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The Aesthetics of Graph Visualization

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Abstract

The discipline of graph visualization produces pictorial representations of node–link structures. Much effort has been directed toward making such diagrams visually pleasing. A variety of aesthetic heuristics have been proposed, with the assumption that these will improve readability and understanding. We look at a perceptual basis for these heuristics, including Gestalt principles and Norman's emotional design framework. Next, we review the work to date on aesthetic heuristics and examine what has been done to evaluate these heuristics. We summarize this in a framework that outlines graph drawing heuristics, their perceptual basis, and evaluation status.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Line and Curve Generation

1. Introduction

Whether visualizations are designed to convey an existing idea or to support the formulation of new ideas, the key question remains "what makes a good visualization?" [HBW05]. In the field of graph drawing, a good visualization emphasizes readability and promotes understanding [Fis06]. Research in this area has led to aesthetic heuristics for drawing graphs. Recently, these efforts have expanded to empirically evaluate the effectiveness of these heuristics and to examine their basis in perceptual processing.

Except for a few special cases (e.g. visualizing websites as graphs [Vog06]), aesthetics are not applied to graph drawing in a purely artistic sense. Creating aesthetically appealing graphs is more than a quest for the beautiful – it has the practical aim of revealing underlying meaning and structure. In general, researchers associate aesthetics with readability, and readability with understanding.

Why is it difficult to create a readable graph? For small or sparsely connected graphs (i.e. graphs with few edges between the nodes), laying out a graph in a legible fashion is trivial. However, as graphs get larger and more densely connected, producing a readable layout becomes a challenge. Following the lead of Purchase [WPCM02], the difficulties can be partitioned into two major areas – syntactic (or structural) and semantic (or domain specific). Syntactic issues include avoiding occlusion with overlapping edges and nodes and preventing edges from becoming long and convoluted. Semantic issues are concerned with highlighting the important characteristics of the underlying model and are influenced by the task to be performed with this data. While syntactic issues have received the most attention, there has been some research into domain specific issues in the areas of software engineering [PCA02] and social networks [HHE05, MBK97].

In this survey, we focus on syntactic aesthetics, limiting ourselves primarily to the aesthetics of node, edge, and graph layout. The aesthetics of labeling and node drawing, such as the use of colour and shape, have received little attention and are outside the scope of this survey.

Figure 1 provides an overview of the concepts and relationships we explore, beginning with perceptual principles that apply to graph drawing. We place these principles in the context of Norman's levels of processing (visceral, behavioural, and reflective). Processing principles provide the context for a survey of graph drawing aesthetic heuristics and a discussion of heuristic evaluation in terms of performance and preference. We also discuss the influence of domain and task. We summarize our findings in a table that outlines heuristics, related perceptual principles, and references to their evaluation.

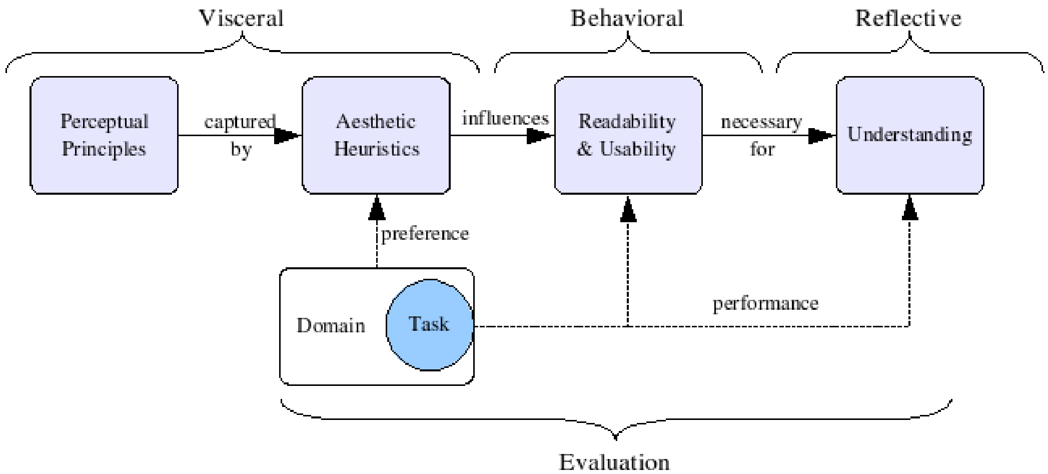

Figure 1: *Conceptual model of the factors involved in the interpretation of graph visualizations.*

