Internet Topology Research Redux

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1 Introduction

Internet topology research is concerned with the study of the various types of connectivity structures that are enabled by the layered architecture of the Internet. More than a decade of Internet topology research has produced a number of high-profile "discoveries" that continue to fascinate the scientific community, even though (or, especially because) they have been simultaneously touted by different segments of that community as either seminal, controversial, seriously flawed, or simply wrong. Among these highly-popularized discoveries are the observed power-law relationships of the Internet topology, the network's scale-free nature, and its extreme vulnerability to attacks that target the highly-connected nodes in its core (*i.e.,* the Achilles' heel of the Internet).

The purpose of this chapter is to bring order to the current state of Internet topology research and separate "the wheat from the chaff". In particular, by relying on carefully vetted data and readily available domain knowledge, we re-examine the reported discoveries and expose them to higher standards with respect to statistical inference and model validation. In the process, we reveal the superficial nature of many of these discoveries and provide alternative solutions that reflect networking reality and do not collapse under scrutiny with high-quality data or when examined in detail by domain experts.

1.1 The many facets of Internet connectivity

Internet topology research is concerned with the study of the various types of connectivity structures that are enabled by the layered architecture of the Internet. These structures include the inherently physical components of the Internet's infrastructure (*e.g.,* routers and switches and the fiber cables connecting them) as well as a wealth of more logical topologies that can be defined and studied at the higher layers of the Internet's TCP/IP protocol stack (*e.g.,* IP-level graph, AS-level network, Web-graph, P2P networks, Online Social Networks or OSNs).

As early as the ARPANET, researchers were drawing maps of the network representing its connectivity [25]. The earliest date to 1969. In those days, the entire network was simply enough to draw on the back of an envelope[1], and accurate maps could be drawn because every piece of equipment was expensive, installation was a major task, and only a few people worked on the network.

As the network grew, its complexity also grew, until the point where no one person could draw such a map. At that point, automated strategies started to arise for measuring the topology. The earliest Internet topology studies date back to the time of the NSFNET and focused mainly on the network's physical infrastructure consisting of routers, switches and the physical links connecting them (*e.g.,* see [23, 119]). The decommissioning of the NSFNET around 1995 led to a transition of the Internet from a largely monolithic network structure (*i.e.,* NSFNET) to a genuinely diverse "network of networks." Also known

[1] For instance see http://personalpages.manchester.ac.uk/staff/m.dodge/cybergeography/atlas/roberts_arpanet_large.gif

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as Autonomous Systems (ASes), together these individual networks form what we now call the "public Internet" and are owned by a diverse set of organizations and companies that includes large and small Internet Service Providers (ISPs), transit providers, network service providers, Fortune 500 companies and small businesses, academic and research organizations, content providers, Content Distribution Networks (CDNs), Web hosting companies, and cloud providers.

With this transition came an increasing fascination of the research community with a largely economics-driven connectivity structure commonly referred to as the Internet's AS-graph; that is, the logical Internet topology where nodes represent individual ASes and edges reflect observed relationships among the ASes (*e.g.*, customer-provider, peer-peer, or sibling-sibling relationship). It is important to note that the AS-graph says little about how two ASes connect with one another at the physical level; in particular, it says nothing about if or how they exchange actual traffic. Nevertheless, starting shortly after 1995, this fascination with the AS-graph has resulted in thousands of research publications covering a range of aspects related to measuring, modeling, and analyzing the AS-level topology of the Internet and its evolution over time [60, 135].

At the application layer, the emergence of the World Wide Web (WWW) in the late 1990 as a killer application generated general interest in exploring the Web-graph, where nodes represent web pages and edges denote hyperlinks [18]. While this overlay network or logical connectivity structure says nothing about how the servers hosting the web pages are connected at the physical or AS level, its scale and dynamics differ drastically from its physical-based or economics-driven underlays – a typical Web-graph has billions of nodes and even more edges and is highly dynamic; a large ISP's router-level topology consists of some thousands of routers, and today's AS-level Internet is made up of some 30,000-40,000 actively routed ASes and an order of magnitude more links.

Other applications that give rise to their own "overlay" or logical connectivity structure and have attracted some attention among researchers include email and various P2P systems such as Gnutella, Kad, eDonkey, and BitTorrent. More recently, the enormous popularity of Online Social Networks (OSNs) has resulted in a staggering number of research papers dealing with all different aspects of measuring, modeling, analyzing, and designing OSNs. Data from large-scale crawls or, in rare circumstances, OSN-provided data have been used to examine snapshots of many real-world OSNs or OSN-type systems, where the snapshots are generally simple graphs with nodes representing individual users and edges denoting some implicit or explicit friendship relationship among the users.

1.2 Many interested parties with different objectives

The above-mentioned list of possible connectivity structures that exist in today's Internet is by no means complete, but illustrates how these structures arise naturally within the Internet's layered architecture. It also highlights the many different meanings of the term "Internet topology," and sensible use of this term requires explicitly specifying which facet of Internet connectivity is considered because the differences are critical.

The list also reflects the different motivations that different researchers have for studying Internet-related graphs or networks. For example, engineers are mainly concerned with the physical facets of Internet connectivity, where technological issues generally dominate over economic and social aspects. However, the more economics-minded researchers are particularly interested in the Internet's AS-level structure where business considerations and market forces mix with technological innovation and societal considerations and shape the very structure and evolution of this logical topology. Moreover, social scientists see in the application-level connectivity structures that result from large-scale crawls of the various OSNs new and exciting opportunities for studying different aspects of human behavior and

technology-enabled inter-personal communication at previously unheard of scale.

In addition, mathematicians are interested in the different connectivity structures mainly because of their many novel features and properties that tend to require new and creative modeling and analysis methodologies. From the perspective of many computer scientists, the challenges posed by many of these intricate connectivity structures are algorithmic in nature and arise from trying to solve specific problems involving a particular topological structure. For yet another motivation, many physicists turned network scientists see the Internet as one of many examples of large-scale complex networks that awaits the discovery of universal properties that do not depend on system-specific details and advance our understanding of these complex networks irrespective of the domain in which they arose in the first place.

1.3 More than a decade of Internet topology research

When trying to assess the large body of literature in the area of Internet topology research that has accumulated since about 1995 and has experienced enormous growth especially during the last 10+ years, the picture that emerges is at best murky.

On the one hand, there are high-volume datasets of detailed network measurements that have been collected by domain experts. These datasets have been made publicly available so other researchers can use them. As a result, Internet topology research has become a prime example of a measurement-driven research effort, where third-party studies of the available datasets abound and have contributed to a general excitement about the topic area, mainly because many of the inferred connectivity structures have been reported to exhibit surprising properties (*e.g.,* power-law relationships for inferred quantities such as node degree [49]). In turn, these surprising discoveries have led network scientists and mathematicians alike to develop new network models that are provably consistent with some of this highly-publicized empirical evidence. Partly due to their simplicity and partly due to their strong predictive power, these newly proposed network models have become very popular within the larger scientific community [5, 11, 12]. For example, they have resulted in claims about the Internet that have made their way into standard textbooks on complex networks, where they are also used to support the view that a bottom-up approach dominated by domain-specific details and knowledge is largely doomed when trying to match the insight and understanding that a top-down approach centered around a general quest for "universality" promises to provide [10, 45, 113, 123].

On the other hand, there is a body of work within the networking research literature that argues essentially just the opposite and presents the necessary evidence in support of a inherently engineering-oriented approach filled with domain-specific details and knowledge [7, 93, 156]. In contrast to being measurement-driven, this approach is first and foremost concerned with notions such as a network's purpose or functionality, the hard technological constraints that the different devices used to build a network's physical infrastructure have to obey, or the sources of uncertainty in a network's "environment" with respect to which the built network should be robust. As for the measurements that have been key to the top-down approach, the reliance on domain knowledge reveals the data's sub-par quality and highlights how errors of various forms occur and can add up to produce results and claims that create excitement among non-experts but quickly collapse when scrutinized or examined by domain experts. While there exist currently no textbooks that document these failures of applying detail- and domain knowledge-agnostic perspective to the Internet, there is an increasing number of papers in the published networking research literature that detail the various mis-steps and show why findings and claims that look at first glance impressive and conclusive to a science-minded reader turn out to be simply wrong or completely meaningless when examined closely by domain experts [6, 85, 156].

In short, a survey of the existing literature on Internet topology research leaves one with the distinct

impression that "too many cooks spoil the broth." We hope that in the not-too-distant future, this impression will be replaced by "many hand make light work", and we see this chapter as a first step towards achieving this goal.

1.4 Themes

In writing this chapter there are a number of themes that emerge, and it is our intention to highlight them to bring out in the open the main differences between a detail-oriented engineering approach to Internet topology modeling versus an approach that has become a hallmark of network science and aims at abstracting away as many details as possible to uncover "universal" laws that govern the behavior of large-scale complex networks irrespective of the domains that specify those networks in the first place.

Theme 1: When studying highly-engineered systems such as the Internet, "details" in the form of protocols, architecture, functionality, and purpose matter.

Theme 2: When analyzing Internet measurements, examining the "hygiene" of the available measurements (*i.e.,* an in-depth recounting of the potential pitfalls associated with producing the measurements in question) is critical.

Theme 3: When validating proposed topology models, it is necessary to treat network modeling as an exercise in reverse-engineering and not as an exercise in model-fitting.

Theme 4: When modeling highly-engineered systems such as the Internet, beware of M.L. Mencken's quote "For every complex problem there is an answer that is clear, simple, and wrong."

2 Primer

We start first by defining some common ideas, motives, and problems within the scope of network topology modelling.

2.1 A Graph Primer

In this context *topology* usually refers to the structure of the *graph* representation of a network. That is, the common notion used to describe network topology is the mathematical *graph*. A graph $\mathcal{G}$ is defined by a set of nodes $\mathcal{N}$ (often called vertices) and edges (or links) $\mathcal{E} \subset \mathcal{N} \times \mathcal{N}$, so we usually write $\mathcal{G} = (\mathcal{N}, \mathcal{E})$. Here, we shall denote the number of nodes $N = |\mathcal{N}|$, and the number of edges $E = |\mathcal{E}|$.

Nodes are usually associated with some logical of physical structure in a network: a router, switch, PoP, or AS. Edges are associated with the appropriate type of logical or physical link between these nodes.

A graph describes connectivity between logical resources such as routers, or IP address, but simple connectivity is rarely as useful as when additional information such as names, capacity or distance are attached to these abstract objects. Such can easily be included in these descriptions by creating labelling functions of the node or edge sets, in the form: $f : \mathcal{N} \to \mathbb{R}$ or $f : \mathcal{E} \to \mathbb{R}$ in the case of real-valued labels. We could similarly defined labelling functions with text labels, or integer or vector values, and so on. However, it is naive to treat labels as an "add-on" as they carry semantics that can be important in the network. For instance, when we define link distances (be these geographic or semantic), that can change the notion of distance in the network as a whole.

We can also define functions of groupings of nodes or edges, though in this case it is not as conceptually obvious why we might. However, an exemplary case is that of "on-net" where we might define a function that classifies pairs of nodes as on the same subnet or not. Thus, such functions can ascribe meaning to groupings of nodes.

Many of the Internet graphs have symmetric links (that is, if $i \to j$ is a link, then $j \to i$ is also a link) and so these networks are *undirected*, but we also need sometimes to represent asymmetric links, and do so with a *directed graph* or *digraph*, and we call the links in such a digraph *arcs*.

In the study of network topology we might come across the more generalized graph concepts of the *multi-graph* and *hyper-graph*.

- *hypergraph*: links connect more than two nodes
  - *e.g.,* where you have a connective medium (rather than a wire), for instance in a wireless network.
- *multigraph* or *pseudograph*: has multiple parallel links between two nodes
  - *e.g.,* it is easy to have two links between two routers.

We'll exclude these cases unless explicitly stated, but it is worth noting that each of these do apply to particular aspects of the Internet.

We say two nodes are *connected* if a path exists between them, and that a graph is connected if all pairs of nodes are connected. A graph is $k-$node connected if the graph remains connected after the removal of any set of $k-1$ or fewer nodes (and corresponding links) and $k-$edge connected if the graph remains connected after the removal of any $k-1$ edges.

For an undirected graph G, define the *neighborhood* of node i by

$$N_i = \{ j \mid (i,j) \in E \},$$

i.e., the set of adjacent nodes to i, and we define the degree of the node to be the number of elements in the neighborhood to be

$$k_i = |N_i|.$$

In a directed graph, we define two concepts: the *in-degree* (the number of links connecting to the link) and the *out-degree* (the number of links originating from it).

$$\begin{aligned} \text{in-degree}(i) &= \left| \{(j,i) | (j,i) \in \mathscr{E} \} \right|, \\ \text{out-degree}(i) &= \left| \{(i,j) | (i,j) \in \mathscr{E} \} \right|. \end{aligned}$$

We often consider statistics of the degree distribution p_k (which gives the probability that a node has degree k), the average node degree being the most obvious such. It can be easily calculated from the sum of degrees, which has the interesting property

$$\sum_{i \in N} k_i = 2|E|,$$

generally referred to the Handshake lemma.

The node-degree distribution provides a common characterization of a graph (though by no means a complete characterization). It is noteworthy, however, that although this distribution is frequently discussed, the concept is somewhat ill-defined. It can be directly measured for a real network, in which

case p_k is the probability that a randomly selected node from the measured graph has degree k. However, it is often used in the context of a set of simulated graphs, where it is used to mean the probability that a node in the ensemble of networks has degree k with this probability. The difference is subtle, but it is worth keeping track of such discrepancies.

There are many other graph *metrics*. For instance, the *distance*[2] between two connected nodes in an unweighted graphs is generally defined to be the number of edges in the shortest path connecting them. We can then examine quantities such as the average distance, and the *diameter* of the network (the maximum distance).

And there are many other metrics: assortativity, clustering coefficient, centrality, and so on. They are all attempts to capture the nature of a graph in a small set of measures, and as such provide simpler, seemingly more intuitive ways to consider graphs. For other discussions of these, and comparisons in the context of Internet topologies see [68, 79]. We must be wary though, as it should be clear that the potential for problems is immediate. No small set of numbers can truly represent graphs. For instance, consider the Hamiltonian cycle[3] problem. The problem of determining if a network has such a path is well known to be NP-complete, and as such no small set of statistics of the graph will provide a characterization that is sufficient to consider this problem. Thus, these simple statistics must miss important properties of the network.

It may be useful to the reader to consider some of the tools that are available for working with graphs. They have different sets of feature, but perhaps the most important is whether they are used in conjunction with a programming language and which one, so we have listed a (no doubt incomplete) set below with some very basic information.

- MatlabBGL http://www.stanford.edu/~dgleich/programs/matlab_bgl/
  - Graph libraries for Matlab,
  - using Boost Graph Library (BGL) http://www.boost.org/doc/libs/1_42_0/libs/graph/doc/index.html
- igraph http://igraph.sourceforge.net/
  - Libraries for working with graphs in R or Python
- GraphVis http://www.graphviz.org/
  - Toolkit for visualization of graphs
- NetworkX http://networkx.lanl.gov/
  - Python toolkit for working with graphs
- GDToolkit http://www.dia.uniroma3.it/~gdt/gdt4/index.php
  - OO C++ library for handling and drawing graphs
- JUNG http://jung.sourceforge.net/
  - Java universal network/graph framework
- IGen http://informatique.umons.ac.be/networks/igen/
  - A toolkit for generating IP network topologies based on network design heuristics.

[2] The graph distance has a long history. In mathematics, perhaps the best known example is the Erdős number, which is the distance of a author from Erdős in the co-authorship graph. In popular culture there is an equivalent: the Bacon number, or the distance between actors in the graph of co-appearances.

[3] A Hamiltonian cycle is a path (on the graph) that visits each node exactly once, and then returns to the start point.

2.2 Motivations for network topology investigations

Underlying the whole research area is often an only vague notion of why we study topology. The motives for such studies are in fact quite diverse, and the implications are important. Topology studies motivated by network managers with operational imperatives have profoundly different requirements to those of the scientific research community. Broadly speaking, we can divide the motivations as follows:

- **Scientific:** Despite the fact that computer networks are designed (rather than grown as organic networks), little is known about their generic properties. Such knowledge would be useful (apart from satisfying simple curiosity) because there are many future protocols (for instance multicast protocols), and network-engineering algorithms (for instance see [54]) whose design could benefit from an understanding of typical networks, rather than the typically very small, and unrealistic test examples often employed.

- **Adversarial:** Some network operators (though not all [84]) believe that commercial rivals might gain advantage through obtaining proprietary information about their network design. Similarly, there is a general belief that such information might facilitate an attack on the network. For instance, knowledge of a competitor's customers might be used by an adversary to target Denial of Service (DoS) attacks. One possible motivation for topology discovery is for just such an adversary to gain information to target attacks.

- **Managerial:** It is often assumed that a network operator has a "database of record" that contains all the important information about their network. While this may be true in some cases, it is more often the case that such databases are hard to keep up-to-date and consistent with other data sources. This is actually a common problem in database management [37]. Such databases must be maintained by humans, and as soon as they grow large, and complex (particularly when they are dynamic), it becomes exceedingly difficult to eradicate all human errors. In addition, when the network undergoes change, particularly unplanned changes (failures), the database is unlikely to be accurate. Hence, for management of complex, dynamic networks, another source of data about the network is needed. It should be no surprise that obtaining this data from the network itself is the best solution for ensuring up-to-date, accurate records.

