Title: When Causality Is Relaxed: Classical Correlations, Computation, and Time Travel

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Abstract: Following Stefan Wolfâ€™s talk, we address the doubts expressed on fundamental space-time causality. Usually it is assumed that causal structures represent a definite partial ordering of events. By relaxing that notion one risks problems of logical nature. Yet, as we show, there exists a logically consistent world beyond the causal, even in the classical realm where quantum theory is not invoked. We explore the classical correlations within and the computational limits of that world. It turns out that relaxing causality in that fashion does not allow for efficient computation of NP-hard problems. These results are related to closed time-like curves: Contrary to previous models of time travel, which necessitate quantum theory and violate the NP-hardness assumption, we obtain a computationally tame model for classical and reversible time travel where freedom of choice is unrestricted.

When Causality is Relaxed:

Classical Correlations, Computation, and Time Travel

Ämin Baumeler (IQOQI, Vienna)
with great support by many

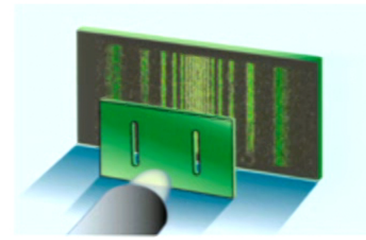
Algorithmic Information, Induction and Observers in Physics
PI
9. April 2018

Background image: M.C. Escher, „*Drawing Hands,*" (Lithograph, 1948)

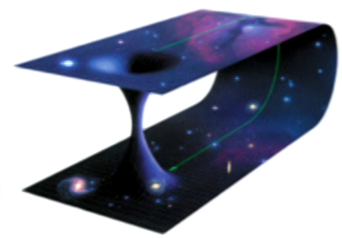

Explaining Correlations in a Causal Structure
The law of causality is a relic of a bygone age, surviving, like the monarchy, only because it is erroneously supposed to do no harm
Bertrand Russell
1913
Drop the Causal Structure?
1956
Hans Reichenbach

Motivations for Relaxing Causality

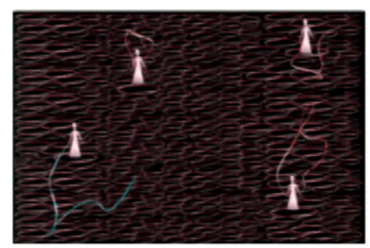
(1) Quantum theory
Quantum superpositions
Bell correlations



(2) Relativity theory
Closed time-like curves (CTCs)
e.g., Lanczos (1924), Gödel (1949), Thorne (1988)



(3) Quantum gravity
GR: dynamic causal structure & deterministic
QT: fixed causal structure & probabilistic

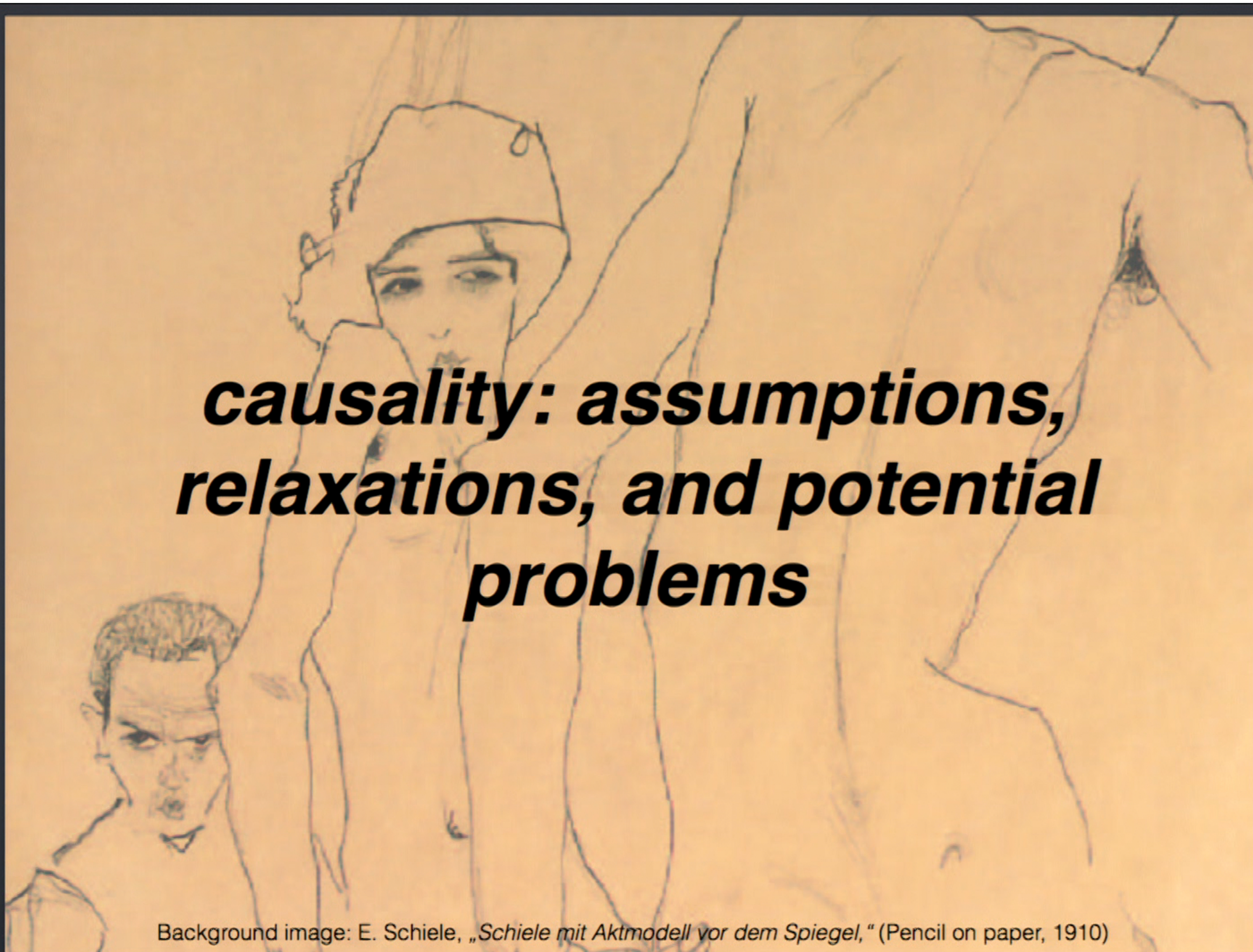


L. Hardy, *arXiv:0509120 [gr-qc]* (2005);
Images: A. Albrecht, *Nature* **412**, 687 (2011); A. Jaffe, *Nature* **537**, 616 (2016); A. Ashtekar, *Nature Physics* **2**, 725 (2006)

Outline

- Motivations
- Causality: assumptions, relaxations, and potential problems
- Classical non-causal correlations
- Non-causal computation
- Time travel
- Conclusion

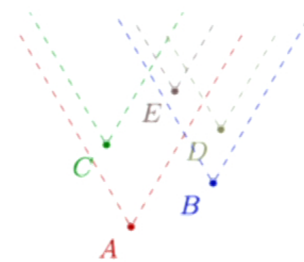
causality: assumptions, relaxations, and potential problems



Background image: E. Schiele, *„Schiele mit Aktmodell vor dem Spiegel,“* (Pencil on paper, 1910)

Causal Structures

- *Cause-effect* relations
  When I click on this little button *(cause)* you will see the next slide *(effect)*



- Relativity theory: light-cone structure*
- Modeled as *directed acyclic* graph

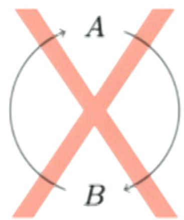
* with *postulated* arrow of time

- Traditionally: *definite partial ordering* of events

  Based on intuition, observations; we are used to that

- Partial ordering: no causal loops

  An effect cannot be the cause of the effect's cause (antisymmetric)



- Definite: predetermined, independent of observer

  Fixed causal relations, *e.g.*, no quantum superpositions

$$\frac{1}{\sqrt{2}}|\text{A before B}\rangle + \frac{1}{\sqrt{2}}|\text{A after B}\rangle$$

Relaxing Causality

- Drop assumption: *definite partial ordering* of events

- Keep:
  - Local assumptions
    In accordance with local observations
  - Logical consistency ⚠

Antinomies

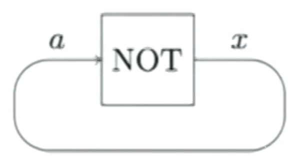
- Grandfather antinomy
  Overdetermination
  An effect suppresses its own cause

- Information antinomy
  Underdetermination
  Multiple effects confirm their own causes, yet the theory fails to predict with what probability which cause-effect pair will take place

Grandfather Antinomy

- Travel to the past and prevent the younger self from traveling to the past

- Overdetermination (contradiction):
  x=f(a),
  a=g(x),
  no pair *a,x* satisfies both equations



$$x = \neg a$$

$$a = x$$

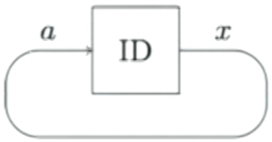
Information Antinomy

Also known as Bootstrap Antinomy

- One morning you find a book on your table, publish it, win the Fields Medal, then you travel back in time to place the book on the table.