2. Perception & Cognition

Node-link diagrams are simply a collection of points and lines. Involuntary and voluntary processes drive the viewer's ability to extract shapes and draw meaning from such diagrams. Norman [Nor04] groups these processes into three levels: visceral, behavioural, and reflective. The visceral level includes the basic perceptual tasks of distinguishing objects and forming our true first impressions. The behavioural level builds upon output from the perceptual level, and focuses on issues such as readability and usability. The reflective level refers to the higher levels of emotion and cognition. Originally applied to the design of everyday things, this model can help us to understand how we process and evaluate graph visualizations.

2.1. Visceral Level

At the visceral level, rapid involuntary processes group and organize information collected by our senses. Through processes such as edge detection, we perceive properties (e.g., symmetry and collinearity) [Bie87], and ultimately create objects that help us interact with our environment. There is a possible evolutionary basis for these perceptual processes inlcuding our ability to rapidly distinguish symmetrical objects [KBO03]. Further, it has been suggested that our attention is first drawn to abrupt changes, including heavier marks or brighter colours [Kos89].

Beginning in 1911, psychologists in the Gestalt school proposed generic principles that describe how humans group various stimuli based on points and lines [Kan79]. This work has been credited with identifying fundamental perceptual phenomena [KBO03]. Recently, these principles have been applied to graph visualization [WS06, WPCM02, SC05, Kos89, Fis06]. Wong and Sun [WS06] have given the most thorough treatment of Gestalt principles as they apply to graph drawing, assigning the principles to perceptual grouping and perceptual segregation categories.

Perceptual grouping principles include:

- Good figure – refers to the simplicity and stability of a figure [WS06];
- Similarity – elements with common features, such as colour or shape, appear to be grouped [WS06];
- Continuation – colinear or near colinear elements tend to be grouped [DS06];
- Proximity – elements that are closer are more likely to be grouped [DS06, WS06];
- Connectedness – physically connected elements are usually grouped [WS06]; and
- Familiarity – elements that seem familiar or meaningful are more likely to be grouped [WS06].

Perceptual segregation principles are based on the idea that objects (or figure) can be differentiated from the background (or ground). Also, objects are more memorable than the background [WS06]. These principles include:

- Symmetry – areas demonstrating symmetry tend to be seen as a distinct figure [WS06];
- Orientation – horizontal and vertical orientations are more likely to be seen as a figure [WS06]; and
- Contour – boundary edges and contours assist in figure-ground perception [WS06, KBO03].

Perceptual principles can be applied to graph drawing through the use of aesthetic heuristics. As House et al. state, "perception provides a sensible order to what we see, and aesthetics govern our receptiveness to our perceptions" [HBW05]. E.g., proximity is applied in heuristics that minimize the distance between related nodes. These heuristics are syntactic. Semantic heuristics are not applicable at this level because these require an understanding of the meaning behind the graph that only comes with further cognition. In Section 5 we map the perceptual principles introduced above to the aesthetic heuristics described below.

2.2. Behavioural Level

The result of perceptual organization at the visceral level leads to behavioural level processing. In this level, reactions are still largely subconscious and focus on responses to features such as usability, function, and performance [Nor04]. Research in graph visualization has often focused on processes that occur at this level because the fundamental requirement of any graph is that it should be readable [Fis06]. Graph visualization researchers often equate aesthetics with readability. Support for this belief can be found in Norman's assertion that attractive things work better, and that our initial visceral reactions can influence our behavioural reactions. This means that aesthetics affect our receptiveness to viewing something further or making the effort to understand it. Palmer [LP91] puts this simply when he asserts that people can better remember "good" figures.

