Unravelling Graph-Exchange File Formats

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Abstract—A graph is used to represent data in which the relationships between the objects in the data are at least as important as the objects themselves. Over the last two decades nearly a hundred file formats have been proposed or used to provide portable access to such data. This paper seeks to review these formats, and provide some insight to both reduce the ongoing creation of unnecessary formats, and guide the development of new formats where needed.

I. INTRODUCTION

Exchange of data is a basic requirement of scientific research. Accurate exchange requires portable file formats, where portability means the ability to transfer (without extraordinary efforts) the data both between computers (hardware and operating system), and between software (different graph manipulation and analysis packages).

A short search of the Internet revealed that there are well over 70 formats used for exchange of graph data: that is networks of vertices (nodes, switches, routers, ...) connected by edges (links, arcs, ...)

It seems that every new tool for working with graphs derives its own new graph format. There are reasons for this: new tools are often aimed at providing a new capability. Sometimes this capability is not supported by existing formats. And inventing your own new format isn’t hard.

More fundamentally, exchange of graph information just hasn’t been that important. Standardised formats for images (and other consumer data) are crucial for the functioning of digital society. Standardised graph formats affect a small community of researchers and tool builders. This community is growing, however, and the need for exchange of information is likewise growing, particularly where the data represent some real measurements that were expensive to collect.

The tendency to create new formats in preference to using existing tools is unhelpful though, particularly as the time to “create” a format might be small, but the time to carefully test formats and read/write implementations is extensive. Reliable code is critical to maintain data quality, but many tool developers seem to focus on features instead of well-audited code. Moreover support of formats, for instance clear documentation and ongoing bug fixes, is often lacking.

An explosion of formats is therefore a poor state of affairs. The existing formats do include many of the features one might need, and some are quite extensible, so the bottleneck is not the existing formats so much as information about those formats. This is the gap this paper aims to fill.

This work concentrates on graph exchange formats. Such formats have certain requirements above and beyond simple storage: most obviously portability. However, portability in this context is not purely about syntax. Exchange also requires common definitions of the meaning of the attributes.

On the other hand, file size is not a primary consideration. Hence many exchange formats pay little attention to this and related details (e.g., read/write performance).

We concentrate on exchange formats, but some of the formats considered here were not originally developed with exchange in mind, but have become de facto exchange formats through use. In these cases we see reversals of objectives compared to some purpose-built exchange formats. We shall therefore consider a large range of such features for comparison, noting as we do so that as exchange of very large datasets becomes important, the requirements will change.

Many of the formats presented may seem obsolete. Some are quite old (in computer science years). Some have clearly not survived beyond the needs of the authors’ own pet project. However, we have listed as many as we could properly document, partially for historical reference, and partially to show the degree of reinvention in this area. But more importantly, because old and obscure isn’t bad. For instance NetML, a format that doesn’t seem to be used at all by any current toolkits, incorporates some of the most advanced ideas of any format presented. A good deal could be learnt by current tool builders if they were to reread the old documentation on this format.

It is important to note that this paper does not present yet another format of our own. It is common in this and other domains for the discussion of previous works to be coloured by the need to justify the authors’ own proposals. Here we aim to be unbiased by the need to motivate our own toolkit, and so (despite temptation) do not provide any such.

We do not argue that new graph formats should never be developed. In some applications new features are needed that are not present in the existing formats. However, it is critical that those who wish to propose new ideas should understand whether they are really needed. Moreover, in studying the existing formats, and their features, we learn what should be required in any new format to make it more than a one-shot, aimed at only one application. In fact, the results suggest that new formats are desirable for several reasons, but that perhaps what would be more useful would be a container format capable of providing self-documentation and meta-data-like features, while encapsulating a set of formats with variable levels of feature support.

So the value of this work is threefold: firstly it provides a relatively complete set of information about the currently available formats, secondly it provides a basis for selection of a suitable format, and thirdly it provides information about the nature of the features that can and have been used in future developments of graph exchange strategies.

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II. BACKGROUND

Graphs (alternatively called networks) have been used for many years to represent relationships between objects or people. A mathematical graph $G$ is a set of nodes (or vertices) $\mathcal{N}$ and edges (or links or arcs) $\mathcal{E} \subseteq \mathcal{N} \times \mathcal{N}$.

An alternative representation of a graph can be given through its adjacency matrix $A$, defined by

$$A_{ij} = \begin{cases} 1, & \text{if } (i, j) \in \mathcal{E}, \\ 0, & \text{otherwise}. \end{cases}$$

Other representations exist (and are discussed below in detail). These alternatives are often used to create computationally efficient operations on the graph. Underlying these alternatives is the choice of the first-class objects to be represented: mathematically, the graph is the first-class object, and nodes and edges are components of the graph, but it is useful, for instance, to represent the edges as a set of objects each with their own components (including their end-points), or to represent the nodes as the first-class objects, with edges as properties of the nodes. Each alternative has advantages in terms of particular algorithms that can be applied.

Additional information is often added to a graph: for instance

- node or link labels (names, types, ...);
- values (distances, capacity, size, ...); and
- routing (paths taken when traversing the graph).

This additional information is often critical to make use of the graph data in any real application.

It has been necessary for many years for researchers in sociology, biology, chemistry, computer science, mathematics, statistics and other areas to be able to store graphs representing concepts as diverse as state-transition diagrams, computer-software structure, social networks, biochemical interactions, neural networks, Bayesian inference networks, genealogies, computer networks, and many more. Researchers also need to share data. They have done so by sharing files. As a result portable file formats for describing graphs have been around for decades.

This document is concerned with providing information about these formats, specifically with the intention of moving towards a smaller number of standard formats (the current trend seems to be progressing in the other direction).

We only look here at publicly disclosed formats, for the obvious reason that a format can’t really be called a data exchange format unless its definition is public. It is fair to say that although many were intended for exchange of information, most failed at this and were only really used for a single tool or database of graphs. In a few other cases, the format was not intended as an exchange format, but has become a de facto exchange format by virtue of the inclusion of IO routines in other software than its originator. In any case, we have tried to be inclusive here: we include anything that might be reasonably called an exchange format (and which is publicly documented to some degree), rather than trying to exclude those which we guess are not.

There are many subtypes of graphs, and generalisations. For instance: the general description above is that of a directed graph. An undirected graph has the property that if $(i, j) \in \mathcal{E}$ then so too is $(j, i)$.

It is important to note that it is often possible to represent one type of graph in terms of the other: for instance an undirected graph may be represented by a directed graph by including all reverse links in the data. However, this is inefficient.

Moreover there is the issue of intention. The intention of the person storing the data is important: for instance, an undirected graph that is stored as a directed graph may be edited to become directed. A native undirected format enforces the correct semantics. Thus when considering the type of graph being stored, we consider the native or explicitly supported subtypes, not those that can be implicitly supported.

Other generalisations of graphs include multi-graphs, hyper-graphs, and meta-graphs (described in more detail below). Subtypes include trees and DAGs (Directed Acyclic Graphs). Once again, it is often possible to represent these in terms of the simple directed graph, but often this will be inefficient, and deficient in terms of intention. We will therefore look for native support for these generalisations and subtypes.

A. Related work

We distinguish this work from the study of graph databases, which have a similar role in storing data where the relationships have at least as much importance as the entities they relate. However, although they may hold the same type of data that we are considering here, the motivations for a graph database are different. Typically, those concerned with databases are interested in ACID (Atomicity, Consistency, Isolation, Durability) and other similar properties. The underlying assumption is that the data is changing dynamically according to some set of transactions and operations and that the database should work correctly under these conditions. Consequently graph databases are not simply concerned with the structure and description of the data, but also how that data may be operated on, and queried. On the other hand, the standard assumption in data exchange is that the data itself is relatively static, but portability is important.

There is a wide-ranging survey of graph databases [1], which is more concerned with the underlying database aspects, e.g., the relationship between a graph database and other more traditional databases such as a relational database, and the properties of various exemplar graph databases.

There is some overlap of concerns: in both cases there is some interest in data integrity, compression, and the like, but it is fair to say that these issues have typically taken second place in the design of graph exchange formats.

There have been a number of other efforts to gather similar information on graph exchange formats by researchers [2]–[4] and software distributors [5], [6]. The results provided inspiration for some of the descriptors used here, but this paper aims to provide a more comprehensive summary.

One additional paper to consider is [7], which was written specifically with the view of designing a new, more universal graph format. We deliberately avoid this approach in order to avoid bias in our discussion.
III. THE FILE FORMATS

As noted the aim here is to describe graph exchange formats, i.e., formats that are used to exchange data between scientists and programming environments. Not all of the formats started out that way – some were intended as internal formats for a particular software system, but have become de facto exchange formats when another system sought to leverage existing data by incorporating an existing format. A few of the formats are still primarily internal to a single system, but are important to describe because they exhibit an interesting feature. In the main we concentrate on those that were designed with data exchange in mind, or have been used in that way in practice.

