Forking, Fragmentation, and Splintering

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July 7, 2019

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Abstract

Although economic theory suggests that markets may "tip" towards a dominant platform or standard, there are many prominent examples of persistent incompatibility, inter-platform competition and standards proliferation. This paper examines the phenomena of forking, fragmentation and splintering in markets with network effects. We illustrate several causes of mis-coordination, as well as the tools that firms and industries use to fight it, through short cases of standardization in railroad gauges, modems, operating systems, instant messaging and Internet browsers. We conclude by discussing managerial implications and directions for future research.

Keywords: Compatibility, standards, network effects, platforms, forking.

JEL Codes: L15, Q55, Q58

1 Introduction

Standards, platforms and protocols are defining features of the digital economy (Tassey, 2000; Rochet and Tirole, 2003; Parker and Van Alstyne, 2005; Hagiu and Wright, 2015). By adhering to pre-defined rules such as file formats, communications protocols and programming languages, independently designed products can work together as a system. The resulting interoperability produces a wide range of potential benefits (Farrell and Simcoe, 2012), including the ability of users to communicate with a larger installed base of other users and devices (direct network effects); the provision to users of a larger supply of complementary goods and services (indirect network effects); increased product variety through mixing and matching of standardized components; and increased competition among suppliers of standardized goods and services.

In economic models, network effects often cause markets to "tip" towards a dominant standard (Katz and Shapiro, 1985; Farrell and Saloner, 1986; Arthur, 1989; Schilling, 2002). In practice, however, the very markets that these theories are meant to explain often exhibit persistent incompatibility, inter-platform competition and standards proliferation. For example, U.S. cell phones would not work in Europe for many years because European carriers adopted different transmission standards. Similarly, modern web browsers support dozens of audio and video file formats, and smartphone users can choose among incompatible platforms for ride sharing, instant messaging and music streaming.

Strategy scholars have developed a number of explanations for persistent incompatibility, including heterogeneity in network externalities (Suarez, 2005; Lee et al., 2006; Afuah, 2013), differences in platform quality (Zhu and Iansiti, 2012) and the creation of exclusive complements (Cennamo and Santalo, 2013). Moreover, because interoperability can produce complex patterns of technological interdependence, a number of leading scholars liken platform and technology standards based industries to natural ecosystems where firms in distinct niches both cooperate and compete with one another (Adner and Kapoor, 2010; Gawer and Cusumano, 2014; Davis, 2016; Parker et al., 2017).

Although scholars in strategy and economics offer numerous perspectives (e.g., Balzer and Schneider 2018), there is no unified view of the causes of incompatibility. Thus, both scholars and practitioners use terms like forking, fragmentation and splintering without clearly distinguishing between them. Some authors view "failure to tip" as evidence of market inefficiency (Farrell, 2007), while others advocate for laissez-faire standards policy (Leibowitz and Margolis, 1990; Tsai and Wright, 2015). Large firms may even find themselves on both sides of the debate between those who favor and oppose intervention in support of interoperability. For example, Google has recently been criticized (and sued) for forking Java to create the Android operating system, and at the same time, drawn heavy fines from European regulators for including anti-forking provisions in its Android licensing agreements.[1]

This paper proposes a unified view of "failure to tip" in markets with network effects. Our research question, then, asks why we observe incompatibility in markets that exhibit demand-side increasing returns to scale? To answer this question, we use both simple theory and illustrative case studies. The theoretical framework illustrates how asymmetries across firms in the private versus coordination benefits of technology adoption can interfere with incentives to tip. The case studies illustrate a variety of factors that influence both private and coordination benefits, and show how incompatibilities arise in practice.

Our main contribution is conceptual: we propose a classification scheme that distinguishes between forking, fragmentation and splintering as the root cause of mis-coordination. The framework is particularly relevant to strategy scholars because it distinguishes between strategic incompatibility, where one or more firms seek to avoid inter-operability out of self-interest, and coordination failure, where all firms would benefit from standardization.

A second contribution of this study is to shift attention from network effects, tipping and lock-in towards a different set of factors that regulate the inexorable logic of increasing returns. There have been numerous reviews of the literature on standards, platforms and network effects. For example, Rysman (2009), Shy (2011), Evans and Schmalensee (2015) and Parker and Van Alstyne (2016) discuss platform strategies, network effects, policy towards platforms and the winner-take-all dynamics of platform competition. However, these surveys rarely acknowledge the possibility of mis-coordination or persistent incompatibility. Kapoor (2018) highlights the importance of studying bottlenecks in the ecosystems literature. In many cases, persistent incompatibility can create an ecosystem bottleneck. Our cases and examples show, however, that forking is not necessarily harmful. Thus, although many authors have touched upon the ideas we discuss below, this paper is perhaps the first to provide a unified treatment and a precise characterization of the alternative mechanisms behind forking, fragmentation and splintering.

The first part of the paper uses a simple and stylized economic model to define these three different types of coordination failure, to explain why each one may persist (or not), and to describe the conditions that make them more likely. The second part of the paper uses several

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[1] For a contemporaneous account of the Java-Android forking dispute see, for example, `http://www.cnet.com/news/googles-android-parts-ways-with-java-industry-group/`. The European Commission's views on anti-forking provisions in Android licenses are at `http://europa.eu/rapid/press-release_IP-18-4581_en.htm`

short case studies to illustrate the causes of forking, fragmentation and splintering, as well as the tools that firms and industries use to combat mis-coordination. The cases examine standardization and platform competition in railroad gauges, modems, operating systems, instant messaging and Internet browsers. The paper's final section provides managerial implications and some suggestions for future research.

2 Forking, Fragmentation and Splintering

Scholars use the terms forking, fragmentation and splintering to describe incompatibility in the presence of network effects (e.g., Lerner and Tirole 2002; Kretschmer 2008; Farrell and Klemperer 2007; Eisenmann et al. 2009; Yoo et al. 2012; Wareham et al. 2014; Kretschmer and Claussen 2016; Vakili 2016; Karhu et al. 2018). It is not clear, however, whether these terms are merely synonyms, or refer to subtly different phenomena. In this section, we propose a classification scheme that distinguishes among four broad explanations for incompatibility. Table 1 provides an overview.

[[PLEASE INSERT TABLE 1 HERE]]

2.1 A Classification Scheme for Coordination Failure

To highlight the key distinctions between forking, fragmentation and splintering, we employ a stylized game-theoretic framework. This framework is meant to illustrate the incentives and strategies of technology suppliers. The cases and discussion below consider more realistic environments, along with implications for customers and complementers.

To keep things as simple as possible, consider a game with two-players $i \in \{1, 2\}$ who must choose between two technologies $j \in \{1, 2\}$. Player i's choice is denoted by a_i. Each player receives a private benefit $b_i > 0$ if they choose their preferred technology ($a_i = i$) and a coordination benefit c_i if they both choose the same technology ($a_1 = a_2$). Thus, player 1's payoffs are $b_1 + c_1$ if both choose $j = 1$; b_1 if each player chooses their preferred technology; c_1 if they coordinate on $j = 2$; and zero if they each choose the other's preferred technology. Table 2 depicts these payoffs.

