25

Computer Networks

Giuseppe Di Battista
Roma Tre University

Massimo Rimondini
Roma Tre University

25.1 Introduction

Communication systems are nowadays fundamental to support various applications, and this is especially true for computer networks as their utmost expression. Some examples include information interchange for critical operations, such as bank transfers or military data, as well as commonly used services such as the web, email, or streaming of multimedia contents. It is therefore essential to be able to ensure an uninterrupted and efficient operation of a computer network.

However, the task of maintaining a computer network may get considerably harder as the complexity of the network increases, either in terms of the topology or in terms of the enabled services. Therefore, as it often happens in other contexts, a significant aid in the maintenance comes from the ability to obtain a visual representation of the network.

25.1.1 Benefits of Visualizing Computer Networks

The availability of a methodology and a tool to visualize computer networks brings benefits both to network administrators and to researchers that work on studying network related phenomena.

Network administrators can exploit visualization tools to accurately design a network before deploying it. This includes, for example, defining the topology as well as tuning link bandwidths. At a higher level of abstraction, a visual representation of the interconnections

between Internet Service Providers (ISPs) can help to better plan future commercial relationships among them. On the other hand, once the network is operational, a visualization system can significantly help in maintaining it, by providing graphical monitoring facilities that also simplify troubleshooting potential problems.

The research community can also benefit from the existence of a methodology to visualize networks. For example, it is possible to validate a theoretical model by spotting anomalies in the generated layout at a glance. This is particularly useful for the case of techniques to infer network topologies based on a limited amount of information and for the case of random network generators. Also, a graphical representation of a network can support reconstructing the root cause and the impact of a particular routing event.

25.2   The Very Basics of Computer Networking

This section briefly recalls some basic concepts about the operation of computer networks.

25.2.1   A Network Model

A computer network essentially consists of an interconnection of devices (computers, printers, routers, etc.) that exchange information with each other. In order to do this, a device encodes data in a format that other devices can understand, which is called *protocol*. To support a flexible configuration and ensure a good scalability, several encodings are usually stacked upon each other, so that data are first encoded (*encapsulated*) using a certain protocol, then the encoded data are encapsulated using another protocol, the resulting information is again encoded using a different protocol, and so on. After the last encapsulation step, information is actually sent to the destination, which performs the steps in reverse order: interprets the protocol used in received information and decapsulates the data, then again the decoded information is analyzed to interpret a different protocol and its payload is decapsulated, etc. After the last decapsulation step, the information that was originally forwarded by the sender is available for processing by the receiver.

This mechanism allows to consider and configure separately the different features of a network. For example, a high level protocol such as HTTP (HyperText Transfer Protocol), that is typically used to transfer web pages, can be configured and used independently of the actual protocol spoken on the transmission medium (copper cable, fiber, wireless link, etc.).

This kind of operation is defined in the ISO/IEC Open Systems Interconnection (OSI) model [fS, Com, ISO]. That is, computer networks usually operate according to a layered model, where each layer corresponds to an encapsulation/decapsulation step and is associated with a specific protocol used to communicate with the corresponding layer at the destination. According to the ISO OSI model, network protocols are organized as a *stack* consisting of 7 layers. Therefore, the setup of a network link consists at least of the specification of the stack of protocols to be used.

The following sections briefly describe some of the most commonly adopted network protocols.

25.2.2   Interconnection Technologies

Network links can be implemented using different physical media, usually wire, fiber, or air. The usage of a physical medium rather than another implies a choice for the implementation of the *physical layer*, the lowest layer of the ISO OSI protocol stack. At this layer,

the implementation contains the specification of parameters such as electrical signals or frequencies, that are used to encode the information transmitted on the physical medium. Examples of protocols at the physical layer are SDH and DWDM [SS96, IMN84].

Often, the choice of a physical medium is associated with the choice of a *data link layer* protocol that exploits the medium in such a way as to provide a reasonably fast and reliable communication channel. For example, wired communication can happen by using Ethernet on a local network or SDLC on a wide area network [Sta07, Sys09b]. On the other hand, wireless communication can take place using either the IEEE802.11 protocol or the IEEE802.16/WiMAX protocol, the choice depending on parameters such as the distance between antennas, the transmitting power, or the desired communication speed [IEE09, wim09]. Communication over optical fiber often takes place on Gigabit Ethernet links [Nor02].

25.2.3 Routing and Routing Protocols

Once the protocols for the physical and data link layers have been chosen, there must be a mechanism to allow the delivery of a piece of information from any source in the network to any destination. This is accomplished by *network layer* protocols such as the well-known Internet Protocol [Pos81b] (IP), which are usually run by devices known as *routers*.

Actually, network layer protocols support the reachability of remote destinations based on the knowledge of a previously built *routing table*, a data structure stored on the routers that specifies the physical port to be used to forward information to a given destination. Since network topologies frequently change, there must also be a way to update the routing tables without human intervention. This is achieved by running *routing protocols* that are designed for this purpose, such as OSPF, IS-IS, and BGP [Moy94, Ora90, YTS06]. While these protocols often exploit layers of the ISO OSI stack that are higher than the network layer, their function is still to support the operation of the network layer.

25.2.4 The Internet Structure

The structure of the Internet, both from the point of view of the topology and from the point of view of the configuration, is rather complex. The Internet embraces lots of different, yet interacting, physical media and data link protocols. The only commonly adopted standard is on the network layer protocol which, for almost all network nodes, can be assumed to be IP [Pos81b]. Actually, it is very common to hear about the TCP/IP stack: this is just a shortcut to indicate that the routing layer is implemented by IP and the transport layer (which is on top of the routing layer) is implemented by TCP.

Further complexity is brought about by the fact that different ISPs may be interested in adopting their own routing mechanisms, protocols, and policies, and they may establish different economical agreements with neighboring ISPs. This poses a big challenge because different parties, using different protocols, and adopting different configuration policies, must be enabled to communicate with each other.

For this reason, Internet devices are usually grouped into *Autonomous Systems* (ASes), such that within each AS a single routing protocol and consistent routing configurations are adopted. Routing between different ASes (*interdomain routing*) is made possible by the Border Gateway Protocol (BGP) [YTS06]. BGP has been conceived to support routing optimization as well as the specification of political or economical constraints on the routing. Because of its features, BGP is the ideal solution to implement, for example, commercial relationships.

Two BGP-speaking routers that are configured to exchange BGP routing information are

said to have a *peering*. Routing information exchanged over a peering includes at least data about the reachability of blocks of contiguous network addresses called *network prefixes*. Because of the relevance to the operation of Internet routing, a common requirement for both operators and researchers is to get a visual representation of the Internet topology at the level of peerings between Autonomous Systems.

25.2.5   The User's Point of View

The configuration of a network, even of a local area network, consists of a plenty of settings. However, depending on the type of usage and on the skill level of a network user, only a few settings may be relevant and, therefore, interesting candidates for visualization.

An ordinary user is typically only interested in getting plug-and-play connectivity, if possible without having to explicitly configure any parameter. In this case, getting a graphical representation of the network would be helpful for the user, because he could get an automatically generated representation of the topology without having to fiddle with any devices or advanced settings. Some modern operating systems provide this feature out of the box, usually as a support to automatic network troubleshooting procedures [Mic09].

Network administrators and operators have full knowledge of network settings and may also be responsible for its design. In this case, the purpose of a graphical representation would be to make maintenance easier, and for this reason the visualization should be enriched with additional information such as link usage and capacities, commercial relationships, routing changes, etc. Sometimes the visualization system may allow the administrator to interact with the network, so that he can quickly reconfigure some settings without using uncomfortable router interfaces.

Researchers have strong interests in studying the behavior of a network in order to build models that capture well network events and design algorithms and protocols that support a more efficient and robust operation. For this purpose, researchers may resort to examining different kinds of data, depending on the kind of analysis to be performed. Therefore, a visual representation that is augmented with additional information from those data can aid in pointing out interesting patterns and validating existing models against real world data.

25.3   A Taxonomy of Visualization Methods and Tools

It has been shown in previous sections that several aspects in the operation of a network can be better investigated by taking advantage of a visualization system. For this reason, a variety of methodologies and tools have been made available, each designed to address a certain kind of analysis.

The literature about the visualization of computer networks includes some interesting survey contributions. A paper by Withall et al. [WPP07] first considers some basic guidelines that network visualization systems should obey, then it distinguishes between contributions where the network topology is laid out using real geographic coordinates for network nodes and contributions where this constraint is relaxed. The same paper also surveys techniques focused on the visualization of data from a single point in the network, typically in the form of a plot. In 2002, Dodge et al. published a comprehensive book [KD01] that classifies visualization systems according to the type of information to be displayed. In particular, the book introduces visualization systems putting them in a historical perspective. Next, it spans over techniques for visualizing network topologies augmented with traffic volumes, the relationships among web pages, the structure of social networks, and some cues for futurist

visualizations of the Internet. A report by Vandenberghe et al. [VT06] briefly reviews some layout algorithms, then shows their effectiveness on a reference network topology. The same paper also provides a quick comparative evaluation of the described algorithms.

In this section we review methodologies and tools for the visualization of computer networks by proposing a classification according to some fundamental coordinates: the set of data being visualized, the drawing paradigm that is used to display information, and the features of the tools that implement visualization methodologies. Consider that some visualization methodologies may be conceived to work on nearly arbitrary data sets and to support different drawing paradigms. Such methodologies do not fit this classification and in the following will be gathered in groups called "Other." The following conventions are adopted in the classification:

- If a contribution adopts multiple approaches or, in general, falls into multiple classes, its citation is repeated for all the applicable values of the affected classification coordinate. For example, [BEW95] supports visualization at different scales and therefore may appear multiple times in the same table.

- If the methodology adopted in a paper or in a tool applies to arbitrary values of some classification coordinate, the contribution is considered in the Arbitrary or Customizable class.

- Contributions which do not fit any of the proposed values for a classification coordinate appear in the Other class. There are also contributions which we could not classify along some coordinate, for example because the approach is scarcely documented, and they appear in the Unknown class. Moreover, contributions that cannot be perfectly fit into a value of a classification coordinate because of some specificities (e.g., visualization at the level of granularity of countries instead of Autonomous Systems, or visualization of the nodes of a circuit-switched network instead of the routers of a packet-switched one) are accommodated in the best reasonably fitting class.

- All the contributions that are relevant within a certain section appear in every table in that section. For example, Tables 25.1 through 25.7 provide the reader with a general classification of the literature and therefore each of them considers all the contributions about visualization. Instead, each of the Tables from 25.10 to 25.13 considers all the contributions about Internet-scale visualization.

Some of the classification coordinates that we introduce in the following could be further refined. For example, the scale could consider the span of time considered in visualizations of historical data, or the number of packets that are transmitted during an observation period. In order to make the classification simpler and better understandable, we have picked values for the classification coordinates that offer a compromise between precision of the classification and ease of lookup.

25.3.1 Visualized Data

Depending on the specific goal, a network visualization system may visualize different kinds of data. We classify these data according to the following coordinates.

Scale : The visualization may span a local network, the entire network of an Internet Service Provider, or even the whole Internet. Table 25.1 classifies the contributions in the literature with respect to the scale of the visualization. As shown in the table, a significant number of contributions consider the whole Internet, and there are some that support visualization at different scales.

Scale		
	Internet	[BBGW04], [BBP07], [BEW95], [HPF07], [PH99], [PN99], [Jac99], [CAI09], [Dit09], [CBB00], [CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CE95], [CEH96], [CRC$^+$08], [GGW07], [GKN04], [GT00], [kc97], [GMO$^+$03], [LMZ04], [LMZ06], [MB95], [OCP$^+$07], [OCLZ08], [Piz07], [YSS05], [Sii01], [RIS09], [Oli09], [OC07], [oANTtE08], [AS06], [Gro00], [RTU09], [Che07], [Pro02], [LUM], [ea05], [Des09], [Map08], [DLV97], [Cor09], [Bou02], [Tel09], [Lim09], [Vis09], [Aug03], [WS04], [YGM05], [YMMW09]
	ISP	[AGL$^+$08], [AGN99], [BCD$^+$04], [BEW95], [Mei00], [kcH97], [EHH$^+$00], [FNMT94], [GMN03], [KMG88], [KNK99], [KNTK99], [Kvi03], [MFKN07], [MHkcF96], [MKN$^+$07], [Piz07], [SMW04], [Sal00], [3Co09], [oANTtE08], [Ent09], [RTU09], [IBM09], [Dar09], [Net09c], [WAN08], [EHH$^+$05], [Com09b], [CP], [Hew09], [Tec09], [Sof09b], [UNI09], [Jon09]
	Local	[AGL$^+$08], [EHH$^+$00], [EW93], [KGS07], [PIP05], [Mic09], [WCH$^+$03], [3Co09], [Ent09], [TvAG$^+$06], [Net09b], [Hir07], [Net09c], [Vol09], [EHH$^+$05], [NoCSNCTUT09], [Wyv09], [net09a], [Tec09], [Sof09a], [Tec05], [Jon09], [Ips09], [WH09], [ZW92]
	Arbitrary	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [McR99], [Mun97], [Hyu05], [Bro01], [AHDBV], [Cor]

Table 25.1   A classification of the state of the art in terms of visualization scale.

