Title: PSI 17/18 - Foundations of Quantum Mechanics - Lecture 4

Date: Feb 01, 2018 10:15 AM

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Abstract:

Denying realism

Scientists sometimes deceive themselves into thinking that philosophical ideas are only at best decorations or parasitic commentaries on the hard objective triumphs of science, and that they themselves are immune to the confusions that philosophers devote their lives to dissolving. But there is no such thing as philosophy-free science. There is only science whose philosophical baggage is taken on board without examination.

–Daniel C. Dennett

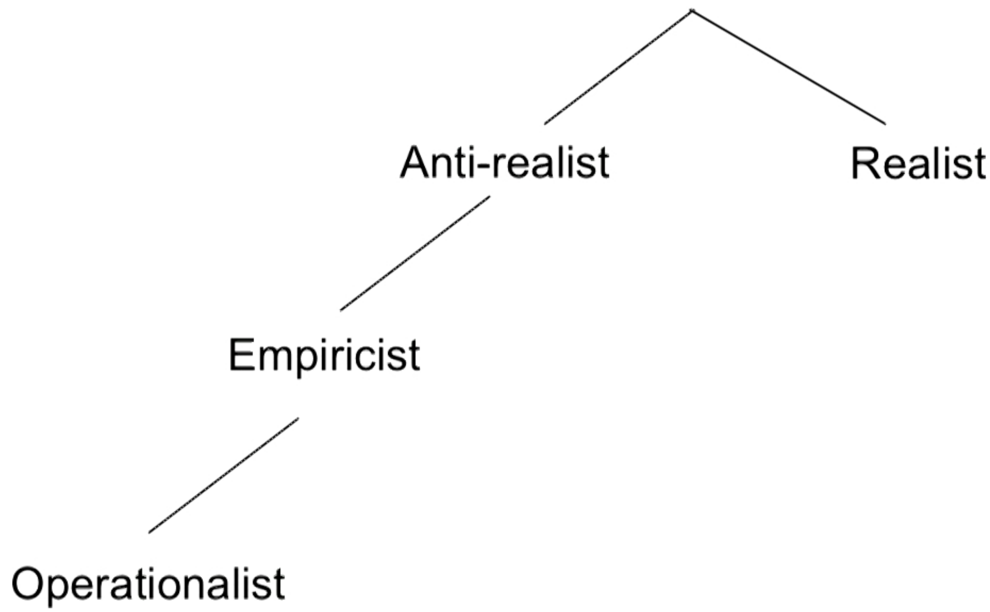
What does a scientific theory aim to do?

Realism

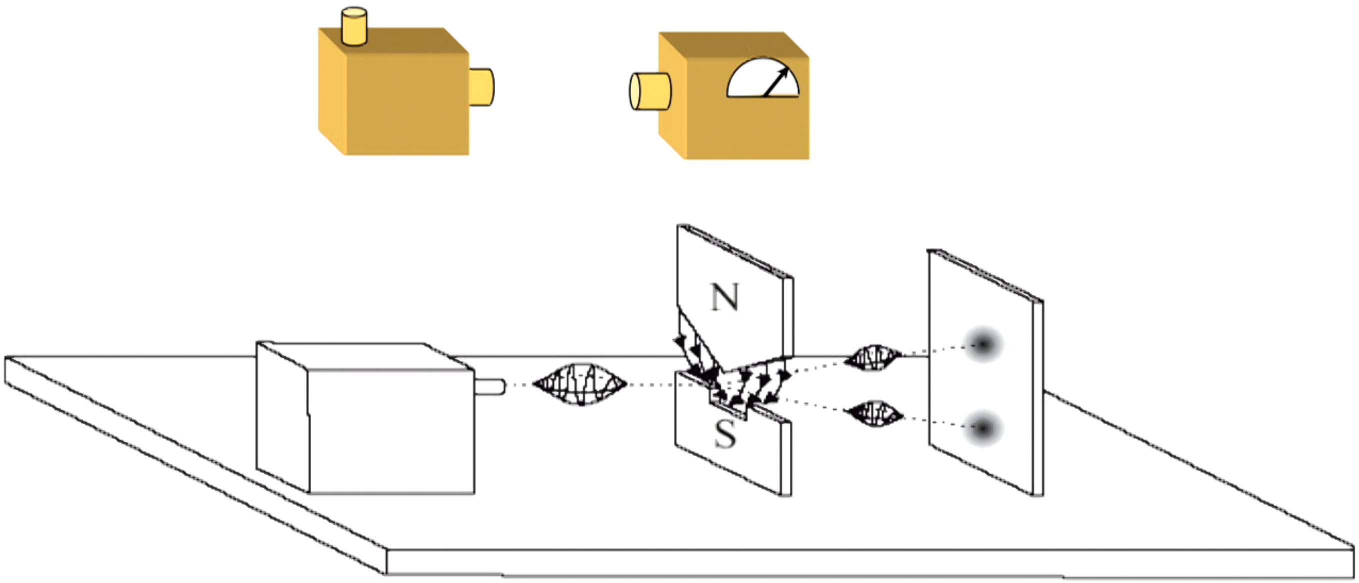
It aims at a true description of physical objects and their attributes, and it aims to provide successively better approximations to the truth over time.

Empiricism

It aims at an efficient summary of our experience. The empiricist seeks to avoid false belief by building on top of what we cannot be mistaken about, such as statements about what we've observed directly.


Anti-realist
Realist
Empiricist
Operationalist

The operational interpretation of quantum theory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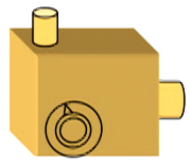
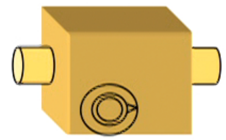
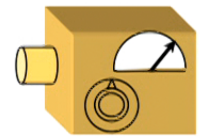






Preparation

P

Transformation

T

Measurement

M

Vector

$|\psi\rangle$

Unitary map

U

Projection valued measure (PVM)

$\{\Pi_k\}$

$$\boxed{Pr(k|\mathsf{P},\mathsf{T},\mathsf{M}) = \langle\psi|U^\dagger \Pi_k U|\psi\rangle}$$

Preparation P

Measurement M

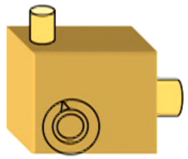
Effective preparation P_k

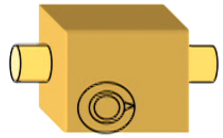
Update map

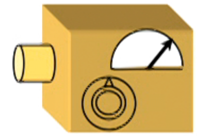
$$|\psi\rangle \rightarrow |\psi_k\rangle = \frac{\Pi_k|\psi\rangle}{\sqrt{\langle\psi|\Pi_k|\psi\rangle}}$$

"In a strict sense, quantum theory is a set of rules allowing the computation of probabilities for the outcomes of tests which follow specified preparations."

- Asher Peres

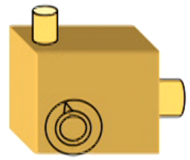


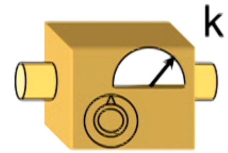




Preparation	Transformation	Measurement
P	T	M
Density operator	Trace-preserving completely positive linear map (CP map)	Positive operator-valued measure (POVM)
ρ	$\mathcal{T}$	$\{E_k\}$

$$\boxed{Pr(k|\mathsf{P},\mathsf{T},\mathsf{M}) = \mathrm{Tr}[E_k \mathcal{T}(\rho)]}$$





Preparation $\quad\quad$ Measurement

$$\underbrace{\mathsf{P} \qquad\qquad\qquad \mathsf{M}}_{\text{Effective preparation}}$$

P_k

Update map

$$\rho \to \rho_k = \frac{\mathcal{T}_k(\rho)}{\mathrm{Tr}[\mathcal{T}_k(\rho)]}$$

where $\mathcal{T}_k^{\dagger}(I) = E_k$

Trace-nonincreasing
completely positive
linear map
$\mathcal{T}_k$

The operational interpretation of quantum theory

Every preparation P is associated with a density operator ρ

Every measurement M is associated with a positive operator-valued measure $\{E_k\}$. The probability of M yielding outcome k given a preparation P is $Pr(k|\mathsf{P},\mathsf{M}) = \mathrm{Tr}(\rho E_k)$

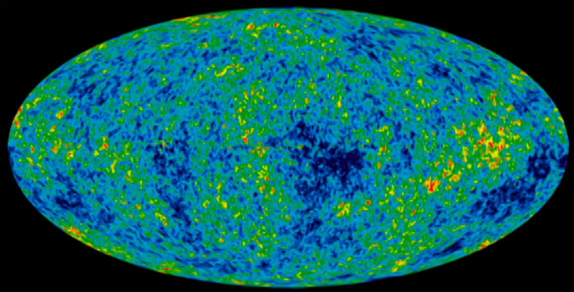
Every transformation is associated with a trace-preserving completely-positive linear map $\rho \to \rho' = \mathcal{T}(\rho)$

