Setting Incentives for Collaboration Among Agricultural Scientists: Application of Principal-Agent Theory to Team Work

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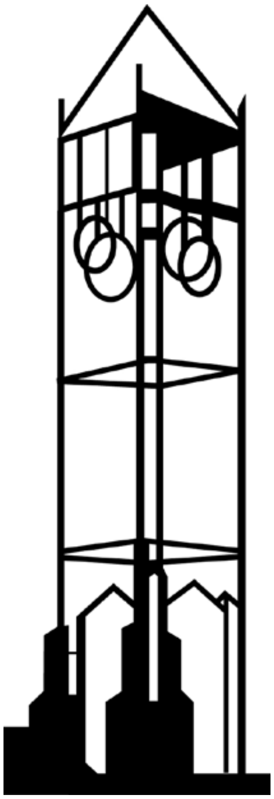

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Setting Incentives for Collaboration among Agricultural Scientists: Application of Principal-Agent Theory to Team Work [*]

By

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Abstract

The USDA is attempting to shift more research funds into competitive grants involving collaboration across disciplines on large projects. This type of research structure raises a host of information and incentive issues. The objective of this paper is to shed new light on principal-agent problems that are likely to arise in this new funding structure.

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Introduction

A provision in the 2008 Farm Bill established the National Institute for Food and Agriculture (NIFA). Within this institute, a new competitive grant research program named the Agriculture and Food Research Initiative has replaced the National Research Initiative Competitive Grant Program. The Secretary of Agricultural has recently drawn attention to a new research emphasis for NIFA: food production and sustainability, improved nutrition and ending child obesity, food safety, biofuels and energy, climate change and the environment. In addition, a new NRC-NAS report on "*A New Biology for the 21st Century*" has shed light on using the new biology to meet societal challenges in food, environment, energy and health.

The new direction of NIFA will be reflected in upcoming requests for research proposals (RFPs) for the new Agricultural and Food Research Initiative (AFRI). Congress has provided NIFA $262.5 million for FY 2010, which is a 30% increase over FY 2009 level (for the NRI) and more than double the amount of five years ago. Dr. Roger Beachy, who is the new Director of NIFA, and his staff indicate that the new funding initiatives will emphasize "focus, scale, and impact." Secretary of Agriculture Vilsack has set the broad agenda for NIFA with an emphasis on food production and sustainability, improving nutrition and ending child obesity, food safety, biofuels and energy, climate change and the environment.

In a December news release, the Director of NIFA indicated that NIFA expects to fund much larger grants than in the past—some grants are expected to be in the neighborhood of $2 million over five years, as opposed to past practices of funding grants at the $100,000-150,000 level over two years. The release also indicated such research initiatives would most likely require multi-disciplinary teams of scientists, and significantly fewer awards would go to single-scientist projects or to two scientists from a single discipline. Moreover, with Obama's focus on obtaining greater impact from all types of federally funded research, NIFA will be looking for research proposals that provide a broad set of benefits to the U.S. and developing countries. In addition, the USDA is planning to use its research, education and extension institutions to help translate research discoveries from its funded projects into real solutions for real people.

New research challenges have been raised in a recent NRC-NAS publication, *A New Biology for the 21st Century: Ensuring the United States Leads the Coming Biology Revolution*. The charge to the NRC committee that authored this report was to find solutions to major societal needs—sustainable food production, protection of the environment, renewable energy, and improvement in human health. In particular the NRC committee recommending that U.S. research institutions set big goals, and then let the problems of attaining these goals drive the scientific research agenda. To provide additional perspective from this report, consider the four main recommendations:

a. A national initiative established to accelerate the emergence and growth of the new biology to achieve solutions to societal challenges in food, environment, energy and health;
b. A new national biological initiative be an interagency effort, that it have a time line of at least a decade, and that its funding be an addition to the current budget;
c. Priority should be given to the development of the information technologies and sciences that will be critical to the sciences of the new biology; and
d. Devote resources to programs that support the creation and implementation of interdisciplinary curricula, grad student training programs, and educational training needed to create and support the new biologists.

Integration is an essential feature of the new biology addressed by the NRC Report. For example, major subdivisions of biology will be expected to collaborate with scholars from physics, chemistry, computer science, engineering, mathematics and economics. A joint research effort attempting to research new depths of understanding and new applications will need to draw upon scientists from universities, government agencies and the private sector and funding from the government and private sector. To function well in the new biology, scientists will need to excel in their own field but also to be knowledgeable enough to work with scientists from other fields of science.

The objective of this paper is to shed new light on principal-agent problems in the new science for agriculture. Agency problems arise under conditions of incomplete and asymmetric information when a principal hires (contracts) with an agent to undertake some activity for her. Asymmetry information describes the situation where one of the two parties has better information than the other or they have different information. This creates an imbalance of power in contracting, which frequently leads to undesirable outcomes. The two main information problems are adverse selection and moral hazard. With adverse selection there is incomplete information before the principal and agent reach a contract, e.g., the agent knows more about his characteristics than the principal and this information weighs against the principal's objective. Moral hazard arises when an agent changes his or her behavior after obtaining a contract, e.g., shirks, but this information is not apparent to the principal and therefore reduces her expected payoff. More specifically, adverse selection in research can arise if a scientist writes well or is inherently good at writing research proposals ("telling a good story") but does not have the complete set of research skills to achieve the full potential once the project is underway. Moral hazard arises when the agent changes his or her behavior after obtaining a grant award, he or she then becomes less diligent or slacks off. Information problems associated with adverse selection and moral hazard are greatest in one-time relationships or contracts, but they may be partially or completely ameliorated in multi-period, repeated contracting. Externally funded research is perhaps best described as scientists having a short-term relationship with a research funding agency or program manager.

In the first section of the paper, I address incentives for implicit contracting in a setting where one scientist undertakes a single project. However, the effort of the scientist and the research output are not contractible because they cannot be enforced by an independent third-party. In the second section, incentive issues in team research are examined. First, communication issues arise in multi-disciplinary team research; there is a need for the team to find a common language, accepted research methods, and agreed upon style. Second, with asymmetric information on effort, a free- easy-rider problem exists among team members, i.e., individual scientist want to obtain the payoff for a successful project, but each of them individually has an incentive to free-ride on the efforts of others. Mutual shirking then undermines the potential success of the research project. I show that when agents are risk neutral and otherwise relatively homogeneous, a hierarchy of incentives and ranking among scientists is critical to the success of a project. Another central decision is whether to use relative performance evaluation or joint performance evaluation of members of a team, and the optimal scheme is sensitive to the likely length (one time or repeated many times) of the contracting relationship. For optimal assignment of more than one scientist to a task, I show that effort levels of agents must have synergy, a type of complementary interaction. Moreover, asymmetric information on pre-existing social status can complicate incentive setting for a team of scientists and potentially undermine the success of a project. One key conclusion of the paper is that competition among scientists has value only to the extent that it is used to reveal information; competition per se raises the uncertainty that scientists face in undertaking research. This translates into higher costs of research and reduced effort of risk averse scientists. The final section presents this and other conclusions.

Incentives for Single Scientist Projects

In this section, I eexplore individual agent based incentive schemes. Huffman and Just (2000) address key issues in setting incentives for scientists who engage in research as a single investigator on a project. They apply principal-agent theory to derive optimal compensation schemes for scientists when scientists differ in ability, risk aversion, cost of effort, and reservation utility. These attributes of scientist turn out to be quite important in the contacting literature, but biological scientists may be quite unaware of their importance. For example, Huffman and Just show how the above attributes matter for optimal incentives and show the optimal trade-off between institutional risk and scientist's abilities. In particular, they show how scientists' incentives should be structured to elicit optimal research efforts and direction.

R&D is a production process that has unusual attributes relative to the production and marketing of industrial goods. First, the R&D output is most accurately described as the “best” of scientists’ outputs, rather than their total output. Second, the research production process is subject to large amounts of ex ante uncertainty, including that the payoff or value of a research project is unknown at the outset of the project and ouput/quality is non-contractible. By this I mean that no contract can be written to cover all contingencies and no contract can be enforce by a dis-interested third-party. Third, asymmetric information exists on scientists’ effort. With uncertainty in the production process, there is no way that an administrator or contract officer can accurately infer effort allocated to a project and the scientist has the best available information about his own ability. Fourth, research administrators are less risk averse than scientists because they have a large pool of projects over which to diversify risk.

First, the research administrator is assumed to observe the research payoff at the end of a project, to compensate scientists for their effort, possibly with a compensation package including a fixed salary and a performance incentive, and to be risk neutral about R&D payoffs. A research project is defined as an attempt to develop a particular innovation or a fixed term contract to conduct research in a particular area. Moreover, an administrator’s task is to maximize expected R&D payoff net of scientists’ compensation.