- **Informational:** This is a fairly general category of motivations, but differs from pure scientific curiosity in the immediacy of its application. For instance, customers of network operators often desire information about the networks to which they currently subscribe (in order to debug services, or obtain quality of service measurements), and also about networks to which they might subscribe (to help make choices about who could provide them with the most effective service). Often, a customer may not entirely trust its provider, or potential provider, and wish to verify information themselves. Hence, there is a need for such customers to be able to discover the networks to which they might subscribe, or where they should place services.

Each of these motivations imposes different requirements on our study in terms of accuracy, immediacy, and the types of measurements available. High degrees of accuracy are needed for network management; and certainly the measurements used scientifically have rarely been very accurate (though this is a significant problem with that research).

2.3 Type of network

The other core aspect we should consider is the type of topology to be examined, as it can have a drastic affect on both observations and behavior of the network. Two obvious dimensions are

Physical vs virtual: Physical networks are built from hardware: routers and cables (copper or optical fiber for the Internet), transformers and cables for electricity, or cities and roads for the road network. Virtual networks may have physical nodes, but virtual edges (as in a social network), or virtual nodes and edges (as in online social networks, or the WWW).

The main difference is that there are usually large costs in building, or adding to a physical network. Virtual networks, on the other hand, have much smaller costs (an HTML link costs almost nothing to create). Costs have a profound affect on network designs, as we shall later see, but also on dynamic behavior. If it is easier to change a network, it can change more quickly.

The other major issue for a physical network is that it is often bound by physical constraints, and this also profoundly affect their design.

Figure 1 illustrates the differences, and also makes the point that it isn't really a binary difference. Networks lie on a spectrum.

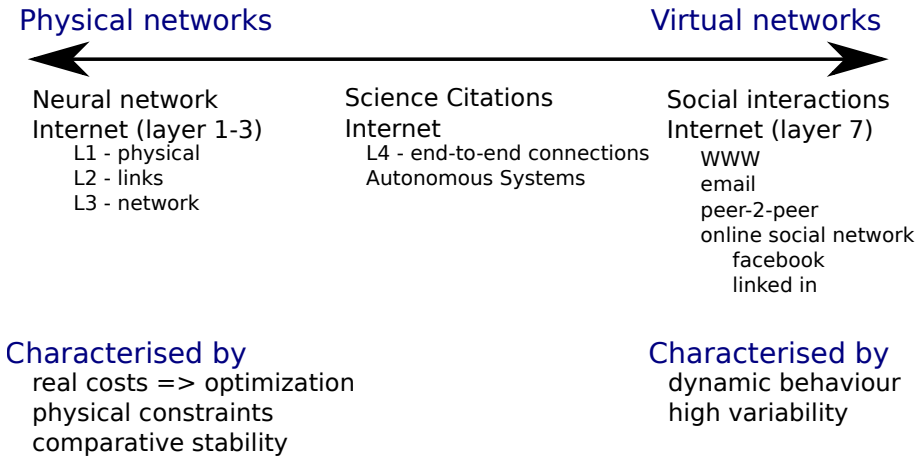


Figure 1: *Physical vs virtual networks.*

Transport vs Information flows: A more subtle differentiator is between what the network carries. Some networks physically transport some type of material (cars, water, ...) whereas the flows in other networks are (almost) pure information (the Internet, ...).

The importance of this distinction for networks may be less immediately obvious, but it certainly does have implications. When physical transport is involved in a network, the constraints on that network are likely to be even more stringent, and the ability to change the network even more limited. Costs for changing the road network, for instance, are usually higher than changing the equivalent proportion of a IP network.

Within this chapter, we are primarily interested in the "Internet", and that includes both physical (OSI layer 1-3) networks, and virtual networks (MPLS, WWW, online social networks, etc.). However, all of the

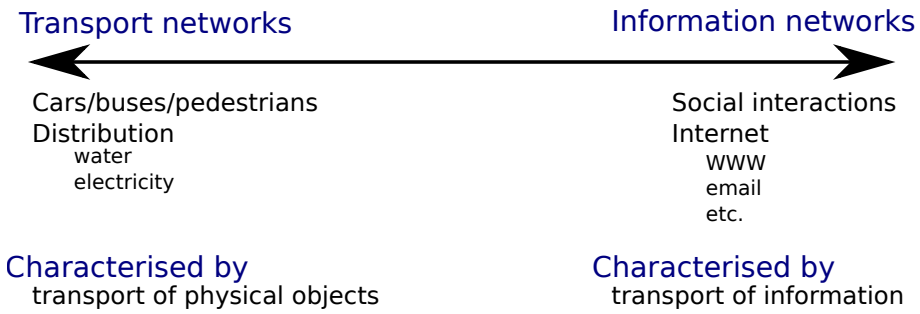


Figure 2: *Transport vs information flows.*

networks considered here are information transportation networks.

There are other dimensions on which networks could be classified. For instance, by the nature of the transport. Does it come in discrete chunks (*e.g.,* cars, packets, or the post) or continuously (*e.g.,* water or electricity)? Is the transport connection oriented (*e.g.,* the telephone network) or packet oriented (*e.g.,* the Internet)?

And there are other general issues we need to deal with:

- Physical networks are embedded in geography, but logical networks often aren't, and yet the same terminology is often applied to each.
- Connectivity often changes over time, with the time-scale varying depending on the type of network.
- The Internet is often said to be a "network of networks". It is often hard to consider one network in isolation, they have relationships, but the situations is even more complicated than often imagined.

  peers Networks may be connected to *peers*, *i.e.,* similar networks that may be competing or co-operating (or both in some cases), *e.g.,* two ISPs operating in the same region.

  parents Networks may have a parent-child relationship in the sense that one network controls the other, *e.g.,* the SS7 network with respect to traditional telephone network.

  layers A single network may have multiple layers, each of which can be represented by a different graph, *e.g.,* the physical- vs the network-layers in the Internet.

  external There is substantial interaction between notionally separated networks, *e.g.,* the power grid and the Internet, both because the Internet uses electricity, but also because spikes in electricity demand could potentially be caused by network flash crowds (certainly TV programs have a very important impact on electricity usage).

That brings us naturally to the particular object of discussion here – the Internet (and its topology). The term "Internet" means (many) different things to (many) different people. Even within the networking community, the term is often used ambiguously, leading to misunderstandings and confusion and creating roadblocks for a genuinely scientific treatment of an engineered system that has revolutionized the way we live.

While mathematics in the form of graph theory has been equally culpable in adopting the use of this vague nomenclature, the "new science of networks" has popularized it to the point where phrases like

"topology of the Internet" or "Internet graph" have entered the mainstream science literature, even though they are essentially meaningless without precisely-stated definitions. For one, "Internet topology" could refer to the connectivity structures encountered in any of layers in the protocol stack, or at various levels of aggregation. Common examples are

1. **Router-level (layer 3):** An often sought topology is the router level. Somewhat ambiguously, this may also be called the network level, or IP level, but "network" is a heavily overloaded term here, and the IP level can also be ambiguous. For instance, IP level could refer to the way IP addresses are connected, that is it could refer to the interfaces of one router as separate nodes [19], but that is rarely what is useful for network operations or research. We could also add at layer 3, in addition to *interface-level* topology described above, the *subnet-level* topology [19, 67, 81, 148, 149], describing the interconnectivity of logical subnets (often described by an IP-level prefix), but here we focus on the more commonly considered router level.

   The router-level graph shows a range of interesting implementation details of a network. This type of information is critical for network management applications, as much of Internet management rests at the IP layer, and it is of great importance for network adversaries. For instance, developing tools to measure network traffic requires an understanding of the router-layer topology, in order to match traffic to links. Similarly traffic engineering, and reliability analyses are carried out at this level. One complication of this layer is that we sometimes wish to obtain the topology extending out to end-hosts, which are not technically routers, but we shall include these in our definition of router-layer topology, unless otherwise specified.

2. **Switch-level (layer 2):** A single IP layer logical link may hide several layer-2 devices (hubs and switches). The increasing prevalence of Ethernet, and the ability to provide redundancy at reasonable cost, has led to a proliferation of such devices, and most Local Area Networks (LANs) are based around such. Hence, very many networks which have trivial, or simple IP layer topologies have complex and interesting layer-2 topologies. Multi-Protocol Label Switching (MPLS) further complicates the situation by creating logical layer-2 networks without physical devices, often in the form of cliques. Measurements often see only one layer, creating misunderstandings of a network's true resilience and more general graph properties. For instance, layer-2 devices can connect large numbers of routers, making them appear to have higher degree at layer-3 [104] (for more detailed discussion see §3.2.3).

3. **Physical-level (layer 1):** Below the link layer (layer 2), lies the physical layer. Again, many physical devices may underly a single logical link. Discovery of this layer is of critical importance in network management tasks associated with reliability. In particular, the concept of Shared Risk Link Groups (SRLG) requires knowledge of which links are carried on which fibers (using Wavelength Division Multiplexing), in which conduits. If a backhoe digs up a single conduit, it will cause a bundle of fibers to fail, and so connections that are in the same SRLG will all fail simultaneously. Clearly redundant links need to be in different SRLG, and discovery of the physical topology is important to ensure that this is the case.

4. **PoP-level:** A Point-of-Presence (PoP) is a loosely defined grouping of devices, often defined by a metropolitan area. PoP level topologies are quite useful, essentially because these graphs describe the logical structure of the network as the designer intended, rather than its particular implementation in terms of individual routers. Such topologies are ideal for understanding tradeoffs between connectivity and redundancy, and also provide the most essential information to competitors or

customers (about where a network is based, or who has the best access network in a region). Network maps are often drawn at this level because it is an easy level for humans to comprehend.

5. **Application layer:** There has been significant interest in logical topologies of the application layer, *e.g.,* for the Web (using HTTP, and HTML), and the P2P applications.

6. **AS-level:** AS topologies have generated much interest in the scientific literature [5, 13, 161], because they appear to show interesting properties (such as power-laws) in common with other un-engineered networks such as biological networks. Also, much data on AS topologies is publicly available. While of interest in the scientific literature, this data's use is confused by many myths and misunderstandings [135]. The data may provide mild competitive benefits, in allowing operators to determine who peers with who, but the measured data often comes without attributes that would make the data truly useful in this regard. Finally, it is hard to see how such data could be used in an attack, although much publicized reports such as [161] suggest, incorrectly (see [93]), that the observed structure of the AS graph may lead to an "Achilles heel" of the Internet.

The number of possible topologies we might wish to discover highlights the complexity of this problem, and why discovery is so valuable for network management. In this chapter we will consider the router-level topology in detail, and then discuss some of the similarities and differences with respect to AS- and PoP-level topologies.

In addition to understanding the Internet network as a simple graph, there are many other features of the graph that one would also wish to know, for instance, its routing, link capacities, and geographic locations. We describe such qualities as graph attributes, and find that most can either be attributed to edges of the graph, for instance

- link capacities,
- link length,
- routing weights (*e.g.,* for shortest-path routing),
- link utilizations,
- link performance (for example, bit-error-rate, delay, loss, jitter, reordering, buffer utilization),
- link status (up/down), and
- a link's lower layer properties (*e.g.,* number of physical hops),

or to the nodes of the graph

- geographic location,
- type of node, *e.g.,* brand of router, or version of software,
- performance measures (*e.g.,* CPU utilization), and
- node status (up/down).

We could further divide this list into *intrinsic* network properties, such as node location, or link capacity (things that cannot change easily), and *extrinsic* properties, such as performance, or traffic related properties, which can change dramatically despite there being no change in the underlying network.

3 Router-level topology

3.1 A look back

Since the early days of the ARPANET, networking researchers have been interested in drawing the type of networks they designed [71]. An early map of the ARPANET is reproduced in Figure 3 and shows the network's logical connectivity structures in April 1971, when the network as a whole consisted of some 15 nodes and a node was little more than one or two state-of-the-art computers connected via an Interface Message Processor or IMP (the modern equivalent would be a router). In this context, logical structure refers to a detailed drawing of the connectivity among those nodes and of node-specific details (*e.g.*, type of machine), by and large ignoring geography. In contrast, geographic structure refers to a map of the US that includes the actual locations of the network's physical nodes and shows the physical connectivity among those nodes. Such accurate maps could be drawn because at that time, each piece of equipment was expensive and needed to be accounted for, only a few groups with a small number of researchers were involved in the design and installation of the network, and the network changed relatively slowly.

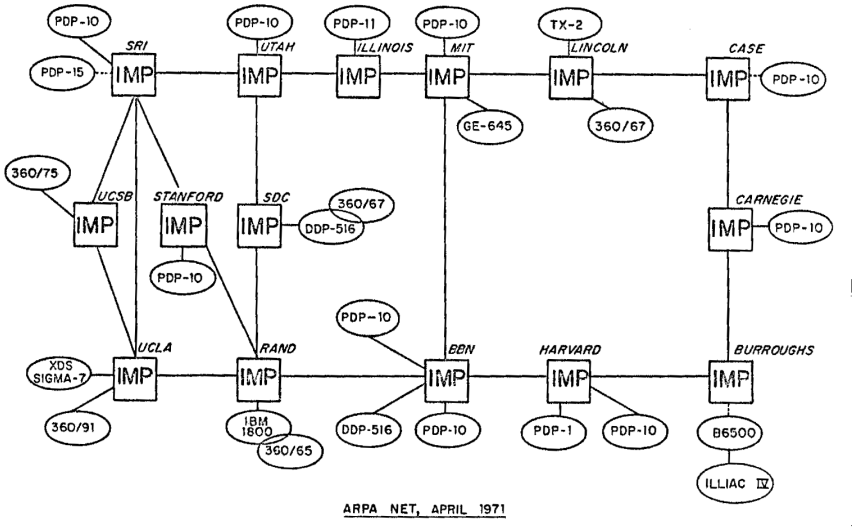


Figure 3: *The ARPANET in 1971 (reprinted from [25]; ©1990 ACM, Inc. Included here by permission.)*

The network quickly grew in size and complexity. For instance, Figure 4 shows the geographic counterpart from 1984 of the ARPANET map depicted in Figure 3. Manually accounting for the increasing number of components quickly became prohibitive and motivated the adoption of automatic strategies for obtaining some of the available connectivity as well as traffic information. A prime example for effectively visualizing this collected information is reproduced from [55] and shown in Figure 5, which depicts a 3D rendering of the (US portion of the) NSFNET around 1991, annotated with traffic-related information. At that time, the NSFNET backbone consisted of some 14 nodes that were interconnected with T1 links as shown and, in turn, connected to a number of different campus networks (*e.g.*, collections of interconnected LANs). However, even though the internal structure of the backbone nodes was well-known (*i.e.*, each node was composed of nine IBM RTs linked by two token rings with an Ethernet interface to attached

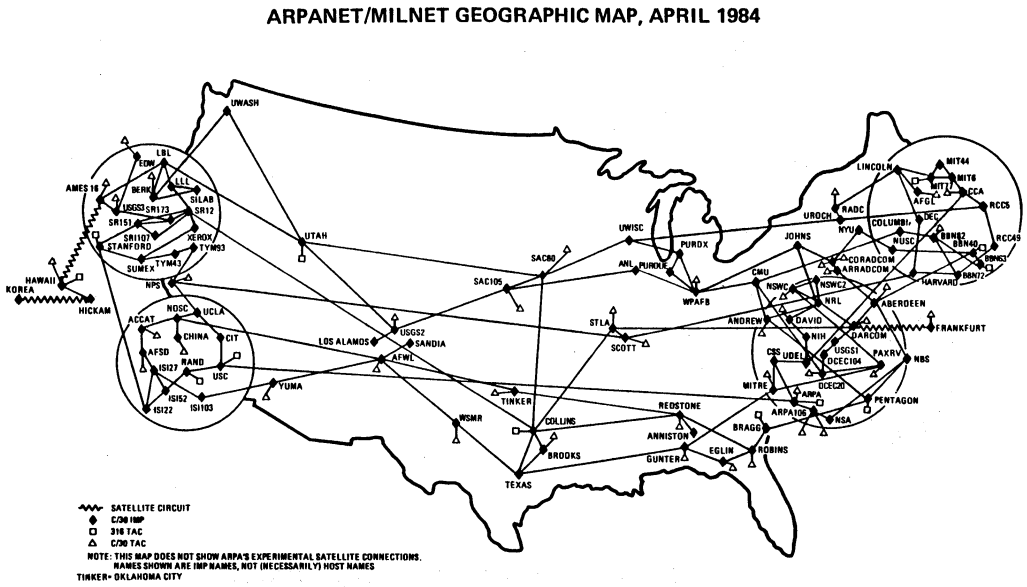


Figure 4: *The early ARPANET (reprinted from [25]; ©1990 ACM, Inc. Included here by permission.)*

networks), nobody had any longer access to the internals of all the different campus networks and as a result, drawing the 1991 NSFNET equivalent of the ARPANET's logical connectivity structure (Figure 3) was no longer possible.

With the decommissioning of the NSFNET in 1995 and the rise of the "public Internet", the researchers' ability to obtain detailed connectivity and component information about the internals of the different networks that formed the emerging "network of networks" further diminished and generated renewed interest in the development of abstract, yet informed, models for router-topology evaluation and generation. For example, the Waxman model [155], a variation of the classical Erdös-Rényi random graph model [47] was the first popular topology generator commonly-used for network simulation studies at the router level. However, it was largely abandoned in the late 1990s in favor of models that attempted to explicitly account for non-random structure as part of the network design. The arguments that favored structure over randomness were largely empirical in nature and reflected the fact that the inspection of real-world router-level ISP networks showed clear signs of non-random structures in the form of the presence of backbones, the appearance of hierarchical designs, and the importance of locality. These arguments also favored the notion that a topology generator should reflect the design principles in common use; *e.g.,* to achieve some desired performance objectives, the physical networks must satisfy certain connectivity and redundancy requirements, properties which are generally not guaranteed in random network topologies. These principles were, for example, advanced in [23, 164, 165] and were ultimately integrated into the popular Georgia Tech Internetwork Topology Models (GT-ITM) [65].

