Distinguished Dissertations

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Causal loops: Logically consistent correlations, time travel, and computation

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Abstract: Causal loops are loops in cause-effect relations, where, say for two events A, B, the event A is a cause of B and, vice versa, B is a cause of A. Such loops are traditionally ruled out due to potential logical problems, *e. g.*, where an effect suppresses its own cause. Motivated by our current physical theories, we show that not only causal loops exist that are logically consistent, but that these loops are computationally tame and help to further investigate on the theoretical foundations of time travel. Causal loops do not necessarily pose problems from a logics, computer-science, and physics point of view. This opens their potential applicability in various fields from philosophy of language to computer science and physics.

Keywords: causality, fixed points, closed time-like curves, $\mathsf{UP} \cap \mathsf{coUP}$

ACM CCS: Theory of computation → Models of computation → Abstract machines, Theory of computation → Computational complexity and cryptography → Complexity theory and logic, Theory of computation → Models of computation → Quantum computation theory

1 Introduction

This article reviews the main findings of the equally titled dissertation [7] with the main message: *Causal loops are less problematic than initially thought*. Causal structures can be represented by directed graphs, where the nodes represent events and the edges point from cause to effect [25]. For instance, a computational circuit can be written in that way, where events are the intermediate states of computation, and the edges point *forward* in computation. Traditionally, causal structures come with two assumptions: 1) the underlying graph is *acyclic*, and 2) the graph is *fixed*. The first assumption forbids *causal loops*. The reason to forbid causal loops is that they might lead to logical problems. In a causal structure with loops, the state of an event does not only depend on the *past* events, but also on *future* events. The second assumption says that a process, *e. g.*, some computation, does not alter the graph; the causal structure is not *part* of the computation, rather, computation takes place *on top of* the causal structure. Furthermore, both assumptions comply with our everyday experience.

What are the logical problems associated with such an endeavor? The most prominent one is called *grandfather antinomy*, where a causal loop leads to a logical contradiction. Assume some person travels to the past to kill his or her grandfather *before* this very same person has been born. By doing so, this person will not be born, and hence will not travel to the past, and hence will not kill his or her grandfather, and hence will be born, and hence, ... – a logical contradiction. This problem has another face: the *information antinomy*. Suppose you wake up one morning and find, next to your bed, a novel you and no one else has ever seen before. A couple of years later you invent a time machine to travel to the past and place that book next to the bed of your younger self. What is the content of the book? Who wrote the book? This situation lacks any causal explanation for the information that becomes present at some time.[1] A theory suffering from the information antinomy fails in certain cases to provide predictions. Both logical problems are schematically presented in Figure 1.

1.1 Motivations, results, and outline

The results stem from the interplay between computer science and physics: physics guides information processing, and limits on information processing restrict physics. We start by borrowing motivations from physics to relax the assumptions made on causality. *General relativity theory* is consistent with *closed time-like curves* [22, 20, 23]. This means, there exist solutions to the equations of general relativity where particles bump into their *younger selves*; the causal structure is *cyclic*.

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1 Deutsch [16] calls this *creationism*.

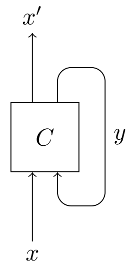

Figure 1: For a circuit $C : (x, y) \mapsto (x, y \oplus 1)$ the grandfather antinomy arises: No consistent "time-travelling" system y exists. For a circuit $C : (x, y) \mapsto (x \oplus y, y)$ the information antinomy arises: All y are consistent, yet the output x' is not well defined: Which y should we select in order to compute the output $x \oplus y$? Note that the "loop" in this figure and as discussed throughout the article is not to be confused with a feedback loop where the overall system evolves in time; instead, the loop represents a causal loop. One way to think about this is to consider the loop as a loop "in time."

