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Abstract

We consider software developers who can either work on an open source project or on a closed source project. The former provides a publicly available signal about their talent, whereas the latter provides a signal only observed by their employer. We show that a talented employee may initially prefer a less paying job as an open source developer to commercial closed source projects, because a publicly available signal gives him a better bargaining position when renegotiating wages with his employer after the signal has been revealed. Also, we derive conditions under which two effects suggested by standard intuition are reversed: a "pooling equilibrium" (with both talented and untalented workers doing closed source) is less likely if differences in talent are large; a highly visible open source job leads to more effort in a career concerns setup. The former effect is because a higher productivity of talented workers raises not only the value but also the cost of signaling; the latter stems from more effort and the choice of a high visibility job being substitutes for the purpose of signaling. Results naturally apply to other industries with high and low visibility jobs, e.g. academic rather than commercial research, consulting rather than management.

Keywords: Open source software, signaling
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1 Introduction

Freely distributed Open Source Software is becoming ever more important. For example, the notional value of investment in Open Source Software in Europe and the US is €58 billion which is 20% of overall software investment.[1] Open source software development involves software developers at many different locations and organizations sharing a code to develop and refine software. In recent years, open source development has generated innovative products such as the Apache web server which have been rapidly diffused and now dominate their product categories. In the personal computer operating system market, the open source software Linux represents an important challenge to Microsoft's dominant position in this market.

One of the puzzling phenomena of open source software is that individuals or firms participating in open source projects often do not earn any money by working on such projects. According to Lerner and Tirole (2001), commercial firms are characterized by a "rather lenient" attitude towards their employees' participation in open source projects. In fact, IBM is reported to have spent more than $1 billion supporting the open source operating system Linux and Google offers its engineers "20-percent time" so that they are free to work on what they like to.[2] As Lerner and Tirole (2005) point out, "the decision to contribute without pay to freely available software may seem mysterious to economists." In our model, we explain activity in open source projects based on the assumption of rational economic behavior by individuals.

Participation of individuals in unpaid open source projects can be ex-

[1] See the study for the European Commission "Economic impact of open source software on innovation and the competitiveness of the Information and Communication Technologies (ICT) sector in the EU" (2006), `http://www.flossimpact.eu/` (accessed on August 12, 2008).

[2] See BusinessWeek, January 13, 2005 and `http://www.google.com/support/jobs/bin/static.py?page=about.html&about=eng` (accessed on August 12, 2008).

plained with signaling: by participating in an open source project a software developer signals to future employers that he is a talented programmer – an idea first mentioned in Lerner and Tirole's (2001) description of key research questions in the economics of open source. As an illustration, there are many examples of prominent open source developers later on accepting a job in a commercial enterprise at good conditions. Linus Torvalds developed the open source operating system Linux during his studies from 1988 to 1996 at the University of Helsinki and was hired after graduation by the California based start-up Transmeta Corp., known for hiring other well known figures from the open source community.[3] The creator of the open source programming language Python, Guido van Rossum, was hired by Google in December 2005; Python has played an important role for software development at Google from the beginning.[4] Jim Hugunin developed in an open source project a version of Python compatible with Sun Microsystem's Java platform. He was hired by Microsoft in 2004 to develop a Python version for their competing .NET platform, a task that had been previously considered as challenging yet important to achieve in a feasibility study done under contract to Microsoft.[5] Microsoft also hired several other prominent open source developers for various projects.[6] And further, as mentioned in Lerner and Tirole (2001), former open source developers have easier access to venture capital: e.g. both Sun and Netscape were founded by former open source developers. Venture capitalists are in many ways similar to the employers in our model.

However, signaling as an explanation raises several questions. Why do talented programmers not get paid jobs and signal their talent to their em-

[3]http://www.linux.org/info/linus.html (accessed on August 28, 2008).

[4]http://www.python.org/~guido and http://www.python.org/about/quotes (accessed on August 28, 2008).

[5]http://www.jython.org/Project/history.html, http://blogs.msdn.com/hugunin/archive/2004/08.aspx (accessed on August 28, 2008) and Watkins, Hammond, and Abrams (2002, p.355).

[6]http://www.microsoft.com/opensource/heroes/heroes.mspx (accessed on August 28, 2008).

ployer in a commercial project?[7] And why do firms let their employees work on open source projects while being paid? At first sight, this seems only to increase the probability of the employee getting a better job offer elsewhere. Further, supporting an open source project might reveal trade secrets to competitors and cannibalize demand for commercial projects of the same firm.

We argue that programmers work on unpaid (or less paid) open source projects to solve a hold-up problem for talented employees: if the signal created by a talented employee is only observable by his employer, the talented employee will only get the average wage of job switchers from other employers in case he switches jobs. As we will show later, this average wage is equal to the productivity of untalented workers in equilibrium. Therefore, he will only get a part of his observed productivity increase when renegotiating his wage after the signal has been revealed. A talented employee may try to avoid this hold-up problem by first signaling his abilities to all employers in an unpaid open source project and then getting a well paid job.

By the same logic, one can argue that a firm may be willing to let programmers develop open source software while being employed. Firms do this in order to credibly commit to paying higher wages after observing a good signal and thus be able to attract talented programmers. We analyze under which conditions an employee chooses to participate in a commercial open source project.

Our model yields several results which are suggested by intuition. However, for two results, standard intuition can be misleading. First, it seems less likely that talented programmers choose to do closed source development if there is a large productivity difference between talented and untalented programmers. Second, one would believe that working in a highly visible

[7]One could argue that in a commercial firm, they would first get "boring" projects with little signaling value; an open source project would allow them to signal immediately. However, one would need an explanation why a commercial firm would not let its employees first do jobs with a high signal first.

open source job leads to a higher effort level in a career concerns setup where future employers cannot distinguish whether success is due to effort or talent. Interestingly, a formalization of the model shows that there are conditions under which these results are reversed. While we derive these conditions explicitly in the main text, we can already state the basic intuitions here. For the first result, a higher productivity of talented programmers has the following two countervailing effects. It increases the value of signaling. But it also increases the opportunity costs of signaling, since initially working on an open source project means giving up the average productivity wage in the first period. The latter effect can dominate. The second result stems from the fact that signaling one's ability through choosing open source development is in a sense a substitute for effort in a career concerns setup. If you are willing to make the success or failure of your project public *ex ante*, then people will attribute say a possible failure of your project less to your abilities and more to bad luck *ex post*.

Even though our main example is open source software development, our results carry over to any industry with highly visible and less visible jobs, in particular to research carried out both in academia and in the private industry. Examples include research in the pharmaceutical and the financial industry, where there is high labor mobility between academia and the private industry. Related to this is also the observation that many business graduates start their career at highly visible jobs with consulting firms and hence signal their abilities not just to their employers but to the clients of their consulting firms as well. They can benefit from this public signal at a later stage of their career when they leave consulting. There are several further examples discussed in the empirical literature. Loveman and O'Connell (1996) report that software developers often get job offers from clients after having worked with them on site. According to Autor (2001), "between 11 and 18 percent of Temporary Help Service workers placed on assignment in a calendar month are directly hired by clients". Chevalier and Ellison (1999) consider mutual fund managers as public figures whose performance is readily observable and find that a mutual fund manager's probability of retaining or improving his current position is increasing in his performance, measured by the risk-adjusted return he achieves. Along the same lines, Massa, Reuter, and Zitzewitz (2006) find that mutual funds administered by managers whose name is disclosed earn slightly higher returns than anonymously managed funds. Even though the concept that some jobs are more visible than others is wide spread, we use open versus closed source as our motivating example because there is a clear technological and legal commitment[8] to disclose workers' contributions in open source projects and hence provide a publicly observable signal.