Second, scientists are assumed to obtain utility from income, disutility from effort or work, to be risk averse, and to have a reservation utility. Reservation utility reflects a shadow value on a scientist’s effort from using it in other activities, e.g., in home production, teaching, or contracting with another research administrator. More specifically, each scientist (differentiated by the subscript i) is assumed to have a quadratic cost of effort, $c_i(e_i) = .5k_i e_i^2$ (which generates a positive-sloped effort schedule with respect to compensation), to have constant absolute risk aversion φ_i, to have a fixed certainty-equivalent reservation utility (μ_i), and to choose effort on research to maximize individual expected utility subject to attaining at least his reservation utility. Third, each scientist is assumed initially to work alone (to avoid team or easy-rider incentive problems) and to undertake only one project per period that produces exactly one indivisible unit of output, but research quality is variable depending on effort. Hence, the production function for quality has one variable input, the scientist's effort. Important to this incentive scheme is the fact that research ability, risk aversion, cost of effort and reservation utility differ across scientists and are known and used by administrators to determine compensation.[1]

Because of the highly uncertain nature of research, the production function for research is stochastic, having a scientist-specific random component ε_i and a common institutional component δ. The scientist-specific component reflects factors other than scientist's effort and ability, e.g., inspiration and luck. The common shock is associated with working in the same research area and might represent unanticipated bureaucratic or scientific problems or unanticipated advances in the public stock of knowledge. The scientist observes the combined shock but does not distinguish between the components. Hence, the production function for research quality, which is the payoff to the principal or administrator, is

(1) $y_i = a_i e_i + \varepsilon_i + \delta$,

where y_i is quality of research produced by scientist i, e_i is scientist's effort, and a_i is the expected marginal product of the scientist's effort. Differences in a_i across scientists reflects scientists' abilities for research (e.g., creativity, efficiency of mental processes, and work routine), organizational aspects of the research environment (e.g., bureaucratization of procedures), and the available stock of relevant public knowledge. The stochastic terms ε_i and δ in the payoff function are assumed to have a zero mean and fixed variance, $\sigma^2_{\varepsilon_i}$ and σ^2_{δ}, respectively, where the variance of the scientist-specific shock differs among scientists; and for simplicity of presentation, ε_i and δ are

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[1] Administrators are assumed to accurately determine ability and other scientist-specific attributes without erro and thus without causing adverse selection.

assumed to be uncorrelated. The variance of the research payoff is the summation of the two variances, $\omega_i^2 = \sigma_{\varepsilon_i}^2 + \sigma_\delta^2$.

A simplifying but plausible assumption is scientist's effort, e_i, is the only source of asymmetric information, i.e., differential information between the scientist and administrator. It is unobservable to the research administrator but known to the scientist. Research quality, y_i, is assumed to be observable to both the administrator and scientist but only at the end of the project. Clearly, this is critical assumption, and quality may not be fully evaluated until a projects results are published and used by others.

The current set of results was obtained for the circumstances where each scientist works independently, but there can be competition among scientists in that the highest quality output contributes to the administrator's R&D payoff. However, to convey some basic results about optimal compensation and the associated R&D payoff, consider contracting between a research administrator (or funding agency) and one scientist. According to principal-agent theory, when contracting is repeated many times and the agent has discretion in actions including the level and timing of effort, the structure of the optimal pay scheme is linear in the observed principal's payoff (Holmstrom and Milgrom 1987). This implies a two-part compensation scheme consisting of (i) a guaranteed salary, α_i, that is independent of the observed R&D payoff, and (ii) an incentive payment that amounts to a positive share, β_i, of the observed R&D payoff,

(2) $w_i = \alpha_i + \beta_i y_i$.

A larger β_i implies a "higher powered" incentive scheme. Substituting equation (1) into (2), the structure of this pay scheme is linear in the scientist's effort,

(3) $w_i(e_i) = \alpha_i + \beta_i a_i e_i + \beta_i \varepsilon_i + \beta_i \delta$.

Equation (3) depicts how ex ante uncertainty in the research production process is transmitted into ex ante income uncertainty for the scientist. From equation (3), the expected wage conditional on effort is $E[w_i(e_i)] = \alpha_i + \beta_i a_i e_i$ and the wage variance is $V(w_i) = \beta_i^2 \omega_i^2$.

Under the assumption of constant absolute risk aversion for utility of the scientist, his expected utility can be expressed in terms of certainty equivalence as

(4) $E[U_i(e_i)] = \alpha_i + \beta_i a_i e_i - .5 k_i e_i^2 - .5 \varphi_i \beta_i^2 \omega_i^2$.

The research administrator's payoff net of scientist's compensation is $\Pi_i = y_i(e_i) - w_i(e_i) = (1-\beta_i) a_i e_i + (1-\beta_i)(\varepsilon_i + \delta_i) - \alpha_i$. Therefore, the expected net payoff is

(5) $E(\Pi_i) = (1-\beta_i) a_i e_i - \alpha_i$.

Clearly if $0 \leq \beta_i < 1$, then the expected net payoff of the research administrator is positively related to a scientists' effort, e_i, as in Levitt (1997), but also to scientists' ability, a_i. However, the administrator's expected net payoff is negatively related to the scientist's guaranteed salary, α_i.

The administrator chooses the parameters of the incentive scheme, α_i and β_i, to maximize her expected net payoff subject to the constraints that the scientist chooses effort to maximize his expected utility and that the scientist attains at least his reservation utility, i.e.,

(6) $$\max_{\alpha_i, \beta_i} \{(1-\beta_i) a_i e_i^* - \alpha_i\}$$

subject to

(7) $$e_i^* = \underset{e_i}{\operatorname{argmax}} \{\alpha_i + \beta_i a_i e_i - .5 k_i e_i^2 - .5 \varphi_i \beta_i^2 \omega_i^2\},$$

and

(8) $$\alpha_i + \beta_i a_i e_i^* - .5 k_i (e_i^*)^2 - .5 \varphi_i \beta_i^2 \omega_i^2 \geq \mu_i.$$

The administrator's problem ensure that the scientist chooses a privately beneficial effort rate when faced with the compensation scheme (i.e., it is incentive compatibility to the scientist), and the administrator offers a compensation package that the scientist will accept (i.e., it meets his participation or reservation constraint).[2]

Because research risk is independent of effort in this model, the optimization problem in (6)-(8) can be solved sequentially. First, the optimal solution to the scientist's decision on effort in equation (7) is

(9) $e_i^* = \beta_i a_i / k_i$,

which depends positively on the scientist's marginal product of effort (a_i) and inversely on his marginal cost of effort (k_i). Second, substituting equation (9) into (6) and (8) and choosing α_i and β_i, Kuhn-Tucker conditions (or direct examination) reveal a boundary solution with $E[U_i(e_i^*)] = \mu_i$ in (8) implying:

(10) $\alpha_i = \mu_i - .5\beta_i^2(p_i - r_i)$,

where $p_i = a_i^2/k_i$ is a scientist-specific "research productivity index" and $r_i = \varphi_i \omega_i^2$ is a scientist-specific "risk premium."[5] Substituting (10) into (6) and (8) and maximizing with respect to β_i reveals the optimal scientist performance incentive,

(11) $\beta_i^* = p_i/(p_i + r_i)$,

which, when substituted into (10), gives the globally optimal guaranteed payment or salary,

(12) $\alpha_i^* = \mu_i - .5p_i^2(p_i - r_i)/(p_i + r_i)^2$.

With this optimal pay scheme, five notable results follow. First, the administrator chooses an incentive scheme to maximize the joint payoff of the administrator and scientist (the administrator's gross payoff minus the scientist's cost of effort and risk bearing) and both have an incentive to fulfill the contract. Second, the administrator compensates the scientist for his effort at a rate that provides partial insurance against income risk. With asymmetric information on the scientist's effort, the administrator does not provide full-income insurance to the scientist because that would provide

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[2] In this model, it is unproductive for the administrator to offer a compensation scheme the scientist rejects because the administrator's expected payoff is zero, i.e., $E(y_i) = 0$.

weak incentives for effort, leading to shirking. Third, the guaranteed salary of a scientist is positively related to his reservation utility μ_i, but his reservation utility has no impact on the incentive component. Fourth, the optimal incentive, β_i^*, is negatively related to scientists' risk premium, $r_i = \varphi_i \omega_i^2$, and the optimal salary or pay guarantee is positively related to scientists' risk premiums if and only if $3p_i > r_i$, which they are is plausible.[6] In other words, low research risk, low scientist risk aversion, low cost of scientist's effort, and/or high marginal research productivity is sufficient to cause the optimal salary guarantee to increase in the research risk. If research is infinitely risky (i.e., $\omega_i^2 \rightarrow \infty$ $r_i \rightarrow \infty$), $\beta_i^* = 0$ and the optimal pay scheme is a fixed salary equal to the certainty-equivalent utility (i.e., $w_i = \alpha_i^* = \mu_i$). In this case, the administrator optimally bears all the risk of the project because he is risk neutral and less risk averse than the scientist. In fact, one finds that an increase in the scientist's risk premium, r_i, decreases the importance of the incentive relative to the salary or guarantee. Fifth, scientists with a higher research productivity index, p_i, receive higher optimal incentives, but lower optimal salary guarantees if the risk premium is small relative to the scientist's research productivity.[7] However, if a scientist's risk premium is sufficiently high relative to scientist's research productivity, the salary guarantee will be increasing in scientist's research productivity.

To obtain further insights, note the optimal effort of scientists is

(13) $e_i^* = a_i p_i/[k_i(p_i + r_i)]$

and expected compensation of the scientist net of his cost of effort is[8]

(14) $E\,[\,w_i(e_i^*) - c_i(e_i^*)] = \mu_i + .5 p_i^2 r_i/(p_i + r_i)^2$,

which is equal to the reservation wage plus the risk premium. The expected R&D payoff for the research administrator net of the scientist's compensation is

(15) $E[\Pi_i(e_i^*)] = .5 p_i^2/(p_i + r_i) - \mu_i$.

