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Octilinear Force-Directed Layout with Mental Map Preservation for Schematic Diagrams

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Abstract. We present an algorithm for automatically laying out metro map style schematics using a force-directed approach, where we use a localized version of the standard spring embedder forces combined with an octilinear magnetic force. The two types of forces used during layout are naturally conflicting, and the existing method of simply combining these to generate a resultant force does not give satisfactory results. Hence we vary the forces, emphasizing the standard forces in the beginning to produce a well distributed graph, with the octilinear forces becoming prevalent at the end of the layout, to ensure that the key requirement of line angles at intervals of 45° is obtained. Our method is considerably faster than the more commonly used search-based approaches, and we believe the results are superior to the previous force-directed approach. We have further developed this technique to address the issues of dynamic schematic layout. We use a Delaunay triangulation to construct a schematic "frame", which is used to retain relative node positions and permits full control of the level of mental map preservation. This technique is the first to combine mental map preservation techniques with the additional layout criteria of schematic diagrams. To conclude, we present the results of a study to investigate the relationship between the level of mental map preservation and the user response time and accuracy.

Keywords: Force Directed · Schematic Layout · Delaunay Triangulation · Mental Map Preservation

1 Introduction

The layout of metro maps and other schematics has been the focus of much recent research effort. The goal of these systems is to take a network diagram, for instance a public transport map, and draw the network as a schematic, so allowing the information contained in the network to be more easily analyzed. One of the key features of a schematic is octilinearity (all edges at angles which are multiples of 45°).

Much research has been undertaken to improve the readability of schematics by automated layout, such as hill-climbing [1], simulated annealing [2], linear programming [3] and path simplification [4]. Although these search-based methods can already compute layouts of a reasonable quality, a force-directed method that could produce comparable results would provide the following benefits: 1. Fast optimisation relative to search-based methods 2. This layout method has been studied in great detail from a number of perspectives and so will be able to piggyback on considerable related work in, for example, performance improvements and scalability 3. Node movements during layout can be viewed in real time as a transition animation.

Our algorithm uses modified versions of two force based techniques: a spring embedder [5] and a magnetic spring model [6] which encourages octilinearity (Section 2). At the beginning of layout only the spring embedder forces are applied and this ensures an even layout of stations. We then transition between the two force types; the octilinear forces are introduced with increasing strength as the spring embedder forces are reduced in strength. Eventually the spring embedder forces reduce to zero and only octilinear forces are present - this final stage ensures that octilinearity is enforced. We then developed a mental map preservation technique using a Delaunay triangulation to construct a proximity graph; the edges of which are modelled as springs in order to constrain node movement to a variable degree by altering spring strength (Section 3). Using this mental map preservation method, we then perform a study to test for significance between level of mental map preservation and user response time and accuracy (Section 4). Finally, Section 5 concludes.

The contribution of this paper is to: 1. Describe a force-directed metro map layout technique that has considerably improved the previous attempt for producing octilinear lines and well distributed stations; and which we believe produces results of a comparable quality to search-based methods in much less time 2. Present a new, fully tuneable, technique for mental map preservation 3. Perform a study on how mental map preservation affects diagram usability in order to augment the current understanding of this potentially useful concept. The technique has been implemented in java and is called FDOL (Force-Directed Octilinear Layout). The application, example schematic files and data from the study are available for download at `http://www.cs.kent.ac.uk/projects/fdol`.

2 Octilinear Force-Directed Layout

As is common in schematic layout, we model the schematic as a graph by treating stations as nodes and line segments between stations as edges. We do not differentiate between different lines, and multiple lines between stations are treated as a single edge. In addition, where some systems remove two degree nodes from the graph before layout [7], we keep them in the graph. This helps ensure a reasonable separation between nodes on the same line and avoids having to use individually weighted lines. The algorithm uses modified versions of two force based techniques: a spring embedder [5] and a magnetic spring model [6].

We use the geographic positions of stations to define our starting layout, as can be seen in Fig. 2a, with the entire schematic scaled to have a mean edge length equal to the length of an edge spring at equilibrium – this prevents the schematic quickly expanding/contracting in the first iteration by minimising large initial forces. The standard spring embedder has two types of force which act upon the nodes to produce the layout [5]. Standard spring embedder forces are intended to produce an aesthetically pleasing graph layout; however, these forces do nothing to ensure edges are aligned to octilinear angles. In order to achieve this, additional forces are required that will cause edges to rotate to desired angles. We use a technique similar to that explained in [6] in which equal and opposite (perpendicular to the edge) forces are applied to the nodes connected to each edge in order to rotate them around the midpoint.

