Metaphorical metro maps: design challenges

Herman Haverkort
Institute of Computer Science
University of Bonn
Bonn, Germany
cs.herman@haverkort.net

***Abstract*—Metaphorical metro maps use the standardised graphical language of maps of urban transport systems to visualise a different kind of network. This may help in interpreting the maps, but the differences between the original use and the metaphorical use may also confuse and call for different design guidelines. In this paper, I propose a framework to analyse use cases for metaphorical metro maps and I identify a number of challenges regarding their design, manual and automated.**

I. The power of metro maps

Schematic maps of urban transport systems probably constitute one of the most widely used types of maps. Figure 1 (top) shows a well-known example. The fairly standardised graphical language of such maps allows users to identify quickly what routes exist between any pair of given stations. Moreover, the map user can see what steps should be taken to follow such a route: which line to take, in which direction, where to change trains and where to get off, and after how many stops—and all of that with full confidence: the metro maps is an authoritative source that shows all relevant connections. Daily use of metro maps is such an essential part of life of inhabitants and visitors of big cities, that such maps sometimes become a symbol of the entire city.

Because metro maps are so familiar, powerful, and easy to use and because they evoke such positive associations, it is not surprising that many designers have tried to communicate other information using metro maps as a metaphor. Metaphorical metro maps use the standardised graphical language of metro maps to show a network of entities and connections between them that may have nothing to do with an urban transport system—see, for example, Figure 1 (bottom). In some cases, designers have even provided algorithms to produce such metaphorical maps automatically—here they may build on a substantial and growing body of literature on automatic layout of metro maps [25], [38].

The metaphor allows map users "to construct one conceptual domain (the target domain) in terms of another (the source domain)" [8]. This is possible because the target domain shares some aspects of the source domain, that is, urban transport systems. Of course, in other aspects, the target domain differs from the source domain. Ideally, the common aspects are the most relevant aspects and the metaphor functions as a filter that helps the map user to focus on exactly these aspects. The use of the familiar graphical language of metro maps may make the metaphorical map look attractive and easily accessible, and it may help users to read the information depicted on the map.

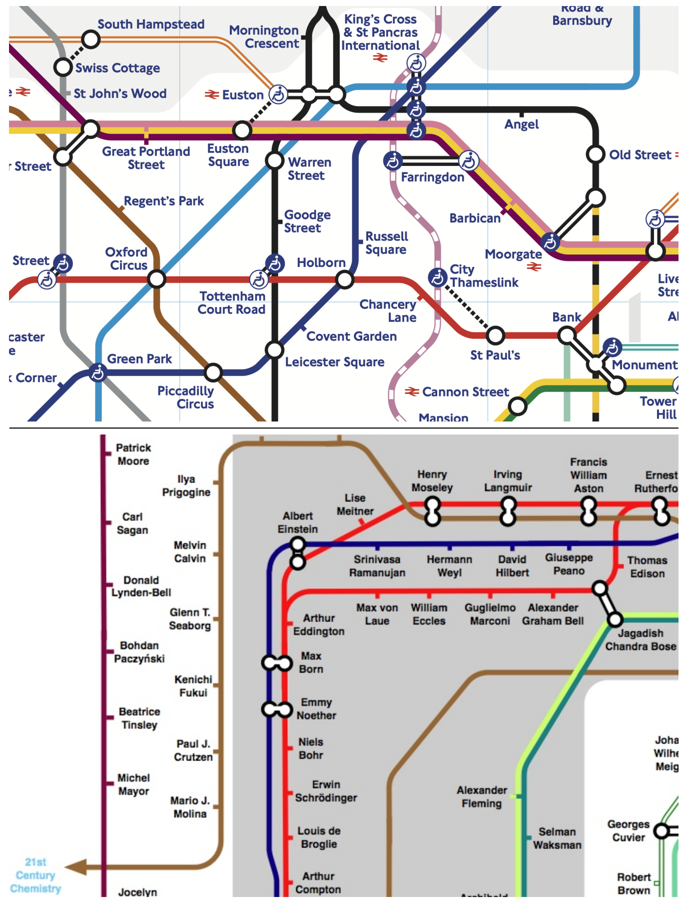

Fig. 1. Top: excerpt from a map of the London underground [33]. Bottom: excerpt from a metaphorical metro map showing scientists organised along lines for astronomy, chemistry, mathematics, physics, and other disciplines [18].

However, metaphors can also lead to confusion. The use of the graphic language of metro maps may prompt users to try to match aspects of urban transport systems to the target domain even if these aspects are unmatched. This may then lead to drawing wrong conclusions from the map. Therefore, the effectiveness of the metaphor depends on whether the audience manages to match the intended aspects without erroneously matching unintended aspects. It is therefore necessary to take into account not only how a target domain is like a metro system, but also how it differs from a metro system—so that we know where confusion could be lurking and where we might want to take countermeasures in the map design.

The goal of this paper is to provide a starting point in an investigation of how metaphorical metro maps are used, and how differences between target domains and metro systems may lead us to reconsider graphical language, layout guidelines, and algorithms that were developed for metro maps. We will first discuss the essential properties of metro maps, which may or may not be maintained when metro maps are used metaphorically, and we discuss what reasons one could have to use metro maps metaphorically. This provides us with a framework to discuss the successful aspects and the limitations of existing metaphorical maps. Based on the findings, I will identify a number of challenges regarding design guidelines and algorithmic solutions for metaphorical metro maps. I will conclude with a short checklist and possible directions for broadening the scope of this work.

Throughout this paper, the focus is on how to draw the *best possible map, given the exact network* to be shown. We do not discuss how to extract that network from the underlying data, which can be a challenge of its own [21], [31], [35]. More specifically, we focus on applications in which the map layout is not given, and deciding the layout thus constitutes the main challenge. In contrast, metaphorical maps based on a given map of an actual metro system may be designed to establish a connection between the metro system and its above-ground environment [9], or they may be designed for entertainment, where arbitrary content is kneaded to match the structure of a known metro map [16], [27]. Such maps, which must adhere to a given layout, are out of the scope of this paper.

By the *user* of a map, we mean whoever is *reading* the map, as opposed to the author or the publisher of the map.

II. What does a metro map show?

To understand metaphorical metro maps, we need to understand what the depicted networks and metro networks have in common. However, the common ground is not the same for all metaphorical metro maps: a metaphorical map only borrows some aspects of true metro maps, and not all metaphorical metro maps borrow the same aspects. To be able to discuss metaphorical metro maps in a structured way, it is therefore helpful to have a characterisation of a metro network from which different aspects can be kept or removed, independently from each other and without causing inconsistencies.

Every metro network has a set of *stations*. The stations have a *location* on Earth and they are often grouped into *zones*. We will make a distinction between two variants of our characterisation: networks can be station-based or link-based:

- In a *station-based* network, the stations are first grouped into *lines*, such that each station belongs to one or more lines. Second, the stations of each line are connected to each other by a network that consists of *links*: each link connects two stations of the line to each other.
- In a *link-based* network, we first establish a set of *links*: each link connects two stations. Second, these links are grouped into *lines*, such that each link belongs to one or more lines. This induces an association of stations with lines: a station is associated with a line if and only if it is an end point of a link of that line.

We will refer to the grouping of links into lines as the *network organisation*, and to the link structure of a line as the *line organisation*. Note that the difference between the two variants of our characterisation is only whether we start with associating stations with lines and then connect these stations by links, or we first establish the links and then associate these with lines. This is a subtlety that does not make a difference for real metro maps. However, it can make a difference for metaphorical metro maps, in which the second step, that is, either the line organisation or the network organisation, may be up to the map designer.

In any case, the network is *explicit* (or: *discrete*), that is, a link connects two stations and nothing else. Intermediate points along the curve that represents a link in a map do not represent meaningful locations; one cannot get out of the train between two consecutive stations.

Often, the links of a line form a *simple path*: it consists of a series of links such that each link (except the first) starts at the end point of the previous link, and each station is visited only once. However, a line may also have multiple branches or loops; in fact, it could be a fairly complicated network by itself. On some maps of actual metro systems, the links of a group do not constitute the route of a single train but rather, for example, all connections operated by a particular operating company or with a particular mode of transportation (tube, street cars, buses etc.). In such cases, the word *line* may not be quite the right word to describe such a group of links, but we will stick to it for the purposes of our discussion. Typically, links are *undirected*, that is, if a line has a link that leads from one station to another, then this implies that it also has a link from the second station to the first, and a typical map would represent both links by a single curve on the map. Many transit networks do, in fact, have some directed links that exist in one direction only. For example, there could be buses that serve one-way streets or make a loop at the end of the line. However, such links would be handled as exceptions that would be marked as such on a map: as a rule, in the absence of special markings, links are undirected.