If the scientist is risk neutral (i.e., $\varphi_i = r_i = 0$), then equation (13) becomes a_i/k_i, equation (14) becomes μ_i, and equation (15) becomes $.5p_i - \mu_i$. With asymmetric information on the scientist's effort, the scientist's risk-averse attribute reduces the administrator's payoff and the scientist's effort from the first-best outcome.[9] Some net R&D payoff (and research quality) is foregone by the administrator when she partially insures the risk averse scientist against risk. Furthermore, given the scientist's reservation wage, μ_i, the scientist must also receive higher net compensation because he must be paid to bear his part of the risk. Because he is more risk averse than the administrator, the risk borne by the scientist is inefficient risk bearing. Hence, only a "second-best" resource allocation is attainable.

Equations (13), (14), and (15) reveal that a risk-neutral research administrator is better off contracting with scientists that have low scientist-specific research risk (i.e., $\sigma_{\varepsilon_i}^2$ is small) and low risk aversion (i.e., small φ_i). The reason is that such scientists require less compensation for bearing risk and exert more effort. Differentiating $E[\Pi_i(e_i^*)]$ in (15) with respect to the scientist-specific research productivity index, p_i, also reveals, not surprisingly, that a research administrator is better off contracting with a scientist who has a higher research productivity (more ability and lower opportunity cost).[10]

Differentiating a scientist's net compensation in equation (14) with respect to p_i gives the result that, other things equal, scientists who have higher marginal products of effort (larger a_i) and/or lower opportunity cost of effort (k_i) receive larger expected net compensation than those with lower scientist-specific research productivity.[11] Differentiating (14) with respect to the scientist-specific risk premium, r_i, reveals that $\partial E[w_i(e_i^*)-c_i(e_i^*)]/\partial r_i > 0$ if and only if $p_i > r_i$.[12] Thus, among scientists with high research productivity relative to their risk premium (i.e., $p_i > r_i$), net compensation is higher as research becomes inherently more risky (i.e., σ_δ^2 increases). Also, those who are more risk averse or have greater scientist-specific variance in research output will receive larger expected net compensation, other things equal. However, among scientists with low research productivity relative to their risk premium (i.e., $p_i < r_i$), these conclusions are reversed. Perhaps, the result that scientists who have lower opportunity cost of effort (which makes p_i higher) receive higher compensation in the former case is surprising, but it is explained by the fact that such scientists are likely to give greater effort. In the latter case, the result that scientists who have higher research risk earn greater compensation may be surprising, but it is explained by the fact that more compensation must be provided to induce such scientists to bear risk. We note that this phenomenon may not be observed in reality because administrators tend not to hire or grant tenure to low-productivity scientists.

Peer-reviewed competitive grant programs shift an unduly large share of research risk onto scientists, who are in an inferior position for risk bearing. This happens in several ways, including unfunded proposal writing, only a small fraction of proposals receive funding, repeat submissions are required, and funded proposal are underfunded relative to costs. Even for a "funded scientist," projects may be prematurely terminated or delayed indefinitely.

Within the principal-agent model of research incentives, low proposal funding rates and underfunding of successful proposals greatly weakens scientists' incentive for effort, including proposal writing, and generally lowers the quality of research relative to optimal incentive contracting. Thus, the principal-agent model predicts low quality research proposals for external competitive grants programs, especially when average awards are small. Hence, the proposed major increase in the size of NIFA funded grants may significantly increase proposal quality. However, this might best be achieved by implementing a two-step process. Short proposals could be submitted and evaluated for their likely long run payoff, and then a modest number of the most promising ones would be asked to prepare fully developed proposals upon which funding decisions would ultimately be based. This is a policy that has been tried in NIH.

If funding of a scientist with a competitive grant is a one-time event, the expected payoff is often quite low, and the efficiency of the research granting process can be expected to increase when the principal and agent engage in repeat contracting over time and establish a long term relationship. Only under these circumstances can administrators be expected to gain the type of information on scientists' ability, degree of risk aversion and reservation utility needed for efficient contracting. Only in this way can problems stemming from asymmetric information be reduced incentives fine-tuned to the riskiness of the research and attributes of the scientist.

When asymmetric information on scientists' research productivities and risk premiums exists before contracting, i.e, the funding agency is trying to decide who to fund and the funding agency has less information than scientists, additional sources of inefficiency may arise. For example, if the scientist knows his ability better than the funding agency and uses this information in deciding whether to accept a grant, then only less able scientists are willing to undertake a particular project at given cost, thus resulting in adverse selection (Mas-Colell, Whinston, and Green, p. 440-42). This potential undoubtedly is a major reason why granting agencies invest heavily in effort and time consuming screening activities, i.e., requiring scientists to write lengthy proposals and frequently must reapply for funding, and use external reviewers of proposals and review panels to rank proposals. However, screening activities reduce able agents' welfare (Mas-Colell, Whinston, and Green, p.460-66).[13] Signaling activities do not guarantee that more able scientists are made better off because they may be compelled to engage in a high level of costly signaling to distinguish themselves (Mas-Colell, Whinston, and Green, p. 450-60).

However, to the extent that funding agencies guarantee "renewal of successful" projects, they become less competitive and similar to a program funding mechanism. For example, the tradition of the National Science Foundation has been to engage in extensive competition where the expected size of awards is small, but little competition or emphasis on the quality of research proposals where the expected size of the award is large. These latter funds have been allocated largely to scientists who have compiled long-term successful research programs in the area where a large grant is to be made (see U.S. GAO for details). It will most likely be an efficiency improving step for NIFA to award larger grants over longer period of time.

Team Research and Incentive Issues

In this section, I explore incentive schemes to induce team production with two or more agents. Research projects that involve teams of scientists introduce new incentive problems. For example, successful completion of a project is a joint-effort and a public good to the team members. However, each team member has an incentive to free-ride on the efforts of the other team members, i.e., there is no way to identify a shirking agent when joint output is the only observable indicator of agents' efforts. This gives rise to a free-rider or easy rider problem (Cornes and Sandler 1996; Holmstrom 1982) that grows as the size of the research team increases.

Second, research teams that span two or more disciplines encounter additional problems. Holding a Ph.D. degree in a field of science indicates that an individual has successfully mastered a body of knowledge and skills needed to advance the state of knowledge in a field of science. But the body of knowledge differs across fields and so frequently do research methods. Hence, a set of scientists across diverse fields must initially invest in establishing a common scientific vocabulary, work out agreed upon standards for evidence to support or refute hypotheses, and work out task assignments. This can be quite time consuming, especially for non-tenured faculty who are in a probationary period in which they must demonstrate substantial research publications and quality teaching in a five-year period.

Development and Organization of Science to Facilitate Communication

By the 1600s, advancement of science settled on a building blocks approach. New discoveries (papers) build on the intellectual foundation of previous ones, and new papers acknowledge the input of prior papers through citation in the references. Moreover, advances in science are frequently held up because a key building block is incomplete, and this gives rise to frontiers of science advancing at different rate and even in a particular field of science, the pace of advances at the frontier varies over time. As the stock of knowledge has grown new fields of science have been borne and the depth of understanding in each existing field has increased.

Citations serve a number of purposes. They acknowledge the prior work of others or building blocks, direct the reader to additional related sources of information, acknowledge conflicts with other results, and provide support for views expressed. Furthermore, citations place a paper or discovery within its scientific context and assign responsibility if errors should later be discovered. Currently, journals, books, and informal arrangements are important channels of scientific communication. The relative importance of each channel has changed over time and this change is partly associated with the size of the total stock of knowledge and the pace of advances in science (Huffman and Evenson 2006, p. 52-53).

The organization of science and technology in the agricultural research and development system can be given a matrix representation (Huffman and Evenson 2006, p. 51). Also, see figure 1. The system consists of six simultaneous ongoing levels or layers of activity with vertical (upstream and downstream) and horizontal feedback and linkages. Level III contains products from innovation. Level I identifies the final users of new technologies, who are also a source of information about technology needs and problems. Level II is the source for final users in the public and private information systems. Level II refers to the commercialized technologies and knowledge that are the products of applied research. Level IV, technology invention, identifies the engineering and applied science fields that generate new technologies. Level V, pre-invention research, is directed specifically toward producing discoveries that advance the knowledge needed to design new technology and institutions. It is linked upstream to Level VI, to the fundamental or core sciences and down-stream to Level IV technology inventions. A distinction between Level V and VI is that research in the Level V fields tends to be demand driven and in Level VI research tends to be supply or scientist driven.

Level IV activities are those public and private applied research effort directed toward the discovery or invention of new technologies. These include mechanical, chemical, biological, managerial, and policy technologies. Much of public invention is in the technology fields where intellectual property rights are not marketable and therefore do not simulate private invention. The distinction between technology invention (Level IV) and pre-invention (or pre-technology) science fields (Level II) is important because the products of pre-invention research are not generally subject to patent protection. Pre-invention science means research directed specifically toward producing discoveries that enable and assist technology invention. Pre-invention science is specifically an intermediate product supplied to invention-producing firms, and it is a key input for both public and private producers. Relatively little pre-invention science is undertaken by the private sector; it is primarily the activities of scientists in universities, the government, and non-profit institutes.