Besides shedding light on the effects of disclosure policies, the purpose of this paper is to describe one effect that makes open source development more attractive. We do not claim that this is the only effect that explains participation in open source development. There are of course other effects as well. For instance developers may be motivated by altruism, the desire of peer recognition, and by enjoying developing software. Firms may participate in open source projects to improve their corporate image, to commit to cooperation with other firms in an incomplete contracts setup (Niedermayer 2007), and to increase sales of a commercial product complementary to the open source software.

Note also that we make the simplifying assumption that visibility can only consist of either of two extremes: potential outside employers observe no signal at all or they observe a signal as good as the employer. In reality, there are intermediate levels of disclosure: closed source projects can list the

[8] In public open source software repositories such as Sourceforge.net, log files of changes made by individual contributors are kept and accessible by the public. On the legal side, the GNU General Public License obliges firms incorporating open source software in one of their products to disclose the source code they add to this product (see http://www.gnu.org).

names of developers,[9] consulting may send a weaker signal about workers' abilities to their clients than to their employers. Results should carry over to an analysis with intermediate levels of disclosure.

Related Literature. This paper relates to the literature on open source software such as Lerner and Tirole (2001) and Johnson (1999). Lerner and Tirole (2001) mention signaling as a possible reason for involvement in an open source project; Spiegel (2005), Lee, Moisa, and Weiss (2003), and Leppämäki and Mustonen (2003) provide a formalization of this idea. We differ from these contributions to the literature by modeling the hold-up problem of the talented programmer and the employer explicitly, by allowing employers to distinguish between talented and untalented programmers after completion of a closed source project, and by assuming that firms can also do open source development.

Further, our analysis is related to the information disclosure literature. Mukherjee (2008a), Mukherjee (2008b), and Bar-Isaac, Jewitt, and Leaver (2007) also consider jobs with different visibility levels. We differ by assuming that the worker knows his ability already before he chooses his first job. This turns out to have a major impact on the outcome, since a worker's choice of a high versus a low visibility job becomes a signal about his ability. This also leads to our finding that a worker may exercise less effort in a high visibility job.

Our analysis of the case where the probability of success depends on the effort level of the programmer relates to the economics of career concerns as first described in the seminal paper by Holmstrom (1999, original version appeared in 1982), who analyzes whether a manager's concern for a future career gives him the incentive to exercise effort (see also Dewatripont, Jewitt,

[9] If a developer's name is listed in the credits of the software, it is hard to tell exactly how much he contributed to its success (or failure). Even if names are grouped in categories such as lead developers and other developers, it is still more difficult to distinguish individual contributions than in open source projects.

and Tirole (1999a) and Dewatripont, Jewitt, and Tirole (1999b)). We depart from the career concerns literature by also considering low visibility (closed source) jobs which only create a private signal about an employee's success besides the high visibility jobs creating a public signal, which are already present in Holmstrom (1999). To keep the analysis analytically tractable, we follow most of the literature related to ours by considering a two period model rather than Holmstrom's infinite horizon.

As in Waldman (1984), Greenwald (1986), Acemoglu and Pischke (1998), and Li (2007) the current employer is better informed than other employers. We depart from these articles in two main points. First, besides low visibility jobs, there are also high visibility jobs creating a public signal about the worker's ability. Second, a worker knows his ability *before* choosing a job. The second point is also considered in Hermalin (2002), but not the first.

In a wider sense, the paper also relates to the literature on "open science", i.e. the disclosure of research findings, starting with Dasgupta and David (1994) (see also Mukherjee and Stern (2007) and the references therein). Such a disclosure is similar in spirit to open source and also creates a public signal about a researcher's abilities – an effect that has not been modeled in the open science literature to the best of our knowledge.

The remainder of the paper is structured as follows. Section 2 starts with a setting where the success of a project is a perfect signal of an employee's abilities and considers open source developers being paid as employees of firms. Results naturally carry over to unpaid open source development. Section 3 extends the analysis to imperfect signals about abilities. Section 4 introduces an unobservable effort level of a developer that influences the probability of success of the project. Section 5 concludes.

2 Perfect Signal

There are two periods. In the first period workers can decide whether to do closed source or open source development. In the second period they can only do closed source development. There are two types of workers: talented and untalented. Let the proportion of talented workers be λ, that of untalented $1-\lambda$. Workers know their own types, but firms do not. A talented programmer working on a closed source project succeeds with probability p_1, an untalented one with probability p_0. For the sake of simplicity, we first assume $p_1 = 1$ and $p_0 = 0$, i.e. success depends deterministically on talent and success or failure is a perfect signal about an employee's abilities. The success of a closed source project is only observed by the employer. Qualitative results should carry over for the case where other employers do observe a signal, but a weaker one. A successful closed source project generates revenues π_s, an unsuccessful one π_f, with $\pi_s > \pi_f$. A talented employee working in an open source project succeeds with probability q_1, an untalented one with probability q_0. Again, assume for simplicity that the signal is perfect, i.e. $q_1 = 1$, $q_0 = 0$. The profits generated by an open source project are given by κ_s and κ_f in case of success and failure, with $\kappa_s \geq \kappa_f$. Note that the situation where open source development is voluntary unpaid work is a special case of our analysis, with profits $\kappa_s = \kappa_f = 0$ and hence zero equilibrium wages, as we will show later. In this case it does not matter whether an employee works for a firm or independently.

After the first period workers get new wage offers from their employers and can switch jobs. Assume that firms are perfectly competitive and pay wages equal to expected profits. Wages in the first period (before the signal) are

$$w_1 = \tilde{\lambda}\Pi_t + (1-\tilde{\lambda})\Pi_u, \tag{2.1}$$

where Π_t (Π_u) stands for overall expected profits generated by hiring a talented (untalented) worker and $\tilde{\lambda}$ stands for the proportion of talented workers among applicants for a certain type of job (open or closed source), i.e. $\tilde{\lambda} = 0$ if only untalented, $\tilde{\lambda} = 1$ if only talented, and $\tilde{\lambda} = \lambda$ if both types of workers apply for the job in equilibrium.

$$\Pi_t = \pi_s + \delta(1 - \nu_s)(\pi_s - w_s), \tag{2.2}$$

$$\Pi_u = \pi_f + \delta(1 - \nu_f)(\pi_f - w_f), \tag{2.3}$$

where ν_s (ν_f) is the probability that a successful (unsuccessful) employee wishes to switch jobs at stage 2 (which will be determined in equilibrium) and w_s, w_f are the wages offered to employees after the signal has been observed, and δ is the "discount rate" (as employment in the second stage may be for a longer time than in the first period, δ may be larger than 1).

2.1 Closed Source Development

In order to introduce our model, we assume in a first step that there is only closed source software. So at stage 2 only the employer observes the signal. We denote the wage that people who did closed source and switch jobs get as $\bar{w}$.

As firms face perfect competition for non-locked-in employees, wages of job switchers are equal to expected productivity:

$$\bar{w} = \frac{\nu_s \lambda \pi_s + \nu_f (1 - \lambda) \pi_f}{\nu_s \lambda + \nu_f (1 - \lambda)},$$

the denominator representing the proportion of job switchers in the total population, i.e. the unconditional probability to switch.

The employer of a successful employee knows that his productivity will be π_s in the next period. He does not face perfect competition, because other employers cannot observe whether the employee was successful or not, and will hence only pay $\bar{w}$. Hence, the surplus generated by continuing the employment is $\pi_s - \bar{w}$. We assume that this surplus is split according to the Nash bargaining solution: the employer gets $(1-\alpha)$, the employee α of $(\pi_s - \bar{w})$, where $0 < \alpha \leq 1$.[10] Note that both parties – employer and employee – have full information in this bargaining process; the third party in the bargaining process – the potential employer providing the outside option – is not participating strategically, he merely stands ready to pay the market equilibrium wage in case negotiations break down. Therefore, the Nash bargaining solution is an appropriate solution concept in our setup.

