An Economic Theory of the Evolutionary Origin of Property Rights

Mukesh Eswaran and Hugh M. Neary
University of British Columbia

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ABSTRACT

In this paper we propose an explanation for how the sense of ownership may have evolved in humans. We see it as an evolutionary response to a fundamentally economic problem: survival under competition for scarce resources. We suggest that natural selection contrived a sense of ownership over first possession or over the fruits of one's action—an entrenched characteristic of the innate sense of self—in order to provide a strategic advantage in confrontation with others seeking to appropriate them. Our results show that, in the evolutionarily stable equilibrium, the value placed on the ownership of property is not the same across individuals: it depends on the role of the individual in the interaction. Specifically, a person who has either acquired first possession of a resource or has produced the output values it more highly than one who seeks to appropriate it. We show that this nuanced sense of ownership increased the incentives to undertake productive investments. The legalization of ownership is, in historic time, a relatively recent institutional contrivance for codifying and fine-tuning the problems pertaining to ownership. It is our contention that evolution has shaped this instrument, albeit more bluntly, in humans in the Pleistocene and probably much earlier. Furthermore, our results provide novel explanations for the endowment effect in the psychological literature. Furthermore, they have important implications such as the impact of Protestantism on the economic growth identified in empirical studies.

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e-mail
Mukesh Eswaran: eswaran@econ.ubc.ca
Hugh M. Neary: neary@econ.ubc.ca

1 Introduction

One of the most fundamental axioms of the analysis of market economies is that property rights are well defined. These rights are taken to be assigned by law. One key presumption in law, which has ancient origins, is that of "first possession", that is, the first person to lay claim to a previously unowned object acquires its ownership. A second approach is due to Locke (1689/1967) who put forward a theory that has come to be known as the labor theory of property. To him, it is the conferring of labor on an object by a person that makes it that person's property.[1]

It is our contention in this paper that these legal approaches to property codify what has been inherently built into human nature by evolution. We claim that the sense of ownership of property is hardwired into the human psyche and precedes and underlies the advent of formal legal institutions. We provide a theory of how natural selection may plausibly have shaped the human sense of property rights. In a formal evolutionary model we demonstrate how it is that first possession, insofar as it provides an incumbent advantage to the claim of the possessor over an object, can lead through an evolutionary process to a hardwiring of perception such that the sense of "mine" and "yours" becomes fixed in an affective rather than a rational center of the brain. The possessor's sense of "mine" and the non-possessor's sense of "yours" result in the possessor being willing to expend more effort defending his claim relative to the non-possessor in a contest between them over the object.

In similar vein the theory we offer provides a rationale for why effort or labor expended on an object leads to an innate psychological claim over objects as property. Again, natural selection hardwires stronger preference for the object in the person who bestowed effort than in an interloper who merely seeks to appropriate the object. As a result, when the producer and the interloper contest their claims on the object, more effort will be forthcoming from the

[1] In his words, "Whatsoever then he removes out of the state of nature hath provided and left it in, he hath mixed his labor with, and joined to it something that is his own, and thereby makes it his property. It being by him removed from the common state nature placed it in, hath by this labor something annexed to it, that excludes the common right of other men" Locke (1967, p. 306).

former. Nature, in other words, has programmed humans so that producers exercise greater claim on objects they have expended labor on; equivalently, it has built in a recognition among interlopers that the producers have greater claim on their output. Insofar as the possessor's advantages of first possession can be enhanced by the expenditure of labor, first possession and the labor expenditure reinforce each other in ownership claims.

Our approach provides a common framework for understanding the two views in the legal and philosophic literature on how property is acquired — through first possession and through labor. In addition our approach emphasizes the crucial role of enforcement. Since the hard-wiring of preferences is done at a psychological level, it is manifest in human behavior even in the absence of any laws. Legal institutions and laws come on the scene much later in time and, in order to save the resources that might have gone into costly conflicts in which the winners can be predicted, formalize and extend what Nature has already wrought.

The need for enforceability has a number of implications. It is not expedient for Nature to hardwire a sense of ownership on an object that an individual has little or no advantage in securing in the event the claim is contested. What cannot be enforced is not likely to be claimed, for such claims are at best worthless (because they are costlessly violated) or at worst very costly in terms of fitness (because they consume energy without commensurate payoff).[2]

Recognizing the issue of enforceability also resolves the problem that has been referred to as the Lockean Proviso. In elaborating on his labor theory of property in which an individual may appropriate through his labor part of what originally belonged in common, Locke added the proviso that this is so as long as enough is left over for others.[3] This has caused considerable debate among legal scholars, for the proviso was deemed to weaken the very premise of private property. Nozick (1974, Ch. 7) and Epstein (1979) wonder how it could be possible for anyone to appropriate a part of commonly owned resource through his effort when there is scarcity, for

[2]This answers the objection that the philosopher Nozick (1974, p. 175) raised to Locke's theory: "If I own a can of tomato juice and spill it into the sea so that its molecules (made radioactive, so I can check this) mingle evenly throughout the sea, do I thereby come to own the sea, or have I foolishly dissipated my tomato juice?"

[3]In his words, "For this labor being the unquestionable property of the laborer, no man but he can have a right to what that is once joined to, *at least where there is enough, and as good left in common for others*". Locke (1967, p. 306, emphasis added)

if his appropriation is followed by others then, sooner or later, not enough will be left over for newcomers. So appropriation by the first person sets the ball rolling in a direction where the Lockean Proviso ultimately negates Locke's original claim of how property can be made private through one's effort. Our explanation of the Lockean proviso is simple: it pertains to enforcement. If the resource is abundant, appropriating a part of it through one's own labor would not undermine the subsistence of others and so the appropriation would go unchallenged, becoming private property. On the other hand, if not enough of the resource is left over for others one's property rights are insecure because they are liable to be challenged. The application of one's labor means little in this instance. The Lockean Proviso, in our view, is not a normative statement about the acceptability of private property, as it has been hitherto interpreted, but rather a positive one about the conditions under which property can be rendered private.

It is a well known argument that property rights ensure efficient use of resources. Demsetz (1967) has claimed that when the benefits and costs associated with the use of a resource change, it may elicit a change in property rights. Posner (1972) has espoused the view that property rights evolve so as to ensure efficiency. Despite the value of these insights, it is unclear in these arguments how ownership is conferred. How, precisely, is the identity of the owner determined? If we take the long view forced on us by evolution, however, the issues of efficiency and of equity may not be so neatly separable. For what is equitable and what is efficient may be both endogenously and jointly determined. In this paper, we demonstrate that natural selection simultaneously hardwires a sense of justice and determines what is efficient.

In the model we develop in this paper, individuals are identical *ex ante*, but Nature may offer production opportunities to some but not to others. If those who are fortunate to receive such an opportunity bestow effort on them, the output is sufficient to enhance their biological fitness. Fitness is usually measured by the number of surviving offspring left behind, because this number captures the (relative) representation of the person's genes in the next generation. If a fortunate individual invests in the effort needed to bring forth output (say, catch a hare), it is possible that he may be confronted by an interloper who contests the output because he was not fortunate enough to receive a production opportunity. In this case, a distribution-contest game ensues between the two players. Although individuals are identical, we allow the value placed on the output to be *different* for the individual in the role of producer and for the individual in the role of interloper. These values, or preferences, are subject to natural selection. The effort that these two players apply in the Nash equilibrium of the distribution contest depends on their perceptions of the worth of the output. We determine the evolutionarily stable set of preferences, namely, preferences (values on output) such that no mutant in the role of producer can do better in terms of fitness than other producers and, likewise, no mutant in the role of interloper can have higher fitness than other interlopers. We demonstrate that this evolutionarily stable set of preferences exhibits an asymmetry: *producers value the output more than interlopers do*. In this way, natural selection hardwires attachment to the fruits of one's own labor more than attachment to the fruits of someone else's labor. This is a built-in enforcement mechanism that ensures that a producer would engage in more vigorous defense of his output than would an interloper in its attempted appropriation. We contend that this result provides the theoretical underpinnings of Locke's labor theory of property.

A variant of our model also readily provides a theoretical basis for the simple first-possession argument, which happens, for example, when no one has prior claim on an object by dint of labor already applied. Rather, the labor may be simultaneously applied or Nature may have capriciously bestowed the object on an individual. Why would evolution endow the possessor with property rights in this scenario? If the mere fact of possession of an object confers on the possessor an advantage in retaining it when ownership is challenged by a contender (a very plausible advantage), we demonstrate that Nature hardwires greater attachment to the object in the possessor than in the contender. Consequently, if a distribution contest ensues to determine ownership, the odds are in favor of the possessor. It is our contention that, in invariably assigning property rights to first possession, legal institutions are merely recognizing this asymmetry built into human nature.

Whether it is first possession or one's labor that is relevant to the determination of property rights, our theory proposes that it is the enforcement of ownership that is the crux of the matter. That enforcement comes through the hardwiring that natural selection has wrought so as to maximize survival chances. That enforcement, it should be noted, is what would have been feasible *in our evolutionary past*—probably when humans were hunters and gatherers, for this is the social organization that prevailed during 99% of the evolutionary history of humans.

Our theory also resolves a profound objection that has been raised to Locke's view of property rights. Epstein (1979) has argued that property rights confer rights to an individual against the claims of the rest of the world and the latter must respect it for these rights to mean anything. How can this be taken for granted? As Epstein puts it, "The essence of any property rights is a claim to *bind the rest of the world*; such cannot be obtained, contra Locke, by an unilateral conduct on the part of one person, without the consent of the rest of the world whose rights are thereby violated or reduced. First possession runs afoul of this principle; so does the labor theory. ... Property may look to be an individualistic institution, but the very nature and definition of the right seems to require some collective social institution to lie at its base. No 'natural' act can legitimate a social claim to property." (p. 1228, emphasis added) In other words, if property rights are a convention between an individual and the rest of the world, how can we expect the latter to respect this? Without such respect, individual property rights would rest on very shaky foundations indeed. Our theory shows why property rights do indeed bind the rest of the world. The evolutionarily stable preferences of those who acquire first possession or who have bestowed labor on an object value it more than, and so exercise greater claim over it than, those in the rest of the world. This fact means that the rest of the world grants de facto ownership of property to the former. *This is no mere convention; it is hardwired behavior*. This insight, we argue, is also the basis of individual property in natural law, to which Locke subscribed. Natural law is claimed to be the same all over the world, irrespective of place and time. Our explanation of this claim is that all humans are products of evolution, which is universal. For the same reason, the innate sense of property ownership is universal, too.

