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Explaining Scientific Collaboration: A General Functional Account

Thomas Boyer-Kassem and Cyrille Imbert

Abstract

The quantum of collaborative scientific research has been continually increasing over the past two centuries, a fact for which philosophers and historians of science have proposed various explanations. We offer a novel functional explanation of this increase in collaboration, grounded in a sequential model of scientific research where the priority rule applies. Robust patterns concerning the differential successfulness of collaborative groups with respect to their competitors are derived, and it is argued that these success patterns feed the development of collaboration. This mechanism, as it increasingly comes to operate on a global scale, may trigger an ‘arms race’, and is compatible with a certain amount of decrease in the productivity of collaborative groups as well as some over-collaboration. The proposed explanation succeeds in integrating various factors usually associated with the rise of collaboration.

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1 Introduction

The past two centuries have seen a continual rise in the quantum of scientific collaboration, a trend which has accelerated especially since the 1950s, but which has been inhomogeneous across fields. Various epistemic and non-epistemic explanations of this collaborative trend have been proposed, turning on factors such as professionalization, scientific specialization, the desire to cross-fertilize research, changing patterns of funding, better research reliability, enhanced efficiency, or the increasing need to access resources. As noted by Katz et al. ([1997], p. 4), this list of possible explanatory factors, which are often conceived of as distinct and exclusive, is potentially endless.

By contrast, we present a general explanatory scheme that encompasses many such factors and handles them in a complementary way. This scheme is functional: it explains a feature by the function it serves, namely the beneficialness of one of its effects (in a technical sense to be presented). More specifically, we claim that the increase in scientists' collaborative behavior can be functionally explained by the relative increase in collaborative scientists' individual successfulness with respect to their competitors. That is, scientists collaborate because, in suitable contexts, they are more successful when collaborating (or, rather, collaborating to a sufficient degree) than otherwise.

Wray ([2002]) has already offered a functional explanation of collaboration. The novelty of our thesis lies in the social and epistemic mechanisms that ground the beneficialness of collaboration and feed the functional explanation. We investigate these

mechanisms through a model of scientific research introduced by Boyer-Kassem and Imbert ([2015]) that highlights the potentially significant beneficialness of collaboration in suitable contexts. Scientific inquiries are pictured as multi-step processes, which require solving sequences of intermediate problems that have communicable results. Even minor differences in the step-efficiency of collaborative groups are shown to make them more successful in competitive contexts. We then derive robust patterns concerning the differential successfulness of collaborative groups with respect to competitors in suitable contexts, and argue that it is these patterns that feed the development of collaboration in science. Because of the priority rule, these mechanisms are compatible with a decrease in the productivity of collaborative groups in some cases, as well as some over-collaboration. All the factors that increase the step-efficiency of groups can be integrated into this general explanatory scheme.

The paper is organized as follows. We first review the literature about collaboration and discuss the application of functional explanations in the present case (sections 2-3). We then introduce and investigate our model, arguing that it can offer a functional explanation of collaboration in science (sections 4-6). We then go on to discuss the modeling assumptions, analyze the scope of the explanation thus provided, and finally highlight some limits of this inquiry (sections 7-9).

2 The Development of Collaboration in Contemporary Science

Collaboration is a complex, multi-faceted phenomenon, and one may reasonably expect that no simple explanation can cover all of its aspects. We here review various empirical findings about collaboration, highlighting the ones that are relevant to the account in the present paper.

Over the last two centuries the co-authoring of papers has become increasingly widespread in academia (Price [1963], Beaver and Rosen [1978]). This increase in co-authoring is commonly taken as evidence of the increase in scientific collaboration, although co-authoring and collaboration are admittedly not synonymous (for example, co-authors who made minor contributions can be mentioned and genuine contributors overlooked (Katz [1997])). Notably, the degree of collaboration varies significantly across fields. Wuchty et al. ([2007]) report that between the mid 1950s and the end of the century, the percentage of collaborative teams grew from 50% to 80% in science and engineering, from 17.5% to 51% in the social sciences, but remained stuck at 10% in the humanities. Mean team size has also steadily grown in the collaborative fields, for example from 1.9 to 3.5 in science.

These general trends supervene on different collaborative behaviors. For example, experimentalists collaborate more than theoreticians. Women show a higher percentage of female collaborators (Bozeman and Corley [2004]), a lower probability of repeating co-authors, and fewer co-authors over their career (Zeng et al. [2016]). Researchers with

large grants tend to have more collaborators (Bozeman and Corley [2004]). Overall, most researchers tend to collaborate with others in their immediate environment (Lee and Bozeman [2005], p. 695). At an individual level, various collaborative profiles exist, for example ‘taskmasters’, ‘nationalists’, ‘mentors’, or ‘buddies’ (Bozeman and Corley [2004], p. 612; see also Li et al. [2013]).

Policy-makers and institutions generally assume that collaboration is beneficial and should be encouraged. Indeed, Nobel prize-winners are known to collaborate more than the average (Zuckerman [1967]), results produced by large teams are cited more often (Wuchty et al. [2007]), and the number of collaborators is strongly associated with the number of publications. However, if one applies a fractional count, the increase in productivity is not that clear (Lee and Bozeman [2005]). Overall, how much collaboration is globally beneficial remains uncertain, since the costs and benefits are not clearly understood (Katz [1997]).

How can the development of collaboration be explained? We cannot take for granted that there will be a purely ‘rational’ explanation of collaboration, based on its supposed epistemic or non-epistemic beneficialness, and such an account would moreover be potentially unsuitable to account for the heterogeneity of these patterns. Simple explanations based on the beliefs of the agents involved fare no better. When asked why they collaborate, scientists provide many varied reasons, such as gaining knowledge, accessing equipment, working necessity, or friendships (Melin [2000]). The development of ‘big’ science and ‘big’ funding, or changes in the norms of authorship, probably do play a role, but this differs wildly across fields (Wuchty et al. [2007], pp. 1037–8). Still, the pervasiveness of the increase in the percentage and size of collaborative means — with the exception of the humanities — strongly suggests that the conditions favoring teamwork are similar across subfields (ibid.).

In the remainder of the paper, we develop a general explanatory schema that can account for the overall rise in the percentage of collaborative works and the size of collaborative groups. It involves factors that are similar across fields but mostly absent from the humanities, where collaboration is barely observed.