[[PLEASE INSERT TABLE 2 HERE]]

We associate forking, fragmentation and splintering with specific Nash equilibria in the simultaneous move complete information version of this game under different configurations of the parameters (b_i, c_i). Before describing the various equilibria, however, it is instructive to consider several examples that motivate the payoff structure of this stylized model.

The private benefit parameter in our framework, b_i, represents firms' "vested interests" in selecting a particular technology. This preference is typically linked to intellectual property rights, proprietary complements, sunk research and development costs, or development lead times.[2] For example, when each firm in our model holds patents on their preferred technology, b_i will reflect the expected profit from licensing to other users (and conversely, avoiding royalty payments to use the alternative). In practice, Standard Essential Patent (SEP) licensing has produced significant profits for several firms involved in the creation of cellular communications standards, and spawned a vast law and economics literature that considers implications for competition and consumers (e.g. Yoffie et al., 2011; Lemley, 2002; Farrell et al., 2007; Rysman and Simcoe, 2008).

Backwards compatibility is another factor that influences the vested interest parameter, b_i. In particular, firms tend to prefer standards and platforms that complement their proprietary technologies. One famous example is Microsoft's efforts to "extend" the HTML and Java standards by tightly integrating its browser (Internet Explorer) and the proprietary Windows operating system — a strategy that ultimately led to several antitrust lawsuits, as described below. In that case, Microsoft tried to prevent entry and competition in a complementary market (operating systems) by controlling the HTML/Java standard. The underlying economics are very similar, however, when a firm seeks to avoid a situation of "stranded assets" (i.e. rapid depreciation of sunk investments in the complementary technology). For instance, video game platforms are often very interested in preserving compatibility with games that ran on previous generations of their own consoles.

Finally, in industries with short product lifecycles, the private interest parameter, b_i, can reflect lead-time advantages in the implementation of a new standard or platform. For example, in a case study of WiFi standards development, Eisenman and Barley (2006) describe how competing chip producers would ship "pre standard" products while maneuvering within the IEEE to push the 802.11 standard in the direction of technology they were already marketing.

The coordination parameter in our stylized model, c_i, is a function of what Farrell (2007) calls *horizontal* compatibility: whether complements for one system can be used with a rival standard or platform.[3] Coordination benefits (i.e., $c_i > 0$) typically arise from network effects

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[2] See also the discussion in Farrell and Simcoe (2012) on this subject.

[3] For example, horizontal incompatibility in the market for video game consoles implies that software developed for the Xbox will not run on the PlayStation. This is distinct from the "vertical" compatibility question of

and consumer preferences for interoperability. We also consider the case where at least one firm incurs a coordination penalty ($c_i < 0$), even in the presence of network externalities, because compatibility would increase competition.[4]

The large literature on platforms and network effects provides many examples to motivate the assumption of coordination benefits (e.g. Besen and Farrell, 1994; Rysman, 2009). These cases are typically classified into direct and indirect effects. Direct network effects occur with a communications technology, such as the telephone or email, where a larger installed base of users leads to a larger addressable audience for any individual user, and therefore increasing marginal benefits to adoption. Indirect network effects occur when there is a positive feedback loop between the adoption decisions of distinct but complementary "sides" to a platform. For example, with video game consoles, game developers favor a console with a large installed base of users, and users favor a console with a wide variety of games. Related to both types of network effects, technology sponsors may also realize benefits from coordination that hastens the arrival of a mass market. In particular, end users and complementers may delay adoption decisions in the absence of a clear industry standard due to a fear of stranded investments (Farrell and Saloner, 1986).

For system goods, coordination benefits ($c_i > 0$) can also emerge from consumers' taste for variety. In particular, component-level interoperability allows end users to mix-and-match parts from diverse vendors (Matutes and Regibeau, 1988). This type of system-level variety effect is widespread in computer hardware and audio-visual electronic where, for example, Sony televisions may connect with Yamaha speakers through a Denon receiver.

Finally, coordination penalties ($c_i < 0$) arise when firms prefer to differentiate their product through incompatibility. In some cases, the effects of compatibility are heterogenous across firms, with incumbents facing a penalty ($c_1 < 0$) from increased competition, and entrants obtaining a benefit ($c_2 > 0$) from interoperability with the incumbent's installed base of users and complements. Although this situation has received relatively little theoretical attention, there are several clear case studies and examples. For instance, there is a long history of third-party game developers seeking to circumvent the access restrictions used by video game console producers. Below, we describe a similar dynamic in the browser wars, and the evolution

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whether game developers can access the installed base for a particular console without first gaining permission from the platform sponsor.

[4] In practice, it may be hard to distinguish $c_i < 0$ (a desire not to coordinate on *any* standard) from $b_i > 0$ (a desire to select a particular technology that just happens to differ from a rivals' favored alternative). As we discuss below, the telling bit of evidence that $c_i < 0$ is when a firm changes its mind about the particular technology it wishes to adopt whenever its rival tries to establish compatibility. Thus, as an empirical matter, identifying the b_i and c_i parameters may require longitudinal data, and not simply a cross-section.

of instant messaging standards.

2.1.1 Forking

Forking refers to the creation of a new version of a standard or application that fails to maintain backwards compatibility. The term is widely used in software development, where the practice is common. The Unix operating system has been forked many times. In the 1990s Microsoft tried to fork Java, and more recently Google has been accused of forking Java to create Android. Amazon forked Android to create the Kindle Fire, and crypto-currencies such as Bitcoin have forked several times (Gandal and Halaburda, 2016; Catalini and Gans, 2019). In our game-theoretic framework, forking arises when players have divergent preferences over compatibility, which we model as $c_1 > 0 > c_2$, so player 1 wants to coordinate while 2 prefers incompatibility.

Forks come in two flavors. Firms or developers may "agree to disagree" and independently pursue separate paths. We call this a stable fork. Alternatively, proponents of the original standard may question the legitimacy of a fork and seek to preserve compatibility. We refer to this second scenario as a contested fork.

A stable fork occurs when $b_i > |c_i|$ for both players. This produces a game with a single equilibrium where each player's dominant strategy is to select its preferred technology.[5] Game theorists refer to this game as "deadlock" and although the equilibrium strategies are not particularly interesting, it provides a useful reminder that compatibility need not be efficient simply because one or more players would like everyone else to adopt its preferred technology.

Contested forking occurs when $b_i < |c_i|$. In that case, the players' preference for (in)compatibility exceeds their desire to select a particular technology, creating a game of "pesky little brother" whose only Nash equilibrium is in mixed strategies.[6] When $b_1 = b_2$ and $c_1 = -c_2$, both players choose technology 1 with probability $\Pr[a_i = 1] = \frac{c-b}{2c}$ in the mixed-strategy equilibrium.[7] Thus, the probability of coordination (on technology 2) is higher when vested interests are large relative to coordination benefits/penalties ($b \approx c$), but as compatibility choices become more salient, the strategies converge towards a coin toss, and coordination will occur only half of the time.

