


# What Entanglement Might be Telling Us

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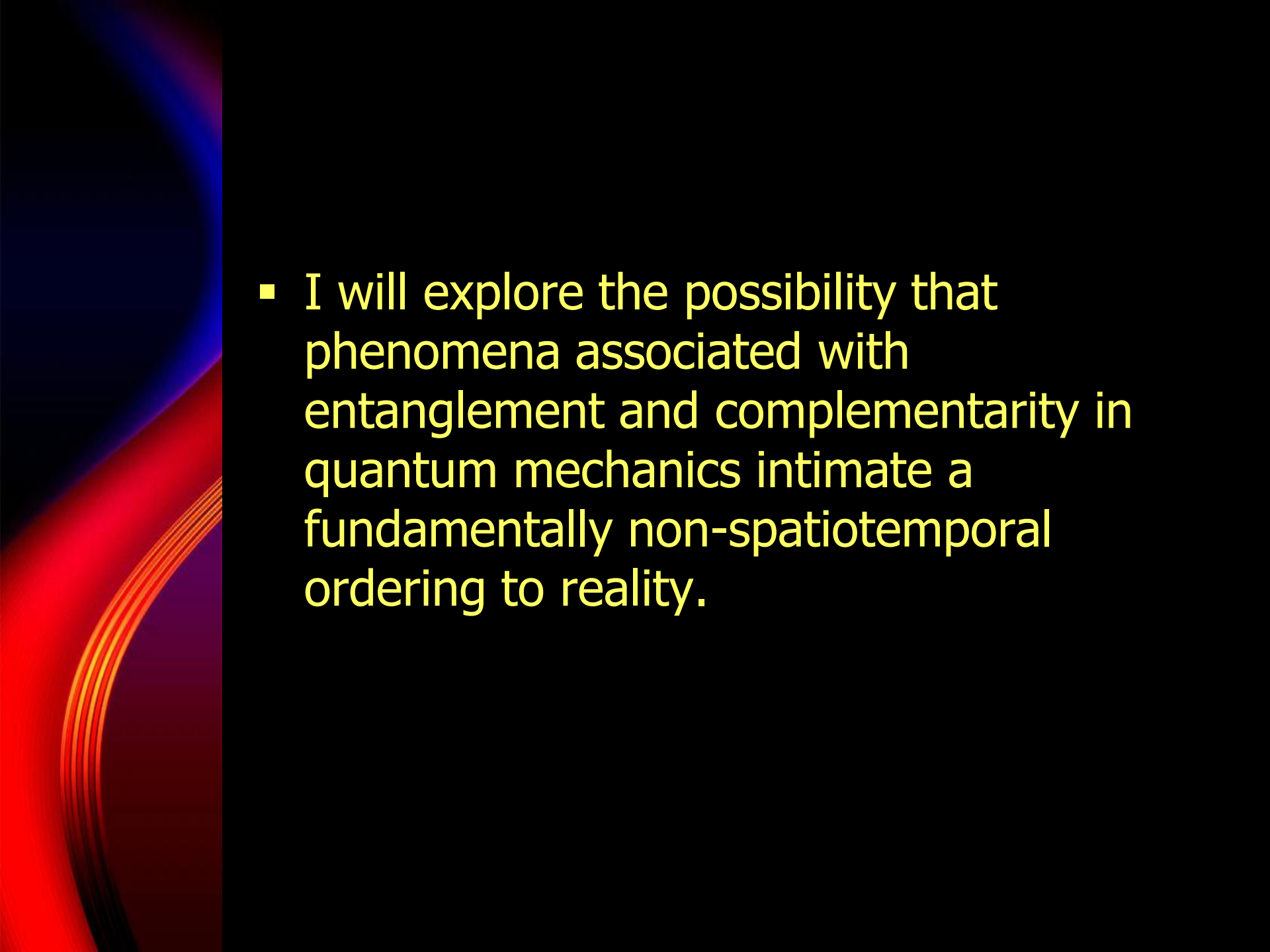
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- “thus many quantum-gravity theorists believe there is a deeper level of reality, where space does not exist... These days, many of us working on quantum gravity believe that causality itself is fundamental and is thus meaningful even at a level where the notion of space has disappeared.” (Lee Smolin)

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- I will explore the possibility that phenomena associated with entanglement and complementarity in quantum mechanics intimate a fundamentally non-spatiotemporal ordering to reality.

