Half a Century of Public Software Institutions:
Open Source as a Solution to Hold-Up Problem

Michael Schwarz* and Yuri Takhteyev†

We discuss the history of institutions for provision of public (open source) software, from the 1950s to the emergence of the modern open source software institutions in the mid 1990s. We explain the evolution of such institutions by considering the inefficiencies inherent in provisioning of software as an excludable good. Such inefficiencies arise first of all due to a hold-up problem created by transactions that do not give the buyer the ability to modify the software. We also argue that the nature of the production function of software makes software cheaper to develop when the code is open to end users. We use this framework to examine the institutions that emerged to capture the efficiency gains afforded by public software. We look in particular at how such institutions have created incentives that not only attract contributions from individual volunteers but have also led to creation of open source products of tremendous commercial importance, which have come to dominate many segments of the software industry. Open source products now form the foundation of core infrastructure of sophisticated technology companies such as Amazon, Google, and Yahoo!

1. Introduction

Nonrival creative works, such as books, music and films, are subject to copyright protection, which makes such works excludable and allows their producers to sell copies for profit, strengthening incentives for private provision of such goods. Since 1980 the copyright law has offered the same protection to producers of software. However, while successful artists and publishers nearly always take full advantage of copyright protection, many successful software engineers and technology companies choose to not only allow others to use their software without paying royalties, but also to modify and redistribute it with almost no restrictions. Such public software, known since late 1990s as "open source," has grown to a staggering quantity, serving a wide range of purposes to the point that it is possible for many people to rely on such public software for all of their personal computing needs.[1] By contrast, consumers of books,

* Yahoo! Research, mschwarz@yahoo-inc.com

† UC Berkeley School of Information, yuri@ischool.berkeley.edu

1 One of the authors has relied on such software almost exclusively for the last several years, making use of a free operating system, free office suite, free software development tools, free image processing equipment and free statistical software among many other applications. The only exception has been the proprietary plugin for

music and films can hardly satisfy their needs exclusively through content that allows unrestricted reproduction.[2]

The academic discussion of open source has primarily focused on understanding the incentives that may lead individual actors to contribute resources to the production of such software. Johnson (2002) considers the incentives of self-interested agents to contribute to open source and investigates the effects of changing the population size of user programmers on provision of open source.[3] Athey and Ellison (2006) consider a model where programmers have altruistic preferences and derive different allocations of efforts.[4] Lerner & Tirole (2002) point out that contributors to open source derive gratification from peer recognition and may increase their future earnings by producing works that can show their skills to employers. Surveys of contributors have found a range of motivations, the simplest of which can be summed up with the phrase "Just for Fun" — the title of the autobiography of the creator of Linux, an open source operating system (Torvalds 2001).[5] Altruism, career concerns, and intrinsic motivations are essential drivers of open source movements. However, the same motives can and do exist in many other industries, without producing the same effect.[6]

The fact that people and firms contribute to public software is therefore not a puzzle *per se*. What requires explanation is the success of such software in competition with proprietary

viewing multimedia content in Adobe Flash format.

2 Wikipedia provides a rare instance of a highly popular written work distributed with a license that allows unrestricted copying and mostly unrestricted modification. (In particular, this license allows any company or individual to download Wikipedia's content *en masse* and to setup an alternative website displaying this content, as long as the content is offered with the original license and acknowledges the authors.) Notably, Wikipedia's license was originally introduced for software manuals, as an adaptation of a license used for distribution of public software such as Linux.

3 There is an extensive literature investigating mechanisms for provision of public good by private actors, e.g., Bliss and Nalebuff (1984), Bergstrom, Blume, and Varian (1986), Bagnoli and Lipman (1989), Varian (1994).

4 Lerner, Pathak and Tirole (2006) investigate the connection between the incentive to contribute to an open source project and the project size and perceived likelihood of success.

5 Lakhani and Wolf (2005) report that 44.9% of their respondents say that they contribute because the work they do for the project is "intellectually stimulating." Hars and Ou (2001) find similar motivation ("desire to code") for 79.7% of the reponders. Other common motivations involve the opportunity to learn (dominant in Ghosh 2005), the need for the software (dominant in Lakhani and Wolf 2005), desire to share with others, and many other.

6 Lerner and Tirole (2002), suggest, that open source developers can use their participation in open source to signal their talent to employers. Note again that while aspiring writers similarly need to demonstrate their ability to publishes, this need has not led to proliferation of free literature.

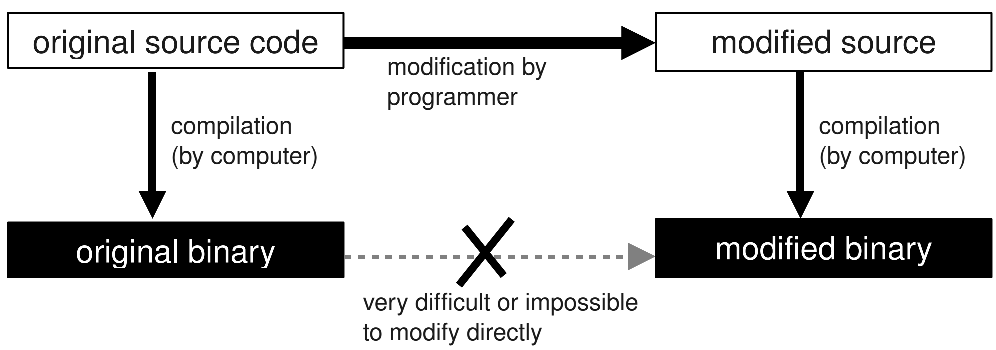
software produced by profit-motivated entities. Why can open source software, created by the efforts of part-time volunteers and weakly incentivized contributors, successfully compete with commercial software created by private enterprise?[7] While open source software has the obvious advantage of being free, price cannot explain its disproportionate popularity among highly sophisticated users (both individuals and businesses) that are likely to value quality and performance at least as much as other users. Individual users of Linux, for example, often use it as a replacement for a proprietary operating system that they have already paid for when purchasing a computer. However, the use of open source by individuals is a tip of the iceberg compared to its use by corporations. Internet companies including Amazon, Facebook, Google and Yahoo! and countless others heavily use open source operating systems and tools for some of the most challenging computing tasks. The world's largest supercomputer (IBM Roadrunner) and the world's largest database (Yahoo!) are both based on open source software (IBM 2008, Lai 2008).

