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The Journal of HISTORICAL NETWORK RESEARCH

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Visualizing the Evolution of Historical Networks Using Small Multiples in Grid Charts

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Keywords Historical time, dynamic networks, small multiples, grid charts, German history

Abstract Historical time presents interesting conceptual problems for network visualization. The manifestations of time in historical network research (HNR) are similarly numerous and distinct. Time in HNR cannot always be reduced to the concept of chronological time, which is often implicit in abstract scientific models of networks, particularly since historical networks do not contain all the data about times and paths, but merely what has been documented. The complexity of historical networks exists at all levels and extends from data to visualization to interpretation. Further, historical datasets do not always contain the kind of accurate timestamps that would allow researchers to plot all time-dependent paths, nor to know which ones are missing, and time markers are rarely as accurate or detailed as those in datasets created by current technology. Thus, a model of time with variable temporal units is more generally appropriate in HNR than a regular chronometric one. Likewise, historical accounts often contain more than one agent's perspective on the evolution of a network. In this article, we present a method for visualizing historical networks that can be used at various timescales and is responsive to various kinds of historical time. To display snapshots of a network, we propose an agent-perspective-time matrix that is flexible and puts the visual emphasis on change in the network rather than states

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of the network. We use small multiples placed within a grid chart to represent states of a network at a particular moment and/or from multiple perspectives.[1] Using examples from German history, we discuss two case studies with different conceptions of time, as well as other problems that we frequently encounter in re-constructing networks. Finally, we propose a visualization technique for use in the small multiples: using color to reveal changes in the network. Whereas color is often used in HNR to represent the static characteristics of nodes, edges, or communities, it is possible to use color to emphasize the evolution of the network. When color is used to highlight the dynamic aspects of the network, nodes and edges are colored according to whether they emerge, persist, or disappear; network growth and dissolution are thus foregrounded. This method is, therefore, preferable when network dynamics are of greater research interest than the static qualities of the network, such as the properties of nodes or communities.

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1 On how to use small multiples, together with large singles, see Van den Elzen and van Wijk 2013. Van den Elzen and van Wijk propose using small multiples as a data exploration tool; their model lets users choose snapshots of the network from among the many that are possible, each of which represents only part of the network. For this reason, a large single can provide context and insight into the complete network structure to contextualize small multiples. This model can be used for interactive exploration of a network but is not directly replicable in print media.

1. Historical Understandings of Time and Networks*

Concepts of historical time are not necessarily the same as concepts of time variance within network analysis. How can we display network dynamics in a way that is responsible to the complexities of historical time? Here we present a method for visualizing the evolution of historical networks using series of static images, or small multiples, placed in grid charts that help the reader to place network 'snapshots' in relation to one another.[2] While drawing on ideas from interactive network visualizations, we limit ourselves to visualizations that can be reproduced in print and static web publications, rather than videos, animations, or interactive network exploration methods. In order to visualize network dynamics without using animations, we also explore ways to color nodes and edges according to network dynamics, rather than static properties of nodes or communities, so that the viewer's attention is drawn to how the network evolves.

In many ways, the conceptualization of change in historical network research mirrors the way that networks are conceived of in history. However, much like other concepts in network studies, those of 'evolution' or 'change' are not clearly defined in the humanities. As Claire Lemercier has claimed, network vocabulary is often used in the humanities in a purely metaphorical way, "without reference to any more or less systematic information on precise ties between specific individuals or organizations."[3] Similarly, when it comes to the evolution of networks, the link between changes in network structure and historical events is often metaphorical, not reducible to network dynamics. Whether time-varying

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2 The problem of how to represent network dynamics is a longstanding one. Visualizing change in networks can mean visualizing various aspects of change, including "the pace of change," "relational pace," the sequence of events, or temporal multiplicity, such as overlapping events (Moody et al 2005). In this article, we consider visualizations that can be produced in static 2D media, rather than video, animations, 3D models, or interactive visualizations that can more easily represent network dynamics by adding time and movement. Such diagrams cannot be easily reproduced in books, articles, or other print media, which is our main concern here.

3 Lemercier 2015, 284. Ahnert et al. 2020 similarly conclude that the use of networks in the humanities, which they call the "network turn," is, in their words, "always metaphorical" (13) but that humanities scholars "who employ networks as a metaphor [...] ought to be familiar with the mathematical formalisations" (14). The question of how meta-

or not, historical network models have often been modified in an ad hoc way via “methodological appropriation” to fit humanities data and concepts.[4]

While we are interested in using network models to understand structural relations between entities, it is worth considering how and why the ideas of time implicit in historical research often differ from undergirding models in computer science. Most notably, historical networks have precise and regular time units less often than contemporary datasets derived from the internet, transportation networks, or communication networks. To use network terminology in a mathematical sense is to reference a set of systematically connected entities in a way that can be represented as a time-varying network graph.[5] In order to create a temporal graph, we must also translate historical events into network events, or changes in the network.

The term ‘network’ describes, at a minimum, a set of social relations among actors or entities that allows for interactions or the transmission of information.[6] A dynamic, or temporal, network is a collection of nodes and edges that vary over time. Simple temporal graphs can visualize the evolution of a network when time is linear. For slightly more complicated use cases, bipartite or multipartite graphs can be used when there are multiple types of entities that are linked, such as people, texts, or cities, whose relations change over time. Temporal networks have been widely described and theorized.[7] There is also a vast literature on use

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phorical digital history models are is debatable. For a general discussion of data models in digital humanities and the difference between ”metaphor-like” models, “image-like” models, and “relational or structural” models, with examples from digital projects, see Ciula and Eide 2017.

4 For a general introduction to the use and abuse of basic network concepts within the digital humanities, see Weingart 2011.

5 For an introduction to mathematical and analytical aspects of dynamic networks, see Holme and Saramäki 2013. Holme and Saramäki define a temporal network as “a collection of events that link nodes at specific times” and argue for the importance of time-dependent paths in structuring and visualizing temporal networks. For Holme and Saramäki, the early focus on visualizing mobile phone and internet data with time-stamps limited researchers’ ability to think through more complex forms of analysis; these more complex models that arose later include higher-order models, mesoscopic models, multilayer representations, and more complex use cases like predicting human behavior from network events; finally, later researchers have studied how network structure can impact the order of changes in the network, rather than vice versa. For a survey on visualization of dynamic networks, see Beck et al. 2014. Beck et al. create a taxonomy of dynamic network diagrams, including animations and diagrams that use timelines, and then survey the number of academic papers that describe each type from 1990 to 2014, with a notable spike after 2005. For an overview of different conceptualizations of ‘time’ in historical research as well as literary studies, see Clark 2018 #3546D, 12–18.

6 Düring and Stark 2011.

7 See Holme and Saramäki 2013.

cases and visualization techniques. When datasets are robust and time sequences are linear, a dynamic network graph can represent the evolution of a network with relatively few modifications. In this article, we focus on scenarios where the data are incomplete and there are temporal gaps.

Our conceptual model draws upon work done in modeling dynamic networks and conceptualizing historical time, specifically the work of historians and social scientists who use social network analysis (SNA) to understand events as configurations of actors.[8] Temporality is a core aspect of any historical research. There is, however, no single concept of historical time.[9] Within historical studies and related social sciences, temporality is most obviously a factor in longitudinal studies, which emphasize long-term diachronic analysis of the *longue durée.* But time is central to any attempt to understand a particular event or historical state, even one that appears to be static or isolated. Any observed state of a network is, from a historical perspective, understood to imply the existence of events both before and after that observed state. Within the narration of a historical event, constellations of actors and entities can themselves appear or disappear; they can also be emphasized or de-emphasized from a particular historical perspective. Because the goal of historical narration is not always a single perspective on reality, a historical narrative may not be reducible to one chronological series of events recounted from a single perspective. Likewise, there is no avoiding historiographical problems like the bounding of events and 'historical casing,' the delineation of one event from another, which is a necessarily messy process.[10] Furthermore, the concept of time implied in the linear development of dynamic networks can be too rigid for scholars in the humanities, especially for those scholars working on indigenous, non-Western, or pre-modern societies with non-linear conceptions of time.[11]

There are three main aspects of historical networks that we have sought to integrate into our model:

8 See Bearman et al. 2003.

9 For a wide-ranging discussion of the semantics of historical time, see Koselleck 2004.

10 Bearman et al. 2003 lay out a model for HNR that relies upon what they call 'historical casing' – that is, the retrospective demarcation of events or modelling of the event. The authors argue that 'historical casing,' or 'bounding the beginning and end of event sequences,' is substantially similar to identifying the boundaries of networks; neither process is an exact science, nor can it be done once and for all. In other words, network analysis provides 'new solutions' for 'old' historical problems.