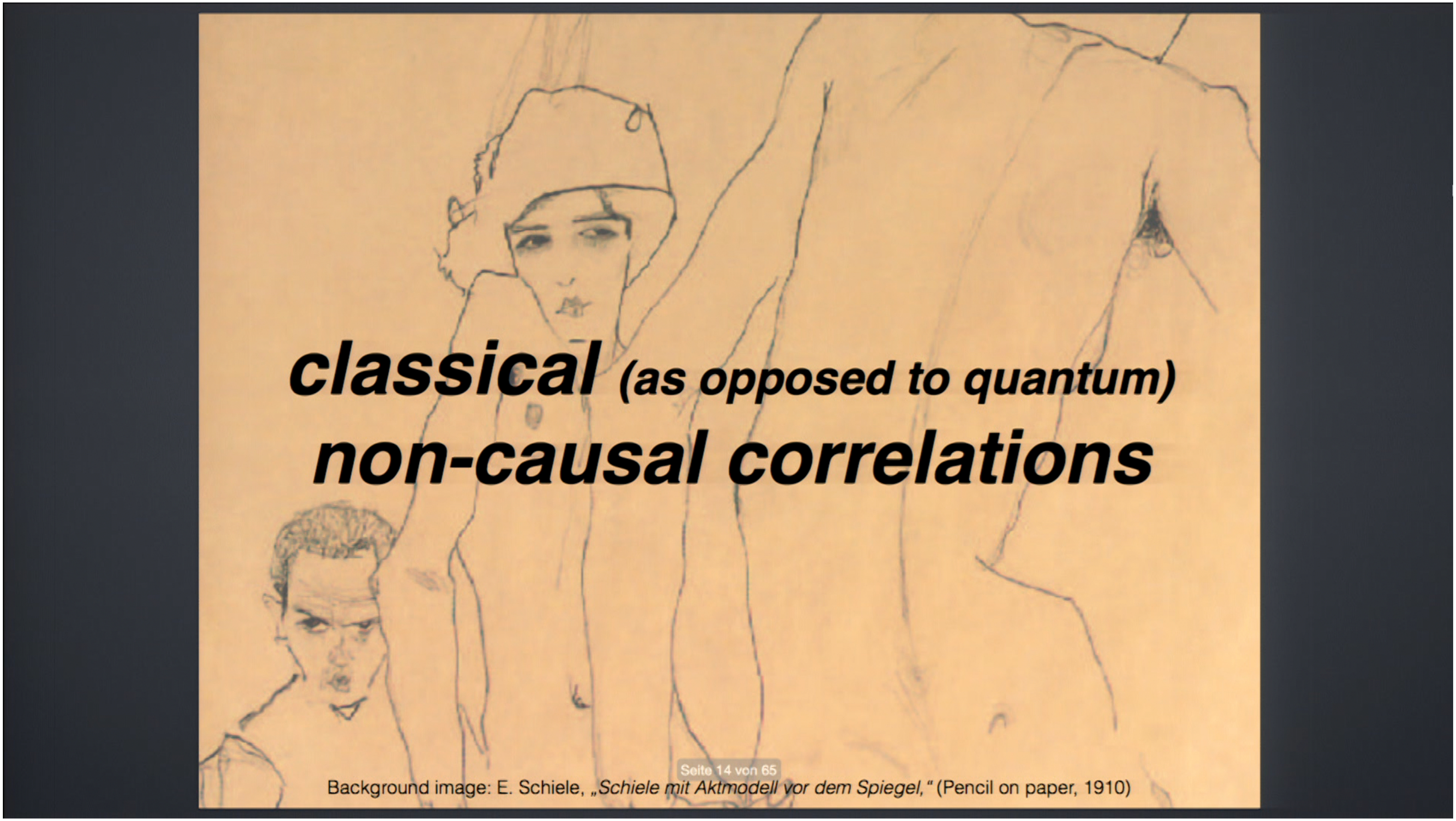
  This is *creationism*.

- Underdetermination:
  x=f'(a)
  a=g'(x)
  multiple pairs *a,x* satisfy both equations



$$x = a$$
$$a = x$$

D. Deutsch, *Physical Review D* **44**, 3197 (1991)


classical (as opposed to quantum)
non-causal correlations
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Background image: E. Schiele, „Schiele mit Aktmodell vor dem Spiegel," (Pencil on paper, 1910)

Process-Matrix Framework

ARTICLE

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DOI: 10.1038/ncomms2076

Quantum correlations with no causal order

Ognyan Oreshkov[1,2], Fabio Costa[1] & Časlav Brukner[1,3]

- Drop assumption: *definite partial ordering* of events

  - Local assumptions only

    In accordance with local observations

  - Logical consistency

O. Oreshkov, F. Costa, Č. Brukner, *Nature Communications* **3**, 1092 (2012)

Classical Non-Causal Correlations

Assumptions

(1) Parties interact with random variables (not quantum)
Each party interacts once
A party is described by a stochastic operation

(2) Parties are isolated
Multiple parties: set of stochastic operations

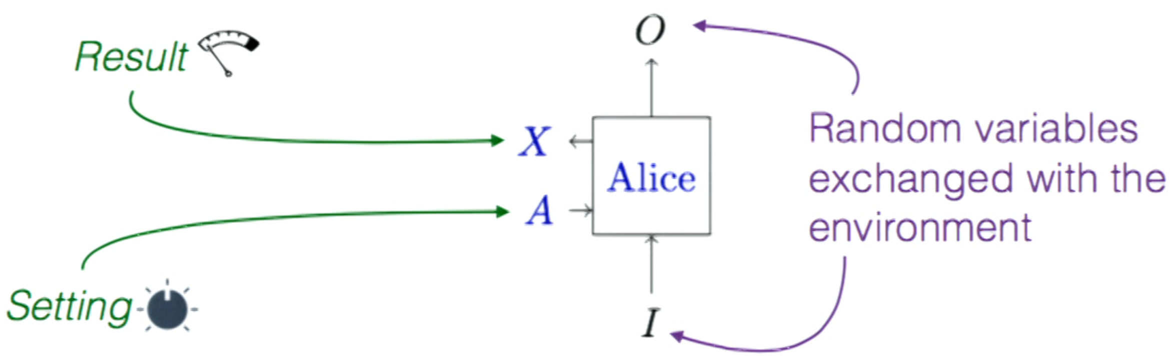
(3) Logical consistency
Probabilities are linear in the choice of operation

Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016)

Classical Non-Causal Correlations

Assumptions

- Parties interact with random variables (as opposed to quantum systems)
  A party is described by a stochastic operation $P_{X,O|A,I} =: L$



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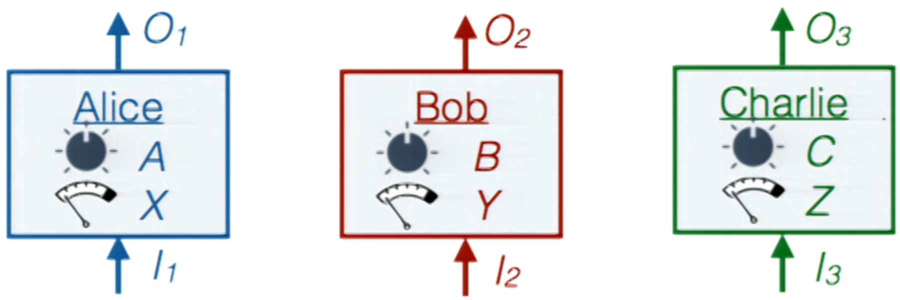
Classical Non-Causal Correlations

Assumptions

- Parties are isolated
  Multiple parties: set of stochastic operations

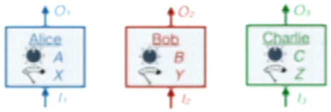


$$\{\underbrace{P_{X,O_1|A,I_1}}_{L_1}, \underbrace{P_{Y,O_2|B,I_2}}_{L_2}, \underbrace{P_{Z,O_3|C,I_3}}_{L_3}, \dots\}$$

Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016)

Classical Non-Causal Correlations

Assumptions



- Logical consistency

  Probabilities are linear in the choice of local operations

$$\forall L_1, L_2, L_3, \cdots : f(L_1, L_2, L_3, \ldots) \text{ is a probability distribution}$$

Local operations (stochastic)

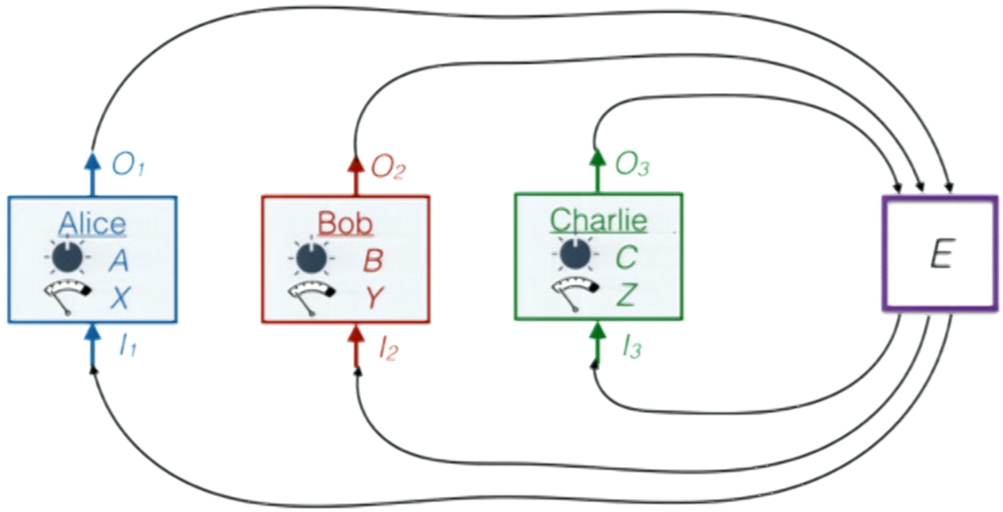
$$P_{X,Y,Z,\cdots|A,B,C,\ldots} = f(L_1, L_2, L_3, \ldots)$$

Linear in choice of local operations

Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016)

