

Temporal Graphs Research at Pomona College

Working Definitions and Vocabulary

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1 About

As we continue researching temporal graphs and their related properties there is an increased need to establish fundamental definitions. Although many papers have established definitions of the terms and concepts contained within this paper, there are subtle details of each of these definitions that vary from paper to paper making it difficult to efficiently communicate exact ideas.

This document shall serve as an ongoing record of the definitions we will use in our research. The definitions contained within should serve as the defaults in conversations; if you intend to use an alternate definition to a concept defined in this document, you should state and/or cite the alternate definition. (In the future, we will look to incorporate alternate definitions in this document as well.) It should be noted that these definitions may change as we continue our research.

2 Preliminary Definitions

Definition 2.0.1. A **temporal graph** or **temporal network**¹ is defined as a tuple $G \in V \times E$ where V is the set of vertices, and $E \in V^2 \times T^2$ is the set of edges such that $T = [0, \infty)$:

$$G = (V, E)$$

Each edge $e \in E$ is a 5-tuple (v_i, v_j, t_0, t_f, w) such that $v_i, v_j \in V$, $t_0, t_f \in T$, and $t_0 \leq t_f$. An edge is said to connect v_i to v_j (with the possibility of $v_i = v_j$) between the time $[t_0, t_f]$ with weight $w \in W$ with $W \subseteq \mathbb{R}$. That is, all edges are to be treated as directed edges with some weight and time-window (possibly instantaneous) in which they are *active*. Additionally, we will maintain the standard definitions of *size* and *order* defined respectively: $|E| = m$, $|V| = n$.

With this generalized definition of a temporal network, we will begin to explain some common, specialized descriptors of these networks:

¹We will treat the terms *graph* and *network* synonymously throughout this paper.

Definition 2.0.2. We will define an **undirected temporal graph** as a temporal network (V, \mathcal{E}) with V a set of vertices and \mathcal{E} is a set such that $e \in \mathcal{E}$ is defined to be an unordered pair of 6-tuples

$$e = ((u, v, t_0, t_f, w), (v, u, t_0, t_f, w))$$

with $u, v \in V, t_0, t_f \in [0, \infty]$, and $w \in W$ with $W \subseteq \mathbb{R}$. For simplicity, we can describe an edge e as above by its first or second 5-tuple, since the existence of one implies the existence of the other.

Definition 2.0.3. We will describe a temporal graph as **unweighted** if every edge in E has equal weight w .

Definition 2.0.4. Edge persistence is the amount of time for which an edge is present. More formally, in a graph (V, E) the persistence of an edge (u, v, t_1, t_2, w) is defined as $t_2 - t_1$ or simply δt .

Definition 2.0.5. An edge $e \in E$ is said to be **infinitely persistent** if $t_f = \infty$.

Definition 2.0.6. A **instantaneous edge** or **contact edge** is any edge $e \in E$ where $t_0 = t_f$.

Definition 2.0.7. Windowed networks shall be defined as any temporal network where for at least one edge $e = (v_i, v_j, t_0, t_f, w)$, $t_0 \neq t_f$.

Definition 2.0.8. Contact networks shall be defined as a temporal network where every edge in the network is an *instantaneous edge* or *contact edge*. It is simply a special case of an interval network.

Definition 2.0.9. An **infinitely-edge-persisting network** shall be defined as a temporal network where every edge is **infinitely persistent**.

Definition 2.0.10. A **co-authorship network** is an undirected interval network in which each node represents an author, and the existence of an edge between two nodes represents a collaboration over the a period of time δt . Unless stated otherwise, we shall assume a *collaboration* to mean two authors worked on 1 or more publications together in δt .

Definition 2.0.11. A **citation network** is a directed interval network (V, E) with infinite edge persistence. For simplicity, we can write edges as $u \rightarrow_{t_1} v$ or $(u, v)_{t_1}$. In this network, each node represents an author, and the existence of an edge $u \rightarrow_{t_1} v$ means that author v cited author u at time t . This way the direction of the arrow represents the flow of information.

Now we will move on to consider the different analysis methodologies that will result from different temporal definitions of ‘shortest path’.

Definition 2.0.12. A graph is a **path** if it is a simple graph whose vertices can be linearly ordered such that there is an edge uv if and only if u and v are adjacent in the ordering. A digraph is a **path** if it is a simple directed graph whose vertices can be linearly ordered such that there is an edge $u \rightarrow v$ if and only if v immediately follows u in the ordering.

Definition 2.0.13. A **shortest path** between v_1, u (di)graph $G = (V, E)$ is $P = v_1, v_2, \dots, v_n, u$ such that $v_i \in V$ for all $i \in [n]$, and $v_j v_{j+1}, v_n u \in E$, for all $j \in [n-1]$, and there is no path $P' = v_1, v_2, \dots, v_m, u$ such that $m < n$.

Note that this definition does not enforce uniqueness of shortest paths.

3 Consecutive Contemporaneity

Here, we consider the addition of paths to include a temporal component, where any two consecutive edges must share some contemporary period. This is a sensible definition as two edges should not be able to form a path in a temporal network if they did not happen at the same time. This is formally defined below.

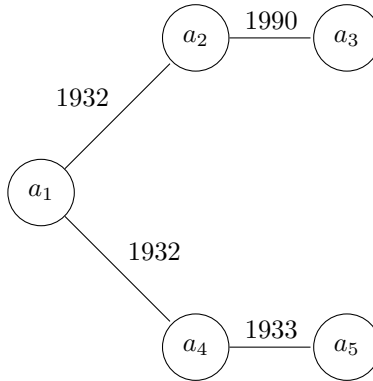
Definition 3.0.14. A **consecutive temporal path** between v_1 and v_n is a path $P = v_1, v_2, \dots, v_n$ such that $v_i \in V$ for all $i \in [n]$, and $v_j v_{j+1} \in E$, for all $j \in [n-1]$, and for every pair of consecutive edges $(v_{i-1}, v_i)_{t_1}$ and $(v_i, v_{i+1})_{t_2}$, $t_1 \leq t_2$.