Our paper is not the first one to adopt an evolutionary approach to understanding property rights.[4] In a pioneering study, Maynard Smith (1982) used the Dove-Hawk-Bourgeois game in an evolutionary setting to understand why possessors seem to invariably win contests for own-

[4] The relevant literature is comprehensively and accessibly summarized in Krier (2009).

ership in the animal world. He showed that the Bourgeois strategy "Play Hawk (aggressive) if an occupant, and play Dove (concede) if an interloper" is an evolutionarily stable strategy under some circumstances. Sugden (2004) has analyzed similar models for the case of humans and obtained analogous results. The difficulty with these results is that the evolutionarily stable strategies are not unique. Theoretically, the anti-Bourgeois strategy "Play Hawk if an interloper and play Dove if an occupant" can be evolutionarily stable also. So in these analyses it becomes a question of which strategy is adopted as a convention, and the former is chosen as an explanation for the role of occupancy in establishing property rights. We believe that conventions cannot be appealed to for explaining property rights. The feeling of ownership is so entrenched in human nature that it elicits visceral and often violent responses when ownership rights are violated. Violations of norms are unlikely to elicit such reactions. Property rights are more than a matter of convention, in our view. The results in our paper support this contention: the sense of ownership is hardwired, and the preferences that kick in depend on whether a person is an interloper or is a producer/occupant.[5] In addition our modeling strategy allows us to deduce that the possessor will play more aggressively and the interloper less aggressively in the unique evolutionarily stable outcome. We do not need to rely on any notion of convention to select between different possible outcomes.

Gintis (2007) has addressed these issues also, taking the view that property rights are initially biological rather than social, and extending the Dove-Hawk-Bourgeois model in a number of ways, to establish circumstances in which the Bourgeois (private property) evolutionarily stable strategy is more likely to obtain than the anti-private property outcome, where the intruder plays Hawk and the incumbent plays Dove.

Our theory has significant implications for economic development. The evolutionary hardwiring that links one's effort to an innate sense of property rights suggests that cultural or religious norms that emphasize a work ethic will automatically trigger greater respect for property rights. Thus, we argue that the Protestant work ethic, which Weber (1905) famously claimed to have heralded capitalism, would have been aided by the greater salience of property rights

[5]These results are consistent with the intuition of Stake (2004).

in Protestant countries induced by that work ethic. Indeed, evidence suggests that Protestant countries offer greater protection for creditors [Stulz and Williamson (2003)]. Our theory may also be pertinent to an explanation of why Japan also, with its renowned work ethic, may have embraced capitalism: any culture that emphasizes a work ethic will also ensure greater respect for ownership of the fruits of one's labor.

The rest of the paper is as follows. In the next section, we spell out a basic model in which producers and interlopers can have different preferences (subject to selection) over a good that promotes survival. In Section 3, we work out the implications of our model; we demonstrate the fundamental asymmetry in the evolutionarily stable preferences between first possessors/producers and interlopers. In Section 4 we provide a discussion of the evidence for our theory and draw out its implications for economic development. In Section 5, we offer some concluding thoughts.

2 The Model

In our model, people live for one period, reproduce, and die. Their offspring inherit their genes and the cycle is repeated. We posit an evolutionary environment in which Nature randomly offers individuals an opportunity to engage in an activity that could enhance their survival. These opportunities, however, are not available to all individuals. The proportion, θ, of individuals who are fortunate is a measure of the munificence of Nature. In harsh environments, this proportion will be small.

It should be mentioned at the outset that the focus here is on *individuals*, not groups. The reason is that it is our goal to understand how the sense of ownership arose in individuals. The sense of "I, me, and mine" is undoubtedly more innate than the sense "we". It appears that Nature evolved a sense of individual identity before it evolved a group identity. It is certainly not our intention to dismiss the latter, which obviously must have been very important to group activities like tribal warfare, trade, etc. The sense of "us" was arguably shaped to facilitate group or team activities like big game hunting or tribal defence [Eaton, Eswaran, and Oxoby

(2011)]. To isolate the emergence of an individual's inveterate sense of ownership, however, it is convenient to abstract from the latter sort of considerations.

In our model, fortunate individuals are those who have been offered a productive opportunity by Nature, and have to exert effort in order to produce fitness-enhancing output. Hunting a hare, for example, requires effort. We shall generally refer to engagement in the productive activity as 'production', and hunting is a useful example to keep in mind. If we denote this effort by K, we posit the output $q(K)$ to be given by

$$q(K) = A\,K^{\alpha}, \quad 0 \leq \alpha \leq 1, \tag{1}$$

where A is the total factor productivity that characterizes the production technology and α is the elasticity of the output with respect to effort. We may interpret (1) as the expected output when the effort applied is K.

Individuals who have not been fortunate have two options available to them. They can attempt to extort output from a producer; we assume that they can try this with at most one such. Or, if scarcity of producers precludes even this possibility, the unlucky ones must fall back on some low fitness activity such as eating roots. We model the challenge of a producer by an unlucky individual as a distribution contest in which their respective effort levels will determine the relative shares they get of the output. How much productive effort the lucky ones will put into pursuit of their opportunity will depend on their anticipation of the likelihood that they will be subsequently confronted by an interloper in a distribution contest, and on how aggressive that interloper may be.

In the distribution contest, we shall always refer to the individual who has engaged in production as Player 1; Player 2 will denote the potential interloper. We denote by e_1 and e_2 their respective effort levels in the distribution contest. The share[6] that Player 1 retains of his output

[6]In the interest of analytical simplicity we assume that conflict results in a sharing of output between the two contestants. A winner-take-all formulation in which the "shares"are interpreted as the probabilities of securing the entire output by each of the two contestants is also possible, and provides a more plausible interpretation in so examples. We do not present the results for this "probability" model because the major thrust of the results is similar to that of the "shares" model that we focus on.

is s_1 and the share that Player 2 appropriates is s_2. We posit that these shares are given by

$$s_1 = \frac{\beta e_1}{\beta e_1 + e_2}; \quad s_2 = \frac{e_2}{\beta e_1 + e_2}, \tag{2}$$

where the parameter β (≥ 1), which we dub the 'incumbent advantage', captures the fact that the individual bringing the output to fruition or who happens to be the first possessor (Player 1) may have an advantage in retaining it. For equal effort levels, we see that $s_1 = \beta/(\beta+1) \geq 1/(\beta+1) = s_2$ since $\beta \geq 1$. We treat β as exogenous initially; later we will endogenize its value, allowing it to be a function of hunting effort K. It is reasonable to think of an incumbent advantage in this way because the individual producing the output is generally better positioned to defend it, or hide it, or even simply consume it.

We draw a distinction between a person's preferences and his fitness. Natural selection maximizes fitness, but Nature may find it expedient to conjure up preferences that deviate from fitness [Bester and Guth (1998), Bolle (2000), Ely and Yilankaya (2001), Dekel, Ely, and Yilankaya (2007), Gintis (2007), Possajennikov (2000), Schaffer (1988, 1989), Eaton and Eswaran (2003), Eswaran and Kotwal (2004)]. We presume that a person's fitness function, $f(c,e)$, is given by:[7]

$$f(c,e) = \ln(c) - (e + K), \tag{3}$$

where c denotes consumption and e and K are efforts. Our assumption that fitness is logarithmic in consumption is convenient for analytics; and, because it severely penalizes very low levels of consumption, it is also suitable for capturing the importance of subsistence.

We allow the person's utility function, $u(c,e;v)$, to deviate from the fitness function in the following simple form:

$$u(c,e;v) = v \ln(c) - (e + K), \tag{4}$$

where the parameter v is the value that the individual places on the worth of consumption. This

[7]The ln function is used for analytical simplicity. To ensure robustness of our results with respect to this functional form we occasionally report parallel calculations done for a square root function.

parameter can differ from unity (and hence utility can deviate from fitness), and is subject to selection. The consumption of a hare may be worth one unit in terms of fitness ($v = 1$), but we allow preferences to either over or undervalue it relative to its fitness value. Furthermore, we allow the value this parameter takes to depend on the role the player ends up in (lucky producer or unlucky interloper). Thus v_1, the value that an individual as hunter places on consumption of a hare, may differ from v_2, the value that the same individual as interloper places on it. Natural selection will determine these. If these v's differ in an appropriate way, specifically if $v_1 > v_2$, then we will conclude that evolution has hard-wired a sense of private property into our preferences.[8] In what follows, we shall identify the parameters (v_1, v_2) that characterize the evolutionarily stable preferences, that is, preferences which are such that no mutant with different preferences would achieve higher fitness than the rest of the population playing the same role. That the evolutionarily stable preference parameters would likely deviate from unity may be expected from previous work on evolutionary preferences [see the references cited earlier]. How these parameters differ between producers and interlopers and how these impinge on the allocation of property is the prime focus of investigation here, for it is the difference in the latter, if any, that we construe as ownership rights in an evolutionary sense.

The sequence of events and the choices of players are as follows. Individuals live for one period. At birth, Nature assigns to them preferences that they take as given because these are part of their genetic makeup. Then Nature randomly assigns productive opportunities to a fraction θ of the individuals. In stage 1, a person with an opportunity (Player 1) applies an amount of effort K and brings forth output given by (1). (We shall also consider a variant of this in which Nature hands these people output without them having to expend effort—where the fortunate individuals get to possess output produced by Nature.) In stage 2, a player who has been unlucky (Player 2) seeks to confront one of the lucky individuals in a distribution contest. If Nature has been munificent ($\theta \geq 1/2$), every unlucky person manages to engage in such a

[8]This pattern of preference parameters represents precisely what is known in the literature as the "endowment effect"—different valuations of an object by an individual depending on whether the individual owns it or not. We do not use this term because it is closely associated with the concept of *loss aversion* in utility, a concept that provides one approach to rationalizing the endowment effect but which we do not use in this paper. [Kahneman et al. (1991) and Gintis (2007).]

game in which he tries to appropriate the fruits of someone else's labor. The probability, μ, that Player 1 would find himself in such a distribution contest after his efforts have borne fruit is thus given by $\mu = (1-\theta)/\theta$. If, on the other hand, Nature has been miserly ($\theta < 1/2$), only a fraction of the unlucky individuals will even find an opportunity to extort. In the case that he has not been successful in locating a lucky type to engage with, he has no option but to choose a low-fitness activity alluded to earlier that gives him some minimal level of consumption, say $\underline{c}$. The probability that a Player 1 will find himself in a distribution contest in this instance is $\mu = 1$.

The distribution game, along with the measure θ of Nature's bounty, determines the allocation of the property between the producer role and the interloper role. We define an index of property rights, Π, by the relative proportions of total output consumed by producers and interlopers:

$$\mathbf{\Pi} = \frac{\text{expected consumption of } q(K) \text{ by a producer}}{\text{epected consumption of } q(K) \text{ by an interloper}},$$

In the event of first possession case that we consider, the output will be exogenous and can be interpreted as the total endowment bequeathed by Nature.

We now spell out the actions of the players in detail. In the first stage of the game Player 1 applies effort K in his productive opportunity with full awareness of the fact that he may subsequently be engaged in a distribution contest. So proceeding backward, we first need to examine the outcome of the game in the latter stage, contingent on Player 1's effort.

