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PAPER SERIES: NO. 37 — JUNE 2016

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Published by the Centre for International Governance Innovation and Chatham House.

This work was carried out with the aid of a grant from the International Development Research Centre (IDRC), Ottawa, Canada.

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ABOUT THE GLOBAL COMMISSION ON INTERNET GOVERNANCE

The Global Commission on Internet Governance was established in January 2014 to articulate and advance a strategic vision for the future of Internet governance. The two-year project conducts and supports independent research on Internet-related dimensions of global public policy, culminating in an official commission report that will articulate concrete policy recommendations for the future of Internet governance. These recommendations will address concerns about the stability, interoperability, security and resilience of the Internet ecosystem.

Launched by two independent global think tanks, the Centre for International Governance Innovation (CIGI) and Chatham House, the Global Commission on Internet Governance will help educate the wider public on the most effective ways to promote Internet access, while simultaneously championing the principles of freedom of expression and the free flow of ideas over the Internet.

The Global Commission on Internet Governance will focus on four key themes:

- enhancing governance legitimacy — including regulatory approaches and standards;
- stimulating economic innovation and growth — including critical Internet resources, infrastructure and competition policy;
- ensuring human rights online — including establishing the principle of technological neutrality for human rights, privacy and free expression; and
- avoiding systemic risk — including establishing norms regarding state conduct, cybercrime cooperation and non-proliferation, confidence-building measures and disarmament issues.

The goal of the Global Commission on Internet Governance is two-fold. First, it will encourage globally inclusive public discussions on the future of Internet governance. Second, through its comprehensive policy-oriented report, and the subsequent promotion of this final report, the Global Commission on Internet Governance will communicate its findings with senior stakeholders at key Internet governance events.

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EXECUTIVE SUMMARY

During current debates over Internet governance, many commentators warn that the Internet could fragment in ways that would cause the benefits associated with the Internet to dissipate. Typically, these arguments reflect an absolutist character that inexorably leads to universal interconnection and interoperability. Although connectivity and standardization yield clear benefits, a review of the existing architecture reveals many circumstances in which the real-world networks have opted in favour of some degree of fragmentation.

This paper describes current examples of fragmentation in the Internet's physical architecture, address space and protocols, and in the legal principles governing the Internet. It then advances analytical principles, such as diminishing marginal returns, heterogeneity in valuation, the lack of unique value in pairwise potential connections, and non-linear increases in cost, that can serve as heuristics for identifying the circumstances in which fragmentation is more likely to be either beneficial or detrimental. Finally, the paper identifies alternative institutional forms, such as gateways and arbitration, that can mitigate some of the problems associated with fragmentation.

INTRODUCTION

The Internet has made it possible for the world's citizens to connect with one another and access information to an unprecedented extent. The convergence of much of the world's communications media and information onto a single platform has yielded benefits that were unimaginable a few decades ago.

But a number of high-profile recent developments have raised concerns among the Internet community that the Internet could fragment. Countries such as China have long asserted control over the content that their citizens can reach. Edward Snowden's revelations about the level of surveillance being conducted by the US government has led to calls for laws requiring that all data associated with a country's citizens be hosted domestically and that companies use only domestically produced software. Other commentators have criticized commercial practices that create fragmentation by favouring some types of Internet traffic over others.

If implemented, such policies could cause the benefits long associated with the Internet to attenuate or dissipate. Standardization, on the other hand, creates real benefits in ensuring that both consumers and producers can reach one another through a common platform, regardless of location, technology or application.

Acknowledging the benefits associated with widespread connectivity and interoperability does not necessarily lead to the conclusion that standardization and interconnection are always preferred over any form of fragmentation. Indeed, some networks running the Internet Protocol (IP) are not interconnected with the rest of the network, and others operate on somewhat different principles. Unless all decisions that are not standardized are simply assumed to be mistakes, the persistence of these networks suggests the existence of considerations cutting in the other direction that need to be understood before all fragmentation is categorically prohibited.

This paper's central claim is that current discourse suffers from two basic problems. The first is that fragmentation is a reality; indeed, as described in the opening section, below, each major area of the Internet is already fragmented. The second is that the discourse has not offered a basis for determining whether and when fragmentation is good or bad. If fragmentation is always detrimental, as some seem to suggest, the optimal outcome would be for every network in the world to interconnect and to operate on a single, unified standard. The fact that this is not the case invites some exploration of the forces tending to favour unification and the forces tending to favour fragmentation as a basis for determining optimal network size.