Understanding public software by focusing on individual incentives is also problematic because such incentives are diverse, vary between projects and participants, and change over time. Such change becomes most apparent when we extend our discussion from modern "open source" institutions that have taken shape over the last ten years, to the different institutions that have provided software as a public good since the early 1950s. For example, today the most important contributors to open source are large corporations: by one estimate, employees of Red Hat, IBM, Novell, Intel and Oracle jointly contributed 32% of the changes for a recent release of the Linux kernel, while the contributions of volunteers likely added up to less than that (Corbet 2007). Such contributions are made for reasons that are quite different from those that motivated individual programmers' contributions to some of the same projects in the 1980s, AT&T's and the US Government's contributions in the 1970s, or IBM's contributions in the 1950s and 1960s. For this reason, instead of focusing on individual incentives *per se*, we start with a look at the inefficiencies inherent in provision of software as an excludable good, stressing that such inefficiencies arise not just because of deadweight loss due to monopoly pricing, but rather due

7 A similar question is asked by Weber (2005), who approaches it from the organizational perspective, looking to understand how open source development is coordinated.

to the hold-up problem and inefficiencies intrinsic to production of proprietary software. We then show how such inefficiencies have historically created space for alternative institutions that would provide software as a public good.

Software can exist in two very different forms, best understood as distinct goods that differ both in their utility and excludability. Software is created by writing instructions in the form of a highly formalized but human-readable text. This representation of the program, called "the source code," can then be automatically converted into a *binary* form that can be executed by the computer. Binary software can be *used*, but cannot be easily *modified*. To change the software, one needs to change its source code and then produce a new binary (see Figure 1). Access to the source code makes it possible to correct the software, improve it, customize it or extend it to new situations. Source code thus offers the user the same or greater utility than binary software.



When users purchases binary software, they must rely on the original vendor to supply them with any modifications that may later prove to be necessary for their continued use of the software. The exact nature and cost of such future modifications cannot be foreseen *ex ante.* Their price and quality must therefore be negotiated *ex post*, when the user has made relationship-specific investments, for instance into training or purchases of complementary hardware and software. This creates a hold-up problem.[8] The problem may be amplified even

8 See Williamson (1975, 1979), Klein, Crawford and Alchian (1978) and Hart and Moore (1990) for the discussion of the hold-up problem.

further if the producer and the user are competing in other markets. This reason alone would lead us to expect a company like Google or Yahoo! to avoid binary software, especially when supplied by current or potential competitors and when used in core infrastructure, where their needs are likely to be unique and where cooperation of the producer will be crucial for continued functioning of the business.

Despite source code's greater utility to the user, software is typically sold in binary form. The reason for this is the higher excludability of binary software. While binary software is non-rival and can be replicated at negligible cost, the law makes it effectively excludable by prohibiting copying it without producer's authorization. The producer can further augment this excludability by adding technical protections against unauthorized copying, for instance requiring the users to enter unique authorization codes to unlock the software. Source code, by contrast, is not as easily excludable. While the same legal protections apply in theory, in practice, selling software in source code form is usually not a viable option. First of all, access to source code allows the user to remove any technical restrictions on unauthorized copying or use. Second, and more importantly, the fact that source code can be modified creates serious problems for establishing its relationship to the original software. When someone makes an unauthorized copy of binary software, they obtain an exact copy, which can later be shown to be "the same" as original software. Access to the source code, however, makes it possible to copy elements of the software into another product in ways that would be difficult to prove. Additionally, the recipient can use the source code as a blue-print to develop an alternative product at a fraction of the original cost but without provable violation of the law. For those reasons, contracts that give one party access to another party's source code while limiting how such source could be used are inherently hard to enforce and expose both parties to the risk of expensive litigation. This risk is best illustrated by the $3 billion dollar lawsuit brought against IBM by SCO over IBM's alleged misuse of Unix source code, which cost each party millions of dollars in legal fees. While such licensing agreements are used occasionally, transaction costs limit their use.[9] Thus, as a first

9 For example, prior to the United States v. Microsoft case trial (1998-2001), Microsoft shared its Windows code with no other organization. (It later started making Windows source code available to select clients in response to the anti-trust charges brought by EU and to the demand of users who threatened to switch to open source.)

order approximation, one can think of software in binary form as an excludable good and software in source code form as non-excludable after the first sale.[10]

In addition to providing users with greater utility, software distributed with the source code often has lower total social cost of development. The limitations of the software are often discovered naturally by the users, while the producer may have to undertake prolonged testing, as errors may occur with low frequency or only when the software is used in specific ways that the programmers could not anticipate.[11] In other words, to improve the software, the producer must acquire users' knowledge of how the software should behave and of how it actually behaves in practice. This process of knowledge transfer can be both costly and error-prone.[12] Letting users change the software and share the modifications among each other may often lead to a substantial reduction of the total social cost in software production.

Finally, trading binary software and withholding its source code increases the overall social cost of software development, because it prevents producers from re-using existing solutions developed by other firms. While software developers can license binary software modules and incorporate them into their own products, this creates a hold-up problem similar to the one described earlier and may involve substantial transaction costs, incurred while the legal and strategic implications of the transaction are analyzed.

For those reasons, the total social cost of software production may often be minimized if software producers allow any party to modify their software and redistribute the modifications.

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10 In addition to the high transaction costs, licensing source code with restrictions may fail to fully resolve the hold up problem. For example, the user may not have the technical capacity to make the necessary modifications, and would need the right to hire a third party to do this work, transferring the code to them. The companies with the best capacity to offer such service may well be competitors of the original vendor. The users may also need the ability to share the modifications, since otherwise they may lack the necessary economies of scale and face prohibitive costs of modifications. Solving the hold-up problem thus requires making the software non-excludable upon the first sale.

11 A variation of this argument was introduced by Raymond in 1997, later published in Raymond (1999/2001).

12 Transfer of such knowledge is costly both because of the inherent duplication of efforts (the producer needs to simulate extended use to discover the problems) and due to the cost of replicating users' circumstances. For example, the producer may have to purchase a wide range of hardware to ensure that the software works successfully on all of it. If the producer avoids such research, they risk developing software that would fail to create value for some or all of the potential users. The argument for the benefits of putting product development in the hands of users is elaborated by van Hippel (1998), who also stresses the importance of "lead users" — users who advanced needs that may anticipate the needs of others.

The hold-up problem largely disappears, allowing users to make optimal investments into complementary goods. Improvements to the software can be made by users as they discover the need in such improvements. Software producers can reuse all existing solutions, including those that anticipate their needs only partly.