11 Schmidt 2018 explores indigenous and non-Western ideas of historical time and the historical process through the case study of northwest Tanzania where, he argues, history and prehistory are not as sharply divided and the historical method not as codified as in Western cultures.

1) Historical events can involve complex configurations of actors, and the changes to these constellations of actors may not be in chronological order within the narrative or the source documents.
2) Network events, or changes in the network – that is, the appearance and disappearance of nodes and edges – may or may not correspond to historical events, as defined by the researcher.
3) Rather than seeing networks from an 'omniscient perspective' – that is, from a single perspective outside of history – there exist multiple perspectives in and on historical networks.

The most important distinction we make here is between a 'network event' and a 'historical event.' A 'network event' is a structural change in the network, such as two actors meeting (the emergence of an edge) or the dissolution of a bond between two actors (the disappearance of an edge). A historical event can be equivalent to a change in the network. However, a historical event can be the passing of a time-marker that does not correspond to any changes in the network. For example, the meeting of two agents could be a novel historical event without creating a new connection if the two agents had previously met. No new edge would be formed, but that meeting may still be of historical importance, and a researcher might want to compare the state of the network before and after this meeting. We refer here to points in time selected by the researcher as 'snapshots' of the network – that is, graphs of the manually selected states. Comparing these time-based small multiples and the rate of change between them allows researchers to study changes in network structure without losing the ability to set the boundaries of events.

Another aspect of historical studies that is inherent to many cases is perspective. Within historical studies, there is a distinction between 'past' and 'history.' The past is gone and cannot be brought back. What historians do is develop a particular perspective on the past. Hence, history becomes a model of that past.[12] Yet each model of the past, each network model, is defined by certain constraints,[13] such as subjectivity, intent, available data, and the intellectual and methodological capacity of the modeler. These constraints can be problematic, but also conceptually interesting; they are irreducibly part of the historical method and can be foregrounded in visualizations, rather than hidden, by presenting other snapshots or other views.

To lay out this method, we work through two case studies, offering examples of visualizations that can communicate historical notions of time. Both are drawn from German history: first, the network of people who unsuccessfully tried to assassinate National Socialist dictator Adolf Hitler on July 20, 1944, and the

12 Rehbein and Donig 2022.
13 Stachowiak 1973.

subsequent investigations by the German secret police; second, the opposition movement in the Jena region in the former German Democratic Republic, as documented in an archive of photography. These case studies exemplify reconstituted historical networks, as both draw on archival documents to reconstitute poorly understood networks. Both case studies involve conspiracies or secret societies in which actors endeavored to hide their activities from authorities. This makes temporality even more dynamic, and since the state of such networks is not well documented, there are historically significant differences between accounts of the formation and evolution of these networks.

2. Constellations of Agents: Visualizing Time-Varying Dynamic Networks

Given the methodological and theoretical heterogeneity of historical research, there is a wide range of possibilities for what can be studied as a network. On meso- or macro-levels, whole institutions or countries can be historical actors; these institutions can form networks, such as political constellations of agents, military alliances, or subnational groups.[14] Historians have frequently followed social scientists in using nodes to represent agents in networks of communication, affiliation, or exchange. Our first case study, however, builds on a micro-level. Its agents are conspirators in the 1944 plot to kill Hitler; information about them is drawn from the subsequent investigations by the German secret police. It is a shifting network observed by multiple agents.

The dynamics of a historical network such as this generally reflect all sorts of human behaviors and attitudes. Whether or not historical agents are aware of their role in the network, these attitudes can affect the network's structure. People may change their attitude towards others in the network; their participation in the network may become less consistent or valuable to other members; people may die or cease interacting with other members of the network. In a time-varying dynamic graph model, often represented as a time-ordered sequence of graphs,[15] changes in the network structure include:

1) The appearance or disappearance of nodes (through death or retreat from participation in the network)
2) The change of attribution of nodes (when, for example, a co-conspirator is unmasked as an enemy of the group)

14 One of the earliest attempts to use network theory systematically in historical scholarship was Wolfgang Reinhard's study of elite historical groups in the Roman oligarchy as networks (Reinhard 1979).

15 Nicosia et al. 2012.

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3) The appearance or disappearance of edges (when relationships are created or end)
4) The change of attribution, certainty, or quantitative aspects of edges (for example, when relationships change in character or intensity)

All of these changes can be gradual or abrupt. Creating time-varying network graphs poses challenges on all three levels of historical network research: data acquisition and modeling, visualization, and analytics.[16] Characteristics of historical data, such as incompleteness, ambiguity, intentionality, and vagueness of reference, need to be considered on all levels. Uncertainty and vagueness can be dealt with in data modeling by using fuzzy data models or multi-value logic.[17] This historical method can be applied to either small-scale networks or large-scale networks, although large-scale networks may pose more significant challenges, due to the possibility of oversimplification in the data model.[18]

In this case, time-varying dynamics occur when actors enter an alliance either out of necessity or for personal benefit. Similarly, when actors eventually leave the alliance or join a different one – sometimes for opportunistic reasons – the state of the network evolves.[19] A similar observation is valid for individual actors on

16 Specifically, the problem of latent incompleteness of data can exist at all these levels since humanities research often involves incomplete datasets or datasets that have unknown biases. Incompleteness of data and biases in data should be considered when drawing conclusions about the relevance of network structures to cultural phenomena. For example, correspondences between archives and the texts of societies that produced them are rarely unproblematic, since we neither have access to all the texts of any one society, nor would such an archive 'represent' that society's textual production in an unproblematic way.

17 Fuzzy logic can be used in network data to encode vague or uncertain values. Fuzzy logic means the attribution of multiple values that in some way contradict each other, such as both 0 and 1, to either a node or an edge. Seising 2016 discusses the difference between multi-value logic and fuzzy logic in general. Akoka et al. 2019 lay out a method for integrating fuzzy logic into prosopographical databases for historical social networks.

18 Oversimplification of data is a general problem in data-driven, 'big data' approaches in the humanities. In network research, this happens when relationships are inferred through weak evidence and without regard for the quality of relationships or their intensity – for example, when a machine-detected co-occurrence of two names in a text is considered a relation between two actors with these names, despite the fact that the co-occurrence alone does not guarantee that a relationship exists, let alone describe the quality of the relation (e.g. friend or foe). In historical network research, more attention should be paid towards the qualities of the relation (e.g. positive vs. negative binding). Cf. Rehbein 2018 and Rehbein 2020.

19 Friend and foe relations are also important to social psychology and game theory. Cartwright and Harary 1956 adapted the work of psychologist Heider 1946 on balance theory, which posited the importance of cognitive consistency for individuals, to social network analysis as structural balance theory, using binary positive/negative attitudes to explain patterns of interdependent properties. Gramsch also built upon the theories on brokerage roles developed by Gould and Fernandez 1989.