CURRENT EXAMPLES OF FRAGMENTATION

Four different types of fragmentation exist on the Internet: fragmentation of physical networks, of the address space, of protocols and of legal regimes.[1] The following section will describe each in turn and provide real-world examples of how each operates.

Physical Networks

Commentators often stress the importance of having a single network through which everyone can reach everyone else. In fact, the need for a single unified telephone system was the primary rationale for ending the competitive era in US telephone service in the early twentieth century (Gabel 1969). The US Federal Communications Commission's (FCCs) 2010 Open Internet Order echoed this sentiment when it declared, "There is one Internet…that…should remain interconnected" (FCC 2010, 17934). The implication is that governments should mandate that all networks interconnect with one another on equal terms.

Despite this lofty rhetoric, a review of actual practices reveals that a large number of IP-based networks do not interconnect with the public Internet. A better understanding of the rationales underlying these practices reveals considerations against mandating universal connectivity.

1 For a more recent paper providing a related taxonomy, see Drake, Cerf and Kleinwachter (2016). For another interesting exposition on fragmentation, see Huston (2015).

Air Gaps

Perhaps the classic reason for a system not to interconnect with the public Internet is security. One of the standard practices for protecting system security is to block interconnection with other networks by maintaining an "air gap" between the system and the rest of the Internet. Such solutions are imperfect, as they can be bridged. For example, the Stuxnet virus that damaged Iranian centrifuges in 2010 may have been transmitted by an infected memory stick used by a Siemens employee to update software. Even though the fact that these networks are not interconnected to the Internet as a whole did not render these networks completely secure, many networks choose not to interconnect to the public Internet in order to reduce the likelihood of a security breach.

Private Networks

Private networks represent a more common example of non-interconnected networks. Although some are disconnected to maintain security, others remain private to connect high-volume access points in the most cost-effective manner. Still others isolate themselves from the rest of the Internet to guarantee quality of service by avoiding bandwidth sharing. A prime example is the financial services industry, which depends on microsecond latencies. Because the public Internet cannot deliver such speeds on a consistent basis, large parts of the financial services industry rely almost entirely on private networks.

Specialized Services for Voice and Video

Quality-of-service concerns also lead different providers to rely on segregated bandwidth to ensure delivery data associated with latency-intolerant applications, such as voice and video, in a timely manner. These providers sometimes dedicate capacity to these applications and do not make that capacity available for other users even when not used for voice or video. Although the channelization is often virtual, the bandwidth remains dedicated for single purposes and is not made available to other Internet users.

Address Space

Maintaining the unity of the address space is a long-standing principle of the Internet, dating back to its earliest days. Indeed, when Vint Cerf and Bob Kahn (1974) first articulated what would become the Internet suite of protocols, one of the central problems motivating their endeavour was the fact that different packet networks had different ways of addressing destination hosts.

Their solution was to create a uniform addressing scheme that could be understood by every network. Telephone networks once faced the same problem, and a unified numbering scheme has long been regarded as essential to maintaining universal reachability.

IPv6

Despite the widespread recognition of the benefits of unified address spaces, important counter-examples exist today. The transition to IP version 6 (IPv6) represents a prime example. As most observers are aware, the original IP version 4 (IPv4) header only allocated 32 bits in the header to the address space. That means that IPv4 can support just under 4.3 billion addresses.

At the time the Internet was created, 4.3 billion addresses seemed like more than the Internet would ever need. But the Internet has succeeded far beyond anything its creators ever imagined. As of November 2015, 3.4 billion of the world's 7.3 billion citizens accessed the Internet, and the rapid diffusion of data-enabled mobile phones and tablets means that individuals increasingly have more than one IP address. In addition, numerous businesses have Internet addresses as well. Moreover, industry observers predict that the advent of the Internet of Things will cause the connection of as many as 25 billion devices to the Internet by 2020.

The net result is that the Internet has run out of IPv4 addresses. To address this problem, the Internet Engineering Task Force created IPv6. The IPv6 header contains an address space that consists of 128 bits, which is enough to assign a separate address to every molecule in the solar system.

