Title: What's Wrong with 'Measurement'?

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Abstract: In his brilliant article "Against 'Measurement'", John Bell famously argued that the word has had such a damaging effect on the discussion, that it should now be banned altogether in quantum mechanics. But in the beginning was the word, and the word is still with us. Indeed, David Mermin responded In Praise of Measurement that within the field of quantum computer science the concept of measurement is precisely defined, unproblematic, and forms the foundation of the entire subject, a verdict reaffirmed by the development of measurement-based quantum computation. Bell's arguments deserve a more direct response: I shall try to give one.

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Prolegomena to a Pragmatist Interpretation of Quantum Theory

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Bell "Six Possible Worlds of Quantum Mechanics"

My view

The pragmatist approach, because of QT's great success and immense continuing fruitfulness, must be held in high respect. Moreover it seems to me that in the course of time one may find that because of philosophical pragmatist progress the 'Problem of Interpretation of Quantum Mechanics' has been encircled. And the solution, invisible from the front, may be seen from the back.

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A different view

To interpret quantum theory is to understand how and why that theory can be viewed as an enormously successful theory, so that its development was a highly progressive step in physics, even though it is *not a theory of beables!*

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If we can do this, we can answer Bell's challenge.

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Bell's semantic charge against 'measurement'

"…the word comes loaded with meaning from everyday life, meaning which is entirely inappropriate in the quantum context.

When it is said that something is 'measured' it is difficult not to think of the result as referring to some pre-existing property of the object in question. …

The word has had such a damaging effect on the discussion, that I think it should now be banned altogether in quantum mechanics."

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ii. Quantum 'measurements' can provide vital information---the essential function of any measurement.

iii? (One *could* claim that a quantum 'measurement' is a way to faithfully reveal a quantum *probability* by transferring it from object to apparatus. But in the end I shall reject this: probabilities aren't properties.)

Bell's more substantial charge against 'measurement'

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The split

- Quantum theory is a probabilistic theory.
- In an application of quantum theory, the Born rule generates probabilities *for measurement outcomes*, given a quantum state.

  $\text{prob}_\rho(A\varepsilon\Delta)=\text{Tr}(\rho\mathbf{P}^A[\Delta])$

- The split is between *system* (assigned state ρ) and *apparatus* (whose final condition is described as registering outcome AεΔ).

Why the split is shifty

Any application of quantum mechanics presupposes a division into system and apparatus.

But there are not two kinds of object in the world---systems and apparatus.

So the division can only be made in the context of a particular application of quantum mechanics.

But there are different *ways* of applying quantum mechanics in a particular situation, corresponding to different ways of making this division. Changing from one to another shifts the split.

Bell's problem

"The problem is this: quantum mechanics is fundamentally about 'observations'. It necessarily divides the world into two parts, a part which is observed and a part which does the observing. The results depend in detail on just how this division is made, but no definite prescription for it is given. All that we have is a recipe which, because of practical human limitations, is sufficiently unambiguous for practical purposes."
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But a measurement on A must be carried out *via* an interaction with some object B. So we need a quantum state ρ_{S+A+B} for $S+A+B$, yielding probabilities of measurement outcomes on B.

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So why does Bell think the results depend in detail on just how this division is made?

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And there is some observable whose measurement outcomes could discriminate among these quantum states!

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- The quantum system is the α-particle *plus* a layer of atoms in every plate. A measurement on this system by a further apparatus collapses it once onto a state in which just one atom *per* plate is excited: the apparatus records its result as a list of all their positions, which very probably lie in a line.

Collapse is not physical!

But a quantum state does *not* represent an object's intrinsic properties,

And collapse is not a physical process, but represents advice updated on new information.

The occurrence of measurements that could discriminate different collapse loci in the chain is ruled out by the assumption that *S* was measured as described.

So the observer need not choose just where to update the quantum state whose advice he follows.

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We started by considering applying quantum mechanics to some physical object *S* by assigning *S* a quantum state ρ_S.

But why start with *S* rather than some larger system? This ignores the pervasive nature of entanglement!

