The Open Past in an Indeterministic Physics

Flavio Del Santo

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(with Nicolas Gisin)

IQI Vienna
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
universität wien
BRCP

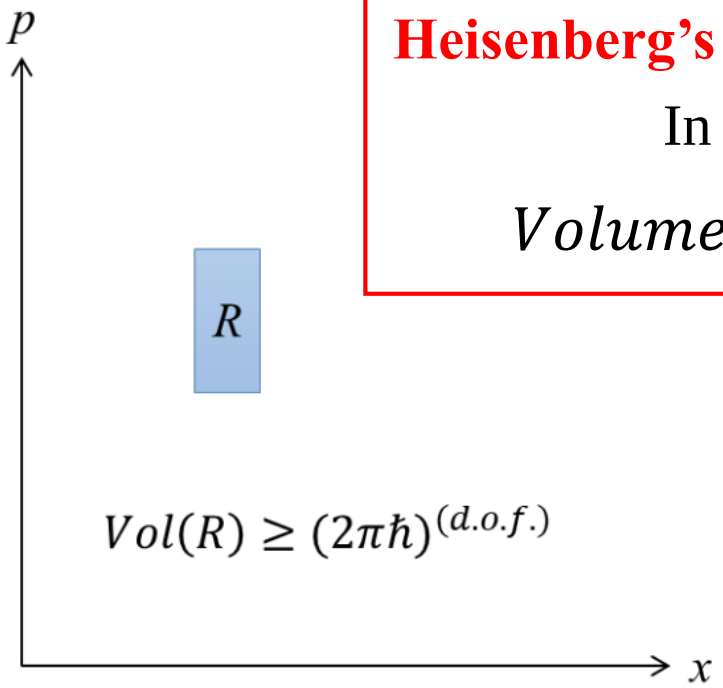
The program: exploring indeterministic physics

Determinism: Laplace and his Demon

"We ought to regard the present state of the universe as the effect of its antecedent state and as the cause of the state that is to follow. An intelligence knowing all the forces acting in nature at a given instant, as well as the momentary positions of all things in the universe, would be able to comprehend in one single formula the motions of the largest bodies as well as the lightest atoms in the world, provided that its intellect were sufficiently powerful to subject all data to analysis; to it nothing would be uncertain, the future as well as the past would be present to its eyes."

(P.-S. Laplace, 1820)

Quantum mechanics: fundamental uncertainty



$Vol(R) \geq (2\pi\hbar)^{(d.o.f.)}$

Heisenberg's uncertainty principle

In phase space:

$$Volume(R) \geq 2\pi\hbar^{(d.o.f.)}$$

$$\Rightarrow \quad N \leq \frac{Volume(R)}{2\pi\hbar^{(d.o.f.)}}$$

Dynamical variables can only take N discrete values within R

Bell's theorem

Quantum indeterminacy cannot be explained away by incompleteness (if one upholds locality)

Two remarks on indeterminism

Remark I: indeterminism as a sufficient condition

Q: How can one explain the observed regularities?

A: Indeterminism is not necessarily "lawless indeterminism" (i.e., total absence of law and regularities).
We define **indeterminism** as the existence of *some* events that are not fully determined by a complete specification of their past state.

*"Indeterminism merely asserts that there exist at least one event (or perhaps, one kind of events […]) which is not predetermined"**

*Popper, K. R. 1950. *The British Journal for the Philosophy of Science*, 1(2), 117-133.

Two remarks on indeterminism

Remark II: all-or-nothing indeterminism

Device independent formulation of Bell's inequalities show that:

- If the inputs (measurement settings) are independent of the state shared by distant parties (an epsilon of initial *measurement independence* suffices)
- Then the outcomes cannot have pre-determined values

Bell's tests performed on quantum entangled states are machines to increase indefinitely the amount of randomness in the universe

Skrzypczyk, P. 2021. Predictably random. *Nat. Phys.*

Is classical physics necessarily deterministic?

	Classical	Quantum
Indeterministic	?	$\|\psi\rangle \in \mathcal{L}^2(\mathbb{R}^N)$ Measurement postulate
Deterministic	IC $\in \mathbb{R}$ Newton's equation	IC (position) $\in \mathbb{R}$ and $\|\psi\rangle \in \mathcal{L}^2(\mathbb{R}^N)$ Bohm's guidance equation Schrödinger's equation
		Many worlds interpretation (?)

Bring classical physics closer to quantum:
what is truly quantum in quantum physics?

Classical Physics and the Principle of infinite precision

"Orthodox"

Principle of infinite precision:

There exists at any instant of time an actual value of every physical quantity, with its infinite, pre-determined digits (in any arbitrary numerical base).