In making the transition from IPv4 to IPv6, network architects chose to make the IPv4 and IPv6 address architectures independent of each other, requiring each router to run both in parallel. This so-called dual-stack approach requires all IPv6 routers to implement parallel address structures simultaneously.

Middleboxes

Another deviation from the universal address space in which each machine has a unique address visible to all other users is the advent of middleboxes, such as network address translation (NAT) boxes. These devices temporary mitigated the exhaustion of IPv4 addresses by allowing multiple hosts to share the same IP address by acting as if they were processes operating on a single machine instead of being distinct hosts. These devices are quite common; indeed, everyone who owns a Wi-Fi router uses them. They have also proven quite controversial in the technical community, because they deviate from the core principle of universal visibility of addresses and make it difficult, if not impossible, to reach certain parts of the network unless the person attempting to contact them has access to specialized state information or employs a NAT-traversal technique. The addition of middleboxes makes network operation more complicated and introduces per-flow state into the core of the network in ways that can make it less robust.

Proprietary Numbering Systems

A number of proprietary numbering systems have emerged in voice over IP. The most important of these is Skype, which provides unique addresses to allow users to connect with other Skype users for free. Skype also interconnects with the public telephone system, so that Skype users may also use traditional telephone numbers for a fee to contact non-Skype users. But the fact remains that Skype users have two parallel, non-interconnected address structures.

The Domain Name System

Address fragmentation is also often raised with respect to the domain name system (DNS). Under the current architecture, the assignment of Universal Resource Locators and IP addresses is done on a distributed basis. Coordination of these different hierarchies of names and numbers depends on the fact that they all refer back to a common root file that determines the authoritative name servers for each top-level domain. The historical role the US government has played in creating the Internet left the Commerce Department with veto power over any changes to the root zone. The Edward Snowden revelations raised serious concerns about the role of the US in Internet governance, which in turn has led some countries to consider shifting their reliance to different root files over which the US government has no control. The controversy over ongoing US oversight over the DNS led the Commerce Department to announce that it would transition oversight of these functions to a non-governmental entity. The current deadline for this transition is September 2016.

Protocols

When trying to connect heterogeneous networks, Cerf and Kahn faced more than just inconsistent address structures. The networks they were attempting to interconnect ran different protocols. They considered translating protocols every time packets crossed from one network to another. The problem was that translation introduces errors. Moreover, translation would have a difficult time operating at scale, as the addition of every new network protocol would require the reconfiguration of every other system attached to the Internet. Instead, as mentioned, Cerf and Kahn required that all networks connected to the Internet operate a single protocol, IP. Insisting that every system would recognize IP would guarantee universal connectivity.

During the network neutrality debate, many advocates have criticized the use of protocols to prioritize certain traffic over others. As an initial matter, what is commonly overlooked is that the Internet was designed from the beginning to support the ability to differentiate among different types of traffic. The need for routing policies can trace its origins to the acceptable-use restrictions prohibiting commercial traffic from traversing the original National Science Foundation Network. A review of the IPv4 header reveals that the designers included a type of service field intended to mark packets for particular kinds of prioritization. Subsequent changes have made this field more customizable. It remained sufficiently important to be retained during the transition to IPv6.

In addition, the most recent version of Border Gateway Protocol (BGP), which provides the basic routing functionality of the Internet, was designed to create routing policies. In other words, BGP was specifically engineered to allow different types of traffic to be treated differently. Although advocates of policies such as network neutrality argue that prioritization should never be used, despite the fact that such functionality has been part of the Internet's design from the outset, using it does not necessarily represent fragmentation of protocols.