# Entanglement

- In (standard, non-relativistic) quantum mechanics, the quantum state of a complex system does not in general permit decomposition into ontologically distinct components.
- Schrödinger regarded entanglement as the defining trait of quantum theory


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- The components of a system in an entangled state behave in ways that are individually unpredictable, but jointly constrained
  - It is possible to forecast with certainty how one component will behave, given information about the measurements carried out on the other even though it is impossible to predict how they will behave individually



# How do they do it?

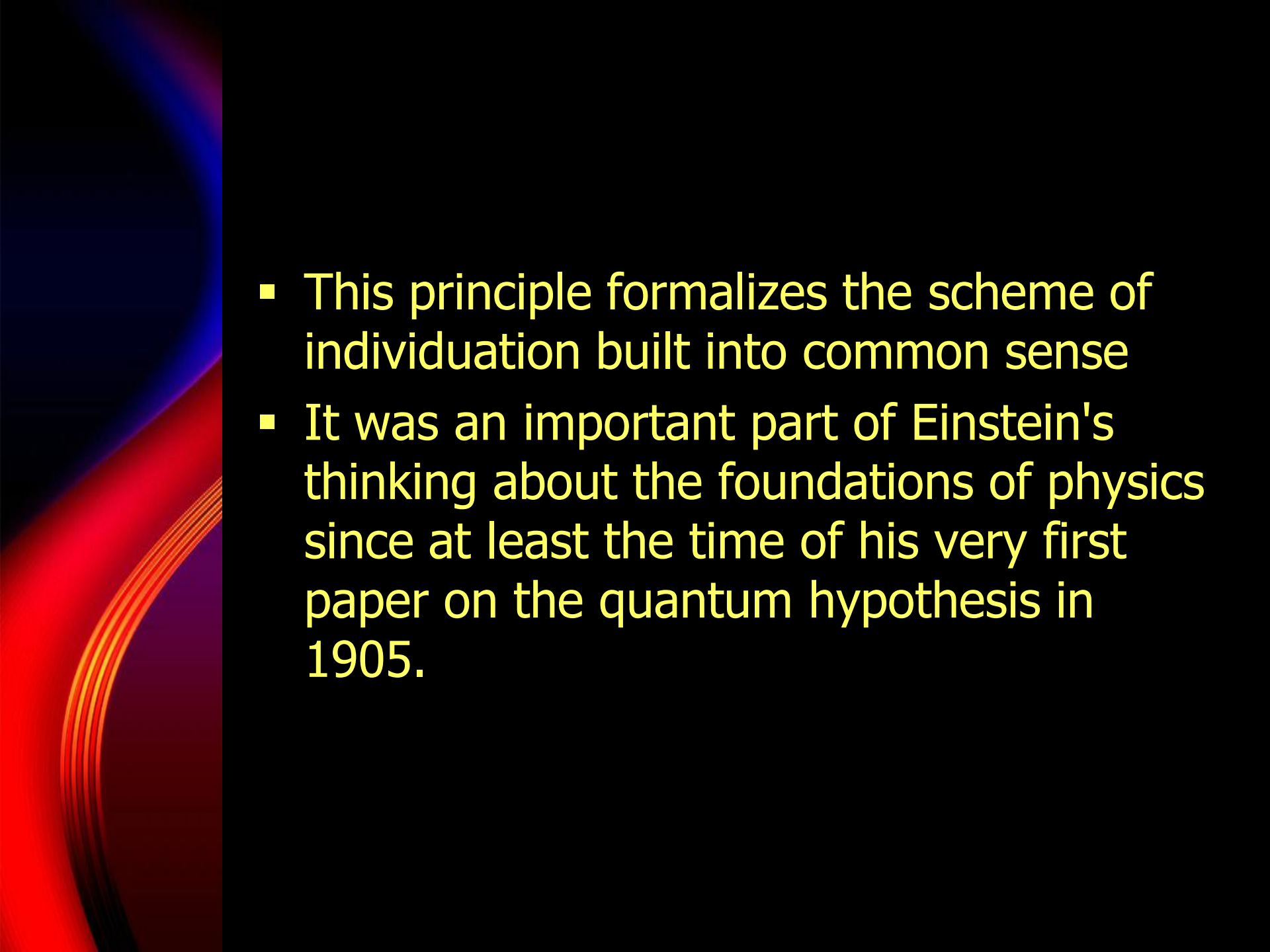
- There is no difficulty understanding how to derive the problematic correlations from the formalism
- Difficulties arise, however, in trying to arrive at a physical understanding of how entangled particles manage to exhibit the coordinated randomness that the formalism predicts