These more structure-oriented router topology generators were viewed as the state-of-the-art until around 2000 when, in turn, they were largely abandoned in favor of a new class of random graph models whose trademark was the ability to reproduce the newly discovered power-law relationship in the observed connectivity (*i.e.,* node degree) of router-level graphs of the Internet. This discovery was originally reported

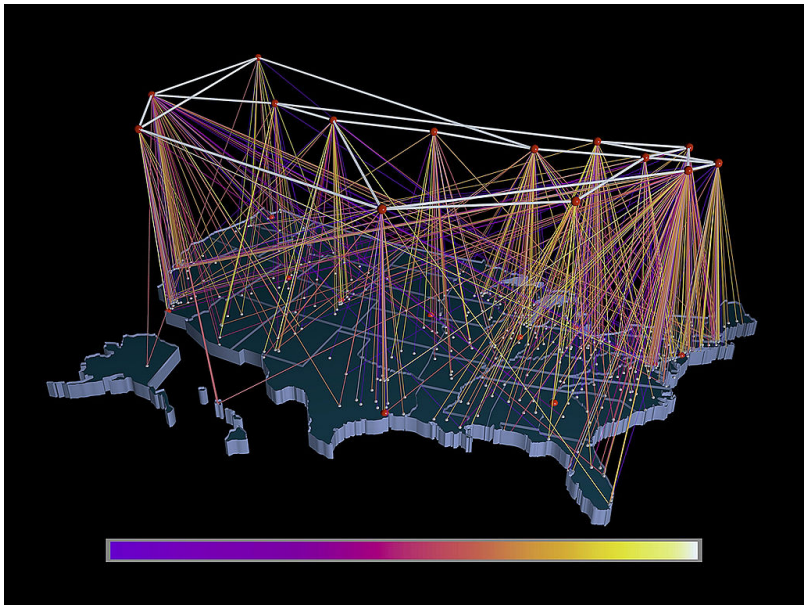


Figure 5: *A visualization of the NSFNET circa 1991 (by Donna Cox and Robert Patterson, National Center for Supercomputing Applications, University of Illinois at Urbana-Champaign. See also* `http://en.wikipedia.org/wiki/File:NSFNET-traffic-visualization-1991.jpg`*).*

in the seminal paper by Faloutsos *et al.* [49], who used a router-level graph constructed from data that was collected a few years earlier by Pansiot and Grad [119] for the purpose of obtaining some experimental data on the actual shape of multicast trees in the Internet. The Boston university Representative Internet Topology gEnerator (BRITE) [103] became a popular representative of this new class of models, in part also because it combined the more structure-oriented perspective of the GT-ITM generator with the new focus that emphasized the ability to reproduce certain metrics or statistics of measured router topologies (*e.g.*, node degree distribution).

One of the hallmarks of networks that have power-law degree distributions and that are generated according to any of a number of different probabilistic mechanisms (*e.g.*, preferential attachment [13], random graphs with a given expected degree sequence [30], power-law random graphs [3]) is that they can be shown to have a few centrally located and highly connected *hubs* through which essentially most traffic must flow. When using these models to represent the router-level topology of the Internet, the presence of these highly connected central nodes has been touted the Internet's "Achilles-heel" because network connectivity is highly vulnerable to attacks that target the high-degree hub nodes [5]. It has been similarly argued that these high-degree hubs are a primary reason for the epidemic spread of computer worms and viruses [112, 122]. Importantly, the presence of highly connected central nodes in a network having a power-law degree distribution is the essence of the so-called scale-free network models. They have been a highly popular theme in the study of complex networks, particularly among researchers inspired by statistical physics [4], and have fuelled the rise of a new scientific discipline that has become known as "Network Science" [12]. In the process, they have also seen wide-spread use among Internet topology researchers.

However, as the general fascination with and popularity of network science in general and scale free network modeling in particular grew, so did the arguments that were voiced by Internet researchers and questioned the appropriateness and relevance of the scale-free modeling approach for studying highly-engineered systems such as the Internet's router topology. In fact, at around 2010, when the number of publications in the area of network science reached a new height, the number of papers that were published in the networking research literature and applied scale-free network models to describe or study router-level topologies of the Internet was close to zero. This begs the question "What happened?", and the answer provided in the next section is really a classic lesson in how errors of various forms occur and can add up to produce results and claims that create excitement among non-networking researchers, but quickly collapse when scrutinized with real data or examined by domain experts.

3.2 Know your measurements

Between 1990 and 2000, Internet topology research underwent a drastic change from being a data-starved discipline to becoming a prime example of a largely measurement-driven research activity. As described earlier, even though the development of abstract, yet informed, models for network topology evaluation and generation has always been a give and take between theoreticians and empiricists, for router topology modeling, the essential role that measurements have started to play came into full focus in a sequence of three seminal papers that appeared between 1998-2000.

3.2.1 Three seminal papers on router topology modeling

The key papers that turned router topology modeling into a full-fledged measurement-driven research activity cover the whole spectrum of modeling activities, from measurement experiments to model construction and validation to graph-theoretical network analysis, and are listed below:

(i) "On routes and multicast trees in the Internet" by J.-J. Pansiot and D. Grad (1998) [119] described the original measurement experiment that was performed in mid-1995 and produced data on actual routes taken by packets in the Internet. This data was subsequently used to construct a router graph of the Internet.

(ii) "On power-law relationships of the Internet topology" by M. Faloutsos *et al.* (1999) [49] reported (among other observations) on the observed power-law relationship in the connectivity of the router-level topology of the Internet measured by Pansiot and Grad [119].

(iii) "Error and attack tolerance of complex networks" by R. Albert *et al.* (2000) [5] proposed a scale-free network model to describe the router topology of the Internet and argued for its validity on the basis of the latest findings by Faloutsos *et al.* [49]. It touted the new model's exemplary predictive power by reporting on the discovery of a fundamental weakness of the Internet (a property that was became known as the Internet's "Achilles' heel") that went apparently unnoticed by the engineers and researchers who have designed, deployed, and studied this large-scale, critical infrastructure, but followed directly from the newly proposed scale-free modeling approach.

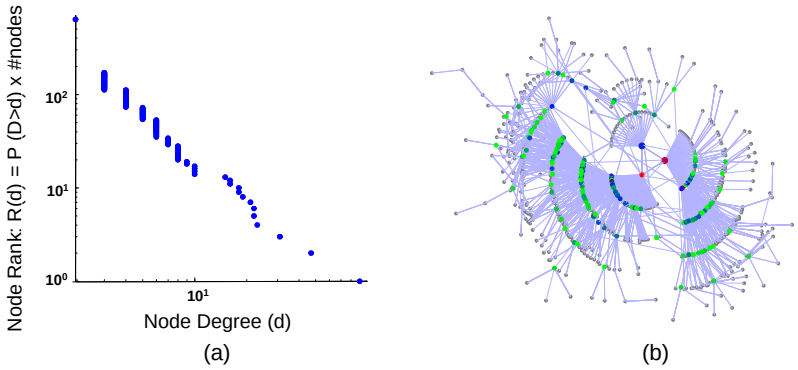


Figure 6: *A toy example of a scale-free network of the preferential attachment type (b) generated to match a power-law type node degree distribution (a). (First published in Notices of the American Mathematical Society, Volume 56, No.3 (May 2009): 586-599 [156]. Included here by permission.)*

At first glance, the combination of these three papers appears to show network modeling at its best – firmly based on experimental data, following modeling practices steeped in tradition, and discovering surprisingly and previously unknown properties of the modeled network. An example of a toy network resulting from taking the findings from these seminal papers at face value is shown in Figure 6. However, one of the beauties of studying man-made systems such as the Internet is that – because of their highly-engineered architectures, a thorough understanding of its component technologies, and the availability of extensive (but not necessarily very accurate) measurement capabilities – they provide a unique setting in which most claims about their properties, structure, and functionality can be unambiguously resolved, though perhaps not without substantial efforts. In the remainder of this section, we will illustrate how in the context of the Internet's router topology, applying readily available domain knowledge in the form of original design principles, existing technological constraints, and available measurement methodologies reveals a drastically different picture from that painted in these three seminal papers. In fact, we will

expose the specious nature of scale-free network models that may appeal to more mathematically inclined researchers because of their simplicity or generality, but besides having no bearing on the Internet's router topology are also resulting in wrong claims about the Internet as a whole.

3.2.2 A first sanity check: Using publicly available information

A first indication of apparent inconsistencies between the proposed scale-free models for the Internet's router topology and the actual Internet comes from the inspection of the router topologies of actual networks that make the details of their network internals publicly available. For example, networks such as Internet2 [77] or GÉANT [57] show no evidence that there exist any centrally located and highly connected "hubs" through which essentially most traffic must flow. Instead, what they typically show is the presence of a more or less pronounced "backbone" network that is fed by tree-like access networks, with additional connections at various places to provide a degree of redundancy and robustness to components failures[4].

This design pattern is fully consistent with even just a cursory reading of the most recent product catalogs or white papers published by the main router vendors [32,33,80]. For one, the most expensive and fastest or highest-capacity pieces of equipment are explicitly marketed as backbone routers. Moreover, due to inherent technological limitations in how many packets or bytes a router can handle in a given time interval, even the latest models of backbone routers can support only a small number of very high-bandwidth connections, typically to connect to other backbone routers. At the same time, a wide range of cheaper, slower or lower-capacity products are offered by the different router vendors and are targeted primarily at to support network access. On the access side, a typical router will have many lower-bandwidth connections for the purpose of aggregating customer traffic from the network's edge and subsequently forwarding that traffic towards the backbone. In short, even the latest models advertised by today's router vendors are limited by existing technologies, and even for the top-of-the-line backbone routers, it is technologically infeasible to have hundreds or thousands of high-bandwidth connections. At the same time, while technically feasible, deploying some of the most expensive equipment and configuring it to support hundreds or thousands of low-bandwidth connections would be considered an overall bad engineering decision (*e.g.*, excessively costly, highly inefficient, and causing serious bottlenecks in the network).

However, the root cause for these outward signs of a clear mismatch between the modeled and actual router topology of the Internet goes deeper and lies in the original design philosophy of the Internet. As detailed in [34], while the top level goal for the original DARPA Internet architecture was *"to develop an effective technique for multiplexed utilization of existing interconnected networks"*, the requirement that *"Internet communication must continue despite loss of networks or gateways"* topped the list of second level goals. To survive in the face of components failing off, the architecture was to mask completely any transient failure, and to achieve this goal, state information which describes an existing connection must be protected. To this end, the architecture adopted the "fate-sharing" model that gathers this state information at the endpoints of connections, at the entities that are utilizing the service of the network. Under this model, it is acceptable to lose the state information associated with an entity if, at the same time, the entity itself is lost; that is, there exists no longer any physical path over which any sort of communication with that entity can be achieved (*i.e.*, total partition). Ironically, these original design principles outlined in [34] favor precisely the opposite of what the scale-free modeling approach yields – no centrally located and highly connected "hubs" because their removal makes partitioning the network easy.

[4] This is not a universal phenomena. For instance [84] notes that some networks do exhibit hub-like structure, but it is the lack of universality that is important here, as exhibited by these and other counter examples.

3.2.3 An in-depth look at traceroute: Examining a popular measurement technique

While the above-mentioned empirical, technological, and architectural arguments cast some serious doubts on the scale-free network modeling approach for the router topology of the Internet, they say nothing about the measurements that form the basis of this approach and has given it a sense of legitimacy among scientists in general and networking researchers in particular. To appreciate the full role that measurements play in this discussion, it is informative to revisit the original paper by Pansiot and Grad [119] that describes the measurement experiment, discusses the measurement technique used, and provides a detailed account of the quality of the data that form the basis of the scale-free approach towards modeling the Internet's router topology.

In essence, [119] describes the first (at that time) large-scale traceroute campaign performed for the main purpose of constructing a router graph of the Internet from actual Internet routes. Although traceroute-based, the authors of [119] quickly point out that their purpose of using the traceroute tool (*i.e.,* obtaining actual Internet routes to construct a router graph) differed from what V. Jacobson [78] had in mind when he originally designed the tool (*i.e.,* tracing a route from a source to a destination for diagnostic purposes). As a result, a number of serious issues arise that highlight why using the traceroute technique for the purpose of constructing a router graph is little more than an "engineering hack" and can certainly not be called a well-understood "measurement methodology."

IP alias resolution problem: One serious problem explained in detail in [119] with using traceroute-based data for constructing router graphs is that the traceroute tool only returns the IP addresses of the interface cards of the routers that the probe packets encountered on their route from the source to their destination. However, most routers have many interface cards, and despite many years of research efforts that have produced a series of increasingly sophisticated heuristics [15, 67, 140], the networking community still lacks rigorous and accurate methods for resolving the IP alias resolution problem; that is, determining whether two different interface IP addresses belong to or can be mapped to the same router. While the essence of this problem is illustrated in Figure 7, the impact it can have when trying to map a router topology of an actual network is shown in Figure 8.

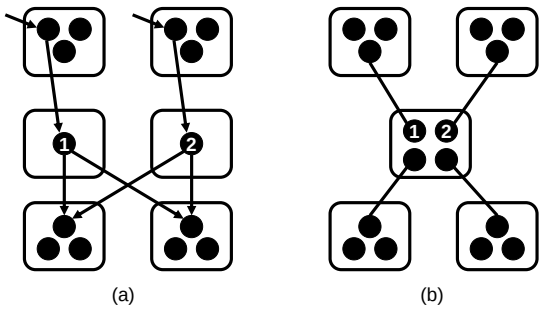


Figure 7: *The IP alias resolution problem. Paraphrasing Fig. 4 of [144], traceroute does not list routers (boxes) along paths but IP addresses of input interfaces (circles), and alias resolution refers to the correct mapping of interfaces to routers to reveal the actual topology. In the case where interfaces 1 and 2 are aliases, (b) depicts the actual topology while (a) yields an "inflated" topology with more routers and links. (First published in Notices of the American Mathematical Society, Volume 56, No.3 (May 2009): 586-599 [156]. Included here by permission.)*

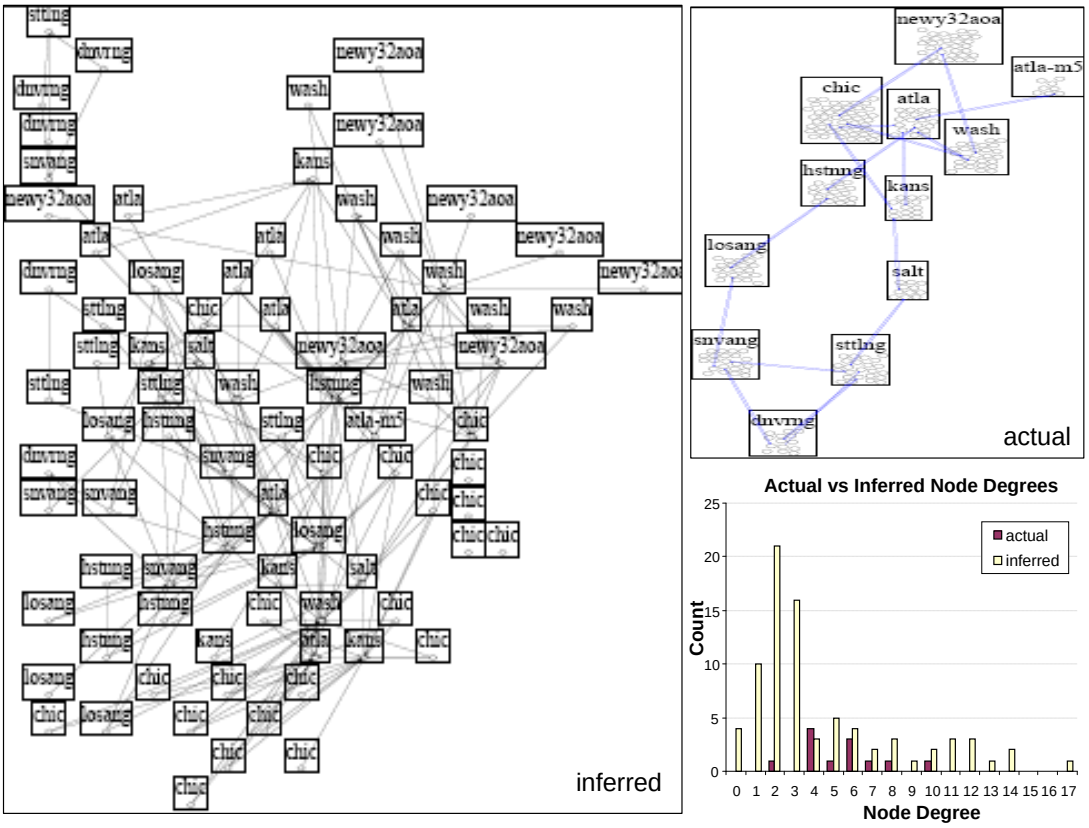


Figure 8: *The IP alias resolution problem in practice. Shown is a comparison between the Abilene/Internet2 topology inferred by Rocketfuel (left) and the actual topology (top right). Rectangles represent routers with interior ovals denoting interfaces. The histograms of the corresponding node degrees are shown in the bottom right plot. (Reprinted from [141]; ©2008 ACM. Inc. Included here by permission.)*

Lesson 1: *Due to the absence of accurate and rigorous methods for solving the IP alias resolution problem, the actual values of the connectivity of each router* (i.e., *node degrees) inferred from traceroute measurements cannot be taken at face value.*

Opaque Layer-2 clouds: Another serious issue with using generic traceroute-based measurements for construction router graphs is also discussed at length in [119] and illustrated in Figure 9. Being strictly limited to IP or layer-3, the problem with traceroute is that it is incapable of tracing through opaque layer-2 clouds that feature circuit technologies such as Asynchronous Transfer Mode (ATM) or Multiprotocol Label Switching (MPLS). These technologies have the explicit and intended purpose of hiding the network's physical infrastructure from IP, so from the perspective of traceroute, a network that runs these technologies will appear to provide direct connectivity between routers that are separated by local, regional, national, or even global physical network infrastructures. An example of using traceroute to map a network that uses MPLS is depicted in Figure 9 and shows an essentially completely connected graph at Layer 3 with multiple high-degree nodes, even though the physical router topology is very sparse. Similarly, if traceroute encounters an ATM cloud, it falsely "discovers" a high-degree node that is really a logical entity – often an entire network potentially spanning many hosts or great distances – rather than a physical node of the Internet's router-level topology. Donnet *et al.* [44] found that at least 30% of the paths they tested traversed an MPLS tunnel.

