



# COMP702 DESIGN & SPECIFICATION

DEPARTMENT OF COMPUTER SCIENCE

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## OPEN-SOURCE TEMPORAL NETWORKS LIBRARY

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## Abstract

This article outlines the specification and design of an Open-Source Temporal Networks library. The document consists of several key sections; an introduction to the subject area; a specification of the library and what it aims to achieve; the design process and proposed architecture; a project plan for the remaining work; a summary of the necessary requirements and skills needed to complete the project. The ultimate goal of the project is to develop a convenient library for the modelling and analysis of temporal networks to aid in the study and research of many real-world applications and systems.

## 1 Introduction

Temporal networks are prevalent across many systems in the modern world, be it natural, social, technological, financial or industrial. A few examples of temporal networks include public transport[4], human interaction[5], stock markets[2] and wireless sensors[3]. These examples show that a diverse amount of systems can be modelled as a temporal network, or are inherently so. The analysis of such networks can yield new and useful information that was previously not obvious from the raw data (for example, message logs). A convenient library which allows for such network modelling and analysis would prove very useful for multiple disciplines and domains.

A static network can be represented as a graph, consisting of nodes and edges. In its simplest form, a graph is a set of points interconnected with lines, where each line connects a pair of points. The graph connectivity is defined in the incidence function, which associates edges and node pairs (ch01 [1]). Mathematically, a graph  $G$  is an ordered triple of nodes, edges and the incidence function:

$$V = (a, b, c)$$

$$G = (V, E, \psi)$$

$$E = (x, y, z)$$

$$\psi(x) = (ab), \psi(y) = (ac), \psi(z) = (bc)$$

A graph may be undirected, where an edge  $z$  connecting nodes  $b$  and  $c$  does not specify a direction, meaning the edge is valid for both directions  $bc$  and  $cb$ . Conversely, a directed graph (digraph) has directional edges. Like the undirected graph, the incidence function describes the relationship between edge and nodes;

$$\psi(xy) = (x, y)$$

where edge  $xy$  connects nodes  $x$  and  $y$ , with node  $x$  being the source and node  $y$  the sink (ch10 [1]). The edges of the graph can hold information (such as weights) that describe the relationship/connections between nodes. Such a graph is known as a labelled graph. It is important to note that modelling a temporal network is fundamentally different from a static network, i.e. you cannot simply generalize a concept/model based on a static network into a temporal one (s2.1 [11]).

In a temporal graph, each edge has a label which indicates some measure of time (discrete or continuous). This could be the start time(s) of when the edge is active, along with a duration of how long the edge is active. A temporal graph can be described as a graph whose connections change over time. The nodes of the graph remain static, while the edges update as time changes. A temporal graph can also be perceived as sequence of static graphs with an (unchanging) set of nodes. Other edge labels could correspond to temporal information if interpreted correctly (s2 [6]). In the discrete

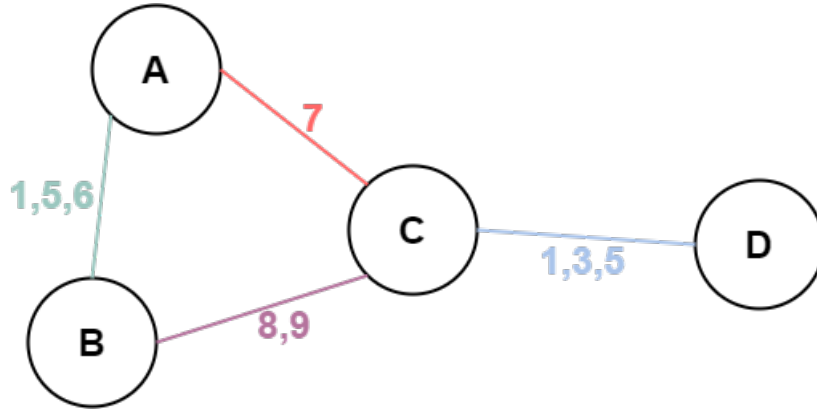


Figure 1: An static graph illustration of a temporal network.