Allowing unlimited replication of the software reduces the producers' ability to charge for it, leading to underinvestment due to free rider problem. For this reason, proprietary software distributed in binary form may emerge as the dominant form of provision. We would especially expect this to be the case for software that does not require large complementary investments, is unlikely to need modifications, and is offered to users that have no capacity to modify software even when the source code is offered to them. Computer games offer a quintessential example of such software: they are typically used for a limited period of time, require no game-specific complementary investments, offer limited opportunities for useful modifications, and are mostly offered to consumers with no programming skills. The share of public software in computer games is in fact negligible.

On the other hand, for software products that require substantial complementary investments and where the users have capacity and frequent need to modify source code, the inefficiencies inherent in excludable software become a substantial factor. In such cases, the actors could reap substantial benefits if they could form a coasian coalition to provide software as a public good. The emergence of such coalitions would be facilitated when a number of potential beneficiaries is so small that they can literally sit at the same table and agree on how to share the cost. Such coalitions have in fact formed repeatedly from the earliest days of software development. Coasian coalitions are harder to form for public goods where the benefits are spread among a very large number of individuals. However, early coalitions may over time evolve into more sophisticated institutions that organize individual incentives for contributing and a reduce transaction costs of cooperation. In the rest of this paper we present the history of the institutions that have provided public software over the last half century, from the early coalitions to their current form, which often makes it possible to together hundreds or thousands of contributors to a single project.[13]

2. SHARE and FORTRAN

In this section we use some of the earliest documented cases of public software to illustrate a number of incentives for contributing. We put those incentives in the context of overall efficiency. Vendors of complementary goods have a natural incentive to provide software for free. However, additional savings are possible if such software is developed collaboratively by the users, who have better knowledge of their own needs. Such users may benefit from sharing their software by receiving improvements made by other users. They can also benefit from network effects if sharing software leads to a larger network.

Open source software first attracted popular attention with the rise of Linux in late 1990s and Netscape's decision to release its browser under a free software license. The practice of developing software as a public good has a long history, however, and in fact predates the earliest attempts at selling proprietary software by over a decade. We start our history of public software with a discussion of collaborative arrangements between IBM and its customers that took shape in the 1950s, before the term "software" was even invented.

In 1952 IBM entered the market for digital computers, following the introduction of the first commercial computer by Remington Rand a year earlier[14] (Ceruzzi 2003). Within the first year, IBM observed that while computer hardware was extremely expensive, many customers spent as much or more programming their computers as they paid IBM for the hardware.[15]

13 For example, Kroah-Hartman et al (2008) report that over 3700 individual developers from over 200 companies have contributed code to the Linux kernel since 2005. This number represents only specific contributions of code to the kernel, itself just a small part of the larger Linux operating system. It does not count thousands of people involved in packaging Linux, finding erros or writing documentation.

14 An earlier computer — the ENIAC — was built in 1944 for the US Army. However, ENIAC was no offered for sale and only one ENIAC was built. The UNIVAC, built by the designers of the ENIAC by then working for Remington Rand, was built in 1951. The production of UNIVAC was increased in the later years: to 2 in 1952, 3 in 1953 and more than a dozen in 1954 (Ceruzzi 2003, p. 28).

15 According to Cerruzi (2003, p. 82), a graph showing the changing ratio between software and hardware expenditures (from 1:4 in 1960s to 4:1 in 1980s) was popularized in 1970s as a marketing move by the newly emerging software companies. According to Cerruzi, later studies have found that the ratio of hardware and software expenditures have remained mostly constant — and roughly equal — over the years. (According to the US Census Bureau, US business spent roughly the same amount of money on software and hardware in 2006 —

Realizing that hardware and programs were highly complementary — or, to be more precise, that programs were complementary to the specific computer models for which they were written — IBM looked for ways to expand its hardware business by lowering the cost of programming for its customers (Campbell-Kelly 2003).[16] Since many of the customers faced the same problems, IBM started to write some of the programs and offer them to the customers for free, thus avoiding duplication of efforts between the customers.

Early on, however, IBM also had a different idea for reducing customers' programming expenses: encouraging the clients to share software among each other. It pursued this strategy by setting up an association for its users in 1952, with a mission of helping IBM customers help each other (Campbell-Kelly 2003). The association was later renamed "SHARE," the new name explicitly representing the objective of sharing knowledge and software (Campbell-Kelly 2003, p. 33, Campbell-Kelly and Garcia-Swartz 2008). While this could be viewed as an attempt to make the customers bear the burden of programming costs, the perfect complementarity between software and hardware would have made such shifting of costs short-sighted, as it would have reduced the demand for IBM hardware. Rather, customer-lead development of software offered efficiency gains. IBM users employed sophisticated teams of engineers and often had a better idea of what they needed and how to achieve it than IBM did. Putting software development in users' hands of course ran a risk of duplication of effort, and would have left out users with less capacity for developing their own software. The user association was created to avoid this problem, aiming to giving IBM customers collectively the same economies of scale that were available to IBM.[17]

SHARE members — two dozen organizations that had purchased IBM 704 — proceeded to share existing software and to develop additional software collaboratively, building on sharing

about $100 billion on each.)

16 IBM appears to have learned this lesson from its earlier experience with tabulating machines. According to Campbell-Kelly (2003), before entering the computer market, IBM was already used to working with customers to help them setup accounting machines applications. Rand didn't offer as much support for its Univac. As a result UNIVAC was notoriously hard to setup. There were stories of UNIVAC customers taking two years to get their UNIVAC working. Rand eventually lost its market share to IBM.

17 Note that in addition to allowing users to pool their work, SHARE enabled transfer of technology from the more experienced and demanding users — von Hippel's (1998) "lead users" — to those that had less experience. This role of SHARE is noted by Armer (1955/1980).

practices that predated the association.[18] The most prominent example of software produced by SHARE members was the SHARE Assembly Program (SAP) — an early version of a tool for automatic generation of a binary programs.[19] SAP was provided by United Aircraft Corporation, and was a modification of its earlier assembly program (UASAP), which was in turn based on a system designed by General Electric and MIT.[20] Armer (1955/1980) estimates that SAP saved SHARE members a total of about $1,500,000 in 1955 dollars (p. 127).

Eyewitness accounts of SHARE history do not address the question of why United Aircraft wished to make this contribution, focusing instead on the issue that they see as a real challenge: getting share members to *accept* each other's work. In fact, SHARE members had to choose from four different assembly programs, offered by different members. According to Greenwald (2008), United Aircraft "browbeat" SHARE into accepting their assembler, threatening to leave the group if another proposal is accepted.

