Awareness:
an operational-theoretical approach

Giacomo Mauro D'Ariano
Università degli Studi di Pavia

Models of Consciousness

Mathematical Institute, University of Oxford
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Ubiquitous information

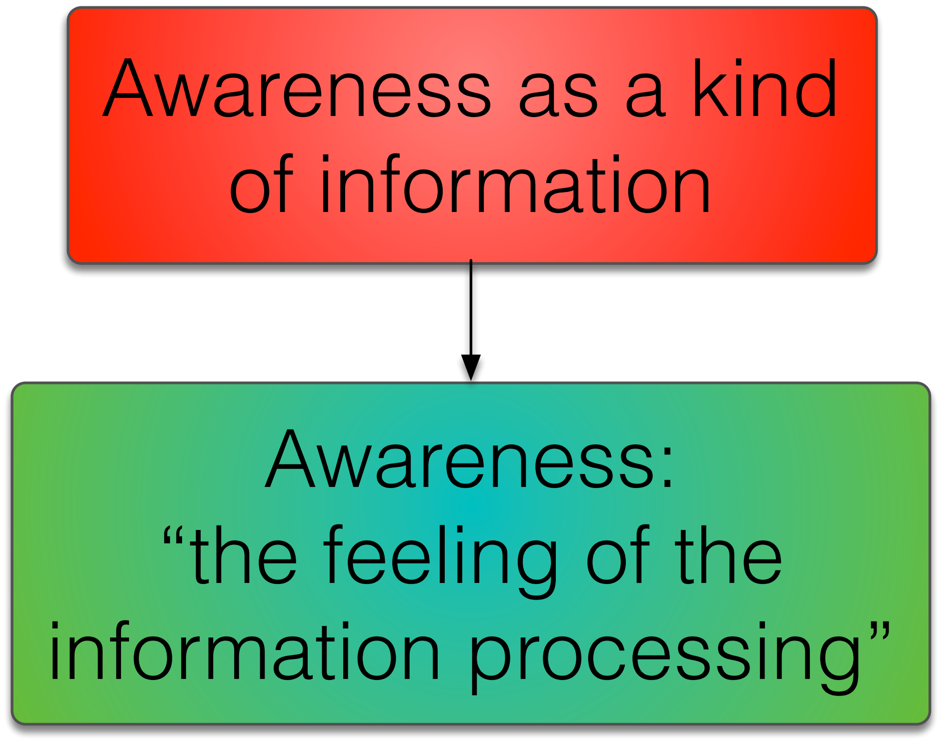
Consciousness

The "hard" Problem (David Chalmers)

1. Consciousness is the direct "experience" of the final information.

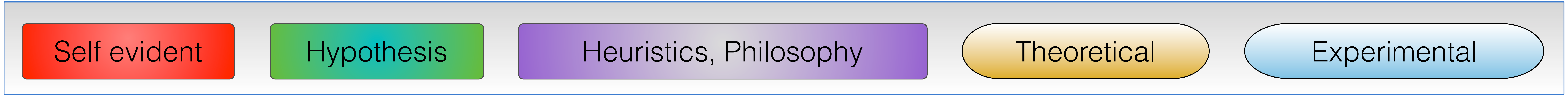
2. It is the most direct fruition of a very structured kind of information, manifesting through different types of qualia (colours, sounds, tastes, smells, touches, somato-sensations, pain, pleasure, sadness, happiness

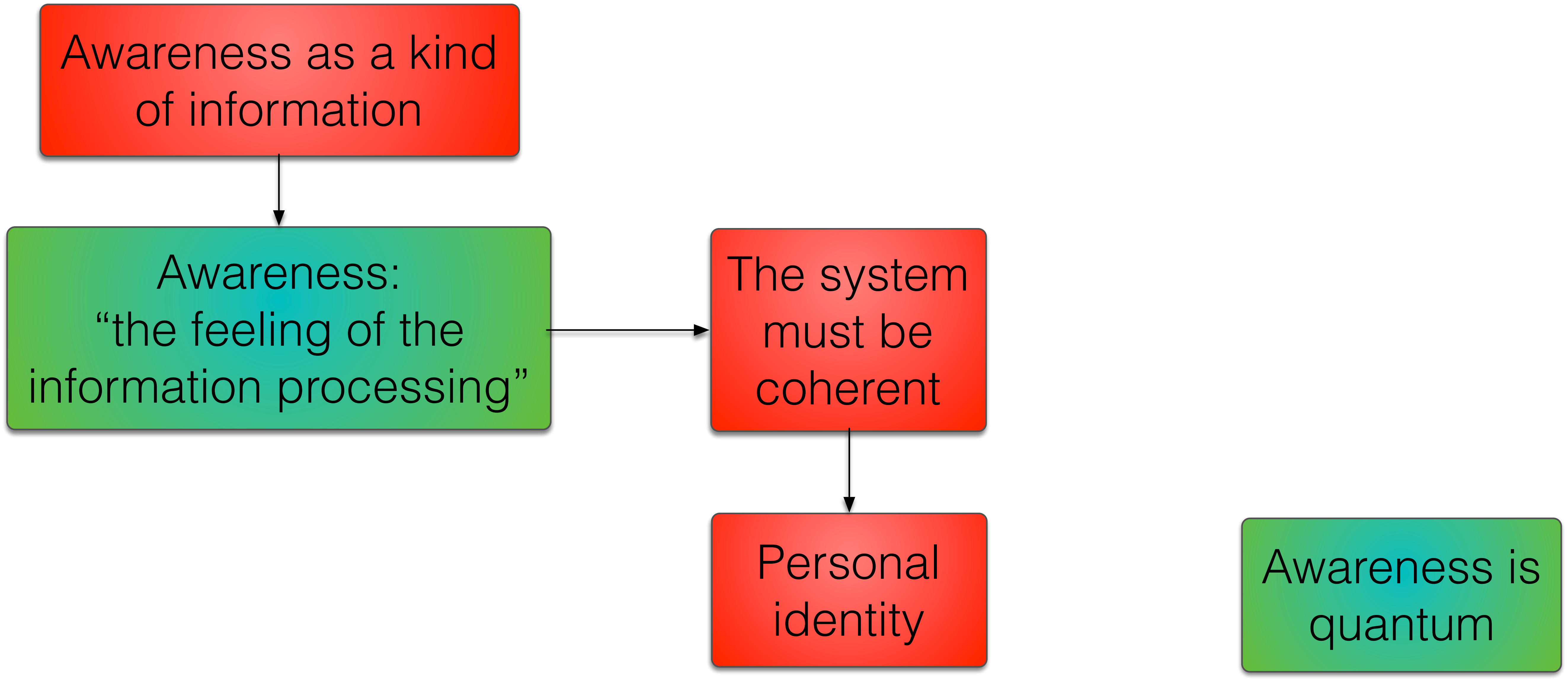
Self evident | Hypothesis | Heuristics, Philosophy | Theoretical | Experimental



awareness as “being the system”

definition of system to be given soon …





the aware system is composite

awareness individuated by coherence

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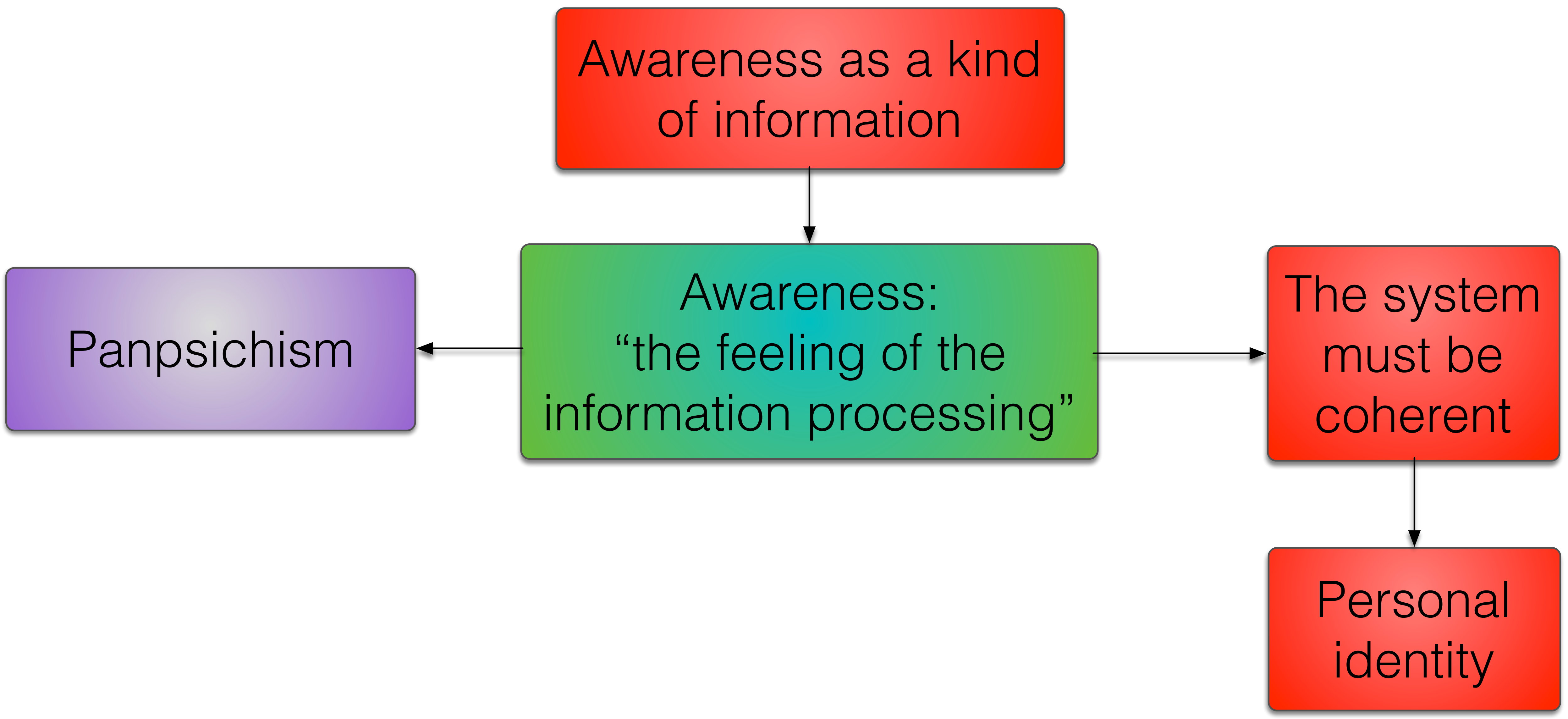
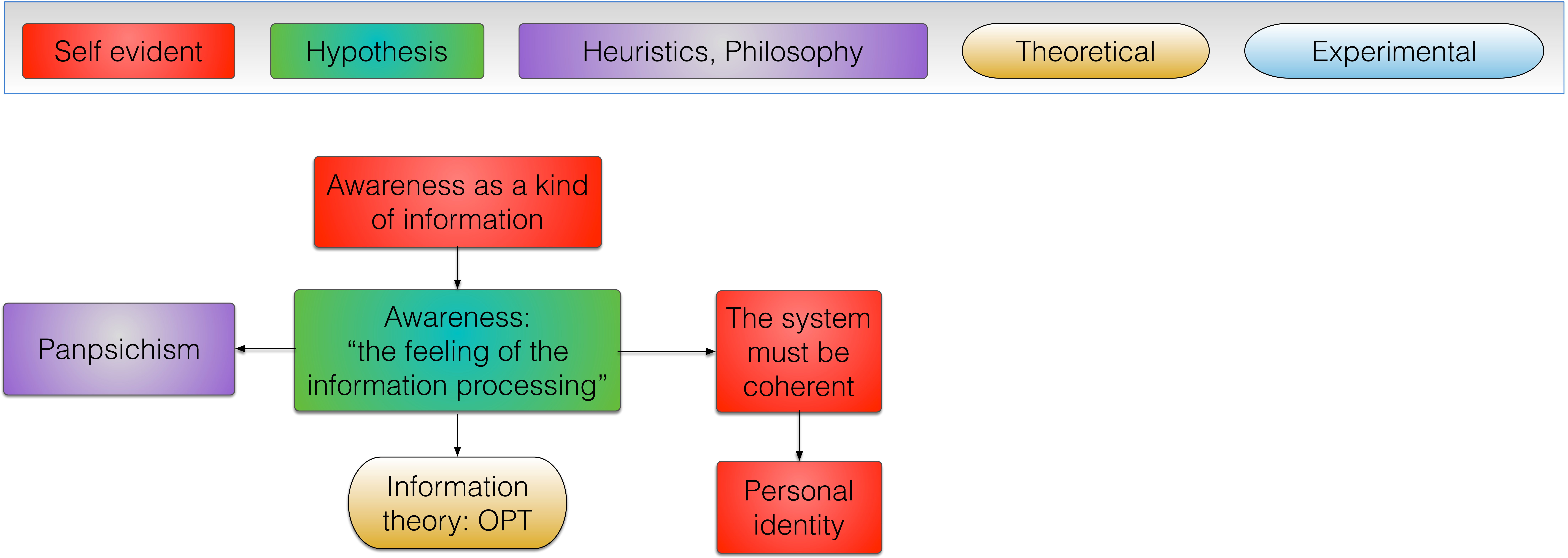
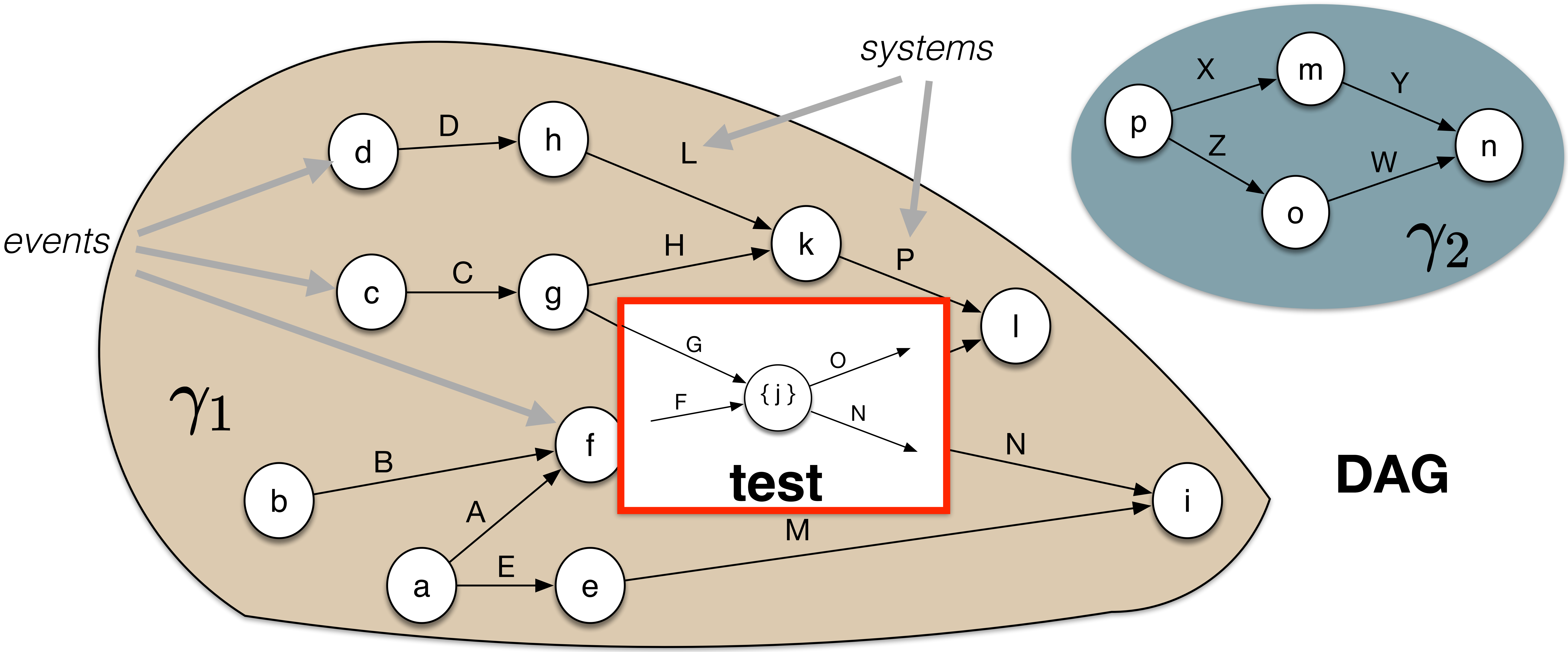