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[5] A dominant strategy is a choice that yield a higher payoff regardless of other players' actions.

[6] The equilibrium will be familiar to anyone who has played "Odds and Evens" where two players each hold out either one or two fingers: one player wins if they make the same choice, and the other wins if the choices are different.

[7] Let p represent the probability that player 2 selects technology 1. The logic of mixed strategies implies that player 1 must be indifferent between technologies given p, so we have $p(b+c)+(1-p)b = (1-p)c$ which implies that $p = \frac{c-b}{2c}$. Similar calculations yield the same mixing probability for player 2. The expected payoffs for player's 1 and 2 are b and $b-c$ respectively.

What do these simple models reveal about actual forking? First, forking can be efficient. In the case of a stable fork, the benefits of variety outweigh the costs of forgone compatibility. Second, when there are strong disagreements over compatibility, contested forking may generate “cat and mouse” games that resemble the unstable dynamics of a mixed-strategy equilibrium, where one actor (or group of actors) seeks to differentiate its offerings while another works to restore compatibility. This can result in a state of partial or intermittent inter-operability, as described below for the case of early HTML standardization. Third, any resolution to these mixed strategy cat-and-mouse games requires a change in payoffs, so the players will either agree to remain compatible or not. In some cases, payoffs change because an outside authority (e.g. a court or a major customer) decides to enforce compatibility.[8] In other cases, such as the Unix wars described below, market developments overtake the compatibility disputes, and the players simply move on.

2.1.2 Fragmentation

Fragmentation occurs when all parties would like to adopt a common standard, but can’t agree what it should be. In practice, fragmentation often occurs at the point of upgrade to a standard or platform, when different parties bring their own technology to the table and push for its adoption. For example, when Digital Video Disc (DVD) standards were revised, suppliers fragmented into two camps supporting the incompatible Blu-ray and HD-DVD formats. Postrel (1990) studies fragmentation in the development of quadrophonic sound, with CBS, JVC and RCA each sponsoring a different standard, leading to weak availability of complements (i.e. recorded music) and slow end-user adoption.

In our framework, incentives to fragment occur when $c_1 = c_2 > b$. This leads to a “battle of the sexes” coordination game with three Nash equilibria.[9] We set aside (for now) the two pure-strategy equilibria where both players choose the same technology, and focus on the mixed-strategy outcome where each player chooses its own technology with probability $\Pr[a_i = i] = \frac{b+c}{2c}$.

What does this model reveal about actual fragmentation? First, note that as b approaches c, both player’s are increasingly likely to choose their own technology, and the probability of coordination falls to zero. This suggests that “vested interests” play an important role in fragmentation, for all of the reasons discussed above.

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[8] For example, in 1968 the Carterfone decision (13 F.C.C.2d 420) forced AT&T to open its network to independent device makers.

[9] See Farrell and Saloner (1988) for an extended analysis and discussion of this type of coordination game.

Second, note that the two pure-strategy equilibria to this game Pareto dominate fragmentation. In particular, the "loser" in pure strategies receives c, which is larger than the expected payoff $\frac{b+c}{2}$ in a fragmented equilibrium. Given the choice, both players would prefer either one of the pure-strategy outcomes. Thus, when b is small relative to c sophisticated firms can often avoid a fragmented equilibrium. In the limit as b approaches zero, cheap talk (Farrell and Rabin, 1996) should suffice to ensure coordination on one of the two technologies. However, when b is large and rooted in sunk investments, it can be hard to resolve technological conflicts via negotiation. Thus, even when choices are few and players are sophisticated, "accidental" fragmentation can emerge from brinkmanship, occasionally leading to an all-out standards war.

Finally, we note that unlike forking, where compatibility is a strategic choice, fragmentation occurs as a side-effect of firms' efforts to encourage the selection of a particular equilibrium. This point is closely related to the observation that fragmentation is a Pareto dominated equilibrium. With forking, the players are trying to coordinate (or not), whereas fragmentation occurs when players agree that coordination is beneficial, but fail in their efforts to achieve compatibility.

2.1.3 Splintering

Splintering occurs when decentralized technology adoption leads to excessive product variety. For example, Thompson (1954) describes how early automotive component manufacturers each assembled parts to their own specifications. As a result, tire manufacturers had to accommodate a wide variety of wheels, wheel manufacturers had to adapt to a host of axle sizes, axle manufacturers had to fit a variety of springs and so forth. The literature on industry life-cycles contains many similar examples, typically associated with the era of technological ferment that often precedes emergence of a dominant new-product design (Suarez and Utterback, 1995; Klepper and Graddy, 1990).

To model splintering, we retain the battle-of-the-sexes payoff structure ($c_1 = c_2 > b$), while adding a third player and assuming that coordination benefits are only realized if *all* firms adopt the same technology.[10] As in the two-player game, it is a Nash equilibrium for all players to adopt a single technology. However, there is now an additional uncoordinated *pure-strategy* equilibrium where each player selects its preferred technology. In this splintered equilibrium, any unilateral deviation yields a zero payoff, while sticking to one's own technology yields b. As with fragmentation, splintering can be viewed a side-effect of decentralized technology

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[10] This strong complementarity assumption can be relaxed. For instance, it is easy to verify that splintering is a Nash equilibrium in the N player battle of the sexes where player i's payoff equals $b + cn$ (where $n \leq N$ is the number of other players who choose the same technology as i), so long as $b < c$.

adoption, as opposed to an intentional strategy of avoiding compatibility.

To be clear, the distinction between fragmentation and splintering is not based on the presence of three or more players. Although forking and fragmentation are more likely to emerge when there are few players or a small number of choices, that number can be greater than two. We focused on two-player examples for expositional convenience. The key difference between fragmentation and splintering is that fragmentation emerges from strategic jockeying among a small number of players seeking to become the *de facto* standard, whereas splintering emerges from decentralized and largely independent technology choices.

The key insight provided by our simple model is that it takes *coordinated* action to escape from splintering.[11] Coordination sometimes occurs through multi-lateral institutions. For example, the costs of managing a wide variety of incompatible auto-components ultimately led to the creation of the Society of Automotive Engineers (SAE), whose early technical standardization work focused on reducing component variety. In other cases, coordination can occur through the actions of a dominant platform leader, such as Ford or General Motors, who can dictate component specifications to their suppliers.

3 Case Studies

This section presents several case studies of forking, fragmentation and splintering. Our game theoretic framework clarifies the different causes of persistent incompatibility, while these cases provide illustrations of those causes. Furthermore, this section demonstrates how our stylized model can be mapped onto more realistic settings. We have selected cases that cover a wide range of industries. To illustrate forking, we describe the Internet browser wars and the fight over instant messaging standards. To explain fragmentation, we consider the case of 56K modems and the Unix operating system. As an example of splintering, we use the history of railroad gauge standards. Collectively, these cases demonstrate the market conditions and incentives that can lead to incompatibility, even in the presence of network effects.

