Markets for Scientific Attribution*

by

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Formal attribution provides a means of recognizing scientific contributions as well as allocating scientific credit. This paper examines the processes by which attribution arises and its interaction with market assessments of the relative contributions of members of scientific teams and communities – a topic of interest for the organizational economics of science and in understanding scientific labor markets. We demonstrate that a pioneer or senior scientist's decision to co-author with a follower or junior scientist depends critically on market attributions as well as the timing of the co-authoring decision. This results in multiple equilibrium outcomes each with different implications for expected quality of research projects. However, we demonstrate that the Pareto efficient organisational regime is for the follower researcher to be granted co-authorship contingent on their own performance without any earlier pre-commitment to formal attribution. We then compare this with the alternative for the pioneer of publishing their contribution and being rewarded through citations. While in some equilibria (especially where co-authoring commitments are possible) there is no advantage to interim publication, in others this can increase expected research quality.

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"Not for us is the limelight and the applause. But that doesn't mean the game is not worth the candle or that we do not in the end win the game. In the long run, the economic scholar works for the only coin worth having – our own applause."

Paul Samuelson (1961)

1 Introduction

This paper examines the organization of scientific teams and, in particular, the provision of non-monetary incentives based on scientific norms. Specifically, the reward structure in science is determined by a series of norms at the heart of which is peer recognition:

> Recognition of what one has accomplished is thus largely a motive derived from institutional emphases. Recognition for originality becomes socially validated testimony that one has successfully lived up to the most exacting requirements of one's role as scientist. The self-image of the individual scientist will also depend greatly on the appraisals by his scientific peers of the extent to which he has lived up to this exacting and critically important aspect of his role. As Darwin once phrased it, "My love of natural science … has been much aided by the ambition to be esteemed by my fellow naturalists." (Merton, 1957)

At least in part, recognition incentives come from the notion of priority – being the acknowledged pioneer of a piece of scientific knowledge. But evaluating the degree of recognition requires that an additional assessment be made by one's peers – an assessment of impact. While relatively simple for a single scientist, such as Darwin seeking esteem from his colleagues, as scientific production is (now) rarely an isolated individual endeavour, the assessment of individual recognition today also involves drawing inferences regarding the relative contribution of different scientists to a particular pioneering body of knowledge. In this regard, *recognition is more than just a currency of reward but a currency of attribution*. Put another way, recognition is not a reward that can be conferred on individual scientists without constraint; rather, it is a reward that must be allocated among colleagues and co-authors.

Scientists have developed a number of mechanisms that play a critical role in determining the allocation of recognition amongst them.[1] One such mechanism is co-authorship. This arises when two scientists each contribute a sufficient amount to a research output that they include both of their names in the contribution. In the simplest case, attribution is then equally shared. In some areas, norms beyond co-authorship – particularly name ordering – potentially influence attribution of relative contribution. Another mechanism comes in the form of formal acknowledgement of contribution. To the extent that scientific work builds on the work of other scholars, that prior contribution is generally acknowledged in the form of a citation. But, even in this context, a citation can take a variety of forms; from the briefest mention of influence to a more extended discussion of the significance of prior work (although these nuances are rarely considered in today's citation counting approaches).

If actual contribution were observable, then such formal mechanisms – co-authorship and citation – would not play a role in the allocation of scientific rewards. In reality, actual attribution is typically imperfectly observed and consequently, the signal provided by formal attribution assists the "peer market" in assessing contribution. This suggests that attribution has a market value. Moreover, that value is determined by expectations and, in equilibrium, the process by which formal attribution is allocated. To

[1] The origins of peer recognition as central to the reward structure in science have been documented by David (2008). He demonstrates that peer review emerged from the desire of scientific patrons to assess that the work produced by their sponsored scholars was actually of high quality. From this evolved a set of social norms that tied scientific achievement to peer recognition. Stern (2004) provides evidence of this socialization; demonstrating that scientists sacrifice monetary income in order to participate in scientific activities (notably publication and presentations) that confer peer recognition.

take an extreme example, if it was customary to permit scientists' authorship even for extremely small contributions, the market could infer little of their relative contribution from a particular scientist's inclusion in the authorship group. In this situation, authorship would have little or no value as a currency for attribution.[2]

The value of scientific attribution as determined by the interaction between scientific practice and the peer market itself determines and can be influenced by instrumental factors; namely, the allocation of rewards and the consequent impact on incentives of scientists to provide effort and attention (Dasgupta and David, 1994). In that regard, the allocation of scientific attribution is akin to a determination of ownership over the stream of credit associated with a research output (thus playing a role similar to equity allocation among founders). Such allocation will have an impact on scientific incentives (in a manner akin to Hart and Moore, 1990). However, beyond this, there is an interaction between those incentives and market assessments of what formal attribution signals. If formal attribution has a limited impact on incentives, it will also send a limited signal to the market as to actual effort expended by scientists and hence, of relative contribution. In other words, formal attribution is potentially fragile and vulnerable to a vicious cycle of devaluation.

Given all of this, it is perhaps surprising that economists have not turned their attention to an understanding of the equity aspects of scientific rewards and precisely how the market for scientific attribution operates.[3] While there is past research in economics that examines the effect of scientific rewards on incentives to produce

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[2] This is perhaps also why "self-citations" tend to carry less weight than external citations. See Gans and Murray (2015) for no real discussion of this issue beyond the mention of the word "citation."

[3] There is a literature on the allocation of credit as a managerial tool for incentivizing team performance (Tumlinson, 2012), but this has been focused on issues of discrimination.

research (e.g., Dasgupta and David, 1994), there are no papers that take a comprehensive examination of the markets for scientific attribution. The closest paper is that of Engers, Gans, Grant and King (1999) whose model we build upon here. They examine the incentives of co-authors with regard to name ordering on papers modelling a situation where co-authors can choose to send a signal of relative contribution or alternatively to choose alphabetical ordering (as is the norm in economics and much of the social sciences). They demonstrate that the signal of relative contribution is muted when the market places some weight on alphabetical ordering; something that damages the author with a "higher" name (such as Acemoglu) relative to one with a "lower" name (such as Zuckerman). The end result could be a drive towards alphabetical ordering and no market signal coming from name ordering. Here, we consider a broader set of instruments for scientific attribution with a consequent set of predictions for the production of most scientific knowledge (well beyond the social sciences).

The goal of the present paper is to provide an analysis that considers a market for attribution that interacts with various organisational regimes for assigning formal attribution (such as co-authorship and, later, citation). Our approach, motivated by the general structure of scientific labs,[4] is based on the interactions between a pioneer and follower scientist. As Stephan (2012) documents, labs are often "owned" by a faculty principal investigator (or PI) and employ a variety of other scientists and staff including those formally in training such as PhD students as well as those engaged in staff-type employment such as post-doctoral fellows. Importantly, output from the lab, whether formally co-authored by the PI or not, is typically known as being undertaken in the PI's lab. Hence, here we consider a pioneer scientist as akin to the PI of a lab and a follower

[4] As opposed to narrower conceptions of collaboration considered by Engers et al. (1999).

as one of the employed scientists in the lab (such as a postdoc or graduate student). Importantly, as Stephan (2012) notes, scientists might collaborate and contribute to a project but not be listed as a co-author. This has raised concerns about exploitation, but also this may impact on the incentives for different scientists in their collaborative efforts.

