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Moore's Law, Metcalfe's Law, and the Theory of Optimal Interoperability

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MOORE’S LAW, METCALFE’S LAW, AND THE THEORY OF OPTIMAL INTEROPERABILITY

CHRISTOPHER S. YOO*

INTRODUCTION	87
I. MOORE’S LAW	90
II. METCALFE’S LAW	91
III. LIMITS TO MOORE’S LAW	94
A. <i>Endogeneity</i>	94
B. <i>Non-Processing Technologies</i>	94
C. <i>Other Sources of Increases in Cost</i>	95
D. <i>Technological Limitations</i>	96
IV. LIMITS TO METCALFE’S LAW.....	96
A. <i>The Law of Diminishing Returns</i>	97
B. <i>Sources of Value Aside from Network Size</i>	99
V. ALTERNATIVE INSTITUTIONAL FORMS	100
A. <i>Partial Compatibility Through Gateways</i>	101
B. <i>Competitive Considerations</i>	101
CONCLUSION	102

INTRODUCTION

The Internet has experienced dramatic growth since it first became a mass-market phenomenon during the mid-1990s.¹ To pick just one Internet application, the World Wide Web has reached widespread adoption faster than any other consumer product.² Indeed, many people find it difficult to recall how they purchased airline tickets, conducted research, or communicated with friends before the Internet existed.³

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1. See Christopher S. Yoo, *Possible Paradigm Shifts in Broadband Policy*, 9 I/S: J.L. & POL’Y INFO. SOC’Y 367 (2014).

2. K.N.C. et al., *Happy Birthday World Wide Web: Society Is Adopting Technology at an Incredibly Fast Pace*, *ECONOMIST* (Mar. 12, 2014, 12:29 PM), <http://econ.st/1qvmJkC>.

3. Drew DeSilver, *Chart of the Week: The Ever-accelerating Rate of Technology*

The meteoric rise of the Internet naturally raises questions about what made it so successful. Many observers attribute the Internet's success to two principles: *Moore's Law* and *Metcalf's Law*. Indeed, then-FCC Chairman Reed Hundt declared that those two ideas "give us the best foundation for understanding the Internet."⁴ Other commentators have drawn similar conclusions.⁵

Together, Moore's Law and Metcalfe's law represent complementary concepts, one operating on the supply side and the other operating on the demand side. On the supply side, in most cases, growth eventually leads to diseconomies of scale that eventually make further expansion in size increasingly costly. Moore's Law suggests that digitization creates a systematic reduction in costs that can offset such increases in costs.⁶ So long as the increase in costs caused by expansion in size remains smaller than the reduction in costs associated with Moore's Law, costs should remain manageable even in the face of continuing growth.⁷

On the demand side, Metcalfe's Law says that the number of potential connections increases quadratically with the number of nodes. To the extent that expanding the number of potential connections increases the value of a network, Metcalfe's Law provides another reason for believing that growth in network size will be economically beneficial.⁸

The engineering community has long viewed both concepts as fundamental, regarding them as central drivers of the digital economy.⁹

Adoption, PEW RES. CTR. (Mar. 14, 2014), <http://www.pewresearch.org/fact-tank/2014/03/14/chart-of-the-week-the-ever-accelerating-rate-of-technology-adoption/>.

4. Reed Hundt, Chairman, Fed. Comm'n Comm'n, Address at the Wall Street Journal Business and Technology Conference (Sept. 18, 1996), <https://transition.fcc.gov/Speeches/Hundt/spreh636.txt>.

5. See, e.g., LARRY DOWNES, UNLEASHING THE KILLER APP 21–28 (1998); Susan Ness, *Preface*, 7 COMM'LAW CONSPECTUS 229, 229 (1999); Ted Leonsis, *Honoring Technology's Power Couple: Moore's Law and the Network Effect*, WASH. POST (Apr. 19, 2015, 10:34 AM), <http://wpo.st/Gpvq0>.

6. Charles C. Mann, *The End of Moore's Law?*, MIT TECH. REV., May–June 2000, at 43, 45.

7. Bob Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, COMPUTER, Dec. 2013, at 26, 31; Bob Metcalfe, *Metcalfe's Law: A Network Becomes More Valuable as It Reaches More Users*, INFOWORLD, Oct. 2, 1995, at 53, 53.

8. See Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, *supra* note 7, at 28; Metcalfe, *Metcalfe's Law*, *supra* note 7.

9. See, e.g., Philip E. Ross, *5 Commandments: The Rules Engineers Live By Weren't Always Set in Stone*, IEEE SPECTRUM (Dec. 1, 2003, 7:51 PM), <http://bit.ly/1NjvoVx>; Bob Metcalfe, *There Oughta Be a Law*, N.Y. TIMES, July 15, 1996, at D7. For more recent statements, see Vladimir Getov, *Computing Laws: Origins, Standing, and Impact*, COMPUTER, Dec. 2013, at 24, 24, <http://www.computer.org/csdl/mags/co/2013/12/mco2013120024.pdf>; David Delony, *The Laws of Computing*, TECHOPEdia (Nov. 15, 2013), <http://tchpd.co/1aW03EJ>; Gary Marshall, *10 Laws of Tech: The Rules That Define Our World*, TECHRADAR (Mar. 5, 2012), <http://www.techradar.com/news/world-of-tech/10-laws-of-tech-the-rules-that->

