Title: PSI 2018/2019 - Foundations of Quantum Mechanics - Lecture 7

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Abstract:

Quantum Foundations
Lecture 7

PSI Review Class: 15th January 2019

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6.1) Realism

- Scientific Realism is the idea that:
  - There exists an objectively real physical world, independent of observers.
  - The job of a physical theory is to attempt to describe it.
  - Successful physical theories are approximately correct descriptions of the objectively real physical world.
- It is more accurate to think of theoretical entities, e.g. electrons, quarks, as referring to things that actually exist than to do otherwise.

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6.2) Anti-Realism

- Varieties: idealism, logical positivism, empiricism, instrumentalism, operationalism.
- The only things we have direct access to are our own perceptions and/or the records of results from our experimental apparatuses.
- Theories are simply systems for organizing/predicting regularities in those perceptions/results.
- Theoretical entities, e.g. electrons, are a convenient fiction used in our calculations.
- Operationalism: Every statement of a theory should boil down to a list of instructions for what to do in the lab and what will be seen as a result.

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6.3) Realism vs. Anti-Realism
Putnam's "No Miracles" Argument

When they argue for their position, realists typically argue against some version of idealism - in our time, this would be positivism or operationalism. (...) And the typical realist argument against idealism is that it makes the success of science a miracle

(...)The modern positivist has to leave it without explanation (the realist charges) that 'electron calculi' and 'space-time calculi' and 'DNA calculi' correctly predict observable phenomena if, in reality, there are no electrons, no curved space-time, and no DNA molecules. If there are such things, then a natural explanation of the success of theories is that they are partially true accounts of how they behave. And a natural account of the way scientific theories succeed each other (...) is that a partially correct/incorrect account of a theoretical object (...) is replaced by a better account of the same object or objects. But if those objects don't really exist at all, then it is a miracle that a theory which speaks of gravitational action at a distance successfully predicts phenomena; it is a miracle that a theory which speaks of curved space-time successfully predicts phenomena; and the fact that the laws of the former theory are derivable 'in the limit' from the laws of the latter theory has no methodological significance

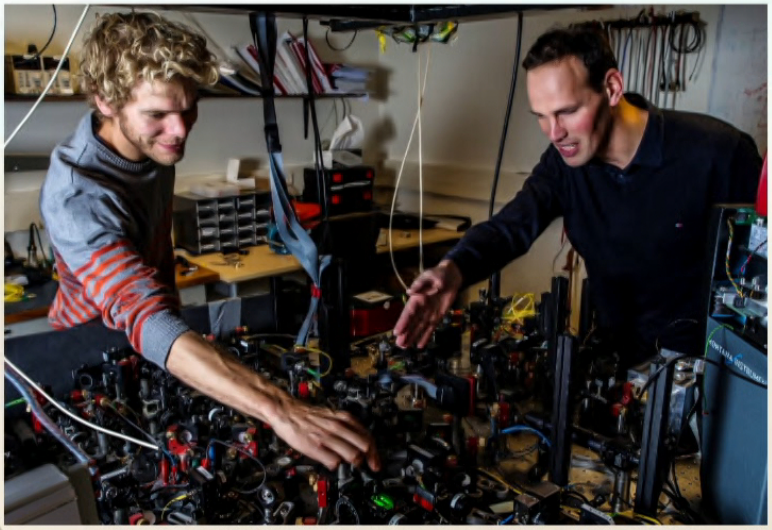
H. Putnam, Meaning and the Moral Sciences, Routledge (1978)

Operational Approaches

- In operational approaches we treat experimental procedures as "black boxes", as if the meaning of "input", "output" and "process" were clear.