Recent extensions of the ICMP protocol, using traceroute to trace through opaque MPLS clouds have become technically feasible [16], but operators often configure their routers to hide the MPLS tunnels by turning off this option [142]. Even then it may be possible to detect the MPLS tunnels [44], but the inference techniques are not a guarantee, and are quite particular to MPLS, which is not the only technique for creating tunnels, so there may still be some opaque networks to deal with. More to the point, even where such inferences are possible, most data sets do not contain this type of analysis, and most subsequent analyses of the data have ignored the issue.

Lesson 2: *Due to an inability of the generic traceroute technique to trace through opaque Layer-2 clouds, or understand the connectivity created by Layer-2 devices [104], the inferred high-degree nodes* (i.e., *routers with a large number of connections) are typically fictitious, an artifact of an imperfect measurement tool.*

Limited vantage points: We have commented earlier that since a router is fundamentally limited in terms of the number of packets it can process in any time interval, there is an inherent tradeoff in router configuration: it can support either a few high-throughput connections or many low-throughput connections. Thus, for any given router technology, a high-connectivity router in the core reflects a poor design decision – it will either have poor performance due to its slow connections or be prohibitively expensive relative to other options. Conversely, a good design choice is to deploy cheap high-degree router near the edge of the network and rely on the very technology that supports easy multiplexing of a large number of relatively low-bandwidth links. Unfortunately, neither the original traceroute-based study of Pansiot and Grad [119] nor any of the larger-scale campaigns that were subsequently performed by various network research groups have the ability to detect those actual high-degree nodes. The simple reason is that these campaigns lack access to a sufficient number of vantage points (*i.e.,* sources for launching traceroute probes and targets) in any local end-system to reveal these actual high connectivity patterns at the network's edge.

Lesson 3: *If there were high-degree nodes in the network, existing router technology relegates them to the edge of the network where no generic traceroute-based measurement campaigns is able to detect them because of a lack of vantage points nearby.*

There are other issues with large-scale traceroute campaigns that impact the quality of the resulting measurements and have received some attention in the literature. For example, the use of traceroute has been shown to make experimental data susceptible to a type of measurement bias in which some nodes

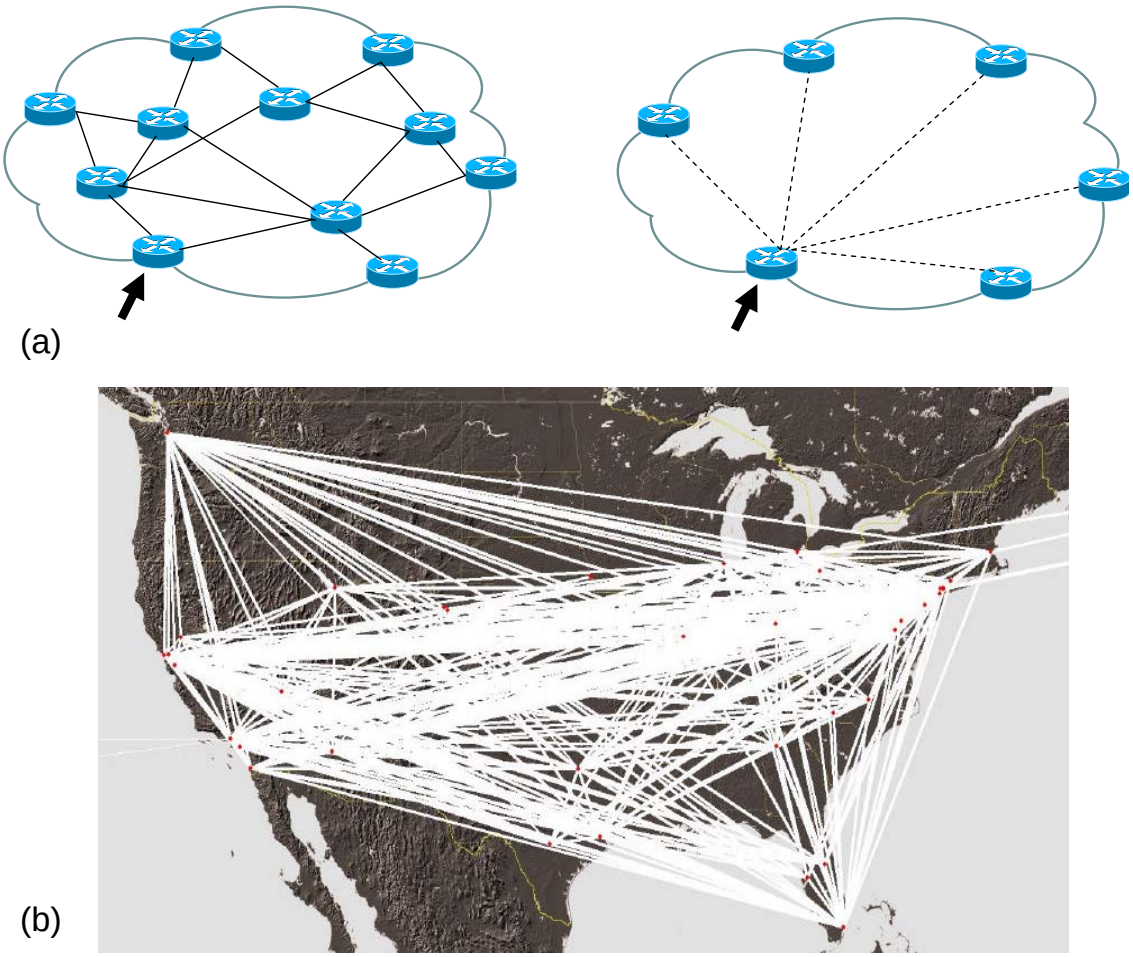


Figure 9: *How traceroute detects fictitious high-degree nodes in the network core. (a) The actual connectivity of an opaque layer-2 cloud, i.e., a router-level network running a technology such as ATM or MPLS (left) and the connectivity inferred by traceroute probes entering the network at the marked router (right). (b) The Rocketfuel-inferred backbone topology of AS3356 (Level3), a Tier-1 Internet service provider and leader in the deployment of MPLS. (Figure (b) reprinted from [144]; ©2002 ACM, Inc. Included here by permission.)*

of the network are oversampled, while others are undersampled. However, while this feature has received considerable attention [1, 91], in the presence of systematic errors due to an inability to perform accurate IP alias resolution or trace through opaque Layer-2 clouds, this work is largely of theoretical interest and of little practical relevance for modeling the Internet's router topology.

3.2.4 Just the facts: power-law scaling and router-level topologies

When applying lessons 1-3 to the main findings reported in the seminal papers discussed in §3.2.1 we are faced with the following facts:

Fact 1: A very typical but largely ignored fact about Internet-related measurements in general and traceroute measurements in particular is that what we can measure in an Internet-like environment is generally not the same as what we really want to measure (or what we think we actually measure). This is mainly because as a decentralized and distributed system, the Internet lacks a central authority and does not support third-party measurements.

Fact 2: A particularly ironic fact about traceroute is that the high-degree nodes it detects in the network core are necessarily fictitious and represent entire opaque layer-2 clouds, and if there are actual high-degree nodes in the network, existing technology relegates them to the edge of the network where no generic traceroute-based measurement experiment will ever detect them.

Fact 3: In particular, due to the inherent inability of traceroute to (i) reveal unambiguously the actual connectivity (*i.e.,* node degree) of any router, and (ii) correctly identify even the mere absence or presence of high-degree nodes (let alone their actual values), statistical statements such as those made in [49] claiming that the Internet's router connectivity is well described by a power-law distribution (or, for that case, any other type of distribution) cannot be justified with any reasonable degree of statistical confidence.

Fact 4: Since historical traceroute-based measurements cannot be taken at face value when (mis)using them for inferring router topologies and the inference results obtained from such data cannot be trusted, the claims that have been made about the (router-level) Internet in [5] are without substance and collapse under careful scrutiny.

In short, after almost 15 years of examining the idiosyncrasies of the traceroute tool, there exists overwhelming evidence that the sort of generic and raw traceroute measurements that have been used to date to infer the Internet's router topology are seriously flawed to the point of being essentially of no use for performing scientifically sound inferences. Yet, the myth that started with [49]; *i.e.,* the router topology of the Internet exhibits power-law degree distributions persists and continues to be especially popular with researchers that typically work in the field of network science and show in general little interest in domain-specific "details" such as traceroute's idiosyncrasies.

At the same time, it is worthwhile pointing out that most of the above-mentioned flaws and shortcomings of traceroute-based measurements are neither new nor controversial with networking researchers. In fact, when discussing the use of the traceroute tool as part of their original measurement experiment, the authors of [119] described many of the issues discussed in this section in great detail and commented on the possible implications that these inherently traceroute-related issues can have for constructing router graphs of the Internet. In this sense, [119] is an early example of an exemplary measurement paper, but unfortunately, it has been largely ignored and essentially forgotten. For one, [49], which critically relies on the data described in [119] for their power law claim for the Internet's router topology, fails to recognize the

relevance of these issues and does not even comment on them. Moreover, the majority of papers that have appeared in this area after the publication of [49] typically cite only [49] and don't even mention [119].

Traceroute-based measurements are not the only approach for obtaining router-level topologies, just the most commonly presented in the research literature. Network operators can obtain measurements of their own networks using much more accurate methods: for instance, from configuration files [52], or using route monitors [137], but those techniques require privileged access to the network, and so haven't been used widely for research. More recently, the mrinfo tool [109] has been used to measure topologies using IGMP (the Internet Group Management Protocol) [105, 120]. IGMP has the advantage that routers that respond provide much more complete information on their interfaces than those responding to traceroutes (so aliasing is less an issue), but there are still coverage problems created by lack of support, or deliberate filtering or rate limiting of responses to the protocol [102].

3.3 Network modeling: An exercise in reverse-engineering

The conclusion from the previous section that the available traceroute measurements are of insufficient quality to infer any statistical quantity of the data (including node degree distribution) with sufficient statistical confidence is a show-stopper for traditional network modeling. Indeed, given that the data cannot be trusted, relying on statistics of unknown accuracy (*e.g.,* by and large arbitrary node degrees) makes model selection precarious, and model validation in the sense of checking if the selected model describes the data "well" is an oxymoron – providing a "good" fit for statistical quantities of unknown accuracy is meaningless.

As such, the scale-free approach to modeling the Internet's router topology advanced in [5] is an example of what can go wrong if serious flaws of the underlying data are ignored and the available measurements are taken at face value. It should therefore come as no surprise that the resulting modeling framework and ensuing claims quickly collapse when scrutinized with readily available domain knowledge or vetted against alternative and solid sources of information. However, the lessons learned from this ill-fated approach to router topology modeling rises the question: What are viable alternative approaches to modeling the Internet's router topology that are by and large independent of the available but problematic traceroute measurements?

3.3.1 Router topology modeling as a constrained optimization problem

Having dismissed traceroute-based data as a source for informing our approach to modeling the Internet's router topology, we turn to readily available domain knowledge as critical alternate information source. To this end, we focus on the specific problem of modeling the physical infrastructure of a regional, national, or global Internet Service Provider (ISP).

The first key ingredient of this "first-principles" approach is the realization that ISPs design their physical infrastructures for a purpose; that is, their decisions are driven by possibly ISP-specific objectives and reflect trade-offs between what is feasible and what is desirable. While in general it may be difficult if not impossible to define or capture the precise meaning of a particular ISP's purpose for designing its network, an objective that expresses a desire to provide connectivity to the rest of the Internet for its end users and an ability to carry an expected traffic demand efficiently and effectively, subject to prevailing economic and technological constraints, is unlikely to be far from the "true" purpose.

The second ingredient concerns the trade-offs an ISP has to made between what is feasible (in terms of available products sold by the different router vendors) and what is desirable (in terms of cost, performance, ease-of-management or other criteria for the built-out router topology). In particular, router

technology constraints are a significant force shaping network connectivity at the router-level and, in turn, router topology design. Due to hard physical limits, even the most expensive and highest-capacity router models available on the market in any given year operate within a “feasible region" and corresponding "efficiency frontier" of possible bandwidth-degree combinations; that is, they can be configured to either have only a few high-bandwidth connections and perform at their capacity or have many low-bandwidth connections and tolerate a performance hit due to the overhead that results from the increased connectivity.

Similarly, economic considerations also affect network connectivity and router topology design. For example, the cost of installing and operating physical links in a network can often dominate the cost of the overall router infrastructure. In essence, this observation creates enormous practical incentives to design the physical plant of an ISP so as to keep the number of links small and avoid whenever possible long-haul connections due to their high cost. These incentives to share costs via multiplexing impact and are impacted by available router technologies and argue for a design principle for an ISP’s router topology that favors aggregating traffic at all levels of network hierarchy, from its periphery all the way to its core.

The third and final key ingredient of the proposed first-principle alternative to router topology modeling is concerned with the role that randomness plays in this approach. Recall that the traditional approach is typically graph theory-based where randomness is explicit and appears in the form of a series of coin tosses (using potentially bias coins as in the case of scale-free networks of the preferential attachment type) that determine whether or not two nodes (*i.e.,* routers) are connected by a physical link, irrespective of the type of routers involved or link considered. In stark contrast, in our approach, randomness enters in a very different and less explicit manner, namely in terms of the uncertainty that exists about the “environment” (*i.e.,* the traffic demand that the network is expected to carry). Moreover, irrespective of the model chosen for quantifying this uncertainty, the resulting network design is expected to exhibit strong robustness properties with respect to changes in this environment.

When combining all three ingredients to formulate an ISP’s router topology design problem, the mathematical modeling language that naturally reflects the objectives of an ISP, its need to adhere to existing technology constraints and respect economic considerations, and its desire to operate effectively and efficiently in light of the uncertainly in the environment is *constrained optimization*. Thus, we have changed network modeling from an exercise in model fitting into an exercise in reverse-engineering and seek a solution to a constrained optimization problem formulation that captures by and large what the ISP can afford to build, operate, and manage (*i.e.,* economic considerations), satisfies the hard constraints that technology imposes on the network’s physical entities (*i.e.,* routers and links), and is robust to changes in the expected traffic that is supposed to handle

3.3.2 Heuristically optimal router topologies

In the process of formulating the design of an ISP’s router topology as a constrained optimization problem, we alluded to a synergy that exists between the technological and economic design issues with respect to the network core and the network edge. The all-important objective to multiplex traffic is supported by the types of routers available on the market. In turn, the use of these products re-enforces traffic aggregation everywhere in the network. Thus, the trade-offs that an ISP has to make between what is technologically feasible versus economically sensible can be expected to yield router topologies where individual link capacities tend to increase while the degree of connectivity tends to decrease as one moves from the network edge to its core.

This consistent picture with regard to the forces that by and large govern the built-out and provisioning of an ISP’s router topology and include aspects such as equipment constraints, link costs, and bandwidth

demands suggests that the following type of topology is a reasonably "good" design for a single ISP's physical plant: (i) Construct a core as a loose mesh of expensive, high-capacity, low-connectivity routers which carry heavily aggregated traffic over high-bandwidth links. (ii) Support this mesh-like core with hierarchical tree-like structures at the edge of the network for the purpose of aggregating traffic from end users via cheaper, lower-capacity, high-connectivity routers. (iii) Augment the resulting structure with additional connections at various selectively-chosen places to provide a degree of redundancy and robustness to component failures. The result is a topology that has a more or less pronounced backbone, which is fed by tree-like access networks, with additional links added for redundancy and resilience. We refer to this design as *heuristically optimal* to reflect its consistency with real design considerations and call the resulting "solutions" *heuristically optimal topologies*, or HOT for short. Note that such HOT models have been discussed earlier in the context of highly organized/optimized tolerances/tradeoffs [24, 48].

An important aspect of the proposed HOT models is that even though we have formulated the design of an ISP's router topology as a constrained optimization problem that could in principle be solved optimally, we are typically not concerned with a network design that is "optimal" in a strictly mathematical sense and is also likely to be NP-hard. Instead, our interest is in solutions that are "heuristically optimal" in the sense that they result in "good" performance. The main reason for not pursuing optimal solutions more aggressively is the imprecise nature of essentially all ingredients of the constrained optimization problem of interest. For one, it is unrealistic to expect that an ISP's true objective for building out and provisioning its physical infrastructure can be fully expressed in mathematical terms as an objective function. Furthermore, a bewildering number of different types of routers and connections make it practically impossible to account for the nuances of the relevant feasible regions or efficiency frontiers. Finally, any stochastic model for describing the expected traffic demand is an approximation of reality or at best based on imprecise forecasts. Given this approximate nature of the underlying constrained optimization problem, we seek solutions that captures by and large what the ISP can afford to build, operate, and manage (*i.e.,* economic considerations), satisfy some of the more critical hard constraints that technology imposes on the network's physical entities (*i.e.,* routers and links), and exhibit strong robustness properties with fluctuations in the expected traffic demands (*i.e.,* insensitivity to changes in the uncertain environment).