Granularity : Determines the level of detail at which information is made available.
A network visualization system may display single routers and hosts, the Points
of Presence (POPs, introduced in Section 25.6), or the OSPF areas in the network
of an Internet Service Provider, or the Autonomous Systems that, all together,
constitute the Internet. It is interesting to correlate the granularity of the vi-
sualization with the scale. From Table 25.2 it is possible to notice that, even
if the most natural granularities are perhaps Autonomous System for the Inter-
net, POP for ISPs, and Router/Host for Local networks, there are several works
that explore different choices. For example the router-level granularity, typically
adopted for local networks, is often used in the visualization of POPs or even
the Internet. Of course, some of the contributions that allow the visualization
with an arbitrary scale and granularity trade quality of the representation for
flexibility.

Additional displayed information : Displayed network topologies may be aug-
mented with auxiliary information that better describe the features of nodes and
links. Such information may include bandwidth, delays, traffic volumes, TCP
ports, geographical locations, etc., and are typically encoded by using different
sizes, colors, and labels for both vertices and edges. Table 25.3 classifies contri-
butions in the literature according to their ability to enrich visualized network
topologies with additional information. It can be easily noticed that only a small
number of visualization approaches is limited to the representation of the sole
topology. The row Unknown accounts for those contributions for which it could
not be determined whether additional information is also displayed.

Data source : Typical sources of information about the operation of a network are
collections of routing data. Since there are lots of different ways to obtain such
data, instead of classifying the literature along this coordinate we separately pro-

		Scale			
		Internet	**ISP**	**Local**	**Arbitrary**
Granularity	**Autonomous System**	[BBGW04], [BBP07], [CAI09], [CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CRC$^+$08], [GGW07], [kc97], [GMO$^+$03], [LMZ04], [LMZ06], [OCP$^+$07], [OCLZ08], [RIS09], [Oli09], [OC07], [Gro00], [Pro02], [Des09], [Cor09], [Bou02], [WS04], [YGM05], [YMMW09]			
	POP	[CE95], [CEH96]	[AGN99], [kcH97], [KNK99], [KNTK99], [SMW04]		
	Router/Host	[BEW95], [PN99], [Jac99], [Dit09], [CBB00], [GT00], [Piz07], [YSS05], [Sii01], [oANTtE08], [AS06], [RTU09], [Che07], [LUM], [ea05], [Vis09], [Aug03]	[AGL$^+$08], [BCD$^+$04], [BEW95], [Mei00], [EHH$^+$00], [FNMT94], [KMG88], [Kvi03], [MHkcF96], [Piz07], [SMW04], [Sal00], [3Co09], [oANTtE08], [Ent09], [RTU09], [IBM09], [Dar09], [Net09c], [WAN08], [EHH$^+$05], [Com09b], [CP], [Hew09], [Tec09], [UNI09], [Jon09]	[AGL$^+$08], [EHH$^+$00], [PIP05], [Mic09], [WCH$^+$03], [3Co09], [Ent09], [TvAG$^+$06], [Net09b], [Hir07], [Net09c], [Vol09], [EHH$^+$05], [NoCSNCTUT09], [Wyv09], [net09a], [Tec09], [Sof09a], [Tec05], [Jon09], [Ips09], [WH09], [ZW92]	[McR99]
	Arbitrary	[HPF07], [PH99], [Map08], [Tel09], [Lim09]	[MFKN07], [MKN$^+$07], [Sof09b]	[EW93]	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [Bro01], [AHDBV], [Cor]
	Other	[GKN04], [MB95], [DLV97]	[GMN03]	[KGS07]	

Table 25.2   A classification of the state of the art that compares visualization granularity against scale.

Additional Displayed Information	**Yes**	[AGN99], [BBP07], [BEW95], [BMB00], [Mei00], [HPF07], [PH99], [PN99], [Jac99], [CAI09], [kcH97], [HNkc97], [HJWkc98], [McR99], [Mun97], [Hyu05], [CBB00], [CDD+00], [CDM+06], [CE95], [CEH96], [EHH+00], [GMN03], [GMO+03], [KGS07], [KNK99], [KNTK99], [Kvi03], [LMZ04], [LMZ06], [MB95], [MFKN07], [MKN+07], [OCP+07], [OCLZ08], [Piz07], [Sal00], [Sii01], [Bro01], [Oli09], [OC07], [TvAG+06], [Gro00], [Hir07], [RTU09], [IBM09], [Dar09], [Che07], [Vol09], [Cor], [LUM], [WAN08], [EHH+05], [Wyv09], [Tec09], [ea05], [DLV97], [Cor09], [Sof09a], [Tel09], [Sof09b], [UNI09], [Lim09], [Vis09], [Jon09], [Ips09], [Aug03], [WS04]
	No	[AHDBV05b], [AHDBV05a], [BBGW04], [BCD+04], [GH02], [Dit09], [CDM+05], [CRC+08], [FNMT94], [GGW07], [GKN04], [GT00], [kc97], [KMG88], [MHkcF96], [PIP05], [SMW04], [YSS05], [Mic09], [WCH+03], [AS06], [Pro02], [AHDBV], [NoCSNCTUT09], [Com09b], [CP], [Bou02], [WH09], [YGM05]
	Unknown	[AGL+08], [EW93], [3Co09], [RIS09], [oANTtE08], [Ent09], [Net09b], [Net09c], [net09a], [Hew09], [Des09], [Map08], [Tec05], [YMMW09], [ZW92]

Table 25.3   Capability of displaying additional information besides the network topology.

vide in Section 25.4 a detailed description of the data sources used in visualization systems.

Collection rate : The displayed data can be gathered on demand, at the moment in which the visualization is requested by the user, or on a periodical basis. This coordinate of the classification determines how often the data is reloaded. Consider that low (e.g., periodical) collection rates may imply a skew between the depicted network and its actual status.

Collection strategies : Visualized information can be retrieved by using different methodologies including, for example, active probing of a network and passive monitoring. Table 25.4 classifies the state of the art according to the rate and strategy adopted to collect the information to be visualized. Most of the contributions fall in the class Other because either the collection process is undocumented, or they provide already drawn network topologies without details about the way they have been laid out.

25.3.2   Graph Drawing Conventions and Methodologies

We focus on visualization methodologies and systems that display network information using a graph. Whereas this is a commonly adopted metaphor, different data sets are better visualized using different graph drawing conventions and methodologies. We classify the graph drawing paradigm according to the following coordinates:

Graph drawing convention : A drawing convention is a basic rule that the drawing must satisfy to be admissible. In this chapter we mainly focus on different conventions for edge representation. Hence, we distinguish among straight-line drawings, where edges are drawn as segments, curved-line drawings, where edges are drawn as curves (e.g., parametric curves), and orthogonal drawings, where edges are represented with polygonal lines composed by horizontal and

		Collection Strategy			
		Passive Monitoring	**Active Probing**	**Customizable**	**Other**
Collection Rate	**Periodic**	[CDD$^+$00], [CRC$^+$08], [OCP$^+$07], [OCLZ08], [Piz07], [RIS09], [Oli09], [OC07], [Gro00], [RTU09]	[CBB00], [Kvi03], [Sii01], [Che07], [LUM], [ea05], [UNI09]		
	On Demand	[TvAG$^+$06]	[Mic09], [3Co09], [Ent09], [Net09b], [Hir07], [IBM09], [Net09c], [Vol09], [Cor], [Wyv09], [Vis09], [Aug03]		[LMZ04], [LMZ06], [Des09]
	Customizable	[CDM$^+$06], [CDM$^+$05], [Com09b], [Tec05], [ZW92]	[Ips09]	[AHDBV05b], [AHDBV05a], [BMB00], [HPF07], [PH99], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [EW93], [KMG88], [Bro01], [AHDBV], [Lim09], [Jon09]	[CE95], [CEH96], [Dar09], [Hew09]
	Other	[BCD$^+$04], [Sof09a], [YMMW09]	[Mei00], [PN99], [Jac99], [CAI09], [Dit09], [GT00], [GMO$^+$03], [MHkcF96], [SMW04], [Sal00], [YSS05], [AS06], [Tec09]		[AGL$^+$08], [AGN99], [BBGW04], [BBP07], [BEW95], [kcH97], [McR99], [EHH$^+$00], [FNMT94], [GGW07], [GKN04], [GMN03], [kc97], [KGS07], [KNK99], [KNTK99], [MB95], [MFKN07], [MKN$^+$07], [PIP05], [WCH$^+$03], [oANTtE08], [Pro02], [WAN08], [EHH$^+$05], [NoCSNCTUT09], [net09a], [CP], [Map08], [DLV97], [Cor09], [Bou02], [Tel09], [Sof09b], [WH09], [WS04], [YGM05]

Table 25.4 A classification of the state of the art according to the rate and strategy by which visualized information is collected.

Graph Drawing Convention	Straight-Line	[AHDBV05b], [AHDBV05a], [AGL$^+$08], [BBGW04], [BBP07], [BEW95], [BMB00], [Mei00], [PH99], [PN99], [Jac99], [CAI09], [kcH97], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [CBB00], [CDM$^+$06], [CDM$^+$05], [CE95], [CEH96], [CRC$^+$08], [EHH$^+$00], [EW93], [FNMT94], [GGW07], [GKN04], [GMN03], [GT00], [kc97], [GMO$^+$03], [KGS07], [KMG88], [Kvi03], [LMZ04], [LMZ06], [MB95], [MFKN07], [MKN$^+$07], [OCP$^+$07], [OCLZ08], [PIP05], [Piz07], [SMW04], [Sal00], [YSS05], [Sii01], [WCH$^+$03], [3Co09], [RIS09], [Bro01], [Oli09], [OC07], [oANTtE08], [AS06], [TvAG$^+$06], [Net09b], [RTU09], [Dar09], [Che07], [Pro02], [Net09c], [AHDBV], [Cor], [LUM], [WAN08], [EHH$^+$05], [NoCSNCTUT09], [CP], [Hew09], [Tec09], [ea05], [Des09], [DLV97], [Cor09], [Bou02], [Sof09a], [Tec05], [UNI09], [Vis09], [Jon09], [Ips09], [WH09], [WS04], [YMMW09], [ZW92]
	Curved-Line	[CE95], [CEH96], [MHkcF96], [oANTtE08], [Hir07], [Com09b], [Jon09], [Aug03], [YGM05]
	Orthogonal-Line	[BCD$^+$04], [CDD$^+$00], [Mic09], [Gro00], [Dar09], [Vol09], [Wyv09], [Tec09]
	Other/Unknown	[AGN99], [HPF07], [Dit09], [McR99], [KNK99], [KNTK99], [Ent09], [IBM09], [net09a], [Map08], [Tel09], [Sof09b], [Lim09]

Table 25.5   Graph drawing conventions adopted in different approaches for the visualization of computer networks.

vertical segments. Table 25.5 shows that the vast majority of the literature adopts a straight-line convention, probably because of its simplicity. The row Other/Unknown includes those contributions for which either the graph drawing convention is arbitrary (e.g., configurable), or it is undocumented. For example, in [Sof09b] the convention can be selected by the user, while in commercial visualization systems such as [Ent09] there is no publicly available specification of the graph layout engine. It is very interesting to point out that most of the visualization methodologies do not consider obtaining a planar drawing as a priority objective.

Readers interested in more details about specific graph drawing conventions may refer to the applicable chapter in this handbook.

Spatial dimension : While most methodologies build the graphical representation on a plane, some systems provide the user with the ability to explore a three-dimensional view of the network. Table 25.6 shows how contributions in the literature are distributed by adopted spatial dimension. For example, [MHkcF96] proposes a visualization of the MBone, namely the Multicast experimental backbone that was deployed around the early 1990s. Figure 25.1 shows an example of this visualization, obtained using tools described in [HNkc99].

Graph drawing methodologies : The graph drawing methodologies adopted in network visualization may include, for example, hierarchical and upward planar drawings, circular layouts, and force-directed methods (we refer in this way to a variety of methods, including spring embedders, magnetic fields, barycenter methods, etc.). See [DETT99] for a survey of existing methodologies. The usage of these methodologies will be discussed in the sections devoted to the different scales of the visualization.