Commentators have also invoked these principles in a wide range of policy contexts. The precept that larger networks are inherently more valuable entails a natural hostility towards anything that tends to balkanize or fragment the network.¹⁰ Metcalfe's Law also suggests new potential sources of market power,¹¹ and may justify mandating interconnection or access to existing networks if they are to compete effectively.¹² Similarly, Moore's Law suggests that reductions in cost will obviate the need for network management.¹³

Astute observers have long recognized the implausibility of the premise that continued growth in network size is always beneficial.¹⁴ Indeed, the luminaries after whom these laws were named have conceded as much.¹⁵ This Article reviews the emerging literature analyzing the limits of both principles. Parts I and II lay out the basic framework of Moore's Law and Metcalfe's Law. Parts III and IV examine the limits to both principles. Part V explores alternative solutions that permit the

define-our-world-1067906.

10. See, e.g., James Grimmelmann, *The Internet Is a Semicommons*, 78 FORDHAM L. REV. 2799, 2820 n.150 (2010).

11. See, e.g., John T. Nakahata, *Regulating Information Platforms: The Challenge of Rewriting Communications Regulation from the Bottom Up*, 1 J. ON TELECOMM. & HIGH TECH. L. 95, 135 (2002); Carl Shapiro, *Exclusivity in Network Industries*, 7 GEO. MASON L. REV. 673, 674 (1999).

12. See, e.g., Philip J. Weiser, *Law and Information Platforms*, 1 J. ON TELECOMM. & HIGH TECH. L. 1, 10 n.44 (2002) (discussing interconnection); Joshua A.T. Fairfield, *Bitproperty*, 88 S. CAL. L. REV. 805, 824 n.89 (2015) (discussing access).

13. See, e.g., Benjamin Lennett, *Dis-Empowering Users vs. Maintaining Internet Freedom: Network Management and Quality of Service*, 18 COMMLAW CONSPECTUS 97, 127–28 (2009).

14. See Andrew McAfee & François-Xavier Oliveau, *Confronting the Limits of Networks*, SLOAN MGMT. REV., Summer 2002, at 85, 86, <http://sloanreview.mit.edu/article/confronting-the-limits-of-networks/> (quoting Paul Krugman in 1998 as saying, “The flaw in Metcalfe's Law . . . becomes apparent: Most people have nothing to say to each other!”).

15. For Moore's views, see Michael Kanellos, *Moore's Law to Roll for Another Decade*, CNET (Feb. 11, 2003, 4:35 AM), <http://cnet.co/1UUi01> (quoting Moore as saying, “No physical quantity can continue to change exponentially forever.”); Stephen Shankland, *Moore's Law: The Rule That Really Matters in Tech*, CNET (Oct. 15, 2012, 12:00 AM), <http://cnet.co/1r8oHow> (quoting Moore as saying in 2007, “Any physical quantity that's growing exponentially predicts a disaster. It comes to some kind of an end. You can't go beyond certain major limits.”); Manek Dubash, *Moore's Law Is Dead, says Gordon Moore*, TECHWORLD (Apr. 13, 2010), <http://www.techworld.com/news/operating-systems/moores-law-is-dead-says-gordon-moore-3576581/> (quoting Moore as saying, “It can't continue forever. The nature of exponentials is that you push them out and eventually disaster happens.”).

For Metcalfe's views, see Metcalfe, *Metcalfe's Law*, *supra* note 7, at 53 (“OK, 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.”); McAfee & Oliveau, *supra* note 14 (quoting Metcalfe as recognizing in 1998, “The law may be optimistic as the number of people on a network gets very large.”).

benefits of both propositions to be realized without requiring increases in network size. The hope is that a more refined understanding will lead to a more refined insight into these principles' implications for public policy.

I. MOORE'S LAW

In 1965, Gordon Moore—Fairchild Semiconductor Director of Research and Development and future Intel co-founder—observed that since 1959 the number of transistors on an integrated circuit had doubled every year and predicted that that pattern would persist until 1975.¹⁶ Ten years later, Moore revised that prediction to forecast that the number of transistors would double every two years through 1980,¹⁷ although Intel executive David House later revised it into its better known formulation projecting that the number of transistors would double every eighteen months.¹⁸ Moore credits California Institute of Technology professor Carver Mead with coining the actual phrase, Moore's Law,¹⁹ but recent attempts to confirm that fact proved inconclusive.²⁰

Unlike laws of nature and science, Moore's Law is not a mathematical or fundamental physical relationship. Instead, it is an empirical prediction based on the current state of technology. Moreover, Moore later revealed that when he made the prediction, he had his doubts about its likely accuracy, admitting that when he made it he "didn't think it would be particularly accurate"²¹ and regarded the ten-year span as a "stretch."²²

Nonetheless, Moore's Law has enjoyed an impressive fifty-year run.²³ Although Moore recognized that the trend could not last forever, he forecasted in 2003, 2007, 2010, and 2015 that it would continue for another decade or so.²⁴ There are signs that the trend may now be

16. Gordon E. Moore, *Cramming More Components onto Integrated Circuits*, ELECTRONICS, Apr. 19, 1965, at 114, http://www.monolithic3d.com/uploads/6/0/5/5/6055488/gordon_moore_1965_article.pdf.

