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The Complexity of Transitively Orienting Temporal Graphs

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Abstract

In a *temporal network* with discrete time-labels on its edges, entities and information can only "flow" along sequences of edges whose time-labels are non-decreasing (resp. increasing), i.e. along temporal (resp. strict temporal) paths. Nevertheless, in the model for temporal networks of [Kempe, Kleinberg, Kumar, JCSS, 2002], the individual time-labeled edges remain undirected: an edge $e = \{u, v\}$ with time-label t specifies that "u communicates with v at time t". This is a symmetric relation between u and v, and it can be interpreted that the information can flow in either direction. In this paper we make a first attempt to understand how the direction of information flow on one edge can impact the direction of information flow on other edges. More specifically, naturally extending the classical notion of a transitive orientation in static graphs, we introduce the fundamental notion of a *temporal transitive orientation* and we systematically investigate its algorithmic behavior in various situations. An orientation of a temporal graph is called *temporally transitive* if, whenever u has a directed edge towards v with time-label t_1 and v has a directed edge towards w with time-label $t_2 \geq t_1$, then u also has a directed edge towards w with some time-label $t_3 \geq t_2$. If we just demand that this implication holds whenever $t_2 > t_1$, the orientation is called *strictly* temporally transitive, as it is based on the fact that there is a strict directed temporal path from u to w. Our main result is a conceptually simple, yet technically quite involved, polynomial-time algorithm for recognizing whether a given temporal graph $\mathcal{G}$ is transitively orientable. In wide contrast we prove that, surprisingly, it is NP-hard to recognize whether $\mathcal{G}$ is strictly transitively orientable. Additionally we introduce and investigate further related problems to temporal transitivity, notably among them the *temporal transitive completion* problem, for which we prove both algorithmic and hardness results.

Due to lack of space, the full paper with all proofs is attached in an Appendix.

2012 ACM Subject Classification Theory of computation → Graph algorithms analysis; Mathematics of computing → Discrete mathematics

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1 Introduction

A *temporal* (or *dynamic*) network is, roughly speaking, a network whose underlying topology changes over time. This notion concerns a great variety of both modern and traditional networks; information and communication networks, social networks, and several physical systems are only few examples of networks which change over time [27,38,41]. Due to its vast applicability in many areas, the notion of temporal graphs has been studied from different perspectives under several different names such as *time-varying*, *evolving*, *dynamic*, and *graphs over time* (see [13–15] and the references therein). In this paper we adopt a simple and natural model for temporal networks which is given with discrete time-labels on the edges of a graph, while the vertex set remains unchanged. This formalism originates in the foundational work of Kempe et al. [28].

▶ **Definition 1** (Temporal Graph [28]). *A* temporal graph *is a pair $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$ is an underlying (static) graph and $\lambda : E \to \mathbb{N}$ is a* time-labeling *function which assigns to every edge of G a discrete-time label.*

Mainly motivated by the fact that, due to causality, entities and information in temporal graphs can only "flow" along sequences of edges whose time-labels are non-decreasing (resp. increasing), Kempe et al. introduced the notion of a *(strict) temporal path*, or *(strict) time-respecting path*, in a temporal graph (G, λ) as a path in G with edges $e_1, e_2, \ldots, e_k$ such that $\lambda(e_1) \leq \ldots \leq \lambda(e_k)$ (resp. $\lambda(e_1) < \ldots < \lambda(e_k)$). This notion of a temporal path naturally resembles the notion of a *directed* path in the classical static graphs, where the direction is from smaller to larger time-labels along the path. Nevertheless, in temporal paths the individual time-labeled edges remain undirected: an edge $e = \{u, v\}$ with time-label $\lambda(e) = t$ can be abstractly interpreted as "u communicates with v at time t". Here the relation "communicates" is symmetric between u and v, i.e. it can be interpreted that the information can flow in either direction.

In this paper we make a first attempt to understand how the direction of information flow on one edge can impact the direction of information flow on other edges. More specifically, naturally extending the classical notion of a transitive orientation in static graphs [24], we introduce the fundamental notion of a *temporal transitive orientation* and we thoroughly investigate its algorithmic behavior in various situations. Imagine that v receives information from u at time t_1, while w receives information from v at time $t_2 \geq t_1$. Then w *indirectly* receives information from u through the intermediate vertex v. Now, if the temporal graph correctly records the transitive closure of information passing, the directed edge from u to w must exist and must have a time label $t_3 \geq t_2$. In such a *transitively oriented* temporal graph, whenever an edge is oriented from a vertex u to a vertex w with time-label t, we have that *every* temporal path from u to w arrives no later than t, and that there is no temporal path from w to u. Different notions of temporal transitivity have also been used for automated temporal data mining [40] in medical applications [39], text processing [45]. Furthermore, in behavioral ecology, researchers have used a notion of orderly (transitive) triads A-B-C to quantify dominance among species. In particular, animal groups usually form dominance hierarchies in which dominance relations are transitive and can also change with time [33].

One natural motivation for our temporal transitivity notion may come from applications where confirmation and verification of information is vital, where vertices may represent entities such as investigative journalists or police detectives who gather sensitive information. Suppose that v queried some important information from u (the information source) at time t_1, and afterwards, at time $t_2 \geq t_1$, w queried the important information from v (the intermediary). Then, in order to ensure the validity of the information received, w might want to verify it by *subsequently* querying the information directly from u at some time $t_3 \geq t_2$. Note that w might first receive the important information from u through various other intermediaries, and using several channels of different lengths. Then, to maximize confidence about the information, w should query u for verification only after receiving the information from the latest of these indirect channels.

It is worth noting here that the model of temporal graphs given in Definition 1 has been also used in its extended form, in which the temporal graph may contain multiple time-labels per edge [35]. This extended temporal graph model has been used to investigate temporal paths [3, 9, 11, 16, 35, 48] and other temporal path-related notions such as temporal analogues of distance and diameter [1], reachability [2] and exploration [1, 3, 20, 21], separation [22, 28, 49], and path-based centrality measures [12, 29], as well as recently non-path problems too such as temporal variations of coloring [37], vertex cover [4], matching [36], cluster editing [18], and maximal cliques [8, 26, 47]. However, in order to better investigate and illustrate the inherent combinatorial structure of temporal transitivity orientations, in this paper we mostly follow the original definition of temporal graphs given by Kempe et al. [28] with one time-label per edge [7, 17, 19]. Throughout the paper, whenever we assume multiple time-labels per edge we will state it explicitly; in all other cases we consider a single label per edge.

In static graphs, the transitive orientation problem has received extensive attention which resulted in numerous efficient algorithms. A graph is called *transitively orientable* (or a *comparability* graph) if it is possible to orient its edges such that, whenever we orient u towards v and v towards w, then the edge between u and w exists and is oriented towards w. The first polynomial-time algorithms for recognizing whether a given (static) graph G on n vertices and m edges is comparability (i.e. transitively orientable) were based on the notion of *forcing* an orientation and had running time $O(n^3)$ (see Golumbic [24] and the references therein). Faster algorithms for computing a transitive orientation of a given comparability graph have been later developed, having running times $O(n^2)$ [43] and $O(n + m \log n)$ [30], while the currently fastest algorithms run in linear $O(n+m)$ time and are based on efficiently computing a modular decomposition of G [31, 32]; see also Spinrad [44]. It is fascinating that, although all the latter algorithms compute a valid transitive orientation if G is a comparability graph, they fail to recognize whether the input graph is a comparability graph; instead they produce an orientation which is non-transitive if G is not a comparability graph. The fastest known algorithm for determining whether a given orientation is transitive requires matrix multiplication, currently achieved in $O(n^{2.37286})$ time [5].

Our contribution. In this paper we introduce the notion of *temporal transitive orientation* and we thoroughly investigate its algorithmic behavior in various situations. An orientation of a temporal graph $\mathcal{G} = (G, \lambda)$ is called *temporally transitive* if, whenever u has a directed edge towards v with time-label t_1 and v has a directed edge towards w with time-label $t_2 \geq t_1$,[1] then u also has a directed edge towards w with some time-label $t_3 \geq t_2$. If we just demand that this implication holds whenever $t_2 > t_1$, the orientation is called *strictly* temporally transitive, as it is based on the fact that there is a strict directed temporal path from u to w. Similarly, if we demand that the transitive directed edge from u to w has time-label $t_3 > t_2$, the orientation is called *strongly* (resp. *strongly strictly)* temporally transitive.

Although these four natural variations of a temporally transitive orientation seem superficially similar to each other, it turns out that their computational complexity (and their underlying combinatorial structure) varies massively. Indeed we obtain a surprising result

[1] That is, whenever there exists a (non-strict) directed temporal path from u to w arriving at time t_2

in Section 3: deciding whether a temporal graph $\mathcal{G}$ admits a *temporally transitive* orientation is solvable in polynomial time (Section 3.2), while it is NP-hard to decide whether it admits a *strictly temporally transitive* orientation (Section 3.1). On the other hand, it turns out that, deciding whether $\mathcal{G}$ admits a *strongly* or a *strongly strictly* temporal transitive orientation is (easily) solvable in polynomial time as they can both be reduced to 2SAT satisfiability.

Our main result is that, given a temporal graph $\mathcal{G} = (G, \lambda)$, we can decide in polynomial time whether $\mathcal{G}$ can be transitively orientable, and at the same time we can output a temporal transitive orientation if it exists. Although the analysis and correctness proof of our algorithm is technically quite involved, our algorithm is simple and easy to implement, as it is based on the notion of *forcing* an orientation.[2] Our algorithm extends and generalizes the classical polynomial-time algorithm for computing a transitive orientation in static graphs described by Golumbic [24]. The main technical difficulty in extending the algorithm from the static to the temporal setting is that, in temporal graphs we cannot simply use orientation forcings to eliminate the condition that a *triangle* is not allowed to be cyclically oriented. To resolve this issue, we first express the recognition problem of temporally transitively orientable graphs as a Boolean satisfiability problem of a *mixed* Boolean formula $\phi_{3\mathrm{NAE}} \wedge \phi_{2\mathrm{SAT}}$. Here $\phi_{3\mathrm{NAE}}$ is a 3NAE (i.e. 3-Not-All-Equal) formula and $\phi_{2\mathrm{SAT}}$ is a 2SAT formula. Note that every clause $\mathtt{NAE}(\ell_1, \ell_2, \ell_3)$ of $\phi_{3\mathrm{NAE}}$ corresponds to the condition that a specific triangle in the temporal graph cannot be cyclically oriented. However, although deciding whether $\phi_{2\mathrm{SAT}}$ is satisfiable can be done in linear time with respect to the size of the formula [6], the problem Not-All-Equal-3-SAT is NP-complete [42].

Our algorithm iteratively produces at iteration j a formula $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$, which is computed from the previous formula $\phi^{(j-1)}_{3\mathrm{NAE}} \wedge \phi^{(j-1)}_{2\mathrm{SAT}}$ by (almost) simulating the classical greedy algorithm that solves 2SAT [6]. The 2SAT-algorithm proceeds greedily as follows. For every variable x_i, if setting $x_i = 1$ (resp. $x_i = 0$) leads to an immediate contradiction, the algorithm is forced to set $x_i = 0$ (resp. $x_i = 1$). Otherwise, if each of the truth assignments $x_i = 1$ and $x_i = 0$ does not lead to an immediate contradiction, the algorithm arbitrarily chooses to set $x_i = 1$ or $x_i = 0$, and thus some clauses are removed from the formula as they were satisfied. The argument for the correctness of the 2SAT-algorithm is that new clauses are *never added* to the formula at any step. The main technical difference between the 2SAT-algorithm and our algorithm is that, in our case, the formula $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is *not* necessarily a sub-formula of $\phi^{(j-1)}_{3\mathrm{NAE}} \wedge \phi^{(j-1)}_{2\mathrm{SAT}}$, as in some cases we need to also add clauses. Our main technical result is that, nevertheless, at every iteration j the formula $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is satisfiable if and only if $\phi^{(j-1)}_{3\mathrm{NAE}} \wedge \phi^{(j-1)}_{2\mathrm{SAT}}$ is satisfiable. The proof of this result (see Theorem 9) relies on a sequence of structural properties of temporal transitive orientations which we establish. This phenomenon of deducing a polynomial-time algorithm for an algorithmic graph problem by deciding satisfiability of a mixed Boolean formula (i.e. with both clauses of two and three literals) occurs rarely; this approach has been successfully used for the efficient recognition of simple-triangle (known also as "PI") graphs [34].

In the second part of our paper (Section 4) we consider a natural extension of the temporal orientability problem, namely the *temporal transitive completion* problem. In this problem we are given a temporal graph $\mathcal{G}$ and a natural number k, and the question is whether it is possible to add at most k new edges (with the corresponding time-labels) to $\mathcal{G}$ such that the resulting temporal graph is (strongly/strictly/strongly strictly) transitively orientable. We prove that all four versions of temporal transitive completion are NP-complete. In contrast

[2] That is, orienting an edge from u to v *forces* us to orient another edge from a to b.

we show that, if the input temporal graph $\mathcal{G}$ is *directed* (i.e. if every time-labeled edge has a fixed orientation) then all versions of temporal transitive completion are solvable in polynomial time. As a corollary of our results it follows that all four versions of temporal transitive completion are fixed-parameter-tractable (FPT) with respect to the number q of unoriented time-labeled edges in $\mathcal{G}$.

In the third and last part of our paper (Section 5) we consider the *multilayer transitive orientation* problem. In this problem we are given an undirected temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, and we ask whether there exists an orientation F of its edges (i.e. with exactly one orientation for each edge of G) such that, for every 'time-layer" $t \geq 1$, the (static) oriented graph induced by the edges having time-label t is transitively oriented in F. Problem definitions of this type are commonly referred to as multilayer problems [10], Observe that this problem trivially reduces to the static case if we assume that each edge has a single time-label, as then each layer can be treated independently of all others. However, if we allow $\mathcal{G}$ to have multiple time-labels on every edge of G, then we show that the problem becomes NP-complete, even when every edge has at most two labels.

2 Preliminaries and Notation

Given a (static) undirected graph $G = (V, E)$, an edge between two vertices $u, v \in V$ is denoted by the unordered pair $\{u, v\} \in E$, and in this case the vertices u, v are said to be *adjacent*. If the graph is directed, we will use the ordered pair (u, v) (resp. (v, u)) to denote the oriented edge from u to v (resp. from v to u). For simplicity of the notation, we will usually drop the parentheses and the comma when denoting an oriented edge, i.e. we will denote (u, v) just by uv. Furthermore, $\widehat{uv} = \{uv, vu\}$ is used to denote the set of both oriented edges uv and vu between the vertices u and v.

Let $S \subseteq E$ be a subset of the edges of an undirected (static) graph $G = (V, E)$, and let $\widehat{S} = \{uv, vu : \{u, v\} \in S\}$ be the set of both possible orientations uv and vu of every edge $\{u, v\} \in S$. Let $F \subseteq \widehat{S}$. If F contains *at least one* of the two possible orientations uv and vu of each edge $\{u, v\} \in S$, then F is called an *orientation* of the edges of S. F is called a *proper orientation* if it contains *exactly one* of the orientations uv and vu of every edge $\{u, v\} \in S$. Note here that, in order to simplify some technical proofs, the above definition of an orientation allows F to be not proper, i.e. to contain *both* uv and vu for a specific edge $\{u, v\}$. However, whenever F is not proper, this means that F can be discarded as it cannot be used as a part of a (temporal) transitive orientation. For every orientation F denote by $F^{-1} = \{vu : uv \in F\}$ the *reversal* of F. Note that $F \cap F^{-1} = \emptyset$ if and only if F is proper.

In a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, whenever $\lambda(\{v, w\}) = t$ (or simply $\lambda(v, w) = t$), we refer to the tuple $(\{v, w\}, t)$ as a *time-edge* of $\mathcal{G}$. A triangle of (G, λ) on the vertices u, v, w is a *synchronous triangle* if $\lambda(u, v) = \lambda(v, w) = \lambda(w, u)$. Let $G = (V, E)$ and let F be a proper orientation of the whole edge set E. Then $(\mathcal{G}, F)$, or (G, λ, F), is a *proper orientation* of the temporal graph $\mathcal{G}$. A *partial proper orientation* F of $\mathcal{G} = (G, \lambda)$ is an orientation of a subset of E. To indicate that the edge $\{u, v\}$ of a time-edge $(\{u, v\}, t)$ is oriented from u to v (that is, $uv \in F$ in a (partial) proper orientation F), we use the term $((u, v), t)$, or simply (uv, t). For simplicity we may refer to a (partial) proper orientation just as a (partial) orientation, whenever the term "proper" is clear from the context.

A static graph $G = (V, E)$ is a *comparability graph* if there exists a proper orientation F of E which is *transitive*, that is, if $F \cap F^{-1} = \emptyset$ and $F^2 \subseteq F$, where $F^2 = \{uw : uv, vw \in F$ for some vertex $v\}$ [24]. Analogously, in a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, we define a proper orientation F of E to be *temporally transitive*, if:

> whenever (uv, t_1) and (vw, t_2) are oriented time-edges in $(\mathcal{G}, F)$ such that $t_2 \geq t_1$, there exists an oriented time-edge (wu, t_3) in $(\mathcal{G}, F)$, for some $t_3 \geq t_2$.

In the above definition of a temporally transitive orientation, if we replace the condition "$t_3 \geq t_2$" with "$t_3 > t_2$", then F is called *strongly temporally transitive*. If we instead replace the condition "$t_2 \geq t_1$" with "$t_2 > t_1$", then F is called *strictly temporally transitive*. If we do both of these replacements, then F is called *strongly strictly temporally transitive*. Note that strong (strict) temporal transitivity implies (strict) temporal transitivity, while (strong) temporal transitivity implies (strong) strict temporal transitivity. Furthermore, similarly to the established terminology for static graphs, we define a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, to be a *(strongly/strictly) temporal comparability graph* if there exists a proper orientation F of E which is *(strongly/strictly) temporally transitive*.

We are now ready to formally introduce the following decision problem of recognizing whether a given temporal graph is temporally transitively orientable or not.

Temporal Transitive Orientation (TTO)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$.
Question: Does $\mathcal{G}$ admit a temporally transitive orientation F of E?

In the above problem definition of TTO, if we ask for the existence of a strictly (resp. strongly, or strongly strictly) temporally transitive orientation F, we obtain the decision problem Strict (resp. Strong, or Strong Strict) Temporal Transitive Orientation (TTO).

Let $\mathcal{G} = (G, \lambda)$ be a temporal graph, where $G = (V, E)$. Let $G' = (V, E')$ be a graph such that $E \subseteq E'$, and let $\lambda' \colon E' \to \mathbb{N}$ be a time-labeling function such that $\lambda'(u, v) = \lambda(u, v)$ for every $\{u, v\} \in E$. Then the temporal graph $\mathcal{G}' = (G', \lambda')$ is called a *temporal supergraph of* $\mathcal{G}$. We can now define our next problem definition regarding computing temporally orientable supergraphs of $\mathcal{G}$.

Temporal Transitive Completion (TTC)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, a (partial) orientation F of $\mathcal{G}$, and an integer k.
Question: Does there exist a temporal supergraph $\mathcal{G}' = (G', \lambda')$ of (G, λ), where $G' = (V, E')$, and a transitive orientation $F' \supseteq F$ of $\mathcal{G}'$ such that $|E' \setminus E| \leq k$?

Similarly to TTO, if we ask in the problem definition of TTC for the existence of a strictly (resp. strongly, or strongly strictly) temporally transitive orientation F', we obtain the decision problem Strict (resp. Strong, or Strong Strict) Temporal Transitive Completion (TTC).

Now we define our final problem which asks for an orientation F of a temporal graph $\mathcal{G} = (G, \lambda)$ (i.e. with exactly one orientation for each edge of G) such that, for every "time-layer" $t \geq 1$, the (static) oriented graph defined by the edges having time-label t is transitively oriented in F. This problem does not make much sense if every edge has exactly one time-label in $\mathcal{G}$, as in this case it can be easily solved by just repeatedly applying any known static transitive orientation algorithm. Therefore, in the next problem definition, we assume that in the input temporal graph $\mathcal{G} = (G, \lambda)$ every edge of G potentially has multiple time-labels, i.e. the time-labeling function is $\lambda : E \to 2^{\mathbb{N}}$.

Multilayer Transitive Orientation (MTO)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$ and $\lambda : E \to 2^{\mathbb{N}}$.
Question: Is there an orientation F of the edges of G such that, for every $t \geq 1$, the (static) oriented graph induced by the edges having time-label t is transitively oriented?

	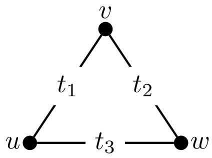			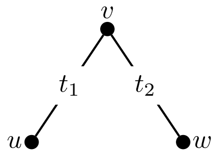	
	$t_1 = t_2 = t_3$	$t_1 < t_2 = t_3$	$t_1 \leq t_2 < t_3$	$t_1 = t_2$	$t_1 < t_2$
TTO	non-cyclic	$wu = wv$	$vw \implies uw$ $vu \implies wu$	$uv = wv$	$uv \implies wv$
Strong TTO	$\bot$	$wu \wedge wv$	$vw \implies uw$ $vu \implies wu$	$uv = wv$	$uv \implies wv$
Strict TTO	$\top$	non-cyclic	$vw \implies uw$ $vu \implies wu$	$\top$	$uv \implies wv$
Str. Str. TTO	$\top$	$vu \implies wu$ $uv \implies wv$	$vw \implies uw$ $vu \implies wu$	$\top$	$uv \implies wv$

Table 1 Orientation conditions imposed by a triangle (left) and an induced path of length two (right) in the underlying graph G for the decision problems (Strict/Strong/Strong Strict) TTO. Here, $\top$ means that no restriction is imposed, $\bot$ means that the graph is not orientable, and in the case of triangles, "non-cyclic" means that all orientations except the ones that orient the triangle cyclicly are allowed.