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[11] In game-theoretic terms, splintering is a non-coalition proof pure-strategy Nash equilibrium. The coalition-proof Nash concept involves players in a non-cooperative environment that are able to openly discuss strategies, but are unable to make binding agreements. Hence, any meaningful agreement must be self-enforcing. See Bernheim et al. (1987) for a formal definition.

3.1 Case Studies: Forking

Contested forking, as described in Section 2.1.1, resembles the equilibrium to a game of "pesky little brother" where compatibility is a strategic decision (because $|c_i| > b_i$) but not all players wish to coordinate on a common standard. We consider two examples of contested forking: the Internet browser wars, and the evolution of instant messaging platforms.

3.1.1 Internet Browsers

Tim Berners-Lee developed the first web browser in 1990, while working at the European Organization for Nuclear Research (CERN). However, the first commercially significant browser was Netscape Navigator. From its early release in 1994, Navigator's feature richness, combined with its free use for non-commercial purposes helped Netscape establish an early lead in browser adoption. The company's business model at the time called for giving away the browser, while charging for both its web server software and support for business users.

By mid-1995, Microsoft clearly perceived Netscape Navigator as a significant threat. Bill Gates' now-famous Internet Tidal Wave memo spells out several elements of Microsoft's catch-up strategy, including "a decent client that exploits Windows95 shortcuts," working to "figure out additional features that will allow us to get ahead with Windows customers" and "get[ting] OEMs to start shipping our browser preinstalled." The memo also discussed the evolution of document standards, suggesting that, "We need to establish OLE [an MS proprietary document protocol] as the way rich documents are shared on the Internet. I am sure the OpenDoc consortium will try to block this."[12] Gates' memo clearly illustrates the tension between Netscape's reliance on open standards, and Microsoft's desire for proprietary alternatives, which in our stylized model can be captured by parameters ($c_1 < 0 < c_2$) that produce a contested fork.

Microsoft released its Internet Explorer (IE) browser in August 1995, and began bundling that browser with its Windows 95 operating system the following year. Starting with just over 3 percent of usage share in 1996, Internet Explorer captured over 30 percent of the market by 1998, and became the market leader by 1999. Bresnahan and Yin (2007) show how Microsoft's strategy of pushing hardware OEMs to pre-install IE played a crucial role in helping IE catch up to, and eventually surpass Netscape.

During Internet Explorer's rise, the web content standards supported by IE and Netscape

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[12] The full memo is available at `http://www.lettersofnote.com/2011/07/internet-tidal-wave.html`.

diverged, with each team adding proprietary features to attract developers. It was common for websites to be specially targeted at either Netscape or Internet Explorer, displaying logos such as "Best Viewed With Internet Explorer" or "Best Viewed With Netscape Navigator."[13] These practices increased costs all around – websites were slower for the end-user to download due to increased markup, web-server load was higher, and developers needed to expend greater effort developing duplicate versions of websites for different browser standards. In response, the World Wide Web Consortium (W3C) – an SSO founded by Tim Berners-Lee in 1994 – worked to prevent forking of key document standards by publishing specifications for Hypertext Markup Language (HTML), Cascading Style Sheets (CSS), and other web content protocols.

By the early 2000's, Internet Explorer had a 90 percent share of the web browser market, and Microsoft's strategy was increasingly characterized as an effort to "embrace, extend and extinguish" a set of standards that might threaten the dominance of its Windows platform. This three-step strategy begins when a platform leader embraces a standard by providing vertical inter-operability. The "extend" stage involves forking the standard by adding proprietary extensions that competitors cannot or will not implement. Finally, when the proprietary extensions become a *de facto* standard – presumably, in this case, because of Microsoft's large installed base – the open specification can be extinguished in the marketplace. Gilbert and Katz (2001) describe some tactics Microsoft used to "pollute" the cross-platform Java standard, such as refusing to incorporate certain Java components, incorporating proprietary extensions into its Java developer tools, and pressuring developers and hardware OEMs to use Internet Explorer and Windows-specific Java technology.[14]

The browser wars illustrate several economic facets of forking. In particular, the battle between Microsoft and Netscape/Sun offers a nice illustration of a contested fork, where one side seeks to preserve compatibility and the other to degrade it. While Microsoft's advantages in distribution helped them win the initial battle for browser share, it is worth noting that the technology advanced rapidly during this time, and the threat of proprietary HTML forks was ultimately averted with help from groups like W3C and the Web Standards Project (WaSP).[15] This case also illustrates the embrace-extend-extinguish strategy, where a platform leader may try to fork an open standard because that specification threatens the firm's dominance in an adjacent market.

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[13] Many web sites also utilized scripts that would detect a visitor's browser version, and then load the appropriate version of their content.

[14] The judge in *U.S. vs. Microsoft* ruled that these actions were inconsistent with Microsoft's arguments that it was merely optimizing Java for the Windows platform.

[15] Founded in 1998, WaSP published a series of influential "acid tests" for browser compliance with key standards, such as HTML, CSS, and ECMAscript

3.1.2 Instant Messaging

Instant messaging (IM or "chat") is a communications technology that caught on among Internet users in the mid-1990s.[16] The first IM applications such as ICQ, PowWow, and AOL Instant Messenger (AIM) were defined by their graphical user interface (GUI), and the ability to hold real-time conversations, which distinguished them from email. Another defining characteristic of first-generation IM platforms was thier lack of horizontal openness. Users of one service could not communicate with the users of another, competing instant messaging application. Although multi-homing was possible, users needed to maintain accounts on each separate IM network, and concurrently run multiple client applications in order to communicate across multiple networks.

AOL Instant Messenger was the largest of the first-wave of messaging platforms. AIM was introduced in 1989, but surged in popularity around 1996 when AOL added a "buddy list" feature that allowed users to see whether their frequent chat partners were currently online. As with many communication technologies, IM was characterized by strong direct network effects – users joined larger networks because they offered more potential connections. Thus, as AIM's user base grew, a number of newer services, such as Microsoft's MSN Messenger and Tribal Voice's PowWow, made efforts to interconnect. While the technical problems were not large – AOL had already published its OSCAR messaging protocol on the Internet – all of the initial attempts to connect without AOL's permission were blocked.[17] This resulted in periods of intermittent compatibility, consistent with the cat-and-mouse dynamics of a contested fork.

During the late 1990s, a number of AOL's competitors deployed proprietary messaging protocols. Microsoft's aforementioned MSN Messenger utilized the MS Notification Protocol (MSNP), and Yahoo Messenger relied on a protocol called YSMG. Given the lack of interoperability among these standards, several efforts to create open instant messaging standards were started within the Internet Engineering Task Force (IETF).[18] However, the initial push for standards-based inter-operability in instant messaging largely failed. Many multi-protocol applications, including Trillian and Gaim, were introduced during this time in attempts to decrease the costs of multihoming across the proprietary networks. Despite these efforts, most of the individual network providers proved willing and able to refuse interconnection with their rivals.