17. Gordon E. Moore, *Progress in Digital Integrated Electronics*, in 21 TECH. DIGEST, 1975 INT'L ELECTRON DEVICES MEETING 11, 11 (1975).

18. See Kanellos, *supra* note 15.

19. *Id.*

20. Rachel Courtland, *The Murky Origins of "Moore's Law,"* IEEE SPECTRUM (Apr. 28, 2015, 4:00 PM), <http://spectrum.ieee.org/tech-talk/semiconductors/devices/the-murky-origins-of-moores-law>.

21. Michael Kanellos, *Moore Says Nanoelectronics Face Tough Challenges*, CNET (Mar. 10, 2005, 7:59 AM), <http://cnet.co/1NjOxH6>.

22. Thomas L. Friedman, Opinion, *Moore's Law Turns 50*, N.Y. TIMES (May 13, 2015), <http://nyti.ms/1JGlp5t>.

23. Dan Hutcheson, *Transistor Production Has Reached Astronomical Scales*, IEEE SPECTRUM, (Apr. 2, 2015, 19:00), <http://spectrum.ieee.org/computing/hardware/transistor-production-has-reached-astronomical-scales>.

24. Kanellos, *supra* note 15; Bryan Gardiner, *IDF: Gordon Moore Predicts the End of Moore's Law (Again)*, WIRED (Sept. 18, 2007, 4:07 PM), <http://www.wired.com/2007/09/idf/>

flagging. Indeed, both Moore and Intel acknowledged earlier this year that the growth in transistor density has fallen below the rate associated with Moore's Law.²⁵ Leading figures at Intel have disagreed over what the future holds.²⁶

Although Moore offered his prediction in terms of computing power, other people have applied it more loosely. Indeed, it is often referred to as a general metaphor applicable to any aspect of computing. Moreover, instead of focusing on increases in the number of transistors, it is often asserted as a claim phrased in terms of reductions in cost.²⁷ Reframed in this manner, Moore's Law stands for the more general principle that the cost of digital technologies will consistently drop.²⁸

Moore's Law now enjoys canonical status in tech industry circles, having been called "the first law of computing," "the bedrock for the computer processor industry,"²⁹ "the most important and powerful law in Silicon Valley,"³⁰ and "[t]he rule that really matters in tech."³¹ Some economists attribute much of the success associated with the digital revolution to it as well.³²

II. METCALFE'S LAW

The supply-side cost reductions associated with Moore's Law are complemented by the demand-side economies of scale associated with network economic effects, which exploded onto the scene in the mid-1980s.³³ Network economic effects exist when the value of a network is

gordon-mo-1/; Dubash, *supra* note 15; Rachel Courtland, *Gordon Moore: The Man Whose Name Means Progress*, IEEE SPECTRUM (Mar. 30, 2015, 7:00 PM), <http://spectrum.ieee.org/computing/hardware/gordon-moore-the-man-whose-name-means-progress>.

25. Don Clark, *Intel Rechisels the Tablet on Moore's Law*, WALL ST. J. DIGITS (July 16, 2015, 10:52 AM), <http://blogs.wsj.com/digits/2015/07/16/intel-rechisels-the-tablet-on-moores-law/>; see Courtland, *supra* note 24.

26. See Leo Kelion, *Moore's Law: Beyond the First Law of Computing*, BBC (Apr. 17, 2015), <http://www.bbc.com/news/technology-32335003> (noting the disagreement between Intel's former and current chief architects over whether Moore's Law will be dead by 2022).

27. See, e.g., Mann, *supra* note 6, at 44–45.

28. See, e.g., *id.*; Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, *supra* note 7, at 26, 31.

29. Kelion, *supra* note 26.

30. Robert X. Cringely, *Breaking Moore's Law*, BETANEWS (Oct. 15, 2013), <http://betanews.com/2013/10/15/breaking-moores-law/>.

31. Shankland, *supra* note 15.

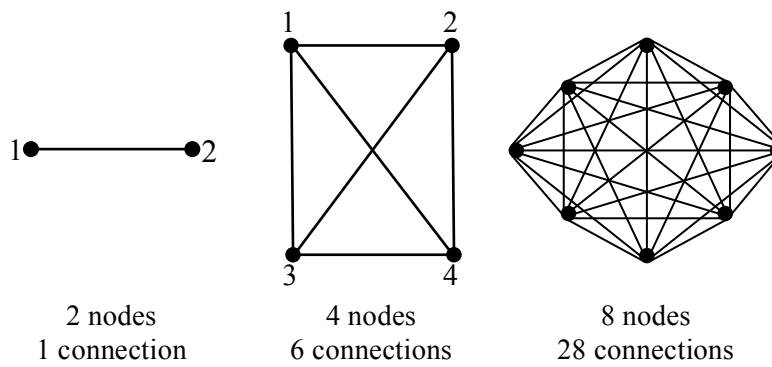
32. See Mann, *supra* note 6, at 44 (quoting Northwestern University economist Robert Gordon as saying, "What's sometimes called the 'Clinton economic boom' is largely a reflection of Moore's Law.").