A *route* is a series of links in which each link starts at the previous link's end station. The *length* of a route is the number of links it contains. A *line change* is a station along the route where the incoming and the outgoing link of the route belong to different lines. The number of line changes along a route is typically perceived as the *complexity* of a route. The complexity of a route is more important than its length: in real metro networks, a change of lines requires much more effort and time than an intermediate stop. In fact, a route implies interaction with the starting station, the stations where line changes take place, and the end station, but not with any of the other stops along the way. Nevertheless, intermediate stops cannot be completely ignored. On a metro line with links (A, B) and (B, C), travelling from A to C requires a stop at B (a traveller might look out of the window to verify its name) and a more direct connection cannot be expected to exist.

Metro networks are, to some extent, *distance-preserving*: stations whose locations are far from each other must also be far from each other along any route (the opposite does not need to be true: stations that are far from each other in the network may still be close to each other geographically).

A typical metro network has *non-trivial connectivity*: lines typically have more than two stations, and some pairs of stations (or even most of them) are connected only via routes that require at least one line change. Lines tend to have a *sparse* structure: the number of links of a line is never much larger than the number of stations on the line.

Metro maps are usually issued by a central authority, which guarantees that the maps are complete and correct: the best (shortest and least complex) connections within the system are indeed on the map.

Of course, real metro maps may be more complicated in many ways. However, for the purposes of this paper, I believe the simple model just described suffices.

III. How does a metro map show it?

A typical metro map has a foreground layer that shows the stations and the links, and a background layer that shows the zones and/or some context (for example, city limits or major landmarks) that enables a rough estimation of locations. Lines are typically distinguished by colour, applied to the links and possibly also to the stations that belong to the line. Effective use of the map is facilitated by its network organisation, its line organisation and its *spatial organisation*: the assignment of locations on the map to the stations.

The fundamental design challenge in metro map design is to maintain or realise useful spatial organisation while at the same time optimising the legibility of the network organisation and the line organisation. This challenge is caused by the fact that stations have meaningful locations and the network has non-trivial connectivity; the fact that metro systems are, to some extent, distance-preserving, prevents the challenge from becoming unsurmountable. Many of the typical design guidelines for metro maps can be seen as an answer to this challenge.

Metro maps are typically heavily schematised. This means that the spatial organisation and the drawing of links does not follow the true locations of stations and links according to a standard map projection. Instead, they are moved with the purpose of eliminating irrelevant detail and improving legibility. Thus, users get a representation of the network that reduces the cognitive load when completing a task, so that they can complete their tasks efficiently [28].

On the schematised map, distances between stations as the crow flies may be heavily distorted as compared to true distances as the crow flies: all that matters are the routes that connect stations through the network. Still, the stations' locations on the map, relative to each other, should correspond roughly to their locations on Earth, relative to each other. This helps users find stations on the map.

Further design guidelines for successful schematisation include: straighten out lines (avoid unnecessary bends), never bend a line under a station marker, create at least one simple axis (for example, a route that runs horizontally or vertically across the entire map, or in a perfect circle), enlarge areas with many links and interchanges, shrink areas with few links and interchanges [26], [28].

Metro maps use a standardised graphical language. Essential elements of this language include the following. There are curves that represent links, markers that represent ordinary stations, and markers that represent interchange stations. When a curve hits a station or interchange marker, it means that the train of the corresponding line stops at that station; where there is no station or interchange marker, the train does not stop. In particular, when two curves cross each other on the map, this does *not* constitute a connection between the corresponding lines: one cannot change trains there. Only in interchange stations do lines connect to each other.

IV. What are metro maps for?

In the introduction I stated what metro maps are "typically" used or designed for. However, for better or for worse, the primary function of metro maps is not necessarily among the properties that are mapped to the target domain when the map is used metaphorically. To understand metaphorical metro maps, we need to have a broader vision on what the maps may be for. Below is a list of possible uses, partially based on Shahaf et al. [31] and Burkhard and Meier [3].

a) Get and keep attention: A map can stand out and get attention by its graphic design, but a good map goes further: "The brilliance of a map lies [...] in [...] how it captures the imagination of its users [...] Visualizing data may gain people's attention, but the map needs to be truly engaging if it is to have any value." [9]. In any case, maps may activate recipients more than other forms of communication: map readers must not and cannot merely follow an author's train of thought as with a written text, but they can and must decide for themselves where to go first and where to go next when they study a map.

b) Coordinate individuals: A map presents a structured view of information that can serve as a common frame of reference for people using the map. Burkhard and Meier mention various related purposes, such as initiating discussions and motivating people.

c) Present overview: Maps allow the discovery of trends, patterns, exceptions, and gaps in current knowledge. A well-designed metro map allows one to see higher-level features of the network that may help in learning how to use the network: hub-and-spokes structures, grid structures, circle lines, connections and stations that are central to many routes, the general direction of each individual metro line, etc.

d) Support exploration: Users can start exploring a map from any starting point, thus finding new information and learning a rich network of relations to previously known information. Learning these relations efficiently while exploring is an aspect in which a map is better than a simple list of facts.

e) Provide detail on demand: With a map, readers can find detailed information about regions that are of interest to their current tasks, without being overwhelmed by details that lie outside the current regions of interest. A metro map allows one to quickly read, for example, only the names of stations along one's route, without looking them up in lists that contain all stations of the lines travelled, or even all stations on the map—worthwhile functionality considering that the London underground, for example, has almost 300 stations.

f) Allow fast look-up of facts: To find a country's climate zone, it may be easier to use a world map than to use an alphabetically ordered list: the world map has a standardised orientation and countries have a fixed place on it. This is helpful for those who remember it, and it is particularly helpful for those who remember the location but not the name. In contrast, the place of a country in an alphabetically ordered list depends on many factors (size of the list, language, formal or colloquial names, with/without articles etc.), possibly making a country hard to find. In a similar way, a metro map enables users to look up basic facts about stations by location instead of by name.

g) Suggest options for people to act, and support the dynamic comparison of different options: A good map can give users the necessary information, even if the possible tasks to be solved with the map cannot be limited to a sufficiently small set at map creation time, or if additional circumstances that are not known in advance need to be taken into account. A real metro map is designed so that one can identify, for any two given stations, by what reasonably short routes these stations are connected to each other, determine how complicated these routes are, and estimate, if only roughly, how much time they take. This requires locating the stations on the map, exploring the network structure between them on a coarse level, then tracing routes along the map to find the details. A simple table with the best connections between each pair of stations could not fulfil this function, not only because it would have to be huge, but also because, depending on real-time information, one may prefer to deviate from predetermined routes. A map provides users with a mental framework that allows them to integrate real-time information and personal preferences while using the map to complete tasks.

h) Support learning and recall: It has been claimed that the spatial layout of a map may enhance our memory of it, thus supporting the learning and recall of information on the map [24]. It definitely works for me: I cannot remember route descriptions, but I can remember what a route looks like on a map and how it relates to other features on the map. A map may provide users with a spatial frame of reference that allows them to learn and remember where entities are on the map, and thus, how entities relate to each other.

i) Focus attention and support concentration: When trying to accomplish a task, spatial memory may help users in maintaining focus on their current position on the map—which would be harder if the information would be presented as a long list. Note that this is task-related: simply going through all items in a list one by one is easy, whereas going through all items on a map one by one is hard—but this is not the type of tasks that metro maps are designed for.

j) Present different perspectives: Different map designs could present different perspectives that may complement each other. For example, many projections for world maps require two poles. Choosing non-standard locations for these poles, for example putting one in the centre of the Pacific Ocean and one in a big city, can provide a different perspective on where regions on Earth are located relative to each other. Metro maps are sometimes created in different versions in the design process, which may be evaluated to see how this affects the routes that users take [13].

k) Increase perceived credibility: Adding irrelevant detail to a story is a well-known method to increase its perceived credibility. To convince the audience that a man-bites-dog story is not just a rumour, describe exactly where it happened, or even better: show that location on a map! A (metaphorical) metro map might get part of its perceived credibility from the fact that the author seems to have put each station on the "right" place on the map—even if most stations are irrelevant and their locations on the (metaphorical) map are fully at the map maker's discretion. Needless to say that any perception of credibility should be regarded critically, but to some extent it can be warranted. A map provides overview and thus makes errors easier to detect. The absence of obvious errors may lend credibility to the map and to the map maker's expertise.