Every measurement outcome k is associated with a trace-nonincreasing completely-positive linear map $\mathcal{T}_k$ such that

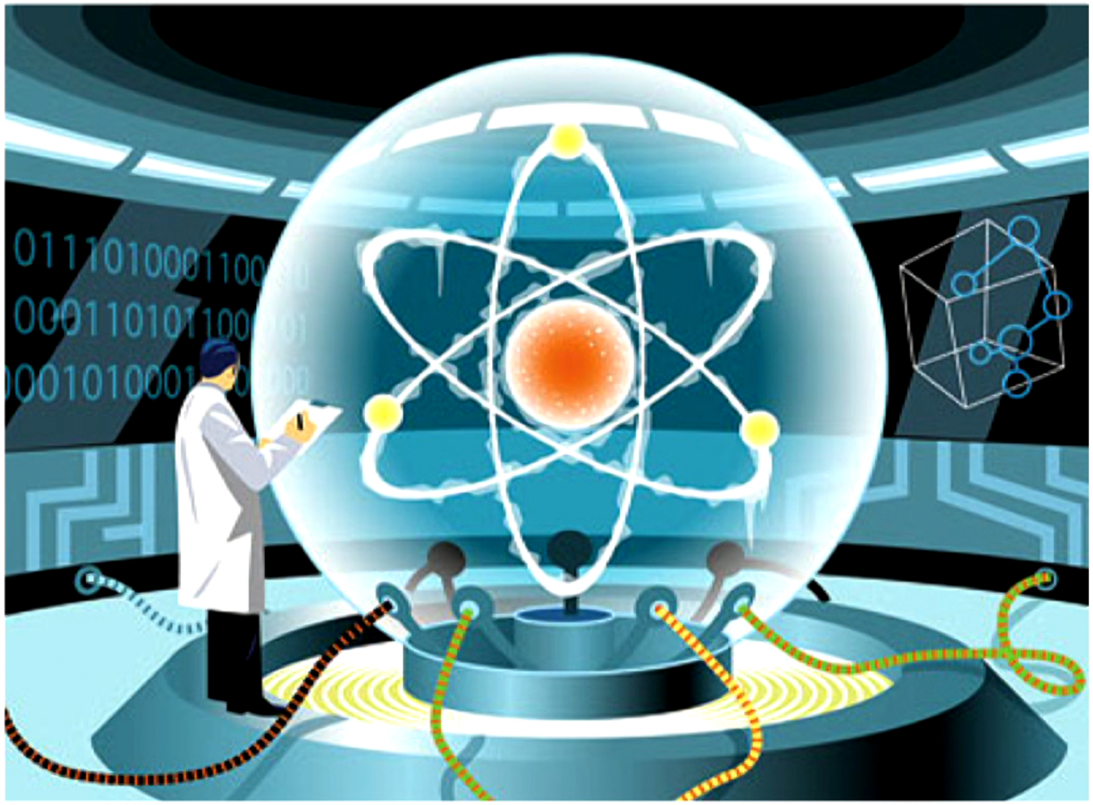
$$\rho \to \rho_k = \frac{\mathcal{T}_k(\rho)}{\mathrm{Tr}[\mathcal{T}_k(\rho)]} \quad \text{where} \quad \mathcal{T}_k^\dagger(I) = E_k$$

No mention of "physical states" or their evolution

Criticisms of the
operational interpretation of
Quantum Theory



The primitives of the empiricist themselves are in need of explanation and it is unclear how an empiricist could hope to achieve consilience across scientific disciplines



Science is more than just making predictions; it is about achieving pragmatic goals.

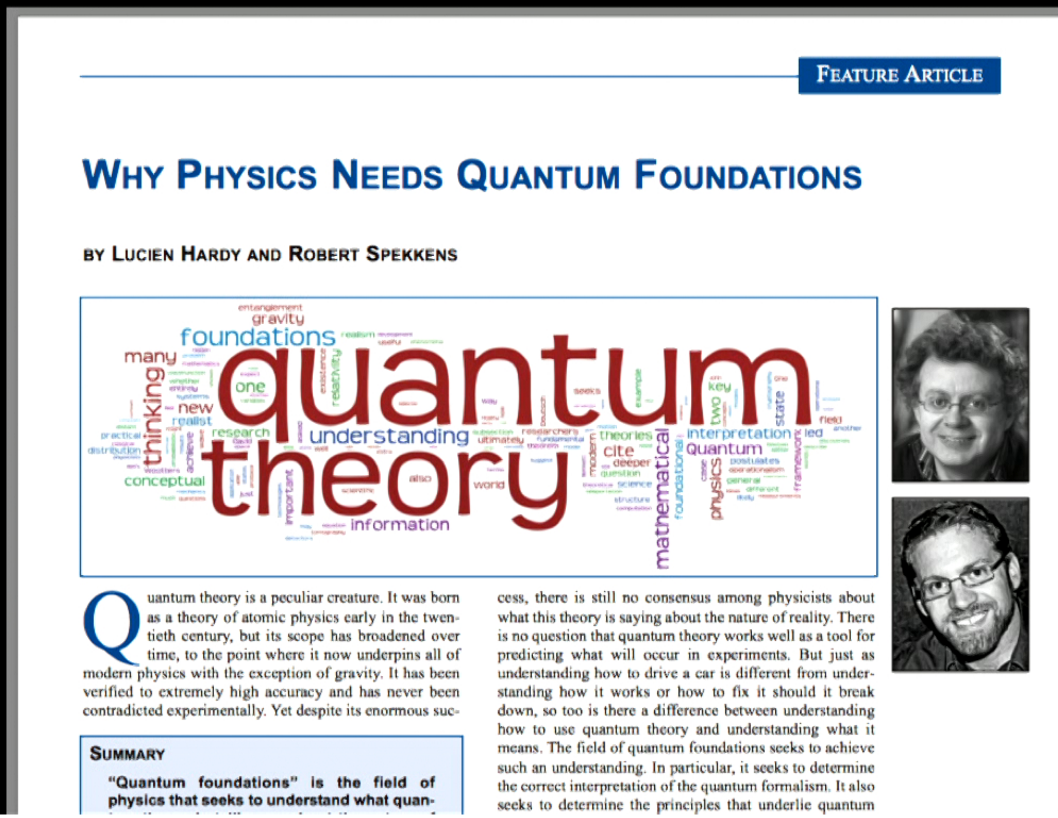
Question

Yes-no answer

Empiricism does not provide explanations, and it is these that are pragmatically useful

Bohm → Bell → Ekert
→ device-independent key distribution (Barrett-Hardy-Kent)

Everett → Deutsch → quantum computation



FEATURE ARTICLE

WHY PHYSICS NEEDS QUANTUM FOUNDATIONS

BY LUCIEN HARDY AND ROBERT SPEKKENS

Quantum theory is a peculiar creature. It was born as a theory of atomic physics early in the twentieth century, but its scope has broadened over time, to the point where it now underpins all of modern physics with the exception of gravity. It has been verified to extremely high accuracy and has never been contradicted experimentally. Yet despite its enormous success, there is still no consensus among physicists about what this theory is saying about the nature of reality. There is no question that quantum theory works well as a tool for predicting what will occur in experiments. But just as understanding how to drive a car is different from understanding how it works or how to fix it should it break down, so too is there a difference between understanding how to use quantum theory and understanding what it means. The field of quantum foundations seeks to achieve such an understanding. In particular, it seeks to determine the correct interpretation of the quantum formalism. It also seeks to determine the principles that underlie quantum

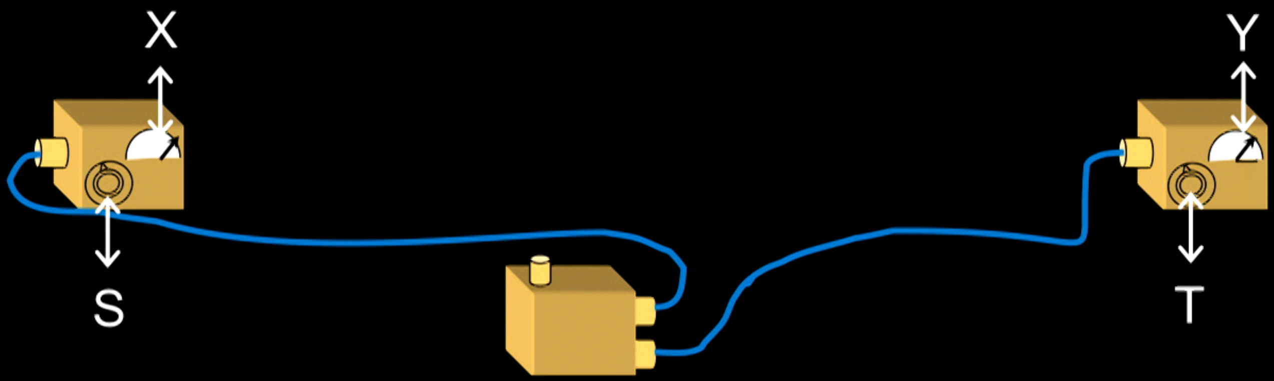
SUMMARY

"Quantum foundations" is the field of physics that seeks to understand what quan-