F.D.S. and Gisin, N., 2019. *Physical Review A*, *100*(6), 062107.

Classical Physics and the Principle of infinite precision

"Orthodox"

Principle of infinite precision:

There exists at any instant of time a factual value of every physical quantity, with its infinite, pre-determined digits (in any arbitrary numerical base).

Relaxing this principle opens a new class of alternative, indeterministic interpretations of classical physics

Alternative

Principle of finiteness of information density:

A finite volume of space can only contain a finite amount of information.

F.D.S. and Gisin, N., 2019. *Physical Review A*, *100*(6), 062107.

Challenging the Principle of infinite precision:

Initial conditions are not real numbers (i.e. infinitely precisely determined) + existence of chaotic systems

The existence of infinite, pre-determined digits of initial conditions is regarded as a "hidden-variable" completion of the theory:

> *one could add supplementary variables to […] alternative classical mechanics in order to restore determinism. […] It suffices to add the mathematical real numbers* (Gisin, 2018)

F.D.S. and Gisin, N., 2019. *Physical Review A*, *100*(6), 062107.

Challenging the Principle of infinite precision:

Removing the "hidden variables" (real number) from classical physics:

Definition – Propensity: A propensity is a rational number $q \in [0,1] \subset \mathbb{Q}$, that quantifies the *tendency* of a binary digit to take the value 1.

Definition – FIQ: A finite information quantity (FIQ) by an infinite, ordered string of propensities $\{q_1, q_2, \cdots, q_j, \cdots\}$, such that the total information content is finite (according to some appropriate measure).

Alternative *indeterministic* interpretation of classical physics:

Physical quantities are not described by mathematical (real) numbers, but are characterized by a FIQ

F.D.S. and Gisin, N., 2019. *Physical Review A*, *100*(6), 062107.

Remarks on (my) propensities

1. Propensities are rational numbers s.t. they contain only finite information

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3. They <u>cannot</u> be probabilities (Humphreys' paradox):

Bayes rule: $p(E|C) = p(C|E)\frac{p(E)}{p(C)}$

$+$

Causality: $p(C|E) = p(C)$

$\Rightarrow p(E|C) = p(E)$

Contradiction: the effect cannot causally depend on the cause!

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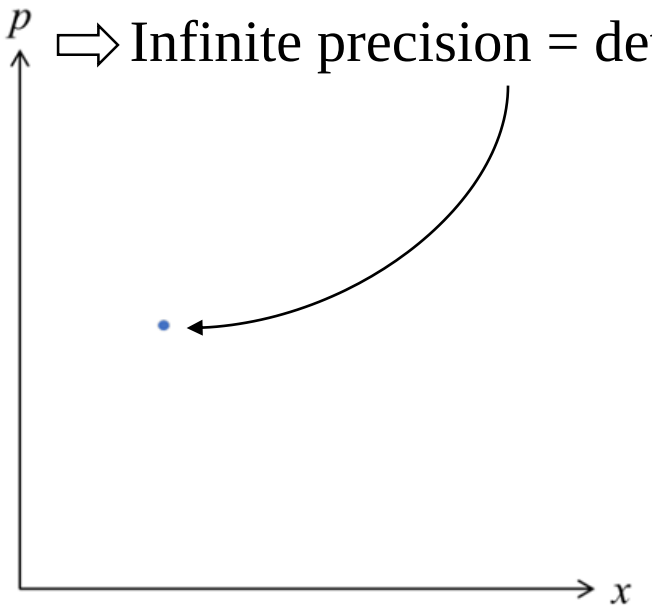
⇨ Propensities are "non-Kolmogorovian" probabilities (Gillies) i.e. they cannot fulfill all the axioms but share a large part of properties of probabilities