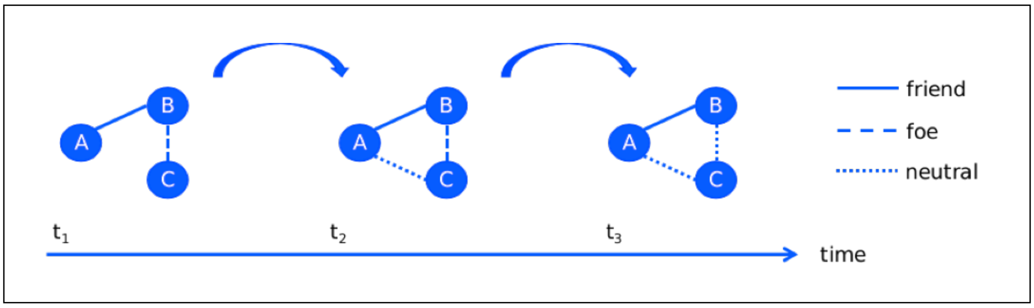

Fig. 1 Model of a Time-Varying Dynamic Network (Friendship and Foe)

a micro level: friends become foes, foes become friends; building particular ties within a network might be a strategic move in a political career, or an attempt to gain social capital. Inspired by the work of Robert Gramsch on medieval political alliances,[20] which was itself based upon Heider's balance theory and the structural balance theory of Cartwright and Harary, Figure 1 illustrates a simple triadic motif in a network with qualified relations. While in a simple time sequence $T = (t_1, t_2, t_3)$, B and C were foes in the first instance t_1, the developing acquaintance of A with both B and C between t_1 and t_2 allows A to act as a mediator and, as a consequence of mediation, the relationship of B and C becomes neutral at t_3.

A multilayer network with variable edges can be used to map conspiracies like the attempted assassination of Hitler.[21] On July 20, 1944, a group of conspirators attempted to kill the German dictator and overthrow the National Socialist regime in a coup d'état. This plot is known today as 'Valkyrie,' the name of the operations plan for the continuity of government. The day of the failed coup marked the endpoint of a long and careful planning process. It included forming and fostering a covert network of about 200 people in various roles with varying degrees of implication in the plot. The attempted coup failed, and the surviving regime spared no effort in investigating its background. After a few weeks of interrogations, the German secret police, or Gestapo, finally realized that the operation was executed not by a few individuals, but by a vast network of civilians and military elites. The investigations and the trials at the *Volksgerichtshof* ('People's Court') continued until the end of the war; most of the accused were sentenced to death.[22]

20 Gramsch 2013.

21 In the case of the conspiracy against Hitler, we must also be attentive to perspective, as well as to the quality of the edges. Where hearsay and subterfuge are significant, relations are built upon mediation, such as t1 = A knows (only) B, t2 = A knows B and now also C, t3 = through mediation by A, now B knows C. Yet these agents may or may not be aware of one another.

22 See Keyserlingk-Rehbein 2018 for a detailed analysis of what the regime eventually knew about this resistance network.

The historical data that document this network and the Gestapo's reconstruction of it are not perfect. The source material is extensive but incomplete; information within the sources is sometimes vague and difficult to classify. For example, let us consider one prospective conspirator establishing a new contact with another, whom he or she does not know, and how that would be described. This event may be described in historical sources as occurring on a precise date (January 3, 1943), a specific month or vague period (January 1943/the beginning of 1943), or less specifically ('They have known each other for many years.'). Sometimes such information is missing altogether.

The source material extant for historians working on this question is highly varied. The documents include reports on interrogations, bills of indictment, verdicts, and reports on lawsuits. The court documents vary in comprehensiveness from fragmentary to expansive. For any given research question, the material may exist and contain the information we seek, or we may have to infer some missing information. For example, a missing bill of indictment may be indirectly reconstructed from investigation reports or verdicts. Since the sources in question are contaminated by National Socialist ideology, we cannot ignore the malicious intent with which these texts were formulated. For instance, the NS-Regime was interested in sullying the resistance fighters' reputation. Hence, these sources are not suitable to evaluate moral questions or the personalities of the resistance members. It is, however, possible to use these sources to explore what the NS-Regime knew about the structure of the conspiracy network.

Through interrogations, the Gestapo tried to determine when and how members of the civil and military conspiracy met and decided to join the conspiracy. In the course of the investigation, the Gestapo identified 132 participants in the attempted coup; they detected 650 contacts among those conspirators. In the end, they realized that many of these contacts were made in pursuit of the conspiracy, not prior to it. A typical pattern occurred when an actor operated as a mediator or broker to connect two other actors who had not previously known each other, thereby fostering a valuable connection for the resistance. The Gestapo detected, for example, that the contact between Carl Goerdeler, the key figure of the civil resistance, and Andreas Hermes, designated as a future minister of a planned post-National Socialist government, was arranged by the trade unionist Jacob Kaiser at the beginning of 1943.[23] The Gestapo knew that Kaiser had introduced another member of the resistance to Goerdeler earlier in 1941.[24] That

23 The court report of 1945-01-12 reads as follows: "[Hermes] Lernte Anfang 1943 durch Kayser [sic!] (Christliche Gewerkschaften) Goerdeler kennen.", S. 707; cited in Keyserlingk-Rehbein 2018, 58.

24 See the investigation report of 1945-08-12: "Die Verbindung zwischen Goerdeler und Leuschner ist offenbar durch Kaiser zustande gekommen (etwa 1941)" Jacobsen 1984, S. 205.

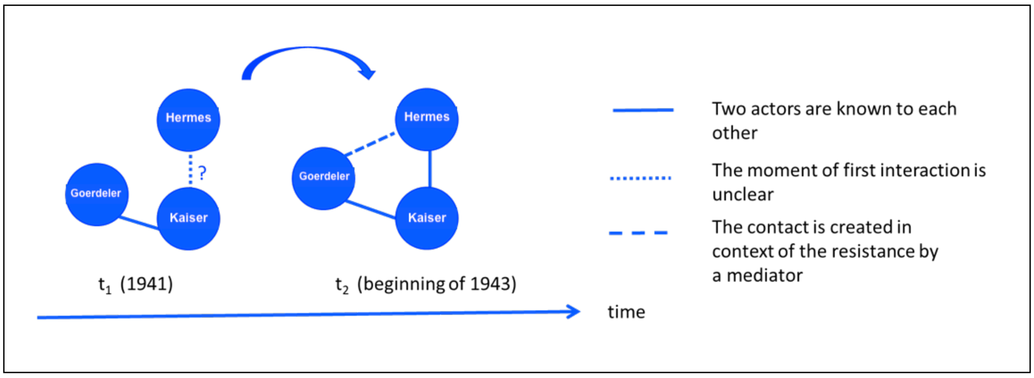

Fig. 2 Model of a Time-Varying Dynamic Network with Variable Edges

means that they had known each other since at least 1941. No further information about precisely when Hermes and Kaiser got to know each other is available in the historical sources.

In the time sequence $T = (t_1, t_2)$ relevant here, with $t_1 = 1941$ and t_2 = beginning of 1943, Goerdeler and Kaiser were already in contact in the first instance t_1 (1941); Hermes and Kaiser might have also known each other at that point, but this is not certain. They were connected by the beginning of 1943 at the latest, when Kaiser created the contact between Goerdeler and Hermes.

Figure 2 illustrates one distinctive aspect of historical dynamic networks: the edges potentially change in quality, as well as in existence. In particular, types of edges may evolve (such as collaboration or defection edges); the certainty of edges may also differ depending on how sure we are of the connection. Thus, change over time cannot be thought of purely as the appearance and disappearance of nodes and edges; it is also a matter of the kind and certainty of ties changing over time.

3. Networks That Vary According to Perspectives of Historical Agents

Historical networks can also appear different from the perspective of different observers. Figure 3 shows a set of such perspectives $P = (p_1, p_2)$, with a series of friend/foe/neutral relations between three agents, according to two different perspectives (p_1 and p_2).