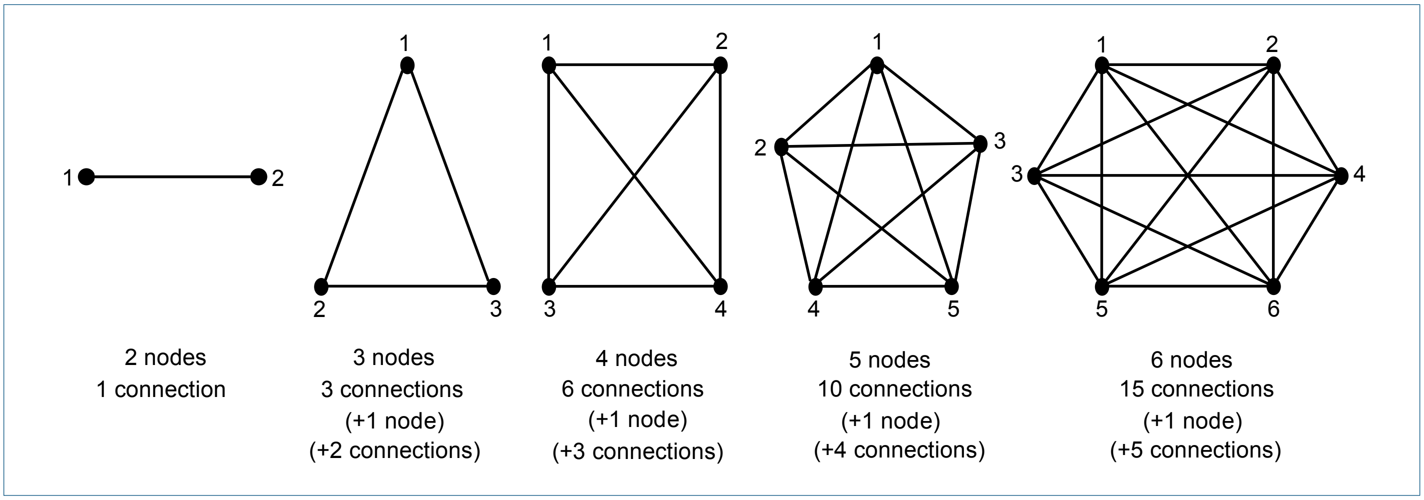
The more fundamental problem is that no one protocol does everything well, and every protocol necessarily involves trade-offs. IP is no exception. Although it has proven incredibly robust, the engineering literature is replete with acknowledgements of functions that the current Internet does not perform well. These include security, mobility, "multihoming", video distribution and cost allocation, to name a few.

While these shortcomings were not that important when the Internet was largely about email and web browsing, in the modern Internet these new functions are now mission critical. This is causing pressure to evolve new protocols. In fact, the Internet is operating a number of protocols that are not completely consistent with the Internet approach. One example is Multiprotocol Label Switching (MPLS), which routes on the basis of specialized labels instead of IP addresses and employs an approach that bears some aspects of circuit switching. Such protocols are widely used to provide the functionality for voice and video that the traditional Internet cannot support. Only firms sharing access to the flow labels associated with MPLS can route traffic associated with these flows. Moreover, firms are using MPLS to implement a wide range of routing policies.

Interestingly, although MPLS initially represented fragmentation of the protocol space, recent changes appear to have incorporated it back into IP architecture. During the transition to IPv6, designers greatly simplified the architecture by removing a large number of fields from the IP header. The one field they added was to introduce a flow label field. This change effectively makes MPLS consistent with the basic architecture rather than representing an example of fragmentation.

The fact that the Internet architecture has now evolved to incorporate MPLS should not overshadow the larger story. Network features emerge that fragment basic architecture. Some will be incorporated into the design,

Figure 1: The Relationship between the Number of Nodes and the Number of Connections



Source: Author.

but they represent deviations during the interim. Still other innovations will never be assimilated into the design.

Legal Regimes

The law has also struggled with the question of optimal fragmentation. Clearly, having the same conduct treated differently by multiple jurisdictions can impose a burden on commerce. Indeed, the desire to harmonize law and to reduce internal barriers to trade was one of the key purposes underlying the founding of the United States, and remains one of the central goals of the European Union.

At the same time, many important areas of the law in America have been left to state jurisdiction. For example, privacy law on data breaches is largely a matter of state law, and reporting requirements remain quite different across the United States and in the European Union. Contract law governing e-commerce is a creature of state law. Taxation remains entirely within the control of states, as does criminal law. Furthermore, in the European Union, individual rights remain a matter of member states' national law. In short, many areas of law are subject to considerable fragmentation.