Different interpretations of Classical Physics

Real numbers

⇨ Infinite precision = determinism

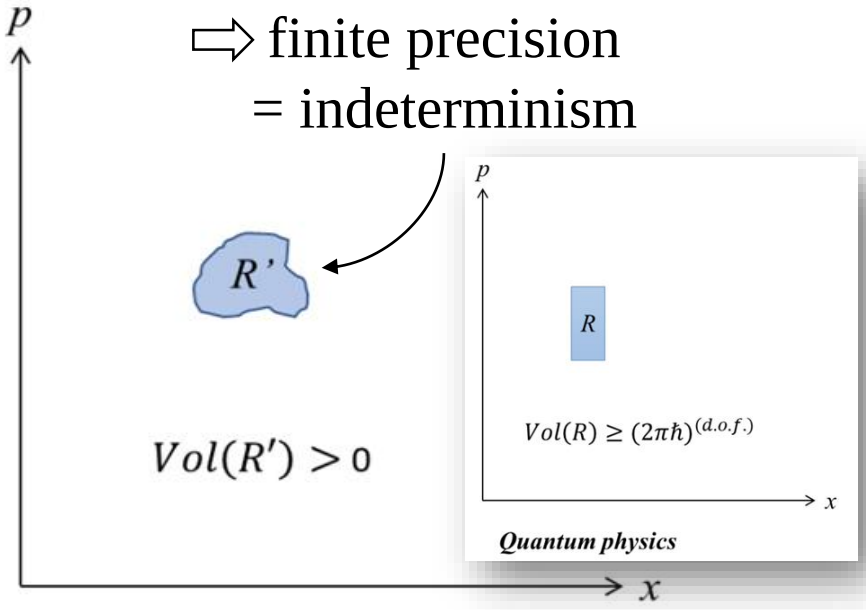


"Orthodox" classical physics

FIQs

⇨ finite precision

= indeterminism



"Alternative" classical physics

F.D.S. 2021. Indeterminism, causality and information: Has physics ever been deterministic?. In *Undecidability, Uncomputability, and Unpredictability* (pp. 63-79). Springer, Cham.

Classical measurement problem?

Tenets of measurement:

- **Stability:** Consecutive measurements of the same quantity leave the significant digits unchanged
- **Intersubjectivity:** Different agents can access the same measurement outcomes
- **Precision improvability:** With more accurate measurement apparata more digits become available (with the previous properties)

Indeterminism

⇩

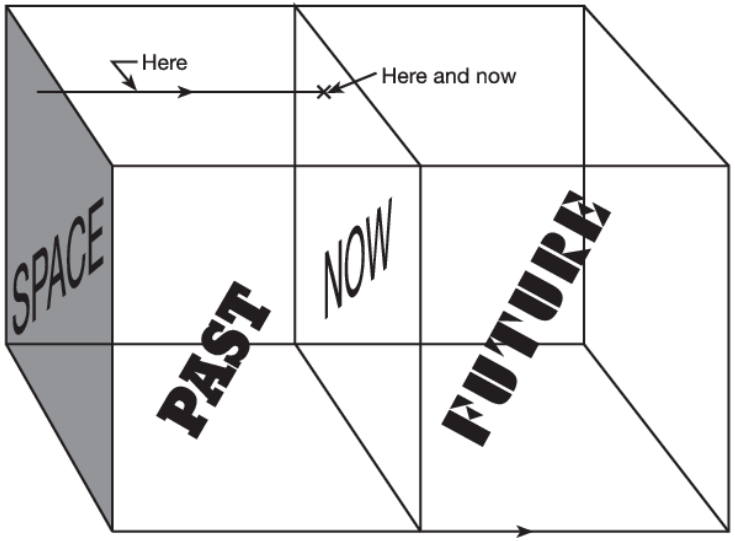
Measurement problem:

When, how and under what circumstances a potential single outcome is realised?

F.D.S. and Gisin, N., 2019. *Physical Review A*, *100*(6), 062107.

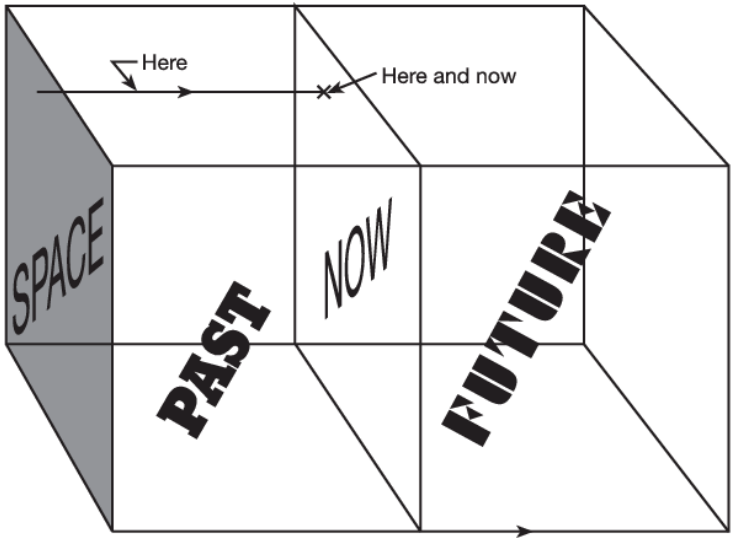
The passage of time

Two views on time



Block-universe picture, wherein space and time are dimensions on an equal footing of a single geometrical space.