In our setup, both the pioneer and follower scientists contribute effort that improves the quality of research with a signal received as to their relative contributions. We explore two mechanisms as to how that private signal is potentially translated into a market signal. In the baseline model, the pioneer and follower scientists negotiate over whether both are included as co-authors or not in the follow-on research. In an extension, the scientists operate at arm's length with a choice made by an editor as to formal attribution of the pioneer in the form of a citation in the follower's paper. The difference between the two models is the weight each places on private factors versus social or efficiency factors in determining attribution, and the environments modelled are ones where we expect private (rather than social) factors to dominate.

Our principal findings are as follows. First, a pioneer scientist's choice of committing to co-authorship prior to a project beginning depends on whether each scientist's efforts are complements in producing high quality research. When they are substitutes, the pioneer chooses not to collaborate. Second, the set of outcomes whereby fruitful collaboration can be facilitated is expanded when the pioneer can choose to formally assign co-authorship at later stages. Indeed, by leaving the follower scientist without formal co-authorship unless they contribute to a significant degree, the follower (a) receives high-powered incentives to expend research effort and (b) can actually realise a higher payoff than other organisational regimes. The latter effect comes from the fact that when outsiders in the market know that follower co-authorship is assigned ex post in this manner, they receive a perfect signal of the follower's contribution if they are, in fact, a co-author. However, this outcome is only possible if, in fact, the pioneer scientist can commit to ex post co-authorship conditional on effort. Without that commitment, the pioneer has an incentive to renege on their promises. Third, we demonstrate that, when such commitment is not possible, an organisational mode whereby the pioneer publishes their research contribution and the follower cites them in subsequent work can lead to the same high-powered incentives so long as the editorial process is able to distil relative contributions. Consequently, our results demonstrate that while practices of assigning co-authorship later in the research production process can be optimal, when such regimes cannot be committed to, a process that divides research outputs into readily identified and solely "owned" constituent parts (or 'slice's as they are often known) can also generate more efficient outcomes.

The paper proceeds as follows. In the next section, we set up the model and our key assumptions. Section 3 then examines equilibrium outcomes when the pioneer scientist is choosing their co-authoring regime. Citations as an organization regime and reward structure are considered in Section 4. Section 5 considers extensions while section 6 offers conclusions.

2 Model Setup

The production of research involves two sequential stages, $t \in \{1, 2\}$ where scientists can generate either a *routine* or an *exceptional* contribution. Those contributions then determine the overall quality of the research produced and both stages must be performed for any useful research output to be generated.

In each stage, by expending effort, $e_i \in [0,1]$, a scientist, *i*, generates a contribution to knowledge. The quality of the contribution at stage *t*, denoted S*t*, can either be (*H*) or (*L*). S*t* = *L*, which arises with probability $1-e_i$, means that the stage 1 research was *routine* whereas S*t* = *H*, which arises with probability e_i, means that it was *exceptional*. It is assumed here that the costs incurred by a scientist at each stage are identical, specifically, $c(e_i)$, with $c(0)=0$, $c', c'' > 0$ for all e_i. Below we will rely upon the specific functional form, $c(e_i) = \frac{1}{2}e_i^2$, to derive closed form solutions, but all results here would hold for the more general cost function specification.

For simplicity, we assume that the significance of the stage 1 contribution does not impact on the costs at stage 2. Instead, the contributions impact on the overall outcome that may arise at the end of stage 2. Specifically, it assumed that research output can be of high quality ($V < 1$), low quality ($v < V$) or no value (0). If (S1, S2) = (*H*, *H*), then research output is *V* with certainty. If (S1, S2) = (*H*, *L*) or (*L*, *H*), then research output is *v*. Finally, if (S1, S2) = (*L*, *L*), then research output has quality 0.[5] The key feature of this specification for the production of research is that the market does not receive a perfect signal of the contribution at each stage from an observation of paper quality. Specifically, an observation of paper quality, *v*, does not provide a signal, in itself, of whether an exceptional contribution was produced in stage 1 or 2. Of course, one can imagine other forms of signal obfuscation, and these will be explored below.

[5] This specification involves a significant departure from Engers et al. (1999) who made the strong assumption that the level of research quality was independent of the relative contribution of each scientist.

Two asymmetries are introduced with respect to the two research stages. First, there are two types of scientists: pioneers (*P*) and followers (*F*). Each is distinguished by their skill competencies for a research stage. Followers can only engage in research for stage 2.[6] Pioneers can engage in research in both stages but they have a diminished competency with regards to stage 2. This is captured by assuming that a pioneer scientist cannot generate an outcome where S2 = *H*. As a consequence, a pioneer scientist engages in no effort in stage 2 even for the case where they are the sole contributor to a project. The second asymmetry is that the scientist conducting research at the second stage knows the quality of the contribution made at the initial research stage. This is a standard assumption in models of cumulative knowledge (Scotchmer, 2004).

We focus on several critical decisions. First, as a pioneer scientist has the option to collaborate with a follower, we consider *P*'s decision to collaborate or not. This mirrors the authority relationship in a laboratory that is our motivation in this paper. Second, a collaboration can result in a formal acknowledgement of that in the form of co-authorship. This is a choice, as many collaborations in a lab environment involve some discretion as to whether a follower is acknowledged as a co-author or not. Third, the timing and nature of the co-authoring contract may be discretionary. For instance, the collaboration and co-authoring decisions may be made ex ante, interim or ex post. An **ex ante** co-authoring commitment is a contract to include both scientists as authors prior to effort being expended by either. An **interim** commitment occurs after the pioneer scientist's contribution has been resolved. Finally, an **ex post** commitment occurs after both scientists' contributions have been resolved. The latter may take the form of an

[6] It could only add a little descriptive complexity to allow followers to conduct research at stage 1 without any changes to the results that follow.

incentive commitment to the follower who, say, receives co-authorship only if S2 = *H* and not otherwise. These decisions may not all be feasible (i.e., capable of the required commitments) and will depend on the scientists involved, but they span a wide range of the options available. To build understanding, we will focus on particular cases where different decisions are feasible.

2.1 Market Attribution

What drives the incentives of scientists is, of course, attribution "awarded" to them by the "market." Following Engers et al. (1999), this is something that we assume enters directly into a scientist's utility function. That is, a scientist can infer, through interactions with other scientists, what their assessment is of them. Thus, we need not model any active assessment by the market for some purpose but only the impact of such an assessment. Of course, one can imagine microfoundations for this process, including assessment of career concerns of junior scientists, the salary determination of all scientists or some sociological model of acknowledgement and peer recognition. However, *the important feature here is that the scientists' themselves care about attribution from the market and so we assume that is a component of their utility*.

In making an assessment, it is assumed that the market (a) knows the roles (or competencies) of each scientist in a team and (b) assesses both the quality of a project and also forms beliefs over each scientist's relative contribution. The rationale for (a) is that the project is coming out of *P*'s lab and so *P*'s status, role and competency are broadly understood. In an extension below, we consider what happens when the market does not have knowledge of the roles or competencies of each scientist.