The design of a map is, ideally, the result of balancing traits that support the purposes of the map according to their relative importance in a given context. To this end, the abstract purposes described above must be made specific: who are the potential map users whose attention is sought, what type of patterns should they be able to see, what tasks will users need to accomplish for which they need to find options to act, etc. The answers to these questions should be concrete enough so that one could derive hypotheses which could, at least in theory, be tested to evaluate how effective the map is. Without such concretisations, purposes such as "present overview" and "support learning and recall" could degenerate into a self-fulfilling "present clearly whatever structure the map presents clearly" and a meaningless "help readers remember the map".

V. A FRAMEWORK TO ANALYSE METAPHORICAL METRO MAP USE CASES

We can now formulate criteria that a use case for a metaphorical metro map should fulfil to be "exactly" like that of a real metro map. No use case would fulfil all criteria. The unfulfilled criteria may inform us about possible shortcomings of a metaphorical map, which we may try to solve by adapting the design guidelines. We distinguish three main components to a use case: content, purpose, and audience.

On the aspect of content, we have a perfect match if the entities and relations in the target domain are in a one-to-one correspondence with those of true metro systems (see Section II). Thus we would answer yes to these questions:

- Is the network *explicit*, that is, are all stations to be shown explicitly on the map, such that each link connects two stations, without implying connections with intermediate, unmarked points?

- Do stations have *meaningful location*, independent from the network structure, to be loosely visualised by spatial organisation? (If yes, what do the locations mean?)
- Can links be grouped into *meaningful lines* in such a way that a change of lines in a route requires a conceptual leap that is not required in a route whose links all belong to same line?
- Do stations along a line have *meaningful order*: are lines sparse and do stations along a line have a more remote relation if they are further apart along the line?
- Are (most) links *undirected*?
- Is the network *certain* and *complete*: are all stations there and are there no closer relations between any pair of stations than the relations to be depicted on the map?
- Does the network have *non-trivial* connectivity: is there, at the very least, a line with more than two stations, and a pair of stations that can only be reached from each other with at least one change of lines?

We should check which purposes, from those listed in Section IV, the map is expected to fulfil. Those purposes should be made more concrete, for example:

- Is the map's purpose to present *overview* (for example, general direction of lines, bottlenecks)? If yes, what kind of questions about the structure of the network should be answerable with the map?
- Is the map's purpose to present relevant *detail* on demand? If yes, what details?
- Is the map's purpose to show *options to act* in response to challenges that cannot effectively be predetermined?
  - Is it, in particular, intended for looking up and *comparing routes* between stations?
  - If yes and if there are meaningful lines, are *connections with few line changes* more important than connections with many line changes?
  - And if there is meaningful line order, are *short connections* more important than long connections between the same stations?
  - If the answer to any of the previous four questions is no, then what kind of *specific questions* should be answerable with the map?

A third, important, component of a potential use case for a metaphorical metro map is the intended audience. If the map is intended to appeal to urban non-experts, the use of the familiar graphical language of metro maps as described in Section III may be a big asset. If, in contrast, a metaphorical metro map is primarily intended for use by experts on the target domain who would need to use the map frequently, familiar graphical language that enables easy first-time use loses importance in comparison to optimal usability in the long run. Therefore, when maps are intended for experts, a wider range of alternative visualisations may become appropriate, and the use of a metro map metaphor should be considered more critically in comparison. The same is true if the maps are intended to be used by an audience that may not be comfortable with real metro maps and may not interpret the standardised graphical language in the same way as regular users of metro maps. In fact, to read a metaphorical metro map, the audience has to reinterpret this graphical language in another context: the audience has to figure out which properties of metro systems are to be carried over to the target domain, and which properties are not. How well people succeed in handling this intellectual challenge may depend on many factors, including intelligence [28] (referring to [22]).

VI. Applying the Framework to Existing Metaphorical Maps

In this section we use the framework of the previous section to discuss a number of published metaphorical metro maps. A metaphorical metro map must at least meet the following criteria to be included in the discussion in this section:

- the network must have non-trivial connectivity (as defined in Section II);
- the map must have meaningful location and/or meaningful network organisation (if neither is the case, the layout challenge becomes a standard graph drawing challenge, about which there is an abundance of literature already).
- the map must show clearly which stations lie on which lines (if we cannot figure out the topology of the network, then we cannot have a critical discussion about what would be the best way to visualise it).

From maps that meet the criteria, I will discuss a small selection that I expect to be representative for a variety of metaphorical map use cases. I will not give a full review of the selected maps, but focus on issues that arise from metaphorical use of the metro map concept. For the sake of informative discussion, we will discuss each map under the assumption that the author intended to make a map that is useful to the map user and whose purpose is not limited to getting attention. Table I at the end of this section gives an overview of key properties of the maps discussed in this section.

A. Geographic networks

Sasha Trubetskoy designed a map in metro map style of the major roads of the classical Roman Empire in Caesar's time [34] (Figure 2, top). Unlike metro systems, the network is not fully explicit: presumably, one can enter and leave a road at practically any point, not only in one of the 250 towns that are marked on the map. As it is a map of an actual, physical transportation network on the surface of the Earth, meaningful location, distance, and order (line organisation) are obvious. The network has non-trivial connectivity (about 30% of the towns on the map are junctions, similar to the London underground map). The network is, of course, not complete with respect to connections over very short distances (just like real metro maps that do not show when it is faster to walk).

The question whether there are meaningful lines is not straightforward to answer in this case. Each line on the map constitutes a road with a particular name (some were invented by the map maker). However, from a traveller's point of view, getting off one road and getting onto another road adds nothing substantial to the complexity of the route travelled.

Fig. 2. Excerpts from road maps from Trubetskoy (top) and Booth (bottom).

As a traveller you would really want to be sure that the map allows you to identify the shortest route, and it is not clear if it does—the schematised drawing style indicates that distances are likely to be heavily distorted.

This brings us to the purpose of Trubetskoy's map. The map provides overview of some sort, and allows looking up certain facts by approximate location, but the map is not really suitable for comparing different routes between towns. What type of questions can we answer with this map? Conceivably, the network organisation may be meaningful for map users who are not focused on navigation and shortest routes, but on the history of the Roman empire. Therefore, it might have been worthwhile to enrich the map with more content that supports a historical study, such as zones that illustrate the expansion of the Roman empire or its road network over time.

There are more road maps in metro map style, for example Cameron Booth's map of the highway system of the USA [1] (Figure 2, bottom). Like with the previous map, the map is not fully explicit. To interpret this map correctly, it is essential to realise that one can enter or leave roads at places that are not marked as stations: one can change from one road onto another whenever they cross on this map, even if there is no interchange symbol. Thus this map uses the graphical language of metro maps but with different semantics.

B. Time-ordered networks

In this subsection we discuss maps that have a temporal component: stations are, at least to some extent, associated with a point in time. Thus, one can give stations a meaningful location on the map by defining a correspondence between time and location on the map.

1) Event networks: Shahaf et al. [30], [31] present an approach to construct a metaphorical metro map from information in a large collection of documents, stemming from "news stories, research areas, legal cases, even works of literature". The idea is that "each metro stop is a cluster of documents, and lines follow coherent narrative threads". For example, when applied to news reports on a political crisis, a station may represent (a cluster of articles reporting) a specific event, and a line could represent the events that involve a particular actor. The clusters (stations) and the threads (lines) are extracted automatically from the data, with the specific purpose, among others, that the lines are defined such that their connectivity captures "how different aspects of the story interact". The clusters and threads are presented as a map, motivated by "strong empirical evidence that map representations help users gain and retain knowledge." An example of the result is the map on the 2009 Greek financial crisis shown in Figure 3 (top left). There is meaningful location in one dimension (events are ordered chronologically from left to right), there are meaningful lines (events affecting the Greek population, the EU, Germany, and the IMF, respectively) and there is meaningful order along each line (namely, forward in time). The connectivity of the networks is non-trivial but quite low. Considering the quoted motivation, the map's purpose seems to be, at the very least, to provide a spatial framework to support learning and recall. The concept obviously provides opportunities for maps to present overview, to present relevant detail on demand, to allow fast look-up of facts by location (that is, time and thread), and to support exploration. Conceivably, the map could also be used to find connections between two events in the form of intermediate events, common preceding events, or common following events—in that case, by Occam's razor, short and simple connections are likely to be the most relevant.