33. For the seminal analysis of network economic effects, see Jeffrey Rohlfs, *A Theory of Interdependent Demand for a Communications Service*, 5 BELL J. ECON. & MGMT. SCI. 16 (1974). For classic analyses of how network economic effects can confer a competitive advantage to early industry leaders, see W. Brian Arthur, *Competing Technologies, Increasing Returns, and Lock-In by Historical Events*, 99 ECON. J. 116 (1989); Paul A. David, *Clio and*

determined by 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 remains the same.³⁴

The theoretical basis for network economic effects is known as Metcalfe's Law, first articulated in the early 1980s by Bob Metcalfe, the inventor of the Ethernet,³⁵ and later named in his honor by George Gilder.³⁶

FIGURE 1: METCALFE'S LAW



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 $(n^2 - n)/2$, which means that the number of potential connections increases quadratically with the number of nodes. In short, doubling the number of nodes will more than quadruple the number of potential connections.³⁷

Metcalfe's Law assumes that each potential connection increases

the Economics of QWERTY, 75 AM. ECON. REV. (Papers & Proc.) 332 (1985); Joseph Farrell & Garth Saloner, *Standardization, Compatibility, and Innovation*, 16 RAND J. ECON. 70 (1985); and Michael L. Katz & Carl Shapiro, *Network Externalities, Competition, and Compatibility*, 75 AM. ECON. REV. 424 (1985).

34. Daniel F. Spulber & Christopher S. Yoo, *Access to Networks: Economic and Constitutional Connections*, 88 CORNELL L. REV. 885, 922 (2003).

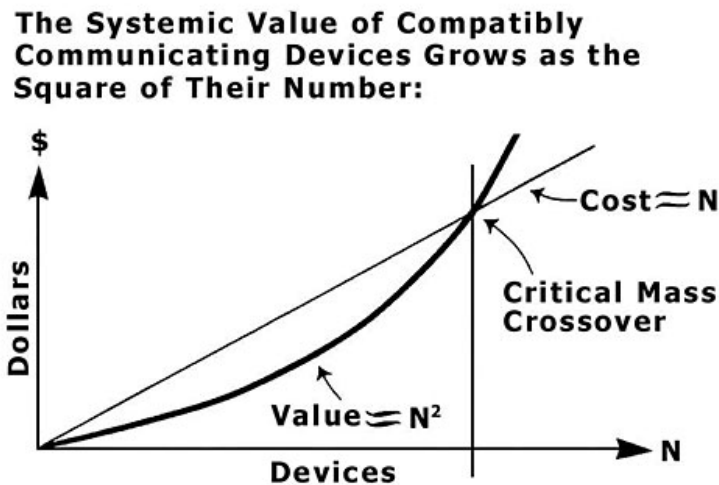
35. See Metcalfe, *Metcalfe's Law*, *supra* note 7; Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, *supra* note 7, at 28.

36. George Gilder, *Metcalfe's Law and Legacy*, FORBES ASAP, Sept. 13, 1993, at 158, 158.

37. Metcalfe, *Metcalfe's Law*, *supra* note 7; see DANIEL F. SPULBER & CHRISTOPHER S. YOO, NETWORKS IN TELECOMMUNICATIONS: ECONOMICS AND LAW 121 (2009).

the value of the network by an equal amount.³⁸ This implies that increases in network size leads to a quadratic increase in network value. If 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 below).³⁹

FIGURE 2: METCALFE'S LAW



Metcalfe's Law provides a demand-side explanation for the success of the Ethernet and Internet-based companies such as America Online,⁴⁰ although some have suggested that the recent experiences of eBay and Facebook raise questions about the relationship.⁴¹ The implication is that combining all networks into a single network will be more valuable than maintaining multiple smaller networks.

38. Metcalfe, *Metcalfe's Law*, *supra* note 7.

39. Bob Metcalfe, *Metcalfe's Law Recurses Down the Long Tail of Social Networking*, VCMIKE'S BLOG (Aug. 18, 2006), <https://vc mike.wordpress.com/2006/08/18/metcalfe-social-networks/>.

40. Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, *supra* note 7, at 27–28; Paul Festa, *Andreessen preaches AOL religion*, CNET (Jan. 2, 2002, 4:43 PM), <http://cnet.co/1Nkjydp>; Gilder, *supra* note 36.

41. Anthony Wing Kosner, *Facebook Values Itself Based on Metcalfe's Law, But the Market Is Using Zipf's*, FORBES TECH (May 31, 2012, 1:14 PM), <http://onforb.es/JCawr4>; Om Malik, *Metcalfe's Law, Meet Market Reality*, GIGAOM (Jan. 21, 2005, 3:15 AM), <https://gigaom.com/2005/01/21/metcalfes-law-meet-market-reality/>.

III. LIMITS TO MOORE'S LAW

Although Moore's Law is often presented as an inevitable, on closer examination, it is subject to a number of caveats. Understanding these limitations is critical to understanding the principle's true policy implications. Any weakening of Moore's Law suggests that increases in network size may not always lead to the cost reductions needed to support the conclusion that bigger is better.

A. Endogeneity

One problem associated with Moore's Law is endogeneity. Because so many industry participants believed that their competitors would realize the prediction of Moore's Law, they made sure to invest enough in research and development to make sure to achieve it.⁴² To some extent, Moore's Law can be regarded more as the driving force behind the technical improvements rather than a milestone that has been achieved. As such, it may be best regarded as a self-fulfilling prophecy.⁴³

B. Non-Processing Technologies

Moore's Law is often misstated as the idea that digitization will cause computing power to double every eighteen months. This would be the equivalent of a 40% drop in cost every year. If Moore's Law were this general, the Internet should be able to grow indefinitely without any increase in cost.