Bohm → Bell → Ekert
→ device-independent key distribution (Barrett-Hardy-Kent)

Everett → Deutsch → quantum computation

To take an empiricist approach is to miss out on the opportunities that realist interpretations provide for pushing the frontier of quantum theory and developing new technologies



P(X,Y|S,T)

	X=0, Y=0	X=0, Y=1	X=1, Y=0	X=1, Y=1
S=0, T=0	0.427	0.073	0.073	0.427
S=0, T=1	0.427	0.073	0.073	0.427
S=1, T=0	0.427	0.073	0.073	0.427
S=1, T=1	0.073	0.427	0.427	0.073

Simpson's Paradox

P(recovery | drug) > P(recovery | no drug)

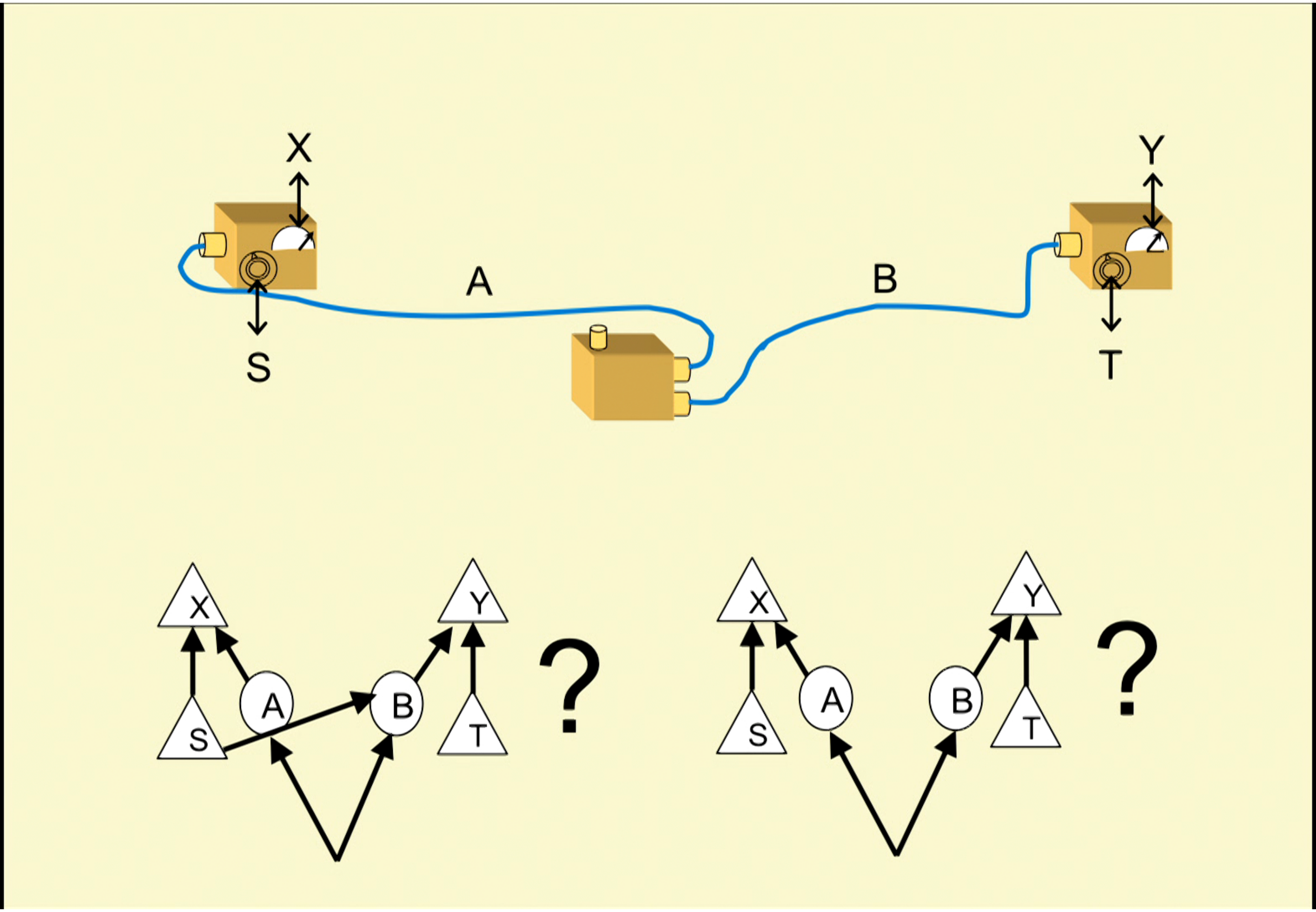
P(recovery | drug, male) < P(recovery | no drug, male)

P(recovery | drug, female) < P(recovery | no drug, female)

Recovery probability

	drug	no drug
male	180/300 = 60%	70/100 = 70%
female	20/100 = 20%	90/300 = 30%
combined	200/400 = 50%	160/400 = 40%


recovery
treatment
gender


X
Y
A
B
S
T
X
Y
A
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S
T
?
X
Y
A
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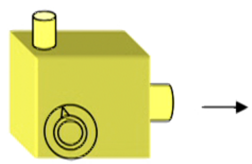
S
T
?

The empiricist approach only makes statements about correlations, not causation. But it is a causal account that is pragmatically useful.

One approach to realism: The ontological models framework

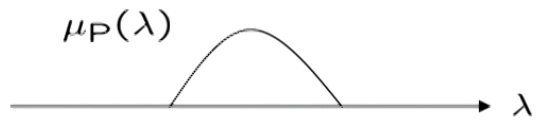
$\lambda \in \Lambda$ a measurable set

Preparation
P

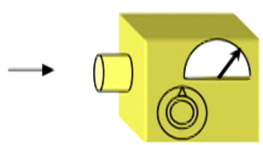


$$\mu_{\mathsf{P}} \geq 0$$

$$\int \mu_{\mathsf{P}}(\lambda) d\lambda = 1$$

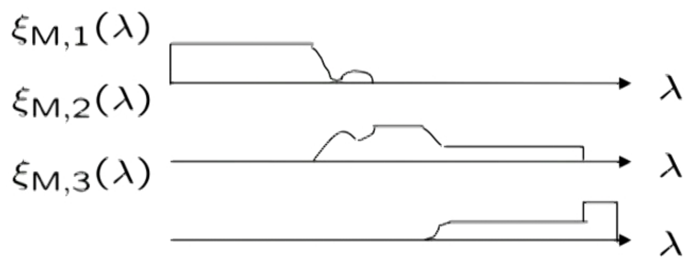


Measurement
M

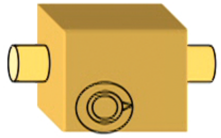


$$0 \leq \xi_{\mathsf{M},k} \leq 1$$

$$\sum_k \xi_{\mathsf{M},k}(\lambda) = 1 \text{ for all } \lambda$$

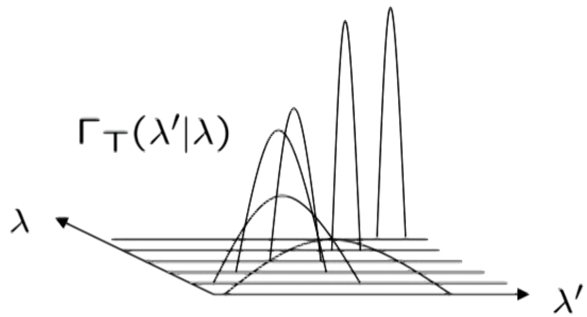


$$\boxed{p(k|\mathsf{P},\mathsf{M}) = \int d\lambda\, \xi_{\mathsf{M},k}(\lambda)\, \mu_{\mathsf{P}}(\lambda)}$$



Transformation

T

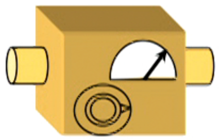


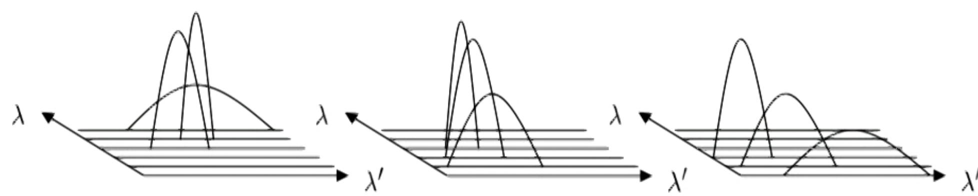
$\Gamma_{\mathsf{T}}(\lambda'|\lambda) \geq 0$ for all λ, λ'