Our method works by applying both force methods in each iteration, but varying the strength of each so as to perform a smooth switch from spring to rotational forces. Variables F_{spr} and F_{oct} are used as respective coefficients for this purpose and are varied throughout the layout process as shown in Fig. 1. At the start only spring embedder forces are applied (S_1) - this stage runs until the energy level of the schematic falls below a set threshold; then there is a switchover in S_2 until only octilinear forces are applied (S_3). The switchover of force types in S_2 is required to allow the octilinear force to have a gradually increasing effect whilst the spring embedder forces still ensure a well distributed layout. If the two force types are applied one after the other, with no switchover period, the octilinearity stage would rotate edges without consideration for features that the spring embedder forces prevent (such as node-node occlusions and preservation of edge lengths). This final stage of layout without any spring embedder forces is necessary in order to achieve the highest possible compliance with the octilinearity criterion. We then perform a post-processing step to straighten periphery line sections. A schematic showing examples of these steps is shown in Figure 2.

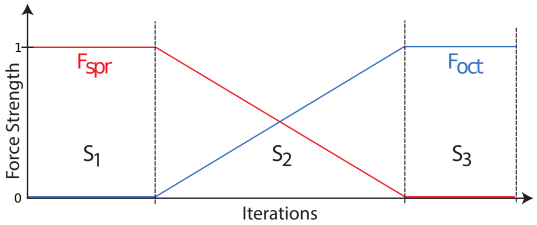
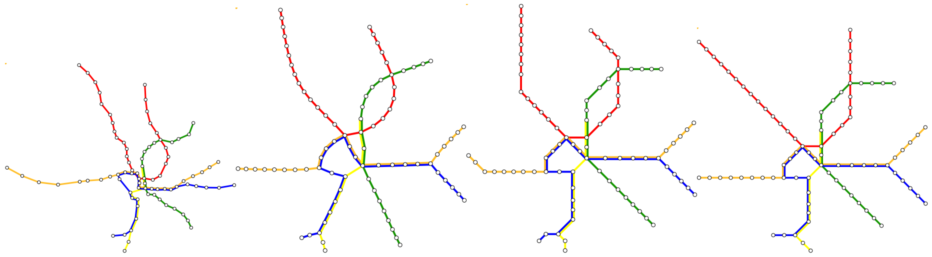


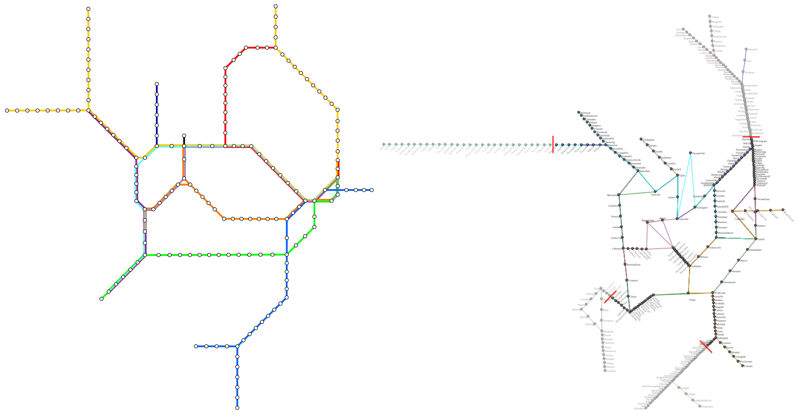
Fig. 1: The application of forces over method duration.



(a) Geographic **(b)** End of S_1 **(c)** End of S_2 **(d)** After post-proc.

Fig. 2: Washington metro map at key stages throughout the layout method.