3 The recognition of temporally transitively orientable graphs

In this section we investigate the computational complexity of all variants of TTO. We show that TTO as well as the two variants Strong TTO and Strong Strict TTO, are solvable in polynomial time, whereas Strict TTO turns out to be NP-complete.

The main idea of our approach to solve TTO and its variants is to create Boolean variables for each edge of the underlying graph G and interpret setting a variable to 1 or 0 with the two possible ways of directing the corresponding edge.

More formally, for every edge $\{u, v\}$ we introduce a variable x_{uv} and setting this variable to 1 corresponds to the orientation uv while setting this variable to 0 corresponds to the orientation vu. Now consider the example of Figure 1(a), i.e. an induced path of length two in the underlying graph G on three vertices u, v, w, and let $\lambda(u, v) = 1$ and $\lambda(v, w) = 2$. Then the orientation uv "forces" the orientation wv. Indeed, if we otherwise orient $\{v, w\}$ as vw, then the edge $\{u, w\}$ must exist and be oriented as uw in any temporal transitive orientation, which is a contradiction as there is no edge between u and w. We can express this "forcing" with the implication $x_{uv} \implies x_{wv}$. In this way we can deduce the constraints that all triangles or induced paths on three vertices impose on any (strong/strict/strong strict) temporal transitive orientation. We collect all these constraints in Table 1.

When looking at the conditions imposed on temporal transitive orientations collected in Table 1, we can observe that all conditions except "non-cyclic" are expressible in 2SAT. Since 2SAT is solvable in linear time [6], it immediately follows that the strong variants of temporal transitivity are solvable in polynomial time, as the next theorem states.

▶ **Theorem 2.** Strong TTO *and* Strong Strict TTO *are solvable in polynomial time.*

In the variants TTO and Strict TTO, however, we can have triangles which impose a "non-cyclic" orientation of three edges (Table 1). This can be naturally modeled by a not-all-equal (NAE) clause.[3] However, if we now naïvely model the conditions with a Boolean formula, we obtain a formula with 2SAT clauses and 3NAE clauses. Deciding whether such a formula is satisfiable is NP-complete in general [42]. Hence, we have to investigate these two variants more thoroughly.

The only difference between the triangles that impose these "non-cyclic" orientations in these two problem variants is that, in TTO, the triangle is *synchronous* (i.e. all its three edges have the same time-label), while in Strict TTO two of the edges are synchronous and the third one has a smaller time-label than the other two. As it turns out, this difference of the two problem variants has important implications on their computational complexity. In fact, we obtain a surprising result: TTO is solvable in polynomial time while Strict TTO is NP-complete.

3.1 Strict TTO is NP-Complete

In this section we show that in contrast to the other variants, Strict TTO is NP-complete.

▶ **Theorem 3.** Strict TTO *is NP-complete even if the temporal input graph has only four different time labels.*

3.2 A polynomial-time algorithm for TTO

Let $G = (V, E)$ be a static undirected graph. There are various polynomial-time algorithms for deciding whether G admits a transitive orientation F. However our results in this section are inspired by the transitive orientation algorithm described by Golumbic [24], which is based on the crucial notion of *forcing* an orientation. The notion of forcing in static graphs is illustrated in Figure 1 (a): if we orient the edge $\{u, v\}$ as uv (i.e., from u to v) then we are forced to orient the edge $\{v, w\}$ as wv (i.e., from w to v) in any transitive orientation F of G. Indeed, if we otherwise orient $\{v, w\}$ as vw (i.e. from v to w), then the edge $\{u, w\}$ must exist and it must be oriented as uw in any transitive orientation F of G, which is a contradiction as $\{u, w\}$ is not an edge of G. Similarly, if we orient the edge $\{u, v\}$ as vu then we are forced to orient the edge $\{v, w\}$ as vw. That is, in any transitive orientation F of G we have that $uv \in F \Leftrightarrow wv \in F$. This forcing operation can be captured by the binary forcing relation Γ which is defined on the edges of a static graph G as follows [24].

$$uv \; \Gamma \; u'v' \quad \text{if and only if} \quad \begin{cases} \text{either } u = u' \text{ and } \{v, v'\} \notin E \\ \text{or } v = v' \text{ and } \{u, u'\} \notin E \end{cases} . \tag{1}$$

We now extend the definition of Γ in a natural way to the binary relation Λ on the edges of a temporal graph (G, λ), see Equation (2). For this, observe from Table 1 that the only cases, where we have $uv \in F \Leftrightarrow wv \in F$ in any temporal transitive orientation of (G, λ), are when (i) the vertices u, v, w induce a path of length 2 (see Figure 1 (a)) and $\lambda(u, v) = \lambda(v, w)$, as well as when (ii) u, v, w induce a triangle and $\lambda(u, w) < \lambda(u, v) = \lambda(v, w)$. The latter situation is illustrated in the example of Figure 1 (b). The binary forcing relation Λ is only

[3] A not all equal clause is a set of literals and it evaluates to `true` if and only if at least two literals in the set evaluate to different truth values.

Figure 1 The orientation uv forces the orientation wu and vice-versa in the examples of (a) a static graph G where $\{u,v\},\{v,w\} \in E(G)$ and $\{u,w\} \notin E(G)$, and of (b) a temporal graph (G,λ) where $\lambda(u,w) = 3 < 5 = \lambda(u,v) = \lambda(v,w)$.

defined on pairs of edges $\{u,v\}$ and $\{u',v'\}$ where $\lambda(u,v) = \lambda(u',v')$, as follows.

$$uv \; \Lambda \; u'v' \quad \text{if and only if} \quad \lambda(u,v) = \lambda(u',v') = t \text{ and } \begin{cases} u = u' \text{ and } \{v,v'\} \notin E, \text{or} \\ v = v' \text{ and } \{u,u'\} \notin E, \text{or} \\ u = u' \text{ and } \lambda(v,v') < t, \text{or} \\ v = v' \text{ and } \lambda(u,u') < t. \end{cases} \tag{2}$$

Note that, for every edge $\{u,v\} \in E$ we have that $uv \; \Lambda \; uv$. The forcing relation Λ for temporal graphs shares some properties with the forcing relation Γ for static graphs. In particular, the reflexive transitive closure Λ^* of Λ is an equivalence relation, which partitions the edges of each set $E_t = \{\{u,v\} \in E : \lambda(u,v) = t\}$ into its Λ-*implication classes* (or simply, into its *implication classes*). Two edges $\{a,b\}$ and $\{c,d\}$ are in the same Λ-implication class if and only $ab \; \Lambda^* \; cd$, i.e. there exists a sequence $ab = a_0b_0 \; \Lambda \; a_1b_1 \; \Lambda \; \ldots \; \Lambda \; a_kb_k = cd$, with $k \geq 0$. Note that, for this to happen, we must have $\lambda(a_0,b_0) = \lambda(a_1,b_1) = \ldots = \lambda(a_k,b_k) = t$ for some $t \geq 1$. Such a sequence is called a Λ-chain from ab to cd, and we say that ab (eventually) Λ-forces cd. Furthermore note that $ab \; \Lambda^* \; cd$ if and only if $ba \; \Lambda^* \; dc$. For the next lemma, we use the notation $\widehat{A} = \{uv, vu : uv \in A\}$.

▶ **Lemma 4.** *Let A be a Λ-implication class of a temporal graph (G,λ). Then either $A = A^{-1} = \widehat{A}$ or $A \cap A^{-1} = \emptyset$.*

▶ **Definition 5.** *Let F be a proper orientation and A be a Λ-implication class of a temporal graph (G,λ). If $A \subseteq F$, we say that F* respects *A.*

▶ **Lemma 6.** *Let F be a proper orientation and A be a Λ-implication class of a temporal graph (G,λ). Then F respects either A or A^{-1} (i.e. either $A \subseteq F$ or $A^{-1} \subseteq F$), and in either case $A \cap A^{-1} = \emptyset$.*

The next lemma, which is crucial for proving the correctness of our algorithm, extends an important known property of the forcing relation Γ for static graphs [24, Lemma 5.3] to the temporal case.

▶ **Lemma 7** (Temporal Triangle Lemma)**.** *Let (G,λ) be a temporal graph and with a synchronous triangle on the vertices a,b,c, where $\lambda(a,b) = \lambda(b,c) = \lambda(c,a) = t$. Let A,B,C be three Λ-implication classes of (G,λ), where $ab \in C$, $bc \in A$, and $ca \in B$, where $A \neq B^{-1}$ and $A \neq C^{-1}$.*

1. *If some $b'c' \in A$, then $ab' \in C$ and $c'a \in B$.*
2. *If some $b'c' \in A$ and $a'b' \in C$, then $c'a' \in B$.*
3. *No edge of A touches vertex a.*

Deciding temporal transitivity using Boolean satisfiability. Starting with any undirected edge $\{u, v\}$ of the underlying graph G, we can clearly enumerate in polynomial time the whole Λ-implication class A to which the oriented edge uv belongs (cf. Equation (2)). If the reversely directed edge $vu \in A$ then Lemma 4 implies that $A = A^{-1} = \widehat{A}$. Otherwise, if $vu \notin A$ then $vu \in A^{-1}$ and Lemma 4 implies that $A \cap A^{-1} = \emptyset$. Thus, we can also decide in polynomial time whether $A \cap A^{-1} = \emptyset$. If we encounter a Λ-implication class A such that $A \cap A^{-1} \neq \emptyset$, then it follows by Lemma 6 that (G, λ) is not temporally transitively orientable.

In the remainder of the section we will assume that $A \cap A^{-1} = \emptyset$ for every Λ-implication class A of (G, λ), which is a *necessary* condition for (G, λ) to be temporally transitive orientable. Moreover it follows by Lemma 6 that, if (G, λ) admits a temporally transitively orientation F, then either $A \subseteq F$ or $A^{-1} \subseteq F$. This allows us to define a Boolean variable x_A for every Λ-implication class A, where $x_A = \overline{x_{A^{-1}}}$. Here $x_A = 1$ (resp. $x_{A^{-1}} = 1$) means that $A \subseteq F$ (resp. $A^{-1} \subseteq F$), where F is the temporally transitive orientation which we are looking for. Let $\{A_1, A_2, \ldots, A_s\}$ be a set of Λ-implication classes such that $\{\widehat{A_1}, \widehat{A_2}, \ldots, \widehat{A_s}\}$ is a partition of the edges of the underlying graph G.[4] Then any truth assignment τ of the variables $x_1, x_2, \ldots, x_s$ (where $x_i = x_{A_i}$ for every $i = 1, 2, \ldots, s$) corresponds bijectively to one possible orientation of the temporal graph (G, λ), in which every Λ-implication class is oriented consistently.

Now we define two Boolean formulas ϕ_{3NAE} and ϕ_{2SAT} such that (G, λ) admits a temporal transitive orientation if and only if there is a truth assignment τ of the variables $x_1, x_2, \ldots, x_s$ such that both ϕ_{3NAE} and ϕ_{2SAT} are simultaneously satisfied. Intuitively, ϕ_{3NAE} captures the "non-cyclic" condition from Table 1 while ϕ_{2SAT} captures the remaining conditions. Here ϕ_{3NAE} is a 3NAE formula, i.e., the disjunction of clauses with three literals each, where every clause $\texttt{NAE}(\ell_1, \ell_2, \ell_3)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2, \ell_3\}$ is equal to 1 and at least one of them is equal to 0. Furthermore ϕ_{2SAT} is a 2SAT formula, i.e., the disjunction of 2CNF clauses with two literals each, where every clause $(\ell_1 \vee \ell_2)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2\}$ is equal to 1.

Description of the 3NAE formula ϕ_{3NAE}. The formula ϕ_{3NAE} captures the "non-cyclic" condition of the problem variant TTO (presented in Table 1). The formal description of ϕ_{3NAE} is as follows. Consider a synchronous triangle of (G, λ) on the vertices u, v, w. Assume that $x_{uv} = x_{wv}$ (resp. $x_{vw} = x_{uw}$, or $x_{wu} = x_{vu}$) is true. Then the pair $\{uv, wv\}$ (resp. $\{vw, uw\}$, or $\{wu, vu\}$) of oriented edges belongs to the same Λ-implication class A_i. This implies that the triangle on the vertices u, v, w is never cyclically oriented in any proper orientation F that respects A_i or A_i^{-1}. Assume, on the contrary, that $x_{uv} \neq x_{wv}$, $x_{vw} \neq x_{uw}$, and $x_{wu} \neq x_{vu}$. In this case we add to ϕ_{3NAE} the clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$. Note that the triangle on u, v, w is transitively oriented if and only if $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ is satisfied, i.e., at least one of the variables $\{x_{uv}, x_{vw}, x_{wu}\}$ receives the value 1 and at least one of them receives the value 0.

Description of the 2SAT formula ϕ_{2SAT}. The formula ϕ_{2SAT} captures all conditions apart from the "non-cyclic" condition of the problem variant TTO (presented in Table 1). The formal description of ϕ_{2SAT} is as follows. Consider a triangle of (G, λ) on the vertices u, v, w, where $\lambda(u, v) = t_1$, $\lambda(v, w) = t_2$, $\lambda(w, v) = t_3$, and $t_1 \leq t_2 \leq t_3$. If $t_1 < t_2 = t_3$ then we add to ϕ_{2SAT} the clauses $(x_{uw} \vee x_{wv}) \wedge (x_{vw} \vee x_{wu})$; note that these clauses are equivalent to

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[4] Here we slightly abuse the notation by identifying the undirected edge $\{u, v\}$ with the set of both its orientations $\{uv, vu\}$.

$x_{wu} = x_{wv}$. If $t_1 \leq t_2 < t_3$ then we add to ϕ_{2SAT} the clauses $(x_{wv} \vee x_{uw}) \wedge (x_{uv} \vee x_{wu})$; note that these clauses are equivalent to $(x_{vw} \Rightarrow x_{uw}) \wedge (x_{vu} \Rightarrow x_{wu})$. Now consider a path of length 2 that is induced by the vertices u, v, w, where $\lambda(u,v) = t_1$, $\lambda(v,w) = t_2$, and $t_1 \leq t_2$. If $t_1 = t_2$ then we add to ϕ_{2SAT} the clauses $(x_{vu} \vee x_{wv}) \wedge (x_{vw} \vee x_{uv})$; note that these clauses are equivalent to $(x_{uv} = x_{wv})$. Finally, if $t_1 < t_2$ then we add to ϕ_{2SAT} the clause $(x_{vu} \vee x_{wv})$; note that this clause is equivalent to $(x_{uv} \Rightarrow x_{wv})$.

Brief outline of the algorithm. In the *initialization phase*, we exhaustively check which truth values are *forced* in $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ by using the subroutine Initial-Forcing. During the execution of Initial-Forcing, we either replace the formulas ϕ_{3NAE} and ϕ_{2SAT} by the equivalent formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$, respectively, or we reach a contradiction by showing that $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ is unsatisfiable.

▶ **Observation 8.** *The temporal graph (G, λ) is transitively orientable if and only if $\phi^{(0)}_{3NAE} \wedge \phi^{(0)}_{2SAT}$ is satisfiable.*

The *main phase* of the algorithm starts once the formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$ have been computed. During this phase, we iteratively modify the formulas such that, at the end of iteration j we have the formulas $\phi^{(j)}_{\text{3NAE}}$ and $\phi^{(j)}_{\text{2SAT}}$. As we prove in our *main technical result* of this section (Theorem 9), $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ is satisfiable if and only if $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ is satisfiable. Note that, during the execution of the algorithm, we can *both add and remove* clauses from $\phi^{(j)}_{\text{2SAT}}$. On the other hand, we can *only remove* clauses from $\phi^{(j)}_{\text{3NAE}}$. Thus, at some iteration j, we obtain $\phi^{(j)}_{\text{3NAE}} = \emptyset$, and after that iteration we only need to decide satisfiability of $\phi^{(j)}_{\text{2SAT}}$ which can be done efficiently [6].

We are now ready to present in the next theorem our main technical result of this section.

▶ **Theorem 9.** *For every iteration $j \geq 1$ of the algorithm, $\phi^{(j)}_{3NAE} \wedge \phi^{(j)}_{2SAT}$ is satisfiable if and only if $\phi^{(j-1)}_{3NAE} \wedge \phi^{(j-1)}_{2SAT}$ is satisfiable.*

Using Theorem 9, we can now conclude this section with the next theorem.

▶ **Theorem 10.** TTO *can be solved in polynomial time.*

Proof sketch. First recall by Observation 8 that the input temporal graph (G, λ) is transitively orientable if and only if $\phi^{(0)}_{\text{3NAE}} \wedge \phi^{(0)}_{\text{2SAT}}$ is satisfiable.

Let (G, λ) be a *yes*-instance. Then, by iteratively applying Theorem 9 it follows that $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ is satisfiable, for every iteration j of the algorithm. Recall that, at the end of the last iteration k of the algorithm, $\phi^{(k)}_{\text{3NAE}} \wedge \phi^{(k)}_{\text{2SAT}}$ is empty. Then the algorithm gives the arbitrary truth value $x_i = 1$ to every variable x_i which did not yet get any truth value yet. This is a correct decision as all these variables are not involved in any Boolean constraint of $\phi^{(k)}_{\text{3NAE}} \wedge \phi^{(k)}_{\text{2SAT}}$ (which is empty). Finally, the algorithm orients all edges of G according to the corresponding truth assignment. The returned orientation F of (G, λ) is temporally transitive as every variable was assigned a truth value according to the Boolean constraints throughout the execution of the algorithm.

Now let (G, λ) be a *no*-instance. We will prove that, at some iteration $j \leq 0$, the algorithm will "NO". Suppose otherwise that the algorithm instead returns an orientation F of (G, λ) after performing k iterations. Then clearly $\phi^{(k)}_{\text{3NAE}} \wedge \phi^{(k)}_{\text{2SAT}}$ is empty, and thus clearly satisfiable. Therefore, iteratively applying Theorem 9 implies that $\phi^{(0)}_{\text{3NAE}} \wedge \phi^{(0)}_{\text{2SAT}}$ is also satisfiable, and thus (G, λ) is temporally transitively orientable by Observation 8, which is a contradiction to the assumption that (G, λ) be a *no*-instance.

Lastly, we prove that our algorithm runs in polynomial time. The Λ-implication classes of (G, λ) can be clearly computed in polynomial time. Our algorithm calls a subroutine Boolean-Forcing at most four times for every variable in $\phi^{(0)}_{3NAE} \wedge \phi^{(0)}_{2SAT}$. Boolean-Forcing iteratively adds and removes clauses from the 2SAT part of the formula, while it can only remove clauses from the 3NAE part. Whenever a clause is added to the 2SAT part, a clause of the 3NAE part is removed. Therefore, as the initial 3NAE formula has at most polynomially-many clauses, we can add clauses to the 2SAT part only polynomially-many times. Hence, we have an overall polynomial running time. ◀

4 Temporal Transitive Completion

We now study the computational complexity of Temporal Transitive Completion (TTC). In the static case, the so-called *minimum comparability completion* problem, i.e. adding the smallest number of edges to a static graph to turn it into a comparability graph, is known to be NP-hard [25]. Note that minimum comparability completion on static graphs is a special case of TTC and thus it follows that TTC is NP-hard too. Our other variants, however, do not generalize static comparability completion in such a straightforward way. Note that for Strict TTC we have that the corresponding recognition problem Strict TTO is NP-complete (Theorem 3), hence it follows directly that Strict TTC is NP-hard. For the remaining two variants of our problem, we show in the following that they are also NP-hard, giving the result that all four variants of TTC are NP-hard. Furthermore, we present a polynomial-time algorithm for all four problem variants for the case that all edges of underlying graph are oriented, see Theorem 12. This allows directly to derive an FPT algorithm for the number of unoriented edges as a parameter.

▶ **Theorem 11.** *All four variants of* TTC *are NP-hard.*

We now show that TTC can be solved in polynomial time, if all edges are already oriented, as the next theorem states.

▶ **Theorem 12.** *An instance $(\mathcal{G}, F, k)$ of* TTC *where $\mathcal{G} = (G, \lambda)$ and $G = (V, E)$, can be solved in $O(m^2)$ time if F is an orientation of E, where $m = |E|$.*

Using Theorem 12 we can now prove that TTC is fixed-parameter tractable (FPT) with respect to the number of unoriented edges in the input temporal graph $\mathcal{G}$.

▶ **Corollary 13.** *Let $I = (\mathcal{G} = (G, \lambda), F, k)$ be an instance of* TTC*, where $G = (V, E)$. Then I can be solved in $O(2^q \cdot m^2)$, where $q = |E| - |F|$ and m the number of time edges.*

5 Deciding Multilayer Transitive Orientation

In this section we prove that Multilayer Transitive Orientation (MTO) is NP-complete, even if every edge of the given temporal graph has at most two labels. Recall that this problem asks for an orientation F of a temporal graph $\mathcal{G} = (G, \lambda)$ (i.e. with exactly one orientation for each edge of G) such that, for every “time-layer” $t \geq 1$, the (static) oriented graph defined by the edges having time-label t is transitively oriented in F. As we discussed in Section 2, this problem makes more sense when every edge of G potentially has multiple time-labels, therefore we assume here that the time-labeling function is $\lambda : E \to 2^{\mathbb{N}}$.