It is also noteworthy that different perspectives on the number and sequence of steps in time can also exist. In p_1, the relation between A and B precedes that of A and C, while in p_2, the opposite is true. Here, each perspective also includes a different perspective on the timing of the developing steps of the network:

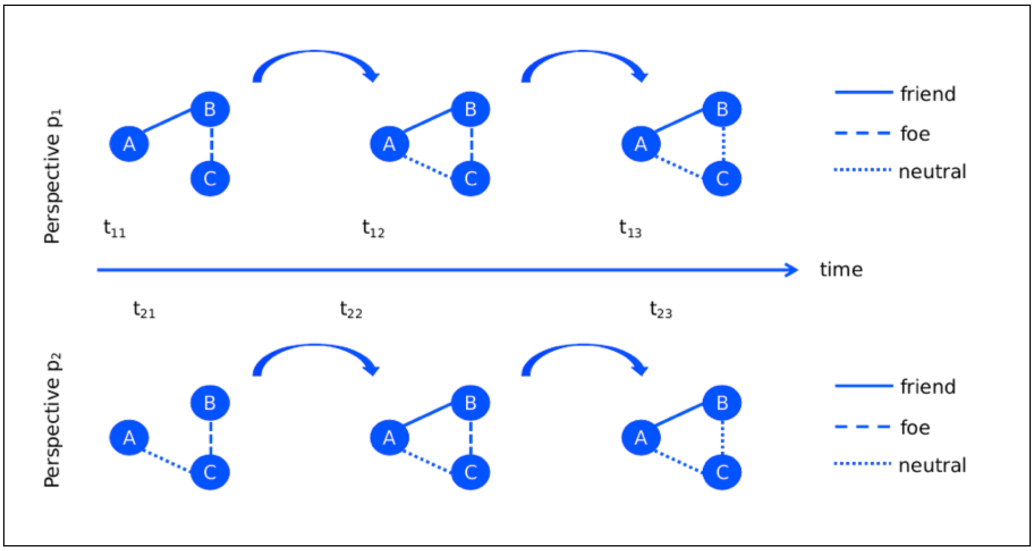

Fig. 3 Interaction Model with Variable Edges in a Perspective Grid Chart

$T_1 = (t_{11}, t_{12}, t_{13})$ and $T_2 = (t_{21}, t_{22}, t_{23})$ – both situated within the same historical time.[25]

The power of this time-perspective model lies in its flexibility. The units of time are left to be chosen by the researcher, and could be specific units like hours, days, or months. They could also be non-numeric units like generations of families, configurations of historical agents, or event series like diplomatic meetings. Similarly, the various perspectives can be those of specific actors, witnesses, or researchers (e.g., different historical viewpoints or viewpoints on history). Distinct perspectives (p_1 and p_2) on the network can come from the same witness at different times or according to different thought processes. An intriguing example of such a process is found within the assassination network of 1944. As already outlined, the National Socialist Regime made a tremendous effort to uncover the events leading up to July 20, 1944. In particular, the contact between the social democrat Carl Goerdeler and leading trade unionist Wilhelm Leuschner appears to have been of interest to the investigators. In the weeks and months after the attempted coup, more and more information was gathered, and the time of the actual first interaction was finally detected. Figure 4 shows the process of these investigations as a temporal sequence of developing perspectives. On August 12, 1944, the Gestapo investigators assumed that Goerdeler and Leuschner got to

25 In any narrated story, different times of narration may exist; in historical narration, differences in the temporality of narration may be considered while comparing constellations that are similar but happened at different points in time (cf. Ernst Bloch's conceptualization of the simultaneity of the non-simultaneous).

know each other via the trade unionist Jacob Kaiser around 1941 (p_1).[26] Exactly one week later, it was revealed that Goerdeler and Leuschner had already been in contact earlier, in 1940/41 (p_2).[27] Finally, the investigators realized that the two central figures of the civil resistance had met much earlier. The report of the verdict of September 7 or 8, 1944 (p_3) mentions that Goerdeler and Leuschner already knew each other from the *Deutscher Städtetag* (German Association of Cities and Towns).[28] This association was dissolved in 1933. Leuschner was imprisoned in the same year as a well-known critic of the National Socialist movement. The first interaction between Goerdeler and Leuschner must, therefore, have occurred before 1933. This example shows the investigators' high degree of interest in when and how the connections within the July 20, 1944 network arose. It also illustrates that the conspirators being interrogated tried to conceal as much information about their contacts as possible, and that they sometimes succeeded. For this reason, it is crucial to track the evolution of the network according to both the timeline of events and the timeline of the investigation.

While some historical models are more plausible than others, any model that we create of the 'real' network of the July 20, 1944 plot is a model of the past from a particular perspective, be it a specific witness or a government agency. While the past cannot be totally retrieved, history may develop a particular view of it, especially when the state or other political agents are involved in the production of historical documents and narratives.[29] In this case, it is highly significant that the network is covert, and there are no complete sources from the historical actors. For this reason, it is all the more evident that we are modeling what the NS-investigators knew about the network and not the network of all 'real' conspirators.[30] Indeed, creating a model of that knowledge (even an imperfect one) is an essential step toward showing how the NS-Regime's knowledge of the network of conspirators was incomplete and evolved over time. That model can be supplemented or compared with other models and other sources, such as diaries and letters of the members of the resistance. Both temporality and incommensurate perspectives can be brought together within a multidimensional space in a layered grid chart, as illustrated in Figure 5.

This method for visualizing historical network relationships from various perspectives (p_1, p_2, p_3, etc.) using a layered grid chart is similar to some 3D models

26 See the investigation report of 1945-08-12, Jacobsen 1984, *loc cit.*

27 See the investigation report of 1945-08-19: "Goerdeler sagt aus, daß er Leuschner 1940/41 darüber befragt habe, wie die Arbeiterschaft denkt." (Jacobsen 1984, S. 264).

28 See the court report of 1944-09-08: "1942 suchte Goerdeler den Angeklagten [Leuschner], den er vom Deutschen-Städtetag kannte, auf, um sich bei ihm zu erkundigen, wie die Arbeiterschaft heute eingestellt sei." (Bundesarchiv Berlin: BArch SAPMO I 2/3/151, fol. 31–38).

29 Berger and Conrad 2015.

30 Keyserlingk-Rehbein 2018, 329–410.

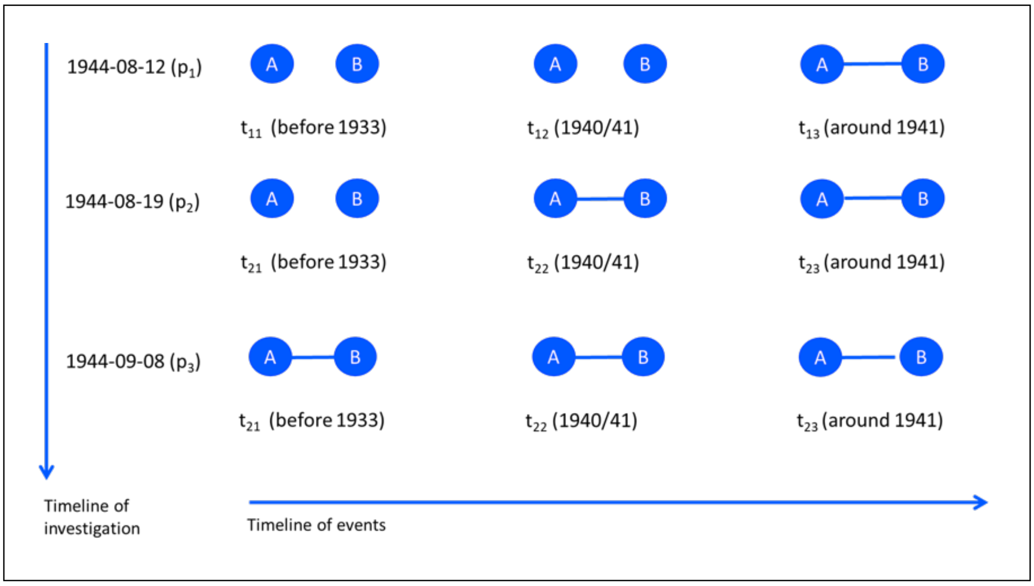

Fig. 4 Small Multiples of the July 20, 1944 Plot Network with Timeline of Events and of the Investigation