$\int \Gamma_{\mathsf{T}}(\lambda'|\lambda) d\lambda' = 1$ for all λ

$$\boxed{p(k|\mathsf{P},\mathsf{T},\mathsf{M}) = \int d\lambda' \, \xi_{\mathsf{M},k}(\lambda') \ \int d\lambda \Gamma_{\mathsf{T}}(\lambda'|\lambda) \mu_{\mathsf{P}}(\lambda)}$$

$\Gamma_{\mathsf{T}_1}(\lambda'|\lambda)$ $\Gamma_{\mathsf{T}_2}(\lambda'|\lambda)$ $\Gamma_{\mathsf{T}_3}(\lambda'|\lambda)$





Measurement-induced transformations

$$\{\mathsf{T}_k\}$$

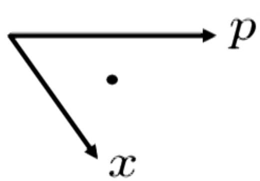
$$\Gamma_{\mathsf{T}_k}(\lambda'|\lambda) \geq 0 \text{ for all } \lambda, \lambda', k$$

$$\int \Gamma_{\mathsf{T}_k}(\lambda'|\lambda) d\lambda' = \xi_{M,k}(\lambda)$$

Ontic versus epistemic

Ontic state

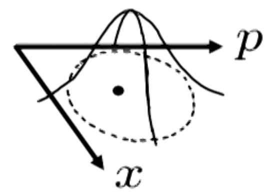
A real state of affairs
= a complete
specification of the
physical properties of
a system



Points in phase space are
ontic states

Epistemic state

A state of knowledge
= a description of an
agent's degrees of belief
concerning a system



Probability distributions over phase
space are epistemic states

For a parameter to be ontic

The real state of affairs varies with this parameter

For a parameter to be epistemic

An agent's state of knowledge varies with this parameter (the real state of affairs may stay the same)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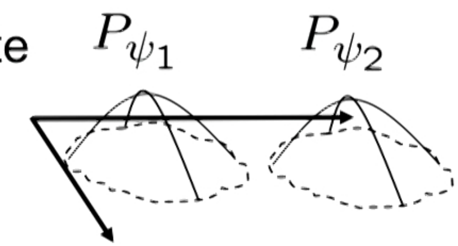
Classifying ontological models

ψ-ontic model:

$\forall$ preparation procedures P_{ψ_1}, P_{ψ_2} with $\psi_1 \neq \psi_2$

$$\mu(\lambda|P_{\psi_1})\mu(\lambda|P_{\psi_2}) = 0 \text{ for all } \lambda$$

Variation of ψ entails a variation of the ontic state



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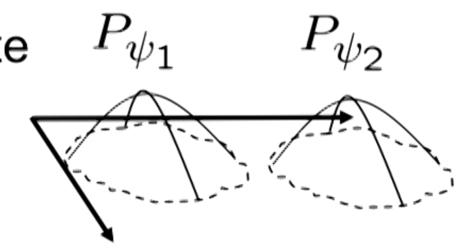

ψ-epistemic model:

Any model that is not ψ-ontic

ψ-ontic model:

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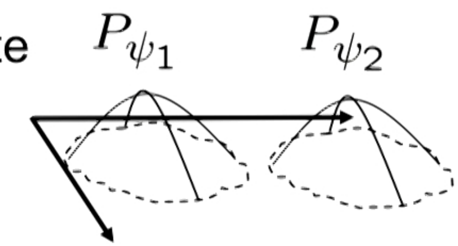
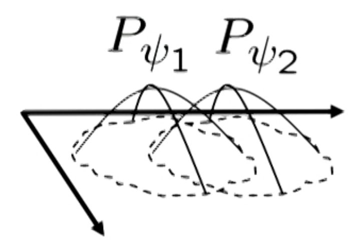


ψ-epistemic model:

Any model that is not ψ-ontic

$\exists$ preparation procedures P_{ψ_1}, P_{ψ_2} with $\psi_1 \neq \psi_2$

$$\mu(\lambda|P_{\psi_1})\mu(\lambda|P_{\psi_2}) \neq 0 \text{ for some } \lambda$$



Variation of ψ is consistent with **no** variation of the ontic state

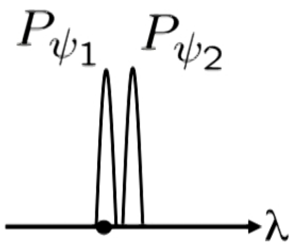
ψ-complete model:

Space of ontic states = space of rays in Hilbert space

$$\Lambda = \text{ projective Hilbert space}$$
$$\lambda = \text{ a ray}$$

$\forall$ preparation procedures P_ψ

$$\mu(\lambda|P_\psi) = \delta(\lambda - \psi)$$



ψ−complete

ψ-complete model:

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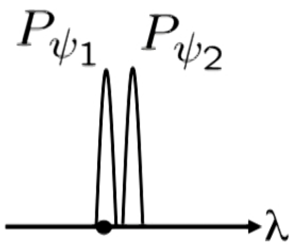
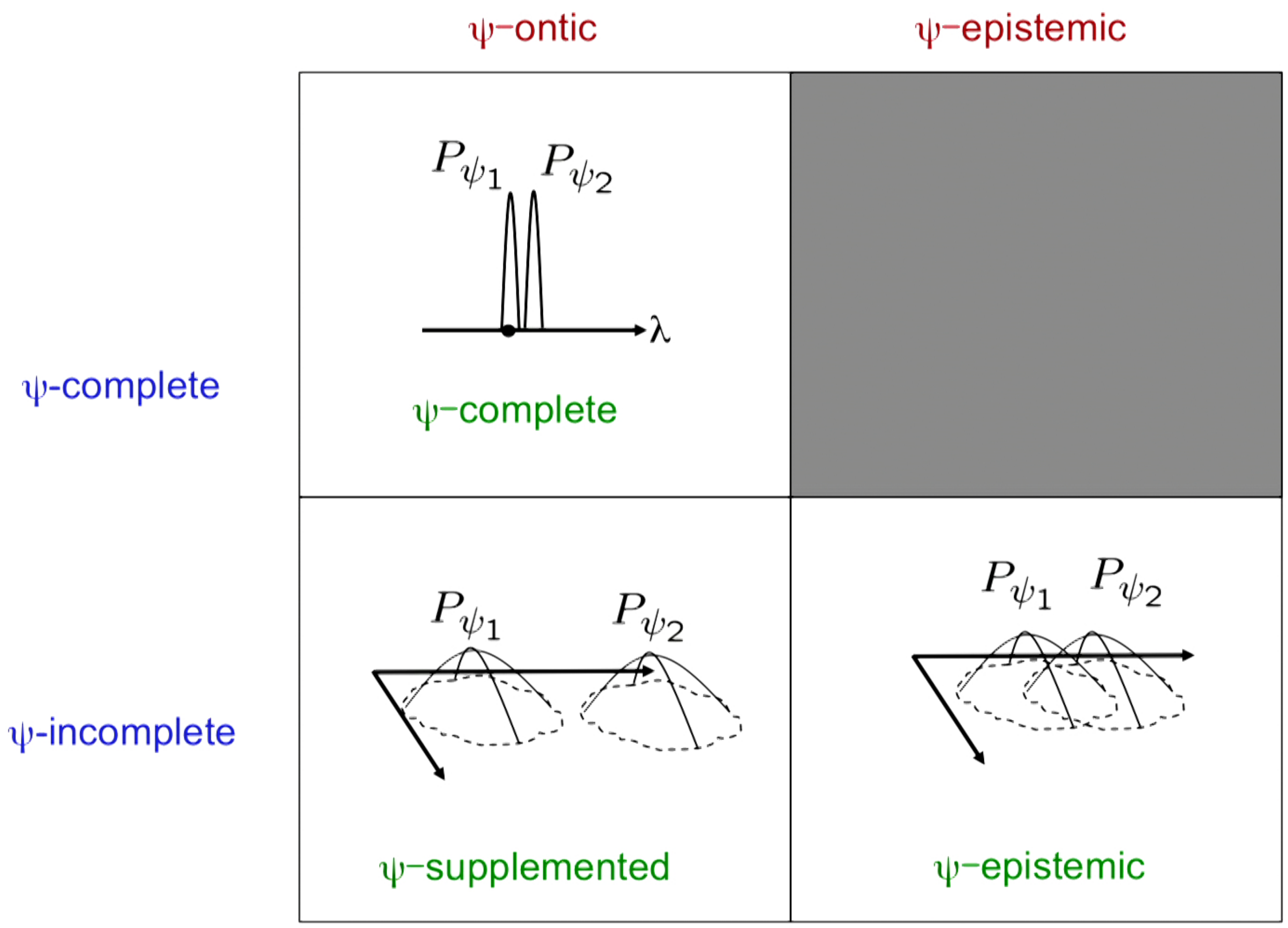
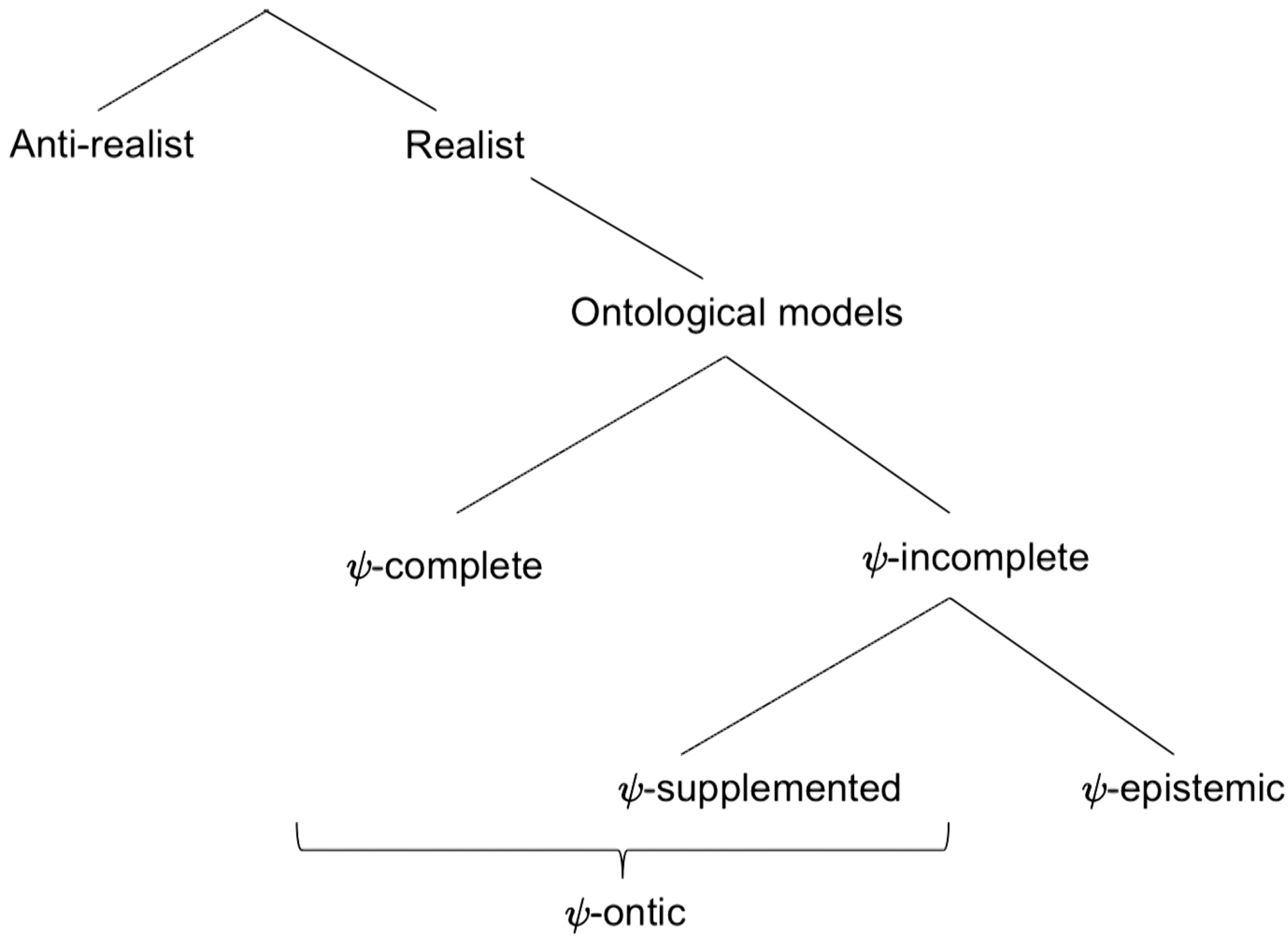


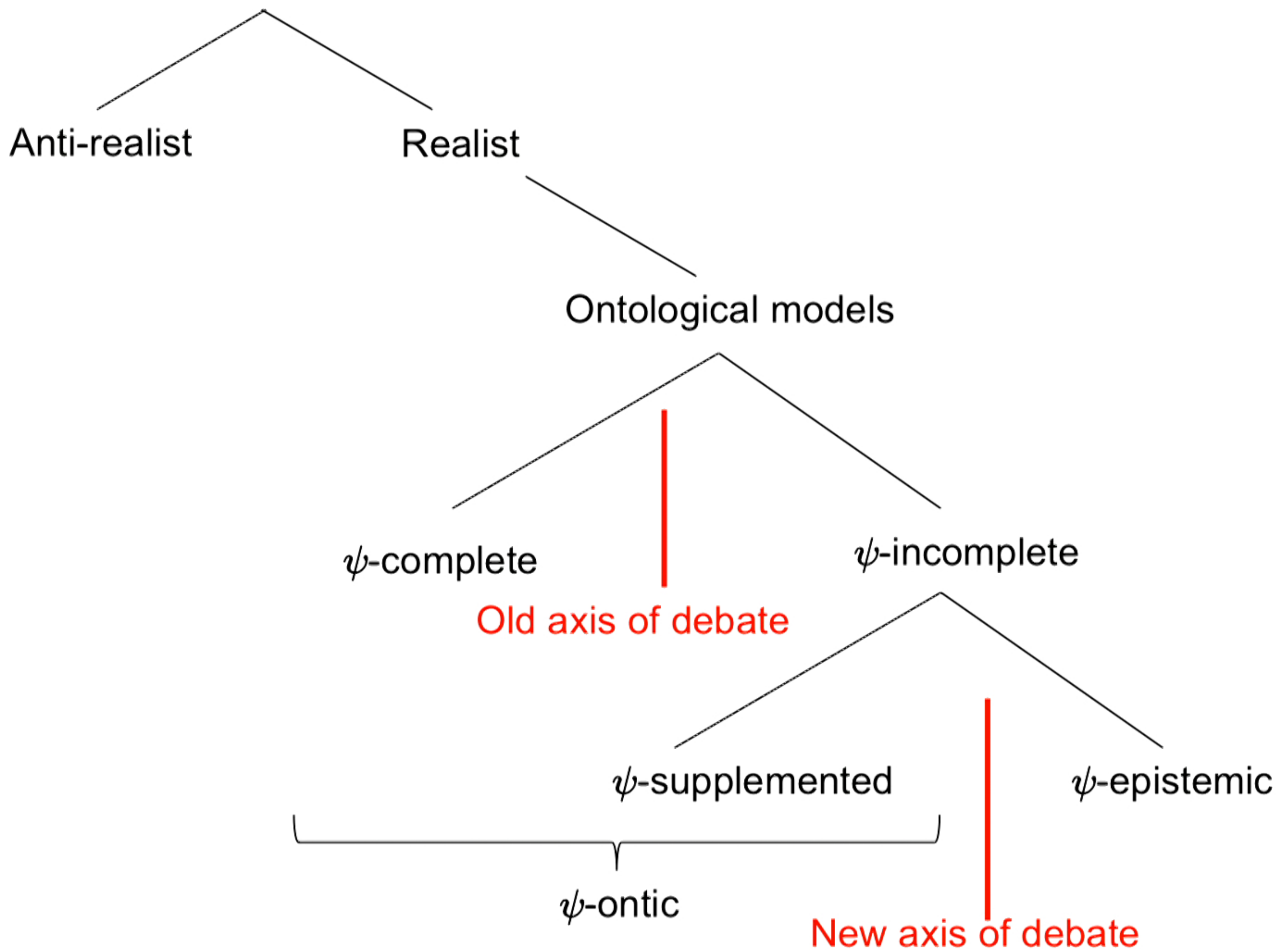
ψ–complete

ψ-incomplete model:

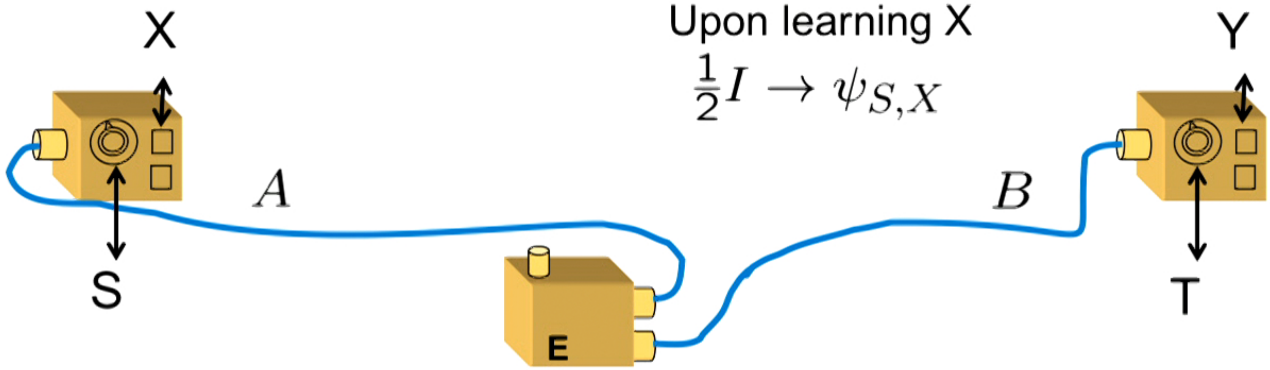
Any model that is not ψ-complete


ψ−ontic
ψ−epistemic
ψ-complete
P_{ψ_1} P_{ψ_2}
λ
ψ−complete
ψ-incomplete
P_{ψ_1} P_{ψ_2}
ψ−supplemented
P_{ψ_1} P_{ψ_2}
ψ−epistemic


Anti-realist
Realist
Ontological models
ψ-complete
ψ-incomplete
ψ-supplemented
ψ-epistemic
ψ-ontic


Anti-realist
Realist
Ontological models
ψ-complete
ψ-incomplete
Old axis of debate
ψ-supplemented
ψ-epistemic
ψ-ontic
New axis of debate

The significance of the ψ-ontic vs. ψ-epistemic dichotomy for causal explanations of quantum phenomena



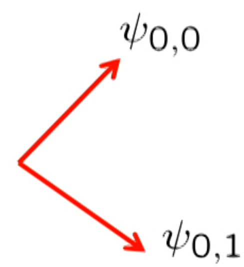
Upon learning X

$\frac{1}{2}I \rightarrow \psi_{S,X}$

Set S=0

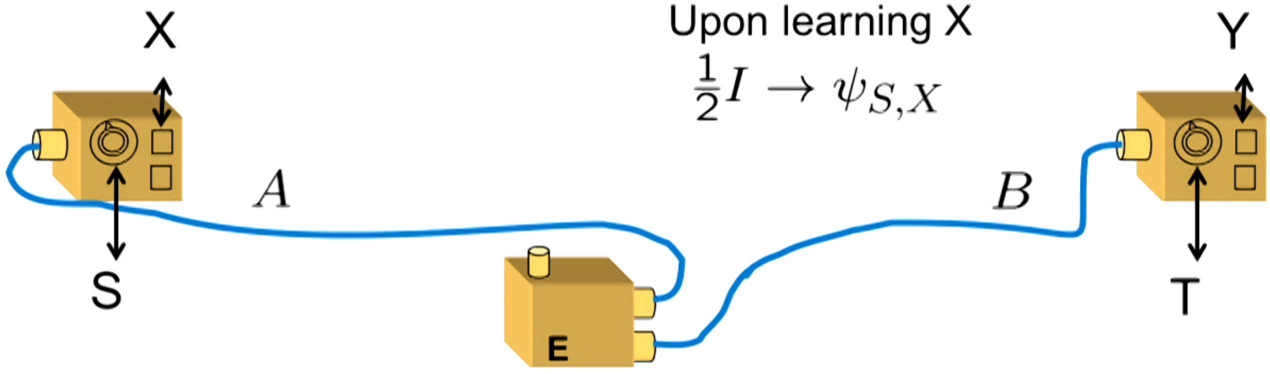
get X=0 $\qquad \frac{1}{2}I \quad \rightarrow \quad \psi_{0,0}$

get X=1 $\qquad \rightarrow \quad \psi_{0,1}$



Upon learning X

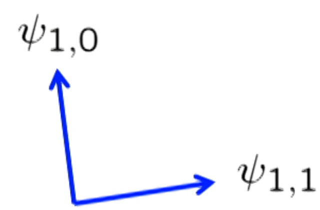
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$



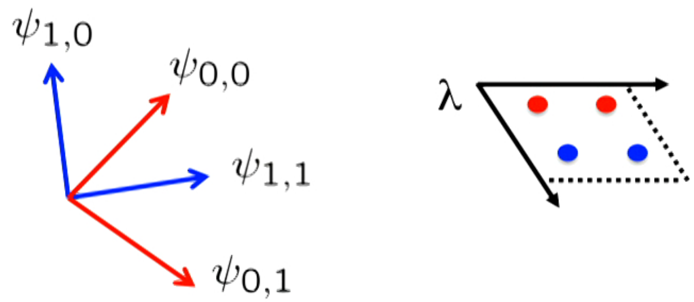
Set S=1

get X=0 $\quad \frac{1}{2}I \quad \rightarrow \quad \psi_{1,0}$

get X=1 $\quad \rightarrow \quad \psi_{1,1}$

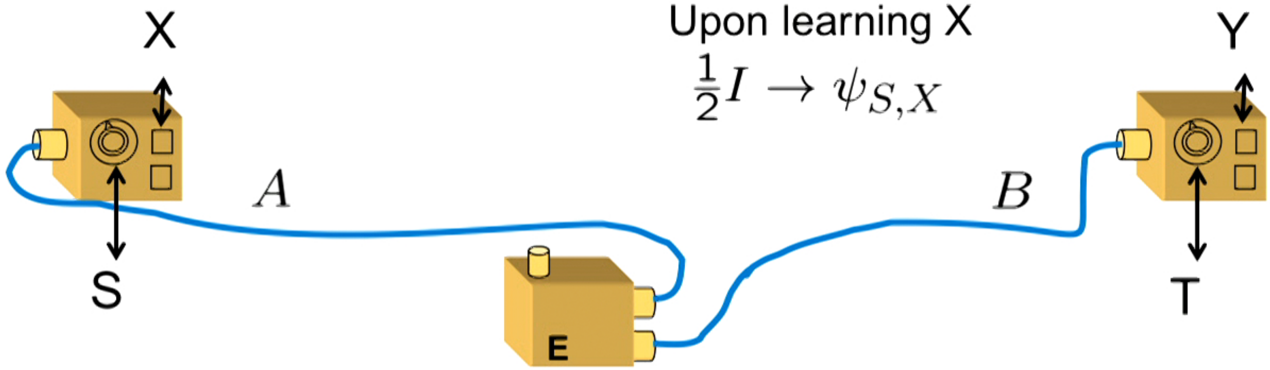


ψ is ontic



Upon learning X

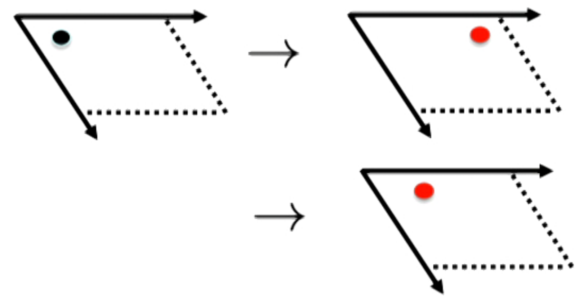
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$



Set S=0

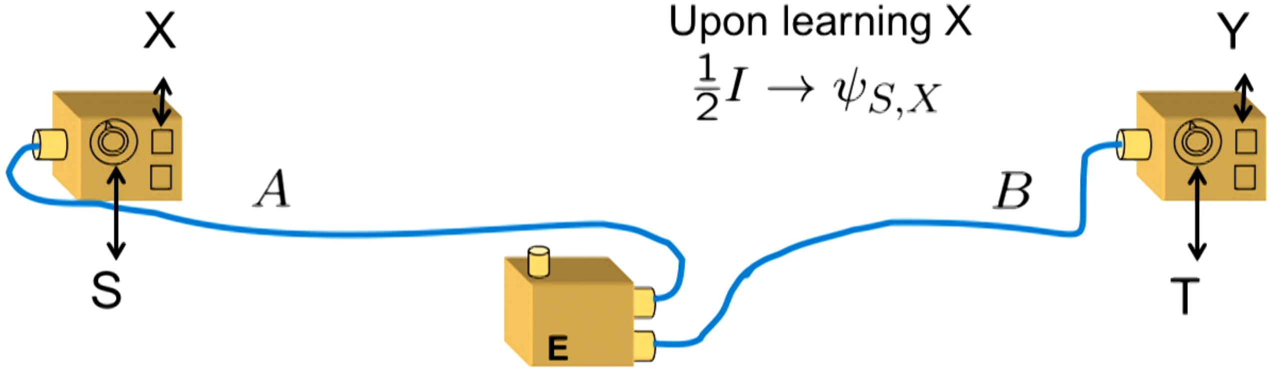
get X=0

get X=1



Upon learning X

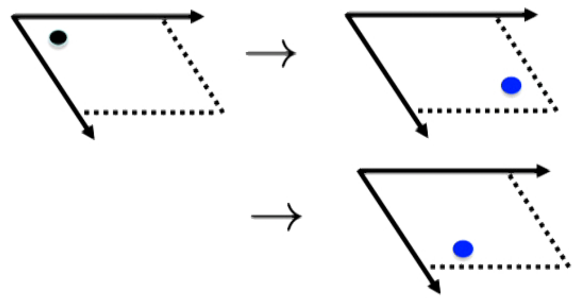
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$