Classical Non-Causal Correlations

Theorem



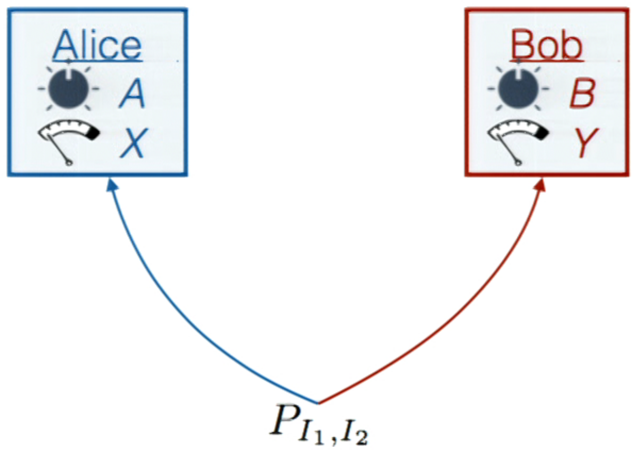
$$P_{X,Y,Z|A,B,C} = \sum_{\substack{i_1,i_2,i_3 \\ o_1,o_2,o_3}} P_{X,O_1|A,I_1} P_{Y,O_2|B,I_2} P_{Z,O_3|B,I_3} \underbrace{P_{I_1,I_2,I_3|O_1,O_2,O_3}}_{E}$$

$E = P_{I_1,I_2,I_3,\cdots|O_1,O_2,O_3,\ldots}$ with some restrictions

Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016)

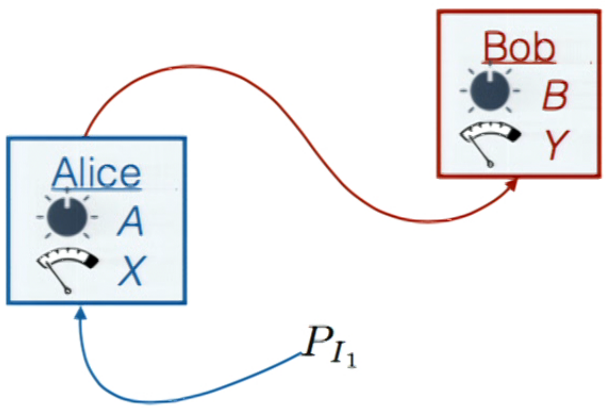
Examples

- <u>Shared State:</u>

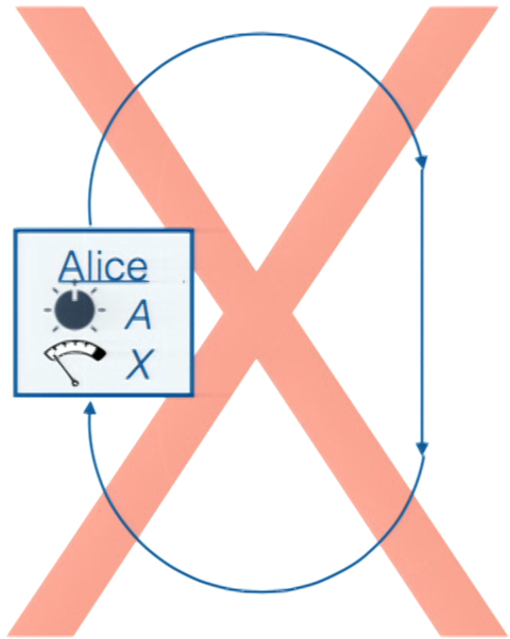


Examples

- Channel:

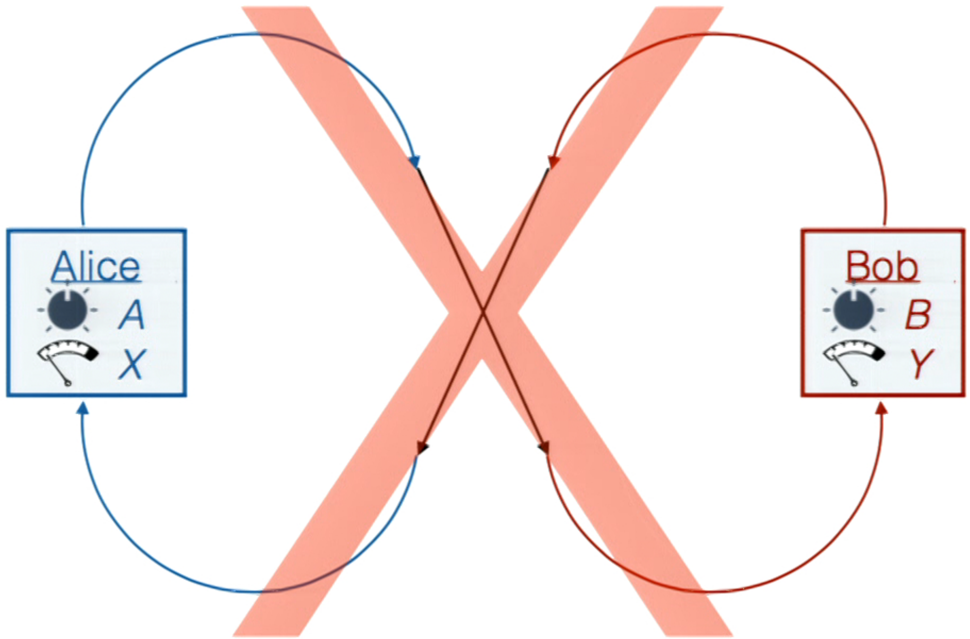


Classical Non-Causal Correlations



O. Oreshkov, F. Costa, Č. Brukner, *Nature Communications* **3**, 1092 (2012)

Classical Non-Causal Correlations



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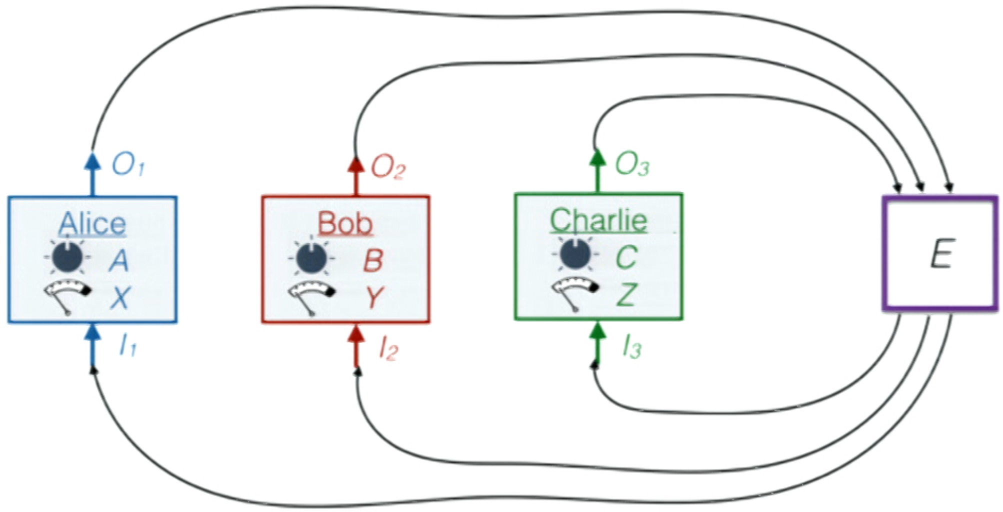
Classical Non-Causal Correlations

What else is possible?



$$P_{X,Y,Z|A,B,C} = \sum_{\substack{i_1,i_2,i_3\\o_1,o_2,o_3}} P_{X,O_1|A,I_1} P_{Y,O_2|B,I_2} P_{Z,O_3|B,I_3} \underbrace{P_{I_1,I_2,I_3|O_1,O_2,O_3}}_{E}$$

$$E = P_{I_1,I_2,I_3,\cdots|O_1,O_2,O_3,\ldots}$$

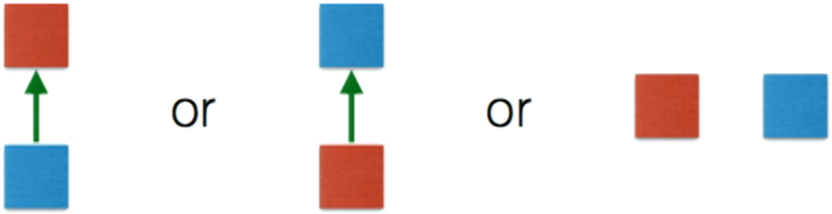
with some restrictions

Causal Correlations

- Correlations among parties $P_{X,Y|A,B}$

- **Definition (Causal Correlations):**
  Correlations obtainable from a predefined partial ordering of the parties

- For two parties:



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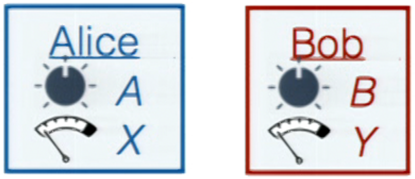
Causal Correlations

- Correlations among parties $P_{X,Y|A,B}$



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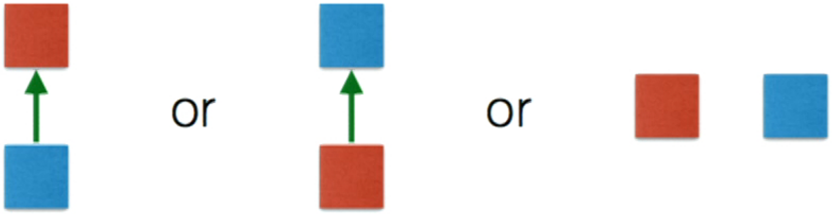
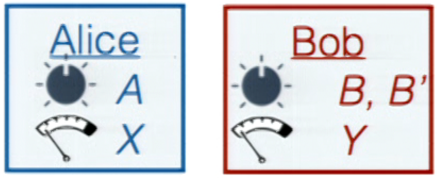


$$P_{X,Y|A,B} = pP_{X|A}P_{Y|A,B,X} + (1-p)P_{X|A,B,Y}P_{Y|B}$$

O. Oreshkov, F. Costa, Č. Brukner, *Nature Communications* **3**, 1092 (2012)

Causal Inequalities

- Inequalities satisfied by all causal correlations
- Example:



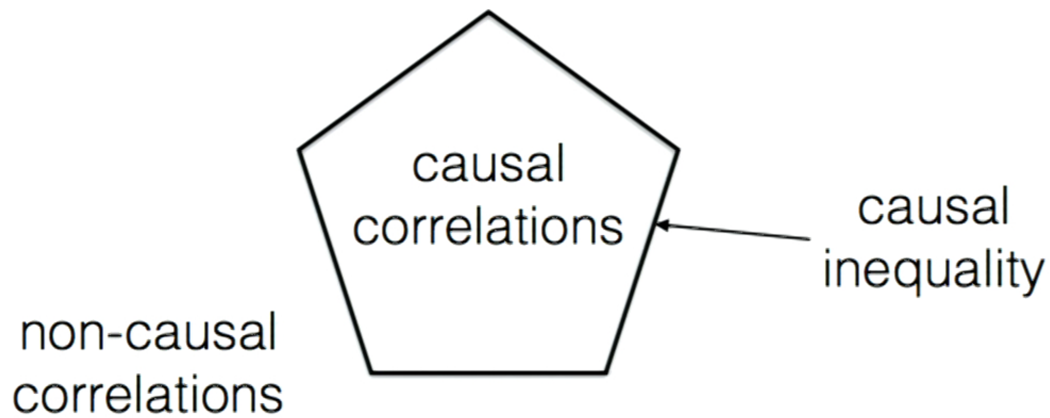
$$\frac{1}{2}\Pr(X = B \mid B' = 0) + \frac{1}{2}\Pr(Y = A \mid B' = 1) \le \frac{3}{4}$$

Bob before Alice

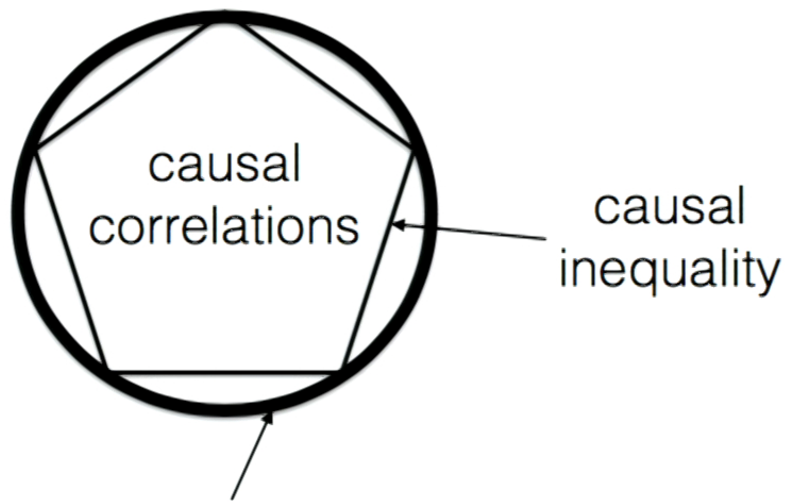
Alice before Bob

O. Oreshkov, F. Costa, Č. Brukner, *Nature Communications* **3**, 1092 (2012)

Causal Inequalities



Causal Inequalities



classical logically consistent correlations

=

causal correlations?

Classical Non-Causal Correlations

Non-Causal Environment

$$\frac{1}{3}(\Pr(X = B \oplus C \mid M = 1) + \Pr(Y = A \oplus C \mid M = 2) + \Pr(Z = A \oplus B \mid M = 3)) \leq \frac{5}{6}$$

Causal:

Ä. B., A. Feix, S. Wolf, *Physical Review A* **90**, 042106 (2014)

Classical Non-Causal Correlations

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$$\frac{1}{3}(\Pr(X = B \oplus C \mid M = 1) + \Pr(Y = A \oplus C \mid M = 2) + \Pr(Z = A \oplus B \mid M = 3)) \leq \frac{5}{6}$$

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Classical Non-Causal Correlations

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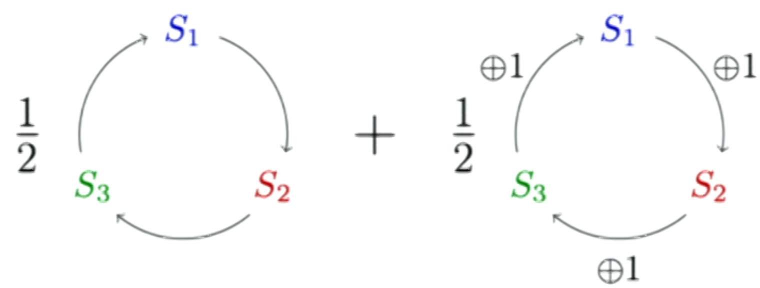

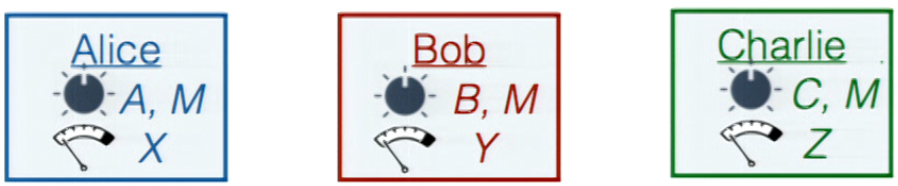

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Ä. B., A. Feix, S. Wolf, *Physical Review A* **90**, 042106 (2014)

Classical Non-Causal Correlations

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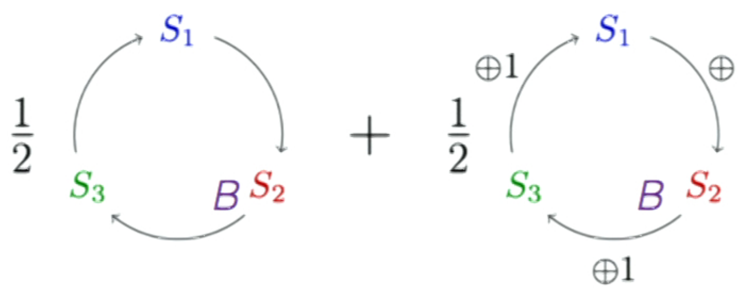

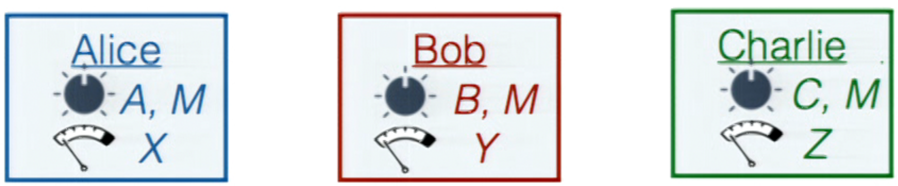

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Classical Non-Causal Correlations

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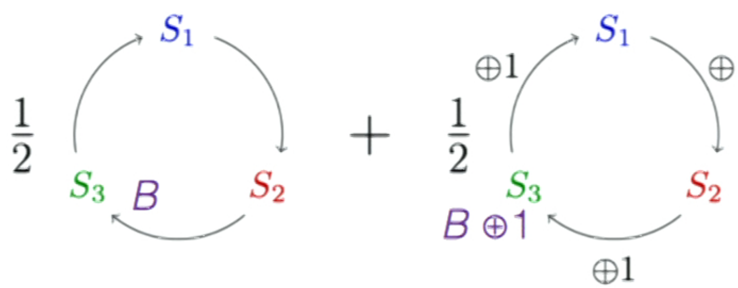

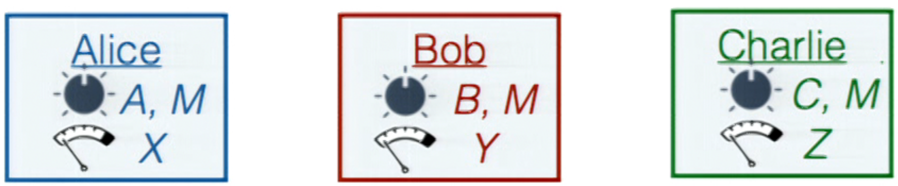

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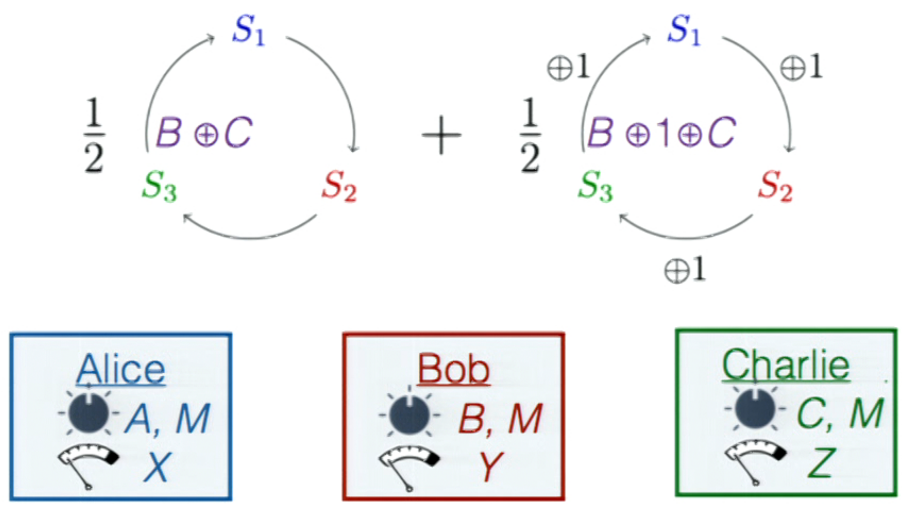
Ä. B., A. Feix, S. Wolf, *Physical Review A* **90**, 042106 (2014)