2.1 Stage 2: Distribution contest

We assume that preferences are observable; so Player 2 knows v_1 and Player 1 knows v_2. In this, we follow a substantial literature on the evolution of preferences [Guth and Yaari (1992), Guth (1995), Bester and Guth (1998), Sethi and Somanathan (2001), Eaton and Eswaran (2003)]. These papers show that Nature may contrive preferences that deviate from fitness for strategic reasons.[9]

[9] There is also a literature demonstrating that, where preferences are *not* observable, evolutionarily stable preferences cannot deviate from fitness because deviations lose their strategic value [Ely and Yilankaya (2001), Ok and Vega-Redondo (2001), Dekel et al (2007)]. Dekel et al (2007) show that, when preferences are general and depend

Here, observability of preferences matters in the distribution game. We justify observability by appealing to work on the psychology of deception. We assume that each player's facial expression and body language in a confrontation reveal the values that they place on the object of contention. In his *Expression of Emotions in Man and Animals*, Darwin argued that not all facial muscles are under voluntary control and, furthermore, that these muscles cannot be entirely suppressed. Thus humans betray their feelings because of what is dubbed "emotional leakage".[10] Recent literature in psychology confirms Darwin's view about the involuntary nature of some facial expressions; Ekman (2003) reports that anger and fear (arguably the emotions most salient to a confrontation between the two players in our model) were among the handful of emotions that fewer than 25% of his experimental subjects could produce deliberately. Furthermore, it has been shown that body language is sometimes even more revealing than facial expressions because humans tend to focus on their facial expressions but neglect to consider the posture of the body [Ekman (2003)].

In the distribution game, then, the players simultaneously apply effort to divide the output produced by Player 1. Utility-maximizing Player 1 solves

$$\max_{e_1} \quad v_1 \ln(s_1\, q(K)) - e_1 - K. \tag{5}$$

The parameter v_1 is the value Player 1 places on the output he has produced and s_1 is given by (2). Likewise, utility-maximizing Player 2 solves

$$\max_{e_2} \quad v_2 \ln(s_2\, q(K)) - e_2. \tag{6}$$

In this model it is easy to verify that the effort levels in the distribution contest are strategic complements: an increase in the rival's effort raises the marginal worth of a player's effort.

on outcomes, efficiency is a necessary condition for evolutionary stability. Such equilibria, however, are seen to be evolutionarily unstable when preferences are allowed to depend not only on outcomes but also on opponents' types [Herold and Kuzmics (2009)].

[10]"They reveal the thoughts and intentions of others more truly than do words, which may be falsified," Darwin concluded when referring to emotions [Darwin (1872, Ch. XIV)].

The unique Nash equilibrium solutions for efforts and shares, depend on the parameters (v_1, v_2, β). We denote the respective solutions by

$$\{e_i^*(v_1, v_2, \beta),\ s_i^*(v_1, v_2, \beta)\} \qquad \text{for} \quad i = 1, 2. \tag{7}$$

Equilibrium efforts are each increasing in own v_i. For example, higher v_1, indicating a higher valuation of consumption, induces Player 1 to increase e_1.

Clearly, asymmetric values of the utility parameters v_i will result in asymmetric efforts and shares in equilibrium. In particular, if v_1 is larger than v_2 then Player 1 will have a larger equilibrium share of the output, $s_1 > s_2$ even when $\beta = 1$. This is important because in the first stage Player 1 chooses his productive effort K in anticipation of the (expected) share of the fruits of his effort that he will receive in the distribution contest.

Note that neither the effort levels in the distribution contest nor the shares depend on the output level $q(K)$ directly. This is an artefact of the assumption that fitness is logarithmic in consumption. This assumption simplifies the analytics and allows us to explicitly solve for the endogenous choices that humans (as opposed to Nature) make in this model.

2.2 Stage 1: Choice of productive effort K

We adopt three different formulations of the first stage problem in which productive effort is chosen. These reflect different potential scenarios for the manner in which the evolution of preference parameters interacts with the fitness functions derived from the two-stage production and distribution game.

For convenience in presentation, we analyze in sequence each of the different formulations of the production decision, together with the associated evolutionary stable preferences.

3 Production and Evolutionary Stable Preferences

3.1 First Possession (No Production)

We look initially at the benchmark case of first possession. In this case output is exogenously handed out by Nature to fortunate individuals, who are thereby first possessors, and no effort of the form K is expended. The only relevant parameter in the model becomes β, which we interpret as representing an incumbency advantage of first possession. This advantage is taken to be determined exogenously, and in general to have a value strictly greater than unity.

3.1.1 Evolutionary stable preferences

Substituting the Nash equilibrium efforts and shares of the players from the distribution contest, and the specification that output is exogenously given as $\overline{q}$, and $K \equiv 0$, into the fitness function of equation (3) we derive players' fitness as functions of $(v_1, v_2; \beta)$.

The fitness of a fortunate individual who has been challenged by an interloper is given by

$$f_1^*(v_1, v_2; \beta) = \ln(s_1^*(v_1, v_2; \beta)\, \overline{q}) - e_1^*(v_1, v_2; \beta), \tag{8}$$

This challenge occurs with probability $\mu \equiv \min[(1-\theta)/\theta, 1]$. When Player 1 is not challenged, which occurs with probability $(1-\mu)$, he retains the entire output and devotes no effort to thwarting an interloper; his fitness is

$$f_1^{nc} = \ln(\overline{q}). \tag{9}$$

Thus the expected fitness of an individual in the Player 1 role is given by

$$\overline{f}_1(v_1, v_2; \beta) = \mu\, f_1^*(v_1, v_2; \beta) + (1-\mu)\, f_1^{nc} \tag{10}$$

$$= \ln(\overline{q}) + \mu[\ln(s_1^*(v_1, v_2; \beta)) - e_1^*(v_1, v_2; \beta)]. \tag{11}$$

For an unlucky individual who gets to contest (as Player 2) the output of a lucky individual, fitness is given by

$$f_2^*(v_1, v_2; \beta) = \ln(s_2^*(v_1, v_2; \beta)\, \overline{q}) - e_2^*(v_1, v_2; \beta). \tag{12}$$

Unlucky individuals who do not even get to enter such a contest have no option but to take up the low-fitness activity that generates consumption $\underline{c}$. Denote by $\phi \equiv \min[\theta/(1-\theta), 1]$ the probability that an unlucky individual gets to contest a lucky individual's output. Then the expected fitness of an individual in the Player 2 role is given by

$$\overline{f}_2(v_1, v_2; \beta) = \phi\, f_2^*(v_1, v_2; \beta) + (1-\phi)\ \ln(\underline{c}) \tag{13}$$

$$= \phi \ln(\overline{q}) + (1-\phi) \ln(\overline{c}) + \phi[\ln(s_2^*(v_1, v_2; \beta)) - e_2^*(v_1, v_2; \beta)]. \tag{14}$$

For ease of reference in what follows, we use the notation

$$g_1(v_1, v_2, \beta) := \ln(s_1^*(v_1, v_2, \beta)) - e_1^*(v_1, v_2, \beta) \tag{15}$$

$$g_2(v_1, v_2, \beta) := \ln(s_2^*(v_1, v_2; \beta)) - e_2^*(v_1, v_2; \beta). \tag{16}$$

to represent the distribution-contest terms in the fitness functions (11) and (14).

How does natural selection operate in the model? Assume that every individual in the population inherits the same pair of parameters (v_1, v_2). Which parameter of the pair becomes relevant to an individual depends on the situation he finds himself in. If Nature grants him a productive opportunity, he will be Player 1 and v_1 would be relevant. If he is in the situation of an unlucky individual who gets to challenge the output of a fortunate individual, v_2 would be relevant. If he is an unlucky individual who does not even get to challenge someone else, neither parameter is relevant.

Suppose now that a mutant with a parameter pair (v_1^m, v_2) has higher fitness in his role as Player 1 than all other individuals in the same role. To the extent that the genes dictating preferences are inherited, the frequency of people with the pair (v_1^m, v_2) will increase relative to those with the pair (v_1, v_2). The only scenario where a mutant in the role of Player 1 cannot do better than others in the same role is when v_1 takes on a value that solves

$$\max_{v_1} \quad \overline{f}_1(v_1, v_2; \beta). \tag{17}$$

That is, when v_1 is the "best response", say $v_1^{br}(v_2)$, to v_2 in the sense that it maximizes the expected fitness of individuals in the role of Player 1. This is what natural selection will bring about by tinkering with the genes.

An analogous argument shows that the only scenario where a mutant in the role of interloper (Player 2) cannot do better than others in the same role is when v_2 takes on a value that solves

$$\max_{v_2} \quad \overline{f}_2(v_1, v_2; \beta), \tag{18}$$

that is, when v_2 is the "best response", say $v_2^{br}(v_1)$, to v_1 in the sense that it maximizes the expected fitness of individuals in the role of Player 2. This, again, is what natural selection will bring about by tinkering with the genes. We denote by the pair $(v_1^{\dagger}, v_2^{\dagger})$ the simultaneous solution to the equations $v_1 = v_1^{br}(v_2)$ and $v_2 = v_2^{br}(v_1)$.

It is straightforward to prove the following result (all proofs are relegated to the Appendix):

Proposition 1 [11] *(i) The best response functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$ are negatively sloped; v_1 and v_2 are strategic substitutes; (ii) the Nash equilibrium $(v_1^{\dagger}(\beta), v_2^{\dagger}(\beta))$ is unique and is evolutionarily stable; (iii) the evolutionarily stable preference parameters satisfy the inequalities $v_2^{\dagger}(\beta) < v_1^{\dagger}(\beta)$ for $\beta > 1$; and (iv) $\Pi > 1$ for $\beta > 1$.*

The pair $(v_1^{\dagger}, v_2^{\dagger})$ constitutes a Nash equilibrium in which nature maximizes Player 1's expected fitness given the preferences of individuals in the role of Player 2, and Player 2's expected fitness given the preferences of individuals in the role of Player 1. The pair $(v_1^{\dagger}, v_2^{\dagger})$ also characterizes the *evolutionarily stable preferences* that Nature would hardwire into humans in their roles

[11] These results can be shown to hold also in a model with fitness given by the square root, rather than the log, of consumption. However, if the model is re-specified to take a "probability" rather than a "shares" interpretation of the s_i functions, then it has no Nash equilibrium in (v_1, v_2) when $\beta > 1$; when $\beta = 1$ all symmetric values of the v_i's satisfy the first-order equilibrium conditions. In this case of probability and exogenous investment, there is no evolutionary force acting on the v_i's.

as possessors and interlopers, respectively. No mutant with parameters different from $(v_1^\dagger, v_2^\dagger)$ can do better in terms of fitness than the rest of the population.

Part (*iii*) of the above proposition contains the key result. The asymmetric outcome, $v_2^\dagger < v_1^\dagger$, occurs whenever a first-possession advantage is enjoyed by Player 1 ($\beta > 1$). This asymmetry in the preference parameters v_i indicates that the possessor values the object more than the non-possessor does. Put slightly differently, an individual values a given object that he himself possesses at $v_1^\dagger$, while he would value the same object if possessed by another at $v_2^\dagger$. This suggests the evolutionary hardwiring of a specific notion of property, whereby an individual values what he himself *holds by first possession* more than what another holds.

The evolutionary logic for this asymmetry is as follows. The parameter v_2 is important only for the share of output, less contest effort, received by the non-possessor in the distribution contest, while the parameter v_1 has a symmetrical importance for the possessor (compare (11) and (14)). The only asymmetry is the parameter $\beta > 1$, which reflects a first-possession advantage to Player 1: even when $v_1 = v_2$, Player 1 has a larger share than Player 2. Since the return to Player 1's effort is greater than that to Player 2's, Nature 'contrives' an increase in v_1 so as to exploit Player 1's advantage. Strategic substitutability between v_1 and v_2 then induces a decline in v_2, and so the evolutionarily stable preferences are such that $v_1^\dagger > v_2^\dagger$. Part (iv) follows from the fact that the incumbent advantage and higher valuation of the first possessor deliver a greater share of the output to him; property rights are in his favor.