3 Functional Explanations and Collaboration

We now set out the idea of functional explanations, and indicate how we apply them in the present case. Functional explanations explain the existence of a feature by reference to one of its effects, typically its beneficialness. For example, one can suggest that the State (resp. the practice of golfing) exists because it serves the interest of the ruling class (resp. enables upper classes to establish networks). Obviously, pointing at a useful effect of a feature is not enough to explain it functionally — the usefulness of the nose to carry glasses cannot explain why humans have noses. Nevertheless, if stringent conditions are met, functional explanations can be satisfactory, typically within biology and the social

sciences.¹

How, then, are we to characterize suitable functional explanations in a way that excludes the spurious ones? Like Wray ([2002]), we follow Kincaid's simple and widely accepted account. For Kincaid ([1996], pp. 110–1; [2006], pp. 214–5), *A* is functionally explained by *B*, or *A* exists 'in order to *B*' if:

- (i) *A* causes *B*;
- (ii) *A* persists because of (i), i.e., because it causes *B*;
- (iii) *A* is causally prior to *B*.

As Kincaid notes ([2006], p. 214), 'The first claim is straightforwardly causal. The second can be construed so as well. [...] *A*'s causing *B* causes *A*'s continued existence.' Finally, the third condition says that the causal loop is initiated by *A* but not by *B*. For example, initiation rites bring about social solidarity and therefore persist, but the converse is false.

To provide a functional explanation of scientific collaboration, we consider the credit which accrues to authors corresponding to the publication of papers divided by the time spent in finding the results on which these papers are based. This quantity, which Boyer-Kassem and Imbert ([2015], p. 672) call 'individual successfulness', depends both on the actual production of results by scientists and their ability to publish them before their competitors, and it may vary across different contexts and for groups of various sizes (see below for details). This quantity thus corresponds to the publishing productivity of scientists over their projects, although the literature often uses that term to describe the sheer number of publications of authors.

Claim. The increase in scientists' collaborative behavior can be functionally explained by the increase in individual successfulness it brings; in other words, scientists collaborate 'in order to' increase their individual successfulness.

Endorsing Kincaid's analysis, this claim amounts to the following:

- (i-c) in suitable contexts, the increase in scientists' collaborative behavior causes an increase in their individual successfulness, up to some point;
- (ii-c) scientists' collaborative behavior persists (and develops) because of (i-c), i.e., because it gives them a higher individual successfulness;

¹Even Elster ([1983]), who favors methodological individualism, considers functional explanations acceptable in the social sciences.

(iii-c) the increase in scientists' collaborative behavior is causally prior to this increased individual successfulness.

As noted by Kincaid ([1996], p. 115), the satisfaction of the third clause is often trivial, and our case is no exception (Wray [2002], p. 161). Many scientists have been successful without collaborating. Also, collaboration is a recent phenomenon while successfulness is not. Thus, if successfulness were the initial cause of collaboration, one would need to explain why for such a long period it did not generate collaboration. So, we consider that (iii-c) is established. Claims (i-c) and (ii-c) are defended in sections 5 and 6. Their respective defenses are distinct issues. The central contribution of this paper is to provide strong evidence in favor of (i-c) (in section 5), thanks to a model of scientific collaboration introduced in section 4.

4 The Sequential Competitive Model

In the model introduced by Boyer-Kassem and Imbert ([2015]), n competitors struggle over the completion of a research project composed of l sequential steps, for which only the last step is publishable. For instance, one of the steps might correspond to the design of an experiment, another to the running of the experiment, another to the statistical analysis of the results, and, finally, the paper is written. What constitutes a step depends on the level of analysis. Here, l is fixed at 10, and each step corresponds to a task that would take between two weeks and a month.

Time is discrete, and at each time interval agents have independent probabilities p of passing a step. If p is close to 1, passing steps is easy; if p is close to 0, it is hard. In the illustrations below, p is set to 0.5,² which means that completing a project takes on average between 10 and 20 months for a single scientist. Agents can either stay on their own or gather into collaborative groups for the whole project. For instance, a community of 3 agents working on the same research problem can gather in a group of 3, or in a group of 2 plus one loner, or all stay on their own: these collaboration configurations are respectively noted (3), (2-1), and (1-1-1).

Importantly, the number n of competitors is not meant to represent the much larger number of researchers who may belong to a scientific domain, such as in high-energy physics or social psychology, but stands for the subset of researchers who are working on the same specific problem and who might collaborate. Further, an agent can be interpreted as an individual researcher but also as a team. Thus, the model can also represent how collaboration develops at an institutional level. For example, $n = 5$ can stand for 5 individuals or 5 labs comprising 10 researchers, which may or may not decide to work together.

²Evidence suggests that the main conclusions don't depend on this choice. See (Boyer-Kassem and Imbert [2015], p. 674 and p. 684) for more details.

Is it reasonable to suppose that several individuals (or teams) might compete over an identical problem? The number of scientific problems is potentially quite large, but within the framework of paradigms, research programs, or organized research communities, it is common knowledge which scientific puzzles and questions are significant and which questions can plausibly be solved (Kuhn [1962], Kitcher [1993]). Overall, the assumption that several individuals or teams often investigate identical problems remains plausible.³ One might think that the model is only applicable to cases where several groups are in a race to gain credit; in fact, though, the case where a collaborative group of n researchers works alone ('in a community of n ') on a problem is also covered, and the model can be used to compare this case with hypothetical situations in which these n individuals would have worked in smaller groups or solo. So the scope of the model and our forthcoming explanation is general and covers cases where collaborative groups do not have competitors.

Because of the priority rule, the first agent or group to reach the final step publishes the results and wins all the scientific credit, while the others get nothing. So all the collaborative groups and loners compete to be the quickest. Within a collaborative group, the credit for a published paper (fixed to 1 for each race) is split equally among agents. Thus, an agent's individual successfulness corresponds to her share of credit, divided by the time needed to complete the inquiry, and this quantity is assessed by averaging over millions of replicas.

An important choice here bears on the value of the probability that a group of size k passes a research step, which is $p_g(k, p) = 1 - (1 - p)^k$. The initial justification by Boyer-Kassem and Imbert ([2015]) is that this represents a situation in which collaborative agents have independent probabilities p of passing a step and share information at no cost: when an agent has passed a step, her collaborators pass it along with her for free and then they all start trying to pass the next step. This interpretation is useful to grasp the model but is not endorsed in this paper. Here, the mathematical quantity $p_g(k, p)$ represents an advantage, though a relatively minor one, for collaborative groups. We discuss this modeling hypothesis at more length in section 7.