This list is incomplete. There are some formats that we have observed in the literature, but have been unable to find documented (e.g., Gem2Ddraw), or which appear to only be used as an internal format for a single tool. The graph formats we know of that have been excluded are the Tom Sawyer format, gem3Ddraw, PROGRES, GTXL, GedML, UXF, GRL, VEGA, BLGF, GraphLab, BNIF, BIF, XGML, NMF, Inflow, GDS, Tnet and RDF. Additional information sources covering these would be welcomed.

There are a few formats that we have lumped together under the general heading of TGF (the Trivial Graph Format) because they are all functionally equivalent to a delimited edge list. There is no point in listing every variant of this approach: there are many and they vary mainly on the choice of storage (plain ASCII through to Excel), and delimiter (tabs and commas are common).

There are many file formats that could, in principle, contain a graph: e.g., XML, JSON, SGML, Avro, YAML (YAML Ain’t Markup Language), RDF (the Resource Description Framework), HDF (the Hierarchical Data Format). For that matter any image file could contain an adjacency matrix. Unless there is a specific extension of these designed to provide support for graphs, in which case we list the specific not the generic. For instance, several software tools say that they can read/write JSON or other generic serialisations of data, but without details of exactly what is being serialised, then these are not useful exchange formats. We treat Matlab’s .mat format as a special case because it has explicitly been used to exchange graph data, at least between instances of Matlab, even though it is a generic data format.

We also aim to avoid, for simple practicality, formats that represent data that has a graph structure, but whose main content is not the graph. For instance HTML: the graph structure of the WWW is vastly smaller than the content and HTML is intended to store both in a distributed fashion. If one wished to represent the graph of the WWW, then another format seems indicated. Other examples include SBML (the Systems Biology Markup Language), and FOAF [8] (Friend Of A Friend).

Table I provides the list of exchange formats we do include, as well as links and references. Check marks in the table indicate that we have had at least cursory feedback about the information in the table from one of the creators or maintainers of the format (we received such feedback on 23 of the formats). Please see the acknowledgements for a list of contributors.

We have also tried to include a reference time frame to provide some historical context for the format. The dates are based on explicit records from the first recorded reference to the format, through to the last recorded date of maintenance. However, this information is often not supplied, so we have used the closest available proxy. For instance, change-logs or copyright dates on format documentation or publication dates for papers. Hence these should not be seen as a completely reliable data. It is an attempt to document the historical development of this field, so much of which is not in the archival journals.

For instance, Figure 1 provides a quick summary. We can see that there was a flurry of activity in the late 90s continuing on until today, but the style of contributions has changed over time. It is interesting to see how XML became flavour of the day around in the late 90s, and then dropped out of popularity in recent years, and in the most recent past there seem to be several efforts to design graph formats on top of JSON. It seems there are fads even within technical fields.

[Fig. 1: New format origination dates.]

\[1\] Please note that some formats that are notionally obsolete according to reference dates, but may still be used by archival stores of graph data.
| Graph Format     | Full Name                                                                 | Reference time frame |
|------------------|---------------------------------------------------------------------------|----------------------|
| bintsv4          | [9] bintsv4 (GraphLab)                                                   | 2009 - present       |
| BioGRID TAB      | [10], [11] BioGRID TAB 2.0 Format                                         | 2003 - present       |
| BLAG, GDToolkit  | [12] Batch layout generator (GDToolkit)                                    | 1998 - 2008          |
| BVGraph          | [13] Boldi-Vigna graph compression                                         | 2004 - 2011          |
| Chaco            | [14] Chaco graph format                                                   | 1994 - 1995          |
| Cluto            | [15] Cluto/Metis/Graculus format                                           | 1999 - 2008          |
| DGS              | [16] Dynamic GraphStream Format                                           | 2010 - 2013          |
| DGML             | [17] Directed Graph Markup Language                                       | 2000 - 2013          |
| DIMACS           | [18] DIMACS graph format                                                  | 2006 - 2006          |
| Dot              | [19] GraphVis Dot Language                                               | 2000 - present       |
| DotML            | [20] Dot Markup Language                                                 | 2002 - 2010          |
| DyNetML          | [21] DyNetML XML                                                         | 2001 - 2009          |
| GAMEF            | [22] A Graph and Matrix Format                                           | 1995 - 1995          |
| GDF              | [23] Guess Data Format                                                   | 2000 - 2010          |
| GDL              | [24] Graph Description Language                                           | 1993 - 1995          |
| GEDCOM           | [25] Genealogical data                                                   | 1987 - 1996          |
| GEXF             | [26] Graph Exchange XML Format                                            | 2007 - 2012          |
| GML              | [27] Graph Modelling Language                                            | 1995 - 1999          |
| Graph6           | [28] Graph6                                                               | 1996 - 2011          |
| Graph::Easy      | [29] Graph::Easy format                                                  | 2004 - present       |
| GraphEd          | [30], [31] GraphEd simple format                                         | 1994 - 1994          |
| GraphJSON        | [32] Graph JSON                                                          | 2013 - 2014          |
| GraphML          | [33] Graph Markup Language                                               | 2000 - present       |
| GraphSON         | [34] XML-Based Graph Description Language                                 | 1998 - 1998          |
| GraX             | [35] GraX                                                                | 1996 - 1999          |
| GRXL             | [36] XML Specification for Grrr Program                                   | 2000 - 2000          |
| GT-ITM           | [37] Georgia Tech Internetwork Topology Models                            | 1998 - 2012          |
| GXL              | [38] Graph Exchange Language                                             | 1999 - 2006          |
| Harwell-Boeing   | [39] Harwell-Boeing sparse (TGFaceny) matri                              | 1992 - 2010          |
| Inet             | [40] Inet Topology Generator file                                         | 2000 - 2002          |
| ITDK             | [41] CAIDA Internet Topology Data Kit                                    | 2002 - present       |
| JSON Graph       | [42] json-graph-specification                                             | 2014 - present       |
| LEDA             | [43] LEDA format                                                         | 2001 - 2008          |
| LGF              | [44], [45] LEMON Graph Format                                            | 2008 - present       |
| LGL              | [46], [47] Large Graph Layout                                            | 2003 - 2005          |
| LibSea           | [48] CAIDA LibSea format                                                 | 2000 - 2005          |
| KrackPlot        | [49] KrackPlot data format                                               | 1993 - present       |
| Matlab           | [50] Matlab saved workspace                                              | 1996 - 2013          |
| Matrix           | [51] Matrix Market sparse matrix                                         | 1996 - 2013          |
| Mivia            | [52], [53] Mivia ARG database format                                     | 2001 - 2003          |
| MultiNet         | [54], [55] MultiNet                                                      | 1999 - 2007          |
| Netdraw VNA      | [56], [57] Netdraw VNA                                                   | 2005 - 2008          |
| NetML            | [58] Network Markup Language                                             | 1995 - 1995          |
| Nccol            | [46], [47] Large Graph Layout                                            | 2000 - 2005          |
| NenF             | [59], [60] Nested Network Format                                         | 2003 - present       |
| Nod              | [49] KrackPlot Node format                                               | 1993 - present       |
| NOS              | [61] Neo Org Stat format                                                 | 2000 - 2013          |
| ns-tcl           | [62], [63] ns-2 Tcl network definition                                   | 1989 - 2011          |
| OGDL             | [64] Ordered Graph Data Language                                         | 2002 - present       |
| OGM1             | [65], [66] Open Graph Markup Language                                    | 2003 - present       |
| Osprey           | [67] Osprey file format                                                  | 2001 - 2008          |
| Otter            | [68] Otter’s native format                                               | 1999 - 1999          |
| Pajek (.net)     | [69]-[71] Pajek Tool’s .net format                                       | 1996 - present       |
| Pajek (.paj)     | [69]-[71] Pajek Tool project (.clu, .vec, .per, ...)                      | 1996 - present       |
| Planar           | [28] Plantri Planar Code andedgeCode                                     | 1996 - 2011          |
| PSI-MI           | [72] Protextomics Standards Initiative Molecular Interaction              | 2002 - present       |
| RSF              | [73] Rigi Standard Format                                                | 1999 - 2010          |
| Rocketfuel       | [74] Rocketfuel ISP Maps                                                 | 2002 - 2003          |
| Rutherford-Boeing| [75] Rutherford-Boeing sparse (TGFaceny) matri                           | 1997 - 1997          |
| SGB              | [76], [77] Stanford GraphBase                                             | 1992 - 2009          |
| SGF              | [78], [79] Structured Graph Format                                       | 1998 - 1999          |
| S-Dot            | [80] S-Dot (lisp interface to Graphviz)                                  | 2006 - 2010          |
| SIF              | [59], [60] Simple Interaction Format                                     | 2003 - present       |
| SNAP             | [81] Stanford Network Analysis Platform                                  | 2005 - present       |
| SoNIA            | [82], [83] So NIA Son format                                             | 2002 - present       |
| Sparse6          | [28] Sparse6                                                             | 1996 - 2011          |
| SiOCNET          | [84] SiOCNET native format                                               | 2002 - 2007          |
| TEL              | [85] Text Encoding Initiative Graph Format (XML-compatible)              | 2008 - present       |
| TGF, TGF         | [86] Trivial Graph Format, and other simpleedgelists (CSV, TSV, Excel, ...) | NA - NA              |
| Tulip TLP        | [87], [88] Tulip graph format                                            | 2002 - 2012          |
| UCINET DL        | [89], [90] UCINET Data Language                                         | 2002 - 2013          |
| XGMML            | [91] eXtensible Graph Markup and Modeling Language                       | 2000 - 2001          |
| XMLBIF           | [92] XML-based BayesNets Interchange Format                              | 1998 - 2013          |
| XTND             | [93] XML Transition Network Definition                                   | 2000 - 2000          |
| YGF              | [94] Y Graph Format                                                     | 2004 - present       |

TABLE I: The format list. Checkmarks indicate formats that have had their details audited by someone associated with creation or maintenance of the format.
IV. DESCRIPTORS AND DISCRIMINATORS

In order to describe the formats we will consider here, we need some simple means to compare and contrast. Of a necessity, these will oversimplify some of the issues. For instance, where a format uses multiple files we have not attempted to explain exactly how data is divided between these files.