“In puro statu, ergo sum”

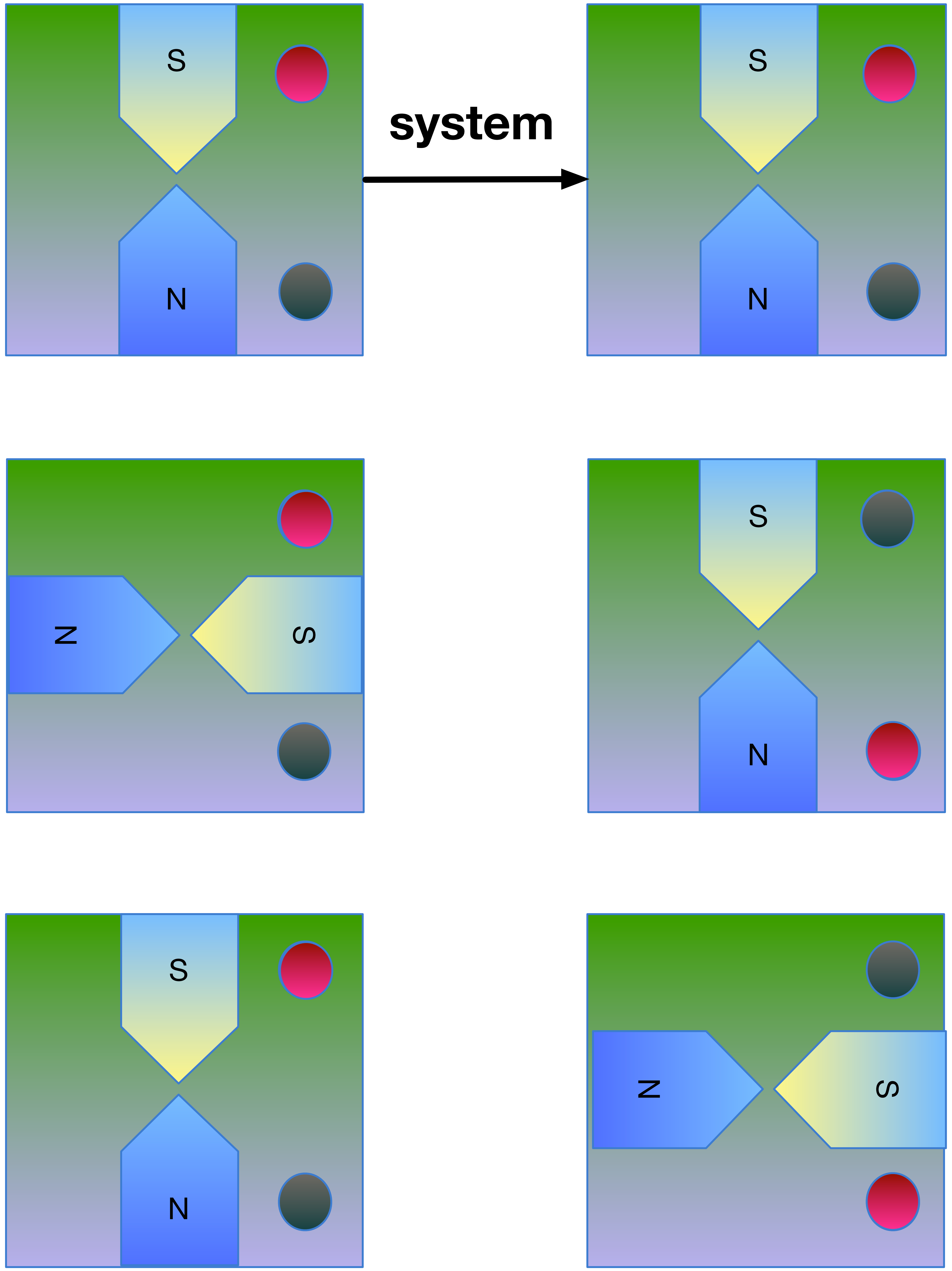

Self evident
Hypothesis
Heuristics, Philosophy
Theoretical
Experimental
Awareness as a kind of information
Awareness: "the feeling of the information processing"
Panpsichism
The system must be coherent
Information theory: OPT
Personal identity

Operational probabilistic theory (OPT)



$$p(abc,\ldots,o|\gamma_1 \cup \gamma_2) = p(abc,\ldots,l|\gamma_1)p(n,\ldots,p|\gamma_2)$$

NOTICE: marginals depend on the marginalised part of the graph!


S
N
system
S
N
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S

OPT and the goal of Science

1. To connect "objective things happening" (events)
2. To devise a theory of such "connections" (systems)
3. To make predictions for future occurrences (predict joint probabilities of events depending on their connections).