Because claims (i-c) and (ii-c) bear on individual successfulness (see section 3), we now review existing results concerning it. Boyer-Kassem and Imbert ([2015]) have computed the individual successfulness for all collaboration configurations up to a community of $n = 10$ agents. Their main finding is that minor differences in the probability of passing steps can be much amplified and that, even for not-so-favorable hypotheses, collaboration can be extremely beneficial for scientists. For example, in a community of 9 agents organized in the configuration (5-4), i.e., with a collaborative group of 5 and another of 4, the group of 5 only has a 3% higher probability of passing a step com-

³Recent papers in the field of social epistemology of science make a similar assumption. For example, Zollman ([2010]) and Frey and Šešelja ([2020]) investigate a community of no more than a dozen distinct researchers who assess the comparative efficiency of two drugs experimentally.

pared to the group of 4, but the individual successfulness for an agent in the group of 5 is 25% higher. As another example, in a community of 3 agents in the configuration (2-1), whereas the difference in the probability of passing a step is 50% higher for the group of 2, the individual successfulness is 700% higher.

However, these results by themselves do not explain scientific collaboration. First, the beneficialness of a feature does not by itself explain its existence. Second, these results merely show that collaborating is beneficial for particular groups in particular collaborative configurations — for example, a group of 2 is very successful in configuration (2-1-1-1-1) but not in (7-2). Thus, the model merely provides results about what can be the case in possible configurations. But the explanandum is a general social feature of contemporary science, not of certain collaborative behavior in some particular case. Thus, the explanans must also involve general statements about the link between collaboration and beneficialness. We discuss this link in the next sections.

5 Does Collaboration Cause Successfulness?

In this section, we use the above model to provide strong evidence that the increase of collaboration causes an increase in individual productivity in suitable contexts (i-c), in a sense that must be carefully specified. As will be argued, this is not incompatible with a global decrease in the productivity of the community.

We first provide an analytical result that covers various cases and gives insight into the model. Then we explore the model via a brute-force method.

A first general result is the following proposition (proof in the appendix):

Proposition.

If m groups, each comprising k agents, merge, the individual successfulness of these agents increases.

That is, whenever there are several collaborative groups of the same size, they improve the individual successfulness of their members by merging. A corollary is that single individuals always have an interest in collaborating rather than staying solo. A result of this type, however, though already general, merely provides a partial order over the successfulness of groups of size k across configurations and cannot provide a general vindication for (i-c). However, its informative value should not be underestimated. It holds for any size and configuration of the rest of the community. For example, in configuration (3-2-2-1-1-1), the loners would achieve a larger individual successfulness if they merged into a group of 2 or of 3, as would the members of the groups of 2 if they merged into a group of 4. The proposition also implies that individuals in a group of even size k have no interest in splitting into two groups of $k/2$. Also, the proof of the proposition gives an insight into why merging can be beneficial: new larger groups keep the gains of the subgroups from which they come, and develop in addition new

gains either by saving time (if one of their subgroups would have finished first anyway, they are now quicker because they share progress) or by earning new gains (by finishing before their competitors in new cases because they now proceed quicker).

Another route to investigate the general link between collaboration and success is to analyze what happens on average over all relevant configurations, which we do in the remainder of this section. For all 138 possible configurations of up to $n = 10$ competitors, we compute the average individual successfulness in all groups.⁴ For each configuration, the successfulness is computed by running the race between the different groups many times and assessing how frequently each group wins. These quantities are computed up to the point where fluctuations become marginal, which takes between hundreds of thousands and millions of runs. Then, to establish the robustness of the causal claim, we study the influence of various parameters such as the total number of competitors, the collaborative group size, and the average level of collaboration in the community.

5.1 Successfulness and community size

Figure 1 shows the average individual successfulness as a function of community size n , for agents in collaborative groups of various sizes. A first observation is that the successfulness of loners quickly collapses with n and is much lower than that of other groups as soon as $n > 2$. This shows that loners are outraced, except in very small communities. Second, for all group sizes, individual successfulness decreases with the community size, which is expected since the number of competing groups and their sizes increase. Nevertheless, for each k , the successfulness of a group of size k starts high and does not decrease much, up to some community size s which is larger than k . In still larger communities, they are eventually outperformed by larger groups. Note that for $n > 2$, the successfulness of groups of size k is in the beginning below that of smaller groups: collaborating as much as possible is not the best strategy.⁵ Third, when groups are larger, this initial plateau of successfulness is longer and flatter, and the subsequent decrease is less steep. Fourth, when n is much larger than k , the successfulness of individuals increases with the size of the group they are in. However, this increase

⁴Technically, we compute the average individual successfulness of an agent in a collaborative group of k over all possible collaboration configurations meeting some constraint. For example, the average individual successfulness when in a group of 4 and a community of 7 is computed as the average of individual successfulness in configurations (4-1-1-1), (4-2-1), and (4-3). Which weight should be attributed to each configuration? The number of combinatorial realizations of these configurations is not necessarily what matters, and the correct weights ultimately depend on the empirical frequency of existing configurations. For lack of information about these frequencies, we privilege simplicity and give equal weights to all configurations.

⁵See (Boyer-Kassem and Imbert [2015], pp. 679–80) for an analysis of over-collaboration in large groups.

is moderate, and small groups still do reasonably well (this is somewhat unexpected given the general amplification mechanism, but see Figure 3 below for more refined analyses). For instance, in a community of 10 researchers, groups of 2 are suboptimal but remain somewhat viable since their average successfulness remains between 1/3 to 1/2 of that of groups of 3 or 4. Overall, the morale is that not collaborating is, in general, not a viable strategy. Collaborating moderately ($k = 2$ or 3) can be very rewarding when there are few competitors, for instance on ground-breaking questions that are only tackled by a handful of scientists. However, when communities of competitors become significantly larger, small groups tend to be outraced. Thus, not collaborating or only moderately collaborating can be risky when uncertainty prevails about other competing groups. These findings suggest that large teams are best at developing normal science (when important research problems are clearly identified within communities), but that achievements and success by individuals or small groups are still possible on ground-breaking issues.⁶ Finally, being in large collaborative groups does not afford a very high successfulness but is a reasonably safe situation. Overall, these results support the claim that up to some point, collaborating more causes more successfulness, and more robustly so.

5.2 Successfulness and group size

Figure 2 shows for various community sizes how individual successfulness changes with the size of collaborative groups. For $n > 2$, the successfulness curve has a one-peaked (discrete) form, which means that there exists an optimal collaborative group size, different from the community size, over which adding new collaborators decreases successfulness. Note that a single-peaked preference function is usually assumed in the literature about coalitions or in social choice theory more generally. Here it emerges from a micro-model, without an *ad hoc* mechanism for over-collaboration. This shows that the model remains reasonable even if the costs of collaboration are idealized away. In particular, in a given context, groups have no incentive to grow indefinitely larger.