A firm observing a bad signal will offer its untalented employees $w_f = \pi_f$: it cannot offer less, since we assume that firms are competitive, neither more, since it would make losses. Wages paid to talented employees are $w_s = \bar{w} + \alpha(\pi_s - \bar{w}) = \alpha\pi_s + (1-\alpha)\bar{w}$.

In order to determine the equilibrium, we have to distinguish two cases, depending on the firm's beliefs about what the employees will do: either only the untalented employees switch jobs or both types of employees switch.[11] First, we will show that it is a rational expectations equilibrium that firms believe that only untalented workers switch jobs in period 2, i.e. there is adverse selection. Then we will show that this equilibrium is unique. If firms believe that only untalented workers switch jobs, switching jobs is interpreted as a signal for being untalented and job switchers are paid the low wage in period 2, i.e. $\overline{w} = w_f = \pi_f$. Wages paid to talented employees are then $w_s = \alpha\pi_s + (1-\alpha)\pi_f$, which is higher than π_f. Hence, talented workers do not want to switch jobs and the expectations of the firms are confirmed. Talented workers do not switch jobs because only their employer knows that they are talented. This allows the talented employees to obtain a higher wage according to the Nash bargaining solution.

This equilibrium is unique because it is not an equilibrium that both

[10] It is shown in Proposition 3 in Appendix A.1 that no equilibrium in pure strategies exists if we assume that the employer has all the bargaining power ($\alpha = 0$).

[11] We do not have to consider the case where firms believe that only the talented employees switch jobs in period 2. If the talented workers find it optimal to switch, the untalented will want to switch too.

talented and untalented workers want to switch jobs in period 2. The reason is that whatever the wage $\bar{w}$ for job switchers is, the employer of a talented employee can always offer a wage between $\bar{w}$ and π_s to the employee and retain him. The wage for job switchers clearly has to be less than π_s, because a new employer has to take into account the possibility of hiring untalented workers.

2.2 Open Source Development

Let us now introduce the possibility of participating in an open source project and sending a public signal about one's talent.

We consider a setting where employees are paid by a firm for doing open source development during work hours. If the employee works on an open source project while being paid, he can work on a project aligned with the interests of the firm. The success of the project will thus typically generate profits for the firm. These profits can e.g. come from money paid by a client for the development of a specific piece of software adjusted for the client's needs or from complementary consulting services offered by the firm. Furthermore, the firm may immediately benefit from the experience that its employees have gained by participating in the open source project. The profits generated by the open source project, κ_s and κ_f (in case of success or failure, with $\kappa_s > \kappa_f$) can be lower or higher than their counterparts π_s and π_f for the commercial project.[12] As noted before, our analysis also holds for open source projects that do not generate profits, i.e. $\kappa_s = \kappa_f = 0$.

Participating in an open source project allows the employee to send a public signal about his talent. We assume that the signal is perfect, i.e. $q_1 = 1$, $q_0 = 0$. Having sent out a perfect signal, the second stage wage of

[12] We will not specify this further, but open source software is usually given away for free and also allows competitors to imitate more easily. This would lead to lower open source profits. But there are also countervailing effects, e.g. the open source community contributing to the development of the software and thus leading to lower costs and higher profits.

first stage open source developers will equal actual productivity, i.e. $w_s = \pi_s$, $w_f = \pi_f$, since firms are competitive.

At stage 1, a firm allows its employees to develop open source software while being employed. For the sake of simplicity, we consider the case where workers can either do only open source development or only closed source development in the first period. Open source development yields profits κ_s or κ_f, closed source development yields profits π_s or π_f. The profit difference between a successful and an unsuccessful closed source project will be denoted by $\Delta\pi := \pi_s - \pi_f$.

We have to distinguish several cases, depending on the beliefs of the firms about what the employees will do. Note that also untalented workers may be interested in doing open source development. If an untalented worker participates in an open source project, this will reveal his lack of talent to all firms. However, depending on relative profits of closed source and open source projects, the first period wage may be high enough to compensate untalented workers for this effect.

In the following we will look at candidates for rational expectations equilibria. We will take the beliefs of firms about the behavior of workers as given and look whether workers' equilibrium behavior fulfills the expectations. In general, multiple equilibria can arise. The following Proposition shows when an equilibrium is possible.

Proposition 1. *(i)* Open-closed case: *The case where talented workers do open source development and untalented workers do closed source development can be sustained as an equilibrium if*

$$\Delta\pi > \frac{\pi_f - \kappa_s}{\delta(1-\alpha)} =: \Delta\underline{\pi}, \quad \textit{and} \quad \pi_f > \kappa_s.$$

(ii) Closed-open case: *The case where talented workers do closed and untalented workers do open source development cannot be sustained as an equilibrium.*

(iii) Open-open case: *The case where both the talented workers and the untalented workers do open source development can be sustained as an equilibrium if*

$$\lambda\kappa_s + (1-\lambda)\kappa_f > \pi_f.$$

(iv) Closed-closed case: *The case where both the talented workers and the untalented workers do closed source development can be sustained as an equilibrium if*

$$\Delta\pi < \frac{\kappa_f - \pi_f}{\beta} =: \Delta\overline{\pi}^{cc} \quad \textit{if} \quad \beta < 0$$

and

$$\Delta\pi > \frac{\kappa_f - \pi_f}{\beta} =: \Delta\underline{\pi}^{cc} \quad \textit{if} \quad \beta > 0$$

with $\beta := \lambda - (1-\lambda)\delta(1-\alpha)$.

Before proceeding to the proof of the Proposition, we describe the intuition behind these results.

Open-closed case: The benefits of open source development are high enough and the talented workers will choose to develop open source software in period 1 if the productivity difference $\Delta\pi$ is sufficiently high, the discount rate δ is sufficiently high, and the employees bargaining position is sufficiently low.

Closed-open case: If open source development is more attractive to untalented workers than closed source development, then open source development also has to be more attractive to talented workers. This is the case because talented workers gain the same as untalented workers in the first period if they do open source development (since the firms cannot distinguish between worker types) and at least as much in the second period. Therefore, this cannot be an equilibrium.

Open-open case: If average productivity in open source development in period 1 is higher than the productivity of the untalented worker in a closed source project, it is an equilibrium that both types of workers will choose to do open source development in the first period.

Closed-closed case: The condition for this case can be interpreted as follows. If $\beta < 0$, we have the intuitive result that a high value of π_s compared to π_f makes it more difficult to sustain the equilibrium where both types of workers do closed source development, since signaling is more valuable. However, for $\beta > 0$, the intuition is reversed: closed-closed is an equilibrium if the productivity difference is *sufficiently large* (or: π_s is sufficiently large)! This unexpected and at first sight counterintuitive result can be explained the following way. There are two countervailing effects of a larger π_s: (1) it makes open source development more attractive since an open source developer earns relatively more in the second period, but (2) also makes closed source development more attractive since first period closed source wages are a sum of the average of π_s and π_f and expected profits from "exploiting" talented workers in the second period. Effect (2) is stronger if β is positive. This can be seen e.g. if β is positive because δ is close to 0 (second period unimportant) and hence effect (1) vanishes. Similarly for λ close to 1 (most people are talented, so no need to prove it) and α close to 1 (second period hold-up problem is unimportant).

Proof. (i) Open-closed case: We will use the following notation to derive conditions for the rational expectations equilibria. V_t and V_u denote the net present value of a talented and an untalented worker, respectively. Superscript o (c) denotes that firms expect a worker to do open (closed) source development in period 1. Subscript o (c) indicates that the worker has chosen to do open (closed) source development. Thus, expectations are fulfilled if superscript and subscript coincide.