Classical Non-Causal Correlations

Non-Causal Environment



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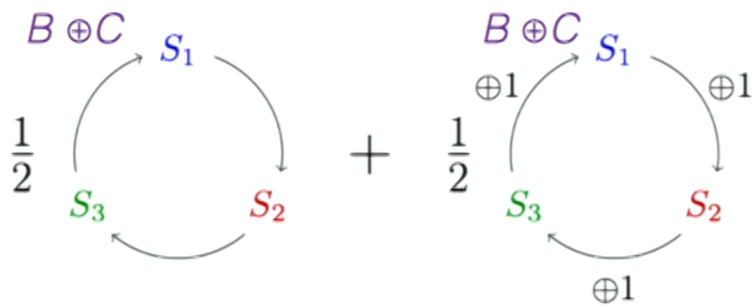
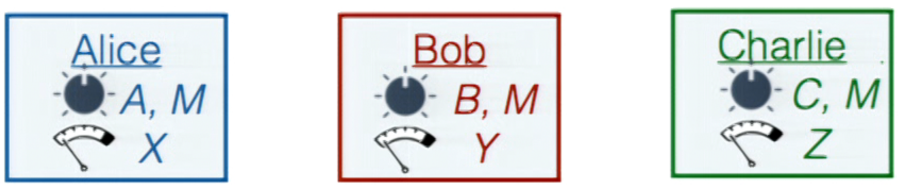
Classical Non-Causal Correlations

Non-Causal Environment





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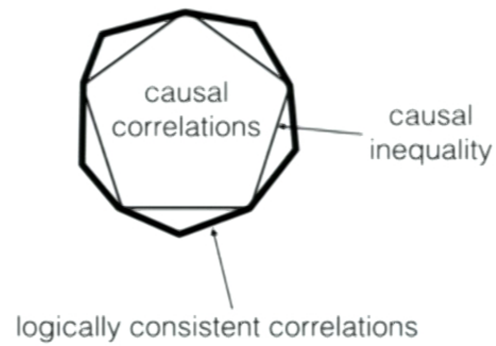
Ä. B., A. Feix, S. Wolf, *Physical Review A* **90**, 042106 (2014)

Classical Non-Causal Correlations

Characterizing the environment

- Characterization with polytopes



- Characterization with fixed-point theorems
  - <u>No</u> fixed point: Grandfather antinomy
  - <u>Multiple</u> fixed points: Information antinomy

  For every choice of operation:

  => deterministic case: *unique* fixed point

  => probabilistic case: *average* number of fixed points is 1

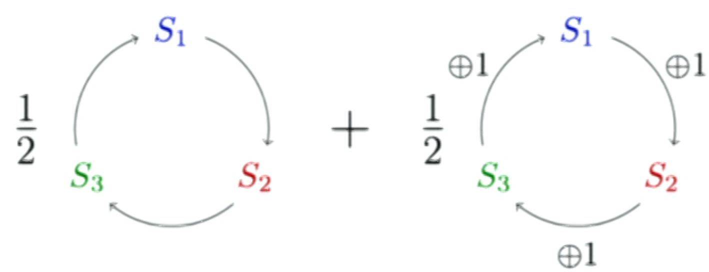
Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016); Ä. B., S. Wolf, *New Journal of Physics* **18**, 035014 (2016)

Classical Non-Causal Correlations

Characterizing the environment

causal
inequality

ions



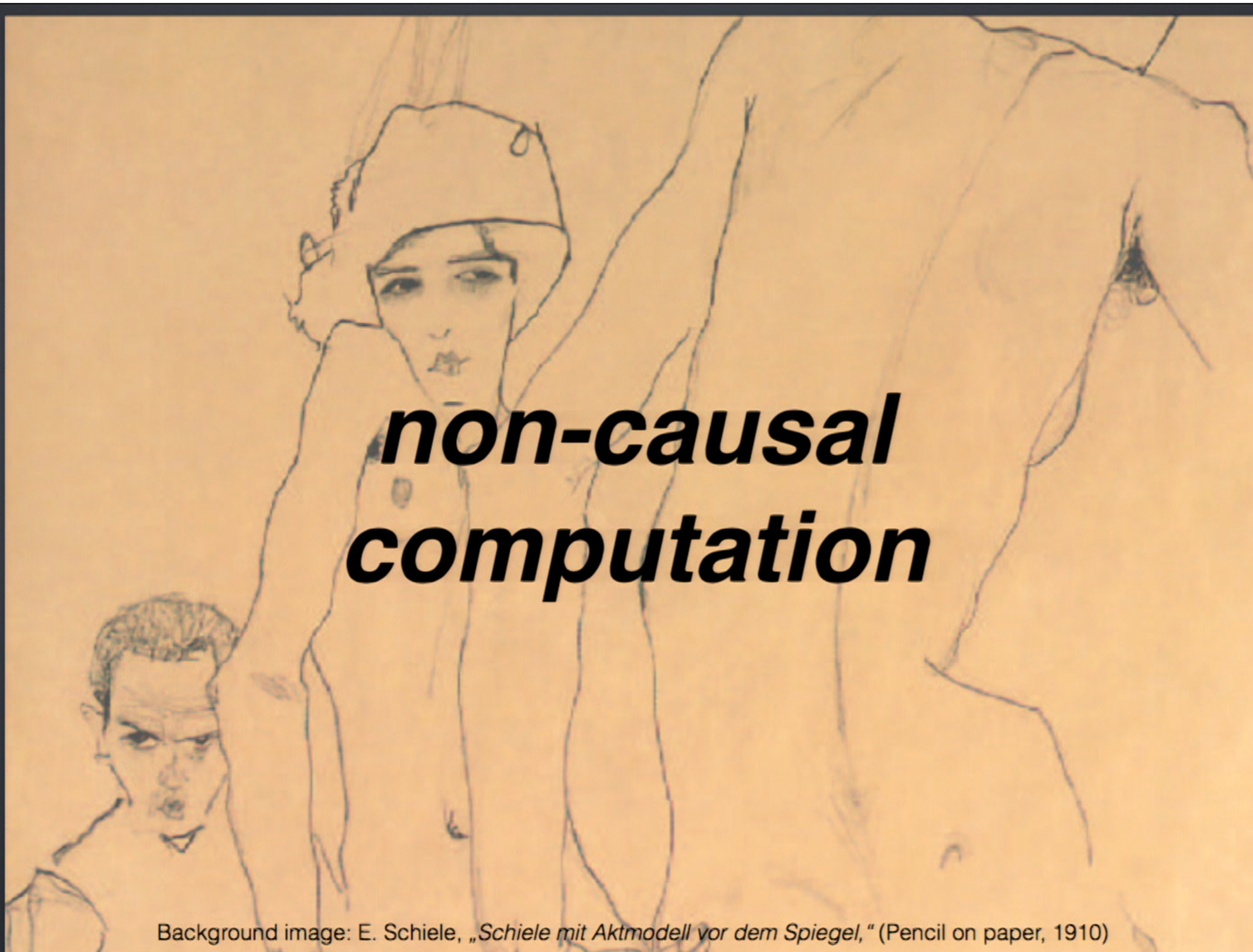
Number of fixed points, where all parties use identity operation:	2	0

=> deterministic case: *unique* fixed point

=> probabilistic case: *average* number of fixed points is 1

Ä. B., S. Wolf, *New Journal of Physics* **18**, 013036 (2016); Ä. B., S. Wolf, *New Journal of Physics* **18**, 035014 (2016)

non-causal computation



Background image: E. Schiele, *„Schiele mit Aktmodell vor dem Spiegel,“* (Pencil on paper, 1910)

Non-Causal Computation

<u>Before:</u>

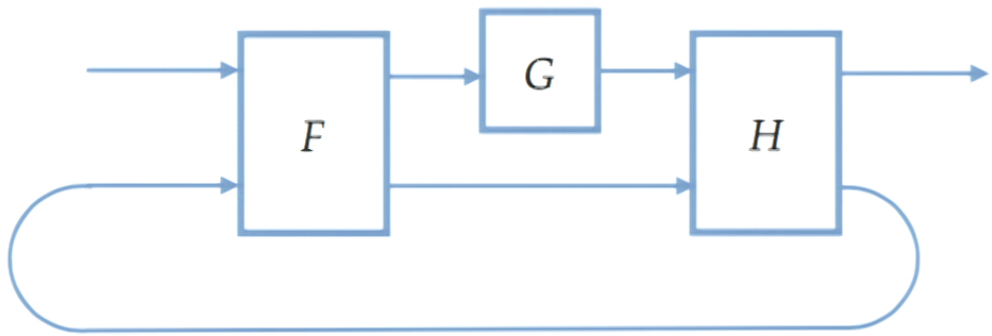
- Parties
- Order not fixed
- Logical consistency: $\forall L_1, L_2, L_3$ unique F.P.

<u>Model of computation:</u>

- Gates (deterministic)
- Arbitrary wiring
- Logical consistency: for every input: loops in circuit have unique F.P.

