TOWARD OPEN SOURCE NANO: ARSENIC REMOVAL AND ALTERNATIVE MODELS OF TECHNOLOGY TRANSFER

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ABSTRACT

In the wake of growing pressures to make scholarly knowledge commercially relevant via translation into intellectual property, various techno-scientific communities have mobilized to create open access/open source experiments. These efforts are based on the ideas and success of free and open source software, and generally try to exploit two salient features: increased openness and circulation, and distributed collective innovation. Transferring these ideas from software to science often involves unforeseen challenges, one of which is that these movements can be deemed, often incorrectly, as heretical by university administrators and technology transfer officers who valorize metrics such as number of patents filed and granted, spin-off companies created, and revenue generated. In this paper, we discuss nascent efforts to foster an open source movement in nanotechnology and provide an illustrative case of an arsenic removal invention. We discuss challenges facing the open source

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nano movement that include making a technology widely accessible and the associated politics of metrics.

How scientific knowledge is created, translated into innovative technologies, and used to enhance the welfare of economy and society are core issues facing policy makers, government officials, community leaders, as well as administrators in universities, research institutes, and corporations. Over the past couple of decades, observers and scholars of innovation systems have noted that the social organization of innovation has shifted away from the linear development model (i.e., the creation of basic science in academia enabling technology development in industry) to a much more interpenetrated model of techno-science that is marked by hybridized arrangements and bidirectional flows between university and industry (Rhoten & Powell, 2007; Kline & Rosenberg, 1986). This has been catalyzed by the rise of biotechnology and legislation such as the Bayh-Dole Act that allowed University ownership of inventions created using federal research funds (see Mowery, Nelson, Sampat, & Ziedonis, 2004), leading to the increased penetration of commercial interests and pressures into the sacred halls of academia (e.g., Slaughter & Leslie, 1999; Slaughter & Rhoades, 2004; Vallas & Kleinman, 2007; Mirowski & Sent, 2002). These developments have dovetailed with the more general rise of neoliberal policies and thought throughout much of the developed and developing world, leading to the valorization of market logics in many societal spheres (McMichael, 1996).

In academia, the growing allure of intellectual property and private funding has, in turn, led to a breakdown of the line demarcating public science and proprietary control of inventions via intellectual property. Most research universities have a technology transfer office (TTO) and formal policies that mandate that scientists are to report all inventions to those offices. In turn, TTOs aim to generate revenue for the university via licensing of patents and the creation of spin-out entrepreneurial ventures. As a result, TTO effectiveness and success is assessed based on metrics such as number of patents filed and granted, number of patents licensed, spin-off companies created and overall revenue generated. Despite the growing efforts of university administrators to valorize such metrics, the reality is that most TTOs have great difficulty generating enough revenue to support their operations, let alone contribute to university coffers (see Trune & Goslin, 1998). More generally, the move toward rationalization, monitoring, and "audit culture" has been identified within the university as one reason for the displacement of a commitment to a public-oriented mission (Strathern, 2000).

In addition, there is growing disquiet regarding the historic openness of academic science and technology and the ability of the general public and marginalized people to access its insights to solve localized problems (e.g., see Sampat, 2003). For instance, some have claimed that patents, in areas such as the life sciences, have inhibited innovation (Heller & Eisenberg, 1998), information sharing among researchers (e.g., Eisenberg, 1996; but see Walsh, Cohen, & Arora, 2003 and Walsh, Cho, & Cohen, 2005), and productive university–industry relationships (Leaf & Burke, 2005). In addition, the valorization of market logics threatens to limit efforts in directions that might have high *social value* but less commercial potential, such as in the development of medicines and solutions to problems in geographic areas with large populations and high rates of disease and poverty. Rhoten and Powell (2007) remark that:

> Traditionally, university settings explored arenas that industry did not pursue. But in the absence of market incentives, it is not obvious where knowledge generation for the public interest and social good may emerge in areas such as vaccines or low-cost technologies. In some circumstances, new models of public and proprietary science have fostered the development of first-to-the-world medicines and affordable communications technologies, but in other realms, such as renewable energy, widely available breakthroughs have not been forthcoming.

Such longer-term distributional consequences of private models of scientific innovation becoming hegemonic over more public domain models have deservedly opened up scrutiny into these issues. Civil society organizations such as the *ETC Group*, *Greenpeace*, *Friends of the Earth*, and the *Pesticide Action Network* have stressed the importance of taking inequalities (e.g., North/South divide) into account when assessing how science can benefit society. Such organizations may be characterized as techno-skeptics, deploying different cultural framings (Lounsbury & Glynn, 2001) than techno-optimists or techno-realists (see ETC, 2005). *Techno-optimists* tend to be functionalists in the sense of believing in the utility of technological development to contribute to societal growth and development without much downside – it is generally viewed that industry and scientists are trustworthy actors that can voluntarily handle risks (e.g., toxicity of chemicals and materials) in a responsible way (recall the Responsible Care program in the US Chemical Industry).

Techno-realists believe that technology can contribute to "pro-poor" applications such as solar power, water clean-up, or cheap vaccines, but requires "upstream engagement" to enable broader societal participation and oversight with regard to the development and governance of technology (see Wynne, 1995; Guston & Sarewitz, 2006). *Techno-skeptics* put justice ahead of technology and are wary of overpromising technological advance and ignoring the history of unintended consequences of nuclear, biotech, and chemical technologies. These techno-skeptics view technology as inextricably bound up in power relations – enhancing the wealth and control of elites and Western corporations while failing to adequately address core issues of poor peoples (see Frickel & Moore, 2006 on the variegated politics of science and technology). Many techno-skeptics are organized as social movement organizations that try to influence public policy, regulations, and discourse. While some are more radical than others, calling for a moratorium on nanotechnology development (e.g. Bill Joy), others are more pragmatic and work with techno-realists to construct progressive alternatives to the prevailing commercial logic that dominates nanotechnology policy.

These disparate views of technological development and the growing commercialization in science do not map easily onto science, industry, and civil society. Many scientists and engineers in different fields may consider themselves techno-skeptics or techno-realists, whereas many civil society actors can be techno-optimists with respect to information and communication technology, but skeptics with respect to genetically modified organisms or nanotechnology. Thus, it is not surprising that alternative possibilities for the governance of techno-scientific development have emerged both within universities and beyond them. Perhaps the most influential alternative model has been free and open source software (FOSS), which has inspired scientists and other scholars beyond the domain of software to mobilize countermovements (e.g., Everts, 2006; Rai, 2005). For instance, *Creative Commons* was created in 2001 to give authors more flexible control over licensing and use of copyrighted creative works while maximizing public access. Members of Creative Commons subsequently created *Science Commons* in 2005 to remove unnecessary legal and technical barriers to scientific collaboration and innovation. "Built on the promise of Open Access to scholarly literature and data, Science Commons identifies and eases key barriers to the movement of information, tools and data through the scientific research cycle" (http://sciencecommons.org/, October 3, 2007).