To understand United Aircraft's interest in getting other organizations to use their software for free, and in fact their readiness to put additional resources into modifying it to suit the needs of some of the other members, we must consider, first of all, that United Aircraft already *had* an assembly program (UASAP) that it had written for its own needs, and quite likely had made a complementary investment into software written for it. If UASAP were accepted as the standard by other members, United Aircraft could benefit from the future software that other organizations would write for it and at the same time get to keep the software that it had written for UASAP. Strong network economies of scale are common in software. An organization or an individual who writes software for their own needs may therefore benefit from letting others use it. They often stand to benefit even more if they let others modify the software and share the

18 Armer (1955/1980) writes: "[Before SHARE] we 'shared' machine wiring diagrams, usually by submitting them to the machine manufacturer, who reproduced them and distributed copies to the field" (p. 123).

19 Today, "an assembly program" is understood to mean a program that converts source code written in a minimalistic programming language into binary format, and is a simpler version of what today is typically called a "compiler." The SHARE Assembly Program, however, simply assembled multiple chunks of binary codes (written by hand) into a single binary program (Salomon 1993, p. 8).

20 Shell, who himself worked for General Electric, writes: "[UASAP] was developed by United Aircraft Corporation and patterned after the first such program for the 704 which was developed under the writer's direction by the General Electric Company. This, in turn, was patterned to a considerable extent after the 'Comprehensive System' which was pioneered at M.I.T. for use on the Whirlwind computer" (1959, p. 123).

modifications. First, liberal licensing would make the software more valuable for potential users, leading to a larger network, and thus additional benefits to all users. Additionally, the user may benefit from improvements made by other users. For example, Stein (2007) shows the potential benefits of sharing even among direct competitors: individual actors may benefit from truthfully sharing underdeveloped ideas with competitors with the expectation that continued truthful exchange would increase the probability of payoff for both competitors, assuming that their markets intersect only partially.

According to Campbell-Kelly and Garcia-Swartz (2008), SHARE did not become a major institution largely because it brought together a number of competing businesses, which made the members concerned that their collaboration may be interpreted as anti-competitive collusion. This led to a decision to avoid joint development of application software, and focus exclusively on generic modules and system software — the kinds of software in which IBM's better understanding of the hardware was more important than the user's better understanding of their needs.

Aside from anti-trust concerns, many SHARE accounts note the high transaction cost of cooperation. SHARE collaboration relied on occasional meetings in different cities (Greenwald 2008), which made it hard to achieve understanding or share the improvements. IBM's centralized organization proved more efficient in providing innovation through 1960s. The difficulty of distributing software projects was formalized by Brooks (1975/1995), who argued that without clear hierarchy, an increase in the number of developers working on a project leads to a quadratic increase in the cost of communication between them, which comes to dominate the linear increase in productivity. This principle, which became known as "Brook's Law," was challenged in 1970s through the introduction of new software development practices, which stressed breaking software down into small and relatively independent modules (e.g., Parnas 1972).

One of the software products developed in late 1950s by IBM itself (though with some participation of SHARE users — Backus 1979) was FORTRAN, a system that allowed generation of binary software from a format that was easier to write than the assembly language used prior to that. FORTRAN dramatically reduced the cost of software development, but at the same time transformed the economics of software development by introducing a potential to run the same program on computer of different models. In the next several years, almost all of IBM's competitors implemented FORTRAN for their hardware (Campbell-Kelly and Garcia-Swartz 2008, p. 9), making it possible to run some of the software written for IBM computers on computers made by IBM's competitors and vice versa.[21] While much of the software continued to be written for specific computers until 1970s, the availability of FORTRAN and similar systems made it possible for hardware manufacturers to free-ride on many of the software investments made by their competitors. As it became harder for hardware manufacturers to capture the value of their investments into development of software, hardware manufacturers like IBM had fewer incentives to offer their software for free.

IBM did not attempt to prevent its competitors from imitating FORTRAN, but in fact helped them by distributing the 1950s equivalent of source code for their FORTRAN, together with detailed explanations of how it worked, making it easy for IBM's competitors to adapt it to their machines. Historians attribute such generosity to the fact that software was nor perceived as having market value (despite the recognized high cost of development!) and to the liberal "spirit of the times" (e.g., Campbell-Kelly and Garcia-Swartz 2008, p. 8). Indeed, since software was not fully covered by copyright law at the time, IBM had few options for selling it and perhaps could not have prevented its competitors from reproducing FORTRAN. However, IBM could have attempted to increase the costs imitation. It chose to do the opposite. The release of FORTRAN's source code made sense for several reasons.

First, by releasing FORTRAN's code and documentation, IBM made it possible for some of its customers to improve FORTRAN.[22] Sharing the code with customers while keeping it

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21 Note, though, that COBOL, released in 1960 and based on an earlier language developed by Remington Rand, was the first language to make it possible to execute the same program on two different computers (Campbell-Kelly 2003, p. 34-36, Ceruzzi, p. 92). Around the same time people start working on other ways to run IBM software on non-IBM machines. In 1963 Honeywell introduces "the Liberator" - a program that allowed users to convert software written for IBM 1401 to Honeywell 200 (Campbell-Kelly 2003, p. 98). But it's the standard languages like FORTRAN and COBOL that really helped commodify the hardware.

22 See for example, Davidson (1984) for a discussion of modifications introduced at the University of Wisconsin in 1961.

away from competitors was probably not viable due to high transaction costs.

Second, while FORTRAN was the first practical product of its kind, IBM's competitors were working on similar products. One of them — COBOL — had the support of the US government, which promised to not purchase or lease equipment that did not support COBOL (Ceruzzi 2003, p. 92). This mandate can be understood as an attempt to prevent the hold-up problem faced by any customer that invested resources into software that could only be used with specific manufacturer's hardware. (The government also had a legitimate reason to worry about the underinvestment by other private actors due to the risk of hold-up.) IBM therefore had interest in making FORTRAN software work with non-IBM hardware, or run the risk of making COBOL a more attractive option for its customers. This was amplified by the fact that FORTRAN and COBOL both promised to create strong network effects, which could create disproportionate benefits for the originators of the technology.

Starting in 1960s, hardware manufacturers faced fewer incentives to provide software for free, though this effect was somewhat reduced by IBM's increasing monopolization of the hardware market. This created opportunities for specialized firms that provided programming services to computer users. As software was increasingly recognized as a potential object of market transactions, software contractors realized that they could offer standard software for sale, starting with Autoflow — a flowchart program offered for sale in 1964 (Campbell-Kelly 2003). Since copyright law and patent law did not provide effective protection for software at the time, such vendors typically relied on trade secrets and non-disclosure agreements to make their software excludable (Menell 2002).