In *quantum theory*, physical properties are allowed to be in *superposition*: The state of a quantum-mechanical system can be in a superposition of being located at one and another point in space, which leads to a situation where the position of that system is not well defined. This superposition principle can be extended beyond the position degree of freedom to the temporal degree of freedom: We obtain a superposition of different causal structures, and by this, the causal structure is not well defined. Hence, the second assumption that a causal structure must be *fixed* is not satisfied. This phenomenon is illustrated in the following thought experiment, where quantum as well as relativistic effects take place [21]. Take a large mass, *e. g.*, a planet, and place it in superposition of being in two different locations. Due to general relativity, this planet transforms the space-time structure, resulting in a superposition of different space-times.

As a last motivation to mention, quantum theory comes with conceptual difficulties that might be overcome if we relax the assumptions made on causality. Most works that deal with such difficulties assume (often implicitly) a traditional notion of causality (see, *e. g.*, References [15, 10] for approaches that do *not* make such an assumption). One such conceptual difficulty is the causal understanding of *non-local* correlations [11]. These correlations violate Reichenbach's principle [26] that asks for correlations to be explained by a direct cause or a common cause.

The findings in the dissertation on causal loops mainly target the first assumption made on causal structures and are based on the "process matrix" formalism by Oreshkov, Costa, and Brukner [24]. The authors show, by generalizing quantum theory, that the requirement for well-defined probabilities (without any assumption on causality) does *not* imply that the causal structure must be fixed and acyclic: Correlations arise that *cannot* be obtained from any fixed acyclic causal structure. We find that the same qualitative result also holds without having to invoke quantum theory, *i. e.*, in classical theories (this is reported in the next section). Taking this as a starting point, we characterize these classical non-causal correlations, discuss time travel (see Section 3), and show that classical computational devices not limited to fixed acyclic causal structures cannot solve NP-hard problems efficiently[2] (see Section 4).

2 Correlations

The fact that logical consistency does not imply a fixed acyclic causal structure is shown via studying correlations among "parties."

Definition 1 (Party, causal, and non-causal correlations). A *party* $S_j = (A_j, X_j, L_j)$ is a tuple consisting of two random variables A_j, X_j and a local operation L_j. The random variable A_j is the *setting* and the random variable X_j the *outcome*.

For k parties, the correlations $P_{X_1,X_2,\ldots,X_k|A_1,A_2,\ldots,A_k}$ are called *causal* if and only if they can be simulated by arranging the parties on a fixed acyclic causal structure; otherwise, they are called *non-causal*.

Causal two-party correlations $P_{X_1,X_2|A_1,A_2}$ can hence be decomposed as

$$pP_{X_1|A_1}P_{X_2|A_1,A_2,X_1} + (1-p)P_{X_2|A_2}P_{X_1|A_1,A_2,X_2}\,,$$

where p is some probability: With probability p party S_1 acts *before* S_2. Note that convex mixtures of fixed acyclic causal structures remain fixed and acyclic: The probability p might arise due to some "ignorance."

Now, we describe how the correlations are obtained based on the local operations L_j. Following Oreshkov, Costa, and Brukner [24], we do not assume an underlying fixed acyclic causal structure of the parties. Instead, we assume that the parties are *isolated* (A1), every party acts *once* (A2), the correlations are *linear* in the choice of local operations (A3), and *logical consistency* (A4). Condition (A1) means that the local operation L_j of any party S_j can be described independently of the other parties' local operations. Then again, (A2) says that every local operation is applied once; this could be generalized, but as

2 Unless the polynomial hierarchy collapses.

it stands, makes calculations easier and is sufficient for our claims. The requirement (A3) of linearity is natural: It translates to the requirement that convex combinations of local operations transform to convex combinations of correlations. Last but not least, (A4) is the core assumption in order to have a consistent theory.