This preference pattern economizes on the total expenditure of effort in the equilibrium of the distribution contest. In our model the evolutionarily stable values for the preference parameters, and the Nash equilibrium effort levels, (e_1^*, e_2^*) evaluated at $(v_1^\dagger, v_2^\dagger)$, are functions of the single parameter β. Comparative static analysis of the equilibrium conditions yields:

Proposition 2 [12] *The evolutionarily stable preferences, and the associated Nash equilibrium effort levels,*

[12] Analogous results hold in a model with fitness given by the square root, rather than the log, of consumption. (i) when $\beta = 1$, $v_1^\dagger = v_2^\dagger = 4/5$, $e_1^* + e_2^* = \bar{q}\sqrt{2}/5$, and $\Pi = 1$; (ii) $v_1^\dagger$ is increasing in β and approaches 2 asymptotically as β goes to infinity; $v_2^\dagger$ is decreasing in β and approaches 1/2 asymptotically as β goes to infinity; (iii) the sum of the efforts in the evolutionarily stable outcome is decreasing in β and goes to 0 as β goes to infinity; and (iv) Π goes to infinity as β goes to infinity.

have the following properties: (i) when $\beta = 1$, $v_1^\dagger = v_2^\dagger = 2/3$, $e_1^*(v_1^\dagger, v_2^\dagger) + e_2^*(v_1^\dagger, v_2^\dagger) = 2/3$, *and* $\Pi = 1$; *(ii)* $v_1^\dagger$ *is increasing in* β *and approaches 1 asymptotically as* β *goes to infinity;* $v_2^\dagger$ *is decreasing in* β *and approaches* $1/2$ *asymptotically as* β *goes to infinity; (iii) the sum of the efforts in the evolutionarily stable outcome is decreasing in* β *and goes to* $1/2$ *as* β *goes to infinity; and (iv)* Π *goes to infinity as* β *goes to infinity.*

The evolution of a hardwired sense of property derives in this model from the impact on fitness of an incumbent advantage derived from first-possession. This advantage is magnified by Nature which exploits the strategic interdependence in the efforts of the two players. Rather than positing by convention a Hawk strategy for the possessor and a Dove strategy for the non-possessor, as Maynard Smith (1982) does, we have derived this pairing as the unique outcome of an evolutionary process involving preference parameters. Our result provides a theoretical rationale for why the rule of first possession is a key precept in a variety of legal systems.[13]

It must be emphasized that, as modeled here, the average fitness that Nature perceives is obtained when individuals maximize their own self-regarding preferences, given the actions of others. Nature, therefore, is constrained in its choices to maximize average fitness in a second best world. This approach is consistent with our focus that Nature shaped the notion of a self-conscious "me" before it undertook to append this with the notion of "us". Thus Nature in effect acknowledges that, given the behavior of the lucky types, the unlucky individuals will do what they need to in order to best survive. To the extent that the survival of unlucky individuals is facilitated by appropriation, Nature will find it expedient to shape preferences that promotes extortion.

3.2 With Production

We turn now to a model that involves effort in production. This will allow articulation of a labor-based theory of property rights, providing evolutionary support for the principle enunciated by Locke. What follows repeats the structure of the analysis that we have just presented, requiring

[13]See Epstein (1979) and Rose (1985). A landmark case is *Pierson v. Post* (see subsection 3.3.3 below).

only the inclusion of the production effort variable, K.

We suppose now that productive effort must be non-trivially chosen in stage 1, and that the utility parameter v_1 characterizes Player 1's utility in both stage 2 and stage 1, that is, the v_1 characterizes utility in the first stage where Player 1 chooses K also characterizes utility in the second stage distribution contest.

Write the utility of Player 1 in the Nash equilibrium of the distribution contest as:

$$u_1^*(v_1, v_2, \beta; K) = v_1 \ \ln(s_1^* \, q(K)) - e_1^* - K. \tag{19}$$

This is the utility that Player 1 can expect, contingent on his prior productive effort, when he is challenged by an interloper. When not challenged his utility is

$$u_1^{nc}(v_1, \beta; K) = v_1 \ln(q(K)) - K. \tag{20}$$

At stage 1 Player 1 will choose K to maximize expected utility

$$\begin{aligned} U_1 &= \mu \, u_1^*(v_1, v_2, \beta; K) + (1-\mu) \, u_1^{nc}(v_1, \beta; K) \\ &= [v_1 \ \ln(q(K)) - K] + \mu[v_1 \ \ln(s_1^*) - e_1^*] \end{aligned} \tag{21}$$

The first term is the full stage-1 utility value to Player 1 of effort K. The second term reduces Player 1's stage-1 utility because of possible engagement in the distribution contest in stage 2. In our model, the solution to this maximization yields a simple, unique optimum for productive effort, $K^*(v_1)$, given by

$$K^*(v_1) = \alpha \, v_1. \tag{22}$$

That the productive effort level of Player 1 depends on the utility parameter v_1 is not surprising. Key here is the fact that both s_1^* and K^* are functions of v_1; this entanglement of v_1 in both production and distribution outcomes will give rise, in the evolutionary stable preferences, to an asymmetry in the values of v_1 and v_2, even when there is no incumbent advantage (i.e.

β=1). These parameters will evolve in a way that balances distribution and conflict issues in the distribution contest against production issues in the stage 1 game.

3.2.1 Evolutionarily Stable Preferences

Substituting the subgame perfect efforts and shares of the players from the distribution contest, and the productive-effort solution $K^*(v_1)$ from (22), into the fitness function (3) gives players' fitness as functions of (v_1, v_2).

Following the logic of the section (3.1.1), the expected fitness of a Player 1 is given by

$$\overline{f}_1(v_1, v_2, \beta) = [\ln(q(K^*(v_1))) - K^*(v_1)] + \mu g_1(v_1, v_2, \beta) \tag{23}$$

Note that v_1 plays a role in both production decisions (first term) and distribution/conflict decisions (second term).

Likewise, the expected fitness of an (unlucky) Player 2 individual, is given by

$$\overline{f}_2(v_1, v_2, \beta) = \phi \; \ln(q(K^*(v_1)) + (1-\phi)\ln(\bar{c}) + \phi g_2(v_1, v_2; \beta). \tag{24}$$

As before, natural selection will choose a pair (v_1, v_2) that simultaneously solve

$$\max_{v_1} \quad \overline{f}_1(v_1, v_2) \qquad \text{and} \qquad \max_{v_2} \quad \overline{f}_2(v_1, v_2). \tag{25}$$

The two optimization programs above identify the evolutionarily stable outcome in the scenario where Player 1 applies productive effort. For the model that we are using it is straightforward to prove the following proposition:

Proposition 3 *(i) The best response functions from* (25), $v_1^{br}(v_2)$ *and* $v_2^{br}(v_1)$, *are negatively sloped;* v_1 *and* v_2 *are strategic substitutes; (ii) the Nash equilibrium* $(v_1^\dagger, v_2^\dagger)$ *is unique and is evolutionarily stable; (iii) the evolutionarily stable preference parameters satisfy the inequalities* $v_2^\dagger < v_1^\dagger$*; and (iv)* $\Pi > 1$.

The pair $(v_1^\dagger, v_2^\dagger)$ constitutes the *evolutionarily stable preferences* that Nature would hardwire into humans in their roles as producers and interlopers, respectively. No mutant with parameters different from $(v_1^\dagger, v_2^\dagger)$ can do better in terms of fitness than the rest of the population.

As before, part (*iii*) of the proposition contains the key result. The evolutionary process again generates the asymmetric outcome, $v_2^\dagger < v_1^\dagger$, which suggests the evolution and hardwiring of a second specific notion of property whereby an individual values what he himself *has produced* more than what another has produced.[14]

As before, while the parameter v_2 is important only for the share of output received by the non-producer in the distribution contest, the parameter v_1 has a symmetrical importance for the producer in the distribution contest. But, in addition, v_1 is crucial for Player 1's incentive to produce. The evolution of v_1 will balance this production effect with the sharing effect, pushing $v_1^\dagger$ to be larger than $v_2^\dagger$ in the evolutionarily stable outcome. In addition to exploiting the incumbent advantage discussed earlier, the hardwired sense of property derives in this model from the impact on fitness of providing the producer with an appropriate incentive to expend effort in production. Note, however, we do not need an incumbent advantage (that is, $\beta > 1$) to obtain $v_1^\dagger > v_2^\dagger$ here, because of the incentive with which Nature finds it expedient to provide Player 1. This ensures that Player 1 gets a higher share of the output (that is, exercises greater property rights) than the interloper, which explains part (iv) of the Proposition.

The parameters exogenous to the model have been suppressed for brevity in all of the functions above. The solution $(v_1^\dagger, v_2^\dagger)$ depends on the production function parameters (A and α) and also on the abundance of fitness-enhancing opportunities (captured by the parameter θ) in the ecological niche. The solution will also depend on the parameter entering the share functions pertinent to the distribution contest (that is, the incumbent advantage, β).

Some comparative static results can be summarized as:

Proposition 4 *(i) For $\theta \leq 1/2$, $v_1^\dagger$ and $v_2^\dagger$ are independent of θ. For $\theta > 1/2$, $v_1^\dagger$ is increasing and $v_2^\dagger$ is decreasing in θ; (ii) $v_1^\dagger$ is increasing in both α and β, $v_2^\dagger$ is decreasing in both; and (iii) Π is increasing in both.*

[14]This asymmetry holds in the absence of an incumbency advantage ($\beta = 1$); the presence of an incumbency advantage would reinforce the asymmetry in the v_i values.

When production opportunities are relatively scarce ($\theta \leq 1/2$) both $v_1^\dagger$ and $v_2^\dagger$ are independent of θ. This is because each producer is confronted by an interloper with certainty, irrespective of θ. When production opportunities are relatively abundant, $\theta > 1/2$, $v_1^\dagger$ is increasing in θ and $v_2^\dagger$ decreasing. This is because, as θ increases, producers will be confronted less often by interlopers and a higher $v_1^\dagger$ will induce greater effort in production. Since opportunities are more abundant, Nature finds it expedient to reduce $v_2^\dagger$ as θ increases. This explains part (*i*) of the proposition. Also, $v_1^\dagger$ is increasing in α and β, while $v_2^\dagger$ is decreasing in both these parameters. This is because the production function is less constrained by diminishing returns when α increases and the producer is more secure in retaining his output in a distribution contest when β increases; so Nature provides more incentive to apply production effort by increasing $v_1^\dagger$. The decline in $v_2^\dagger$ when α increases occurs because Player 1 produces more output and, by contriving a lower $v_2^\dagger$, Nature enhances the interloper's fitness by having him settle for a smaller share of a larger pie. When the incumbent advantage β is higher, Nature reduces $v_2^\dagger$ to reduce wastage in the interloper's effort. Higher α and β both increase the producer's share of the output. This explains parts (*ii*) and (*iii*) of the proposition.