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In other areas of science, most notably biology, there have been small moves toward applying alternative models. Within the corporate pharmaceutical world, the single nucleotide polymorphisms (SNPs) Consortium is often heralded as one example of a limited form of sharing that enables innovation (Sachidanandam et al., 2001). In 1996, Nobel Prize winning biologist Sydney Brenner created the *Molecular Sciences Institute* in Berkeley as an independent, nonprofit research laboratory that combines genomic experimentation with computer modeling. Recently, Molecular Sciences has identified itself as an actor in the open source biology movement devoted to publishing its results in the open access literature and offering freely available data, reagents, and methods to researchers. OpenWetWare and the Biobricks (http://openwetware.org and http://www.biobricks.org/ respectively) foundation at MIT are part of an effort to make the field of "synthetic biology" open source through the sharing of laboratory methods and the creation of a registry of "standardized parts" for doing engineering with biological parts. Similar initiatives include *Synaptic Leap* and the *Institute of OneWorld Health*. In addition, various banking and professional organizations also have begun to consider open source-inspired alternatives such as *GenBank* and *Chemists Without Borders*. Members of such communities believe that open source approaches can enable complex problem solving in areas where narrow profit-driven research is seen to have failed (Kepler et al., 2006).

In this paper, we document some nascent efforts to create and catalyze an open source nanotechnology movement – OS Nano (see http://opensourcenano.net) – that seeks to open up the process of experimentation in nanotechnology by finding ways to "vernacularize" the high-tech, expensive practices conducted in the lab. Over the past two decades, nanotechnology has emerged as a critical area for scientific and commercial development, driven both by the scientific community and industry, and also national governments around the globe. The field of potential applications in nanotechnology, supported by a wide panoply of actors (optimist, realist, and skeptic), ranges from key technological advances for national defense to transformative social and economic applications. The nano race was prominently kicked off with the National Nanotechnology Initiative authorized by President Clinton in 2000. Seeded with $500 million in 2001, the US government has continued to increase the pot, reaching the $1 billion threshold by 2005. Western Europe and Japan also invest hundreds of millions of dollars every year.

The prefix "nano" indicates that research and application are focused on innovations at the nanometer scale – a billionth of a meter (1/75,000th the width of a human hair). What makes research in this area innovative is not just that it is small, but that at this scale, materials exhibit properties that they don't at human scales. Gold, for instance, can appear red when it is less than 100 nm in size. Most researchers in nanotechnology have some kind of engineering interest – they are interested in harnessing the properties of these materials to do something, rather than simply seeking to understand them. The US National Nanotechnology Initiative defines nanotechnology not just as the study of these properties, but their exploitation as well (http://www.nano.gov/html/facts/whatIsNano.html). Essential to this mission are a wide range of disciplines, tools, and approaches, drawing upon knowledge in physics, chemistry, chemical engineering, biology, biological engineering, environmental science, environmental engineering, medical research, molecular biology, electrical engineering, surface science and surface chemistry, and materials science. Commercial interest in nanotechnology has driven many of the current applications that extend existing commercial research areas such as more durable tennis balls, lighter and stronger tennis rackets and golf clubs, stain-resistant clothing, wear-resistant tires, cosmetics and sunscreens. The Project on Emerging Nanotechnologies sponsored by the Woodrow Wilson Center for Scholars has catalogued over 500 manufacturer-identified nanotechnology-based consumer products currently on the market (see http://www.nanotechproject.org/44).

Techno-optimists promulgate dramatic, visionary narratives of nanotechnological potential such as space elevators (cables made of carbon nanotubes that stretch into space) (Pugno, 2006), tiny robots that enter the body to attack tumors or clean up the environment, and computers made entirely of nanoscale components. As part of this techno-optimistic imagery, key technology policy-makers across the globe have additionally emphasized that such nanotechnology developments will provide a powerful engine for economic growth that will benefit all peoples (e.g., Roco & Bainbridge, 2001; see Berube, 2006 for a somewhat critical view on nanotechnology hype). Techno-skeptics have suggested other kinds of visionary uses, such as materials for water treatment and soil remediation, cheap noninvasive diagnostics, and other uses that might contribute to the Millennium Development Goals of the UN (Salamanca-Buentello et al., 2005). Techno-realists are interested in all possibilities, but focus more on the pathways by which technologies get developed for use.

From a techno-realist perspective, if nanotechnologies are to really contribute to the enhancement of societal welfare across the rich/poor and North/South divides, while also helping to facilitate economic growth and development more broadly, it is important to evaluate the various mechanisms by which such seemingly conflicting goals might be balanced. As alluded to earlier, a profit maximization focus at the inventor level currently provides the dominant model for policy and governance. However, such a model rewards primarily those applications that can drive metrics of commercial return and intellectual property rights acquisition.

While the commercial model does not preclude the possibility of economic gain from socially beneficial uses, the metrics and models of profit and IPR force them to focus there. An open source approach provides an alternative model and set of mechanisms that emphasizes collective benefits and goals. At a very basic level, open source models reward *re-use* – they reward people whose ideas and technologies are most widely used by distributing credit and attribution to the individuals who create and contribute. This re-distribution of social capital and reputation is often sufficient incentive to participate, and the widespread use of an idea is seen as a metric of its success (Weber, 2005; Feller, Fitzgerald, Hissam, & Lakhani, 2005). The current reality, however, is that since profit-maximizing models of nanotechnology are dominant, alternative approaches will have little impact unless they are voiced, adequately theorized, and articulated with well understood and accepted metrics.

Open source possibilities are important in the context of nanotechnology because such an approach can help focus more directly on goals such as regional economic growth or innovativeness, as well as *use value* of technology by peoples near and far. This is in contrast to *exchange value* metrics such as patents awarded, start-ups created, and revenues generated that dominate current university TTO thinking and are rooted in the inventor–entrepreneur model of profit maximization (see Mars, Slaughter, & Rhoades, Forthcoming). While the profit-maximization model can also contribute to the achievement of collective outcomes, it is unclear if it is the best model, or at least whether it is the only model that should be utilized. In fact, it may be that a stringent IP focus may be appropriate for the development of some innovations, while open source approaches may be more efficacious for others. If we begin to understand better how to measure the social value of innovations, open source models could expand the range of how universities account for innovation success, enabling the accrual of credits for helping to improve the quality of life of impacted populations and, more broadly, society.

