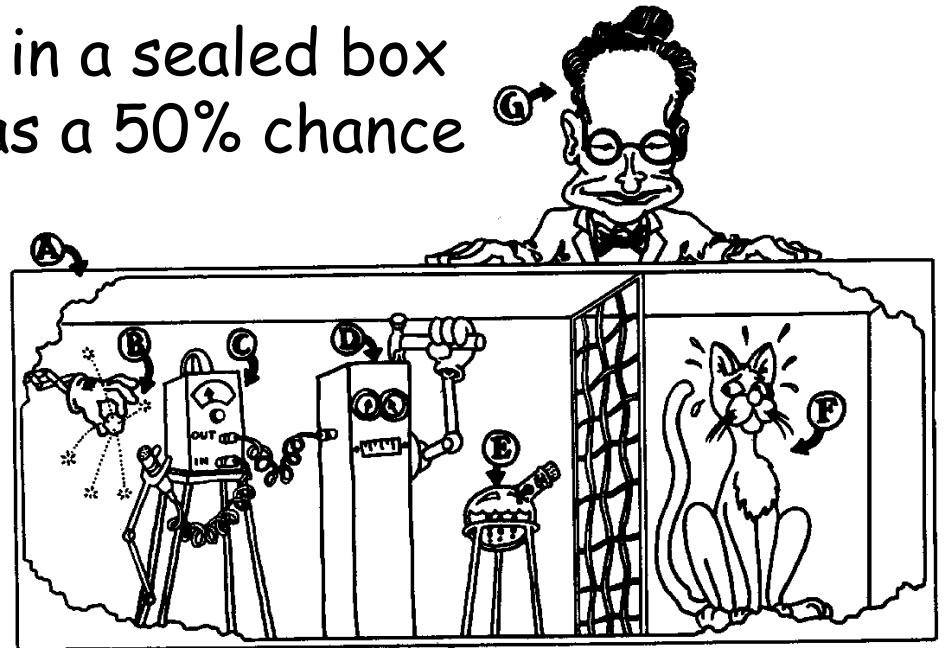- This is in effect an extension of the Pilot-Wave ideas of deBroglie.
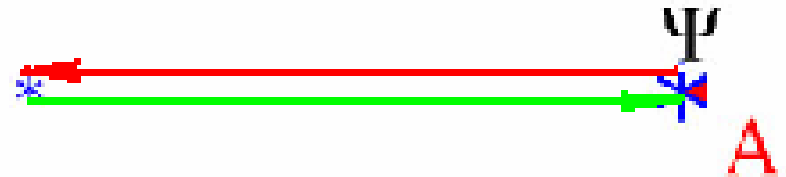
Paradox 2 (Ψ collapse): Schrödinger's Cat

Experiment: A cat is placed in a sealed box containing a device that has a 50% chance of killing the cat.

Question 1: What is the wave function of the cat just before the box is opened?

$$\Psi = \tfrac{1}{\sqrt{2}}\,\text{dead} + \tfrac{1}{\sqrt{2}}\,\text{alive} \;?)$$

When does the wave function collapse? Only after the box is opened?

(William R. Warren, Jr., © 1985, reproduced with permission.)

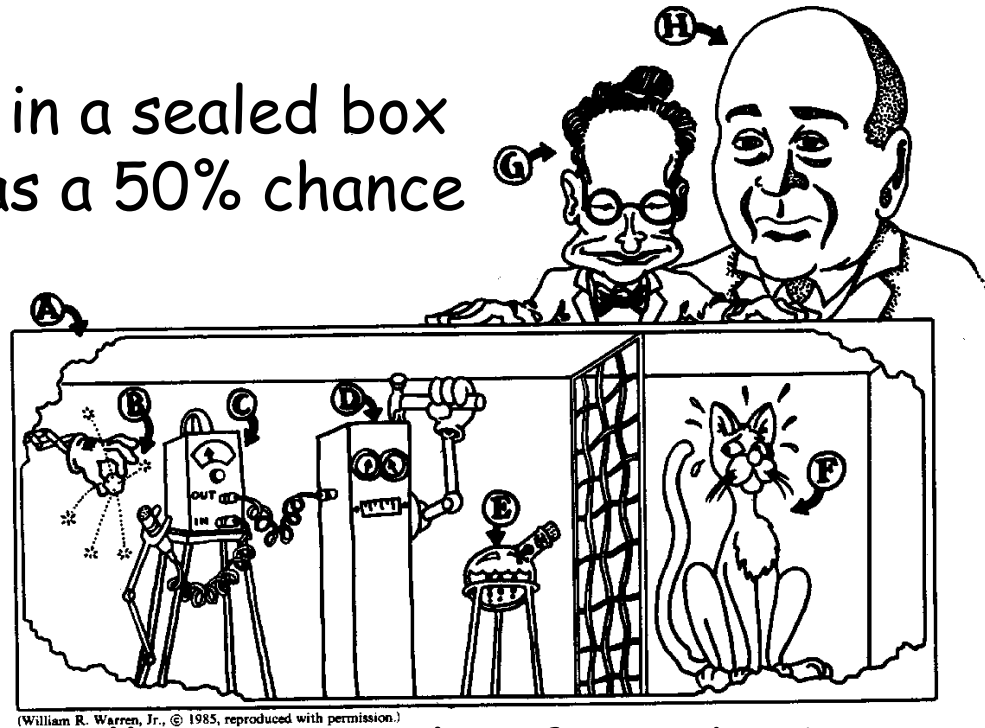# Paradox 2 (Ψ collapse): Schrödinger's Cat

Experiment: A cat is placed in a sealed box containing a device that has a 50% chance of killing the cat.

Question 1: What is the wave function of the cat just before the box is opened?

$(\Psi = \frac{1}{\sqrt{2}}\text{dead} + \frac{1}{\sqrt{2}}\text{alive} \ ?)$

*When* does the wave function collapse? Only after the box is opened?

Question 2: If we observe Schrödinger, what is *his* wave function during the experiment? When does *it* collapse?

(William R. Warren, Jr., © 1985, reproduced with permission.)

Paradox 2 (Ψ collapse): Schrödinger's Cat

The issues are: *when* and *how* does the wave function collapse.

● What event collapses it? (Observation by an intelligent observer?)

● How does the information that it has collapsed spread to remote locations, so that the laws of physics can be enforced there?