With regard to (b), we assume that, if the market observes a paper of quality *V*, it correctly infers that the contribution of both scientists was *H* and, more critically, equal. Thus, the market will assign each an equal share of the paper's "award." In contrast, if the market observes a paper of quality, *v*, that was the output of a collaboration, it faces a more difficult inference problem. We will examine the outcome of that below. However, here we assume that if the market knew with certainty that (S1,S2) = (*H*,*L*), then it would attribute the entire value of the paper to *P* and, similarly, if it knew that (S1,S2) = (*L*,*H*), it would attribute the entire value of the paper to *F*. The rationale here is that without the *H* contribution, the paper's value would be 0 and so the "marginal" contribution of the *H* contributing scientist is *v*. It should be noted that these attribution rules are assumptions but that the results below still apply for variations of those rules.

Of course, market assessments of the contribution of each scientist in a collaboration will depend on the nature of decisions open to them. Thus, like scientist roles, we will make different assumptions of the market's understanding of the nature of attribution decisions scientists can feasibly choose. The modelling challenge, outlined below, is to match these with assessments of contribution. It is assumed that the market never observes (S1, S2) but can observe research quality and whether formal attribution of a co-authoring relationship is given. Based on this information, the market attributes a share of research value, α_V or α_v as the case may be, to the pioneer and a share $1-\alpha_V$ or $1-\alpha_v$ to the follower.[7]

[7] One might ask why these shares should sum to one. A rationale is presented by Gans and Murray (2015) based on generating the joint efficiency of choices to collaborate or not. Additional evidence is contained in Bikard, Murray and Gans (2015).

Given this, if the scientists knew they would be co-authoring ex ante, they would choose their effort levels to maximize the following payoffs:

$$\pi_P = e_P\left(e_F(H)\hat{\alpha}_V V + (1-e_F(H))\hat{\alpha}_v v\right) + (1-e_P)e_F(L)\hat{\alpha}_v v - c(e_P) \text{ and}$$

$$\pi_F = e_P\left(e_F(H)(1-\hat{\alpha}_V)V + (1-e_F(H))(1-\hat{\alpha}_v)v\right) + (1-e_P)e_F(L)(1-\hat{\alpha}_v)v - c(e_F).$$

Here $\hat{\alpha}_V$ and $\hat{\alpha}_v$ are the scientist's expectations of market attribution shares. Importantly, *F* is able to choose effort, $e_F(S1)$, following an observation of *P*'s S1 contribution, and *P* anticipates this. Given this, using the quadratic specification for effort costs, the effort choices of each scientist are:

$$e_F^*(H) = (1-\hat{\alpha}_V)V - (1-\hat{\alpha}_v)v \tag{1}$$

$$e_F^*(L) = (1-\hat{\alpha}_v)v \tag{2}$$

$$e_P^* = \left((1-\hat{\alpha}_V)V - (1-\hat{\alpha}_v)v\right)\left(\hat{\alpha}_V V - \hat{\alpha}_v v\right) + \left(1-(1-\hat{\alpha}_v)v\right)\hat{\alpha}_v v \ . \tag{3}$$

Below we search for full market equilibrium outcomes where each scientist's expectations of market weightings correspond to the actual market weightings.

2.2 *Optimal Attribution*

At this point, it is instructive to consider what attribution shares would generate an optimal outcome – such as maximizing expected paper quality – given the resulting effort choices of scientists.[8] This will assist us in comparing various market outcomes to potential benchmark performance.

[8] An alternative welfare standard that, for example, included the cost of effort could also be used. It gave rise to similar outcomes and so, for simplicity, we choose to use expected paper quality in order to understand the *structure* of optimal attribution shares.

To this end, assume that shares can be related directly to contribution; that is, there is perfect information on contribution. In this case, *P*'s share is a function α_{S1S2} and the resulting effort choices are given by:

$$e_F^*(H) = (1-\alpha_{HH})V - (1-\alpha_{HL})v \tag{4}$$

$$e_F^*(L) = (1-\alpha_{LH})v \tag{5}$$

$$e_P^* = \left((1-\alpha_{HH})V - (1-\alpha_{HL})v\right)(\alpha_{HH}V - \alpha_{HL}v) + \left(\alpha_{HL} - (1-\alpha_{LH})\alpha_{LH}v\right)v \ . \tag{6}$$

Notice that a higher α_{HL} and a lower α_{LH} increase both *P* and *F* effort. Thus, it is optimal to set $\alpha_{HL} = 1$ and $\alpha_{LH} = 0$ in order to maximize expected paper quality. Given this, $e_F^*(H) = (1-\alpha_{HH})V$, $e_F^*(L) = v$ and $e_P^* = (1-\alpha_{HH})V(\alpha_{HH}V - v) + v$ yielding expected paper quality of:

$$\left((1-\alpha_{HH})V(\alpha_{HH}V - v) + v\right)\left((1-\alpha_{HH})V(V-v) + v\right) + \left(1-(1-\alpha_{HH})V(\alpha_{HH}V - v) - v\right)v^2 . \tag{7}$$

The setting of α_{HH} involves a trade-off between *P*'s and *F*'s incentives. When $v \to V$, it can readily be seen that $\alpha_{HH} = 1$ is optimal while if $v = 0$, expected paper quality is $(1-\alpha_{HH})^2 \alpha_{HH} V^4$, which is maximized at $\alpha_{HH} = \frac{1}{3}$. Of course, given our assumptions, the market will always set $\alpha_{HH} = \frac{1}{2}$ and, thus, will not achieve this optimal level.

3 Co-Authorship Equilibria

Having set up the research and market attribution environments, we first consider the pioneer scientist's decision to co-author or work on their own. We will start by examining ex ante co-authorship before adding timing options of interim and ex post co-authorship to consider the equilibria that arise with a full set of options available.

3.1 Market Assessment

As noted above, when paper quality is *v*, the market cannot easily determine whether *P* or *F* had the exceptional contribution. In this situation, the market forms expectations of the effort levels of each scientist, $\hat{e}_P$, $\hat{e}_F(H)$ and $\hat{e}_F(L)$, respectively. Thus, the probability that (S1,S2) = (*H*,*L*) is $\hat{e}_P(1-\hat{e}_F(H))$ while the probability that (S1,S2) = (*L*,*H*) is $(1-\hat{e}_P)\hat{e}_F(L)$. Therefore, conditional on its observation of a paper of quality, *v*, the market's assessment of *P*'s relative contribution is:

$$\hat{\alpha}_v = \frac{\hat{e}_P(1-\hat{e}_F(H))(1)+(1-\hat{e}_P)\hat{e}_F(L)(0)}{\hat{e}_P(1-\hat{e}_F(H))+(1-\hat{e}_P)\hat{e}_F(L)} = \frac{\hat{e}_P(1-\hat{e}_F(H))}{\hat{e}_P(1-\hat{e}_F(H))+(1-\hat{e}_P)\hat{e}_F(L)} \ . \quad (8)$$

Note that this specification for market beliefs easily encompasses other situations other than ex ante co-authorship. For instance, under single authorship, $\hat{e}_F(H)=\hat{e}_F(L)=0$ and so $\hat{\alpha}_v=1$, whereas, in a situation that will be analysed below, it may be that co-authorship is only granted when S1 = *L*. In this case, the probability that paper quality is *v* and there is co-authorship (rather than sole authorship) is $(1-\hat{e}_P)\hat{e}_F(L)$ while the probability that (S1,S2) = (*H*,*L*) is 0, so that, in this case, $\hat{\alpha}_v=0$.