On a range of ten real-world metro maps, our method achieved a layout speedup factor in the range of 2.23 to 27.67 times ($\bar{x} = 10.12$, $\sigma = 8.3$) that of our hill-climbing technique; the speedup factor for Sydney was 20.08 times, with an optimisation time of 0.59s against 11.85s. We have included for comparison images of the Sydney schematic as laid out using our force-directed method (Fig. 3a) and the previous force-directed method by Hong et al. [7] (Fig. 3b). Sydney optimisations using alternate methods can be seen in [3][1][8]. Our method, Fig. 3a, has octilinear lines throughout and fairly even node spacing, achieving our main design goals. The previous force-directed attempt, Fig. 3b, fails on both of these counts; moreover some odd node positioning is



(a) Our method **(b)** Hong et al. [7]

Fig. 3: Comparison of our octilinear force-directed method (3a) against the previous method by Hong et al. (3b). Note: Fig 3b contains additional stations demarcated by short perpendicular red lines and slightly faded.

evident, for instance the blue line is very jagged. We believe these problems are due to the combination of removing 2 degree nodes and because of the way the forces are combined. Each type of force will have different ideal positions for nodes to move to, and combining the two into a composite function creates lowest energy positions which fully satisfy neither. It should be noted that the previous method is drawing a network that is larger than the one we show. Although the schematic used is slightly different, in terms of layout the extra stations should not affect the quality.

3 Dynamic Layout and Mental Map Preservation

This section explains how a Delaunay triangulation is used to constrain node movement by proximity during optimisation and thus help preserve the users' mental map. A Delaunay triangulation is first constructed over the entire schematic. Figure 4 shows an example of this applied to the Vienna metro map; the underlying schematic can be made out under the thinner, red edges of the triangulation. During construction of the triangulation, four "anchor" nodes are created which surround the schematic. These anchor nodes are left in the triangulation but are not represented with nodes, and so cannot move. This has the effect of slightly anchoring the schematic to the underlying canvas, preventing effects such as rotation. The generated triangulation edges are then used during layout as a frame to hold nodes in place. Each edge is modelled as a Hookean spring, with a length at rest equal to its initial length, and a spring strength equal to a user defined value, k. This spring strength value can be varied in order to affect the level of mental map preservation; using a low k value will create weak springs, and will not hold nodes in place. In our algorithm Delaunay frame forces are calculated after the calculation of spring embedder and edge rotation forces, this is to ensure that all node movements from other forces can be counteracted by the mental map preserving frame. In order to allow the Delaunay frame forces to be used in conjunction with octilinear forces, it is required that the Delaunay frame uses a force coefficient similar to that of the standard spring embedder, which decreases over time. This force constant, F_{Del},

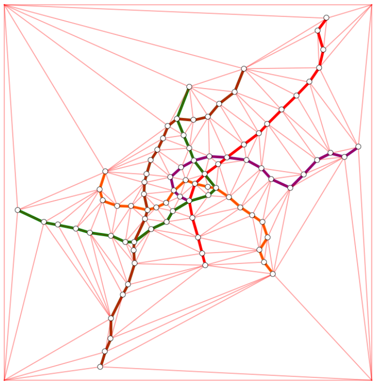
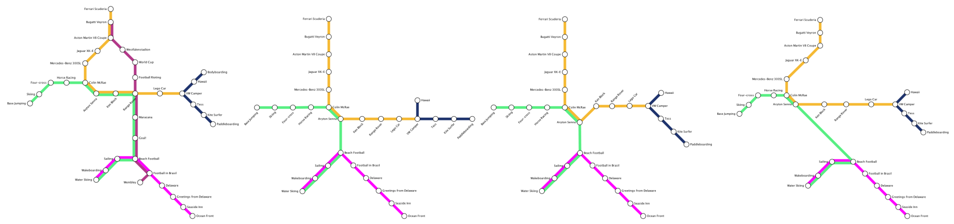


Fig. 4: Delaunay triangulation of the Vienna metro map (including triangulation frame).

mirrors the value of F_{Spr} used for the standard spring embedder. Our system provides a scalable slider from $0-100\%$ which provides a linear mapping to the average resultant mental map preservation level, measured using a similarity metric based upon the change in frame edge lengths.