In 1969, antitrust action brought against IBM by the Justice Department led the company to unbundle its software operation from its hardware business, and to start charging customers for the software. This move gave a major impetus to the proprietary software industry. Even as IBM started to charge customers for software, it continued to provide them with source code and allowed them to modify and share it until the early 1980s (Campbell-Kelly and Garcia-Swartz 2008).

3. ARPANET and Unix

In this section we look at a different set of institutions for providing public software, which started to emerge in the 1960s and the 1970s. Those institutions were quite different from those that IBM tried to create in the 1950s. Production of public software comes to rely heavily on the support of the US government, which funds academic researchers. (An important contribution is also made by AT&T, a regulated monopoly.) Public software also starts to use a system of incentives borrowed from academic institutions. Additionally, the projects described in this section provide technological means for reducing the cost of collaboration, making it easier created public software.

Industry-led collaborative efforts such as IBM SHARE produced a body of public software in 1950s and 1960s, but did not result in lasting institutions for provision of public software. From the mid-1960s, software was increasingly provided as a private good, despite the weak level of protection offered to it by law at the time. By 1970s, however, alternative institutions started to emerge as providers of public software, supported to a large extent by the US Government and AT&T — a highly regulated public utility. The most notable of the government sponsored projects was ARPANET, which attempted to build, starting in 1967, a decentralized network for computer-to-computer communication. This project was later extended to what became known as the Internet. The work was funded by ARPA,[23] an agency of the Department of Defense, but was executed through collaboration of several teams of university researchers and computer companies. After some initial uncertainty about the legal status of the software created by the project, ARPA made a decision to require its contractors to make the source code of all ARPANET software freely available.[24] This move facilitated improvement of

23 ARPA was renamed to "DARPA" in 1972. We use the name appropriate for each historical period.

24 Abbate (2000) writes: "To preserve its strategic advantage in having designed IMP, BBN [one of the firms contributing to ARPANET] tended to treat the IMP's technical details as trade secrets. In addition, Heart was worried that, if BBN shared too much information about the IMP, graduate students at the host sites would try to make unauthorized 'improvements' to IMP software and would break havoc on the system. One of the more heated conflicts within the ARPANET community arose when BBN refused to share the source code for the IMP programs with the other contractors, who protested that they needed to know how the IMPs were programmed in order to do their own work effectively. The authorities at ARPA eventually intervened and established that BBN had no legal right to withhold the source code and had to make it freely available." (p. 76-77.)

the software and protected ARPA from hold-up. Furthermore, since ARPA was a government agency, its decision to make the software public could be understood simply as a matter of public provision of a public good.

ARPA's second decision was to rely on academic researchers in addition to the industry contractors. By involving academic researchers, ARPA brought into software development some of the institutions that underly the provision of science. Production of science is similar to production of software in that its utility can be maximized and its total cost could be minimized if scientists share their intellectual products without attempting to make them excludable. Over time, a set of institutions developed that made it possible to provide science as a public good. Such institutions enabled the scientific community to obtain funding from both public and private sources, relying on a complicated mix of altruistic and self-interested motives by the sponsors. They also provided methods for evaluating scientific output, the most important of those being peer review (Scotchmer 2006), which partially compensates for the lack of a market selection. While modern open source institutions diverge substantially from scientific institutions, both in how they attract external funding and in their handling of credit, they share important characteristics and have clear historical links, the ARPANET project being an important opportunity for a transfer of institutions.[25]

Historians of computing explain ARPA's decision to rely on "collegial" working arrangement by the fact that people who made those decisions have themselves come from academia (Abbate 2000), and the fact that ARPA needed assistance of academic researchers and found that collegial arrangements helped it obtain their cooperation (Abbate 2000, p. 54). To put this differently, however, ARPA administrators faced a need to provide a public good and relied on a known solution for it, which also allowed the scientists to collaborate with ARPA without detriment to their academic careers.

Like SHARE members, ARPANET contributors were distributed between a number of sites located in such places as Boston, Pittsburgh, San Francisco Bay Area and Los Angeles,

25 In open source as in science the contributors may be willing to accept lower wages in exchange for having the output of the work be publicly available. The motives may include career concerns as well as ego gratification. Stern (2004) shows that young scientists except lower wages in order opportunities to publish.

potentially facing the same high costs of collaboration. ARPANET managed to reduce those costs, however, using the very technology that it was building. The computer networking technology produced by ARPANET "itself provided a new way to coordinate dispersed activities and came to function as a meeting place for the computer science community" (Abbate 2000, p. 54). This involved use of such tools as email, developed by ARPANET researchers in 1972 (p. 108).

ARPANET was one of the most notable, but not the only project that involved "collegial" production of public software in 1960s and 1970s and was funded by the US government. ARPA funded numerous projects in many universities, often without asking for very specific deliverables, but rather looking for overall innovation (Abbate 2000, Weber 2005). While the most important product of the ARPA-funded projects were ideas expressed in academic publications, they also produced a large quantity of software, much of which was distributed without restrictions. One small but important product was Emacs, a text editor designed by an MIT programmer named Richard Stallman. Stallman distributed Emacs for free and allowed others to make changes, but demanded that any improvements made to Emacs would be returned to him so that he could incorporate them into Emacs and distribute them to all users. This policy (Stallman called it "communal sharing"), represented an important institutional innovation. While it proved problematic in its original form, it served as a stepping stone towards what later became known as "copyleft" licensing.

Among the less successful projects funded by ARPA in 1960s was a new operating system called "Multics." Multics promised to deliver features that were of interest to AT&T and that IBM had been willing to provide in its software (Ceruzzi 2003, p. 156). AT&T's Bell Laboratories then joined the Multics project with the hope of accelerating it and steering it closer to AT&T's needs (Ceruzzi 2003, p. 155, also Salus 1994, p. 26). The Multics project failed, likely due to its excessive complexity. However, a number of Bell Labs researchers produced a simplified version of Multics which they called "Unix." Unix proved an immediate success.

In 1960s and 1970s, AT&T was operated as a regulated monopoly. Because of an earlier anti-trust decree, AT&T was prohibited from engaging in any business apart from providing telephone service, which AT&T lawyers understood to include sales of software. AT&T was allowed to engage in research and obtain patents, but was required to and license all patents for nominal fees. This prevented AT&T from selling Unix and many of the other innovations that originated in Bell Labs. AT&T lawyers considered it prudent to license Unix for a nominal fee, as they had done with patents and other software before (Salus, p. 56-60). On the other hand, as a regulated monopoly, AT&T could pass its research costs to the consumers, as long as such costs could be justified to the regulators.