Scientific communication within and between fields of science occur. However, each field of science has evolved so as to facilitate low cost and efficient exchange of ideas to meet acceptable standards of credibility. To facilitate exchanges within a field, scientists working in the area have developed specialized language and measurement procedures to achieve exactness and hence credibility. In most sciences, this is the language of statistics, experimental design and exact measurement (Huffman and Evenson 2006, pp. 55-56). Traditionally, scientists have specialized in research problems that are largely in one field but occasionally with not too distant horizontal linkages. Scientists have developed communication systems to facilitate primarily within a field of science and sometimes with a small amount of horizontal or vertical linkage. The journal articles, reference citations, specialized language, and elements of style are chiefly designed to allow scientist working on similar problems to disclose finding quickly and accurately to one another. This disclosure process facilitates refereeing of priority claims to new knowledge and accumulation of verified hypothesis, or the so-called scientific knowledge of a field (Committee on the Conduct of Science 1989, pp. 8-16). Vertical exchanges, upstream or downstream from their area of specialization, are less frequent and more problematic because of differences in language, accepted methods, and style.

The scientific exchange process that originated in Level VI sciences has been modified and used in Level V pre-invention sciences and even to some extent in Level IV activities. At all levels, knowledge must be communicated and exchanged to facilitate the knowledge accumulation process and the building blocks construction of scientific advances. Scientific papers with their specialized language usually associated with a disciple and with standards set by scientists in the disciple, have been a useful vehicle for exchanges within a field and to an extent to horizontal exchange at all levels. Scientific papers have also served as a vehicle for vertical knowledge exchange, but some of the features of scientific papers that facilitate horizontal exchange can hinder vertical exchange. Language and style, for example, facilitate horizontal communication. But across fields and levels of science, they tend to differ significantly. Thus, they tend to hinder vertical exchange in papers and in collaboration across levels of science (Huffman and Evenson 2006, pp. 56).

Figure 1 also shows that four scientific pillars support innovations needed for agriculture—physical sciences, chemical sciences, biological sciences and social sciences. The advances in physical sciences are built upon a foundation of mathematics and physics. In this column, pre-invention sciences are clearly linked up-stream to the applied sciences of agricultural engineering and design, mechanics, and computer information, and software and downstream to pre-invention sciences. Advances in chemical sciences are building a foundation on inorganic and organic chemistry. In this column, the pre-invention sciences—soil physics and chemistry, hydrology and water resources and climatology—are linked upstream to agricultural chemistry, soils and soils sciences, and irrigation. Advances in biological sciences build off of a foundation in biochemistry, microbiology, molecular biology, bacteriology, botany, genetics, zoology and ecology. The pre-invention sciences in this column—plant physiology, plant genetics, phytopathology, entomology environmental sciences and bioinformatics—are linked to the applied science fields of agronomy, horticulture, plant breeding, animal science, animal breeding, animal nutrition, food processing and human nutrition. Advances in the social sciences build from foundations in economics, psychology and mathematics. The pre-invention sciences in this area—applied economics, probability, statistics and econometrics, sociology and politically economy—are linked upstream to farm management and marketing, resource economics, rural sociology and public policy studies.

The new biology is attempting to undertake research organized as multidisciplinary projects with a primary emphasis on biological sciences (at all levels) but also incorporating chemical sciences, physical sciences—physics, mathematics, engineering, computer science—and social sciences, such as economics. Multidisciplinary research requires spanning long distance linkages in figure 1. This is important because language, style, and approaches to advancing science differ in important ways across these fields of science. Hence, not only is there a general free-rider problem that comes with team work of similarly training individuals but now there are additional transactions costs of scientists working together on a team project. This organization of projects has a potential to be quite productive but also quite inefficient at times—progress being unusually slow at times and problems with misunderstandings then may undermine the success of a project.

Team Research and a Hierarchy of Scientists

Consider a research project that includes n tasks and n agents and one principal, and each agent chooses to allocate his effort, indexed by a dichotomous outcome: *effort* = 1(*work*), 0(*shirk*). Each agent is assigned major responsibility for one task. An agent's task is completed with probability α if he "*shirks*" and with probability $\beta(k)$ if he chooses "*work*" and believes that k ($< n$) other agents choose "*work*." Thus, if agent i chooses "*work*," the probability of completion of the task that he is primarily responsible for increases from α to $\beta(k) > \alpha$. The cost of his effort level "*work*" is c_i, and the agents (and principal) are assumed to be risk neutral so differential risk preferences do not enter choices here.

The effort decision of any agent is not directly observable to the principal and other (n-1) agents. This means that each agent's effort choice is noncontractible, and the principal observes and each agent's payoff depends only on the final outcome of the multitask project. The project can be either a "*success*" or a "*failure*." If the project is a "*failure*" then all n agents obtain a zero payoff, but if it is a "*success*," there is a vector of expected payoffs, one to each agent: $\underline{v} = (v_1, v_2,.., v_n)$. The vector $\underline{v}$ is the incentive mechanism, and every incentive mechanism gives rise to a sequence of *n* efforts decisions with outcomes of "*work*" or "*shirk*," indexed as: $effort = (effort_1, effort_{2,} \ldots., effort_n)$. We say that a mechanism $\underline{v}$ is incentive inducing (INI) if $\underline{v}$ indices all *n* agents to choose effort level "*work*" in equilibrium, i.e., $effort =(work_1, work_2, \ldots., work_n)$ at minimum total payments to the *n* agents. This outcome is said to be a Nash equilibrium for this game (Winter 2004).

In particular, define $v(k)$ as the payoff for the $(k+1)$-th agent, $(0 \leq k \leq n\text{-}1)$, that would make him indifferent between working and shirking, given that he believes that exactly *k* other agents also choose "*work*." His expected payoff for "*work*" is $v(k)\alpha^n[\beta(k+1)/\alpha]^{k+1} - c_{k+1}$, whereas if he chooses to "*shirk*" his expected payoff is $v(k)\alpha^n[\beta(k)/\alpha]^k$. Hence, $v(k^*)$ equals

(16) $v(k^*) = c_{k+1}/\{\alpha^{n-(k+1)}\beta(k+1)^{k+1}[1 - \alpha/\beta(k)]\}= c_{k+1}/\{\alpha^n[\beta(k+1)/\alpha]^{k+1}[1 - \alpha/\beta(k)]\}$,

which is decreasing in *k* (Winter 2004). Then the optimal payment scheme $\underline{v}^*$ is obtained by valuing (16) at $k = 0, 1, 2, \ldots, (n\text{-}1)$.

In equation (16), consider the case where the agents have identical cost of effort ($c_i = c$), then it is clear that each agent faces a different expected payoff to his effort, and that the largest expected payoff is to the first agent, and the expected payoff declines as additional agents committee to "*work*" on the project. This follows from $0 \leq \alpha < \beta(0) < 1$. The intuition behind the result is quite simple. *If an agent's effort induces a positive externality on the effectiveness of other agents' effort, it is optimal to promise a higher pay off or reward to some agents so as to make the others confidently believe that these highly paid agents will work rather than shirk.* This allows the principal to offer other agents substantially less. Hence, the optimal incentive mechanism is an endogenous hierarchy of incentives. This strategy is related to the "divide and conquer" strategy of exclusionary contracts (Segal and Whinston 2000).

In this model, we can define a production technology $\underline{p} =\{0,1,2,..,(n\text{-}1)\}\rightarrow[0,1]$ specifying the *probability* of the project being a "*success*" as a function of the number of agents who choose "*work*." A key property of $\underline{p}$ is that of increasing returns to scale (IRS). The technology is defined as IRS if $p(k+1) - p(k)$ is increasing in k, $k = 0, 1, \ldots(n-1)$, which holds for $\alpha = [p(0)]^{1/n}$ and $\beta(k) = [p(k)/p(0)]^{1/k}[p(0)]^{1/n}$. Upon simplifying this expression, we obtain the probability of a project "*success*" if k agents choose to "*work*" (on the task for which they are primarily responsible)

(17) $p(k) = [\beta(k)/\alpha]^{k} \alpha^{n-k}$.

$p(k) > p(0)$ follows from $\alpha < \beta(k)$ for all k. Winter (2004) has shown that increasing returns to scale (IRS) in β implies $\underline{p}$ has IRS for $p(k)$ as defined in (17).

Full discrimination arises if an agent's incentive to work increases with the number of other agents who choose "*work*." This can be either a direct result of the technology's properties or simply a consequence of the psychology of peer pressure. Hence, in an environment that exhibits externalities of the kind described above—divide and conquer—it will be optimal to provide each agent with a different incentive, even if the agents have the same cost of effort. This differential incentive scheme for agents, however, can take different forms. For example, these incentives frequently appear in the form of a hierarchy or ranking of agents when authority otherwise seems inconsequential to the outcome of the project.

Moreover, all agents must know that rewards/payoffs are differentiated by rank. One example is that only one team member assumes or volunteers to be the "Project Head", "Project Director," "Project Manger," or "Principal Investigator," and others are designed "Scientists I" and "Scientist II."[3] Differential pay would also include different salary rates charged to the project, but also in academic research, a share of the institutional overhead on an externally funded project generally is returned to the project's investigators. In my example, the Project Director would get the largest share of the overhead, Scientists I, the next largest share, and Scientist II the lowest share. In the model

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[3] Also, it has been shown that internal supervision across hierarchy layers shapes wage scales within many organizations (Lazear and Rosen 1981).

developed above, rank and hierarchy are instruments for generating differential incentives—agents who are assigned higher incentives are those placed at higher ranks.