4 Mental Map Preservation Study

This section describes the procedure for a study to answer our research question: “Can mental map preservation improve diagram understanding in dynamic schematic layout?”. Our hypothesis was that different levels of mental map preservation would change response time and accuracy. Previous research into the effect of mental map preservation has not shown conclusive benefit [9][10], and we hoped to augment the research in this area. We used three sizes of map as follows: Small (S) 4 lines, 28 nodes; Medium (M) 5 lines, 35 nodes; and Large (L) 6 lines, 42 nodes. There were three modification types as follows: Line addition (A) $+1$ line, $+7$ nodes; Line removal (R) -1 line, -7 nodes; Line addition and removal (A-R) $+1$ line, $+7$ nodes, -1 line, -7 nodes. These variations create nine map cases. Each map was reoptimized with three levels of mental map preservation (MMP); these are 0%, 50% and 100% preservation. We used a between-subject methodology, and therefore each subject viewed only one MMP variant. In order to help alleviate the effect of a learning curve when answering questions,



(a) Original schematic **(b)** 0% MMP **(c)** 50% MMP **(d)** 100% MMP

Fig. 5: Comparison of MMP variants used in the study. 5b-5d show the modified schematic, in which the magenta line has been removed.

the user completed five training maps. Map data was generated using the Flickr API which we used to retrieve a number of photos, represented as nodes, and their associated tags, represented by coloured lines between nodes. Nodes that shared the same tag appeared along the same line, much like LineSets [11]. Figure 5 shows an example of a diagram used in the study. There were two stages for each map: five stage one questions, followed by a map modification and a single stage two question. There were three types of stage two question (X, Y and Z) which were assigned to maps so that each type of question was asked once for each map size, and each modification type. Only stage two questions were used in the data analysis as stage one questions had the purpose of familiarising the participant with the schematic before the modification was made. Example stage two questions were as follows:

X. How many photos contain the “___” or “___” tags and not the “___” tag?
Y. What is the minimum number of tag changes required to travel between the highlighted nodes?
Z. Which tag contains the most photos?

We first performed a pilot study to identify and fix any testing issues. The main study used a total of 60 participants recruited from the University of Kent Job Centre. These participants are from across all disciplines, ranging from 16 to 34 years of age ($\bar{x} = 20.83$, $\sigma = 2.88$), 20 male and 40 female.

In terms of results, the statistical analysis techniques were performed following guidelines in [12]. In our analysis, data from questions which were answered incorrectly are also included as response time is intended to be an indication of cognitive effort required, independent of whether or not the effort resulted in a correct answer. Table 1 shows mean time and mean error against each condition. In the following tests, we used a p-value of < 0.05 to indicate significance. There were no significant differences in response time ($p = 0.207$) or error rate ($p = 0.593$) as represented by the error data according to condition under a non-parametric independent-measures Kruskal-Wallis test. These results indicate that the difference between the conditions can likely be attributed to random chance, rather than being due to the differing nature of the conditions.

Table 1: Mean response time and mean number of errors for the three mental map conditions, over all non-test maps and all post-modification questions.

	Time		Error %	
MMP	$\bar{x}$	σ	$\bar{x}$	σ
0%	19.95	4.31	14.44	13.54
50%	20.27	4.81	10.56	12.73
100%	23.96	7.07	12.78	13.13

This result provides evidence against our hypothesis, for which a possible explanation is due to multiple impacts on diagram comprehension. One impact occurs when the mental map is preserved, the layout is compromised, so making analysis of the diagram difficult because of features such as increased line bends and less effective station spacing. The alternative extreme is that the mental map is not preserved, so the diagram changes a great deal, impacting comprehension because the participant needs to re-examine parts of the diagram that were previously held in their memory. It may be that these two conflicting impacts on comprehension are broadly equal, and so it is not important which approach is taken for dynamic data. There have been a number of studies on the effect of mental map preservation on user readability, e.g. [9][10]; however, none have found conclusive evidence of any effect, supporting this view.

5 Conclusion

We have presented a force-directed method for automatically laying out schematic diagrams whilst enforcing octilinearity. Our method uses a three stage process to transition between types of forces. We have explained how a force based approach can be more beneficial than methods using an explicit target function, and demonstrated that our methodology allows us to produce superior results than those from the previous octilinear force based method. We believe our results are also of comparable quality to those produced by slower techniques that are known for producing high-quality layouts. We have also shown a new technique for the preservation of mental map between two graph states. This technique uses a Delaunay triangulation to preserve node positions relative to connected nodes. This varies from the more common approach of limiting nodes by absolute distance, and allows more node position flexibility with minimal mental map expense, such as moving clusters of nodes whilst maintaining their internal structure.

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