Another map that could be considered to be of similar nature, is Jago's map on scientists of the past five centuries [18] (Figure 3, top right). Fives zones are drawn, corresponding to centuries. Conceptually, it might have been a natural choice to draw the time scale and the map from left to right, but to fit on paper, it spirals out from the centre. Twelve lines represent academic disciplines; stations (almost 500) represent scientists, about 20% of which are marked as an interchange or as an ordinary stop that is served by multiple lines. Along each line, the scientists usually seem to be ordered by year of birth (with some scientists that are on multiple lines appearing out of order). This order may seem somewhat arbitrary, considering that many scientists' productive lives span half a century and would overlap with the productive lives of a dozen or more scientists along their line. Thus, the order of stations along the line is meaningful on a coarse level, but should not be interpreted too strictly on a detailed level.

Makieva et al. [23] designed a map on which stations do not represent events, but molecules that play a role in "signaling pathways" that regulate the human menstrual cycle (Figure 3). There are about 120 stations on the map. Connections link molecules that are directly related by a biochemical reaction; seven lines organise these connections into seven "pathways" that originate, for example, from a hormone and lead to a major process. This seems to be a link-based map: the links are

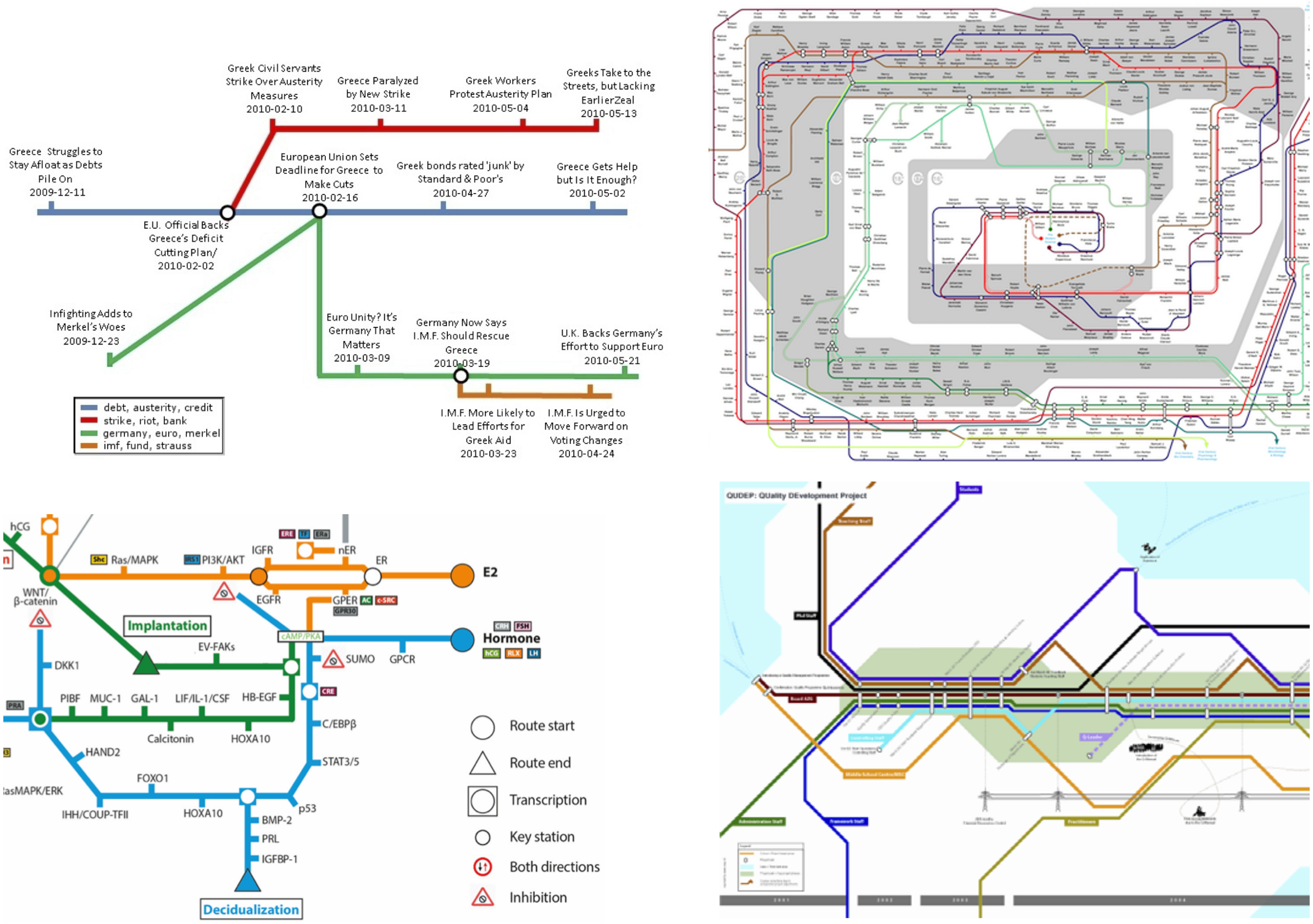

Fig. 3. From the top left in clockwise order: a map by Shahaf et al. [30], and excerpts from Jago [18], Burkhard and Meier [3], and Makieva et al. [23].

real (representing a chemical reaction involving a given input and output); the grouping of links into pathways, however, seems to be an interpretation designed to create overview. Note that lines are directed. A meaningful concept of location does not seem to have been applied and it is not visually obvious in which direction the lines run. I suppose one might want to use this map to look up what are the intermediate steps that lead from one molecule to another. I doubt, however, if one would want to focus on connections that are simple and short while simply ignoring connections that are complicated or long.

2) Schedules: Burkhard and Meier [3] reported on metaphorical metro maps to communicate the planning for long-term projects. Figure 3 shows an excerpt of an example. The complete map has about 30 stations that represent milestones in the project, on ten lines that each represent a group that participates in the project. The stations have meaningful location: they are ordered chronologically from left to right. Most stations lie on multiple lines, which could have made the layout challenging. This was solved by drawing the lines mostly in a tight bundle running straight from left to right. Rather than letting the lines cross so that each line reaches the interchange stations it needs to visit, Burkhard and Meier maintain the order in the bundle and cut the interchange stations into parts that are distributed over the lines that need to "stop" there. The map contains outer zones marked in blue with stations on the edge of it: these seem to represent interactions with external parties, thus adding a second dimension to the concept of location on the map. A related paper by Stott et al. [32] discusses the automatic generation of such maps. Here, the semantics appear to be slightly different: stations represent tasks rather than milestones.

Stott et al. claim that "project members working together are [...] clearly shown where two lines run in parallel". This is, however, not automatically the case: if two actors work together only on a single task, then they meet only in a single point. We could decide to extend the map drawing approach by *requiring* that actors working together become visible as parallel links. Thus the links would get a semantic that goes beyond connecting their end points.

One of the purposes of real metro maps is to allow users to quickly identify the shortest and least complex routes between stations. In project plans, however, the opposite seems to be required: it is the longest and most complex routes between stations that are most vulnerable and may need most attention.