However, the open source model is not particularly well understood yet. In particular, the experimental use of the model in domains other than software, such as biology and nanotechnology, has only been systematically studied recently by one of the authors (Kelty, 2008). In the next section, we outline the components that make FOSS work, and show how they might be modulated for use in the general area of nanotechnology, including the limitations of doing so. We then present a case of a specific technology related to arsenic removal that was invented by chemists at Rice University, the first candidate for an open source nanotechnology project. We conclude with a discussion of the implications of open source nano techno-science for current policy and governance of university science and technology commercialization.

EXPLORING OPEN SOURCE SOFTWARE

Current intellectual property systems are based on the premise that forms of IP such as patents provide crucial incentives for the production of useful and commercially relevant knowledge. However, the success of open source software has shown that the individual incentive model rooted in competitive individualism and profit maximization is not the only route to increasing innovation. These new experiments are rooted in collective approaches to knowledge creation that assume that the common resources produced do not get depleted by individual use. Knowledge commons, therefore, differ markedly from the kinds of commons that have historically been the focal point of scholarly discussions in economic and legal studies (see Murray & O'Mahony, 2007); commons such as pastures, forests, and fisheries where resources can be depleted through individual use, resulting in market failure – the classic "tragedy of the commons" (Hardin, 1968, see also Rose, 1986; Boyle, 2003).

FOSS is an exemplary case of a functioning commons that enables widespread availability by providing legally sound protections that create incentives for cumulative innovation and collective benefit, in contrast to narrow self-interest seeking behavior and aggregate resource depletion. A number of studies have explored the implications for theories of collective action and economic theory (Weber, 2005; Benkler, 2006; Lerner & Tirole, 2002). Here, however, we focus on the core practices of FOSS in order to understand in detail what makes it work: (1) shared source code, (2) a defining and standardized open infrastructure, (3) a set of legal tools for dealing with IP law, (4) a set of software tools for managing distributed collective work on source code, and (5) a social movement or ideology that gives meaning to the four other practices (Kelty, 2008). Each of these components is necessary for FOSS to function, but there can be a great deal of variation within them depending on the goals and people involved.

These five components are described in more detail in this section, along with some speculations about how nanotechnology poses new challenges to the model, and how those challenges might be met by "modulating" the existing practices to see whether the principles and practices translate to new domains. Often modulating one component changes others; for instance, when "source code" no longer refers to software per se, but includes things like film or music or scientific data, it is often necessary to revisit the relevant licenses, the relevant infrastructures, and the relevant modes of collaboration in order to ask whether "open source" is possible in the same manner.

Source Code is the Basis for FOSS

Source code is the human-readable version of the software, not the version that actually runs on a computer, which is compiled from the source code and referred to as the binary or executable. Shared source code allows people in distinct locales, using similar machines to compile, install, read, change, and re-compile the software. Without such shared source code, users would share something they could not easily learn from or change, somewhat like sharing a piece of recorded music instead of a playable piece of sheet music. Needless to say, as in the case of playing music, changing and compiling source code requires a lot of skill; however, most FOSS users gain that skill precisely by downloading, studying, and experimenting with source code. A great deal of very high-quality source code has circulated for almost 30 years. Examples that predate FOSS include the UNIX operating system, upon which Linux was modeled, the TeX typesetting language, the LISP Programming language, all of which circulated with the source code intact, allowing people to examine and learn from it. Facilitating such forms of learning is a very common part of Internet culture as well, exemplified by the fact that a "View Source" command is standard in all browsers.

By contrast, proprietary software vendors have always sought to keep source code secret because it represents their intellectual property, trade secrets, and sometimes the key to their competitive advantage. However, keeping source code secret necessitates employing a much larger staff of people, internal to a corporation, who can fix bugs, respond to user complaints, address new demands and needs, update and check the software as it goes through new versions, and so forth. In the FOSS model, such activities are often handled in a distributed fashion by the users themselves, under the theory that "given enough eyeballs, all bugs are shallow" (Raymond, 2001).

What is the source code of nanotechnology? Given that nanotechnology is an inherently interdisciplinary endeavor, there may be several answers to this question. In the domain of engineering, it may include designs, schematics, or actual source code for software related to an engineered material. In materials chemistry (the domain we explore in our case study), the source code is probably best understood as a recipe for the synthesis of a material – in particular, it is a set of detailed instructions for necessary materials and steps in the process of synthesis. Whatever form it takes, however, it needs to be easy to share, easy (and legal) to modify, and should encourage reciprocal contribution of new ideas and collective learning. Without such circulation it simply becomes a static publication of a method.

An Open and Standard Infrastructure is Essential to FOSS

In terms of software, the definition of what constitutes a properly "open" infrastructure includes all those standards necessary to create software: the personal computer with an open architecture, the Internet with its open protocols and less often noted, but equally important, a shared pedagogical tradition among hackers and computer scientists. Both the Internet and the personal computer represent de facto standards upon which FOSS creators can rely: software can be made to compile across all machines, with a limited amount of architectural variation (thanks in no small part to the near monopoly of chip-maker Intel) and can easily be shared and transported on the Internet using freely available tools. It is not an accident that FOSS emerged with such force only after the Internet became the de facto standard for Internetworking. Without such standard definitions of "openness," it would be impossible to reliably replicate FOSS around the world and on millions of machines.

When considering the applicability of the FOSS model to different domains, it is therefore important to distinguish between the specific characteristics of shareable and re-usable software source code and the extensive, standardized infrastructure that allows it to circulate. Many people suggest that FOSS is possible because of the unique characteristics of source code. For instance, one might argue that the test of whether software "works" is whether it compiles, and this is taken to be an essential feature of software as such. A film, it is suggested, "works" for different reasons (e.g., the director's vision) and cannot meet the same test and therefore it makes no sense to make "open source film." The reason code compiles, however, has as much to do with the extrinsic and extensive nature of the infrastructure (the Internet, standard PC architecture, freely available compilers) that allows it to circulate as it does its intrinsic qualities. Similarly, the question of what constitutes the "source code" of film is different from what infrastructures enable the circulation of film through standardized, open channels (e.g. the existence of cinemas, for instance, or of videotape and DVD players).

What is the "infrastructure of nanotechnology? Here much of the infrastructure overlaps, in the form of the Internet and the standard PC architecture, which allow for the circulation of information about chemistry, physics, or engineering in much the same manner as software is circulated. However, a recipe is only as good as the cook, so such circulation relies on the existence and interest of other chemists or nanotechnologists, be they experts or novices, who are familiar with the "tacit" components of executing a recipe (Collins, 1992). As in the case of software, where there is a great deal of nonexplicit expertise required to get software to work, the largest challenge for an open source nanotechnology will be finding the most "open" infrastructure whereby people all over the world might be able to easily replicate the recipes created in high-tech laboratories.