If *S* is initially entangled with some system *T* involved in a measurement on *S*, their joint state ρ_{S+T} may yield different predictions than ρ_S!

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Objection

- This can't happen, because we can retrieve ρ_S by tracing ρ_{S+T} over the Hilbert space of *T*: then ρ_S, ρ_{S+T} yield identical probabilities for measurements of any observable on *S* alone.

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- <u>Example</u>: measuring the position of an electron in a hydrogen atom.
- <u>Example</u>: measuring the phase of a laser beam by homodyne detection.

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- The quantum system is a test beam of laser light: the measuring apparatus is a reference beam plus detectors in a homodyne measurement. The intensities detected record the phase of the test beam's coherent state.
- The quantum system is *both* beams—test and reference. The apparatus is just the detectors, which record the *relative* phase between test and reference beams.

Now

- The results *may* depend in detail on just how this division is made:
- The detector photocurrents will be the same: But only if the reference beam has an arbitrarily high amplitude, so that its mean photon number tends to infinity, will *all* correlations between the detector photocurrents agree in the two divisions.

Bell's analysis

"the following rule for placing the Heisenberg split, although ambiguous in principle, is sufficiently unambiguous for practical purposes:

Put sufficiently much into the quantum system that the inclusion of more would not significantly alter practical predictions."

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Bell: FAPP is not good enough!

- "In classical mechanics we have a model of a theory which is not *intrinsically* inexact, for it neither needs nor is embarrassed by an observer"
- "At least one can *envisage* an accurate theory, of the universe, to which the restricted account *is* an approximation."
- "...[quantum] theory is fundamentally approximate"
- "...quantum mechanics...is...intrinsically inexact."

(Quantum Mechanics for Cosmologists.)

But every application is FAPP!

- This is true for classical physics just as much as for quantum theory.
- To apply either theory one must consider some physical system and either ignore the rest of the world or model its effect on this system in a highly simplified way.
- In both theories, including more in the system may lead to a more reliable model at the cost of greater complexity.

So what's the difference?

- Only in classical physics can one "envisage" a model representing the whole universe, in all its details. If the theory were true, this model could be perfectly accurate.
- Nothing in the model need be designated "observer": though some parts of the model might be supposed to represent observers as physical systems.
- Simplifications of this model might "in principle" be arrived at by controlled approximations.

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- *Conclusion*: One *cannot* envisage a model representing the whole universe in full detail.

Answers to Bell's rhetorical questions

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A Measurers are not physical devices with special dynamical powers—able to collapse huge wave-functions with a single glance. One must distinguish the role of agent from that of instrument. A measurer is an agent with an instrument: in the limiting case the instrument is (part of) the agent's body. To apply quantum theory an agent must be able to describe some instrument "classically" in its role of recording outcomes.

Q "How long did the wave-function of the world have to wait before jumping?"

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A The world does not have a wave-function: only agents have wave-functions. An agent may assign a wave-function to a system at a time arbitrarily far to the past or future of the moment when he assigns it. The system may be a simplified model of “the world”, excluding the agent. “Jumps” are updates of an agent’s wave-function for a system, not dynamical events.

Q

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A This is more or less true of the suitable physical interactions between one object and another object of a type an agent could have used as an instrument when performing a quantum measurement on it, if only he had been there at the time.

Q "Do we not have jumping then all the time?"

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A No. Even though suitable interactions between an object and an instrument-type object are going on all the time these days, they are not accompanied by jumps in any wave-function. A wave-function jumps only at the behest of an agent whose wave-function it is. No feasible agent is able to represent each of these objects by a wave-function. Even if he could, he could not update this depending on the determinate subsequent condition of every instrument-type object with which it suitably interacts.

about what?”

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A2 Anything you like! In a quantum computer these measurement outcomes may encode useful information about e.g. the prime factors of a product of two prime numbers.

vhom?”

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- These probabilities are not subjective, but neither are they frequencies or chances.
- One who accepts quantum theory adjusts his personal degrees of belief to conform to the probabilities quantum theory prescribes for his situation.
- So the Born Rule yields *prescriptions*, not *descriptions*: quantum probabilities themselves neither describe nor represent anything, in the world or in an agent.