Two views on time



TIME

Block-universe picture, wherein space and time are dimensions on an equal footing of a single geometrical space.

j = ?

j = 0

TIME

There is genuine change in the form of new information that gets created, or when potentiality becomes actuality

Ontic indeterminacy and randomness

Definition –
A **True Random Number Generator (TRNG)** is an abstract device that outputs genuinely random bits. Namely, before each bit is output, its value is not only unknown (epistemic uncertainty), but it actually has no determined value (ontic indeterminacy).

Remark on ontic indeterminacy:
Even having complete knowledge of

(i) the *state*, i.e. the values of all the variables that may influence the outcome of the TRNG (in principle everything in the past light cone of the event associated to the generation of the bit), and

(ii) the *dynamical laws* that govern the evolution of each and every of said variables

there is no way to predict with certainty which will be value of the bit output by the TRNG, not even in principle.

Indeterminism implies an open future

Definition – Ontic indeterminacy as (a lack of) truth values:
A proposition such as "the value of the bit j output by the TRNG at time $\bar{t}$ (in a certain reference frame) is j = 0" has a definite truth value, either true or false, only after $\bar{t}$, whereas it was (ontologically) indeterminate before, i.e. its truth value is neither true nor false.

Indeterminism ⇨ **Open future**

"*The future is open. It is not predetermined and thus cannot be predicted –except by accident. The possibilities that lie in the future are infinite*"

(Popper 1994)

Can the past be open?

While the future is open in an indeterministic world, the past is there to stay:

"*the past is factual, the future is possible*"
(von Weizsäcker 1971)

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- **Can also the past be open?**

Łukasiewicz and Dummet: "*only those statements about the past are true whose assertion would be justified in the light of what is now the case. [T]his means that there is no one past history of the world: every possible history compatible with what is now the case stands on an equal footing*." (Dummet 1968)

- **But if the past is also open, why do we observe such an asymmetry in terms of predictions?**

“Propense” causality framework

The **laws of physics** can be generally regarded as causal relations that connect pure states of a system at different instants of time (given a suitable conception of a time-arrow).

Def. **Pure State**:
The state encapsulating the maximal amount of information existing at present about each relevant degree of freedom of the system under consideration.

Def. **Causally related events**:
In the broadest possible sense, two events –named the cause (C) and the effect (E), respectively– are said to be causally related in the case that if C obtains, it influences the tendency for E to obtain. (Note that for this to happen, C must happen before E.)

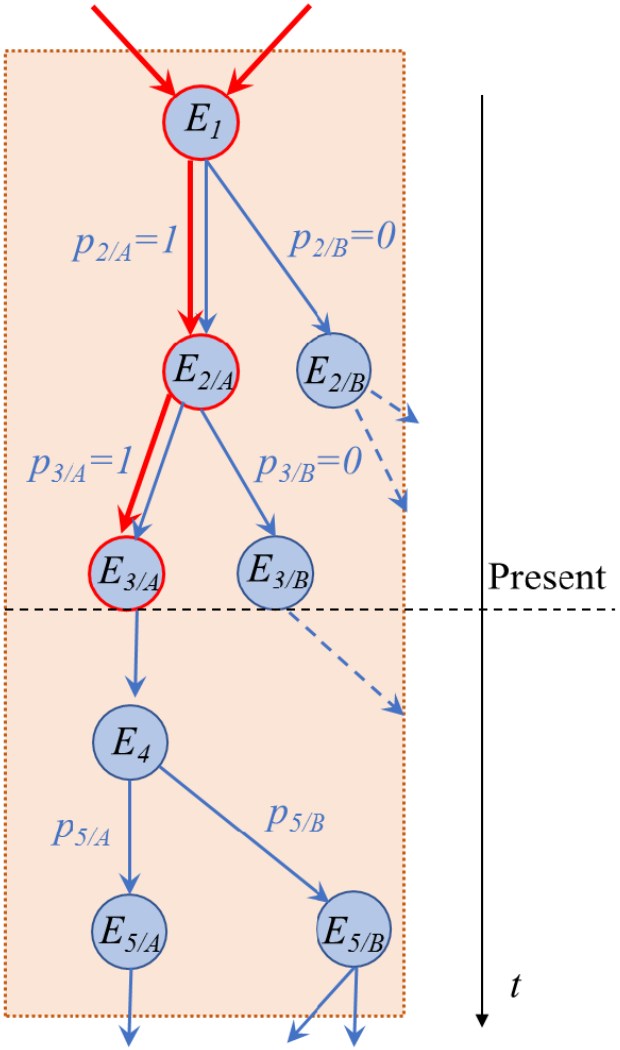
↳ Generalization of the Leibnitzian principle of sufficient reason: “there is nothing without a reason, or no effect without a cause”

“Propense” causality framework

The Framework:
Events that are one the cause of the other are represented as nodes in a directed (because causes precede their effects), acyclic (because an event is never the cause of itself) multigraph with two types of edges:

- Blue: “potential” causal connections, each weighted with the *propensity* that relates two events, i.e. associated with a non-negative rational number such that the sum of the weights connecting a cause to all possible, mutually exclusive events is equal to 1.