Non-Causal Computation

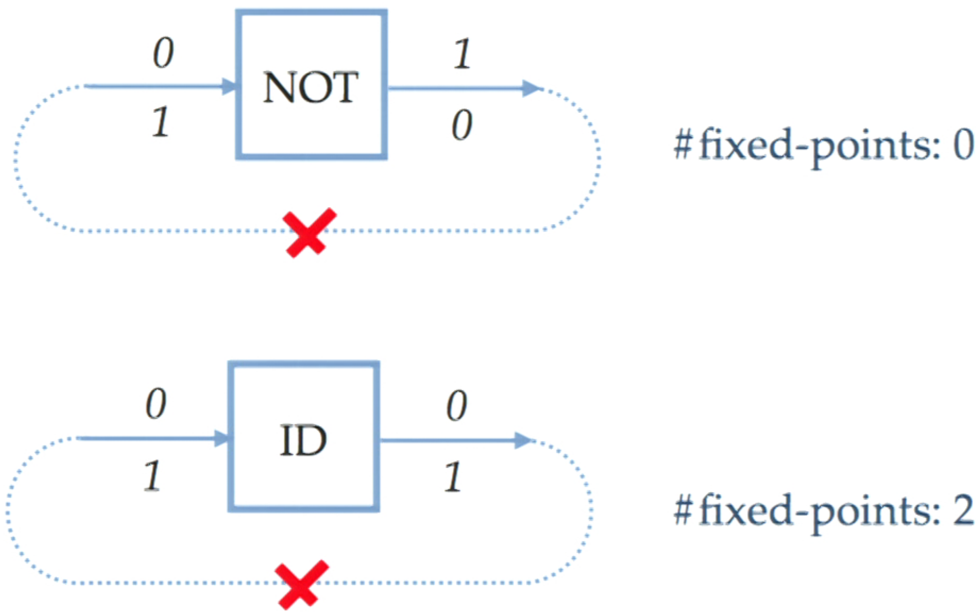
- Arbitrary wiring of gates



- Logical consistency:
  Unique fixed point on looping wires

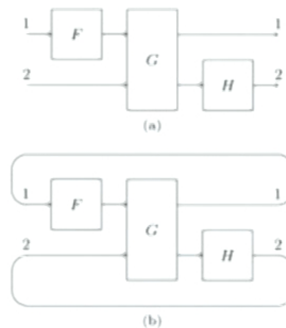
Non-Causal Computation

- Not all wirings are logically consistent



Non-Causal Computation

- Language: $L \subseteq \{0,1\}^*$



- Instance: $x \in \{0,1\}^*$
  Question: $x \in L$?

- <u>Definition (NCCAlgo):</u>
  A deterministic NCCAlgo *A* is a polytime algorithm that takes as input *x* and outputs a Boolean circuit c_x over AND, OR, NOT such that:

$$\forall x \in \{0,1\}^*, \exists! y : c_x(y) = y$$

If *y=1z*: *A <u>accepts</u> x*, otherwise *A <u>rejects</u> x*.
A <u>decides</u> *L* if it accepts every *x* in *L* and rejects every other *x*

Ä.B., S. Wolf, *Entropy* **19**, 326 (2017); Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)

Non-Causal Computation

- <u>Definition (NCCAlgo):</u>
  A deterministic NCCAlgo *A* is a polytime algorithm that takes as input *x* and outputs a Boolean circuit c_x over AND, OR, NOT such that:

$$\forall x \in \{0,1\}^*, \exists! y : c_x(y) = y$$

  If *y=1z*: *A* *<u>accepts</u>* *x*, otherwise *A* *<u>rejects</u>* *x*.
  A *<u>decides</u>* *L* if it accepts every *x* in *L* and rejects every other *x*

- <u>Definition (P_{NCC}):</u>
  The class P_{NCC} contains all languages decidable by some NCCAlgo *A*.

Ä.B., S. Wolf, *Entropy* **19**, 326 (2017); Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)

Non-Causal Computation

- Definition (P_{NCC}):
  The class P_{NCC} contains all languages decidable by some NCCAlgo *A.*

- Definition (UP ∩ coUP):
  The class UP ∩ coUP contains all languages *L* for which there exist two polytime verifiers
  V_{yes}: $\{0,1\}^* \times \{0,1\}^* \longrightarrow \{0,1\}$
  V_{no}: $\{0,1\}^* \times \{0,1\}^* \longrightarrow \{0,1\}$
  such that:

$$x \in L \implies \exists! y : V_{\mathrm{yes}}(x,y) = 1 \quad \wedge \quad \forall y : V_{\mathrm{no}}(x,y) = 0$$
$$x \notin L \implies \forall y : V_{\mathrm{yes}}(x,y) = 0 \quad \wedge \quad \exists! y : V_{\mathrm{no}}(x,y) = 1$$

L.G. Valiant, *Inf. Proc. Lett.* **5**, 20 (1976);
Ä.B., S. Wolf, *Entropy* **19**, 326 (2017); Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)

Non-Causal Computation

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UP | coUP

L.G. Valiant, *Inf. Proc. Lett.* **5**, 20 (1976);
Ä.B., S. Wolf, *Entropy* **19**, 326 (2017); Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)

Non-Causal Computation

- Theorem: $P_{NCC} = UP \cap coUP$

- Proof sketch:
  $\subseteq$: We can translate a Circuit c_x into the verifiers:

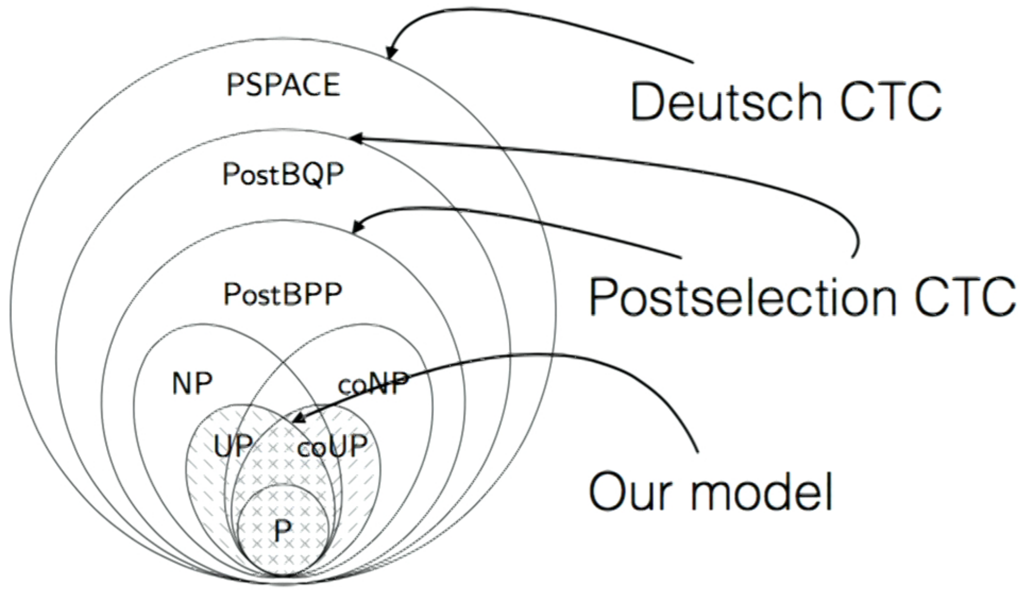
$$V_{\text{yes}} : (x, z) \mapsto c_x(z) = z \wedge z = 1w\,,$$
$$V_{\text{no}} : (x, z) \mapsto c_x(z) = z \wedge z = 0w\,.$$

  $\supseteq$: We can construct c_x from the verifiers:

$$c_x : \{0,1\} \times \{0,1\}^{q(|x|)} \to \{0,1\} \times \{0,1\}^{q(|x|)}\,,$$
$$: (b, w) \mapsto \begin{cases} (0, w) & V_{\text{no}}(x, w) = 1\,, \\ (1, w) & V_{\text{yes}}(x, w) = 1\,, \\ (b \oplus 1, w) & \text{otherwise}, \end{cases}$$

Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)

Non-Causal Computation



Known problems in UP ∩ coUP: Factorization

Ä. B., S. Wolf, *Proc. Royal Soc. A* **474**, 20170698 (2018)


time travel
Background image: E. Schiele, „Schiele mit Aktmodell vor dem Spiegel," (Pencil on paper, 1910)

Time Travel

Logically problematic?
- Grandfather antinomy
- Information antinomy

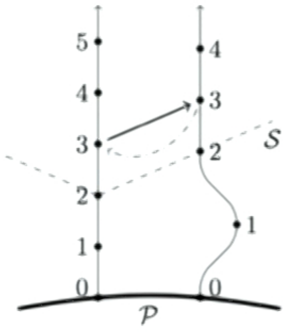
Computationally problematic?
- NP-Hardness assumption

Physically problematic?
- Reversibility of deterministic laws
- No new physics

Time Travel
(previous works)

- <u>Assumptions:</u>
  Novikov's principle of self-consistency
  (no grandfather antinomy)

  No „new physics“ at the surface *P*

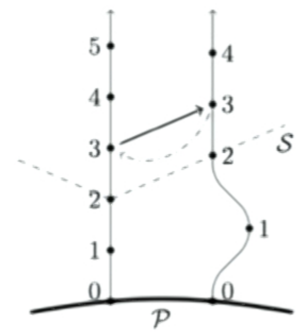


J. Friedman, M. Morris, I. Novikov, F. Echeverria, G. Klinkhammer, K. Thorne, U. Yurtsever, *Physical Review D* **42**, 1915 (1990);
F. Echeverria, G. Klinkhammer, K. Thorne, *Physical Review D* **44**, 1077 (1991);
K. Thorne, *Black Holes and Time Warps* (W. W. Norton & Company, New York, 1994)

Time Travel
(previous works)

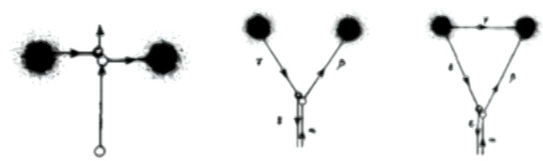
- <u>Assumptions:</u>
  Novikov's principle of self-consistency
  (no grandfather antinomy)

  No „new physics“ in the past



- <u>Implications:</u>

The Billiard Ball Crisis:
An Infinity of Trajectories



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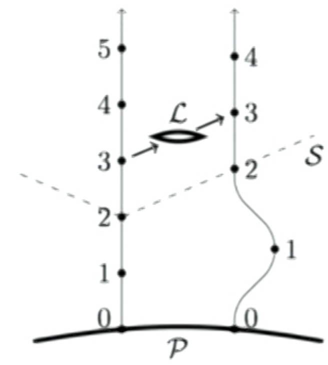
Time Travel



- <u>Assumptions:</u>
  Novikov's principle of self-consistency
  (no grandfather antinomy)

  No „new physics" in local regions
  (not only at *P*)

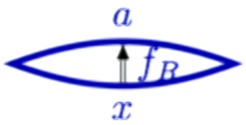
- <u>Implications:</u>
  Unique dynamics, reversibility, computationally tame

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

- Local region R consists of *past* and *future* boundary

- Dynamics within R is described by a function f_R

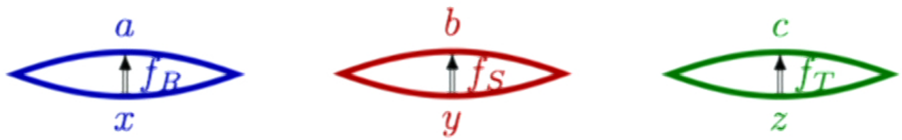


- No new physics: Any function f_R can be applied.