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- The felt need to explain the correlations dynamically has prompted stories about tachyons, superluminal influence, and cosmic conspiracy.
  - No single explanation has gained wide acceptance.

# Einstein's Principle (EP)

- "That which we conceive as existing ('actual') should somehow be localized in time and space. That is, the real in one part of space, A, should (in theory) somehow 'exist' independently of that which is thought of as real in another part of space, B."

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- This principle formalizes the scheme of individuation built into common sense
  - It was an important part of Einstein's thinking about the foundations of physics since at least the time of his very first paper on the quantum hypothesis in 1905.

# EP and Entanglement


- Quantum entanglement violates Einstein's Principle
- according to quantum mechanics, there is at best an approximate and qualified separation of the contents of different volumes of space

# No half-way house

- Einstein recognized that entanglement undermined the scheme of individuation expressed by his principle.
- In his view, there was no question of allowing non-local influences and maintaining his principle.
- If one allows immediate dependencies between the systems located in different parts of space, the claim that they are distinct no longer has any meaning.

# Einstein's hope


- He thought that there must be a way of filling in the quantum mechanical state description with hidden local variables that screen off any immediate, apparent dependence between the states of separated components.


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- "... If one [allows immediate dependencies between the states of spatially separated systems] then *I do not at all see what physics is supposed to describe.* ... I do not see how one is supposed to divide up the world objectively so that one can make statements about the parts"




An intriguing possibility




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- Suppose that the tank is being filmed by one camera from the front and another camera from the side.
  - Suppose that the cameras project side-by-side images on a flat screen in an adjacent room, integrated seamlessly so that the screen displays just a two-dimensional expanse of color and moving shapes.


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- What we will see there is a certain relationship between the images appearing on the two screens.
  - For example, on screen A we may see an image of a lionfish from the side and on screen B we will see another such image rotated through 90 degrees.

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- There will be instantaneous dependences between events at different locations in the screen.
  - These arise because objects and events located at a single place in the tank produce multiple copies at different places on the screen.

# Another example

- A **kaleidoscope** is an optical toy in a tube that produces symmetrical patterns as bits of colored glass are reflected by mirrors.
- It consists of mirrors that run the full-length of the inside of the scope.
- There is a fixed or detachable object case at the end of the mirror tube that gives the scope its images.

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- The viewer doesn't directly see the three-dimensional beads or pieces of colored glass located in the casing.
  - He sees those pieces reflected and refracted through the mirrors to produce a two dimensional image in which each piece of glass is redundantly represented.

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- Facts about the way a given scope is put together determine the invariant features of the image (i.e., its boundaries, symmetries and topology)
  - The changing configuration of beads determine its variable features




# Kaleidoscope images












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- In both the fish-tank and kaleidoscope examples, we have a one-many correspondence between events in real space and events in the image-space.
  - This redundancy expresses itself as instantaneous dependence between events at different image-space locations.

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- No attempt to explain the correlations dynamically in the lower dimensional space will be correct.
  - One may have an interest in producing a descriptive history of image space, but the *physics* is given in three dimensions.


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- Entangled particles exhibit exactly the kind of non-dynamical dependencies that intimate the kind of redundancy that we have in the image spaces in the examples.
  - We have here a potentially new explanation of their source.



# Deepening the analogy; occlusion


- The view of a fish from one angle occludes another if they can appear on the screen individually but never together.
- Relations of mutual occlusion provide constraints on simultaneous observability of different views
- It would be natural to think of views that excluded one another as **complementary**.