Free Software Licenses Help Manage the Complex Legal Relations of Collaborative Creation

Free software licenses are well known because of the way that they cleverly invert the strong rights granted through copyright law. Copyright law, which is broadly applicable in the domain of software, automatically grants creators rights to copy, distribute, reproduce, modify, perform, or display the material. It also gives them the right to license this work to others. While all FOSS is copyrighted (a common misconception is that FOSS is anti-copyright), it does not insist on "all rights reserved" (see O'Mahony, 2003). Instead, free software is made available with a very minimal set of restrictions, which usually include only the requirement of attribution (so called BSD-style licenses), and in stronger cases, the requirement that subsequent users offer their modifications on the same terms (GPL-style licenses, also called share-alike, reciprocal, or viral licenses). There are two reasons for using free software licenses. The first is that many in FOSS want to see software be freely available because it enhances the liberty and freedom of individuals to experiment with and transform the software they use; the second is that such licensing actually lubricates the circulation of software, and facilitates the widespread re-use, testing, and improvement of software. Most software projects rely instead on *trademark law* to maintain the identity of their "property" without interfering with the rights of others to take the material in new directions.

The Linux operating system kernel, one of the most well-known FOSS projects is exemplary in this respect. It uses the GPL license, which demands that re-uses or modifications of the Linux kernel be offered under the same terms. There is only one Linux kernel project however, because of the strong incentives created to contribute back to this project, rather than "forking" a new project (Weber, 2005; Raymond, 2001). In addition, trademark protection around the name Linux, which is very loosely policed, seeks to prevent derived works from being confused with the original project. Patent law, by contrast, is not explicitly invoked in FOSS, although it is an area of deep concern, given the ease with which it is possible to infringe on software patents that make broad claims. Contributors to the project are asked to ensure that their contributions do not infringe on known patents.

Licensing nanotechnology data and recipes is trivial where copyright is concerned, thanks to the existence of FOSS. Numerous different licenses (such as the Creative Commons licenses) are easily available. Where the challenges are greater is with respect to patents, which are much more common in the various fields of chemistry, physics, and engineering than they are in software, and harder to work around. As yet, there is no standard open source patent license, though in principle, such a thing is possible.

FOSS Requires Tools for Managing and Facilitating Contributions

Although it is popular to imagine that FOSS relies on a form of emergent self-organization to create software, there are actually a number of concrete ways in which FOSS projects manage the creation of software. Many of these are already familiar to modern organizations, but differ in this case because of their entirely voluntary character. FOSS relies on governance schemes of various sorts: individual "benevolent dictatorship" as in the case of Linux, structured oligarchy as in the case of the Apache Foundation, or hierarchies of various sorts (see O'Mahony & Ferraro, 2007). In addition, software tools like mailing lists, bug tracking systems, and most importantly source code management (SCM) tools allow for a minimalistic approach to management, and combine technical and social forms of coordination into a meaningful technical practice available to all volunteers.

One can categorize various FOSS and FOSS-like projects by the kinds of technical and social forms of governance they use. Wikipedia, for instance, disavows any explicit form of governance, and instead relies entirely on the technology to mediate disputes and resolve differences. Anyone can contribute or make a change without asking permission. Over time, some long-term contributors develop credibility and reputation to which new entrants often defer, and which has developed into a recognized hierarchy. Order in Wikipedia emerges through the kinds of social interactions that persist throughout the life of an entry, and through the continued interactions of users. Linux, by contrast has a very highly ordered hierarchy of responsibilities, and while anyone can propose changes, or make changes and redistribute them on their own, only a limited number make it into the official release of Linux. This kind of order also developed through the course of the project, but there has always been an explicit hierarchy of decision-making about which contributions to include. Other projects, like the Apache Webserver, or the Perl scripting language, have developed yet other systems of governance and coordination.

The success of coordination also relies to a large extent on the design strategy, and background knowledge of participants. Projects that are highly modularized, clearly documented, and which encourage extensibility from a core, are often much more successful than those that have a monolithic top-down design strategy. Similarly, most FOSS projects are re-inventions of established technologies (Linux replicates UNIX, Open Office replicates Microsoft Word), which means that projects can rely on a base of design and engineering expertise regarding how to build such objects. Similarly the success of Wikipedia rests on the widespread recognition of the encyclopedia entry as an established and well-developed form of writing. Creating something fundamentally new poses challenges in FOSS as much as in any other realm.

The challenges and resources for collaboration in software are easily transported to the domain of nanotechnology, but remain no less daunting. An open source nanotechnology project needs constant communication, clear leadership, clear goals for its participants, a liberal sharing of credit and attribution of contributions, and a clever use of available software tools for keeping information updated, responsive, noncontradictory as well as legal and safe. There is much to learn from how successful FOSS projects manage collaboration among volunteers, but very little of it is well codified to date.

FOSS is a Social Movement, Not an Organization

Particular projects can be organized in different ways, often as a result of different goals and strategies. However, participants are often deeply sensitive to the difference between a free and open project and one that is not. A key reason for this, and a key component of the movement, is dialogue – participants talk to and learn from and argue with one another continuously and do so in open forums – mailing lists, bulletin boards, publications, and so forth. As they do so, they develop more and more sophisticated understandings of the four practices listed above. The fact that there are two names, free software and open source software, was largely a result of this kind of dialogue. In 1998, when IBM and Netscape were convinced to release some of their software as free software, a group of the more high-profile hackers and programmers and supporters of free software – Eric Raymond, Bruce Perens, Tim O'Reilly, and others – made a bid to re-brand free software as open source in order to appeal more broadly to the business and investment climate of the dot-com era (DiBona & Ockman, 1999; Kelty, 2008). Neither term has become ubiquitous, and both have enthusiastic supporters, even though there is no practical difference between the two with regard to the four practices outlined above.

Over time, the five components of FOSS have captured the attention of people in domains far from software programming. Different groups have tried to apply bits and pieces in different ways. The aforementioned Creative Commons has perhaps been the most visible and successful; it was created primarily by lawyers (Lawrence Lessig and James Boyle), not hackers or programmers, and has created a global dialogue about the problems of intellectual property law, the challenges and promises of "remix culture," and the need for clarity in legal terms. The licenses they provide are applied to a wide variety of cultural productions, but principally digital text, audio, and video. A related project that emerged at the same time was The Connexions project at Rice University, which seeks to create a repository of openly licensed, collaboratively authored textbooks for use in education. Connexions replaces "source code" with "textbook modules" (short chapters or lessons), uses Creative Commons licenses, and tries to encourage communities of scholars to work collaboratively on and re-use material in the Connexions repository (Henry, Baraniuk, & Kelty, 2003).