(William R. Warren, Jr., © 1985, reproduced with permission.)
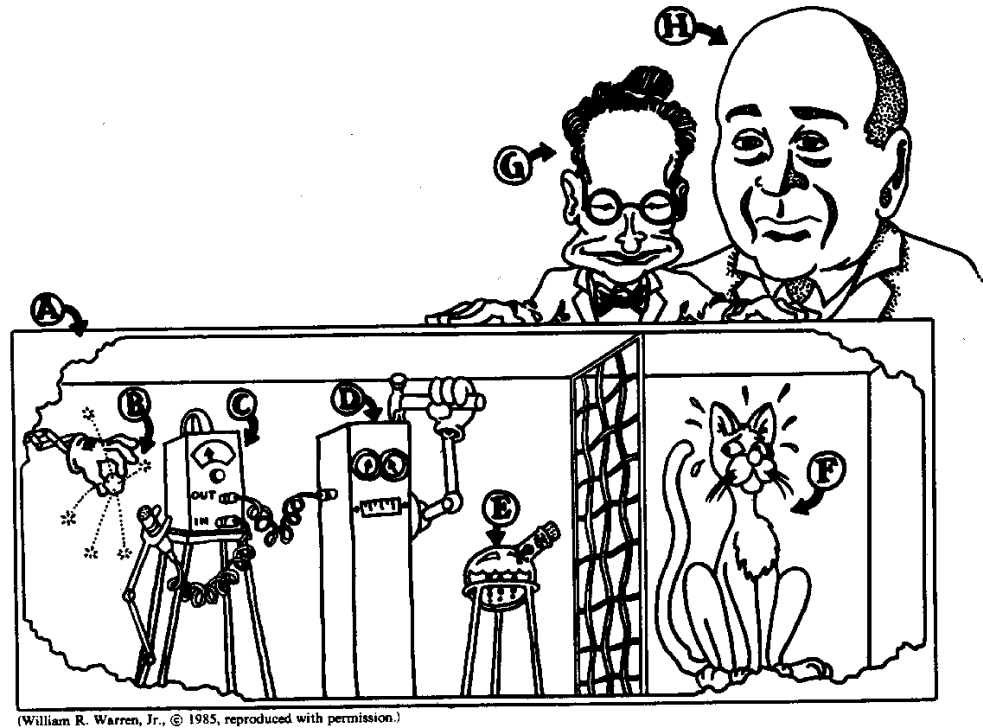
Paradox 2 (Ψ collapse): Schrödinger's Cat

TI Explanation:

● A transaction <u>either</u> develops between the source and the detector, <u>or else</u> it does not. If it <u>does</u>, the transaction forms atemporally, not at some particular time.

● Therefore, asking *when* the wave function collapsed was asking the <u>wrong</u> question.
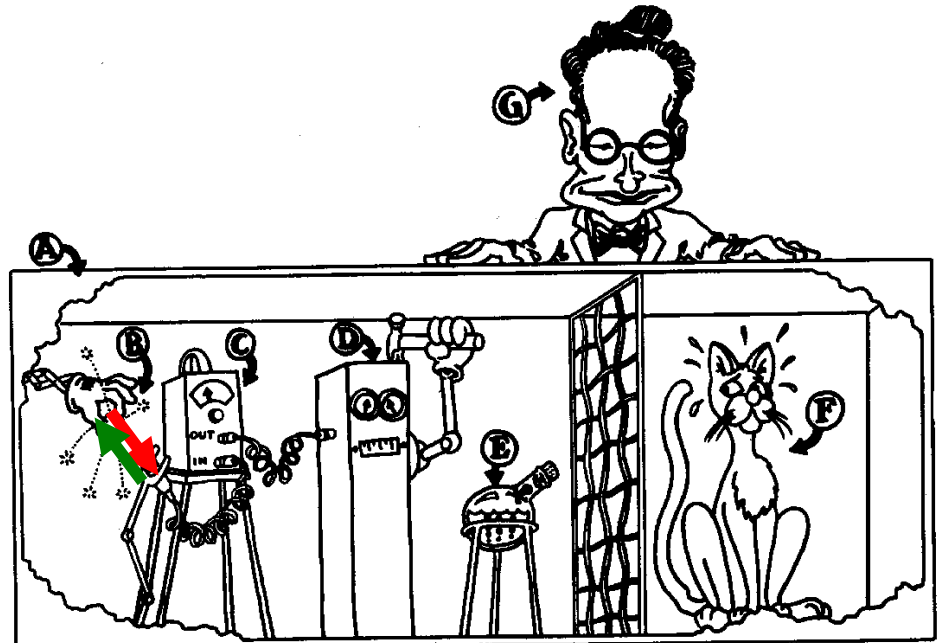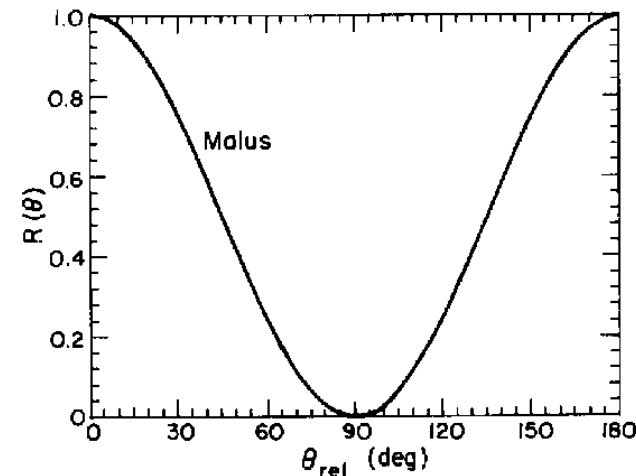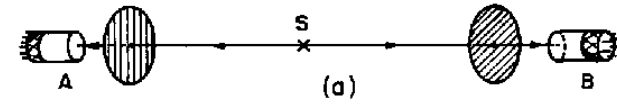
(William R. Warren, Jr., © 1985, reproduced with permission.)