Note also that the decrease after the peak is slower than the increase before it: over-collaborating is globally less harmful and risky than under-collaborating. For stable large networks that collaborate a lot, adding or removing some collaborators does not substantially change their (high) successfulness. So, the successfulness of these groups is robust. In addition, the position of the maximum grows with the community size, which suggests that in larger, more international communities, optimal collaborative groups are larger.

⁶This is particularly in line with recent findings by Wu et al. ([2019]) that large teams develop science while small teams disrupt it.

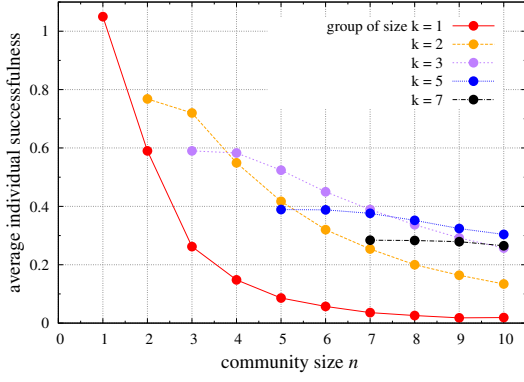


Figure 1: Variation of individual successfulness with community size.

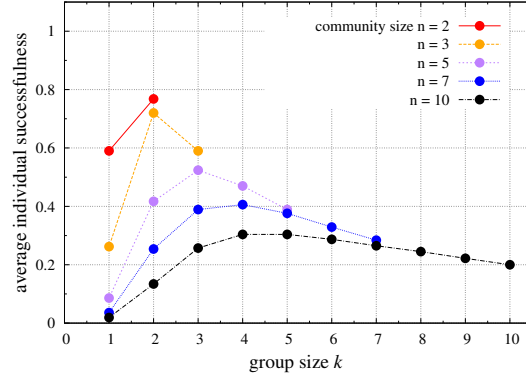


Figure 2: Variation of individual successfulness with the size of groups.

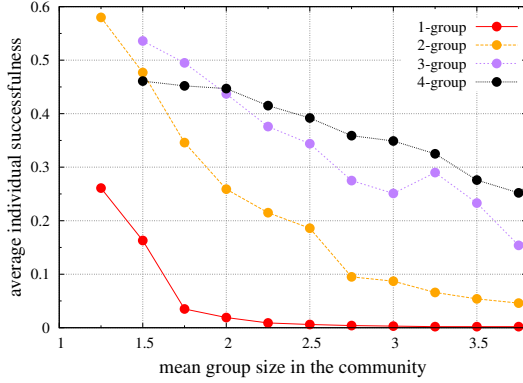


Figure 3: Variation of successfulness with the degree of collaboration in communities.

5.3 Successfulness in more or less collaborative communities

Figure 3 displays how the successfulness of members of collaborative groups of size k varies with the mean group size in the community, i.e., with the degree of collaboration in the group environment.⁷ Consider how the various curves stand relative to one another. Whatever the mean group size of the community, loners are always outstripped by collaborative groups. Individuals in groups of size 2 attain a much lower successfulness (compared to larger groups) as soon as the mean group size is larger than 1.5. Individuals in groups of size 3 have lower successfulness than those in groups of 4 as soon as the mean group size is larger than 2 or so. Overall, this shows that success-

⁷For each collaboration configuration, we compute the mean group size, for instance, 1.75 for collaboration configuration (3-2-1-1). Then, for each group size k , we compute the average successfulness over configurations having a degree of collaboration within intervals $[1, 1.5]$ (represented at coordinate ‘1.25’ on the x -axis), $[1.25, 1.75]$ (represented at coordinate ‘1.5’), $[1.5, 2] \dots [3.5, 4]$.

fulness depends less on the absolute size of the group than on how the relative size of the group compares to the mean group size of competitors. The main point is that scientists who collaborate more than average are very successful; those who collaborate as much as their peers do reasonably well; and those who collaborate less than average are outpaced by a large margin. This general result is not unexpected given previous results, but the graph highlights that the success for intensively collaborating scientists, as well as the underachievement for under-collaborators, can be very large. This shows that collaborating does cause more successfulness compared to not collaborating at all. Moreover, collaborating more than average also causes more successfulness. Resources do not accrue simply to successful scientists, but to more successful ones, and the reward structure favors the degree of collaboration going upward, creating a sort of unintentional arms race.

The above patterns have been obtained for competing communities of up to $n = 10$, but remember from section 4 that n stands for the number of scientists who compete on the very same problem (not the whole scientific community) and that agents can further be interpreted as teams or institutions. Hence, our results cover a large number of actual cases.

Let us sum up the findings of this section. Within a competing community, when collaboration is possible it entails successfulness. This relation is robust under changes in the size of communities or the exact size of groups. Also, those who collaborate more than average are more successful; collaborating too much is slightly problematic, while under-collaborating is strongly so, which means that collaborating a lot is a safe working habit, especially in the absence of information about competitors. All this shows that claim (i-c) is adequately supported: in suitable contexts, when scientists collaborate, this causes an increase in their individual successfulness, up to some point.

These results are compatible with the empirical finding that when adopting a fractional count (dividing the number of publications by the number of authors, like here), the number of collaborators does not clearly significantly boost publishing productivity (Lee and Bozeman [2005]), even if it increases the number of journal papers of collaborating authors. Indeed, we do not claim *simpliciter* that the productivity of scientists is positively correlated with the size of their group. Our claim is relative to a given community: productivity can be higher for groups of size 3 surrounded by groups of average size 1.5, than for a group of size 4 surrounded by groups of average size 2.5 (see Fig. 3). In brief, if they remain in an ecological niche where collaboration is low, individuals and small groups can do better than larger groups.

6 Collaborative Behaviors Develop Because of the Differential Successfulness of Collaborative Scientists

We now argue that, because of the differential successfulness of collaborative scientists, collaborative habits persist and develop in scientific communities (ii-c). This feedback loop can be caused by various well-attested social mechanisms across scientific contexts, and in this section we review a variety of evidence about these mechanisms.

6.1 Transmission

Knowing when, with whom, and how to collaborate is not straightforward. Like other know-how skills, it is usually developed by exercising it with people already possessing it. People that already collaborate may fulfill a role of cultural transmission for colleagues (Thagard [2006]), and, above all, for students, as collaborating with them is an efficient way to train them (Thagard [1997], pp. 248–50). The cultural transmission of collaborative practice, therefore, does not require any particular effort on top of that.⁸ The very circumstances that make collaboration possible and beneficial also make its transmission easier: when a research project can be divided into well-defined tasks, the solutions of which can be publicly assessed and shared, it is easier to enroll other people and thereby transmit collaborative skills to them (ibid.). Thus, collaborative habits and skills can be passed on and need not be reinvented by newcomers.