Theory Laden Nature of Experiments

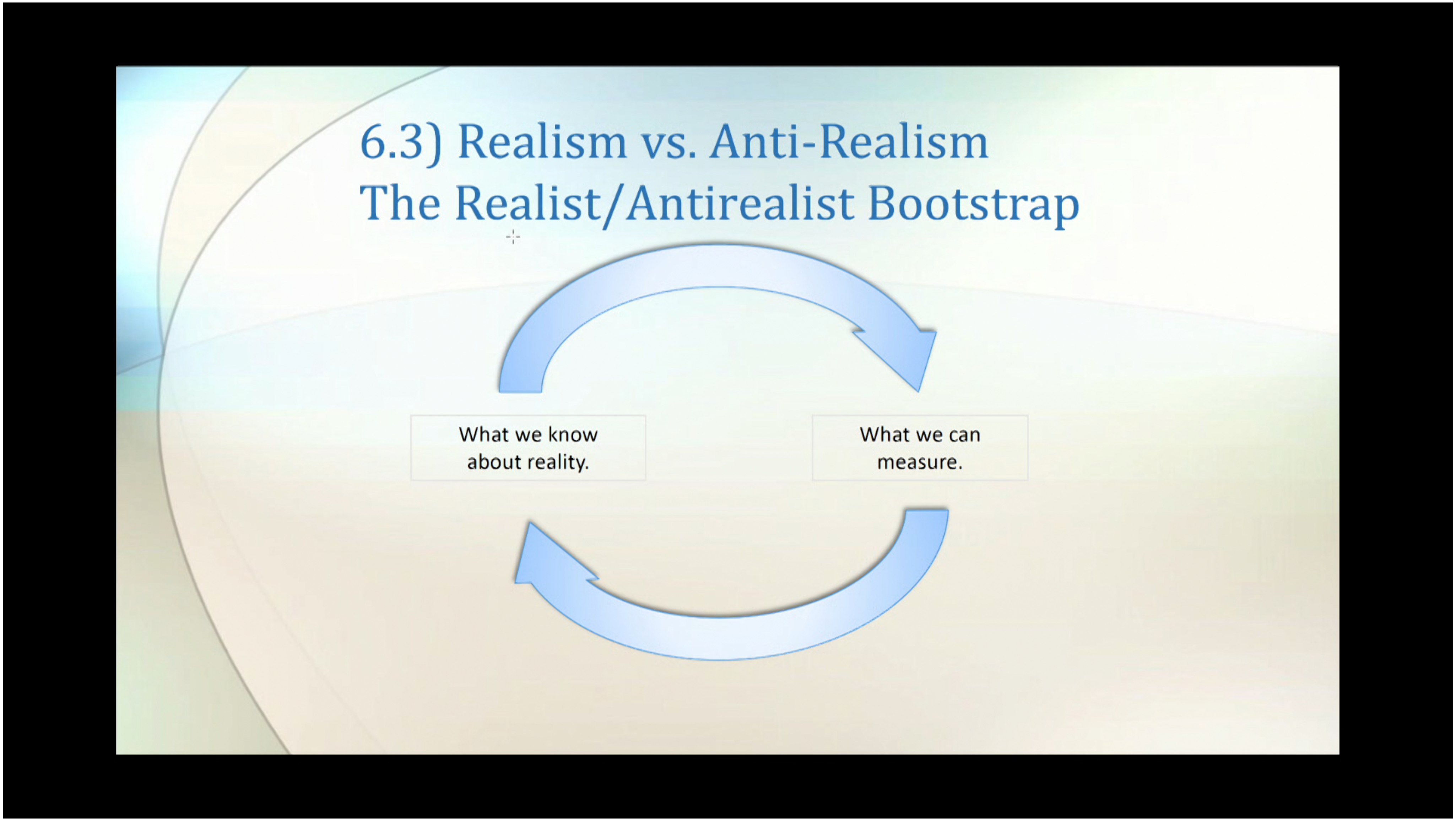
Physics experiments can be complicated. You have to know a lot of background theory to understand how they work.



Bas Hensen and Ronald Hanson with the equipment used for the first loophole free Bell experiment in 2015 - credit QuTech http://qutech.nl

6.3) Realism vs. Anti-Realism
Realism vs. Anti-Realism

- It is undeniable that what we can measure affects what we can theorize about.
  - Anti-Realists insist that this is primary.
- It is also undeniable that we rely on our theories to define/interpret what we can measure.
  - e.g. An anti-realist has a hard time explaining how we can redefine the metre.
  - Realists insist that this is primary.


6.3) Realism vs. Anti-Realism
The Realist/Antirealist Bootstrap
What we know about reality.
What we can measure.