▶ **Theorem 14.** MTO *is NP-complete, even on temporal graphs with at most two labels per edge.*

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APPENDIX

The Complexity of Transitively Orienting Temporal Graphs

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Abstract

In a *temporal network* with discrete time-labels on its edges, entities and information can only "flow" along sequences of edges whose time-labels are non-decreasing (resp. increasing), i.e. along temporal (resp. strict temporal) paths. Nevertheless, in the model for temporal networks of [Kempe, Kleinberg, Kumar, JCSS, 2002], the individual time-labeled edges remain undirected: an edge $e = \{u, v\}$ with time-label t specifies that "u communicates with v at time t". This is a symmetric relation between u and v, and it can be interpreted that the information can flow in either direction. In this paper we make a first attempt to understand how the direction of information flow on one edge can impact the direction of information flow on other edges. More specifically, naturally extending the classical notion of a transitive orientation in static graphs, we introduce the fundamental notion of a *temporal transitive orientation* and we systematically investigate its algorithmic behavior in various situations. An orientation of a temporal graph is called *temporally transitive* if, whenever u has a directed edge towards v with time-label t_1 and v has a directed edge towards w with time-label $t_2 \geq t_1$, then u also has a directed edge towards w with some time-label $t_3 \geq t_2$. If we just demand that this implication holds whenever $t_2 > t_1$, the orientation is called *strictly* temporally transitive, as it is based on the fact that there is a strict directed temporal path from u to w. Our main result is a conceptually simple, yet technically quite involved, polynomial-time algorithm for recognizing whether a given temporal graph $\mathcal{G}$ is transitively orientable. In wide contrast we prove that, surprisingly, it is NP-hard to recognize whether $\mathcal{G}$ is strictly transitively orientable. Additionally we introduce and investigate further related problems to temporal transitivity, notably among them the *temporal transitive completion* problem, for which we prove both algorithmic and hardness results.

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1 Introduction

A *temporal* (or *dynamic*) network is, roughly speaking, a network whose underlying topology changes over time. This notion concerns a great variety of both modern and traditional networks; information and communication networks, social networks, and several physical systems are only few examples of networks which change over time [27,38,41]. Due to its vast applicability in many areas, the notion of temporal graphs has been studied from different perspectives under several different names such as *time-varying*, *evolving*, *dynamic*, and *graphs over time* (see [13–15] and the references therein). In this paper we adopt a simple and natural model for temporal networks which is given with discrete time-labels on the edges of a graph, while the vertex set remains unchanged. This formalism originates in the foundational work of Kempe et al. [28].

▶ **Definition 1** (Temporal Graph [28]). *A* temporal graph *is a pair* $\mathcal{G} = (G, \lambda)$*, where* $G = (V, E)$ *is an underlying (static) graph and* $\lambda : E \to \mathbb{N}$ *is a* time-labeling *function which assigns to every edge of* G *a discrete-time label.*

Mainly motivated by the fact that, due to causality, entities and information in temporal graphs can only "flow" along sequences of edges whose time-labels are non-decreasing (resp. increasing), Kempe et al. introduced the notion of a *(strict) temporal path*, or *(strict) time-respecting path*, in a temporal graph (G, λ) as a path in G with edges $e_1, e_2, \ldots, e_k$ such that $\lambda(e_1) \leq \ldots \leq \lambda(e_k)$ (resp. $\lambda(e_1) < \ldots < \lambda(e_k)$). This notion of a temporal path naturally resembles the notion of a *directed* path in the classical static graphs, where the direction is from smaller to larger time-labels along the path. Nevertheless, in temporal paths the individual time-labeled edges remain undirected: an edge $e = \{u, v\}$ with time-label $\lambda(e) = t$ can be abstractly interpreted as "u communicates with v at time t". Here the relation "communicates" is symmetric between u and v, i.e. it can be interpreted that the information can flow in either direction.

In this paper we make a first attempt to understand how the direction of information flow on one edge can impact the direction of information flow on other edges. More specifically, naturally extending the classical notion of a transitive orientation in static graphs [24], we introduce the fundamental notion of a *temporal transitive orientation* and we thoroughly investigate its algorithmic behavior in various situations. Imagine that v receives information from u at time t_1, while w receives information from v at time $t_2 \geq t_1$. Then w *indirectly* receives information from u through the intermediate vertex v. Now, if the temporal graph correctly records the transitive closure of information passing, the directed edge from u to w must exist and must have a time label $t_3 \geq t_2$. In such a *transitively oriented* temporal graph, whenever an edge is oriented from a vertex u to a vertex w with time-label t, we have that *every* temporal path from u to w arrives no later than t, and that there is no temporal path from w to u. Different notions of temporal transitivity have also been used for automated temporal data mining [40] in medical applications [39], text processing [45]. Furthermore, in behavioral ecology, researchers have used a notion of orderly (transitive) triads A-B-C to quantify dominance among species. In particular, animal groups usually form dominance hierarchies in which dominance relations are transitive and can also change with time [33].

One natural motivation for our temporal transitivity notion may come from applications where confirmation and verification of information is vital, where vertices may represent entities such as investigative journalists or police detectives who gather sensitive information. Suppose that v queried some important information from u (the information source) at time t_1, and afterwards, at time $t_2 \geq t_1$, w queried the important information from v (the intermediary). Then, in order to ensure the validity of the information received, w might

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want to verify it by *subsequently* querying the information directly from u at some time $t_3 \geq t_2$. Note that w might first receive the important information from u through various other intermediaries, and using several channels of different lengths. Then, to maximize confidence about the information, w should query u for verification only after receiving the information from the latest of these indirect channels.

It is worth noting here that the model of temporal graphs given in Definition 1 has been also used in its extended form, in which the temporal graph may contain multiple time-labels per edge [35]. This extended temporal graph model has been used to investigate temporal paths [3, 9, 11, 16, 35, 48] and other temporal path-related notions such as temporal analogues of distance and diameter [1], reachability [2] and exploration [1,3,20,21], separation [22,28,49], and path-based centrality measures [12,29], as well as recently non-path problems too such as temporal variations of coloring [37], vertex cover [4], matching [36], cluster editing [18], and maximal cliques [8, 26, 47]. However, in order to better investigate and illustrate the inherent combinatorial structure of temporal transitivity orientations, in this paper we mostly follow the original definition of temporal graphs given by Kempe et al. [28] with one time-label per edge [7, 17, 19]. Throughout the paper, whenever we assume multiple time-labels per edge we will state it explicitly; in all other cases we consider a single label per edge.

In static graphs, the transitive orientation problem has received extensive attention which resulted in numerous efficient algorithms. A graph is called *transitively orientable* (or a *comparability* graph) if it is possible to orient its edges such that, whenever we orient u towards v and v towards w, then the edge between u and w exists and is oriented towards w. The first polynomial-time algorithms for recognizing whether a given (static) graph G on n vertices and m edges is comparability (i.e. transitively orientable) were based on the notion of *forcing* an orientation and had running time $O(n^3)$ (see Golumbic [24] and the references therein). Faster algorithms for computing a transitive orientation of a given comparability graph have been later developed, having running times $O(n^2)$ [43] and $O(n + m \log n)$ [30], while the currently fastest algorithms run in linear $O(n+m)$ time and are based on efficiently computing a modular decomposition of G [31, 32]; see also Spinrad [44]. It is fascinating that, although all the latter algorithms compute a valid transitive orientation if G is a comparability graph, they fail to recognize whether the input graph is a comparability graph; instead they produce an orientation which is non-transitive if G is not a comparability graph. The fastest known algorithm for determining whether a given orientation is transitive requires matrix multiplication, currently achieved in $O(n^{2.37286})$ time [5].

Our contribution. In this paper we introduce the notion of *temporal transitive orientation* and we thoroughly investigate its algorithmic behavior in various situations. An orientation of a temporal graph $\mathcal{G} = (G, \lambda)$ is called *temporally transitive* if, whenever u has a directed edge towards v with time-label t_1 and v has a directed edge towards w with time-label $t_2 \geq t_1$,[1] then u also has a directed edge towards w with some time-label $t_3 \geq t_2$. If we just demand that this implication holds whenever $t_2 > t_1$, the orientation is called *strictly* temporally transitive, as it is based on the fact that there is a strict directed temporal path from u to w. Similarly, if we demand that the transitive directed edge from u to w has time-label $t_3 > t_2$, the orientation is called *strongly* (resp. *strongly strictly)* temporally transitive.

Although these four natural variations of a temporally transitive orientation seem superficially similar to each other, it turns out that their computational complexity (and their underlying combinatorial structure) varies massively. Indeed we obtain a surprising result

[1] That is, whenever there exists a (non-strict) directed temporal path from u to w arriving at time t_2

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in Section 3: deciding whether a temporal graph $\mathcal{G}$ admits a *temporally transitive* orientation is solvable in polynomial time (Section 3.2), while it is NP-hard to decide whether it admits a *strictly temporally transitive* orientation (Section 3.1). On the other hand, it turns out that, deciding whether $\mathcal{G}$ admits a *strongly* or a *strongly strictly* temporal transitive orientation is (easily) solvable in polynomial time as they can both be reduced to 2SAT satisfiability.

Our main result is that, given a temporal graph $\mathcal{G} = (G, \lambda)$, we can decide in polynomial time whether $\mathcal{G}$ can be transitively orientable, and at the same time we can output a temporal transitive orientation if it exists. Although the analysis and correctness proof of our algorithm is technically quite involved, our algorithm is simple and easy to implement, as it is based on the notion of *forcing* an orientation.[2] Our algorithm extends and generalizes the classical polynomial-time algorithm for computing a transitive orientation in static graphs described by Golumbic [24]. The main technical difficulty in extending the algorithm from the static to the temporal setting is that, in temporal graphs we cannot simply use orientation forcings to eliminate the condition that a *triangle* is not allowed to be cyclically oriented. To resolve this issue, we first express the recognition problem of temporally transitively orientable graphs as a Boolean satisfiability problem of a *mixed* Boolean formula $\phi_{3\text{NAE}} \wedge \phi_{2\text{SAT}}$. Here $\phi_{3\text{NAE}}$ is a 3NAE formula, i.e., the disjunction of clauses with three literals each, where every clause $\texttt{NAE}(\ell_1, \ell_2, \ell_3)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2, \ell_3\}$ is equal to 1 and at least one of them is equal to 0. Note that every clause $\texttt{NAE}(\ell_1, \ell_2, \ell_3)$ corresponds to the condition that a specific triangle in the temporal graph cannot be cyclically oriented. Furthermore $\phi_{2\text{SAT}}$ is a 2SAT formula, i.e., the disjunction of 2CNF clauses with two literals each, where every clause $(\ell_1 \vee \ell_2)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2\}$ is equal to 1. However, although deciding whether $\phi_{2\text{SAT}}$ is satisfiable can be done in linear time with respect to the size of the formula [6], the problem Not-All-Equal-3-SAT is NP-complete [42].

Our algorithm iteratively produces at iteration j a formula $\phi^{(j)}_{3\text{NAE}} \wedge \phi^{(j)}_{2\text{SAT}}$, which is computed from the previous formula $\phi^{(j-1)}_{3\text{NAE}} \wedge \phi^{(j-1)}_{2\text{SAT}}$ by (almost) simulating the classical greedy algorithm that solves 2SAT [6]. The 2SAT-algorithm proceeds greedily as follows. For every variable x_i, if setting $x_i = 1$ (resp. $x_i = 0$) leads to an immediate contradiction, the algorithm is forced to set $x_i = 0$ (resp. $x_i = 1$). Otherwise, if each of the truth assignments $x_i = 1$ and $x_i = 0$ does not lead to an immediate contradiction, the algorithm arbitrarily chooses to set $x_i = 1$ or $x_i = 0$, and thus some clauses are removed from the formula as they were satisfied. The argument for the correctness of the 2SAT-algorithm is that new clauses are *never added* to the formula at any step. The main technical difference between the 2SAT-algorithm and our algorithm is that, in our case, the formula $\phi^{(j)}_{3\text{NAE}} \wedge \phi^{(j)}_{2\text{SAT}}$ is *not* necessarily a sub-formula of $\phi^{(j-1)}_{3\text{NAE}} \wedge \phi^{(j-1)}_{2\text{SAT}}$, as in some cases we need to also add clauses. Our main technical result is that, nevertheless, at every iteration j the formula $\phi^{(j)}_{3\text{NAE}} \wedge \phi^{(j)}_{2\text{SAT}}$ is satisfiable if and only if $\phi^{(j-1)}_{3\text{NAE}} \wedge \phi^{(j-1)}_{2\text{SAT}}$ is satisfiable. The proof of this result (see Theorem 20) relies on a sequence of structural properties of temporal transitive orientations which we establish. This phenomenon of deducing a polynomial-time algorithm for an algorithmic graph problem by deciding satisfiability of a mixed Boolean formula (i.e. with both clauses of two and three literals) occurs rarely; this approach has been successfully used for the efficient recognition of simple-triangle (known also as "PI") graphs [34].

In the second part of our paper (Section 4) we consider a natural extension of the temporal orientability problem, namely the *temporal transitive completion* problem. In this problem

[2] That is, orienting an edge from u to v *forces* us to orient another edge from a to b.

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we are given a temporal graph $\mathcal{G}$ and a natural number k, and the question is whether it is possible to add at most k new edges (with the corresponding time-labels) to $\mathcal{G}$ such that the resulting temporal graph is (strongly/strictly/strongly strictly) transitively orientable. We prove that all four versions of temporal transitive completion are NP-complete. In contrast we show that, if the input temporal graph $\mathcal{G}$ is *directed* (i.e. if every time-labeled edge has a fixed orientation) then all versions of temporal transitive completion are solvable in polynomial time. As a corollary of our results it follows that all four versions of temporal transitive completion are fixed-parameter-tractable (FPT) with respect to the number q of unoriented time-labeled edges in $\mathcal{G}$.

In the third and last part of our paper (Section 5) we consider the *multilayer transitive orientation* problem. In this problem we are given an undirected temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, and we ask whether there exists an orientation F of its edges (i.e. with exactly one orientation for each edge of G) such that, for every 'time-layer" $t \geq 1$, the (static) oriented graph induced by the edges having time-label t is transitively oriented in F. Problem definitions of this type are commonly referred to as multilayer problems [10], Observe that this problem trivially reduces to the static case if we assume that each edge has a single time-label, as then each layer can be treated independently of all others. However, if we allow $\mathcal{G}$ to have multiple time-labels on every edge of G, then we show that the problem becomes NP-complete, even when every edge has at most two labels.

2 Preliminaries and Notation

Given a (static) undirected graph $G = (V, E)$, an edge between two vertices $u, v \in V$ is denoted by the unordered pair $\{u, v\} \in E$, and in this case the vertices u, v are said to be *adjacent*. If the graph is directed, we will use the ordered pair (u, v) (resp. (v, u)) to denote the oriented edge from u to v (resp. from v to u). For simplicity of the notation, we will usually drop the parentheses and the comma when denoting an oriented edge, i.e. we will denote (u, v) just by uv. Furthermore, $\widehat{uv} = \{uv, vu\}$ is used to denote the set of both oriented edges uv and vu between the vertices u and v.

Let $S \subseteq E$ be a subset of the edges of an undirected (static) graph $G = (V, E)$, and let $\widehat{S} = \{uv, vu : \{u, v\} \in S\}$ be the set of both possible orientations uv and vu of every edge $\{u, v\} \in S$. Let $F \subseteq \widehat{S}$. If F contains *at least one* of the two possible orientations uv and vu of each edge $\{u, v\} \in S$, then F is called an *orientation* of the edges of S. F is called a *proper orientation* if it contains *exactly one* of the orientations uv and vu of every edge $\{u, v\} \in S$. Note here that, in order to simplify some technical proofs, the above definition of an orientation allows F to be not proper, i.e. to contain *both* uv and vu for a specific edge $\{u, v\}$. However, whenever F is not proper, this means that F can be discarded as it cannot be used as a part of a (temporal) transitive orientation. For every orientation F denote by $F^{-1} = \{vu : uv \in F\}$ the *reversal* of F. Note that $F \cap F^{-1} = \emptyset$ if and only if F is proper.

In a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, whenever $\lambda(\{v, w\}) = t$ (or simply $\lambda(v, w) = t$), we refer to the tuple $(\{v, w\}, t)$ as a *time-edge* of $\mathcal{G}$. A triangle of (G, λ) on the vertices u, v, w is a *synchronous triangle* if $\lambda(u, v) = \lambda(v, w) = \lambda(w, u)$. Let $G = (V, E)$ and let F be a proper orientation of the whole edge set E. Then $(\mathcal{G}, F)$, or (G, λ, F), is a *proper orientation* of the temporal graph $\mathcal{G}$; for simplicity we may also write that F is a proper orientation of $\mathcal{G}$. A *partial proper orientation* F of a temporal graph $\mathcal{G} = (G, \lambda)$ is an orientation of a subset of E. To indicate that the edge $\{u, v\}$ of a time-edge $(\{u, v\}, t)$ is oriented from u to v (that is, $uv \in F$ in a (partial) proper orientation F), we use the term $((u, v), t)$, or simply (uv, t). For simplicity we may refer to a (partial) proper orientation just

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as a (partial) orientation, whenever the term "proper" is clear from the context.

A static graph $G = (V, E)$ is a *comparability graph* if there exists a proper orientation F of E which is *transitive*, that is, if $F \cap F^{-1} = \emptyset$ and $F^2 \subseteq F$, where $F^2 = \{uw : uv, vw \in F$ for some vertex $v\}$ [24]. Analogously, in a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, we define a proper orientation F of E to be *temporally transitive*, if:

> whenever (uv, t_1) and (vw, t_2) are oriented time-edges in $(\mathcal{G}, F)$ such that $t_2 \geq t_1$, there exists an oriented time-edge (wu, t_3) in $(\mathcal{G}, F)$, for some $t_3 \geq t_2$.

In the above definition of a temporally transitive orientation, if we replace the condition "$t_3 \geq t_2$" with "$t_3 > t_2$", then F is called *strongly temporally transitive*. If we instead replace the condition "$t_2 \geq t_1$" with "$t_2 > t_1$", then F is called *strictly temporally transitive*. If we do both of these replacements, then F is called *strongly strictly temporally transitive*. Note that strong (strict) temporal transitivity implies (strict) temporal transitivity, while (strong) temporal transitivity implies (strong) strict temporal transitivity. Furthermore, similarly to the established terminology for static graphs, we define a temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, to be a *(strongly/strictly) temporal comparability graph* if there exists a proper orientation F of E which is *(strongly/strictly) temporally transitive*.

We are now ready to formally introduce the following decision problem of recognizing whether a given temporal graph is temporally transitively orientable or not.

Temporal Transitive Orientation (TTO)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$.
Question: Does $\mathcal{G}$ admit a temporally transitive orientation F of E?

In the above problem definition of TTO, if we ask for the existence of a strictly (resp. strongly, or strongly strictly) temporally transitive orientation F, we obtain the decision problem Strict (resp. Strong, or Strong Strict) Temporal Transitive Orientation (TTO).

Let $\mathcal{G} = (G, \lambda)$ be a temporal graph, where $G = (V, E)$. Let $G' = (V, E')$ be a graph such that $E \subseteq E'$, and let $\lambda' \colon E' \to \mathbb{N}$ be a time-labeling function such that $\lambda'(u, v) = \lambda(u, v)$ for every $\{u, v\} \in E$. Then the temporal graph $\mathcal{G}' = (G', \lambda')$ is called a *temporal supergraph of* $\mathcal{G}$. We can now define our next problem definition regarding computing temporally orientable supergraphs of $\mathcal{G}$.

Temporal Transitive Completion (TTC)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$, a (partial) orientation F of $\mathcal{G}$, and an integer k.
Question: Does there exist a temporal supergraph $\mathcal{G}' = (G', \lambda')$ of (G, λ), where $G' = (V, E')$, and a transitive orientation $F' \supseteq F$ of $\mathcal{G}'$ such that $|E' \setminus E| \leq k$?

Similarly to TTO, if we ask in the problem definition of TTC for the existence of a strictly (resp. strongly, or strongly strictly) temporally transitive orientation F', we obtain the decision problem Strict (resp. Strong, or Strong Strict) Temporal Transitive Completion (TTC).

Now we define our final problem which asks for an orientation F of a temporal graph $\mathcal{G} = (G, \lambda)$ (i.e. with exactly one orientation for each edge of G) such that, for every "time-layer" $t \geq 1$, the (static) oriented graph defined by the edges having time-label t is transitively oriented in F. This problem does not make much sense if every edge has exactly one time-label in $\mathcal{G}$, as in this case it can be easily solved by just repeatedly applying any known static transitive orientation algorithm. Therefore, in the next problem definition, we assume that in the input temporal graph $\mathcal{G} = (G, \lambda)$ every edge of G potentially has multiple time-labels, i.e. the time-labeling function is $\lambda : E \to 2^{\mathbb{N}}$.