What are measurement outcomes?

- Bell hoped for "some increase in precision by concentration on the beables, which can be described in "classical terms", because they are there. The beables must include the settings of switches and knobs on experimental equipment, the currents in coils and the readings of instruments."

(The Theory of Local Beables)

Are measurement outcomes beables?

But *can* we say instrument readings “are there” now classical physics has been undercut by quantum theory?

It is *useful* to do so. This is useful in everyday life, and in continuing to apply classical physics when quantum effects are irrelevant.

More importantly (in the present context).....

They must be assumed

One *must* say such things in order to apply quantum theory at all! Without "classical" descriptions of measurement outcomes, quantum theory would be useless, since it could offer no advice on what to believe.

Any application of quantum theory *requires* use of descriptive terminology that theory does not provide.

This is the essential role of "classical" descriptions in quantum theory.

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The success of quantum theory shows that one can say instrument readings “are there” in some contexts. Since measurement outcomes can be assumed, I propose to call them assumeables.

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But descriptions have their limitations

- Accepting quantum theory means limiting the inferences one is prepared to make based on "classical" descriptions:
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That question was already answered, for a pragmatist!

Unfinished Business

"In the beginning natural philosophers tried to understand the world around them. … Experimental science was born. But experiment is a tool. The aim remains: to understand the world. To restrict quantum mechanics to be exclusively about piddling laboratory operations is to betray the great enterprise."

Wanted!

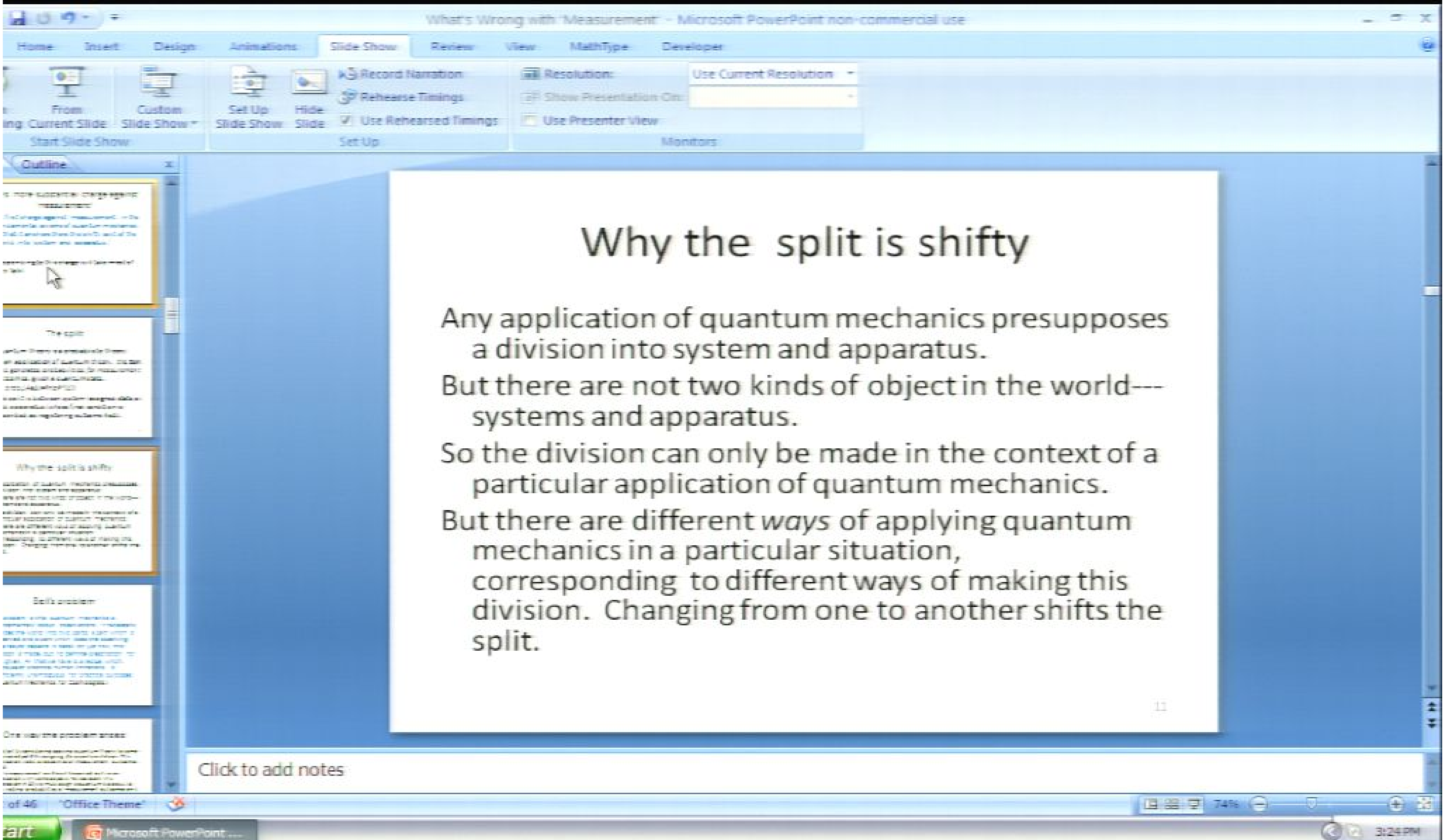
A pragmatist account of explanation capable of showing how quantum theory can be applied to *explain* natural phenomena, in and outside the laboratory.