A talented employee working on a closed source project in the first period earns the net present value $V_{tc}^o = \pi_f + \delta[\alpha\pi_s + (1-\alpha)\pi_f]$. If he works in open source, he earns $V_{to}^o = \kappa_s + \delta\pi_s$, since the competitive firms pay wages equal to (expected) productivity. An untalented worker earns $V^c_{uc} = \pi_f + \delta\pi_f$ if he chooses closed source in the first period. If he chooses open source, he earns $V^c_{uo} = \kappa_s + \delta\pi_f$, since firms initially believe him to be talented, but his lack of talent is revealed after the first period.

Open-closed is a rational expectations equilibrium if no one has an incentive to deviate from expectations, i.e. $V^o_{to} > V^o_{tc}$ and $V^c_{uc} > V^c_{uo}$. Substituting in the Vs and rearranging yields

$$\Delta\pi > \frac{\pi_f - \kappa_s}{\delta(1-\alpha)} \stackrel{\text{def}}{=} \Delta\underline{\pi} \quad \text{and} \quad \pi_f > \kappa_s.$$

(ii) Closed-open case: Assume to the contrary that closed-open is an equilibrium. A talented employee doing closed source earns $V^c_{tc} = \pi_s + \delta\pi_s$. Deviation from equilibrium strategy yields $V^c_{to} = \kappa_f + \delta\pi_s$, since in the second period firms notice that the worker is talented contrary to their first period beliefs. An untalented worker earns $V^o_{uo} = \kappa_f + \delta\pi_f$ if he chooses open source in the first period. If he chooses closed source, he earns $V^o_{uc} = \pi_s + \delta\pi_s$, since firms believe that job switchers in the second period are talented.

Closed-open is a rational expectations equilibrium if $V^c_{tc} > V^c_{to}$ and $V^o_{uo} > V^o_{uc}$, which is equivalent to $\kappa_f - \delta\Delta\pi > \pi_s > \kappa_f$ and therefore a contradiction.

(iii) Open-open case: We choose the firms' beliefs off the equilibrium path such that the equilibrium is most easily supported: firms believe in the first period that a worker who chooses to do closed source is untalented. Hence, deviation from the equilibrium strategy by a talented worker yields $V^o_{tc} = \pi_f + \delta[\alpha\pi_s + (1-\alpha)\pi_f]$. If he works in open source, he earns $V^o_{to} = \tilde{w}_1 + \delta\pi_s$, where $\tilde{w}_1$ is similar to the first-period wage w_1 in (2.1), (2.2), and (2.3), but now we have $\tilde{w}_1 = \lambda\tilde{\Pi}_t + (1-\lambda)\tilde{\Pi}_u$, where

$$\tilde{\Pi}_t = \kappa_s + \delta(1-\nu_s)(\pi_s - w_s) = \kappa_s,$$

$$\tilde{\Pi}_u = \kappa_f + \delta(1-\nu_f)(\pi_f - w_f) = \kappa_f,$$

since workers will be paid their productivity after their ability is publicly observed after the first period.

Deviation from the equilibrium strategy by an untalented worker yields $V^o_{uc} = (1+\delta)\pi_f$. An untalented worker earns $V^o_{uo} = \tilde{w}_1 + \delta\pi_f$ if he chooses open source in the first period.

Open-open is a rational expectations equilibrium if $V^o_{to} > V^o_{tc}$ and $V^o_{uo} > V^o_{uc}$. If the second inequality is true, then the first inequality is also true, since $\pi_s > \alpha\pi_s + (1-\alpha)\pi_f$. Thus, we only need the second inequality as equilibrium condition, which reduces to $\pi_f < \tilde{w}_1 = \lambda\kappa_s + (1-\lambda)\kappa_f$.

(iv) Closed-closed case: Again, we assume that if the workers deviate from firms' beliefs, they will be considered to be untalented. In this setting, the net present values are $V^c_{tc} = w_1 + \delta[\alpha\pi_s + (1-\alpha)\pi_f]$, $V^c_{to} = \kappa_f + \delta\pi_s$, $V^c_{uc} = w_1 + \delta\pi_f$, and $V^c_{uo} = \kappa_f + \delta\pi_f$, where w_1 is given by the results from section 2.1:

$$w_1 = \lambda[\pi_s + \delta(\pi_s - \alpha\pi_s - (1-\alpha)\pi_f)] + (1-\lambda)\pi_f$$

Closed-closed is a rational expectations equilibrium if $V^c_{tc} > V^c_{to}$ and $V^c_{uc} > V^c_{uo}$. If the first inequality is true, then the second inequality is also true, since $\alpha\pi_s + (1-\alpha)\pi_f < \pi_s$. Hence we only need the first inequality as the equilibrium condition, which reduces to

$$\Delta\pi[\lambda - (1-\lambda)\delta(1-\alpha)] > \kappa_f - \pi_f,$$

after substituting in w_1 and rearranging. Note that the signs of both the expression in the brackets and the right hand side are ambiguous. Hence, writing the equilibrium condition in terms of the productivity difference $\Delta\pi$ gives

$$\Delta\pi < \frac{\kappa_f - \pi_f}{\beta} =: \Delta\overline{\pi}^{cc} \quad \text{if} \quad \beta < 0$$

and

$$\Delta\pi > \frac{\kappa_f - \pi_f}{\beta} =: \Delta\underline{\pi}^{cc} \quad \text{if} \quad \beta > 0$$

with $\beta = \lambda - (1-\lambda)\delta(1-\alpha)$. □

Discussion. For an interpretation of our model we can consider different constellations of the parameter values of π_s, π_f, κ_s, and κ_f.

For the "standard" case $\pi_s > \pi_f \geq \kappa_s \geq \kappa_f$ it is possible to have an equilibrium where talented workers participate in open source projects to signal their talent and untalented workers do closed source development, even though open source development is wasteful in this setup. If open source projects create only small positive externalities (which are not modeled here), then the existence of open source projects would decrease social welfare. Of course, for externalities being large enough, it is welfare enhancing.

Another, less obvious case is $\pi_s > \kappa_s > \kappa_f > \pi_f$. If open source projects (or academic jobs) did not create positive externalities, it would be socially efficient that talented workers choose to work in the closed source development (private sector) and that only the untalented workers choose an open source or academic job. However, it is a possible equilibrium that both the talented and the untalented workers will choose a highly visible job such as e.g. open source developer (or teaching assistant at a university) first as described in the open-open case above. Talented workers choose the high visibility job to publicly signal their ability, untalented workers get a higher wage in the first period by doing open source development and get the low wage in the second period anyway.[13] In such a situation, it may be socially efficient to forbid open source/academic jobs if the difference between π_s and κ_s is large enough.[14] This is of course only a theoretical argument, we do not believe that such a policy would be meaningful in practice for a variety of reasons. Most importantly, open source development and academic research provide a public good, an effect that is stronger than the

[13] Note that our assumption that open source development is not possible in the second period does not matter for most setups. Here, however, it does. The model could be easily extended to allow for second-period open source development.

[14] The policy implication, that banning signaling may be socially efficient, resembles Spence (1973). However, here both talented and untalented workers engage in signaling by participating in an open source project.

inefficiencies described above.

A further case is $\pi_s > \kappa_s > \pi_f > \kappa_f$. Here again, it is possible that both types of workers do open source development, even though none of them would in a world without informational asymmetries.

It is to be noted that if the provision of open source software is an important public good problem, then informational asymmetries and the hold-up problem are actually welfare enhancing, since they give incentives to the creation of a public good.

As a special case of the "standard" case, we can consider a setting where open source projects are non-commercial, i.e. open source developers do not earn any money. In our model, this means that $\kappa_s = \kappa_f = 0$. In a setting with non-commercial open source development and under the plausible assumption that $\pi_f > 0$ Proposition 1 implies that we can exclude the case where both types of workers do open source development.[15] This is intuitive, because an untalented worker will clearly not want to signal his ability since he can get a wage at stage 1 (contrary to unpaid open source development) and get at least π_f at stage 2 if his lack of talent is not revealed.