2.3. Reflective Level

In contrast to the previous levels, the reflective level involves conscious thought. Within this level, a person tries to find meaning and understanding from the results of earlier processing. The reflective level is highly influenced by a person's environment – culture, experience, education, et cetera [Nor04]. In light of these influences, it is not surprising that directly linking understanding to underlying aesthetics is difficult. Graph visualization researchers have tried to do this by measuring the effect of syntactic heuristics on performance with inconsistent results (see Section 4.1).

In contrast to syntactic heuristics, semantic heuristics are directly linked to understanding, because the meaning of the data influences the graph's layout. Little work has been done on proposing and evaluating such heuristics, but initial research [PMCC01] indicates that these heuristics may have equal or greater importance when creating easily understood graphs.

3. Survey of Graph Visualization Heuristics

Aesthetic heuristics for graph visualization can be divided into those for node placement, edge placement, graph layout, and domain-specific heuristics. Note that these heuristics may conflict with each other and balancing their simultaneous use involves a tradeoff based on the semantics of the graph and its intended use.

3.1. Node Placement Heuristics

From a purely aesthetic viewpoint, an even distribution of nodes throughout a graph gives a more regular appearance and increases visual appeal. It is important to *distribute nodes evenly* [Har98, DH96, TR05, TBB88]. Unless nested, *nodes should not overlap*, and there should be a minimum distance between nodes [WS79]. A heuristic with a semantic basis is that of *clustering related nodes* [TR05, TBB88]. This heuristic is in conflict with the requirement to distribute nodes evenly. To accommodate both these heuristics when clustering nodes, the distance between nodes in a cluster should be equal, and the number of different distance levels between nodes should be minimized.

Davidson and Harel [DH96] presented the heuristic of *keeping nodes from coming too close to edges* to avoid visual elements becoming clustered together, which may lead to misinterpretations of graph structure. A more general approach to enforcing separation is to *maximize node orthogonality* [Pur02], fitting nodes to an imaginary two dimensional grid of points.

3.2. Edge Placement Heuristics

By far the most agreed-upon edge placement heuristic is to *minimize the number of edge crossings* in a graph [BMRW98, Har98, DH96, Pur02, TR05, TBB88]. The importance of avoiding edge crossings has also been extensively validated in terms of user preference and performance (see Section 4). Similarly, based on perceptual principles, it is beneficial to *minimize the number of edge bends* within a graph [Pur02, TR05, TBB88]. Edge bends make edges more difficult to follow because an edge with a sharp bend is more likely to be perceived as two separate objects. This leads to the heuristic of *keeping edge bends uniform* with respect to the bend's position on the edge and its angle [TR05]. If an edge must be bent to satisfy other aesthetic criteria, the angle of the bend should be as little as possible, and the bend placement should evenly divide the edge.

When considering the length of edges, *edge length should be minimized* to reduce the area of the graph and an attempt made to *minimize the maximum edge length* [Har98, TR05, TBB88]. Both of these heuristics contribute to *generating uniform edge lengths* [BMRW98, DH96, TR05] to produce a graph with greater regularity.

Edges connected to a node, especially one with high degree, should be spaced at even angles around the node; one should *maximize minimum edge angles* between all edges of a node [CT03, Pur02, TR05]. This may have the side effect of placing nodes of high degree, which are likely to be important nodes, closer to the center of the graph. Tamassia et al. [TBB88] listed the goal of placing important nodes near the center as a constraint on aesthetic guidelines. We classify this as a semantic heuristic that may have to be balanced against competing structural heuristics.

Similar to the related node placement metric, Purchase claimed that edges and edge segments should be placed to match the lines of an imaginary cartesian grid [Pur02]. This arrangement, *maximizing edge orthogonality*, reduces edge crossings and maximizes the angles between nodes, as discussed above.