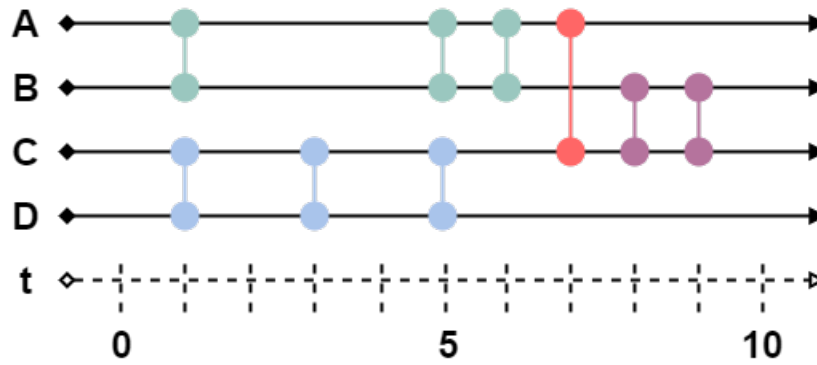


Figure 2: An timeline illustration of a temporal network.

time case, the temporal graph can be presented as a static graph  $G = (V, E)$  with each edge labelled with a list of natural numbers corresponding to when that edge is active (figure 1). This time-edge (or contact/link) triple  $e = (i, j, t)$  of source, sink and active time are the fundamental building blocks of temporal graphs.

The above figures illustrate a temporal network in two representations. The first figure is a static graph, with each edge labelled with the active/available times (time-edges/links). The second figure shows the timeline of the network, with the times-edges become available represented as connections between the node rows. The timeline representation better illustrates the temporal connectivity of the graph, while the static representation shows the structure of the network. Note that in the static graph, while node D is 'connected' to node A,B through C, it is in fact not possible to traverse from A/B to D, as the time-edges from C to D are, in a sense, too early. This indicates the lack of temporal information/intuition a static representation has, and further indicates that static and temporal networks are indeed fundamentally distinct. Once a temporal graph is built, there are many measurements and algorithms that can be applied to the network in order to produce temporal metrics. Network latency, reachability and centrality are all distinctive properties of temporal networks, and can have a large impact on the performance of the network being modelled.

The research and interest in the domain of temporal networks is increasing as technology advances, and there is growing evidence [12] that the modelling and analysis of such networks can produce useful results and information. Therefore, a convenient and purposeful library to enable this effort would be advantageous.

## 2 Specification & Aim

The overall aim of the project is to build an open-source library that enables temporal network modelling and analysis in an intuitive, user-friendly and powerful manner. The library will also allow for multiple contributors to develop the project further, in an open-source environment. The specification of the library can be split into some key areas; core functionality, extendable functionality, selected language/platform and open-source setup.

### 2.1 Core Functionality

The core functionality of the library is divided into several items.

- Input handling:

Raw temporal data can be acquired and stored in a multitude of manners and formats. This is unsurprising considering the wide scope of temporal networks. It is therefore important that the library has the ability to handle multiple types of input while also allowing for new input handling methods to be added easily. There is also the possibility of having input data with no clear set of nodes or edges specified, that needs a conversion process to first decide the nodes & edges, along with the time labels and other information. An example of this could be messaging logs from a social network, or a transport network timetable.

CSV	GraphML	GEXF
GDF	GML	XML

Table 1: Possible input formats [7].

- Graph creation/generation:

The graph can be created in two ways; either from the post-processed input data, or a generated graph from a model. A generated graph could simply be a randomly generated set of time-edges labelled from within some probability distribution, or from a set of linear functions (s7,s8 [6]).

- Graph functions:

There are multiple functions that can be developed once the graph has been created. These can range from selecting a node or edge, retrieving information from the graph/nodes/edges, adding/removing edges/nodes and so on.