Paradox 3 (non-locality):
EPR Experiments
Malus and Furry

An EPR Experiment measures the correlated polarizations of a pair of entangled photons, obeying Malus' Law: $[P(\theta_{rel}) = Cos^2\theta_{rel}]$
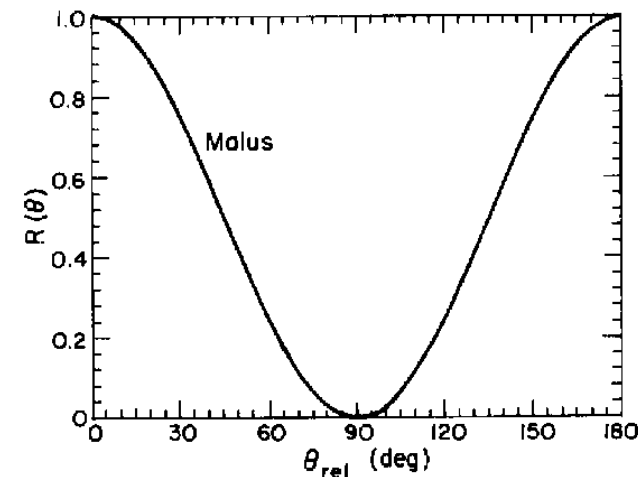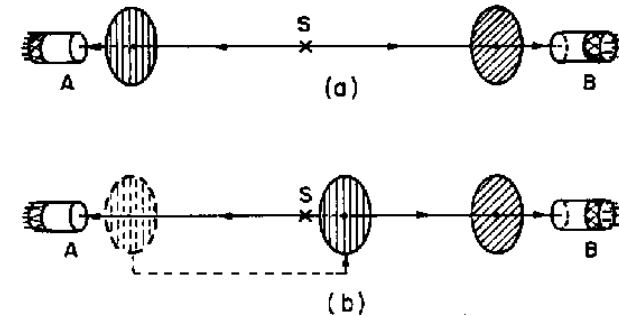
Paradox 3 (non-locality): EPR Experiments Malus and Furry

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The measurement gives the same result as if both filters were in the same arm.
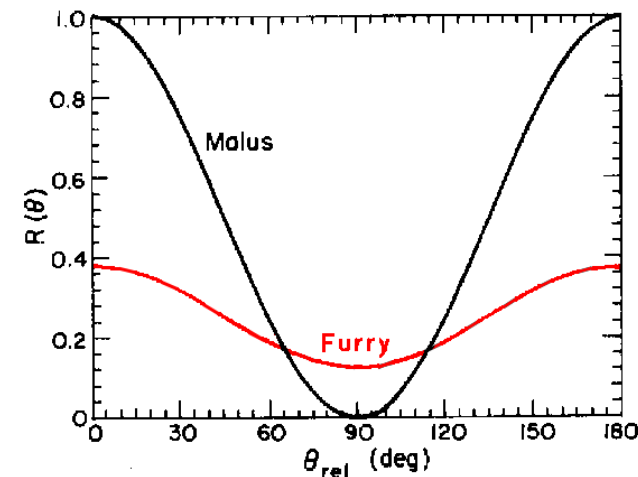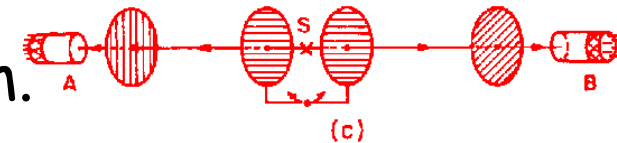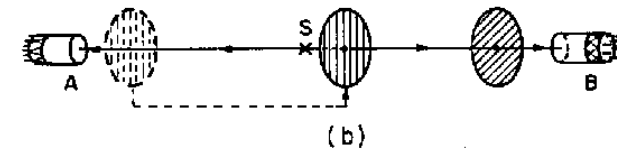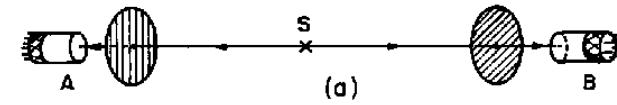
Paradox 3 (non-locality): EPR Experiments Malus and Furry

An EPR Experiment measures the correlated polarizations of a pair of entangled photons, obeying Malus' Law: $[P(\theta_{rel}) = Cos^2\theta_{rel}]$

The measurement gives the same result as if both filters were in the same arm.

Furry proposed to place both photons in the <u>same</u> random polarization state. This gives a different and weaker correlation.
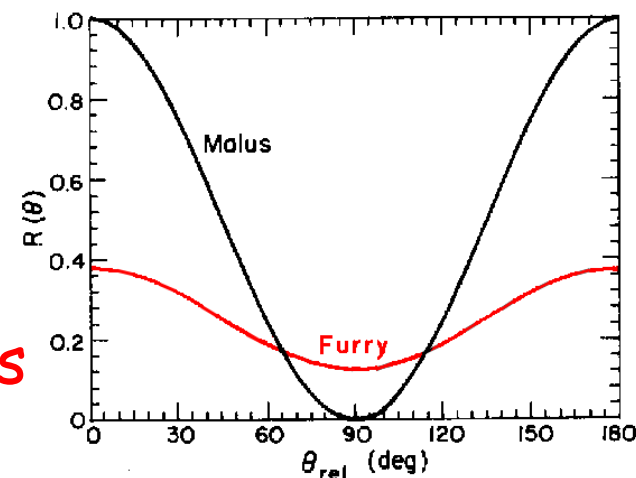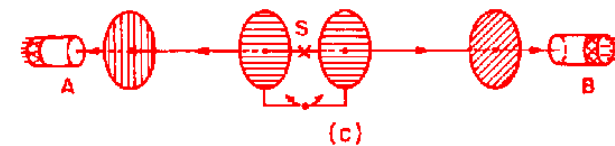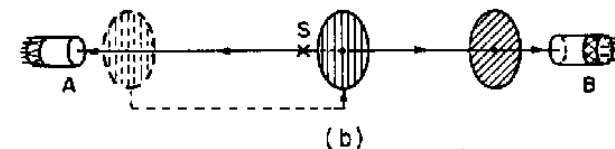
Paradox 3 (non-locality):
EPR Experiments
Malus and Furry

Apparently, the measurement on the right side of the apparatus causes (in some sense of the word *cause*) the photon on the left side to be in the *same* quantum mechanical state, and this does not happen until well after they have left the source.

This EPR "influence across space time" works even if the measurements are kilometers (or light years) apart.

Could that be used for faster than light signaling?