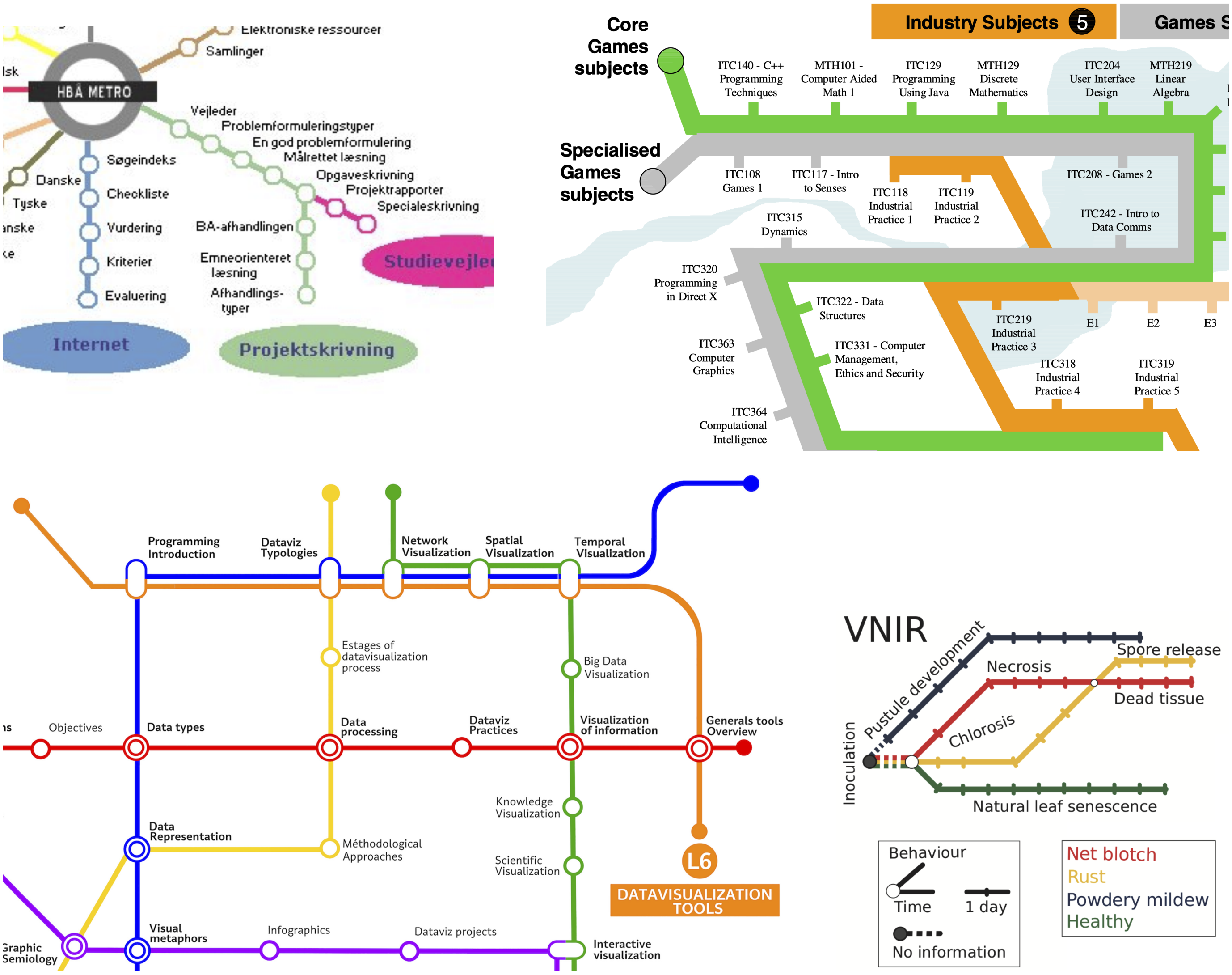

Fig. 4. Excerpts from content and curriculum navigation networks by Sandvad et al. [29] (top left), Nesbitt [24] (top right), and Gonzales [8] (bottom left), and a plant disease map by Wahabzada et al. [35] (bottom right).

3) Content navigation networks: Sandvad et al. [29] developed a metro map style presentation of hypermedia content; an excerpt is shown in Figure 4. Stations correspond to topics; lines to sequences of topics that make up a "guided tour". There is a one-dimensional concept of location and line organisation: tours have a common starting point shown in the centre of the map, lines radiate from there and stations appear on lines in the order in which they appear in the tours. Similar maps have been proposed by Nesbitt [24] and by Gonzales et al. [8]: here, stations are courses in a curriculum and lines represent different tracks or study programmes.

What questions can we answer with such maps? When navigating hypermedia content, there is no point in asking: "I am currently at page A, what is the shortest route to page B", as one can simply look up page B right away. One might want to know: "What pages are recommended for reading first so that I can make sense of page B?" Unfortunately, one's starting position is not a single station in this case, but rather the set of *all* stations one has seen before. At best, a map could show what route to take when starting without any prior knowledge.

As a thought experiment, we might consider designing networks in which some stations can be reached via different routes. For example, a station showing a particular painting may be reached via a "19th century society" line, an "art movements" line, or a "painting materials" line. Thus, viewers will pay attention to different aspects of the painting when they arrive there, depending on which route they took. After visiting the painting, the lines may separate again. Note, however, that it would probably not be recommendable to change lines at the painting: to make sense of a line, it must be followed from the beginning, not from an interchange station half-way. In a metro map of plant diseases by Wahabzada et al. [35] (see Figure 4) we find a similar situation. In their map, the horizontal dimension represents time, the vertical dimension represents, roughly, how different a plant looks as compared to a healthy plant. Each of four lines represents the progression of symptoms that comes with a specific disease. In particular, the lines of the *Net Blotch* and *Rust* diseases arrive at a common stop after six days, and then diverge again. Clearly that does not mean that after six days, a plant that, so far, was ill with *Net Blotch*, can now change to suffering from *Rust* instead. So, as in the painting example, the route that can be followed after the common stop depends on the route that was followed up to that stop. This is where the metro map metaphor breaks down: a true metro system enables connections by making lines meet so that travellers can change lines, but in the networks such as the aforementioned [8], [24], [29], [35], such line changes would be problematic. Indeed, on Nesbitt's map, the metro map metaphor gives us no clue about how the lines interact (there are no interchange stations at all) and Nesbitt mentions the representation of course prerequisites as an open problem.

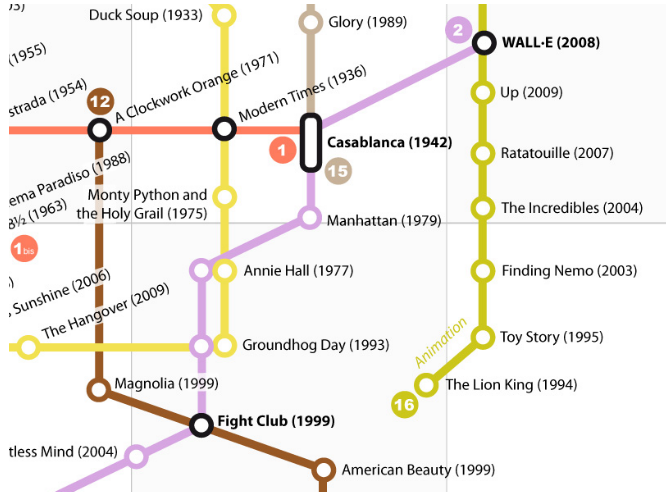

Fig. 5. An excerpt from a map by Honnorat [15].

C. Set systems

David Honnorat's "The Best Movies of All Time Map" [15] (see Figure 5) is typical of a kind of metaphorical metro maps that show what I would call "set systems". The stations represent 250 movies arranged into different sets (genres): each genre is represented by a metro line, which passes through the stations (movies) that are members of the genre. The order of stations along a line is arbitrary: the links are not part of the data to be visualised; thus, it is a station-based network. When a movie belongs to more than one genre, the corresponding station is an interchange station on each of the corresponding lines. Given the nature of the map, one may wonder if the connections are complete though: can the question, whether a particular movie belongs to a certain genre, always be answered with a clear yes or no? Can a movie belong to a genre just a little bit, so that its station would have to lie on the line just a little bit?

What questions can we answer with this map? The map does not seem to be suitable for questions about a particular movie, such as when it was released. That information is actually on the map, but there does not seem to be any recognisable concepts of location and distance or meaningful line organisation in this map. This implies that, given any movie I know well, I would have an idea on what line(s) to look for it, but not where along that line. Can we answer meaningful questions about the relations between movies? The metro map metaphor suggests that the simplest relation between *American Beauty* (1999) and *The Lion King* (1994) is that *American Beauty* is dark or weird drama (line 12), like *Fight Club* (1999), which seems related by romance in the fifth degree (five stops on line 2 "romance") to *Wall-E* (2008), which is also animated, like *The Lion King* (1994). This is hard to interpret in a meaningful way. Instead, the map seems to answer questions about genres. For any combination of genres, we can ask what movies are in that combination of genres, and we find the answer by finding the places on the map where the corresponding lines intersect. Given, however, that no movie is in more than two genres (if we do not count "Universally Acclaimed Masterpieces" as a genre), one wonders if this information could not have been presented in an easier way. A key property of a map is that spatial organisation is used to convey information, but in the movie map, the spatial organisation does not help in finding information.

Could this map have been drawn differently to communicate the information it contains more effectively and to put spatial organisation to good use? We could try to put the movies on a time scale, with lines going clockwise around a "centre" point at the bottom of the page, each decade of movies covering between half an hour and an hour on the clock. In periods in which a genre spawns many movies, we may try to put them far from the centre point, where more movies fit in a decade's sector; in periods where a genre spawns few movies, we may try to put them at the bottom. Thus, we would see which genres are highly active in what eras, and the map becomes a more interesting landscape to explore (but at the expense of more crossings).

In contrast to the above, we consider the *Routes Through Brexit* maps by Maxwell Roberts [11] (see Figure 6 for an example). On each of these maps, each station represents an "issue" that belongs to an economical sector *and* to a policy sphere (international standards, EU rules, opportunities, people, or trade). Thus, we have a combination of two set systems. The Brexit maps use the spatial organisation to advantage here: the spatial organisation encodes the policy spheres, while the network organisation encodes economical sectors.