Other projects have drawn inspiration from FOSS without necessarily transferring all of the practices. "Open Access," for instance, is a movement to improve access to scientific and scholarly work, and while it takes the form of a movement, and may promote the use of free software-style licenses, it does not challenge the conventional forms of collaborative production in the sciences or humanities, only the process by which the results are made available (Suber, 2002; Harnad et al., 2004). Other supposed uses of FOSS principles may share nothing but the name, such as "Open Source yoga" which was primarily an anti-Bikram Yoga movement that objected to the idea that yoga poses might be the intellectual property of an individual or corporation (Fish, 2007).

Finally, movements cannot be created – they emerge from the interactions of people who share a set of goals and ideals, but are free to voluntarily contribute and to become leaders if they wish to. In many ways, the success of FOSS has depended on it being independent of both the university and the commercial world, free to evolve and maintain its own identity without being owned by one or another. This is perhaps the greatest challenge for open source nanotechnology. Universities and corporations foster a very strong sense of both formal and informal ownership of ideas and successes (both through norms of competition and through intellectual property rules as well), creating an environment in which it is difficult to share credit widely. Without taking that step, the invitation to the wider world to participate will fall on deaf ears.

TOWARD OPEN SOURCE NANO: MAGNETITE NANOCRYSTALS FOR ARSENIC REMOVAL (AND BEYOND)

The OS Nano project we report on here currently consists of only one case of research in nanotechnology: synthesizing magnetite nanocrystals, potentially useful for removing arsenic from water (see http://opensourcenano.net). We briefly review the specifics of this technology (a full recipe can be found on the website) followed by a discussion of the challenges for the development of opens source approaches to nanotechnology.

The goal of the OS Nano Magnetite project is to enable widespread access to technological know-how that can address pressing social problems such as removing arsenic from water to make it potable. Magnetite nanocrystals may have an array of uses not limited to arsenic removal; however, the project differs in some crucial ways from similar efforts to provide ‘‘appropriate technology’’ to developing nations. In terms of the older, linear model of development, OS Nano is inviting people to participate very far ‘‘upstream’’ in the process, by communicating with scientists who have sought to make the process easier to perform outside of the relatively elite and scarce labs of research universities. In terms of a richer ‘‘hybridized’’ model of innovation, what OS Nano offers, is the chance to introduce feedback loops into research that includes direct engagement with potential users of a technology even as it is being invented, refined, developed, and deployed.

The specific technological innovation we describe involves the process of synthesizing magnetite nanocrystals (Fe_3O_4). Magnetite (along with its crystal sister maghemite (γ-Fe_2O_3)) have been extensively studied because of their unique and tunable magnetic properties (Cornell & Schwertmann, 2003). Their magnetic features have found widespread use in applications as diverse as environmental remediation, magnetic recording, and magnetic resonance imaging (Tartaj, Morales, Veintemillas-Verdaguer, Gonzalez-Carreno, & Serna, 2003). What makes magnetite nanocrystals different from normal magnetite is that the size of each of the individual crystals is precisely controlled during the synthesis of the crystals. Which is to say, these magnetite crystals are *made*, not found in nature, and as a result we can control some of their properties, such as producing a regular size, in order to take advantage of their magnetic properties. In order to test the materials and to develop these properties, it is necessary to produce large amounts of identically sized and shaped particles of magnetite (i.e., they must be "monodisperse"), generally having diameters from 10 to 25 nm. This gives them large and permanent magnetic dipole moments (Kryszewski & Jeszka, 1998).

There are currently four different laboratory methods for synthesizing magnetite nanocrystals in nonaqueous solutions. The method we employ is called the "solvothermal decomposition of iron oxide hydrate in the presence of oleic acid" (Yu, Falkner, Yavuz, & Colvin, 2004). The method is simple, requiring only one step and three reagents, whereas the others (Jana, Chen, & Peng, 2004; Park et al., 2004; Sun & Zeng, 2002) employ either multiple steps or five or more reagents. All of the methods are costly, however, rendering them unfeasible in a large, multi kilogram scale applications such as water treatment and arsenic removal (Yavuz, 2006; Yean et al., 2005; Mayo et al., 2007).

An alternative approach to reducing cost without sacrificing quality is simply to replace the costly reagents with less pure ones. This is the strategy we chose – the "vernacularization" of the synthesis method. We replaced iron oxide hydrate with rust and high-grade oleic acid with a fatty-acid mixture made from household cooking oil, drain cleaner, and vinegar. Table 1 shows the 100-fold decrease from the original synthesis to the affordable, green synthesis route (see Woodhouse, 2006 for a discussion of the limited development of green chemistry in nanoscience).

In the field of nanotechnology there are currently few existing green and affordable synthesis methods. Sapra, Rogach, and Feldmann (2006) used olive oil and terminol 66 (Asokan et al., 2005) as the solvent to create cadmium selenide (CdSe) nanocrystals. As they report, the quality of the

Table 1. Cost Comparison of the Synthesis of Magnetite Nanocrystals with Pure Lab Chemicals and the Everyday Chemicals.

AU :1

Pure Lab Chemicals		Everyday Chemicals	
Chemical	Price per kg	Chemical	Price per kg
FeOOH	\$778.00	Rust	\$0.20*
Oleic acid	\$20.60	Edible oil (coconut oil)	\$0.25
1-Octadecene	\$24.75	Crystal drain opener (NaOH)	\$1.24
		Vinegar	\$0.65
Magnetite nanocrystals	\$2,624.00	Magnetite nanocrystals	\$21.7

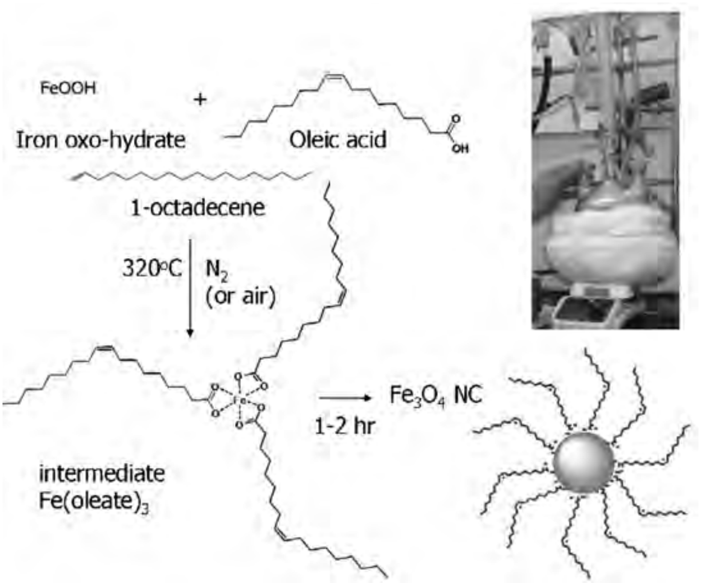


Fig. 1. Mechanism of the Solvothermal Decomposition of Iron Oleate for Magnetite Nanocrystals. Inset is a Picture from the Batch Setup.

nanocrystals remained the same, but the cost was drastically reduced. Based on previous work (Yu et al., 2004; Jana, Chen, & Peng, 2004; Park et al., 2004; Sun & Zeng, 2002), we discovered that a major intermediate is iron (III) oleate (a direct salt of iron (III) with oleate anions). Fig. 1 shows a schematic outline of the reaction.