Dimensions of the Visualization		
2D	[BBP07], [BCD$^+$04], [BEW95], [Mei00], [HPF07], [PH99], [PN99], [Jac99], [CAI09], [kcH97], [HNkc97], [HJWkc98], [GH02], [Dit09], [McR99], [CBB00], [CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CRC$^+$08], [EHH$^+$00], [EW93], [FNMT94], [GGW07], [GKN04], [GMN03], [GT00], [KGS07], [KMG88], [Kvi03], [LMZ04], [LMZ06], [MFKN07], [MKN$^+$07], [OCP$^+$07], [OCLZ08], [PIP05], [Piz07], [SMW04], [Sal00], [Sii01], [Mic09], [WCH$^+$03], [3Co09], [RIS09], [Oli09], [OC07], [oANTtE08], [Ent09], [TvAG$^+$06], [Net09b], [Gro00], [Hir07], [RTU09], [IBM09], [Dar09], [Che07], [Pro02], [Net09c], [Vol09], [Cor], [LUM], [WAN08], [EHH$^+$05], [NoCSNCTUT09], [Com09b], [Wyv09], [net09a], [Hew09], [Tec09], [Des09], [Map08], [DLV97], [Cor09], [Bou02], [Sof09a], [Tec05], [Tel09], [UNI09], [Vis09], [Jon09], [Ips09], [WH09], [WS04], [YMMW09], [ZW92]	
3D	[AHDBV05b], [AHDBV05a], [AGL$^+$08], [AGN99], [BBGW04], [BMB00], [Mun97], [Hyu05], [CE95], [CEH96], [kc97], [GMO$^+$03], [KNK99], [KNTK99], [MB95], [MHkcF96], [YSS05], [Bro01], [AS06], [AHDBV], [CP], [ea05], [Aug03], [YGM05]	
Customizable	[Sof09b], [Lim09]	

Table 25.6   Spatial dimension adopted in different visualization approaches.

DST MBONE2.NSI.NASA.GOV MOUNTAIN VIEW   CA 37.39 -122.08
SRC IKI-GW.RSSI.RU MOSCOW   RUSSIA 55.75 37.62
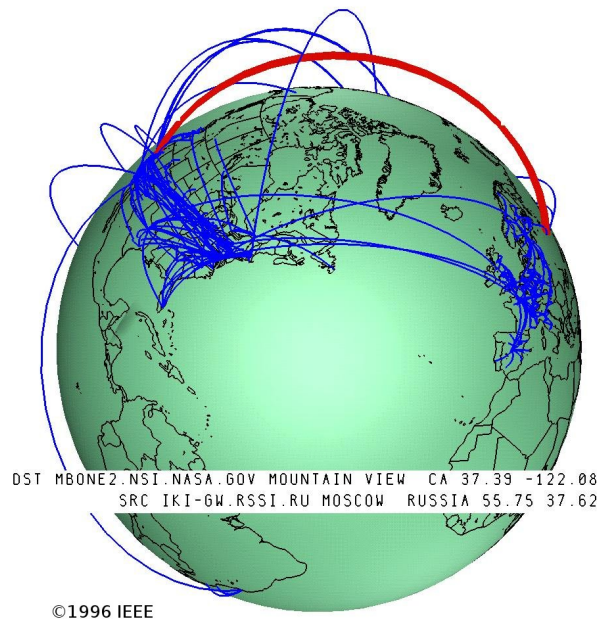
©1996 IEEE

Figure 25.1   A three-dimensional visualization of the global topology of the MBone, the Internet's multicast backbone, as it appeared in 1996. The picture is taken from [MHkcF96].

	Yes	[AGN99], [BEW95], [Mei00], [HPF07], [PH99], [PN99], [Jac99], [kcH97], [HNkc97], [HJWkc98], [Dit09], [CE95], [CEH96], [KNK99], [KNTK99], [Kvi03], [MHkcF96], [SMW04], [oANTtE08], [Dar09], [CP], [Bou02], [Tel09], [UNI09], [Lim09], [Vis09], [Aug03], [YGM05], [YMMW09]
Uses absolute geographic coordinates	**No**	[AHDBV05b], [AHDBV05a], [AGL$^+$08], [BBGW04], [BBP07], [BCD$^+$04], [BMB00], [CAI09], [GH02], [McR99], [Mun97], [Hyu05], [CBB00], [CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CRC$^+$08], [EHH$^+$00], [EW93], [FNMT94], [GGW07], [GKN04], [GMN03], [GT00], [kc97], [GMO$^+$03], [KGS07], [KMG88], [LMZ04], [LMZ06], [MB95], [MFKN07], [MKN$^+$07], [OCP$^+$07], [OCLZ08], [PIP05], [Piz07], [Sal00], [YSS05], [Sii01], [Mic09], [WCH$^+$03], [RIS09], [Bro01], [Oli09], [OC07], [AS06], [TvAG$^+$06], [Net09b], [Gro00], [Hir07], [RTU09], [IBM09], [Che07], [Pro02], [Net09c], [AHDBV], [Vol09], [LUM], [WAN08], [EHH$^+$05], [NoCSNCTUT09], [Com09b], [Wyv09], [net09a], [Hew09], [Tec09], [ea05], [Des09], [DLV97], [Cor09], [Sof09a], [Tec05], [Ips09], [WH09], [WS04], [ZW92]
	Unknown	[3Co09], [Ent09], [Cor], [Map08], [Sof09b], [Jon09]

Table 25.7   A classification of visualization methodologies according to the usage of absolute geographic coordinates for the placement of network nodes.

Detailed information about specific graph drawing methodologies can be found in the applicable chapters of this handbook.

Usage of absolute geographic location coordinates : If the visualization includes the network topology, some methodologies envisage arranging network nodes on the basis of real geographic coordinates. This is the case, e.g., for popular visual traceroute tools [Aug03, Vis09]. Quite often the geographic coordinates of network components are not deemed relevant. Also, determining the actual position of network nodes is not an easy task. Therefore, as shown in Table 25.7, most contributions rely on layout approaches that do not consider geographic coordinates. Further, it may happen that the entities to be visualized do not have specific geographic coordinates. For example, an Autonomous System can span multiple countries or even continents, having routers in many geographic locations.

25.3.3   Visualization Tools

For the cases in which the visualization methodology has been implemented in the form of a visualization tool, it is interesting to classify the tool according to the functions offered by the user interface.

Possibility of user interaction : Some tools display the network as a static image, without any possibility of interaction. Others allow to adjust the visualization, for example by zooming and rotating the view, selecting a different layout, and manually dragging vertices. Other tools allow to directly configure the network by interacting with the visualization. This is especially useful for network operators, and is often possible only with commercial tools.

Static/Dynamic(Animated) : If the tool is aimed at visualizing dynamically changing information (e.g., routing data), the changes may be displayed by animation.
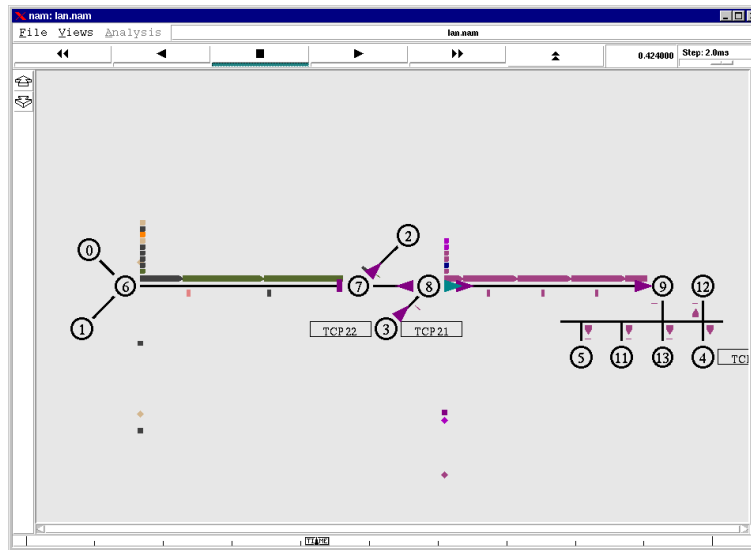
Figure 25.2   A screenshot of the NAM Network Animator, taken from [EHH+05].

Consider that this poses very interesting challenges in the optimization of the layout. The classification of the state of the art according to the ability to animate the visualization is further discussed in the following sections. Figure 25.2 shows a screenshot of a well-known tool for network simulation, that is able to display the flow of packets along the pipes.

Visualization tools are made available as software pieces in different flavors:

Type of tool : The tool may consist of a library of drawing functions, a standalone application, or an applet that can be embedded in a web browser. If a certain approach only consists of a methodological contribution and we were not able to identify a publicly available implementation, we classify that contribution separately.

License : Depending on the target users, the tool may be distributed commercially or freely, possibly with an open source license.

25.4   Data Sources

The information to be visualized can be gathered from different data sources. The available sources can vary depending on whether the network to be visualized is managed by the same entity requesting the visualization or not. In the first case, one can use two main strategies:

- Routers maintain a rich database containing information about their current status. This database is called Management Information Base (MIB) and can be accessed by a widely available protocol called Simple Network Management Protocol (SNMP) [MR91, CFSD90]. A visualization tool can query the MIB of routers via SNMP in order to collect information about the network. This is the approach adopted by the Polyphemus tool [BCD+04].

- Providers quite often store information about the configuration of network devices in a database that is maintained outside of the devices themselves and can be used to quickly manage and configure them. Such a database is implemented within a network management platform, like, e.g., HP Operations Manager [Hew09] or WANDL IP/MPLSView [WAN08]. A visualization tool can extract information from this database. Sometimes the visualization tool is embedded in the network management platform itself, which makes data extraction even easier.

If the entity requesting the visualization does not have control over the network, information can still be gathered by resorting to the following strategies:

- Network devices are usually responsive to probe packets that, in troubleshooting sessions, can be used to determine whether they are alive and reachable. Such packets are commonly transmitted according to the Internet Control Message Protocol [Pos81a] (ICMP). The same kind of packets can be used to discover the links on a foreign network. Of course, the applicability of this technique is limited by the presence of firewalls and other intrusion prevention systems.
- Some organizations maintain, typically for research purposes, repositories of publicly available information collected from routers. This is the case, for example, of the RIPE Routing Information Service [RIP] (RIS) or the Oregon Route Views project [oO]. These services collect information about the reachability of Autonomous Systems on a periodic basis. Information about router configurations is also maintained in a worldwide Internet Routing Registry [NCC] (IRR), which is also used to extract network topologies at the Autonomous System level. Unfortunately, the IRR is not always up-to-date with actually deployed configurations.

From another point of view, it is possible to consider the strategy adopted to collect the visualized information. Roughly speaking, there are two possible ways of achieving this: actively probing or passively monitoring the network. An example of active probing strategy is the usage of the traceroute tool to discover the routers along paths to certain destinations. This is the approach adopted in the CAIDA Archipelago measurement infrastructure [CAI07]. On the other hand, passive monitoring may consist in observing the status of the network by accessing routing information stored at the routers.

Table 25.8 shows the relationship between the visualization scale and the adopted collection strategy. It is clear from the table that the approaches for Internet visualization exploit many different collection strategies, while data for visualizing local and ISP-scale networks is often collected using active probing.

The collection strategy also influences the timing of data accesses. In particular, data may be collected periodically or just when it is needed to generate a visualization (see Table 25.9). Interestingly, collecting data on a periodic basis for the sole visualization purpose is rather unusual on local networks. We recall that, depending on the adopted collection rate, the displayed information may not reflect the current status of the network.

Table 25.4 puts in evidence the relationships between the collection strategy and the collection rate. As shown in the table, those tools whose collection strategy can be customized usually allow to customize the collection rate as well. Works for which the collection rate and/or the strategy are unspecified typically focus on a single snapshot of a network (e.g., a graph of an ISP's infrastructure at a given time instant) or simply provide a visualization methodology without considering the data sets to be displayed.