3.3. Overall Layout Heuristics

Along with the spatial relationships between nodes and edges, the overall layout of the graph is an important aesthetic factor. Symmetry, area, flow, and aspect ratio determine the overall aesthetics of the graph. *Maximizing global symmetry* and *maximizing local symmetry of subgraphs* [BMRW98, Pur02, TR05, TBB88] are the most widely studies heuristics. When drawing trees, the centering parents in a hierarchy achieves local symmetry and thus does not warrant the separate consideration given in previous work.

Heuristics that address node separation and edge length may have the side effect of *minimizing total graph area* [TR05, TBB88] while still retaining readability. In addition, Taylor and Rodgers [TR05] asserted that the *aspect ratio of the overall graph shape* should match that of its container (e.g., a screen, page, or containing node). This minimizes the number of distinct shapes in the layout, reducing visual complexity.

Tammasia described the metric of *maximizing convex faces* [TR05] – a goal which is possible to achieve for any three-connected planar graph, while other graphs may only achieve partial compliance. Specific to directed graphs, and in line with the overall goal of maximizing consistency within a graph, Purchase introduced the metric of *ensuring a consistent overall flow direction* [Pur02].

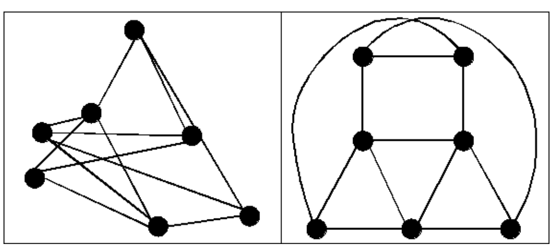

Figure 2: *The effect of applying aesthetic heuristics.*

Figure 2 shows the effect of applying aesthetic heuristics during graph layout. The graph on the left exhibits problems of node and edge layout including edge crossings, random node layout, irregular edge length, occlusion, and small angles between incident edges. In the corrected graph, edge crossings have been eliminated and most edges are of equal length. Nodes are also laid out in an orthogonal manner, incident edges are spaced more evenly, and the graph shows global symmetry. Note that removing edge crossings requires a compromise in edge length and edge bending.

3.4. Domain Specific Heuristics

Some heuristics apply to specific domains (e.g., heuristics for drawing software engineering UML diagrams or social network diagrams). As will be discussed in Section 4, using underlying model and task information can produce layouts that go beyond what is possible using general graph heuristics [PMCC01, HHE05] .While such semantic heuristics are oustide the scope of this survey, many proposed domain specific heuristics can be generalized to one of the heuristics described above. For example, Eichelberger [Eic03] proposed heuristics to improve the aesthetics and readability of UML diagrams. The majority of these, such as those dealing with edge crossings, graph width, and node orthogonality, are covered by general graph drawing heuristics. When a domain-specific heuristic has no equivalent in the general heuristics, the goals for both are often still the same. For example, the heuristic of joining inheritance edges for UML diagrams [PCA02, Eic03] is not covered by one of the edge placement heuristics for general graphs. However, it has the effect of reducing visual complexity.

3.5. Beyond Graph Drawing Heuristics

Taylor and Rodgers [TR05] provided an interesting extension to the aesthetic heuristics commonly found in graph drawing. Although not the primary focus of their paper, the authors examine heuristics used in the field of graphical design and contrast these with those used in graph drawing. They claim that the heuristics for graphical design have been more extensively validated, and more attention has been paid to aesthetically pleasing layouts versus merely functional ones.

In many cases, the aesthetic heuristics for graphical design tasks encompass those designed for graph drawing, with extra consideration for more complex visual attributes. For example, the graphical design heuristic of balance includes symmetry. Balance extends symmetry to include the additional concerns of component visual weight (this being affected by colour, shape, and size).

In most papers discussing graph drawing aesthetics, little attention is paid to graphs that are more complex than simple monochrome nodes connected with lines. For graphs requiring display of several node or edge parameters, the colour, shape, and size of elements can be changed to convey these additional parameters. This suggests that the more detailed heuristics from graphical design may be valuable in improving the aesthetics of visually complex graphs.