Since we are interested in the case where the underlying theory is classical probability theory (as opposed to quantum theory), the most general form of the local operation L_j is $P_{O_j,X_j|I_j,A_j}$ for some random variables O_j, I_j: a stochastic channel that depends on the *setting* A_j and produces an *outcome* X_j. Hence, up to the *logical consistency* assumption that we formulate shortly, the most general correlations $P_{X_1,X_2,\dots,X_k|A_1,A_2,\dots,A_k}$ – without assuming an underlying fixed acyclic causal structure – are given by

$$f(L_1, L_2, \dots, L_k),$$

for some multi-linear function f. Note that f can be interpreted as a "supermap:" It maps operations to an operation $P_{X_1,X_2,\dots,X_k|A_1,A_2,\dots,A_k}$. *Logical consistency*, finally, asks that for any choice of local operations, the distribution $P_{X_1,X_2,\dots,X_k|A_1,A_2,\dots,A_k}$ is well defined. This means that the parties are *unrestricted* in what local operation they want to perform.

Definition 2 (Logical consistency). A supermap f is called *logically consistent* if and only if $\forall L_1, L_2, \dots, L_k$: $f(L_1, L_2, \dots, L_k)$ is a probability distribution of the form $P_{X_1,X_2,\dots,X_k|A_1,A_2,\dots,A_k}$.

Given a supermap f' that is *not* logically consistent, a set of local operations of the parties exists such that the result is not a probability distribution (the "probabilities" are not normalized or negative).

Note that *causal correlations* satisfy all the assumptions (A1–A4). The question we are interested in now is: Do the four assumptions (A1–A4) imply causal correlations? If the underlying theory is quantum theory, then Oreshkov, Costa, and Brukner [24] answered this question negatively. In the same work the authors showed that if the underlying theory is classical, then for *two parties* the question is answered *positively*. This suggested that fixed acyclic causal structures might be the result from quantum-to-classical transitions (the quantum world may be causally exotic, yet the classical is not – supporting our everyday view on nature). In the dissertation we show that the latter is not true; classical theories allow for non-causal correlations if more than two parties are involved. Before we illustrate this result with an example, we present two theorems that help to understand logically consistent supermaps f.

Theorem 1 (Logically consistent supermaps (informal) [4]). *Logically consistent supermaps represent (stochastic) channels E from the $\{O_j\}_J$ variables to the $\{I_j\}_J$ variables (see Figure 2).*

Following this theorem, the resulting distribution is calculated according to probability theory by taking the product over all local operations and the channel E, and by marginalizing over the $\{O_j, I_j\}_J$ variables. Note that some channels E do *not* lead to a logically consistent supermap, *e. g.*, if we would plug in the identity channel, then a set of local operations exists such that the result is *not* a valid probability distribution as required.

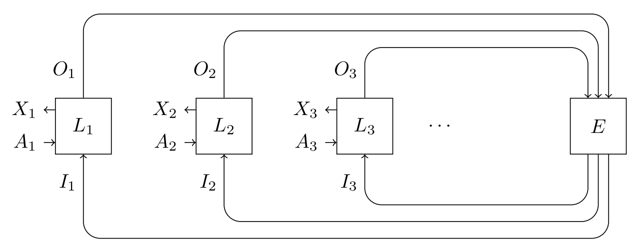

Figure 2: A box L_j represents the local operation L_j of party S_j which can be understood as a channel. Likewise, logically consistent supermaps can be understood as stochastic channels. The average number of deterministic fixed points of $E \circ (L_1, L_2, L_3, \dots)$ is 1.

Theorem 2 (Fixed-point characterization (informal) [5]). *A supermap f is logically consistent if and only if the average number of fixed points of $P_{I_1,I_2,\dots|O_1,O_2,\dots}$ concatenated with any choice of deterministic local operations is 1 (see Figure 2).*

A corollary of the latter theorem is that a *deterministic* supermap is logically consistent if and only if for any choice of deterministic local operations, a *unique* fixed point exists. This result is tantamount to avoiding the grandfather as well as the information antinomy discussed in the introduction.