By exploring the details of this theory of the synthesis of magnetite, we were able to propose replacements for the key ingredients. Rust (collected from any available source, in our case on the Rice University campus) is a perfectly affordable, nearly free replacement for FEOOH, which is the iron precursor we used in the lab. Similarly, household oils combined with lye, or drain cleaner can produce soap (a common household chemical reaction in most parts of the world) and can be used to replace the oleic acid used in the lab. If we acidify the soap by adding vinegar and cooking it, we obtain what we call a "fatty acid mixture" (FAM) which has four significant constituents: oleic acid, linoleic acid, stearic acid, palmitic acid (see Fig. 2).

In a typical green synthesis route, we first produce soap from the edible oils. One could also use nonedible triglycerides since triglyceride is one of the essential ingredients. The recipe is relatively simple, and a detailed version can be found on the website. First, we make soap using oil and crystal drain opener (or potash). It takes about 15 min to make the mixture, and a couple of days to a week for the soap to dry and cure.

Once the soap is made, it could be used for normal household cleaning purposes (though making soap that doesn't dry your skin is obviously a fine art!). We use it here for making the FAM. We used a cheese grater to grind the soap and mixed it with the white vinegar and heated it until it dissolved

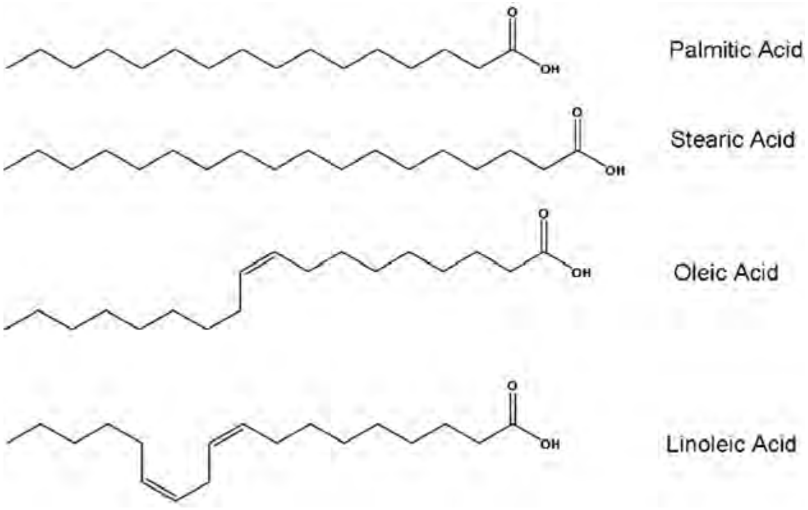


Fig. 2. Four Major Fatty Acids that are Mostly Found in the Oils. Twelve of Oil Types Contain these 90% (w/w) or More (Gan Food Chemistry).

(it boils and takes about 15–30 min). When the solution cools, two layers form: the top more yellowish layer is separated, using a funnel, or fat separator (or a spoon, syringe, etc.) into a clean glass/steel jar. Further heating and boiling clears the yellowish cloudy solution to produce the FAM. Fig. 3 shows the entire chemical scheme for the production of FAM.

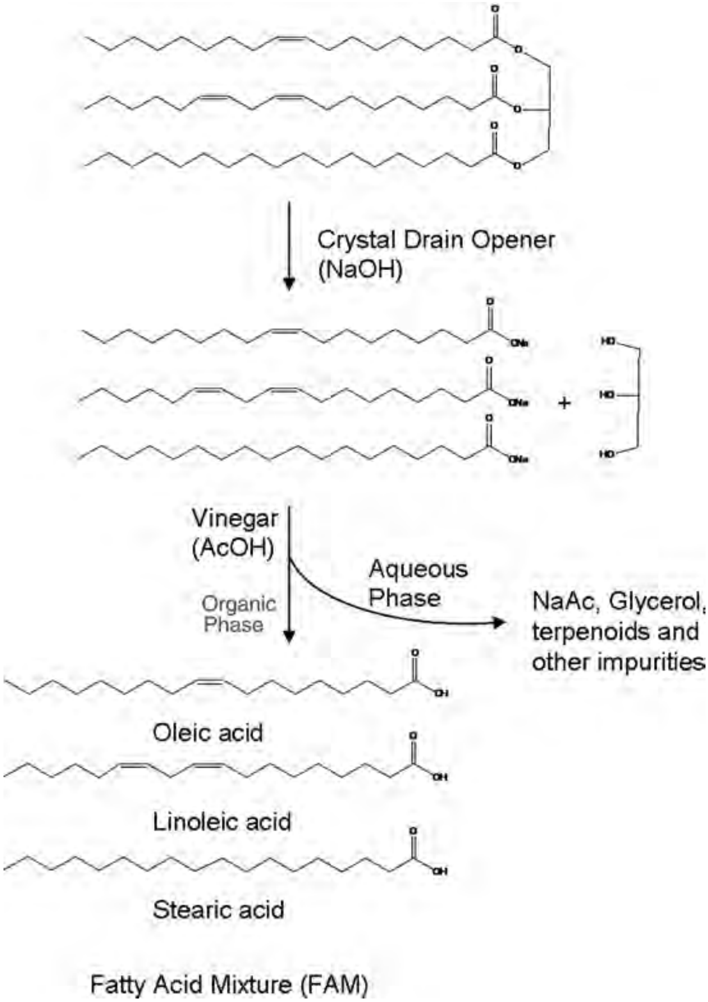


Fig. 3. Production of Fatty Acid Mixture (FAM) from a Triglyceride.