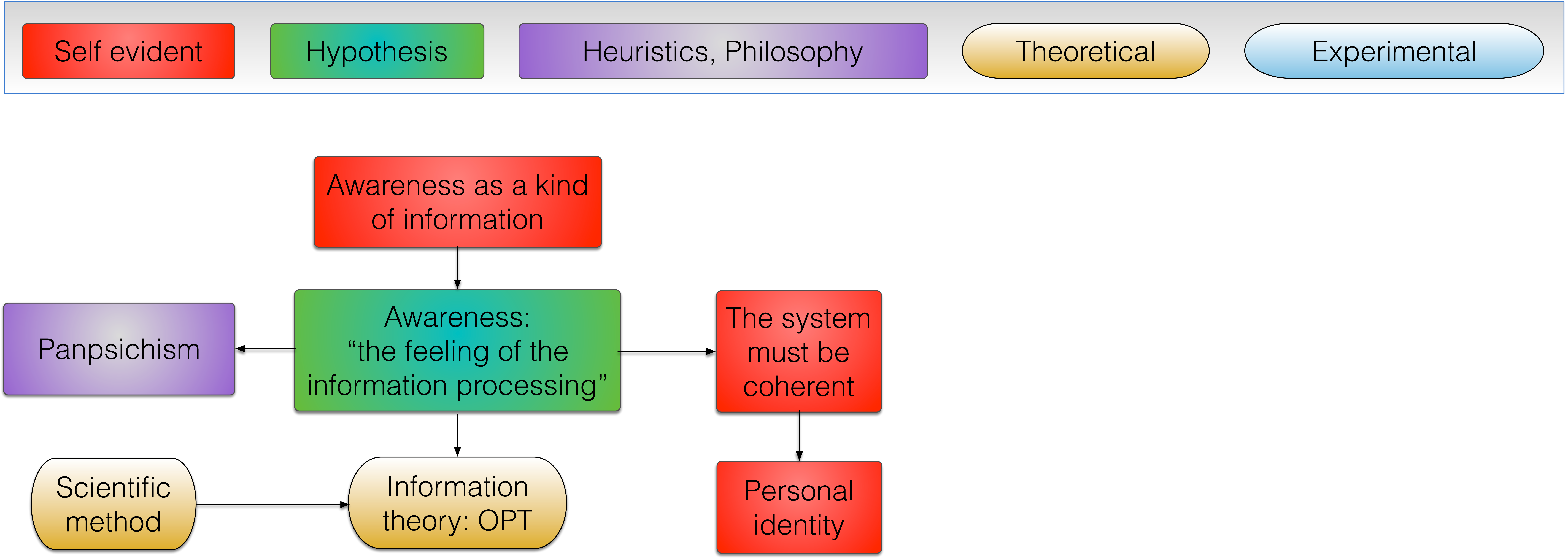
Which events happen is **objective**

Systems are **theoretical**

OPT: methodologically fit, falsification-ready

Goal of the OPT

To provide a mathematical description of systems and events consistent with their composition rules, allowing to evaluate their joint probability distribution depending on the graph of connections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Scientific method
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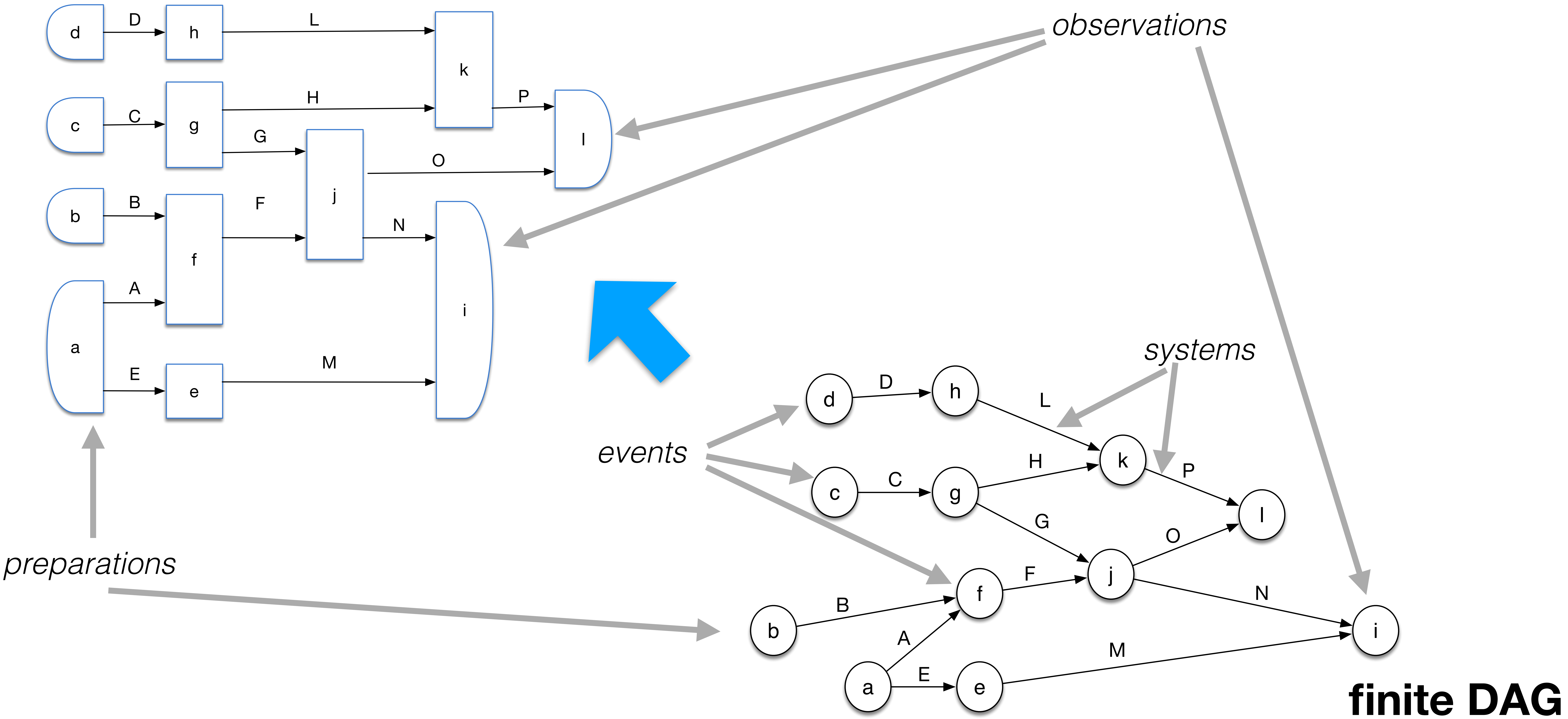
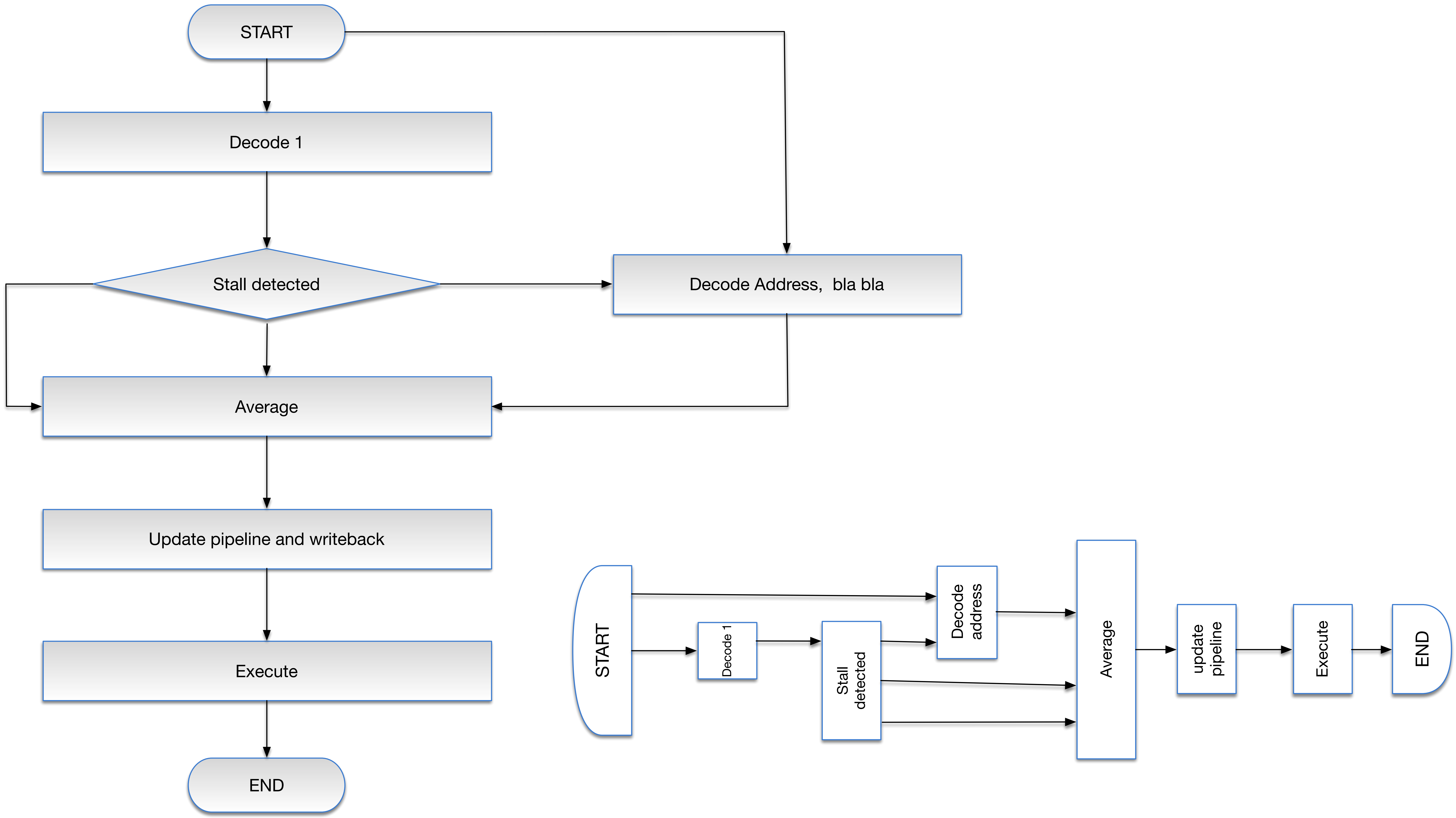
An OPT is an Information Theory



An OPT is an Information Theory



Operational probabilistic theory (OPT)

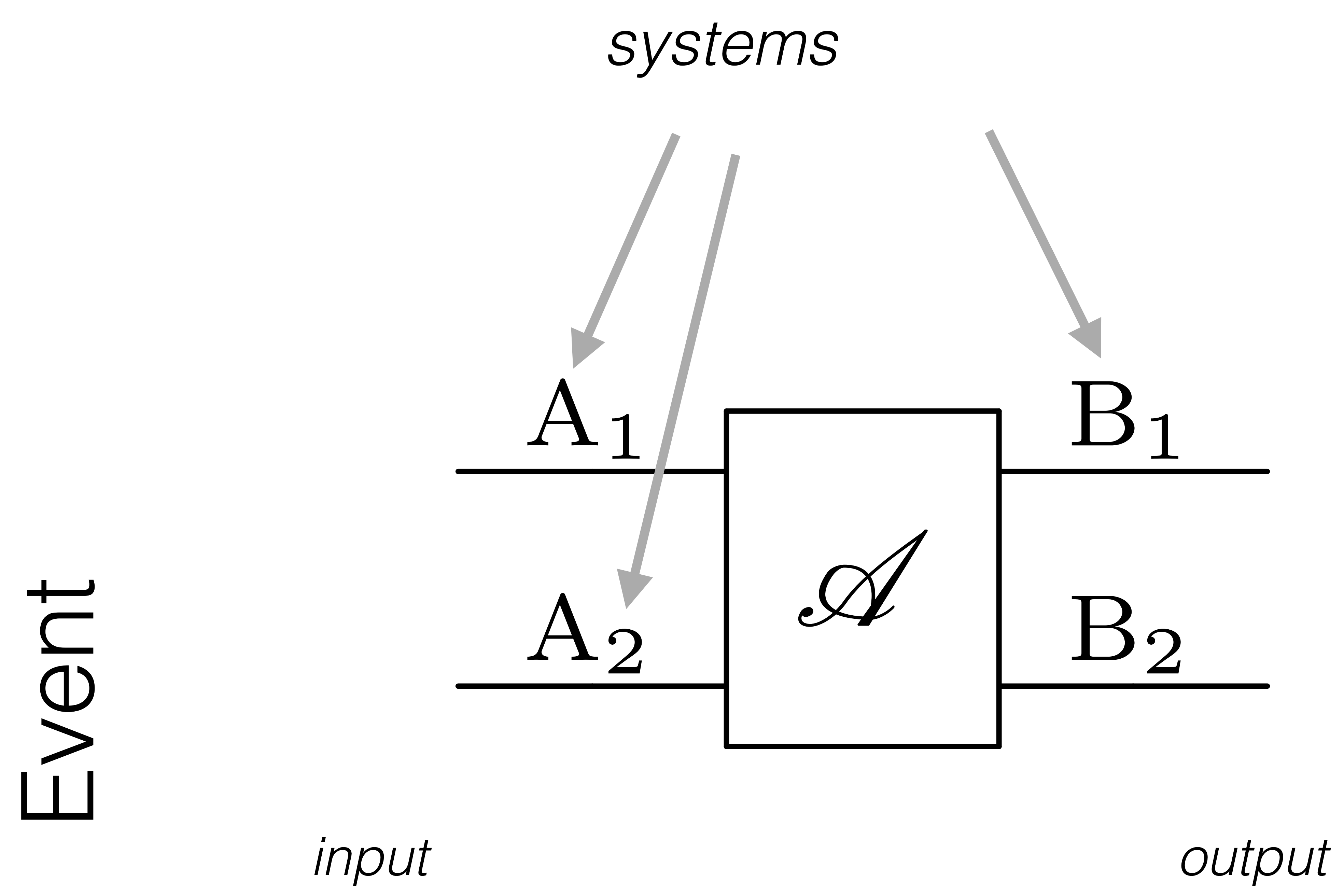
- Very general framework (compare with causal graphs and Tononi's "integrated information theory")
- Mathematically formalised (compare with Tononi IIT)
- Black-box device-independent approach:
  - Tools: tomography, separating sets, complementary observations, …