Sorry, NIAC, Eberhard's Theorem tells us that the answer is No!
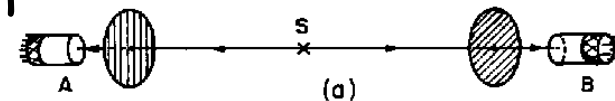
Paradox 3 (non-locality):
EPR Experiments
Malus and Furry

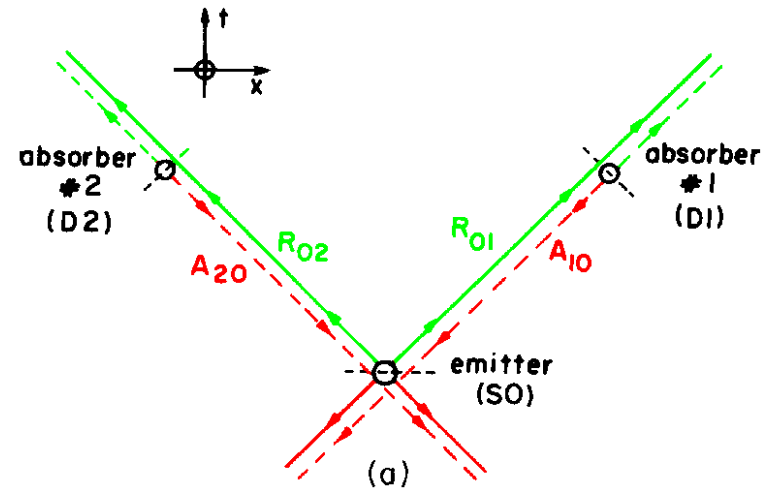**TI Explanation:**

An EPR experiment requires a consistent double advanced-retarded handshake between the emitter and the two detectors.
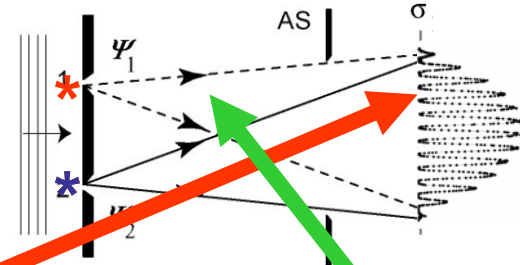
The "lines of communication" are not spacelike but negative and positive timelike. While spacelike communication has relativity problems, timelike communication does not.

Paradox 4 (wave/particle): Wheeler's Delayed Choice

A source emits one photon.
Its wave function passes through slits 1 and 2, making interference beyond the slits.

The observer can choose to either:
(a) measure the interference pattern at plane σ_1, requiring that the photon travels *through both slits*.

or

(b) measure at which slit image it appears in plane σ_2, indicating that it has passed *only through slit 2*.

The observer waits until after the photon has passed the slits to decide which measurement to do.

Paradox 4 (wave/particle): Wheeler's Delayed Choice

Thus, in Wheeler's account of the process, the photon does not "decide" if it is a particle or a wave until *after* it passes the slits, even though a particle must pass through only *one slit* while a wave must pass through *both slits*.
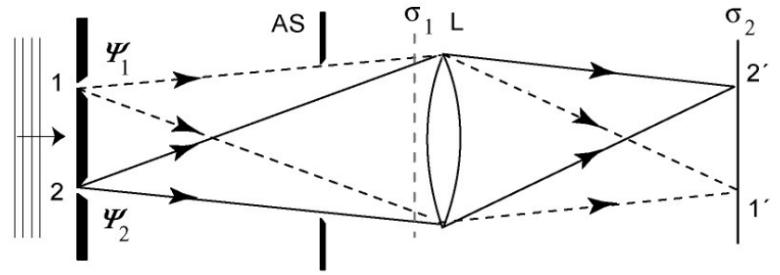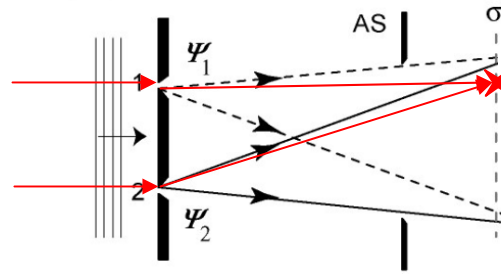

Wheeler asserts that the measurement choice determines whether the photon is a particle or a wave *retroactively!*

Paradox 4 (wave/particle): Wheeler's Delayed Choice

TI Explanation:

● If the screen at σ_1 is <u>up</u>, a transaction forms between σ_1 and the source and involves waves passing through both slits 1 and 2.

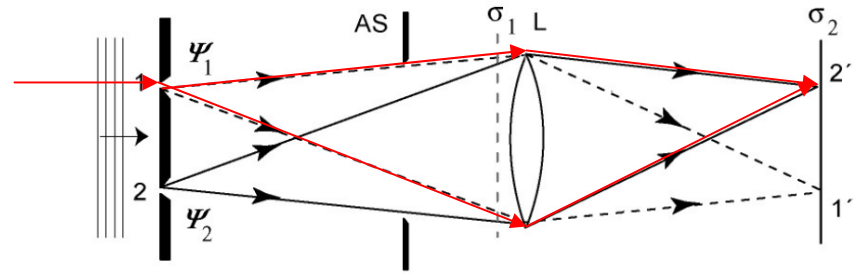# Paradox 4 (wave/particle): Wheeler's Delayed Choice

TI Explanation:

● If the screen at s1 is up, a transaction forms between σ_1 and the source and involves waves passing through both slits 1 and 2.

● If the screen at σ_1 is <u>down</u>, a transaction forms between detectors 1' or 2' and the source S, and involves waves passing through only one slit.

# Paradox 4 (wave/particle): Wheeler's Delayed Choice

TI Explanation:

- If the screen at σ_1 is <u>up</u>, a transaction forms between σ_1 and the source S through both slits.

- If the screen at σ_1 is <u>down</u>, a transaction forms between one of the detectors (1' or 2') and the source S through only one slit.