The remaining ingredient needed was rust. Rust was collected by shaving off rusted tools and metal objects and ground into fine powder. The rust is mixed with the FAM and once again cooked. This stage produces smoke and steam, so it is best done under some kind of ventilation hood or outside. The mixture is cooked for 2 h until achieving a fully black, waxy, sticky mess with little or no further smoking. With this setup, 50–90 nm nanocrystals were achieved but if 15–20 nm nanocrystals were desired a steam/pressure cooker is suggested.

Since the magnetite crystals we are using are intended to be used for removing arsenic from water, making the crystals waterborne is an important step. We achieved this by mixing the waxy black deposit into soapy water, then filtering the water. At this point, the nanocrystals could be separated from the water by using a magnet, washing them with water or alcohol, resulting in the final product of pure nanocrystal magnetite of regular size. The entire process of magnetite nanocrystals synthesis is shown in Fig. 4. Results show that the crystals produced in the kitchen are comparable to lab synthesis using expensive chemicals (see Fig. 5). The resultant crystals can then be used to absorb arsenic in water. Selected as one of Esquire magazine's *six ideas that will change the world*, this technology requires no electricity or manufacturing infrastructure, enabling those at the bottom of the pyramid to easily and efficiently purify water at point-of-use (Ajudua, 2007).

Challenges for OS Nano

This case exemplifies the challenge of finding an ''open infrastructure'' for nanoscience and nanotechnology. The fundamental insight in this case was that that recipes and procedures that are possible in the lab need to be made ''vernacular'' – widely accessible, simplified, and transferable to multiple contexts. By transforming the recipe from something that requires access to a high-tech, expensive laboratory in an elite university, to something that can be conducted in nearly any kitchen around the world, OS Nano's magnetite project takes a huge step toward facilitating the core of a FOSS model: the ability to download, tinker, change bits and pieces, and contribute the changes back to the project. But this is also a point of important difference: there is no strict equivalent to the standard PC architecture for nanotechnology, so any given OS Nano project needs to identify and exploit the most standard possible infrastructure in order to be widely re-usable. In the case of magnetite production, this infrastructure is

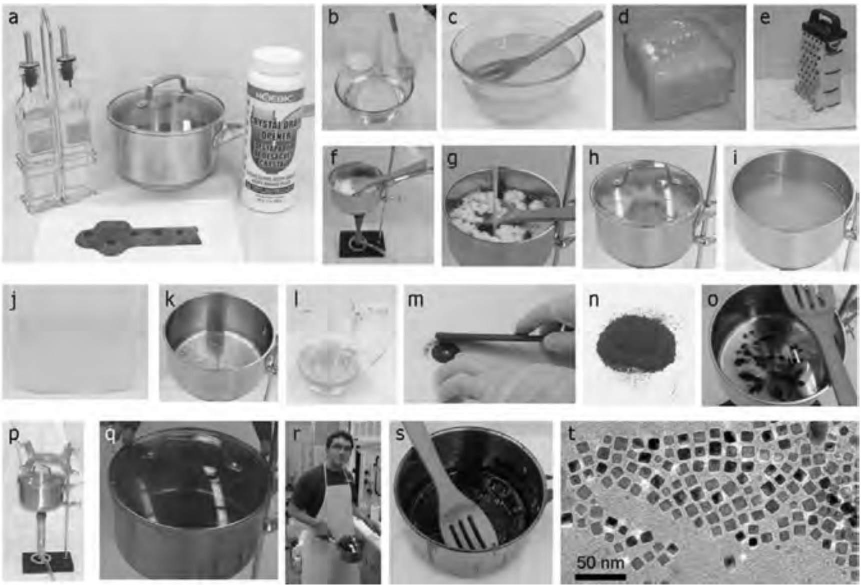
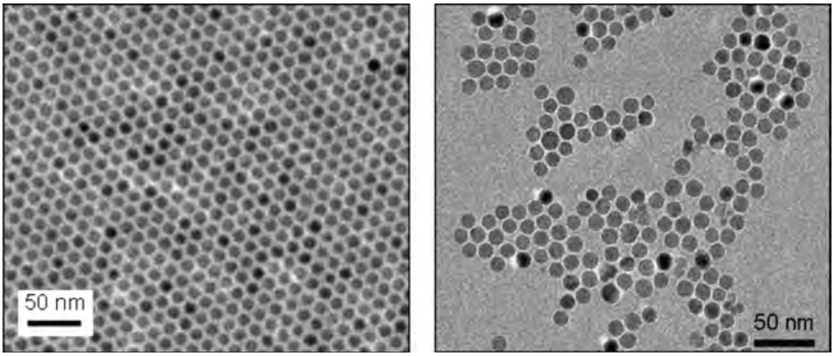


Fig. 4. Scheme of the Synthetic Process. (a) Ingredients for a Typical Nanocrystal Synthesis Include: Oil, Vinegar, Pan, Crystal Drain Opener™, and rust. (b–c) Synthesis Begins with Soapmaking. For This the Oil is Mixed with Crystal Drain Opener and Water. (d) After Curing for a Day the Soap Solidifies. (e) For Efficient Dissolution in Subsequent Steps, the Soap is Ground to a Fine Powder, (f) Then Mixed with Vinegar (g–h) While Heating on a Stove. (i–j) Once all the Soap is Dissolved the Solution Forms Two Layers: A Yellow Top Layer and a Cloudy White/Yellow Bottom Layer. (k) The Top Layer is the Fatty Acid Mixture (FAM). This Needs to be Heated at 110°C to Remove Excess Water and Vinegar By-Products. (l) Clear Yellow FAM is Collected. (m–n) Rust was Scraped off of Rusted Metals and was Ground to a Fine Powder. (o) FAM and Rust were Mixed. (p–q) Mixture was Heated for 2 h at Below and Near Boiling Temperatures. The Temperature was Measured Using a Standard Mercury Thermometer. (r–s) Magnetite (Black) Began to Form. (t) TEM Micrograph was Obtained After Magnetic Separation in Chloroform. Scale Bar is 50 nm.

literally the kitchen (or more generally, tools, materials, and machines available at the broadest consumer level).

In terms of licensing, the recipe itself is licensed under a Creative Commons Attribution license, which allows both commercial and non-commercial exploitation of the recipe. The difficult part of the project, however, is the relatively more important influence of patents in chemistry,



Lab Synthesis (10.84 ± 0.55 nm) Kitchen Synthesis (12.04 ± 1.23 nm)

Fig. 5. Magnetite Nanocrystal Synthesis from FeOOH in the Lab Versus the Kitchen.

biology, and engineering. Whereas FOSS does not employ patents, and seeks primarily to avoid infringing on them, engineers, TTOs at universities and corporations are extremely likely to patent widely, and aim to make broad claims in the patents they file. This creates two classes of patents that threaten the success of OS Nano: the first are those patents that the recipe infringes upon, if any; the second is the patent on the procedure itself. In the former case, if the recipe infringes on existing patents, the onus is on OS Nano to find an alternate procedure. The strategy of "vernacularization" serves well in this instance, since it seeks to identify not only a widely available set of materials and processes, but hopefully those that are not covered by patents as well. In other cases, there may be no feasible way around a patented procedure, vernacular or otherwise.