3 Imperfect Signal

In this section, we consider imperfect signals in a setting where open source projects are non-commercial, i.e. open source developers do not earn any money (which means $\kappa_s = \kappa_f = 0$ in the notation used above). In the previous sections, we have assumed for simplicity that the signals are perfect. Both in the closed source project and in the open source project, a talented employee succeeded for sure. On the other hand, an untalented employee always failed to develop a successful project. Now, a talented programmer working on a closed source project succeeds with probability p_1, an un-

[15]Negative values of π_f would mean that an untalented worker does some harm to the firm. Such a worker would earn a negative wage in period 2 and thus would decide not to work.

talented one with probability p_0, with $0 < p_0 < p_1 < 1$. In case of the open source project, a talented employee succeeds with probability q_1, an untalented one with probability q_0, with $0 < q_0 < q_1 < 1$.

In this setting, firms cannot observe that a certain project was successful and deduce that the employee in charge of this project is talented. For instance, a talented employee may have bad luck and fail to develop a successful project. Conversely, an untalented worker may be lucky and develop a successful project. However, firms condition their expectations about the productivity of a certain worker on their observations. In period 1, firms don't have any observations indicating the talent of a worker. We introduce the following notation: $E[\pi|T]$ denotes the expected productivity of a talented worker (T) working on a closed source project. We have

$$E[\pi|T] = p_1\pi_s + (1 - p_1)\pi_f.$$

Similarly, the expected productivity of an untalented worker (U) working on a closed source project is given by

$$E[\pi|U] = p_0\pi_s + (1 - p_0)\pi_f.$$

In period 2, firms observe an imperfect signal (namely whether the project was successful or not) both in case of the open source project and in case of the closed source project. Hence, they will form their expectations about the productivity of a certain worker conditional on the signal observed in the previous period. We denote these expectations by $E(\pi|S \cap C)$ and $E(\pi|F \cap C)$ for the closed source project. In case of the open source project, the expectations are given by $E(\pi|S \cap O)$ and $E(\pi|F \cap O)$.

For the calculations below, we introduce the following notation. The probability of a talented worker (T) to succeed in a commercial project is denoted by $P(S|T \cap C) = p_1$. The probability of an untalented worker (U) to succeed in a commercial project is denoted by $P(S|U \cap C) = p_0$. In case of the open source project we have $P(S|T \cap O) = q_1$ and $P(S|U \cap O) = q_0$.

The untalented worker can either strictly prefer closed source development, strictly prefer open source development, or be indifferent and hence play a mixed strategy: open source with probability γ, closed source with probability $1-\gamma$. The same applies for the talented worker, the probability to develop open source software being denoted as ϵ. Both γ and ϵ are endogenously determined by the parameters of the model. There are 9 combinations of these possibilities as depicted in Fig. 1.

The probability of a worker being successful (S) and doing open source development is

$$P(S \cap O) = P(S|T \cap O)P(O|T)P(T) + P(S|U \cap O)P(O|U)P(U)$$

where $P(S|T \cap O) = q_1$ is the probability that a talented worker doing open source is successful, $P(O|T) = \epsilon$ the probability that a talented worker does open source, and $P(T) = \lambda$ the probability that a worker is talented. By Bayes' rule, a firm observing that a worker does open source and was successful attributes the following probability to the worker being talented:

$$P(T|S \cap O) = \frac{P(S|T \cap O)P(O|T)P(T)}{P(S \cap O)} = \frac{q_1\epsilon\lambda}{q_1\epsilon\lambda + q_0\gamma(1-\lambda)}.$$

Analogously, the probability of a worker being untalented is

$$P(U|S \cap O) = \frac{q_0\gamma(1-\lambda)}{q_1\epsilon\lambda + q_0\gamma(1-\lambda)}.$$

The expected productivity of a worker who succeeded in an open source project in period 1 is then given by

$$E(\pi|S \cap O) = P(T|S \cap O)E[\pi|T] + P(U|S \cap O)E[\pi|U].$$

The probability of a worker failing to develop a successful project (F) and doing open source development is

$$P(F \cap O) = (1-q_1)\epsilon\lambda + (1-q_0)\gamma(1-\lambda).$$

Using the same calculations as above, we get

$$P(T|F\cap O) \quad = \quad \frac{(1-q_1)\epsilon\lambda}{(1-q_1)\epsilon\lambda+(1-q_0)\gamma(1-\lambda)}.$$

and

$$P(U|F\cap O) \quad = \quad \frac{(1-q_0)\gamma(1-\lambda)}{(1-q_1)\epsilon\lambda+(1-q_0)\gamma(1-\lambda)}.$$

The expected productivity of a worker who failed in period 1 is given by

$$E(\pi|F\cap O) \quad = \quad P(T|F\cap O)E[\pi|T]+P(U|F\cap O)E[\pi|U]$$

For the case of closed source development the expressions $P(T|S\cap C)$, $P(U|S\cap C)$, $P(T|F\cap C)$, and $P(U|F\cap C)$ are calculated by the same logic, but with p instead of q, $(1-\epsilon)$ instead of ϵ and $(1-\gamma)$ instead of γ.

The expressions above will be used when firms do Bayesian updating after they see whether a worker had success or not. Since the signal does not perfectly reveal a worker's type, there are now more possibilities on firms' off-equilibrium beliefs than in the previous setting with perfect signals. In the previous section, if a talented worker chose to do open source development, firms could not rationally believe that he is untalented, since it would have been impossible for him to be successful.

In order to determine the equilibria, we distinguish several cases which are represented in Figure 1. γ denotes the fraction of the untalented workers who decide to do open source development in period 1. Similarly, ϵ denotes the fraction of the talented workers who decide to do open source development in period 1. For instance, in point 1 both the talented and the untalented workers do closed source development in period 1. In point 8, all the talented workers and a fraction γ of the untalented workers do open source development in period 1.

We find that the cases 1, 5, 8, and 9 can be an equilibrium and that the remaining cases can be excluded, because they cannot be sustained as

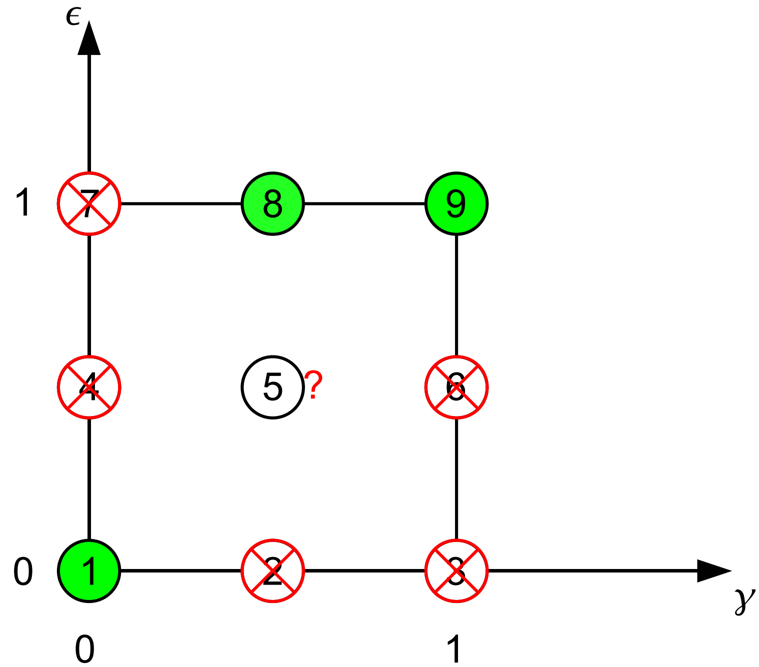

Figure 1: The equilibrium candidates. γ is the probability that the untalented worker develops open source software, ϵ is the corresponding probability for the talented worker. Edges and corners represent cases where a worker strictly prefers open (or closed) source. At points between corners or edges, a worker is indifferent between open source and closed source, and hence plays a mixed strategy. Cases which cannot be sustained as rational expectations equilibria are crossed out.

rational expectations equilibria. These results are illustrated in Fig. 1 and stated in Prop. 2.