Example. Let S_1, S_2, S_3 be parties with local operations $L_j = P_{O_j,X_j|I_j,A_j}$, where all random variables are binary and where the *settings* $\{A_1, A_2, A_3\}$ are uniformly distributed. To decide whether correlations are *non-causal*, we make use of *causal inequalities* [24, 13]. If for a given distribution $P_{X_1,X_2,X_3|A_1,A_2,A_3}$ the inequality

$$\Pr\big((X_1 = \neg A_2 \wedge A_3) \wedge (X_2 = \neg A_3 \wedge A_1) \wedge \\ (X_3 = \neg A_1 \wedge A_2)\big) \le 3/4$$

is violated, then this distribution must be *non-causal*. The reason for this is that for *causal* correlations (the parties are positioned on a fixed acyclic causal structure), *at least one party* S_j has no other parties in her past and therefore no access to the settings $\{A_1, A_2, A_3\} \setminus \{A_j\}$ of the other parties; hence, X_j takes the correct value with probability at most 3/4.

Yet, in the framework presented, the supermap constructed from

$$E(i_1, i_2, i_3, o_1, o_2, o_3) = \begin{cases} 1 & (i_1 = \neg o_2 \wedge o_3) \wedge \\ & (i_2 = \neg o_3 \wedge o_1) \wedge \\ & (i_3 = \neg o_1 \wedge o_2) \\ 0 & \text{otherwise,} \end{cases}$$

along with the local operations

$$L_j(o_j, x_j, i_j, a_j) = \begin{cases} 1 & o_j = a_j \wedge i_j = x_j \\ 0 & \text{otherwise,} \end{cases}$$

allow to violate the above inequality maximally: It is *impossible* to arrange the parties on a fixed acyclic causal structure in order to obtain the same correlations. By consulting the second theorem above, the reader can convince herself/himself that E indeed leads to a *logically consistent* supermap. The underlying causal structure is *cyclic* (see Figure 3).

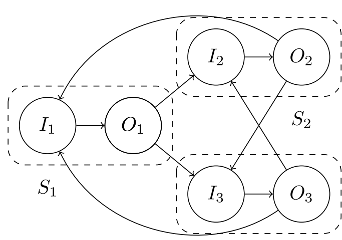

Figure 3: The value of the variable O_j is determined by the local operation L_j and I_j. The value of I_j, then again, is a function of $\{O_1, O_2, O_3\} \setminus \{O_j\}$. For simplicity this figure is blind of the X_j, A_j variables.

3 Time travel

Scientific studies on time travel – even though controversial – obtained great interest after the development of general relativity. Already Einstein [17] was suspecting that his theory might allow for such a behavior, and approached [18] Carathéodory to resolve this issue – without any answer. To our knowledge, the first solution to the Einstein equations with closed time-like curves was discovered a decade later by Lanczos [22]. We briefly discuss the more intuitive approach by Morris, Thorne, and Yurtsever [23] to time travel in general relativity. Their solution is based on wormholes. A wormhole has two mouths, and the proper times of both mouths are identified with each other, *i. e.*, if a particle is dropped into one mouth at time τ, then it exists the other mouth at time τ. As the authors suggest, if we take one mouth, accelerate it to some high velocity and bring it back, we introduce some time dilation, which allows for time travel (see Figure 4).

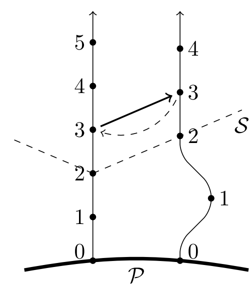

Figure 4: Time goes from bottom to top. The arrows represent the world lines of the two mouths of a wormhole, and the numbers the proper times associated to the mouths. In the future of $\mathcal{S}$ closed time-like curves exist, *e. g.*, a particle can travel, without exceeding the speed of light, trough ordinary space-time from 3 on the left to 3 on the right, where it enters the wormhole and exists on the left at point 3.