4. Validation and Evaluation

While much of the work on graph aesthetics appears to be based on intuition, recent efforts [PCA00, WPCM02, Pur97, PCA02] have attempted to evaluate aesthetic heuristics through experiments. Ware et al. [WPCM02] based their experiments directly on theories of human perception. In a similar vein, other authors have validated heuristics by analyzing them in terms of how well they support these theories of human perception [WS06]. We look first at empirical studies. This information is also summarized in Table 1 below.

4.1. Empirical Evaluation

Purchase et al. [PCA02] proposed an evaluation framework of three components: usability measurement, the nature of the graph, and the effect under investigation. Usability can be measured by performance of a specific task or, more qualitatively, by user preference. However, as shown in Figure 1, we propose that the subjective measure of preference depends on aesthetics that influence, but do not directly control, usability. The nature of the graph can be either abstract (syntactic) or domain-specific (semantic). The effect investigated can be one or more specific aesthetic heuristics or the overall layout of a graph. This framework is quite useful when considering the studies that have been carried out to date.

One of the earliest studies in graph aesthetics dates from 1995 by Purchase et al. [PCJ97]. This was a syntactic (domain independent) experiment in which task performance was evaluated to understand the effect of minimizing edge bends, minimizing edge crossings, and improving symmetry. The authors found that minimizing bends and edge crossing improved task accuracy, while symmetry as defined did not yield significant results.

Purchase et al. [PCA02] reported on three earlier studies of aesthetic based graph layout. A 1996 study evaluated five heuristics, again using domain independent task performance on syntactic graphs. The results showed that minimizing edge length, minimizing the number of bends, and increasing symmetry improved task performance. However, maximizing the minimum edge angle or increasing orthogonality had no impact. The second study evaluated syntactic task performance for eight graph drawing algorithms. The results were inconclusive, finding little difference in performance between algorithms as a whole, although symmetry may have an impact on task performance. The final study had a domain-specific (semantic) design that determined preference for individual aesthetics in UML diagrams. A subsequent study was run to address possible confounds. Both studies suggested that task performance using UML class and collaboration diagrams could be improved by minimizing edge crossings and bends, increasing orthogonality, providing consistent information flow and horizontal text labels, reducing the width of the layout, and using consistent font type. In class diagrams, joined inheritance edges were preferred over separate ones and the use of two edge labels with directional indicators was preferred to a single relationship label. In collaboration diagrams, placing arrows on the lines was preferred to having them adjacent, which incidentally, is contrary to the UML specifications. It is clear that semantics plays a role in the relative importance of aesthetics in graph layout (e.g., the importance of orthogonality in UML diagrams compared to general graphs).

Purchase et al. [PMCC01] also examined how human comprehension is influenced by the choice of aesthetics for automatic layout of UML class diagrams. This was a syntactic, performance measuring experiment that tackles five aesthetic heuristics. Measures of aesthetics were used to rate each diagram in terms of number of edge bends, degree of orthogonality, edge length variation, node distribution, and flow. The design measured both speed and accuracy of subjects. Interestingly, this study used computer generated layouts with computed aesthetics and yielded unexpected and, at times, inconsistent results. The authors theorized that this was due to the computer's measure of aesthetics being out of alignment with a human perceptual measure. They reran the experiment with hand drawn graphs that were each pre-rated for various aesthetic measures using a separate human perception measure. They also changed the definition of symmetry to account for more subtle local symmetries rather than using an overall 'computed' symmetry. The revised experiment confirmed that minimizing edge bends is a good thing. Edge length results conflicted with previous results, and no significant results were found for symmetry, orthogonality, direction of flow, node distribution, and edge length. They concluded that these syntactic aesthetics may not be that important in support of comprehension and hypothesized that semantic issues may actually have more weight (e.g., grouping of semantically related nodes). Significantly, they warn that a 'nice' graph layout is unlikely to be sufficient for intuitive use.

