Title: Time Symmetry in Decoherence and Stable Facts

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Collection: Quantizing Time

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Abstract: It has been previously discussed how events (interactions) in quantum mechanics are time-symmetric and an arrow of time is only due to the arrow of inference in the paper â€œQuantum information and the arrow of timeâ€•, arXiv:2010.05734 by Andrea Di Biagio, Pietro Dona, and Carlo Rovelli. In the relational interpretation of Quantum Mechanics, these interactions are relative facts. Stable facts result from relative facts through the process of decoherence as shown in the paper "Di Biagio, A., Rovelli, C., Foundations of Physics 51, 30 (2021)". They are separate from observed facts in laboratories due to the reason that they do not depend on a decision-making agent for their creation. In my talk, I will discuss my work with Carlo Rovelli and Andrea Di Biagio where we show that the process of decoherence and the notion of stability of facts is indeed time-symmetric. This is in contrast to the observed facts of our everyday world where an arrow of time emerges due to the presence of agents and traces.


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Quantizing Time
Time Symmetry in Decoherence and Stable Facts
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Time Symmetry in Quantum Mechanics

Motivations:

- Quantum Mechanics is Fundamentally Time Symmetric

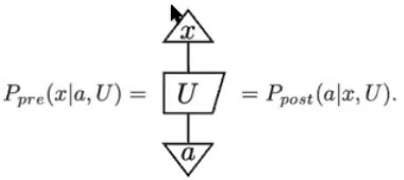


Figure: Pictorial Representation (Di Biagio, A., Dona, P., Rovelli, C. 2020, arXiv:2010.05734)

Postdiction and Prediction have equal probability in a closed system. Time Symmetry for Closed Systems!

Time Symmetry in Quantum Mechanics

Motivations:

- Quantum Mechanics is Fundamentally Time Symmetric
- Emergence of Arrow of Time?
- Time Symmetry in Decoherence
- Asymmetry in our Arrow of Inference from Abundance of Traces!

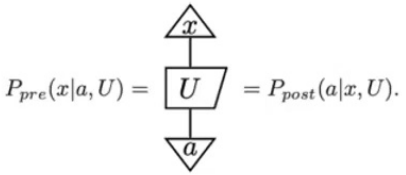


Figure: Pictorial Representation (Di Biagio, A., Dona, P., Rovelli, C. 2020, arXiv:2010.05734)

Postdiction and Prediction have equal probability in a closed system. Time Symmetry for Closed Systems!

Open Quantum Systems

- Input Hilbert Space: $A \otimes B$
- Output Hilbert Space: $X \otimes Y$
- Tracing out the environment gives Identity operator.
- The Normalised Identity is the maximally mixed state.
- The non-normalised Identity is the discard operator.

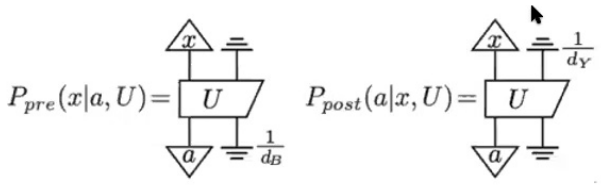


Figure: Pictorial Representation (Di Biagio, A., Dona, P., Rovelli, C. 2020, arXiv:2010.05734)

Time Symmetry Broken??

- Arrow of Time emerging from Asymmetry in Direction of Inference.
- Asymmetry in Information!
- Need for a Perspectival Arrow of Time!

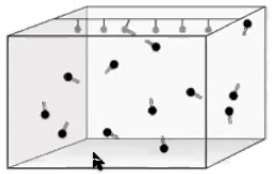
Thermodynamic Model of Memory

- Perspectival Arrow of Time: Direction of increase of entropy depends upon the macroscopic coarse-graining
- Coarse graining is determined by the coupling between subsytems
- Thermodynamic System modelling Memory

Thermodynamic Model for Traces

- Moving Black Balls are Environment, Pendulums initially at rest hold Memory by Collision (Coupling)
- Information created from Increase in Entropy:

$$I \leqslant \Delta S/k = C_m \frac{(T_s - T_m)^2}{kT_s T_m}(1 - e^{-t_m/t_{sm}})$$



Rovelli, C. 2020, arXiv:2003.06687

Relative and Stable Facts

What are Relative Facts and Stable Facts?