Since quantum theory adds no descriptive resources of its own, this will be an account of how a theory may be used to explain a phenomenon *without itself describing it*.

THE END

Pragmatism

- Does *not* rely on a distinction between the observable and the unobservable.
- Regards some sentences in theories not as statements but instructions to the user—as prescriptive, not descriptive.
- Considers *every* descriptive statement as licensing different inferences in different contexts and relative to different purposes: as "moves in a language-game".


Why the split is shifty
Any application of quantum mechanics presupposes a division into system and apparatus.
But there are not two kinds of object in the world---systems and apparatus.
So the division can only be made in the context of a particular application of quantum mechanics.
But there are different ways of applying quantum mechanics in a particular situation, corresponding to different ways of making this division. Changing from one to another shifts the split.
Click to add notes

Objection

- This can't happen, because we can retrieve ρ_S by tracing ρ_{S+T} over the Hilbert space of T: then ρ_S, ρ_{S+T} yield identical probabilities for measurements of any observable on S alone.

One way the problem arises

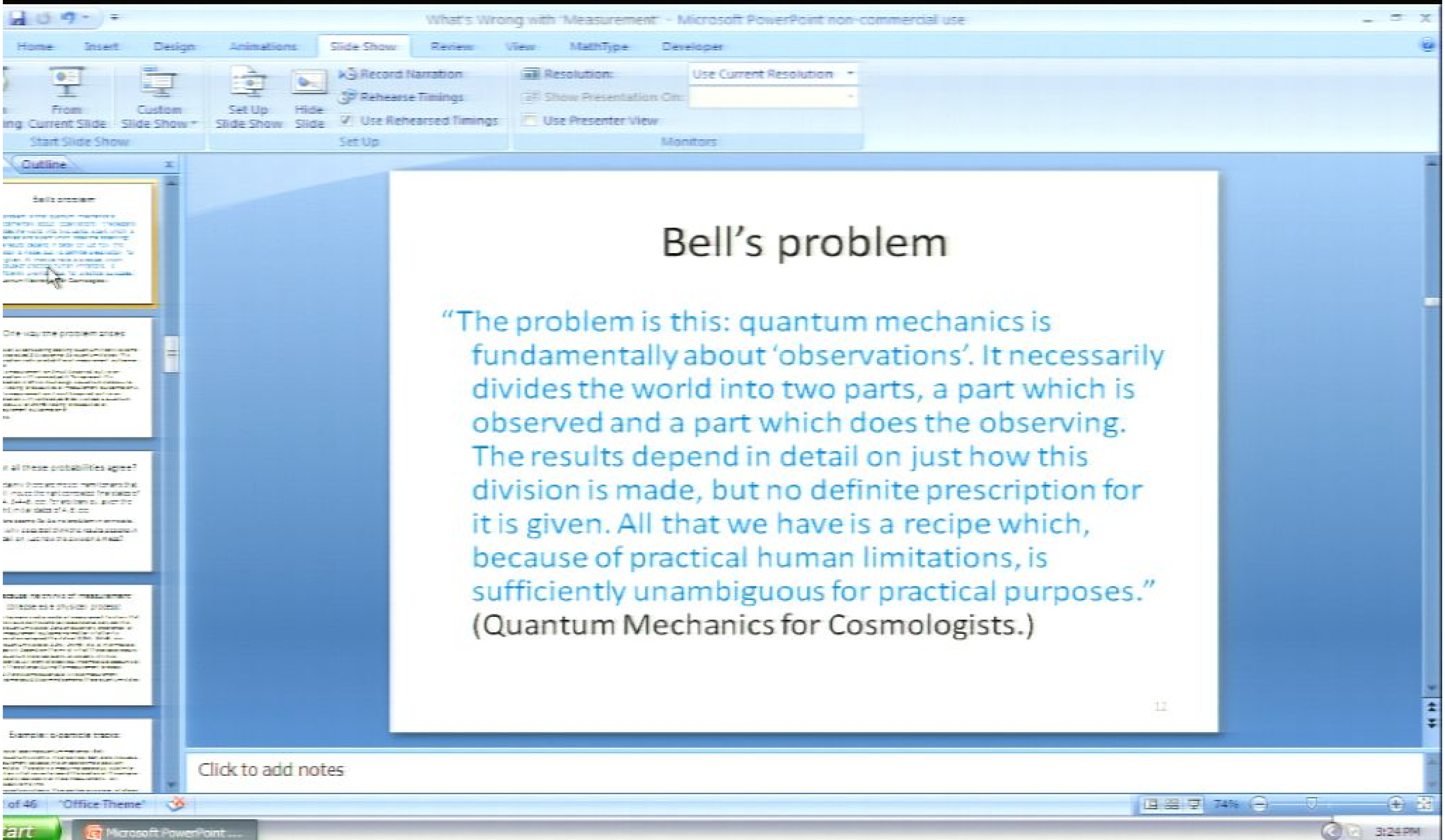
We start by considering applying quantum theory to some physical object *S* by assigning *S* a quantum state ρ_S. This application yields probabilities of measurement outcomes on *S*.