Properly understood, however, Moore's Law applies only to one aspect of digitization: computer processing. Other principles govern other aspects affecting overall performance. For example, *Kryder's Law* is the equivalent of Moore's Law for storage. Initially advanced by the VP of Research of Seagate in 2005, Kryder's Law claims that magnetic disk storage density doubles every eighteen months.⁴⁴ Similarly, *Nielsen's Law* predicts that network bandwidth doubles every twenty-one

42. Roger Cheng, *Moore's Law Is the Reason Your iPhone Is So Thin and Cheap*, CNET (Apr. 16, 2015, 5:00 AM), <http://cnet.co/1azMBI2>; Cyrus Mody, *What Kind of Thing Is Moore's Law?*, IEEE SPECTRUM (Apr. 6, 2015, 7:00 PM), <http://spectrum.ieee.org/semiconductors/devices/what-kind-of-thing-is-moores-law>; Jonathan Strickland, *How Moore's Law Works*, HOW STUFF WORKS (Feb. 26, 2009), <http://computer.howstuffworks.com/moores-law4.htm/printable>.

43. See, e.g., Harro van Lente & Arie Rip, *Expectations in Technological Developments: An Example of Prospective Structures Filled in by Agency*, in GETTING NEW TECHNOLOGIES TOGETHER 205, 206–07 (Cornelius Disco & Barend van der Meulen eds., 1998); Chris Mack, *The Multiple Lives of Moore's Law*, IEEE SPECTRUM, (Mar. 30, 2015, 3:00), <http://spectrum.ieee.org/semiconductors/processors/the-multiple-lives-of-moores-law>; Strickland, *supra* note 42.

44. Chip Walter, *Kryder's Law*, SCI. AM. (July 25, 2005), <http://www.scientificamerican.com/article/kryders-law/>.

months,⁴⁵ while *Butter's Law* posits that the cost of transmitting data over optical fiber drops in half every nine months.⁴⁶

Despite public expectations, not all aspects of technology have adhered to Moore's Law. For example, battery life has not enjoyed the same rate of improvement as processing has under Moore's Law.⁴⁷ Moreover, Moore's Law does not apply to labor intensive improvements, like those that require digging ditches and running wires.⁴⁸

The net result is that different aspects of the cost function of digital technologies are likely falling at different rates. Determining the precise rate for any particular technology depends on closer analysis of the changes in cost of the various components at any particular time that is not easily reducible into high-level generalities.

C. Other Sources of Increases in Cost

The assumption that improvements in technology consistently cause costs to decline ignores the fact that there are other important sources of cost 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.⁴⁹ As congestion becomes severe, the costs can grow much faster than linear.⁵⁰ Indeed, when buffers become completely full, the network can suffer from complete and sharply discontinuous lockout.⁵¹

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

45. Jakob Nielsen, *Nielsen's Law of Internet Bandwidth*, NN/G NIELSEN NORMAN GROUP (Apr. 5, 1998), <http://www.nngroup.com/articles/law-of-bandwidth/>.

46. Rich Tehrani, *As We May Communicate*, TMCNET (Jan. 2000), <http://www.tmcnet.com/articles/comsol/0100/0100pubout.htm>.

47. Fred Schlachter, *No Moore's Law for Batteries*, 110 PROC. NAT'L ACAD. SCI. 5273 (2013); Todd Woody, *When It Comes to Car Batteries, Moore's Law Does Not Compute*, N.Y. TIMES: GREEN (Sept. 6, 2010, 10:42 AM), <http://nyti.ms/1O9AYsy>; Katie Fehrenbacher, *Dear Friedman: There Is No Moore's Law for Batteries*, GIGAOM (Sept. 27, 2010, 9:30 AM), <https://gigaom.com/2010/09/27/dear-friedman-there-is-no-moores-law-for-batteries/>.

48. NEMERTES RESEARCH, INTERNET INTERRUPTED: WHY ARCHITECTURAL LIMITATIONS WILL FRACTURE THE 'NET 16 (2008).

49. Christopher S. Yoo, *Network Neutrality and the Economics of Congestion*, 94 GEO. L.J. 1847, 1860 (2006).

50. Van Jacobson, *Congestion Avoidance and Control*, COMPUTER COMM. REV., Aug. 1988, at 314.

51. Bob Braden et al., *Recommendations on Queue Management and Congestion Avoidance in the Internet* 3–6 (IETF Network Working Grp. RFC 2309, 1998), <http://tools.ietf.org/pdf/rfc2309.pdf>.

preferences.⁵² The problems associated with this have led some to question whether certain social networks, such as Facebook, have become too big.⁵³

D. Technological Limitations

The achievement of the cost reductions associated with Moore's Law have traditionally relied on a specific technological strategy: chip designers have been able to fit more transistors on a chip by making them smaller. In this manner, they have been able to achieve a significant increase in transistor density. But the laws of physics impose a natural limit on how long innovators can rely on this strategy. Smaller chips tend to generate more heat, which in turn causes the interconnects to degrade.⁵⁴ Moreover, once the gates that determine whether a particular circuit is open or closed are smaller than two nanometers, quantum effects emerge that can allow electrons to tunnel through gates that are supposedly closed.⁵⁵ That is why many have been predicting the end of Moore's Law for almost two decades.⁵⁶