3.3 Heterogeneous Utility Valuations for Player 1

The property-right results of the production model just examined follow because the same parameter v_1 determines both production and distribution decisions, resulting in $v_1^\dagger > v_2^\dagger$. In this section we consider the implications of breaking the link between production and distribution decisions. To this end we allow Player 1's utility valuation to differ between the consumption and the production of output, applying a utility parameter, v_1, to utility in stage 2, as above, but applying a potentially different parameter, V_1, to utility in stage 1. This breaks the specific link between production and distribution that was key in the previous section. The reason for investigating this scenario is that Nature may craft one valuation over output when a player is producing without knowledge of whether he will be challenged subsequently and another valuation when he is actually confronted with a challenge. We allow Nature to select both V_1

and v_1. In the presence of this production-specific utility parameter, Player 1, at stage 1, chooses K to maximize

$$U_1 = V_1 \ln(q(K)) - K + \mu[V_1 \ln(s_1^*(v_1, v_2, \beta)) - e_1^*(v_1, v_2, \beta)]. \tag{26}$$

In what follows we consider two cases, the first in which β is exogenous, and the other in which β is specified to be an increasing function of K.

3.3.1 Exogenous β

When β is exogenous, the maximization of (26) gives a solution analogous to that of the previous model:

$$K^*(V_1) = \alpha V_1. \tag{27}$$

Now productive effort is independent of the value of v_1. This severs the connection between distribution in the distribution contest and production effort, which occurred when v_1 pertained to both stages. As we show below, natural selection now picks V_1 to be unity, giving efficiency of the production decision. And because v_1 and v_2 are relevant only to the distribution contest v_1 is selected greater than v_2 (and, therefore, the producer exercises greater property rights on his output than the interloper) if and only if there is an incumbent advantage ($\beta > 1$); this is as in the first possession case. To summarize:

Proposition 5 *The evolutionary stable preference parameters* $(V_1^\dagger, v_1^\dagger, v_2^\dagger)$ *satisfy (i)* $V_1^\dagger = 1$ *and (ii)* $v_1^\dagger \geq v_2^\dagger$ *and* $\Pi \geq 1$*, if and only if* $\beta \geq 1$.

3.3.2 Endogenous β

While introduction of the utility parameter V_1 separates production and consumption in this model, this separation also depends critically on the use of the logarithmic specification in fitness and utility. This specification erases any dependence of distribution-contest effort solutions, e_i^*, on the magnitude of the prize $q(K)$, and hence on first-period investment decisions. A non-log specification such as the square root will typically involve dependence of distribution efforts directly on $q(K)$, providing a channel whereby choice of K can impact the distribution-contest solution directly, re-entangling v_1 in both production and distribution/conflict issues even in the presence of the second utility parameters V_1. This brings back asymmetry of the v_i's, even when $\beta = 1$.

For example, when fitness is the square-root rather than the log of consumption, numerical analysis of the model for a wide range of parameter values shows that invariably the evolutionary stable preference parameters (V_1, v_1, v_2) satisfy $V_1^\dagger = 1$, $v_1^\dagger > v_2^\dagger$, and $\Pi > 1$ for $\beta \geq 1$.

In the present log model, there are alternative channels that can link production and distribution, and affect the evolution of the preference parameters. It is plausible, for example, that the magnitude of the incumbent advantage, β, in the distribution contest is endogenous to the productive effort applied in stage 1. That is, K may be interpreted not merely as effort designed to produce output, but also to secure it to some extent from potential interlopers. This is a reasonable assumption, for those who produce are typically in a better position to consume or to hide output than are interlopers. The possibility of production effort helping to secure output by raising β will typically affect the relative values of the utility parameters, v_1 and v_2. To consider the possibilities we specify

$$\beta = \beta_0 + \gamma K \qquad \beta_0 \geq 1; \quad \gamma \geq 0. \tag{28}$$

The outcome of the distribution contest depends on the value of production effort K through the endogenous β.

We assume that the cognitive abilities of humans when the sense of property rights was being shaped by evolution were such that Player 1 does not take the strategic effect of K on the distribution-contest equilibrium into account when choosing K. Looking only at the direct effect of K on the production outcome, maximization of (26) with respect to K gives a solution that depends only on V_1:

$$K^* = \alpha V_1. \tag{29}$$

Substituting $K^*(\cdot)$ into the fitness functions (23) and (24) and maximizing $\bar{f}_1$ with respect to V_1 gives

$$\frac{\partial \bar{f}_1}{\partial V_1} = [(\frac{1}{q(K)}\frac{\partial q}{\partial K} - 1) + \mu\,\gamma\,\frac{\partial g_1}{\partial \beta}]\frac{\partial K^*}{\partial V_1} = 0. \tag{30}$$

Natural selection takes the dependence of β on K into account, through the second term in (30), which is positive because a higher β benefits Player 1 in the distribution contest that may follow. Since the second term in (30) is positive, the first term must be negative. This, combined with the first-order condition for non-strategic maximization of (26), requires $V_1^\dagger > 1$. Player 1 ignores the (positive) strategic effect of productive input K on β, and so under-supplies K. Evolution guided by fitness considerations takes the strategic effect fully into account, and so conjures up a $V_1^\dagger$ that is *larger* than the fitness value 1, inducing higher-than-efficient productive input from the player.

Because K^* is independent of (v_1, v_2), the first-order conditions for maximizing $\bar{f}_1$ and $\bar{f}_2$ with respect to v_1 and v_2 are

$$\frac{\partial g_1}{\partial v_1} = 0 \qquad \text{and} \qquad \frac{\partial g_2}{\partial v_2} = 0. \tag{31}$$

These equations are symmetric and yield $v_1^\dagger \geq v_2^\dagger$ if and only if $\beta \geq 1$. If we normalize $\beta_0 = 1$ then in equilibrium $\beta = 1 + \gamma K^* > 1$; as a result, $v_1^\dagger > v_2^\dagger$ and $\Pi > 1$.

Proposition 6 *When β is endogenous, but the producer does not take into account the strategic effect of the choice of productive effort on the distribution-contest equilibrium, the evolutionary stable equilibrium values of the preference parameters, $(V^\dagger, v_1^\dagger, v_2^\dagger)$, exhibit $V_1^\dagger > 1$ and, when $\beta_0 = 1$, $v_1^\dagger > v_2^\dagger$, and $\Pi > 1$.*

In summary, the basic labour theory model presented shows $v_1 > v_2$ because v_1 has a role in both the distribution game, as v_2 does, and also in the production game where it encourages production. The result is an evolutionary outcome of private property hardwired in preferences, $v_1 > v_2$. It might be thought that the presence of an additional utility parameter V_1, that would allow preference over output at the time of production to evolve independently of preference over output at the time of consumption, might result in symmetric evolutionary pressure on v_1 and v_2 in a fully symmetric game ($\beta = 1$). This is true for the log model, where the distribution game is fully independent of the production game. However, if we reintroduce a natural dependence of the distribution game on the production decision, by making β endogenous to the choice of K, or use a non-log functional form where equilibrium distribution-game efforts depends naturally on K, then we find that the labour theory result holds robustly, even when there is no exogenous incumbent advantage.

An objection to our analysis might be that our model ignores the possibility of agents masking their true preferences. Such a possibility, of course, has been ruled out by our assumption that players correctly observe others' preferences. But what if this were not the case? For example, it is conceivable that Nature may costlessly endow an interloper mutant, whose true valuation is v_2, with the ability to display a higher valuation, say v_2^d, to his rival. Then Player 1, being taken in by Player 2's false signal, would lower his Nash equilibrium effort. This would work to the former's detriment and the latter's advantage.[15] Similarly, Nature might also find it expedient to have Player 1 display a valuation much higher than it truly is. The difficulty with pursuing this line of argument is that we can further conceive that Nature may costlessly conjure up a detection technology which renders useless a particular mode of masking of preferences. In fact, we can conceive of a whole 'arms race' type of evolution between masking and detection technologies. The outcome of this process, of course, is unclear and in reality will depend non-trivially on the fitness costs of displaying fake signals and of detecting such signals. Such an analysis (which will require an estimate of the costs of deception and detection, among other things) is quite outside the scope of this paper. We have opted to cut the process short by assuming that preferences are observed. As mentioned earlier, we appeal to evidence from literature in psychology which is consistent with Darwin's claims (1872, Ch. XIV) that facial expressions cannot be entirely suppressed and betray true information about emotions. In an experimental setting, Porter and Brinke (2008) recently found that participants asked to conceal or

[15] Robson (1990) analyzes the effects in some evolutionary games of mutants possibly signalling cooperative behavior through "secret handshakes". He shows that Pareto inferior equilibria can be destabilized by such mutants.

fake emotions invariably exhibited expressions that were inconsistent with the emotion.[16] This was particularly true of the negative emotions. This suggests that there are substantial costs to masking or suppressing preferences, and we may tentatively infer that this is why Nature has not found it feasible to eliminate all telltale signs that betray deception in humans.

3.3.3 Summary of Findings

The results of this section provide the essential basis of our claim that humans are programmed by Nature to exercise property rights when they either have first possession or they have bestowed labor on an object. The technological advantage conferred by possession invites an endogenous "response" by Nature to enhance fitness, which it does by grafting a sense of ownership in the agent. Interlopers who arrive on the scene after first possession or after someone's labor has been bestowed on the object place a lower value on the object. Thus the "rightful" owner's claims are respected by others, though they may desire the object. *Property rights, as instilled by Nature, bind the rest of the world to some extent.* This answers Nozick's (1974) and Epstein's (1979) objection to Locke's labor theory of property.

We contend that it is the innate sense of ownership that the law formalizes by granting property rights both to first possession and to the product of one's labor. In *Pierson v. Post*, a landmark case in legal history, Post caught a fox that Pierson had been independently chasing. The law conferred ownership on Post based on first possession. In a subsequent landmark case, *Swift v. Gifford*, the courts modified *Pierson v. Post*. In *Swift v. Gifford*, the crew of the whaling ship Rainbow (owned by Gifford) wounded a whale. While their harpoon was still lodged in the whale, the crew of another ship, Hercules, owned by Swift, intercepted and took in the whale. When the captain of the Rainbow contested the haul, the captain of Hercules conceded and handed it over. Swift later sued Gifford, claiming that the whale belonged to him because the Hercules had acquired first possession. Gifford countered that his crew was in active pursuit of the whale

[16] This is clearly a matter of utmost importance in courts of law, where the credibility of witnesses cannot be taken for granted. The Supreme Court of Canada—no doubt drawing on extensive experience in the matter—believes that judging the credibility of a witness is common sense as long as the judge or jury can see the witness's face [Porter and Brinke (2008)].

and had lodged a harpoon in it. The court favored Gifford, that is, the labor of pursuit was rewarded at the expense of what was technically first possession. The reason offered was that the harpoon that was successfully lodged in the whale had brought the mammal within the grasp of the Rainbow. In our interpretation, the labor of Rainbow's crew had produced some concrete output (a wounded whale) that was appropriated by the crew of Hercules. In an evolutionary setting, this act of production through the expenditure of labor would have created a stronger sense of property rights in the producers than in the interlopers. The court's ruling in this case was consistent with the implications of this view.