Thus, an efficiently organized research project spanning several diverse disciplines and involving perhaps 5 to 10 total scientists will need to pay serious attention to setting differential incentives for work on the project. The role of the Project Direction or Principal Investigator will almost certainly be assigned to a senior scientist. This individual will need to have a set of attributes: (i) to have a well-established reputation for excellence in discovery (signally skill in discovery and general respect in his own discipline, (ii) prior experience working with and coordinating others in undertaking projects, and (iii) optimism about the potential for success of the project, as reflected in his willingness to work tirelessly on the project. Hence, junior scientists/faculty members would potentially fit into lower rank positions. However, a junior faculty member who is part of a large multi-disciplinary project may believe that the "*success*" and timely completion of the project is out of his control. This would be a plausible reason for junior faculty member/scientist to decline voluntary participation in such projects (but might be assigned involuntarily by the Department Chair to the project). After a faculty member achieving tenure, working in a hierarchy or ranked system may have an acceptable expected payoff. Moreover, it opens up the possibilities for many new directions of future research.

The Use of Relative versus Joint Performance Evaluation

Lazear and Rosen (1981) and Holmstrom (1982) have papers on team-based incentives in which they suggest that relative performance evaluation (RPE), such as agents organized in a team compete in a tournament, is an efficient contract under some conditions.[4] RPE has value to the principal when agents face a common uncertainty or shock, e.g., the discovery of the electronic

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[4] This is true only for cases where agents are risk neutral. In the first section of this paper, I have reviewed the Huffman and Just (2000) results showing how risk agents affect optimal incentives for research. Scientists are most likely to be risk averse, but there may be selection into the professions such that scientists are only modestly risk averse due to selection operating a number of levels to eliminate the most risk averse.

digital computer, of the internet, of computer software spreadsheets and word processing. In this case, a tournament organized by a principal (and not by the agents) is recognized as having potential for easing the free-rider problem and creating relatively high powered short-run incentives.[5] The reason is that competition is useful for revealing or extracting information from agents that would otherwise remain concealed (Holmstrom 1982). He shows that if agents' outcomes are unrelated, pitting them against each other in rank-order tournaments will lead to worse performance than rewarding agents on the basis of their individual outcomes (or signals of effort alone). When agents are pitted against each other, there is more randomness in the payoff/reward system without any gains in the power of inference about agents' effort. Hence, competition per se is does not have value.

Moreover, RPE is open to counterproductive behavior. In the short run, agents have an incentive to manipulate signals in an unproductive way, e.g., to undertake direct and indirect *sabotage* of other agents or team member's efforts or exert excess peer pressure against "high performers." Hence, there is a weak incentive for cooperation, including sharing useful information. For example, team members working on different parts of the project may not pass on important information in a timely fashion to other agents in the project. In a multi-period, repeated contracting the agents have an incentive to collude against the incentives by jointly slacking off or shirking.

However, we can gain some useful insights by assuming that principals and agents are risk neutral, agents are liquidity constraint such that they cannot be taxed up front for participating in a project and agents undertake one or more projects per period. In each period, each agent chooses *effort*(e) = *work*(1), *shirk*(0), and has c_i as the cost of effort. The principal's objective is to induce both agents to work but at a minimum total compensation.

Let an agent's utility or expected wage not of cost of effort be

(18) $U(e_i| e_j, \mathrm{K}) = \mathrm{E}(w_i| e_i, e_j, \mathrm{K}) - c_i e_i, i \neq j, i, j = 1, 2; K = \mathrm{R}, \mathrm{J},$[6]

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[5] A rank-order tournament rewards agents merely on their performance rank, and not on the value of the output for the project itself (Lazear and Rosen 1981).

[6] I can allow for more than two agents but at a cost of making the notation more cumbersome.

so that the payoff to the *i*-th agent dependent on his and his partner's *effort* under both Relative Performance Evaluation (R) and Joint Performance Evaluation (J). The principal has imperfect and independent signals about the *effort* levels of the two scientists. With probability σ, a benevolent common shock strikes both agents (and the project) and with probability $(1 - \sigma)$ no common benevolent shock occurs. Some example of benevolent common shocks include the discovery of the electronic digital computer, discovery of the desktop and laptop computers, discovery of the internet, discovery of the structure of DNA, discovery of computer software for data analysis and word-processing. If no common shock occurs, then the principal's information come only from signals about effect levels of the agents, "*effort*" e_i, which occurs with probability p_{e_i}, $0 \leq p_{e_i} \leq 1$, $p_{i1} > 0.5 > p_{i0}$, and the principal receives a signal of "*work*" for the *i*-th agent of p_{i1}, which is assumed to be larger than one-half, and a signal of "*shirk*" of $p_{i0} < p_{i1}$, i = 1,2. Let $w_{s_i s_j}$ be the wage that the principal pays to the *i*-th agent when the principal receives signal (s_i, s_j), each of which a value of 1(*work*) or 0(*shirk*).

With two agents there is a combination of four realizations of signals that the principal might receive on the two agents. For the *i*-th agent, the combinations of wages associated with these signals is $\underline{w}_i$

(19) $\underline{w}_i = \{ w^i_{11}, w^i_{10}, w^i_{01}, w^i_{00} \}$, $i = 1, 2$.

Then the expected wage for the *i*-th agent is

(20) $E(w_i \mid e_i, e_j, K) = \sigma w^i_{11} + (1-\sigma)[p_{i1} p_{j1} w^i_{11} + p_{i1}(1- p_{j1}) w^i_{10} + (1- p_{i1}) p_{j1} w^i_{01} + (1- p_{i1})(1- p_{j1}) w^i_{00}]$

Note that if there is no common shock, i.e., $\sigma = 0$, then the first term on the right-hand side of (20) drops out of the expression, and the expected wage is dependent on the probability of the principal receiving a signal of "*work*," indexed by a 1, and of "*shirk*," indexed by a 0, on both agents.

Following Chen and Yoo (20010), a wage scheme exhibits JPE if $(w_{11}, w_{01}) > (w_{10}, w_{00})$. In this case, $E(w_i \mid e_i, 1, J) > E(w_i \mid e_i, 0, J)$ or the expected wage for the i-th agent is always higher when his partner works than when he shirks. Thus, an agent's decision to work yields positive externalities to his partner's effort decision. The nature of the interaction of agents' effort is that they are cooperative; they work together, share information and fill-in temporarily for lagging members. The advantages of this type payoff scheme increases as we shift from a one-time relationship to a multi-period, repeated contracting relationship. In contrast, a wage scheme exhibits RPE if $(w_{11}, w_{01}) < (w_{10}, w_{00})$. In this case, $E(w_i | e_i, 1, R) < E(w_i | e_i, 0, R)$, or the expected wage of an agent is lower when his partner works than when he shirks. In this case, the partner generates a negative externality. In this setting, agents are uncooperative; they do not share information, engage in negative helping or sabotage, and do no fill-in for temporarily lagging team mates.

First, a benchmark needs to be established, which is an environment of one-period decision making. An incentive scheme induces both agents to work as a Nash equilibrium if

(ICs) $E(w | 1,1, K) - c \geq E(w | 0,1, K)$.[7]

The left hand side of (ICs) is the expected wage to the *i*-th agent when both agent chooses to work net of the cost of effort and it is greater or equality to the expected payoff to the *i*-th agent when he shirks, given that his partner chooses to work. Hence, the principal's problem is

(R) $\min_{w \geq 0} E(w | 1,1, K)$ subject to (ICs).

This solution has wide-ranging possible outcomes (Che and Yoo 2001). However, the optimal static (single period) wage scheme for each agent is RPE such that

(21) $\underline{w}^R = \{0,\ w^R_{10},\ 0,\ 0\},\quad w^R_{10} = c / [(1-\sigma)(p_1 - p_0)(1 - p_1)]$.

An agent chooses to work even though he knows that his partner will shirk with positive probability. Given that the two agents can changes roles of being the *i*-th or *j*-th agent, they both in equilibrium choose "*work*." Hence, in the framework developed in this section of the paper relative performance evaluation (RPE) is preferred in a one-time contracting relationship. Some attributes of (21) are

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[7] The agent subscripts (*i, j*) are not necessary and are suppressed in the remainder of this section.

readily apparent. A higher cost of effort, higher probability of a common technology shock, probability of choosing "*work*" all increase the wage under JPE.

In multi-period, repeated relationship, new opportunities in contracting arise. First, RPE becomes generally less attractive because the agents have an incentive to collude against the payment scheme by jointly slacking off or shirking. Second, JPE becomes more attractive because as agents observe past of their partner, they can punish bad behavior. For example, if one agent should choose to shirk in the first period, his partner has the opportunity to punish him in future periods by shirking, too. This possibility helps police the tendency for shirking in the first place.

Let a history at time $t = 1, 2,..$ be a sequence of effort decisions made by the two agents up to $t - 1$. Then a strategy profile is a sequence of functions that map from any possible history at each period into a probability distribution over effort choice profiles at that period. With two agents, we are most interested in a multi-period, repeated relationship over an infinite horizon $(e_1, e_2)^\infty$.