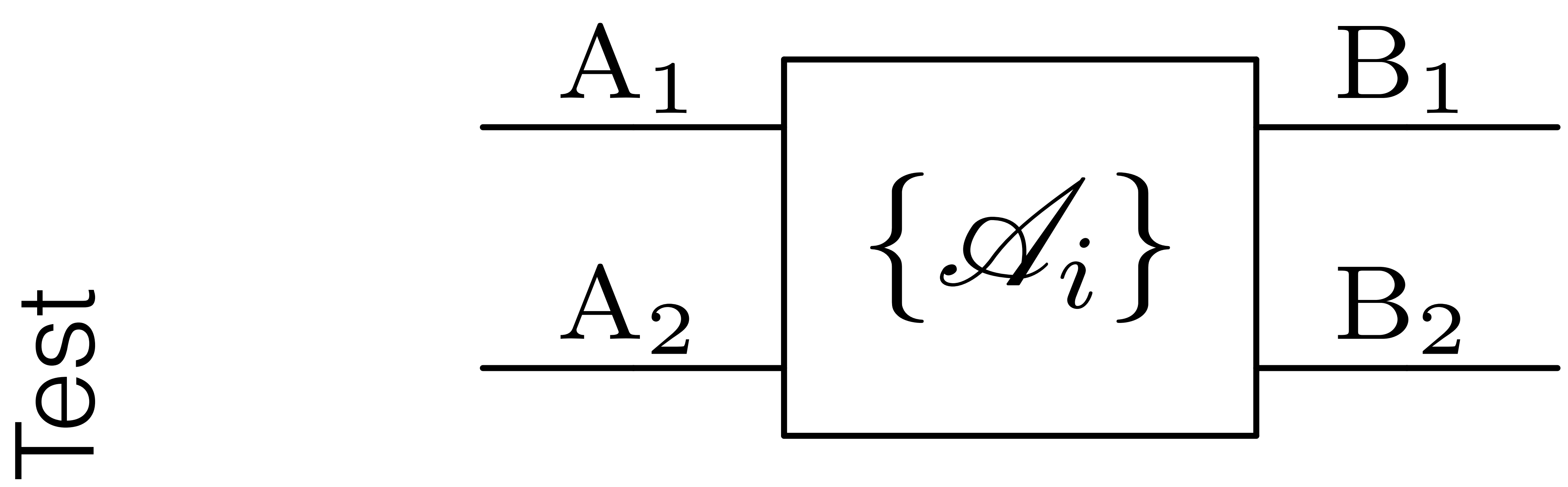
OPT framework

joint probabilities + connectivity

Marginal probability

$$\sum_{ijk} p(ijk, \ldots | DAG) = p(j|DAG)$$





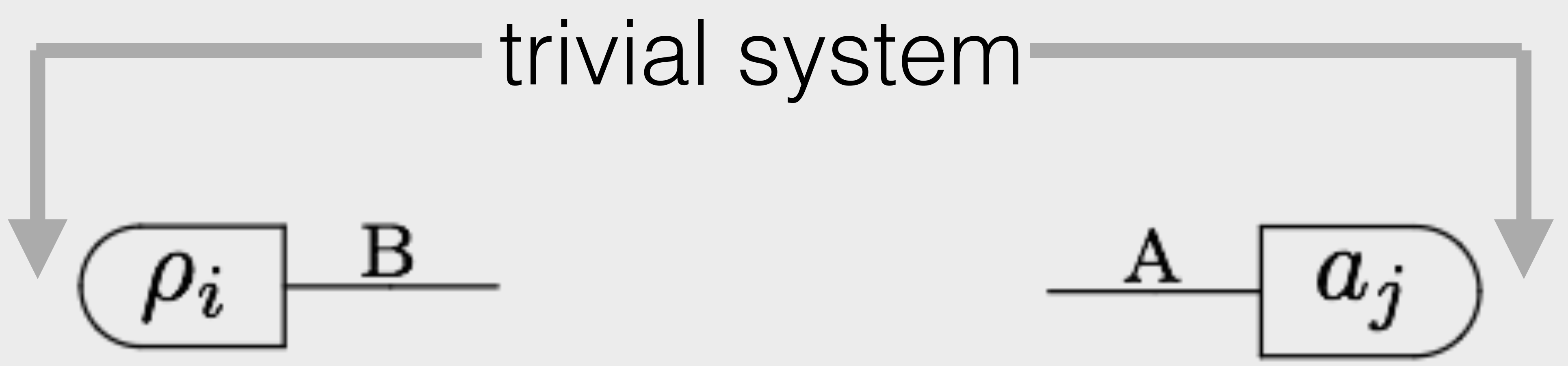
OPT framework

joint probabilities + $\boxed{\text{connectivity}}$

Probabilistic
equivalence classes

category theory:
transformations ➡ morphisms
systems ➡ objects

OPT: strict monoidal braided category

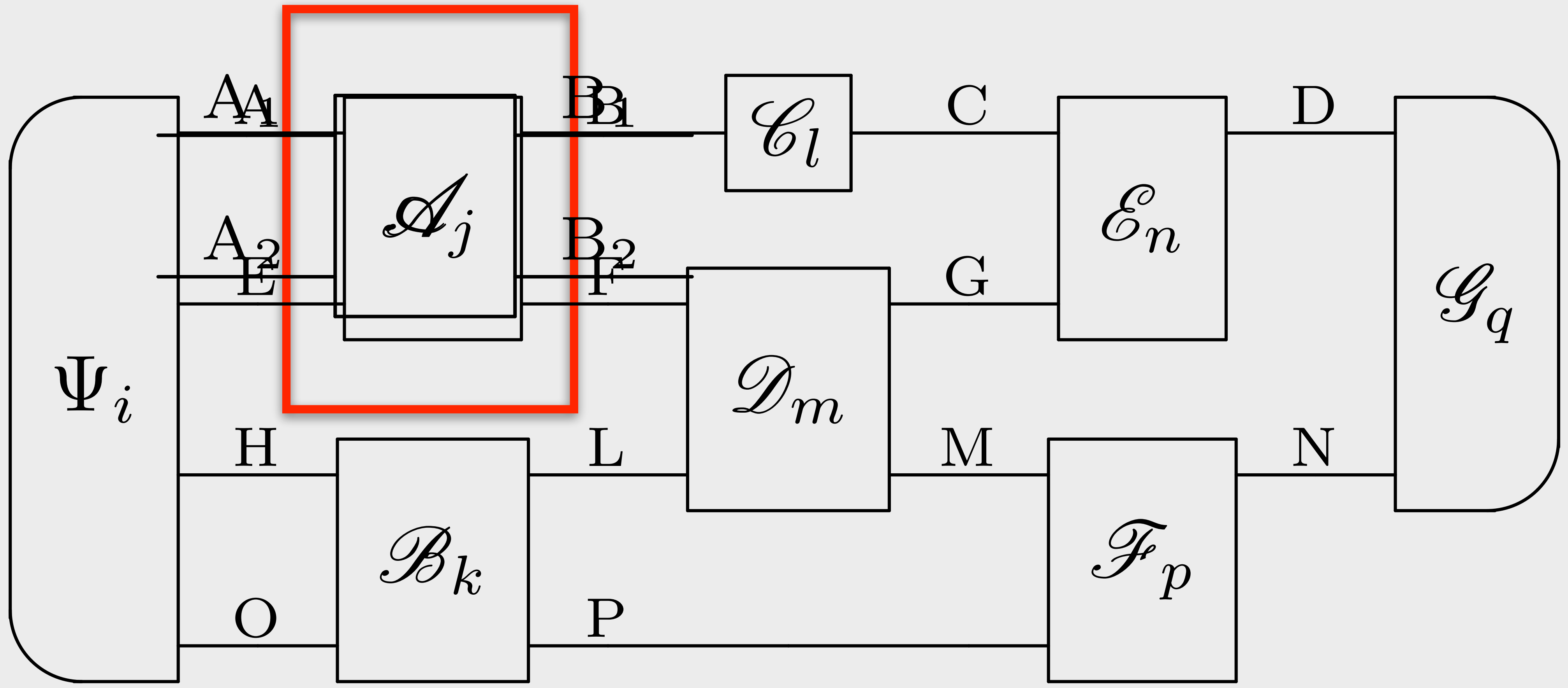


state

effect

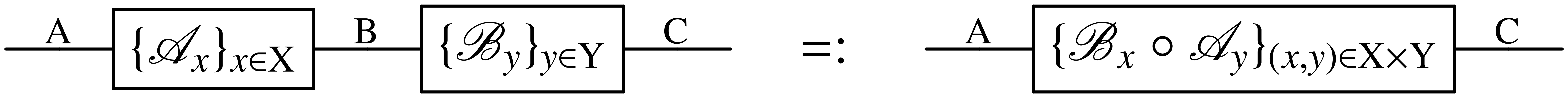
transformation

$$p(i,j,k,l,m,n,p,q|\text{circuit})$$

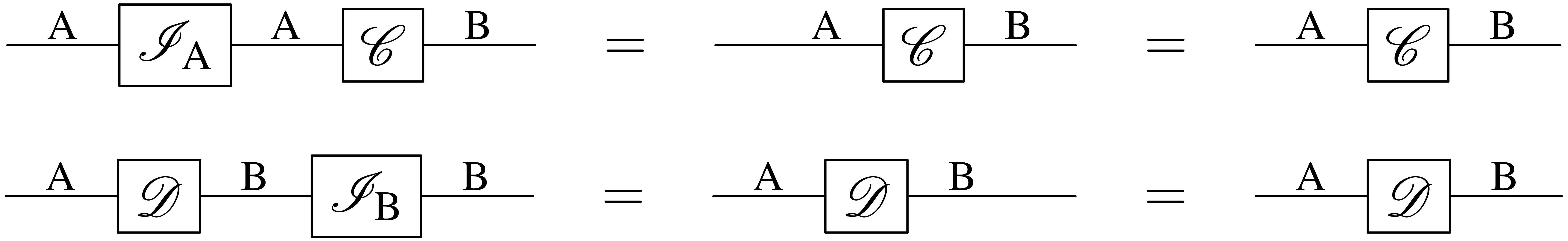


OPT framework

Sequential composition (associative)



Identity test

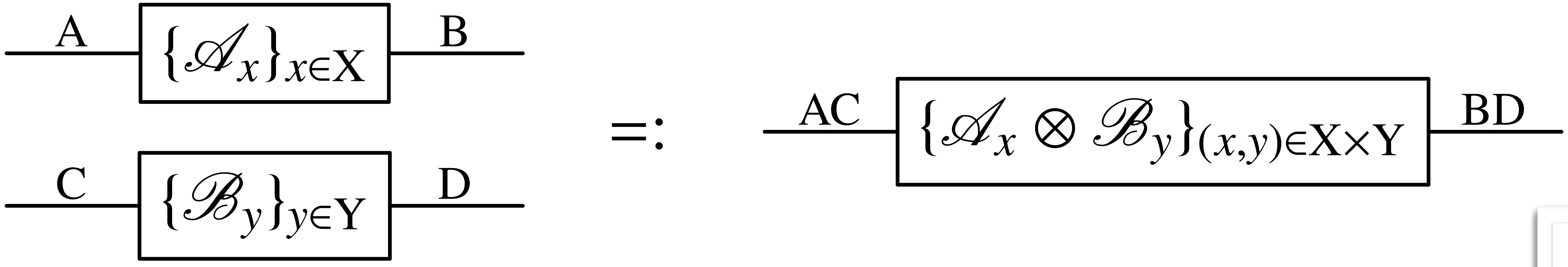


OPT framework

OPT: strict monoidal braided category

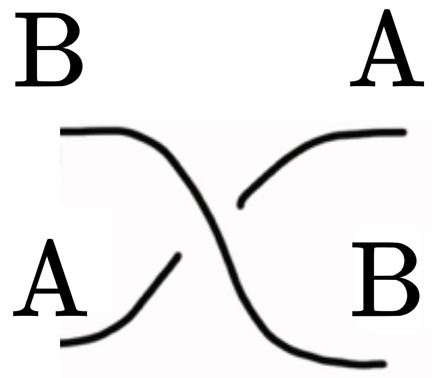
Quantum Theory: symmetric OPT

Parallel composition (associative)

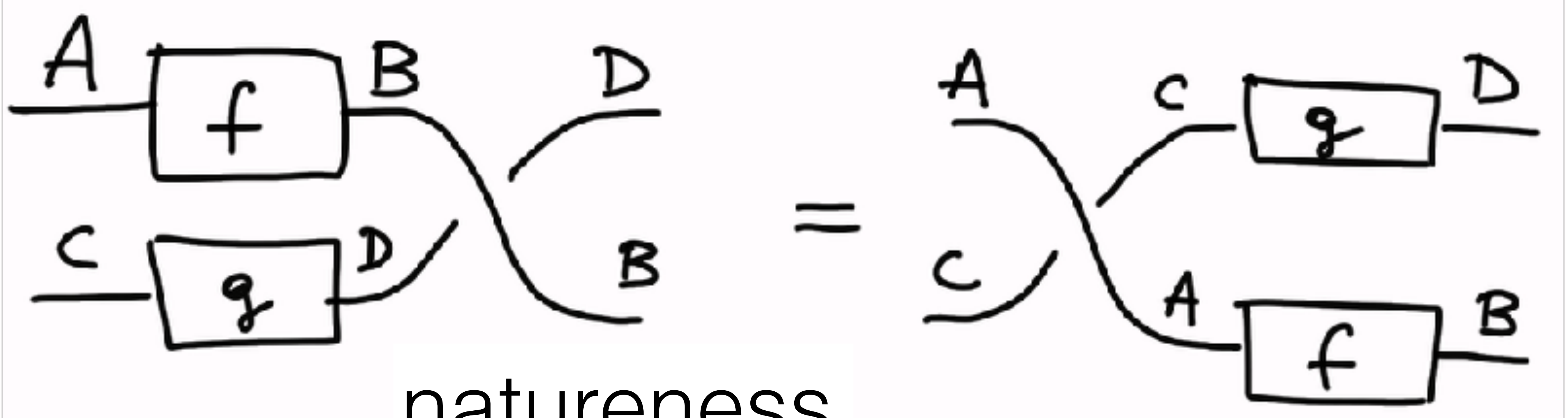


swap

$$S_{\mathrm{A,B}}\mathrm{AB} = \mathrm{BA}$$



$$\mathrm{AB} \simeq \mathrm{BA} =: S_{\mathrm{A,B}}\mathrm{AB} \quad \text{(braided)}$$



natureness

$$\left.\begin{array}{l} \mathrm{AI} = \mathrm{IA} \\ (\mathrm{AB})\mathrm{C} = \mathrm{A}(\mathrm{BC}) \end{array}\right\} \quad \text{(strict monoidal)}$$

$$(\mathrm{AB})\mathrm{C} \simeq \mathrm{A}(\mathrm{BC}) \quad \text{(monoidal)}$$

$$S^{-1}_{\mathrm{A,B}} = S_{\mathrm{B,A}} \quad \text{(symmetric)}$$

OPT framework

Parallel composition (associative)

Pentagon rule

$$\begin{tikzcd}
(A(B(CD)) \arrow[r, "\alpha"] \arrow[d, "1\alpha"] & (AB)(CD) \arrow[r, "\alpha"] & ((AB)C)D \arrow[d, "\alpha 1"] \\
A((BC)D) \arrow[rr, "\alpha"] & & (A(BC))
\end{tikzcd}$$

Triangle rule

$$\begin{tikzcd}
A(IB) \arrow[rr, "\alpha"] \arrow[dr, "1\lambda"] & & (AI)B \arrow[dl, "\rho 1"] \\
& AB &
\end{tikzcd}$$

Exagon rule

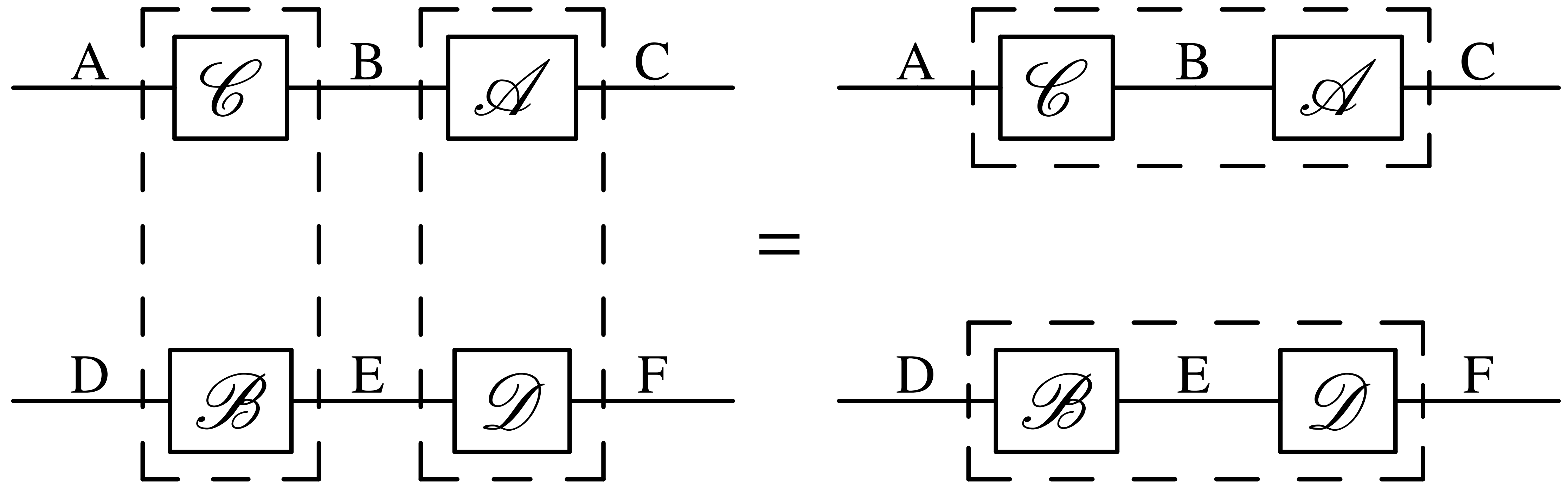
$$\begin{tikzcd}
(AB)C \arrow[r, "\gamma"] \arrow[d, "\alpha^{-1}"] & C(AB) \arrow[d, "\rho 1"] \\
A(BC) \arrow[d, "1\gamma"] & (CA)B \arrow[d, "\gamma 1"] \\
A(CB) \arrow[r, "\alpha"] & (AC)B
\end{tikzcd}
\qquad
\begin{tikzcd}
A(BC) \arrow[r, "\gamma"] \arrow[d, "\alpha^{-1}"] & (BC)A \arrow[d, "\alpha^{-1}"] \\
(AB)C \arrow[d, "\gamma 1"] & B(CA) \arrow[d, "1\gamma"] \\
(BA)C \arrow[r, "\alpha^{-1}"] & B(AC)
\end{tikzcd}$$