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[16] Our account draws heavily from the description provided in Faulhaber (2002, 2004).

[17] Perhaps ironically, OSCAR stands for Open System for Communicating in Realtime.

[18] Examples include the Session Initiation Protocol (SIP), Session Initiation Protocol for Instant Messaging and Presence Leveraging Extentions (SIMPLE), Application Exchange (APEX), Instant Messaging and Presence Protocol (IMPP), and the Extensible Messaging and Presence Protcol (XMPP).

The period of contested forking in IM applications ended in the early 2000s, largely because of external changes to the competitive environment. In 2001, as a condition for approving the merger between AOL and Time-Warner, the U.S. Federal Communications Commission required AOL to commit that it would provide rivals with access to the AIM Names and Presence Directory (NPD) before offering "advanced" IM services, such as voice and video communications. As explained in Faulhaber (2002), the NPD is the critical component in terms of IM network effects because it provides real-time information on user availability. Thus, rival networks could see who was active on AIM, and offer that connection to their own users. This regulatory step was followed by a series of deals that facilitated cross-network communications. In 2003, Reuters signed agreements that allowed users of its proprietary Reuters Messenger service to communicate with users of AIM, ICQ and Microsoft Messenger. In 2005, Microsoft's SIP/SIMPLE based enterprise IM product, Live Communications Server 2005, was opened to communicate with users of AIM, MSN Messenger, and Yahoo! Messenger. And in 2007, Google's XMPP-based Google Talk service allowed for communication with AIM users.

By the late 2000s, new technologies and platforms were providing consumers with alternatives to the previous generation of stand-alone desktop-based instant messaging applications. These alternatives included SMS text messaging services operated by wireless carriers, proprietary text-messaging protocols such as Apple's iMessage, and standalone messaging applications such as WhatsApp. Popular social networks, such as Facebook and Twitter, also added instant messaging features to their platforms.

What does this IM case teach us about forking? First, AOL's initial refusal to interconnect with rivals suggests that even when there are strong direct network effects, market leaders may prefer incompatibility because they hope to exploit the size of their proprietary installed base as a competitive advantage.[19] Second, the mere existence or availability of open protocols may not be sufficient to alter the incentives behind a contested fork. The open messaging protocols developed by the IETF during the late-1990s were not initially embraced by proprietary IM networks, but did eventually facilitate bilateral interconnection. This reinforces a theme that appears in the case of OSF Unix below – even when open protocols fail the marketplace, they often provide a foundation for subsequent iterations of the platform. Finally, it often takes an external shock to alter the incentives that produce an episode of contested forking. In this case, that shock came through the actions of the FCC and the emergence of powerful social media substitutes to traditional IM applications.

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[19] Gabel (1994) describes a similar competitive dynamic in the early telephone industry.

3.2 Case Studies: Fragmentation

As described in Section 2.1.2, fragmentation occurs when a small number of rival technology sponsors compete to have their preferred solution become the industry standard. Because the relevant parties all prefer a single standard, fragmentation is not characterized by the protracted cat-and-mouse games of a contested fork. Rather, it is an undesirable but often short-lived side effect of competition to tip the market in a particular direction. As an examples of fragmentation, we consider the case of 56K modem standards and the evolution of the Unix operating system.

3.2.1 Modems

During the early 1990s, many U.S. consumers accessed the Internet by using a modem to connect with an Internet Service Provider (ISP) over the public telephone network. Prior to 1997, modems operated at a maximum speed of 33K, and the market for 33K modem chipsets was dominated by Rockwell Semiconductor, who licensed its technology to various resellers with a combined market share exceeding 80 percent. The largest of these resellers was US Robotics.

The invention of the web browser and growth of the World Wide Web generated significant demand for faster Internet connections, and by early 1997 modem suppliers and ISPs were both poised for an upgrade to equipment with a maximum transmission rate of 56 kilobits per second (56K). US Robotics developed a 56K standard called X2. Rockwell entered into a consortium with Motorola and Lucent to develop an alternative standard called K56Flex (henceforth Flex). These parallel R&D efforts led to a situation where firms' intellectual property was concentrated in one standard or the other. In our stylized model, this corresponds to a setting where the benefits of coordination are large, but so is the vested interest parameter b_i, so that all sides have an incentive to promote their own technology.

The two incompatible standards – X2 and Flex – reached the market around the same time in early 1997. While there were some early reports of problems with Flex modems, the two technologies had similar quality and pricing within six months of introduction. However, because the standards were incompatible with one another, ISPs needed to purchase separate equipment in order to support Flex and/or X2. A mismatch between consumer and ISP hardware would limit speeds to 33K at best. This created indirect network effects in the diffusion process: consumer adoption of one standard increased ISPs' incentives to select similar technology, and vice versa.

Contemporaneous reports suggest that adoption of X2 and Flex modems was slow relative to expectations and the size of the market. By October 1997, just over 50 percent of ISPs had made the upgrade, but neither standard had emerged as the market leader. None of the major ISPs adopted 56K during this time.[20] The wait-and-see posture of both consumers and large ISPs suggests that fragmentation was leading to excess momentum for the 33K technology. Moreover, while smaller ISPs did have an incentive to upgrade, it is not clear that they had strong incentives to coordinate on a single standard. In fact, Augereau et al. (2006) provide evidence that small ISPs used incompatibility as a source of differentiation. Specifically, their study shows that when competing ISPs adopted 56K, they tended to divide local markets, with roughly half of ISPs serving X2 and the other half Flex.

During the development and rollout of X2 and Flex, efforts were underway at both the Telecommunications Industry Association (TIA) and the International Telecommunications Union (ITU) to reach consensus on a single 56K standard.[21] There are several reasons why these efforts failed to yield a consensus before fragmentation occurred. First, participants in the formal standards process are typically interested parties, which in this case would include members of both the US Robotics and Rockwell-led consortia. Moreover, because SSOs lack formal enforcement power, it is not unusual for them to wait and see whether there are signs that a *de facto* standard will emerge in the market prior to endorsing any particular solution.[22] Nevertheless, Greenstein and Rysman (2007) report that both the X2 and Flex consortia expected to adopt an ITU standard. The slow adoption of 56K technology by consumers and large ISPs pressured the SSOs to act quickly, in order to break the logjam that was holding back demand.

Thus, in February 1998, the ITU announced that there was consensus for a new 56K modem standard called V.90. (This represented a new "record" for elapsed time to develop an ITU standard, and was well ahead of the SSO's two-year forecast.) Although V.90 was an amalgam of X2 and Flex technology, the standard was not "plug and play" interoperable with either of the proprietary specifications.[23] In September 1998, the V.90 standard was approved, and modem sales were strong following the adoption of a coordinated standard.