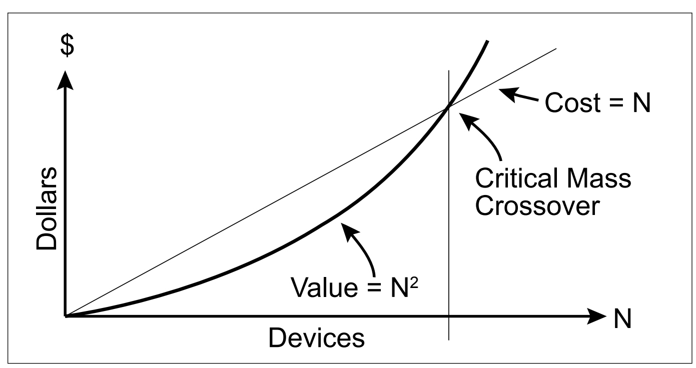
THE BENEFITS OF UNIFICATION

The primary argument against fragmentation is based in the economics of network effects. Network effects exist when the primary determinant of a network's value is the number of other users connected to the network. The more people that an individual subscriber can reach through the network, the more valuable the network becomes, even when the nature of the service and the price paid for it remain the same.

The theoretical basis for network economic effects is known as Metcalfe's law, named after Robert Metcalfe, the inventor of the Ethernet, who first highlighted the importance of this relationship.[2] Metcalfe's law is based on the insight that as a network grows in size, the number of potential connections increases faster than the number of nodes.

Stated more generally, if the number of nodes equals n, the number of potential connections equals $(n2 - n)/2$, which means that the number of potential connections increases quadratically with the number of nodes. This causes the number of connections to increase very rapidly. For example, the first 100 nodes create almost 5,000 potential connections. Adding another 100 nodes (to 200) increases the number of potential connections to just under 20,000, an increase of nearly 15,000. Adding yet another 100 nodes (from 200 to 300) increases the number of potential connections to almost 45,000, an increase of nearly 30,000. Further additions by increments of 100 nodes will cause even larger increases in the number of potential connections.

Figure 2: The Systematic Value of Compatibly Communicating Devices Grows as the Square of Their Number



Source: Metcalfe (2006).

2 For discussions on the connection between Metcalfe's law and network economic effects, see Yoo (2012; 2015).

Assuming that each potential connection increases the value of the network by an equal amount, increases in network size cause a quadratic increase in network value. Assuming that the cost of adding nodes is constant, increases in network size cause a linear increase in cost. The result is inexhaustible returns to scale, in which bigger is always better, as demonstrated by the figure Metcalfe used to communicate the concept during the early 1980s (reproduced above). Metcalfe's law is widely celebrated as the foundation of the Internet's success.

OFFSETTING CONSIDERATIONS

Metcalfe's law provides a clear theoretical basis for opposing the fragmentation of networks. The larger a network becomes, the greater the surplus between benefits and costs. Indeed, if Metcalfe's law were the only consideration, every part of the industry would consist of a single network. But as shown in the opening section, many parts of the industry consist of multiple fragmented networks. This makes it important for us to identify those factors pushing against the tendency for networks to combine into a single large network.

Diminishing Marginal Returns

Consider first the assumption that increases in the number of potential connections cause quadratic increases in network value. This presumes that potential connections increase value no matter how many links have already been established.

Empirically, such a result is quite unlikely. As a seminal article on network economic effects has noted, because those who place the highest value on the network are most likely to be the first to adopt, one would expect later users to provide less value (Rohlfs 2001, 29). A moment's reflection undercuts the expectation that adding more connections would continue to add value. If an end user has access to only one auction or sports news site, the marginal value of adding another is very high. If, on the other hand, the end user already has access to one hundred different versions of each type of site, the incremental value of having access to another version is much smaller.

Bob Briscoe, Andrew Odlyzko and Benjamin Tilly (2006) have provided the most sophisticated critique of Metcalfe's law. They argued that the inexhaustibility of the returns to scale is the direct result of the assumption of the model. They argue that the diminishing marginal returns inherent in the network are better captured by a rule of thumb known as Zipf's law, which holds that if some large collection of elements is ordered by size or popularity, the second element in the collection will be about half the measure of the first one, the third one will be about one-third the measure of the first one, and so forth. Stated more generally, the value of the nth item in the collection will be $1/n$ of the first item. In other words, the value of additional items decays exponentially.