Further support for the importance of task-specific graph layout is found in the work by Huang et al. [HHE05]. Like the second study described in Purchase et al. [PCA02], the authors found little correlation between preferred layout and performance on a given task. This study was carried out in the context of modeling social networks and considered readability and communication to be the important aspects of such graphs. The paper discussed a user study where five layouts were evaluated - circular, radial, hierarchical, group, and free layout. They found little overall correlation between layout type and performance although layouts varied in usefulness across different tasks. They found the highest usability rating for a grouped/clustered layout even with edge crossings, which otherwise had a negative impact. Next preferred were hierarchical and radial layouts. Participants also had a preference for placing important nodes in the center and using clustering to highlight relationships.

McGrath et al. [MBK97] explored the effect of "spatial arrangement" (or layout) on various tasks related to social networks. The authors carried out an experiment with five different spatial arrangements of the same social network. They concluded that node spatial arrangement affected viewer's perception of prominence, bridging (where a node bridges two subgroups), and grouping of nodes. Perceived prominence increased as a node was brought to the centre. Physical proximity influenced detection of node grouping. However, perceptions of the most prominent nodes were not influenced substantially by layout, since high structural prominence may override any layout effect. The authors acknowledged that the ideal layout was influenced by what the graph was intended to convey. This is related to both underlying semantics and selected task (e.g., prominence detection versus finding groups).

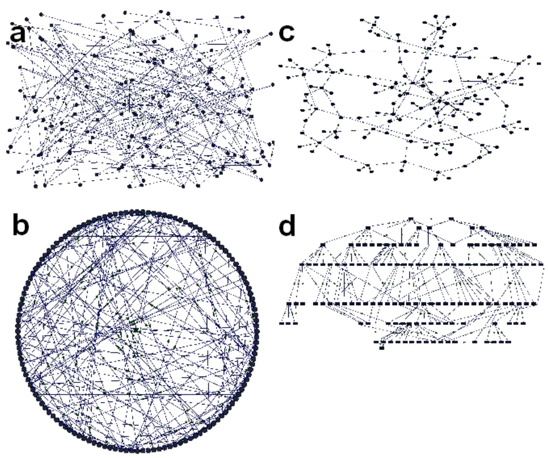

Figure 3: *Layouts showing the importance of semantics.*

Figure 3 shows layouts of the same graph. Figure 3a places nodes and edges randomly. Figure 3b uses a circular layout with symmetrical nodes that ignores edge placement and does not facilitate understanding. Figure 3c is a force directed layout that results in even spacing and clustering of leaf nodes. This clustering may mislead because it does not consider semantics. Figure 3d imposes a syntactic hierarchy on the underlying data. While this may look ordered, the hierarchy is artificial, does not consider semantics, and may actually impede understanding. It is clear that while a layout algorithm may improve aesthetics, this does not ensure understanding.

Ware et al. [WPCM02] proposed a method for evaluating the cognitive costs of graph aesthetics based on human pattern perception. The paper argued that Gestalt principles and neurophysiology can help explain which aesthetics might be important and why. In particular, the paper explained how human image processing experiments have shown that detection of continuous contours/lines is pre-attentive (processed in parallel). The authors pointed out that minimizing edge crossings may mean increasing the path length and making the path less continuous or more bent. Hence, these heuristics may need to be weighed against each other.

The evaluation techniques used by Ware et al. [WPCM02] were taken from the field of human computer interaction, where specific tasks are tested by carefully controlling a set of variables. The following edge-related variables were tested: continuity, edge crossings, average angle, number of branches in shortest path, shortest path length, total geometric length, and total crossings in graph. Participants were asked to find the shortest path in a variety of graphs visualized with a spring layout algorithm. Diagrams were domain independent. Their study found that continuity, edge crossings (those that directly affect the path being examined), and number of branches were significant. Additionally, for pathfinding tasks, it was important to trade off continuity versus edge crossing minimization. The authors argued that the approach taken by this study can serve as a basis for further validation of aesthetic heuristics.