Set S=1

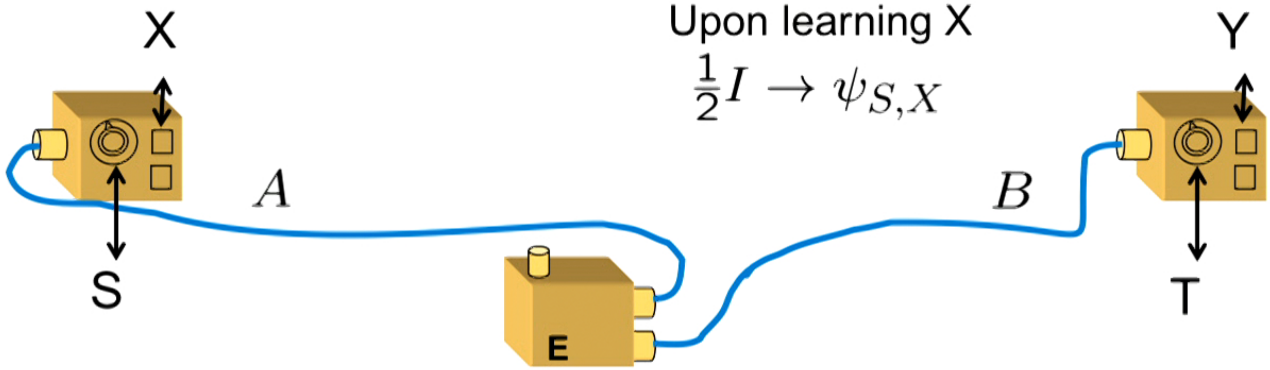
get X=0

get X=1



Upon learning X

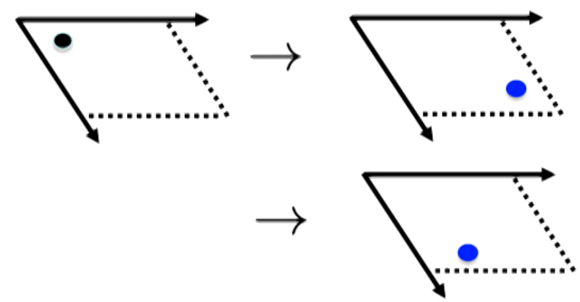
$$\frac{1}{2}I \to \psi_{S,X}$$



Set S=1

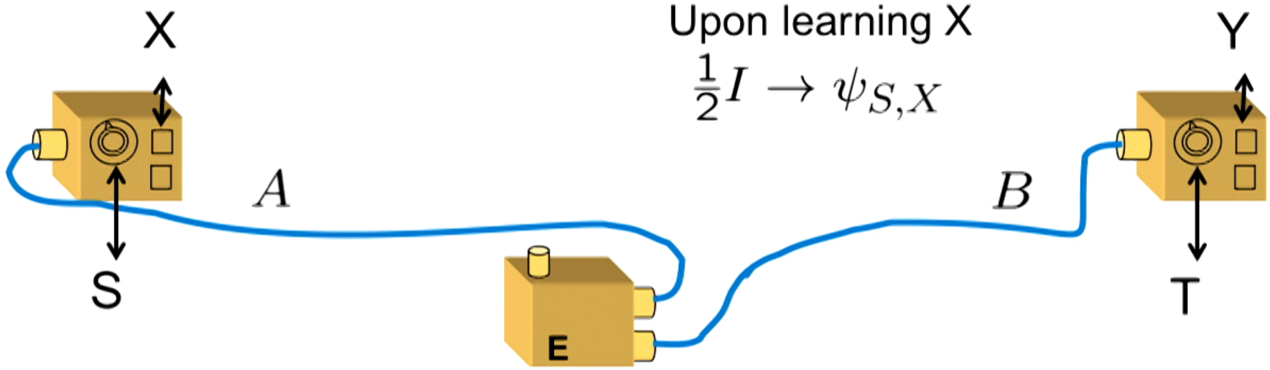
get X=0

get X=1



Upon learning X

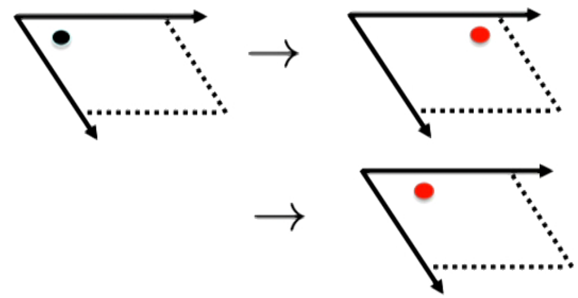
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$

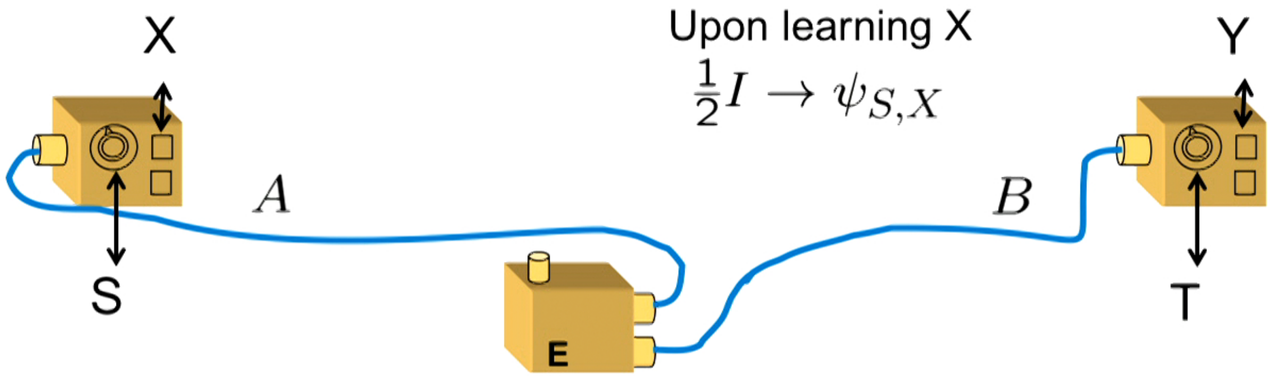


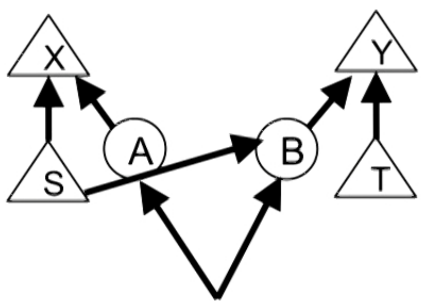
Set S=0

get X=0

get X=1

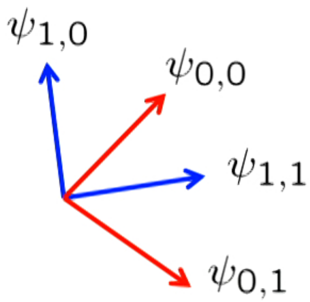


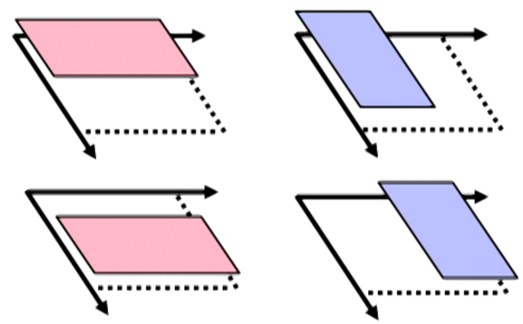




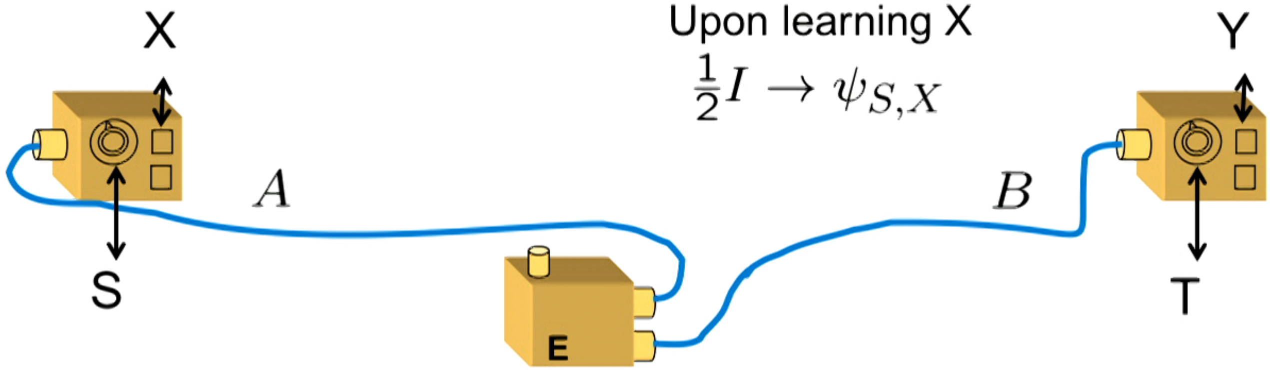
Like “treatment influences recovery”