- Graph visualization:

The created graph should be discernible in a intuitive and clear manner.

- Graph analysis:

The user should be able to collect measurements on the graph, such as centrality, reachability and latency. The user should also be able to run and test algorithms on the graph, such as computing foremost time [8].

- Output handling:

Any metrics generated from the graph should be presentable in a report or file (.csv, for example). The graphs should also be save-able into a format which can be used to later recreate the graph.

### 2.2 Extendable Functionality

While the library will offer a lot of functionality, as described in the previous section, it is important for the design architecture to allow for easy extension from the core functionality. This is especially

true in the case of an open-source project, where there is the possibility of contribution from the community. For example, if an individual wanted to add a new algorithm to calculate the shortest path, then this should be easily integrated in the current core library.

## 2.3 Language & Platform

The selected language for this library is Python. Python is one of the most popular languages amongst developers and has many useful libraries on offer, such as numpy, matplotlib, scikit, pandas, tensorflow and more. All the source code and documentation will be hosted on GitHub, including this document, user-guides and readmes.

An important note is that this library is not aiming to be extremely efficient in order to handle large temporal graphs or data. A more appropriate choice of language for this would be C++. This library is essentially trying to emulate what NetworkX [9] has achieved for static graphs, in terms of convenience, functionality and open-source, communal deployment.

## 2.4 Open-source

The idea of making a project open-source is powerful since it allows people to freely contribute to the project without the usual barriers to collaboration. If there is enough interest and motivation in the project domain, the library can develop rapidly. It also allows the users to freely modify and customize the library to suit their own needs and the needs of others. Any customization that could benefit the user base can be requested to be added as a permanent feature in the next release, improving the overall quality of the library. There are a number of important steps involved in launching a project as open-source [10].

### 3 Design Overview

Based on the project specification, there are a number of important functions the library needs to provide. These functions can be summarized in a flowchart (figure 3). The following subsections will move down the flowchart, discussing the planned design and architecture of each component. All classes will then be summarized in a UML diagram (figure X).