- Red: “actual” causal connections, picking only one among the mutually exclusive “potential” causal connections

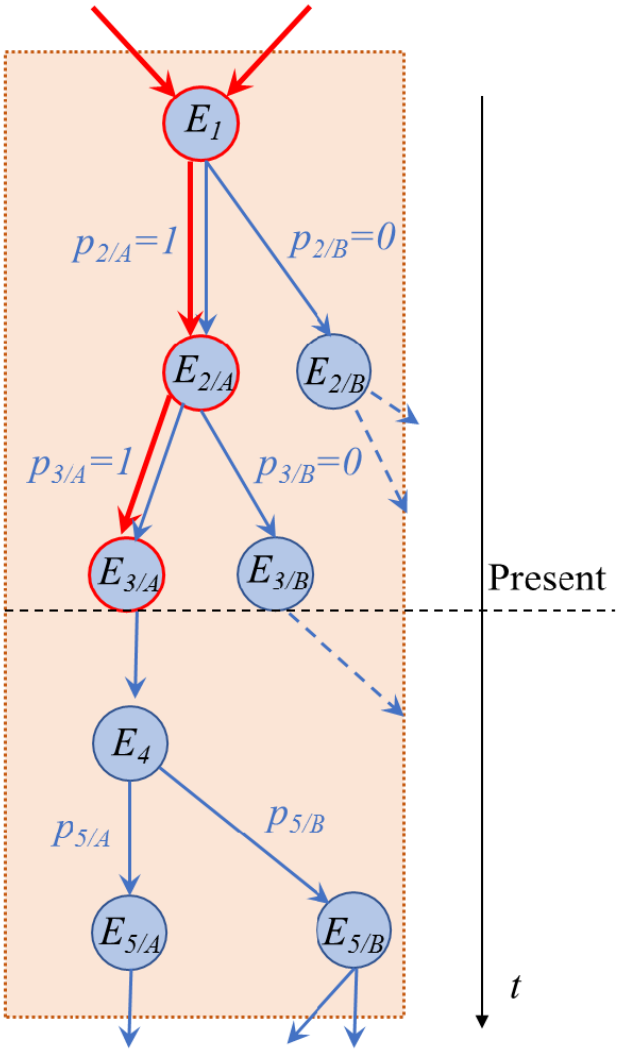


“Propense” causality framework

Formally the multigraph is an ordered collection

$$G(t) : [E(t), \Omega(t), P(t)]$$

E(t) is the set of all events (nodes)
Ω(t) is the set of all potential causal connections (edges)
P(t) is the set of propensities (weights) all at the considered (present) time *t*.



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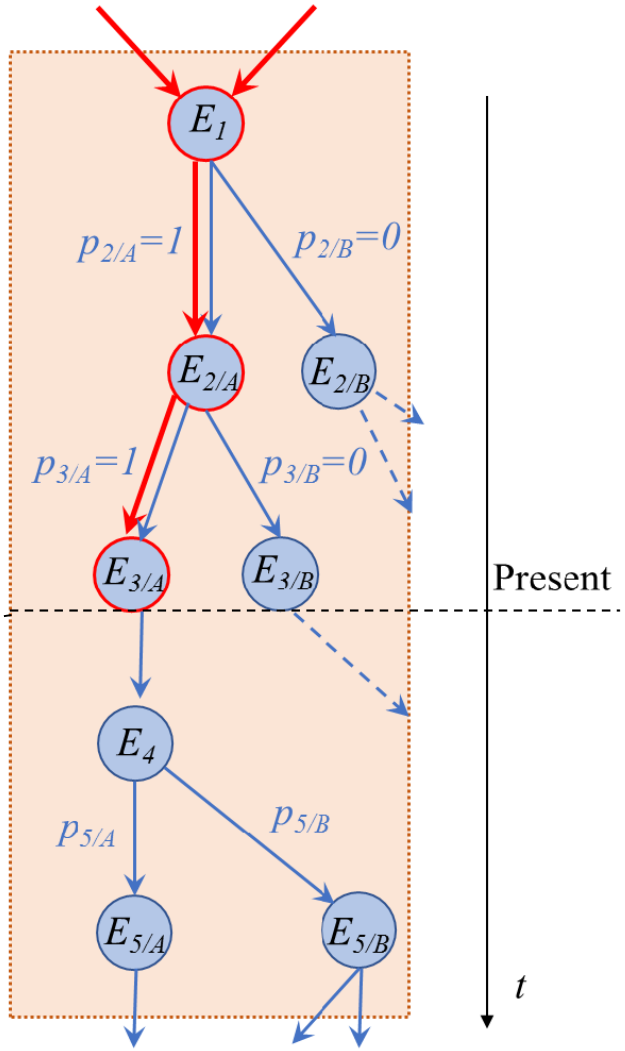