6.2 Transmission opportunities

We now give evidence that collaborative scientists, because they are more successful, are more often in a position to transmit their collaborative habits: hence the persistence and development of collaboration.

Within pure science, where the extension of certified knowledge is the official goal, successful scientists can be expected to have better chances of getting good positions and grants, developing research programs, and passing on their collaborative habits. Although scientific institutions are imperfect, it seems that this is often the case. Within applied science, in which collaboration is also widespread (Wuchty [2007]), research projects are usually directed at finding profitable and patentable applications. Thus, fund providers are strongly interested in hiring and providing resources to successful scientists. Note that the link between average success and pragmatic rewards is needed on average only, and it may be that some epistemically successful scientists get few resources while some unsuccessful scientists get a lot.

⁸The fact that students reproduce the practices of their supervisors is a key ingredient of models analyzing selection mechanisms in science: see, for example, (Smaldino et al., [2016]) or (O'Connor, [2019]).

In practice, non-epistemic factors may even tend towards an over-crediting of successful scientists, and in particular collaborative ones. First, individual successfulness has been assessed in the model using a conservative estimate, and an agent’s publication within a group of size k is often assessed more than just $1/k$ a single-authored publication. For instance, a large French research institution in medicine officially weights the citations of a paper with ‘a factor 1 for first or last author, 0.5 for second or next to last, and 0.25 for all others’ (Inserm [2005]). Second, a publication within a group of 10 is generally more visible than one single-authored publication, as more people can promote it. Third, the sociology of science suggests that scientific credit tends to accrue to a subset of scientists who are perceived as highly successful — a phenomenon known as the Matthew effect (Merton [1968]). Thus, the model shows that collaborating more than average can be extremely rewarding, and then, given that access to resources increases with scientific credit, successful collaborative scientists can be expected to benefit more from this effect.

Other types of mechanisms may contribute to this process, including conscious ones.⁹ Once winners of the scientific race publish co-authored articles, it becomes easy for others to see that successful scientists are highly collaborative. For instance, if agents in a group of three are 4 times more successful than a single agent, this means that their group will publish 12 more articles than the singleton. Accordingly, the belief that collaborating is beneficial may also be acquired by non-collaborating scientists by looking at journals. Furthermore, resources may accrue to scientific institutions that host individually successful scientists and so accrue indirectly to these scientists. Agents in the model may also be reinterpreted as teams or collective entities that decide to share results or combine their expertise to produce collective articles. Then, these institutions and their members turn out to be more successful, attract more resources, and keep on developing and transmitting their working habits.

Overall, there is a wealth of evidence that scientists and scientific institutions that are successful (in terms of published results) have more opportunities to develop, to school research students, and to place them in the academic world¹⁰. Hence, the causal connection between the success of collaborative scientists and the persistence and development of collaborative practices (ii-c) is highly plausible.

7 Discussion: Modeling Assumptions

Our model does not purport to represent faithfully all situations in which collaboration occurs. As we shall argue, however, this does not threaten our general argument.

⁹Kincaid mentions that ‘complex combinations of intentional action, unintended consequences of intentional action, and differential survival of social practices might likewise make these conditions [(i)–(iii) in our section 3] true’ (Kincaid [1996], p. 112).

¹⁰This feature is also used in formal models that investigate potential selection mechanisms in science, see again (Smaldino et al. [2016]) and (O’Connor, [2019]).

First, the winner-takes-all scheme is not always strictly implemented, as identical or similar findings may be published in less-renowned venues. For this reason, in section 8 we discuss at length the case of the humanities. However, note that scientists usually get far less credit for such publications, and major journals explicitly require novel material. This legitimates investigating what takes place in the idealized situation in which the priority rule is strictly applied.

Second, the modeling choice concerning the step-efficiency of groups should be taken with a certain grain of salt. Actual collaboration takes place in various ways. Not all collaborative mechanisms are equally efficient, rewarding, or beneficial to all types of members of a group (see, for example, (Abbasi et al., [2011], Li et al. [2013], Parish et al. [2017])). So it would be preposterous to assume that one single step-efficiency function can represent all cases adequately. However, this is not what we do here. Since we are studying how the effects of the priority rule can feed into a functional explanation of collaboration, it is argumentatively better to assume that the epistemic benefits of collaboration are low. Accordingly, the step-efficiency of collaborating groups in the model is chosen on a pessimistic basis, so that if collaboration is efficient in this case, it should be even more efficient in more realistic ones. In this way, our results highlight the successfulness and potential development of groups in cases where their differential advantage is larger than (or equal to) the low key estimate within the model. The fact that the step-efficiency function is not favorable can be seen in two ways.

Firstly, remember that it can be interpreted as the step-efficiency of a somewhat inefficient group of researchers who work independently and sequentially on identical sub-tasks, share intermediate results, and do not interact otherwise. Experimental research in social psychology has shown that collaborative groups are often better at solving problems than individuals, even if various pitfalls can spoil the epistemic activity of these groups. For highly intellectual tasks which have demonstrably correct solutions, a group performs better than the best of its individual members (see (Laughlin [2011]) for a review). Thus, groups are faster at solving a succession of intellectual tasks. By contrast, in the model, at each step, a group does just as well as its most successful member, not better. Further, evidence shows that group performance increases with the number of high-ability members within the group (*ibid.*, chapter 4). In collaborative groups, specific tasks can be ascribed to experts, i.e., high-ability members. Accordingly, the probability of passing steps in such groups is higher than that chosen in the model, in which all agents have the same probability of passing steps. Finally, the model assumes that research is sequential, whereas in actual groups it can sometimes be made parallel. All these differences point in the same direction: real collaborative groups tend to complete research projects faster than individuals, and our modeling choice is reasonably pessimistic (see also Boyer-Kassem and Imbert [2015], p. 672). Therefore, if collaboration is beneficial with these hypotheses in force, it should be even more so with more realistic ones.