- In either case, *when* the measurement decision was made is irrelevant.
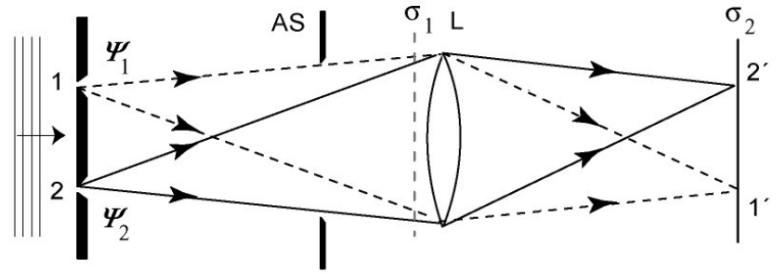
Paradox 5 (interference): The Afshar Experiment
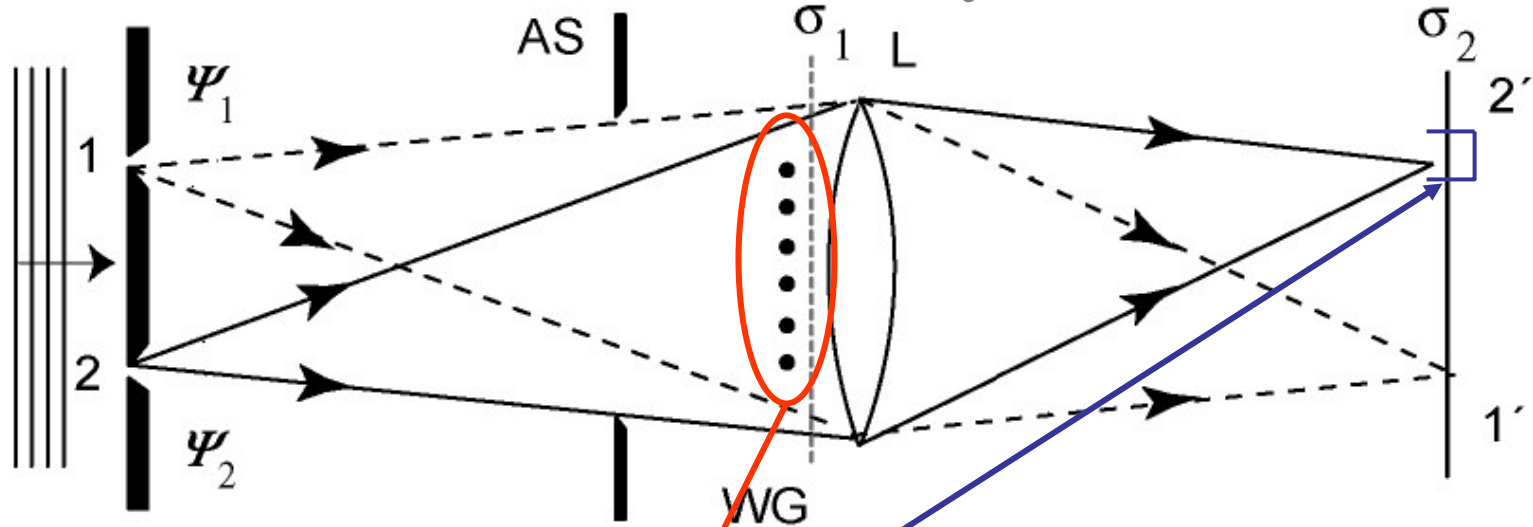
- In a Delayed Choice setup, place wires with 6% opacity at the positions of the interference minima at σ_1;

- Place detector at 2' on plane σ_2 and observe the particles passing through slit 2.

- *Question:* What fraction of the light is blocked by the grid and not transmitted to 2'? (i.e., is the *interference pattern* still there when one is measuring *particle behavior*?)

Paradox 5 (interference): The Afshar Experiment
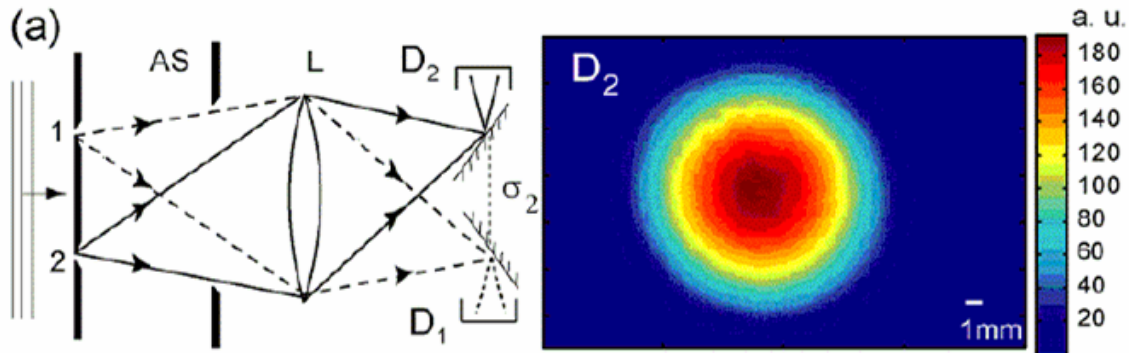
No Grid & 2 Slits