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6.4) A Synthesis?
Realism vs. Realist Explanations

- You don't have to be a realist to realize that realist explanations are often useful.
  - If I have a story about what exists and how it behaves then I have a framework for reasoning about novel physical situations and for generalizing the theory.
- It is interesting that all of our physical theories prior to quantum theory admit a realist account, even if you don't believe they are literally (approximately) true.
- We might ask why we cannot find a realist account that we all agree upon for quantum theory.

6.4) A Synthesis? Operationalism vs. Operational Methodology

- You don't have to be an operationalist to realize that stepping back from a realist account and temporarily defining things in terms of things we can do in the lab is often useful.
  - E.g. Einstein's derivation of special relativity, the development of thermodynamics prior to statistical mechanics.
- Since the operational implications of quantum theory are the only part we all agree upon, it may be useful to reformulate the theory operationally and come back to the realism question later.

6.5) Making the Problem Precise

"We always have had … a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it. And therefore, some of the younger students … you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. It has not yet become obvious to me that there's no real problem. **I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.**" – R. P. Feynman, "Simulating Physics with Computers", *International Journal of Theoretical Physics*, volume 21, 1982, p. 467-488

6.5) Making the Problem Precise

If quantum theory is an approximately correct theory of physics:

1. What kinds of things exist and how do they behave?
2. How do they save the phenomena?
3. Do so in such a way that leads to progress in physics.

The ontology question

1. What kinds of things exist and how do they behave?
   - Ontology is the study of what exists, so this is asking for the ontology underlying quantum theory.
   - We are not asking what actually exists in the world, but rather what would exist in a world where quantum theory is an exact theory of physics?
   - It is more about the internal explanatory structure of the theory than about the actual physical world.
   - This does not assume realism: only measurement outcomes exist is an acceptable answer (but you also have to answer the other two questions).

Saving the phenomena

2. How do they save the phenomena?
   - What we see in experiments should be explained in terms of the answer to 1.
   - How do the things that exist give rise to the predictions that we observe in experiments.
   - Explain the emergence of the classical world in terms of the things that exist.
   - E.g. if I say that quantum theory is about a bunch of green aliens running around on mars then that is a valid answer to 1, but will probably fail to provide a compelling answer to 2.

The pragmatic criterion

3. Do so in such a way that leads to progress in physics.
   - Most quantum foundationists will probably agree with 1 and 2. 3 will be more controversial.
   - We already have several viable answers to 1 and 2. How do we know which one is the scientific truth?
     - If it makes a prediction that conflicts with standard quantum theory and is subsequently confirmed.
     - If it allows us to generalize quantum theory beyond its current scope, e.g. to quantum gravity, in a way not suggested by standard quantum theory.
     - If it provides better explanations: i.e. leads to new developments that could have been derived from standard quantum theory, but it would have been difficult to do so.

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7) Epistricted Theories

1) Setup of the Toy Theory
    a) The Knowledge-Balance Principle
    b) Epistemic States
    c) Measurements
    d) Reversible Dynamics
    e) Composite Systems
2) Explanations of Quantum Phenomena
    a) EPR
    b) Non-Uniqueness of Mixed State Decompositions
    c) Indistinguishability of Pure States
    d) No-Cloning
    e) Interference

7.1) Setup of the Toy Theory

- Rob Spekkens (Phys. Rev. A 75, 032110 (2007)) devised a toy theory designed to show how many apparently weird quantum phenomena could be accounted for via a ψ-epistemic, local, noncontextual model.
- Some versions of the theory accurately reproduce subtheories of quantum theory
  - Quantum theory with Gaussian states, measurements and operations (Bartlett et. al. Phys. Rev. A 86, 012103 (2012)).
  - Stabilizer quantum theory in odd prime dimensions (arXiv:1409.5041).
- The simplest version of the theory for “toy bits” (the analogue of qubits) does not exactly reproduce part of quantum theory, but is qualitatively similar.