It remains to be seen whether engineers will find ways to avoid the impending end to Moore's Law. Some are experimenting with making chips from materials other than silicon. Others are experimenting with fundamentally different approaches, such as quantum computing, chemical computing, wetware computing, fluidic computing, and ternary computing.⁵⁷ Which, if any, of these technologies will succeed is anybody's guess. The uncertainty surrounding the future development path of computing underscores the extent to which Moore's Law has lost its aura of inevitability. If so, it is quite possible that the reductions in cost will not be sufficient to compensate for the growth in network size.

IV. LIMITS TO METCALFE'S LAW

Just as Moore's Law is subject to limitations, so too is Metcalfe's Law. The caveats that apply to Metcalfe's Law have an equally profound impact on policy implications as the caveats to Moore's Law.

52. McAfee & Oliveau, *supra* note 14.

53. Christopher S. Yoo, *When Antitrust Met Facebook*, 19 GEO. MASON L. REV. 1147, 1152 (2012).

54. Adam L. Penenberg, *The End of Moore's Law*, SLATE (Dec. 20, 2005, 3:15 PM), http://www.slate.com/articles/technology/technology/2005/12/the_end_of_moores_law.html.

55. Mann, *supra* note 6, at 48.

56. See, e.g., William J. Broad, *Incredible Shrinking Transistor Nears Its Ultimate Limit: The Laws of Physics*, N.Y. TIMES (Feb. 4, 1997), <http://nyti.ms/1NkliE3>.

57. Gabriel Popkin, *Moore's Law Is About to Get Weird*, NAUTILUS (Feb. 12, 2015), <http://nautil.us/issue/21/information/moores-law-is-about-to-get-weird>.

A. *The Law of Diminishing Returns*

While it is undeniably true that the number of potential connections increases quadratically with the number of connections, that by itself is not enough to establish the inherent superiority of larger networks. Metcalfe's Law also depends on the assumption that the additional connections continue to provide additional value. As the commentary on network economic effects recognizes, the assumption that additional connections continue to contribute equal value has the effect of positing inexhaustible economies of scale.⁵⁸ As such, the bias towards large networks may be regarded more as an artifact of the model than as an aspect of any actual market. Allowing for the possibility of heterogeneity in consumer preferences causes the bias towards a single network to disappear and permits stable equilibria with multiple networks.⁵⁹

The literature on Metcalfe's Law offers a similar critique. For example, Jeffrey Rohlfs points out that if the first users are the ones who place the highest value on the network, one would expect the addition of later users to provide less value.⁶⁰ Failure to take this into account is "likely to substantially overstate the value of large networks."⁶¹ In addition, "small user sets can embody substantial value."⁶² Rohlfs then offered a mathematical formulation that could accommodate a wide range of assumptions about consumer heterogeneity.⁶³ Andrew McAfee and François-Xavier Oliveau similarly noted that network participants who place a particularly high value on a small number of users can realize most of that value by clustering on a single network regardless of its size.⁶⁴ They also emphasized how additional connections are subject to diminishing returns.⁶⁵

These insights were further emphasized in an oft-cited article by Bob Briscoe, Andrew Odlyzko, and Benjamin Tilly.⁶⁶ Briscoe, Odlyzko,

58. S.J. Liebowitz & Stephen E. Margolis, *Are Network Externalities a New Source of Market Failure?*, 17 RES. L. & ECON. 1, 13–15 (1995); see Yoo, *supra* note 53, at 1151 (citing literature showing how telephone networks are subject to diminishing marginal returns).

59. Christopher S. Yoo, *Vertical Integration and Media Regulation in the New Economy*, 19 YALE J. ON REG. 171, 281 (2002) (reviewing the literature suggesting that heterogeneity of consumer preferences may permit the development of multiple networks).

60. JEFFREY H. ROHLFS, BANDWAGON EFFECTS IN HIGH-TECHNOLOGY INDUSTRIES 29 (2001).

61. *Id.* at 55, 195.

62. *Id.* at 85. Indeed, unlocking the value of smaller subgroups is the central insight of the Chris Anderson's work on "the long tail" that is also often regarded as identifying one of the keys to the Internet's success. See Chris Anderson, *The Long Tail*, WIRED (Oct. 1, 2004, 12:00 PM), <http://www.wired.com/2004/10/tail/>.

63. *Id.* at 211–16.

64. McAfee & Oliveau, *supra* note 14.

65. *Id.*

66. Bob Briscoe, Andrew Odlyzko & Benjamin Tilly, *Metcalfe's Law Is Wrong*, IEEE SPECTRUM (July 1, 2006, 6:15 PM), <http://spectrum.ieee.org/computing/networks/metcalfes->

and Tilly modeled the principle of diminishing marginal returns through a rule-of-thumb known as *Zipf's Law*.⁶⁷ Zipf's Law 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.⁶⁸ Stated more generally, the value of the n th item in the collection will be $1/n$ of the first item. In other words, the value of additional items decays exponentially.⁶⁹ Eventually, the benefits associated with further expansion of the network will no longer justify the cost.