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[20] The list of large non-adopters included AOL, AT&T, UUNET, MSN, GTE, BellSouth and EarthLink.

[21] The TIA is a U.S. industry association that develops standards under the auspices of ANSI, and can therefore serve as the U.S. representative to ITU, which is a Geneva-based UN treaty organization. ITU has set a variety of international telecommunications standards since the late 1800s.

[22] For example, the Internet Engineering Task Force requires several tiers of formal endorsement, and will only advance a specification from "Proposed Standard" to "Draft Standard" if there have been multiple independent implementations.

[23] Customers could, however, use a firmware upgrade to make their existing X2 or Flex modem work with an ISP's V.90 equipment.

The 56K modem case illustrates how fragmentation can occur when it becomes time for a technical upgrade, and how SSOs can be pivotal in resolving an impasse in standards adoption. One of the more interesting features of this case is the role of ISPs. Large ISPs sat on the sidelines, rather than make a risky bet on a single standard that might lead to stranded investments, as in the model developed by Kretschmer (2008). Smaller ISPs viewed incompatibility as a potential source of differentiation in a highly competitive industry, and consequently exacerbated the fragmentation problem. Thus, even in the presence of indirect network effects, the early ISP adopters were not especially keen to coordinate.

The 56K modem case also highlights the interaction between market and non-market paths to compatibility. In their review of this episode, Greenstein and Rysman (2007) ask why US Robotics, who seemed to be ahead in the marketplace with X2, was keen to adopt V.90. They propose that US Robotics never believed that the market would tip towards X2, and only expected to obtain some temporary advantages by establishing an early lead in adoption. In particular, one of the major benefits of X2's edge in the market was that Rockwell and others agreed to include a substantial amount of US Robotics' intellectual property in the V.90 standard. This meant that US Robotics would no longer be in the position of licensing and distributing Rockwell's technology, as they had been for 33K modems. With these intellectual property concessions in place, the benefits of accelerated adoption outweighed the costs of moving from X2 to V.90, and US Robotics quickly endorsed the ITU specification.

3.2.2 Unix

Unix is one of the most technically and commercially significant operating systems in the history of computing. The original Unix operating system was developed at Bell Laboratories in the early 1970s, and there have been hundreds of different implementations and offshoots since then. This short case study focuses on the "Unix Wars" that took place in the 1980s and 1990s. The first phase of the Unix wars illustrates the incentives to fragment a standard in the absence of alternative tools for product differentiation, and the second phase illustrates how fragmentation can be undone through both platform leadership and collective action within SSOs.

When engineers at AT&T first developed Unix, the company was prohibited from entering the computing industry under the terms of a 1956 antitrust consent decree. Bell Labs therefore decided to license the source code "as-is" for a nominal fee, but without a guarantee of support or bug fixes. The inexpensive OS quickly diffused among minicomputer users, who were often located at universities and other large institutions that had the resources to buy and operate these machines. Many early Unix users contributed to the ongoing development of the operating system. For example, a graduate student named Bill Joy released the first Berkeley Software Distribution (BSD) as an add-on to Version 6 Unix in 1977. This fork would go on to become one of the major branches in the upcoming Unix wars.

Several key events leading to the first round of Unix wars occurred around 1982. The break-up of the Bell System produced a new consent decree that freed AT&T to enter the computer industry. One year later, AT&T released Unix System V, one of the first commercially available versions of the OS. Meanwhile, Sun Microsystems was founded (by Bill Joy, among others), and enjoyed early success at commercializing Unix through bundling SunOS, derived from BSD, with hardware aimed at the nascent workstation industry. These early BSD implementations possessed a key technical advantage with built-in support for TCP/IP networking. However, until 1988, implementations of BSD still required a license from AT&T because it was derived from their original source code.

As sales of workstations accelerated, Sun's business model of bundling hardware with a proprietary flavor of Unix – typically a derivative of either BSD or System V – was quickly adopted by many of the incumbent minicomputer manufacturers. The resulting market combined stable forking with fragmentation. BSD and System V persisted as stable forks, while technology experimentation and feature additions by downstream manufacturers fragmented these respective forks.[24] Salus (2015) describes the market for Unix implementations in the early 1980s:

> "Apollo, DEC, Eakins, Gould, Integrated Solutions, Masscomp, NSC, and Wollongong were marketing Berkeley UNIX. System III or System V derivatives were being marketed by AT&T, Altos, Apollo, Compaq, Convergent, HP, Honeywell, IBM, ITT, Intel, Interactive, Masscomp, Microport, Microsoft, Motorola, NCR, NUXI, Opus, SCO, Silicon Graphics, Sperry, Sun, Tandy, UniSoft, and Wollongong. Finally, a host of vendors, including Amdahl, Apple, Cray, DEC, Data General, HP, IBM, and Motorola, offered proprietary versions of UNIX, some based on 4.1 or 4.2BSD."

With Unix fragmentation leading to interoperability and portability concerns, AT&T began requiring vendors to conform to a variety of standards in order to use the System V brand. Another significant effort to promote Unix standardization was started within the IEEE, un-

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[24] Technological innovation in the complementary semiconductor industry exacerbated this issue, as the development of Intel's inexpensive 386 microprocessor vastly increased the number of hardware/software combinations offered by vendors (Raymond, 2003).

der the POSIX (Portable Operating System Interface) trademark. Although these efforts at platform leadership did increase interoperability, the first round of the Unix Wars essentially ended in a stalemate between the BSD camp and the System V camp.[25]

This first round of Unix wars contain several lessons about the economics of forking and fragmentation. First, the early work on BSD shows how forking need not always be harmful. In particular, the experimentation of Bill Joy and others in the academic community arguably fostered the development and improvement of an operating system that AT&T had all but abandoned. At the same time, those forks created an environment in which camps could easily form around the competing BSD and System V specifications. From these forks, downstream complementers and users developed extensions to tailor Unix to a wide array of hardware configurations, encompassing mainframe, minicomputer, server, and workstation use.

There is also an interesting parallel between fragmentation in Unix and 56K modems. With Unix, even though there were arguably positive network effects among end-users and software developers who all favored a greater level of inter-operability, the key *adopters* were minicomputer and workstation producers that often preferred a proprietary flavor of Unix that could provide a greater level of product differentiation. A similar role was played by small ISPs in the fragmented 56K modem standards war.

Unix: Second Round

The second round of the Unix Wars began in 1987 when AT&T announced a large investment in Sun Microsystems. Sun simultaneously announced that its future Unix OS development (Sun Solaris) would be based on AT&T's System V Release 4 (SRV4), as opposed to previous BSD-derived SunOS releases. Although this collaboration was hailed by customers and the press as helping to resolve the prior incompatibility issues, many of Sun's competitors – who were also often AT&T licensees – feared that they would be placed at a significant competitive disadvantage. In 1988 these competing vendors formed the Open Software Foundation (OSF), a consortium whose key members included Digital Equipment, Hewlett Packard, and IBM.[26]

OSF members jointly developed the OSF/1 operating system, which did not incorporate any of AT&T's intellectual property. In response, AT&T, Sun and a group of SVR4 licensees formed Unix International (UI) as a counter-consortium. Despite the significant resources spent on its development, OSF Unix was not a commercial success. Digital Equipment was the only

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[25] Salus (2015) relates how the two camps had marketing campaigns at the 1988 USENIX (user group) conference with the competing tag-lines "System V: Consider it Standard" and "4.2 > V."