No Loss

Grid & 1 Slit

6% Loss

Grid & 2 Slits

<0.1% Loss

Paradox 5 (interference):
The Afshar Experiment

One open
Wire present

Astra Image Line Plot - Rotate - Row [531]
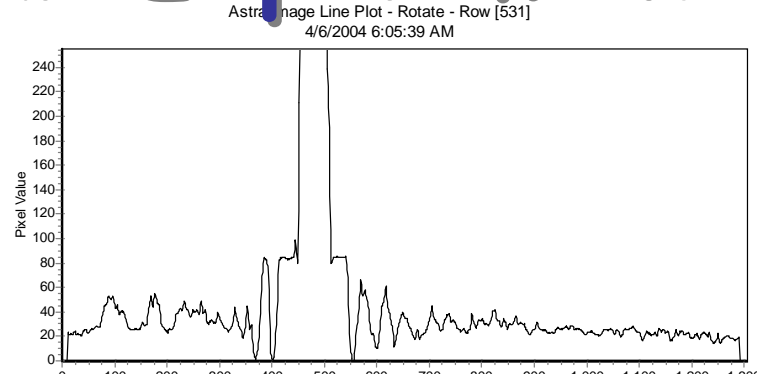4/6/2004 6:05:39 AM
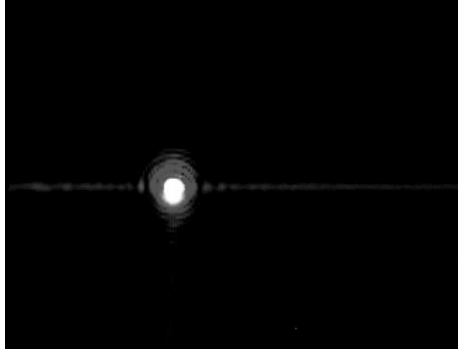
Paradox 5 (interference):
The Afshar Experiment
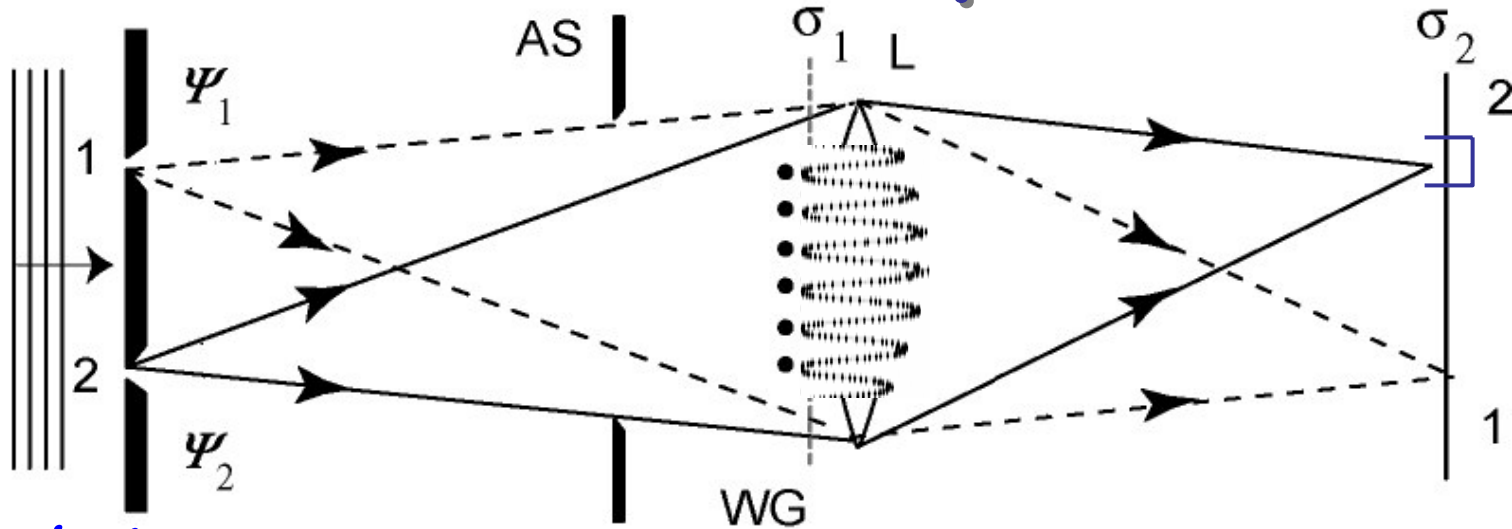
Conclusions:

● Interference is *still* present, even when an unambiguous Welcher-Weg (which-way) experiment is performed.

● Measuring particle-like behavior does *not* suppress wave-like behavior, if careful non-interactive measurements are made.

● It appears that light waves must pass both slits to create the interference, but the photon passes through only one slit.

Paradox 5 (interference): The Afshar Experiment
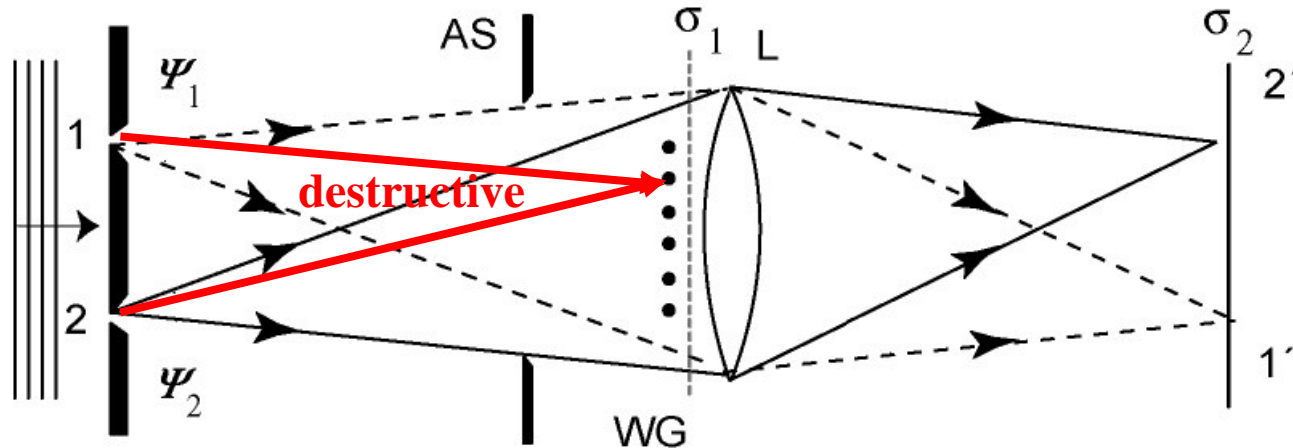
TI Explanation: The initial offer waves pass through *both* slits on their way to possible absorbers. At the wires, the offer waves cancel in first order, so that no transactions can form and no photons can be intercepted by the wires.

Therefore, the absorption by the wires should be *very small* (<<6%) and consistent with what is observed.