Multilayer Transitive Orientation (MTO)

Input: A temporal graph $\mathcal{G} = (G, \lambda)$, where $G = (V, E)$ and $\lambda : E \to 2^{\mathbb{N}}$.
Question: Is there an orientation F of the edges of G such that, for every $t \geq 1$, the (static) oriented graph induced by the edges having time-label t is transitively oriented?

3 The recognition of temporally transitively orientable graphs

In this section we investigate the computational complexity of all variants of TTO. We show that TTO as well as the two variants Strong TTO and Strong Strict TTO, are solvable in polynomial time, whereas Strict TTO turns out to be NP-complete.

The main idea of our approach to solve TTO and its variants is to create Boolean variables for each edge of the underlying graph G and interpret setting a variable to 1 or 0 with the two possible ways of directing the corresponding edge.

More formally, for every edge $\{u, v\}$ we introduce a variable x_{uv} and setting this variable to 1 corresponds to the orientation uv while setting this variable to 0 corresponds to the orientation vu. Now consider the example of Figure 3(a), i.e. an induced path of length two in the underlying graph G on three vertices u, v, w, and let $\lambda(u, v) = 1$ and $\lambda(v, w) = 2$. Then the orientation uv "forces" the orientation wv. Indeed, if we otherwise orient $\{v, w\}$ as vw, then the edge $\{u, w\}$ must exist and be oriented as uw in any temporal transitive orientation, which is a contradiction as there is no edge between u and w. We can express this "forcing" with the implication $x_{uv} \implies x_{wv}$. In this way we can deduce the constraints that all triangles or induced paths on three vertices impose on any (strong/strict/strong strict) temporal transitive orientation. We collect all these constraints in Table 1.

When looking at the conditions imposed on temporal transitive orientations collected in Table 1, we can observe that all conditions except "non-cyclic" are expressible in 2SAT. Since 2SAT is solvable in linear time [6], it immediately follows that the strong variants of temporal transitivity are solvable in polynomial time, as the next theorem states.

▶ **Theorem 2.** Strong TTO *and* Strong Strict TTO *are solvable in polynomial time.*

In the variants TTO and Strict TTO, however, we can have triangles which impose a "non-cyclic" orientation of three edges (Table 1). This can be naturally modeled by a not-all-equal (NAE) clause.[3] However, if we now naïvely model the conditions with a Boolean formula, we obtain a formula with 2SAT clauses and 3NAE clauses. Deciding whether such a formula is satisfiable is NP-complete in general [42]. Hence, we have to investigate these two variants more thoroughly.

The only difference between the triangles that impose these "non-cyclic" orientations in these two problem variants is that, in TTO, the triangle is *synchronous* (i.e. all its three edges have the same time-label), while in Strict TTO two of the edges are synchronous and the third one has a smaller time-label than the other two. As it turns out, this difference of the two problem variants has important implications on their computational complexity.

[3] A not all equal clause is a set of literals and it evaluates to `true` if and only if at least two literals in the set evaluate to different truth values.

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		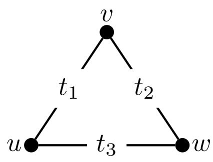			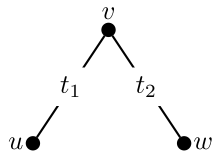
	$t_1 = t_2 = t_3$	$t_1 < t_2 = t_3$	$t_1 \leq t_2 < t_3$	$t_1 = t_2$	$t_1 < t_2$
TTO	non-cyclic	$wu = wv$	$vw \implies uw$ $vu \implies wu$	$uv = wv$	$uv \implies wv$
Strong TTO	$\perp$	$wu \wedge wv$	$vw \implies uw$ $vu \implies wu$	$uv = wv$	$uv \implies wv$
Strict TTO	$\top$	non-cyclic	$vw \implies uw$ $vu \implies wu$	$\top$	$uv \implies wv$
Str. Str. TTO	$\top$	$vu \implies wu$ $uv \implies wv$	$vw \implies uw$ $vu \implies wu$	$\top$	$uv \implies wv$

Table 1 Orientation conditions imposed by a triangle (left) and an induced path of length two (right) in the underlying graph G for the decision problems (Strict/Strong/Strong Strict) TTO. Here, $\top$ means that no restriction is imposed, $\perp$ means that the graph is not orientable, and in the case of triangles, "non-cyclic" means that all orientations except the ones that orient the triangle cyclicly are allowed.

In fact, we obtain a surprising result: TTO is solvable in polynomial time while Strict TTO is NP-complete.

In Section 3.1 we prove that Strict TTO is NP-complete and in Section 3.2 we provide our polynomial-time algorithm for TTO.

3.1 Strict TTO is NP-Complete

In this section we show that in contrast to the other variants, Strict TTO is NP-complete.

▶ **Theorem 3.** Strict TTO *is NP-complete even if the temporal input graph has only four different time labels.*

Proof. We present a polynomial time reduction from (3,4)-SAT [46] where, given a CNF formula ϕ where each clause contains exactly three literals and each variably appears in exactly four clauses, we are asked whether ϕ is satisfiable or not. Given a formula ϕ, we construct a temporal graph $\mathcal{G}$ as follows.

Variable gadget. For each variable x that appears in ϕ, we add eight vertices $a_x, a'_x, b_x, b'_x, c_x, c'_x, d_x, d'_x$ to $\mathcal{G}$. We connect these vertices as depicted in Figure 1, that is, we add the following time edges to $\mathcal{G}$: $(\{a_x, a'_x\}, 1)$, $(\{a'_x, b_x\}, 2)$, $(\{b_x, b'_x\}, 1)$, $(\{b'_x, c_x\}, 2)$, $(\{c_x, c'_x\}, 1)$, $(\{c'_x, d_x\}, 2)$, $(\{d_x, d'_x\}, 1)$, $(\{d'_x, a_x\}, 2)$.

Clause gadget. For each clause c of ϕ, we add six vertices $u_c, u'_c, v_c, v'_c, w_c, w'_c$ to $\mathcal{G}$. We connect these vertices as depicted in Figure 2, that is, we add the following time edges to $\mathcal{G}$: $(\{u_c, u'_c\}, 2)$, $(v_c, v'_c\}, 1)$, $(\{w_c, w'_c\}, 2)$, $(\{u_c, v_c\}, 2)$, $(\{v_c, w_c\}, 3)$, $(\{w_c, u_c\}, 3)$, $(\{v_c, w'_c\}, 3)$, $(\{w_c, v'_c\}, 3)$.

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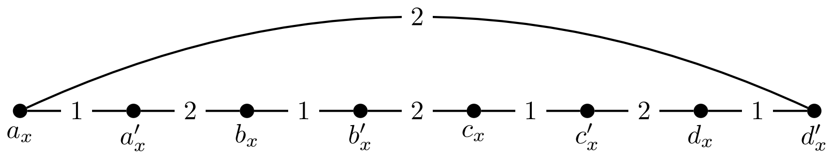

Figure 1 Illustration of the variable gadget used in the reduction in the proof of Theorem 3.

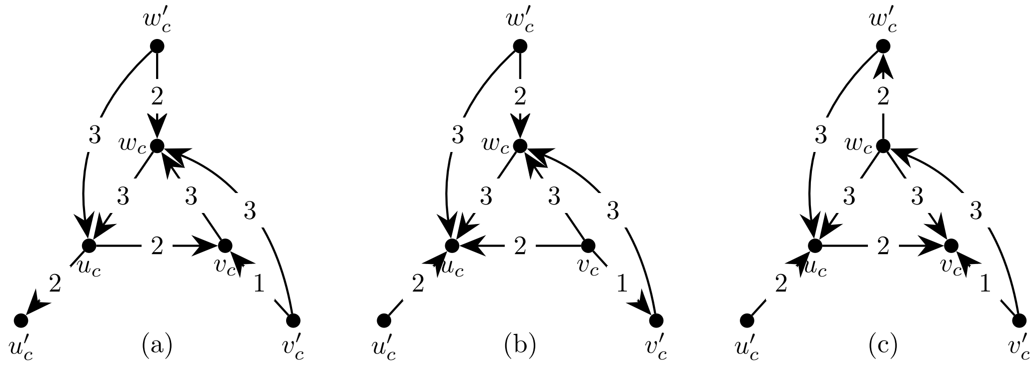

Figure 2 Illustration of the clause gadget used in the reduction in the proof of Theorem 3 and three ways how to orient the edges in it.

Connecting variable gadgets and clause gadgets. Let variable x appear for the ith time in clause c and let x appear in the jth literal of c. The four vertex pairs $(a_x, a'_x), (b_x, b'_x), (c_x, c'_x), (d_x, d'_x)$ from the variable gadget of x correspond to the first, second, third, and fourth appearance of x, respectively. The three vertices u'_c, v'_c, w'_c correspond to the first, second, and third literal of c, respectively. Let $i = 1$ and $j = 1$. If x appears non-negated, then we add the time edge $(\{a_x, u'_c\}, 4)$. Otherwise, if x appears negated, we add the time edge $(\{a'_x, u'_c\}, 4)$. For all other values of i and j we add time edges analogously.

This finishes the reduction. It can clearly be performed in polynomial time.

(⇒): Assume that we have a satisfying assignment for ϕ, then we can orient $\mathcal{G}$ as follows. Then if a variable x is set to `true`, we orient the edges of the corresponding variable gadgets as follows: $(a_x, a'_x), (b_x, a'_x), (b_x, b'_x), (c_x, b'_x), (c_x, c'_x), (d_x, c'_x), (d_x, d'_x), (a_x, d'_x)$. Otherwise, if x is set to false, we orient as follows: $(a'_x, a_x), (a'_x, b_x), (b'_x, b_x), (b'_x, c_x), (c'_x, c_x), (c'_x, d_x), (d'_x, d_x), (d'_x, a_x)$. It is easy so see that both orientations are transitive.

Now consider a clause in ϕ with literals u, v, w corresponding to vertices u'_c, v'_c, w'_c of the clause gadget, respectively. We have that at least one of the three literals satisfies the clause. If it is u, then we orient the edges in the clause gadgets as illustrated in Figure 2 (a). It is easy so see that this orientation is transitive. Furthermore, we orient the three edges connecting the clause gadgets to variable gadgets as follows: By construction the vertices u'_c, v'_c, w'_c are each connected to a variable gadget. Assume, we have edges $\{u'_c, x\}, \{v'_c, y\}, \{w'_c, z\}$. Then we orient as follows: $(x, u'_c), (v'_c, y), (w'_c, z)$, that is, we orient the edge connecting the literal that satisfies the clause towards the clause gadget and the other two edges towards the variable gadgets. This yields a transitive in the clause gadget. Note that the variable gadgets have time labels 1 and 2 so we can always orient the connecting edges (which have time label 4) towards the variable gadget. We do this with all connecting edges except (x, u_c'). This edge is oriented from the variable gadget towards the clause gadget, however it also corresponds to a literal that satisfies the clause. Then by construction, the edges incident to x in the variable gadget are oriented away from x, hence our orientation is transitive.

Otherwise and if v satisfies the clause, then we orient the edges in the clause gadgets as illustrated in Figure 2 (b). Otherwise (in this case w has to satisfy the clause), we orient the edges in the clause gadgets as illustrated in Figure 2 (c). It is easy so see that each of these orientation is transitive. In both cases we orient the edges connecting the clause gadgets to the variable gadgets analogously to the first case discussed above. By analogous arguments we get that the resulting orientation is transitive.

(⇐): Note that all variable gadgets are cycles of length eight with edges having labels alternating between 1 and 2 and hence the edges have to also be oriented alternately. Consider the variable gadget corresponding to x. We interpret the orientation $(a_x, a_x'), (b_x, a_x'), (b_x, b_x'), (c_x, b_x'), (c_x, c_x'), (d_x, c_x'), (d_x, d_x'), (a_x, d_x')$ as setting x to `true` and we interpret the orientation $(a_x', a_x), (a_x', b_x), (b_x', b_x), (b_x', c_x), (c_x', c_x), (c_x', d_x), (d_x', d_x), (d_x', a_x)$ as setting x to true. We claim that this yields a satisfying assignment for ϕ.

Assume for contradiction that there is a clause c in ϕ that is not satisfied by this assignment. Then by construction of the connection of variable gadgets and clause gadgets, the connecting edges have to be oriented towards the variable gadget in order to keep the variable gadget transitive. Let the three connecting edges be $\{u_c', x\}, \{v_c', y\}, \{w_c', z\}$ and their orientation $(u_c', x), (v_c', y), (w_c', z)$. Then we have that (u_c', x) forces (u_c', u_c) which in turn forces (w_c, u_c). We have that (v_c', y) forces (v_c', v_c) which in turn forces (v_c, u_c). Furthermore, we now have that (w_c, u_c) and (v_c, u_c) force (w_c, v_c). Lastly, we have that (w_c', z) forces (w_c', w_c) which in turn forces (v_c, w_c), a contradiction to the fact that we forced (w_c, v_c) previously. ◀

3.2 A polynomial-time algorithm for TTO

Let $G = (V, E)$ be a static undirected graph. There are various polynomial-time algorithms for deciding whether G admits a transitive orientation F. However our results in this section are inspired by the transitive orientation algorithm described by Golumbic [24], which is based on the crucial notion of *forcing* an orientation. The notion of forcing in static graphs is illustrated in Figure 3 (a): if we orient the edge $\{u, v\}$ as uv (i.e., from u to v) then we are forced to orient the edge $\{v, w\}$ as wv (i.e., from w to v) in any transitive orientation F of G. Indeed, if we otherwise orient $\{v, w\}$ as vw (i.e. from v to w), then the edge $\{u, w\}$ must exist and it must be oriented as uw in any transitive orientation F of G, which is a contradiction as $\{u, w\}$ is not an edge of G. Similarly, if we orient the edge $\{u, v\}$ as vu then we are forced to orient the edge $\{v, w\}$ as vw. That is, in any transitive orientation F of G we have that $uv \in F \Leftrightarrow wv \in F$. This forcing operation can be captured by the binary forcing relation Γ which is defined on the edges of a static graph G as follows [24].

$$uv \; \Gamma \; u'v' \quad \text{if and only if} \quad \begin{cases} \text{either } u = u' \text{ and } \{v, v'\} \notin E \\ \text{or } v = v' \text{ and } \{u, u'\} \notin E \end{cases} . \tag{1}$$

We now extend the definition of Γ in a natural way to the binary relation Λ on the edges of a temporal graph (G, λ), see Equation (2). For this, observe from Table 1 that the only cases, where we have $uv \in F \Leftrightarrow wv \in F$ in any temporal transitive orientation of (G, λ), are when (i) the vertices u, v, w induce a path of length 2 (see Figure 3 (a)) and $\lambda(u, v) = \lambda(v, w)$,

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Figure 3 The orientation uv forces the orientation wu and vice-versa in the examples of (a) a static graph G where $\{u,v\},\{v,w\} \in E(G)$ and $\{u,w\} \notin E(G)$, and of (b) a temporal graph (G,λ) where $\lambda(u,w) = 3 < 5 = \lambda(u,v) = \lambda(v,w)$.

as well as when (ii) u,v,w induce a triangle and $\lambda(u,w) < \lambda(u,v) = \lambda(v,w)$. The latter situation is illustrated in the example of Figure 3 (b). The binary forcing relation Λ is only defined on pairs of edges $\{u,v\}$ and $\{u',v'\}$ where $\lambda(u,v) = \lambda(u',v')$, as follows.

$$uv \; \Lambda \; u'v' \quad \text{if and only if} \quad \lambda(u,v) = \lambda(u',v') = t \text{ and } \begin{cases} u = u' \text{ and } \{v,v'\} \notin E, \text{or} \\ v = v' \text{ and } \{u,u'\} \notin E, \text{or} \\ u = u' \text{ and } \lambda(v,v') < t, \text{or} \\ v = v' \text{ and } \lambda(u,u') < t. \end{cases} \qquad (2)$$

Note that, for every edge $\{u,v\} \in E$ we have that $uv \; \Lambda \; uv$. The forcing relation Λ for temporal graphs shares some properties with the forcing relation Γ for static graphs. In particular, the reflexive transitive closure Λ^* of Λ is an equivalence relation, which partitions the edges of each set $E_t = \{\{u,v\} \in E : \lambda(u,v) = t\}$ into its Λ-*implication classes* (or simply, into its *implication classes*). Two edges $\{a,b\}$ and $\{c,d\}$ are in the same Λ-implication class if and only $ab \; \Lambda^* \; cd$, i.e. there exists a sequence

$$ab = a_0b_0 \; \Lambda \; a_1b_1 \; \Lambda \; \ldots \; \Lambda \; a_kb_k = cd, \text{ with } k \geq 0.$$

Note that, for this to happen, we must have $\lambda(a_0,b_0) = \lambda(a_1,b_1) = \ldots = \lambda(a_k,b_k) = t$ for some $t \geq 1$. Such a sequence is called a Λ-chain from ab to cd, and we say that ab (eventually) Λ-forces cd. Furthermore note that $ab \; \Lambda^* \; cd$ if and only if $ba \; \Lambda^* \; dc$. The next observation helps the reader understand the relationship between the two forcing relations Γ and Λ.

▶ **Observation 4.** *Let $\{u,v\} \in E$, where $\lambda(u,v) = t$, and let A be the Λ-implication class of uv in the temporal graph (G,λ). Let G' be the static graph obtained by removing from G all edges $\{p,q\}$, where $\lambda(p,q) < t$. Then A is also the Γ-implication class of uv in the static graph G'.*

For the next lemma, we use the notation $\widehat{A} = \{uv, vu : uv \in A\}$.

▶ **Lemma 5.** *Let A be a Λ-implication class of a temporal graph (G,λ). Then either $A = A^{-1} = \widehat{A}$ or $A \cap A^{-1} = \emptyset$.*

Proof. Suppose that $A \cap A^{-1} \neq \emptyset$, and let $uv \in A \cap A^{-1}$, i.e. $uv, vu \in A$. Then, for any $pq \in A$ we have that $pq \; \Lambda^* \; uv$ and $qp \; \Lambda^* \; vu$. Since Λ^* is an equivalence relation and $uv, vu \in A$, it also follows that $pq, qp \in A$. Therefore also $pq, qp \in A^{-1}$, and thus $A = A^{-1} = \widehat{A}$. ◀

▶ **Definition 6.** *Let F be a proper orientation and A be a Λ-implication class of a temporal graph (G,λ). If $A \subseteq F$, we say that F* respects *A.*

▶ **Lemma 7.** *Let F be a proper orientation and A be a Λ-implication class of a temporal graph (G,λ). Then F respects either A or A^{-1} (i.e. either $A \subseteq F$ or $A^{-1} \subseteq F$), and in either case $A \cap A^{-1} = \emptyset$.*

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Proof. We defined the binary forcing relation Λ to capture the fact that, for any temporal transitive orientation F of (G, λ), if $ab\ \Lambda\ cd$ and $ab \in F$, then also $cd \in F$. Applying this property repeatedly, it follows that either $A \subseteq F$ or $F \cap A = \emptyset$. If $A \subseteq F$ then $A^{-1} \subseteq F^{-1}$. On the other hand, if $F \cap A = \emptyset$ then $A \subseteq F^{-1}$, and thus also $A^{-1} \subseteq F$. In either case, the fact that $F \cap F^{-1} = \emptyset$ by the definition of a temporal transitive orientation implies that also $A \cap A^{-1} = \emptyset$. ◀

Let now $ab = a_0b_0\ \Lambda\ a_1b_1\ \Lambda\ \dots\ \Lambda\ a_kb_k = cd$ be a given Λ-chain. Note by Equation (2) that, for every $i = 1, \dots, k$, we have that either $a_{i-1} = a_i$ or $b_{i-1} = b_i$. Therefore we can replace the Λ-implication $a_{i-1}b_{i-1}\ \Lambda\ a_ib_i$ by the implications $a_{i-1}b_{i-1}\ \Lambda\ a_ib_{i-1}\ \Lambda\ a_ib_i$, since either $a_ib_{i-1} = a_{i-1}b_{i-1}$ or $a_ib_{i-1} = a_ib_i$. Thus, as this addition of this middle edge is always possible in a Λ-implication, we can now define the notion of a canonical Λ-chain, which always exists.

▶ **Definition 8.** *Let $ab\ \Lambda^*\ cd$. Then any Λ-chain of the from*

$$ab = a_0b_0\ \Lambda\ a_1b_0\ \Lambda\ a_1b_1\ \Lambda\ \dots\ \Lambda\ a_kb_{k-1}\ \Lambda\ a_kb_k = cd$$

is a canonical *Λ-chain.*

The next lemma extends an important known property of the forcing relation Γ for static graphs [24, Lemma 5.3] to the temporal case.