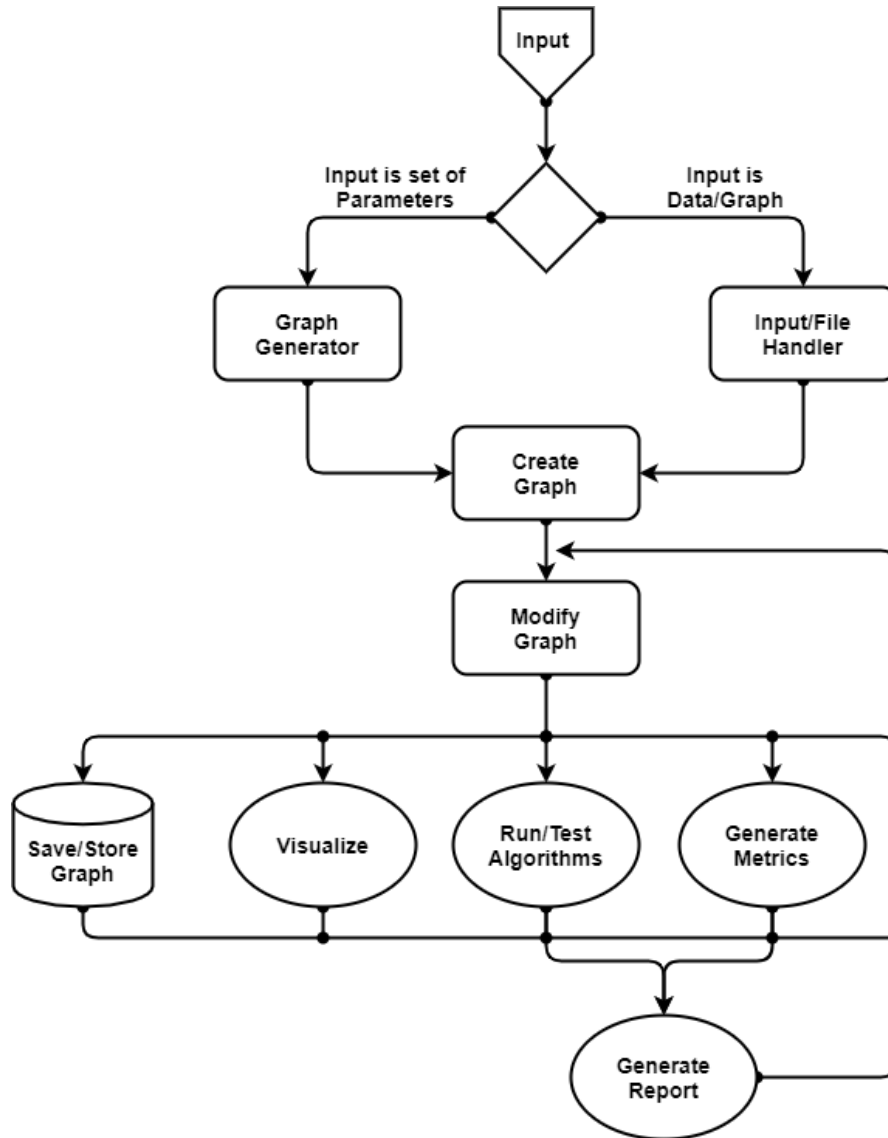


Figure 3: Functionality flowchart.

#### 3.1 Input

The flowchart input can be of multiple types; raw temporal data that has been collected from a system, a previously created graph that was stored in a file, or a set of parameters for a graph generator. Given that there are expected to be many types of input formats, a modular approach to input handling is required. Each type of input should be handled with a new subclass and produce the same set of outputs for graph creation. The parent input class should hold any properties and methods that are common across all inputs.

### 3.2 File Handler

Each file format will be handled by creating an input handler subclass from the input class. For example, if the input is a .csv file with a list of time-edges (figure 5), then this should be handled using the CSVInput class (figure 4). A common output format across the input handler classes would

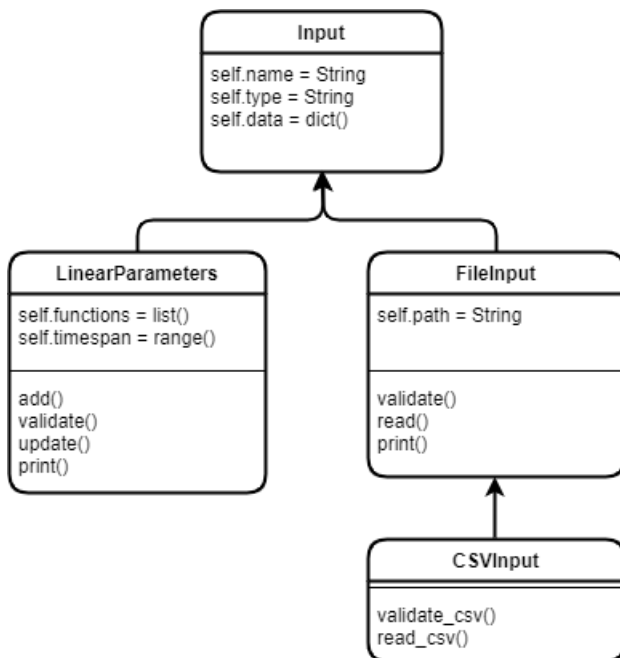


Figure 4: Example input handlers.

```

source,sink,time
a,e,2
d,b,9
a,c,10
b,c,9
d,c,7
b,d,6
e,b,4
a,d,7
d,c,8
b,c,10
  
```

Figure 5: Sample csv file; list of time-edges.

be very useful. This would allow for the construction of the graph to remain the same for an ambiguous set of inputs, as each input is handled within its own class. Any input validation unique to the input should also be added to this class, prior to passing the output to the graph constructor.