7.1.a) The Knowledge-Balance Principle

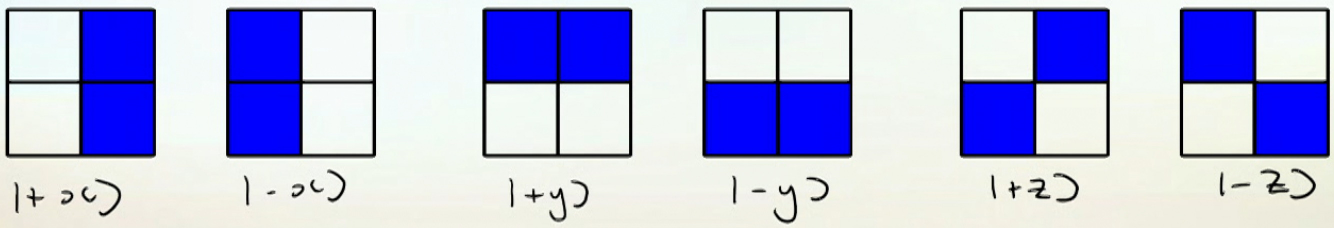
- Impose an "epistemic restriction" on how much we can know about a physical system.
  - In a state of maximal knowledge, we know as much about the system as we don't know.
- Simplest case: A system that has 4 possible ontic states called a toy bit.

$(-,+)$	$(+,+)$
$(-,-)$	$(+,-)$

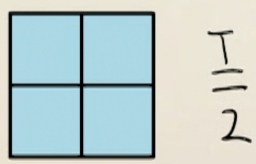
- It takes a minimum of two binary questions to determine the ontic state:
  - e.g. Is the first entry + or -? Is the second entry + or -?
- We can know the exact answer to one such question in a pair, but then must be completely uncertain about the answer to the other one.

7.1.b) Epistemic States

- There are six epistemic states (probability distributions) compatible with the knowledge-balance principle.



- We can also have a state of non-maximal knowledge:



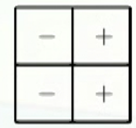
7.1.b) Measurements

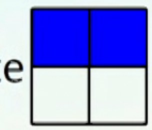
- We demand that measurements on toy bits must:
  1. Be repeatable, i.e. yield the same result if performed twice in a row.
  2. Not violate the knowledge-balance principle, i.e. they should leave the system in a valid epistemic state.
- This immediately implies that there cannot be a measurement that reveals the exact ontic state because this would have to leave us in an epistemic state like:

- But we can have measurements that reveal coarse grained information, provided they disturb the ontic state.

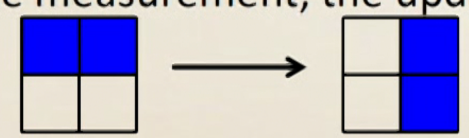
Example of a Valid Measurement

- An X measurement gives outcomes ± 1 as follows:

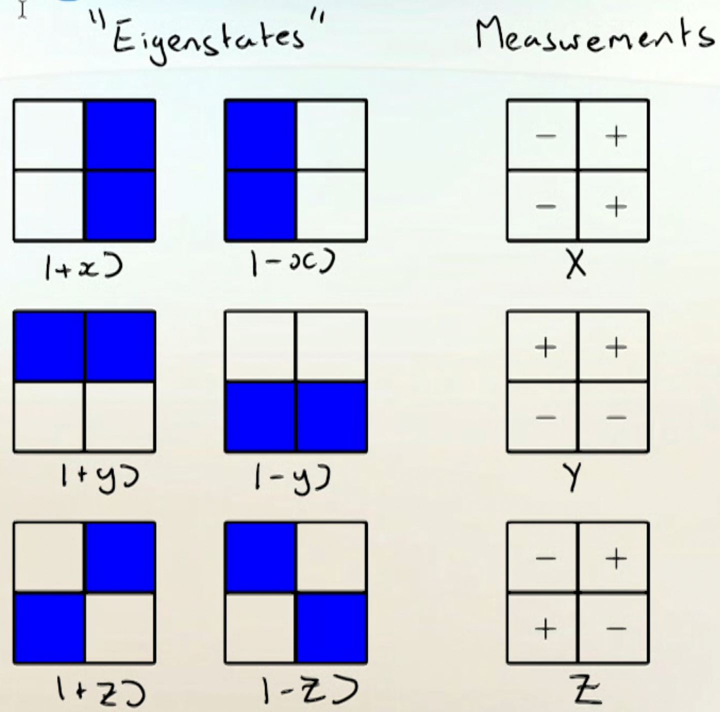


- If we apply it to the $|+y\rangle$ state 

  and get the $+1$ outcome, then we will know that the ontic state must have been $(+,+)$ before the measurement.
- To preserve the knowledge-balance principle and maintain repeatability (+,+) and (+,-) must get swapped with probability ½ during the measurement.
- Thus, after the measurement, the updated epistemic state will be $|+x\rangle$.