▶ **Lemma 9** (Temporal Triangle Lemma). *Let (G, λ) be a temporal graph and with a synchronous triangle on the vertices a, b, c, where $\lambda(a, b) = \lambda(b, c) = \lambda(c, a) = t$. Let A, B, C be three Λ-implication classes of (G, λ), where $ab \in C$, $bc \in A$, and $ca \in B$, where $A \neq B^{-1}$ and $A \neq C^{-1}$.*

1. *If some $b'c' \in A$, then $ab' \in C$ and $c'a \in B$.*
2. *If some $b'c' \in A$ and $a'b' \in C$, then $c'a' \in B$.*
3. *No edge of A touches vertex a.*

Proof. **1.** Let $b'c' \in A$, and let $bc = b_0c_0\ \Lambda\ b_1c_0\ \Lambda\ \dots\ \Lambda\ b_kc_{k-1}\ \Lambda\ b_kc_k = b'c'$ be a canonical Λ-chain from bc to $b'c'$. Thus note that all edges b_ic_{i-1} and b_ic_i of this Λ-chain have the same time-label t in (G, λ). We will prove by induction that $ab_i \in C$ and $c_ia \in B$, for every $i = 0, 1, \dots, k$. The induction basis follows directly by the statement of the lemma, as $ab = ab_0 \in C$ and $ca = c_0a \in B$.
Assume now that $ab_i \in C$ and $c_ia \in B$. If $b_{i+1} = b_i$ then clearly $ab_{i+1} \in C$ by the induction hypothesis. Suppose now that $b_{i+1} \neq b_i$. If $\{a, b_{i+1}\} \notin E$ then $ac_i\ \Lambda\ b_{i+1}c_i$. Then, since $c_ia \in B$ and $b_{i+1}c_i \in A$, it follows that $A = B^{-1}$, which is a contradiction to the assumption of the lemma. Therefore $\{a, b_{i+1}\} \in E$. Furthermore, since $b_ic_i\ \Lambda\ b_{i+1}c_i$, it follows that either $\{b_i, b_{i+1}\} \notin E$ or $\lambda(b_i, b_{i+1}) < t$. In either case it follows that $ab_i\ \Lambda\ ab_{i+1}$, and thus $ab_{i+1} \in C$.
Similarly, if $c_{i+1} = c_i$ then $c_{i+1}a \in B$ by the induction hypothesis. Suppose now that $c_{i+1} \neq c_i$. If $\{a, c_{i+1}\} \notin E$ then $ab_{i+1}\ \Lambda\ c_{i+1}b_{i+1}$. Then, since $ab_{i+1} \in C$ and $b_{i+1}c_{i+1} \in A$, it follows that $A = C^{-1}$, which is a contradiction to the assumption of the lemma. Therefore $\{a, c_{i+1}\} \in E$. Furthermore, since $b_{i+1}c_i\ \Lambda\ b_{i+1}c_{i+1}$, it follows that either $\{c_i, c_{i+1}\} \notin E$ or $\lambda(c_i, c_{i+1}) < t$. In either case it follows that $c_ia\ \Lambda\ c_{i+1}a$, and thus $c_{i+1}a \in C$. This completes the induction step.
2. Let $b'c' \in A$ and $a'b' \in C$. Then part 1 of the lemma implies that $c'a \in B$. Now let $ab = a_0b_0\ \Lambda\ a_1b_0\ \Lambda\ \dots\ \Lambda\ a_\ell b_{\ell-1}\ \Lambda\ a_\ell b_\ell = a'b'$ be a canonical Λ-chain from ab to $a'b'$.

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Again, note that all edges $a_i b_{i-1}$ and $a_i b_i$ of this Λ-chain have the same time-label t in (G, λ). We will prove by induction that $c'a_i \in B$ and $b_i c' \in A$ for every $i = 0, 1, \ldots, k$. First recall that $c'a = c'a_0 \in B$. Furthermore, by applying part 1 of the proof to the triangle with vertices a_0, b_0, c and on the edge $c'a_0 \in B$, it follows that $b_0 c' \in A$. This completes the induction basis.

For the induction step, assume that $c'a_i \in B$ and $b_i c' \in A$. If $a_{i+1} = a_i$ then clearly $c'a_{i+1} \in B$. Suppose now that $a_{i+1} \neq a_i$. If $\{a_{i+1}, c'\} \notin E$ then $a_{i+1}b_i \; \Lambda \; c'b_i$. Then, since $a_{i+1}b_i \in C$ and $b_i c' \in A$, it follows that $A = C^{-1}$, which is a contradiction to the assumption of the lemma. Therefore $\{a_{i+1}, c'\} \in E$. Now, since $a_i b_i \; \Lambda \; a_{i+1} b_i$, it follows that either $\{a_i, a_{i+1}\} \notin E$ or $\lambda(a_i, a_{i+1}) < t$. In either case it follows that $c'a_i \; \Lambda \; c'a_{i+1}$. Therefore, since $c'a_i \in B$, it follows that $c'a_{i+1} \in B$.

If $b_{i+1} = b_i$ then clearly $b_{i+1}c' \in A$. Suppose now that $b_{i+1} \neq b_i$. Then, since $c'a_{i+1} \in B$, $a_{i+1}b_i \in C$, and $b_i c' \in A$, we can apply part 1 of the lemma to the triangle with vertices a_{i+1}, b_i, c' and on the edge $a_{i+1}b_{i+1} \in C$, from which it follows that $b_i c' \in A$. This completes the induction step, and thus $c'a_k = c'a' \in B$.

3. Suppose that $ad \in A$ (resp. $da \in A$), for some vertex d. Then, by setting $b' = a$ and $c' = d$ (resp. $b' = d$ and $c' = a$), part 1 of the lemma implies that $ab' = aa \in C$ (resp. $c'a = aa \in B$). Thus is a contradiction, as the underlying graph G does not have the edge aa. ◀

Deciding temporal transitivity using Boolean satisfiability. Starting with any undirected edge $\{u, v\}$ of the underlying graph G, we can clearly enumerate in polynomial time the whole Λ-implication class A to which the oriented edge uv belongs (cf. Equation (2)). If the reversely directed edge $vu \in A$ then Lemma 5 implies that $A = A^{-1} = \widehat{A}$. Otherwise, if $vu \notin A$ then $vu \in A^{-1}$ and Lemma 5 implies that $A \cap A^{-1} = \emptyset$. Thus, we can also decide in polynomial time whether $A \cap A^{-1} = \emptyset$. If we encounter at least one Λ-implication class A such that $A \cap A^{-1} \neq \emptyset$, then it follows by Lemma 7 that (G, λ) is not temporally transitively orientable.

In the remainder of the section we will assume that $A \cap A^{-1} = \emptyset$ for every Λ-implication class A of (G, λ), which is a *necessary* condition for (G, λ) to be temporally transitive orientable. Moreover it follows by Lemma 7 that, if (G, λ) admits a temporally transitively orientation F, then either $A \subseteq F$ or $A^{-1} \subseteq F$. This allows us to define a Boolean variable x_A for every Λ-implication class A, where $x_A = \overline{x_{A^{-1}}}$. Here $x_A = 1$ (resp. $x_{A^{-1}} = 1$) means that $A \subseteq F$ (resp. $A^{-1} \subseteq F$), where F is the temporally transitive orientation which we are looking for. Let $\{A_1, A_2, \ldots, A_s\}$ be a set of Λ-implication classes such that $\{\widehat{A_1}, \widehat{A_2}, \ldots, \widehat{A_s}\}$ is a partition of the edges of the underlying graph G.[4] Then any truth assignment τ of the variables $x_1, x_2, \ldots, x_s$ (where $x_i = x_{A_i}$ for every $i = 1, 2, \ldots, s$) corresponds bijectively to one possible orientation of the temporal graph (G, λ), in which every Λ-implication class is oriented consistently.

Now we define two Boolean formulas ϕ_{3NAE} and ϕ_{2SAT} such that (G, λ) admits a temporal transitive orientation if and only if there is a truth assignment τ of the variables $x_1, x_2, \ldots, x_s$ such that both ϕ_{3NAE} and ϕ_{2SAT} are simultaneously satisfied. Intuitively, ϕ_{3NAE} captures the "non-cyclic" condition from Table 1 while ϕ_{2SAT} captures the remaining conditions. Here ϕ_{3NAE} is a 3NAE formula, i.e., the disjunction of clauses with three literals each, where every clause $\texttt{NAE}(\ell_1, \ell_2, \ell_3)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2, \ell_3\}$ is

[4] Here we slightly abuse the notation by identifying the undirected edge $\{u, v\}$ with the set of both its orientations $\{uv, vu\}$.

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Algorithm 1 Building the Λ-implication classes and the edge-variables.

Input: A temporal graph (G, λ), where $G = (V, E)$.
Output: The variables $\{x_{uv}, x_{vu} : \{u, v\} \in E\}$, or the announcement that (G, λ) is temporally not transitively orientable.

$s \leftarrow 0$; $E_0 \leftarrow E$
while $E_0 \neq \emptyset$ **do**
  $s \leftarrow s + 1$; Let $\{p, q\} \in E_0$ be arbitrary
  Build the Λ-implication class A_s of the oriented edge pq (by Equation (2))
  if $qp \in A_s$ **then** $\{A_s \cap A_s^{-1} \neq \emptyset\}$
    return "NO"
  else
    x_s is the variable corresponding to the directed edges of A_s
    for every $uv \in A_s$ **do**
      $x_{uv} \leftarrow x_s$; $x_{vu} \leftarrow \overline{x_s}$ $\{x_{uv}$ and x_{vu} become aliases of x_s and $\overline{x_s}\}$
    $E_0 \leftarrow E_0 \setminus \widehat{A_s}$
return Λ-implication classes $\{A_1, A_2, \ldots, A_s\}$ and variables $\{x_{uv}, x_{vu} : \{u, v\} \in E\}$

equal to 1 and at least one of them is equal to 0. Furthermore $\phi_{2\text{SAT}}$ is a 2SAT formula, i.e., the disjunction of 2CNF clauses with two literals each, where every clause $(\ell_1 \vee \ell_2)$ is satisfied if and only if at least one of the literals $\{\ell_1, \ell_2\}$ is equal to 1.

For simplicity of the presentation we also define a variable x_{uv} for every directed edge uv. More specifically, if $uv \in A_i$ (resp. $uv \in A_i^{-1}$) then we set $x_{uv} = x_i$ (resp. $x_{uv} = \overline{x_i}$). That is, $x_{uv} = \overline{x_{vu}}$ for every undirected edge $\{u, v\} \in E$. Note that, although $\{x_{uv}, x_{vu} : \{u, v\} \in E\}$ are defined as variables, they can equivalently be seen as *literals* in a Boolean formula over the variables $x_1, x_2, \ldots, x_s$. The process of building all Λ-implication classes and all variables $\{x_{uv}, x_{vu} : \{u, v\} \in E\}$ is given by Algorithm 1.

Description of the 3NAE formula $\phi_{3\text{NAE}}$. The formula $\phi_{3\text{NAE}}$ captures the "non-cyclic" condition of the problem variant TTO (presented in Table 1). The formal description of $\phi_{3\text{NAE}}$ is as follows. Consider a synchronous triangle of (G, λ) on the vertices u, v, w. Assume that $x_{uv} = x_{wv}$ (resp. $x_{vw} = x_{uw}$, or $x_{wu} = x_{vu}$) is true. Then the pair $\{uv, wv\}$ (resp. $\{vw, uw\}$, or $\{wu, vu\}$) of oriented edges belongs to the same Λ-implication class A_i. This implies that the triangle on the vertices u, v, w is never cyclically oriented in any proper orientation F that respects A_i or A_i^{-1}. Assume, on the contrary, that $x_{uv} \neq x_{wv}$, $x_{vw} \neq x_{uw}$, and $x_{wu} \neq x_{vu}$. In this case we add to $\phi_{3\text{NAE}}$ the clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$. Note that the triangle on u, v, w is transitively oriented if and only if $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ is satisfied, i.e., at least one of the variables $\{x_{uv}, x_{vw}, x_{wu}\}$ receives the value 1 and at least one of them receives the value 0.

Description of the 2SAT formula $\phi_{2\text{SAT}}$. The formula $\phi_{2\text{SAT}}$ captures all conditions apart from the "non-cyclic" condition of the problem variant TTO (presented in Table 1). The formal description of $\phi_{2\text{SAT}}$ is as follows. Consider a triangle of (G, λ) on the vertices u, v, w, where $\lambda(u, v) = t_1$, $\lambda(v, w) = t_2$, $\lambda(w, v) = t_3$, and $t_1 \leq t_2 \leq t_3$. If $t_1 < t_2 = t_3$ then we add to $\phi_{2\text{SAT}}$ the clauses $(x_{uw} \vee x_{wv}) \wedge (x_{vw} \vee x_{wu})$; note that these clauses are equivalent to $x_{wu} = x_{wv}$. If $t_1 \leq t_2 < t_3$ then we add to $\phi_{2\text{SAT}}$ the clauses $(x_{wv} \vee x_{uw}) \wedge (x_{uv} \vee x_{wu})$; note that these clauses are equivalent to $(x_{vw} \Rightarrow x_{uw}) \wedge (x_{vu} \Rightarrow x_{wu})$. Now consider a path of length 2 that is induced by the vertices u, v, w, where $\lambda(u, v) = t_1$, $\lambda(v, w) = t_2$, and

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$t_1 \leq t_2$. If $t_1 = t_2$ then we add to ϕ_{2SAT} the clauses $(x_{vu} \vee x_{wv}) \wedge (x_{vw} \vee x_{uv})$; note that these clauses are equivalent to $(x_{uv} = x_{wv})$. Finally, if $t_1 < t_2$ then we add to ϕ_{2SAT} the clause $(x_{vu} \vee x_{wv})$; note that this clause is equivalent to $(x_{uv} \Rightarrow x_{wv})$.

In what follows, we say that $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ is *satisfiable* if and only if there exists a truth assignment τ which simultaneously satisfies both ϕ_{3NAE} and ϕ_{2SAT}. Given the above definitions of ϕ_{3NAE} and ϕ_{2SAT}, it is easy to check that their clauses model all conditions of the oriented edges imposed by the row of "TTO" in Table 1.

▶ **Observation 10.** *The temporal graph (G, λ) is transitively orientable if and only if $\phi_{3NAE} \wedge \phi_{2SAT}$ is satisfiable.*

Although deciding whether ϕ_{2SAT} is satisfiable can be done in linear time with respect to the size of the formula [6], the problem Not-All-Equal-3-SAT is NP-complete [42]. We overcome this problem and present a polynomial-time algorithm for deciding whether $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ is satisfiable as follows.

Brief outline of the algorithm. In the *initialization phase*, we exhaustively check which truth values are *forced* in $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ by using Initial-Forcing (see Algorithm 2) as a subroutine. During the execution of Initial-Forcing, we either replace the formulas ϕ_{3NAE} and ϕ_{2SAT} by the equivalent formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$, respectively, or we reach a contradiction by showing that $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ is unsatisfiable.

The *main phase* of the algorithm starts once the formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$ have been computed. During this phase, we iteratively modify the formulas such that, at the end of iteration j we have the formulas $\phi^{(j)}_{\text{3NAE}}$ and $\phi^{(j)}_{\text{2SAT}}$. As we prove in our *main technical result* of this section (Theorem 20), $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ is satisfiable if and only if $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ is satisfiable. Note that, during the execution of the algorithm, we can *both add and remove* clauses from $\phi^{(j)}_{\text{2SAT}}$. On the other hand, we can *only remove* clauses from $\phi^{(j)}_{\text{3NAE}}$. Thus, at some iteration j, we obtain $\phi^{(j)}_{\text{3NAE}} = \emptyset$, and after that iteration we only need to decide satisfiability of $\phi^{(j)}_{\text{2SAT}}$ which can be done efficiently [6].

Two crucial technical lemmas. For the remainder of the section we write $x_{ab} \overset{*}{\Rightarrow}_{\phi_{\text{2SAT}}} x_{uv}$ (resp. $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{uv}$) if the truth assignment $x_{ab} = 1$ forces the truth assignment $x_{uv} = 1$ from the clauses of ϕ_{2SAT} (resp. of $\phi^{(j)}_{\text{2SAT}}$ at the iteration j of the algorithm); in this case we say that x_{ab} *implies* x_{uv} in ϕ_{2SAT} (resp. in $\phi^{(j)}_{\text{2SAT}}$). We next introduce the notion of *uncorrelated* triangles, which lets us formulate some important properties of the implications in ϕ_{2SAT} and $\phi^{(0)}_{\text{2SAT}}$.

▶ **Definition 11.** *Let u, v, w induce a synchronous triangle in (G, λ), where each of the variables of the set $\{x_{uv}, x_{vu}, x_{vw}, x_{wv}, x_{wu}, x_{uw}\}$ belongs to a* different *Λ-implication class. If* none *of the variables of the set $\{x_{uv}, x_{vu}, x_{vw}, x_{wv}, x_{wu}, x_{uw}\}$ implies any other variable of the same set in the formula ϕ_{2SAT} (resp. in the formula $\phi^{(0)}_{2SAT}$), then the triangle of u, v, w is* ϕ_{2SAT}-uncorrelated *(resp.* $\phi^{(0)}_{\text{2SAT}}$-uncorrelated*).*

Now we present our two crucial technical lemmas (Lemmas 12 and 13) which prove some crucial structural properties of the 2SAT formulas ϕ_{2SAT} and $\phi^{(0)}_{\text{2SAT}}$. These structural properties will allow us to prove the correctness of our main algorithm in this section (Algorithm 4). In a nutshell, these two lemmas guarantee that, whenever we have specific implications in ϕ_{2SAT} (resp. in $\phi^{(0)}_{\text{2SAT}}$), then we also have some specific *other* implications in the same formula.

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▶ **Lemma 12.** *Let u, v, w induce a synchronous and ϕ_{2SAT}-uncorrelated triangle in (G, λ), and let $\{a, b\} \in E$ be an edge of G such that $\{a, b\} \cap \{u, v, w\} \leq 1$. If $x_{ab} \overset{*}{\Rightarrow}_{\phi_{2SAT}} x_{uv}$, then x_{ab} also implies at least one of the four variables in the set $\{x_{vw}, x_{wv}, x_{uw}, x_{wu}\}$ in ϕ_{2SAT}.*

Proof. Let t be the common time-label of all the edges in the synchronous triangle of the vertices u, v, w. That is, $\lambda(u, v) = \lambda(v, w) = \lambda(w, u) = t$. Denote by A, B, and C the Λ-implication classes in which the directed edges uv, vw, and wu belong, respectively. Let $x_{ab} = x_{a_0b_0} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_1b_1} \Rightarrow_{\phi_{2\text{SAT}}} \ldots \Rightarrow_{\phi_{2\text{SAT}}} x_{a_{k-1}b_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$ be a $\phi_{2\text{SAT}}$-implication chain from x_{ab} to x_{uv}. Note that, without loss of generality, for each variable $x_{a_ib_i}$ in this chain, the directed edge a_ib_i is a representative of a different Λ-implication class than all other directed edges in the chain (otherwise we can just shorten the $\phi_{2\text{SAT}}$-implication chain from x_{ab} to x_{uv}). Furthermore, since $x_{a_kb_k} = x_{uv}$, note that a_kb_k and uv are both representatives of the same Λ-implication class A. Therefore Lemma 9 (the temporal triangle lemma) implies that $wa_k \in C$ and $b_kw \in B$. Therefore we can assume without loss of generality that $u = a_k$ and $v = b_k$. Moreover, let $A' \notin \{A, A^{-1}, B, B^{-1}, C, C^{-1}\}$ be the Λ-implication class in which the directed edge $a_{k-1}b_{k-1}$ belongs. Since $x_{a_{k-1}b_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k}$, note that without loss of generality we can choose the directed edge $a_{k-1}b_{k-1}$ to be such a representative of the Λ-implication class A' such that either $a_{k-1} = a_k$ or $b_{k-1} = b_k$. We now distinguish these two cases.

Case 1: $u = a_k = a_{k-1}$ **and** $v = b_k \neq b_{k-1}$**.** Then, since $x_{a_{k-1}b_{k-1}} = x_{a_kb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$ and $\lambda(a_k, b_k) = t$, it follows that $\lambda(u, b_{k-1}) \geq t+1$. Suppose that $\{w, b_{k-1}\} \notin E$. Then $x_{ub_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{uw}$, which proves the lemma. Now suppose that $\{w, b_{k-1}\} \in E$. If $\lambda(w, b_{k-1}) \leq \lambda(u, b_{k-1}) - 1$ then $x_{ub_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{uw}$, which proves the lemma. Suppose that $\lambda(w, b_{k-1}) \geq \lambda(u, b_{k-1})+1$. Then $x_{ub_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{wb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{wu}$, i.e. $x_{ub_{k-1}} \overset{*}{\Rightarrow}_{\phi_{2\text{SAT}}} x_{wu}$, which again proves the lemma. Suppose finally that $\lambda(w, b_{k-1}) = \lambda(u, b_{k-1})$. Then, since $\lambda(u, w) = t < \lambda(w, b_{k-1}) = \lambda(u, b_{k-1})$, it follows that $wb_{k-1} \; \Lambda \; ub_{k-1}$. If $\{v, b_{k-1}\} \notin E$ then $x_{ub_{k-1}} = x_{wb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{wv}$, which proves the lemma. Now let $\{v, b_{k-1}\} \in E$. If $\lambda(v, b_{k-1}) \leq \lambda(w, b_{k-1}) - 1$ then $x_{ub_{k-1}} = x_{wb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{wv}$, which proves the lemma. If $\lambda(v, b_{k-1}) \geq \lambda(w, b_{k-1}) + 1$ then $x_{ub_{k-1}} = x_{wb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{vb_{k-1}} \Rightarrow_{\phi_{2\text{SAT}}} x_{wv}$, which proves the lemma. If $\lambda(v, b_{k-1}) = \lambda(w, b_{k-1})$ then $ub_{k-1} \; \Lambda \; vb_{b-1}$, and thus $x_{ub_{k-1}} = x_{a_{k-1}b_{k-1}} \not\Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$, which is a contradiction.