### 3.3 Generators

As mentioned in the specification, there are multiple methods available for generating temporal networks. Two examples are random generation of time-edges, and the generation of time-edges from a set of linear functions. Each generator would be defined as a class and produce the same output format in order to remain compatible with the graph constructor. This allows an ambiguous set of generators to be created/defined without having to redesign the graph constructor for each.

### 3.4 Graph Construction

The construction of a temporal graph can be achieved in multiple ways. One idea is to simply store all the time-edges in a data structure, such as a dictionary, as a property of a temporal graph object. Another is to create a static graph for every instance of (discrete) time, or over a set of time intervals. These static snapshots could be represented in a class, and added into a data structure which would be stored as a property of the temporal graph object.

The chosen architecture looks at the temporal graph at a more granular level; modelling the components of the graph. Static graphs are built from nodes and edges, while temporal graphs are built from nodes and time-edges/links. The idea is that one could create a base class definition for nodes and edges, and then extend that definition to the temporal domain. Further extensions could also be realized for other graph constructions, custom specifications and use-cases.



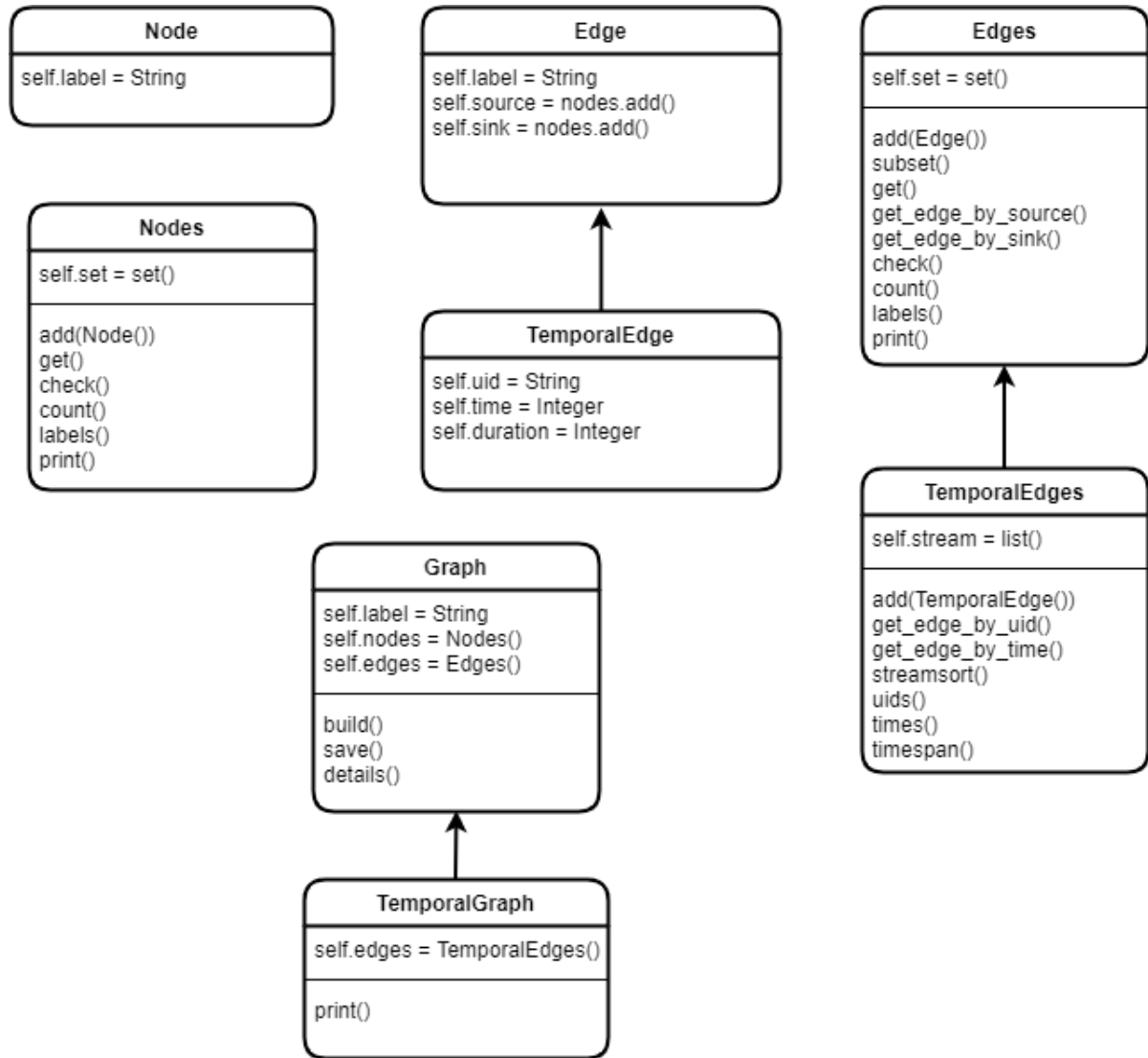


Figure 6: Graph components and graph UML diagram.

This modular building block approach offers a flexible and powerful way of expressing a graph. Figure 6 shows some basic class definitions for the components of the **Graph** and **TemporalGraph** classes (digraph and discrete digraph respectively). A **Graph** has the properties `nodes` and `edges`, which are classes that define collections of the **Node** and **Edge** components, respectively. **Nodes** describes a set of **Node** objects, each of which has a `label` property. Similarly, the **Edges** describes a list of **Edge** objects, each of which has a `label`, `source` and `sink` property (here we are dealing with directed edges). The `source` and `sink` of an **Edge** object are **Node** objects themselves, stored in a **Nodes** collection. The idea here is that, when adding an **Edge** to a graph, the graph's `Nodes` collection is passed as a parameter, in order to maintain and update the graph's nodes. This process occurs in the constructor method of the **Edge** class.