If so, adding more connections will not necessarily make the network more valuable. A simple thought experiment will verify this. Once a network is extremely large, Metcalfe's Law predicts that adding each additional node would create an ever-increasing amount of value. In a manner similar to a traditional pyramid scheme, eventually that amount added would equal the value of the entire economy.⁷⁰

These critiques underscore that simply assuming that all connections contribute equal value represents a potentially fundamental flaw. In fact, people do not value all connections equally. For example, empirical studies show that in traditional telephone service, people tend to make frequent calls to a small group of people.⁷¹ The same appears to be true for Internet-based communications, as shown by recent empirical studies indicating that the average Facebook user actively exchanges personal messages with no more than four people per week and six people per month.⁷² 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.⁷³

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 particular locations. Speaking personally, my own 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

law-is-wrong.

67. *Id.*

68. Lada A. Adamic & Bernardo A. Huberman, *Zipf's Law and the Internet*, 3 GLOTTOMETRICS 143, 144 (2002).

69. Briscoe et al., *supra* note 66.

70. *Id.*

71. Douglas Galbi, *Telephone Social Networks*, PURPLE MOTES (Nov. 29, 2009), <http://purplemotes.net/2009/11/29/telephone-social-networks/> (empirically showing that the average American calls only five people more than once in a given month).

72. Yoo, *supra* note 53, at 1151 (citing PAUL ADAMS, GROUPED: HOW SMALL GROUPS OF FRIENDS ARE THE KEY TO INFLUENCE ON THE WEB 23 (2012)).

73. R.I.M. Dunbar, *Coevolution of Neocortex Size, Group Size and Language in Humans*, 16 BEHAV. & BRAIN SCI. 681, 685–87 (1993).

payment, and a few news sites and blogs. I would place a higher value on connectivity to the sites I visit the most, such as my email server, remote desktop access to my office computer, the website for my bank and credit cards, and certain blogs, than I would on the ability to connect to other locations.⁷⁴

The Briscoe, Odlyzko, and Tilly article spawned a vigorous debate over the merits of Metcalfe's Law.⁷⁵ Metcalfe himself responded by emphasizing that his point was to establish the importance of establishing a critical mass, not to prove inexhaustible returns to network size, and that Zipf's Law also resulted in inexhaustible returns to scale.⁷⁶ He also presented an empirical analysis based on Facebook data tending to confirm that value growth more resembled Metcalfe's Law than Zipf's Law.⁷⁷

More work needs to be done before the merits of this debate can be resolved. At this point, it suffices to note that these concerns are sufficient to deflect the simplistic versions of Metcalfe's Law that led to unrealistic business models that emphasized revenue and customer growth to the exclusion of profitability.

B. Sources of Value Aside from Network Size

Another problem associated with being part of the same network is the need to conform to a particular standard. More specifically, everyone who is part of the same network must use the same suite of protocols.

The reality is that no protocol does everything well. Consider the fact that the current Internet is based on a best-efforts architecture.⁷⁸ This design leaves responsibility for recovering from any dropped packets to the hosts operating at the edge of the network. This greatly simplifies the tasks that the routers operating in the core of the network have to perform. At the same time, it does not provide support for applications that require guaranteed levels of quality of service.⁷⁹

If everyone wants the same thing from the network, the architects can simply optimize the network for what everyone wants. The decision

74. Christopher S. Yoo, *Wickard for the Internet?: Network Neutrality After Verizon v. FCC*, 66 FED. COMM. L.J. 415, 439 (2014).

75. See *Metcalfe's Law: Right? Wrong?*, IEEE SPECTRUM, (Nov. 1, 2006, 5:00 AM), <http://spectrum.ieee.org/computing/networks/metcalfes-law-right-wrong/>; Simeon Simeonov, *Metcalfe's Law: More Misunderstood Than Wrong?*, HIGHCONTRAST (July 26, 2006), <http://blog.simeonov.com/2006/07/26/metcalfes-law-more-misunderstood-than-wrong/>.

76. Metcalfe, *supra* note 39.

77. Metcalfe, *Metcalfe's Law After 40 Years of Ethernet*, *supra* note 7, at 30.

78. Christopher S. Yoo, *Network Neutrality, Consumers, and Innovation*, 2008 U. CHI. LEGAL F. 179, 228.

79. Christopher S. Yoo, *Protocol Layering and Internet Policy*, 161 U. PA. L. REV. 1707, 1755–56 (2013).

is more complicated if different users want different things from the network. Users can achieve the benefits of being part of a larger network. But because the network cannot be designed to satisfy all users, some will necessarily have to live with a network not optimized for what they want. The optimal outcome depends on which of these two considerations dominates the other. Those who place the highest value on a different configuration may find it beneficial to use their own protocol even if it means not being part of the larger network.⁸⁰

The point is demonstrated eloquently by a simple model put forth by Joseph Farrell and Garth Saloner, who wrote some of the pioneering papers on network economic effects. Assume that two different populations of end users each would 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.⁸¹

The considerations driving the equilibrium are clear. If the value that either group derives from consuming its preferred standard is sufficiently large, the greater value will induce it to adopt its preferred standard even if it means being part of a smaller network.⁸² 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.