Secondly, the mathematical features of the step-efficiency function are rather unfavorable, and the beneficialness of groups is not bluntly assumed in the model. Indeed, $p_g(k, p)$ has a decreasing growth rate below 1, is bounded, and converges quickly. Consider these features in turn. First, because the growth rate is below 1, k heads are not k times more efficient than 1 (as, for example, Thagard 2006, p. 194). Second, because the game is a race against others, the relative, not absolute, values of p_g for groups of different sizes are what primarily matter. Since the marginal increase in $p_g(k, p)$ vanishes as the size k of the group increases, after a while having more collaborators makes a tiny difference for larger groups. Third, the boundedness of $p_g(k, p)$ means that the speed of larger teams cannot go beyond one stage per time step, whereas in real cases adding more people can help in passing thresholds and so complete the task more quickly. Two persons can push a car, ten can carry it.¹¹ Finally, because the convergence is quick, the advantage of adding more collaborators shrinks quickly. In any case, our choice of $p(k)$ is aimed at explaining the development of collaboration in general, not at making quantitative predictions about the general efficiency of collaborative groups or of specific types of them having different ages, genders, country-types, collaborative strategies, etc.

Let us finally discuss the collaboration costs — for instance, those of communicating intermediate results within the team. By not including them in the model, we do not claim that collaboration costs are never obstacles to collaboration nor are always negligible. This would be unreasonable, since potential collaborators may not share a common scientific culture, may be geographically far apart, or may lack communication facilities, as used to be the case. In other cases, though, neglecting collaboration costs in the model is a fairly reasonable assumption, typically for teams of well-connected scientists whose research problem can be divided into well-defined subproblems with quickly communicable solutions. Thus, though idealized, the model applies fairly well to common existing situations. For such cases, the global balance in the model between modeling assumptions that are favorable to collaboration versus ones that are unfavorable is clear: the benefits of collaboration are strongly underestimated, which might make up for the idealization of some collaboration costs. Moreover, as the model shows that the benefits of collaborating are, in the end, large, it is safe to conclude that collaborating is beneficial. We discuss the issue of collaboration costs further in the next section.

8 Scope of the Explanation

What is the scope of the explanation we have defended? We first discuss the case of the humanities, in which collaboration is rarely to be found; next, we turn to the

¹¹The average speed of groups could be made higher than 1 by using an appropriate speed probability distribution, but this would be more favorable to groups.

issue of collaborative costs; and finally we discuss to what extent our explanation can encompass the collaborative mechanisms discussed in the literature.

8.1 Objection: what about the humanities?

As mentioned above, collaboration is widespread in the sciences, less developed in the social sciences, and almost absent in the humanities. Yet research in the humanities arguably also involves certain successive steps (for example, reading the literature, developing ideas, drafting a paper), and researchers in these fields also strive for publication and credit. Do these facts not falsify the proposed explanation?

No, because other crucial hypotheses of the model are not met in this case. First, the conditions for a general, straightforward, and uncontroversial application of the priority rule are hardly present. In the humanities, well-posed problems can be hard to single out, their solutions difficult to assess uncontroversially, and the contributions of co-authors hard to delineate. Subfields where the priority rule can be applied (to some extent), like formal or analytic philosophy, are something of an exception. Similarly, the importance of interpretative methods and the coexistence of incompatible traditions may prevent a consensus emerging on the nature of significant problems or on what counts as a solution. For instance, in philosophy, the question of the freedom of human beings may be approached from a naturalistic philosophy of science viewpoint or from a phenomenological tradition, and philosophers from one tradition may not accept as satisfactory the ‘solutions’ advanced by researchers from the other.

Second, the model assumes that research problems should be dividable into subtasks, and the solutions of these subtasks should be communicable. However, in the humanities, where interpretative practices play a prominent role, it is not that easy to communicate the results of subtasks, if that notion makes sense at all. In the history of philosophy, almost every specialist on Hegel has her own interpretation of the master’s writings. Thus, collaborating Hegelians would not agree on the validity of the intermediate results! Similarly, Thagard [1997], p. 249) notes that the humanities do not easily lend themselves to the division of labor.

Third, the successfulness of scientists needs to be clearly identifiable by institutions for (ii-c) to hold. Nevertheless, in the humanities, scholars generally do not share paradigms, methods, or norms concerning what is scientifically sound and significant, and cultural or linguistic barriers can constrain the emergence of unified communities.

8.2 Communication and collaboration costs

Universally acknowledged publication venues are needed for the priority rule to apply, and these venues should be easily accessible to the scientists. Arguably, these conditions have progressively been fulfilled by the development of scientific journals and

more efficient means of transportation and communication over the 19th and 20th centuries, which corresponds to the period in which scientific collaboration began and hence developed.

As mentioned above, the model does not include collaboration costs, in particular communication ones. The collaboration benefits in the model are significant, which can make up for the various collaborative costs. Some empirical input is here enlightening. The burden of collaboration costs can be studied historically by looking at technology shocks that have lowered transmission costs and reshaped the network structure of scientists and informational exchanges. An example is the development of air transportation and cheaper flights (Catalini et al. [2016]). Another example, analyzed by Agrawal and Goldfarb ([2008]), is the introduction of the network Bitnet among American universities in the 1980s and 1990s, which increased collaboration within engineering communities. Bitnet disproportionately benefited middle-tier universities, especially those co-located with top-tier institutions, and had democratizing and equalizing effect (Ding et al. [2010]). Conversely, top-tier universities benefited less from such shocks since their internal collaborative potential was already exploited. These examples suggest that the parallel between the decrease in communication costs and the increase in collaboration is not accidental. High collaborative costs can remove much of the interest of collaborating. Returning to our model, the fact that no collaboration costs are present should be seen as representing an ideal situation. The closer the actual situation is to this ideal, the more collaboration is beneficial according to the model, and the more our functional explanation is supported. These findings are consistent with the historical material presented above. In brief, our explanatory scheme is not restricted to cases where transmission costs are negligible, but provides insights into a broader spectrum of situations. In the context of other inquiries, collaboration costs, spatial constraints, or factors unfavorable to collaborative activities and their development could easily be integrated into the model, but we leave this for future work.

8.3 A general, encompassing explanation

As pointed above, scholars studying collaborations have proposed a wealth of ‘explanations of collaboration’. Not all these explanations are compatible, but the coexistence of a plurality of explanations is not abnormal. Typically, different types of explanations can be considered depending on the scale at which an explanation is sought, and micro and macro explanatory schemes can be compatible. Also, different causal processes can contribute to some target phenomenon (for example, global warming). Further, different factors belonging to the same causal process can be correlated with the advent of a target explanandum. Finally, a factor can be embedded in different ways within distinct explanatory schemes (for example, functional, causal, rational, unificatory).