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

- Multiple regions *R,S,T*



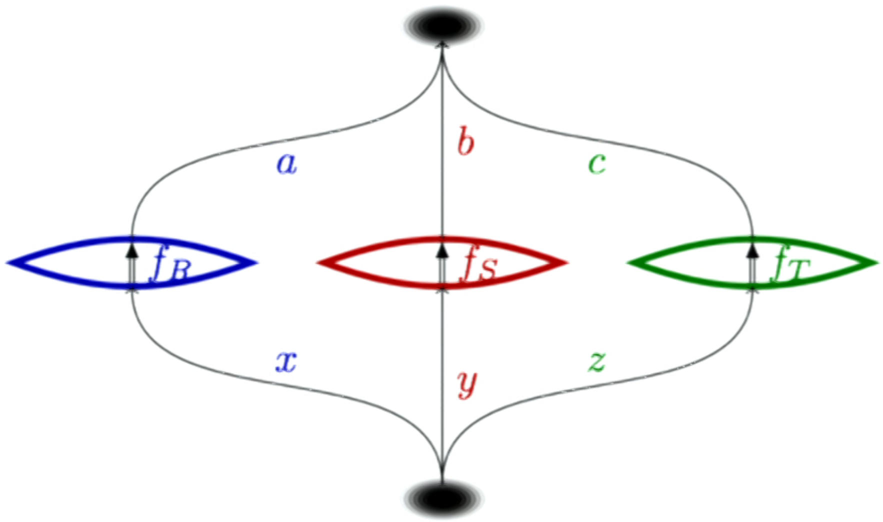
- Closed time-like curve as function

$$w : (a, b, c) \mapsto (x, y, z)$$

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

- Closed time-like curve

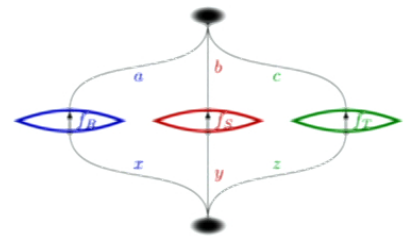


$$w : (a, b, c) \mapsto (x, y, z)$$

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

- Novikov's self-consistency principle and **strong** „no new physics“ principle

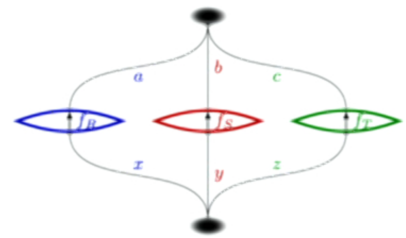


$$\forall f_R, f_S, f_T, \exists (x, y, z) : (x, y, z) = w(f_R(x), f_S(y), f_T(z))$$

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

- Novikov's self-consistency principle and **strong** „no new physics" principle



$$\forall f_R, f_S, f_T, \exists (x,y,z) : (x,y,z) = w(f_R(x), f_S(y), f_T(z))$$

- This implies (unique dynamics, no information antinomy):

$$\forall f_R, f_S, f_T, \exists ! (x,y,z) : (x,y,z) = w(f_R(x), f_S(y), f_T(z))$$

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

Time Travel

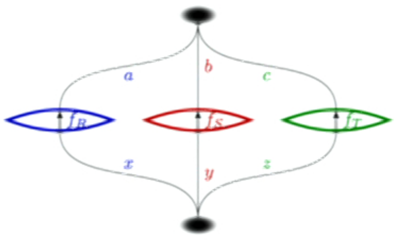
- Proof idea for:

$$\forall f_R, f_S, f_T, \exists!(x,y,z) : (x,y,z) = w(f_R(x), f_S(y), f_T(z))$$

N=1: Trivial
Induction: N -> N+1:
  Assume *w* for N+1 regions has more than one fixed point.
  Construct *w'* for N regions with more than one fixed point.

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

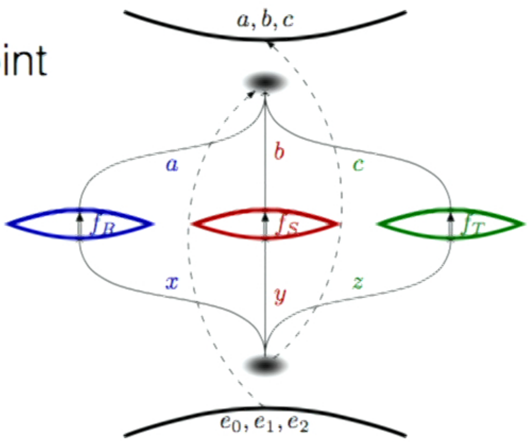
Time Travel



- Novikov's self-consistency principle and **strong** „no new physics" principle

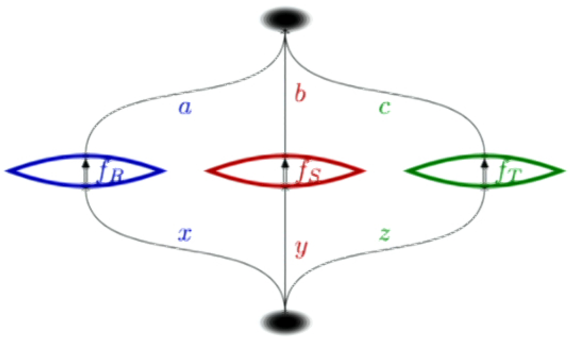
$$\forall f_R, f_S, f_T, \exists(x, y, z) : (x, y, z) = w(f_R(x), f_S(y), f_T(z))$$

- Every *w* that satisfies the fixed-point condition can be embedded in a reversible *w'* with two additional local regions



Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

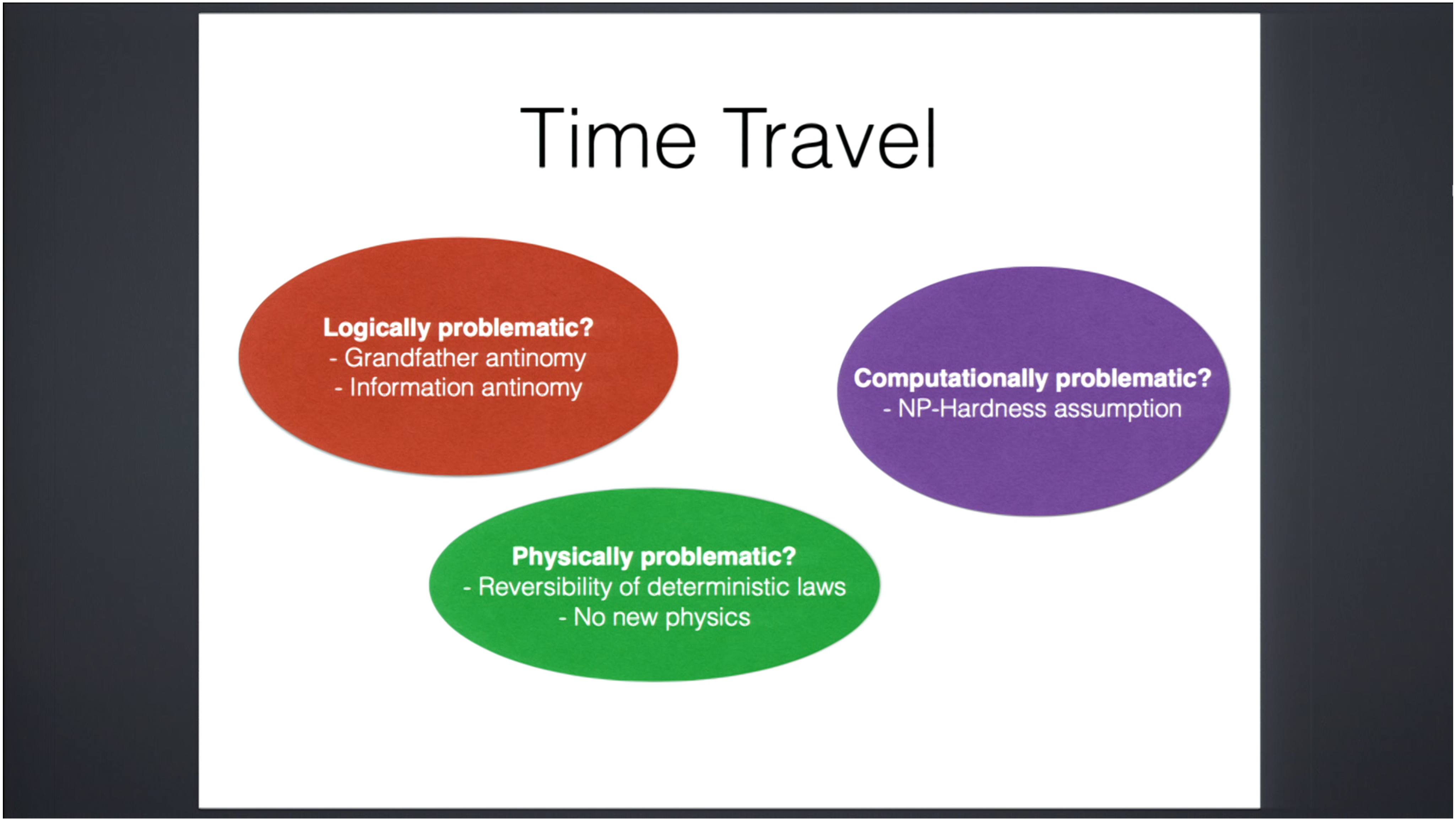
Time Travel: Example



$$x = \neg b \wedge c$$
$$y = \neg c \wedge a$$
$$z = \neg a \wedge b$$

$$a = 0 \implies S \prec T$$
$$a = 1 \implies S \succ T$$

Ä. B., F. Costa, T. Ralph, S. Wolf, M. Zych, *arXiv:1703.00779 [gr-qc]* (2017)