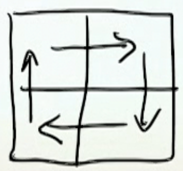


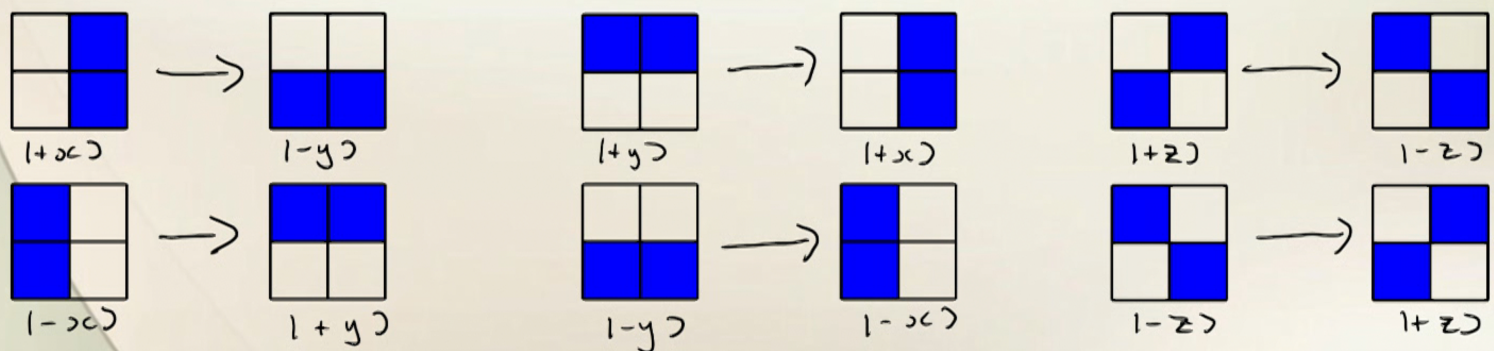
Valid Measurements on a toy bit and their "eigenstates"



7.1.c) Reversible Dynamics

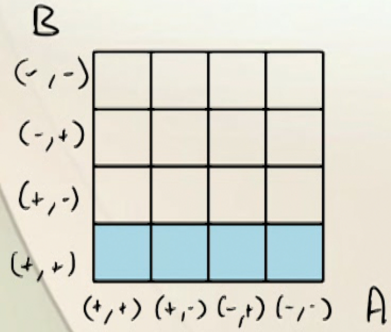
- Reversible dynamics (the analogue of unitary dynamics) on a toy bit is just a permutation on the underlying ontic states. We can then compute the action on the epistemic states.
- Example:





7.1.d) Composite systems

- When we have two toy bits, each toy bit has its own ontic state $(\pm,\pm)_A$, $(\pm,\pm)_B$.
- There are $4 \times 4 = 16$ possible ontic states, so it takes 4 binary questions to specify the exact ontic state.
- By the knowledge-balance principle, we can only know the answer to 2 of them.
- Subtlety: We not only apply the knowledge-balance principle to the global system, but also to the individual subsystems.



This is not a valid epistemic state because we know the exact ontic state (+,+) of system B.