		Collection Strategy			
		Passive Monitoring	Active Probing	Customizable	Other
Scale	Internet	[CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CRC$^+$08], [OCP$^+$07], [OCLZ08], [Piz07], [RIS09], [Oli09], [OC07], [Gro00], [RTU09], [YMMW09]	[PN99], [Jac99], [CAI09], [Dit09], [CBB00], [GT00], [GMO$^+$03], [YSS05], [Sii01], [AS06], [Che07], [LUM], [ea05], [Vis09], [Aug03]	[HPF07], [PH99], [Lim09]	[BBGW04], [BBP07], [BEW95], [CE95], [CEH96], [GGW07], [GKN04], [kc97], [LMZ04], [LMZ06], [MB95], [oANTtE08], [Pro02], [Des09], [Map08], [DLV97], [Cor09], [Bou02], [Tel09], [WS04], [YGM05]
	ISP	[BCD$^+$04], [Piz07], [RTU09], [Com09b]	[Mei00], [Kvi03], [MHkcF96], [SMW04], [Sal00], [3Co09], [Ent09], [IBM09], [Net09c], [Tec09], [UNI09]	[KMG88], [Jon09]	[AGL$^+$08], [AGN99], [BEW95], [kcH97], [EHH$^+$00], [FNMT94], [GMN03], [KNK99], [KNTK99], [MFKN07], [MKN$^+$07], [oANTtE08], [Dar09], [WAN08], [EHH$^+$05], [CP], [Hew09], [Sof09b]
	Local	[TvAG$^+$06], [Sof09a], [Tec05], [ZW92]	[Mic09], [3Co09], [Ent09], [Net09b], [Hir07], [Net09c], [Vol09], [Wyv09], [Tec09], [Ips09]	[EW93], [Jon09]	[AGL$^+$08], [EHH$^+$00], [KGS07], [PIP05], [WCH$^+$03], [EHH$^+$05], [NoCSNCTUT09], [net09a], [WH09]
	Arbitrary		[Cor]	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [Bro01], [AHDBV]	[McR99]

Table 25.8 Data collection strategies adopted for different visualization scales.

		Collection Rate			
		Periodic	**On Demand**	**Customizable**	**Other**
Scale	**Internet**	[CBB00], [CDD$^+$00], [CRC$^+$08], [OCP$^+$07], [OCLZ08], [Piz07], [Sii01], [RIS09], [Oli09], [OC07], [Gro00], [RTU09], [Che07], [LUM], [ea05]	[LMZ04], [LMZ06], [Des09], [Vis09], [Aug03]	[HPF07], [PH99], [CDM$^+$06], [CDM$^+$05], [CE95], [CEH96], [Lim09]	[BBGW04], [BBP07], [BEW95], [PN99], [Jac99], [CAI09], [Dit09], [GGW07], [GKN04], [GT00], [kc97], [GMO$^+$03], [MB95], [YSS05], [oANTtE08], [AS06], [Pro02], [Map08], [DLV97], [Cor09], [Bou02], [Tel09], [WS04], [YGM05], [YMMW09]
	ISP	[Kvi03], [Piz07], [RTU09], [UNI09]	[3Co09], [Ent09], [IBM09], [Net09c]	[KMG88], [Dar09], [Com09b], [Hew09], [Jon09]	[AGL$^+$08], [AGN99], [BCD$^+$04], [BEW95], [Mei00], [kcH97], [EHH$^+$00], [FNMT94], [GMN03], [KNK99], [KNTK99], [MFKN07], [MHkcF96], [MKN$^+$07], [SMW04], [Sal00], [oANTtE08], [WAN08], [EHH$^+$05], [CP], [Tec09], [Sof09b]
	Local		[Mic09], [3Co09], [Ent09], [TvAG$^+$06], [Net09b], [Hir07], [Net09c], [Vol09], [Wyv09]	[EW93], [Tec05], [Jon09], [Ips09], [ZW92]	[AGL$^+$08], [EHH$^+$00], [KGS07], [PIP05], [WCH$^+$03], [EHH$^+$05], [NoCSNCTUT09], [net09a], [Tec09], [Sof09a], [WH09]
	Arbitrary		[Cor]	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [Bro01], [AHDBV]	[McR99]

Table 25.9   Collection rates adopted for different visualization scales.

25.5 Visualization of the Internet

The visualization of the whole Internet poses important challenges, because the amount of information to be displayed is generally very large and still the drawing presented to the user must preserve readability. To get a feeling of how complex the Internet can be, consider that its size can be roughly estimated in more than 20,000 Autonomous Systems and more than 60,000 links between them, and these sizes keep growing with time [MKF+06, RTM08]. Given that an ISP can span over several Autonomous Systems, managing tens of thousands of routers on its own [SMW04], and that there exist tens of thousands of ISPs, it can be easily imagined how complex it is to provide a complete yet useful visualization that spans the whole Internet.

In order to provide an overview of the most commonly adopted approaches for Internet visualization, Table 25.10 proposes a comparison of the graph drawing conventions against the graph drawing methodologies used in the literature about this field. There is a clear predominance in the adoption of the straight-line convention, and many approaches rely on force-directed methods for vertex placement. Figures 25.3(a) and 25.3(b) contain screenshots of two well-known systems for visualizing Internet routing at the Autonomous System level: BGPlay [CDM+05] and LinkRank [LMZ06]. Both tools use a spring embedder as node placement algorithm. Also, these tools make the choice of presenting only a small portion of the Internet. BGPlay focuses on how a network prefix is seen from a collection of vantage points, while LinkRank tries to put in evidence links that may have undergone faults. CAIDA's Walrus [Mun97, Hyu05] is a tool that exploits a three-dimensional hyperbolic geometry to display graphs under a fisheye-like distortion. Walrus is able to visualize network topologies consisting of more than 500,000 nodes and more than 600,000 links.

| (a) | (b) |
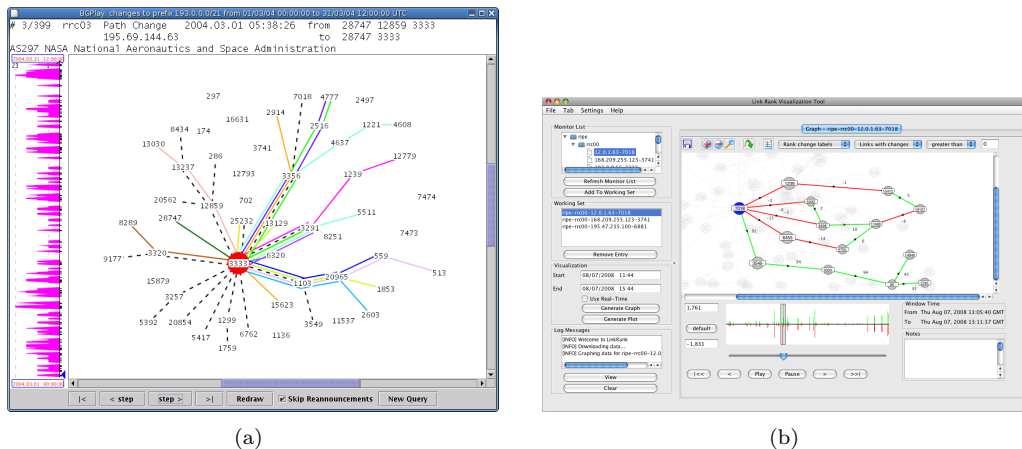
Figure 25.3 The BGPlay [CDM+05] ((a)) and LinkRank [LMZ06] ((b)) tools provide an animated visualization of routing changes at the Autonomous System level. The screenshots are taken from [Rom09] and [Lab09], respectively.

Table 25.11 matches graph drawing methodologies against the ability to provide an animated visualization. Most of the tools that provide an animation rely on a force-directed drawing methodology. In order to achieve a smooth transition between different frames of the animation, sometimes the placement of nodes is influenced by constraints.

| Graph Drawing Methodology | | Graph Drawing Convention | | | |
		Straight-Line	Curved-Line	Orthogonal-Line	Other/Unknown
	Force Directed	[BBGW04], [BEW95], [CBB00], [CDM$^+$06], [CDM$^+$05], [GGW07], [LMZ04], [LMZ06], [OCP$^+$07], [OCLZ08], [Piz07], [Sii01], [RIS09], [Oli09], [OC07], [RTU09], [Che07], [Pro02], [LUM]			
	Circular	[AHDBV05b], [AHDBV05a], [CAI09], [HNkc97], [HJWkc98], [Mun97], [Hyu05], [CE95], [CEH96], [AHDBV], [Cor09]	[CE95], [CEH96]		
	Clustering	[GMO$^+$03], [WS04]		[CDD$^+$00], [Gro00]	
	Layering	[BBGW04], [CRC$^+$08], [DLV97]			
	Topology-Shape-Metrics			[CDD$^+$00], [Gro00]	
	Customizable/Various	[GH02], [GT00], [kc97], [ea05]			[Lim09]
	Other/Unknown	[BMB00], [PH99], [PN99], [Jac99], [GKN04], [YSS05], [Bro01], [oANTtE08], [AS06], [Cor], [Des09], [Bou02], [Vis09], [YMMW09]	[oANTtE08], [Aug03], [YGM05]		[HPF07], [Dit09], [McR99], [Map08], [Tel09]

Table 25.10   Graph drawing conventions and methodologies adopted for the visualization of the Internet.

		Static	Animated
Graph Drawing Methodology	**Force Directed**	[BBGW04], [CBB00], [GGW07], [Sii01], [Che07], [Pro02], [LUM]	[BEW95], [CDM+06], [CDM+05], [LMZ04], [LMZ06], [OCP+07], [OCLZ08], [Piz07], [RIS09], [Oli09], [OC07], [RTU09]
	Circular	[AHDBV05b], [AHDBV05a], [CAI09], [HNkc97], [Mun97], [Hyu05], [AHDBV], [Cor09]	[HJWkc98], [CE95], [CEH96]
	Clustering	[CDD+00], [GMO+03], [Gro00], [WS04]	
	Layering	[BBGW04], [CRC+08], [DLV97]	
	Topology-Shape-Metrics	[CDD+00], [Gro00]	
	Customizable/ Various	[GH02], [GT00], [kc97], [ea05]	[Lim09]
	Other/Unknown	[PH99], [PN99], [Jac99], [Dit09], [McR99], [GKN04], [YSS05], [oANTtE08], [AS06], [Cor], [Map08], [Bou02], [Tel09], [Vis09], [Aug03], [YGM05], [YMMW09]	[BMB00], [HPF07], [Bro01]

Table 25.11   Visualization of the Internet: ability to animate the visualizations with respect to the adopted graph drawing methodology.
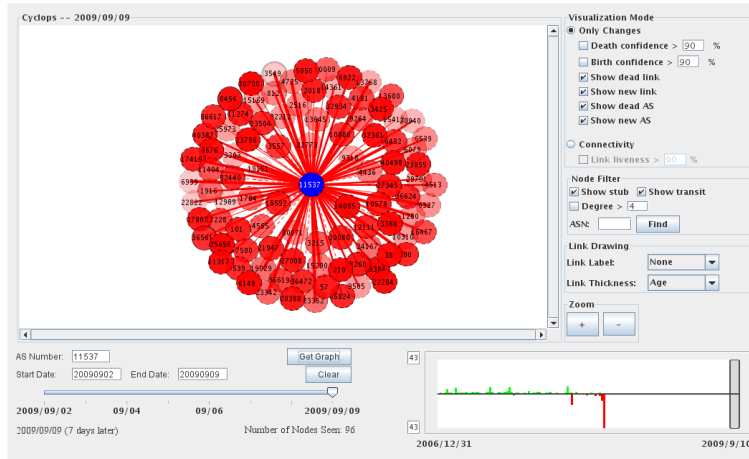
Figure 25.4   The Cyclops tool provides an animated visualization of the changes in the relationships between Autonomous Systems. This is a snapshot of the running tool available at [OC07].

Animations are typically used to convey information about historical data sets (see, e.g., [BBP07]), and often facilitate the exploration of topological changes. An example of a tool providing an animation of Internet routing changes is Cyclops [OCP$^+$07], whose screenshot is provided in Figure 25.4. The tool visualizes disappeared and newly detected peerings between Autonomous Systems over a user-selected time period. The time instant the visualization refers to can be picked by using a slider. Although Table 25.11 shows that many contributions take advantage of animation, in our opinion the obtained results are not always satisfactory. Hence, the animation of network topologies, that combines methodological challenges and practical relevance, is one of the promising fields of research for future developments.

Despite its sheer size, there are efforts to map and visualize the Internet not just at the Autonomous System level, but also at finer levels of granularity. Table 25.12 provides an overview of the graph drawing methodologies exploited in the visualization with different granularities. It can be easily seen that the Internet is sometimes visualized at the router level, like it happens in [CBB00]. More often, network nodes are aggregated to provide a visualization at the Autonomous System level. The Internet topology maps provided by CAIDA [CAI09] are a famous example of this kind of visualization.

It is interesting to observe that some proposals display the Internet topology combined with other topological aspects. As an example, the approach in [CDM$^+$06] allows to visualize the Internet topology in the context of a customer-provider hierarchy. Actually, Autonomous Systems establish commercial agreements in order to gain connectivity. In these agreements each ISP plays the role of provider of certain ISPs and is in turn a customer of others. In [CDM$^+$06] the Internet is displayed within a topographic metaphor that visually renders the customer-provider hierarchy in a pretty intuitive way.