- In the Relational Interpretation of Quantum Mechanics, relative facts occur at every interaction.
- Stable facts are subset of relative facts, where the interference can be approximately neglected. Fact relative to F becomes true for W, without W interacting with F. (Di Biagio, A., Rovelli, C., Foundations of Physics 51, 30 (2021))
- Probability of event b given probabilities of a: $P(b^W) = \sum_i P(b^W|a_i^F)P(a_i^F)$. (Stability condition)
- Stable facts emerge from relative facts through the process of decoherence.
- Stability is relational- Depends upon Coupling between systems

Time Symmetry in Decoherence

- Previous works discuss that the process of decoherence requires an increase of entropy.
- Introduces an irreversible arrow of time in laboratory measurements?
- Unlike Relative facts, Stable facts are time-oriented?

Three systems W, F and S

- Qubits F and S describe physics relative to W.
- When W does not interact with F-S, these two evolve unitarily (with respect to W).
- $U((n+1)\Delta t, n\Delta t)$ = Control-Unitary(CU) = $|0\rangle\langle 0| \otimes \mathbb{1} + |1\rangle\langle 1| \otimes U(2)$
- In RQM, the Z observable of S becomes a fact relative to F after Δt intervals.

Time Symmetry in Decoherence

Three systems W, F and S

- W interacts with S at t=0 in a way that makes the spin of the qubit S along some arbitrary direction a fact for W. W assigns the state $a|0\rangle + b|1\rangle$ to S at $t = 0$.
- W never interacts with F. At t=0, W assigns for F the normalised thermal state diag $(p, 1-p)$.

State of system S after time interval Δt:

$$\begin{aligned}\mathrm{tr}_F\left(\rho(\Delta T)\right) = &|a|^2 |0\rangle\langle 0| + |b|^2 |1\rangle\langle 1| \\ &+ ab^\dagger e^{-i\theta}\left(pc^\dagger + (1-p)c\right)|0\rangle\langle 1| \\ &+ ba^\dagger e^{i\theta}\left(pc + (1-p)c^\dagger\right)|1\rangle\langle 0|\end{aligned}$$

For facts to become stable after Δt, $pc^\dagger + (1-p)c = 0$.

Time Symmetry in Decoherence

For time reversal, evolved state of system S at $-\Delta t$,

$$\mathrm{tr}_F(\rho(-\Delta t)) = |a|^2 |0\rangle\langle 0| + |b|^2 |1\rangle\langle 1|$$
$$+ab^\dagger e^{i\theta}\left(pc+(1-p)c^\dagger\right)|0\rangle\langle 1| + ba^\dagger e^{-i\theta}\left(pc^\dagger+(1-p)c\right)|1\rangle\langle 0|.$$

For facts to be stable after $-\Delta t$, $pc^\dagger + (1-p)c = 0$.

No Arrow of Time needed for Decoherence!

- When decoherence happens forward in time it also happens backward in time. Time Symmetry!
- For decoherence, we can replace prediction probabilities by postdiction probabilities.
- Stability of facts does not rely on whether we are predicting or postdicting.

A Quantum Mechanical Model of Traces

- Asymmetry in Arrow of inference emerges in Laboratories from Abundance of Traces.
- Future events predicted using Born's rule.
- Past events recorded in form of traces.
- New notion of traces: Simple quantum mechanical model for this reduction of uncertainty.

System S and Register R

- At t1, S and R projected on computational basis.
- S-R evolved from t1 to t2.
- S evolves under a unitary operation.
- At t2, S and R projected again on computational basis.
- To know with certainty the state at t1 of S, from information available at t2 (trace).

A Quantum Mechanical Model of Traces

- We use the fundamental entangling gate CNOT to evolve S-R.
- CNOT $|\psi 0\rangle = |U(\psi)\psi\rangle$
  CNOT $|\psi 1\rangle = |U(\psi)\overline{\psi}\rangle$
- Cannot know with certainty initial state of S, without knowing initial state of R.
- To know initial state of R, correlation with a second register and so on
- Results in infinite regression

Figure: Quantum Circuit operating on $S \otimes R$

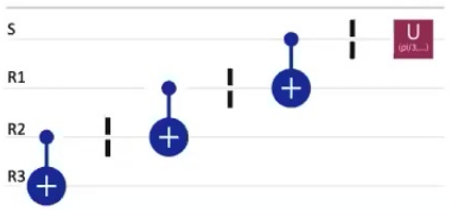
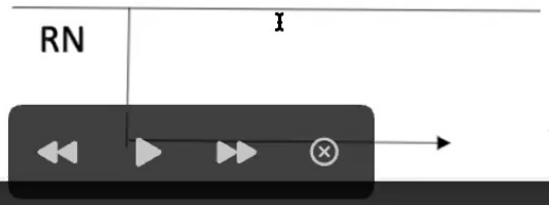