Proposition 2. *(i) Cases 1, 5, 8, and 9 can be an equilibrium.*

(ii) Cases 2, 3, 4, 6, and 7 cannot be sustained as rational expectations equilibria.

Next, we discuss case 8, where all talented and a fraction of the untalented workers choose to do open source development. The proof of the results for the remaining cases is banned to the appendix.

Case 8: All talented and fraction of untalented workers do open source. In case 8 all the talented workers ($\epsilon = 1$) and a fraction $0 < \gamma < 1$ of the untalented workers do open source development in period 1.

A talented worker who chooses to work on a closed source project from the beginning (contrary to the firms' expectations) earns the net present value $E[V_{tc}^o] = (1+\delta)E[\pi|U]$.

If the talented worker chooses to participate in an open source project in period 1, he will earn a wage equal to his expected productivity after the signal has been revealed:

$$E[V_{to}^o] = \delta(q_1 E[\pi|S \cap O] + (1-q_1)E[\pi|F \cap O])$$

The payoffs of the untalented workers are $E[V_{uc}] = (1+\delta)E[\pi|U]$. if they do closed source development and

$$E[V_{uo}] = \delta(q_0 E[\pi|S \cap O] + (1-q_0)E[\pi|F \cap O])$$

if they do open source development in period 1.

Case 8 is an equilibrium if the talented worker prefers to do open source

$$E[V_{to}^o] > E[V_{tc}^o]$$

and the untalented worker is indifferent

$$E[V_{uo}] = E[V_{uc}].$$

Inserting the different expressions for $E[V_{to}^o]$ and $E[V_{tc}^o]$ and using $\epsilon = 1$ (since we are in case 8) yields

$$\begin{aligned}
&\delta\left(q_1\left\{\frac{q_1\lambda E[\pi|T] + q_0\gamma(1-\lambda)E[\pi|U]}{q_1\lambda + q_0\gamma(1-\lambda)}\right\}\right.\\
&\left.+(1-q_1)\left\{\frac{(1-q_1)\lambda E[\pi|T] + (1-q_0)\gamma(1-\lambda)E[\pi|U]}{(1-q_1)\lambda + (1-q_0)\gamma(1-\lambda)}\right\}\right)\\
&> (1+\delta)E[\pi|U]
\end{aligned}$$

With $p_0 = q_0 \to 0$ this condition simplifies to

$$\begin{aligned}&\delta\,(q_1(p_1\pi_s+(1-p_1)\pi_f)\\&+(1-q_1)\left\{\frac{(1-q_1)\lambda(p_1\pi_s+(1-p_1)\pi_f)+\gamma(1-\lambda)\pi_f}{(1-q_1)\lambda+\gamma(1-\lambda)}\right\}\Bigg)\\&>(1+\delta)\pi_f\end{aligned}$$

The fraction γ of the untalented workers who do open source development in period 1 can be determined by inserting the expressions for $E[V_{uo}]$ and $E[V_{uc}]$ into the equation above. Using $\epsilon = 1$, this yields

$$\begin{aligned}&(1+\delta)E[\pi|U]=\\&\delta\left(q_0\left\{\frac{q_1\lambda E[\pi|T]+q_0\gamma(1-\lambda)E[\pi|U]}{q_1\lambda+q_0\gamma(1-\lambda)}\right\}\right.\\&\left.+(1-q_0)\left\{\frac{(1-q_1)\lambda E[\pi|T]+(1-q_0)\gamma(1-\lambda)E[\pi|U]}{(1-q_1)\lambda+(1-q_0)\gamma(1-\lambda)}\right\}\right).\end{aligned}$$

With $p_0 = q_0 \to 0$ this condition simplifies to

$$(1+\delta)\pi_f=\delta\left(\frac{(1-q_1)\lambda(p_1\pi_s+(1-p_1)\pi_f)+\gamma(1-\lambda)\pi_f}{(1-q_1)\lambda+\gamma(1-\lambda)}\right).$$

It can be shown that the inequality condition is always fulfilled if the equality condition is fulfilled (the inequality reduces to $\pi_s > \pi_f$, which is true by assumption). This reflects the following intuition: if untalented workers are indifferent between open source and closed source, then talented workers must prefer open source development.[16]

Solving the equation above for γ yields

$$\gamma=\frac{\lambda}{1-\lambda}\frac{[\delta p_1(\pi_s-\pi_f)-\pi_f]}{\pi_f}(1-q_1),$$

a result that will be helpful in the next section.

[16] Note that this result stems from $p_0 = q_0 \to 0$. Without this simplifying assumption, the relation is not clear, as shown for case 5 in Prop. 2.

4 Effort

The analysis can be extended to a career concerns setup (see e.g. Holmstrom (1999)) where the probability of success depends on the effort level of the programmer. In the first period a worker will exercise effort to increase the probability of success and hence appear more likely to be talented. In the second period he does not exercise effort.

Coexistence of Open Source and Closed Source Development (Case 8). Assume that a talented programmer's probability of success depends on his effort e and is equal for the open source and the closed source case $p(e) = q(e)$. Further $p' > 0$, $p'(0) = \infty$, $p'(\infty) = 0$, and $p'' < 0$. For the untalented worker we assume the probability of success to be positive, so that the previous section's analysis carries over, but to converge to zero $p_0 = q_0 \to 0$ in order to simplify the analysis. We will first focus on case 8 of the previous section, i.e. all talented workers develop open source software and untalented workers randomize between open source and closed source with probability γ.

The probability γ of untalented workers doing open source software development can be derived from the equation $E[V_{uo}] = E[V_{uc}]$ of the previous section by replacing p_1 with the equilibrium probability of success $p(e^*)$ of talented workers and p_0 with 0 and solving for γ:

$$\gamma = \frac{\lambda}{1-\lambda}\frac{[\delta p(0)(\pi_s - \pi_f) - \pi_f]}{\pi_f}(1 - p(e^*)). \tag{4.1}$$

In the second period a talented worker has probability of success $p(0)$ since he does not exercise effort. The talented worker's utility is

$$E[V_{to}^o] - e = \delta\left(p(e)E[\pi|S \cap O] + (1 - p(e))E[\pi|F \cap O]\right),$$

Taking the derivative with respect to e, substituting in the $E[\pi|...]$s, and rearranging yields the first order condition

$$p'(e^*)[\delta p(0)(\pi_s - \pi_f) - \pi_f] = 1, \tag{4.2}$$

which is sufficient since our assumptions on p ensure that the second order condition is satisfied.

Using the concavity of p we get to the following conclusions by invoking the implicit function theorem. The equilibrium effort level e^* is increasing with the discount factor δ, the difference of profits between successful and unsuccessful projects $\Delta\pi = \pi_s - \pi_f$, and the probability of success $p(0)$ of a talented worker who does not exercise effort in the second period. Effort is decreasing in the profit of an unsuccessful project π_f.

Only Closed Source Development (Case 1). We can compare this to case 1 where both types of workers develop closed source projects. The comparison can be understood as either a situation where there are multiple equilibria, including cases 1 and 8, or where open source development is not possible for exogenous (e.g. technological or legal) reasons.