For most of the visualization methodologies, an implementation in the form of a software tool is also available. As shown in Table 25.13, most of the implementations can be accessed freely. Among them, there are several tools that are made available in the form of Java applets, so that the user can benefit from the visualization without having to install any application or to obtain source data.

		Granularity				
		Autonomous System	**POP**	**Router/Host**	**Arbitrary**	**Other**
Graph Drawing Methodology	**Force Directed**	[BBGW04], [CDM$^+$06], [CDM$^+$05], [GGW07], [LMZ04], [LMZ06], [OCP$^+$07], [OCLZ08], [RIS09], [Oli09], [OC07], [Pro02]		[BEW95], [CBB00], [Piz07], [Sii01], [RTU09], [Che07], [LUM]		
	Circular	[CAI09], [Cor09]	[CE95], [CEH96]		[AHDBV05b], [AHDBV05a], [HNkc97], [HJWkc98], [Mun97], [Hyu05], [AHDBV]	
	Clustering	[CDD$^+$00], [GMO$^+$03], [Gro00], [WS04]				
	Layering	[BBGW04], [CRC$^+$08]				[DLV97]
	Topology-Shape-Metrics	[CDD$^+$00], [Gro00]				
	Customizable/ Various	[kc97]		[GT00], [ea05]	[GH02], [Lim09]	
	Other/Unknown	[Des09], [Bou02], [YGM05], [YMMW09]		[PN99], [Jac99], [Dit09], [McR99], [YSS05], [oANTtE08], [AS06], [Vis09], [Aug03]	[BMB00], [HPF07], [PH99], [Bro01], [Cor], [Map08], [Tel09]	[GKN04]

Table 25.12 Graph drawing methodologies adopted for the visualization of the Internet at different levels of granularity.

		License		
		Free	**Commercial**	**Other/Unknown**
Type of Tool	**Application**	[AHDBV05b], [AHDBV05a], [BEW95], [BMB00], [HPF07], [PN99], [Jac99], [CAI09], [HNkc97], [HJWkc98], [GH02], [McR99], [Mun97], [Hyu05], [CDM$^+$06], [CDM$^+$05], [CE95], [CEH96], [LMZ04], [LMZ06], [YSS05], [Bro01], [AS06], [AHDBV], [ea05], [DLV97], [Aug03]	[Cor], [Vis09]	[GMO$^+$03], [YMMW09]
	Java Applet	[PH99], [Dit09], [CDD$^+$00], [CDM$^+$06], [CDM$^+$05], [CRC$^+$08], [OCP$^+$07], [OCLZ08], [Piz07], [RIS09], [Oli09], [OC07], [Gro00], [RTU09], [Pro02], [DLV97]	[Vis09]	
	None Publicly Available		[Map08], [Tel09]	[BBGW04], [BBP07], [CBB00], [GGW07], [GKN04], [GT00], [MB95], [Sii01], [Che07], [LUM], [WS04]
	Other/Unknown		[Des09], [Cor09]	[kc97], [oANTtE08], [Bou02], [Lim09], [YGM05]

Table 25.13   License policies used for Internet visualization tools.

Granularity		
	Autonomous System	
	POP	[AGN99], [kcH97], [KNK99], [KNTK99], [SMW04]
	Router/Host	[AGL$^+$08], [BCD$^+$04], [BEW95], [Mei00], [McR99], [EHH$^+$00], [FNMT94], [KMG88], [Kvi03], [MHkcF96], [Piz07], [SMW04], [Sal00], [3Co09], [oANTtE08], [Ent09], [RTU09], [IBM09], [Dar09], [Net09c], [WAN08], [EHH$^+$05], [Com09b], [CP], [Hew09], [Tec09], [UNI09], [Jon09]
	Arbitrary	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [Mun97], [Hyu05], [MFKN07], [MKN$^+$07], [Bro01], [AHDBV], [Cor]
	Other	[GMN03]

Table 25.14   A classification of the state of the art on the visualization of ISP networks according to the granularity of the visualization.

25.6   Visualization of an Internet Service Provider Network

The difficulty of visualizing the network of a single ISP is comparable to the one of visualizing the Internet at the Autonomous System level. In fact an ISP has roughly as many network devices as the number of Autonomous Systems in the Internet. In some cases ISP networks may be displayed at a coarser granularity, taking into account the Points of Presence (POP). A POP is a set of network devices housed at a certain location that are used to provide access to the Internet. CAIDA's Mapnet [kcH97] provides a visualization of the interconnections between the POPs, for different ISPs. More often, ISP-scale visualization considers every router or host on the network. This is the case, for example, of the commercial system InterMapper [Dar09], which visualizes routers and their interconnections superimposed on a geographical map. Table 25.14 provides a classification of the literature according to the granularity adopted in the visualization.

Table 25.15 classifies the graph drawing conventions and methodologies adopted within approaches for the visualization of ISP-scale networks. Most notably, almost every contribution adopts a straight-line convention. A very popular visualization tool is Otter [HNkc97], which is at the basis of the famous Internet maps provided by CAIDA. Node placement in Otter happens on the basis of geographic coordinates. Those nodes for which the coordinates are not available are laid out in semi-circles around their parent node. Otter has been exploited to generate several visualizations, including, e.g., the multicast backbone of an ISP.

Some of the contributions exploit clustered drawings. This is the case, for example, of [Sal00], where different virtual communication channels are grouped together to highlight the interconnections established by the ATM protocol [Sta07]. In [CP] the authors visualize the NSFnet, a wide-area network developed by the National Science Foundation (NSF). In a three-dimensional space, they arrange backbone nodes on a higher layer, and client nodes that utilize the backbone on a lower layer. Everything is displayed in the context of a geographical map. The Systrax community proposes a prototype of a tool for visualizing traffic flows collected by the NetFlow tool [Com09b, Sys09a]. The visualization exploits curved lines to represent device interconnections. The Polyphemus tool [BCD$^+$04] visualizes the routing of an ISP by collecting information about the OSPF protocol [Moy94], and exploits an orthogonal drawing with a topology-shape-metrics methodology.

		Graph Drawing Convention			
		Straight-Line	Curved-Line	Orthogonal-Line	Other/Unknown
Graph Drawing Methodology	Force Directed	[BEW95], [GMN03], [Piz07], [RTU09], [Hew09]			
	Circular	[AHDBV05b], [AHDBV05a], [HNkc97], [HJWkc98], [Mun97], [Hyu05], [KMG88], [AHDBV]	[Com09b]		
	Clustering	[AGL$^+$08], [SMW04], [Sal00]			
	Layering	[CP]			
	Topology-Shape-Metrics			[BCD$^+$04]	
	Customizable/Various	[GH02], [EHH$^+$00], [EHH$^+$05], [Tec09]		[Tec09]	[IBM09]
	Other/Unknown	[BMB00], [Mei00], [kcH97], [FNMT94], [Kvi03], [MFKN07], [MKN$^+$07], [SMW04], [3Co09], [Bro01], [oANTtE08], [Dar09], [Net09c], [Cor], [WAN08], [UNI09], [Jon09]	[MHkcF96], [oANTtE08], [Jon09]	[Dar09]	[AGN99], [McR99], [KNK99], [KNTK99], [Ent09]

Table 25.15   Graph drawing conventions and methodologies adopted in the visualization of the network of an ISP.

		Uses absolute geographic coordinates		
		Yes	**No**	**Unknown**
Graph Drawing Convention	**Straight-Line**	[BEW95], [Mei00], [kcH97], [HNkc97], [HJWkc98], [Kvi03], [SMW04], [oANTtE08], [Dar09], [CP], [UNI09]	[AHDBV05b], [AHDBV05a], [AGL⁺08], [BMB00], [GH02], [Mun97], [Hyu05], [EHH⁺00], [FNMT94], [GMN03], [KMG88], [MFKN07], [MKN⁺07], [Piz07], [Sal00], [Bro01], [RTU09], [Net09c], [AHDBV], [WAN08], [EHH⁺05], [Hew09], [Tec09]	[3Co09], [Cor], [Jon09]
	Curved-Line	[MHkcF96], [oANTtE08]	[Com09b]	[Jon09]
	Orthogonal-Line	[Dar09]	[BCD⁺04], [Tec09]	
	Other/Unknown	[AGN99], [KNK99], [KNTK99]	[McR99], [IBM09]	[Ent09]

Table 25.16 Graph drawing conventions used in the visualization of ISP-scale networks when geographic location coordinates are or are not considered.

Most of the approaches in which network nodes are placed according to their geographic location make use of a straight-line drawing convention. This is highlighted in Table 25.16.

There are few contributions that support an animated visualization of the ISP under consideration. Table 25.17 relates these contributions with the graph drawing methodology they adopt. Interestingly, some of the tools that arrange nodes according to geographic coordinates also provide support for animated visualizations. For example, the system described in [KNK99, AGN99] displays traffic flows over time, where traffic sources are placed over a geographic map.

Finally, Table 25.18 shows the license policies under which ISP-scale visualization tools are distributed. These tools are sometimes released as standalone applications within network management suites (see, e.g., [Hew09, IBM09, WAN08]).

		Static	Animated
Graph Drawing Methodology	**Force Directed**		[BEW95], [GMN03], [Piz07], [RTU09]
	Circular	[AHDBV05b], [AHDBV05a], [HNkc97], [Mun97], [Hyu05], [KMG88], [AHDBV], [Com09b]	[HJWkc98]
	Clustering	[AGL$^+$08], [SMW04], [Sal00]	
	Layering	[CP]	
	Topology-Shape-Metrics	[BCD$^+$04]	
	Customizable/Various	[GH02], [IBM09], [Tec09]	[EHH$^+$00], [EHH$^+$05]
	Other/Unknown	[Mei00], [kcH97], [McR99], [FNMT94], [Kvi03], [MHkcF96], [SMW04], [3Co09], [oANTtE08], [Ent09], [Dar09], [Net09c], [Cor], [WAN08], [UNI09]	[AGN99], [BMB00], [KNK99], [KNTK99], [MFKN07], [MKN$^+$07], [Bro01], [Jon09]

Table 25.17 Graph drawing methodologies adopted for static/animated visualizations of an ISP's network.

		License		
		Free	Commercial	Other/Unknown
Type of Tool	**Application**	[AHDBV05b], [AHDBV05a], [BCD$^+$04], [BEW95], [BMB00], [HNkc97], [HJWkc98], [GH02], [McR99], [Mun97], [Hyu05], [Bro01], [AHDBV], [Jon09]	[3Co09], [Ent09], [IBM09], [Dar09], [Net09c], [Cor], [WAN08], [Hew09], [Tec09]	[AGL$^+$08], [EHH$^+$00], [GMN03], [SMW04], [Sal00], [EHH$^+$05]
	Java Applet	[kcH97], [Piz07], [RTU09], [Com09b]		[Sal00]
	None Publicly Available	[CP]		[AGN99], [FNMT94], [KMG88], [KNK99], [KNTK99], [Kvi03], [MFKN07], [MHkcF96], [MKN$^+$07], [UNI09]
	Other/Unknown			[Mei00], [oANTtE08]

Table 25.18 Licensing policies for different kinds of ISP-scale visualization tools.

		Graph Drawing Convention			
		Straight-Line	**Curved-Line**	**Orthogonal-Line**	**Other/Unknown**
Graph Drawing Methodology	**Force Directed**				
	Circular	[AHDBV05b], [AHDBV05a], [HNkc97], [HJWkc98], [Mun97], [Hyu05], [TvAG$^+$06], [AHDBV]			
	Clustering	[AGL$^+$08]			
	Layering				
	Topology-Shape-Metrics				
	Customizable/ Various	[GH02], [EHH$^+$00], [Net09b], [EHH$^+$05], [Tec09]		[Tec09]	
	Other/Unknown	[BMB00], [EW93], [PIP05], [WCH$^+$03], [3Co09], [Bro01], [Net09c], [Cor], [NoCSNCTUT09], [Sof09a], [Tec05], [Jon09], [Ips09], [WH09], [ZW92]	[Hir07], [Jon09]	[Mic09], [Vol09], [Wyv09]	[McR99], [Ent09], [net09a]

Table 25.19   Graph drawing conventions and methodologies adopted for the visualization of local networks.

25.7   Visualization of Local Networks

A local network typically consists of a few hundreds of devices, hence it is meaningful to visualize it as a whole.