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- If these were systematized, we would get a quite complex network of relations between views from different angles.
  - A full three-dimensional portrait could be pieced together from a collection of complementary, two-dimensional views, and would provide information about the images that the fish would project in image-space if it were turned through different angles.


# Categorical vs. modal properties

- We distinguish categorical from modal properties. **Categorical** properties are properties that involve no admixture of possibility.
- They describe what *is* the case, but not what *could*, *might*, or *would* be the case under some possible circumstance.
- That sort of information is considered modal because it makes reference to possible, non-actual situations.

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- The categorical description of a fish is properly given in three-dimensions.
  - But it embodies a good deal of complex, **modal information** about the images the fish *would* cast when viewed from different angles in image space.


# Image-space observables

- Observations in image space correspond to image-space observables.
- The image a fish presents when viewed from angle  $\alpha$  corresponds to the value it has for the observable 'view from  $\alpha$ '.
- Relations of occlusion and partial occlusion among image-space observables derive from the three-dimensional structure of the fish

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- One who didn't know that and who tried to interpret image-space observables as abiding properties of a two-dimensional object would end up with a Picasso-esque construction of two-dimensional images from different angles superimposed on top of one another in a geometrically impossible configuration.

# Fishtank wave-functions


- He could express all of the information contained in a three-dimensional description in a mathematical object (a fish-tank  $\Psi$ -function) which embodied modal information about the 'values' of different 'image-space observables'.

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- But it would be impossible to ground all of the dispositions that a fish has to appear thus and so when viewed from different angles in a description of how *it is* insofar as that description is given in two dimensions.




# Classical mechanics

- The space of possible states for an  $n$ -particle system is a  $6n$ -dimensional space, parameterized by the positions and momenta of constituent particles.
- Any function of these basic variables is itself an observable.

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- Every system always has a full set of values for all observables.
  - The dynamics is given by differential equations governing the behavior of the basic observables (Newton's equations for the positions or Hamilton's for positions and momenta).

# Quantum mechanics

- The space of possible states of a quantum system is a **Hilbert space**.
- Physical properties are represented by Hermitian operators on that space.
- The dynamics is given by **Schrodinger's equation** when the system is not observed.
- **Born's Rule** tells us that we observe the value for observable  $A$  *iff* the vector representing its state is an eigenstate of the  $A$ -operator.

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- For any Hermitian operator on a Hilbert space, there are others on the same space with which it doesn't share a full set of eigenvectors and some with which it has *no* eigenvectors in common.
  - It follows that we can never observe simultaneous values for all observables and indeed that there are pairs of quantities whose values we never observe simultaneously.

# Canonically conjugate quantities

- Quantities represented by operators that have no eigenstates in common are called canonically conjugate quantities.
- The most famous example of such a pair are the position  $x$  and momentum  $p_x$  in the  $x$  direction of a point particle in one dimension.

# Uncertainty relations

- Relations of occlusion and partial occlusion among quantum observables are summarized by the Uncertainty relations.
- In the example just mentioned these are given by,  $[x, p_x] = i\hbar$  (where  $[x, p_x] = xp_x - p_x x$ ,  $x$  is the commutator of  $x$  and  $p_x$ ,  $i$  is the imaginary unit, and  $\hbar$  is the reduced Planck's constant  $h/2\pi$ ).

# No hidden variables

- It is natural to think there must be more basic observables that ground the dispositions attributed by the quantum state in the way that positions and momenta ground the dynamical dispositions of classical systems.
- But we get absurd results if we try derive those dispositions from hidden, categorical properties of systems that live in three-space.



# Notice

- We would expect precisely analogous results if we tried to ground the information embodied in the 3-d description of a fish in categorical properties in two dimensions

# The moral

- Quantum observables do not behave like categorical properties of a three-dimensional system

# The suggestion

- We should be looking to see if we can derive the commutation relations among quantum observables from categorical properties of higher dimensional objects in a manner that mirrors the derivation of the algebra of two-dimensional aspects from the three-dimensional description of a fish.