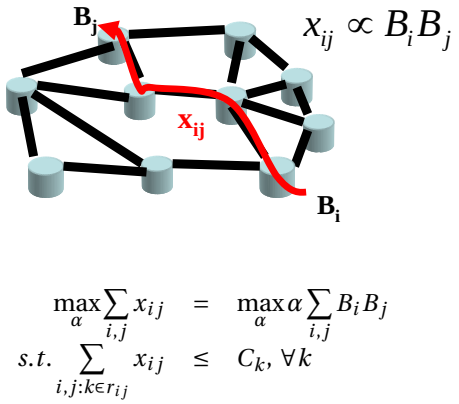
3.3.3 A toy example of a HOT router topology

To illustrate the proposed HOT approach, we use a toy example that is rich enough to highlight the key ingredients of the outlined first-principles methodology and demonstrate its relevance for router topology modeling as compared to the popular model-fitting approach. It's toy nature is mainly due to a number of simplifying assumptions we make that facilitate the problem formulation. For one, by simply equating throughput with revenues, we select as our objective function the maximum throughput that the network can achieve for a given traffic demand and use it as a metric for quantifying the performance of our solutions. Second, considering an arbitrary distribution of end-user traffic demand B_i, we assume a gravity model for the unknown traffic demand; that is, assuming shortest-path routing, the demands are given by the traffic matrix element $x_{i,j} = \alpha B_i B_j$ between routers i and j for some constant α. Lastly, we consider only one type of router and its associated technologically feasible region; that is, (router degree, router capacity)-pairs that are achievable with the considered router type, and implicitly avoid long-haul connections due to their high cost.

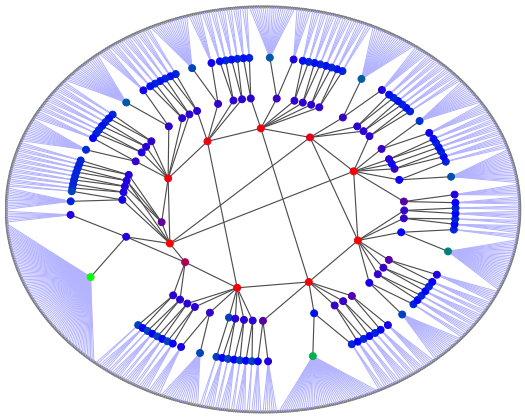
The resulting constrained optimization problem can be written in the form

$$\max_{\rho} \sum x_{i,j} \quad \text{such that} \quad A\mathscr{X} \leq C, \tag{1}$$

where $\mathscr{X}$ is the vector obtained by stacking all the demands $x_{i,j}$; A is the routing matrix obtained by using standard shortest path routing and defined by $A_{k,l} = 1$ or 0, depending on whether or not demand l passes through router k; and C is the vector consisting of the router degree-bandwidths constraints imposed by the technologically feasible region of the router at hand.



(a) *Optimisation.*



(b) *Result.*

Figure 10: *Generating networks using constrained optimization. (a) Engineers view network structure as the solution to a design problem that measures performance in terms of the ability to satisfy traffic demand while adhering to node and arc capacity constraints. (b) A network resulting from heuristically optimized tradeoffs (HOT). This network has very different structural and behavioral properties, even when it has the same number of nodes, links, and degree distribution as a scale free network shown in Figure 9. (First published in Notices of the American Mathematical Society, Volume 56, No.3 (May 2009): 586-599 [156]. Included here by permission.)*

While all the simplifying assumptions can easily be relaxed to allow for more realistic objective functions, more heterogeneity in the constraints, or more accurate descriptions of the uncertainty in the environment, Figure 10 illustrates the key characteristics inherent in a heuristically optimal solution of such a problem. First, the cost-effective handling of end user demands avoids long-haul connections (due to their high cost) and is achieved through traffic aggregation starting at the edge of the network via the use of high-degree routers that support the multiplexing of many low-bandwidth connections. Second, this aggregated traffic is then sent toward the *backbone* that consists of the fastest or highest-capacity routers (*i.e.,* having a small number of very high-bandwidth connections) and that forms the network's mesh-like core. The result is a network of the form described earlier: a more or less explicit backbone representing the network core and tree-like access networks surrounding this core, with additional connections as backup in case of failures or congestion.

The realism of this reverse-engineering approach to router topology modeling is demonstrated in Figure 11 which shows the router topologies of two actual networks – CENIC (circa 2004) and Abeline (circa 2003).

3.3.4 On the (ir)relevance of node degree distributions

The above description of our engineering-based first-principles approach to router topology modeling shows that node degree distributions in general and power low-type node degree distributions in particular

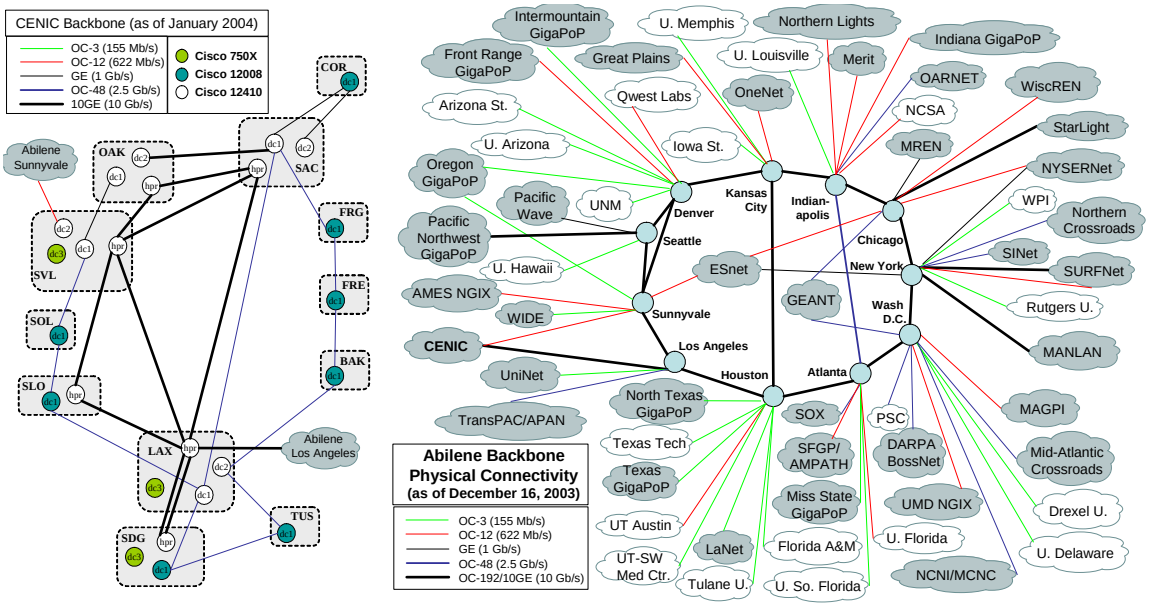


Figure 11: *CENIC and Abilene networks. (Left): CENIC backbone. The CENIC backbone is comprised of two backbone networks in parallel – a high performance (HPR) network supporting the University of California system and other universities, and the digital California (DC) network supporting K-12 educational initiatives and local governments. Connectivity within each POP is provided by Layer-2 technologies, and connectivity to the network edge is not shown. (Right): Abilene network. Each node represents a router, and each link represents a physical connection between Abilene and another network. End user networks are represented in white, while peer networks (other backbones and exchange points) are represented in gray. Each router has only a few high bandwidth connections, however each physical connection can support many virtual connections that give the appearance of greater connectivity to higher levels of the Internet protocol stack. ESnet and GÉANT are other backbone networks. (Reprinted from [93]; ©2004 ACM, Inc. Included here by permission.)*

are clearly a non-issue and play no role whatsoever in our formulation of an ISP router topology design as a constrained optimization problem. Thus, we achieved our goal of developing a network modeling approach that does not rely in any way on the type of measurements that have informed previous network modeling approaches but have been shown earlier to be of insufficient quality to be trusted to form the basis of any scientifically rigorous modeling pursuit.

However, even if the available traceroute measurements could be trusted and taken at face value, the popular approach to network modeling that views it as an exercise in model fitting is by itself seriously flawed, unless it is accompanied by a rigorous validation effort. For example, assuming that the data can be trusted so that a statistic like an inferred node degree distribution is indeed solid and reliable. In this case, who is to say that a proposed model's ability to match this or any other commonly considered statistics of the data argues for its validity, which is in essence the argument advanced by traditional approaches that treat network modeling as an exercise in model fitting? It is well known in the mathematics literature that there can be many different graph realizations for any particular node degree sequence and there are often significant structural differences between graphs having the same degree sequence. Thus, two models that match the data equally well with respect to some statistics can still be radically different in terms of other properties, their structures, or their functionality. A clear sign of the rather precarious current state of network-related modeling that is rooted in the almost exclusive focus on model fitting is that the same underlying data set can give rise to very different, but apparently equally "good" models, which in turn can give rise to completely opposite scientific claims and theories concerning one and the same observed phenomenon. Clearly, network modeling and especially model validation ought to mean more than being able to match the data if we want to be confident that the results that we derive from our models are relevant in practice.

To illustrate these points, Figure 12 depicts five representative toy networks, constructed explicitly to have one and the same node degree distribution. This distribution is shown in plot (a) and happens to be the one of our HOT router topology example in Figure 10. While plots (b) and (c) show two scale-free networks constructed according to the preferential attachment method and general random graph method, respectively, plots (d)-(f) are three different HOT examples, including our earlier example in Figure 10 (plot (e)) and a sub-optimal or poorly-engineered HOT topology in (f). While the differences among these five topologies with identical node degree distributions are already apparent when comparing their connectivity structures, they can be further highlighted by considering both a performance-related and a connectivity-only topology metric. In particular, the performance-related metric *Perf(g)* for a given network g is defined as $Perf(g) = max_{\alpha} \sum x_{i,j}$ s.t. $RX \leq C$ and represents the maximum throughput with gravity flows of the network g. In contrast, the connectivity-only topology metric *S(g)* is the network likelihood of g defined as $S(g) = \sum_{(i,j) \in E(g)} \omega_i \omega_j / s_{max}$ where ω_i denotes the degree of node i, $E(g)$ is the set of all edges in g, and s_{max} is a normalization constant. For a justification of using the $S(g)$ metric to differentiate between random networks having one and the same node degree sequence, we refer to [92].

While computing for each of the five networks their *Perf(g)*-value is straightforward, evaluating their network performance requires further care so as to ensure that the different network have the same total "cost", where cost is measured in number of routers. When simultaneously plotting network performance versus network likelihood for all five networks models in Figure 13, a striking contrast is observed. The well-engineered HOT networks (d) and (e) have high performance and low likelihood while the random degree-based networks (b) and (c) have high likelihood but low performance. To contrast, network (f) has both low performance and low likelihood and is proof that networks can be designed to have poor performance. The main reason for the degree-based models to have such poor performance is exactly the presence of the highly connected "hubs" that create low-bandwidth bottlenecks. The two HOT models' mesh-like cores, like real ISP router topologies, aggregate traffic and disperse it across multiple

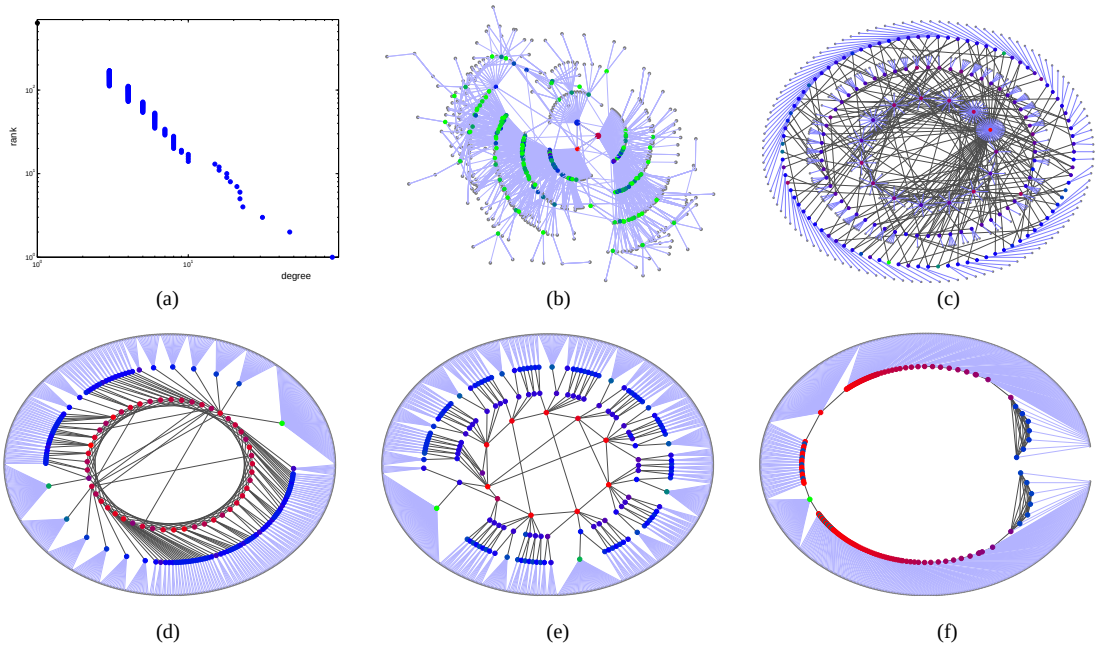


Figure 12: *Five networks having the same node degree distribution. (a) Common node degree distribution (degree versus rank on log-log scale); (b) Network resulting from preferential attachment; (c) Network resulting from the GRG method; (d) Heuristically optimal topology; (e) Abilene-inspired topology; (f) Sub-optimally designed topology. (Reprinted from [93]; ©2004 ACM, Inc. Included here by permission.)*

high-bandwidth routers.

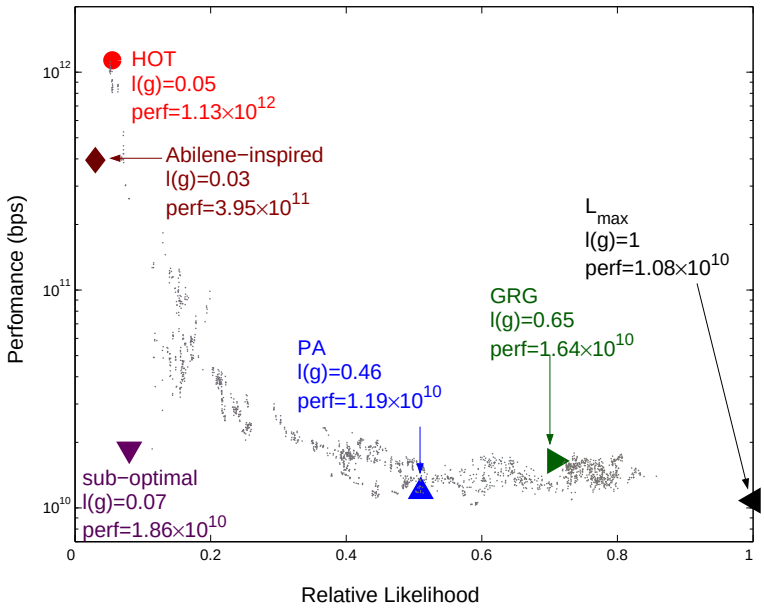


Figure 13: *Performance vs. likelihood for each of the topologies in Figure 12, plus other networks (grey dots) having the same node degree distribution obtained by pairwise random rewiring of links. (Reprinted from [93]; ©2004 ACM, Inc. Included here by permission.)*

The interpretation of this picture is that a careful design process explicitly incorporating technological constraints can yield high-performance topologies, but these are extremely rare from a probabilistic graph point of view. In contrast, equivalent scale-free networks constructed by generic degree-based probabilistic constructions result in more likely, but poorly-performing topologies. Consistent with this, the "most likely" network (included in Figure 13) has also sub-par performance. This picture can be further enhanced when considering alternative performance measures such as the distribution of end user bandwidths and router utilization. As detailed in [93], the heuristically optimal networks (d) and (e) achieve high utilization in their core routers and support a wide range of end-user bandwidth requirements. In contrast, the random degree-based networks (b) and (c) saturate only their "hub" nodes and leave all other routers severely underutilized, thus providing uniformly low bandwidth and poor performance to their end-users. A main lesson from this comparison of five different networks with identical node degree distributions for network modeling is that *functionality* (e.g., *performance) trumps structure* (e.g., *connectivity)*. That is, connectivity-only metrics are weak discriminators among all graph of a given size with the same node degree distribution, and it requires appropriate performance-related metrics to separate "the wheat from the chaff."

We explained earlier that on the basis of currently available traceroute measurements, claims of power-law relationships have no substance as far as the Internet's router topology is concerned. However, by examining available router technologies and models, we have also shown that it is certainly conceivable that the actual node degrees of deployed routers in an actual ISP can span a range of 2-3

orders of magnitude; that is, the corresponding node degree distribution exhibits high variability, without necessarily conforming to a power law-type distribution. At the same time, Figure 12 illustrates that irrespective of the type of node degree distribution, graphs with identical node degree distributions can be very different in their structure and differ even more drastically in terms of their functionality (*e.g.*, performance). What is also true is that the same core network design can support many different end-user bandwidth distributions and that by and large, the variability in end-user bandwidth demands determines the variability of the node degrees in the resulting network. To illustrate, consider the simple example presented in Figure 14, where the same network core supports different types of variability in end user bandwidths at the edge (and thus yields different overall node degree distributions). The network in Figure 14(a) provides uniformly high bandwidth to end users; the network in Figure 14(b) supports end user bandwidth demands that are highly variable; and the network in Figure 14(c) provides uniformly low bandwidth to end users. Thus, from an engineering perspective, not only is there not necessarily any implied relationship between a network node degree distribution and its core structure, there is also no implied relationship between a network's core structure and its overall degree distribution.