In a series of texts, Thorne and coauthors [19, 30] study the dynamics of time-travelling billiard balls. Motivated by the potential logical problems of time travel, they ask the following question: Are there some initial conditions of a billiard ball at a time *before* a closed time-like curve exists (*e. g.*, at $\mathcal{P}$ in Figure 4), such that the billiard ball travels to the past and collides with its younger self in such a way that it will not travel to the past? – Do some initial conditions lead to a logical contradiction *à la* grandfather antinomy? If yes, this would have rather strong consequences: It would mean that these initial conditions could not have been chosen even though at the time when we would have chosen them no time travel is possible – we would be restricted in todays actions if time travel were possible in the future. They answer: For any choice of initial conditions, consistent trajectories exist, even for time-travelling billiard balls! Yet, their result is surprisingly more extreme, and has been called the *billiard-ball crisis* [30]: Not only consistent trajectories exist, but an *infinity* of such trajectories exist (information antinomy).

By abstracting away the general-relativistic settings, others [16, 12] studied time travel on the basis of quantum theory; more concretely, on the basis of quantum circuits. The reason to avoid classical circuits is that classical circuits are prone to the grandfather antinomy (see Figure 1). If such a circuit is replaced by a quantum circuit, a self-consistent quantum state can always be found [16]. These approaches, however, modify quantum theory in a way that it becomes *non-linear*, and hence unsatisfactory from a physical point of view.

The causal loops we study avoid and resolve the above raised issues. First, the logical consistency condition asks for consistent trajectories for all *initial conditions* and all *intermediate transformations* of the billiard ball. The second theorem above then states that the "trajectory" is *uniquely* defined – the billiard-ball crisis is avoided. Furthermore, we do not have to pursue a quantum-theoretic setup: Certain classical circuits avoid the mentioned logical problems and do not alter the underlying theory (whether it is classical or quantum) to a non-linear one. Moreover, we show that time travel in this fashion is reversible [8].

4 Computation

Since we cannot rule out causal loops on logical nor on physical grounds, what objections (apart from appealing to our everyday experiences where no exotic causal structures seem to pop up) against causal loops are left? Aaronson [2] suggests the NP-hardness assumption: "NP-*complete problems are intractable in the physical world.*" This assumption says that if we build a computer based on some theory T and we find that this device can solve NP-hard problems efficiently, then we would suspect that T is *not physical*. This assumption might be debatable; yet, and what gives some weight to this assumption is that, all approaches to solve NP-hard problems efficiently by the use of exotic computational models implemented (*e.g.*, with soap bubbles [2]), failed. Interestingly, the above mentioned circuit-based models [16, 12] of time travel are ruled out by this assumption – NP-complete problems become solvable in polynomial time [1].

Motivated by Aaronson's thesis, and out of general computer-science interest, we study the computational power of causal loops. Clearly, a computational model where causal loops are possible can efficiently solve all problems efficiently solvable without loops; but maybe more.

Before we discuss the results on this track, we introduce the computational model. The second theorem above states that a deterministic supermap is logically consistent if and only if for any choice of deterministic local operations, a *unique* fixed point exists. In a computational model, we usually do not think in terms of "parties," but rather in terms of gates. So, the assumption that parties are *unrestricted* in their choice of local operations becomes obsolete. Instead, we say that a circuit with causal loops is logically consistent if and only if a unique fixed point on the looping wires exists. This is formulated in the following definition:

Definition 3 (Non-causal circuit [6]). A circuit $C : \{0,1\}^k \to \{0,1\}^k$ together with an integer $1 \leq \ell \leq k$ is a *non-causal circuit* if and only if

$$\forall y \in \{0,1\}^{k-\ell}, \exists! z \in \{0,1\}^{\ell} : C(z,y) = (z,y')\,,$$

where $\exists!$ is the *uniqueness* quantifier, and y' is some bitstring of length $k-\ell$.