For the **TemporalGraph** definition, the `edges` property is simply replaced with the **TemporalEdges** class, which is a subclass of the **Edges** class. **TemporalEdges** is a stream (list, ordered by time) of **TemporalEdge** objects. **TemporalEdge** is a subclass of **Edge**, with some new properties, such as `uid` (label name + time), `time` (discrete) and `duration` (discrete). By construction, the **TemporalGraph** class is already fundamentally different than that of the **Graph** class, which is expected and was

mentioned in the introduction. When building the graph, the nodes and edges are added connected through the node properties source and sink, while adding the edges themselves. Any unconnected nodes can then be added afterwards by directly calling the Nodes `add()` method.

### 3.5 Graph Functions

The created graph can have a number of functions associated with the overall graph, and the components themselves. Typical graph functions include printing the graph details, and generating a visualization. The edges can be retrieved through methods like `graph.edges.get_edge_by_source('b')`, `graph.edges.get_edge_by_sink('a')`, `graph.edges.get_edge_by_time(3)`. Nodes can be retrieved through `graph.nodes.get('x')`. Each of these methods returns a new Edges/Nodes collection, which is a subset of the graph itself. All of the methods are callable on the subset. Figure 7 demonstrates this functionality.

```
>>> graph.edges.get_edge_by_time(7)
<components.edges.TemporalEdges object at 0x7f12290d8950>
>>>
>>> graph.edges.get_edge_by_time(7).labels()
['ad', 'dc']
>>>
```

Figure 7: Graph functions example.

### 3.6 Graph Modification

New nodes and edges can be added to the graph through the respective `add()` functions of the collection classes. Similarly, nodes and edges should be removable from the graph, taking care to handle any unconnected edges. Furthermore, the properties of edges and nodes should be editable, provided the edit is valid and does not violate graph integrity or any added constraints.

### 3.7 Saving a Graph

The Graph class includes a `save()` method, which will run through the graph components and save all structural information (basic save) into a file, including any new metrics generated during the session (full save). The file can also include a complete summary of the graph. By saving into a specified format, the graph should be reproducible from the file.