In our view the law on property rights employs the machinery of the state to prevent costly distribution contests to establish ownership. The cost of enforcement to the state would be greater if the law reversed the ownership "established" by Nature and granted property rights to an interloper instead—for the grievance following the perceived loss of ownership would be greater for the possessor/producer than for the interloper. Furthermore, the perverse incentive effects of such a switch would clearly be very counterproductive. Thus, in conferring property rights to the first possessor or the person who bestowed labor on an object, the law serves justice *and* also efficiency. Our theory may be seen as providing the theoretical underpinnings of the view espoused by Demsetz (1967) and Posner (1972) that the law on property rights may be dictated by efficiency considerations. Our theory does more: it not only explains how property rights get assigned, it also shows how the *identity* of the owner is determined. The transactions costs associated with assigning property rights will not be negligible since the claimants in our scenario have the option of engaging in dissipative distribution contests. Furthermore, since the hardwiring of Nature is asymmetric between possessors/producers and interlopers, the transactions costs will differ depending on who is assigned the rights. Since the scenario we analyze necessarily falls outside the purview of the Coase theorem, the identity of the individual who is assigned the property rights matters. In effect, our theory shows that justice and efficiency cannot be separated.

Finally, the labor theory model predicts behavior that may appear to be governed by the sunk cost fallacy. Nature has found good reason to cause an individual who has bestowed labor on an object to therefore have greater claim on it and value it more highly than would a third party; this idiosyncratic personal valuation may result in the individual expending future resources on maintaining or securing the object that appear to be unwarranted from the point of view of a third-party valuation. While it is rational to consider only future costs and benefits in a decision about a project, future benefits will appear as being idiosyncratically larger to someone who has expended past effort on the project. Sunk cost effects are controversial in biology [see Trivers (1972) and Dawkins and Carlisle (1976)]. It is possible to reformulate our labor theory model in biological (non-utility) terms to explain, for example, why a digger wasp would defend a burrow with effort that is related to its own past effort in stocking it, but that is not (as would be rational) related to the total value of stock previously placed in the burrow by both itself and its competitor [Dawkins and Brockmann (1980)].

4 Experimental Evidence Supporting Findings

The asymmetric valuation of the consumption good by the possessor/producer and the interloper derived in the previous section is so strong in humans that even when a person does not produce the good but has uncontested ownership of it, he exhibits an 'endowment effect' that is well documented in the psychology literature [Kahneman et al (1980)] and summarized in Gintis (2007). Experimental results reveal that the minimum compensation people are willing to accept for an object they own can greatly exceed what they would be willing to pay to acquire it. This, we argue, is likely a hangover from our evolutionary past, where a sense of ownership automatically conferred greater attachment to it so that it may be defended more vigorously in potential contests and thereby dissuade such challenges. We may interpret the parameter v_1 as the minimum compensation people are willing to accept for something they own, and v_2 as a measure of how much they would be willing to pay to acquire it. We expect the effect to be much stronger when the person has bestowed his effort to produce it. It follows from this that, in the distribution contest that occurs after Player 1 has produced the output, the outcomes are necessarily asymmetric. It cannot be modeled as a scenario where Player 1 produces the output and then symmetrically battles an interloper. The outcome of the distribution contest is rigged by Nature to favor the producer/possessor.

Our theory finds confirmation from recent experimental findings. It is an established fact that, in dictator games where unearned sums of money are to be allocated by the dictator between himself and a passive recipient, experimental results show that the dictator allocates an average of about 20% of the sum to the receiver. This contradicts the prediction that, if agents maximize self-interest, this amount should approach zero [see Camerer (2003, Ch. 2) for an overview of experimental findings]. This experimental outcome remains valid independent of culture [Henrich et al (2001)]. The allocation, however, changes quite dramatically when the endowment to be divided is *earned*. Ruffle (1998) examined a scenario where the size of this endowment is determined by the recipient, who is engaged in a skill-testing exercise and is rewarded according to performance. The allocation here was compared to that in a scenario where the recipient's reward was randomly obtained through a coin toss. Ruffle found that dictators rewarded recipients who did well in the skill-test in comparison to recipients who received the same amount in a coin-toss. Furthermore, they mildly punished recipients who did poorly in the skill-test in comparison to recipients who did equally poorly in a coin-toss. This demonstrates that the offers of dictators are influenced by the application of effort by the recipients and not merely by strategic considerations. Cherry et al (2002) investigated dictator games in which the dictators' previously earned wealth was to be allocated by them. The authors find that altruism virtually vanishes; the gap between experimental findings and theoretical predictions of subgame perfection (assuming income-maximization as the objective) is essentially eliminated. This finding is in conformity with our theory that an agent who has earned income through his effort is hardwired to exercise property rights over it. Furthermore, Oxoby and Spraggon (2008) recently found that, while legitimizing the dictators' wealth reduced their offers to recipients, they offered more to receivers if they were distributing the wealth earned by receivers. Thus, not only do agents exercise property rights over what they have earned, they also recognize the property rights of others over what they (others) have earned. This is consistent with our theoretical result that natural selection has evolved the means to bind humans into respecting the property rights of others.

5 Discussion and Implications for Economic Development

The innate sense of property we have rationalized would clearly have important effects on economic development. Besley and Ghatak (2009) provide a comprehensive survey of the various channels through which property rights impinge on economic development. However, there is an evolutionary link between work and property rights that has gone unnoticed. Before we discuss this, we note that our analysis of evolutionarily stable preferences has held constant the environment in which evolution takes place. When the environment changes, preferences will also change as long as the new environment lasts long enough for evolution to operate. So the preference structure should more accurately be represented as (v_1, v_2, E), where E denotes the environment, say as represented by the relative abundance of opportunities. We would probably be correct in assuming that, in the course of human evolution, there were many episodes of varying abundance. Each such episode would have an associated evolutionarily stable preference structure (assuming it lasted long enough). Indeed, it is well-known that humans have adapted themselves to many environments. It is reasonable to posit that what is handed down through genes from generation to generation is a whole menu of (v_1, v_2, E) triplets, which embody the preferences over our entire evolutionary history. According to our theory, those scenarios in which the environment was abundant would exhibit a substantial gap between v_1 and v_2, and would have elicited high productive effort; and those in which the environment was harsh would exhibit a narrow gap between v_1 and v_2, and would have elicited low productive effort. In contemporary times, a socially generated work ethic that emphasizes hard work would only survive if the property rights compatible with hard work were implemented from the menu of hardwired preferences. Since hard work was induced in scenarios where property rights were strong (v_1 high relative to v_2), a social ethic that emphasizes hard work would have to ensure strong property rights, that would elicit hard work.

This line of argumentation rationalizes the recent empirical findings on the correlation between various religions and property rights. Using a sample of 49 countries, Stulz and Williamson (2003) found that Protestant countries not only have stronger creditor rights than do Catholic countries but also enforce creditor property rights better. Our theory provides a causal link. As is well-known, Weber (1905) has argued that the Protestant work ethic was instrumental in the rise of capitalism. Calvin emphasized that one's vocation is divinely ordained and so one should work diligently. Since our paper validates Locke's labor theory of property, this should automatically accentuate the salience of property rights in that culture. In other words, since the Protestant culture emphasizes the ethic of hard work it would also emphasize the sanctity of property rights. This provides an explanation for the empirical finding of Stulz and Williamson (2003).

The case for the link between work ethic and the protection of property, in fact, is more general than in its application to Protestantism. *Any* culture that emphasizes the importance of a work ethic would also enforce stricter property rights. The famed Japanese work ethic has its roots in Confucianism, Buddhism, and Shintoism, which urged individuals to achieve salvation (Nirvana) through means vaguely similar to those espoused by Calvin for Protestants [Bellah (1957)]. Work, it was believed, was to be done for its own sake and Japanese individuals were to discover their identity with the transcendent unity through single-minded devotion to work. This practice, however, would have called forth institutions to help secure the fruits of one's labor. Medieval Japan had weak governments that could not enforce property rights. However, the ownership of land rights were secured and contracts were enforced in an alternative manner. The historical details of how this came about is described in the recent work of Adolphson and Ramseyer (2009). Farmers donated their land to Buddhist temples and monasteries for a fixed share to acquire the tax-exempt status of the temples. This provided an incentive for the temples to protect farmers' properties against outsiders by employing warriors. They also resolved disputes between insiders in what was tantamount to private judicial services through their educated monks. Adolphson and Ramseyer (2009) argue that temples later diversified into providing enforcement of contracts for creditors, merchants, industrialists, etc.

In our view, the correlation between the Japanese work ethic and the strict enforcement of property rights is not an accident. Whatever the motivation for one's action—be it for profit in the here and now, or some perceived intangible benefit in the distant future or simply the aesthetics of actions carried to perfection—our evolutionary hardwiring induces institutions that ensure that the fruits of one's labor are not appropriated by others. Protestantism and the religions of Japan, through their cultural norms, inadvertently harnessed the machinery put in place by Nature for securing the property created by one's labor. It follows that the quality of labor devoted to innovation and production does not capture the full effect on economic development of a culture that emphasizes a stringent work ethic. The attendant emphasis on property rights may have greatly enhanced those benefits. Indeed, this causal link may provide the evolutionary underpinnings of the most pertinent avenue through which some religions impinge on economic development. In this view, culture is a proximate—not an ultimate—cause in the emergence of capitalism. The usual causal argument is that secure property rights motivate individuals to invest and work hard. Our reasoning underlines the fact that the causality between hard work and property rights goes both ways: hard work will also have the effect of bringing more secure property rights in its wake.

The above line of reasoning has a bearing on an intriguing, albeit suggestive, argument made by De Long (1989). He compares two hypotheses regarding the factors that influence economic growth. One is Weber's (1905) claim about the Protestant ethic and the other is the security of property, emphasized first by Adam Smith (1776/1976, Book II, Ch. 1). De Long identified 14 countries of 1870 which might have been deemed likely to make it into First World membership in the twentieth century. (He leaves out Japan because its low GDP per capita in 1870 wouldn't have warranted inclusion.) He then ranks these countries by GDP per capita in 1979 to see whether performance in the twentieth century was influenced by the Protestant work ethic. He finds reasonably suggestive evidence for Weber's claim. The line of reasoning we have outlined above, based on our theory, suggests however that the two hypotheses (work ethic v. property rights) are not independent hypotheses; they reinforce each other. In that sense, the effect of property rights may be overstated because it may be receiving credit for some explanatory power that it owes to the competing hypothesis (Protestant work ethic).

The implications of our theory may also extend to economic growth in the distant past—during the Neolithic Revolution. Our theory suggests that the returns to productive activity in our prehistory were probably higher than would be surmised under the presumption that all players treat the output to be of equal worth. Theft of farming output during the Neolithic Revolution was probably less widespread than what the standard models of violent confrontation for property would lead us to believe. This hardwired sense of ownership would have served humans well in the transition from hunting and gathering to agriculture. In the former phase, this sense of ownership would have been of little use because meat is perishable and so had to be given away, especially if the animals comprised large game. North and Thomas (1977) have argued that property was common in this phase, whereas with the transition to agriculture property became communal. In their view, this transition, along with the emergence of social norms of appropriate behavior within the community, led to more efficient use of resources because it effectively privatized property.[17] If this view is correct, an entrenched sense of ownership such as we have demonstrated here would have lowered the transactions costs of enforcing property rights and thereby facilitated the Neolithic Revolution. This would have been all the more true because, arguably, there is less production in hunting and gathering than in farming. Thus property rights would be more salient in the latter scenario.