In 1973 Unix was re-written in C, a new language also developed at AT&T. While FORTRAN and COBOL had already enabled portability for certain kinds of software, a combination of C and Unix made it possible to write almost any software in a way that would allow it to be moved between computers. Doing so, however, required access to the source code, because different binary software had to be generated for each machine and modifications to the source code were often required. Being able to move software between computers also meant being able to use it on *later* computers, increasing the time horizons for software users. While much of the software written in 1960s (including all of the ARPANET software) was hardware-specific and could be expected to become obsolete eventually, most of the software written for Unix in 1970s can be used today.[26] Increased time horizons made access to source code even more important, as some users could now plan to use their software for decades.

Unix introduced an important technical innovation that helped defeat Brook's Law and paved the way for larger scale collaboration. Learning from the failure of Multics, Unix designers took a minimalistic approach, designing the system as a collection of simple tools, each designed to serve a specific purpose, and providing a mechanism for chaining such tools together for more complex task. This approach reduced the amount of interdependencies in the system, making it possible for a larger number of people to collaborate effectively.[27]

Researchers at several universities that licensed Unix from AT&T made improvements to

26 This software would in fact be still in active use today, if not for the legal reasons that we discuss below, which led to a re-implementation of much of this software in 1980s.

27 The notion of "decomposition" was quite new at the time. Parnas (1972) is considered the seminal paper on this topic. The first Unix paper was published in 1974 (Ritchie and Thompson 1974).

Unix, both improving tools provided by AT&T and writing new ones. Computer Systems Research Group (CSRG) at University of California, Berkeley emerged as a particularly important site of such work, performed as a matter of research activities. In 1977, a Berkeley graduate student started compiling tapes of Berkeley modifications to Unix and offering them at nominal cost to other researchers. This collection of software, soon expanded to a full operating system based on AT&T's Unix but modified to run on new hardware, became known as "Berkeley Software Distribution" or "BSD." CSRG charged a small fee for the BSD tapes ($50 in 1978, according to Salus 1994, p. 143), but allowed the recipients to make copies and share them with others.

In late 1970s, Unix attracted attention of DARPA, which was looking for a unified base for its projects, including the emerging Internet. DARPA was in particular attracted to the fact that Unix code was available (Weber 2005, p. 34).[28] DARPA offered support to Berkeley CSRG to extend BSD for DARPA's needs. Funded by DARPA, Berkeley researchers made many further improvements to BSD and integrated into it networking code originally developed by a DARPA contractor. The new version of BSD, with improvements commissioned by DARPA, was released in 1983 and proved to be an immediate success, turning BSD Unix into a foundation of the Internet (ibid, p. 35).

The future of BSD, however, was soon clouded by the uncertainty of the property rights around it. While use of BSD was always assumed to require a license for the original Unix, this restriction was not important, as AT&T had been offering the license at nominal prices. Around 1980, however, several changes led AT&T to reconsider this policy and to try to treat Unix as a proprietary software product. This move created serious challenges to public software, since AT&T was not only making a claim to a specific software product, but was asserting control over what was emerging as a popular preferred platform for public software development. As we will see, the public software institutions managed to overcome this challenge through a number of institutional innovations.

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28 While avoiding hold-up would be an obvious reason for DARPA to choose software with open code, Weber mentions a rather different reason: the researcher's lack of interest in working with closed-source solutions (p. 34).

4. The New Copyright Regime

Around 1980, the legal protection for software in the United States underwent an important change. Prior to 1964 software was understood to be outside the bounds of copyright law and was offered no protection beyond trade secrecy. In 1964 the Copyright Office extended copyright protection to software, giving software producers a new mechanism for making software excludable. This mechanism suffered from an important drawback, however. As other works, software had to be *published* and *registered* to be protected by copyright. Specifically, the source code of the software had to be published and deposited with the Office (Menell 2002). Software producers could thus protect their work using either copyright or trade secrets, but not both. As we discussed earlier, legal restrictions cannot make software effectively excludable if the source code is shared. To make software truly excludable, the producer needs dual protection: trade secrecy for the source code (which is never revealed), and copyright protection for the binary that is offered on the market. A 1980 amendment to the Copyright Act of 1976 offered software producers exactly this protection.[29]

This change created obvious incentives to trade in binary software. The growing software industry in turn attracted some of the people who prior to that were working on public software. Bill Joy, one of the key people behind BSD, left Berkeley in 1982 to co-found SUN Microsystems, which used BSD as the foundation for its own proprietary Unix variety (Salus 1994). Many members of MIT's AI Lab similarly left to start private ventures in early 1980s (Levy 1984/2001). The legal changes also transformed the practices of those who continued to provide public software by making the public status of such software more explicit. Prior to 1980, if the code had not been registered with the Copyright Office (which was rarely done), its very transfer removed the only other form of protection — trade secrecy. Simple sharing of the

29 The 1976 act, which took effect in 1978, extended copyright protection to unpublished works, but did not cover software explicitly. The issue of software protection was then investigated by a congressional committee, which issued a report recommending copyright as the preferred form of protection for software (CONTU 1978). This suggestion was implemented with an amendment in 1980 (Menell 2002, p 18). The same year US Congress passed Bayh-Dole Act, which allowed universities to get patents for inventions created with the use of federal funds. This did not have any immediate effect on public software, however, patents were rarely used to protect software until 1990s (Graham and Mowery 2002).

source code thus resolved the hold-up risks. From 1980, however, a party could offer source code to others yet keep all rights to it. To avoid hold-up, the recipient had to obtain an explicit license for the code. Responding to this change, programmers started sharing code with explicit licenses, which consisted first of simple notes stating that the code was "in public domain," and then gradually evolving to a more formal licenses, with proper legal terms and safeguards such as disclaimers of warranty.

The move towards keeping public code pure of proprietary claims was also encouraged by a change in AT&T's position on Unix. In 1978 the US government brought another antitrust case against AT&T, leading to a settlement in 1982, in which AT&T agreed to divest of its local exchange business. As a part of the settlement, however, AT&T received a permission to sell software (Salus 1994, p. 190). It attempted to use this right to sell Unix, offering a version of Unix to clients for a increasingly high license fees.[30] Such fees have often been described as "prohibitive" (e.g., Weber 2005), a term that may suggest deadweight loss. It may be more appropriate to say, however, that AT&T's increasing licensing fees demonstrated its position as a profit-taker, holding up those who had contributed improvements to Unix or made complementary investments. While a court later found that AT&T had lost copyright in the code that had been included in BSD, this outcome was uncertain at the time.