Symmetrical monoidal category

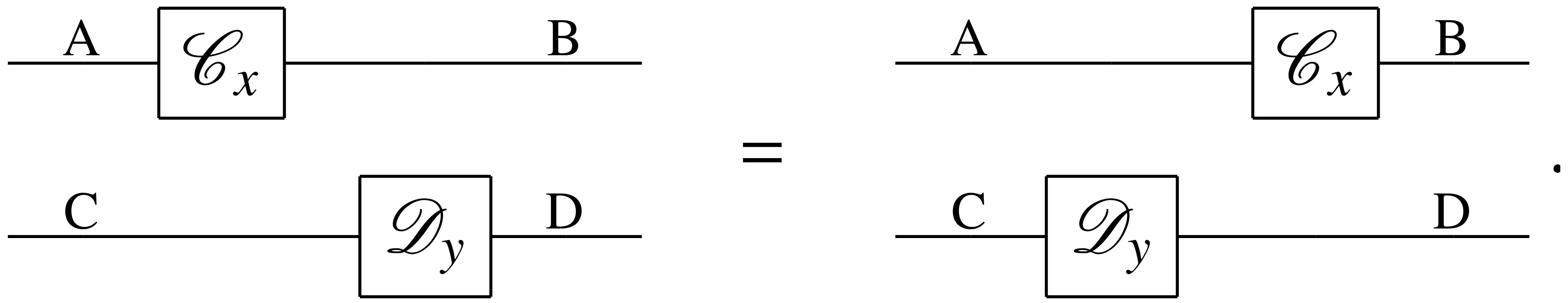
$$\begin{tikzcd}
AB \arrow[r, "\gamma_{AB}"] \arrow[dr] & BA \arrow[d, "\gamma_{BA}"] \\
& AB
\end{tikzcd}$$

OPT framework

Second naturalness condition: sequential and parallel compositions commute



$$(\mathscr{A} \otimes \mathscr{D}) \circ (\mathscr{C} \otimes \mathscr{B}) = (\mathscr{A} \circ \mathscr{C}) \otimes (\mathscr{D} \circ \mathscr{B})$$

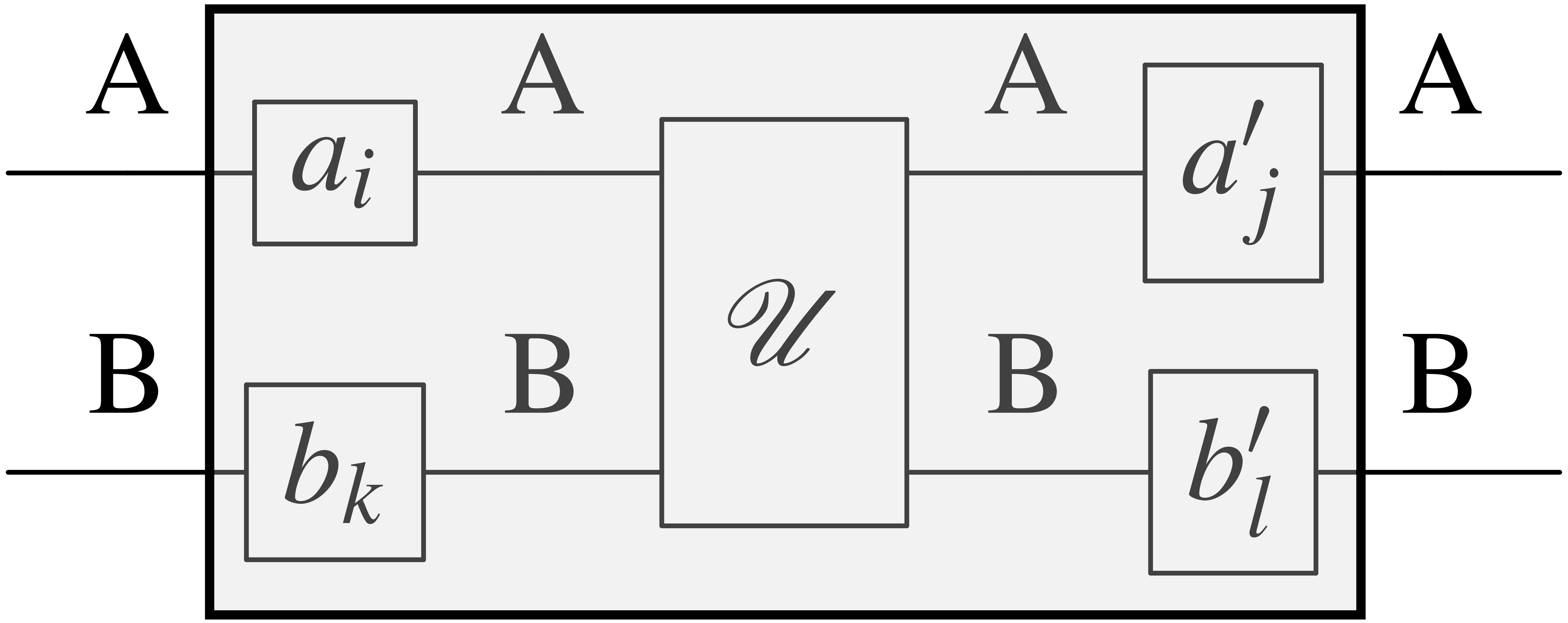


wire-stretching

(foliations)