TI Diagrams

The TI makes it possible to diagram for analysis complicated situations in quantum optics and other areas. The diagrams below are from a TI analysis (FoP, 2005) of a Quantum-Zeno version of the Elitzur and Vaidmann interaction-free "Photon Bomb" experiment.
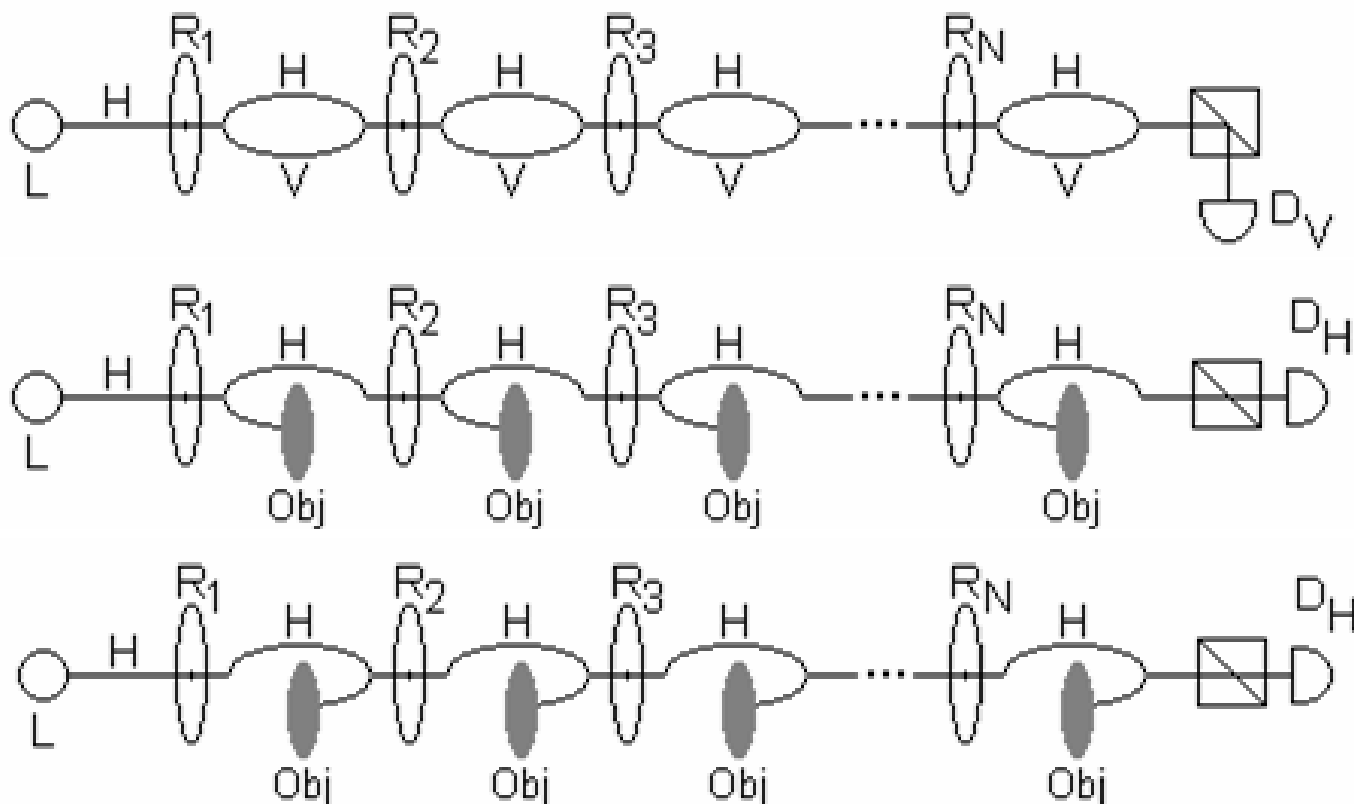
Time, Pseudo-Time, and Causal Loops

Competing Transactions and Maudlin's Paradox

In the pseudo-time scenario, the competition of possible future transactions can be viewed as generating the Born Probability Law $P = \psi \psi^*$, because each $\psi_i \psi_i^*$ is the strength of an "echo" from a possible future absorber. All such echos are present together at the emitter, which chooses probabilisically on the basis of echo strength which transaction (if any) to complete.

Maudlin has used this scenario to construct a paradox, in which the failure of an early transaction to form creates conditions that set up a later competing transaction that would otherwise not be there. He argues that both offer waves cannot be present at the emitter to compete.
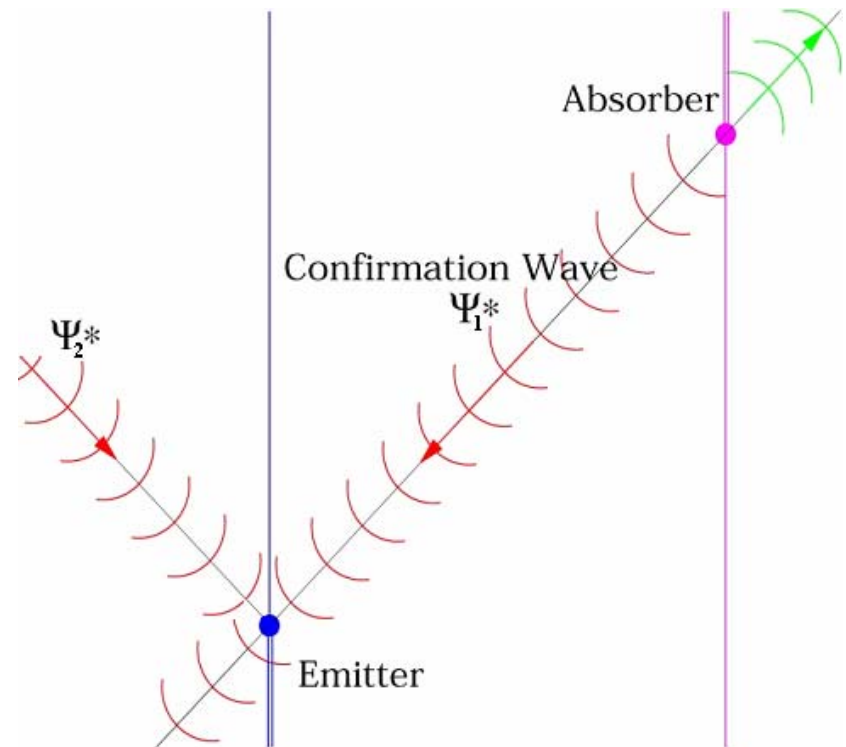
Hierarchical Pseudo-Time

Maudlin's argument is not actually a paradox, but a demonstration that the pseudo-time scenario is too naïve and requires modification.

There must be a *hierarchy of transaction formation*, in which transactions across small space-time intervals must form or fail before transactions from larger intervals can enter the competition. This give the nice result of building *the emergence of the future* into the pseudo-time transaction competition scenarios.