The new BSD promised great value to the users, offering them a system capable of connecting to the Internet, with full source code. Such benefits, however, could be fully captured by AT&T, which asserted that use of BSD required an AT&T license. Since most of BSD code had been contributed by Berkeley, replacing AT&T's code with new code would be substantially less expensive than writing an equivalent of BSD from scratch. It was still a rather monumental task — more than CSRG could take on — but it could be done if the potential beneficiaries could form a coasian coalition and pull their efforts. In 1989, Keith Bostic, one of CSRG staff members, decided to try to build such a coalition, asking BSD users for help in replacing AT&T code.

The large number of beneficiaries (CSRG's 1988 release of parts of BSD led to over a

30 $100,000 in 1988 according to Weber (p. 39).

thousand requests for copies at $1000 processing fee), however, created an obvious free rider problem. Bostic attempted to solve this problem by setting up matching contributions: convincing some of the CSRG staff to agree to contribute the most difficult part of the system (the kernel), if Bostic could find contributors for other parts. Bostic then recruited contributors over the Internet and in user meetings, telling them that an effort to replace AT&T code was underway but that help was needed. He offered no rewards other than inclusion in the list of contributors — and an opportunity to help create a public good of obvious value. While Bostic's call invited people to contribute their time for largely altruistic reasons, potential contributors knew that the effect of their work would be amplified by the fact that it was unlocking the value of the software that had already been written by CSRG.[31] The strategy proved successful: within eighteen months, Bostic collected most of the necessary utilities, after which CSRG staff re-wrote the kernel (McKusick 1999). The complete system was released in 1991. AT&T Bell Labs sued Berkeley to stop its release but lost. The case closed in 1993 with Berkeley's right to release BSD upheld.

The crisis of public software in 1980s also led to a different and more radical response, which introduced important additional innovations into public software. In 1983, Richard Stallman, the programmer at MIT who had earlier led development of Emacs, announced his plan to write a completely free version of Unix, which he called GNU. Stallman's announcement of his plan expressed his motivation in ethical rather than economic terms: "I consider that the golden rule requires that if I like a program I must share it with other people who like it. I cannot in good conscience sign a nondisclosure agreement or a software license agreement. So that I can continue to use computers without violating my principles, I have decided to put together a sufficient body of free software so that I will be able to get along without any software that is not free." (Stallman 1983). In other words, Stallman believed that it was unethical to refuse to share with others tools he used himself. Since copyright law prohibited sharing proprietary software, Stallman believed that he had to avoid using it, and instead dedicate his time to providing an alternative.

31 Effect of matching contributions on public good provision was studied Guttman (1978), Andreoni (2006), and Ghosh and Mahdian (2008).

Stallman's manifesto provided a radical articulation of some of the assumptions of the public software culture. A well articulated ideology has proven to be useful to public software institutions, as it helped the members organize for collective action. While earlier production of public software primarily drew on the institutions of public science, Stallman's approach drew on an entirely different set of institutions: political movements. Unlike scientific institutions, which seek public funding for provision of a public good, political movements seek to provide a type of public good (positive social change) by seeking contributions from individuals who believe in the cause advocated by the movement. While many contributors to public software have rejected Stallman's "political" approach, many others mention political motivations for contributing. In a study by Ghosh (2005), 30% percent of contributors indicated their belief that software should not be a proprietary good as one of the reasons for contributing to public software.

An important element of Stallman's ideology was a stress on libertarian rationale over the simpler issue of cost. This issue was obscured by his choice of the name for the movement: "free software." Stallman told his supporters that "free software is a matter of liberty not price," and asked them to think of "free speech" rather than "free beer." To put this in terms that we have used in this paper, Stallman's "free" could be understood as "free from hold-up."

Stallman's rethinking of public software as a political movement led him to seek independence from existing institutions. In a major diversion from earlier public software practices, Stallman resigned from MIT and ran his project independently, relying on private consulting and Emacs sales to support himself.[32] (MIT supported him indirectly by offering a computer and an office.[33]) Stallman then set up a non-profit foundation (Free Software Foundation) to support the project. Non-profit foundations have since become a key element of public software institutions, making it possible for public software contributors to attract financial resources from a wide range of actors, thus achieving independence vis-á-vis other

32 Stallman offered Emacs for a price of $150, but allowed users to make unlimited copies and modifications. The scheme brought him up to $1000 a month (Moody 2001). Such submissions could be understood as donations masqueraded as purchases: Stallman's supporters could essentially make their employer donate to Stallman by purchasing Emacs instead of seeking a free copy.

33 This offer was particularly important as Stallman was allowed to sleep in this office, as he proceeded to do for twelve years according to Moody (2001).

institutions (O'Mahony 2005). By 1988, Free Software Foundation started to attract substantial cash and hardware donations from a range of actors, who also loaned Stallman their programmers. The early donors included Sony and Hewlett Packard — both of them hardware manufacturers that stood to gain from the Foundation's efforts to create a free complementary good.[34]

Stallman's third innovation aimed to protect public software from companies that might make modifications and then treat the improved software as private. He attempted to do with a peculiar licensing solution, which became known as "copyleft" licensing, based on the "communal sharing" arrangement he earlier attempted with Emacs. Instead of declaring GNU software to be "in public domain" or using what later became the BSD license, Stallman and his followers offered all recipients of their software the right to modify and redistribute it, but with an important restriction. If the user chose to redistribute GNU software, whether in its original or modified form, they had to disclose the source code and to do so under the same license. Any software based on copyleft software would thus have to retain its copyleft status. Note that copyleft license does not require that the users share their modifications. It gives the licensee a choice of either not sharing their modifications with anyone or releasing them under the same terms as the original authors. What they cannot do is distribute the software to others with additional restrictions.[35]

The GNU Project produced a lot of software that is used to this day but was never completed in the form in which Stallman envisioned it, having ran into a serious technical problem in early 1990s. The project had everything but the "kernel" — the center piece of an operating system. Stallman wanted to use a particular type of kernel called "microkernel," which was widely considered to be superior but turned out to be difficult in practice. In 1992, however, Linus Torvalds, an undergraduate student living in Finland, decided to write an alternative kernel

34 The GNU project reported its first large donation — $10,000 from Sony — in February 1988. Sony also lent GNU a programmer for six months, and provided two Sony workstations (GNU's Bulletin 1988, #4, 1989, #5). It then reported two donation of $100,000 — one from Hewlett Packard and another from "Anonymous Contributor" — in 1989 (GNU's Bulletin 1989, #7). In 1990 Stallman received the MacArthur Genius Award for his work in 1990 which provided him with $250,000 (Williams 2002).