A talented worker maximizes his utility

$$E[V_{tc}^c]-e = w_1+\delta\left[p(e)(\alpha E[\pi|S\cap C] + (1-\alpha)E[\pi|F\cap C]) + (1-p(e))E[\pi|F\cap C]\right]-e,$$

by choosing effort level e. This leads to the first order condition

$$\delta\alpha p'(e^*)\left\{E[\pi|S\cap C] - E[\pi|F\cap C]\right\} = 1.$$

Substituting for the expected probabilities the results of the previous section and using the assumption $\gamma = \epsilon = 0$ (since we are in case 1) and $p_0 \to 0$, we get

$$p'(e^*)\alpha\frac{1-\lambda}{1-\lambda p(e^*)}\left[\delta p(0)(\pi_s-\pi_f)\right] = 1. \tag{4.3}$$

Again, by concavity of p and the implicit function theorem we get to the following conclusions.[17] Effort level is increasing in the employee's bargain-

[17]The fact that firms' expectations about equilibrium effort level enter the developers' effort choice problem through the term $1-\lambda p(e^*)$ strengthens the effects of the different parameters on effort, since higher expectations of e^* lead to a higher chosen effort and vice versa. This could lead to multiple equilibria: if firms expect high effort, employees have to exert high effort, otherwise they exert low effort. We assume that there is a unique equilibrium effort level, e.g. because p is sufficiently concave: $p''(e) < -\lambda p'(e)/[\alpha(1-\lambda)\delta p(0)(\pi_s-\pi_f)]$ for all e.

ing power α, the discount factor δ, the productivity difference $\Delta\pi$, and the probability of success $p(0)$ of a talented worker not exercising effort. It is decreasing with the proportion of talented workers λ.

Comparison. Our results allow us to compare effort levels when talented workers do open source development (case 8, Eq. (4.2)) and when they do closed source development (case 1, Eq. (4.3)). Rather than finding thresholds for parameters, we show that certain statements hold for certain extreme values of parameters. The exact thresholds depend on the specific functional form of p. Clearly, for $\alpha \to 1$, $\lambda \to 0$, $\pi_f \to 0$,[18] effort levels are the same for both cases. For $\alpha \ll 1$, $\lambda \to 0$, $\pi_f \to 0$, more effort is exercised if open source development coexists with closed source development. This seems rather intuitive: higher visibility of a project leads to more effort (see Lerner and Tirole (2002)). However, contrary to standard economic intuition, the opposite may hold as well. For $\alpha \to 1$, $\lambda \to 0$, $\pi_f \gg 0$, *more effort* is exercised if talented workers do *closed source* development! The reason is that for large values of π_f, open source is less attractive for untalented workers and hence only a small proportion γ of them choose to develop open source software (Eq. (4.1)). Therefore, a talented programmer already sends a strong signal about his talent by choosing open source development and does not need to exercise that much effort to prove his ability in an open source project. This effect may be stronger than the countervailing effect of having a worse bargaining position in a closed source project if α is large enough. Note that with $p_0 \to 0$ the two inequality conditions for equilibrium 1 and the inequality condition for equilibrium 8 are always ensured.[19] One

[18] Convergence of parameters has to be such that the proportion of untalented workers γ remains in the permissible range $(0, 1)$.

[19] In case 8, if untalented workers are indifferent between open source and closed source, then talented workers must prefer open source development. In case 1, if firms believe that the off-equilibrium behavior of doing open source means being untalented, then it does not pay off to deviate. Note that firms will not update their beliefs after an open source developer was successful, since an untalented programmer can be unsuccessful with a positive probability.

only has to make sure that π_s and π_f are such that the value of γ that solves the equality condition for case 8 (4.1) is between 0 and 1.

As an illustration, take the example

$$p(e) = 1 - \frac{1}{2(\sqrt{e}+1)},$$

and $\lambda = 1/4$, $\pi_f = 1$, $\pi_s = 5$, and $\delta = 3/4$. For $\alpha = 3/4$ case 8 equilibrium effort level is $e_8^* \approx 0.1$ and case 1 effort level is $e_1^* \approx 0.3$. Changing α to 1/4 results in an outcome more expected by standard intuition, $e_8^* \approx 0.1 > e_1^* \approx 0.05$.[20]

5 Conclusions

We have analyzed the economic reasons of individual software developers and commercial companies to participate in open source projects. A talented software developer has an incentive to work on an open source project in order to make his talent observable for all employers rather than only his own. This improves his bargaining position after the signal about his talent has been revealed. By letting employees work on open source projects, firms can credibly commit to pay high future wages for talented programmers. Our model yields several results which are expected by intuition. However, for two results, standard intuition can be misleading. First, it is more likely that talented programmers choose to do open source development if there is a large productivity difference between talented and untalented programmers. Second, working in a highly visible open source job leads to a higher effort level in a setup where future employers cannot distinguish whether success is due to effort or talent. Interestingly, a formalization of the model shows that there are conditions under which these results are reversed. We have also provided some examples that illustrate that even though open versus

[20]This example satisfies the abovementioned conditions $p' > 0$, $p'(0) = \infty$, $p'(\infty) = 0$, and is sufficiently concave $p''(e) < -\lambda p'(e)/[\alpha(1-\lambda)\delta p(0)(\pi_s - \pi_f)] < 0$ in the relevant region. For both values of α, the case 8 fraction of untalented workers doing open source is $\gamma_8 \approx 0.76 \in [0, 1]$.

closed source development is the best fitting case, there is a more general principle at work: the level of visibility of jobs. High and low visibility jobs are observed in academic (open) versus commercial (closed) research, consulting versus management, positions with versus without client contact in general, mutual fund managers whose names are disclosed versus those whose are not.

Appendix

A Proofs

A.1 No Equilibrium in Pure Strategies

Proposition 3. *If the employer has all the bargaining power* ($\alpha = 0$)*, no equilibrium in pure strategies exists.*

Proof. If the employer has all the bargaining power, he can afford paying the talented employee the same wage as to someone who switches jobs at stage 2, $\overline{w}$. No pure strategy equilibrium exists for any $\overline{w}$ as we will show in the following. If $\overline{w} = w_f$, a firm can offer $\overline{w} = w_f + \varepsilon$ (with ε very small), attract all workers (both talented and untalented) and make profits, since it pays a wage lower than expected productivity. The same argument applies for $w_f < \overline{w} < E(\pi)$: a firm can offer $\overline{w} + \varepsilon < E(\pi)$, attract all workers and make profits. A firm offering $\overline{w} = E(\pi)$ would make losses, because only untalented workers will switch jobs, since talented workers are indifferent and hence do not switch. Finally, $\overline{w} > E(\pi)$ obviously cannot be an equilibrium, since a firm offering a wage above expected productivity would make losses. $\square$

A.2 Proof of Proposition 2

Cases 2 and 3: $\epsilon = 0, \gamma \in (0, 1]$: In this case a fraction $0 < \gamma \leq 1$ of the untalented workers do open source development and all the talented workers do closed source development. In such a case, doing open source development would be a perfect signal for being untalented and the untalented workers would choose to do closed source development.

Cases 3 and 6: $\gamma = 1, \epsilon \in [0, 1)$: In this case all the untalented workers and a fraction $0 \leq \epsilon < 1$ of the talented workers do open source development. In such a case, doing closed source development would be a perfect signal for being talented and the talented workers would choose to do closed source development.

Cases 4 and 7: $\gamma = 0, \epsilon \in (0, 1]$: In this case all the untalented workers do closed source development and a fraction $0 < \epsilon \leq 1$ of the talented workers do open source development. In such a case, doing open source development would be a perfect signal for being talented and the untalented workers would choose to do open source development as well.