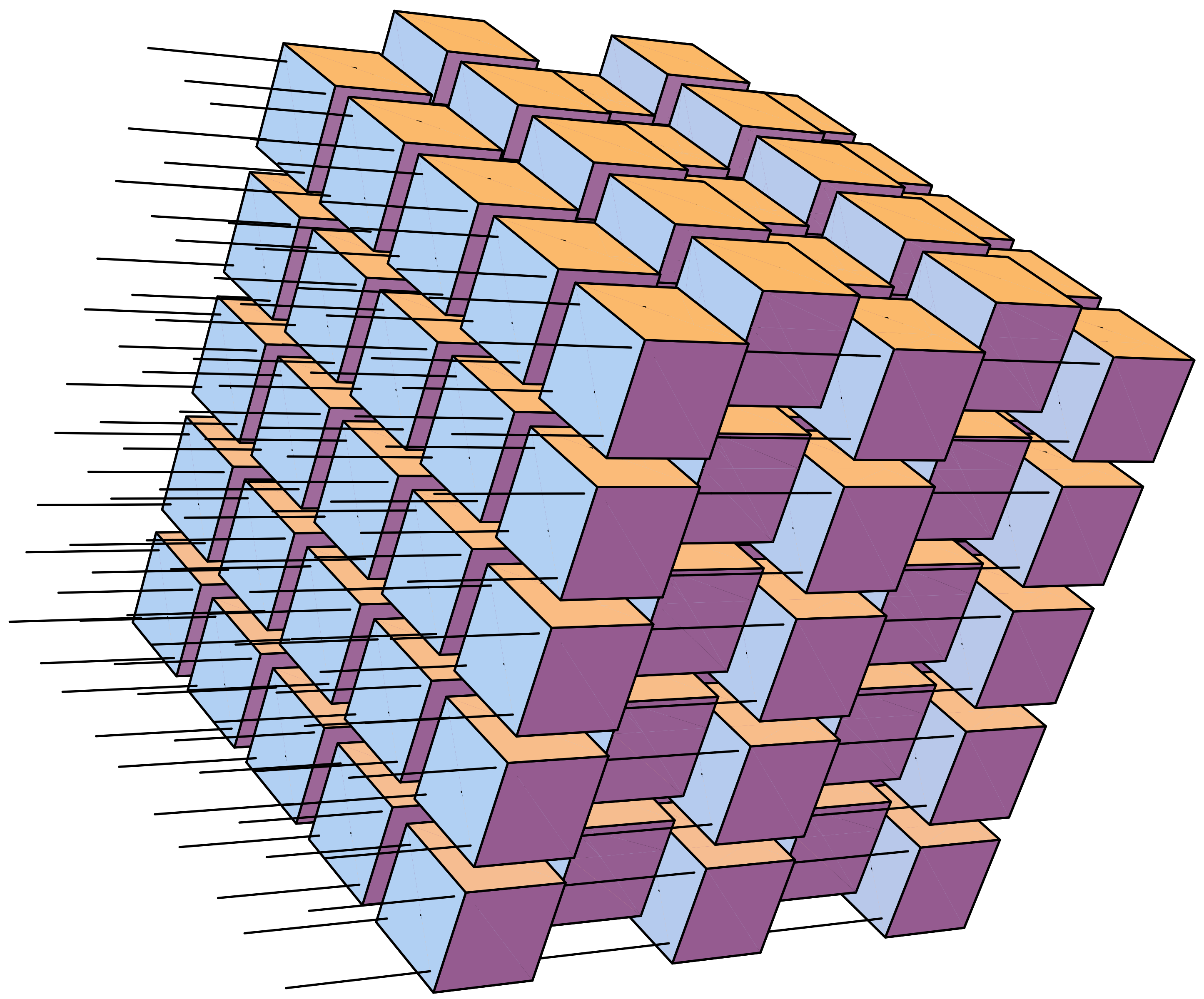
OPT framework

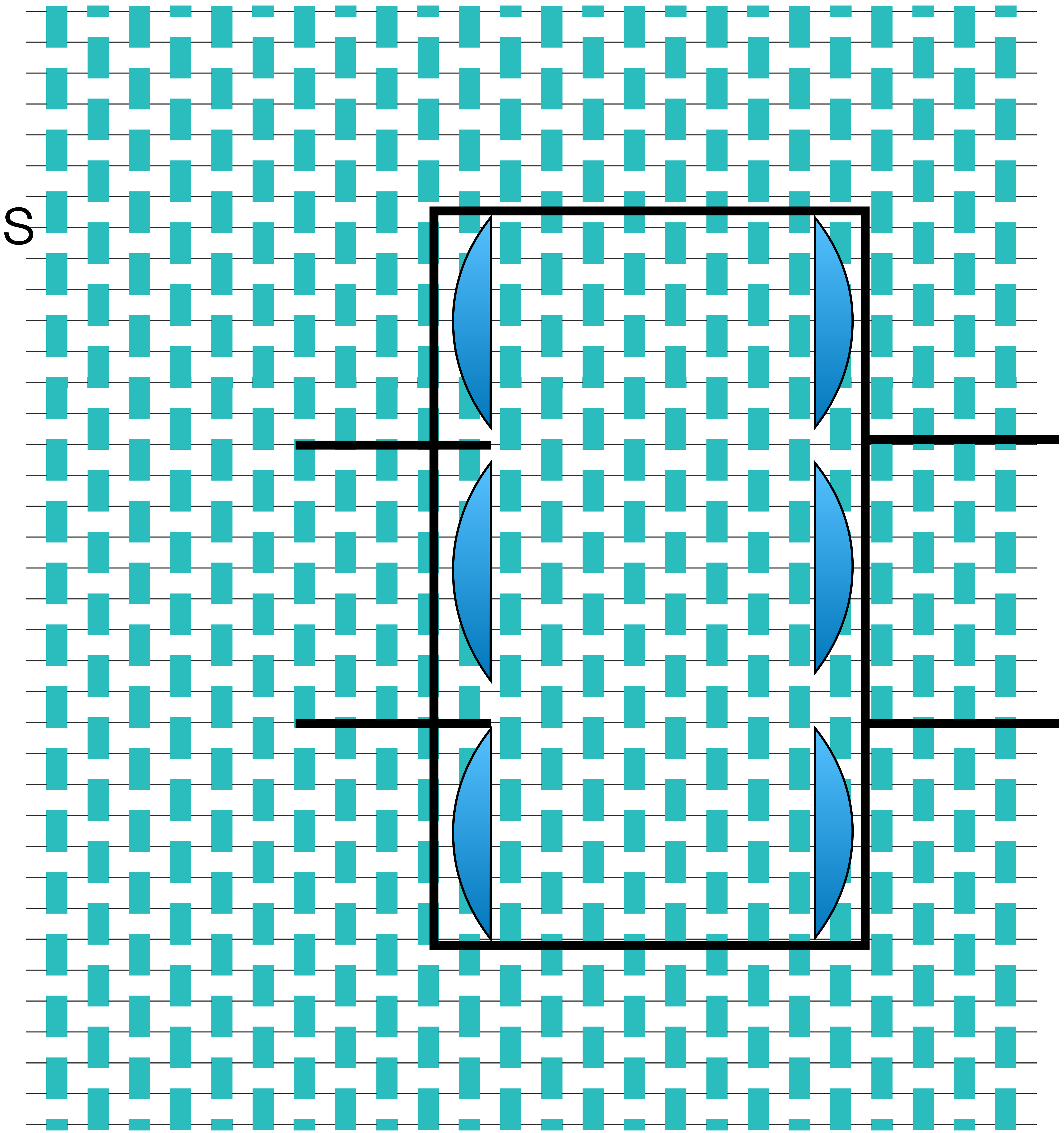
Finer and coarser descriptions



OPT framework

Finer and coarser descriptions



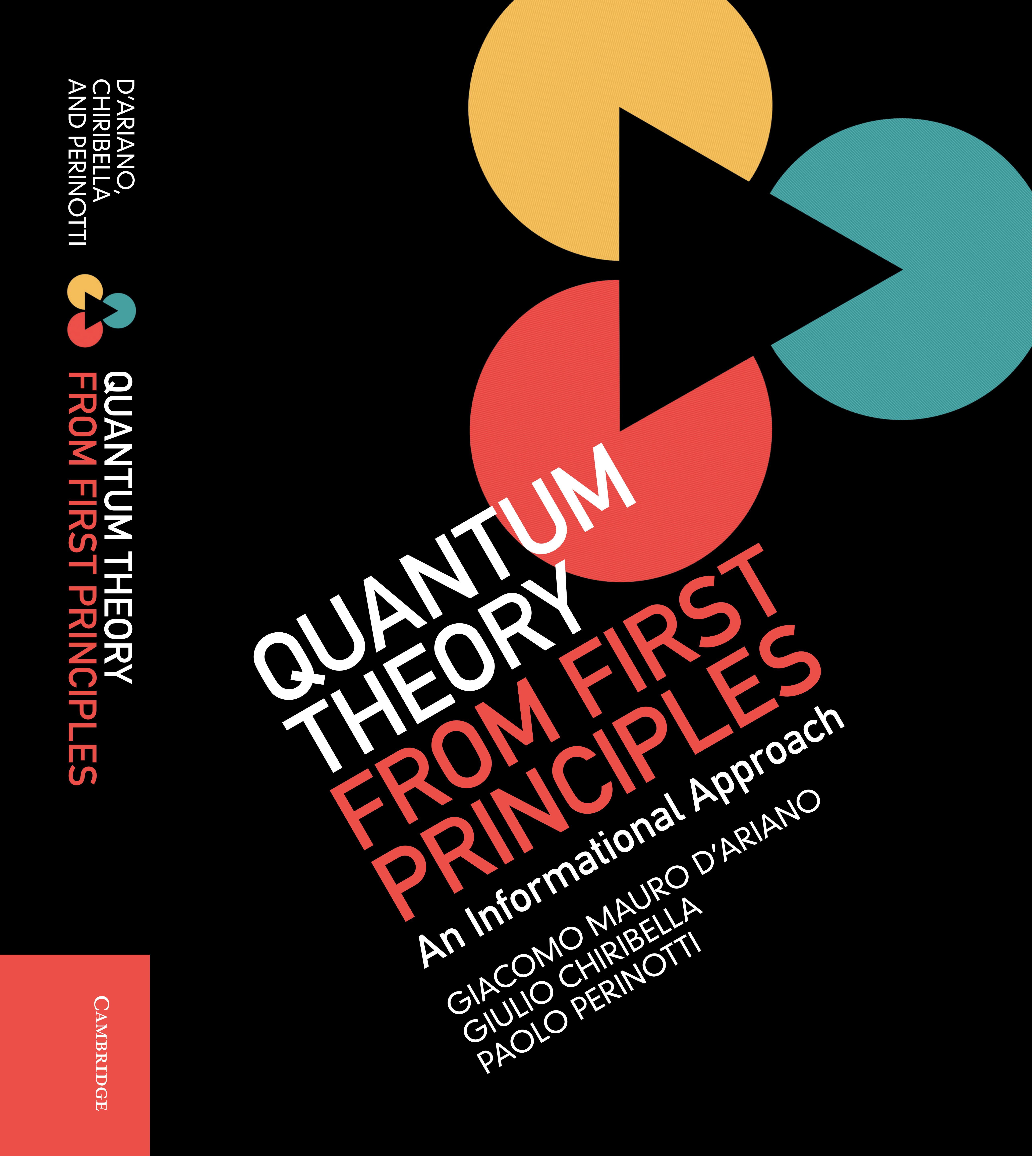


Quantum Theory: the “grammar” of Physics

Quantum Theory is an OPT

Quantum Theory as OPT		
system	A	$\mathscr{H}_{\mathrm{A}}$
system composition	AB	$\mathscr{H}_{\mathrm{AB}} = \mathscr{H}_{\mathrm{A}} \otimes \mathscr{H}_{\mathrm{B}}$
transformation	$\mathscr{T} \in \mathrm{Transf}(\mathrm{A} \to \mathrm{B})$	$\mathscr{T} \in \mathrm{CP}_{\leq}(\mathrm{T}(\mathscr{H}_{\mathrm{A}}) \to \mathrm{T}(\mathscr{H}_{\mathrm{B}}))$

Theorems		
trivial system system	I	$\mathscr{H}_{\mathrm{I}} = \mathbb{C}$
deterministic transformation	$\mathscr{T} \in \mathrm{Transf}_1(\mathrm{A} \to \mathrm{B})$	$\mathscr{T} \in \mathrm{CP}_{=}(\mathrm{T}(\mathscr{H}_{\mathrm{A}}) \to \mathrm{T}(\mathscr{H}_{\mathrm{B}}))$
states	$\rho \in \mathrm{St}(\mathrm{A}) \equiv \mathrm{Transf}(\mathrm{I} \to \mathrm{A})$	$\rho \in \mathrm{T}^{+}_{\leq 1}(\mathscr{H}_{\mathrm{A}})$
	$\rho \in \mathrm{St}_1(\mathrm{A}) \equiv \mathrm{Transf}_1(\mathrm{I} \to \mathrm{A})$	$\rho \in \mathrm{T}^{+}_{=1}(\mathscr{H}_{\mathrm{A}})$
	$\rho \in \mathrm{St}(\mathrm{I}) \equiv \mathrm{Transf}(\mathrm{I} \to \mathrm{I})$	$\rho \in [0,1]$
	$\rho \in \mathrm{St}_1(\mathrm{I}) \equiv \mathrm{Transf}(\mathrm{I} \to \mathrm{I})$	$\rho = 1$
effects	$\varepsilon \in \mathrm{Eff}(\mathrm{A}) \equiv \mathrm{Transf}(\mathrm{A} \to \mathrm{I})$	$\varepsilon(\cdot) = \mathrm{Tr}_{\mathrm{A}}[\cdot E],\ 0 \leq E \leq I_A$
	$\varepsilon \in \mathrm{Eff}_1(\mathrm{A}) \equiv \mathrm{Transf}_1(\mathrm{A} \to \mathrm{I})$	$\varepsilon = \mathrm{Tr}_{\mathrm{A}}$



Principles for Quantum Theory

P1. Causality

P2. Local discriminability

P3. Purification

P4. Atomicity of composition

P5. Perfect distinguishability

P6. Lossless Compressibility

G. Chiribella, G. M. D'Ariano, P. Perinotti, *Probabilistic Theories with Purification* Phys. Rev. A **81** 062348 (2010)

G. Chiribella, G. M. D'Ariano, P. Perinotti, *Informational derivation of Quantum Theory* Phys. Rev A **84** 012311 (2011)

Other OPTs

	Caus.	Perf. disc.	Loc. discr.	n-loc. discr.	At. par. comp.	At. seq. comp.	Compr.	∃ Purification	∃! Purification	NIWD
QT	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CT	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗
QBIT	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓
FQT	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓
RQT	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓
NSQT	?	?	✗	✗	?	?	?	?	?	?
PR	✓	?	✓	✓	✓	?	✗	✗	✗	✓
DPR	✓	?	✓	✓	✓	?	✗	✗	✗	✓
HPR	✓	?	✓	✓	✓	✓	✓	✓	✓	✓
FOCT	✗	?	✓	✓	✓	?	?	✗	✗	?
FOQT	✗	?	?	✓	?	?	?	?	?	?
NLCT	✓	✓	✗	✓	✗	?	✓	✗	✗	✗
NLQT	?	?	?	✓	?	?	?	?	?	?

QT: Quantum theory

CT: Classical theory

QBIT: Qubit theory

FQT: Fermionic quantum theory

RQT: Real quantum theory

NSQT: Number superselected quantum theory

PR: PR-boxes theory

DPR: Dual PR-boxes theory

HPR: Hybrid PR-boxes theory

FOCT: First order classical theory

FOQT: First order quantum theory

NLCT: Non-local classical theory

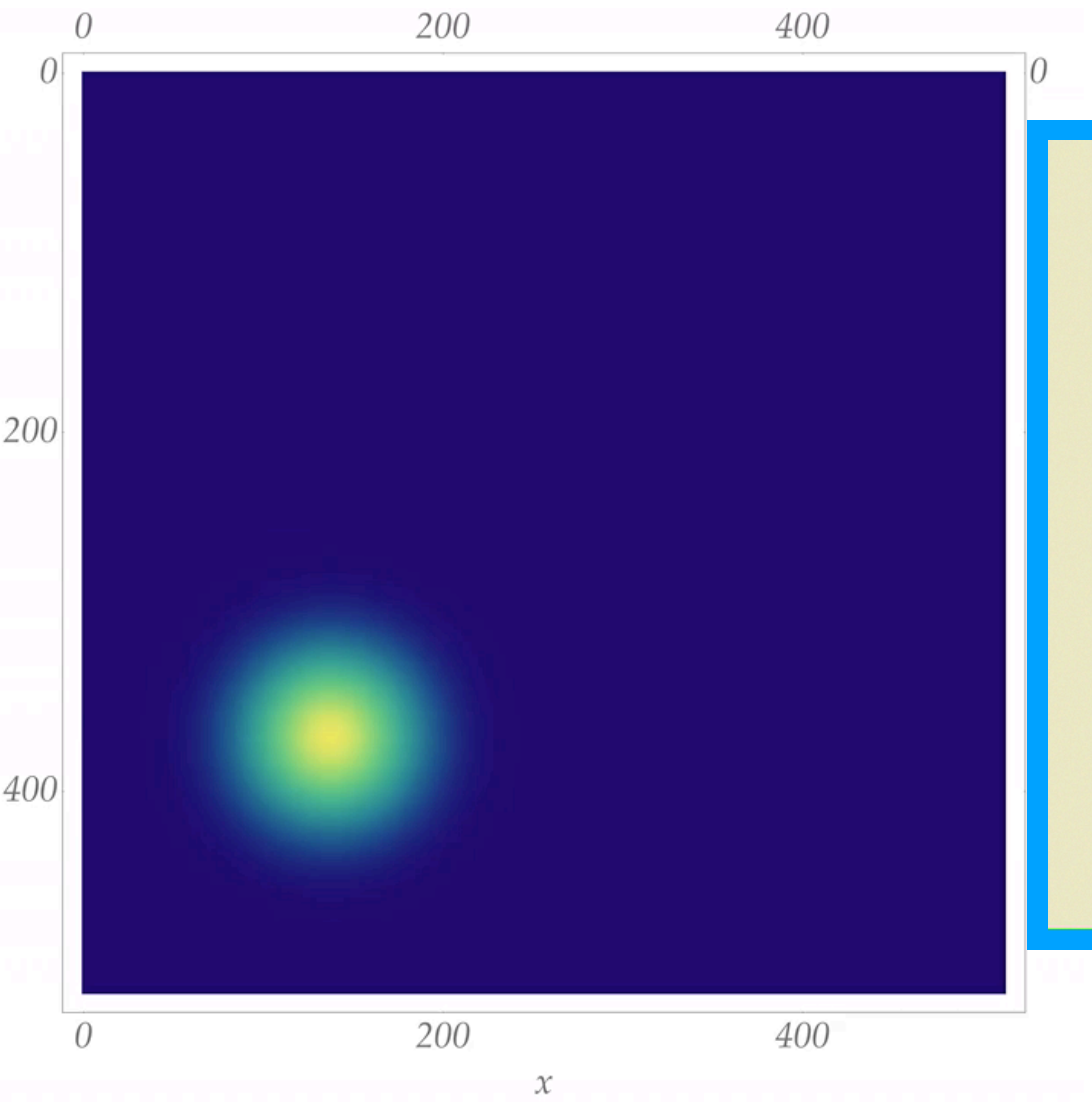
NLQT: Non-local quantum theory

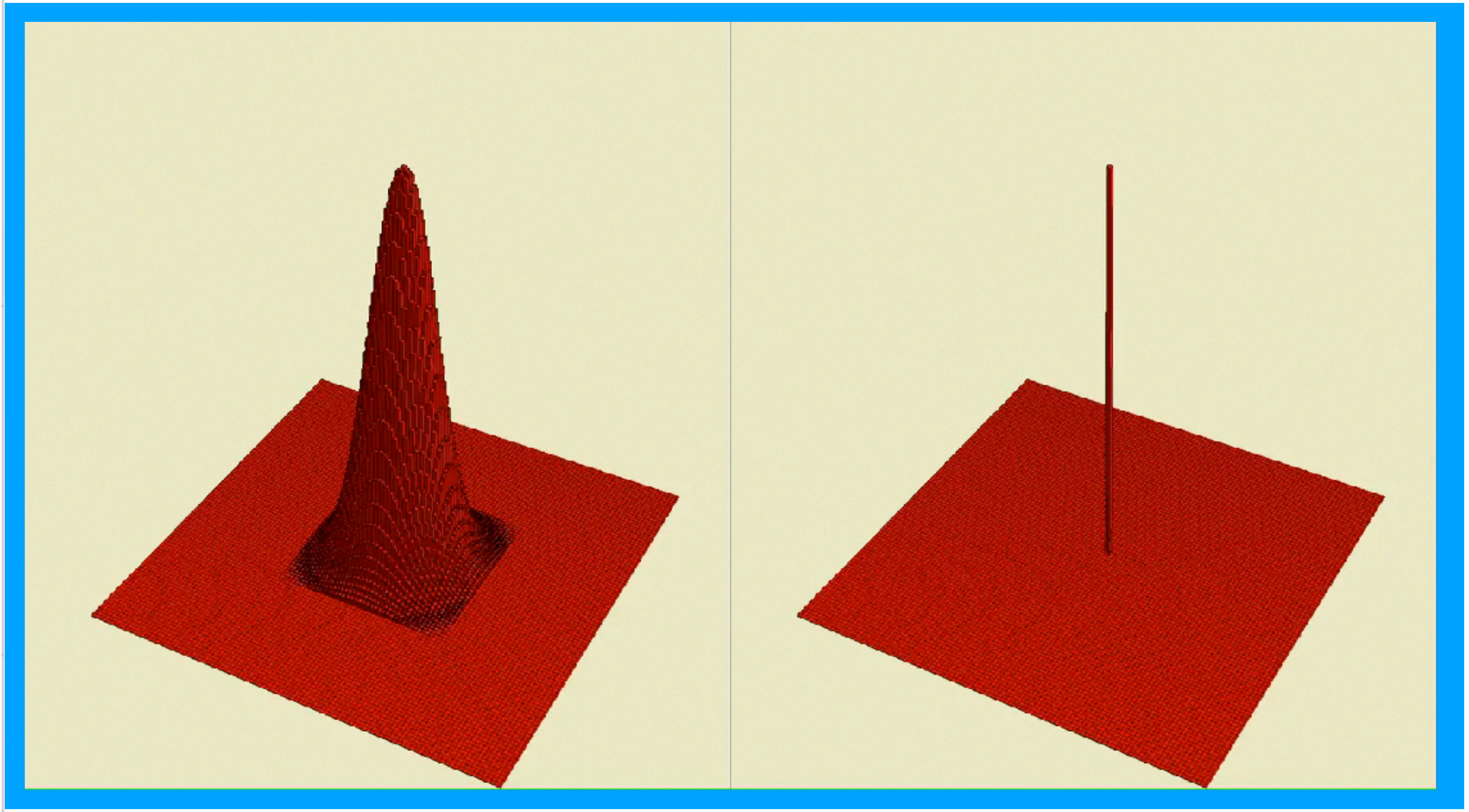
“HOW TO GET THE “MECHANICS?”