Huang and Eades [HE05] looked at how users explore graphs by tracking user eye movements. Primarily due to the design of their experiment they did not draw explicit conclusions regarding specific heuristics. They observed that users took more time to complete tasks when graphs contained distracting edges or dense clusters of nodes. To be more specific, extra eye movements were observed when there were many edges incident to highlighted nodes and many edges going toward the target node for a specified task. They concluded that graph layout has an effect on a user's eye movement patterns.

5. Summary of Aesthetic Heuristics

Table 1 summarizes the aesthetic heuristics discussed in this paper, their grounding in perceptual principles, and whether they have been experimentally validated. Heuristics are organized by whether they apply to nodes, edges, or overall graph layout. The table includes references to papers that proposed or evaluated the heuristic, the perceptual basis for each heuristic and the domain to which each applies.

6. Conclusion

Aesthetic heuristics promise to make graphs easier to read and understand. We have surveyed the research in this area and identified a core set of syntactic heuristics. We found that work remains to be done to validate these heuristics and to fully understand their perceptual basis. Balancing potentially conflicting heuristics poses an additional research challenge.

It is clear from domain specific studies that semantics and task may be just as important as structure when creating graphs that can be understood. More research is needed in this area. Finally, little work has been done in applying aesthetic heuristics from other fields, such as graphical design, information visualization, or even cartography. Node and edge shape, size, texture, and colour are just a few of the variables that could play a significant role in improving graph aesthetics.

Heuristic	Proposed by	Perceptual Support	Evaluated by	Domain
Node Metrics				
Cluster similar nodes	[TR05, TBB88]	[WS06] – symmetry, proximity	[HHE05]	General
Distribute nodes evenly	[Har98, DH96, TR05, TBB88]	–	–	General
Keep nodes apart from edges	[Har98, DH96]	[CT03] – resolution limits of human eye	–	General
Maximize node orthogonality	[Pur02]	[WS06] – orientation	–	General
Nodes should not overlap (except for nested nodes)	[WS79]	[WS06] – connectedness	–	General
Edge Metrics				
Minimize edge crossings	[BMRW98, Har98, DH96, Pur02, TR05, TBB88]	[WS06] – continuation	[PCJ97, PCA02, WPCM02]	General
Keep edge lengths uniform	[BMRW98, DH96, TR05]	[WS06] – similarity	–	General
Minimize edge length (total and maximum)	[Har98, TR05, TBB88]	[WS06] – proximity	–	General
Minimize edge bends	[Pur02, TR05, TBB88]	[WS06] – continuation	[PCA02, PCJ97, PMCC01]	General
Keep edge bends uniform (angle/position)	[TR05]	[WS06] – similarity	[WPCM02]	General
Maximize edge orthogonality	[Pur02]	[WS06] – orthogonality	[PCA02]	General
Maximize minimum edge angles	[CT03, Pur02, TR05]	[CT03] – resolution limits of human eye	–	General
Overall Layout Metrics				
Maximize consistent flow direction	[Pur02]	[WS06] – orientation	–	Directed graphs
Keep correct aspect ratio	[TR05]	–	–	General
Minimize area	[TR05, TBB88]	[WS06] – good figure	[PCA02] – narrow graph width	General
Maximize convex faces	[TBB88]	–	–	General (planar)
Maximize global symmetry	[BMRW98, Pur02, TR05, TBB88]	[WS06] – symmetry	–	General
Maximize local symmetry	[BMRW98, Pur02, TR05, TBB88]	[WS06] – symmetry	[PCA02, PMCC01]	General
Domain Specific (UML)				
Join inheritance edges	[PCA02, Eic03]	[WS06] – good figure, familiarity	[PCA02]	UML
Use directional indicators	[PCA02]	–	[PCA02]	UML
Avoid separate arrows on edges	[PCA02]	–	[PCA02]	UML

Table 1: *Graph Drawing Heuristics.*

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