### 3.8 Visualization

It is important for the user to be able to visualize the graph, or subsections of the graph. Visualization can provide a means of quick verification by the user to see if the graph has been created or modified correctly. It can also aid in the verification of any results produced in testing. A simple command line means of visualization is shown in figure 8. Ultimately, the library would allow for circle and slice plots (figure 2) of the graph, by using the matplotlib package.

```
>>> graph.print()

5 nodes;
c a b e d

      ad db bc ac eb bd ae dc
2 | - - - - - - + -
4 | - - - - + - - -
6 | - - - - - + - -
7 | + - - - - - - +
8 | - - - - - - - +
9 | - + + - - - - -
10 | - - + + - - - -
>>>
```

Figure 8: Text-based link activity matrix for a discrete temporal network.

### 3.9 Algorithms

### 3.10 Metrics

### 3.11 Reports

The results of any measurements and algorithms run/tested on the graph should be printable in an intuitive and clear format.

### 3.12 Design Evaluation

Bearing this in mind, it is important for the code to be designed in a modular way. This can be achieved by using class inheritance and by defining the classes well to avoid a 'super-class' situation.

## 4 Project Plan

Outline the timeline of the project. Include Gantt chart and reference to Gantt planning.

## 5 Requirements & Skills

Outline what will be required to complete the project and any skills necessary. Outline new skills expected to be acquired.

## Appendix

## References

- [1] J. A. Bondy, Graph Theory With Applications. GBR: Elsevier Science Ltd., 1976.
- [2] L. Zhao, G.-J. Wang, M. Wang, W. Bao, W. Li, and H. E. Stanley, ‘Stock market as temporal network’, *Physica A: Statistical Mechanics and its Applications*, vol. 506, pp. 1104–1112, Sep. 2018, doi: 10.1016/j.physa.2018.05.039.
- [3] K. Römer, Temporal Message Ordering in Wireless Sensor Networks. 2002.
- [4] R. Gallotti and M. Barthélemy, ‘The multilayer temporal network of public transport in Great Britain’, *Sci Data*, vol. 2, no. 1, p. 140056, Dec. 2015, doi: 10.1038/sdata.2014.56.
- [5] S. Lee, L. E. C. Rocha, F. Liljeros, and P. Holme, ‘Exploiting Temporal Network Structures of Human Interaction to Effectively Immunize Populations’, *PLoS ONE*, vol. 7, no. 5, p. e36439, May 2012, doi: 10.1371/journal.pone.0036439.
- [6] O. Michail, ‘An Introduction to Temporal Graphs: An Algorithmic Perspective’, arXiv:1503.00278 [cs], Mar. 2015, Accessed: Jun. 29, 2020. [Online]. Available: <http://arxiv.org/abs/1503.00278>.
- [7] ‘Supported Graph Formats’. <https://gephi.org/users/supported-graph-formats/> (accessed Jun. 30, 2020).
- [8] H. Wu, J. Cheng, Y. Ke, S. Huang, Y. Huang, and H. Wu, ‘Efficient Algorithms for Temporal Path Computation’, *IEEE Transactions on Knowledge and Data Engineering*, vol. 28, no. 11, pp. 2927–2942, Nov. 2016, doi: 10.1109/TKDE.2016.2594065.
- [9] ‘NetworkX — NetworkX documentation’. <https://networkx.github.io/> (accessed Jun. 30, 2020).
- [10] ‘Starting an Open Source Project’, Open Source Guides. <https://opensource.guide/starting-a-project/> (accessed Jun. 30, 2020).
- [11] P. Holme and J. Saramäki, Eds., Temporal Network Theory. Springer International Publishing, 2019.
- [12] J. Tang, M. Musolesi, C. Mascolo, and V. Latora, ‘Temporal distance metrics for social network analysis’, in *Proceedings of the 2nd ACM workshop on Online social networks*, Barcelona, Spain, Aug. 2009, pp. 31–36, doi: 10.1145/1592665.1592674.
- [13]
- [14]