Table 25.19 shows that most of the contributions to the visualization of local networks adopt a straight-line drawing convention and different, sometimes customizable methodologies. There are some notable exceptions to this rule: for example the "Full Map View" embedded in the Microsoft Windows Vista$^{\text{TM}}$ operating system (see Figure 25.5) and the LanTopolog [Vol09] discovery tool adopt an orthogonal convention, while the Weathermap application [Jon09] exploits curved lines for the visualization.

Methodologies targeted at the visualization of local networks may also support animated displays. This is useful, for example, to monitor traffic exchanges among network devices or the distribution of bandwitdh usage over time. Tables 25.20, 25.21, and 25.22 classify the literature by correlating the ability of animating the visualization with the graph drawing methodology, the rate, and the strategy by which visualized data are collected, respectively. Some interesting considerations can be derived from these tables.

First of all, providing an animated view is not a fundamental requirement, as there are fewer contributions that have this capability.
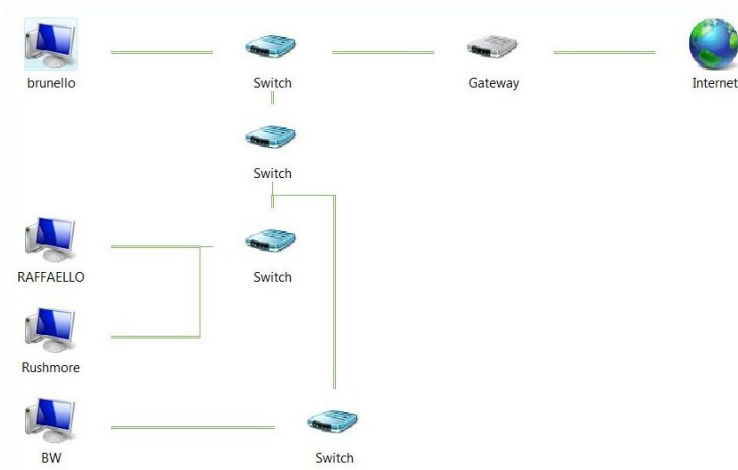
Figure 25.5   A snapshot of the Windows Vista^{TM} "Full Map View" feature.

		Static	Animated
Graph Drawing Methodology	**Force Directed**		
	Circular	[AHDBV05b], [AHDBV05a], [HNkc97], [Mun97], [Hyu05], [AHDBV]	[HJWkc98], [TvAG⁺06]
	Clustering	[AGL⁺08]	
	Layering		
	Topology-Shape-Metrics		
	Customizable/Various	[GH02], [Net09b], [Tec09]	[EHH⁺00], [EHH⁺05]
	Other/Unknown	[McR99], [EW93], [PIP05], [Mic09], [WCH⁺03], [3Co09], [Ent09], [Hir07], [Net09c], [Vol09], [Cor], [NoCSNCTUT09], [Wyv09], [net09a], [Sof09a], [Ips09], [WH09]	[BMB00], [Bro01], [Tec05], [Jon09], [ZW92]

Table 25.20   Graph drawing methodology adopted for static and animated visualizations of local networks.

		Static	Animated
Collection Rate	**Periodic**		
	On Demand	[Mic09], [3Co09], [Ent09], [Net09b], [Hir07], [Net09c], [Vol09], [Cor], [Wyv09]	[TvAG$^+$06]
	Customizable	[AHDBV05b], [AHDBV05a], [HNkc97], [GH02], [Mun97], [Hyu05], [EW93], [AHDBV], [Ips09]	[BMB00], [HJWkc98], [Bro01], [Tec05], [Jon09], [ZW92]
	Other	[AGL$^+$08], [McR99], [PIP05], [WCH$^+$03], [NoCSNCTUT09], [net09a], [Tec09], [Sof09a], [WH09]	[EHH$^+$00], [EHH$^+$05]

Table 25.21   Data collection rate for static and animated visualizations of local networks.

		Static	Animated
Collection Strategy	**Passive Monitoring**	[Sof09a]	[TvAG$^+$06], [Tec05], [ZW92]
	Active Probing	[Mic09], [3Co09], [Ent09], [Net09b], [Hir07], [Net09c], [Vol09], [Cor], [Wyv09], [Tec09], [Ips09]	
	Customizable	[AHDBV05b], [AHDBV05a], [HNkc97], [GH02], [Mun97], [Hyu05], [EW93], [AHDBV]	[BMB00], [HJWkc98], [Bro01], [Jon09]
	Other	[AGL$^+$08], [McR99], [PIP05], [WCH$^+$03], [NoCSNCTUT09], [net09a], [WH09]	[EHH$^+$00], [EHH$^+$05]

Table 25.22   Strategies by which data are collected for static and animated visualizations of local networks.

		License		
		Free	**Commercial**	**Other/Unknown**
Type of Tool	**Application**	[AHDBV05b], [AHDBV05a], [BMB00], [HNkc97], [HJWkc98], [GH02], [McR99], [Mun97], [Hyu05], [WCH+03], [Bro01], [TvAG+06], [AHDBV], [Vol09], [NoCSNCTUT09], [Jon09], [WH09]	[Mic09], [3Co09], [Ent09], [Net09b], [Hir07], [Net09c], [Cor], [Wyv09], [net09a], [Tec09], [Sof09a], [Ips09]	[AGL+08], [EHH+00], [EHH+05], [Tec05], [ZW92]
	Java Applet			
	None Publicly Available			[EW93], [PIP05]
	Other/Unknown			

Table 25.23   License policies applied for visualization tools targeted at local networks.

Second, the graph drawing methodology adopted for animated visualizations is often undocumented. An exception to this rule is, for example, the well-known network animator Nam [EHH+00] (Figure 25.2), which provides a dynamic visualization of the packets that traverse the links of a network. The tool keeps network nodes in a fixed position while the animation is displayed.

Another interesting observation based on the tables is that tools for animated visualizations usually do not collect data on their own ("Periodic" or "On Demand" collection rate), but rather are fed with data sets that have been gathered separately and contain enough information to support the animation. This is the case, for example, of the Cichlid visualization tool [BMB00], which provides three-dimensional views of resource utilization in a network over time. The gathering process is typically based on a passive observation of the network. This is the approach pursued in the Etherape tool [TvAG+06], which displays network nodes and links with different sizes depending on their network activity.

Table 25.23 shows that most of the tools aimed at the visualization of local networks are distributed, either freely or under a commercial license, in the form of standalone applications. A possible motivation is that Java applets are more suited for the case in which information about the network to be visualized is only available remotely.

25.8   Visualization of Basic Internet Services and Specific Network Contexts

As highlighted in the previous sections, the topology of computer networks can be considered at different levels of granularity. Besides the topology itself, computer networks very often consist of overlapping logical infrastructures called *overlays*, that are set up in order to provide additional services and optimize network usage. These logical infrastructures only exist in the form of configuration statements on board the network devices, and support commonly used services such as peer-to-peer content sharing.

There is a class of visualization systems that, instead of visualizing the topology of a network, aim at displaying the exchanges of information that are happening on an overlay network.

For example, [Mai02], [BB07], and [FHN$^+$07] propose a visualization of email exchanges between users. The first one is an orthogonal drawing showing the relationships among Internet domains that generate spam. The second one proposes to visualize email exchanges as an example of application of a layout algorithm of graphs with different levels of detail. The last one is a paper describing the visualization of mail exchange patterns with different drawing methodologies. Other contributions focus on monitoring the usage of distributed services like the Domain Name System (DNS). For example, the approach in [DSN12] allows to observe how the workload shifts between different name servers, thus showing how clients migrate from one server to another and simplifying the recognition of unusual operational patterns.

An emerging hot topic is the visualization of relationships in social networks. Users registered on Facebook [web09] can visualize their friendship relationships using a tool called Nexus [Net09d]. In [Tri06] and [BdM06] the authors describe methodologies and tools to display communication relationships between entities (for example, a student and a teacher). In particular, the tool SoNIA [MBd07] also offers animated views of these relationships.

Peer-to-peer networks are more and more widespread, mainly due to the simplicity of setup and to the effectiveness for content sharing. Thanks to the fact that participating devices are self-organizing, the network attempts to preserve connectivity and performance levels even in the presence of frequent topology changes. The problem of displaying the topology of a peer-to-peer network has been considered in [JD08], where a method to generate animated visualization of simulated networks is proposed.

The new version of the Internet Protocol, IPv6 [DH98], has received much attention in the last years due to the technical challenges associated with its deployment. Besides studying transition mechanisms [6ne05], researchers have also focused on visualizing the growth of some test networks. In [NSM99] the authors illustrate the design and implementation of a tool for three-dimensional visualization of the topography of an IPv6 network and of the hierarchy of its address space. The paper proposes sample drawings of an experimental IPv6 network in Japan.

Wireless and sensor networks, due to their continuously changing topology, have also caught the interest of the community interested in visualization. For example, in [GK05] the authors describe a graph drawing algorithm that is based on inter-sensor communication and exploits a force-directed layout. A visualization of the connectivity graph of simulated sensor networks is proposed in [MBS08]. There are also collaborative projects aimed at collecting information about the presence of wireless access points around the world: they usually exploit contour-like maps to visualize network coverage rather than a graph of the topology [oKIC02, com09a].

Another attractive field of research is the analysis of relationships between pages in the World Wide Web. Lots of efforts have been put in analyzing the logical topology implied by hyperlinks between web pages, also known as *web graph*. Even though most of the literature aims at building a compact and efficient representation of the web graph, there are contributions also on the visualization side. In [MB95] the authors used a custom web spider to construct graphical representations of sections of the web graph in 3D hyperbolic space. The structure of the web graph has also been graphically analyzed in a historical perspective in [TK05]. The authors of [YDZ04] apply data mining and visualization techniques to analyze large web data sets. The TouchGraph Google Browser available at [Tou09] offers the user a visual representation of the results of web searches in the form of a clustered graph, where pages are grouped by similarity.

A number of papers are devoted to the visualization of anomalies that are a symptom of intrusion attempts into a networked system. A survey on techniques to visualize security-

related information as a graph is provided in [Tam08]. The three-dimensional visualization tool Flamingo has been exploited as an engine to visualize network topologies [OKB06] and to perform network monitoring [OGK06], and is also at the basis of anomaly detection approaches [TJKMW04]. In [WJA05] the authors propose a visualization of BGP routing that aids in detecting abnormal changes. The visualizations exploit the Graphviz [Res09] library and can also be animated. VisFlowConnect [YYT04] is a tool that visualizes traffic exchanges between hosts in order to detect interesting and potentially anomalous patterns. Chapter 20 overviews related work on the visualization of network security aspects.

There also exist tools that provide drawing functionalities. Instead of automatically laying out the topology of a network, these tools provide an environment with ready-to-use symbols that users can exploit to draw networks on their own. An example of a commercial tool that supports creating network diagrams is SmartDraw [Sma09]. Such contributions are outside the scope of this chapter.

References

[3Co09]   3Com. H3C intelligent management center, 2009.

[6ne05]   6net. Large-scale international IPv6 pilot network. `http://www.6net.org/`, 2005.

[AGL+08]   P. Abel, P. Gros, D. Loisel, C. R. Dos Santos, and J.P. Paris. CyberNet: A framework for managing networks using 3D metaphoric worlds. *Annals of Telecommunications*, 55(3–4), 2008.

[AGN99]   J. Abello, E. R. Gansner, and S. C. North. Large-scale network visualization. *Computer Graphics*, 33:13–15, 1999.

[AHDBV]   I. Alvarez-Hamelin, L. Dall'Asta, A. Barrat, and A. Vespignani. Large network visualization tool (LaNet-vi). `http://xavier.informatics.indiana.edu/lanet-vi/`.

[AHDBV05a]   I. Alvarez-Hamelin, L. Dall'Asta, A. Barrat, and A. Vespignani. k-core decomposition: a tool for the visualization of large scale networks. ArXiv Computer Science e-prints, 2005.

[AHDBV05b]   I. Alvarez-Hamelin, L. Dall'Asta, A. Barrat, and A. Vespignani. Large scale networks fingerprinting and visualization using the k-core decomposition. In *Proc. NIPS 2005*, 2005.

[AS06]   S. Asafi and M. Sandler. DIMES4DVisualizer, 2006.

[Aug03]   B. Augustsson. Xtraceroute. `http://www.dtek.chalmers.se/~d3august/xt/`, 2003.

[BB07]   M. Baur and U. Brandes. Multi-circular layout of micro/macro graphs. In *Proc. GD 2007*, 2007.

[BBGW04]   M. Baur, U. Brandes, M. Gaertler, and D. Wagner. Drawing the AS Graph in 2.5 dimensions. In *Proc. Graph Drawing 2004*, pages 43–48, 2004.