3.2 P's Decision to Co-Author

Given the setting here, we assume that *P* makes the decision to co-author and does so with regard to their expected payoff. Of course, that payoff is constrained by market expectations that are not influenced by *P*'s decision. Several issues arise in this regard.

First, what is *P*'s alternative option? Given the setup here, *P* can choose not collaborate with *F*. We denote this choice as (S) for "sole" authorship. In this case, S2 always equals *L*, ruling out a paper quality of *V*. On the other hand, *P* appropriates all of the paper's value. Hence, by sole authoring, *P* chooses effort to maximize $e_P v - c(e_P)$ which yields $e_P^* = v$, expected paper quality of v^2 and an expected payoff to *P* of $\frac{1}{2}v^2$.

Second, when can *P* make a decision to bring *F* on as a co-author? *P* could make the decision ex ante (prior to any effort being expended), at an interim stage (following the revelation of S1) or ex post (after the revelation of S2). Let us denote these choices as (C0), (C1) and (C2), respectively, where "C" indicates co-authorship and {0, 1, 2} indicate the stage co-authorship is given. We examine cases where some or all of these choices are feasible options for *P*.

Third, when *P* can choose the timing of co-authorship, is *P* able to commit to a co-authoring offer? In some situations, we can imagine that a co-authoring offer is a binding commitment. In others, there may be some contractual incompleteness that means that *P*'s decision must be self-enforcing ex post. We will examine varying assumptions with regard to commitment to better understand the mechanisms of co-authorship.

3.3 Ex Ante Co-Authorship (C0)

To consider the possible equilibrium outcomes, it is instructive to consider, first, a situation where the decision to co-author can only be made ex ante (prior to effort choices). In this situation, it is assumed that both *P* and *F* will be listed as co-authors on the paper and that the market understands that this is the process. Thus, the market assessment will be as described in (8).

Given this, the following proposition lists the pure strategy equilibrium outcomes of the full game under an assumption of rational expectations where $\hat{e}_P = e_P^*$, $\hat{e}_F(H) = e_F^*(H)$ and $\hat{e}_F(L) = e_F^*(L)$.

Proposition 1. *The following are pure strategy rational expectations equilibrium of the full game when only (C0) is feasible.*

(i) (all attribution to P): for all (V, v), $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = 0$*;*

(ii) (all attribution to F): for $V \le 2v$ $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, $e_P^* = 0$, $e_F^*(H) = 0$ *and* $e_F^*(L) = v$*;*

(iii) (mixed attribution): for $V \le 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, \frac{V(2+2v-V)}{4v})$, $e_P^* = \frac{1}{2}V$, $e_F^*(L) = \frac{1}{4}(2v - V)(2 - V)$, $e_F^*(H) = V(1 - \frac{1}{4}V) - v(1 - \frac{1}{2}V)$.

To find the equilibrium outcomes, we take the effort subgame outcomes, (4) – (6), and impose the requirement that expectations regarding market weights are met and look for the resulting fixed point(s). The third equilibrium in Proposition 1 is listed for completeness but can be readily demonstrated to be unstable, and so it will not be considered in the discussion that follows. The equilibrium (i) where all "equity" in a paper of quality *v* is assigned to *P* (i.e., $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$) exists for any range of paper quality values. In this equilibrium, *F* only receives a positive return if *V* arises. Thus, *F* will only expend effort when S1 = *H* and so will only end up being a co-author of a paper of quality *v* if S2 = *L*. This reinforces the market assignment to *P* as, in equilibrium, it is always the case that quality, *v*, signals that *P*'s contribution is *H*. In this situation, the equilibrium expected paper quality is $\frac{1}{8}\left(v(2-V)+V^2\right)\left(2v(2-V)+V^2\right)$, which increases with *V*.

There also exists an equilibrium where all equity in a paper of quality *v* is assigned to *F* (i.e., $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$). In this situation, S1 = *H* does not arise in equilibrium. Thus, expected paper quality is v^2. This is the same paper quality that would arise if P were a sole author. To see that this is an equilibrium, note that, if S1 = H did arise, then $e_F^*(H) = \max[\frac{1}{2}V - v, 0]$. If $V > 2v$, this effort would be positive and it would be easy to see that P would have an incentive to expend positive effort, deviating from the equilibrium. However, when $V \leq 2v$, F's effort remains at 0, reinforcing the equilibrium outcome. It is important to note that when $V \leq 2v$, this equilibrium outcome co-exists with the outcome where $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$.

Proposition 1 assumes that the co-authoring decision has been made. When P can choose whether to co-author or not, what survives? Note first, that P does not earn any value in the equilibrium where $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ and thus, under these market expectations, P would choose to single author. This would result in a paper of the same quality as would result under co-authorship in that case. Second, when $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, P earns $\frac{1}{32}(V^2 + 2v(2 - V))^2$. Comparing this to P's sole authorship payoff of $\frac{1}{2}v^2$, it is easy to demonstrate that P prefers to co-author if $V \geq 2v$.

Proposition 2. *The only pure strategy rational expectations equilibrium of the full game, when only (C0) and (S) are feasible, are (i) if* $V \geq 2v$ *, co-authorship with* $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$ *and (ii) if* $V \leq 2v$*, sole authorship.*

The intuition is fairly straightforward. Under co-authorship, the most that P can receive is $\frac{1}{2}V$ but under single authorship the most P can achieve is v. As it always appropriates the full value of v should it arise in either case, P loses nothing by ceding co-authorship for this scenario. However, co-authorship reduces the probability of this scenario by the same amount that it increases the probability of the scenario where P receives half of V. Thus, the marginal value of co-authorship is driven by whether $\frac{1}{2}V$ is greater than v or not.

Note, however, that in terms of maximizing expected paper quality or joint surplus, *P*'s decision to co-author is socially suboptimal and should occur for a threshold value of *V* lower than 2*v*. The reason for this is that it would be preferable to allow *F* some equity when *v* arises with (S1,S2) = (*L*,*H*) but, instead, the equity the market attributes is the same regardless of how *v* arises.

3.4 Interim Co-Authorship (C1)

The above analysis assumed that the only time a co-authoring decision could be made is ex ante (prior to effort being expended). Here, we consider what happens when the decision by *P* can be made after the resolution of S1. As before, we begin by considering what happens when interim co-authorship is the only option (with a decision of sole authorship being only available after the realization of S1) before considering what happens when ex ante co-authorship or sole authorship is possible.

Note, first, that if S1 = *L*, then it is always (weakly) optimal for *P* to offer co-authorship to *F*. In this situation, sole authorship nets *P* a payoff of 0 whereas co-authorship could net *P* more if $\hat{\alpha}_v > 0$. Second, as before, a paper quality of *V* is only observed if there is interim co-authorship and, in this case, (S1,S2) = (*H*,*H*) so that $\hat{\alpha}_V = \frac{1}{2}$ always. Otherwise the following proposition characterises the possible equilibrium outcomes:

Proposition 3. *The following are pure strategy rational expectations equilibrium of the full game when only (C1) is feasible.*

(i) for $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, *with co-authorship both when S1 = L and H and with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = 0$*;*

(ii) for $(V - 2v)V \leq 4v$ $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, *with co-authorship only arising when S1 = L with* $e_P^* = v$ *and* $e_F^*(L) = v$.