Case 1: both closed source. In case 1, both the talented and the untalented workers do closed source development in period 1. We assume that if the workers deviate from the firms' beliefs, they will be considered to be untalented. The payoffs of a talented worker who chooses to do closed source development is given by

$$E[V_{tc}^c] = w_1 + \delta[p_1(\alpha E(\pi|S \cap C) + (1-\alpha)E(\pi|F \cap C) + (1-p_1)E(\pi|F \cap C)].$$

with

$$w_1 = \lambda\{E(\pi|T) + \delta[E(\pi|S \cap C) - \alpha E(\pi|S \cap C) - (1-\alpha)E(\pi|F \cap C)]\} + (1-\lambda)E(\pi|U).$$

The expression above reflects that firms do Bayesian updating after they see whether a worker had success or not. The second period wage of an unsuccessful worker is $E[\pi|F \cap C]$ and the wage of a successful worker is again determined by the Nash bargaining solution: $\alpha E(\pi|S \cap C) + (1 - \alpha)E(\pi|F \cap C)$. The first period wage is determined by a similar logic as in section 2: you pay more than the expected first period productivity, since you expect to exploit talented workers in the second period.

If the talented worker chooses to participate in an open source project in period 1 (contrary to the firm's expectation), he earns $E[V^c_{to}] = \delta E[\pi|U]$.

The payoffs for the untalented worker are

$$E[V^c_{uc}] = w_1 + \delta[p_0(\alpha E(\pi|S\cap C) + (1-\alpha)E(\pi|F\cap C)) + (1-p_0)E(\pi|F\cap C)].$$

and

$$E[V^c_{uo}] = \delta E[\pi|U].$$

Case 1 is an equilibrium if

$$w_1 + \delta[p_0(\alpha E(\pi|S\cap C) + (1-\alpha)E(\pi|F\cap C)) + (1-p_0)E(\pi|F\cap C)] > \delta E[\pi|U].$$

Substituting for the expected probabilities with $\gamma = \epsilon = 0$ (since we are in case 1) and, we get

$$\begin{aligned}
&\lambda \left\{ E(\pi|T) + \delta \left[(1-\alpha) \left(\frac{p_1\lambda E(\pi|T) + p_0(1-\lambda)E(\pi|U)}{p_1\lambda + p_0(1-\lambda)} \right.\right.\right. \\
&\quad \left.\left.\left. - \frac{(1-p_1)\lambda E(\pi|T) + (1-p_0)(1-\lambda)E(\pi|U)}{(1-p_1)\lambda + (1-p_0)(1-\lambda)} \right) \right] \right\} + (1-\lambda)E(\pi|U) \\
&\quad + \delta \left[p_0 \left(\alpha \frac{p_1\lambda E(\pi|T) + p_0(1-\lambda)E(\pi|U)}{p_1\lambda + p_0(1-\lambda)} + (1-\alpha) \frac{(1-p_1)\lambda E(\pi|T) + (1-p_0)(1-\lambda)E(\pi|U)}{(1-p_1)\lambda + (1-p_0)(1-\lambda)} \right) \right. \\
&\quad \left. + (1-p_0) \frac{(1-p_1)\lambda E(\pi|T) + (1-p_0)(1-\lambda)E(\pi|U)}{(1-p_1)\lambda + (1-p_0)(1-\lambda)} \right] > \delta E(\pi|U)
\end{aligned}$$

Assuming $p_0 \to 0$, the expression simplifies to

$$\begin{aligned}
&\lambda \left\{ E(\pi|T) + \delta \left[(1-\alpha) \left(E(\pi|T) - \frac{(1-p_1)\lambda E(\pi|T) + (1-\lambda)\pi_f}{(1-p_1)\lambda + (1-\lambda)} \right) \right] \right\} \\
&\quad + (1-\lambda)\pi_f + \delta \left[\frac{(1-p_1)\lambda E(\pi|T) + (1-\lambda)\pi_f}{(1-p_1)\lambda + (1-\lambda)} \right] > \delta \pi_f
\end{aligned}$$

Case 5: A fraction of both talented and untalented workers do open source. In case 5, a fraction $0 \leq \epsilon \leq 1$ of the talented workers and a fraction $0 \leq \gamma \leq 1$ of the untalented workers do open source development in period 1. If a talented worker chooses to do closed source development in period 1, he earns the net present value

$$E[V_{tc}] = w_1 + \delta[p_1(\alpha E(\pi|S \cap C) + (1-\alpha)E(\pi|F \cap C)) + (1-p_1)E(\pi|F \cap C)].$$

with

$$w_1 = P(T|C)\{E(\pi|T) + \delta[E(\pi|S \cap C) - \alpha E(\pi|S \cap C) - (1-\alpha)E(\pi|F \cap C)]\} + P(U|C)E(\pi|U).$$

where

$$P(T|C) = \frac{(1-\epsilon)\lambda}{(1-\epsilon)\lambda + (1-\gamma)(1-\lambda)}.$$

If the talented worker chooses to participate in an open source project in period 1, he will earn a wage equal to

$$E[V_{to}] = \delta[q_1 E(\pi|S \cap O) + (1-q_1)E(\pi|F \cap O)].$$

The payoffs for the untalented workers are

$$E[V_{uc}] = w_1 + \delta[p_0(\alpha E(\pi|S \cap C) + (1-\alpha)E(\pi|F \cap C)) + (1-p_0)E(\pi|F \cap C)].$$

and

$$E[V_{uo}] = \delta[q_0 E(\pi|S \cap O) + (1-q_0)E(\pi|F \cap O)].$$

Case 5 is an equilibrium if both types of workers are indifferent between doing closed source or open source development. Hence the equilibrium conditions are given by:

$$E[V_{tc}] = E[V_{to}].$$

and

$$E[V_{uc}] = E[V_{uo}].$$

One obtains the equilibrium fractions of talented and untalented workers choosing open source development, ϵ and γ, respectively, by solving the equilibrium conditions. The question is whether solutions exist such that $\epsilon, \gamma \in [0,1]$. That such cases exist can be illustrated by the following numerical example. Take parameter values $\lambda = 3/5$, $\delta = 5/2$, $\alpha = 3/5$, $p_1 = q_1 = 3/4$, $p_0 = q_0 = 0$, $\pi_s = 5/2$, $\pi_f = 1/2$.[21] This results in the solution $\epsilon \approx 0.82$ and $\gamma \approx 0.36$.

Case 9: both open source. In case 9, both types of workers do open source development in period 1. We choose the firms' beliefs off the equilibrium path as follows: firms believe that a worker who chooses to do closed source is untalented. Hence, if a talented worker deviates from the equilibrium strategy, he earns $E[V_{tc}^o] = (1+\delta)E[\pi|U]$.

If the talented worker chooses to participate in an open source project in period 1, he will earn a wage equal to the expected productivity over all workers in the future

$$E[V_{to}^o] = \delta[q_1 E(\pi|S \cap O) + (1-q_1)E(\pi|F \cap O)].$$

The payoffs for the untalented workers are

$$E[V_{uc}^o] = (1+\delta)E[\pi|U].$$

and

$$E[V_{uo}^o] = \delta[q_0 E(\pi|S \cap O) + (1-q_0)E(\pi|F \cap O)].$$

Case 9 is an equilibrium if

$$\delta[q_0 E(\pi|S \cap O) + (1-q_0)E(\pi|F \cap O)] > (1+\delta)E[\pi|U].$$

Writing down this condition explicitly yields

$$\begin{aligned} \delta \Bigg(& q_0 \left\{ \frac{q_1\epsilon\lambda E[\pi|T] + q_0\gamma(1-\lambda)E[\pi|U]}{q_1\epsilon\lambda + q_0\gamma(1-\lambda)} \right\} \\ & +(1-q_0) \left\{ \frac{(1-q_1)\epsilon\lambda E[\pi|T] + (1-q_0)\gamma(1-\lambda)E[\pi|U]}{(1-q_1)\epsilon\lambda + (1-q_0)\gamma(1-\lambda)} \right\} \Bigg) \\ & > (1+\delta)E[\pi|U] \end{aligned}$$

[21] Note that the discount rate can be larger than 1, since employment in the second stage may be for longer time than employment in the first stage. However, there are also examples with $\delta < 1$.

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