To see why our account is compatible with other accounts in the literature, note that, from a formal point of view, the model shows that the sequential race greatly amplifies

differences in the step-efficiency p_i , whatever the origin of these differences. In other words, any factor, whether epistemic or not, that causes an increase in p_i for group i (for example, if a collaborator is an expert concerning specific steps, if increased resources improve the probability of passing steps, etc.) can provide a decisive differential advantage to this group. This grounds the generality of the model: the information-sharing hypothesis of the initial model (Boyer-Kassem and Imbert [2015]) no longer applies, and only the step-efficiency differences matter. Therefore, readers may interpret the model in terms of their favorite accounts of what boosts the step efficiency of groups (for example, outstanding expertise or access to resources) and get the amplification-of-differences result with the general robust patterns. Note also that the differences in collaborative patterns across fields may be rooted in differences concerning the factors that boost efficiency in these fields. For example, if collaborating helps harvest money (see (Wray, [2002])) and if money makes a step-efficiency difference in science but not in the humanities (or if money is a booster but is rare in the humanities), collaboration will develop in the former but not in the latter.

This is what enables the present explanation to encompass several existing accounts. Consider first the explanation proposed by Muldoon ([2017]): because acquiring new skills comes with high costs for scientists, complex problems which require a wide range of skills are solved more easily by groups gathering scientists with varied specialties.¹² This can be framed in the model we consider here: a complex problem involves steps that can only be solved by specific agents. Thus, a larger group of scientists with different types of expertise has a higher probability of passing steps. Then, the above results concerning how differences in probabilities are amplified by the sequential race favor the development of these groups. So Muldoon's explanation of scientific collaboration is compatible with and encompassed by our own.

Consider next the explanation by Thagard ([1997], p. 251), that 'peer-similar collaborations can improve reliability by virtues of members of a team noticing mistakes that would get past them working alone'. That is, a larger group has higher chances of passing the research steps correctly. Since our model assumes that a step is either passed correctly or is not passed at all, Thagard's point is just that larger groups have larger probabilities of passing steps, and this is another possible interpretation of the origin of the larger speed of larger groups. Thus, his account is compatible with the model we consider, and our explanation encompasses his.

Wray ([2002]) argues that scientific collaboration's function is to enable scientific communities to realize their epistemic goals, in particular by accessing the substantial resources often required to conduct research efficiently. For example, one can imagine that, with more resources, collaborative groups may have better instruments, and more

¹²Explanations of collaboration in terms of specialization have a longer history (see, for example, (Beaver and Rosen [1978], p. 69)). Muldoon more specifically compares the various costs involved and discusses the relationships between recent models of the division of cognitive labor in science and collaboration.

administrative and teaching assistants, which overall helps researchers to pass steps more quickly. So, Wray's explanation, which may apply in fields where big money can make a difference, can be made to fit in the present explanation, with larger groups having higher probabilities of passing steps.

Overall, the explanation of collaboration is probably a multi-factorial issue, and the various authors cited may have identified some part of the truth. The advantage of our functional explanation is that it can encompass various such factors because it relies on a formal model in which the origin of the differences in probability of passing steps can be interpreted in various ways. This makes the present explanation general and unifying.

9 Limits, Morals, and Future work

Some limits of the present model are worth highlighting. The model assumes a general step-efficiency function which depends only on the number of agents and makes no specific assumptions about how collaborative groups work internally. This is a strength as far as generality and scope are concerned. However, the downside is that it does not provide fine-grained information that could explain collaborative patterns or yield normative implications about scientists with particular features such as age, gender, place in a collaborative network, access to technical resources, or funding. Arguably, this would require developing fine-grained micro-models representing the various inner workings of collaborative groups and their epistemic effects. In any case, our results suggest that participation in collaborative groups is a crucial step in the pathway of individuals to scientific success. Thus, (proactive) inclusion of (apprentice) scientists in collaborative groups could be a lever to counter existing social biases.

Let us now discuss whether the above results concerning the development of collaboration should be welcomed. It is widely believed that collaboration should be encouraged because it bolsters scientific productivity. The picture that emerges from our results is more nuanced: a global increase in collaboration remains compatible with a global decrease in the productivity of collaborative groups. Indeed, when the conditions of the models are met, collaborative groups have a differential advantage, and even moderately efficient groups may thereby develop. However, this advantage vanishes when the degree of collaboration increases in the field. The advantage can be retained if groups grow even bigger, which may feed a potentially detrimental arms race. The culprit seems to be the priority rule. As it rewards only the first competitor that reaches a scientific goal, it may disproportionately favor quicker groups, notwithstanding their productivity, which may be, in fact, low. Thereby, the priority rule can encourage over-collaboration, if not indeed research waste. This phenomenon can be further amplified if funding is tied to apparent indicators such as the sheer number of publications. This suggests that the historical development of collaboration may be, to some extent, artificial and counterproductive as a side effect of the priority rule. However, collaborat-

ing also brings distinct advantages above and beyond productivity, such as the quicker completion of scientific inquiries (for example, when investigating medical treatments), cross-fertilization and the development of novel ideas, the transmission of skills, or the completion of inquiries that individuals cannot do alone. Overall, our results highlight the need for further investigation of the pros and cons of scientific collaboration, and serve as another ‘reminder that scientists and policy-makers need to have something more than a knee-jerk reaction to the presumed benefits of collaboration’ (Bozeman and Corley [2004]).

Regarding the priority rule, philosophers of science have highlighted that it could have unexpected benefits, for example by leading to a better division of cognitive labor (Strevens [2003]) or providing an incentive system that makes the best of scientists’ non-epistemic motivations (Zollman [2018]). The present results highlight other important and potentially detrimental effects of the priority rule (see also (Muldoon and Weisberg [2011])), which suggest that more systematic investigations are needed.

Finally, the above findings show that the sequentiality of inquiries can be a core ingredient of the dynamics of scientific communities. Former research in philosophy of science, like the pioneering works by Kitcher ([1990]) or Strevens ([2003]), tended to represent research problems as piecemeal units. The present results extend existing work by Boyer ([2014]) or Heesen ([2017]) that highlight that sequentiality can be crucial.

10 Conclusion

We have provided a general, functional explanation of the development of collaboration. Its core ingredients are the existence of common scientific goals, the competition triggered by the priority rule, and the possibility to divide research projects into subtasks and to share intermediate results. In this framework, collaborating more than other competitors provides a differential advantage. Then, to the extent that the successfulness of researchers gives them more opportunities to transmit their research habits within scientific subfields, the existence and the development of collaborative practices in communities are favored, and a kind of unintentional arms race may take place. This functional scheme is an encompassing one, since any factor that increases the step-efficiency of groups (including features usually related to the development of scientific collaboration) can provide such a decisive differential advantage. Finally, this global mechanism is compatible with a global decrease in the productivity of scientific groups. In other words, it provides more evidence that the beneficialness of scientific collaboration cannot be blindly assumed, and requires more scrutiny in the future.