Figure: Quantum Circuit operating on $S \otimes R1 \otimes R2 \otimes R3$

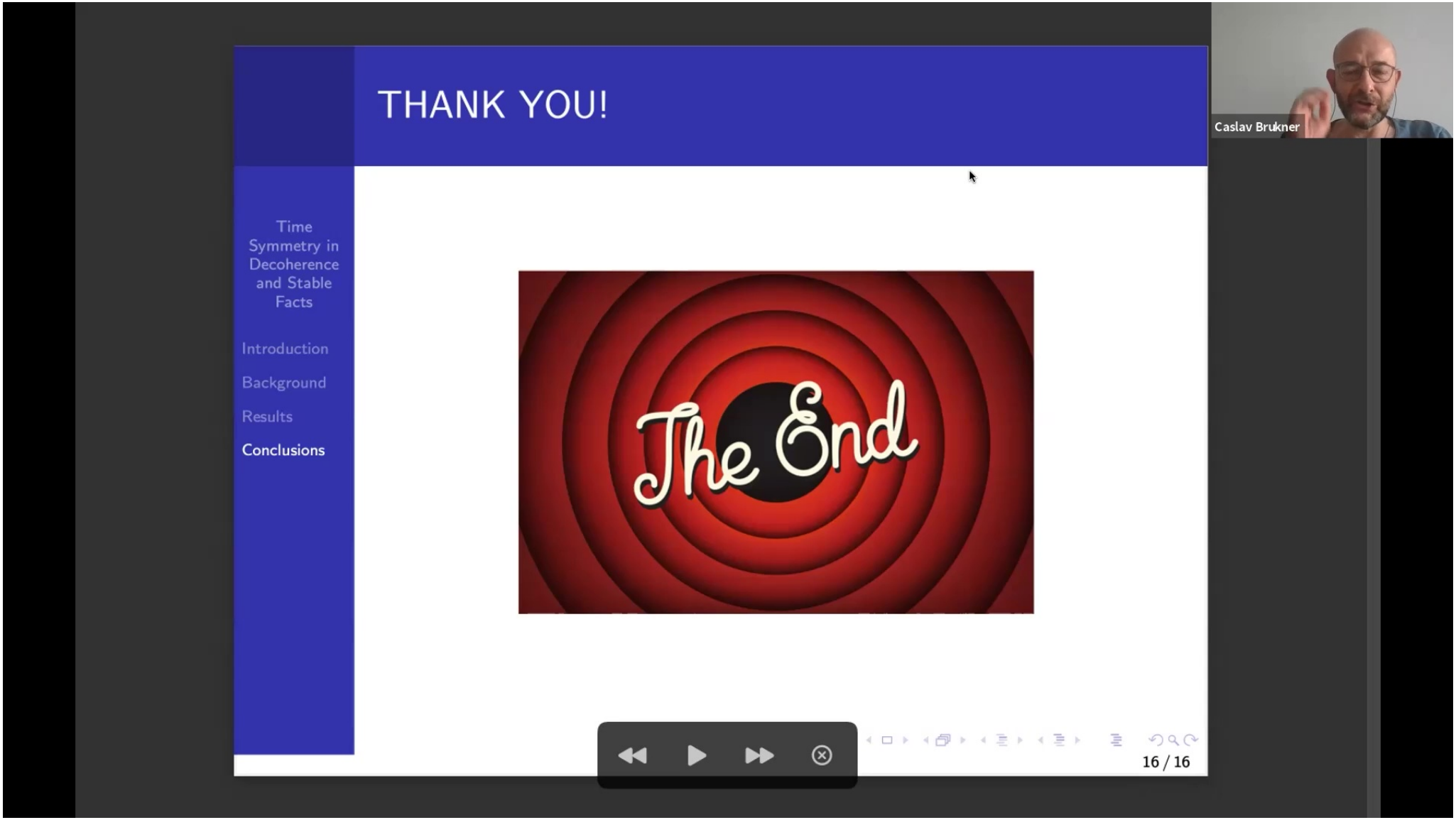
A Quantum Mechanical Model of Traces

- Infinite regression will be broken by adding an irreversible circuit component.
- Irreversible classical gate can always be "purified" into an equivalence class of reversible quantum gates and extra qubits.
- Simplest classical circuit component: For Nth register RN, irreversible operation of using same input twice.
- No longer need to know about the initial state of register $R(N+1)$. Infinite regression breaks!
- Coarse-graining of quantum correlations (microstates) between the registers RN and $R(N+1)$ in the quantum circuit.Loss of information! Increase in entropy!



Conclusions

- Two Different Notions of Coarse Graining-Decoherence and Traces
- Time symmetry in Decoherence and Stable Facts
- Simple Quantum mechanical model of traces for reduction of uncertainty-found in one time direction (Irreversibility)
- Novel information in traces from loss of information-Increase in entropy.


THANK YOU!
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The End
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