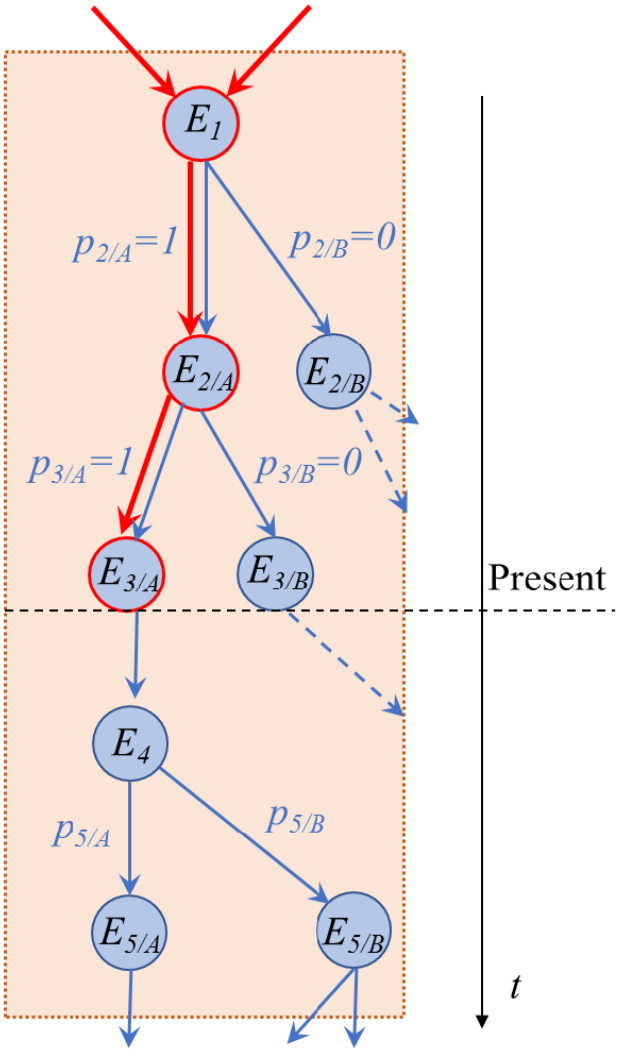
This multigraph implicitly defines the concept of **present**, which is the time slice that separates the subgraph containing exclusively events connected by propensities 0 or 1 (i.e. the past) from the subgraph that contains arbitrary propensities (i.e. the future).

A toymodel of open past with finite information

All the information contained in *G(t)* is stored in some degrees of freedom of the finite universe.

Principle of finiteness of information density:

$$I(G(t)) = I(E(t)) + I(\Omega(t)) + I(P(t)) < \infty$$



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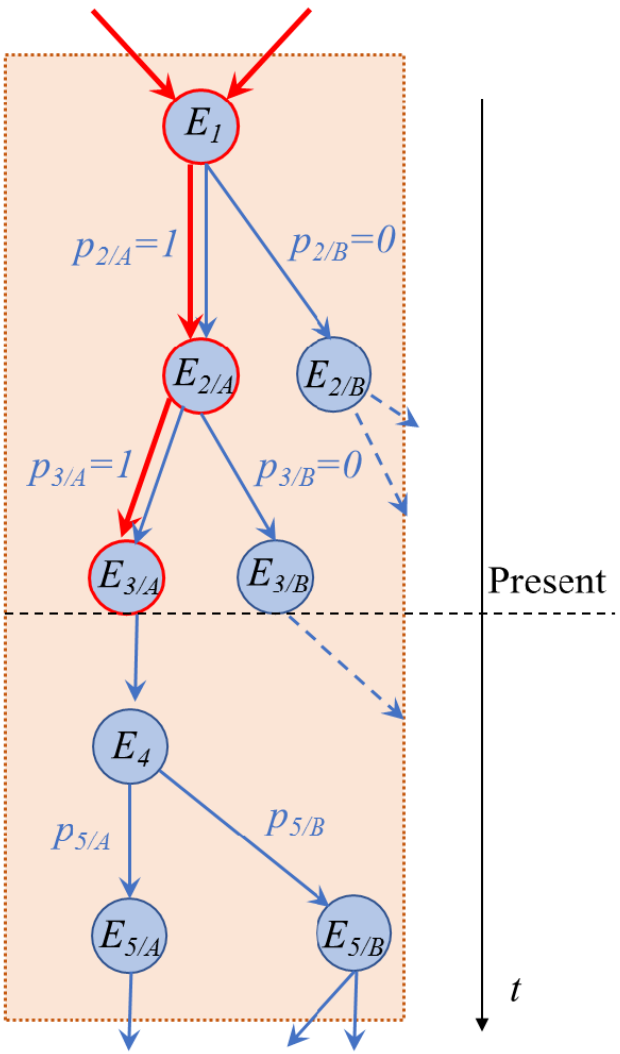
$$I(G(t)) = I(G(t))_{past} + I(G(t))_{fut}$$