What’s more, many descriptions of file formats are imprecise. It is common to describe the format by reference to examples. Although useful for simple cases, these leave out important details: for instance: the character set supported, and even more surprisingly, the format of identifiers. It is often vaguely suggested that these are numbers, but without formal definition of what is allowed (presumably non-negative integers, but are numbers outside the 32 bit range supported?).

In the following, we make the best estimate of the capabilities of each format through reference to online documentation, and through a survey of the file format creators. In many cases the results are inferences, so in this section we will outline the features we describe, and the assumptions made in compiling our data. However, we have made the best effort possible to contact authors of formats, and their comments about capabilities have been given precedence.

There are three main types of descriptors here:

**file type**: these are simple issues of the type of file storing the data: binary vs ASCII, etc.

**graph types**: this refers to the nature of the graph data that can be stored.

**attributes**: these are features related to supplemental data about nodes and edges, such as labels and values associated with these.

**general**: this is a grab bag for additional features that don’t fit in either of the previous classes.

We’ll describe each of these in detail below, and then provide a table of the features vs file formats.

One last point, this is not intended as a pejorative list. We do not mean to imply that having a feature is good or bad. The aim is to provide potential users with the background to choose the right format for their purposes.

A. File Type

**encoding**: This is, in principle, a simple distinction in file type between text and binary files. However, text files today can use multiple different character sets, and this is important because some graphs will be labelled with non-English character sets. However, the majority of file format definitions leave unspecified the character set to be used. We assume here that the character set is ASCII, unless there is some indication otherwise, either an explicit statement, or in the case of applications of XML it is assumed that the character set supported is Unicode. Figure 2 indicates the proportions of files providing each type of encoding.

**representation**: Methods to represent a graph include:

matrix: The graph’s full adjacency matrix.

dge: A list of the graph’s edges [95].

smatrix: The matrix representation is poor for sparse graphs, which are common in real situations. However, some tools actually store a sparse matrix, which is almost equivalent to an edge list. There is a subtle difference in that a matrix view of the edges in a network cannot contain much detail about the edges (only one number), and so we have a separate name, *smatrix*, for formats that use this type of representation.

neighbour lists: This is a list of the graph’s nodes, each giving a list of neighbours for each node. Often called *adjacency lists* we avoid that term because it is easily confused with the edge list.

path: One can also implicitly represent a graph as a series of path descriptions (essentially a path is a list of consecutive edges). This could be useful, for instance, with a tree or ring.

Moreover, graph data is often derived from path data, i.e., a series of paths are analysed, and the edges on these become the graph. In other cases, one might like to store path information, for instance related to routes along with the graph.

constructive: Graphs can often be described in terms of mathematical operations used to construct the graphs: for instance graph products on smaller graphs [96]. See [58] for a description of “levels” of graph formats. Apart from simple incremental construction, the only format that seems to allow this is NetML [58].

procedural: Many graphs can be concisely defined by a set of procedures, rather than explicit definition of the nodes and links. This type of graph format could be very concise, but verges on creating another programming language. In fact, many graph libraries for particular programming languages essentially provide this, but in a non-portable manner.

The only generic (language independent) format that seems to allow this is NetML [58]. Any procedural approach admits the possibility of defining a method for constructive graph description.

Fig. 2: Support for different encodings.

2There is one exception to this: Cluto stores sparse matrices in a format more closely resembling the neighbour representation.
A = \begin{pmatrix}
0 & 1 & 1 \\
0 & 0 & 0 \\
1 & 0 & 0
\end{pmatrix}

(a) Adjacency matrix

\begin{align*}
&1, 2 \\
&1, 3 \\
&3, 1
\end{align*}

(b) Edge list.

\begin{align*}
&1 : 2, 3 \\
&2 : 3 \\
&3 : 1
\end{align*}

(c) Neighbour lists.

\begin{align*}
&3, 1, 2 \\
&1, 3
\end{align*}

(d) Paths.

Fig. 3: Simple directed graph with representations.

Fig. 4: Proportions supporting different representations.

but we do not automatically count any procedural approach as constructive, unless it provides explicit graph-related operations as part of the toolkit.

These representations are given varying names in the literature, but we use the names above to be clear. Figure 3 illustrates four of these, and Figure 4 shows the proportions.

The representation is important: for a graph with \( N \) vertices and \( E \) edges, the adjacency matrix requires \( O(N^2) \) terms, the edge list \( O(E) \) terms, and the neighbour list \( O(N + E) \) terms. However, the terms in a matrix are \{0, 1\} whereas the terms in the edge and neighbour lists are node identifiers (consider they might be 64 bit integers), so the size of a resulting file based on each representation depends on many issues, including the way the data is stored in the file. No approach is universally superior.

Moreover, some may be easier to read and write: for instance a neighbour listing may be slightly more compact than an edge list, but the latter has the same number of elements per line, potentially making it easier to perform IO in some languages.

More subtly, a neighbour-list representation treats edges as properties of nodes, whereas an edge list treats edges as objects in their own right; and the matrix representation treats the graph as the only object with nodes and edges as properties of the graph. Although a program can internally represent data however it likes, and read in a neighbour list into structures that treat edges as objects in their own right, the native treatment of data is reflected in the ease with which attributes can be added. For instance, in a neighbour list it is intrinsically harder to record attributes for edges, and in the matrix representation it is harder to record attributes for nodes. This is, fundamentally, why we regard edge-list and sparse-matrix formats as different.

Some graph file formats allow alternative representations, and so we list all that are possible. However note that this is often actually multiple file formats under one name. It seems rare to allow a mixed representation.

We haven’t (yet?) reported on whether edge-list formats explicitly lists nodes or only implicitly lists them as a consequence of edges. The latter is briefer, but requires a special case for degree 0 nodes.

When considering generalisations of graphs, other representations are possible (for instance tensors can generalise the concept of an adjacency matrix for multi-layer networks). However, codification of these is an ongoing research topic [97] and so we will not try to encapsulate it here.

structure: This field describes how the file format’s structure is defined. The cases are:

simple : the typical approach to create a graph format is to use one line per data item (a node, an edge, or a neighbourhood), with the components of a line separated by a standard delineator (a comma, tab, or whitespace). There are many variations on this theme, some more complex than others, for instance including labels, comments or other information. These formats
As noted above, one approach to defining programming languages is to use XML, JSON, SGML, or similar generic, extendible file formats. This is a natural approach to the problem, and allows a specification as precise as BNF, though only through reference to the format being extended. Thus it is precise, but sometimes rather difficult to ascertain all of the details, unless one is an expert in XML, etc.

On the other hand, these approaches draw on the wealth of tools and knowledge about these data formats. On the other hand again, to use those tools the model of your graph object has to map to the XML model (or at least be easily transformed into that form).

**Tel, Lisp, ...**: As noted above, one approach to defining a graph is procedural. Most of the approaches that allow this are extensions or libraries for common programming languages. We will not list every programming language and library as a data format though because, generically, such approaches are not portable between programming languages. We do mention a few formats though (ns-2 and S-Dot), because translators exist from/or to these from other data formats.

**Built-in compression**: It is easy enough to compress a graph-file using common utilities such as gzip, and typical compression ratio will be reasonably good as graph files often have many repeated strings. However, one format (BVGraph) provides for compression of the graph as it is written, in much the way image file formats allow intrinsic compression of the image.

**Graph Compression algorithms** have been a topic of study at least since 2001 [13], [98], [99], with numerous followups. So it is interesting that only one format is designed around this feature. However, two other formats provided some crude mechanisms to reduce the size of the file. Finally DGS formally acknowledges the role of compression by requiring that a gzipped file be accepted.
Table II provides the information on file types.

B. Graph Types

directed/undirected: The two basic forms of graph are the directed and undirected graph. In the former edges (or arcs) imply a relation from one node to another. In the later an edge implies a relationship in both directions. Some graph formats specify one or the other; others allow the user to specify either, and the most general allow the user to specify the type of each edge\(^3\). In one case, the format is explicitly restricted to DAGs (Directed Acyclic Graphs).