# Wave-functions & ontology

- There are two attitudes one can take to the wave-function
  - Assume a broadly classical ontology of three dimensional objects and think of the wave-function as embodying complex, conditional information about how these behave
  - Assume the wave-function describes a higher-dimensional reality and the three-dimensional space of classical physics is a derivative structure

# Gestalt shift

- There's a gestalt shift involved in moving from the first to the second.
- Making it has important methodological implications.
- It means abandoning the idea that there should be a well-behaved story about what happens in three-space.

# More specifically

- It means
  - calling off the search for a physical mechanism by which the components of an entangled system influence one another
  - relinquishing the call for continuous trajectories, and
  - rejecting any attempt to describe what is happening in three-space in the moments between measurements.

# Recovering space-time

- The need to recover spatiotemporal structure from the formalism is a requirement that the higher dimensional view shares with other interpretations of quantum mechanics that recognize only unitary evolution





# Decoherence

- The most promising approach claims that the form of the Hamiltonian ensures that the wave-function for the universe decomposes into decoherent components
- Each of these corresponds to a system of wavepackets well-localized in 3-space for macroscopic degrees of freedom evolving according to approximately classical laws possessing the familiar three-dimensional symmetries.

# A theory of local beables

- John Bell argued that qm can't stand by itself as a physical theory because it lacks an ontological underpinning.
- He calls for the development of a theory of 'local beables'

# Bell

- “The theory of local beables is... a pretentious name for a theory that hardly exists otherwise, but which ought to exist . . . . ‘Observables’ must be *made* somehow, out of beables. The theory of local beables should contain, and give precise physical meaning to, the algebra of local observables.”

# Being vs. Appearance

- A theory of **Appearance** describes systems in terms of how they are disposed to affect certain classes of other systems (e.g., measuring instruments, observers).
- A theory of **Being**, by contrast, characterizes systems in terms of the way they *are* intrinsically and in actuality.

# Theories of Being

- A theory of Being should
  - allow for the derivation of the appearances,
  - have a clear, separable ontology,
  - Provide a catalogue of basic entities, quantities, and relations, and
  - come with a dynamics that is local and that grounds law-governed dispositions in categorical properties.



# A quantum theory of Being

- An approach to quantum phenomena which treats the appearances as a projection of a higher dimensional reality would provide an account of the categorical structure of reality that explained the law-governed dispositions attributed by the quantum state.
- It would give us somewhere in the actual world to house and ground the dispositions attributed by the quantum state.




# Physics and higher dimensional spaces

- Physics has explored higher-dimensional spaces in connection with string theory and other approaches to quantum gravity.
- But these have preserved the principle that spatial separation is a sufficient condition for individuation of systems.



# Why the conservatism?

- Einstein insisted we couldn't recognize immediate dependences between spatially separated components and continue to hold what we observe in different parts of space are really distinct existences.
- But he didn't put forward as an *a priori* truth that the world was made out of spatially localized building blocks.

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- “If one renounces [that] assumption then. ... *I do not see how* one is supposed to divide up the world objectively so that one can make statements about the parts ”
  - His own attitude reflects one of the reasons that the higher dimensional option has been relatively unexplored



*viz.*

- ... the absence of a clearly conceived or vividly imagined understanding of what a universe in which Einstein's principle failed would be like.