Assume the amount of events and causal connections in the past and in the future are roughly the same, but for each 0 or 1 in the past there is an arbitrarily complex (in the sense of Kolmogorov) propensity in the future, s.t.:

$$I(G(t))_{past} < I(G(t))_{fut}$$



A toymodel of open past with finite information

Assume:

(i) The universe is finite, (i.e., finite resources occupying a finite volume of space)

+

the principle of finiteness of information density

⇩

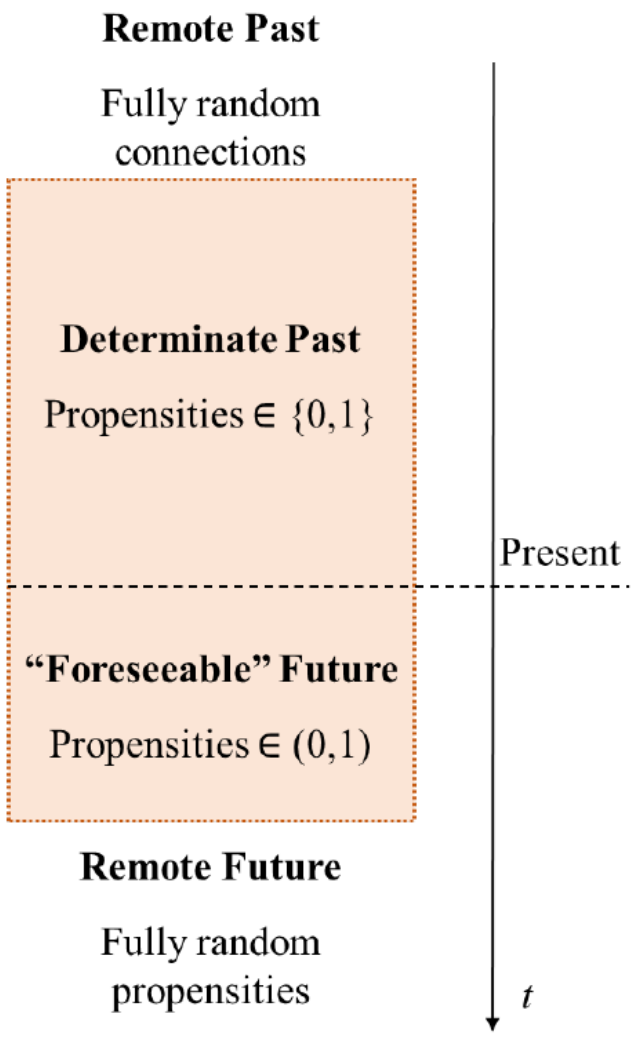
the total amount of information in the universe is also finite. Suppose that this total amount of information storable in the universe is upper bounded by N bits.

(ii) By homogeneity of time, this maximal amount of storable information in the universe is roughly symmetrically centered around the present. Namely, about N/2 bits are used to record information about the past, i.e. $I(G(t))_{past}$, and roughly the other N/2 are recording $I(G(t))_{fut}$.

A toymodel of open past with finite information

(i) The past is open

While time passes the finiteness of the information requires some past information to be erased. Having lost information about the propensities of the past event, it remains only to assign equal weight to the alternative "potential" past events.