Many graph formats fail to specify their type. In that case we assume it is directed if the edges/arcs are specified by directional nomenclature (e.g., from/to or source/destination). We also assume that matrix formats are directed unless there is specific mention of mechanism to represent the upper triangular part of the matrix alone.

multi-graph: A multi-graph is a graph generalisation that allows (i) self-loops, and (ii) more than one edge between a single pair of nodes. Some formats specifically allow, or disallow multi-graphs. A few allow loops, but not multi-edges. Many, however, say nothing on the topic. We assume in this case that formats presenting either matrix or neighbour lists representations don’t allow multi-graphs. It is technically possible to represent a multi-graph in these cases, but this would require special processing of the information, and unless we see an indication this is present we assume it is not. Edge lists, however, can easily cope with multi-graphs. We suspect it is left to the software supporting the data format to make a decision about how to deal with these cases, and the decision may be inconsistent between supporting software. Hence it seems important that when an edge-based representation leaves the question unspecified, we note this status.

hyper-graphs: A hyper-graph allows edges that connect more than two nodes. These are useful for some problems: for instance indicating a multi-access medium in a computer network (such as a wireless network).

One can realise hyper-graphs using existing graph representations by adding a new type of node (representing the hyper-edge) and creating simple edges from this to all the hyper-edge adjacencies (which can then be represented by a node-neighbour or adjacency list for a bipartite graph); or by creating “groups”, whose membership represents the hyper-edge. Hence existing formats can often support hyper-edges in principle. However, true support needs specialised data for hyper-edges in the software reading or writing the data, so unless a format explicitly states it can support these and presents the mechanism, we assume it cannot.

As a point to note, if hyper-graph support is intended to be included in a data format, then the list of graph representations is expanded to include the means of describing a hyper-edge:

direct: The groups/hyper-edges are directly defined by listing the set of nodes included in each;

indirect: Node definitions include a group-membership attribute that defines which nodes are connected by the defined group;

hmatrix: A \(\{0, 1\}\) matrix of size \(N \times E\) (where there are \(N\) nodes and \(E\) hyper-edges) maps nodes to hyper-edges. A sparse \(shmatrix\) version of this could be stored.

These representations are illustrated in Figure 8. As before none is universally superior, though the direct method seems likely to win for most realistic graphs.

hierarchy: It is common for graphs to have sub-structure, for instance nodes that themselves contain graphs. Several formats provide mechanisms to record this sub-structure. Unfortunately, there does not seem to be a consistently used definition of this type of structure \([100]\), and so we see differences not just in the representation, but also what exactly is being represented. The problem

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\(^3\)Of course a directed graph format can contain an undirected graph by including edges in both directions, but we are considering here whether it can do this a little more succinctly.
| Graph Format   | encoding | representation | structure | integral metadata | built-in compression |
|---------------|----------|----------------|-----------|-------------------|---------------------|
| bintsv4       | binary   | edge           | simple    |                   |                     |
| BioGRID TAB   | ASCII    | edge           | simple    | comments          |                     |
| BLAG, GDToolkit | ASCII   | neigh          | BNF       | fixed             |                     |
| BVGraph       | binary   | neigh          | simple    |                   | ✓                   |
| Chaco         | ASCII    | neigh          | simple    | comments          |                     |
| Cluto         | ASCII    | matrix/matrix  | simple    |                   | limited             |
| DGS           | UTF-8    | edge           | BNF       | arbitrary         |                     |
| DGL           | Unicode  | edge           | XML       | fixed             |                     |
| DIMACS        | ASCII    | edge/path      | simple    | fixed             |                     |
| Dot           | UTF-8    | edge           | BNF       | arbitrary         |                     |
| DotML         | Unicode  | edge           | XML       | arbitrary         |                     |
| DyNetML       | Unicode  | edge           | XML       | fixed             |                     |
| GAMMFF        | ASCII    | smatrix/matrix | BNF       | fixed             |                     |
| GDF           | ASCII    | edge           | intermediate |                |                     |
| GDL           | ASCII    | edge           | BNF       | fixed             |                     |
| GEDCOM        | UTF-8    | neigh          | BNF       | fixed             |                     |
| GEXF          | UTF-8    | edge           | XML       | arbitrary         |                     |
| GML           | ISO 8859 | edge           | BNF       | arbitrary         |                     |
| Graph6        | coded ASCII | matrix        | simple    |                   | limited             |
| Graph::Easy   | UTF-8    | edge/neigh    | intermediate | fixed         |                     |
| GraphEd       | ASCII    | neigh          | BNF       |                   |                     |
| GraphJASON    | UTF-8    | edge           | JSON      |                   |                     |
| GraphML       | Unicode  | edge           | XML       | arbitrary         |                     |
| GraphSON      | UTF-8    | edge           | JSON      | arbitrary         |                     |
| GraphXML      | Unicode  | edge           | XML       | arbitrary         |                     |
| GraX          | Unicode  | edge/neigh    | XML       |                  |                     |
| GRXL          | Unicode  | edge           | XML       | arbitrary         |                     |
| GT-ITM        | ASCII    | edge           | simple    |                   |                     |
| GXL           | Unicode  | edge           | XML       | arbitrary         |                     |
| Harwell-Boeing| ASCII    | smatrix        | simple    |                   |                     |
| Inet          | ASCII    | edge           | simple    |                   |                     |
| ITDK          | ASCII    | edge           | simple    | comments          |                     |
| JSON Graph    | ASCII    | edge           | JSON      | arbitrary         |                     |
| LEDA          | ASCII    | edge           | simple    |                   |                     |
| LGF           | ASCII    | edge           | intermediate | arbitrary     |                     |
| LGL           | ASCII    | neigh          | simple    |                   |                     |
| LibSea        | ASCII    | edge/path      | BNF       | arbitrary         |                     |
| KrackPlot     | ASCII    | matrix         | simple    |                   |                     |
| Matlab        | binary   | matrix/matrix  | HDF5      | arbitrary         | ✓                   |
| Matrix        | ASCII    | smatrix        | simple    | comments          |                     |
| Mivia         | ASCII/binary | edge          | simple    | comments          |                     |
| MultiNet      | ASCII    | edge/matrix    | intermediate |                |                     |
| Netdraw VNA   | ASCII    | edge           | simple    |                   |                     |
| Ncol          | ASCII    | edge           | simple    |                   |                     |
| Nencl         | ASCII    | edge           | simple    | comments          |                     |
| NIFF          | ASCII    | edge           | simple    |                   |                     |
| Nod           | ASCII    | neigh          | simple    |                   |                     |
| NOS           | ASCII    | matrix         | simple    |                   |                     |
| ns-tcl        | ASCII    | edge/procedural | Tcl      |                  |                     |
| OGDG          | ASCII    | edge/paths     | BNF       | comments          |                     |
| OGML          | Unicode  | edge           | XML       | fixed             |                     |
| Osprey        | ASCII    | edge           | simple    |                   |                     |
| Otter         | ASCII    | edge           | intermediate | fixed         |                     |
| Pajek (.net)  | UTF-8    | edge/neigh/matrix | intermediate | comments     |                     |
| Pajek (.paj)  | UTF-8    | edge/neigh/matrix | intermediate | comments     |                     |
| Planar        | binary   | neigh          | simple    |                   |                     |
| PSI MI        | Unicode  | edge           | XML       | arbitrary         |                     |
| RSF           | ASCII    | edge           | BNF       | comments          |                     |
| Rocketfuel    | ASCII    | edge/path      | intermediate |                |                     |
| Rutherford-Boeing | ASCII | smatrix        | intermediate | fixed         | limited             |
| SGB           | ASCII    | edge/neigh     | intermediate | fixed         |                     |
| SGF           | Unicode  | edge           | XML       | arbitrary         |                     |
| S-Dot         | ASCII    | edge/procedural | lisp     | arbitrary         |                     |
| SIF           | ASCII    | edge/neigh     | simple    |                   |                     |
| SNAP           | ASCII    | edge           | simple    | comments          |                     |
| SoNIA         | ASCII    | edge           | intermediate | comments     |                     |
| Sparse6       | coded ASCII | neigh          | simple    |                   | limited             |
| SiOCNET       | ASCII    | matrix         | simple    |                   |                     |
| TGF, TGF      | ASCII    | edge           | XML       | fixed             |                     |
| Tulip TLP     | ASCII    | edge           | BNF       | fixed             |                     |
| Ucinet DL     | ASCII    | neigh/edge/matrix | intermediate |                |                     |
| XGMML         | Unicode  | edge           | XML       | arbitrary         |                     |
| XMLBIF        | Unicode  | edge           | XML       | arbitrary         |                     |
| XTND          | Unicode  | edge           | XML       | comments          |                     |
| YGF           | binary   | edge           | simple    |                   | ✓                   |

TABLE II: File types (see § IV-A for explanation of columns).
becomes even more complicated when hierarchy and hyper-graphs are combined [97] (there is at least one proposed solution [100] but it does not seem to be widely used yet).

Here, we simply note whether the format provides a version of hierarchy.