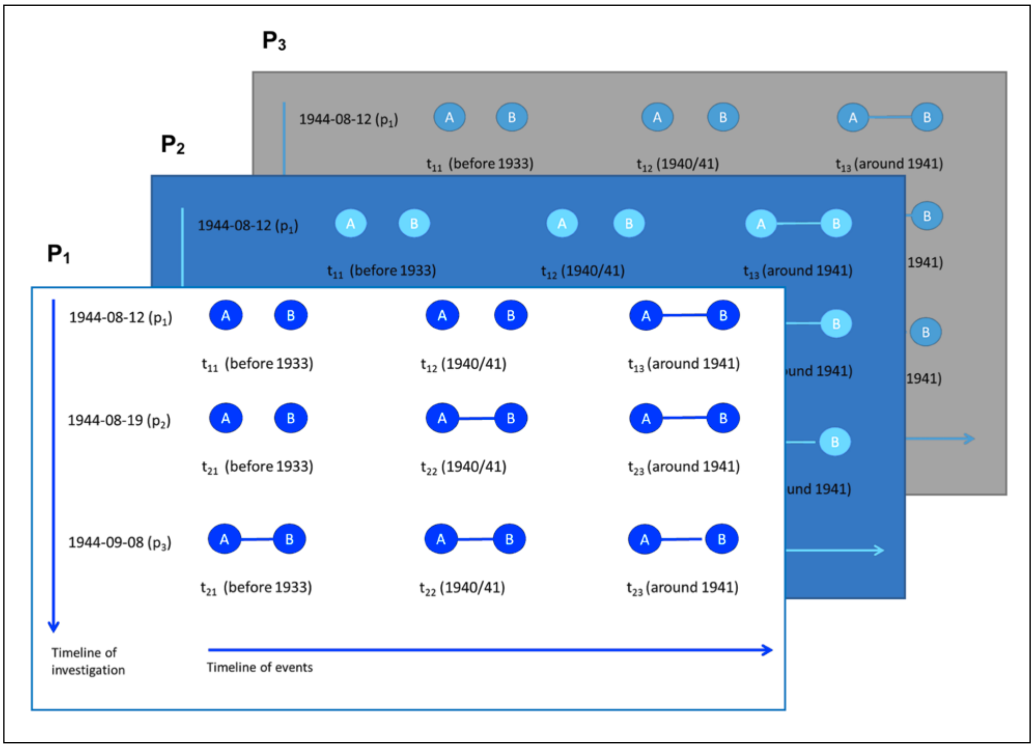

Fig. 5 Model of a Layered Grid Chart (Time-Perspective Matrix)

of dynamic networks, such as those using hypercubes.[31] Of course, grid charts could also be compared to each other by placing them side by side, instead of layering them, or creating a series of small multiples presented as a flip-book or animation.[32] Layers make the comparison of one perspective easier with large amounts of data; labeling and numbering the axes is another way to compare one network diagram to another within different perspectives while giving sufficient guidance to the reader.[33] While a layered diagram allows for the display of a large number of perspectives and temporal sequences, the value of retaining so much information must be weighed against the limits of the methods of analysis currently available.[34] In the next section, we will show how analytics can display changes in a network over time in a series of graphs.

4. A Method for the Visualization of Historical Networks

In this section, we will use a function in Cytoscape to automatically produce network graphs that are colored to highlight changes from a previous snapshot.[35] We will visualize metadata drawn from a photographic corpus of 60,000 photographs, digitized and maintained by the Robert Havemann Society in Berlin as part of its archive on the East German Opposition.[36] The data retrieved from this website include the names of identified individuals who appear in the photographs, along with the place and the year that the picture was taken. This photographic archive is relatively heterogeneous and has rich metadata, making it a good test case for our method. The archive focuses on the opposition movement in the Jena region in the former German Democratic Republic (GDR). In the history of the East German opposition, Jena was, together with the Berlin region, one of the most important for characterizing the structure, means, motives, and dynamics of opposition groups in the GDR.[37] Throughout the history of the GDR, Jena was one of the cities where the discrepancy between democracy and dictatorship often resulted in open conflict. After the 1968 protests in Western

31 A similar solution has been presented for visualizing dynamic social networks using hypercubes, that is, 3D cubes, rather than small multiples in grid charts in Bach et al. 2014.

32 For the flip-book solution to this problem, see Burch and Weiskopf 2014.

33 Grandjean 2019 uses multilayer networks in his model to simultaneously represent the evolution of networks and their constitution from various perspectives.

34 Ahnert et al. 2020,77

35 Cytoscape is an open-source software platform that can be used for visualizing networks. Although the platform was developed for molecular and biological networks, it can be used for HNR. https://cytoscape.org/what_is_cytoscape.html [online. Last visited: 16 July 2021]

36 See https://www.havemann-gesellschaft.de/archiv-der-ddr-opposition/bildarchiv/ [online. Last visited: 21 February 2020]

37 Key figures and subgroups of the dissident network can be found in Neubert 1998 and Veen 2000. For more on political structures of the GDR, see Schroeder 1998.

Europe, especially during the Prague spring, Jena rapidly became the linchpin of political opposition in the GDR. Jena was sometimes called the 'secret capital' of the GDR opposition, revealing the multifarious internal conflict between the state apparatus, the church, and the opposition in the GDR.

The dataset used in this section was created in four steps. First, the metadata of all photographs taken between 1975 and 1990 were selected to create a persons-to-photograph table; the metadata contain the names of the persons in many of the pictures. Next, this data table was cleaned by correcting and standardizing misspelled or heterogeneously recorded names.[38] Then, we selected the ten most prominent dissidents in the Jena region in the late 1970s based on previous studies and altered the dataset to contain only photographs tagged with these names. The last step was creating a long table, in which each row contains information about when a person is marked as occurring in a photograph. The final dataset includes 334 distinct persons appearing over 2,000 times in different pictures between 1975 and 1990. Unlike in our first case study, we are not interested here in visualizing more than one perspective on the data, nor do we have multiple timelines. Only the timeline of events – that is, the appearance of the known individuals in photos – is of interest to us. For the sake of this discussion, we are not focusing on the timelines of the collection or the archiving of the images. One complication is that the number of photos varies considerably from year to year (from fewer than 10 to 120), as seen in Figure 6. Therefore, changes in the network could reflect either changes in contacts between the ten individuals or less thorough documentation of these contacts. In this case, we suspect that it is primarily a matter of more photos being taken over time and some gaps in the record, rather than problems with documentation. That said, even the least represented years are still represented in the archive, so we have no large gaps.[39]

Solutions to modeling dynamic networks with software are often applicable across multiple platforms. Many network visualization software packages (e.g., Visone, Cytoscape, Gephi) offer functions to create dynamic network visualizations. Dynamic networks have certain common characteristics – the most critical being that nodes (vertices) and edges (links) come and go, so an existing node/edge can disappear or re-emerge, and previously nonexistent edges can emerge. Further, the popular statistical software environment R offers a few packages for dynamic network analysis (e.g., ndtv, networkDynamic). These packages make it

38 For more on evaluating data quality, collecting archival data, and cleaning photographic metadata, see Elo 2020.

39 Of course, we do not have access to all of the photographs taken of the Jena dissidents in this period, much less information about all of the underlying contacts.