The first equilibrium involves the same outcome as equilibrium (i) in Proposition 1 but only exists over a limited domain. The reason is that when S1 = *H*, sole authorship earns *P*, v from that point on whereas co-authorship nets *P*, $\frac{1}{2}V(\frac{1}{2}V-v)+v$. Thus, co-authorship is only preferable if $V \geq 2v$. The second equilibrium involves no co-authorship when S1 = *H*. If the market expects that this is the case then, when a paper quality of v arises, the market assesses with certainty that S2 = *H* and so sets $\hat{\alpha}_v = 0$. In this case, expected paper quality is $v^2+(1-v)v^2$; higher than the level that arises under sole authorship. The only possible deviation is that *P* chooses to co-author when S1 = *H*. If it did this then, given that $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, $e_F^*(H) = \max[\frac{1}{2}V - v, 0]$ and, from that point, *P* would earn $(\frac{1}{2}V-v)\frac{1}{2}V$ rather than v. This deviation is not profitable if $V-2v \leq 4\frac{v}{V}$. Thus, for $0 \leq V-2v \leq 4\frac{v}{V}$, equilibria (i) and (ii) in Proposition 3 co-exist.

Proposition 3 considers situations where *P* could not commit upfront to ex ante co-authorship or sole authorship. It can be easily seen that when $V \geq 2v$, then *P* would be indifferent between ex ante co-authorship and interim co-authorship under equilibrium (i). However, what if $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ (as consistent with equilibrium (ii))? In this case, we know that for $V-2v \leq 4\frac{v}{V}$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ is an equilibrium and could earn *P* an ex ante payoff of v^2, the same as sole authorship. If *P* committed to *F* to allow co-authorship when S1 = *H*, *P*'s ex ante payoff would be $\frac{1}{4}V^2(\frac{1}{2}V-v-\frac{1}{2})$ as *P* would choose an effort level of $\frac{1}{2}V$ in this case. Note that this payoff is non-positive. Hence, *P* would not find it optimal to commit to ex ante co-authorship. Interestingly, this occurs despite the fact that *P* would, for $V \geq 2v$, prefer the ex ante co-authorship as in

Proposition 1 (i). However, given the market expectations of an interim co-authorship decision, P cannot achieve that outcome.

What are the efficiency implications of having an option to choose interim co-authorship? To examine this, observe that when $V \geq 2v$, expected paper quality is the same under both ex ante and interim co-authorship when $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$; i.e., $\frac{1}{8}\left(v(2-V)+V^2\right)\left(2v(2-V)+V^2\right)$. For $V < 2v$, equilibrium (ii) of Proposition 3 involves a higher expected paper quality of $v^2(2-V)$ than the expected paper quality of v^2 that can be achieved under P's sole authorship (the expected outcome from Proposition 2). In this situation, interim co-authorship as an option improves efficiency.

It is less straightforward to rank outcomes based on expected paper quality when $0 \leq V - 2v \leq 4\frac{v}{V}$ and, under interim co-authorship, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$. In this case, expected paper quality in equilibrium (i) of Propositions 2 and 3 and that for equilibrium (ii) in Proposition 3 cannot be easily ranked except to say that for v sufficiently low, interim co-authorship involves expected paper quality no higher than ex ante co-authorship and for $V < \frac{2}{3}$, there exists v close to V where interim co-authorship with $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ results in higher expected paper quality than the equilibria where $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$. In effect, P ends up expending more effort to ensure that it does not lose attribution to F; thus, raising expected paper quality.

3.5 *Ex Post Co-Authorship*

We now consider what happens when P can offer F an "option" contract contingent on F's contribution in stage 2. Specifically, what if co-authorship is granted if

S2 = *H* while it is not granted if S2 = *L*? The following proposition characterises the equilibrium outcome contingent upon this contract being offered and committed to.

Proposition 4. *Suppose that only (C2) is feasible. Then, if* $V \geq 2v$*, a pure strategy rational expectations equilibrium of the full game with a contingent contract exists and involves* $(\hat{a}_V, \hat{a}_v) = (\frac{1}{2}, 0)$*, with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$*,* $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = v$*.*

Before explaining why this is an equilibrium, it is useful to note that this involves both *P* and *F* choosing the highest levels of effort associated with any organisational regime considered this far. Consequently, expected paper quality is $\frac{1}{8}\left(v\left(2-V\right)\left(4v(2-v)+3V^2\right)+V^4\right)$, which is higher than any other equilibrium outcome where $V \geq 2v$.

Recall that, in our earlier analysis of optimal attribution, it was optimal to set $\alpha_{HL} = 1$ and $\alpha_{LH} = 0$. This would maximize, $e_F^*(L) = (1-\alpha_{LH})v$ and $e_F^*(H) = (1-\alpha_{HH})V - (1-\alpha_{HL})v$. What prevented this outcome under ex ante and interim co-authorship was that either $\alpha_{HL} = \alpha_{LH}$ or, under one equilibrium in interim co-authorship, co-authorship would not arise when S1 = *H*. Under ex post co-authorship, co-authorship is contingent upon the realisation of S2 allowing both α_{HL} to differ from α_{LH} and for co-authorship to arise when S1 = *H*. This combines the good features of both ex ante and interim co-authorship. Thus, if S2 = *L*, no co-authored paper arises and *P* receives full attribution; that is, $\alpha_{HL} = 1$. By contrast, if S2 = *H* then a co-authored paper arises and, if it is of quality *v*, then *F* receives full attribution; that is, $\alpha_{LH} = 0$. Thus, both α_{HL} and α_{LH} end up being at their optimal levels.

3.6 Equilibria under Commitment

We now turn to consider which organizational regimes survive as equilibrium outcomes when all options considered thus far can be chosen and agreed upon ex ante. That is, when each option can be committed to by *P*.

To build intuition, suppose that the market assumes, consistent with the ex post co-authorship equilibrium in Proposition 4, that when a paper of quality *v* is co-authored then S2 = *H* with certainty; hence, they set the attribution share at $\alpha_v = 0$. The chosen effort levels are consistent with this expectation. In this case, it can be demonstrated that *P* receives the same ex ante expected payoff as equilibrium (i) in Proposition 1 for ex ante co-authorship and will be indifferent between these. Suppose, however, that ex ante, *P* offers co-authorship given expectations $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$. Then $e_F^*(H) = \frac{1}{2}V - v$, $e_F^*(L) = v$ and $e_P^* = \max[e_F^*(H)\frac{1}{2}V, 0]$. If $V \leq 2v$, *P*'s payoff would be 0 while if $V > 2v$, it would be $(\frac{1}{2}V - v)^2 \frac{1}{4}V^2 - \frac{1}{8}(\frac{1}{2}V - v)^2 V^2 = (\frac{1}{2}V - v)^2 \frac{1}{8}V^2$ which is a lower payoff. Thus, a deviation to ex ante co-authorship is not profitable. What about a deviation to interim co-authorship? When S1 = *L*, offering *P* co-authorship at that stage with market expectations of $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ is equivalent to what would arise under ex post co-authorship. At S1 = *H*, denying *P* co-authorship would net *P* *v* instead of $\frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$. This deviation is not profitable if $V \geq 2v$. Finally, note that *P*'s payoff under the contingent contract equilibrium in Proposition 4 is the same as under equilibrium (i) in Proposition 1. Therefore, *P* will not prefer to commit to sole authorship so long as $V \geq 2v$.