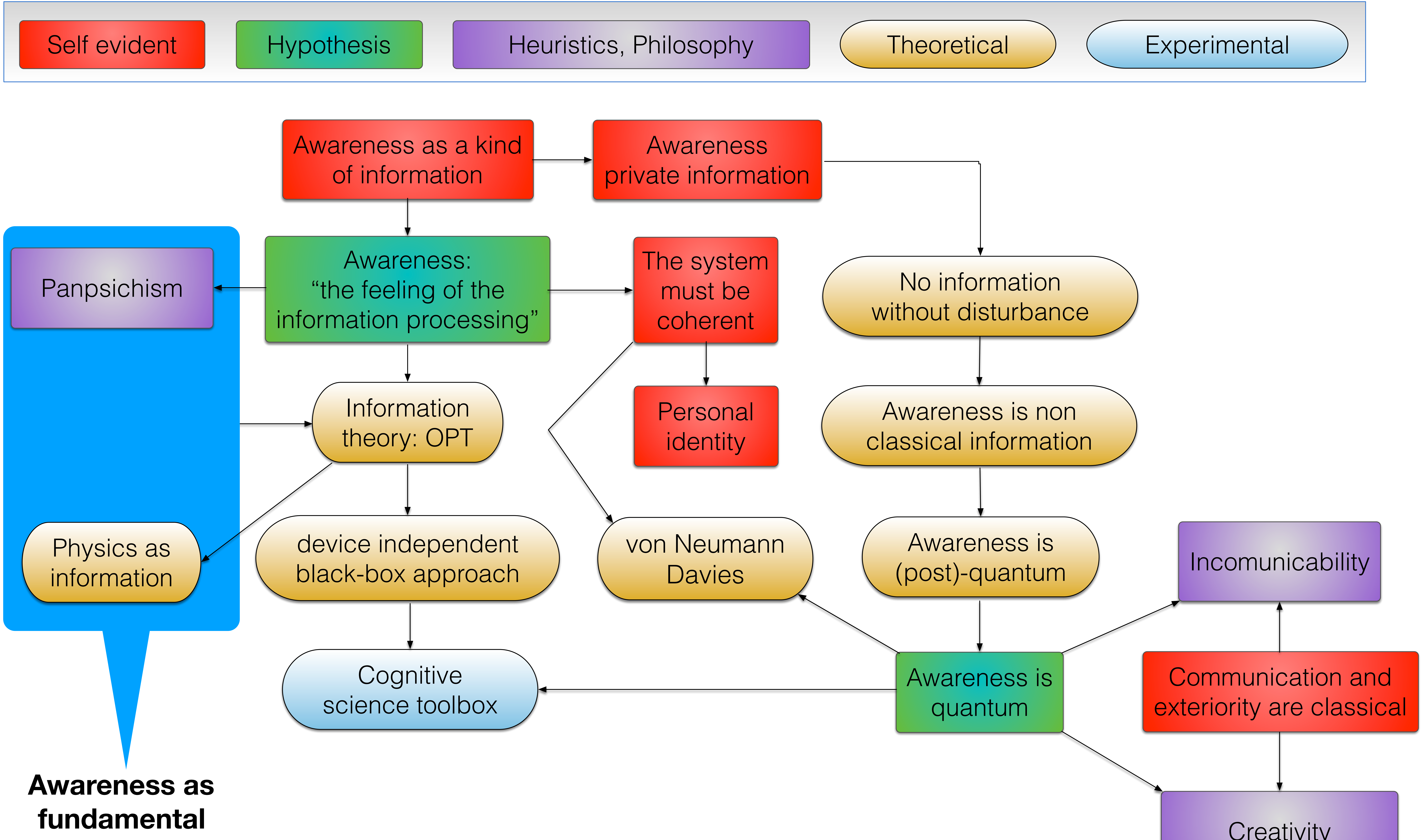
QUANTUM FIELD THEORY: an ultra-short account

PRINCIPLES
THEORY
RESTRICTIONS
INTERPRETATION
MATH. FRAMEWORK
equivalence
B needs A
A
B
Info-theoretical principles for Quantum Field Theory
Strict monoidal symmetric category theory dressed with probability
Operational Information framework
Causality
Local discriminability
Purification
Atomicity of composition
Perfect discriminability
Ideal compressibility
Quantum Theory
Locality
Homogeneity
Isotropy
Unitarity
Quantum Cellular Automata on a Cayley graph of G
Linearity
Quantum Walk on Cayley graph of G
Cayley graph quasi-isometrically embeddable in Euclidean space
G virtually Abelian
Quantum Walk on Cayley graph of Abelian G
Relativity Principle without space-time
m>0: deformed De Sitter
Particle as Poincaré invariant
m=0: deformed Lorentz
GR heuristics
Relativistic limit
Free Quantum Field Theory
LTM Standards
$m \in S^1$ discrete proper time

Info-theoretical principles for Quantum Field Theory







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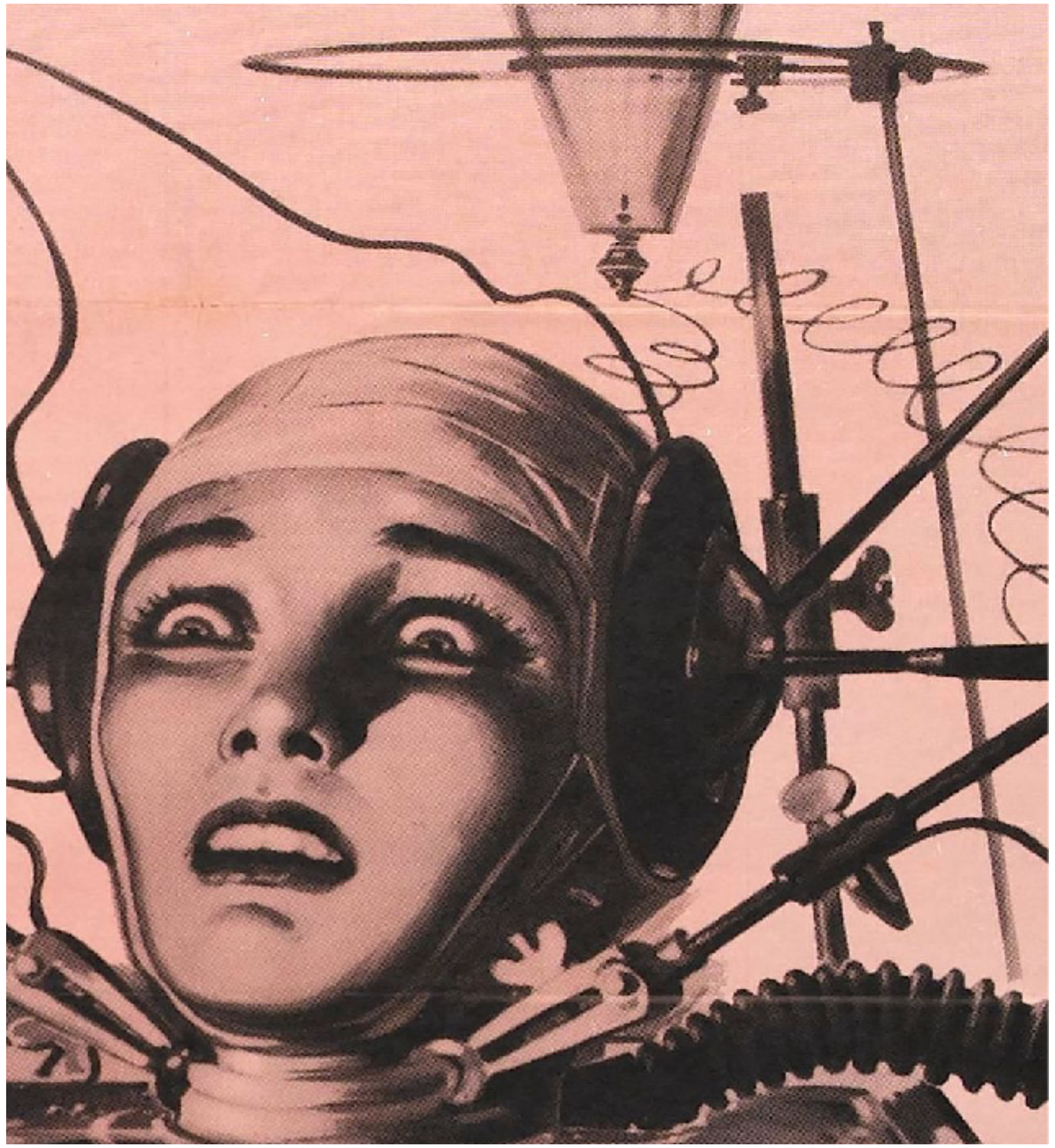
Personal identity
Awareness is non classical information
Physics as information
device independent black-box approach
von Neumann Davies
Awareness is (post)-quantum
Incomunicability
Cognitive science toolbox
Awareness is quantum
Communication and exteriority are classical
Creativity
Awareness as fundamental

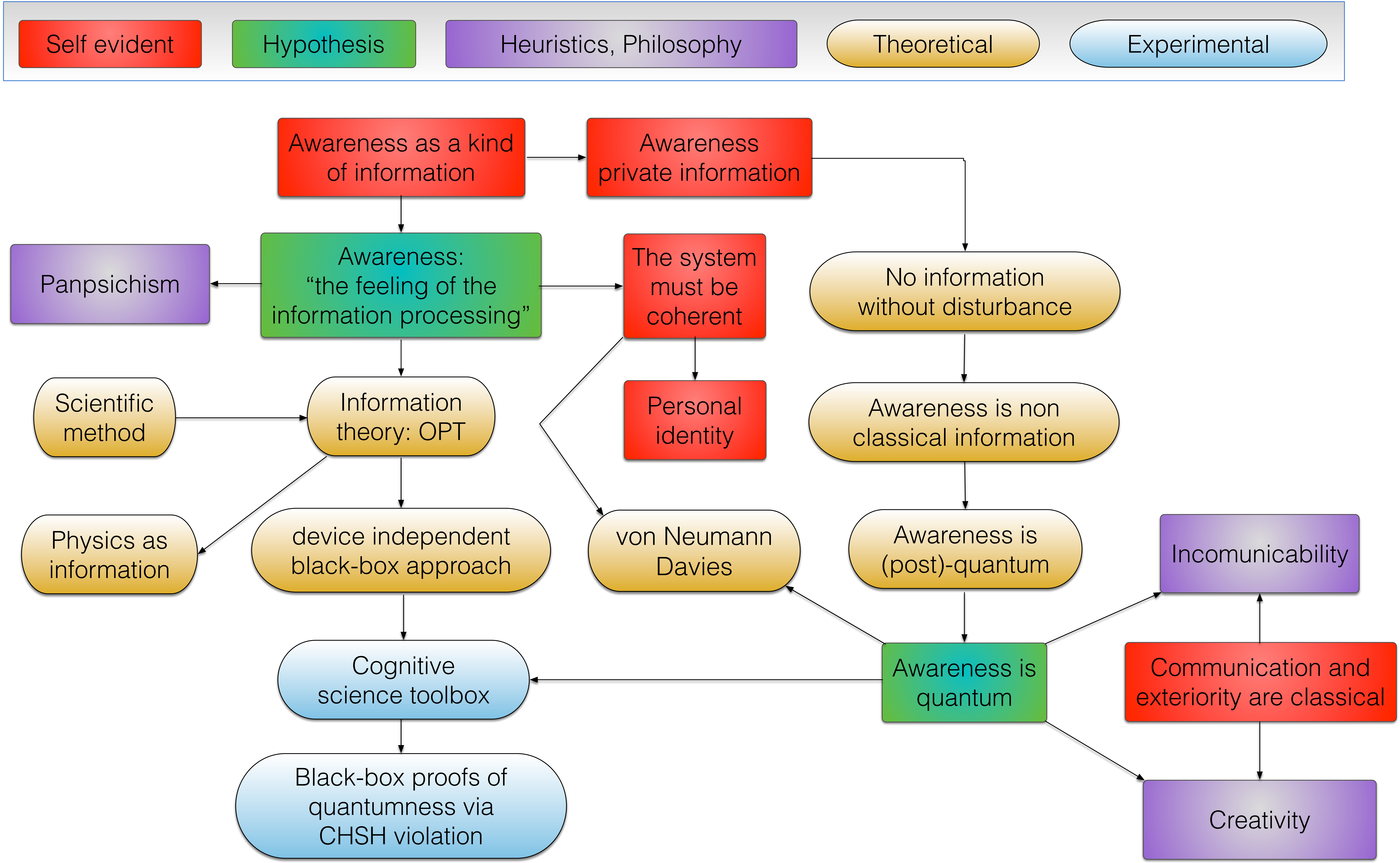
Take home for cognitive scientists

Build a *sufficient toolbox* by doing the following *calibration* procedure (d=2):