Absorber

Confirmation Wave
Ψ_1*

Ψ_2*

Emitter
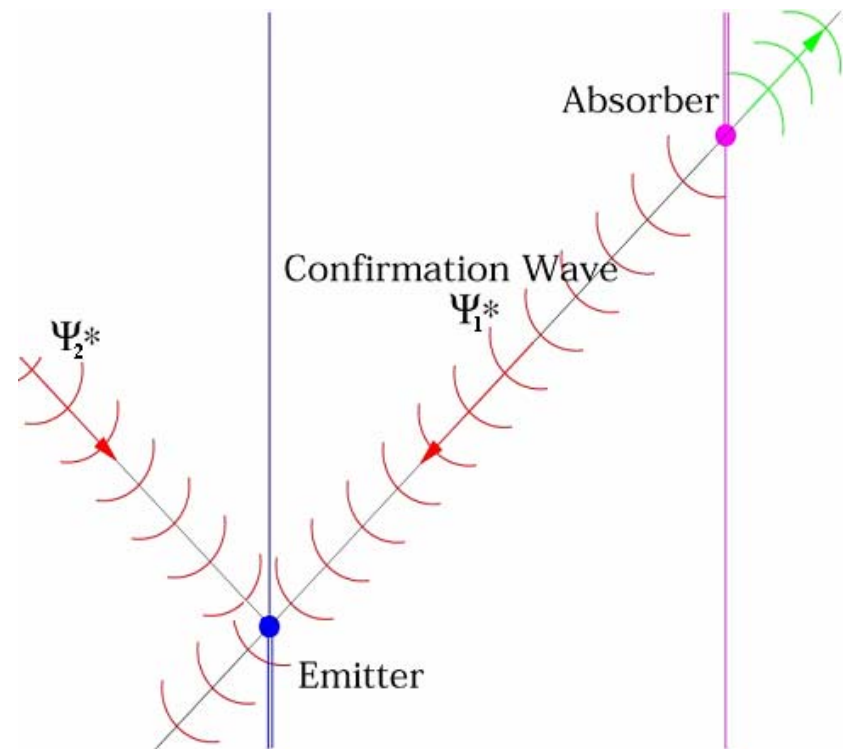
Is the TI Deterministic?

Of course, Maudlin's argument is irrelevant if the TI is deterministic. But is it?

In my view, it is not. The constraints of a transaction do not determine the future, but rather place the constraints of physical conservation laws on it.

It is rather like the transaction that occurs at the grocery store when you present your debit card to the cashier.

There is an electronic handshake transaction between the cash register and the bank, which insures that you have enough in your account to pay for your purchases and deducts the money, but does *not* determine what you decide to purchase. (It enforces the Law of Conservation of Money.)

The emergence of the future from the present is rather like frost forming on a cold window pane. Long fingers of causal handshakes probe the future, but the present is not determined by them, only constrained.

The TI and the Arrows of Time

There are several distinct Arrows of Time in our universe, and their hierarchy and relationship is a very interesting question.

The orthodox view (see Hawking) is that some CP-violation in the early universe lead to the matter-antimatter asymmetry and the cosmological arrow of time, which produced the thermodynamic arrow of time, leading separately to the dominance of EM retarded waves and to our perception that we remember the past but not the future.

The Transactional Interpretation leads to a somewhat different scenario. The Big Bang in our past terminated the back-propagation of advanced waves, leading to the electromagnetic arrow of time, the time-delay of which leads to the thermodynamic arrow of time, which produces the subjective arrow of time.

Kaon Arrow of Time → Cosmological Arrow of Time → Thermodynamic Arrow of Time → Electromagnetic Arrow of Time → Subjective Arrow of Time
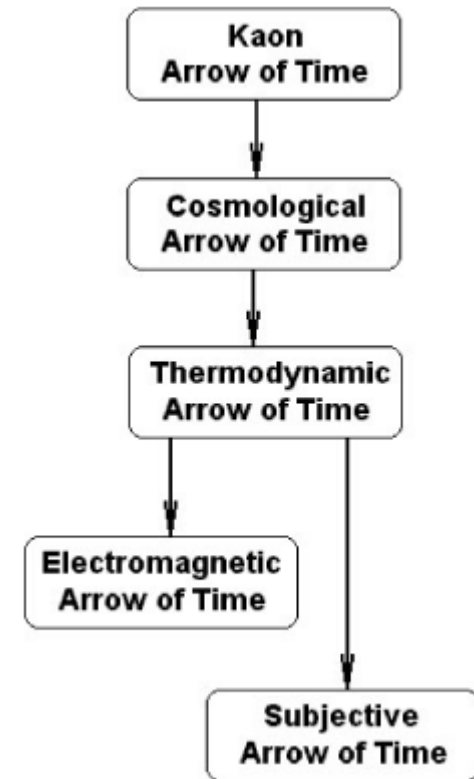
Last
Words

Conclusions

- The Transactional Interpretation provides a way of understanding the counter-intuitive aspects of quantum mechanics.

- Its advance-retarded handshake provides a way of understanding the intrinsic nonlocality of quantum mechanics, while preserving the constraints of special relativity.

- Among quantum interpretations, the TI is unusual in providing a graphic way of visualizing quantum processes (including quantum computing).

- It also provides insights into the nature of time and the emergence of the future from the present.

References
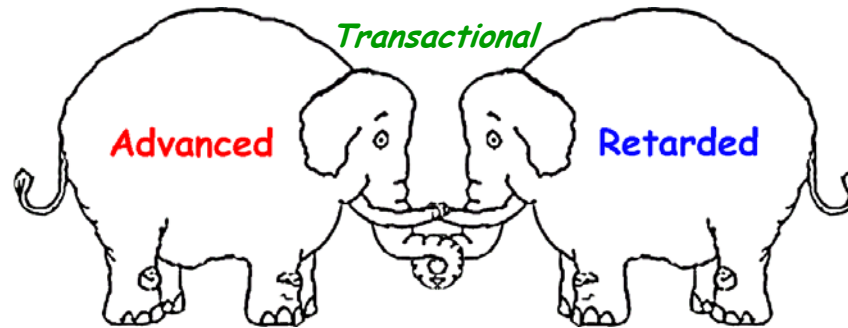
● "The Transactional Interpretation of Quantum Mechanics", *Reviews of Modern Physics 58, 647 (1986).* Available at http://www.npl.washington.edu/TI or the RMP web site.

● "The Plane of the Present and the Transactional Paradigm of Time", Chapter 9 of *Time and the Instant*, Robin Drurie, ed., Clinamen Press, UK (2001); ArXiv reprint: *quant-ph/0507089*

● The PowerPoint version of this talk will soon be available at: http://faculty.washington.edu/jcramer

The
End