What other equilibria are possible when ex post contingent contracting is feasible? Note, first, that when $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ and $V \geq 2v$, P will find it optimal to offer an ex post contingent contract. Thus, the parameter range allowing the interim contract (ii) in Proposition 3 narrows to $V \leq 2v$. Second, when $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, offering a contingent contract does not change *F*'s incentives. Thus, ex ante co-authorship (equilibrium (i) of Proposition 1) and its ex post variant (equilibrium (ii) of Proposition 3) continue as possible equilibrium outcomes. Summarizing we have:

Proposition 5. *The following are pure strategy rational expectations equilibria of the full game when P can commit to (S), (C0), (C1) or (C2).*

(i) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, *with ex ante and interim co-authorship both when S1 = L and H and with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = 0$;

(ii) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ *with ex post contingent co-authorship when S2 = H with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = v$;

(iii) *for* $V \leq 2v$ $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, *with interim co-authorship only arising when S1 = L with* $e_P^* = v$ *and* $e_F^*(L) = v$;

(iv) *for* $V \leq 2v$ *sole authorship with* $e_P^* = v$.

Proposition 5 demonstrates that when there is a full range of co-authoring timing choices that can be committed to by *P* that there are multiple equilibrium outcomes for each parameter range. Specifically, when $V \geq 2v$, ex ante, interim and ex post co-authorship are all equilibrium outcomes. However, as already noted, the equilibrium (ii) with ex post contingent co-authorship involves the highest expected paper quality and joint surplus for *P* and *F*. *Interestingly, the equilibrium with ex post co-authorship also involves the highest expected payoff for F.* This is because it involves *F* receiving the highest equity when S2 = *H*. Importantly, this equilibrium is (weakly) Pareto superior to equilibrium (i) as *P*'s expected payoff is the same as ex ante co-authorship.

In contrast, when $V \leq 2v$, both interim co-authorship and sole authorship are equilibrium outcomes. Each of these involves the same expected payoff to *P* while interim co-authorship involves a higher expected payoff to *F,* and so Pareto is superior. However, because of its efficiency, the equilibrium with interim co-authorship results in a higher expected paper quality and joint surplus than what is expected with sole authorship by *P*.

3.7 No Commitment to Co-Authorship

The above analysis assumes that *P* commits to a co-authoring agreement and that the market understands that this commitment is possible. But what happens when *P* cannot commit to a co-authoring agreement? Specifically, what happens if co-authorship is an incomplete contract meaning that *P* can ask for collaboration but ex post not offer formal co-authorship?

First, note that for equilibria where $\hat{\alpha}_v = 1$, then *P* has no reason not to offer co-authorship if paper quality is *v*. In contrast, for equilibria where $\hat{\alpha}_v = 0$, then *P* can appropriate more by not having *F* formally listed as a co-author. This might arise under contingent ex post co-authorship or interim co-authorship when S1 = *L*. In each of these cases, a single authored paper of quality *v* is achievable on the equilibrium path and so *P* can appropriate *v* as a payoff by not co-authoring, regardless of *F*'s contribution. As *P* cannot commit to co-author in this situation equilibria (ii) and (iii) in Proposition 5 are not feasible under any commitment.

Second, what happens when (S1, S2) = (*H*, *H*)? In this situation, *P* could omit *F* as a co-author. However, in that scenario, the market still understands that *P* could not have achieved a paper with a quality of *V* without assistance. Thus, the attribution to *V* remains at $\alpha_V = \frac{1}{2}$ even if the market is not able to attribute the remaining share to a particular scientist. Thus, as single authorship with a paper quality, V is not on the equilibrium path, P has no incentive to renege on co-authorship under this scenario. Thus, the equilibrium outcomes (i) and (iv) in Proposition 5 remain feasible.

In summary, an inability to commit to co-authorship removes the Pareto superior equilibria from Proposition 5 as possible outcomes. This suggests that mechanisms that allow P to commit to co-authoring contracts will be welfare enhancing. This might be achieved by a relational contracting outcome (in a broader multi-agent setting), but the establishment of that relies on market expectations – namely, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, consistent with such outcomes. If those expectations are not present in the market, it may be difficult for an individual research team to establish them. However, in the next section, we focus on a situation whereby a third party (journal editors) may play a commitment role.

4 Citations

Both sole authorship and co-authorship are "integrated" solutions to the organization of collaborative research. They are integrated in the sense that the entire output of research is owned by one or both scientists. This stands in contrast to a "non-integrated" solution to organizing collaborative research whereby both scientists produce separate outputs that are "owned" by separate parties. Such a solution would arise if P published their stage 1 research as a separate publication with F publishing their stage 2 research as a follow-on publication. The linkage between them would then be described by a citation contained in *F*'s publication. Here we consider this "publish and cite back" alternative and compare it to the various forms of co-authorship considered above.

To keep the model here consistent with the model thus far, we assume that, should *P* publish their research prior to stage 2, that research has no intrinsic value. Instead, it is only after *F* completes stage 2 and publishes their research that the entire body of research can be ascribed a value of *V*, *v* or 0 as the case may be. Admittedly, this assumption is contrary to what is usually assumed about publications per se, but it does capture the notion that what is valuable are "bodies" of works rather than individual works themselves. In addition, it has the second effect of providing no reason for *P* to publish other than to receive a citation and receive some attribution from the entire body of work. To be sure, in reality, there are other reasons to publish, but this specification allows us to abstract away from those.

Another reason for publication of interim results is that *P* may not know who might be able to carry on follow-on research. To rule this out, we assume that only *F* has the ability to complete the body of work for valuable research. Again, the purpose of this is to provide the pioneer with a stark choice between publishing interim results and co-authoring with the (already identified) follow-on researcher. To the extent that searching for follower-on researchers is of productive value, this will increase the motivation for publishing interim results above and beyond the reasons explored here (Jiang, Thursby and Thursby, 2012).

This setup allows us to preserve the structure of the model – including effort to research relationships and market assessment assumptions. What changes is how formal attribution of contribution occurs. Formal attribution in the form of co-authorship came from internal processes – in this case, the choice of *P* whether to allow a formal attribution or not. Formal attribution in the form of citation could arise in a similar way (via agreement between the scientists), but here we consider a more natural alternative that it is determined by a journal editor. The process we have in mind is that all research is published in a journal with the editor of that journal being interested in maximizing expected paper quality for the journal. In setting citation policy, the editor is (potentially) constrained by market expectations as to what a citation means for the allocation of credit between *P* and *F*. What the editor could do is receive, through referees, a perfect signal of (S1, S2) and offer a citation as a mapping from (S1, S2) outcomes. For instance, an editor may choose to request a citation by *F* to *P*'s work whenever S1 = *H*. Or, instead, an editor may choose to request a citation in all instances or none at all.

We assume that, if a research body of quality, *v*, involves a paper by *F* that cites *P*'s work, then the market attributes a share, α_v, for that body of research to *P* and the remainder to *F*. If there is no citation, then *F* appropriates the entire value, *v*, in this instance. On the other hand, if the research body is of quality, *V*, then regardless of whether there is a citation or not, the market attributes a share, $1-\alpha_V$, to *F*. If there is a citation, the remainder is attributed to *P*; otherwise, that share is "lost."