**meta-graph** : A meta-graph [101] is a generalisation of a graph, multi-graph, hyper-graph, and hierarchical graph. Once again, a meta-graph could in principle be represented using existing data structures (in much the same way that any data can in principle be represented in XML), so this fields refers to whether the format defines the representation. As far as we know, no format yet supports meta-graphs\(^4\), but this is included as a feature as an indication of the type of feature that might require a new format, or extended version of an existing format.

**edge-edge links** : Generally, a graph has links between nodes, but we could generalise the concept to allow meta-edges that join edges as well (this is different from a meta-graph).

This idea isn’t supported by many formats, and in the case of GraphML it is specified using the extensibility of GraphML, but again it is a useful example of the types of features that may be needed in the future.

**default values** : Specifying the value of a weight or attribute for every edge or node can be laborious (if it has to be done by hand), and wasteful of space. Moreover, it makes it hard to see structure in the data. Simply providing a default value for the common case can improve the situation. We include here the case of simple inheritance of values through a tree of “class” structures on the objects. For instance, nodes can be given a type which conveys a default value to be overridden by a more specific type or particular value. Notice here we are not speaking of inheritance through the graph itself, but a structure on top of the graph.

**multiple inheritance** : A few formats allow values to be derived through inheritance of values from multiple classes to which they belong. Thus they allow a node to have, for instance, a type “router” which conveys that it is an Internet router, with appropriate characteristics for such a device, from vendor “Cisco” which appropriate...
| Graph Format   | directed | multi-graph | hyper-graph | hierarchy | meta-graph | edge-edge |
|---------------|----------|-------------|-------------|-----------|------------|-----------|
| buntsv4       | directed |             |             |           |            |           |
| BioGRID TAB   | directed |             |             | ✓         |            |           |
| BLAG, GDToolkit | either   |             |             |           |            |           |
| BVGraph       | directed |             |             |           |            |           |
| Chaco         | undirected|             |             |           |            |           |
| Cluto         | directed |             |             |           |            |           |
| DGS           | mixed    | ✓           |             |           |            |           |
| DGML          | unspecified| unspecified|             |           |            |           |
| DIMACS        | either   | ✓           |             |           |            |           |
| Dot           | mixed    | ✓           | ✓           | ✓         |            |           |
| DotML         | mixed    | ✓           | ✓           | ✓         | ✓         |           |
| DyNetML       | directed | unspecified|             |           |            |           |
| GAMFF         | either   | unspecified| ✓           |           |            |           |
| GDF           | unspecified| unspecified|             |           |            |           |
| GDL           | directed | unspecified|             |           |            |           |
| GEDCOM        | mixed    | unspecified|             |           |            |           |
| GEXF          | mixed    | ✓           | ✓           | ✓         |           |           |
| GML           | either   | ✓           | ✓           | ✓         | ✓         |           |
| Graph6        | directed | loops only  |             |           |            |           |
| Graph::Easy   | mixed    | ✓           | ✓           | ✓         | ✓         |           |
| GraphEd       | unspecified| ✓           |             |           | ✓         |           |
| GraphJSON     | mixed    | unspecified|             |           |            |           |
| GraphML       | mixed    | ✓           | ✓           | ✓         | ✓         |           |
| GraphSON      | directed | unspecified|             |           |            |           |
| GraphXML      | directed | unspecified|             |           | ✓         |           |
| GraX          | directed | unspecified|             |           | ✓         |           |
| GRXL          | directed | unspecified|             |           | ✓         |           |
| GT-ITM        | undirected|             |             |           |            |           |
| GXL           | mixed    | ✓           | ✓           | ✓         |           |           |
| Harwell-Boeing| directed |             |             |           |            |           |
| Inet          | undirected|             |             |           |            |           |
| ITDK          | undirected|             |             |           |            |           |
| JSON Graph    | either   | ✓           |             |           | ✓         |           |
| LEDA          | either   | unspecified|             |           | ✓         |           |
| LGF           | either   | unspecified|             |           |           |           |
| LGL           | undirected| unspecified|             |           |           |           |
| LibSea        | directed | unspecified|             |           |           |           |
| KrackPlot     | directed |             |             |           |            |           |
| Matlab        | directed |             |             |           |            |           |
| Matrix        | either/bipartite|         |             |           | ✓         |           |
| Mivia         | directed | unspecified|             |           | ✓         |           |
| MultiNet      | unspecified| unspecified|             |           | ✓         |           |
| Netdraw VNA   | directed | unspecified|             |           | ✓         |           |
| NetML         | either   | unspecified|             |           | ✓         |           |
| Ncol          | undirected|             |             |           | ✓         |           |
| NNF           | either   | ✓           | ✓           |           |           |           |
| Nod           | directed |             |             |           |           |           |
| NOS           | directed |             |             |           |           |           |
| ns-tcl        | directed | ✓           | ✓           | ✓         |           |           |
| OGDML         | directed |             |             |           | ✓         |           |
| OGMML         | directed | unspecified|             |           | ✓         |           |
| Osprey        | undirected|             |             |           |           |           |
| Otter         | mixed    | unspecified|             |           |           |           |
| Pajek (.net)  | mixed    | loops only  |             |           | ✓         |           |
| Pajek (.paj)  | mixed    | loops only  |             |           | ✓         |           |
| Planar        | planar   |             |             |           |           |           |
| PSIMI         | unspecified| ✓           |             |           | ✓         |           |
| RSF           | directed | unspecified|             |           | ✓         |           |
| Rocketfuel    | undirected|             |             |           | ✓         |           |
| Rutherford-Boeing| either  |             |             |           | ✓         |           |
| SGB           | unspecified| unspecified|             |           | ✓         |           |
| SGF           | directed | unspecified|             |           | ✓         |           |
| S-Dot         | mixed    | ✓           | ✓           | ✓         |           |           |
| SIF           | mixed    | ✓           | ✓           | ✓         |           |           |
| SNAP          | either   | ✓           |             |           |           |           |
| SoNIA         | directed | ✓           |             |           | ✓         |           |
| Sparse6       | undirected|             |             |           | ✓         |           |
| StOCNET       | directed |             |             |           | ✓         |           |
| TGF, TGF      | either   | unspecified|             |           | ✓         |           |
| TGF           | either   | unspecified|             |           | ✓         |           |
| Tulip TLP     | directed | unspecified|             |           | ✓         |           |
| UCINET DL     | directed |             |             |           | ✓         |           |
| XGMML         | either   | unspecified|             |           |           |           |
| XMLBIF        | DAG      |             |             |           |            |           |
| XTND          | directed | unspecified|             |           | ✓         |           |
| YGF           | mixed    | ✓           |             |           |           |           |

**TABLE III:** Graph types (see §IV-B for explanation of columns).
characteristics for that vendor. Once again, inheritance is not through the structure of the graph, but through a further structure defined on the graph objects.

**visualisation data**: Files that allow arbitrary attributes can always provide data to be used in visualising the graph, but here we refer to formats that explicitly provide such data.

The level of visualisation data varies dramatically: some formats only allow position information for nodes, whereas others allow SVG definitions to be used in drawing the nodes. Still others provide guidance about which layout algorithms to use in displaying the graph. There is not space here to document all of the variations possible, so we simply indicate whether any such data is defined or not.

**ports**: These are a specialised piece of layout information: often ports\(^5\) are often specified by a compass direction, and indicate where on a node the link should join to it. We include ports in addition to the previous field because port-based information can also carry semantic information about the relationship between links on a complex node: e.g., the arrangement of links on a real device like an Internet router.

**temporal data/dynamics**: A topic of interest is analysis of graphs as they change [95]. One way to store this information is as a series of “snap-shot” graphs, but storing it all together in the same file has some appeal. A few formats provide some variant on this: allowing links or nodes to be given a lifetime, or proving “edits” to the graph at specific epochs.

Table IV explains the attribute features that are supported by each format.

**D. General**

**extensible**: Some formats allow extensibility in varying forms. We only consider them to have this facility, however, if they provide an explicit mechanism. For instance, we do not regard all XML derivatives as intrinsically extensible because they could, in principle, be extended using standard XML techniques. The format has to explain the explicit mechanism whereby it is extended. Simply adding extra attributes is not considered extensibility.

**schema checking**: A format that provides an explicit mechanism to check that a file is in a valid format is useful. We only say it has this facility if a tool exists to perform the check (a schema-checking program, DTD, or other similar formal tool).

**checksums**: It is possible for large data files to become corrupted. A common preventative (or at least check for this problem) is to use a checksum. This is possible for all files, but we say that a given format has this capability if it includes it as an internal component (usually checking everything except the checksum itself). Only a few formats contain this check.

\(^5\)Ports are also called hooks in Pajek.

**external data references**: Some formats allow reference to external files. This could be for visualisation data, metadata, or other purposes. There are several approaches and views on external references, but we record whether it is expected that all relevant information will be in the file, or whether there might be something external. Again, we look for an explicit explanation of the mechanism, not implicit inheritance from the parent file format.

**multiple graphs**: Some formats allow multiple graphs to be held in one file. Again, we only count this as a feature if the specification explains how explicitly.