Lets fix an agent at his wage scheme $w \geq 0$. By shirking, the agent can guarantee a payoff of at least $\min\{E(w| 0,0, K), E(w| 0,1, K)\}$ in each period. Hence, this is a lower bound for the worst payoff sustainable in any equilibrium of the game. Therefore, for an equilibrium in which both agents work, we must have

$$(IC_L)\quad E(w| 1, 1, K) - c \geq (1 - \delta) E(w| 0,1, K) + \delta \min\{E(w| 0,0, K), E(w| 0,1, K)\}.$$

The left-hand side of (IC_L) represents the average present-discounted value payoff from working—the expected wage net of the cost of effort. On the right-hand side, a weighted average of the expected wage to the i-th agent, given that he knows that his partner will shirk with positive probability and the minimum sustainable payoff. Here δ is the discount factor; zero corresponds to a one-period horizon, and as δ gets larger, greater weight is given to the future, but with an upper bound on δ of one. Hence, the weighting factor on the first term on the right-hand side declines as the length of the relationship increase and on the second term rises are the length of the project increases.

Inspection of (IC_L) shows why JPE may be more effective than RPE—it permits exploiting the strategic interaction among the agents in a repeated relationship.

Under JPE, $E(w|\,0,1,J) > E(w|\,0,0,J)$.

Thus, (IC_L) becomes

(IC_L') $E(w|\,1,1,J) - c \geq (1-\delta)\,E(w|\,0,1,J) + \delta E(w|\,0,0,J)$.

Since $E(w|\,0,1,J) > E(w|\,0,0,J)$, i.e., the expected wage when the partner works and the agent does not is larger than when they both shirk. The implication is that a shirking team member can be more severely punished by his partner in a repeated or multi-period relationship. The reason is that he is not just punished by a lowered chance of obtaining the good signal (the static incentive) but also punished by the subsequent shirking of his partner in the future, which lowers the initial shirker's future expected payoff. Thus, the agents assist the principal with enforcement of the cont contract when this behavior is self-enforcing behavior. In contrast, RPE cannot generate implicit incentives (Che and Yoo 2001).[8]

The optimal wage scheme in multi-period repeat contracting is obtained from

(L) $\min_{w \geq 0} E(w|\,1,1,K)$ s.t. (IC_L).

Then define $\hat{\delta}(\sigma) = \sigma / [(1-\sigma)p_1p_0]$ where $\hat{\delta}(\sigma) \leq \delta \leq 1$, and the solution to (L) is the JPE scheme

(22) $\underline{w}^J = \{ w_{11}^J, 0,0,0 \}$, $w_{11}^J = c/[(1-\sigma)(p_1^2 - (1-\delta)\,p_1p_0 - \delta\,p_0^2)]$,

where both agents work in every period $(work, work)^\infty$, a long-term team equilibrium exists. In contrast, if $0 \leq \delta \leq \hat{\delta}(\sigma)$, including $\delta = 0$, then the solution to (L) is RPE as in $\underline{w}^R$. Hence, the value of δ is quite critical to the type of incentive scheme that is optimal.

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[8] Consider any RPE scheme where $E(w|\,0,0,R) > E(w|\,0,1,R)$, then $E(w|\,1,1,R) - c = E(w|\,0,1,R)$. This implies that RPE is at least as costly to implement in the repeated setting as in one-time contracting.

Since (22) is a JPE scheme, E(w| 0,1, J) > E(w| 0,0, J), and, hence, min{E(w| 0,0, J), E(w| 0,1, J)} = E(w| 0,0, J), so the worst possible equilibrium punishment is attained when both workers shirk every period in future, (*shirk*, *shirk*)$^\infty$, under $\underline{w}^J$. In particular, Che and Yoo (2001) show that this is self-enforcing given (22). In other words, (*shirk*, *shirk*) is a stage-game Nash equilibrium, which implies that its repeated play forms a subgame-perfect equilibrium. Thus, the worst possible sustainable punishment in this case is self-enforcing under (22). Since (22) satisfies the constraint of (L), repeated play of (*work*, *work*) is subgame perfect given the threat of such a punishment. Furthermore, (22) has a virtue of being collusion-proof: (*work*, *work*)$^\infty$ yields a higher joint payoff to the agents than all other possible subgame-perfect equilibria, e.g., agents are better off when they both "*work*" than when they both "*shirk*." Also, the joint payoff is higher when both agents choose "*work*" than when one of them chooses "*shirk*" and the other chooses "*work*." *Hence, under JPE, each agent's work confers positive externalities on his team member's work,* and in the implemented equilibrium, these positive externalities are already realized. Thus, the two agents of the team cannot benefit from colluding against the JPE multi-period, repeated contracting scheme, and the JPE scheme, $\underline{w}^J$ implements (*work*, *work*)$^\infty$ as a team equilibrium.

Furthermore, there exists a $\hat{\delta}'(\sigma) \leq \hat{\delta}(\sigma)$ such that the above JPE scheme is optimal for $\hat{\delta}'(\sigma) \leq \delta \leq 1$. *Since* $\hat{\delta}(\sigma)$ *is increasing in* σ, *the JPE scheme is optimal for generally small values of* σ *and large values of* δ, *as displaced in figure* 2. In particular, the figure is divided into two regions; one where JPE is optimal and another where RPE is optimal. There is a large area in the NE part of the graph where JPE is optimal. In contrast, the area where RPE is optimal is optimal is small. A major reason for this is that under repeated contracting (i.e., large δ), it is costly for the principal to police the incentive of the agents to collude against the incentive scheme by jointly slacking off or shirking.

Returning to JPE, the optimal scheme in (22) can be implemented by a single group or team output signal rather than by separate signals of effort for each agent in the team. However, for a single team signal to be optimal, it must adequately aggregate the individual signals (about *effort*). Let signal S = min$\{e_i, e_j\}$, then the optimal joint performance evaluation can be implemented if the principal's payoff to each agent of a wage equal to w_{11}^J S, i.e., each is paid either w_{11}^J or 0.

One can measure the intensity of an incentive scheme for work by comparing E(w| 1,1, K) - E(w| 0,1, K), the expected net-payoff to an agent when he chooses "*work*" rather than "*shirk*," given that his partner chooses to work. Under the static optimal scheme of RPE, $\underline{w}^R$, (IC$_R$) binds, so that E(w| 1,1, R) - E(w| 0,1, R) = c. With the optimal JPE scheme, $\underline{w}^J$, E(w| 1,1, J) - E(w| 0,1, J) = $p_1\, c / (p_1 + \delta p_0) < c$. *Hence, the principal's optimal incentive for agent's effort is lower powered under the optimal JPE scheme.* In particular, the power of the incentive falls discontinuously as δ increases because of a shift from RPE being optimal to JPE being optimal. Moreover, it falls further from the fact the team relations is expected to last many periods.

The intuition behind the lower-powered incentives and JPE evaluation compared to RPE are of two types. First, the explicit incentive does not have to be too high powered to motivate an agent to work, given the presences of additional implicit incentives. Second, the explicit incentive must be sufficiently low powered for shirking to be a credible punishment strategy when a partner shirks. Moreover, given the assumption that the principal has no memory in repeated relationship with the two team members, it is an equilibrium strategy for the principal to offer $\underline{w}^J$ every period. This does mean that the principal always has a zero prior for shirking even after repeated events of shirking by agents. Hence, the principal interprets this sequence of negative signals as just bad luck.[9]

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[9] Mohnen et al. (2008) have shown that in settings when agents cannot monitor each others efforts, total effort increases if the agents periodically provide reports to each other (at group meetings) about the state of their progress at interim stages before the project is completed. In contrast, with the absence of interim information exchanges among agents, significant shirking will occur. They argue that his outcome is driven at least partially by the fact that agents have *inequity aversion* on effort devoted to a project that has two or more reporting periods. Hence, there may be a payoff to regular meetings of agents working on different tasks in a team research project.

Synergy among Team Members

Should more than one scientist be assigned to a task? A advantage of team production arises when there is a synergy among the team members, i.e., joint task assignment is an optimal job design. The task can either "*succeed*" or "*fail*" with gross payoffs to the principal of $R > 0$ and 0, respectively. However, a principal has a choice of assigning only one agent to a task or two (or more) agents. It is well known that if there is no synergy, then two agents should not be assigned to one task. Holmstrom (1981) and Holmstrom and Milgrom (1991) conclude that two or more agents should not be made jointly responsible for a single task because sharing responsibility increases the total risk that each agent faces of successfully completing the task without increasing the expected payoff. In addition, Holmstrom and Milgrom (1991) recommend that tasks be grouped together based on the cost of measuring and rewarding performance. Some agents should be assigned easy-to-measure tasks, and their pay should be contingent on performance or incentive pay (see first section of paper), but other agents should be assigned hard-to-measure tasks and be rewarded by a fixed wage. The reason being that if an agent has both easy and hard-to-measure tasks, he or she will concentrate on the easy-to-measure tasks at the expense of the hard-to-measure tasks.

Clearly many research projects consist of a sequence of multiple tasks that need to be completed in order for the project to be a "success." Let's assume that in the case of *single agent production*, an agent makes a choice of effort $e = 0, 1, 2$ at a cost of $c \cdot e$, which implies that the marginal cost of effort (c) is constant and not increasing. The task succeeds with probability p_e, where $1 > p_2 > p_1 > p_0$. The highest probability of the task being a success occurs if the agent allocated two units of effort to the task, and the probability drops as one than then finally zero units of effort are allocated to the task. Furthermore, assume that $p_2 + p_0 \geq 2\, p_1$, i.e., the probability of the project being a success if the agent allocates two units of effort and zero units of effort is greater than if two agents allocate one unit of effort. This condition ensures that an agent will never choose one unit of effort.