[26] According to Axelrod et al. (1995), Sun's CEO Scott McNealy joked that OSF actually stood for "Oppose Sun Forever."

company to produce a complete implementation, and Cargill (2011) summarizes this round of the Unix battles by writing that, “OSF/1 was an idea whose time had come and gone, and the proprietary offering (UNIX SVR4) won.”

By the early 1990s, the market for workstations appeared mature compared to the fast growing desktop market, which was increasingly dominated by Microsoft. GNU/Linux had also emerged as a fully open source alternative to the various proprietary flavors of SVR4 then on the market. With these commercial developments as a backdrop, the members of both UI and OSF formed the Common Open Software Environment (COSE) initiative in March 1993, with UI and OSF merging into what eventually became The Open Group. The second round of the UNIX wars came to a close when AT&T sold its Unix rights to Novell. The Open Group continues to hold the trademarks to Unix, and offers testing and certification programs based on the Single Unix Specification (SUS), whose core specification development takes place under the auspices of the IEEE POSIX program.

This second round of Unix wars illustrates the potentially complex interplay among various paths to compatibility, including decentralized adoption of proprietary standards, platform leadership, “sponsored” consortia such as UI and OSF, and more neutral SSOs such as the IEEE. OSF’s commercial failure illustrates how divided governance of a standard may fail in the face of strong competition from a proprietary alternative. Furthermore, the creation of The Open Group illustrates how slower market growth, along with the introduction of outside threats (in this case from Linux and Windows), can help resolve a stalemate over standards that once appeared to be a stable fork.

Another lesson from the Unix wars is the importance of intellectual property. AT&T’s licensing activities played a role in both the early BSD vs. System V fights, and the later formation of OSF. BSD’s developers also worked to strip their fork of AT&T’s proprietary code during the second Unix wars, eventually releasing their distribution under a permissive commercial open source license, the BSD license. Some modern proprietary operating systems, such as Apple’s iOS and macOS, continue to utilize pieces of BSD, perhaps in part due to this permissive licensing.

3.3 Case Studies: Splintering

Splintering occurs when decentralized technology adoption leads to excessive variety, but no single user has the incentive to move toward compatibility unless they expect others to do the same. This often occurs early in the life-cycle of a new technology, when technical uncertainty leads to experimentation with a variety of alternative designs. As technical uncertainty recedes, however, achieving interoperability often requires coordinated action by market participants. We apply our model from Section 2.1.3 to study this coordination process in the context of gauge-width standards for the early U.S. railroad industry.[27]

3.3.1 Railroads

The first efforts to build commercial rail service in the United States occurred in the 1820s and 1830s. Most lines offered only local point-to-point service, and there was substantial technological experimentation, including trials of various gauge-width specifications. From the 1830s through the 1860s there was major investment in building out the U.S. railroad network, and rail came to replace waterways as a dominant mode of transport. During this period, technological advances such as telegraphy allowed for increased network utilization, and greater integration. However, in the absence of any mechanism for creating or coordinating a national network, the initial heterogeneity in gauge standards persisted. Siddall (1969) reports that there were at least 23 different gauge standards in use during the 1860s.

Network effects did influence the choice of early railroad builders, as new lines often chose a gauge that allowed for interoperability with existing adjacent lines. However, instead of producing a single national network these early decentralized choices led to the formation of "gauge regions" that allowed for seamless intraregional transport, with incompatibilities concentrated at geographic borders (Puffert, 2009). Although the companies operating in different gauge regions presumably had a preference for their own standard, railroad gauge standardization does not seem to be a case where splintering emerged from intense competition between a few sponsored alternatives. Rather, the lack of coordination emerged from a combination of initial experimentation, path-dependence and decentralized decision-making.

As regional networks grew and merged, the costs of incompatibility became clear. The largest costs were associated with trans-shipment: the process of moving goods from one gauge to another at the point where incompatible networks met. The direct costs of trans-shipment included hiring labor to perform the task, and maintaining specialized capital to facilitate the switch. There were also substantial opportunity costs from delayed arrival (the process often took a day or more) and the cost of maintaining extra rolling stock and other capital.

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[27] Our account draws heavily on the historical section of Gross (2016) and the references cited therein. It is also worth noting that rail gauge standardization is not merely an intriguing historical episode: there are more than five gauge standards currently used in Asia, and some incompatible national networks have been negotiating towards technical interoperability for over 50 years (UNESCAP, 1996; UNTC, 2006).

Railroads used a variety of technologies to reduce the costs of incompatibility. For example, many railroads experimented with adjustable width rolling stock, multi-gauge track (i.e. a third rail), and bogie exchange (the process of changing the wheels under a carriage in order to operate on otherwise incompatible track). However, none of these converter technologies were completely effective at removing delays or matching the overall performance of a uniform gauge.[28]

Over time, the costs of incompatibility scaled with utilization of the rail network, creating strong incentives for further convergence during the Civil War and reconstruction. In our stylized model, increasing demand for compatibility would be captured by an increase in the benefits of coordination c relative to vested interest b_i, which at some point produce a transition from stable fork ($b_i > c$) to splintering ($b_i < c$). By the 1880's, through both conversion and new construction, the U.S. rail network gradually converged to a system with two incompatible gauge standards, 5 feet and 4 feet 8.5 inches, with the former gauge highly concentrated in the South.

The final step in the process of achieving nationwide interoperability was a remarkable conversion of roughly 13,000 miles of track during an extremely short period in May and June 1886, making them compatible with the bulk of the Northern rail network. Just before this conversion, the majority of Southern freight carriers – including both rail and steamship – had organized themselves into a cartel called the Southern Rail and Steamship Association (SRSA). Although the main purpose of the cartel was rate-setting, they quickly realized the large potential efficiencies of converting to a gauge standard that would allow seamless interconnection with the Northern network. The conversion of the SRSA network to standard gauge was a carefully orchestrated engineering feat, described in detail by Hudson (1890) and more recently Puffert (2009).

From an economic perspective, the SRSA played two very important roles. First, it helped coordinate the switch, which was clearly more beneficial for members who were operating at the geographic boundary of the network than for those deep in the South, who would not regularly incur the costs of incompatibility. Evidence suggests that networks in the deep South were more reluctant to switch, and could only be brought along because the SRSA convinced them that all of their adjacent neighbors would be changing gauge. The SRSA's second role was to ensure (through coordinated pricing) that interoperability benefits flowed to its members, and were not dissipated through *ex post* competition.