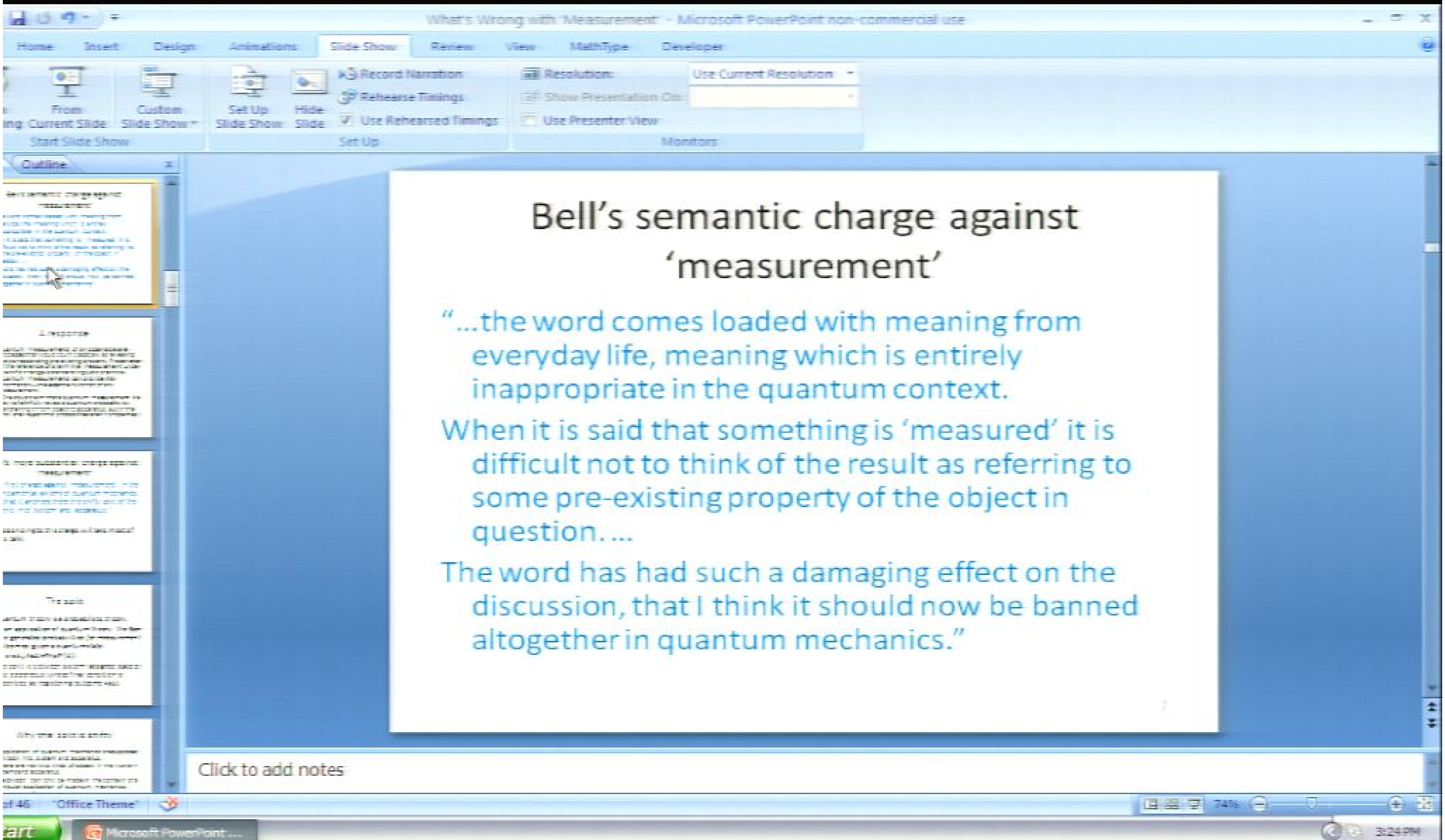
But a measurement on *S* must be carried out *via* an interaction with some object *A*. To represent this interaction in QT we must assign a quantum state ρ_{S+A} to *S+A*, yielding probabilities of measurement outcomes on *A*.

But a measurement on *A* must be carried out *via* an interaction with some object *B*. So we need a quantum state ρ_{S+A+B} for *S+A+B*, yielding probabilities of measurement outcomes on *B*.

..... *etc.*

Click to add notes


Bell's problem
"The problem is this: quantum mechanics is fundamentally about 'observations'. It necessarily divides the world into two parts, a part which is observed and a part which does the observing. The results depend in detail on just how this division is made, but no definite prescription for it is given. All that we have is a recipe which, because of practical human limitations, is sufficiently unambiguous for practical purposes."
(Quantum Mechanics for Cosmologists.)
Click to add notes


What's Wrong with 'Measurement' - Microsoft PowerPoint non-commercial use
Bell's semantic charge against 'measurement'
"…the word comes loaded with meaning from everyday life, meaning which is entirely inappropriate in the quantum context.
When it is said that something is 'measured' it is difficult not to think of the result as referring to some pre-existing property of the object in question. …
The word has had such a damaging effect on the discussion, that I think it should now be banned altogether in quantum mechanics."
Click to add notes