We also assume that R is sufficiently large that the principal finds it optimal to induce the agent to choose two units of effort, which is denoted as "*work*" (verses "*shirk*").

Now, consider an alternative technology where two agents or a team is assigned to the same task. Each agent either chooses "*work*" or "*shirk*" where the cost of *working* is c and of *shirking* is 0. The task is either a "*success*" or "*failure*," which is the only signal going to the principal, i.e., not indicators of effort for individual agents, and the principal sets the wage scheme for each agent based on whether the project succeeds or fails. The probability of project "*success*" with two agents is denoted $p_{e_i e}$, where $1 > p_{11} > p_{10} = p_{01} \geq p_{00} \geq 0$.

The interpretation is that the lowest probability of a project succeeding occurs when both agents shirk. If one agent work and one agent shirts, the probability of success of the project is higher than if they both shirk. However, the highest probability of the project being successful occurs when both agents work on the project.

Furthermore, let's assume that $p_{10} > p_0$, so that the project is more likely to succeed when a team of two is assigned to the task than when it is assigned to one agent who "*shirks*." Also, assume that

(23) $p_{11} + p_{00} \geq 2\, p_{01}$.

Condition (23) implies that an agent's work tends to increase his partner's productivity gain from working. Again assume that R is large enough that it is optimal for the principal to induce both agents to choose "*work,*" and the principal wants to implement the same aggregate amount of *effort* in both regimes. Furthermore, a team has *synergy* on a task if $p_{11} > p_2$. Hence, team production is more productive than single agent production, assuming that the agent(s) work in both cases. Moreover, we define that a team member engages in "negative helping" or *sabotage* of a task when $p_{00} < p_0$, the success of a project is low when a team of two agents shirks than if on a single agent is assigned to the task and shirks.[10] Also, defined the extent to which an agent's productivity depends on the effort decision of his partner as $\Delta_e = p_{e1} - p_{e0}$. Then a measure of technological independence between the agents effort under team production can be denoted as (Δ_0, Δ_1). Hence, the higher (Δ_0, Δ_1), the more interdependent is the technology of production.

The choice of *single agent* versus *team production* is now clear. Let $w \geq 0$ denote the principal's payoff to an agent when the project succeeds. Clearly the payoff would be zero when the project is a "*failure*"(or agents *shirk*). First, consider single agent production. Given this scheme, an agent will choose two units of *effort* rather than zero if $p_2 w - 2c \geq p_0 w$. The minimum payoff is then

(24) $w^* = 2c/(p_2 - p_0)$.

Given this payoff, the agent chooses two units of effort, and principal's net expected payoff is

(25) $p_2 R - 2 p_2 c/(p_2 - p_0)$.

Second, under team production, an agent will work if

(26) $p_{11} w - c \geq p_{01} w$.

A team equilibrium is now optimal, and the optimal incentive wage is

(27) $W^* = c/(p_{11} - p_{01})$,

which results in the following net payoff to the principal

(28) $p_{11} R - 2 p_{11} W^* = p_{11} R - 2 p_{11} c/(p_{11} - p_{01})$.

Comparing (25) and (28), it is clear that the synergy among the team members is necessary for team assignment to a task to be optimal in a one period, static relationship, i.e., the principal prefers individual production to team production if the team has no synergy, team production does not produce more than single agent production— $p_{11} \leq p_2$. To gain additional insight, assume that $p_{11} = p_2$, then a team produces with two workers, each with one unit of effort, which the same amount of total effort as a single agents investing two units of his effort. Yet the principal will choose single

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[10] Itoh (1991) considers agents who are part of a team project where each agent is given primary responsibility for one task, but each may also engage in helping other agents with their task(s). The non-specialization of task structure leads to team production as an optimal outcome proved that "negative helping," or *sabotage* does not occur (Lazear 1989).

agent production because the incentive cost is higher in team production due to fixed costs associated with providing incentives for each agent. With team production, a wage used to motivate an agent's effort simply confers positive externalities to his partner without generating the latter's incentive for effort. With single-agent production, the wage used to motivate the first unit of effort for an agent will have a spillover effect onto his second unit of his effort. Hence, to provide the same incentives in team production, the principal must pay a larger total payoff to the two agents than what he would need to pay one agent to perform two units of work.

However, in a multi-period, long-term relationship, team production on a task is more attractive. The outcome for single agent production remains unchanged as it is replayed in each subsequent period. However, the outcome for team output changes because of the strategic interaction among the team members. Now consider the strategy of each agent: "start and keep playing "*work*" unless an agent shirks in a previous period, in which case both "*shirk*" repeatedly thereafter." This penalty strategy generates the worst sustainable payoff for each agent.

For this strategy to sustain itself, two conditions must hold. First, it must be self-enforcing for both agents to choose "*shirk*" repeatedly, which holds if it is a stage-game Nash equilibrium for each agent to shirk: $p_{00}w \geq p_{01}w - c$, or

(29) $w \geq W^*(\delta) = c / [p_{11} - (1 - \delta)\, p_{01} - \delta p_{00}]$.

Given condition (23), $W^*(\delta)$ is the lowest payoff that implements $(work, work)^{\infty}$ as a team equilibrium. Hence, $W^*(\delta)$ is the optimal level of incentive payoff to agents. The resulting expected payoff to the principal is

(30) $p_{11} R - 2\, p_{11}\, c / [p_{11} - (1 - \delta)\, p_{01} - \delta p_{00}]$.

Comparing (30) and (23), we see that p_{01} in the denominator of (23) is replaced by an expression that is smaller, $(1 - \delta)\, p_{01} + \delta p_{00}$. The new element in (30) is the p_{00}, which is attributed to the dynamic penalty strategy of the agents. Consequently, it is less costly for the principal to motivate an agent in the multi-period, repeated environment that in a single period, static environment as long as $\delta > 0$ because $W^*(\delta) < W^*$. Moreover, the denominator of (30) can be written as $\Delta_1 + \delta\Delta_0$. Thus, team production becomes more favorable as the technology of production becomes more interdependent in agent's effort.

In conclusion, team production on a task with payoffs to each agent of $W^*(\delta)$ implements $(work, work)^\infty$ as a team equilibrium. If $p_{11} > p_2$, i.e., the team has synergy and $p_{11} - (1 - \delta)\, p_{01} - \delta p_{00} \geq p_2 - p_0$, then the principal prefers team production to individual agent production on a particular task in multi-period, repeated production. Alternatively, if $p_{11} < p_2$ and $p_{11} - (1 - \delta)\, p_{01} - \delta p_{00} < p_2 - p_0$, the principal prefers individual agent assignment to a task rather than team production. Clearly, the incentives for team production requires a weaker set of conditions to hold in a multi-period, repeated relationships than in single period, static settings. The term p_{00}, probability that the project is a success if both agents shirk, does not have any role in a single period, static relationship. When $p_{00} < p_0$ or *sabotage*-type activities occur (when two agents are assigned to a task and both shirks, the probability of success of the project is lower than when only one agent is assigned to a project and he shirks), the potential for sabotage in the future can be used to sustain a cooperative future relationship among agents. It makes the mutual sanctioning power of shirking in the future more credible and effective. This result supports related research that has concluded that a team assignment to a task is optimal in an organization when there is internal monitoring and peer pressure to enforce "*work*."[11]

The model developed in this section shows that relative performance evaluation, as in tournaments, may be optimal in settings of one-period contacting for a project, provided the agents are not too risk averse. This means incentives create competition among agents in a team. However,

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[11] When agents are risk averse rather than risk neutral, team production becomes less attractive. For example, Corts (2007) shows that when there is a multi-task problem and production is stochastic, then individual production is preferred to teams if agents are highly risk-averse. Individual accountability is preferred to team accountability. Given that women are generally more risk averse than men, team research would have the effect of discriminating against women.

individual members of a team project face weak incentives to cooperate—reducing the probability of the project being a success. This setting describes scientist-participation in external funding agency relationships, which are relatively infrequent events. In contrast, block grants to the scientists' institutions for such diverse research could create an environment where multi-period repeated contracting occurs under a more favorable organizational setting. A team equilibrium becomes more likely in this setting, which implies less competition among agents, more cooperation, and weaker incentives. Hence, the team structure may be better suited to research managed by institutions that employ the scientists and not for research projects funded by external agencies.

With a research project requiring expertise from multiple disciplines, efforts of diversely trained scientists have the potential to be synergenic. However, this has value primarily in multi-period, repeated relationships. This does not in general represent reasonable expectations in the externally funding research environment.

Status, Cognitive Bias and Incentives

Frequently, individuals do not have an accurate assessment of their status relative to that of others. Although social status does not have an inherent effect on worker productivity, low status individuals tend to underestimate their competence and underperform in a group task when paired with high-status individuals, who display over confidence in their abilities. In teams of agents with different, low-status agents, they have a weak incentive to perform in activities that are status worthy. Because principals do not know the status of their team members or cannot operate on it because of anti-discrimination laws, asymmetric information on social status in a group leads to incentive problems for the principal. In particular, the principal must offer all agents in a team the same contract.