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[28] Levinson (2006) provides a related account of the costs of break-bulk shipping in ocean transport prior to the arrival of containerization.

Gross (2016) uses data from SRSA and other freight schedules to study the economic impacts of the 1886 switchover. He finds that there was a substantial reallocation of traffic from steamship to rail for routes that would have formerly required trans-shipment, or interchange via bogie exchange. The effect is concentrated on shorter routes, where the costs of delay were proportionally larger. However, he finds that there was little change in price or aggregate volume, presumably because of the price discipline imposed by the cartel. Using a model of supply and demand, he also computes counterfactual impacts of standardization in a competitive market, which suggest that under competitive conditions, the gauge change would have lead to a 10 percent average price decline, and a resulting 9 percent increase in traffic for the routes in his sample.

The railroad case study offers several important lessons about splintering. First, it demonstrates how a combination of decentralized adoption and technological uncertainty can lead to splintering. It also shows how splintering can persist, even in the presence of substantial opportunity costs, when the sunk costs of replacing installed capital are large. The case also illustrates two paths to compatibility. One is the use of converter technologies, like bogies and adjustable wheels, to reduce costs of incompatibility. The second is for a large "platform leader" such as the SRSA to step in and coordinate a switch.

The empirical work by Gross (2016) provides some quantitative evidence of the welfare gains from inter-operability in this setting. However, it also raises the interesting question of whether the large counter-factual benefits of interoperability *plus* competition could have been achieved in the absence of the SRSA, since that organization played an important role in coordinating the switch and ensuring that Southern railroads would benefit from it.

4 Implications for Management and Research

The preceding case studies provide examples from each category in our classification scheme: stable forks (BSD and System V Unix), contested forks (Instant messaging, or HTML and Java during the browser wars), fragmentation (X2 and Flex in 56K modems) and splintering (early railroad gauges).[29] They also illustrate how forking, fragmentation and splintering can influence the evolution of commercially significant technology, regardless of whether that technology is a hardware standard as with 56K modems, a software standard such as HTML, or a communications protocol like AIM.

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[29] Of course, the cases do not tell us about the overall incidence of fragmentation and forking, since they are not drawn from a representative sample of standards and platforms.

The case studies also illustrate how firms seek to avoid the costs of mis-coordination and incompatibility. There were several examples of coordination through SSOs, such as the ITU in the 56K modem case, IEEE/OSF for Unix and W3C for web standards. These organizations provide a forum for reaching consensus on the standard itself, and also work to promote widespread *ex post* adoption and compliance. We also observed how platform leaders, such as the SRSA railroad cartel, can provide a push for standardization. And perhaps most interestingly, the cases illustrate how converters and multi-homing can provide temporary solutions, as in the railroad gauge and Instant Messaging cases. When they work well, converters allow users to make independent *ex ante* choices, but restore *ex post* compatibility in the event of forking, fragmentation or splintering. This can even prolong periods of incompatibility by reducing its costs. On the other hand, converters often underperform a dedicated standard (Baldwin and Clark, 2000). And like multi-homing, converters impose costs on end users, who must keep track of various "plugs and dongles" in an effort to engineer a degree of inter-operability.

Based on our classification scheme and case studies, we can offer – tentatively – a set of managerial implications. These ideas flow from the observation that a messy coordination process that produces forking, fragmentation or splintering must (by definition) leave some economic surplus unrealized. This creates an opportunity for entrepreneurial managers, who may be able to capture some of the benefits created by engineering a switch to a more efficient outcome.

First, managers should be on the lookout for windows of opportunity that can emerge when there is an unmet need for coordination, or an imminent upgrade to a standard or platform. For example, in the early railroad industry, many entrepreneurs made a living by finding ways to reduce trans-shipment costs at inter-connection points between incompatible rail networks. And in the 56K modem case study, US Robotics took advantage of the upgrade cycle to achieve intellectual property parity with Rockwell Semiconductor. Managers should also take a broad view of adjacent markets that are held up by costly incompatability. Technological innovations may provide opportunities for substitute technologies or platforms to usurp a forked, fragmented, or splintered market, as happened in the case of instant messaging.

Second, in order to take advantage of windows of opportunity, managers should have a good sense of the comparative advantages of different types of platform governance. SSOs provide a useful forum for reaching a compromise, as we saw in the modem and Unix cases. Platform leaders are often better positioned to engineer major upgrades, as we observed with the SRSA in railroads. For small firms, seeking to become a platform leader can be a risky and resource intensive strategy. Thus, it will often be wise to establish a strong presence within relevant SSOs, where technical expertise and coalition-building create opportunities to influence technology selection. Large firms may also find SSOs useful, particularly when they aim to promote innovation in complementary markets. However, as Microsoft's browser war victory illustrates (perhaps too well, from an antitrust standpoint), platform leadership may be called for when core technologies experience rapid technological change.

Third, managers should not naively presume that all participants in an industry face the same incentives to coordinate or diverge. Instead, a good strategy should account for particularities in the costs and benefits of adopting a specific technology, and in the relative benefits of coordinating with other firms. This type of strategic analysis will allow managers to understand the underlying causes of coordination and incompatibility, and improve predictions of rival behavior.

Finally, the conceptual framework offered in this paper highlights several directions for future research. As a starting point, it would be useful for empirical studies to characterize the degree of (in)compatibility in markets characterized by direct or indirect network effects. We were initially motivated by the observation that complete "tipping" is rare in practice, despite its theoretical prominence. To our knowledge, however, there has been no systematic effort to measure the number of platforms or standards in network-effect markets, or to check whether they are fewer than in more traditional industries. Alternatively, if one takes the technology, rather than the industry, to be the unit of analysis, our framework clearly calls for more research into the probability that a particular platform forks, fragments or splinters, and also the factors that increase the likelihood of those outcomes.

On the theoretical front, there are many ways to potentially enrich our model. The simple model we offer is suitable, in our view, for characterizing broad categories of explanation for the presence of persistent incompatibility in markets with network effects. But a more detailed theory is required to understand how firms are likely to behave in more realistic environments. For instance, where our framework focuses on a single technology choice (compatible or incompatible), richer models could allow for endogenous price setting and product design. Where our stylized model restricts attention to technology sponsors, future research could make the actions of customers and complementers more explicit.

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Tables and Figures

Table 1: Types of Incompatibility

	Root Conflict	Game	Equilibrium	Example
Forking (stable)	Compatibility	Deadlock	Dominant	Unix
Forking (contested)	Compatibility	Pesky Little Brother	Mixed	Java
Fragmentation	Technology	Battle of Sexes ($n = 2$)	Mixed	56k
Splintering	Technology	Battle of Sexes ($n > 2$)	Pure	SAE

Table 2: Payoff Matrix

		Player $i = 2$	
		$j = 1$	$j = 2$
Player $i = 1$	$j = 1$	$(b_1 + c_1, c_2)$	(b_1, b_2)
	$j = 2$	$(0, 0)$	$(c_1, b_2 + c_2)$