**incremental specification**: A small number of formats that present multiple graphs allow these graphs to be specified incrementally. This is subtly different from including temporal dynamics, as there is no implication of time, and the different graphs could potentially be unrelated (for instance, this might be used to describe graph edit distance problems).

In a sense incremental specification is a simple case of constructive graph definition, but it is a very limited case, with specific application, so we list it separately.

Table V provides information on the other features of the file formats.

**V. Data statistics**

In this section we statistically summarise the necessarily large tables presented earlier. Some of the charts already presented provide some details, but we explore in more detail by looking at the others to calculate the proportion of formats supporting each of the features listed. This is plotted in Figure 11. Note that in regard to features with multiple answers (e.g., representation), we break the possibilities into categories and list the proportion that support each category.

Most obviously, there is a large support for edge representations along with an edge weight. Visualisation data is also widely supported.

Next we look at bivariate correlation between columns in the tables. For each pair of columns, we calculate a contingency table and then a P-value for the Fisher exact test [102], which is used because we have lots of small strata. Figure 11 shows the significantly correlated pairs, where this is defined as having a significant P-value after Bonferroni adjustment [103].

Many of the results are obvious. For instance, it is hardly surprising that there should be a significant correlation between the file structure and schema checking.

On the other hand there are many surprising effects:

- hyper-graphs and ports are often associated; and
- multi-graph and default values are also associated.

These seem to be indications that the type of file author who thinks carefully about certain aspects of the file (e.g., the types of graphs that will be represented) also thinks about other aspects that require care. Thus dividing the formats in “careful” and “quick and dirty”. More work is required to establish if this connection is genuine or merely accidental.
| Graph Format | edgeweights | multiple attributes | default values | multiple inheritance | visualisation data | ports | temporal data/dynamics |
|--------------|-------------|---------------------|----------------|-----------------------|-------------------|-------|-----------------------|
| binetv4      | ✓           | fixed               |                |                       |                   |       |                       |
| BioGRID TAB  | ✓           | fixed               |                |                       |                   |       | ✓                     |
| BLAG, GDToolkit | ✓         | fixed               |                |                       |                   |       |                       |
| BVGraph      | ✓           | fixed               |                |                       |                   |       |                       |
| Chaco        | ✓           | fixed               |                |                       |                   |       |                       |
| Cluto        | ✓           | fixed               |                |                       |                   |       | ✓                     |
| DGS          | ✓           | arbitrary            | ✓              | ✓                     |                   |       |                       |
| DGML         | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| DIMACS       | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| Dot          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| DotML        | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| DyNetML      | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GAMFF        | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GDF          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GDL          | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GEDCOM       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GEXF         | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| GML          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Graph6       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| Graph::Easy  | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GraphEd      | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GraphJSON    | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| GraphML      | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| GraphSON     | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GraphXML     | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GraX         | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GRXL         | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       |                       |
| GT-ITM       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| GXL          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Harwell-Boeing | ✓         | fixed               |                |                       |                   |       | ✓                     |
| Inet         | ✓           | fixed               |                |                       |                   |       | ✓                     |
| ITDK         | ✓           | fixed               |                |                       |                   |       | ✓                     |
| JSON Graph   | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| LEDA         | ✓           | fixed               |                |                       |                   |       | ✓                     |
| LGF          | ✓           | ✓                   |                |                       |                   |       | ✓                     |
| LGL          | ✓           | ✓                   |                |                       |                   |       | ✓                     |
| LibSea       | ✓           | ✓                   |                |                       |                   |       | ✓                     |
| KrackPlot     | ✓           |                     |                |                       |                   |       | ✓                     |
| Matlab       | ✓           | almost              |                |                       |                   |       |                       |
| Matrix       | ✓           |                     |                |                       |                   |       |                       |
| Mivia        | ✓           |                     |                |                       |                   |       |                       |
| MultiNet     | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Netdraw VNA   | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| NetML        | ✓           | ✓                   |                |                       |                   |       | ✓                     |
| Ncol         | ✓           | ✓                   |                |                       |                   |       | ✓                     |
| NNF          | ✓           |                     |                |                       |                   |       | ✓                     |
| Nod          | ✓           |                     |                |                       |                   |       | ✓                     |
| NOS          | ✓           |                     |                |                       |                   |       | ✓                     |
| ns-tcl       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| OGDML        | ✓           | fixed               |                |                       |                   |       | ✓                     |
| OGMML        | ✓           | fixed               |                |                       |                   |       | ✓                     |
| Osprey       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| Otter        | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Pajek (.net) | ✓           | fixed               |                |                       |                   |       | ✓                     |
| Pajek (.paj) | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Planar       | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| PSI MI       | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| RSF          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Rocketfuel   | ✓           | fixed               |                |                       |                   |       | ✓                     |
| Rutherford-Boeing | ✓       | fixed               |                |                       |                   |       | ✓                     |
| SGB          | ✓           | fixed               |                |                       |                   |       | ✓                     |
| SGF          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| S-Dot        | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| SIF          | ✓           |                     |                |                       |                   |       | ✓                     |
| SNAP         | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| SoNIA        | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| Sparse6      | ✓           |                     |                |                       |                   |       | ✓                     |
| SiOCNET      | ✓           | fixed               |                |                       |                   |       | ✓                     |
| TEI          | ✓           | fixed               |                |                       |                   |       | ✓                     |
| TGF, TGF     | ✓           |                     |                |                       |                   |       | ✓                     |
| Tulip TLP    | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| UCINET DL    | ✓           |                     |                |                       |                   |       | ✓                     |
| XGMML        | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |
| XMLBIF       | ✓           | fixed               |                |                       |                   |       | ✓                     |
| XTNM         | ✓           | fixed               |                |                       |                   |       | ✓                     |
| YGF          | ✓           | arbitrary            | ✓              | ✓                     | ✓                 |       | ✓                     |

**TABLE IV**: Allowed attributes (see §IV-C for explanation of columns).
| Graph Format                      | extensible | schema checking | checksums | external references | data | multiple graphs | incremental specifications |
|----------------------------------|------------|-----------------|-----------|---------------------|------|-----------------|---------------------------|
| bintsv4                          |            |                 |           |                     |      |                 |                           |
| BioGRID TAB                      |            |                 |           |                     |      |                 |                           |
| BLAG, GDToolkit                  |            |                 |           |                     |      |                 |                           |
| BVGraph                          | ✓          |                 | ✓         |                     |      |                 |                           |
| Chaco                            |            |                 |           |                     |      |                 |                           |
| Cluto                            |            |                 |           |                     |      |                 |                           |
| DGS                              | ✓          |                 |           |                     |      |                 |                           |
| DGML                             | ✓          |                 |           |                     |      |                 |                           |
| DIMACS                           | ✓          |                 | ✓         |                     |      |                 |                           |
| Dot                              | ✓          |                 | ✓         |                     |      |                 |                           |
| DotML                            |            |                 |           |                     |      |                 |                           |
| DyNetML                          | ✓          |                 | ✓         |                     |      |                 | ✓                         |
| GAMIFF                           | ✓          |                 | ✓         |                     |      |                 |                           |
| GDF                              | ✓          |                 |           |                     |      |                 |                           |
| GDL                              | ✓          |                 |           |                     |      |                 |                           |
| GEDCOM                           | ✓          |                 |           |                     |      |                 |                           |
| GEXF                             | ✓          |                 |           |                     |      |                 | ✓                         |
| GML                              | ✓          |                 | ✓         |                     |      |                 |                           |
| GraphEasy                        | ✓          |                 |           |                     |      |                 | ✓                         |
| GraphEd                          | ✓          |                 |           |                     |      |                 |                           |
| GraphJSON                        | ✓          |                 |           |                     |      |                 |                           |
| GraphML                          | ✓          |                 |           |                     |      |                 | ✓                         |
| GraphSON                         | ✓          |                 |           |                     |      |                 |                           |
| GraphXML                         | ✓          |                 |           |                     |      |                 |                           |
| GraX                             | ✓          |                 |           |                     |      |                 |                           |
| GRXL                             | ✓          |                 |           |                     |      |                 |                           |
| GT-ITM                           | ✓          |                 |           |                     |      |                 |                           |
| GXL                              | ✓          |                 |           |                     |      |                 |                           |
| Harwell-Boeing                    |            |                 |           |                     |      |                 |                           |
| Inet                             |            |                 |           |                     |      |                 |                           |
| ITDK                             |            |                 |           |                     |      |                 |                           |
| JSON Graph                       | ✓          |                 |           |                     |      |                 |                           |
| LEDA                             | ✓          |                 |           |                     |      |                 |                           |
| LGF                              | ✓          |                 |           |                     |      |                 |                           |
| LGL                              | ✓          |                 |           |                     |      |                 |                           |
| LibSea                           | ✓          |                 |           |                     |      |                 |                           |
| KrackPlot                        |            |                 |           |                     |      |                 |                           |
| Matlab                           |            |                 |           |                     |      |                 |                           |
| Matrix                           |            |                 |           |                     |      |                 |                           |
| Mivia                            |            |                 |           |                     |      |                 |                           |
| MultiNet                         |            |                 |           |                     |      |                 |                           |
| Netdraw VNA                      | ✓          |                 |           |                     |      |                 | ✓                         |
| NetML                            |            |                 |           |                     |      |                 |                           |
| Ncol                             |            |                 |           |                     |      |                 |                           |
| NNF                              |            |                 |           |                     |      |                 |                           |
| Nod                              |            |                 |           |                     |      |                 |                           |
| NOS                              |            |                 |           |                     |      |                 |                           |
| ns-tcl                           | ✓          |                 |           |                     |      |                 |                           |
| OGDCL                            | ✓          |                 |           |                     |      |                 |                           |
| OGML                             | ✓          |                 |           |                     |      |                 |                           |
| Osprey                           |            |                 |           |                     |      |                 |                           |
| Otter                            |            |                 |           |                     |      |                 |                           |
| Pajek (.net)                     | ✓          |                 |           |                     |      |                 |                           |
| Pajek (.paj)                     | ✓          |                 |           |                     |      |                 |                           |
| Planar                           | ✓          |                 |           |                     |      |                 |                           |
| PSI MI                           | ✓          |                 |           |                     |      |                 |                           |
| RSF                              |            |                 |           |                     |      |                 |                           |
| Rocketfuel                       | ✓          |                 |           |                     |      |                 |                           |
| Rutherford-Boeing                 |            |                 |           |                     |      |                 |                           |
| SGB                              | ✓          | partial         | ✓         |                     |      |                 |                           |
| SGP                              | ✓          |                 |           |                     |      |                 |                           |
| S-Dot                            | ✓          |                 |           |                     |      |                 |                           |
| SIF                              | ✓          |                 |           |                     |      |                 |                           |
| SNAP                             | ✓          |                 |           |                     |      |                 |                           |
| SoNIA                            |            |                 |           |                     |      |                 |                           |
| Sparse6                          | ✓          |                 |           |                     |      |                 |                           |
| SiOCNET                          | ✓          |                 |           |                     |      |                 |                           |
| TEI                              | ✓          |                 |           |                     |      |                 |                           |
| TGF, TGF                         |            |                 |           |                     |      |                 |                           |
| Tulip TLP                        |            |                 |           |                     |      |                 |                           |
| UCINET DL                        | ✓          |                 |           |                     |      |                 |                           |
| XGMML                            | ✓          |                 |           |                     |      |                 |                           |
| XMLBIF                           | ✓          |                 |           |                     |      |                 |                           |
| XTND                             | ✓          |                 |           |                     |      |                 |                           |