The journal editor's citation policy and market expectations $(\hat{\alpha}_V, \hat{\alpha}_v)$ are known prior to either *P* or *F* beginning research. Thus, if *P* were to pursue an interim publication of their results, then, I_{S1S2} is an indicator function that takes on a value of 1 if a citation occurs under outcome (S1, S2), the optimal effort choices are as follows:

$$e_F^*(H) = (1-\hat{\alpha}_V)V - (1 - I_{HL}\hat{\alpha}_v)v \qquad (9)$$

$$e_F^*(L) = (1 - I_{LH}\hat{\alpha}_v)v \tag{10}$$

$$e_P^* = \left((1 - I_{HH}\hat{\alpha}_V)V - (1 - I_{HL}\hat{\alpha}_v)v\right)(I_{HH}\hat{\alpha}_V V - I_{HL}\hat{\alpha}_v v) + \left(I_{HL}\hat{\alpha}_v - (1 - I_{LH}\hat{\alpha}_v)I_{LH}\hat{\alpha}_v v\right)v\,. \tag{11}$$

Note that by setting I_{LH} equal to 0 and I_{HL} equal to 1, the journal editor can raise all effort levels. Thus, to maximize journal quality, it is always optimal for the editor to require a citation if (S1, S2) = (*H*, *L*), but not if (S1, S2) = (*L*, *H*). Similarly, note that setting I_{HH} equal to 1 boosts *P*'s effort while not reducing *F*'s (as the market will not change its attribution to *F* for a paper of quality *V*). Thus, it is clear that, regardless of expectations of market attribution, the journal editor will maximize expected paper quality that commits to a policy of requiring a citation of *F* by *P* whenever S1 = *H*.

Given this, noting that $\hat{\alpha}_V = \frac{1}{2}$, the optimal efforts will become:

$$e_F^*(H) = \tfrac{1}{2}V \tag{12}$$

$$e_F^*(L) = v \tag{13}$$

$$e_P^* = \tfrac{1}{4}V^2 + (1 - \tfrac{1}{2}V)v\,. \tag{14}$$

Setting $\hat{e}_P = e_P^*$, $\hat{e}_F(H) = e_F^*(H)$ and $\hat{e}_F(L) = e_F^*(L)$, it is clear that, if a citation is observed for paper quality, *v*, then $\hat{\alpha}_v = 1$. Notice that this is equivalent to the equilibrium outcome that can be achieved under ex post contingent co-authorship. Recall that for $V \geq 2v$, this generated the highest expected paper quality and joint surplus and for all parameter values, this was preferable to sole authorship.

4.1 The interim publication choice

Given this expected outcome from citation, when will *P* choose to have an interim publication? The following proposition states the equilibrium outcomes:

Proposition 6. *The following are pure strategy rational expectations equilibria of the full game when P can commit to (S), (C0), (C1), (C2) or publish after stage 1:*

(i) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, *with ex ante and interim co-authorship both when S1 = L and H and with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = 0$;

(ii) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ *with ex post contingent co-authorship when S2 = H or interim publication when S1 = L* $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ *with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = v$;

(iii) *for* $V \leq 2v$ $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, *with interim co-authorship only arising when S1 = L with* $e_P^* = v$ *and* $e_F^*(L) = v$;

(iv) *for* $V \leq 2v$ *sole authorship with* $e_P^* = v$.

The following are pure strategy rational expectations equilibria of the full game when P cannot commit to co-authorship but can publish after stage 1:

(v) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 1)$, *with ex ante and interim co-authorship both when S1 = L and H and with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = 0$;

(vi) *for* $V \geq 2v$, $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$ *with interim publication with* $e_P^* = \frac{1}{4}V^2 + (1 - \frac{1}{2}V)v$, $e_F^*(H) = \frac{1}{2}V$ *and* $e_F^*(L) = v$;

(vii) *for* $V \leq 2v$ $(\hat{\alpha}_V, \hat{\alpha}_v) = (\frac{1}{2}, 0)$, *with interim co-authorship only arising when S1 = L with* $e_P^* = v$ *and* $e_F^*(L) = v$;

(viii) *for* $V \leq 2v$ *sole authorship with* $e_P^* = v$.

Importantly, interim publication is always an equilibrium when $V \geq 2v$ now just as sole authorship is when $V \leq 2v$, regardless of whether *P* can commit to co-authorship or not and regardless of market expectations under co-authorship. Basically, interim publication allows *P* to commit to evaluation by a journal editor motivated to maximize expected paper quality. However, when $V < 2v$, this leaves *P* worse off than sole authoring both stages of research.

This analysis presumes that the journal editor does not take into account *P*'s incentives to sole author or engage in interim co-authorship when setting the journal's citation policy. At the moment, no citation to *P* is given when (S1, S2) = (*L*, *H*). Could granting a citation in this situation increase *P*'s incentive to engage in interim publication and increase expected paper quality?

This option is only relevant when $V \leq 2v$, for it is here that *P* might not choose interim publication. When S1 = *H*, the only possible outcomes with interim publication are that *P* receives *v* or *V*/2 whereas with sole authorship, *P* receives *v* with certainty and so prefers this. There is no instrument available to the journal editor to ensure *P* receives more under interim publication. In contrast, when S1 = *L*, the journal editor can ensure *P* receives more by offering a citation with some probability, *p*, in this instance. This is only valuable if $\hat{\alpha}_v(p) > 0$ is sustainable as a set of equilibrium market beliefs. However, given that when S1 = *H*, there is no interim publication, and when S1 = *L*, there is interim publication, the market can correctly infer that S1 = *L* and so will set $\hat{\alpha}_v(p) = 0$, regardless of whether there is a citation or not. Consequently, the journal editor is not able to use an increased citation rate as a means of inducing *P* to engage in interim publication.

In recent times, there has been a push amongst some scientists to encourage or even require publication of interim results (Nielsen, 2012). Proposition 6 demonstrates that while interim publication might arise as an equilibrium outcome when $V \geq 2v$, when $V < 2v$, this does not occur. Thus, what if interim publication was mandated? If $V < 2v$, there would be a citation issued if S1 = *H* and none if S1 = *L*. Thus, the market receives an accurate signal of *P*'s contribution and so will set $\alpha_v = 1$ if a citation is observed. As has already been noted, this involves a higher expected paper quality than other outcomes and so compulsory publication can improve efficiency. The reason it does this is because it ensures that, for marginal improvements, there is a way of dividing up "equity" between *P* and *F* that otherwise *P* would want to avoid. However, it should be stressed that this outcome is a result of the "editorial review" system being able to make assessments of individual contributions in the first place. If such assessments can be made, even if signals are imperfect (i.e., to cite or not), the market can properly infer attribution.

5 Extensions

We now turn to consider extensions that will be useful in identifying exogenous variation that may assist future empirical researchers in understanding the organisation of science and choices for attribution in more depth.

5.1 No market knowledge of roles

The model here assumes that the "market" (or, more specifically, scientists' understanding of the market) has somewhat detailed knowledge about the roles of *P* and *F* in co-authored outcomes. This may come from actual knowledge of the roles (e.g., the paper came out of "*P*'s Lab") or from signals embedded in the ordering of names (or other details elaborating contributions) on a paper. However, because of the aggregation of results and statistics through online platforms such as a Google Scholar, it is arguable that metrics (such as the H-Index or paper counts) may have more weight for scientists than the more "personalized" market feedback assumed thus far. Moreover, it is the rise of such metrics that may have potentially altered the choices of scientists regarding the organisation of collaborative activities.