Together these caveats underscore the fact that claims that increases in network size necessarily lead to exponential increases in network value may be overly simplistic. Whether network growth will create the types of benefits associated with Metcalfe's Law ultimately depend on the heterogeneity of consumer demand.

V. ALTERNATIVE INSTITUTIONAL FORMS

The monolithic way in which Moore's Law and Metcalfe's Law are usually framed tends to cast the policy question as a polar choice between networks that are completely interoperable and those that are completely non-interoperable. The literature reveals a reality that is

80. Christopher S. Yoo, *Beyond Network Neutrality*, 19 HARV. J.L. & TECH. 1, 34–36 (2005).

81. Joseph Farrell & Garth Saloner, *Standardization and Variety*, 20 ECON. LETTERS 71 (1986).

82. Yoo, *supra* note 80, at 34.

populated by a wide range of intermediate institutional forms between these two extremes.

A. Partial Compatibility Through Gateways

One way that networks can mitigate the problems associated with fragmentation is through gateways between networks (also sometimes called adapters or converters). Many of the leading scholars on network economic effects have shown that perfect gateways can completely mitigate the problems of fragmentation.⁸³ Farrell and Saloner further showed that even when gateways are imperfect, they can mitigate the problems of incompatibility.⁸⁴ On the other hand, more dynamic models indicate that imperfect gateways can reduce the overall adoption of a technology and can prevent the market from reaching a stable equilibrium.⁸⁵ The ambiguity of this result should not obscure the fact that circumstances exist in which the presence of gateways can offset any reduction in welfare from non-interoperability.

B. Competitive Considerations

In addition, competitive considerations can counterbalance the push against fragmentation implicit in Metcalfe's Law. As an initial matter, it has long been recognized that exclusivity can enhance consumer welfare under certain circumstances.⁸⁶ Conversely, mandating interconnection can dampen competition by homogenizing access and making it possible to reach every customer through any network, which removes the incentives for choosing one network over another.⁸⁷ Moreover, interconnection may be socially undesirable if competition dissipates the surplus needed to incentivize creating the network in the first place.⁸⁸

83. See Paul A. David & Julie Ann Bunn, *The Economics of Gateway Technologies and Network Evolution: Lessons from Electricity Supply Industry*, 3 INFO. ECON. & POL'Y 165, 197 (1988); Katz & Shapiro, *supra* note 33, at 439; Carmen Matutes & Pierre Regibeau, "Mix and Match": *Product Compatibility Without Network Externalities*, 19 RAND J. ECON. 221, 232 (1988).

84. Joseph Farrell & Garth Saloner, *Converters, Compatibility, and the Control of Interfaces*, 40 J. INDUS. ECON. 9, 32 (1992).

85. Soumya Sen et al., *Modeling the Dynamics of Network Technology Adoption and the Role of Converters*, 18 IEEE/ACM TRANSACTIONS ON NETWORKING 1793, 1802 (2010).

86. See, e.g., David Besanko & Martin K. Perry, *Equilibrium Incentives for Exclusive Dealing in a Differentiated Products Oligopoly*, 24 RAND J. ECON. 646, 662 (1993); Howard P. Marvel, *Exclusive Dealing*, 25 J.L. & ECON. 1, 24–25 (1982); Ilya Segal & Michael D. Whinston, *Exclusive Contracts and Protection of Investments*, 31 RAND J. ECON. 603, 617 fig.1 (2000); Shapiro, *supra* note 11, at 678.

87. MILTON MUELLER, *UNIVERSAL SERVICE: COMPETITION, INTERCONNECTION, AND MONOPOLY IN THE MAKING OF THE AMERICAN TELEPHONE SYSTEM* 22–25 (1997); Robin Mason & Tommaso M. Valletti, *Competition in Communication Networks: Pricing and Regulation*, 17 OXFORD REV. ECON. POL'Y 389, 406–07 (2001).

88. Katz & Shapiro, *supra* note 33, at 439 n.14.

Theoretical models also indicate that the optimal outcome may be hybrid competition between proprietary and nonproprietary standards. Competition between nonproprietary standards tends to give the first mover an advantage that eventually collapses into natural monopoly, while competition between a proprietary and a nonproprietary standard or between two proprietary standards may lead to more efficient technology adoption.⁸⁹

In short, the economic literature on gateways and competition among partially or completely incompatible networks provide additional reasons to question whether forming a larger network is always desirable. The literature on these subjects provides nuances that any simplistic invocation of Moore's Law and Metcalfe's Law must take into account.

CONCLUSION

Moore's Law and Metcalfe's Law have long captured the imagination of the technology community and has long seemed to provide a compelling explanation for the Internet's success. As the foregoing analysis shows, however, the push towards ever-cheaper technologies and inexhaustible returns to scale implicit in Moore's Law and Metcalfe's Law is more complex than it initially seems.

This argument should not be misconstrued as advocating exchanging reflexive support for greater interconnectivity with reflexive hostility towards it. On the contrary, interoperability often represents the most natural and efficient outcome in many, if not most, cases. That said, understanding the potential countervailing considerations and developing heuristics for identifying the circumstances that may tend to tip the balance in the either direction would help place policymaking on a better informed foundation.

89. Michael L. Katz & Carl Shapiro, *Technology Adoption in the Presence of Network Externalities*, 94 J. POL. ECON. 822, 835, 838–39 (1986).