Oxoby (2002) shows that if agents have status-biased distortions in their beliefs, a principal should use JPE or team-based incentives. An agent's social rank affects his or her perceptions regarding the role of sending a positive signal to the principal about effort. While the principal faces the objective probabilities of effort contingent on signals of effort, agents' beliefs are distorted by status effects, and these beliefs affect behavior on a project. The issue is that agents react to subjective beliefs about signals rather than objective beliefs. In his model, when agents have biased beliefs about status, than RPE and team incentives are optimal. The main issue here is that when agents have biased beliefs, it takes a large payoff to the low-status agent to induce effort on the project. Moreover, status-induced biases may also affect the assignment of tasks within a team. More confident agents may more easily fall into leadership roles in which they delegate tasks or assume a larger share of the duties. These assignments may result from over-confidence in one's abilities but also from an attempt to garner more "status worthy duties."

Furthermore, this approach highlights a strategic aspect of team assignments in which a principal may put together teams or assign tasks to exploit the status induced biases of agents. It may be easier for a principal to motivate some individuals in the presence of lower-status agents, and the principal may want to organize teams to exploit status differences. In particular, several studies have found gender differences in risk aversion; men being less risk averse than women. Hence, men and women may respond differently to research and other types of job-related risk. Alternatively, if agents do not make errors in beliefs about social status, a relative performance (RPE) contract may be optimal.

Conclusion

A provision in the 2008 Farm Bill established the National Institute for Food and Agriculture. Within this institute, a new competitive grant research program named the Agriculture and Food Research Initiative has replaced the National Research Initiative Competitive Grant Program. The Secretary of Agricultural has recently drawn attention to a new research emphasis for NIFA: food production and sustainability, improved nutrition and ending child obesity, food safety, biofuels and energy, climate change and the environment. In addition, a new NRC-NAS report on "*A New Biology for the 21st Century*" has shed light on using the new biology to meet societal challenges in food, environment, energy and health. The essence of these events is that new NIFA competitive grants may focus more heavily on the new biology, with an emphasis on multidisciplinary teams of scientists in larger projects for longer period of time. However, team research raises complex organizational and incentive issues.

When a single agent undertakes a single research project and there is a random component to the transformation of agent's effort into project output, there is no way for a principal or project director to contract on a scientist's effort or project output. The main problem is that the contract is unenforceable by the courts or a third-party arbitrator. However, the principal and agent can engage in a incentive compatible implicit contract—one when the marginal expect return to scientific effort exceed its expected cost and one where the agent's payoff exceeds his reservation utility or best alternative use of his time. However, a scientist's productivity also depends on his ability, risk aversion, cost of effort and reservation utility. Even when the principal has full knowledge of these latter attributes, setting an efficient incentive for effort is a challenge.

The optimal contract is linear in the effort of the scientist, containing a fixed wage (guarantee) and an incentive component (or share of the project output). Major implications include that the guaranteed salary is positively related to his reservation utility, but his reservation utility has no impact on the incentive component of pay. In addition, the optimal incentive rate is negatively related to scientist's risk premium, and the optimal salary or pay guarantee is positively related to the scientists risk premium under plausible conditions. Moreover, an increase in the riskiness of research, e.g., reduced certainty of funding, reduces a scientist's effort and size of the expected payoff to the project director or funding agency. Hence, creating greater competition for research funds and lowering the funding rate for new projects can be counter productive for scientists and funding agencies.

Research with a team of scientists raises free-rider problems but a project consisting of a research team that spans a number of disciplines have additional costs associated with effective and efficient communication. These problems translate into additional fixed costs of research, which weigh heavily against one-time projects, which are the norm in externally funded research. However, they are less of a burden for tenured scientists employed by an established research institution, such as a state agricultural experiment station that has steady funding from block grants from external sources, e.g., federal and/or state governments.

If a research project has multiple tasks and one scientist is assigned primary (or exclusive) responsibility for it, and the success of the project requires the successful completion of each task in the project, then there is a vector of optimal payoffs to the scientists in the research team. The optimal set of incentives is one where the first scientist to commit to the project receives the highest expected payoff, the second to commit gets the second highest expected payoff, etc. The reason is that the commitment of the first one or two scientists to the project creates a positive externality on the successful completion of the project—it induces a positive externality on the effectiveness of other scientists who commit later. Hence, it is optimal to promise a higher payoff to some scientists so as to make the others confidently believe that these highly paid agents will work hard to make the project a success rather than to shirk. Hence, the optimal incentive mechanism in this setting is an endogenous hierarchy of incentive.

In fact, those with highest pay should be assigned highest rank in the research team. The implication is that the title of Project Directors will be assigned to a senior scientist, one who has a well established reputation for excellence in discovery, prior experience working with and coordinating others, and one who has boundless enthusiasm about the potential success of the project's objectives. Junior scientists without tenure are unlikely to volunteer to participate in such projects.

The decision of the principal to use relative versus joint performance evaluation of team members is important to the success of a project. Relative performance evaluation (a tournament) among team members may be optimal in a one-time research relationship. Problems with this scheme are that incentives are weak for cooperation—best to withhold relevant information, and to be generally uncooperative. Clearly this is problematic, especially for long-term relationships. In a long-term relationship, spanning multiple periods, and with noisy translation of scientists' effort into project success, joint performance evaluation, such as sharing the project's payoff has major advantages. Under the latter incentive scheme, the optimal incentive for scientists' effort is lower powered, and team members have an incentive to cooperate, including helping one another and sharing information. With long-term, repeated contracting, diligent scientists can punish a shirking team member by shirking themselves in the future. This mechanism of internal-enforcement of effort reduces the costs to the principal of team research.

Should more than one scientist be assigned to a task? This can be optimal if the team of scientists has synergy of their efforts. Although a multi-disciplinary research team has the potential for synergy of efforts, in a one-time relationship there is low probability that it will be optimal to assign a team of scientists to a single task, but it can occur if the efforts of these scientists have synergy. However, if the scientists can secure funding for a long-term repeated relationship, the probability of team assignment to a single task increases dramatically.

External social status of scientists can undermine the success of team research. Problems arise when subjective beliefs about social status affect agents' decisions to "*work*" or "*shirk*." The incentive problem here is that it takes a large payoff to the "low status" scientist to induce "*work*." Given that a number of studies have shown that women are more risk averse than men for almost all types of uncertain outcomes, female and male scientists are likely to respond differently to research risk. A likely prediction is that women will be reluctant to volunteer to participate in team research.

A very important conclusion is that competition among scientists has value only to the extent that it is used to reveal information; competition per se raises the uncertainty that scientists face in undertaking research. This translates into higher costs of research and reduced effort of risk averse scientists.

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Figure 1. Science and Technology in the Agricultural Research and Development System (Huffman and Evenson 2006)

Layer/Activity		User and Use Types						
I. FINAL USERS/ Source of Clientele Problems[a]	↕	Producers		Governments			↕	Consumers
II. EXTENSION (Public and private)		Resources & Environment ⇄	Commodity or Product Oriented	Management & Marketing	Public Policy ⇄			Family & Human Resources
III. PRODUCTS FROM INNOVATION (Agri-industrial development)	↕ ↑	Farm Machinery & Equipment Farm Buildings Computer Equipment/ Software	Commercial Fertilizers Agricultural Irrigation Systems Pest Control Systems	Crop/Plant Varieties Horticultural/Nursery Species Livestock Feed	Animal Breeds Animal Health Products Food Products		↕ ↑	Management Systems Marketing Systems Institutional Innovations Health Care Child Care
		Major Areas of Science and Technology for Agriculture						
		Physical Sciences	Chemical Sciences	Biological Sciences				Social Sciences
IV. TECHNOLOGY INVENTION (Public and private research)	↓	Agricultural Engineering & Design Mechanics Computer and Inform. Equipment & Software	Agricultural Chemistry Soils & Soil Sciences Irrigation & Water Methods	Agronomy Horticulture Plant Breeding Applied Plant Pathology Integrated Pest Management Environmental Studies	Animal Science Animal Breeding Animal Nutrition Vet. Medicine	Food-Processing Food-Human-Nutrition	↓	Farm Management & Marketing Resource Economics Rural Sociology Public Policy Studies
		⇄			⇄			
V. PRE-INVENTION SCIENCES (University and public agency research primarily)	↕	Applied Math Applied Physics Engineering Computer Science	Climatology Soil Physics & Chemistry Hydrology & Water Resources	Plant Physiology Plant Genetics Phytopathology Entomology Environmental Sciences Bioinformatics	Animal Physiology Animal Genetics Animal Pathology		↕	Applied Economics Probability, Statistics & Econometrics Nutrition Human Ecology Political Science
		⇄			⇄			
VI. GENERAL OR CORE SCIENCES (University and public agency research primarily)	↓	Physics Meteorology & Atmospheric Sciences Mathematics	Inorganic Chemistry Organic Chemistry Geological Sciences	Bacteriology Biochemistry Botany Ecology	Genetics Microbiology Molecular Biology Zoology		↓	Economics Psychology Mathematics

[a] Arrows indicate the direction of linkages, upstream, downstream, or horizontal.

Figure 2. Regions of Optimal Joint Performance Evaluation (JPE) and Relative Performance Evaluation (RPE), assuming $w_{01} = w_{00} = 0$, $p_0 = 0.4$ and $p_1 = 0.8$. Figure adapted from Che and Yoo (2001)