Thus, the proposed engineering-based first-principles approach to modeling the Internet router topology demystifies power law-type node degree distributions altogether by identifying its root cause in the form of high variability in end-user bandwidth demands. In view of such a simple physical explanation of the origins of node degree variability in the Internet's router-level topology, Strogatz' question, paraphrasing Shakespeare's Macbeth, "... power-law scaling, full of sound and fury, signifying nothing?" [145] has a resounding affirmative answer.

3.4 A look ahead

Late in the last century, when router-level topology modeling started to turn into a measurement-driven research activity, the conventional wisdom was to start with traceroute-based measurements, use them to infer router-level connectivity, and argue for the validity of a proposed model if it faithfully reproduces certain statistics of the inferred connectivity structure (*e.g.*, node degree distribution). However, the last decade of Internet topology research has shown that this traditional and widely-used approach to router-

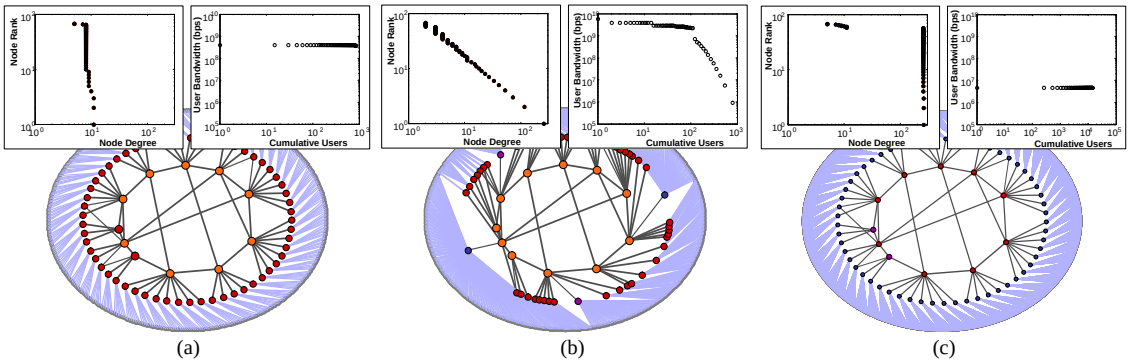


Figure 14: *Distribution of node degree and end-user bandwidths for several topologies having the same core structure: (a) uniformly high bandwidth end users, (b) highly variable bandwidth end users, (c) uniformly low bandwidth end users. (Reprinted from [93]; ©2004 ACM, Inc. Included here by permission.)*

topology modeling is flawed in more than one way, and we have collected and presented this gradually accumulating evidence in this section – the underlying measurements are highly ambiguous (§3.2), the inferred connectivity structures are erroneous (§3.3), and the resulting models are infeasible and/or do not make sense from an engineering perspective because they are either too costly, have extremely poor performance, or cannot be built with from existing technology in the first place.

This section also describes and reports on an alternative design-based approach to router-level topology modeling and generation that has come into focus during the last 5-10 years and represents a clean break with tradition. The most visible sign of this break is the emergence of constrained optimization as new modeling language, essentially replacing the traditional language of random graph theory. While the latter treats nodes and links as largely generic objects and focuses almost exclusively on structural aspects such as connectivity, the former supports a much richer treatment of topologies – nodes and links are components with their own structure, constraints, and functionality, and their assembly into a topology that is supposed to achieve a certain overall objective and should do so efficiently and effectively within the given constraints on the individual components or the system as a whole is the essence of the constrained optimization-based network design approach. In essence, this approach echoes what was articulated some 15 years ago in [23, 42, 165], but it goes beyond this prior work in terms of empirical evidence, problem formulation, and solution approach. As a result, the described design-based approach has by and large put an end to graph theory-based router topology modeling for the Internet.

At the same time, the design-based approach that has been developed and reported in bits and pieces in the existing literature and is presented in this section for the benefit of the reader in one piece has also far-reaching implications for Internet topology research in general and router-level topology modeling, analysis, and generation in particular. For one, it shows the largely superficial nature of router-level topology generators that are based on graph-theoretic models. As appealing as they may be to a user because of their simplicity (after all, all a user has to specify is in general the size of the graph), they are by and large of no use for any real application where details like traffic, routing, capacities, or functionality matter.

Second, while the design-based approach yields realistic router-level topology models that are inherently generative in nature, it puts at the same time an end to the popular request for a largely generic black-box-type topology generator. Users in real need for synthetic router-level maps have to recognize that this need doesn't come for free. Instead, it comes with the responsibility to provide detailed input in terms of expected customers – their geographic dispersion, and the traffic matrix (see [150] for more details) – design objectives and constraints, etc. In addition, the level of detail required of a generated ISP router-level topology (*e.g.,* POP-, router-, interface card-level) depends critically on and cannot be separated from the purpose for which these generated maps will be used. Again, this puts a considerable burden on the user of a synthetically generated map and tests her understanding of the relevant issues to a degree unheard of in Internet topology modeling in the past.

Third, the explicit focus of the design-based approach on ISPs as crucial decision makers renders the commonly-expressed desire for synthetic router-level maps of the global Internet largely pointless. The Internet is a network of networks, with the sovereign entities being the autonomous systems (ASes). A subset of these ASes that are in the business of providing network service to other ASes or Internet access to end users are owning and operating their networks that together make up much of the physical infrastructure of the global Internet. As a result, a key first step in understanding the structure and temporal evolution of the Internet at the different physical and logical layers is to study the physical infrastructures of the service and access providers' networks and how they react in response to changes in the environment, technology, economy, etc.

Finally, once we have a more-or-less complete picture of the router-level topology for the individual

ISPs, we can start interconnecting them at common locations, thereby bringing ISP router-level and AS-level topology under one umbrella. In the process, it will be critical to collapse the detailed router-level topologies into their corresponding PoP-level maps which are essentially the geographic maps mentioned in the context of the ARPANET in §3.1 and serve as glue between the detailed router-level topologies and an appropriately defined and constructed AS-level topology of the Internet. For a faithful and realistic modeling of this combined router-, POP-, and AS-level structure of the Internet, it will be important to account for the rich structure that exists in support of network interconnections in practice. This structure includes features such as third-party colocation facilities that house the PoPs of multiple ASes in one and the same physical building. It also includes components of the Internet's infrastructure such as Internet eXchange Points (IXPs). This existing structure is inherently non-random but is a reflection of the incentives that exist, on the one hand, for network and access providers to build, manage, and evolve their physical infrastructures and, on the other hand, for content providers, CDNs, and cloud providers to establish peering relationships with interested parties. Importantly, neither such structures nor incentives precludes an application of the described constrained optimization-based approach to network design; they merely require being creative with respect to formulating a proper objective function, identifying the nature of the most critical constraints, and being able to pinpoint the main sources of uncertainty in the environment.

3.5 Notes

The primary sources for the material presented in this section are:

[93] L. Li, D. Alderson, J.C. Doyle and W. Willinger. A first principles approach to understanding the Internet's router-level topology, *Proc. ACM SIGCOMM'04, ACM Computer Communication Review* 34(4), 2004.

[46] J. C. Doyle, D. L. Alderson, L. Li, S. Low, M. Roughan, S. Shalunov, R. Tanaka, and W. Willinger. The "robust yet fragile" nature of the Internet, *PNAS* 102(41), 2005.

[156] W. Willinger, D. Alderson, and J.C. Doyle. Mathematics and the Internet: A Source of Enormous Confusion and Great Potential, *Notices of the AMS* 56(5), 2009.

An excellent short treatment of the discussion in §3.3 about network modeling as an exercise in reverse-engineering vs. as an exercise in model fitting can be found in Chapter 10 of the recent book

[29] M. Chiang. Networked Life: 20 Questions and Answers. Cambridge University Press, 2012.

For additional and more in-depth reading materials we point to

[7] Alderson, D., Li, L., Willinger, W., and Doyle, J.C. Understanding Internet Topology: Principles, Models, and Validation, *IEEE/ACM Transactions on Networking* 13(6): 1205-1218, 2005.

[85] B. Krishnamurthy and W. Willinger. What are our standards for validation of measurement-based networking research? *Computer Communications* 34, 2011.

For some "food for thought" regarding topics such as power law distributions and scale-free networks, and network science, we recommend

[157] W. Willinger, D. Alderson, J.C. Doyle, and L. Li. More "normal" than normal: Scaling distributions and complex systems. In: R.G. Ingalls, M.D. Rossetti, J.S. Smith, and B.A. Peters (Editors). IEEE. Proc. of the 2004 Winter Simulation Conference, Piscataway, NJ, 2004.

[106] M. Mitzenmacher. A Brief History of Generative Models for Power Law and Lognormal Distributions, Internet Mathematics 1(2):226-251, 2004.

[82] E. Fox Keller. Revisiting "scale-free" networks, BioEssays 27(1)):1060-1068, 2005.

[11] A.-L. Barabasi. Scale-free Networks: A Decade and Beyond, Science 325, 2009.

[12] A.-L. Barabasi. The network takeover, Nature Physics 8, pp. 14-16, 2012.

[107] M. Mitzenmacher. Editorial: The Future of Power Law Research. *Internet Mathematics*, vol. 2. no. 4, pp. 525-534, 2006.

4 AS-level topology

When trying to establish a precise meaning or interpretation of the use of "Internet topology," in much of the existing literature, we find that the phrase has often been taken to mean a virtual construct or graph created by the Border Gateway Protocol (BGP) routing protocol. Commonly referred to as the inter-domain or Autonomous-System (AS) topology — named after the logical blocks (ASes) that are used in BGP to designate the origin and path of routing announcements — it is this particular connectivity structure that we focus on in this section, though we will see that the notion of the AS-topology is more slippery than commonly imagined. In particular, we will discuss some of the main issues that arise in the context of studying the Internet's AS topology (ranging from proper definitions and interpretations of this construct to measurements) and focus less on modeling-related aspects as they are still in their infancy, especially when compared to the advances in router-topology modeling described in §3.

4.1 A look back

As far as we know, the first researchers to use BGP-based measurements in the form of route monitor data for topology-related work were Govindan and Reddy [60], who introduced the notion of the *inter-domain topology* defined as "the graph of domains and the inter-domain peering relationships." However, although they were quite specific in regard to being interested in routing, the concept was reused when Faloutsos *et al.* [49] coined the term "Internet topology", a paper that is more widely cited (at least outside of the network research literature) than [60]. The paper [49] is responsible for advancing the alluring notion that the inter-domain topology of the Internet is a well-defined object and can be *accurately* obtained and reconstructed from the available BGP route monitor data. As we shall see, this is not at all the case, and it has fed into a large subsequent scientific literature, already discussed earlier, *e.g.*, [13, 161].

The problems lie in the very definitions of the AS-topology and the measurements that have been used to study this topology (we return to the measurements in §4.2 below). In terms of definitions, in the context of the AS-level Internet, it is tempting to simply equate a node with an AS, but this begs the question what an AS really is. The term refers formally to the AS number (ASN) allocated by IANA (Internet Assigned Numbers Authority) or the Regional Internet Registries (RIRs). An ASN is tendered to enable routing using BGP. This is **not** equivalent to the popular view that associates an AS with a set of routers that appear to the outside as if they formed a single coherent system with a 1:1 mapping between it and some administering company.

For instance, an organization may often own a router which has at least one interface IP address belonging to another organization. In fact, many point-to-point IP links occur across a "/30" subnet. When the link joins two networks, this subnet must be allocated from the IP blocks of one or the other

connecting network, and so most such connections result in IP addresses from neighboring ASes appearing locally.

Another problem arises from the fact that although an AS is often considered to correspond to a single technical administrative domain, *i.e.,* a network run by one organization, it is common practice for a single organization to manage multiple ASes, each with their own ASN [22]. For instance, Verizon Business (formerly known as UUNET) uses ASNs 701, 702, 703 to separate its E-BGP network into three geographic regions, but runs a single IGP instance throughout its whole network. In terms of defining nodes of a graph, these three networks are all under the same operational administrative control, and hence should be viewed as a single node. On the other hand, as far as ASNs are concerned, they are different and should be treated as three separate nodes. The situation is actually more complex since corporations like Verizon Business own some 200+ ASNs [22] (not all are actually used, though). In many of these cases, a clear boundary between these multiple ASes may not really exist, thus blurring the definition of the meaning of a node in an AS graph. Similar problems can arise when a single AS is managed by multiple administrative authorities which consist of individuals from different corporations. For example, AS 2914 is run partially by NTT/America and partially by NTT/Asia.

All this presumes that an AS is a uniform, contiguous entity, but that is not necessarily true [110, 111]. An AS may very well announce different sets of prefixes at different exit points of its network, or use BGP to balance traffic across overloaded links (other reasons for heterogeneous configurations are reported in [21]). Figure 15 illustrates the problem. The AS-graph simplifies, in some cases grossly, the very complicated structure of the entities involved, which are often heterogeneous, and not necessarily even contiguous either geographically or logically.

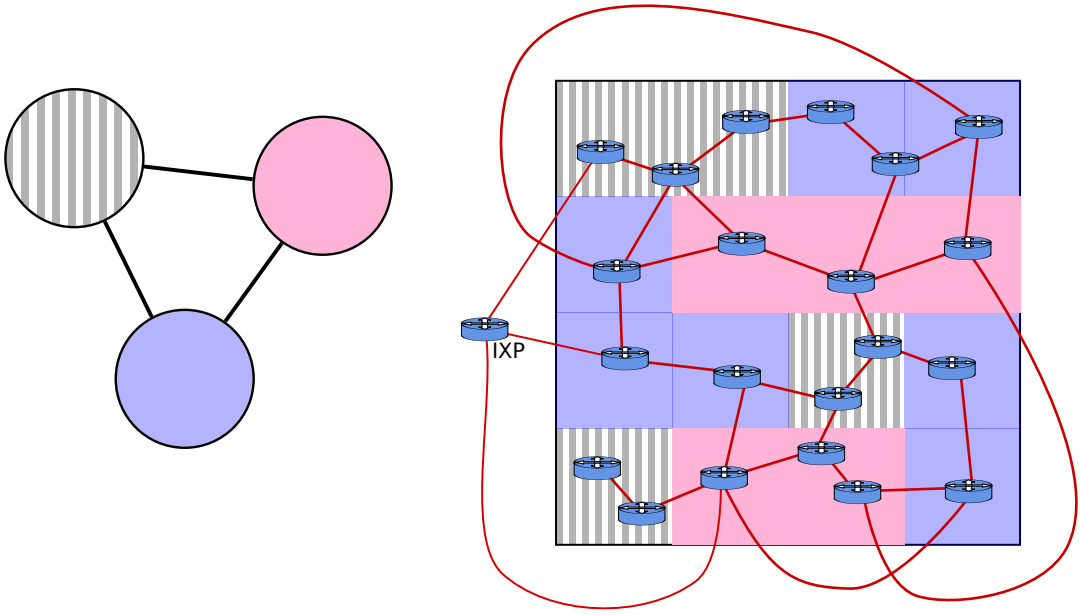
For all these reasons, it should be clear that modeling an AS as a single *atomic* node without internal (or external) structure is overly simplistic for most practical problems. Moreover, these issues cannot simply be addressed by moving towards graph representations that can account for some internal node structure (such as in [110]), mainly because BGP is unlikely to reveal sufficient information to infer the internal structure for the purpose of faithful modeling.

Moreover, the AS-graph treats ASes as nodes, with connecting edges, but the real situation is much more complex. ASes are complex networks in their own right, and are connected sometimes by multiple edges (Mérindol *et al.* [105] found that over half of the ASes they studied were connected by multiple links), and sometimes through Internet eXchange Points (IXPs) that connect multiple ASes. In fact, the traditional approach of modeling the AS-level Internet as a simple connected di-graph is an abstraction incapable of capturing important facets of the rich semantics of real-world inter-AS relationships, including different interconnections for different policies and/or different interconnection points [110, 111]. The implications of such abstractions need to be recognized before attributing network-specific meaning to findings derived from the resulting models.

4.2 Know your measurements

In studying the AS-level Internet, there are some critical differences compared to looking at the router-level Internet:

- No-one "owns" the AS structure. There isn't anyone with the type of privileged view that a network operator has of its own network. There are tens of thousands of ASes, and so we can't reasonably expect to consult all of them to collate a picture either.
- ASes are not "nodes". They are complex in their own right, so viewing the AS-level Internet as an AS-graph is a big abstraction of reality.



(a) *A simple section of the "AS-graph".* **(b)** *A possible picture of the router-level connectivity.*

Figure 15: *An illustration of the obfuscation of the AS-graph (in the vein of [61]). The graph may appear simple, but hides heterogeneous, non-atomic, dis-contiguous entities and interconnects. At the minimum, this should illustrate the dangers of talking about the "Internet" graph.*

- Routing between ASes is very different from routing within ASes and highlights the difference between graph representations that reflect "reachability" vs. "connectivity" information.

These differences create interesting problems and opportunities for measurements, some with parallels to the router-level measurement problems and others without any such parallels.

4.2.1 Data-plane vs. control-plane measurements

As discussed in §3.2, despite all its deficiencies, traceroute has been the method-of-choice for obtaining router-level measurements. As a prime example of an active measurement tool that is confined to the data plane (*i.e.*, probe packets take the same paths as generic data packets), traceroute has also been used to obtain information about the AS topology but has additional problems in this domain.