Case 2: $u = a_k \neq a_{k-1}$ **and** $v = b_k = b_{k-1}$**.** Then, since $x_{a_{k-1}b_{k-1}} = x_{a_{k-1}b_k} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$ and $\lambda(a_k, b_k) = t$, it follows that $\lambda(v, a_{k-1}) \leq t-1$. Suppose that $\{w, a_{k-1}\} \notin E$. Then $x_{a_{k-1}v} \Rightarrow_{\phi_{2\text{SAT}}} x_{wv}$, which proves the lemma. Now suppose that $\{w, a_{k-1}\} \in E$. If $\lambda(w, a_{k-1}) \leq t - 1$ then $x_{a_{k-1}v} \Rightarrow_{\phi_{2\text{SAT}}} x_{wv}$, which proves the lemma. Suppose that $\lambda(w, a_{k-1}) = t$. Then, since $\lambda(v, a_{k-1}) \leq t-1$, it follows that $vw \; \Lambda \; a_{t-1}w$. If $\{u, a_{k-1}\} \notin E$ then also $a_{t-1}w \; \Lambda \; uw$, and thus $x_{wv} = x_{wu}$, which is a contradiction to the assumption that the triangle of u, v, w is uncorrelated. Thus $\{u, a_{k-1}\} \in E$. If $\lambda(u, a_{k-1}) \leq t-1$ then again $a_{t-1}w \; \Lambda \; uw$, which is a contradiction. On the other hand, if $\lambda(u, a_{k-1}) \geq t$ then $x_{a_{k-1}v} = x_{a_{k-1}b_{k-1}} \not\Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$, which is a contradiction.

Finally suppose that $\lambda(w, a_{k-1}) \geq t+1$. Then, since $\lambda(v, w) = t$ and $\lambda(v, a_{k-1}) \leq t-1$, it follows that $x_{vw} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_{k-1}w} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_{k-1}v}$. However, since $x_{a_{k-1}v} = x_{a_{k-1}b_k} \Rightarrow_{\phi_{2\text{SAT}}} x_{a_kb_k} = x_{uv}$, it follows that $x_{vw} \overset{*}{\Rightarrow}_{\phi_{2\text{SAT}}} x_{uv}$, which is a contradiction to the assumption that the triangle of u, v, w is uncorrelated. ◀

▶ **Lemma 13.** *Let u, v, w induce a synchronous and $\phi^{(0)}_{2SAT}$-uncorrelated triangle in (G, λ), and let $\{a, b\} \in E$ be an edge of G such that $\{a, b\} \cap \{u, v, w\} \leq 1$. If $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(0)}_{2SAT}} x_{uv}$, then*

x_{ab} also implies at least one of the four variables in the set $\{x_{vw}, x_{wv}, x_{uw}, x_{wu}\}$ in $\phi^{(0)}_{2SAT}$.

Proof. Assume we have $\{a, b\} \cap \{u, v, w\} \leq 1$ and $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(0)}_{\text{2SAT}}} x_{uv}$. Then we make a case distinction on the last implication in the implication chain $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(0)}_{\text{2SAT}}} x_{uv}$.

1. The last implication is an implication from ϕ_{2SAT}, i.e., $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(0)}_{\text{2SAT}}} x_{pq} \Rightarrow_{\phi_{\text{2SAT}}} x_{uv}$. If $\{p, q\} \subseteq \{u, v, w\}$ then we are done, since we can assume that $\{p, q\} \neq \{u, v\}$ because no such implications are contained in ϕ_{2SAT}. Otherwise Lemma 12 implies that x_{pq} also implies at least one of the four variables in the set $\{x_{vw}, x_{wv}, x_{uw}, x_{wu}\}$ in ϕ_{2SAT}. If follows that x_{ab} also implies at least one of the four variables in the set $\{x_{vw}, x_{wv}, x_{uw}, x_{wu}\}$ in $\phi^{(0)}_{\text{2SAT}}$.
2. The last implication is *not* an implication from ϕ_{2SAT}, i.e., $x_{ab} \overset{*}{\Rightarrow}_{\phi^{(0)}_{\text{2SAT}}} x_{pq} \Rightarrow_{\phi_{\text{INIT}}} x_{uv}$, there the implication $x_{pq} \Rightarrow_{\phi_{\text{INIT}}} x_{uv}$ was added to $\phi^{(0)}_{\text{2SAT}}$ by Initial-Forcing. If $x_{pq} \Rightarrow_{\phi_{\text{INIT}}} x_{uv}$ was added in Line 7 or Line 10 of Initial-Forcing, then we have that $\{p, q\} \subseteq \{u, v, w\}$ and $\{p, q\} \neq \{u, v\}$, hence the u, v, w is not a $\phi^{(0)}_{\text{2SAT}}$-uncorrelated triangle, a contradiction. If $x_{pq} \Rightarrow_{\phi_{\text{INIT}}} x_{uv}$ was added in Line 14 of Initial-Forcing, then we have that $x_{pq} \Rightarrow_{\phi_{\text{INIT}}} x_{uw}$, hence we are done. ◀

Detailed description of the algorithm. We are now ready to present our polynomial-time algorithm (Algorithm 4) for deciding whether a given temporal graph (G, λ) is temporally transitively orientable. The main idea of our algorithm is as follows. First, the algorithm computes all Λ-implication classes $A_1, \ldots, A_s$ by calling Algorithm 1 as a subroutine. If there exists at least one Λ-implication class A_i where $uv, vu \in A_i$ for some edge $\{u, v\} \in E$, then we announce that (G, λ) is a *no*-instance, due to Lemma 7. Otherwise we associate to each Λ-implication class A_i a variable x_i, and we build the 3NAE formula ϕ_{3NAE} and the 2SAT formula ϕ_{2SAT}, as described in Section 3.2.

In the *initialization phase* of Algorithm 4, we call algorithm Initial-Forcing (see Algorithm 2) as a subroutine. Starting from the formulas ϕ_{3NAE} and ϕ_{2SAT}, in Initial-Forcing we build the formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$ by both (i) checking which truth values are being *forced* in $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ (lines 2-10), and (ii) adding to ϕ_{2SAT} some clauses that are implicitly implied in $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ (lines 11-14). More specifically, Initial-Forcing proceeds as follows: (i) whenever setting $x_i = 1$ (resp. $x_i = 0$) forces $\phi_{\text{3NAE}} \wedge \phi_{\text{2SAT}}$ to become unsatisfiable, we choose to set $x_i = 0$ (resp. $x_i = 1$); (ii) if $x \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} a$ and $x \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} b$, and if we also have that $\texttt{NAE}(a, b, c) \in \phi^{(0)}_{\text{3NAE}}$, then we add $x \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} \overline{c}$ to $\phi^{(0)}_{\text{2SAT}}$, since clearly, if $x = 1$ then $a = b = 1$ and we have to set $c = 0$ to satisfy the NAE clause $\texttt{NAE}(a, b, c)$. The next observation follows easily by Observation 10 and by the construction of $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$ in Initial-Forcing.

► **Observation 14.** *The temporal graph (G, λ) is transitively orientable if and only if $\phi^{(0)}_{3NAE} \wedge \phi^{(0)}_{2SAT}$ is satisfiable.*

The *main phase* of the algorithm starts once the formulas $\phi^{(0)}_{\text{3NAE}}$ and $\phi^{(0)}_{\text{2SAT}}$ have been computed. Then we iteratively try assigning to each variable x_i the truth value 1 or 0. Once we have set $x_i = 1$ (resp. $x_i = 0$) during the iteration $j \geq 1$ of the algorithm, we call algorithm Boolean-Forcing (see Algorithm 3) as a subroutine to check which implications this value of x_i has on the current formulas $\phi^{(j-1)}_{\text{3NAE}}$ and $\phi^{(j-1)}_{\text{2SAT}}$ and which other truth values of variables are forced. The correctness of Boolean-Forcing can be easily verified by checking all subcases of Boolean-Forcing. During the execution of Boolean-Forcing,

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Algorithm 2 Initial-Forcing

Input: A 2-SAT formula ϕ_{2SAT} and a 3-NAE formula ϕ_{3NAE}

Output: A 2-SAT formula $\phi_{\text{2SAT}}^{(0)}$ and a 3-NAE formula $\phi_{\text{3NAE}}^{(0)}$ such that $\phi_{\text{2SAT}}^{(0)} \wedge \phi_{\text{3NAE}}^{(0)}$ is satisfiable if and only if $\phi_{\text{2SAT}} \wedge \phi_{\text{3NAE}}$ is satisfiable, or the announcement that $\phi_{\text{2SAT}} \wedge \phi_{\text{3NAE}}$ is not satisfiable.

1: $\phi_{\text{3NAE}}^{(0)} \leftarrow \phi_{\text{3NAE}}$; $\phi_{\text{2SAT}}^{(0)} \leftarrow \phi_{\text{2SAT}}$ {initialization}
2: **for** every variable x_i appearing in $\phi_{\text{3NAE}}^{(0)} \wedge \phi_{\text{2SAT}}^{(0)}$ **do**
3:     **if** Boolean-Forcing $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}, x_i, 1\right) =$ "NO" **then**
4:         **if** Boolean-Forcing $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}, x_i, 0\right) =$ "NO" **then**
5:             **return** "NO" {both $x_i = 1$ and $x_i = 0$ invalidate the formulas}
6:         **else**
7:             $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}\right) \leftarrow$ Boolean-Forcing $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}, x_i, 0\right)$
8:     **else**
9:         **if** Boolean-Forcing $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}, x_i, 0\right) =$ "NO" **then**
10:             $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}\right) \leftarrow$ Boolean-Forcing $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}, x_i, 1\right)$
11: **for** every clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ of $\phi_{\text{3NAE}}^{(0)}$ **do**
12:     **for** every variable x_{ab} **do**
13:         **if** $x_{ab} \overset{*}{\Rightarrow}_{\phi_{\text{2SAT}}^{(0)}} x_{uv}$ and $x_{ab} \overset{*}{\Rightarrow}_{\phi_{\text{2SAT}}^{(0)}} x_{vw}$ **then** {add $(x_{ab} \Rightarrow x_{uw})$ to $\phi_{\text{2SAT}}^{(0)}$}
14:             $\phi_{\text{2SAT}}^{(0)} \leftarrow \phi_{\text{2SAT}}^{(0)} \wedge (x_{ba} \vee x_{uw})$
15: Repeat lines 2 and 11 until no changes occur on $\phi_{\text{2SAT}}^{(0)}$ and $\phi_{\text{3NAE}}^{(0)}$
16: **return** $\left(\phi_{\text{3NAE}}^{(0)}, \phi_{\text{2SAT}}^{(0)}\right)$

we either replace the current formulas by $\phi_{\text{3NAE}}^{(j)}$ and $\phi_{\text{2SAT}}^{(j)}$, or we reach a contradiction by showing that, setting $x_i = 1$ (resp. $x_i = 0$) makes $\phi_{\text{3NAE}}^{(j-1)} \wedge \phi_{\text{2SAT}}^{(j-1)}$ unsatisfiable. If each of the truth assignments $\{x_i = 1, x_i = 0\}$ leads to such a contradiction, we return that (G, λ) is a *no*-instance. Otherwise, if at least one of the truth assignments $\{x_i = 1, x_i = 0\}$ does not lead to such a contradiction, we follow this truth assignment and proceed with the next variable.

Correctness of the algorithm. We now prove formally that Algorithm 4 is correct. More specifically, we show that if Algorithm 4 gets a *yes*-instance as input then it outputs a temporally transitive orientation, while if it gets a *no*-instance as input then it outputs "NO". The *main technical result* of this section is Theorem 20, in which we prove that, at every iteration of Algorithm 4, the current formula $\phi_{\text{3NAE}}^{(j)} \wedge \phi_{\text{2SAT}}^{(j)}$ is satisfiable if and only if the formula $\phi_{\text{3NAE}}^{(j-1)} \wedge \phi_{\text{2SAT}}^{(j-1)}$ of the previous iteration is satisfiable.

We start by proving in the following auxiliary lemma that, if the algorithm returns "NO" at the jth iteration, then the formula $\phi_{\text{3NAE}}^{(j-1)} \wedge \phi_{\text{2SAT}}^{(j-1)}$ of the previous iteration is not

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Algorithm 3 BOOLEAN-FORCING

Input: A 2-SAT formula ϕ_2, a 3-NAE formula ϕ_3, and a variable x_i of $\phi_2 \wedge \phi_3$, and a truth value VALUE $\in \{0,1\}$

Output: A 2-SAT formula ϕ_2' and a 3-NAE formula ϕ_3', obtained from ϕ_2 and ϕ_3 by setting $x_i =$ VALUE, or the announcement that $x_i =$ VALUE does not satisfy $\phi_2 \wedge \phi_3$.

1: $\phi_2' \leftarrow \phi_2$; $\phi_3' \leftarrow \phi_3$

2: **while** ϕ_2' has a clause $(x_{uv} \vee x_{pq})$ and $x_{uv} = 1$ **do**
3:   Remove the clause $(x_{uv} \vee x_{pq})$ from ϕ_2'

4: **while** ϕ_2' has a clause $(x_{uv} \vee x_{pq})$ and $x_{uv} = 0$ **do**
5:   **if** $x_{pq} = 0$ **then return** "NO"
6:   Remove the clause $(x_{uv} \vee x_{pq})$ from ϕ_2'; $x_{pq} \leftarrow 1$

7: **for** every variable x_{uv} that does not yet have a truth value **do**
8:   **if** $x_{uv} \overset{*}{\Rightarrow}_{\phi_2''} x_{vu}$, where $\phi_2'' = \phi_2' \setminus \phi_2$ **then** $x_{uv} \leftarrow 0$

9: **for** every clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ of ϕ_3' **do** {synchronous triangle on vertices u, v, w}
10:   **if** $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ **then** {add $(x_{uv} \Rightarrow x_{uw}) \wedge (x_{uw} \Rightarrow x_{vw})$ to ϕ_2'}
11:     $\phi_2' \leftarrow \phi_2' \wedge (x_{vu} \vee x_{uw}) \wedge (x_{wu} \vee x_{vw})$
12:     Remove the clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ from ϕ_3'

13:   **if** x_{uv} already got the value 1 or 0 **then**
14:     Remove the clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ from ϕ_3'

15:     **if** x_{vw} and x_{wu} do not have yet a truth value **then**

16:       **if** $x_{uv} = 1$ **then** {add $(x_{vw} \Rightarrow x_{uw})$ to ϕ_2'}
17:         $\phi_2' \leftarrow \phi_2' \wedge (x_{wv} \vee x_{uw})$

18:       **else** {$x_{uv} = 0$; in this case add $(x_{uw} \Rightarrow x_{vw})$ to ϕ_2'}
19:         $\phi_2' \leftarrow \phi_2' \wedge (x_{wu} \vee x_{vw})$

20:     **if** $x_{vw} = x_{uv}$ and x_{wu} does not have yet a truth value **then**
21:       $x_{wu} \leftarrow 1 - x_{uv}$

22:     **if** $x_{vw} = x_{wu} = x_{uv}$ **then return** "NO"

23: Repeat lines 2, 4, 7, and 9 until no changes occur on ϕ_2' and ϕ_3'

24: **if** both $x_{uv} = 0$ and $x_{uv} = 1$ for some variable x_{uv} **then return** "NO"

25: **return** (ϕ_2', ϕ_3')

---

satisfiable.

▶ **Lemma 15.** *For every iteration j of Algorithm 4, if Algorithm 4 returns "NO" in Line 16, then $\phi^{(j-1)}_{3NAE} \wedge \phi^{(j-1)}_{2SAT}$ is not satisfiable.*

Proof. Assume otherwise that $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ is satisfiable, and let x_i be the variable of $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ that is considered by the algorithm at iteration j. Let τ be a satisfying truth assignment of $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$. If $x_i = 1$ (resp. $x_i = 0$) in τ then the algorithm will proceed by computing the next formula $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ in Line 11 (resp. in Line 14) and thus it will not return "NO" in Line 16, which is a contradiction. ◀

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Algorithm 4 Temporal transitive orientation.

Input: A temporal graph (G, λ), where $G = (V, E)$.
Output: A temporal transitive orientation F of (G, λ), or the announcement that (G, λ) is temporally not transitively orientable.

Execute Algorithm 1 to build the Λ-implication classes $\{A_1, A_2, \ldots, A_s\}$ and the Boolean variables $\{x_{uv}, x_{vu} : \{u, v\} \in E\}$
if Algorithm 1 returns "NO" **then return** "NO"
Build the 3NAE formula $\phi_{3\text{NAE}}$ and the 2SAT formula $\phi_{2\text{SAT}}$
if Initial-Forcing $(\phi_{3\text{NAE}}, \phi_{2\text{SAT}}) \neq$ "NO" **then** {Initialization phase}
    $\left(\phi^{(0)}_{3\text{NAE}}, \phi^{(0)}_{2\text{SAT}}\right) \leftarrow$ Initial-Forcing $(\phi_{3\text{NAE}}, \phi_{2\text{SAT}})$
else $\{\phi_{3\text{NAE}} \wedge \phi_{2\text{SAT}}$ leads to a contradiction$\}$
    return "NO"
$j \leftarrow 1$; $F \leftarrow \emptyset$ {Main phase}
while a variable x_i appearing in $\phi^{(j-1)}_{3\text{NAE}} \wedge \phi^{(j-1)}_{2\text{SAT}}$ did not yet receive a truth value **do**
    if Boolean-Forcing $\left(\phi^{(j-1)}_{3\text{NAE}}, \phi^{(j-1)}_{2\text{SAT}}, x_i, 1\right) \neq$ "NO" **then**
        $\left(\phi^{(j)}_{3\text{NAE}}, \phi^{(j)}_{2\text{SAT}}\right) \leftarrow$ Boolean-Forcing $\left(\phi^{(j-1)}_{3\text{NAE}}, \phi^{(j-1)}_{2\text{SAT}}, x_i, 1\right)$
    else $\{x_i = 1$ leads to a contradiction$\}$
        if Boolean-Forcing $\left(\phi^{(j-1)}_{3\text{NAE}}, \phi^{(j-1)}_{2\text{SAT}}, x_i, 0\right) \neq$ "NO" **then**
            $\left(\phi^{(j)}_{3\text{NAE}}, \phi^{(j)}_{2\text{SAT}}\right) \leftarrow$ Boolean-Forcing $\left(\phi^{(j-1)}_{3\text{NAE}}, \phi^{(j-1)}_{2\text{SAT}}, x_i, 0\right)$
        else
            return "NO"
    $j \leftarrow j + 1$
for $i = 1$ to s **do**
    if x_i did not yet receive a truth value **then** $x_i \leftarrow 1$
    if $x_i = 1$ **then** $F \leftarrow F \cup A_i$ **else** $F \leftarrow F \cup \overline{A_i}$
return the temporally transitive orientation F of (G, λ)

The next crucial observation follows immediately by the construction of $\phi_{3\text{NAE}}$ in Section 3.2, and by the fact that, at every iteration j, Algorithm 4 can only remove clauses from $\phi^{(j-1)}_{3\text{NAE}}$.

▶ **Observation 16.** *If Algorithm 3 removes a clause from $\phi^{(j-1)}_{3NAE}$, then this clause is satisfied for all satisfying assignments of $\phi^{(j)}_{2SAT}$.*

Next, we prove a crucial and involved technical lemma about the Boolean forcing steps of Algorithm 4. This lemma will allow us to deduce that, during the *main phase* of Algorithm 4, whenever a new clause is added to the 2SAT part of the formula, this happens only in lines 17 and 19 of Algorithm 3 (Boolean-Forcing). That is, whenever a new clause is added to the 2SAT part of the formula in line 11 of Algorithm 3, this can only happen during the *initialization phase* of Algorithm 4.

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▶ **Lemma 17.** *Whenever* Boolean-Forcing *(Algorithm 3) is called in an iteration $j \geq 1$ (i.e. in the main phase) of Algorithm 4, Lines 11 and 12 of* Boolean-Forcing *are not executed if this call of* Boolean-Forcing *does not output "NO".*

Proof. Assume for contradiction that Lines 11 and 12 of Algorithm 3 are executed in iteration j of Algorithm 4 and Algorithm 3 does not output "NO". Let j be the first iteration where this happens. This means that there is a clause $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ of ϕ_3' and an implication $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ during the execution of Algorithm 3. Let $\texttt{NAE}(x_{uv}, x_{vw}, x_{wu})$ and $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ appear in the first execution of Lines 11 and 12 of Algorithm 3.

We first partition the implication chain $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ into "old" and "new" implications, where "old" implications are contained in $\phi_{2\text{SAT}}^{(0)}$ and all other implications (that were added in previous iterations) are considered "new". If there are several NAE clauses and implication chains that fulfill the condition in Line 9 of Algorithm 3, we assume that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ is one that contains a minimum number of "new" implications. Observe that since we assume $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ is a condition for the first execution of Lines 11 and 12 of Algorithm 3, it follows that all "new" implications in $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ were added in Line 17 or Line 19 of Algorithm 3 in previous iterations.

Note that by definition of $\phi_{2\text{SAT}}^{(0)}$, we know that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains at least one "new" implication. Furthermore, we can observe that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains at least two implications overall.

We first consider the case that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains at least one "old" implication. We assume w.l.o.g. that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains an "old" implication that is directly followed by a "new" implication (if this is not the case, then we can consider the contraposition of the implication chain).