ψ is epistemic

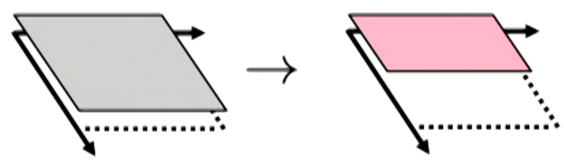


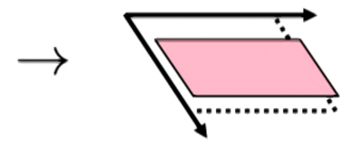


Upon learning X
$\frac{1}{2}I \rightarrow \psi_{S,X}$



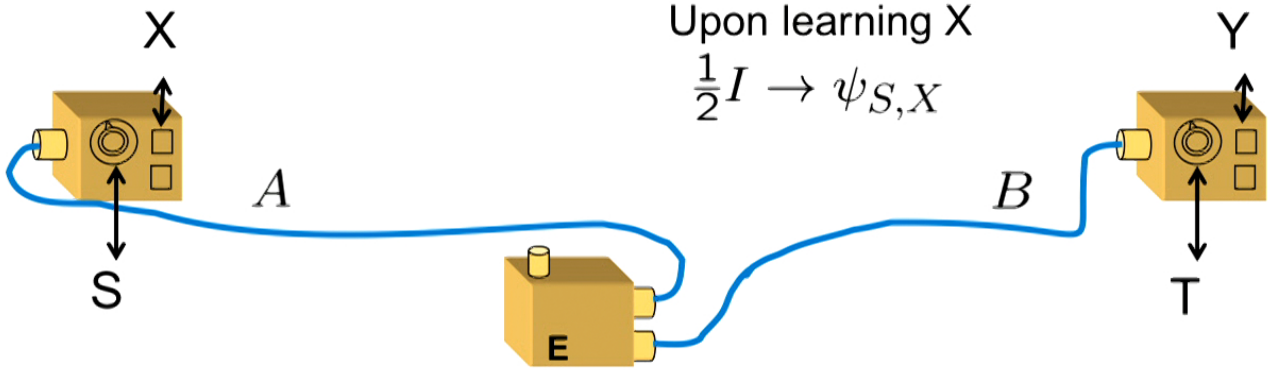
Set S=0

get X=0 

get X=1 

Upon learning X

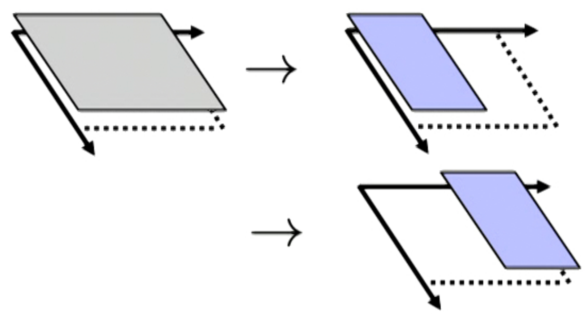
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$



Set S=1

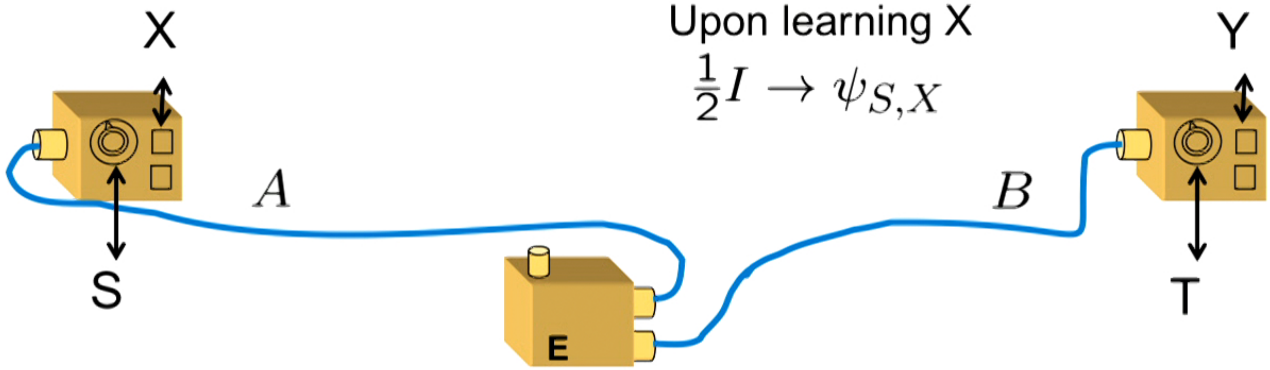
get X=0

get X=1



Upon learning X

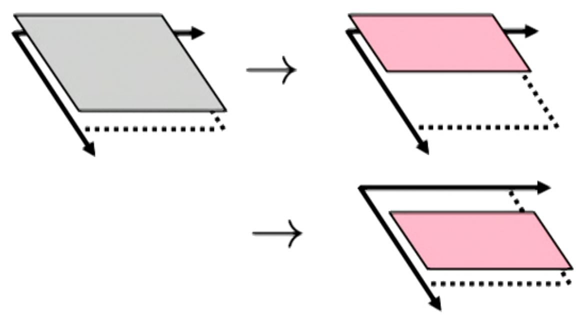
$$\frac{1}{2}I \rightarrow \psi_{S,X}$$



Set S=0

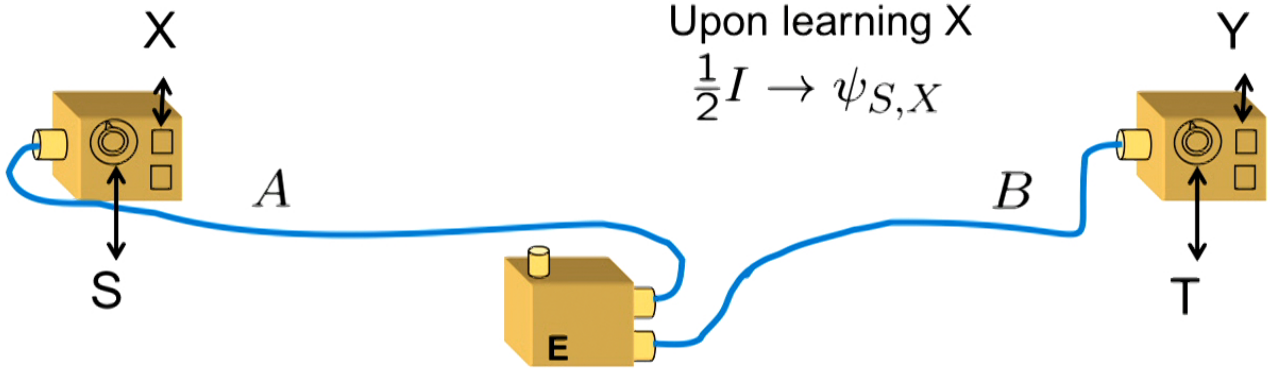
get X=0

get X=1



Upon learning X

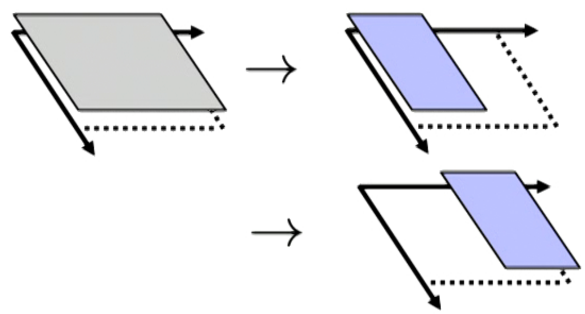
$\frac{1}{2}I \rightarrow \psi_{S,X}$



Set S=1

get X=0

get X=1



Like “treatment informs us about recovery”