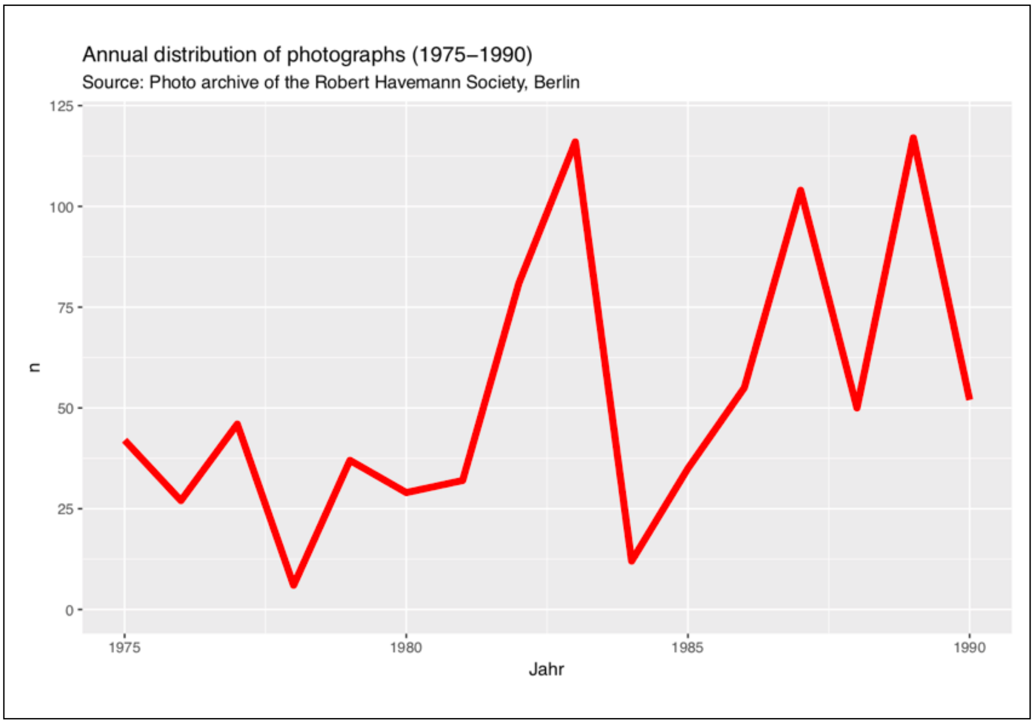

Fig. 6 Annual Distribution of Photographs, 1975–1990

possible to create small multiples and visualize the transformations between one snapshot and another.[40]

To represent changes between a snapshot and the previous one, we must enrich the network data by adding information about the change. While the 'network' package available for R introduces the idea of nodes/edges being 'on' or 'off,' it offers no tools to easily understand what has changed. To solve this problem, we have written a simple R script capable of turning any dynamic network data into enriched data containing distinctly coded information about changes between stages.[41] Both the nodes and the edges can be coded for dynamics. Colors

40 In order to model historical networks using such packages, it is, however, important to understand network structure and what is being modeled since the data model has a great impact on the output. While all of these packages offer transformation effects and other useful features, none of the tools allow us to easily understand what has changed from one snapshot to another since their focus is on modeling the entire dynamic network. For example, to understand how many of the nodes or edges have 'survived' a certain tipping point is difficult; this is the sort of question in which historians are often deeply invested, given that much historical research is concerned with well-defined events.

41 Elo 2021. The R script file consists of two functions to create dynamic network data.

can be used, as seen below, to visualize structural changes in the network. Here is the process:

1) Input data must be an edge table in the long format structured as follows: 'Source,' 'Target,' 'TemporalInfo.' The variable 'TemporalInfo' indicates when the edge is present and can be just a number, time-related (month, year), or a timestamp.
2) A specific variable 'nw.windows' defines how the data should be chunked by defining the starting points for each 'snapshot'.
3) The function itself codes the status change from the stage t_n to the stage t_{n+1}. The change value describes three different changes:
   a) 'disappeared' = the node/edge was present in t_n but not in t_{n+1}
   b) 'emerged' = the node/edge was not present in t_n, but was present in t_{n+1}
   c) 'remained' = the node/edge was present in both t_n and t_{n+1}
4) The method produces separate long tables for the edge and node data.

As we can see in Figure 7, the solution presented here allows us to understand what has changed in the nodes and edges.

How such enriched data can be used to tackle changes with network visualizations is illustrated in Figure 7.[42] We have used the package 'RCy3' to visualize the networks in Cytoscape. In order to exemplify how the data can help us to understand structural changes, the following visual effects have been used:[43]

- Blue nodes indicate nodes with the status 'remained';
- Green nodes indicate nodes with the status 'emerged';
- Red nodes indicate nodes with the status 'disappeared';
- Straight-lined edges in black indicate edges with the status 'remained';
- Sine-waved edges in green indicate edges with the status 'emerged';
- Dotted-lined edges in light grey indicate edges with the status 'disappeared.'

All of these visualizations use a standard force-directed layout in Cytoscape. The standardized, enriched dataset can be quickly processed in multiple software packages.

Once we have this basic model to display changes in the network using color, we can create variations on that model to compare states of the network at various times by placing the network graphs inside a grid chart. Figure 7 shows a series of network diagrams with nodes and edges colored according to whether or not they persist at stages 0, 1, 2, and 0 vs. 2. Since the color blue represents nodes that have

42 Figures 7–10 were produced in Cytoscape.
43 We have also removed node labels in order to improve readability. Node labels can be added whenever necessary.