To explore this, here we consider a situation where the market (a), if it observes a formal collaboration (with co-authorship acknowledge), has no knowledge of which scientist performed which role, and (b), if it does not observe a formal collaboration, presumes that the sole author is responsible for all of the contributions in the project. Thus, if there is formal co-authorship, the market places equal weight on each scientist being the stage 1 researcher regardless of the quality of the resulting output. Thus, the market weight assignment problem is trivial, and it sets $\alpha_V = \alpha_v = \frac{1}{2}$.

In this situation, it is clear that the efforts under ex ante co-authorship would be (from (1) – (3)): $e_F^*(H) = \frac{1}{2}(V - v)$, $e_F^*(L) = \frac{1}{2}v$ and $e_P^* = \frac{1}{4}(V-v)^2 + \left(1 - \frac{1}{2}v\right)\frac{1}{2}v$ resulting in a payoff to P of $\frac{1}{32}\left(4v(1-V)V^2 + V^4 + 4v^2\left(3-(2-V)V\right)\right)$ and expected paper quality of $\frac{1}{8}\left(4v(1-V)V^2 + V^4 + 4v^2\left(2-(2-V)V\right)\right)$. It is straightforward to show that both P's payoff and the expected paper quality are lower in this equilibrium than the equivalent equilibrium (Proposition 1(i)) where the market has knowledge of scientists' roles. This is because when the market has more knowledge, P appropriates more ex post surplus and engages in higher effort, while F engages in higher effort as they are not insured if a paper of high quality is not produced. This also means that P would be less inclined to co-author with F when the market does not have knowledge of their roles.

From this it naturally follows that under ex post co-authorship, P earns even less when market roles are obscured, but what happens under interim co-authorship is subtler. In this situation, suppose that $V < 2v$ and so, when market roles are observed, the equilibrium where there is co-authorship only when S1 = L is relevant (Proposition 3 (ii)). In this case, P appropriates a share of any resulting co-authored paper (where previously they appropriated none). Thus, P is not indifferent between sole and interim co-authorship and will favour the latter.

This implies that, if the market moves towards metrics that do not easily identify scientists' roles, then for projects where the marginal contribution of each scientist is likely to be very high, fewer co-authored projects will be observed. By contrast, where the marginal contribution of the follow-on researcher is relatively low, such changes would result in more co-authored projects.

5.2 Larger Research Teams

The model considered in this paper is very simple in that there are only two scientists. When there are more scientists who might be part of a collaborative project, more complexity is introduced, but it is likely that the same issues will arise. In particular, when *P* chooses whether to give formal attribution to another, it must consider both the dilution of their own "equity" and the impact that will have on incentives. When there is only one other scientist to consider, that latter impact is likely to be smaller. Hence, considerations here might tend to suggest that there is a natural tendency for scientists to limit the number of formal collaborators.

That said, the organisational regimes that involved higher powered incentives, such as ex post co-authorship and interim publication, would become relatively more important as they solved some of the free-riding issues that may arise. Thus, if larger research teams are warranted, we expect to see an evolution in organisational forms alongside them that allow for more substantial interim publication as well as different modes of ex post co-authorship.

Of course, larger research teams might also be associated with a dilution of the market's ability to identify the individual roles of scientists. In this case, the considerations identified in the previous subsection may come into play. However, this is likely to be associated with the visibility of individual scientists; something that we leave to a future paper to consider in more detail.[9]

5.3 Alternative Reasons for Citations

Thus far, we have considered citations as a formal mechanism to signal attribution amongst a body of work. However, citations also play another role. They can direct scientists to the cited work and, so long as it is relevant, improve the productivity of future research.

> The first of these involves directing readers to the sources of knowledge that have been drawn upon in one's work. This enables research-oriented readers, if they are so minded, to assess for themselves the knowledge claims (the ideas and findings) in the cited source; to draw upon other pertinent materials in that source that may not have been utilized by the citing intermediary publication; and to be directed in turn by the cited work to other, prior sources that may have been obliterated by their incorporation in the intermediary publication. (Merton, 1988, p. 621)

How does the instrumental or productivity value of a "relevant" citation affect the role of interim publication discussed so far? In particular, what happens when editors request citations for instrumental value and, hence, include some citations even when S1 = L?

Earlier we demonstrated that when $V < 2v$, increasing the citation rate when S1 = L, would not change market assessments of *P's* and *F*'s contribution. This is because *P* would not choose interim publication if S1 = H and thus, the market would correctly assess S1 = L, whether there was a citation or not. What about when $V > 2v$? In this case, if the editor requires a citation when S1 = L as well, the citation is no longer a pure signal.

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[9] Merton (1988, p. 448) documented discussions by famous scientists that they sometimes agree to be a co-author of a junior researcher to increase their visibility. The model here could be interpreted as applying to that situation as well. Simcoe and Waguespack (2011) studied the effect of author visibility by examining the changes in publication rates of papers were some authors became obscured in the "et al." of multi-authored papers. On the Internet Engineering Task Force, a publication platform for engineers and computer scientists, a change in policy led to some authors' names being concealed as "et al." This permitted a study of the effects of obscuring a relatively well-known authors on the publication chances of a paper they have co-authored. That obscurity explained three-quarters of the differences in publication rates of known versus relatively unknown scientists.

Indeed, if citations always occur, this is akin to there being no signal when paper quality is *v*, and so it is the same outcome as ex ante co-authorship. This will reduce expected paper quality.

6 Conclusion

The goal of this paper has been to embed an organisational economics approach (namely, how ownership determines incentives for non-contractible actions) into the economics of science. The bridge between those two literatures is provided by considering the non-pecuniary motivations of scientists to receive favorable market assessments of their relative contribution to collaborative projects. Our modelling innovation was to embed that market not only in the processes by which formal attribution is allocated – in our model, by a pioneer scientist – but also in a broader environment for attribution that involves third-party editors or referees.

The contributions arising from this were threefold. First, there is a difference between formal attribution and equilibrium attribution. This is because formal attribution provides an imperfect signal of real attribution and, in equilibrium, these differences must resolve themselves. Second, as a consequence, it is not within the power of scientists, by merely choosing their processes of formal attribution, to implement any desired real attribution. The market constrains those outcomes in equilibrium. Third, as a consequence of this, different organisational regimes have different incentive implications. Most notably, delaying the formal assignment of co-authorship until later in the research production process can enhance incentives in a Pareto improving manner.

This model, we believe, is a starting point for further analyses of the organisational economics of science. While we have not explored some additional dimensions in this paper, our model could be expanded to consider issues of the supply of scientists in a context where there are career hierarchies and career concerns (Stephan, 2012). It could, therefore, be used to both study those labor markets and also inform policies designed to change the supply of scientists. In addition, our model could provide a framework for considering the efficacy of certain measures of contribution utilised by public funding agencies and how these impact incentives and, also, career paths. Finally, here we have dealt with a fairly abstract and utility-grounded approach to scientist preferences. In reality, there are many more instruments that assist in the acknowledgement of scientific contributions and these themselves interact with market assessments and incentives. Consider, for instance, the recent issues raised in economics over the Nobel Prizes for contributions to general equilibrium theory (Duppe and Weintraub, 2014) as well as the long-standing concerns regarding the presence of a Matthew effect in science (Merton, 1968; Azoulay, Stuart and Wang, 2014).

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