[BBP07]   K. Boitmanis, U. Brandes, and C. Pich. Visualizing Internet evolution on the Autonomous System level. In *Proc. Graph Drawing 2007*, pages 364–376, 2007.

[BCD+04]   G. Barbagallo, A. Carmignani, G. Di Battista, W. Didimo, and M. Pizzonia. Polyphemus and Hermes – Exploration and visualization of computer networks. In *Graph Drawing Software*, Mathematics and Visualization Series, pages 341–364. 2004.

[BdM06]   S. Bender-deMoll and D. McFarland. The art and science of dynamic network visualization. *Journal of Social Structure*, 7(2), 2006.

[BEW95]   R. A. Becker, S. G. Eick, and A. R. Wilks. Visualizing network data. *IEEE Trans. on Visualization and Computer Graphics*, 1(1):16–28, 1995.

[BMB00]   J. A. Brown, A. J. McGregor, and H. W. Braun. Network performance visualization: Insight through animation. In *Proc. PAM '00*, pages 33–41, 2000.

[Bou02]   P. Bourcier. Rootzmap - Mapping the Internet. `http://sysctl.org/rootzmap/`, 2002.

[Bro01]   J. Brown. Cichlid data visualization software. `http://moat.nlanr.net/Software/Cichlid/`, 2001.

[CAI07]   CAIDA. Archipelago measurement infrastructure. Network mea-
             surement tool, 2007.

[CAI09]   CAIDA.   Visualizing IPv4 and IPv6 Internet topology at a
             macroscopic scale. `http://www.caida.org/research/topology/`
             `as_core_network/`, 2009.

[CBB00]   B. Cheswick, H. Burch, and S. Branigan. Mapping and visualizing
             the Internet. In *Proc. USENIX '00*, pages 1–12, 2000.

[CDD+00]   A. Carmignani, G. Di Battista, W. Didimo, F. Matera, and M. Piz-
             zonia. Visualization of the Automous Systems interconnections with
             HERMES. In *Proc. Graph Drawing 2000*, pages 150–163, 2000.

[CDM+05]   L. Colitti, G. Di Battista, F. Mariani, M. Patrignani, and M. Pizzo-
             nia. Visualizing interdomain routing with BGPlay. *Journal of Graph
             Algorithms and Applications, Special Issue on the 2003 Symposium
             on Graph Drawing, GD '03*, 9(1):117–148, 2005.

[CDM+06]   P. F. Cortese, G. Di Battista, A. Moneta, M. Patrignani, and
             M. Pizzonia. Topographic visualization of prefix propagation in
             the Internet. *IEEE Transactions on Visualization and Computer
             Graphics*, 12(5):725–732, 2006.

[CE95]   K. C. Cox and S. G. Eick. 3D displays of Internet traffic. In *Proc.
             INFOVIS '95*, page 129, 1995.

[CEH96]   K. C. Cox, S. G. Eick, and T. He. 3D geographic network displays.
             SIGMOD Record, 25(4):50–54, 1996.

[CFSD90]   J. D. Case, M. Fedor, M. L. Schoffstall, and J. Davin. Simple Net-
             work Management Protocol (SNMP). RFC 1157 (Historic), May
             1990.

[Che07]   B. Cheswick. Internet mapping project. `http://www.cheswick.`
             `com/ches/map/`, 2007.

[Com]   International Electrotechnical Commission. Web site. `http://www.`
             `iec.ch/`.

[com09a]   Mimezine community. Wigle – wireless geographic logging engine.
             `http://www.wigle.net/gps/gps/main`, 2009.

[Com09b]   Plixer International Systrax Community. Visualization of NetFlow
             data, 2009.

[Cor]   Lumeta Corporation. IPsonar MapViewer.

[Cor09]   Renesys Corporation. Routing intelligence tools. `http://www.`
             `renesys.com/`, 2009.

[CP]   D. Cox and R. Patterson.   NSFNET growth until 1995.
             `http://www.caida.org/projects/internetatlas/gallery/`
             `nsfnet/data.xml`.

[CRC+08]   L. Cittadini, T. Refice, A. Campisano, G. Di Battista, and C. Sasso.
             Measuring and visualizing interdomain routing dynamics with BG-
             Path. In *Proc. ISCC 2008*, 2008.

[Dar09]   LLC Dartware.   Intermapper.   `http://www.intermapper.com/`
             `products/intermapper/`, 2009.

[Des09]   Packet Design. Route explorer. `http://www.packetdesign.com/`,
             2009.

[DETT99]   G. Di Battista, P. Eades, R. Tamassia, and I. G. Tollis. *Graph Drawing*. Prentice Hall, 1999.

[DH98]   S. Deering and R. Hinden. Internet Protocol, Version 6 (IPv6) Specification. RFC 2460 (Draft Standard), December 1998.

[Dit09]   W. Dittmer. World-wide mapping of reverse traceroute and looking glass servers, 2009.

[DLV97]   G. Di Battista, R. Lillo, and F. Vernacotola. Ptolomaeus. `http://www.dia.uniroma3.it/~ptolemy/`, 1997.

[DSN12]   G. Di Battista, C. Squarcella, and W. Nagele. How to visualize the K-Root name server. *Journal of Graph Algorithms and Applications, Special Issue of GD 2011*, 2012.

[ea05]   B. Lyon et al. The Opte project. `http://www.opte.org/`, 2005.

[EHH⁺00]   D. Estrin, M. Handley, J. Heidemann, S. McCanne, Y. Xu, and H. Yu. Network visualization with the VINT network animator Nam. *IEEE Computer*, 33(11):63–68, 2000.

[EHH⁺05]   D. Estrin, M. Handley, J. Heidemann, S. McCanne, Y. Xu, and H. Yu. Nam: Network Animator. `http://isi.edu/nsnam/nam/`, 2005.

[Ent09]   Enterasys. NetSight Atlas Console, 2009.

[EW93]   S. G. Eick and G. J. Wills. Navigating large networks with hierarchies. In *Proc. Visualization '93*, pages 204–209, 1993.

[FHN⁺07]   X. Fu, S. H. Hong, N. S. Nikolov, X. Shen, Y. Wu, and K. Xu. Visualization and analysis of email networks. In *Proc. IEEE Asia Pacific Symposium on Visualization (APVIS '07)*, pages 1–8, 2007.

[FNMT94]   H. Fuji, S. Nakai, H. Matoba, and H. Takano. Real-time bifocal network-visualization. In *Proc. NOMS 1994*, 1994.

[fS]   International Organization for Standardization. Web site. `http://www.iso.org/`.

[GGW07]   R. Görke, M. Gaertler, and D. Wagner. LunarVis – Analytic visualizations of large graphs. In *Proc. Graph Drawing 2007*, pages 352–364, 2007.

[GH02]   J. Gallagher and B. Huffaker. PlotPaths. `http://www.caida.org/tools/visualization/plotpaths/`, 2002.

[GK05]   C. Gotsman and Y. Koren. Distributed graph layout for sensor networks. *Journal of Graph Algorithms and Applications*, pages 1–15, 2005.

[GKN04]   E. Gansner, Y. Koren, and S. North. Topological fisheye views for visualizing large graphs. In *Proc. INFOVIS '04*, pages 175–182, 2004.

[GMN03]   E. R. Gansner, J. M. Mocenigo, and S. C. North. Visualizing software for telecommunication services. In *Proc. SOFTVIS 2003*, pages 151–157, 2003.

[GMO⁺03]   P. A. Aranda Gutiérrez, P. Malone, M. ÓFoghlú, S. Michaelis, and J. Seger. Acquisition, modelling and visualisation of inter-domain routing data. In *Proc. IPS 2004*, 2003.

[Gro00]   Roma Tre University Computer Networks Research Group. Hermes.
               `http://tocai.dia.uniroma3.it/~hermes/`, 2000.

[GT00]   R. Govindan and H. Tangmunarunkit. Heuristics for Internet map
               discovery. In *Proc. INFOCOM 2000*, 2000.

[Hew09]   Hewlett-Packard. HP Operations Manager (formerly OpenView),
               2009.

[Hir07]   Hirschmann. Industrial HiVision, 2007.

[HJWkc98]   B. Huffaker, J. Jung, D. Wessels, and kc claffy.   Visualiza-
               tion of the growth and topology of the NLANR caching hier-
               archy. `http://www.caida.org/tools/visualization/plankton/`
               `Paper/plankton.xml`, Mar 1998.

[HNkc97]   B. Huffaker, E. Nemeth, and kc claffy.   Otter: A general-
               purpose network visualization tool.   `http://www.caida.org/`
               `tools/visualization/otter/`, 1997.

[HNkc99]   B. Huffaker, E. Nemeth, and kc claffy. Tools to visualize the internet
               multicast backbone. In *Proc. INET 99*, 1999.

[HPF07]   B. Huffaker, J. Polterock, and M. Fomenkova.   Cuttlefish
               geographic visualization tool.   `http://www.caida.org/tools/`
               `visualization/cuttlefish/`, Jun 2007.

[Hyu05]   Y. Hyun. Walrus – Graph visualization tool. `http://www.caida.`
               `org/tools/visualization/walrus/`, 2005.

[IBM09]   IBM. Tivoli network manager topology visualization, 2009.

[IEE09]   IEEE. Working group for 802.11 WLAN standards, 2009.

[IMN84]   H. Ishio, J. Minowa, and K. Nosu. Review and status of wavelength-
               division-multiplexing technology and its application.   *Journal of
               Lightwave Technology*, 2(4), 1984.

[Ips09]   Ipswitch, Inc.   WhatsUpGold network mapping.   `http://www.`
               `whatsupgold.com/`, 209.

[ISO]   ISO/IEC. Open Systems Interconnection – basic reference model.
               ISO/IEC standard 7498.

[Jac99]   V.   Jacobson.   Gtrace.   `http://www.caida.org/tools/`
               `visualization/gtrace/`, 1999.

[JD08]   K. Juenemann and J. Dinger. Ovlvis: Visualization of peer-to-peer
               networks in simulation and testbed environments. In *Proc. Com-
               munications and Networking Simulation Symposium (CNS 2008)*,
               2008.

[Jon09]   H.   Jones.   Network   weathermap.   `http://www.`
               `network-weathermap.com/`, 2009.

[kc97]   kc claffy. IETF presentation BGP MPEG animations. `http://www.`
               `caida.org/publications/presentations/Ietf199712/Movie/`,
               1997.

[kcH97]   kc claffy and B. Huffaker.   Mapnet, macroscopic Internet vi-
               sualization and measurement.   `http://www.caida.org/tools/`
               `visualization/mapnet/`, 1997.

[KD01]   R. Kitchin and M. Dodge. *Atlas of Cyberspace*. Addison-Wesley,
               2001.

[KGS07]   H. Kang, L. Getoor, and L. Singh. Visual analysis of dynamic group membership in temporal social networks. *SIGKDD Explorations Newsletter*, 9(2), 2007.

[KMG88]   G. Kar, B. Madden, and R. Gilbert. Heuristic layout algorithms for network management presentation services. In *Proc. IEEE Network 1988*, 1988.

[KNK99]   E. E. Koutsofios, S. C. North, and D. A. Keim. Visualizing large telecommunication data sets. *IEEE Computer Graphics and Applications*, 19:16–19, 1999.

[KNTK99]   E. E. Koutsofios, S. C. North, R. Truscott, and D. A. Keim. Visualizing large-scale telecommunication networks and services. In *Proc. Visualization '99*, pages 457–461, 1999.

[Kvi03]   O. Kvittem. Scaling network management tools. In *Proc. NANOG 2003*, 2003.

[Lab09]   UCLA Internet Research Lab. LinkRank visualization. `http://linkrank.cs.ucla.edu/`, 2009.

[Lim09]   M. Lima. VisualComplexity.com Internet visualizations. `http://www.visualcomplexity.com/vc/index.cfm?domain=Internet`, 2009.

[LMZ04]   M. Lad, D. Massey, and L. Zhang. LinkRank: A graphical tool for capturing BGP routing dynamics. In *Proc. NOMS 2004*, 2004.

[LMZ06]   M. Lad, D. Massey, and L. Zhang. Visualizing Internet routing changes. *IEEE Transactions on Visualization and Computer Graphics, Special Issue on Visual Analytics*, 12(6), 2006.

[LUM]   LUMETA. Internet mapping project. `http://www.lumeta.com/internetmapping/`.

[Mai02]   Clueless Mailers. Spamdemic map poster. `http://www.cluelessmailers.org/spamdemic/index.html`, 2002.

[Map08]   Peacock Maps. Internet posters. `http://www.peacockmaps.com/`, 2008.

[MB95]   T. Munzner and P. Burchard. Visualizing the structure of the World Wide Web in 3d hyperbolic space. In *Proc. VRML 1995*, pages 33–38, 1995.