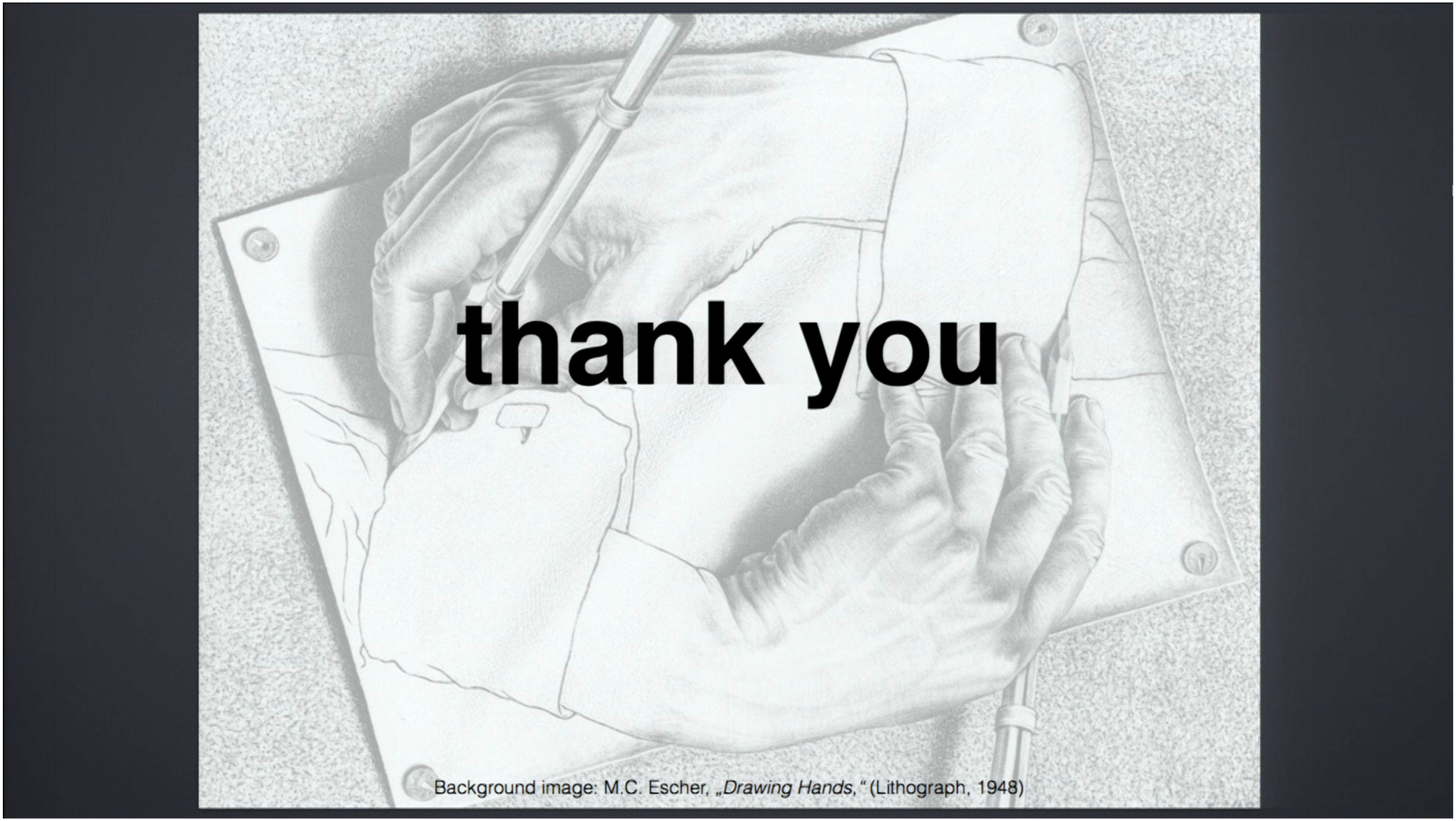

Time Travel
Logically problematic?
- Grandfather antinomy
- Information antinomy
Computationally problematic?
- NP-Hardness assumption
Physically problematic?
- Reversibility of deterministic laws
- No new physics

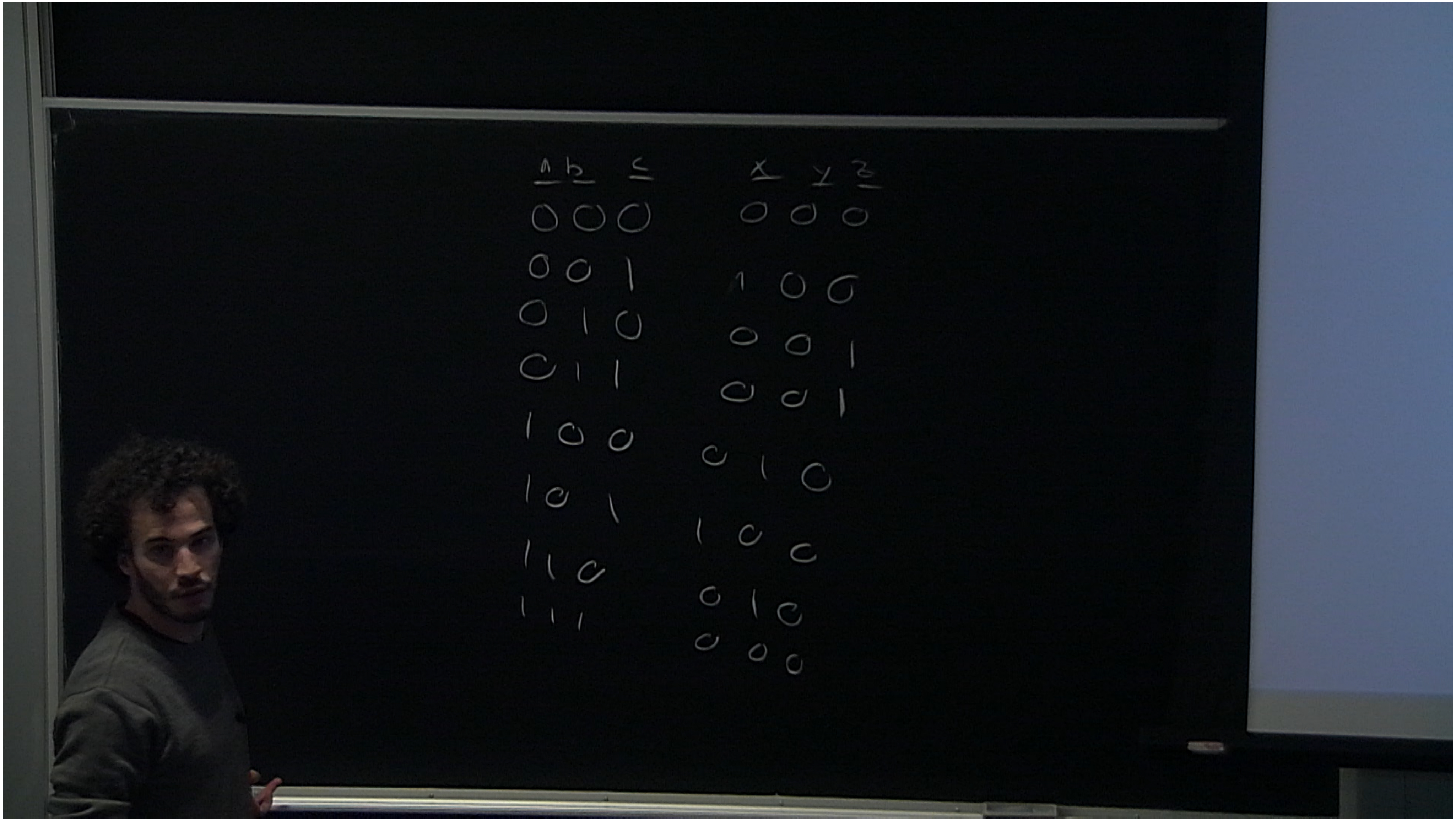
Conclusion

take home message

The logically consistent, classical world outside of the causal is

- *non empty*
- *computationally tame*
  (in the deterministic case; cannot efficiently solve NP-hard problems)
- *reversible with unique dynamics*
  (in the deterministic case)


thank you
Background image: M.C. Escher, „Drawing Hands," (Lithograph, 1948)


a b c
0 0 0
0 0 1
0 1 0
0 1 1
1 0 0
1 0 1
1 1 0
1 1 1
x y z
0 0 0
1 0 0
0 0 1
0 0 1
0 1 0
1 0 0
0 1 0
0 0 0