Apart from the already problematic issues (*e.g.*, load-balancing, aliasing, missing data), IP addresses along traceroute paths must now be mapped to ASes. This mapping is even harder than the mapping to routers, not just because the data for doing so is inaccurate or incomplete (*e.g.*, IP to organization allocations may not work because an organization does not directly correspond to an AS), but also because the border of an AS is not well-defined in terms of IP addresses. It is common for a link between two ASes to come from a subnet allocated by one of the ASes, resulting in an interface in the other network with an address that is not its own [100, 101]. The problem is further complicated by variations such as anycast or Multiple Origin ASes [167], which provide yet another set of counter-examples to a straightforward mapping between AS and address space. Some work has concentrated on trying to improve

the mapping [120], and these represent technical advances, but it is important to understand that the fundamental difficultly lies in the fact that the boundaries of the "business" are not equivalent to the AS boundaries.

The other major alternative to obtaining information about the AS topology is to collect control plane data in the form of directly measured routing information. The primary example of such control plane data are BGP-derived measurements. BGP is a path-vector routing protocol, and as such each node transmits to its neighbors information about the *best* path that it knows to a destination. Each node then takes the information it has received about best paths, and computes its own best path, which it transmits to its neighbors. A route monitor receives this information as would any router, and from the transmitted path information, can infer links between ASes. The two best known projects that rely on BGP route monitors, Oregon RouteViews [118], and RIPE (Réseaux IP Européens)'s Routing Information Service [131] both use this approach, and each connects to a few dozen different ASes.

However, by its very design, BGP is an information-hiding rather than an information-revealing routing protocol. In addition, by its very design, BGP is all about reachability and **not** connectivity. Using it for mapping the Internet inter-domain topology is a "hack", and so it should come as no surprise that it has its own set of problems, including the following:

- The AS-path information in the announcements is primarily included for loop detection and does not have to correspond to reality. It is easy (and not uncommon) to insert additional ASes into a path for various purposes, *e.g.*, traffic engineering or measurement [21, 35], and moreover, the AS-path does not have to represent the data path.
- Path-vector protocols do not transmit information on every path in the network. For instance, backup paths may never appear in any routing announcements (unless there is a failure), and so may not be seen by a route monitor.
- Path-vector protocols only transmit "best" paths, and so there is a large loss of visibility from any one viewpoint. It is sometimes argued that a large number of viewpoints would alleviate this, but the viewpoint locations are highly biased towards larger networks, and this known "vantage point problem" severely biases the possible views of the network [134].

The BGP measurement data being provided by RIPE and RouteViews was originally intended to help debug networks, not for mapping. While this data collections have been invaluable for that intended original purpose, it is unsurprising that it is inadequate when used for a rather different purpose such as mapping the AS Internet. However, when this aspect is carefully taken into account, good work can be done but requires a critical evaluation of the data. Problems arise primarily when this data is used uncritically. Other useful sources of AS-level measurements such as looking glass servers and route registries suffer from similar problems [69, 96], and do so for similar reasons: they weren't intended to draw a map of the AS Internet.

4.2.2 Attribute discovery

The AS topology may be interesting to scientists in itself, but to be useful to network engineers, the routing policies that accompany it should also be known. It has been common to approximate the range of policies between ASes by a simple set of three relationships: (a) customer-provider, (b) peer-peer, and (c) siblings. This reduction was at least in part motivated by Huston [72, 73] and has been used in various places [146, 153, 159]. While many relationships fall into these three categories, there are frequent exceptions [75, 110, 126], for instance, in the form of partial transit in a particular region [115, 163].

Forgetting for the moment the simplification in assuming all policies fit this model and the simplifications the AS-graph itself makes, the relationships can be represented in the graph by providing simple labels for each edge. Typically, the next step after inferring network topology is to infer policies between ASes. The most common approach to this problem is to assume the universality of the peer-peer, customer-provider, sibling-sibling model, and to infer the policies by finding an allocation of policies consistent with the observed routing [14, 41, 56, 153, 159].

Once relationships are established, a seemingly reasonable next step is to estimate the hierarchical structure as in [146]. However, the effect of large numbers of (biased) missing links has not really been considered in these algorithms. In fact, the tier structure of the Internet seems to be largely an illusion. Recent work has shown that there is little value in the model at present [58, 88]; but, in contrast to the claims of these papers, there is no strong evidence that the situation has actually changed or that the tier model was ever a good model (except maybe in the early stage of the "public" Internet in the latter 20th century) particularly in light of the problems in the data.

Alternatively, we can infer a generic set of policies consistent with routing observations using a more detailed set of routing measurements [98, 110] and estimate performance by comparing predicted routes to real routes (held back from the inference process).

4.2.3 The "missing link" problem: Extent and impact

Perhaps the most obvious problem that results from relying on BGP measurement data to map the AS-level Internet is that there are many missing links in the resulting AS-graph. To illustrate the extent of this problem, years of concentrated research efforts that relied on a combination of improved inference methods and additional data sources [9, 27, 28, 39, 41, 69, 70, 110, 117, 134, 136, 166] have produced a picture of the Internet's AS topology that — as of 2011 — consisted of some 35,000-40,000 ASes (nodes) and about 115,000-135,000 edges (AS links), with about 80,000-90,000 of them being of the customer-provider type and 35,000-45,000 of the peer-peer type.

More recently, this supposedly up-to-date and most complete view of the AS-level Internet changed drastically thanks to [2] that relied on ground truth data from one of the largest IXPs in Europe (and worldwide) that had at the time of this study almost 400 member ASes. The main finding of this recent study is that in this single location, the number of actively used AS links of the peer-peer type was more the 50,000 — larger than the number of all AS links of the peer-peer type in the entire Internet known as of 2011. Moreover, being extremely conservative when extrapolating from this IXP to the Internet as a whole, [2] shows that there are easily more than 200,000 AS links of the peer-peer type in the entire Internet, more than twice the number of all AS links of the customer-provider type Internet-wide. Importantly, the main reason for this abundance of AS links of the peer-peer type at IXPs is well understood — many IXPs, especially the larger ones, offer as free service to their member ASes the use of their route server. This service greatly facilitates the establishment of peer-peer links between the members of an IXP and has become enormously popular with members that have an "open" (as compared to restrictive or selective) peering policy. Especially for the larger IXPs, such networks typically constitute the vast majority of IXP member ASes. Figure 16 provides an illustration of the connectivity through this IXP and shows that a majority of its member ASes have an open peering policy (some 300+ members) and establish AS links of the peer-peer type with one another.

In short, for many years, researchers have worked with AS-graphs that are typically complete in terms of nodes, but easily miss more than half the edges. Importantly, these graphs have generally a 2:1 ratio of customer-provider type vs. peer-peer type links when a 1:3 ratio is much more likely to reflect Internet reality. Clearly, for gaining any economic-based understanding of the AS Internet, getting

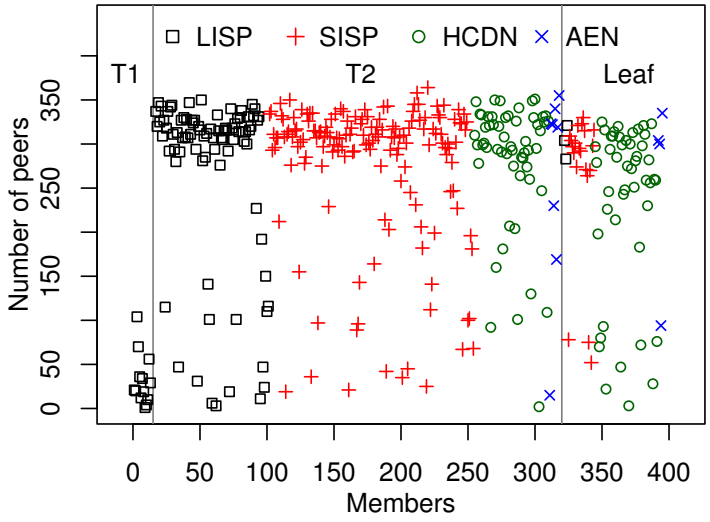


Figure 16: *Scatter-plot of number of peers per member, based on a classification of the member ASes in the four business categories defined above: LISP (Large ISP), SISP (Small ISP), HCDN (Hosting/service and Content Distribution Network)), and AEN (Academic and Enterprise Networks), and by tier. (Reprinted from [2]; ©2012 ACM, Inc. Included here by permission.)*

that ratio approximately correct is paramount because it is directly impacting how money flows in the Internet — while in a customer-provider relationship, the former pays the latter for bandwidth, peer-peer relationships are typically settlement-free (*i.e.,* no money is exchanged between the involved parties).

Besides their immediate economic impact, the above missing edges cause also significant problems in inferring the AS graph. For instance, it is a requirement that a network be multi-homed to obtain an ASN. This means the AS needs to intent to connect to at least two upstream providers. In this sense a "single-homed stub-AS" does not exist. Without any doubt, there are exceptions to this rule. However, the second link is often a backup link which is invisible to BGP outside of the immediate connection, because of BGP's information hiding[5]. Thus, it may appear as if a large number of ASes are single-homed stubs.

In [117], the authors separate the missing links into *hidden* and *invisible*. Whereas the latter are links that are missing from the data for structural reasons (*i.e.,* it is not just a question of quantity (*i.e.,* numbers of monitors) but quality (*i.e.,* location of monitor)), the *hidden* links may be found with enough measurements (over time, or multiple viewpoints). In [134] the authors extend that by dividing links into a number of classes based on their observability.

The "missing link" problem in the AS context is much more serious than if those links were "missing at random". In particular, the bias in the type of links that are missing [134] is critical when calculating some metrics on the graph, such as distances, precisely because such links are often *designed* to cut down on the number of ASes traffic must traverse. The missing data is also crucial for understanding reliability: for instance, papers such as [5] that argue that high-degree nodes create vulnerabilities in the Internet ignore the backup links that are invisible in these dataset, but obviously crucial when studying the resilience of the network.

4.3 The Internet's AS-level topologies

Despite the limitations of measurements, there is a considerable amount known about the AS-level topology of the Internet, and we talk here about the issues in defining and modelling that topology. We have seen that the definition of an AS is fraught with problems. Assuming for the time being that the concept of an AS is well defined so that it makes sense to equate each AS with a node in a graph, then what is the set of links? Unfortunately, the question of which ASes are "adjacent" also has no simple answer, and defining the meaning of a "link" between two ASes requires further consideration.

Does a link mean the ASes have a business relationship, physical connectivity, connecting BGP session, or that they share traffic? All the above are reasonable definitions, and none are equivalent. A common definition is that two ASes are said to be connected (at a particular time), if they can exchange routing data (and presumably IP traffic) without the help of an intermediary AS that provides *transit*. However, this says little about the true business relationships that are sometimes discussed as a matter of course when the AS-graph is considered. Moreover, this abstraction looses considerable information. In reality there are multiple topologies we want to model, each with its own meaning, structure, potential applications, and inference problems.

- *Business relationship graph:* in its simplest form this graph simply indicates (by an edge) that a business relationship exists between the corporations that own two ASNs. Edges could be usefully labelled by the type of business relationship, and we list a small subset of the possible relationships in Table 1.

- *Physical link-level graph:* this graph indicates whether two ASNs have a physical (layer 1) connection, and how many such connections they have. The multiple nature of such connections leads this

[5] Note that complex BGP policies may play a role in this as well [36, 63].

Graph	Edge Annotation	Graph Type
business relationship	subsidiary, partner, customer,...	directed graph
physical link-level	link capacity	multi- hyper-graph
connectivity graph	-	multigraph
BGP routing graph	-	undirected graph
policy graph	BGP policies	directed multigraph
traffic graph	traffic volumes	directed graph

Table 1: Example elements of the set of AS graphs.

to being a multigraph, as it is very common for two ASes to be connected by multiple links and in different geographic locations [94, 114, 143]. The idea is clearly illustrated by Figure 1 in [94], which shows a "pancake" diagram of the North American Internet backbone. Perhaps the reason this critical aspect of the topology is typically ignored is that it is very hard to measure—BGP monitor data is in general blind to this facet of the topology. In addition, this graph should really be a hypergraph. A single "edge" can connect multiple ASes, for example through an IXP [9, 75, 160]. One might argue that they are joined by a switch/router, each using point-to-point links, but in at least some cases, that switch has no place in a AS graph (*i.e.,* it has no ASN). The graph's edges could be usefully annotated with link capacity and potentially other features such as geographic location.

- *Connectivity graph:* this graph indicates that layer-2 connectivity exists between two ASNs. In many cases the layer-2 connectivity between ASNs would be congruent with the layer-1 connectivity, but with recent advances in network virtualization this may not hold for long [154].
- *BGP routing graph:* the edges in this graph indicate pairs of ASes that have an active BGP session exchanging routing information (*i.e.,* a BGP session that is in the 'established' state [130]).
- *Policy graph:* the edges in this graph are the same as those in the BGP routing graph, but include directed policy annotations [62]. We define this separately from the BGP routing graph because it may require a multigraph to allow for policy differences between different regions.
- *Traffic graph:* it is the same as the BGP routing graph, but the edges are annotated with the amount of traffic exchanged between the corresponding ASes.

This is hardly a complete set of possibilities, but already we can see the potential complexity here. Nevertheless, it appears unusual for studies to even define precisely what graph they examine (exceptions being papers such as [60, 117] where the BGP routing graph is explicitly considered). In Table 1, we list some of the possible graphs, and their basic properties. There is no clean 1:1 mapping between "network" and "organization" and "AS" [22, 75], and so it is highly non-trivial to map between these graphs, and they are certainly not equivalent.

4.4 A look ahead

Given our list of problems described here, one might be tempted to think that the AS-graph and routing data in general are useless until these datasets are drastically improved. However, apart from their operational utility, RouteViews and RIPE RIS have provided the essential ingredients for many important studies that match those services' goals [116]. A number of these studies have improved the Internet

significantly, and in the majority of such successful papers there is no need to exploit the "graph" view of the network. Examples include: (a) The discovery of slow convergence and persistence oscillation in routing protocols [64, 86, 87, 89, 90, 151, 152]. (b) Understanding of the impacts (positive and negative) of route flap dampening [97, 124]. (c) Determining how much address space and how many ASNs are being actively used [74]. (d) Looking for routing "Bogons" often related to Internet address hijacking [17, 40, 50, 128, 147]. (e) Debugging network problems [20, 53, 133].

On the measurement side, there have also been many advancements towards improving our view of AS topology. For instance:

1. As BGP routing changes, often multiple potential paths are explored and these paths (which are unlikely to actually be used as a final choice) can show some of the alternative routes available in the network [166], and thus a more complete topology.

2. Missing edges can be found using additional datasets, *e.g.,* RIRs and looking glasses [27, 69, 70, 166], or IXP data [9, 69, 70, 136], though care must be exercised with any additional dataset.

3. A routing beacon [21, 89, 99] is just a router that advertises and withdraws certain prefixes on a regular schedule. Examination of the observed announcements and withdrawals by various route monitors then allows estimates of protocol behavior such as convergence time.

4. Route poisoning prevents announcement from reaching certain parts of the Internet. As with beacons, it allows one to examine the behavior of BGP in a more controlled manner. This is perhaps the only way to see (some) backup paths, or to understand whether an ISP uses default routing [21, 35].

5. There are also attempts to not just estimate the topology but derive some quality measure for the resultant AS-graph [76, 134, 158].

There is often an unfortunate side-effect to some of these types of measurement in form of a Heisenberg-like uncertainty principle. That is, it is not clear whether observed changes are due to the micro-phenomenon of path exploration or macro-phenomena of link changes, new entrants, etc. The longer we make observations, the more complete they may seem, but we then do not know whether all of those links existed at the same time. Such uncertainty principles appear to be present in a number of Internet measurement contexts [132] where we trade off "accuracy" of the measurements against "time localization". In any case, this approach does not overcome the structural bias mentioned earlier.

At the same time, the above-mentioned and other advances on the measurement side suggest that the missing link problem may be improved, providing "more complete" AS graphs. However, there is a profound need (illustrated by the above) for better data accuracy measurements, and better response to data quality issues from subsequent users of the data. Obvious ways to improve are to conduct sensitivity analysis (of results) to missing or incorrect input data.

In addition, it is to be hoped that more controlled experiments are conducted (*i.e.,* experiments that have a "control" sample against which the experimental data can be compared) in order to precisely derive which factors of interest affect which variables. Controls allow one to discriminate alternative explanations for results, and prevent the affects of one confounding factor drowning out the affects of others (see [21, 99]). This is basic tenet of the scientific method, but seems to have been ignored in this area of research. Most studies have been "observational", and while there is a valid role for such experiments, for instance in epidemiology, they are intrinsically harder to interpret.

Lastly, another aspect of this richer set of AS topologies is that it should be obvious by now that economic or commercial objectives by and large determine and shape the structure and evolution of

their real-world counterparts, and that these constructs are once again naturally expressed through optimization rather than random graph models, though in this case the optimization problems may come from game theory or economics rather than mathematical programming.

4.5 Notes

The primary sources for the material presented in this section are

[135] M. Roughan, W. Willinger, O. Maennel, D. Perouli, and R. Bush. 10 Lessons from 10 Years of Measuring and Modeling the Internet's Autonomous Systems, in: *IEEE Journal on Selected Areas in Communications* 29(9):1810-1821, 2011.

[2] B. Ager, N. Chatzis, A. Feldmann, N. Sarrar, S. Uhlig, and W. Willinger. Anatomy of a large European IXP, in: *Proc. ACM SIGCOMM'12, ACM Computer Communication Review* 42(4), 2012.

and they contain lengthier discussions of many of the issues touched upon here.