1. Find two *incompatible observation-tests* for system A and for system B
2. Use them as a *separating set of observations* to calibrate states for systems A and B by tomography
3. Perform *tomography* of transformations from A to B and from B to A

$$\{\rho_i\}_{i\in \mathrm{X}} \xrightarrow{\mathrm{A}} \mathscr{T}_l \xrightarrow{\mathrm{B}} \{a_j\}_{j\in \mathrm{Y}}$$

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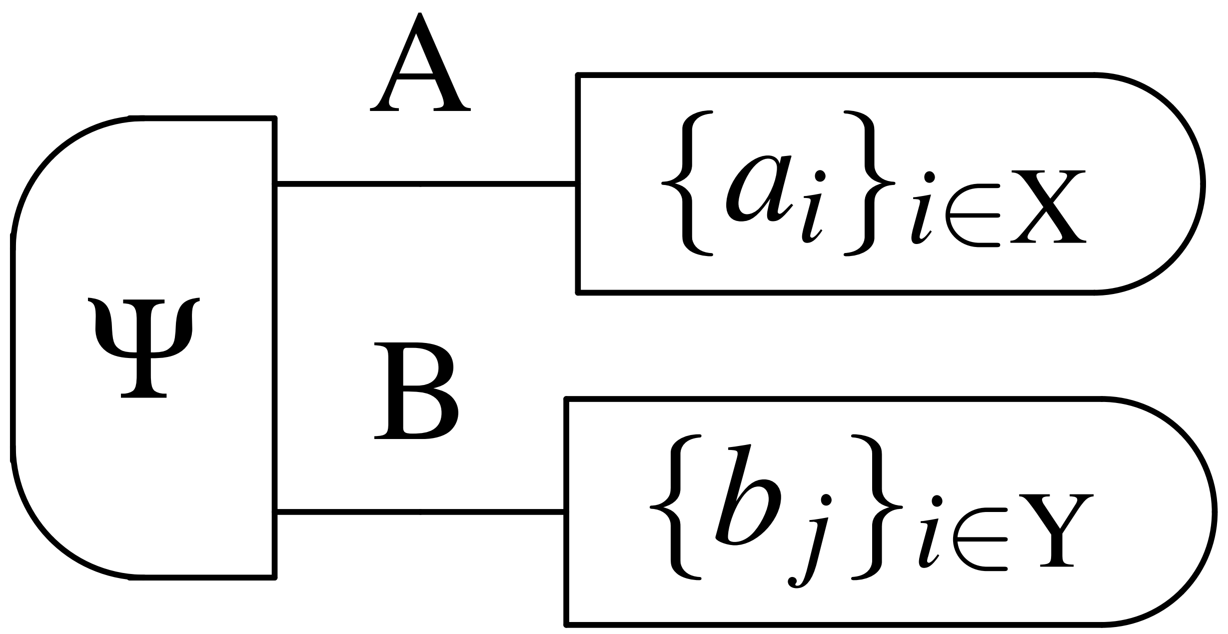
Cognitive science toolbox
Awareness is quantum
Communication and exteriority are classical
Black-box proofs of quantumness via CHSH violation
Creativity

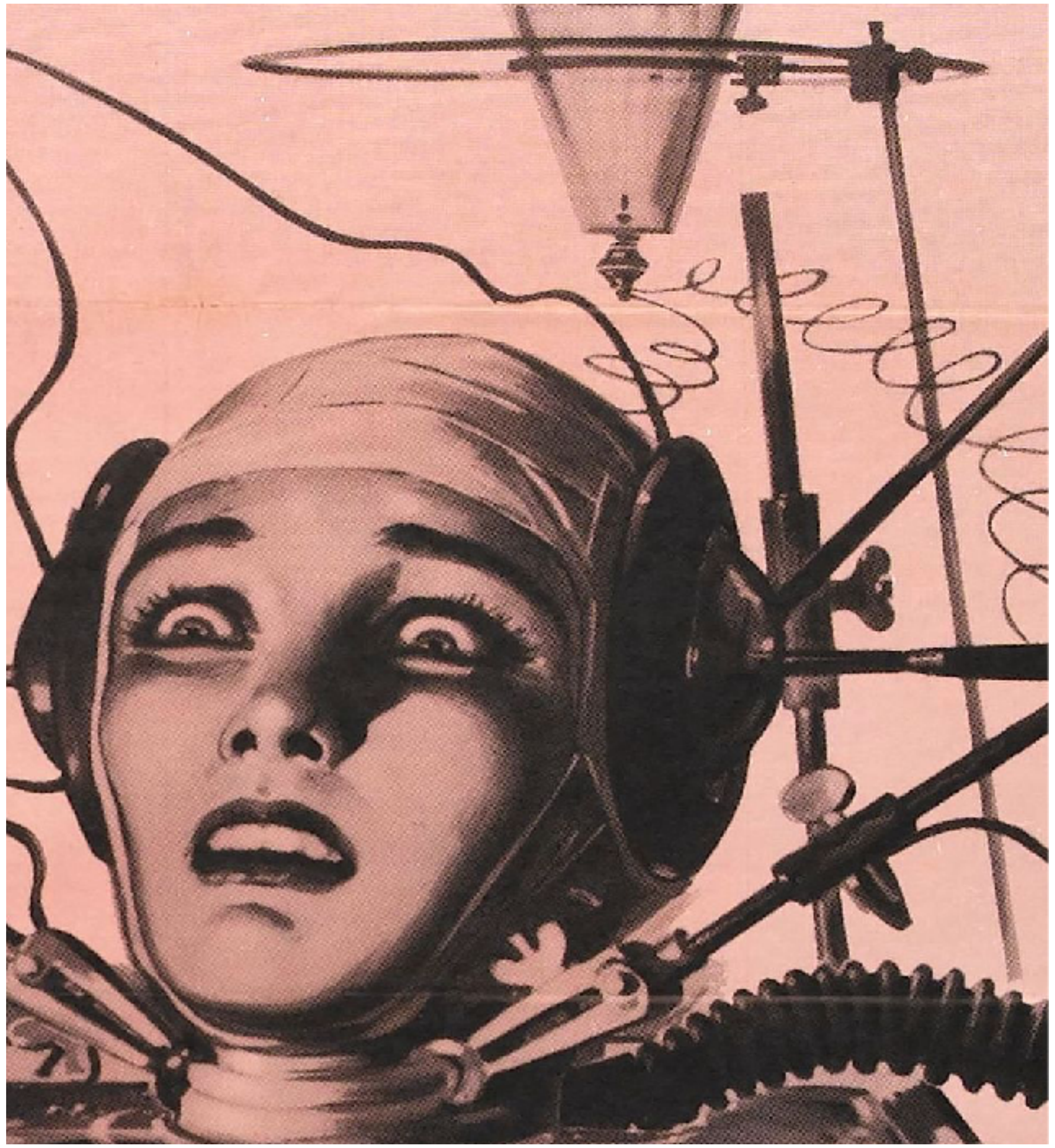
Take home for cognitive scientists

Black-box proof of nonlocality

1. Provide *incompatible observation-tests*—two for system A and two for system B—that can be performed locally (e.g. within 1cm)

2. <u>Prove *quantumness of consciousness through nonlocality*</u>, e.g. violation of CHSH bound upon performing two pairs of incompatible observation-tests locally in two different places (causal disconnection Dt=10^{-9} s for Dx=3 cm)





This is more or less what I wanted to say

Thank you for your attention

QUit quantum information theory group

JOHN TEMPLETON FOUNDATION

INFN Istituto Nazionale di Fisica Nucleare

A Quantum-Digital Universe, Grant ID: 43796

Quantum Causal Structures, Grant ID: 60609

G. Chiribella, G. M. D'Ariano, P. Perinotti, *Informational derivation of Quantum Theory,* Phys. Rev A **84** 012311 (2011)

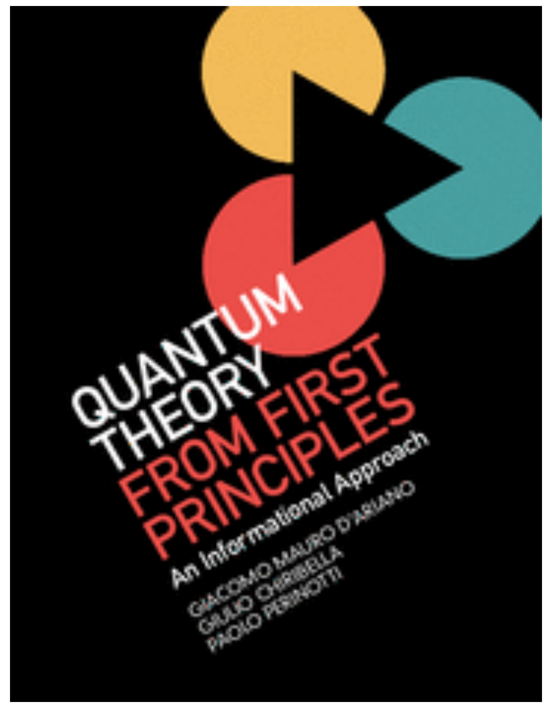
G. M. D'Ariano, P. Perinotti, T*he Dirac Equation from Principles of Information processing,* Phys. Rev. A **90** 062106 (2014)

A. Bisio, G. M. D'Ariano, P. Perinotti, *Quantum Cellular Automaton Theory of Light,* Ann. Phys. **368** 177 (2016)

A. Bisio, G. M. D'Ariano, P. Perinotti, *Special relativity in a discrete quantum universe,* Phys. Rev. A **94** 042120 (2016)

A. Bisio, G. M. D'Ariano, P. Perinotti, A. Tosini, *The Thirring quantum cellular automaton,* Phys. Rev. A **97** 032132 (2018)

Follow **project on Researchgate**: *The algorithmic paradigm: deriving the whole physics from information-theoretical principles.*

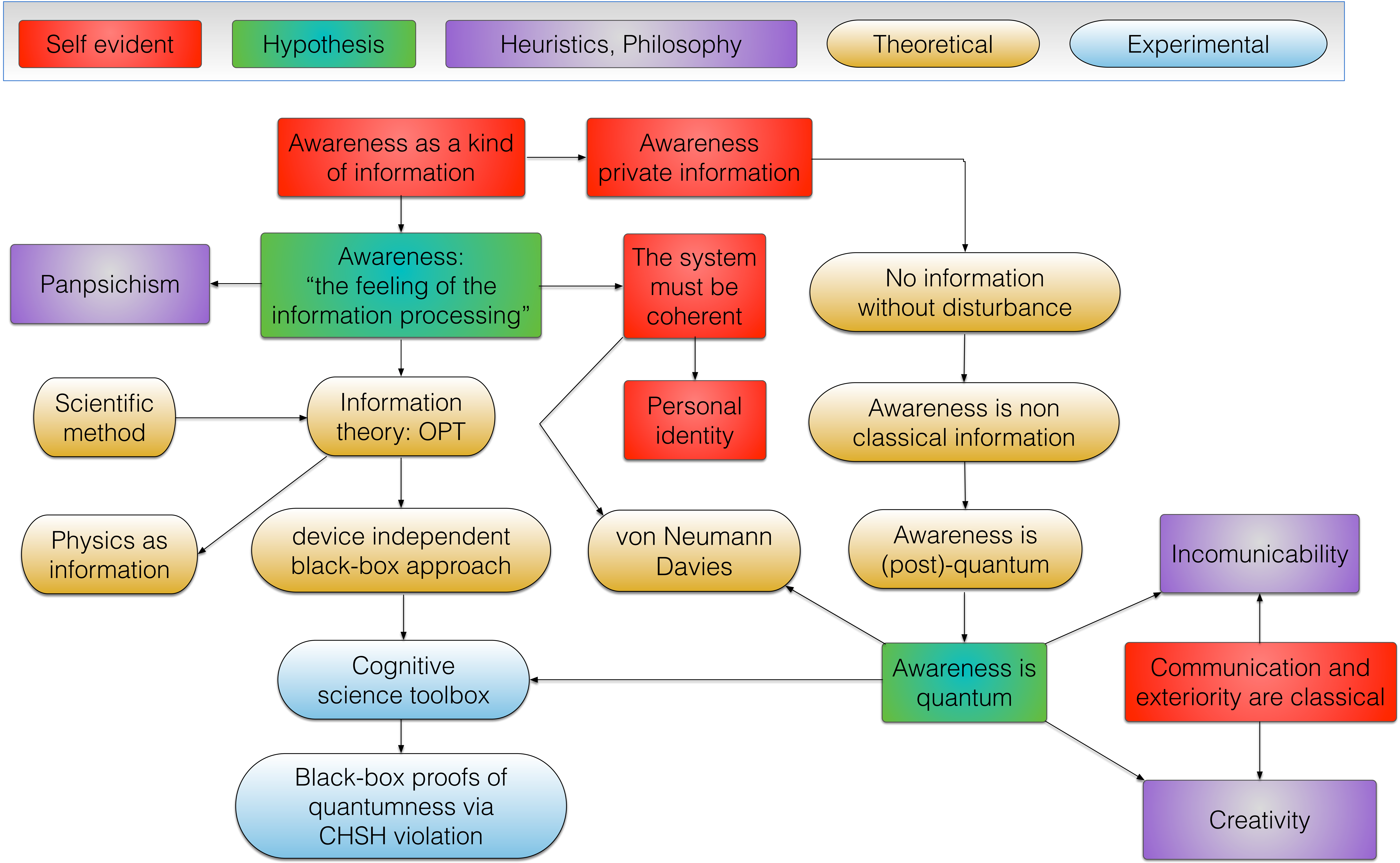


REVIEW

G. M. D'Ariano, *Physics without Physics*, Int. J. Theor. Phys. **128** 56 (2017), [in memoriam of D. Finkelstein]

RELATED TO THIS TALK

G. M. D'Ariano, P. Perinotti, A.Tosini, arXiv:1907.07043: "Information and disturbance in operational probabilistic theories"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