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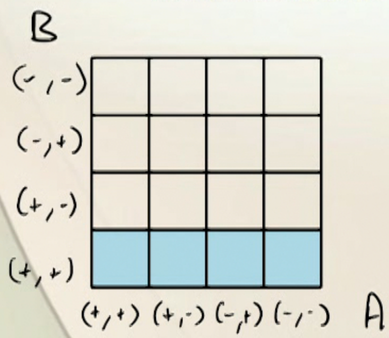

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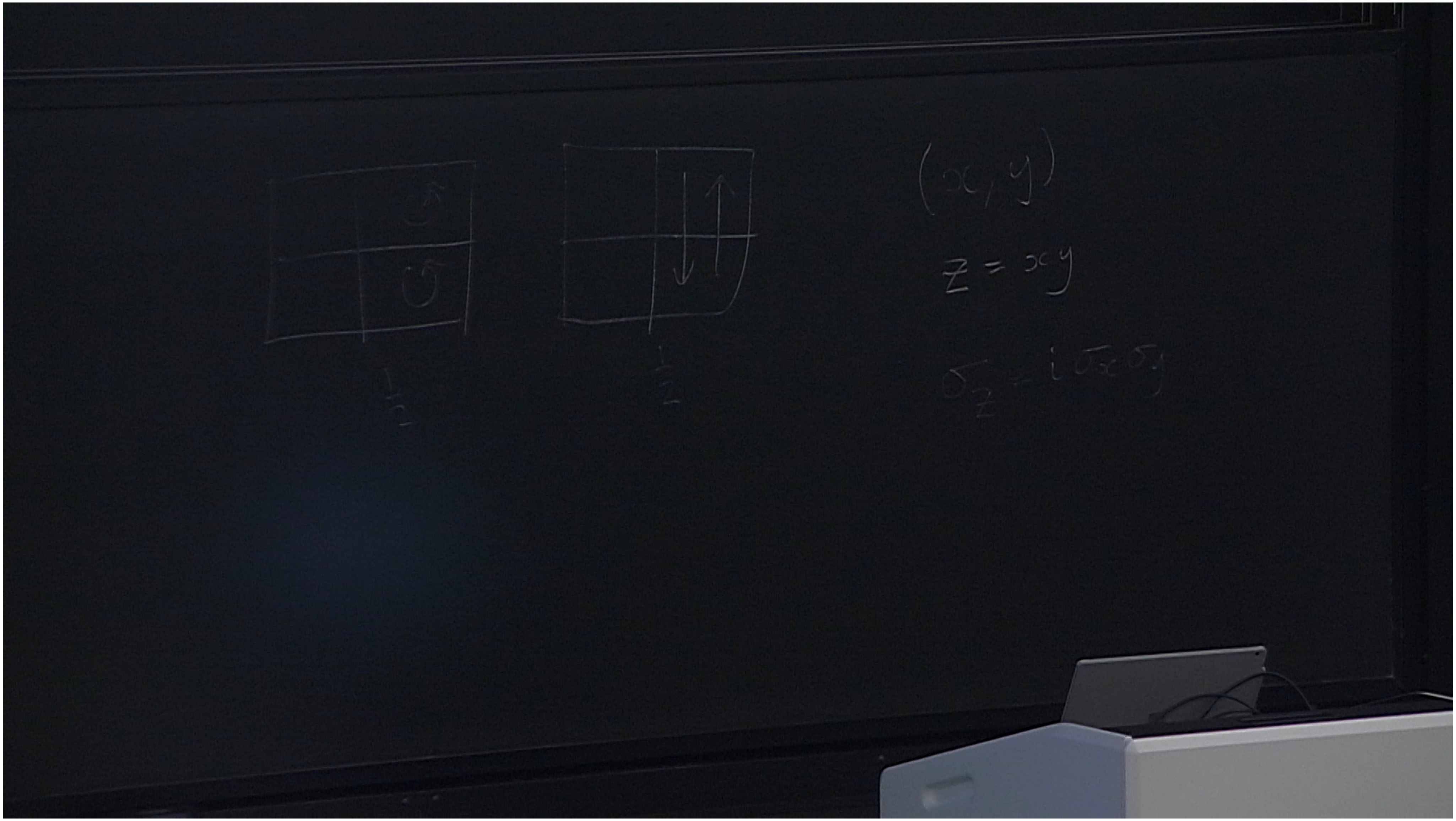
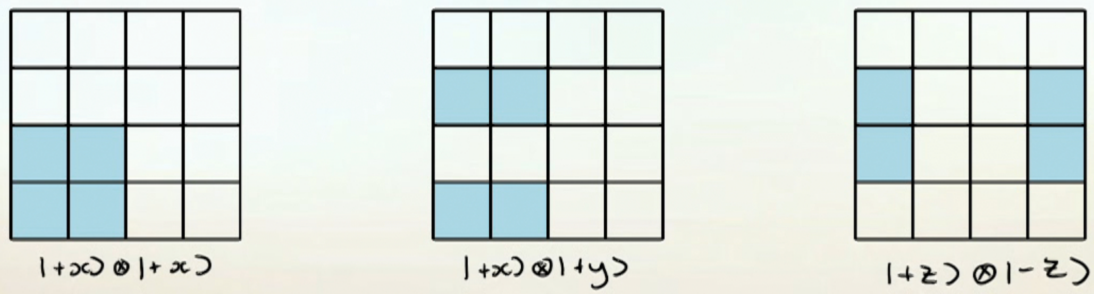
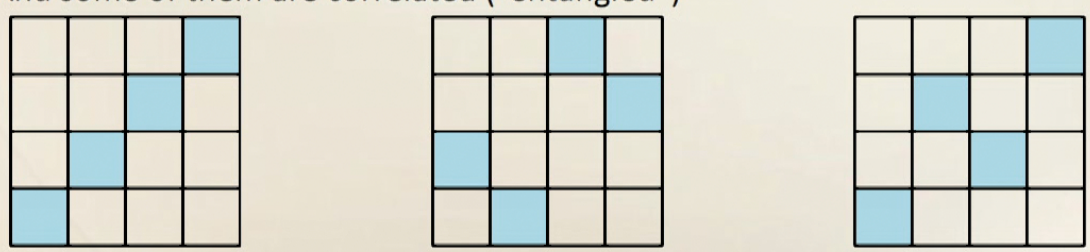