For additional and more in-depth reading materials (in addition to the references indicated throughout) we point to

[26] H. Chang. Modeling the Internet's Inter-Domain Topology and Traffic Demand Based on Internet Business Characterization, PhD Thesis, University of Michigan, 2006.

[43] B.Donnet and T. Friedman, Internet Topology Discovery: A Survey, IEEE Communications Surveys & Tutorials, 9(4), pp.56-69, 2007.

[38] A. Dhamdhere. Understanding the Evolution of the AS-level Internet Ecosystem, PhD Thesis, Georgia Institute of Technology, 2008.

[68] H. Haddadi, M. Rio, G. Iannaccone, A. Moore and R. Mortier, Network topologies: inference, modeling and generation, IEEE Communications Surveys, 10(2), 2008.

[39] A. Dhamdhere and C. Dovrolis. Twelve Years in the Evolution of the Internet Ecosystem, in: *IEEE/ACM Transactions on Networking* 19(5), 2011.

5 PoP-level topology

When designing or reconfiguring the physical infrastructure of an ISP, network operators are often guided by a design principle that emphasizes *hierarchy* [31,59,108]. There are two main reasons for implementing hierarchical network designs: *scalability* and *simplicity*. Compared to non-hierarchical designs, hierarchical networks can often be built at scale, mainly because hierarchy makes a network easier to visualize — a key feature towards making it easier to manage. The situation is analogous to modularity in programming languages — ideally it allows consideration of network components in isolation.

A common form of hierarchy in IP networks is based on the concept of the PoP (or Point of Presence). A PoP is a loosely defined term. Some providers may use the term to mean a physical building (housing a group of routers, switches and other devices), whereas others mean a metropolitan area where service is provided. However it is defined, though, it is a useful construct because it describes the logical structure of the network as the designer intended, rather than its particular implementation in terms of individual routers. Moreover, irrespective of the meaning, PoPs have an explicit geography (*e.g.,* street address or

city/metropolitan area). This then leads to our third major category of "Internet topology" — the PoP-level topology.

PoP-level topologies are ideal for understanding tradeoffs between connectivity and redundancy, and also provide the most essential information to competitors or customers (about where a network is based, or who has the best access network in a region). Additional reasons why the PoP-level view of networks is interesting include

- Network maps are often drawn at this level because it is an easy level for humans to comprehend.
- Network optimization is often conducted at this level because the problem size is generally reasonable (*e.g.*, dozens of PoPs as compared to potentially hundreds of routers) and because inter-PoP links are much more expensive than intra-PoP links.
- The internal design of PoPs is almost completely determined by simple templates [31, 59, 108].
- Networks change less frequently at the PoP level than at the router level [138]; and
- The PoP level is the more interesting level for many activities because it is less dependent on the details of protocol implementations, router vendor and model, and other technological details.

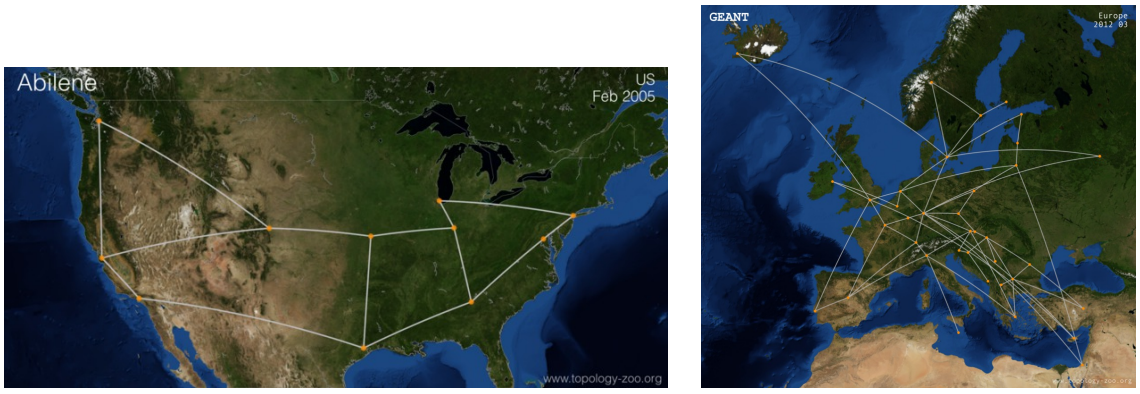


Figure 17: *PoP-level network topologies taken from* `www.topology-zoo.org`.

The last point is subtle but important for modelling. For instance, when using a network as part of a simulation, one would like to have a network that is *invariant* to the method being tested. If a network designer might change his/her network in response to a new protocol, say a routing or traffic engineering algorithm, then the test will be ambiguous if it uses existing networks as models. PoP-level networks are less sensitive to these details than router-level networks, because routers impose physical and technological constraints that are almost completely dependent on the details of the router vendor, model and even the version of software running on the router.

Two examples of PoP-level topologies are depicted in Figure 17, showing the structure of two of the largest research networks (Abilene, and GÉANT) in the world.

5.1 A look back

The study of PoP-level topologies has a briefer history than the major alternatives. Although the concept has existed for almost as long as networks, the work on modelling and measurement has typically focussed on routers (or their equivalent) though it is noteworthy that in simple networks (with one router per PoP) the two are the same.

The first steps were taken when real data-networks were observed and it was noted that they had structure in the form of hierarchy that was not well represented in simple random graphs. This observation led to the development of *structural topology generators* [165], based on the idea that a topology generator should reflect the obvious hierarchical structures visible in real networks (*e.g.,* the Georgia Tech Internetwork Topology Models (GT-ITM) [66] generator). However, this model was not specifically aimed at modelling the PoP-level. PoPs have been used in more advanced structural topology generators such as IGen [127]. IGen explicitly treats network design as an optimization, rather than following simple stochastic rules, in order to mimic the manner in which real networks are designed. IGen uses this not only for topology but also to create some of the other important details of the network, such as the link metrics or iBGP configurations.

The Rocketfuel project [144] sought to measure (using traceroute with all the problems described earlier) individual ISPs, and as part of this, presented data and maps at the PoP level. The idea was extended by the iPlane project [95], and by DIMES [139]. However, the flaws in traceroute make this data and the ensuing maps suspect from the start. However, [144] raised the bar with respect to validating the obtained PoP-level maps by trying to solicit feedback from the operators in charge of the mapped ISPs.

More recently, the concept of a PoP has been explicitly used to help guide measurement approaches, in the hope to overcome some of the limitations of traceroute [51, 138, 162]. However, in the absence of strong validation and given traceroute's many problems, it is likely that most of the known issues still exist in these approaches.

Alternatively, Knight *et al.* [84] have collected a set of over 200 maps published by ISPs themselves, and transcribed these into an open set of data available from `www.topology-zoo.org`. Much of this data is at the PoP-level, indicating the importance of this level of network representation to ISPs. For a similar but complementary effort, see [8].

5.2 Know your measurements

The problems in measuring PoPs are essentially the same as in any traceroute-based survey, though it is thought (or perhaps just hoped) that mapping IP addresses to PoPs is more straight-forward than mapping IPs to either routers or to ASes. To the best of our knowledge, no rigorous testing of this hypothesis has been conducted to date, but there are some indications (*e.g.,* see [84]) that the PoP-level maps provided by traceroute are no better than their router- or AS-level counter-parts.

The topology-zoo data [84], on the other hand, is provided by ISPs themselves and should in principle be much more accurate. However, this dataset must also be treated carefully (as should all data) because of potential transcription errors, or mistakes or approximations in the maps provided by the ISPs. While such errors are much less frequent than those encountered in measured networks, an added concern with respect to ISP-provided maps is stale data because there is little incentive to provide up-to-date maps.

As mentioned earlier, another important component of many PoP-level topologies is the geographic element. Such topologies are much easier to visualize geographically [83], and so a frequent interest is geolocation of the PoPs. While this is not a chapter on geolocation, it suffices to say that many research papers have been written on the problems of accurately mapping IP addresses to their geolocation (*e.g.,* see [125]). Moreover, while the routers and switches of a PoP are typically located in a single location,

city, or metropolitan area, the “eyeballs” (*i.e.,* end users) connected to the PoP will be spread over some area [129]. However, if the researcher is willing to diligently mine various data sources, there is hope of at least being able to geolocate PoPs as they house potentially hundreds or thousands of IP addresses and reside in locations with known physical addresses (*e.g.,* carrier hotels) [8].

5.3 The nature of the PoP-level graph

There is a common meme in network modelling that the design of a US ISP backbone network involves simply selecting the NFL cities, and then joining them up with a few lines on a map. While the real process of network design is rarely so trite, the picture above isn't entirely unfair.

Most notably, PoPs are usually selected based on commercial criteria (*e.g.,* the desirability and size of the potential customer base in an area). So network engineers get little choice over the locations that they are connecting. They could be the NFL cities in the US, or the larger cities of another country, or the capitals of countries on a continent, and so on. Once the PoP locations have been selected, they need to be connected in some redundant fashion to ensure some degree of robustness to node or link failures. Historically, connecting these PoPs may have been done in a mostly *ad hoc* manner; see for instance `http://personalpages.manchester.ac.uk/staff/m.dodge/cybergeography/atlas/roberts_arpanet_large.gif`.

However, since the burst of the Internet bubble (*circa* 2000), capital investment has become harder to obtain, and network operators and engineers had to justify such investment more carefully. At this point, network capacity started to be more carefully planned, not always using formal mathematical optimization, but certainly using traffic measurements to ensure less wasted capacity. Much of this planning and optimization is performed at the PoP-level simply because the router-level is much more complicated (in size, and complexity of constraints), and because inter- and intra-PoP link costs vary by a large margin.

We have discussed network design by constrained optimization extensively in §3 (see also references such as [93]), and so here we shall only consider the main differences for PoP-level design (apart from those already listed above).

Perhaps the most important difference is that the physical and engineering constraints on a router do not directly apply for a PoP. At least in theory, a PoP can use as many routers as needed to provide sufficient number of ports for any arbitrary node degree and sufficient throughput per port. Naturally, the constraints in this case will arise in the form of costs, and optimization-based formulations of the PoP-level network design problem will feature budget constraints to reflect this aspect. As budget constraints can vary greatly among different companies, when we look at actual PoP-level ISP backbone networks, we see a wide variety of designs ranging from the meshy designs with high-degree nodes only at the edge predicted by the HOT model, to hub and spoke like networks [84]. In fact, the sheer variety of network designs we observe in reality suggest that while some network operators seem to aim at optimizing performance (given some lenient cost constraints), others appear to be willing to sacrifice performance in order to keep costs low. Moreover, network operators in different countries can encounter very different link costs depending on the local geographic and commercial environment.

A critical but rarely discussed property of the PoP-level topology is that it provides the “glue" between the more physical router-level topology on the one hand and the more logical AS-level topology on the other hand. Functioning as an “intermediary" between these two topologies highlights the important aspect of the PoP-level topology that its granularity is “just right" for many networking problems of practical interest — not too coarse as to ignore important context (*e.g.,* the case with various AS topologies) but also not too fine as to be overwhelmed with unnecessary details (*e.g.,* the case with various physical

topologies). We next discuss this property in more detail.

5.3.1 From PoP-level to router-level connectivity

Given a PoP-level network, there is an additional interesting question: "Can we map this network down to the router level?" The GT-ITM model addressed this through random generation of its subnetworks, but in practice the design process of network engineers in this case is a text-book application of repeating patterns [31, 59, 108] and hence anything but random.

The main reason for following this design process is that network designers often apply "cookie cutter" methods to design networks as a whole or the internals of PoPs, though that term unnecessarily trivializes the importance of repeated patterns. Repetition makes network operations vastly simpler: the management of two PoPs requires the same skills. Equipment can be bulk purchased, debugging is easier, and adding new PoPs is simpler. Finally, networks based on templated design lead to simple design methodologies. For instance, the inter-PoP level network topology can be optimized relatively simply, as details such as redundancy will be supplied by the provision of pairs of redundant routers in each PoP, with redundant links between them. Design often refers to the graph topology of router interconnections, but templated design can extend to other details, such as physical configuration within racks, connections with external networks, or additional servers such as Domain Name Service or Network Management Systems.

This type of design can be mathematically described using graph-products, though for more details, we invite the reader to consult [121].

5.3.2 From PoP-level to AS-level connectivity: The pancake-view of the Internet

Until now we have only really discussed the PoP-level topology of a single network. However, there is considerable interest in how these networks interconnect.

The most prominent and commonly-accepted view of the Internet is as a "network of networks" or ASes in the AS-graph representation discussed in §4. A much neglected and rarely-mentioned representation is the "pancake view" where we consider each network to be a layer and where the different layers (networks) are stacked on top of one another to form a pancake-like structure [94]. To show where the different networks inter-connect, we add links across layers; intra-network connectivity is shown as links within each layer. For a set of "peer" networks, one advantage of this pancake view is that these networks often cover similar geographic areas and inter-connect in multiple locations, but at a limited set of cities (determined either by where private interconnects are seen as commercially viable, or where IXPs are available). Importantly, depending on the types of networks, many of them host their PoPs in one and the same commercial colocation facilities whose street addresses are generally known[6]. As such, the pancake view allows one to visualize not only this connectivity inside and between such providers but also the geography of their PoP-level topologies.

However, as far as we are aware, there has been no significant work studying this pancake view together with the different inter-connections, other than noting that it exists. The dearth of studies and models perhaps stems from the problems in obtaining the measurements necessary for constructing this view (see the discussions in §4), but it is perhaps one of the most interesting areas for future Internet topology research.

[6] One problem in establishing such a view lies in the limitations of current IP geolocation services [125].

5.4 A look ahead

We have focused in this section and the earlier sections mostly on traditional ISPs or network service providers which operate networks that have more or less pronounced backbones and cover geographic areas ranging from individual countries to entire geographic regions to the entire globe. However, there are many other networks that are not ISPs and consist of PoPs without their own physical infrastructures to connect them (*e.g.,* content providers, CDNs, Web-hosting companies). The PoPs of these networks are typically located in commercial colocation facilities or data centers that are operated by third-party companies for the explicit purpose of interconnecting such infrastructureless networks among one another or with ISPs or network service providers.

The importance of the role of such dedicated Internet infrastructure in the form of colocation facilities is best illustrated with a concrete example. As of December 2012, Equinix `www.equinix.com`, one of the leading companies in global interconnection and data centers, owned and operated in 14 countries in 5 continents some 30 colocation facilities. In these 30+ colocation facilities that are located in the major cities around the world, more than 4,000 networks connected directly to their customers and partners.

Another largely under-researched topic concerns the fact that in this chapter, we treated router-, PoP-, and AS-level topologies as static objects, when in reality, they evolve over time. In particular, it is rarely the case that a network operator designs a new network from scratch. Network design typically has to include as important aspects awareness and knowledge of the existing network that the operator intends to change due to, for example, drastic changes in the traffic demand that the original network design can no longer handle efficiently.

In view of these an other added challenges, the PoP-level view promises to be one of the more useful and interesting direction for future Internet topology research. In particular, measurements and models at this level have considerable scope for the future, and extensions of HOT-like optimization models may provide much more realistic synthetic networks than are currently available. At the same time, work on interconnection of networks at this level also provides considerable scope, but will require significant advances in our ability to measure and model the flow of traffic across the different networks as it is the traffic that ultimately determines much of the structure and evolution of the different topologies that we discussed in this chapter.

5.5 Notes

The primary source for the material presented in this section (and a much lengthier discussion of many of the issues) is

[84] S.Knight, H.Nguyen, N.Falkner, R.Bowden, M.Roughan, The Internet topology zoo. IEEE Journal on Selected Areas in Communications (JSAC) 29, 9, 1765-1775, October 2011.

For additional and more in-depth reading materials (in addition to the references indicated throughout) we point to

[139] Y.Shavitt and N.Zilberman, Geographical Internet PoP-level maps. In Proceedings of the 4th international conference on Traffic Monitoring and Analysis (Berlin, Heidelberg), TMA'12, Springer-Verlag, pp. 121-124, 2012.

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6 Conclusion

This chapter has aimed at clarifying the state of the art in Internet topology measurement and modelling, and correcting a number of clear and present flaws in reasoning. As we outlined in the introduction, we can see a number of themes recurring at multiple levels of hierarchy in topology modelling:

Theme 1: When studying highly-engineered systems such as the Internet, "details" in the form of protocols, architecture, functionality, and purpose matter.

Theme 2: When analyzing Internet measurements, examining the "hygiene" of the available measurements (*i.e.,* an in-depth recounting of the potential pitfalls associated with producing the measurements in question) is critical.

Theme 3: When validating proposed topology models, it is necessary to treat network modeling as an exercise in reverse-engineering and not as an exercise in model-fitting.

Theme 4: When modeling highly-engineered systems such as the Internet, beware of M.L. Mencken's quote "For every complex problem there is an answer that is clear, simple, and wrong."

We have not tried to survey the entire literature in this area, and we apologize to those whose work has not appeared here, but there are other extant surveys mentioned at the relevant points throughout this chapter, for specific components of the work. We also have not tried to critique every model, but rather tried to provide general guidance about modelling. It is intended that the readers could themselves critique existing and new models based on the ideas presented here.

In addition, we do not claim to have covered every type of topology associated with the Internet. Specifically, we have avoided topologies at the applications layer, for instance those associated with the WWW or online social networks. We made this choice simply because these topologies are (despite being "Internet" topologies) profoundly different from the topologies we have included. They are almost purely virtual whereas all of the networks considered here have a physical component, which leads to the arguments for optimization as their underlying construction. An important open problem in this context is the role that societal-related factors play over more economic- or technology-based drivers in the formation and evolution of these virtual topologies.

Finally, in each section, we have aimed at illuminating some of the current problems and identifying hopefully fruitful directions for future research in this area.

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