**TABLE V:** Other properties (see § IV-D for explanation of columns).
VI. DECISIONS

The list above is not intended to be pejorative. However, it is potential users need to make decisions about which format to use. There are several issues that need be considered in such a decision, and although the first is the feature list required, there are others:

**data size**: The size of the graph data to be recorded and used is an important factor in file format decisions. This is sometimes glossed over when XML-style formats are considered: these are very redundant formats, and hence much larger than needed, but they compress well. Hence, the compressed version may be no longer than a tighter initial specification. However, the issue of read/write time (and indeed compression/decompression time) still depends greatly on the format’s wordiness. Large graphs need tighter formats: either binary formats, or at least those that avoid unnecessary bloat.

On the far end of the spectrum is the possibility of graph-specific compression being part of the storage process (much as many image formats provide image compression as an integral features). Only one format we found provides true graph-based compression: BVGraph.

**edge density**: Edge density affects the choice of best representation of a graph. Very sparse graphs are best represented by edge lists, moderately sparse graphs are (perhaps) slightly better stored as neighbour lists, and
Fig. 11: P-values for significant associations between columns.

dense graphs may be better stored as a full adjacency matrix.

**access method**: Most graph formats are designed to be read serially directly into memory in their entirety. Only BV-Graph seems to provide support for random (or indexed subgraph) access to part of a graph.

Another example of alternative access methods is that many graph algorithms can be reduced to a generalised matrix-vector product, and can be performed by repeatedly streaming the edges from disk without loading the graph into memory, which is necessary if the data is truly large [104].

Further, formats could potentially enable reading the graph in parallel to exploit clustered computing [104].

In other cases, a single graph might be part of a larger database.

In general these issues seem to have been left in the field of graph databases [1], and not considered for exchange of data.

**human readability**: Portability requires the file to be machine readable, but a file that is more easily understood by humans is potentially better because it is easier to enter and check. Many of graph examples datasets were entered at least in part by hand: often through a spreadsheet or text editor, and are maintained in the same way. In the case of the Internet topology Zoo [105] the data were entered “semi-manually” through yED (a graph editing program).

Human readability requires a text file in a logical format, but it also needs to avoid: (i) bloat, which distracts the reader with unnecessary text, and (ii) the file to be organised neatly. XML formats often fail on these: the first because of the volume of tags, and the second because they allow organisations which are unreadable, e.g., with all the text on one line.

Ultimately, human readability is a highly subjective criteria. Some people may find XML easy to read, and others get distracted by the tags. As such, we won’t comment on it further here.

**maintenance**: The document [106] deals with the use cases for graphs, which we can broadly classify (in simpler nomenclature) as

- **creator**: originally creates the data set,
- **investigator**: uses the data for some purpose, and
- **curator**: refines and corrects the data.

Most current graph-exchange formats are oriented at creation and investigation, but not curation.

Data can easily contain errors, and correcting these *ex post facto* should be supported, but most formats do not deal with issues such as

- **version control**: to allow, for instance, users to know exactly which dataset was used in a particular publication; and
- **diff**: the ability to find semantic differences between
two files to learn what changed between the two (as opposed to simply seeing syntactical differences).

Taking differences of arbitrary graph data is hard (it involves solving the near-isomorphism problem), but much graph data is labelled and in this case differences can be found easily.

**Documentation**: Through compiling the information used in this paper it has become obvious that a key limitation of many formats is incomplete documentation. Hidden assumptions, specification by (limited) examples, and/or documentation by source code are all common. Ideally, any truly portable format should have a complete, highly-specific schema; human readable documentation (with examples); and source code. All of these together provide the ideal documentation.

**Support**: Finally, the support for the format in a variety of tools is a crucial requirement for exchange of data. Likewise, support for formats in a variety of public databases makes it more useful. We shall consider this issue in more detail below.

### A. Software Support

The most difficult issue surrounding software support is that a piece of software may notionally support a file format, and yet still be incompatible with other software notionally supporting the same format.

For instance, software might

- fail to accept integers outside a particular range;
- have varying case sensitivity;
- be unable to read the right character set;
- be unable to read strings beyond a particular length (very few formats specify buffer or string lengths); or
- fail to cope with files larger than some size.

Size is interesting, because almost no documentation exists for size limits for any data formats. However, it should be reasonably obvious that if 32 bit integers are used, then the largest number of (integer) identifiers is around 4 billion. In the past this was large enough that the need to specify it may have seemed small. With today’s graphs, this could be an important limitation.

Even more pernicious is partial support for a format. Even when documented this makes our job hard, but partial support is not often documented. Instances include:

- hyper-graphs supported in the format, but not in software;
- or
- some small number of formats make mention of allowing complex numbers; or
- partial support for hierarchy (i.e., the file can be read, but the subgraph structure is not retained).

Even more complex is the fact that some features may be supported on read or write, but not both.

The list of potential software is long, even more so than the list of formats, so we won’t try to survey them here as well. Instead we refer readers to [2], which contains a cross-section of both formats and their software support.

A common conclusion amongst those who look at this type of data is that GraphML and Pajek are the most commonly supported in modern systems, but they are by no means universal or even supported by the majority of tools.

Another related issue is how hard it would be to provide support for a format in a new tool. This is a complex issue, but there are several factors that influence it. Documentation, as mentioned above, is a critical issue, as is the ability to use existing tool-sets such as those for XML or JSON. However, one issue hasn’t been discussed, which is the provision of an adequate test dataset.

1) **Test cases**: It’s a tautology that implementation of a new graph format isn’t terribly hard, except for the hard bits. The point is, though, that many formats don’t tackle these.

Many areas of difficulty are listed above. One we have not discussed in detail is the existence of test cases. Ideally, in addition to a complete specification, there should be a set of accompanying files providing encoded data to demonstrate each feature over a reasonable range of values [107]. These files could then be used by other developers to check their parser implementations.

The concept of test cases is from software engineering 101. However, we are not aware of a single format that provides a truly complete set. Some provide a set of small examples, but these don’t express all of the features of the data. For instance, encoding, size limits, advanced features and so on are rarely considered in these examples. Other formats are used for exchange of datasets, and these form a de facto standard.

More often, only a small set of examples is provided, and these don’t express all of the features of the data. For instance, encoding, size limits, advanced features and so on are rarely considered in these examples. Other exchange sets are used to provide large datasets, but these two are unsuitable for test purposes because they are large and complex, and don’t exercise features in isolation. What is needed, is a set of test cases that exercise the features in a controlled and testable manner.

### B. Public DB Support

The other type of support we might wish to see is general support amongst those who provide data publicly. There are many public databases that provide example networks for benchmarking or research. We provide a list in Table VI of some of the better known of these with their format choices. Additional data sources are listed in [108], and a detailed taxonomy and examples of computer-network data appears in [109].