VII. Implications for Design Guidelines and Optimisation Criteria

In Section VI we have seen that metaphorical metro maps often differ substantially from real metro maps, due to:

- *fuzzy stations:* sometimes, one cannot decide with certainty to which line(s) a station should belong, or one can only determine approximately where a station should be placed on a line;

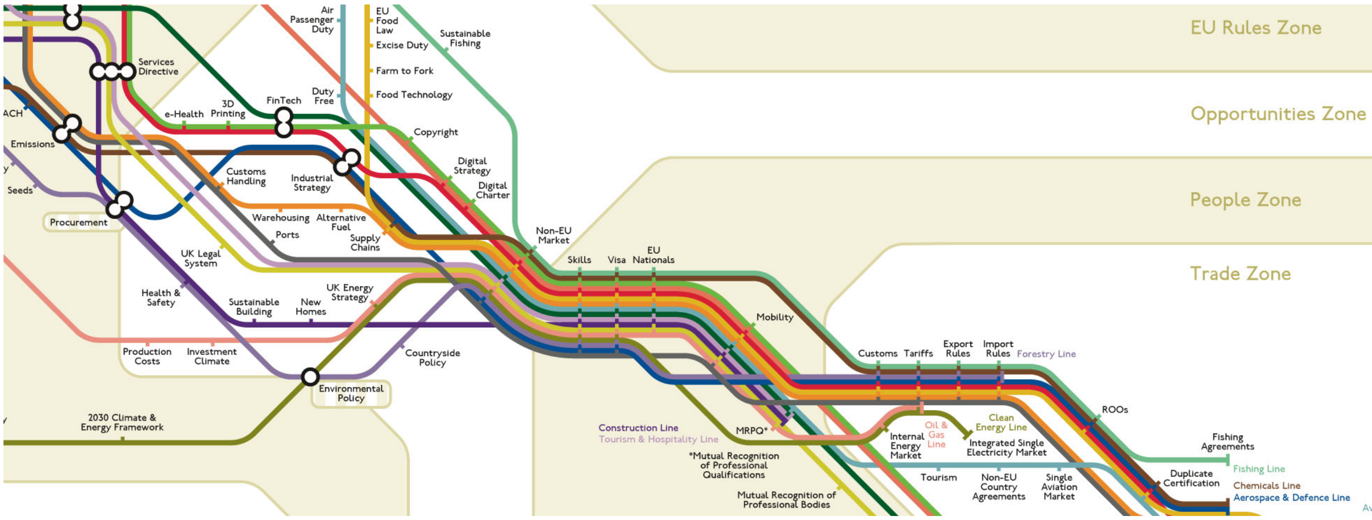

Fig. 6. An excerpt from a map by De Groot and Roberts [11].

TABLE I
KEY PROPERTIES OF MAPS DISCUSSED IN SECTION VI.

	London tube (TfL)	Roman roads (Trubetskoy)	US highways (Booth)	Greek crisis (Shahaf+)	Modern science (Jago)	Menstrual cycle (Makieva+)	Project plan (Burkhard+)	Hypermedia (Sandvad+)	Curriculum (Nesbitt)	Curriculum (Gonzales)	Plant disease (Wahabzada+)	Movies (Honnorat)	Brexit (Roberts)
size													
stations (total)	300	250	700	15	500	120	30	50	30	25	?	250	150
interchange stations	100	75	600	3	100	15	25	2	—	15	3	40	50
lines	17	50	100	4	12	7	10	9	4	6	4	20	17
zones	10	—	—	—	5	—	2	—	—	—	—	—	5
content													
explicit network	●	—	—	●	●	●	●	●	●	●	—	●	●
meaningful location	●	●	●	○	○	—	○	○	○	—	●	—	—
meaningful lines	●	○	○	●	●	○	●	●	●	●	●	●	●
meaningful order	●	●	●	●	○	●	●	●	●	?	●	—	—
undirected links	●	●	●	—	—	—	—	—	—	?	—	●	●
certain and complete	●	○	●	—	—	○	●	?	●	●	○	●	—
non-trivial connectivity	●	●	●	●	●	●	●	○	—	●	○	●	●
purpose													
get and keep attention	●	●	●	—	●	○	●	●	●	●	—	●	●
coordinate individuals	—	—	—	—	—	●	●	—	●	●	—	—	●
present overview	○	●	●	●	—	●	●	●	●	●	●	—	●
support exploration	—	●	●	●	●	●	●	●	●	●	—	●	●
detail on demand	●	●	●	●	—	●	●	—	●	●	?	—	?
look-up of facts	●	○	○	●	—	●	●	●	●	●	●	●	—
suggest/compare actions:	●	—	—	●	—	●	?	●	●	●	?	?	?
● finding routes?	●			○		○	?	—	●	●			
● of low complexity?	●			○		?	—	—	—	—			
● of short length?	●			○		?	—	—	?	?			
learning and recall	●	?	?	●	?	●	●	?	?	?	●	?	?
focus attention	●	?	?	●	?	●	●	●	●	●	●	?	●
different perspectives	—	—	—	●	—	—	—	—	—	—	—	—	—
increase credibility	●	—	—	—	—	—	●	—	●	●	—	●	●
audience													
laypersons (no domain experts)	●	●	●	●	●	—	●	●	●	●	—	●	?
highly-educated	—	○	—	—	○	●	●	—	●	●	●	—	●
urban	○	?	?	—	?	—	?	?	?	?	—	?	?

The numbers of stations, interchanges and lines are approximate.

- ● applies
- ○ partially applies
- — (probably) does not apply

Purpose and audience are speculative, sometimes highly so. My aim was not to uncover the authors' true intentions with certainty. Rather, I tried to decide by the looks, the contents and the accompanying commentary of the maps what they could be suitable or intended for—in order to collect use cases, even if they may be speculative, as a starting point for our discussion. The reader is invited to question the bullets in this table and consider what implications this may have for an optimal map design.

- *nonsensical interchanges:* often, routes between stations that require a change of lines are not meaningful;
- *meaningful parallel links:* in schedule maps, there may be a need to add meaning to how links are drawn;
- *directed cycles:* sometimes, all links are directed and they form cycles;
- *meaningful link lengths:* sometimes, it is the actual length, not the number of stops and interchanges on a route that matters;
- *meaningful long connections:* sometimes, it it the longest routes, rather than the shortest, that are most important.
- *free spatial organisation and line organisation:* in many cases, stations do not have meaningful locations, so the spatial organisation and line organisation is entirely up to the designer of the map;
- *one-dimensional location:* in some cases, stations have meaningful one-dimensional locations (e.g. time stamps);

In this section, we will discuss challenges for manual and automatic map design that arise from these differences.

A. Fuzzy stations and nonsensical interchanges

If we cannot answer with an absolute "yes" or "no" to the question whether a station belongs to a particular line, or if it is questionable whether routes that require a change of lines are meaningful, then this takes the heart out of the metro map metaphor. Rather than presenting the network as a metro map, we may seek to develop a different solution for such maps. Such a solution may still be based on a schematic network drawing, but with a different graphical language. Thus we may avoid the confusion that could arise from trying to interpret metro-map-style stop and interchange symbols.

In particular, we may want to put the "stations" next to the "lines" instead of on the lines. A station's proximity to a curve (a "line") that represents a particular category can express how much the entity represented by that station belongs to that category. Since the lines do not pass through the stations, there are no interchange stations, thus eliminating confusion about their semantics. Stations that belong to more than one line are placed between those lines, in a spot where the lines run close to each other (possibly near an intersection).

This approach could be compared to a map in which we do not use lines at all, but rather subdivide the drawing area into connected regions, and place all points that belong to a particular group in the corresponding region. The limitation of this common approach would be that a planar map with n regions has at most $5n$ different border regions in which stations can be placed that belong to two or more regions. Using a network of curves instead of a subdivision into connected regions, we can create in-between areas for *all* possible combinations of multiple categories to which we want to assign stations. Algorithms to draw such maps might start from a metro map representation [17] and then move the stations off the lines. However, it is not clear whether we would realise the full potential like that.

Challenge 1: Develop and evaluate maps with off-line stations for set systems. Investigate if they can be derived effectively from metro map representations, or develop a "native" algorithmic solution.

B. Meaningful parallel links

In metaphorical metro maps that represent schedules [3], [32], there may be a need to represent (i) milestones, that is, the deadlines of tasks; (ii) the period during which participants work on the tasks. As discussed in Section VI-B2, it may be useful to represent the latter by lines running in parallel. This could be realised by making the start of the task a station too, so that on every line that represents an actor involved in that task, there is a link from the start-of-task station to the end-of-task station (the start-of-task station could be omitted from the drawing.) To be interpreted correctly, such a solution would require a drawing in which links are strictly *prevented* from running in parallel immediately next to each other if they do *not* represent a common task. This can be a challenge for, for example, octilinear drawing styles, in which stations can have incoming lines from only three directions. It might help to draw intersection stations larger to create room to separate incoming links.