Note that since the "new" implication was added in Line 17 or Line 19 of Algorithm 3, we can assume w.l.o.g that the "new" implication is $x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ and that $x_{ca} = 1$ for some synchronous triangle on the vertices a, b, c, that is, we have $\texttt{NAE}(x_{ab}, x_{bc}, x_{ca}) \in \phi_{3\text{NAE}}^{(0)}$ (this is the Line 17 case, Line 19 works analogously). Let $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ab}$ be the "old" implication. Then we have that $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$. Furthermore, by definition of $\phi_{2\text{SAT}}^{(0)}$, we have that $|\{p, q\} \cap \{a, b, c\}| \leq 1$, hence we can apply Lemma 13 and obtain one of the following four scenarios:

1. $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{cb}$:
   In this case we can replace $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ with $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{cb}$ in the implication chain $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ to obtain an implication chain from x_{uv} to x_{vw} with strictly fewer "new" implications, a contradiction.
2. $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{bc}$:
   Now we have that $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ab}$ and $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{bc}$. Then by definition of $\phi_{2\text{SAT}}^{(0)}$ we also have that $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ac}$ and hence $x_{ca} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{qp}$. Recall that we know that $x_{ca} = 1$. It follows that $x_{pq} = 0$ in iteration j, a contradiction to the assumption that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ exists.
3. $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ca}$:
   Now we have that $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ab}$ and $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ca}$. Then by definition of $\phi_{2\text{SAT}}^{(0)}$ we also have that $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{cb}$. From here it is the same as case 1.
4. $x_{pq} \Rightarrow_{\phi_{2\text{SAT}}^{(0)}} x_{ac}$: Same as case 2.

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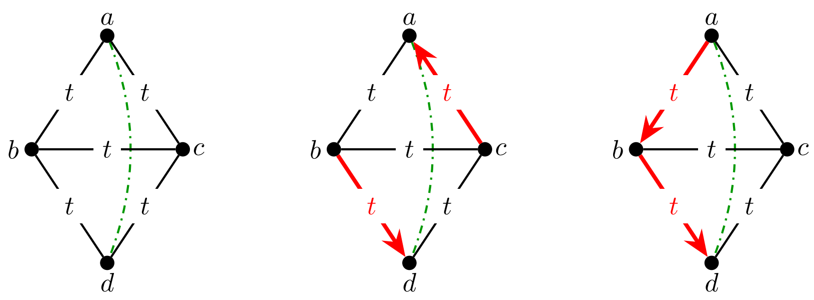

(a) (b) (c)

Figure 4 Illustration of the scenario of two consecutive "new" BF implications (a) appearing in the proof of Lemma 17. The green dash-dotted line indicates that edge $\{a, d\}$ may exist with some time label or not. The proof makes a case distinction here. Subfigure (b) illustrates the case that $x_{ab} \Rightarrow_{\mathrm{BF}} x_{cb} \Rightarrow_{\mathrm{BF}} x_{cd}$ and $x_{ca} = x_{bd} = 1$, indicated by the red arrows. Subfigure (c) illustrates the case that $x_{ca} \Rightarrow_{\mathrm{BF}} x_{cb} \Rightarrow_{\mathrm{BF}} x_{cd}$ and $x_{ab} = x_{bd} = 1$, indicated by the red arrows.

Hence, we have a contradiction in every case and can conclude that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ does not contain any "old" implications.

Now consider the case that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ only contains "new" implications. We first assume that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains exactly two "new" implications. Then the first implication is either $x_{uv} \Rightarrow_{\mathrm{BF}} x_{wv}$ or $x_{uv} \Rightarrow_{\mathrm{BF}} x_{uw}$. Note that we cannot add the implication $x_{wv} \Rightarrow x_{vw}$ in Boolean-Forcing, hence the first implication has to be $x_{uv} \Rightarrow_{\mathrm{BF}} x_{uw}$ which implies that $x_{vw} = 1$, which is a contradiction to the existence of the implication chain $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$.

From now on we assume that $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ contains strictly more than two implications. Consider two consecutive BF implications in $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$. Denote these two implications by $x_{ab} \Rightarrow_{BF} x_{cd}$ and $x_{cd} \Rightarrow_{BF} x_{fg}$. By the Boolean-Forcing algorithm, we have that either $b = d$ or $a = c$, and in both cases the edges ab and cd belong to a synchronous triangle. Suppose that $b = d$ (the case $a = c$ can be treated analogously), i.e., we have the implication $x_{ab} \Rightarrow_{BF} x_{cb}$. Let a, b, c be the vertices of the synchronous triangle for this implication. Similarly, for the implication $x_{cd} = x_{cb} \Rightarrow_{BF} x_{fg}$ we know that either $b = g$ or $c = f$. Suppose that $b = g$ (the case $c = f$ can be treated analogously), i.e., we have the implication $x_{cb} \Rightarrow_{BF} x_{fb}$. Let f', c', b' be the vertices of the synchronous triangle for this implication; that is, the edges cb and $c'b'$ are both representatives of the Λ-implication class of the variable x_{cb}. Therefore Lemma 9 (the temporal triangle lemma) implies that ab' (resp. ac') exists in the graph and belongs to the same Λ-implication class of ab (resp. ac). Therefore we can assume without loss of generality that $b = b'$ and $c = c'$. Summarizing, we have a synchronous triangle on the vertices a, b, c and another synchronous triangle b, c, f'. For convenience of the presentation, in the remainder of the proof we rename f' to d; that is, the two synchronous triangles from the two consecutive BF implications are on the vertices a, b, c and b, c, d, respectively. Note that both of these triangles must be also synchronous to each other, i.e., all their edges have the same time label t, see Figure 4 (a).

We now have the following cases for the two consecutive implications:

(A) $x_{ab} \Rightarrow_{\mathrm{BF}} x_{cb} \Rightarrow_{\mathrm{BF}} x_{cd}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ and $x_{ca} = 1$ and $x_{bd} = 1$ (Figure 4 (b)).

(B) $x_{ca} \Rightarrow_{\mathrm{BF}} x_{cb} \Rightarrow_{\mathrm{BF}} x_{cd}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi_2'} x_{vw}$ and $x_{ab} = 1$ and $x_{bd} = 1$ (Figure 4 (c)).

All other cases are symmetric to one of the two cases above. We now make a case-distinction on the (possibly missing) edge $\{a, d\}$ (dash-dotted green line in Figure 4). Cf. Table 1 for the following cases.

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1. $\{a, d\}$ is a non-edge or $\lambda(a, d) < t$:
   (A) In this case $\phi^{(0)}_{\text{2SAT}}$ by definition then contains $x_{bd} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ba}$. Hence, we have that $x_{ab} = 0$, a contradiction to the assumption that $x_{ab} \Rightarrow_{\text{BF}} x_{cb} \Rightarrow_{\text{BF}} x_{cd}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$.
   (B) Contradiction since $\phi^{(0)}_{\text{2SAT}}$ by definition then contains $x_{ab} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{db}$.
2. $\lambda(a, d) > t$:
   (A) In this case $\phi^{(0)}_{\text{2SAT}}$ by definition then contains $x_{ca} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{da}$ and $x_{bd} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ad}$, a contradiction.
   (B) In this case we know that $x_{ad} = 1$, since by definition $\phi^{(0)}_{\text{2SAT}}$ then contains $x_{bd} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ad}$. Furthermore, $\phi^{(0)}_{\text{2SAT}}$ by definition then contains $x_{ad} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ac}$ and hence we have $x_{ca} = 0$, a contradiction to the assumption that $x_{ca} \Rightarrow_{\text{BF}} x_{cb} \Rightarrow_{\text{BF}} x_{cd}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$.
3. $\lambda(a, d) = t$:
   Note that the above two cases do not apply, we can assume that all pairs of consecutive implication appearing in $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$ fall into this case. In particular, also the first one. Hence, we have that $x_{uv} \Rightarrow_{\text{BF}} x_{pv} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ or $x_{uv} \Rightarrow_{\text{BF}} x_{up} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$.
   Assume that $x_{uv} \Rightarrow_{\text{BF}} x_{pv} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$. Then in particular, using Lemma 9 (the temporal triangle lemma) similarly as described above, we get that vertices p, v, w induce a synchronous triangle and $\texttt{NAE}(x_{pv}, x_{vw}, x_{wp}) \in \phi^{(0)}_{\text{3NAE}}$. Hence, $x_{pv} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ is an implication chain that fulfills the condition in Line 9 but contains less "new" implication than $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$, a contradiction.
   Now assume that $x_{uv} \Rightarrow_{\text{BF}} x_{up} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$. Then we have that $x_{vp} = 1$, otherwise the implication $x_{uv} \Rightarrow_{\text{BF}} x_{up}$ would not have been added by Algorithm 3. In this case we also consider the second implication in the chain. There are two cases:
   - $x_{uv} \Rightarrow_{\text{BF}} x_{up} \Rightarrow_{\text{BF}} x_{uq} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ and $x_{pb} = 1$. Since we have both $x_{vp} = 1$ and $x_{pq} = 1$, we have that Algorithm 3 also sets $x_{vq} = 1$. It follows that we have that $x_{uv} \Rightarrow_{\text{BF}} x_{uq}$ and hence $x_{uv} \Rightarrow_{\text{BF}} x_{uq} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$, an implication chain that fulfills the condition in Line 9 but contains less "new" implication than $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$, a contradiction.
   - $x_{uv} \Rightarrow_{\text{BF}} x_{up} \Rightarrow_{\text{BF}} x_{qp} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ and $x_{qu} = 1$. In this case we also have $x_{uv} \Rightarrow_{\text{BF}} x_{bv}$ and $x_{qv} \Rightarrow_{\text{BF}} x_{qp}$. Hence, we have an alternative implication chain $x_{uv} \Rightarrow_{\text{BF}} x_{qv} \Rightarrow_{\text{BF}} x_{qp} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ that fulfills the condition in Line 9 of the same length. Now if $\{q, w\}$ is a non-edge, $\lambda(q, w) < t$, or $\lambda(q, w) > t$, then one of the previous cases applies to the new implication chain and we get a contradiction. Hence, assume that $\lambda(q, w) = t$. Then (using Lemma 9) we have that vertices q, v, w induce a synchronous triangle and $\texttt{NAE}(x_{qv}, x_{vw}, x_{wq}) \in \phi^{(0)}_{\text{3NAE}}$. It follows that $x_{qv} \Rightarrow_{\text{BF}} x_{qp} \overset{*}{\Rightarrow}_{\text{BF}} x_{vw}$ is an implication chain that fulfills the condition in Line 9 but contains less "new" implication than $x_{uv} \overset{*}{\Rightarrow}_{\phi'_2} x_{vw}$, a contradiction.

This finished the proof. ◀

We next show that for all iterations the 2SAT part of the formula does not contain an implication chain from a variable to its negation or vice versa.

▶ **Lemma 18.** *For every iteration $j \geq 1$ of Algorithm 4 we have that if $\phi^{(j-1)}_{3NAE} \wedge \phi^{(j-1)}_{2SAT}$ is satisfiable and there is no x_{uv} in $\phi^{(j-1)}_{2SAT}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j-1)}_{2SAT}} x_{vu}$, then there is no x_{uv} in $\phi^{(j)}_{2SAT}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{2SAT}} x_{vu}$.*

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Proof. By Lemma 15 we have that if $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ is satisfiable, then $\phi^{(j)}_{\text{2SAT}}$ is well-defined. Assume for contradiction that there is no x_{uv} in $\phi^{(j-1)}_{\text{2SAT}}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j-1)}_{\text{2SAT}}} x_{vu}$ but we have a x_{uv} in $\phi^{(j)}_{\text{2SAT}}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vu}$.

Then we can partition the implication chain $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vu}$ into "old" parts, that are also present in $\phi^{(0)}_{\text{2SAT}}$ and "new" implications, that were added by Boolean-Forcing during some iteration $j' \leq j$.

Note that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vu}$ contains at least one "new" implication. Consider an "old" implication in the implication chain followed by a "new" implication (if there is none, then there is one in the contraposition of the implication chain). By Lemma 17 the "new" implication was added by Algorithm 3 in Line 17 or Line 19. We can assume w.l.o.g that the "new" implication is $x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ and that $x_{ca} = 1$ for some synchronous triangle on the vertices a, b, c, that is, we have $\texttt{NAE}(x_{ab}, x_{bc}, x_{ca}) \in \phi^{(0)}_{\text{3NAE}}$ (this is the Line 17 case, Line 19 works analogously). Let $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ab}$ be the "old" implication. Then we have that $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ is contained in $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vw}$. Furthermore, by definition of $\phi^{(0)}_{\text{2SAT}}$, we have that $|\{p, q\} \cap \{a, b, c\}| \leq 1$, hence we can apply Lemma 13 and obtain one of the following four scenarios:

1. $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{cb}$:
   In this case we can replace $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ab} \Rightarrow_{\text{BF}} x_{cb}$ with $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{cb}$ in the implication chain $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vw}$ to obtain an implication chain from x_{uv} to x_{vw} with strictly fewer "new" implications, a contradiction.
2. $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{bc}$:
   Now we have that $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ab}$ and $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{bc}$. Then by definition of $\phi^{(0)}_{\text{2SAT}}$ we also have that $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ac}$ and hence $x_{ca} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{qp}$. Recall that we know that $x_{ca} = 1$. It follows that $x_{pq} = 0$ in iteration j, a contradiction to the assumption that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vw}$ exists.
3. $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ca}$:
   Now we have that $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ab}$ and $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ca}$. Then by definition of $\phi^{(0)}_{\text{2SAT}}$ we also have that $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{cb}$. From here it is the same as case 1.
4. $x_{pq} \Rightarrow_{\phi^{(0)}_{\text{2SAT}}} x_{ac}$: Same as Case 2. ◀

In the next lemma we show that, if Algorithm 4 gets a *yes*-instance as input, it will compute a valid orientation.

▶ **Lemma 19.** *For every iteration $j \geq 1$ of Algorithm 4 we have that if $\phi^{(j-1)}_{3NAE} \wedge \phi^{(j-1)}_{2SAT}$ is satisfiable and there is no x_{uv} in $\phi^{(j-1)}_{2SAT}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j-1)}_{2SAT}} x_{vu}$, then $\phi^{(j)}_{3NAE} \wedge \phi^{(j)}_{2SAT}$ is satisfiable and there is no x_{uv} in $\phi^{(j)}_{2SAT}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{2SAT}} x_{vu}$.*

Proof. By Lemma 15 we have that if $\phi^{(j-1)}_{\text{3NAE}} \wedge \phi^{(j-1)}_{\text{2SAT}}$ is satisfiable, then $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ is well-defined.

Note that if $\phi^{(j-1)}_{\text{3NAE}} = \emptyset$, this also implies that $\phi^{(j)}_{\text{3NAE}} = \emptyset$, and then $\phi^{(j)}_{\text{3NAE}} \wedge \phi^{(j)}_{\text{2SAT}}$ is satisfiable and there is no x_{uv} in $\phi^{(j)}_{\text{2SAT}}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{\text{2SAT}}} x_{vu}$ by Lemma 18.

From now on we assume that $\phi^{(j-1)}_{\text{3NAE}} \neq \emptyset$. We now argue that whenever $\phi^{(j-1)}_{\text{3NAE}} \neq \phi^{(j)}_{\text{3NAE}}$, we have removed some clauses from $\phi^{(j-1)}_{\text{3NAE}}$ in Line 12 or in Line 14 of Algorithm 3. By Observation 16 the removed clauses are satisfied for all satisfying assignments of $\phi^{(j)}_{\text{2SAT}}$ and

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by Lemma 18 we know that $\phi^{(j)}_{2\mathrm{SAT}}$ is satisfiable and there is no x_{uv} in $\phi^{(j)}_{2\mathrm{SAT}}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{2\mathrm{SAT}}} x_{vu}$. It follows that $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is also satisfiable. ◀

We are now ready to present our main technical result of this section.

▶ **Theorem 20.** *For every iteration $j \geq 1$ of Algorithm 4, $\phi^{(j)}_{3NAE} \wedge \phi^{(j)}_{2SAT}$ is satisfiable if and only if $\phi^{(j-1)}_{3NAE} \wedge \phi^{(j-1)}_{2SAT}$ is satisfiable.*

Proof. Suppose that $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is satisfiable, and let τ be a satisfying truth assignment of it. Let X_{j-1} (resp. X_j) be the set of variables which have not been assigned any truth value until iteration $j-1$ (resp. until iteration j). Note that $X_j \subseteq X_{j-1}$. Furthermore let τ^* be the truth assignment of the variables $X_{j-1} \setminus X_j$, which the algorithm has assigned during iteration j. Then, clearly $\tau \cup \tau^*$ is a satisfying truth assignment of $\phi^{(j-1)}_{3\mathrm{NAE}} \wedge \phi^{(j-1)}_{2\mathrm{SAT}}$.

Conversely, suppose that $\phi^{(j-1)}_{3\mathrm{NAE}} \wedge \phi^{(j-1)}_{2\mathrm{SAT}}$ is satisfiable. Then, by iteratively applying the arguments of the previous paragraph, it follows that also $\phi^{(k)}_{3\mathrm{NAE}} \wedge \phi^{(k)}_{2\mathrm{SAT}}$ is satisfiable, for every $0 \leq k \leq j-1$. In particular, $\phi^{(0)}_{3\mathrm{NAE}} \wedge \phi^{(0)}_{2\mathrm{SAT}}$ is satisfiable. Moreover, by construction, $\phi^{(0)}_{2\mathrm{SAT}}$ does not contain any x_{uv} such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(0)}_{2\mathrm{SAT}}} x_{vu}$. Therefore by inductively applying Lemma 19, it follows that $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is satisfiable and that there is no x_{uv} in $\phi^{(j)}_{2\mathrm{SAT}}$ such that $x_{uv} \overset{*}{\Rightarrow}_{\phi^{(j)}_{2\mathrm{SAT}}} x_{vu}$. ◀

Using our main technical result of Theorem 20, we can now conclude this section with the next theorem.

▶ **Theorem 21.** *Algorithm 4 correctly solves* TTO *in polynomial time.*

Proof. First recall by Observation 14 that the input temporal graph (G, λ) is transitively orientable if and only if $\phi^{(0)}_{3\mathrm{NAE}} \wedge \phi^{(0)}_{2\mathrm{SAT}}$ is satisfiable.

Let (G, λ) be a *yes*-instance. Then, by iteratively applying Theorem 20 it follows that $\phi^{(j)}_{3\mathrm{NAE}} \wedge \phi^{(j)}_{2\mathrm{SAT}}$ is satisfiable, for every iteration j of the algorithm. Recall that, at the end of the last iteration k of the algorithm, $\phi^{(k)}_{3\mathrm{NAE}} \wedge \phi^{(k)}_{2\mathrm{SAT}}$ is empty. Then, in line 19, the algorithm gives the arbitrary truth value $x_i = 1$ to every variable x_i which did not yet get any truth value yet. This is a correct decision as all these variables are not involved in any Boolean constraint of $\phi^{(k)}_{3\mathrm{NAE}} \wedge \phi^{(k)}_{2\mathrm{SAT}}$ (which is empty). Finally, the algorithm orients in line 20 all edges of G according to the corresponding truth assignment. The returned orientation F of (G, λ) is temporally transitive as every variable was assigned a truth value according to the Boolean constraints throughout the execution of the algorithm.

Now let (G, λ) be a *no*-instance. We will prove that, at some iteration $j \leq 0$, the algorithm will "NO". Suppose otherwise that the algorithm instead returns an orientation F of (G, λ) after performing k iterations. Then clearly $\phi^{(k)}_{3\mathrm{NAE}} \wedge \phi^{(k)}_{2\mathrm{SAT}}$ is empty, and thus clearly satisfiable. Therefore, iteratively applying Theorem 20 implies that $\phi^{(0)}_{3\mathrm{NAE}} \wedge \phi^{(0)}_{2\mathrm{SAT}}$ is also satisfiable, and thus (G, λ) is temporally transitively orientable by Observation 14, which is a contradiction to the assumption that (G, λ) be a *no*-instance.