In terms of any patents on the recipe itself, a licensing scheme similar to that of the BSD-style licenses can be employed, which grants anyone commercial or noncommercial rights to employ the process. If, however, one wanted to replicate the function of the GPL-style license (reciprocal, share-alike licenses), it would be necessary to grant the right to the patent contingent on the requirement that any infringing use of the patent would also be released under similar terms. To date, there are no examples of such patent licensing schemes, and given the costs associated with simply filing, it creates an incentive to commercialize the procedure in order to recoup costs, rather than distributing it widely. With regard to coordination, the major challenge to OS Nano's magnetite project is in finding collaborators willing to experiment with the recipe and to help improve it. The recipe itself can be managed in the same way that source code is, using software that allows for updating and versioning of text. The governance of the project at the outset is extremely open, since the project seeks primarily to disseminate the process, and has as yet no need of a mechanism for solving disputes, or determining which kinds of changes to the recipe to allow. Historically, such governance structures in FOSS have evolved more or less organically along with the software, and there is reason to follow this lead in order to maintain maximum flexibility.

Finally, there is as yet no "open source nanotechnology movement" since there is not yet any open source nanotechnology. However, such a movement is perforce a result and not a precursor of an experiment such as OS Nano. Generating interest in an open source magnetite nanocrystal recipe will require active work to find those people interested in participating, rather than simply expecting a world of eager contributors to emerge from the Internet.

CONCLUSION

OS Nano and the magnetite project are in the experimental stage, but they emerge out of and draw on debates and practices that stretch back at least 20 years, and which are a response to the changing conditions in which science and technology are pursued today, after Bayh-Dole, after the growth of biotechnology, after the dot-com boom and the spread of the Internet. The questions they raise go straight to the heart of how we conceive of innovation, and more generally the relationship of scientific knowledge production to its effective use, and commercialization, in the world at large.

The OS Nano project envisioned here raises two separate points for discussion: the first is how much of FOSS is necessary for OS Nano to be successful? and the second is will a successful OS Nano translate into a successful alternative to conventional technology transfer? The first question can only be answered experimentally, as part of the process of creating and promoting OS Nano itself. The second question is the one we dwell on here at more length.

First off, what metrics should one use to measure the success of FOSS? There is of course, no reason to stop measuring success in terms of profit and revenue, but in the case of FOSS, that revenue is not tied directly to patent and copyright portfolios. The value chain created by FOSS creates new possibilities for revenue at other levels such as service, support, customization, and certain forms of value-added innovation, all of which can produce measurable revenue, if one discovers ways to capture and track that revenue other than by relying on the monopoly grant of intellectual property.

The value that FOSS creates, as we have mentioned, is not in the direct revenue from IPR, but the model by which its innovations are widely adopted and used, and through which individuals and institutions receive credit and a form of social capital that institutions and corporations are slowly learning to measure. For most scientists and engineers, there is more satisfaction in knowing that their innovations are being widely used, and that their name is associated with that innovation, than there is in a yearly royalty check from a patent.

Nonetheless, it is possible, though difficult, to continue to use patents as a metric even in a FOSS-inspired model. However, what would count is not revenue from patents so much as the *number of users of a patent*. If TTOs experimented with ways to freely (or at least very, very cheaply and easily) license the patents they hold, on the condition that subsequent uses credit the inventor and/or the university, they could begin to measure impact in a different way. This requires, of course, that patents be licensed nonexclusively.[1] In this way, TTOs might also be able to measure different uses of one patent – some for commercial purposes which fulfills a university's mission, even if the revenue generated does not return directly to the university, and some for the social justice, environmental or health uses that the process or product fulfills. In contrast to prevailing patenting practices that seek licensing deals that necessitate contractual obligations to produce revenue and royalties (or else languishing in a corporate patent profile until they expire), the FOSS model at least opens up the possibility for using patents as a kind of innovation measurement tool.

AU :3

Another issue raised by the analysis presented here is how to capture the value of the "lateral transfer of knowledge" – the case where two different users of a technology learn from each other, because of a shared problem or context, rather than a measurable flow of knowledge among designated and contracted entities. Lateral transfer of knowledge is at the heart of FOSS innovation, because there is no requirement to ask permission, or to go through a principal in order to make a change or improvement in a technology; additionally there is an incentive to contribute the knowledge gained in these local contexts back to a global project, under the theory that there may be others who can learn from it as well. Such an activity is too context-driven and too dispersed to yield large revenues, but is a practice that is actually prevented by the current IP system.

Finally, in terms of metrics for use and re-use (rather than revenue and royalty), a FOSS model encourages TTOs to pursue more than one path at once. In the world of patents, the only thing that matters is the exclusive license, so TTOs are betting on a single licensee to commercialize and make a success out of a university's work. In an open source model, TTOs can bet on many horses. Some might yield revenue, but more likely because of the requirement of attribution, they will yield social capital and recognition (Goode, 1978).

Many proponents of the existing system like to imagine that we live in a world where the patent system works well, if not seamlessly. In this model, all knowledge is patented, and if you need someone else's knowledge, you simply purchase it, and the more valuable it is, the more expensive it is. But in practice, the system doesn't always work this way. Instead it can lock up knowledge in 20-year chunks, force negotiations for even the most trivial of uses, and force people to work around what they cannot purchase. FOSS models provide an alternative that not only creates better possibilities for socially valuable uses of knowledge, but might also contribute to a more competitive innovation-based economy. In addition, it can open up important discussions about the nature of the university as well as how to maximize societal impact in a way that takes seriously the reality of societal and global inequalities.

NOTE

1. It is possible, even in this case, to imagine a way to "have one's cake and eat it too": TTOs could employ a dual-licensing strategy, in which all the patents are nonexclusively licensed with a GPL-like restriction (i.e., if you want to use this patent, your use of it also has to be openly licensed). If a corporation wanted to avoid this requirement, they could then re-negotiate a separate non-GPL license for a fee. Such a strategy would provide a way to collect licensing fees from multiple users, rather than negotiating only one, complex, exclusive, royalty-sharing license. It could increase the possible benefits of the patent, because multiple parties can compete to commercialize it, and if they see no incentive to, neither the TTO nor any corporation has lost any money on the patent, which is still freely available for them to use.

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