There is no clear winner here: slightly preferred is a variant of the Trivial Graph Format due to its least-common-denominator status (but note that this isn’t really one format, so much as a collection of equivalent formats). Overall, however, the formats seem to be written for the data rather than the other way around. That, in itself, is an illustration of the problem.

### C. Future considerations

There are many considerations or features that we could consider. The set chosen above were chosen for the illustrative value, given current graph exchange concerns. In the future, there are other features that could become interesting, and we
| Dataset     | Full name                                                                 | Format                                                                 |
|-------------|---------------------------------------------------------------------------|------------------------------------------------------------------------|
| ARG/VF      | Mivia ARG Database and VF Library                                         | Mivia                                                                  |
| BioGRID     | Biological General Repository for Interaction Datasets                    | PSI MI, Osprey, BioGRID, PTMTAB                                        |
| CASOS       | CMU CASOS Datasets                                                        | DyNetML, GML, UCINET, GraphML                                          |
| ClueWeb09   | ClueWeb09 Web Graph                                                       | BVGraph, TGF                                                           |
| DIMACS10    | DIMACS Implementation Challenges                                          | DIMACS                                                                 |
| DSI         | Web Algorithms Lab Data                                                   | BVGraph                                                                |
| Enron       | Enron email dataset                                                       | TGF                                                                    |
| Graph-Archive | GraphArchive - Exchange and Archive System for Graphs                      | GraphML                                                                |
| GraphBench  | GraphBench                                                                | TGF                                                                    |
| HOG         | The House of Graphs                                                       | TGF, Graph6, Multicode, Planar                                         |
| HPRD        | Human Protein Reference Database                                          | PSI MI, TSV                                                            |
| Hyperlink   | Web Data Commons - Hyperlink Graphs                                       | Pajek, WebGraph                                                        |
| IAM         | IAM Graph Database Repository                                             | GXL                                                                    |
| ITDK        | CAIDA Macroscopic Internet Topology Data Kit                              | ITDK                                                                  |
| Zoo         | Internet Topology Zoo                                                     | GML, GraphML                                                           |
| Matrix Market | Matrix Market                                                            | Matrix Market                                                          |
| NAS         | NAS (NASA) Graph Collection                                               | GAMFF                                                                  |
| Pajek       | Pajek Data Sets                                                           | Pajek                                                                  |
| Rocketfuel  | Rocketfuel                                                                | Rocketfuel                                                             |
| SGB         | Stanford GraphBase                                                        | SGB                                                                    |
| SNAP        | Stanford Network Analysis Platform                                        | SNAP                                                                   |
| Tore        | Tore Opsahl Datsets                                                       | UCINET, tnet                                                           |
| Twitter     | What is Twitter, a Social Network or a News Media?                        | TGF                                                                    |
| UF          | The University of Florida Sparse Matrix Collection                        | Matrix Market, Rutherford-Boeing, Matlab                                |
| WF          | Wasserman and Faust datasets                                              | Pajek                                                                  |

Table VI: Public Databases. NB: there is some overlap in the data kept in these repositories.

list and discuss some of these in the following. In general, we have not tried to classify the file formats by these features simply because it seems that few formats support these, but information is sparse and it is difficult to be certain in many cases. Many of the issues cross over into issues that have been considered in the domain of graph databases [1], and so techniques to tackle the problems exist, but have not been applied to the world of exchanging data. We will discuss at least a few of these issues below.

**self-describing**: this refers to whether a file provides its own definition of its format. XML arguably has this property, but still relies on correct semantic interpretation of arbitrary labels, for instance link “weight” could mean several different things, and have any number of different units.

**data distribution**: most graph formats are monolithic in that the entire graph is held in one file. Even those that allow multiple files use this to structure the type of information each contains, not to spread the information evenly. As graph data becomes larger, and the need to query subsections of the graph grows, we need to be able to create modularity in the graph representation. Formats that provide the ability to distribute the graph information over multiple (indexed) files provides a capability that could be very useful [100].

This type of consideration, however, seems to have been limited primarily to graph databases [1], not exchange formats.

**node list**: does the format have a separate node list, or is this list implicit in the edges?

**multi-layer**: generalisations of graphs can have a layer structure [97] (resembling in some cases hierarchy, and in some cases temporal evolution, but more flexible than either by itself). Multi-layer graphs can naturally be described by adjacency tensors, however, complete multi-layer support doesn’t yet appear in any format.

**linear indexing**: Another consideration in classifying network graph formats in the future is whether they use linear indices [131], by which we mean that if the network has \( n \) nodes, then they are labelled 1, 2, \ldots, \( n \) (equivalently we could start at 0).

Linear indexes make a dataset easier to deal with at two levels. Firstly, it is more efficient to store integers than arbitrary strings: so both node and edge lists can be read/written more quickly, but also when the data is read into a program if the node names are arbitrary then the node data needs an extra layer of indirection such as provided by an associative array, and for large datasets this can reduce performance compared to storing the data in a simply indexed array.

The issue is primarily important for very large datasets, but these are becoming more common.

Note that it doesn’t mean that nodes can’t be named: they can have all the usual meta-data one might associate with the node, but it means that the primary reference to the node is arithmetically simple to work with.
In general, matrix representations have an implicit linear indexing, but other formats are less clear about the issue. However, some illustrative examples include SNAP, which uses integer but not linear indices and Matlab and BVGraph, which both use linear indices. One can also imagine creating simple indexes into the edges, but this goes a step beyond any exchange formats goals so far.

Serialisation: Many graph data formats are designed to be read into memory in their entirety. They do not support the ability to read through the data serially, and perform analysis on the fly.

Random access and/or queries: As noted, most graph data formats are designed to be read into memory in their entirety. But an even bigger limitation, even of those that can be read serially is that they do not support the ability to find information about an arbitrary link or node (or subset of such) without reading the whole data set (at least through to the relevant point). Again, this is only a problem for very large datasets, but clearly is a huge issue for such sets. Not least because it is easy to imagine datasets to large to be read into realistic RAMs, but also because this is hopelessly inefficient for certain types of analysis.

Again, graph databases deal with this issue, but exchange formats have not, so far.

Parallel read/write: The monolithic nature of most graph exchange formats make them unsuitable for parallel writing. It is hard to separate parts of a graph and write them independently. The fact that it is assumed that most files will be read in their entirety also limits the ability to parallelise read operations.

Again graph databases attack this problem, whereas exchange formats have not.

D. Discussion

The point of all this: what should be done here, how should one proceed. There are three major considerations:

- what representation of a graph (or generalised graph) will be used: edge or neighbour list, adjacency matrix, paths, or some constructive or procedural approach;
- what additional information is to be added, and how flexible this information should be; and
- what encapsulation of the data is to be used (XML and more recently JSON seem to be favourites).

Then there are a substantial set of other features and aspects of the dataset that should be considered in the choice of formats.

VII. Conclusion

The science of graphs and networks needs portable, well-documented, precisely-defined, exchange formats. There are many existing formats, and this paper seeks to unravel this mess, most notably with the aim of reducing the number of new formats developed.

One size probably does not fit all though. There is a clear need for at least three major types of file format:

- a general, flexible, extensible approach such as GraphML;
- a quick and dirty approach that satisfies the least common denominator for the exchange of information to/from the simplest software; and
- a very efficient (compressed) format for very large graphs.

It’s not clear that any format at present has a complete enough list of features to take the roll of the first format. No doubt this will continue to evolve as well, as new features are required. Moreover, the requirement human readability of the data is evolving as more datasets are generated through automated means rather than entered by hand.

The second is easy, but there are very many contenders, and settling on one will be hard.

The final one should be seen as an interesting research topic given there are multiple compression techniques available. However, the only true example of a compressive format is BVGraph does not allow attributes, and so some thought might be devoted to that topic.

Finally, although having arbitrarily extendable attributes for the graph and its components seems an attractive feature, it is easy to see why specialised applications would prefer a pre-defined list. Most obviously to make support for those attributes easier (both in terms of parsing\(^6\), and in terms of exchange\(^5\)). However, there is also the subtle issue of what attributes could be included vs those that should be included. Explicit definition of the required attributes can create a better overall set of data by forcing the lowest-common-denominator to be higher.

In the end, maybe what is needed is actually a container format: allowing specification of parts of a graph in alternative formats. Or allowing specification of meta-data and labels in an XML-like format, but the edge data in a more compact form.

Alternatively, good conversion programs could simplify the issue, but at present most software tools are not designed with this in mind (for instance, such a tool needs to be lightweight, but warn about different available features, and support a large range of possibilities).

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\(^6\) The ability to specify arbitrary attributes usually comes at the cost of a more complex mechanism being required to read and write these. The cost is usually in terms of supporting code complexity, and read/write times.

\(^5\) Exchange requires common definitions of the meaning of the attributes, not just syntax. If the attributes are arbitrary then some information might be mistranslated by use of different attributes to hold similar information, or the same attribute to hold different information. For example, for graphic attributes, including the size of a vertex to be drawn is not very useful without well-defined units.
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