# An example from physics

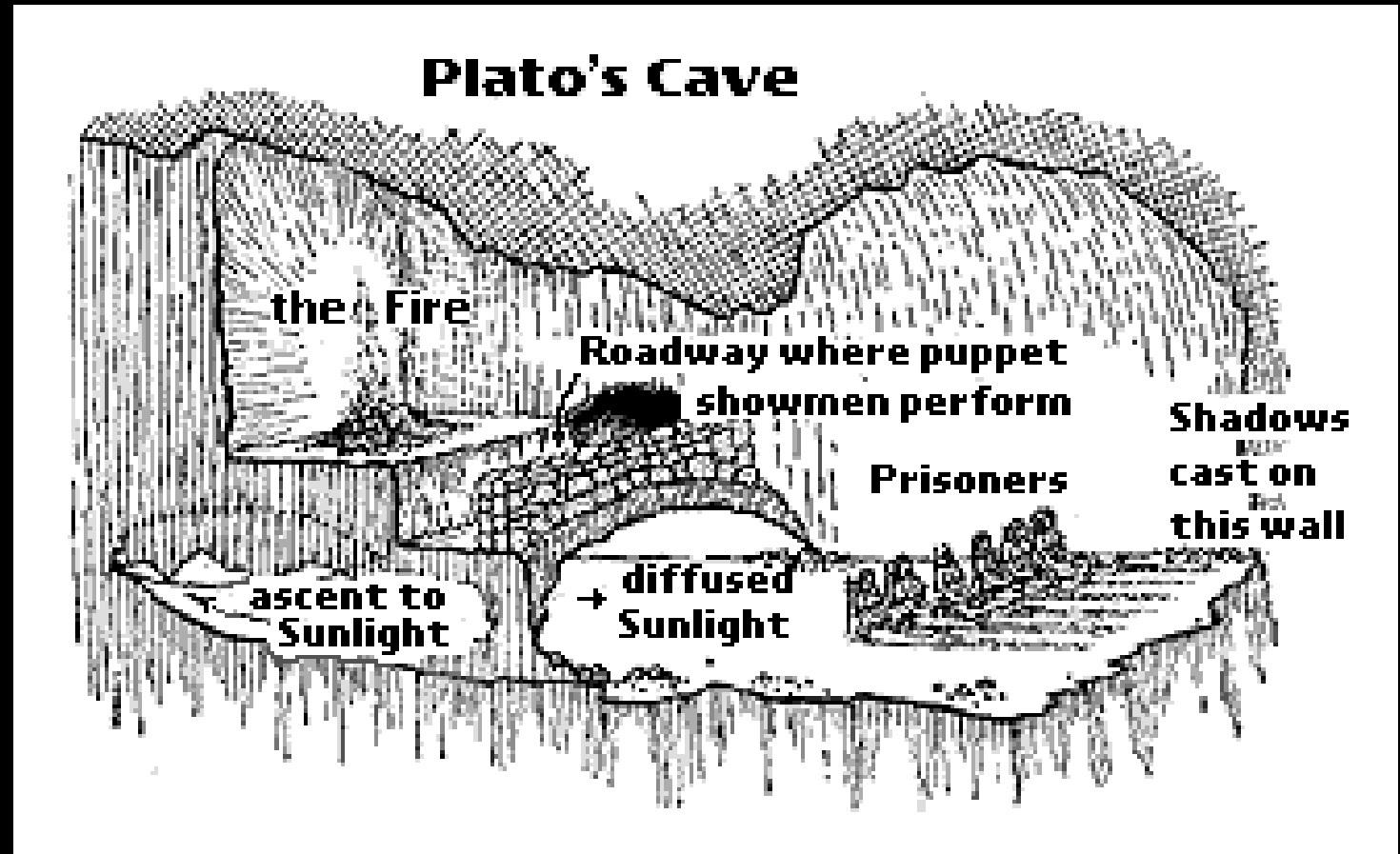
- [http://www.physicsweb.org/articles/world/18/9/3.](http://www.physicsweb.org/articles/world/18/9/3)
- In this article, cosmologists argue that recent data measuring cosmic microwave background suggest that the universe might be multiply connected
- An object that travels away from the Earth in a straight line in such a universe will eventually return from the other side of the universe rotated by  $36^\circ$



# Kaleidoscopic cosmology?

- “Space might therefore act like a cosmic hall of mirrors by creating multiple images of faraway light sources.”


# Philosophical precedent



# Conclusions

- There is no good *a priori* argument that space has to provide the ground of individuation of objects
- Once we admit as a conceptual possibility that the world doesn't decompose along spatial lines, the imagination is freed to take seriously the idea that what we see in space are lower-dimensional manifestations of a non-spatiotemporal reality



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- The strongest argument in favor of a higher-dimensional approach is the ease and elegance with which a higher dimensional model may allow us explain some of the most puzzling quantum phenomena.



# New Directions...

- “It may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal” (Bell)
- The multi-dimensional framework might provide one direction from which that sort of renewal could come.