Our theory may also explain some observed correlations between social capital and religion [Guiso et al (2003)]. Using World Value Surveys the authors investigated, among other things, the effect of religion on various measures of social capital. One of these measures was how much people in a society trusted strangers. The authors provide evidence to suggest that predominantly Protestant societies exhibit higher levels of trust than those that are predominantly Catholic, confirming a hypothesis originally made by Putnam (1993). Various explanations have been offered to explain this empirical fact. Putnam (1993) has argued that Catholicism promotes distrust by emphasizing the hierarchical (vertical) relationship between individuals and the Church, at the expense of non-hierarchical (horizontal) relations between individuals. This

[17]Weisdorf (2005) surveys the various theories that have been proposed to explain the transition from hunting and gathering to agriculture.

argument appears strained to us, for it is difficult to see why the Church would persist in cultivating distrust amongst it members. Our theory suggests an alternative reason. Protestant societies, we have argued above, will exhibit greater respect for property rights. We have seen that one of the features of hardwired preferences is that they exhibit asymmetry between the owner/producer's value and the potential interloper's. The more trenchant this distinction is in the mind of the population, the less disposed will people be towards appropriating what is not theirs. In such an environment, people will automatically be more trusting. In our reckoning, therefore, Protestantism elicits greater trust among people than Catholicism does because Calvin's this-worldly theology inadvertently taps into the innate sense of ownership fashioned by natural selection. Where the proclivity for appropriation and opportunism is less manifest, trust in others will follow. Furthermore, this explains the positive correlation found by Knack and Keefer (1997) between trust and the GDP growth rates of countries. Our reasoning, we think, also explains why these authors find that associational memberships (memberships of unions, church groups, etc.)—which have a narrower focus on one's immediate group and, therefore, are not likely to trigger a general respect for property rights—show no correlation with trust or with GDP growth rates.

6 Summary

We have presented a simple evolutionary model of the emergence of an innate sense of property rights in humans. One key element of the model is resource scarcity, which results in a distribution contest between individuals for the limited goods available. This contest involves expenditure of effort by both parties, which reduces evolutionary fitness. The outcome of the contest depends, *inter alia*, on how strongly individuals value the contested object. These valuations or preferences can differ from a valuation based simply on fitness. We allow the valuations of an individual for an object which he possesses to differ from that of the same individual for the same object possessed by another individual. This set-up thereby allows for the possibility that an object is valued differently by an individual according to the criterion of being "mine" or “yours".

When these valuations are allowed to be subject to natural selection, and if there is an exogenous asymmetry that confers a first possession incumbent advantage, selection hardwires the sense of private property. In particular, a given object is valued more by the individual if he possesses it than if he does not. This model provides an evolutionary basis for the importance of the concept of first possession, which is crucial ingredient of the philosophical and legal approaches to property rights.

A natural extension of the model shows a role for Locke’s labour theory of property rights. If production is included in the model, in a manner that affects the outcome of the distribution contest, evolutionarily stable valuations are generated in which the producer values the output more highly than does an interloper.

Our theory explains a wide range of empirical regularities observed in diverse scenarios. It explains why the law in most countries gives a great deal of importance to first possession. By providing the evolutionary underpinnings of Locke’s theory of property rights, our theory explains why property rights are more firmly enforced in Protestant countries than in Catholic ones. It also explains why the Japanese work ethic probably contributed to Japan’s rapid economic development, despite the fact that Japan was not Protestant. It explains recent experimental findings in dictator games where the experiments were done with wealth earned by dictators or by the recipients differ from results of experiments performed when the players were simply given the wealth by the experimenter. Finally, our theory offers an explanation for why social capital is higher in Protestant countries than in Catholic ones.

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APPENDIX

We present the proofs of the propositions here.

Preliminaries

The Nash effort levels in the distribution contest are

$$e_1^* = \frac{v_1\sqrt{v_2}}{\sqrt{\beta v_1}+\sqrt{v_2}}; \qquad e_2^* = \frac{\sqrt{\beta}\sqrt{v_1}v_2}{\sqrt{\beta v_1}+\sqrt{v_2}} \tag{A.1}$$

and the share solutions are

$$s_1^* = \frac{\sqrt{\beta}\sqrt{v_1}}{\sqrt{\beta v_1}+\sqrt{v_2}}; \qquad s_2^* = \frac{\sqrt{v_2}}{\sqrt{\beta v_1}+\sqrt{v_2}}. \tag{A.2}$$

For future reference we note from (A.2) we see that s_1^* is increasing in β and v_1 and decreasing in v_2, while s_2^* is decreasing in β and v_1 and increasing in v_2.

Define

$$g^1(v_1, v_2, \beta) = \ln(s_1^*) - e_1^*; \qquad g^2(v_1, v_2, \beta) = \ln(s_2^*) - e_2^*. \tag{A.3}$$

These functions and their derivatives are key to many expressions in this Appendix. A listing of derivatives is provided here. First-order derivatives include

$$\frac{\partial g^1}{\partial v_1} = \frac{\sqrt{v_2}(1-v_1-e_1^*)}{2v_1(\sqrt{\beta v_1}+\sqrt{v_2})} \qquad \frac{\partial g^2}{\partial v_2} = \frac{\sqrt{\beta v_1}(1-v_2-e_2^*)}{2v_2(\sqrt{\beta v_1}+\sqrt{v_2})} \tag{A.4}$$

$$\frac{\partial g^1}{\partial \beta} = \frac{\sqrt{v_2}(1+v_1 s_1^*)}{2\beta(\sqrt{\beta v_1}+\sqrt{v_2})} > 0 \qquad \frac{\partial g^2}{\partial \beta} = \frac{-\sqrt{\beta v_1}(1+v_2 s_2^*)}{2\beta(\sqrt{\beta v_1}+\sqrt{v_2})} < 0. \tag{A.5}$$

Second-order derivatives include

$$\frac{\partial^2 g^1}{\partial v_1^2} = \frac{-\sqrt{v_2}[2v_2 + (5-3v_1)\sqrt{\beta v_1 v_2} + (3-v_1)\beta v_1]}{4v_1^2(\sqrt{\beta v_1}+\sqrt{v_2})^3} < 0 \quad \text{for} \quad v_1 \leq \frac{5}{3} \tag{A.6}$$

$$\frac{\partial^2 g^2}{\partial v_2^2} = \frac{-\sqrt{\beta v_1}[2\beta v_1 + (5-3v_2)\sqrt{\beta v_1 v_2} + (3-v_2)v_2]}{4v_2^2(\sqrt{\beta v_1}+\sqrt{v_2})^3} < 0 \quad \text{for} \quad v_2 \leq \frac{5}{3} \tag{A.7}$$

$$\frac{\partial^2 g^1}{\partial \beta^2} = \frac{-\sqrt{v_2}[2v_2 + (5+v_1)\sqrt{\beta v_1 v_2} + 3\beta v_1(1+v_1)]}{4\beta^2(\sqrt{\beta v_1}+\sqrt{v_2})^3} < 0 \tag{A.8}$$

$$\frac{\partial^2 g^2}{\partial \beta^2} = \frac{\sqrt{v_1}[2\beta v_1 + 3\sqrt{\beta v_1 v_2}(1+v_2) + v_2(1+v_2)]}{4\beta^{3/2}(\sqrt{\beta v_1}+\sqrt{v_2})^3} > 0. \tag{A.9}$$

Cross-partial derivatives include

$$\frac{\partial^2 g^1}{\partial \beta \partial v_1} = \frac{-\sqrt{v_2}(1-v_1-2e_1^*)}{4\sqrt{\beta v_1}(\sqrt{\beta v_1}+\sqrt{v_2})^2} > 0 \qquad \frac{\partial^2 g^2}{\partial \beta \partial v_2} = \frac{\sqrt{v_1}(1-v_2-2e_2^*)}{4\sqrt{\beta v_2}(\sqrt{\beta v_1}+\sqrt{v_2})^2} < 0 \tag{A.10}$$

$$\frac{\partial^2 g^1}{\partial v_1 \partial v_2} = \frac{\sqrt{\beta}(1-v_1-2e_1^*)}{4\sqrt{v_1 v_2}(\sqrt{\beta v_1}+\sqrt{v_2})^2} < 0 \qquad \frac{\partial^2 g^2}{\partial v_2 \partial v_1} = \frac{\sqrt{\beta}(1-v_2-2e_2^*)}{4\sqrt{v_1 v_2}(\sqrt{\beta v_1}+\sqrt{v_2})^2} < 0 \tag{A.11}$$

$$\frac{\partial^2 g^1}{\partial \beta \partial v_2} = \frac{\sqrt{v_1}[\sqrt{v_2}(1-v_1) + \sqrt{\beta v_1}(1+v_1)]}{4\sqrt{\beta v_2}(\sqrt{\beta v_1}+\sqrt{v_2})^3} > 0. \tag{A.12}$$

The signs of these cross-partial derivatives follow from the fact (to be established) that in equilibrium $1 - v_i - e_i^* \leq 0$, requiring $1 - v_i - 2e_i^* < 0$, and $v_1 < 1$.

The determinant of second-order derivatives of g^1 and g^2 with respect to v_1 and v_2 is

$$\Delta = \frac{\sqrt{\beta}[\beta v_1(3-v_1) + 3\sqrt{\beta v_1 v_2}(2-v_1-v_2) + v_2(3-v_2)]}{8(v_1 v_2)^{3/2}(\sqrt{\beta v_1}+\sqrt{v_2})^4} > 0 \quad \text{for} \quad v_i \leq 1. \tag{A.13}$$

Proof of Proposition 1

Here output is simply $\bar{q}$, and there is no expenditure of effort K on production. The expected fitness functions are

$$f^1 = \ln(\bar{q}) + \mu g^1(v_1, v_2, \beta) \qquad \text{and} \qquad f^2 = \phi \ln(\bar{q}) + (1-\phi)\ln(\bar{c}) + \phi g^2(v_1, v_2, \beta).$$

The first-order conditions for maximization of f^1 with respect to v_1, and f^2 with respect to v_2, are:

$$f_1^1 = \mu \frac{\partial g^1}{\partial v_1} = 0$$
$$f_2^2 = \phi \frac{\partial g^2}{\partial v_2} = 0.$$

From (A.4) the first-order conditions imply that, in equilibrium,

$$(1 - v_1^\dagger - e_1^*) = 0 = (1 - v_2^\dagger - e_2^*). \tag{A.14}$$

It is immediate that

$$v_i^\dagger = 1 - e_i^* < 1$$

so both equilibrium parameter values $v_i^\dagger$ are less than the objective fitness value of 1.