[MBd07]   D. McFarland and S. Bender-deMoll. Sonia – social network image animator, 2007.

[MBS08]   C. Morrell, T. Babbitt, and B. K. Szymanski. Visualization in sensor network simulator, sense and its use in protocol verification. Technical Report cs-08-13, Department of Computer Science, Rensselaer Polytechnic Institute, 2008.

[McR99]   D. W. McRobb. Skping. `http://www.caida.org/tools/measurement/skitter/skping/`, 1999.

[Mei00]   M. Meiss. Abilene weather map. `http://www.caida.org/projects/internetatlas/gallery/mping/`, 2000.

[MFKN07]   F. Mansmann, F. Fischer, D. A. Keim, and S. C. North. Visualizing large-scale IP traffic flows. In *Proc. International Workshop on Vision, Modeling, and Visualization, 2007*, 2007.

[MHkcF96]   T. Munzner, E. Hoffman, kc claffy, and B. Fenner. Visualizing the global topology of the MBone. In *Proc. INFOVIS '96*, pages 85–92, 1996.

[Mic09]   Microsoft. Windows Vista^TM Full Map View, 2009.

[MKF+06]   P. Mahadevan, D. Krioukov, M. Fomenkov, B. Huffaker, X. Dimitropoulos, kc claffy, and A. Vahdat. The internet as-level topology: Three data sources and one definitive metric. *ACM SIGCOMM Computer Communication Review*, Jan 2006.

[MKN+07]   F. Mansmann, D. A. Keim, S. C. North, B. Rexroad, and D. Sheleheda. Visual analysis of network traffic for resource planning, interactive monitoring, and interpretation of security threats. *IEEE Trans. on Visualization and Computer Graphics*, 13(6):1105–1112, 2007.

[Moy94]   J. Moy. OSPF Version 2. RFC 1583 (Draft Standard), March 1994.

[MR91]   K. McCloghrie and M. Rose. Management Information Base for Network Management of TCP/IP-based internets:MIB-II. RFC 1213 (Standard), March 1991.

[Mun97]   T. Munzner. H3: Laying out large directed graphs in 3D hyperbolic space. In *Proc. INFOVIS 1997*, pages 2–10, Oct 1997.

[NCC]   RIPE NCC. The Internet Routing Registry: History and Purpose. `http://www.ripe.net/db/irr.html`.

[net09a]   neteXpose. DNA network topology visualization, 2009.

[Net09b]   Brocade (Foundry Networks). IronView network manager, 2009.

[Net09c]   Juniper Networks. Network and security manager, 2009.

[Net09d]   Ludios Networks. Nexus facebook graph. `http://nexus.ludios.net/`, 2009.

[NoCSNCTUT09] Network and System Laboratory Dep.t of Computer Science National Chiao Tung University Taiwan. NCTUns. `http://nsl10.csie.nctu.edu.tw/`, 2009.

[Nor02]   M. Norris. *Gigabit Ethernet Technology and Applications*. Artech House Publishers, 2002.

[NSM99]   S. Nakamae, Y. Sekiya, and J. Murai. A study into a visualization of an ipv6 network. In *Proc. INET 99*, 99.

[oANTtE08]   DANTE (Delivery of Advanced Network Technology to Europe). Topology maps. `http://www.dante.net/`, 2008.

[OC07]   R. Oliveira and Y. J. Chi. Visualizing Internet topology dynamics with Cyclops. `http://irl.cs.ucla.edu/cyclops/`, 2007.

[OCLZ08]   R. Oliveira, Y. J. Chi, M. Lad, and L. Zhang. Cyclops: the AS-Level connectivity observatory. Presentation at NANOG 43, 2008.

[OCP+07]   R. Oliveira, Y. J. Chi, I. Pefkianakis, M. Lad, and L. Zhang. Visualizing Internet topology dynamics with Cyclops. Poster at SIGCOMM 2007, 2007.

[OGK06]   J. Oberheide, M. Goff, and M. Karir. Flamingo: Visualizing internet traffic. In *Proc. NOMS 2006*, pages 150–161, 2006.

[OKB06]   J. Oberheide, M. Karir, and D. Blazakis. Vast: Visualizing autonomous system topology. In *Proc. Workshop on Visualization for Computer Security (VizSEC '06)*, pages 71–80, 2006.

[oKIC02]   University of Kansas Information and Telecommunication Technology Center. Wireless network visualization project. `http://www.ittc.ku.edu/wlan/`, 2002.

[Oli09]   R. Oliveira. Cyclops: the AS-Level connectivity observatory. `http://cyclops.cs.ucla.edu/`, 2009.

[oO]   University of Oregon. Route views project. `http://www.routeviews.org/`.

[Ora90]   D. Oran. OSI IS-IS Intra-domain Routing Protocol. RFC 1142 (Informational), February 1990.

[PH99]   R. Periakaruppan and B. Huffaker. Geoplot. `http://www.caida.org/tools/visualization/geoplot/`, 1999.

[PIP05]   N. Patwari, A. O. Hero III, and A. Pacholski. Manifold learning visualization of network traffic data. In *Proc. SIGCOMM 2005*, 2005.

[Piz07]   M. Pizzonia. From BGPlay to iBGPlay: Graphical inspection of your routing data. In *55th Re'seaux IP Europe'ens Meeting (RIPE 55)*, 2007.

[PN99]   R. Periakaruppan and E. Nemeth. GTrace – A graphical traceroute tool. In *Proc. LISA '99*, Nov 1999.

[Pos81a]   J. Postel. Internet Control Message Protocol. RFC 792 (Standard), September 1981.

[Pos81b]   J. Postel. Internet Protocol. RFC 791 (Standard), September 1981.

[Pro02]   M. Prodanovic. Java Autonomous System Path Visualization Interface (JASPVI). `http://lab.verat.net/Jaspvi/`, 2002.

[Res09]   AT&T Research. Graphviz graph visualization software. `http://www.graphviz.org/`, 2009.

[RIP]   Réseaux IP Européens – RIPE. Routing information service. `http://www.ripe.net/ris/`.

[RIS09]   RIPE RIS. BGPviz. `http://www.ris.ripe.net/bgpviz/`, 2009.

[Rom09]   Roma Tre University, Computer Networks Research Group. BGPlay @ Route Views. `http://bgplay.routeviews.org/bgplay/`, 2009.

[RTM08]   M. Roughan, S. J. Tuke, and O. Maennel. Bigfoot, sasquatch, the yeti and other missing links: What we don't know about the as graph. In *Proc. ICM 2008*, 2008.

[RTU09]   Computer Networks Research Group Roma Tre University. iBGPlay. `http://www.ibgplay.org/`, 2009.

[Sal00]   T. Salo. Real-time visualization of IP over connection-oriented WANs. In *Proc. NANOG 2000*, 2000.

[Sii01]   K. Siil. Using topological mapping to manage and secure large networks. In *Proc. NANOG 2001*, 2001.

[Sma09]   SmartDraw. Network topology drawing software. `http://www.smartdraw.com/`, 2009.

[SMW04]   N. Spring, R. Mahajan, and D. Wetherall. Measuring ISP topologies
             with RocketFuel. *IEEE Trans. on Networking*, 12(1):2–16, 2004.

[Sof09a]   Inc. SoftConcept. SeeNet. `http://www.softconcept-inc.com/`
             `seenetweb/`, 2009.

[Sof09b]   Tulip Software. Tulip. `http://www.tulip-software.org/`, 2009.

[SS96]   C. A. Siller and M. Shafi. *SONET/SDH: A Sourcebook of Syn-*
             chronous Networking. Wiley – IEEE Press, 1996.

[Sta07]   W. Stallings. *Data and Computer Communications*. Prentice Hall,
             2007.

[Sys09a]   Cisco Systems. NetFlow. `http://www.cisco.com/go/netflow`,
             2009.

[Sys09b]   Cisco Systems. Synchronous Data Link Control (SDLC) and deriva-
             tives, 2009.

[Tam08]   R. Tamassia. Graph drawing for security visualization. GD 2008,
             2008.

[Tec05]   BBN Technologies. BBN SpyGlass animation of application traf-
             fic flow.   `http://www.dist-systems.bbn.com/tech/spyglass/`,
             2005.

[Tec09]   OPNET Technologies. NetMapper. `http://www.opnet.com/`, 2009.

[Tel09]   TeleGeography. Cartographic maps. `http://www.telegeography.`
             `com/maps/index.php`, 2009.

[TJKMW04]   S. T. Teoh, T. J. Jankun-Kelly, K.-L. Ma, and S. F. Wu. Visual
             data analysis for detecting flaws and intruders in computer network
             systems. *Computer Graphics and Applications, Special Issue on*
             Visual Analytics, 24(5):27–35, 2004.

[TK05]   M. Toyoda and M. Kitsuregawa. A system for visualizing and an-
             alyzing the evolution of the web with a time series of graphs. In
             Proc. ACM Conference on Hypertext and Hypermedia, pages 151–
             160, 2005.

[Tou09]   LLC TouchGraph. Touchgraph google browser. `http://www.`
             `touchgraph.com/TGGoogleBrowser.html`, 2009.

[Tri06]   M. Trier. Towards a social network intelligence tool for visual analy-
             sis of virtual communication networks. In *Virtuelle Organisationen*
             und Neue Medien, 2006.

[TvAG$^+$06] J. Toledo, V. van Adrighem, R. Ghetta, E. Mann, and F. Peters.
             EtherApe. `http://etherape.sourceforge.net/`, 2006.

[UNI09]   UNINETT. Operations center network maps. `http://drift.`
             `uninett.no/index.en.html`, 2009.

[Vis09]   Visualware. Visualroute. `http://visualroute.visualware.com/`,
             2009.

[Vol09]   Y. Volokitin. Lantopolog physical network discovery software.
             `http://www.lantopolog.com/`, 2009.

[VT06]   G. Vandenberghe and J. Treurniet. Automating the presentation
             of computer networks. Technical Report ADA477079, Defence Re-
             search and Development, Canada, Ottawa, 2006.

[WAN08]   Wide Area Network Design Laboratory – WANDL. IP/MPLSView. `http://www.wandl.com/html/mplsview/`, 2008.

[WCH⁺03]   S. Y. Wang, C. L. Chou, C. H. Huang, C. C. Hwang, Z. M. Yang, C. C. Chiou, and C. C. Lin. The design and implementation of the NCTUns 1.0 network simulator. *Computer Networks*, 42(2):175–197, 2003.

[web09]   Facebook. `http://www.facebook.com/`, 2009.

[WH09]   S.Y. Wang and Y.M. Huang. *NCTUns Tool for Innovative Network Emulations*, chapter 13. Nova Science Publishers, 2009.

[wim09]   WiMAX forum, 2009.

[WJA05]   T. Wong, V. Jacobson, and C. Alaettinoglu. Internet routing anomaly detection and visualization. In *Proc. DSN 2005*, 2005.

[WPP07]   M. S. Withall, I. W. Phillips, and D. J. Parish. Network visualization: A review. *Loughborough University IET Communications*, 1(3), 2007.

[WS04]   A. Wool and G. Sagie. A clustering approach for exploring the Internet structure. In *Proc. IEEE Convention of Electrical and Electronics Engineers in Israel (IEEEI '04)*, pages 149–152, 2004.

[Wyv09]   Wyvernsoft. Netpalpus. `http://www.wyvernsoft.com/`, 2009.

[YDZ04]   A. H. Youssefi, D. J. Duke, and M. J. Zaki. Visual web mining. In *Proc. WWW 2004*, 2004.

[YGM05]   B. Yip, S. Goyette, and C. Madden. Visualising Internet traffic data with three-dimensional spherical display. In *Proc. APVIS 2005*, 2005.

[YMMW09]   H. Yan, D. Massey, E. McCracken, and L. Wang. BGPMon and NetViews: Real-time BGP monitoring system. Demo at INFOCOM 2009, 2009.

[YSS05]   Y. Shavitt and E. Shir. DIMES: Let the Internet measure itself. *Computer Communication Review*, 35(5), 2005.

[YTS06]   Y. Rekhter, T. Li, and S. Hares. A Border Gateway Protocol 4 (BGP-4). RFC 4271, Jan 2006.

[YYT04]   X. Yin, W. Yurcik, and M. Treaster. Visflowconnect: Netflow visualizations of link relationships for security situational awareness. In *Proc. Workshop on Visualization and Data Mining for Computer Security (VizSEC/DMSEC '04)*, pages 26–34, 2004.

[ZW92]   J. A. Zinky and F. M. White. Visualizing packet traces. In *Proc. SIGCOMM 1992*, 1992.