Challenge 2: Adapt schematization algorithms so that, as a hard constraint, links are prevented from running in parallel over any distance unless they connect the same two stations.

C. Directed cycles

The map by Makieva et al. [23] consists of directed links, resulting in a number of cycles. It is difficult to see the direction of the cycles in an instant. Could we draw the network such that all cycles run in clockwise direction around a central point? Alternatively, there could be multiple centre points, around some of which cycles run in clockwise direction, whereas around the other centre points, cycles run counterclockwise. Such solutions may go at the expense of introducing crossings that would not be necessary otherwise. This would raise questions such as: given a maximum number of crossings, how many centre points do we need?

Challenge 3: Define a measure of the *cycle complexity* of a drawing of a directed graph, verify that it is correlated with the readability of the drawing, and design an algorithm to draw a directed graph such that the cycle complexity is minimised.

D. Meaningful link lengths

In the road maps, the focus is not on paths that are shortest or simplest with respect to the number of stops or line changes. If one would want to use such maps for navigation, the focus would have to be on connections that are shortest according to their actual length in the real world. How could we make sure that those connections also look shortest on the map?

Challenge 4: Design a practical way to schematise a network such that for any pair of stations, the shortest connection between them according to the map is guaranteed to be the shortest connection between them in reality [2].

Even with a solution to this challenge, the map might still be unusable for determining shortest routes, because the schematised look of it will tell users not to trust the distances on the map. This leads us to the following paradoxical challenge:

Challenge 5: Design a schematised style that looks realistic and convinces users to trust shortest routes on the map.

E. Meaningful long connections

In maps showing a schedule of tasks that depend on each other, there is particular significance to *critical paths*: the *longest* routes from one station to another, measured by the total duration of the tasks on the way. These routes represent the sequences of tasks that are critical in the sense that any delay in such a sequence can delay the completion of the whole project. A map designer may want to consider drawing attention to such long routes by making them more conspicuous than short routes—maybe even making sure that long routes look crowded relative to short routes. This might be achieved by doing something paradoxical:

Challenge 6: Design a map schematization style and algorithm that makes long routes as straight as possible, while making short routes bend and swerve.

The challenge includes how to turn the general idea into an algorithmically usable optimitisation criterion, and how to design algorithms that optimise the map accordingly.

F. Free spatial organisation and line organisation

If the spatial organisation and line organisation is entirely up to the map designer, then this has profound consequences.

a) Look-up by location is impossible: A priori, there is no hint as to where a station could be on the map. There does not seem to be a way around this, other than adding an index.

b) Potential for misinterpretation of distances: If line organisation is arbitrary because there is no concept of distance, then this may result in unwanted biases. For example, consider a map showing bands or artists, on which each line corresponds to a musical style, and a line passes through (consists of) all bands whose music fits in a particular style (Shahaf et al. [31] show an example of such a map by Alberto Antoniazzi). Although the map could correctly show the available data, it might wrongly suggest that the ordering of stations along a line is meaningful, as it is for true metro maps. Even if map users would be aware of this and would be able to suppress any tendency to infer meaning from the ordering of stations along a line, the map maker would have to choose in what order to put stations along the line. Thus, the map maker chooses for which pairs of bands it is easy to see that their work is similar and for which pairs of bands it is hard. That is undesirable and may call for creative solutions to mitigate such effects. For example, would it be better to use circle lines, so that we do not have to select two arbitrary stations as terminal stations? Or would it be better to use lines with several branches or shortcuts to make the distances between stations on a line more uniform?

How would such solutions affect readability then? To make lines visually easy to track, Jacobsen et al. [17] explicitly strive to make lines *monotone*, that is, ideally the drawing of a line has a simple path structure (no branching) and always goes forward in the projection on the straight geometric line that connects its terminal stations. Naturally, this might push the terminal stations far apart, as compared to a line that twists its way around in a small part of the map.

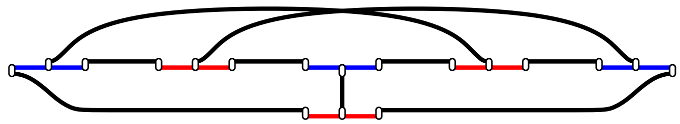

Fig. 7. 18 stations on 15 lines; each station is on two lines. The lines cannot be drawn such that they meet or cross only in the stations. The construction is based on $K_{3,3}$: a graph with three blue nodes and three red nodes, with a connection between every pair of a blue node and a red node. It is known that at least one crossing is necessary to draw these connections.

Challenge 7: How can we draw metaphorical metro maps for set systems such that we reduce biases introduced by arbitrary map layout decisions, and still get a readable map?

This is a question of modelling and balancing conflicting requirements which may need user studies to answer; the work by Wallinger et al. [36], which compares several set visualisation styles, may serve as a starting point. One might say that the elephant in the room is that metaphorical metro maps are far from ideal as a visualisation method of set systems. But alternative solutions for set system visualisation, such as Venn and Euler diagrams, only work for very simple set systems. For more complex set systems, metaphorical metro maps may still be a good starting point, whose shortcomings we should try to identify and then work around. Special attention may be given to systems such as the one in Jago's map of scientists, where the ordering of stations along a line is meaningful on a coarse scale, whereas the ordering is rather arbitrary and possibly subject to unintended bias on a small scale.

c) A bigger need, and more opportunities, for crossing minimisation: The main type of question that a set system map answers is: for any combination of lines (categories), tell me what stations are shared by that combination of lines. So we will look on the map for the places where those lines meet or cross. Any crossing of those lines on which there is no station, may constitute a false positive for our visual system—it would surely be good to avoid these if we can, and it is among the optimisation criteria underlying the design of the algorithm for metro-map style set system visualisations from Jacobsen et al. [17]. Indeed, meaningless crossings in Honnorat's movie map make it harder to spot the intersections that matter.

However, avoiding meaningless crossings is not always possible, even if no station is on more than two lines. Ehrlich et al. [6] show that there is a graph G with 15 nodes (which may represent "metro" lines), each of which is a neighbour of only two or three other nodes (lines), that cannot be realised as the intersection graph of "pseudosegments" (curves that do not cross themselves and that do not cross each other more than once). That means that we cannot draw these metro lines such that they cross only their neighbours in G and no other lines: at least one meaningless crossing must be drawn (see Figure 7). However, most metaphorical metro maps seem to have fewer than 15 lines. Could it be that, in practice, avoiding meaningless crossings altogether is usually possible?

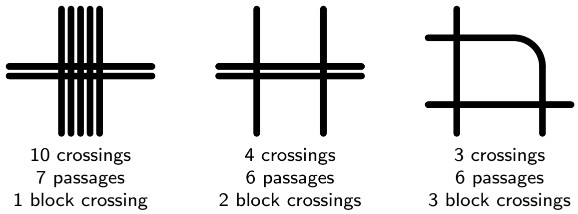

Fig. 8. Which figure has the smallest crossing complexity?

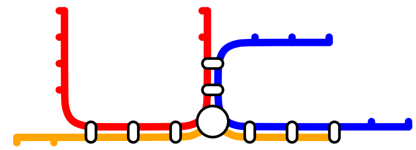

Fig. 9. Conjointness: all stations that are on both the red and the orange lines are consecutive along both the red line and the orange line; all stations that are on both the red and the blue line are consecutive along both lines; all stations that are on both the blue and the orange line are consecutive along both lines; all stations that are on all three lines are consecutive along all three lines (trivially so, because there is only one such station).

Challenge 8: Are there intersection graphs with fewer than 15 nodes that cannot be realised as the intersection graph of pseudosegments in the plane?

In a standard metro map it is almost fixed which lines really cross each other and where. To minimise the number of crossings, one can do little more than deciding the transversal ordering of lines on shared links (a difficult optimisation problem by itself). With full freedom in where to place the stations, and maybe even in how to connect the stations of a line up by links, there is much more room for optimisation. In that case, one needs to consider carefully what types of crossings are allowed, and how crossings are counted.