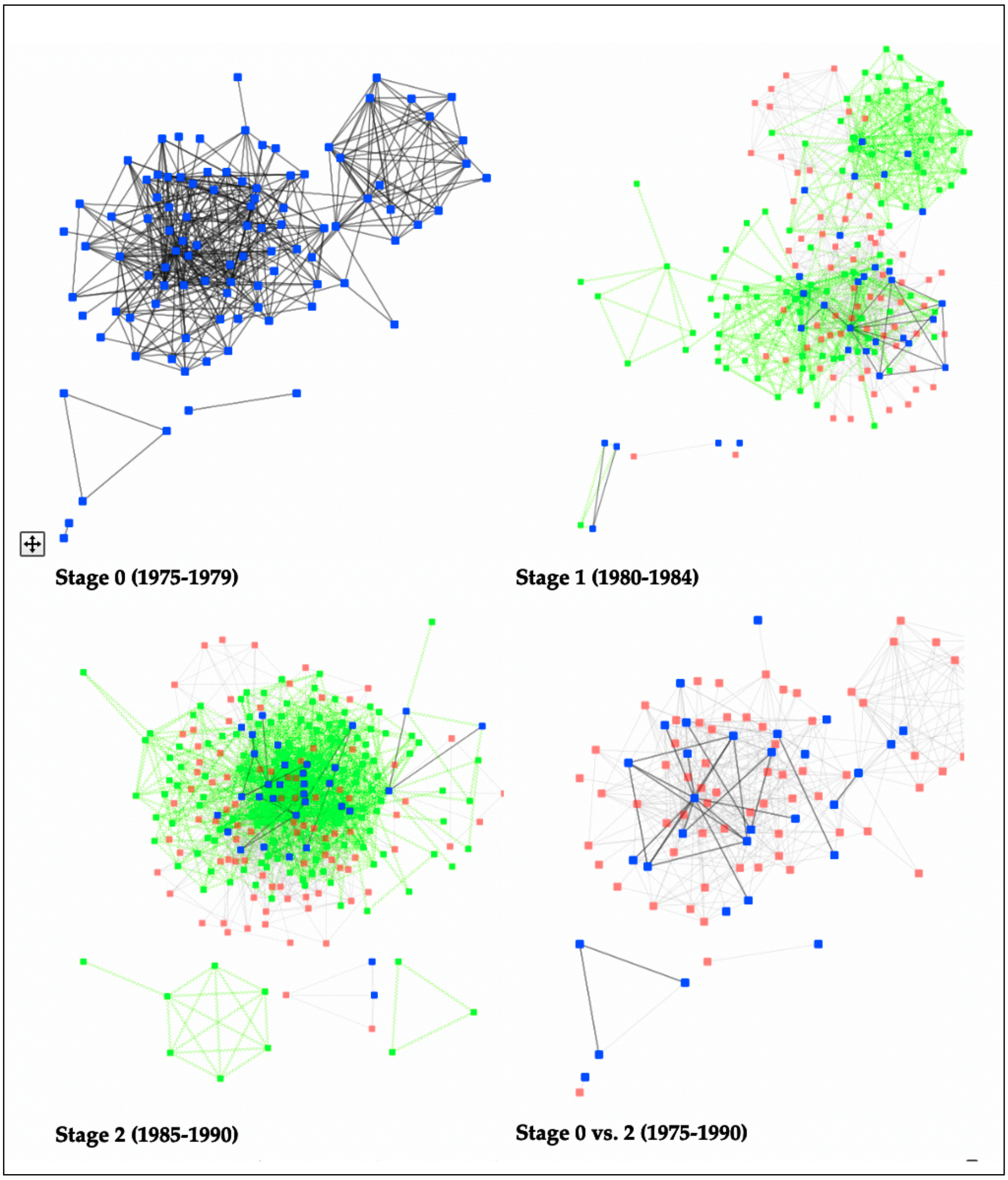

Fig. 7 Small Multiples of Jena Dissident Network (1975–1990) at Various Stages

remained and red represents nodes which have disappeared, it is not surprising that the comparison of the first and last years contains primarily red and blue. Similarly, the first snapshot (1975–77) is naturally blue, since all of the nodes 're-main' in the first snapshot of the network. The other snapshot comparisons show more disappearing (red) and emerging (green) nodes, with many nodes emerging in the later years of the dataset. Given that this archive documents photos over a period of 15 years, it is notable that a large number of nodes remain from one snapshot to the next, even if they are not the majority in the later snapshots.

Another example of how grid charts can be used to compare changes in the network across different time scales is Figure 8, a grid chart juxtaposing a sequence of small multiples (top) with changes throughout the lifetime of the network (bottom). In this case, we see that few nodes remained throughout the duration of the network's evolution. In each stage after 0, nodes emerge (green) and disappear (red). It would appear that more nodes disappear in the 1978–1979 and 1985–87 stages, and more emerge in the 1980–1982 and 1988–1990 stages. Most nodes have disappeared between stage 0 and stage 5, with only a few remaining nodes.

Node and edge dynamics are measures of changes in the network which can be difficult to perceive in network diagrams and can be most easily understood numerically. It can be challenging to see precisely which and how many nodes remain, emerge, or disappear in a network diagram. Figure 9 shows the same data presented in a bar chart. We can see the same patterns of more nodes emerging in

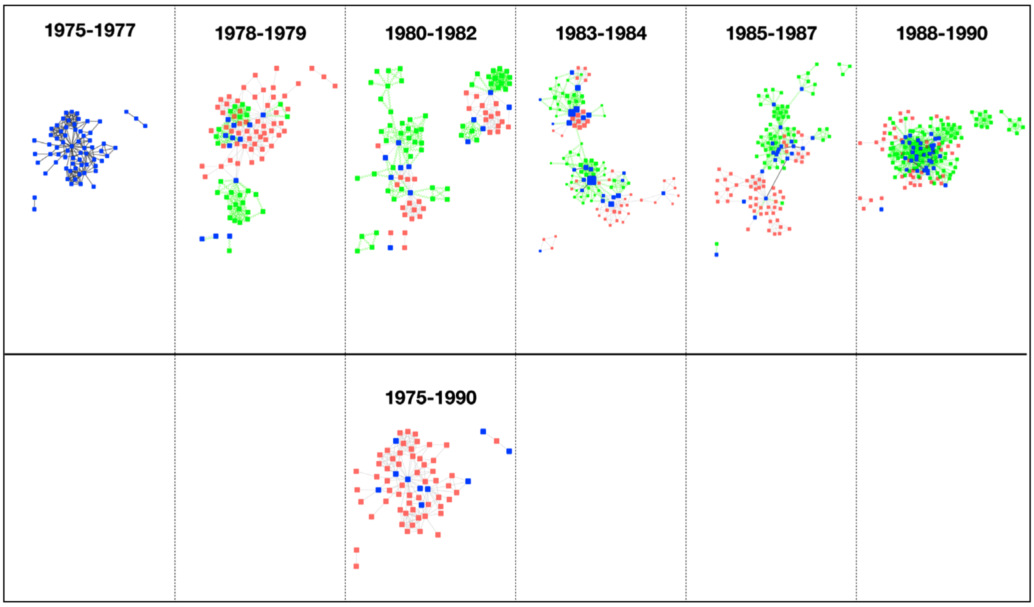

Fig. 8 Small Multiples of the Network of Jena Dissidents (1975–1990)

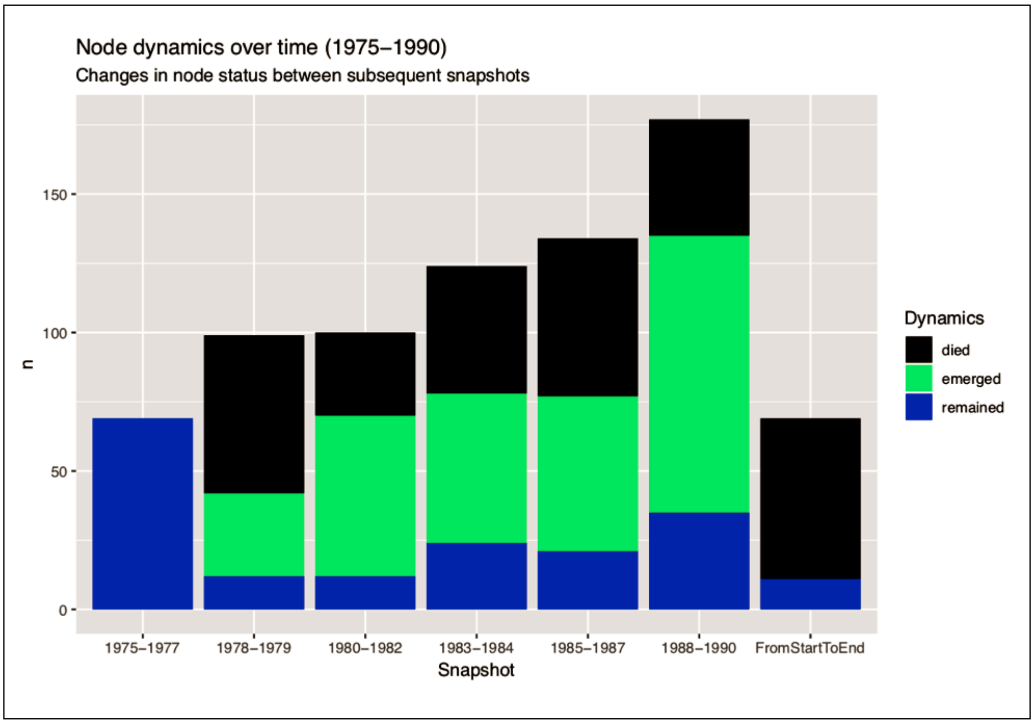

Fig. 9 Node Dynamics Over Time in Photo Co-Occurrences of Jena Dissidents (1975–1990)

the late 1980s. We can also see that most of the nodes have 'disappeared' between the start and the end of this process in the last bar of the chart, even more clearly than in the network diagrams.