Lastly, we prove that Algorithm 4 runs in polynomial time. The Λ-implication classes of (G, λ) can be clearly computed by Algorithm 1 in polynomial time. Algorithm 3 (Boolean-Forcing) iteratively adds and removes clauses from the 2SAT formula ϕ'_2, while it can only remove clauses from the 3NAE formula ϕ'_3. Whenever a clause is added to ϕ'_2, a clause of ϕ'_3 is removed. Therefore, as the initial 3NAE formula ϕ_3 has at most polynomially-many clauses, we can add clauses to ϕ'_2 only polynomially-many times. Thus, as in all other steps, Algorithm 3 just checks clauses of ϕ'_2 and ϕ'_3 and it forces certain truth values to

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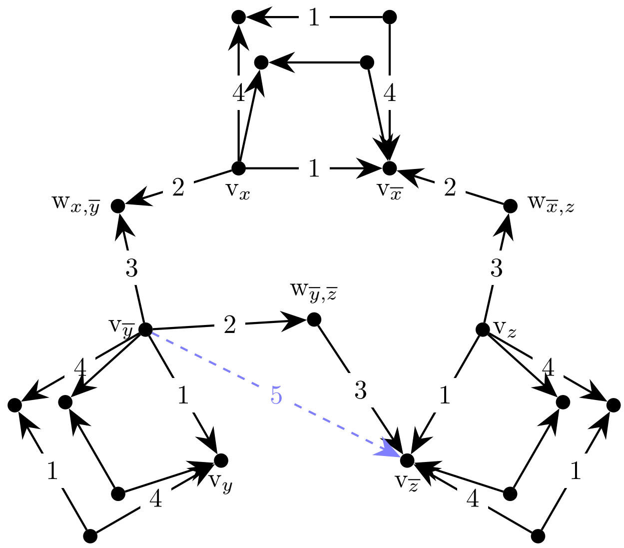

Figure 5 Temporal graph constructed from the formula $(x \Rightarrow \overline{y}) \wedge (\overline{x} \Rightarrow z) \wedge (\overline{y} \Rightarrow \overline{z})$ for $k = 1$ with orientation corresponding to the assignment $x =$ `true`, $y =$ `false`, $z =$ `true`. Since this assignment does not satisfy the third clause, the dashed blue edge is required to make the graph temporally transitive.

variables, the total running time of Algorithm 3 is polynomial. Furthermore, in Algorithm 2 (Initial-Forcing) and Algorithm 4 (the main algorithm) the Boolean-Forcing-subroutine (Algorithm 3) is only invoked at most four times for every variable in $\phi^{(0)}_{\text{3NAE}} \wedge \phi^{(0)}_{\text{2SAT}}$. Hence, we have an overall polynomial running time. ◀

4 Temporal Transitive Completion

We now study the computational complexity of Temporal Transitive Completion (TTC). In the static case, the so-called *minimum comparability completion* problem, i.e. adding the smallest number of edges to a static graph to turn it into a comparability graph, is known to be NP-hard [25]. Note that minimum comparability completion on static graphs is a special case of TTC and thus it follows that TTC is NP-hard too. Our other variants, however, do not generalize static comparability completion in such a straightforward way. Note that for Strict TTC we have that the corresponding recognition problem Strict TTO is NP-complete (Theorem 3), hence it follows directly that Strict TTC is NP-hard. For the remaining two variants of our problem, we show in the following that they are also NP-hard, giving the result that all four variants of TTC are NP-hard. Furthermore, we present a polynomial-time algorithm for all four problem variants for the case that all edges of underlying graph are oriented, see Theorem 23. This allows directly to derive an FPT algorithm for the number of unoriented edges as a parameter.

▶ **Theorem 22.** *All four variants of* TTC *are NP-hard.*

Proof. We give a reduction from the NP-hard Max-2-Sat problem [23].

Max-2-Sat
Input: A boolean formula ϕ in implicative normal form[5] and an integer k.
Question: Is there an assignment of the variables which satisfies at least k clauses in ϕ?

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We only describe the reduction from Max-2-Sat to TTC. However, the same construction can be used to show NP-hardness of the other variants.

Let (ϕ, k) be an instance of Max-2-Sat with m clauses. We construct a temporal graph $\mathcal{G}$ as follows. For each variable x of ϕ we add two vertices denoted v_x and $\mathrm{v}_{\overline{x}}$, connected by an edge with label 1. Furthermore, for each $1 \le i \le m-k+1$ we add two vertices v_x^i and $\mathrm{v}_{\overline{x}}^i$ connected by an edge with label 1. We then connect v_x^i with $\mathrm{v}_{\overline{x}}$ and $\mathrm{v}_{\overline{x}}^i$ with v_x using two edges labeled 4. Thus $\mathrm{v}_x, \mathrm{v}_{\overline{x}}, \mathrm{v}_x^i, \mathrm{v}_{\overline{x}}^i$ is a 4-cycle whose edges alternating between 1 and 4. Afterwards, for each clause $(a \Rightarrow b)$ of ϕ with a, b being literals, we add a new vertex $\mathrm{w}_{a,b}$. Then we connect $\mathrm{w}_{a,b}$ to v_a by an edge labeled 2 and to v_b by an edge labeled 3. Consider Figure 5 for an illustration. Observe that $\mathcal{G}$ can be computed in polynomial time.

We claim that $(\mathcal{G} = (G, \lambda), \emptyset, m-k)$ is a yes-instance of TTC if and only if ϕ has a truth assignment satisfying k clauses.

For the proof, begin by observing that $\mathcal{G}$ does not contain any triangle. Thus an orientation of $\mathcal{G}$ is (weakly) (strict) transitive if and only if it does not have any oriented temporal 2-path, i.e. a temporal path of two edges with both edges being directed forward. We call a vertex v of $\mathcal{G}$ *happy* about some orientation if v is not the center vertex of an oriented temporal 2-path. Thus an orientation of $\mathcal{G}$ is transitive if and only if all vertices are happy.

($\Leftarrow$): Let α be a truth assignment to the variables (and thus literals) of ϕ satisfying k clauses of ϕ. For each literal a with $\alpha(a) = \texttt{true}$, orient all edges such that they point away from v_a and v_a^i, $1 \le i \le m-k+1$. For each literal a with $\alpha(a) = \texttt{false}$, orient all edges such that they point towards v_a and v_a^i, $1 \le i \le m-k+1$. Note that this makes all vertices v_a and v_a^i happy. Now observe that a vertex $\mathrm{w}_{a,b}$ is happy unless its edge with v_a is oriented towards $\mathrm{w}_{a,b}$ and its edge with v_b is oriented towards v_b. In other words, $\mathrm{w}_{a,b}$ is happy if and only if α satisfies the clause $(a \Rightarrow b)$. Thus there are at most $m-k$ unhappy vertices. For each unhappy vertex $\mathrm{w}_{a,b}$, we add a new oriented edge from v_a to v_b with label 5. Note that this does not make v_a or v_b unhappy as all adjacent edges are directed away from v_a and towards v_b. The resulting temporal graph is transitively oriented.

($\Rightarrow$): Now let a transitive orientation F' of $\mathcal{G}' = (G', \lambda')$ be given, where $\mathcal{G}'$ is obtained from $\mathcal{G}$ by adding at most $m-k$ time edges. Clearly we may also interpret F' as an orientation induced of $\mathcal{G}$. Set $\alpha(x) = \texttt{true}$ if and only if the edge between v_x and $\mathrm{v}_{\overline{x}}$ is oriented towards $\mathrm{v}_{\overline{x}}$. We claim that this assignment α satisfies at least k clauses of ϕ.

First observe that for each variable x and $1 \le i \le m-k+1$, F' is a transitive orientation of the 4-cycle $\mathrm{v}_x, \mathrm{v}_{\overline{x}}, \mathrm{v}_x^i, \mathrm{v}_{\overline{x}}^i$ if and only if the edges are oriented alternatingly. Thus, for each variable, at least one of these $k+1$ 4-cycles is oriented alternatingly. In particular, for every literal a with $\alpha(a) = \texttt{true}$, there is an edge with label 4 that is oriented away from v_a. Conversely, if $\alpha(b) = \texttt{false}$, then there is an edge with label 1 oriented towards v_b (this is simply the edge from $\mathrm{v}_{\overline{b}}$).

This implies that every edge with label 2 or 3 oriented from some vertex $\mathrm{w}_{c,d}$ (where either $a = c$ or $a = d$) towards v_a with $\alpha(a) = \texttt{true}$ requires $E(G') \setminus E(G)$ to contain an edge from $\mathrm{w}_{c,d}$ to some $\mathrm{v}_{\overline{a}}^i$. Analogously every edge with label 2 or 3 oriented from v_a with $\alpha(a) = \texttt{false}$ to some $\mathrm{w}_{c,d}$ requires $E(G') \setminus E(G)$ to contain an edge from $\mathrm{v}_{\overline{a}}$ to $\mathrm{w}_{c,d}$.

Now consider the alternative orientation F'' obtained from α as detailed in the converse orientation of the proof. For each edge between v_a and $\mathrm{w}_{c,d}$ where F' and F'' disagree, F'' might potentially require $E(G') \setminus E(G)$ to contain the edge $\mathrm{v}_c\mathrm{v}_d$ (labeled 5, say), but in turn saves the need for some edge $\mathrm{w}_{c,d}\mathrm{v}_{\overline{a}}^i$ or $\mathrm{v}_{\overline{a}}\mathrm{w}_{c,d}$, respectively. Thus, overall, F'' requires at

[5] i.e. a conjunction of clauses of the form $(a \Rightarrow b)$ where a, b are literals.

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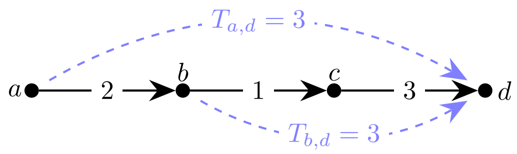

Figure 6 Example of a tail-heavy path.

most as many edge additions as F', which are at most $m - k$. As we have already seen in the converse direction, F'' requires exactly one edge to be added for every clause of ϕ which is not satisfied. Thus, α satisfies at least k clauses of ϕ. ◀

We now show that TTC can be solved in polynomial time, if all edges are already oriented, as the next theorem states. While we only discuss the algorithm for TTC the algorithm only needs marginal changes to work for all other variants.

▶ **Theorem 23.** *An instance $(\mathcal{G}, F, k)$ of* TTC *where $\mathcal{G} = (G, \lambda)$ and $G = (V, E)$, can be solved in $O(m^2)$ time if F is an orientation of E, where $m = |E|$.*

The actual proof of Theorem 23 is deferred to the end of this section. The key idea for the proof is based on the following definition. Assume a temporal graph $\mathcal{G}$ and an orientation F of $\mathcal{G}$ to be given. Let $G' = (V, F)$ be the underlying graph of $\mathcal{G}$ with its edges directed according to F. We call a (directed) path P in G' *tail-heavy* if the time-label of its last edge is largest among all edges of P, and we define $t(P)$ to be the time-label of that last edge of P. For all $u, v \in V$, denote by $T_{u,v}$ the maximum value $t(P)$ over all tail-heavy (u, v)-paths P of length at least 2 in G'; if such a path does not exist then $T_{u,v} = \perp$. If the temporal graph $\mathcal{G}$ with orientation F can be completed to be transitive, then adding the time edges of the set

$$X(\mathcal{G}, F) := \{(uv, T_{u,v}) \mid T_{u,v} \neq \perp\},$$

which are not already present in $\mathcal{G}$ is an optimal way to do so. Consider Figure 6 for an example.

▶ **Lemma 24.** *The set $X(\mathcal{G}, F)$ can be computed in $O(m^2)$ time, where $\mathcal{G}$ is a temporal graph with m time-edges and F an orientation of $\mathcal{G}$.*

Proof. For each edge vw, we can take G' (defined above), remove w and all arcs whose label is larger than $\lambda(v, w)$, and do a depth-first-search from v to find all vertices u which can reach v in the resulting graph. Each of these then has $T_{u,w} \geq \lambda(v, w)$. By doing this for every edge vw, we obtain $T_{u,w}$ for every vertex pair u, w. The overall running time is clearly $O(m^2)$. ◀

Until the end of this section we are only considering the instance $(\mathcal{G}, F, k)$ of TTC, where $\mathcal{G} = (G, \lambda)$, $G = (V, E)$, and F is an orientation of $\mathcal{G}$. Hence, we can say a set X of oriented time-edges is a *solution* to I if $X' := \{\{u, v\} \mid (uv, t) \in X\}$ is disjoint from E, satisfies $|X| = |X'| \leq k$, and $F' := F \cup \{uv \mid (uv, t) \in X\}$ is a transitive orientation of the temporal graph $\mathcal{G} + X := ((V, E \cup X'), \lambda')$, where $\lambda'(e) := \lambda(e)$ if $e \in E$ and $\lambda'(u, v) := t$ if X contains (uv, t) or (vu, t).

The algorithm we use to show Theorem 23 will use $X(\mathcal{G}, F)$ to construct a solution (if there is any) of a given instance $(\mathcal{G}, F, k)$ of TTC where F is a orientation of E. To prove the correctness of this approach, we make use of the following.

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▶ **Lemma 25.** *Let $I = (\mathcal{G} = (G, \lambda), F, k)$ be an instance of* TTC*, where $G = (V, E)$ and F is an orientation of E and X an solution for I. Then, for any $(vu, T_{v,u}) \in X(\mathcal{G}, F)$ there is a (vu, t) in $\mathcal{G} + X$ with $t \geq T_{v,u}$.*

Proof. Let $(v_0v_\ell, T_{v_0,v_\ell}) \in X(\mathcal{G}, F)$, and $G' = (V, F)$. Hence, there is a tail-heavy (v_0, v_ℓ)-path P in G' of length $\ell \geq 2$. If $\ell = 2$, then clearly $\mathcal{G} + X$ must contain the time edge (v_1v_ℓ, t) such that $t \geq T_{v_1,v_\ell}$. Now let $\ell > 2$ and $V(P) := \{v_i \mid i \in \{0, 1, \ldots, \ell\}\}$ and $E(P) = \{v_{i-1}v_i \mid i \in [\ell]\}$. Since there is a tail-heavy $(v_{\ell-2}, v_\ell)$-path in G' of length 2, $\mathcal{G} + X$ must contain a time-edge $(v_{\ell-2}v_\ell, t)$ with $t \geq T_{v_0,v_\ell}$. Therefore, the (directed) underlying graph of $\mathcal{G} + X$ contains a tail-heavy (v_0, v_ℓ)-path of length $\ell - 1$. By induction, $\mathcal{G} + X$ must contain the time edge (v_1v_ℓ, t') such that $t' \geq t \geq T_{v_0,v_\ell}$. ◀

Form Lemma 25, it follows that we can use $X(\mathcal{G}, F)$ to identify *no*-instances in some cases.

▶ **Corollary 26.** *Let $I = (\mathcal{G} = (G, \lambda), F, k)$ be an instance of* TTC*, where $G = (V, E)$ and F is an orientation of E. Then, I is a* no*-instance, if for some $v, u \in V$*

1. *there are time-edges $(vu, t) \in X(\mathcal{G}, F)$ and $(uv, t') \in X(\mathcal{G}, F)$,*
2. *there is an edge $uv \in F$ such that $(vu, T_{v,u}) \in X(\mathcal{G}, F)$, or*
3. *there is an edge $vu \in F$ such that $(vu, T_{v,u}) \in X(\mathcal{G}, F)$ with $\lambda(v, u) < T_{v,u}$.*

We are now ready to prove Theorem 23.

Proof of Theorem 23. Let $I = (\mathcal{G} = (G, \lambda), F, k)$ be an instance of TTC, where F is a orientation of E. First we compute $X(\mathcal{G}, F)$ in polynomial time, see Lemma 24. Let $Y = \{(vu, t) \in X(\mathcal{G}, F) \mid \{v, u\} \notin E\}$ and report that I is a *no*-instance if $|Y| > k$ or one of the conditions of Corollary 26 holds true. Otherwise report that I is a *yes*-instance. This gives an overall running time of $O(m^2)$.

Clearly, if one of the conditions of Corollary 26 holds true, then I is a *no*-instance. Moreover, by Lemma 25 any solution contains at least $|Y|$ time edges. Thus, if $|Y| > k$, then I is a *no*-instance.

If we report that I is a *yes*-instance, then we claim that Y is a solution for I. Let $F' \supseteq F$ be a orientation of $\mathcal{G} + Y$. Assume towards a contradiction that F' is not transitive. Then, there is a temporal path $((vu, t_1), (uw, t_2))$ in $\mathcal{G} + Y$ such that there is no time-edge (uw, t) in $\mathcal{G} + Y$, with $t \geq t_2$. By definition of $X(\mathcal{G}, F)$, the directed graph $G' = (V, F)$ contains a tail-heavy (v, u)-path P_1 with $t_1 = t(P_1)$ and a tail-heavy (u, w)-path P_2 with $t_2 = t(P_2) \geq t_1$. By concatenation of P_1 and P_2, we obtain that the G' contains a (v, w)-path P' of length at least two such that $t_2 = t(P')$. Thus, $t_2 \leq T_{v,w}$ and $(vw, T_{v,w}) \in X(\mathcal{G})$—a contradiction. ◀

Using Theorem 23 we can now prove that TTC is fixed-parameter tractable (FPT) with respect to the number of unoriented edges in the input temporal graph $\mathcal{G}$.

▶ **Corollary 27.** *Let $I = (\mathcal{G} = (G, \lambda), F, k)$ be an instance of* TTC*, where $G = (V, E)$. Then I can be solved in $O(2^q \cdot m^2)$, where $q = |E| - |F|$ and m the number of time edges.*

Proof. Note that there are 2^q ways to orient the q unoriented edges. For each of these 2^q orientations of these q edges, we obtain a fully oriented temporal graph. Then we can solve TTC on each of these fully oriented graphs in $O(m^2)$ time by Theorem 23. Summarizing, we can solve TTC on I in $2^q \cdot m^2$ rime. ◀

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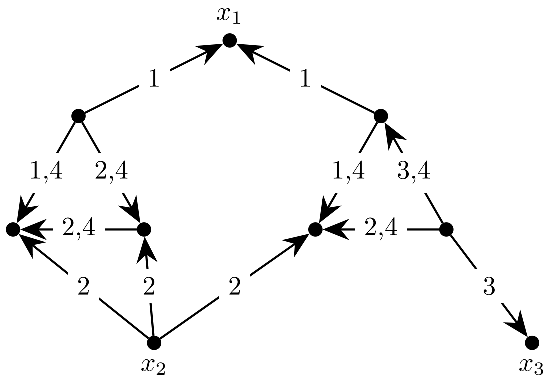

Figure 7 Temporal graph constructed from the formula $\texttt{NAE}(x_1, x_2, x_2) \wedge \texttt{NAE}(x_1, x_2, x_3)$ and orientation corresponding to setting $x_1 = \texttt{false}$, $x_2 = \texttt{true}$, and $x_3 = \texttt{false}$. Each attachment vertex is at the clockwise end of its edge.

5 Deciding Multilayer Transitive Orientation

In this section we prove that Multilayer Transitive Orientation (MTO) is NP-complete, even if every edge of the given temporal graph has at most two labels. Recall that this problem asks for an orientation F of a temporal graph $\mathcal{G} = (G, \lambda)$ (i.e. with exactly one orientation for each edge of G) such that, for every "time-layer" $t \geq 1$, the (static) oriented graph defined by the edges having time-label t is transitively oriented in F. As we discussed in Section 2, this problem makes more sense when every edge of G potentially has multiple time-labels, therefore we assume here that the time-labeling function is $\lambda : E \to 2^{\mathbb{N}}$.

▶ **Theorem 28.** MTO *is NP-complete, even on temporal graphs with at most two labels per edge.*

Proof. We give a reduction from monotone Not-All-Equal-3Sat, which is known to be NP-hard [42]. So let $\phi = \bigwedge_{i=1}^{m} \texttt{NAE}(y_{i,1}, y_{i,2}, y_{i,3})$ be a monotone Not-All-Equal-3Sat instance and $X := \{x_1, \ldots, x_n\} := \bigcup_{i=1}^{m} \{y_{i,1}, y_{i,2}, y_{i,3}\}$ be the set of variables.

Start with an empty temporal graph $\mathcal{G}$. For every clause $\texttt{NAE}(y_{i,1}, y_{i,2}, y_{i,3})$, add to $\mathcal{G}$ a triangle on three new vertices and label its edges $\mathrm{a}_{i,1}, \mathrm{a}_{i,2}, \mathrm{a}_{i,3}$. Give all these edges label $n+1$. For each of these edges, select one of its endpoints to be its *attachment vertex* in such a way that no two edges share an attachment vertex. Next, for each $1 \leq i \leq n$, add a new vertex v_i. Let $A_i := \{\mathrm{a}_{i,j} \mid y_{i,j} = x_i\}$. Add the label i to every edge in A_i and connect its attachment vertex to v_i with an edge labeled i. See also Figure 7.

We claim that $\mathcal{G}$ is a *yes*-instance of MTO if and only if ϕ is satisfiable.

(⇐): Let $\alpha : X \to \{\texttt{true}, \texttt{false}\}$ be an assignment satisfying ω. For every $x_i \in X$, orient all edges adjacent to v_i away from v_i if $\alpha(x_i) = \texttt{true}$ and towards v_i otherwise. Then, orient every edge $\mathrm{a}_{i,j}$ towards its attachment vertex if $\alpha(y_{i,j}) = \texttt{true}$ and away from it otherwise.

Note that in the layers 1 through n every vertex either has all adjacent edges oriented towards it or away from it. Thus these layers are clearly transitive. It remains to consider layer $n+1$ which consists of a disjoint union of triangles. Each such triangle $\mathrm{a}_{i,1}, \mathrm{a}_{i,2}, \mathrm{a}_{i,3}$ is oriented non-transitively (i.e. cyclically) if and only if $\alpha(y_{i,1}) = \alpha(y_{i,2}) = \alpha(y_{i,3})$, which never happens if α satisfies ϕ.

(⇒): Let ω be an orientation of the underlying edges of $\mathcal{G}$ such that every layer is transitive. Since they all share the same label i, the edges adjacent to v_i must be all oriented towards

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or all oriented away from v_i. We set $\alpha(x_i) = \texttt{false}$ in the former and $\alpha(x_i) = \texttt{true}$ in the latter case. This in turn forces each edge $\mathrm{a}_{i,j}$ to be oriented towards its attachment vertex if and only if $\alpha(\mathrm{a}_{i,j}) = \texttt{true}$. Therefore, every clause $\texttt{NAE}(y_{i,1}, y_{i,2}, y_{i,3})$ is satisfied, since the three edges $\mathrm{a}_{i,1}, \mathrm{a}_{i,2}, \mathrm{a}_{i,3}$ form a triangle in layer $n+1$ and can thus not be oriented cyclically (i.e. all towards or all away from their respective attachment vertices). ◀

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