35 See Lerner and Tirole (2005) for a discussion of factors that may influence developer's choice of a public software license with and without a "copyleft" clause.

for GNU, basing his kernel on another one, called “Minix.” His kernel, which became known as “Linux,” was a “monolithic” kernel — an approach that was derided by many people, including the author of Minix. Linux worked quite well in practice, however, and Linus managed to attract many volunteers who helped improve it. The combination of GNU and Linux produced a complete operating system. This combination came to be known as “Linux,” though purists call it “GNU/Linux.”

While Linus’s efforts were originally disregarded by GNU, Linux an important benefit of public software: by granting others unconditional right to modify the software, Stallman made it possible for others to correct his mistakes (over his disapproval) and to complete the project.

5. Public Software Goes Corporate

In addition to completing GNU, Linux introduced an important additional change. As nearly all Unix-like systems of the time, Stallman’s GNU was intended to run on “workstation” computers, which were considered cheap in comparison to many other computers of the time, but were an order of magnitude more expensive than the emerging personal computers. ($30,000 dollars is a typical price quoted for a workstation around 1990. By contrast, personal computers typically cost under $3,000.) The price of workstations was hardly prohibitive for programmers Stallman, Bostic and others, who had access to university machines (having been purchased with public funds in most cases). Linus Torvalds, an undergraduate student at the time, was only in possession of a $3,000 personal computer. His goal was to make a Unix-like system run on it.

While personal computers had been introduced in late 1970s, until 1990 they presented little competition for the larger machines. Such computers were small and could not perform functions that were of interest to DARPA- and AT&T-funded Unix programmers. In 1980s, following the introduction of the IBM PC, personal computers spread in popularity, but did so among non-technical users, who typically used them for word processing and games. Access to the source code offered little benefit to such users, who instead put highest premium on ease of installation and use. Unlike the diverse world of workstations, the PCs also quickly converged to just two processor types, which made it possible to run the same binary software on most PCs. Consequently, the PC software industry quickly converged to a proprietary model. An important exception to this rule was shareware — software distributed with a license that allowed unlimited copying, but accompanied with a requested users for donations. Shareware benefited from certain gains in efficiency — the distributors saved on marketing and could achieve large network effects by including users that were not willing to pay for the software. However, shareware producers typically did not share the source code and thus did not benefit form the efficiencies associated with public software.[36]

By adapting GNU's software for his personal needs, Torvalds introduced GNU to a pool of users that had been overlooked until then: technical users of personal computers. Linux was not the first Unix-like system for personal computers, but it differed in an important respect from the two that preceded it: Minix, developed as an instructional tool by a university professor, and 386BSD, a PC version of BSD. Minix and 386BSD were both popular among PC users, but suffered from many deficiencies. Individual users attempted to contribute both ideas and actual modifications, often fixing specific problems that they encountered. (Both systems were distributed with source code and allowed modifications.) Such modifications, however, were often rejected by the original authors who had different plans for the software.[37] Torvalds, on the other hand, tried to capitalize on the users' interest in submitting improvements. The credits for Linux 1.0, released in 1994 include eighty names. By contrast, the BSD kernel, was written by a handful of people at Berkeley.

The availability of Linux offered many companies an opportunities to rely on cheap personal computers for functions that earlier required more expensive equipment. A number of companies arose to facilitate this, offering business clients a more polished version of the GNU/Linux system. This change resembled the proliferation of Unix companies such as Sun

36 The concept of shareware was introduced in early 1980s. Curiously, one of its inventors was a former Microsoft programmer Bob Wallace. Wallace later said that he thought that letting people use the software would help them understand why it is useful and the desire to reach more users. Wallace made some money with shareware, building a business that brought in around $2,000,000 in revenue per year at one point (Callahan 1990).

37 In case of Minix, Tanenbaum wanted to keep the system simple enough to work as an instructional tool (Tanenbaum 2004). (Linux was largely based on Minix design.) In case of 386BSD, the reluctance to accept users' modifications stemmed more from author's desire to build the system the right way (Raymond 1999/2001).

Microsystems in early 1980s, but differed in an important way. Unlike Sun Microsystems, which had an opportunity to distribute an improved version of BSD as proprietary software, the Linux companies of 1990s were constrained by the "copyleft" licencing terms of GNU/Linux, which required them to share the source code with their users. Private underinvestment was partly made up by the development of the non-profit model and the development of foundations similar to Stallman's (see O'Mahony 2005).

While Stallman's licensing terms have proven crucial for the growth of public software in 1990s, the ethics-based ideology of the "free software" movement was impeding private investments. In 1997, Eric Raymond, a Unix programmer, wrote an essay arguing for the efficiency gains arising from sharing the source code.[38] The essay was read by the management of Netscape Corporation, which was at the time driven out of its web browser market by Microsoft's Internet Explorer, offered for free to all users of Windows. The essay convinced Netscape to release the source code of its browser in order to enable user-driven innovation and to compete with the Internet Explorer on quality rather than price, while making money on complementary goods. Following Netscape's decision, Raymond convened with other open source enthusiasts to discuss the opportunities offered by Netscape's decision. The meeting concluded with a realization that public software would benefit from a "marketing campaign" and "that it would require marketing techniques (spin, image-building, and rebranding) to make it work" (Raymond 1999/2001). As a re-branding effort, the meeting participants decided to start using the term "open source" instead of "free software," finding that the new term would make it easier for corporate America to embrace open source.

Netscape's decision to "open source" their browser did succeed in giving it a second life, attracting contributions from various actors that were either interested in having a browser for specific platforms or in maintaining competition in the browser market. The open source browser based on Netscape's code, first released as "Mozilla" and later as "Firefox," currently serves about 20% of the browser market and was a major factor in reducing Internet Explorer's share from 95% in 2002 to 71%. Since 2003 the development is coordinated by a non-profit

38 The essay was later reprinted as a chapter ("Cathedral and the Bazaar") in Raymond (1999/2001).

Mozilla Foundation, which currently receives most of its funding from “a search engine provider,” typically understood to be Google.[39]

Since 1998, development of “open source” software has been increasingly supported by private companies, which discovered that open source often offers a cost-effective way to create or improve products complementary to the core business. In 2001 IBM announced its plans to contribute $1 billion to Linux and later reported that the investment paid off in a single year. In 2007, Sun released as open source the implementation of Java — by some counts the most popular programming language in use today.

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39 According to the Foundation’s 2006 report, the foundation received 85% of its 2006 revenue from “a contract with a search engine provider for royalties” (p. 11). Those are assumed to be fees paid by Google for making Google search the default option in Mozilla Firefox.

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