Suppose a bundle of k lines crosses a bundle of m lines, forming a so-called *block crossing* [5] or *bundled crossing* [4]. Following the standard definition in the graph theory literature, this would constitute $k \cdot m$ crossings, but arguably this number overestimates the visual complexity of a block crossing as compared to $k \cdot m$ separate crossings sprinkled across the map without much recognisable structure. Therefore, some authors [4], [5] have studied settings in which a block crossing is counted as a single crossing. Arguably this underestimates the visual complexity: when our goal is to optimise the number of crossings in a map, then, if we can choose between a single crossing of one line with one other line, or a block crossing of two lines with two lines, we would rather choose the first. Therefore, I would propose to count a block or bundled crossing by the number of lines involved. Put differently, I propose to define a *passage* as an ordered pair of a line and a bundle that crosses it. An ordinary crossing of two lines now counts for two passages (each line takes on the role of the bundle once), and a block crossing counts for $k + m$ passages; see Figure 8 for an example.

Challenge 9: Investigate the effects of counting passages instead of elementary or bundled crossings: find examples for which the optimal drawings differ under these criteria, and identify which drawings are better. What is the computational complexity of finding a minimum-passages drawing?

d) A need for conjointness: Meaningless intersections are not all that matters. Jacobsen et al. [17] argue that it is also important to avoid distributed intersections. Ideally, for any particular subset of lines, the network that consists of all stations and all links that are shared by that combination of lines is connected. They call this *conjointness*; see Figure 9 for an example. Note the annoying implications if conjointness is violated: a map user, after finding one region on the map where those lines meet, could not be sure to have found all stations that are shared by those lines, and would still have to continue searching the rest of the map. Unfortunately, there are small networks with as few as 4 lines and 15 stations where conjointness must be violated by any drawing in which lines do not branch. If we allow lines to have a tree structure (not to be confused with a *tree support* [19], in which *all* links form a tree), then we can ensure conjointness for larger networks, but how much larger? Would the flexibility of trees outweigh their disadvantages?

Challenge 10: What is the smallest set system, if any, that cannot be drawn without violations of conjointness if lines are restricted to have a tree structure?

e) A bigger need, and more opportunities, for recognisable shapes: Without any a-priori concept of location, if the map is to serve as a spatial framework to support learning and recall, it is entirely up to the map designer to give lines memorisable shapes. To this end, one may want to adapt drawing algorithms so that they take non-local optimisation criteria into account. For example, if a line has many bends in total, one more bend may not matter so much—it is going to be the bendy line in any case. In contrast, if a line does not have any bends, one more bend matters a lot, since it is going to make the difference between a conspicuous, memorisable entirely straight line and a less conspicuous rather ordinary line. This might be just one concrete example of what could contribute to a map's coherence and harmony as defined by Roberts [28].

Challenge 11: Design mathematically well-defined criteria whose optimisation improves non-local map properties of coherence, harmony and recognisability.

f) A bigger need, and more opportunities, for different versions of a map: With full freedom of spatial organisation, the same network can de drawn in many ways, each of them drawing attention to different properties of the network. Compare, for example, the many possible drawings of the Peterson graph [37], the McGee graph or the Heawood graph. The drawing that happens to be slightly better than its competitors with respect to some selection of optimisation criteria, is not necessarily the one and only best drawing. If one chooses a good drawing arbitrarily, arbitrary interesting properties of the network may show and arbitrary interesting properties of the network may remain hidden. To get a complete picture of the network, we may need to look at different drawings with radically different spatial organisation.

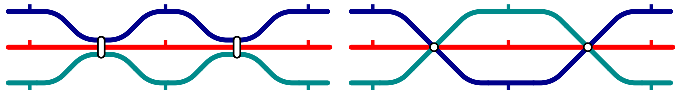

Fig. 10. Which design is better: the one on the left or the one on the right?

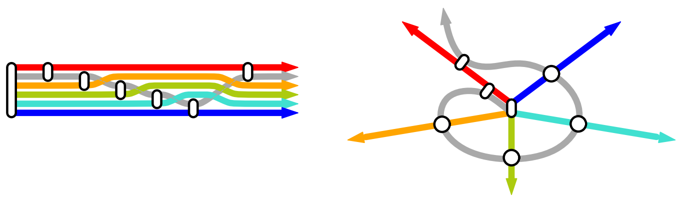

Fig. 11. The grey line must meet the red, orange, green, turquoise, blue, and red lines in that order. On the left: linear spatial organisation with six crossings. On the right: radial spatial organisation with four crossings.

Challenge 12: Design algorithms to draw schematised networks with free spatial and line organisation, that are good by standard criteria *and* sufficiently different from prior drawings.

G. One-dimensional location

We have seen several maps where stations have a location on a time scale. The line organisation of such maps follows the chronological ordering. The spatial organisation is *linear* (lines run from left to right) or *radial* (lines go outward from the centre). In a weak version of this spatial organisation, we require that each line conforms to this pattern; in a strict version, we require that *all* stations are ordered chronologically in this way, not only on a per-line basis.

For optimal readability of the map, our goal would probably be to minimise the number of crossings, although this may be disputable: it may go at the expense of a substantial increase in the number of bends—see Figure 10. So before taking to designing algorithms, more work may be needed to decide how to balance different design guidelines in this context.

Challenge 13: Find out how to best model and balance the objectives line crossing minimisation, vertex crossing minimisation (crossings under station markers [7]), and bend minimisation for optimal readability of maps with meaningful one-dimensional location.

For a strictly linear spatial organisation, there is substantial work on the more general problem of crossing minimisation for *storyline visualisation* [5], [10], [20] already. In contrast, a weakly linear spatial organisation provides more freedom to avoid crossings by moving stations on different lines relative to each other. A radial spatial organisation provides more freedom to avoid crossings because a line may cross the other lines to reach a new position in the ordering around the centre point in two ways: it may cross over to its new position in clockwise direction, or in counterclockwise direction (see Figure 11).

Challenge 14: Design algorithms to minimise the number of passages (see Section VII-F) in storyline visualisation with strictly/weakly linear/radial spatial organisation.

Note that for some types of maps, it may be desirable that lines can branch, so that a single actor can be involved in more than one task or event at once. Branching could also be used as a means to reduce crossings. Di Giacomo et al. [12] study branching storyline visualisation in which each line has a tree structure, rooted on the left; branches split off as one reads from left to right. Alternatively, one could adopt a model in which branches that split off must also rejoin the main branch again, thus avoiding dead ends (which could be misinterpreted as the end of the line) but possibly at the expense of introducing more crossings.

Challenge 15: Design algorithms to minimise the number of passages in storyline visualisation with (strictly?) linear spatial organisation, in which lines may branch, but must rejoin.

VIII. Recommendations

A. A checklist for metaphorical metro map design

A metaphorical metro map is an easy target for ridicule. It does not map a true metro system. Therefore, as with any metaphor (or any map, for that matter), there is always some aspect in which it is "wrong". But that does not mean the map is useless. It makes sense to check explicitly in what aspects the use case for a metaphorical metro map matches the case of mapping a metro system, and in what aspects it does not. As we have seen above, the answers may point us to opportunities to improve the map. The following is a proposal for a checklist to follow if one plans to create a metaphorical metro map.

1. Decide on the purpose of the map. Formulate examples of questions that users should be able to answer with the map, or of facts that users should be able to discover using the map.
2. Decide if there is no easier visualization.
3. Define meaningful lines and meaningful order of stations along the lines. If either of these is missing, the map may communicate incorrect ideas or biases (Section VII): consider avoiding the typical graphical language of metro maps.
4. Find, or try hard to find, a meaningful concept of location so that the network preserves distance, and that may guide the spatial organisation and help users locate things on the map.
5. Check what makes the metaphorical metro map different from true metro maps (see Section V) and what implications this has for design guidelines (Section VII).
6. Define exactly what data (stations) are going to be on the map. True metro maps are complete and authoritative for their region, and so must be the metaphorical map: users should understand the criteria by which stations have been included.
7. Design the map.

B. Possible directions for further work

Metaphorical metro maps can be a powerful tool to visualise a network, or a confusing tool. In this paper I tried to shed some light on how to identify the strengths, the weaknesses and the design challenges for metaphorical metro maps. To put this into context, it would be good to complement this work with 1) a survey of the work that comes before: how do we construct a mappable network from sometimes massive data; how do we choose a network organisation (assignment of stations and links to lines) if it is not given; and 2) what happens afterwards: how do people experience, interpret and use metaphorical metro maps? As far as the current literature evaluates this, it often evaluates the question: do people say they like the metaphorical metro map as compared to having no map at all? (e.g. [3], [24], [29], [31], with [36] as a notable exception). From the perspective of identifying good practices for map design, however, we should answer the question: when are schematised network drawings the best possible map? And what is the effect of a map that looks like a metro map as compared to a map with roughly the same layout but without the typical graphical symbols of a metro map?

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