The "power" of such circuits with polynomial size *equals* an already known complexity class:

Theorem 3 (Polynomial-time logically consistent circuits (informal) [9]). *The set of languages* P_{NCCirc} *decidable in polynomial time with a non-causal circuit equals* $\mathsf{UP} \cap \mathsf{coUP}$.

Only few problems are known that are in $\mathsf{UP} \cap \mathsf{coUP}$ and conjectured to be outside of P: Factoring numbers, discrete logarithms, simple stochastic games, ... The computational-complexity class $\mathsf{UP} \cap \mathsf{coUP}$ is conjectured to be *strictly* contained in NP as otherwise, the polynomial hierarchy would collapse. For the first two examples mentioned, efficient quantum algorithms exist that can solve them [28]. This leaves open the question for simple stochastic games (or parity games, which are believed to be easier [14] than simple stochastic games). Unfortunately, this open question has remained unresolved. The above theorem states that allowing computers to make use of logically consistent causal loops may alter the computational power, but just not strong enough in order to violate the NP-hardness assumption.

Example. We sketch an efficient non-causal circuit for factoring some number N into its prime factors. The circuit takes as input a bit b, $n = \lceil \log N \rceil$ pairs $(a_1,e_1),(a_2,e_2),\ldots,(a_n,e_n)$, with $1 \leq a_i \leq N$ and $1 \leq e_i \leq N$, where all wires are looped ($\ell = 1 + 2n^2$). The circuit performs multiple tests. If at least one test fails, then the circuit outputs $(b \oplus 1,(a_1,e_1),\ldots,(a_n,e_n))$, otherwise, the circuit outputs $(0,(a_1,e_1),\ldots,(a_n,e_n))$. The tests are:

– all $a_i \neq 1$ are distinct,
– all $a_i \neq 1$ are prime (this can be done efficiently [3]),
– the a_i are ordered decreasingly,

– the implication $a_i = 1 \implies e_i = 1$ holds,
– and finally, $N = a_1^{e_1} a_2^{e_2} \dots a_n^{e_n}$.

This circuit has a *unique* fixed point which corresponds to a 0 on the first wire and the prime factorization on the remaining wires. To read out the fixed point one can simply double the number of wires and copy the information from the loop. Note that this circuit is "programmed" in a similar fashion as in "anthropic computing" [2]: In the undesired event that the input to the circuit is *not* the prime factorization, a logical contradiction is introduced.

5 Conclusions

Causal loops have been ruled out mainly based on logical grounds. The most common objection against causal loops is the grandfather antinomy; with the liar paradox "All Cretans are liars," as has been attributed to Epimenides from Crete [27], as a prime example. This motivated, *e. g.*, Tarski [29] to rule out self-referential statements in language. In the dissertation, however, we show that such a restriction might be too strong: Some causal loops comply with the requirements of logics, computer science as well as physics. The motivations to study causal loops at all stem from taking our current physical theories (quantum theory and general relativity) seriously. The main message is that not only time travel now appears *less implausible* – which is anyways a controversial topic –, but that causal loops might be considered as theoretical building blocks for approaching problems in physics, computer science and possibly other fields.

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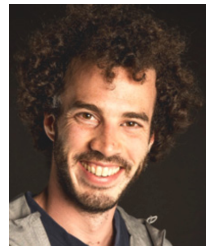
Bionotes



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Dr. Ämin Baumeler studied computer science at ETH Zurich, Switzerland. His master's project on quantum cryptography was conducted at the Institute for Quantum Computing in Waterloo, Canada, under the supervision of Prof. Anne Broadbent. After having obtained the master's degree from ETH, he started his PhD studies in the research group of Prof. Stefan Wolf at the Faculty of Informatics, Università della Svizzera italiana, Lugano, Switzerland. The research performed in his PhD studies are on causal structures, foundations of quantum theory, and complexity theory. After having obtained the PhD degree in 2016, he moved to Vienna to join Prof. Časlav Brukner's group at the Institute for Quantum Optics and Quantum Information.