We will consider the consequences of this definition in the context of different edge-behaviors, infinite persistence, and windowed persistence.

3.1 Infinitely Persistent Edges

The first model we will consider is the simplest of the three, where we disallow edge-deletion. We will define the persistent coauthorship network to have this property. [note about semantic equivalence to railway network?]

Definition 3.1.1. The **persistent co-authorship network** a co-authorship network $G = (V, E)$, where for all $(u, v, t_1, t_2) \in E$, $t_2 = \infty$. For simplicity, we can denote an edge by $(u, v)_{t_1}$ or $u -_{t_1} v$. Since this network is undirected, $(u, v)_{t_1} = (v, u)_{t_1}$.



Then, we can consider what a reasonable definition of ‘shortest path’ might be. In this model, once an edge exists, it is always traversible, so if author a_1

wrote a paper with author a_2 in 1932, and author a_2 wrote a paper with a_3 in 1990, we can find a path between a_1 and a_3 . It is also feasible that a_1 wrote a paper with a_4 in 1932 as well, and then a_4 and a_3 wrote a paper in 1933. These two paths $P_1 = a_1 -_{1932} a_2 -_{1990} a_3$, and $P_2 = a_1 -_{1932} a_4 -_{1933} a_3$ should have some manner of differentiation, since the difference in start times of the edges is 58 in P_1 and only 1 in P_2 . This distinction motivates a difference in fastest vs. shortest path.

Definition 3.1.2. The **persistent shortest path** between u and v is a consecutive temporal path u, v_1, \dots, v_n, v such there exists no other u, u_1, \dots, u_m, v such that $m < n$.

The **persistent fastest path** between v_1 and v_n is consecutive temporal path v_1, v_2, \dots, v_n , with first edge $(v_1, v_2)_{t_1}$ and last edge $(v_{n-1}, v_n)_{t_{n-1}}$, such that there exists no other u_1, u_2, \dots, u_m with first edge $(u_1, u_2)_{s_1}$, last edge $(u_{m-1}, u_m)_{s_{m-1}}$ and $s_{m-1} - s_1 < t_{n-1} - t_1$.

Corollary 3.1.3. *Shortest path in persistent coauthorship network is the same as the shortest path in the aggregated static graph.*

Proof. (Idea). Since the edges have infinite persistence, can just wait at a vertex until the desired edge in the aggregated graph shows up. \square

3.2 Windowed edges

Now consider that we in fact limit the persistence of the edges with an endpoint specific to each edge (as is specified in the definition of an interval network temporal graph). We call this graph a **windowed co-authorship network** or simply a **co-authorship network**. If we specify a universal edge-persistence Δt such that for all edges (u, v, t_1, t_2) in the network, $\Delta t = t_2 - t_1$, then we call this co-authorship network Δt -**windowed**.

When we consider the above definition of a path it is clearly too simplistic, as it does not consider that an edge may cease to exist. So let us consider a new definition of a temporal path.

Definition 3.2.1. A **windowed temporal path** between v_1 and v_n is a collection of edges $(v_1, v_2, s_1, t_1), (v_2, v_3, s_2, t_2), \dots, (v_{n-1}, v_n, s_{n-1}, t_{n-1})$ such that v_1 and v_n have degree n , and the remaining vertices have degree 2. Most importantly, $t_i \geq s_{i+1}$ for all $i \in [n - 2]$.

The definitions for fastest and shortest path will be the same as in definition [?].

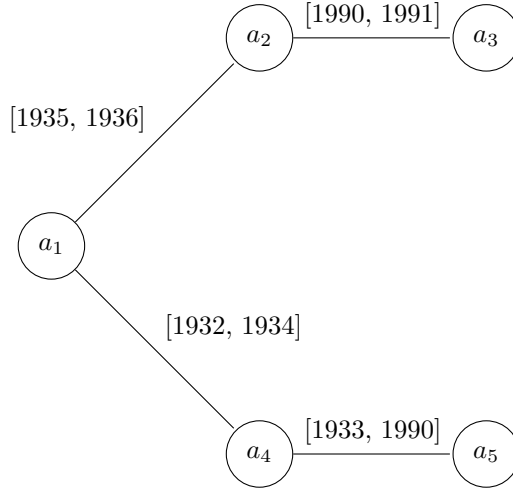
4 Pairwise Contemporaneity

Here we can consider many of the same definitions, but under a different lens of contemporaneity for paths. Here we want all edges to have some overlap in their time interval.

Definition 4.0.2. A **pairwise contemporary temporal path** between v_1 and v_n is a collection of edges $(v_1, v_2, s_1, t_1), (v_2, v_3, s_2, t_2), \dots, (v_{n-1}, v_n, s_{n-1}, t_{n-1})$, such that $\bigcap_{i \in [n-1]} [s_i, t_i] \neq \emptyset$.

As might be expected, pairwise contemporary temporal paths behave the same way that consecutive temporal paths do in the persistent co-authorship network. Since the edges have infinite persistence, all edges are contemporary ‘at infinity.’

In the case of the windowed co-authorship network, the definitions remain the same for shortest and fastest paths.



In the above figure, there exists a pairwise contemporary path P_1 such that $P_1 = a_5 - a_4 - a_1$, but there does NOT exist a pairwise contemporary path P_2 such that $P_2 = a_5 - a_4 - a_1 - a_2$.