Appendix: Proof of the Proposition

Proposition (formal version). Consider a community of n agents, including m groups of k agents in a particular collaborative configuration. Let $\mathbf{E}(P_k)$ be the expected individual productivity of an agent in a group of size k in this configuration, and $\mathbf{E}(P_{mk})$ the expected individual productivity of an agent if these m groups of k agents merge. Then $\mathbf{E}(P_k) < \mathbf{E}(P_{mk})$.

Proof. The general idea of the proof is that when collaboration occurs, agents win when they would have won without collaborating and, in addition, can save time. Though this is not needed for the proof, it is also noted that, by saving time, they can also win in more races.

By definition, $\mathbf{E}(P) = \Sigma(p(r)\rho_r)/\Sigma(p(r)\tau_r) = \mathbf{E}(\rho)/\mathbf{E}(\tau)$, where ρ_r , τ_r respectively denote the reward an agent gets and the time she spends in a particular race r , and $p(r)$ the probability of this race.

Consider first the simple case when two individual agents, α and β , compete with no other competitors: $n = 2$, $k = 1$, $m = 2$. To model the passing of step s by agent α in race r , consider the infinite sequence of independent random binary variables $V_{s,i}^{\alpha,r}$, with $p(V_{s,i}^{\alpha,r} = 1) = p$ and $p(V_{s,i}^{\alpha,r} = 0) = 1 - p$. By definition, the time $\tau_s^{\alpha,r}$ for agent α to pass step s alone is $\text{Min}(i|V_{s,i}^{\alpha,r} = 1)$.¹³ Thus, the time $\tau_s^{\alpha,r}$ α would need in race r to complete the inquiry if β was not competing is $\Sigma_s \tau_s^{\alpha,r}$. When actually competing against agent β in race r , agent α wins and gets a finite reward $R^{\alpha,r}$ if $\Sigma_s \tau_s^{\alpha,r} \leq \Sigma_s \tau_s^{\beta,r}$ and gets 0 otherwise. For a given race, as soon as an agent wins the race, all agents stop the inquiry. Thus, for any race r , the time τ_r that α and β actually spend on inquiry r is equal to $\text{Min}(\tau_s^{\alpha,r}, \tau_s^{\beta,r})$. Thus, both agents have the same expected spent time $\mathbf{E}(\tau^{\{\alpha,\beta\}})$. Further, by symmetry, $\mathbf{E}(\rho^{\alpha,r}) = \mathbf{E}(\rho^{\beta,r}) = R/2$, where R denotes the reward in each run. Overall, their expected individual productivity is identical: $\mathbf{E}(P^{\{\alpha,\beta\}}) = R/(2\mathbf{E}(\tau^{\{\alpha,\beta\}}))$.

Suppose now that α and β collaborate (still without other competitors). The group has probability 1 of winning the race and the reward is shared between α and β . Thus, their individual expected reward $\mathbf{E}(\rho^{\alpha+\beta})$ is still $R/2$. However, they are now faster: when one agent passes a step, the other one passes it too at the same time, so the time $\tau_s^{\alpha+\beta,r}$ spent to pass step s in race r is $\min(\tau_s^{\alpha,r}, \tau_s^{\beta,r})$. Thus, it takes all agents $\Sigma_s \min(\tau_s^{\alpha,r}, \tau_s^{\beta,r})$ to complete a race r . Since $\Sigma_s \min(\tau_s^{\alpha,r}, \tau_s^{\beta,r}) \leq \min(\Sigma_s \tau_s^{\alpha,r}, \Sigma_s \tau_s^{\beta,r})$, this establishes that $\mathbf{E}(\tau^{\{\alpha+\beta\}}) \leq \mathbf{E}(\tau^{\{\alpha,\beta\}})$, and $\mathbf{E}(P^{\{\alpha+\beta\}}) \leq \mathbf{E}(P^{\{\alpha,\beta\}})$ (inequality (1)).

To establish that the inequality is strict, note that for a particular race $\Sigma_s \min(\tau_s^{\alpha,r}, \tau_s^{\beta,r}) = \min(\Sigma_s \tau_s^{\alpha,r}, \Sigma_s \tau_s^{\beta,r})$ exactly if for all s , $\tau_s^{\alpha,r} \leq \tau_s^{\beta,r}$ or if for all s , $\tau_s^{\alpha,r} \geq \tau_s^{\beta,r}$ (condition A). For a particular s , $p(\tau_s^{\alpha,r} \leq \tau_s^{\beta,r}) = \gamma$ with γ finite and strictly inferior to 1 because of the independence of the random variables describing the attempts by individuals to pass a step. The two parts of condition A overlap only if for all s , $\tau_s^{\alpha,r} = \tau_s^{\beta,r}$, which has

¹³For instance, in this representation all sequences that start with (0, 0, 0, 1) correspond to the event in which the agent takes 3 + 1 steps to pass the step, and this event has probability $p \cdot (1 - p)^3$.

probability ϵ strictly inferior to 1. Overall, the probability that condition A is not met and that inequality (1) is strict is $1 - 2 * \gamma^k + \epsilon$ (by the standard rules for calculating the probability of compound events, here the passing of the various steps), and, therefore, it is finite. Further, since for all configurations in which condition A is not met, the gain in time is finite (superior or equal to one time step), eventually on average, the total gain of time is also finite. Thus, on average, the gain in productivity is finite, which establishes the strict inequality in (1).

Mutatis mutandis, the same reasoning holds (i) for a number of m individual agents competing against each other; (ii) for m groups of size k (with no other competitors), for example by considering that a group of k is equivalent to an agent having probability $1 - (1 - p)^k$ of passing a step; and (iii) when there are other competitors besides the m groups: a collaborative group of size $g.h$ wins whenever one of its g subgroups would have won, and in addition $\mathbf{E}(\tau)$ strictly decreases. QED.

Addendum. Note that in the context of the existence of other competitors, because collaborative groups work quicker than their subgroups, they win the race in a larger finite fraction of cases in which other competitors would have won otherwise, thus, $\mathbf{E}(\rho^{\{\alpha;\beta\}}) < \mathbf{E}(\rho^{\{\alpha+\beta\}})$, which also contributes to the increase in productivity for groups of equal size that start collaborating.

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