(x, y)
z = xy
σ_z = i σ_x σ_y

Product and Correlated States

- Of the valid epistemic states, some of them are products of independent distributions of the two toy bits.



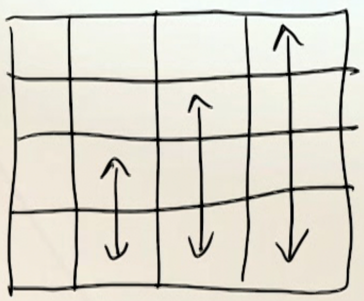
- And some of them are correlated ("entangled")

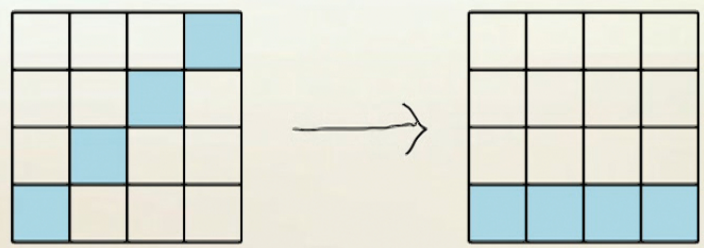


These have uniform marginal distributions

Reversible Dynamics on Composites

- Because we need to preserve the knowledge-balance principle for subsystems, not all permutations represent valid dynamics for a composite system.
- Example:





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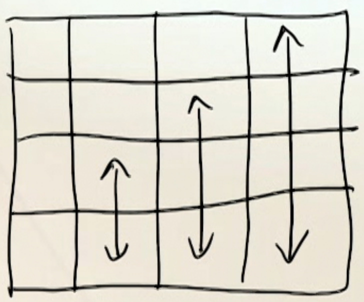
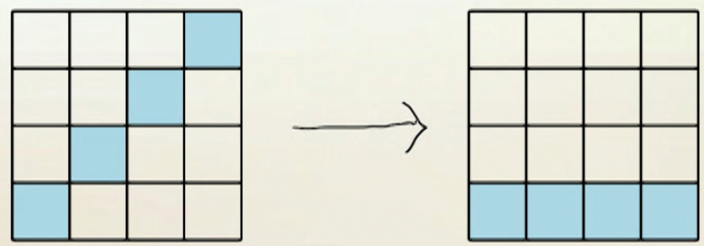
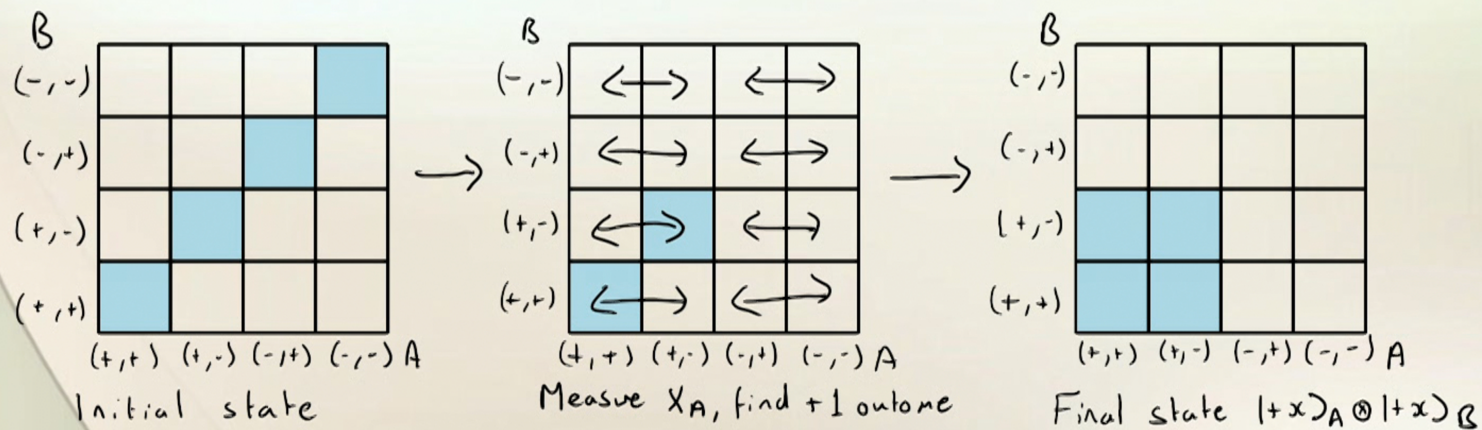


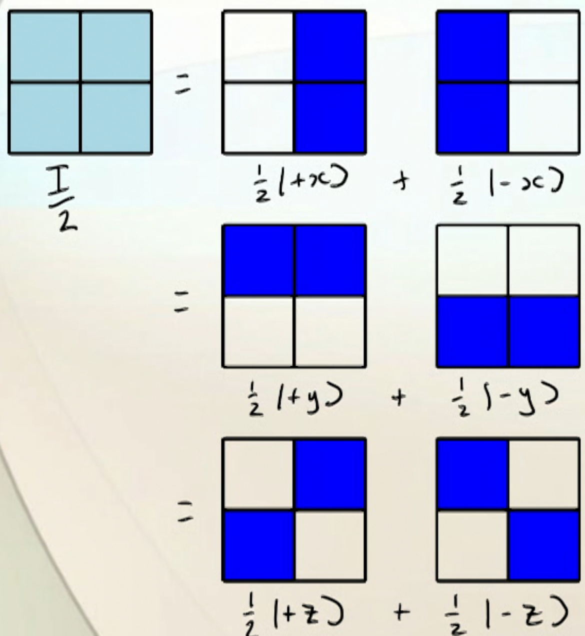


7.2.a) EPR

- The EPR experiment works as EPR expected in this theory:
  - The outcomes of all measurements are predetermined.
  - The two systems are initially in a correlated probability distribution.
  - The collapse is just updating information, followed by a local randomization of the system being measured.

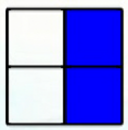


7.2.b) Non-Uniqueness of Mixed State Decompositions

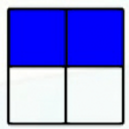


Because pure states correspond to overlapping probability distributions, mixtures of different sets of pure states can give the same probability distribution.

7.2.c) Indistinguishability of Pure States



$|+x\rangle$



$|+y\rangle$

- It is impossible to perform a measurement that distinguishes $|+x\rangle$ from $|+y\rangle$ with certainty because, in both cases, the ontic state is $(+,+)$ with probability $\frac{1}{2}$