Metcalfe (2006) responded by arguing that Briscoe, Odlyzko and Tilly had misunderstood his work. His point was not to assert that returns to scale in network size are inexhaustible, but rather to underscore how the adoption of a network depended on reaching a critical mass of users. In a later publication, Metcalfe (2013) recognized that the effect he described would not apply to very large networks: "Metcalfe's Law might overestimate the value of a network for a very large N. A user equipped to communicate with 50 million other users might not have all that much to talk about with each of them. So maybe the growth of systemic network value rolls off after some N." Metcalfe pointed out that inexhaustible returns to scale were also a feature of the Zipf's law approach advocated by Briscoe, Odlyzko and Tilly. He also presented empirical evidence based on Facebook usage, suggesting that Metcalfe's law represented a better measure of value than Zipf's law.

Ultimately, the impact of diminishing marginal returns is an empirical question. Fortunately, the claim advanced here does not depend on resolving who has the better of the argument. It suffices to point out that circumstances may exist where further increases in network size will not yield substantial value. This means that whether fragmentation or unification is the better strategy is a question that must be studied empirically, not merely be asserted.

The Value of Heterogeneity

Complementary to the problem of diminishing marginal returns is the fact that people may place different absolute value on different potential connections. In other words, the locations that end users frequent on the Internet are not randomly distributed across the entire Internet. Instead, end users typically focus their visits on a small number of locations.

For example, empirical studies have shown that the average telephone user exchanges calls more than once a month with only five other people (Galbi 2009). Studies of Facebook reveal that users similarly exchange personal messages with no more than four people per week and six people per month (Adams 2012). Indeed, Facebook patterns confirm a concept known as Dunbar's number, which suggests that the human brain can maintain no more than 150 close relationships at any one time (Dunbar 1993).

The result is that end users may not value the number of potential connections in the abstract as much as they value particular connections to specific locations. Speaking personally, my Internet usage is disproportionately concentrated on a handful of locations, including my office computer via remote desktop access, my email server, my bank and a handful of other financial institutions, a number of utilities for bill payment, and a few news sites and blogs. I would place a higher value on connectivity to the sites I visit the most than I would on the ability to connect to other locations.

Heterogeneity can also place pressure toward fragmentation in the context of protocols. The point is demonstrated eloquently in a simple paper authored by Joseph Farrell and Garth Saloner (1986), who wrote some of the pioneering papers on network economic effects. Assume that two different populations of end users (*A* and *B*) would each prefer a slightly different standard and that both would benefit from network economic effects if they were part of the same network. Each group has two options: It can join the other group's standard, in which case it gains from being part of a larger network, but loses value from adopting a standard that it prefers less. Or it can adhere to its preferred standard, in which case it benefits from consuming its preferred standard, but foregoes the benefits of network economic effects should the other group adhere to its preferred standard as well.

The considerations driving the equilibrium are clear. If the value that either group derives from consuming its preferred standard is sufficiently large, it will always adopt its preferred standard even if it means being part of a smaller network. Any welfare losses from network fragmentation are more than offset by gains in allowing groups of end users to consume a standard that is a better fit with their preferences.

Heterogeneity also explains fragmentation in law, as exemplified by the debate over federalism. In any federal system, an issue may be addressed at the federal level or at the regional level. Two of the primary reasons to address issues at the regional level are a diversity of values and/or conditions, and the facilitation of experimentation. Allowing each regional jurisdiction to tailor its own solution allows the law to effect a better fit with local circumstances, but at a cost of greater legal fragmentation. Indeed, in the United States, many key areas of the law remain governed by state law and thus face fragmentation, including contract law, corporate law and data-breach notification. Admittedly, there are other considerations tending toward federal resolution, including externalities, scale economies, "races to the bottom," expertise and the potential of interest-group capture. Whether fragmentation or unification is the optimal outcome depends on which of these considerations dominates.

Determining Value Based on the Total Number of Nodes Instead of the Total Number of Unique Connections

Metcalfe's law also presumes that the value of a network is determined by the total number of unique pairwise connections. In other words, the value is determined by the ability to reach specific people. One can easily imagine situations where value depends on the total number of people one can reach through the network without placing any value on the ability to reach discrete people. A prime example of this is advertising. Many advertisers do not care if they can reach any particular person. Instead, they care only about the total size of audience.

Shifting the focus to the total number of people a network can reach without placing any value on the ability to reach particular individuals fundamentally changes the underlying economics (Nuechterlein and Yoo 2015). The fact that advertising represents the dominant source of revenue on the Internet suggests that heuristics such as Metcalfe's law may well overstate the value of preventing any action that may cause the network to fragment.