In this bar chart, blue indicates how many nodes remain, green the number of new nodes, and black the number of nodes that have disappeared. As in Figure 8, we can see here that most of the nodes disappeared between stage 0 and stage 5. What we can see more clearly here, however, is that far more nodes emerged in stage 5 (1988–1990) than in the other stages. We can also see that more nodes disappeared in stage 1 as a proportion of changes in node status than in other stages. Likewise, we can see that there were similar numbers of emergences of nodes across stages 2, 3, and 4. As we have seen previously in Figure 6, the quantity of photographs in the archive varies by year; thus, differences in node dynamics are not necessarily reflective of an underlying variance in social relations among the Jena dissidents.[44] We discovered in analyzing the node and edge dynamics of this network that the edges are even more volatile than the nodes. In other words,

44 For more on networks of Jena dissidents as reflected in this photographical archive, see Elo 2018a and 2018b, as well as Conroy and Elo 2020.

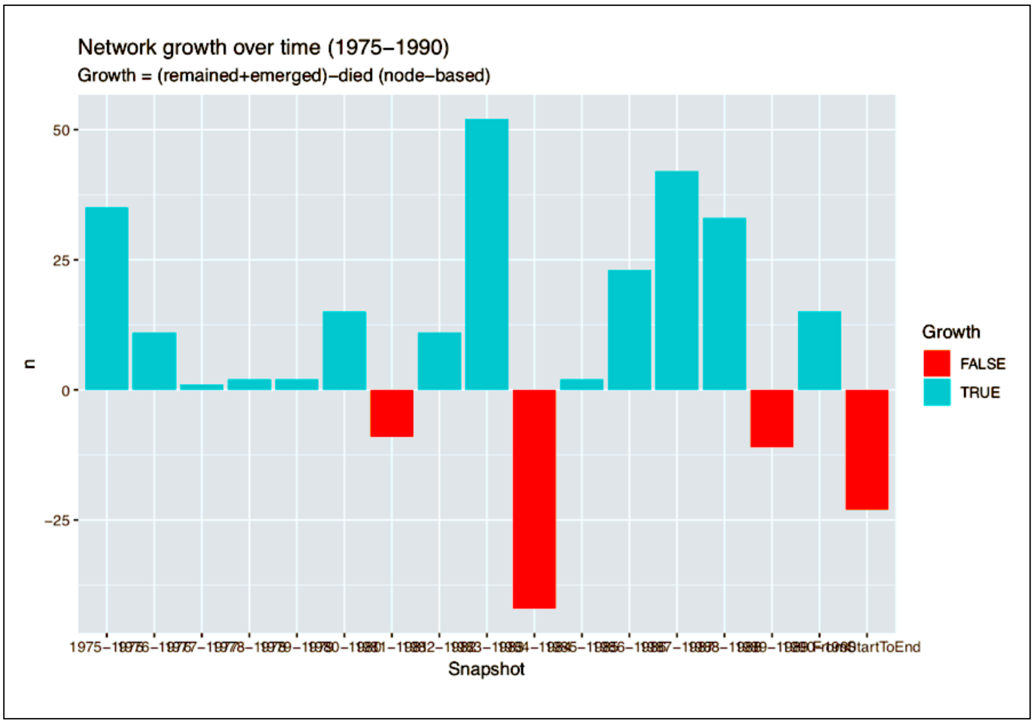

Fig. 10 Network Growth Over Time, Photo Co-Occurrences of Jena Dissidents (1975–1990)

connections between individuals are changing more rapidly than new individuals are appearing. The network of Jena dissidents was not a closed network with stable relationships; it was a highly dynamic and open group that admitted new members who found novel relations with a low degree of clustering. The high volatility of edges and nodes shows that the dissident movement was not inward-looking or stable.

Another way of visualizing and analyzing the sequence of events or changes in the network is to look at the rate of network growth. Figure 10 shows the network's growth over time, with turquoise representing growth in the network (measured by the number of nodes) and red representing the shrinking of the network. In this case, we display the rate of growth of the network by year, rather than by stage, so that we can see the extent to which the variations in the number of photographs per year affect the rate of growth or contraction of the network. We can see that there were significant contractions of the network in the years 1984 and 1990, both years in which there were fewer photographs in the archive than in the previous year (Figure 6).

Some years, such as 1978, saw downturns in the number of photos (Figure 6) yet a positive rate of growth in the network (Figure 10). The years of the highest rate of growth in the network – notably 1983 and 1987 – corresponded to years with the most photographs. The size of the archive for each year is, thus, a significant yet not determinative factor in the growth of the network. The best way to encourage such an awareness of changes in the size of the archive is to present a visualization like Figure 6 or Figure 10, which shows changes in the underlying archive or dataset, alongside network graphs like Figures 7 and 8 that show the structure of the network at selected times. Such diagrams give the viewer a sense of the overall size of the network and the number of nodes and edges that are present at any one time, data which can be compared against the structure of the network shown in the small multiples.

5. Conclusions

We have presented a method to visualize historical networks with flexible timescales and from different perspectives, by placing small multiples within grid charts to create an agent-perspective matrix. Using color (when available as a printing option), researchers can code changes in the network into the network diagrams themselves. When graphs are created, both nodes and edges can be coded with temporal information – a timestamp, number, or date. This temporal information can be used in visualization tools that use edge tables like Visone, Cytoscape, or Gephi. Both nodes and edges can be colored to indicate whether they have remained, emerged, or disappeared so that the change in network structure is visible. This method allows us to compare the network at two or more points (t_n, t_{n+1}, t_{n+2}, etc.). The grid chart can combine different timelines with perspectives (p_n, p_{n+1}, p_{n+2}, etc.) by using the x and y axes. In theory, many colors could be added to visualize differences between the network structure at more points in time; in practice, there are limits to the number of colors that the viewer can readily perceive.

Alongside these technical considerations, the question we have explored here on a theoretical level is what it means for a network to exist in historical time. There are four fundamental temporal elements of historical networks that we have identified:

1) The meaning of the appearance and disappearance of particular nodes (or agents) in the network is not fixed, and the reasons for disappearance from a network may vary.
2) Structural changes to the network over time (the appearance and disappearance of edges) may be of different qualities or have different attributes, such as friendship or foe relations.
3) Changes in perspective on the network over time can alter the network structure itself – for example, when one investigator perceives an agent to be part of a network, and another does not.

4) The temporal context of the state of the network (events before and after the state of the network graphed) can be significant for interpreting what counts as an event and what the boundaries of that event are.

One question that persists is to what extent historical events correspond to changes in constellations of actors or the state of the network. It is still up to the individual researcher to decide what exactly constitutes an 'event' and which agents should be considered part of the network of agents implicated in the event. As we have seen, changes in network structure may not correspond to what an individual researcher means by a historical 'event.'

Rather than providing one totalizing theory about what historical events and networks should be, we have sought to offer a framework for visualizing changes in networks. We have shown how the time-perspective model fits conspiracies and other networks in which documents may be limited or contradictory, or historical agents have a significant interest in *their* version of the network. The visualization of various perspectives may be less relevant to the study of networks where sources' perspectives are less suspect or biased than the interrogation documents of the Gestapo or photographic archives created by a network of dissidents. Nevertheless, in most cases, the inclusion of multiple timelines or perspectives better reflects the complexity of historical time than a single model. Similarly, color-coding nodes and edges based on network dynamics may not fit every historical use case. At the same time, coloring the network according to network dynamics can be an effective alternative to the use of color only to distinguish static properties of nodes. By embracing multiple timelines and highlighting network dynamics, historical network graphs can approximate many of the complexities of historical time. This departure from the 'whole graph' or 'large single' model of network visualization is already present to a large extent in HNR, where we are far from the first to use small multiples.[45] The addition of coloring according to network dynamics presents a novel solution to the problem of representing historical time as a network visualization.

45 Newspapers like *The New York Times* have so far made greater use of small multiples than historical journals have. More often than presenting small multiples side-by-side, HNR articles place selected snapshots in the article sequentially. For a sophisticated version of this presentation layout, see Van Vugt, 2017.

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