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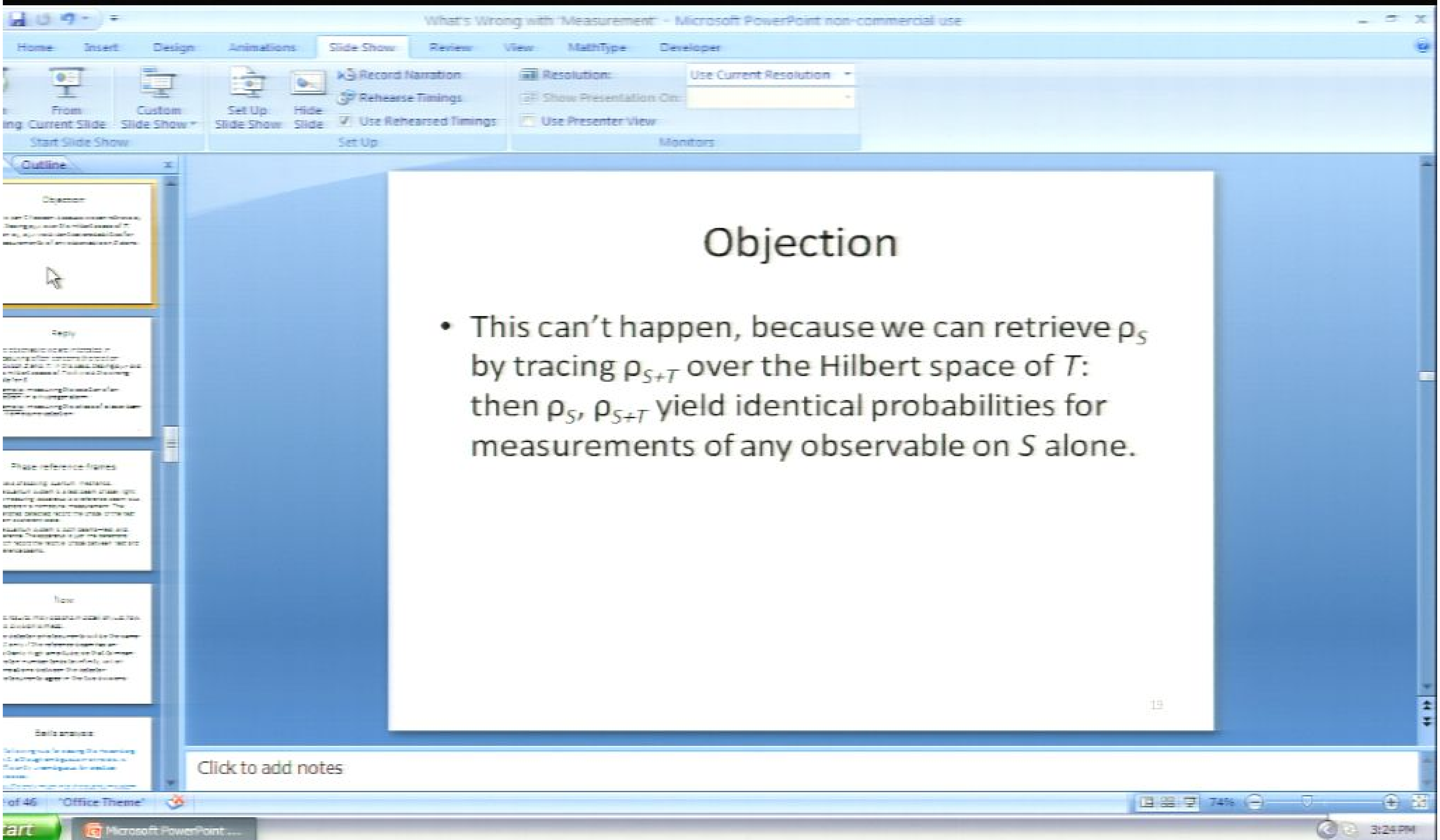
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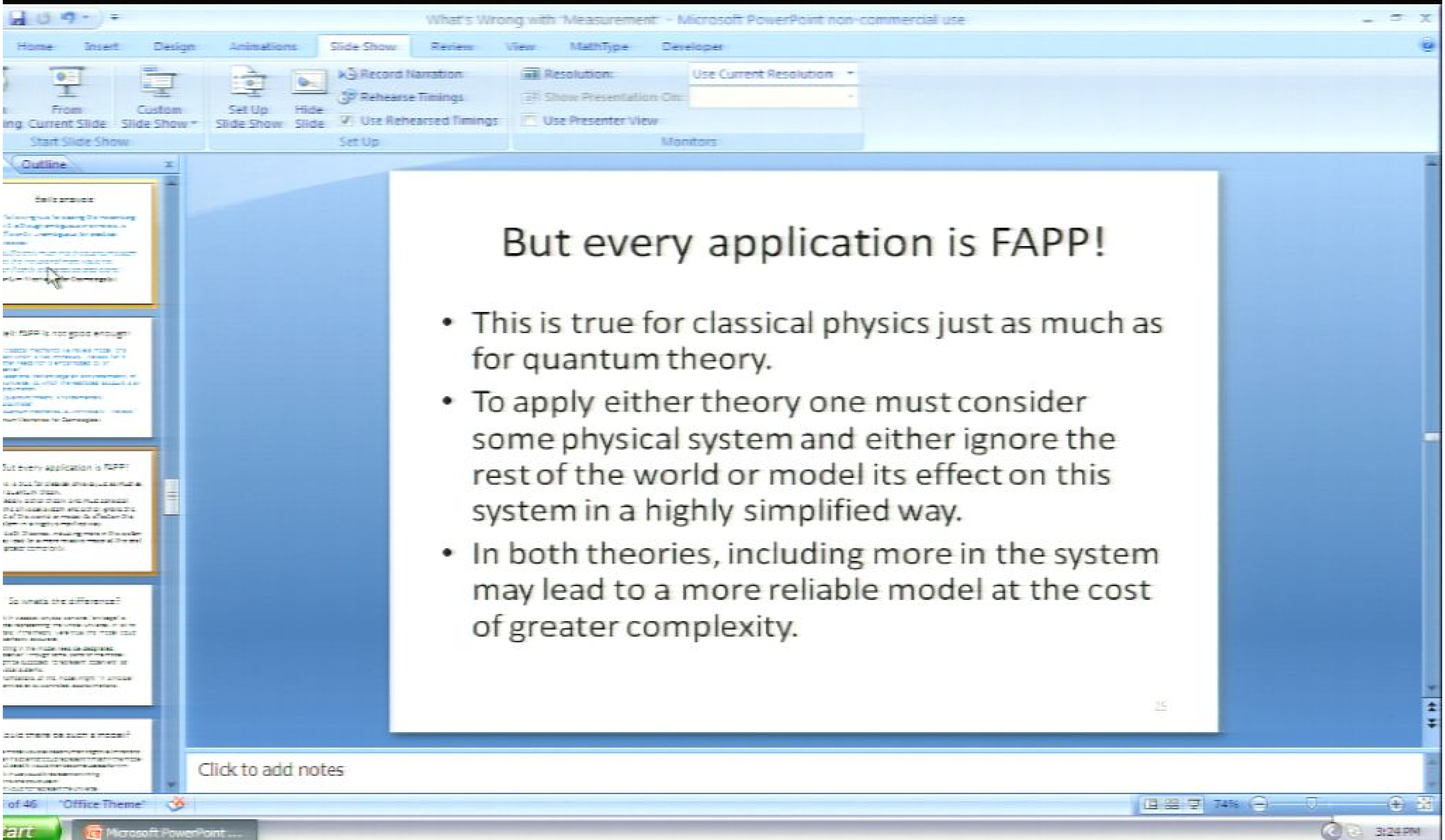
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But every application is FAPP!
• This is true for classical physics just as much as for quantum theory.
• To apply either theory one must consider some physical system and either ignore the rest of the world or model its effect on this system in a highly simplified way.
• In both theories, including more in the system may lead to a more reliable model at the cost of greater complexity.
Click to add notes

Could there be such a model?

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- The model would exceed human cognitive limitations.
- Even if a scientist could represent *himself* in the model in full detail it would then become useless for him.
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- Only *in use* would it represent anything.
- But no-one could use it!
- So it would *not* represent the universe.
- **Contradiction!**
- *Conclusion*: One *cannot* envisage a model representing the whole universe in full detail.