Nonlinear Increase in Costs

Metcalfe's law also depends on the assumption that costs would increase linearly, which in turn is based on the assumption that the equipment costs of adding each additional node would be precisely the same. The problem with this assumption is that there are other important sources of costs in the Internet.

The most important source of costs is congestion. The Internet is a shared medium. Indeed, the ability to multiplex streams of data across the same connection is one of the primary advantages associated with packet switching. Like any shared medium, the Internet can become congested if too many people attempt to use it at the same time. As congestion becomes severe, the costs grow much faster than linearly. Indeed, when buffers become completely full, the network can suffer from complete and sharply discontinuous lockout.

Another problem associated with the growth of the Internet is search costs. As more nodes are attached to the network, those who wish to use the network must incur higher search costs to find content that fits their preferences. The problems associated with this have led some to question whether certain social networks, such as Facebook, have become too big.

REAL-WORLD SOLUTIONS TO FRAGMENTATION

The presence of opposing considerations provides a framework for evaluating when unification is the optimal approach and when fragmentation might yield benefits. As such, it also provides a basis for describing the world as it exists today, in which some matters are unified or addressed at the federal level and others are fragmented or handled at a regional level.

Even when fragmentation exists, both engineering and law have developed institutions to manage the heterogeneity.

The most important of these are partial compatibility and informal harmonization.

Partial Compatibility through Gateways

One way that networks can mitigate the problems associated with fragmentation is through gateways (also called adapters or converters) between networks. Many of the leading scholars on network economic effects have shown that perfect gateways can completely mitigate the problems of fragmentation (Matutes and Regibeau 1988; David and Bunn 1988; Katz and Shapiro 1994; Farrell and Saloner 1992). Farrell and Saloner further showed that even if the gateway is imperfect, it can mitigate the problems of incompatibility in whole or in part. Such gateways can ameliorate potential fragmentation in the physical architecture, the address space and the protocols.

Arbitration

For legal fragmentation, the most prominent means of harmonization is the resort to commercial arbitration. Commercial arbitration is honored internationally now by almost every jurisdiction and allows parties to opt in to a unified legal regime. Indeed, an arbitration clause can avoid national jurisdiction by opting to be bound by a pre-existing body of arbitral precedents.

CONCLUSION

Debates about Internet fragmentation often take on an alarmist tone that intimates that any practice that introduces a degree of heterogeneity into the network must be stopped. If followed to its logical conclusion, this point of view would mandate that all networks interconnect with one another on equal terms and operate the exact same protocols to ensure maximum interoperability.

The pragmatic perspective that animates network engineering generally regards such absolutist perspectives with suspicion. Often, multiple forces push particular outcomes in opposite directions. The natural response is to understand those forces and to study them empirically to determine how they should best be optimized. Undertaking such an analysis does not deny the value of wide-scale interoperability. There is no doubt that the "open Internet" standards have created tremendous benefits to the world and have proven more robust than anyone could have imagined.

The goals of this paper are far more limited. It raises a defensive argument designed to raise the possibility that universal connectivity and interoperability may not be the preferred solution in every circumstance, and to try to identify heuristics to help guide the determination of when fragmentation is bad and when it might good. Part of the argument is empirical: fragmentation and non-standardization are pervasive phenomena that exist in the physical network, the address space, the protocol space, and the law governing the Internet. Any evaluation of whether and when fragmentation is good or bad must seek to understand the forces that tend to push toward unification and toward fragmentation to help inform the proper balance in any particular case.

Finally, any assessment of fragmentation must take into account that participation in the Internet architecture is always voluntary. Those who operate IP-based networks always remain free not to interconnect them with the public Internet, to use different address structures or to use different protocols. Because interconnection and standards adoption remains voluntary, individual actors can be expected to interconnect or adopt the standard only when the individual benefits exceed the individual costs. Importantly, individual optimization decisions do not always lead to equilibria that are optimal for the network as a whole. Thus, any assessment of fragmentation requires not only an understanding of when fragmentation and unification would be optimal globally, it also requires careful attention to the incentives of individual actors to determine whether the decentralized decision making that characterizes the Internet is likely to lead to good outcomes.

A version of this paper was presented at the October 2014 meeting of the Global Commission on Internet Governance held in Seoul, Korea.

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