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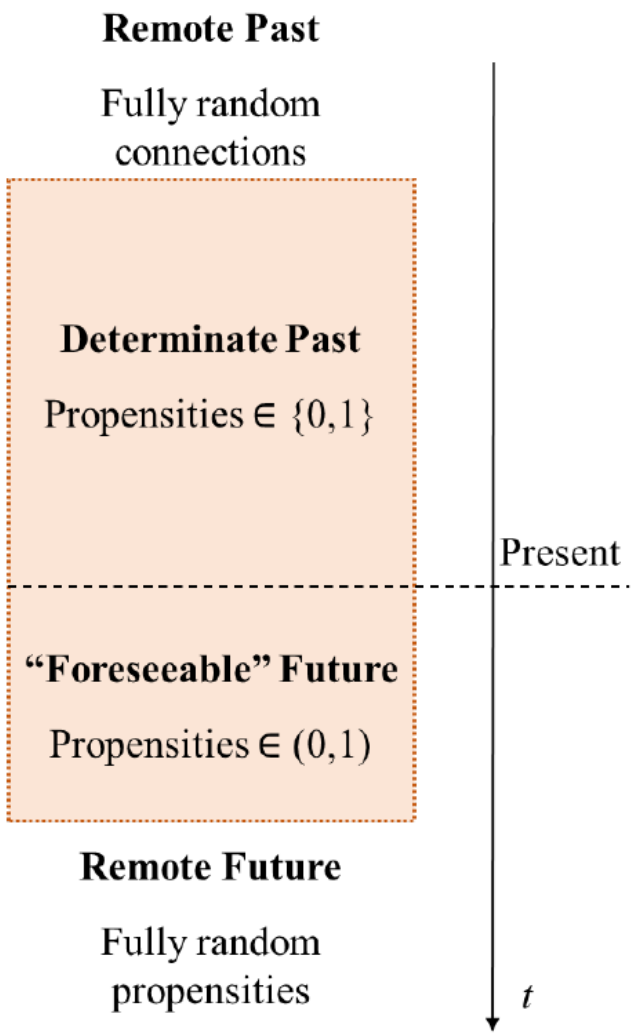
There is (again) ontic indeterminacy in the past: the question "was the event E at time tj caused by the event C at time ti < tj?" is in general neither true nor false (i.e. undecidable) for times ti sufficiently far away in the past



Wheeler: "*The past exists only insofar as it is recorded in the present*"

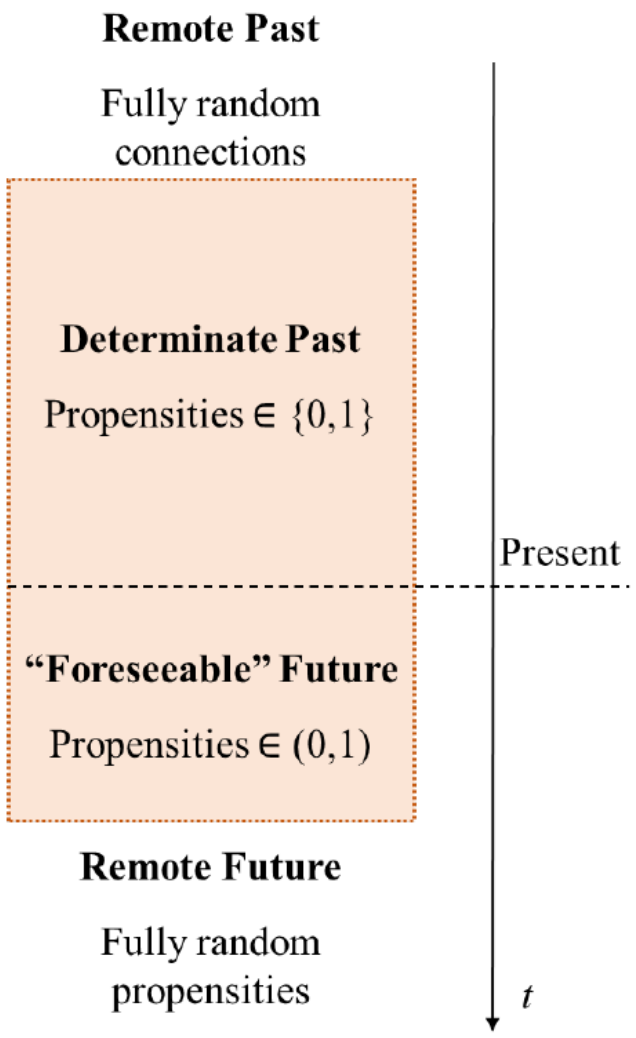
A toymodel of open past with finite information

(i) The past is open

While time passes the finiteness of the information requires some past information to be erased. Having lost information about the propensities of the past event, it remains only to assign equal weight to the alternative "potential" past events.

(ii) We remember more the past than the future

Both the past and the future are thus indeterminate, and yet we can know more about the past and less about the future as our intuition and experience suggest.



The past is the past...

"*Facts that have disappeared altogether, and which even an omniscient mind could not infer from those occurring, belong to the realm of possibility. […] It is well that it should be so. There are moments of suffering and still harder ones of guilt in everyone's life. We should be glad to be able to erase them not only from our memory but also from existence […], when all the effects of those fateful moments are exhausted […] then their causes too will be effaced from the world of actuality and pass into the realm of possibility. Time calms our cares and brings us forgiveness*"

(Łukasiewicz 1946)

Thank you