From (A.6) and (A.7), the second-order conditions are satisfied for $v_i \leq 1$:

$$f_{11}^1 = \mu \frac{\partial^2 g^1}{\partial v_1^2} < 0$$
$$f_{22}^2 = \mu \frac{\partial^2 g^2}{\partial v_2^2} < 0.$$

The slopes of the best-response functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$ are easily seen to be

$$\frac{dv_1^{br}}{dv_2} = -\frac{f_{12}^1}{f_{11}^1} < 0 \quad \text{and} \quad \frac{dv_2^{br}}{dv_1} = -\frac{f_{21}^2}{f_{22}^2} < 0.$$

Since the fitness functions are strictly concave at any point where the first-order conditions hold, the equilibrium values $(v_1^\dagger, v_2^\dagger)$ are unique. These solution values are independent of

$(\bar{q}, \bar{c}, \theta, \mu, \phi)$. They depend only on the value of β. Since the best response functions are unique and a strict Nash equilibrium is sufficient for evolutionary stability [see e.g. Maynard-Smith (1982, Ch. 5), Samuelson (1997, Ch. 2)], it follows that $v_1^\dagger$ and $v_2^\dagger$ characterize the *evolutionarily stable preferences*.

We now look at the comparative statics with respect to β. The comparative static matrix equation is given by

$$\begin{bmatrix} f_{11}^1 & f_{12}^1 \\ f_{21}^2 & f_{22}^2 \end{bmatrix} \begin{bmatrix} dv_1 \\ dv_2 \end{bmatrix} = \begin{bmatrix} -f_{1\beta}^1 d\beta \\ -f_{2\beta}^2 d\beta \end{bmatrix}$$

where

$$f_{12}^1 = \mu \frac{\partial^2 g^1}{\partial v_2 \partial v_1} < 0, \qquad f_{21}^2 = \phi \frac{\partial^2 g^2}{\partial v_1 \partial v_2} < 0,$$

$$f_{1\beta}^1 = \mu \frac{\partial^2 g^1}{\partial \beta \partial v_1} > 0, \qquad f_{2\beta}^2 = \phi \frac{\partial^2 g^2}{\partial \beta \partial v_2} < 0.$$

The signs in all four cases follow because $1 - v_i - e_i^* = 0$ from (A.14), which implies $1 - v_i - 2e_i^* < 0$.

The determinant

$$\Delta = \begin{vmatrix} f_{11}^1 & f_{12}^1 \\ f_{21}^2 & f_{22}^2 \end{vmatrix} = \mu\phi[\frac{\partial^2 g^1}{\partial v_1^2}\frac{\partial^2 g^2}{\partial v_2^2} - \frac{\partial^2 g^1}{\partial v_1 \partial v_2}\frac{\partial^2 g^2}{\partial v_2 \partial v_1}]$$

is positive for $v_i \leq 1$, from (A.13).

The comparative static expressions are then

$$\frac{dv_1^\dagger}{d\beta} = \frac{1}{\Delta}(-f_{1\beta}^1 f_{22}^2 + f_{2\beta}^2 f_{12}^1) > 0,$$
$$\frac{dv_2^\dagger}{d\beta} = \frac{1}{\Delta}(-f_{11}^1 f_{2\beta}^2 + f_{21}^2 f_{1\beta}^1) < 0.$$

The overall signs follow from substituting the signs of the various second-order derivatives noted previously into the two expressions.

We now consider the relative magnitudes of $v_1^\dagger$ and $v_2^\dagger$. The functions $g^i(v_1, v_2, \beta)$ are fully symmetric at $\beta = 1$ and hence the equilibrium in that case has $v_1^\dagger = v_2^\dagger$. However, as β increases, $v_1^\dagger$ increases and $v_2^\dagger$ decreases, so that

$$v_1^\dagger \geq v_2^\dagger \quad \Longleftrightarrow \quad \beta \geq 1.$$

With a probability μ Player 1's consumption is $s_1^* \bar{q}$ and with probability $(1-\mu)$ it is $\bar{q}$. The expected consumption of a first possessor is $[\mu s_1^* + (1-\mu)]\bar{q}$. The expected consumption of an interloper from this property is $\phi s_2^* \bar{q}$. Thus our property right index is

$$\Pi = \frac{[\mu s_1^* + (1-\mu)]}{\phi s_2^*} = \frac{\mu}{\phi}\frac{s_1^*}{s_2^*} + \frac{(1-\mu)}{\phi}\frac{1}{s_2^*}.$$

If $\theta \leq 1/2$, $\mu = 1$ and while the second term vanishes the first term necessarily exceeds 1 because $s_1^* > s_2^*$ when $\beta > 1$. When $\theta > 1/2$, $\phi = 1$ and the second term necessarily exceeds 1. Thus $\Pi > 1$ when $\beta > 1$.

Proof of Proposition 2

When $\beta = 1$, the distribution contest is perfectly symmetric and we obtain $v_1^\dagger = v_2^\dagger$. From (A.1), we see that $e_1^* = e_2^* = v_1^\dagger/2$. Using (A.4), the solution to the first order condition for $v_1^\dagger$ yields $v_1^\dagger = v_2^\dagger = 2/3$ and $e_1^* = e_2^* = 1/3$. That $v_1^\dagger$ increases (and $v_2^\dagger$ decreases) with β has been demonstrated in the proof of Proposition 1. As $\beta \longrightarrow \infty$, we see that $e_1^* \longrightarrow 0$ and

$e_2^* \longrightarrow v_2$. From the first order conditions for v_1 and v_2, we see that $v_1^\dagger \longrightarrow 1$ and $v_2^\dagger \longrightarrow 1/2$. The aggregate effort falls from $2/3$ when $\beta = 1$ to $1/2$ when $\beta \longrightarrow \infty$. The monotonicity in β has been demonstrated in the proof of Proposition 1. From (A.2) if follows that, as $\beta \longrightarrow \infty$, $s_1^* \longrightarrow 1$, $s_2^* \longrightarrow 0$ and so $\Pi \longrightarrow \infty$.

Proof of Proposition 3

Here output depends on production effort K

$$q(K) = aK^\alpha.$$

K is chosen by Player 1 to maximize his expected utility

$$U_1 = v_1 \ln(aK^\alpha) - K + \mu[v_1 \ln(s_1^*) - e_1^*].$$

The first order condition and solution are

$$\frac{\partial U_1}{\partial K} = \frac{\alpha v_1}{K} - 1 = 0 \quad \Longrightarrow \quad K^* = \alpha v_1.$$

Note that full production efficiency requires $v_1 = 1$.

The expected fitness functions are

$$f^1 = \ln(q(K^*)) - K^* + \mu g^1(v_1, v_2, \beta)$$
$$f^2 = \phi \ln(q(K^*)) + (1-\phi)\ln(\bar{c}) + \phi g^2(v_1, v_2, \beta).$$

The first-order conditions for maximization of f^1 with respect to v_1, and f^2 with respect to v_2, are:

$$f_1^1 = \alpha\left(\frac{1}{v_1} - 1\right) + \mu \frac{\partial g^1}{\partial v_1} = 0 \qquad (A.15)$$

$$f_2^2 = \phi \frac{\partial g^2}{\partial v_2} = 0. \qquad (A.16)$$

A sufficient condition for the respective second-order conditions,

$$f_{11}^1 = \frac{-\alpha}{v_1^2} + \mu\frac{\partial^2 g^1}{\partial v_1^2} < 0 \qquad \text{and} \qquad f_{22}^2 = \phi\frac{\partial^2 g^2}{\partial v_2^2} < 0$$

to be satisfied is $v_i < 5/3$. We will see shortly that this condition must be satisfied because the first-order conditions require $v_i < 1$.

Condition (A.16) implies that, in equilibrium,

$$(1 - v_2^\dagger - e_2^*) = 0. \tag{A.17}$$

It is immediate that

$$v_2^\dagger = 1 - e_2^* < 1.$$

Condition (A.15) evaluated at $v_1 = 1$, gives

$$f_1^1 = \mu\frac{\partial g^1}{\partial v_1} < 0.$$

Given strict concavity of the function f^1 in v_1 for $v_1 < 5/3$, this implies that $v_1^\dagger < 1$ in the solution.

Since the fitness functions are strictly concave wherever the first-order conditions hold, the equilibrium values $(v_1^\dagger, v_2^\dagger)$ are unique.

The evolutionary selection of v_1 balances two margins: ceteris paribus higher v_1 would result in higher productive input and therefore higher fitness; however, lower v_1 reduces the cost of conflict in the distribution contest. In equilibrium, v_1 is such that productive effort is under-provided $\alpha(\frac{1}{v_1} - 1) > 0$ and $\partial g^1/\partial v_1 < 0$, implying from (A.4) and (A.15)

$$1 - v_1^\dagger - e_1^* < 0. \tag{A.18}$$

Suppose now that $v_2^\dagger \geq v_1^\dagger$ in the solution. Then conditions (A.17) and (A.18), together with

(A.1), can be combined to generate

$$\frac{1-v_1}{1-v_2} < \frac{e_1^*}{e_2^*} = \frac{1}{\sqrt{\beta}}\frac{\sqrt{v_1}}{\sqrt{v_2}} \leq 1$$

since $\beta \geq 1$ and $v_2 \geq v_1$ by supposition. However the inequality

$$\frac{1-v_1}{1-v_2} < 1$$

implies that $v_1 > v_2$ and thus contradicts the original supposition. Therefore it must be that $v_1^\dagger > v_2^\dagger$ in the solution even when $\beta = 1$ and there is no incumbent advantage. So $v_1^\dagger > v_2^\dagger$ for $\beta \geq 1$. Since $s_1^* > s_2^*$, it follows that $\Pi > 1$ for all θ.

The slopes of the best-response functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$ are seen to be negative from:

$$\frac{dv_1^{br}}{dv_2} = -\frac{f_{12}^1}{f_{11}^1} < 0 \quad \text{and} \quad \frac{dv_2^{br}}{dv_1} = -\frac{f_{21}^2}{f_{22}^2} < 0.$$

Proof of Proposition 4

The first-order condition for v_2 in (A.16) is multiplicative in $\phi = \theta/(1-\theta)$ and so $v_2^\dagger$ does not depend directly on θ. In (A.15), $\mu = 1$ for all values $\theta \leq 1/2$, so $v_1^\dagger$, and therefore $v_2^\dagger$, are independent of θ for $\theta \leq 1/2$. When $\theta > 1/2$ then $\mu = (1-\theta)/\theta$ and the comparative statics with respect to θ, α and β are obtained below.

The comparative static matrix equation is given by

$$\begin{bmatrix} f_{11}^1 & f_{12}^1 \\ f_{21}^2 & f_{22}^2 \end{bmatrix} \begin{bmatrix} dv_1 \\ dv_2 \end{bmatrix} = \begin{bmatrix} -f_{1\beta}^1 d\beta & -f_{1\alpha}^1 d\alpha & -f_{1\mu}^1 d\mu \\ -f_{2\beta}^2 d\beta & 0 & 0 \end{bmatrix}$$

where, as in the previous case,

$$f_{12}^1 = \mu \frac{\partial^2 g^1}{\partial v_2 \partial v_1} > 0, \qquad f_{21}^2 = \phi \frac{\partial^2 g^2}{\partial v_1 \partial v_2} < 0,$$

$$f^1_{1\beta} = \mu \frac{\partial^2 g^1}{\partial \beta \partial v_1} > 0, \qquad f^2_{2\beta} = \phi \frac{\partial^2 g^2}{\partial \beta \partial v_2} < 0$$

$$f^1_{1\alpha} = \frac{1}{v_1} - 1 > 0, \qquad f^1_{1\mu} = \frac{\partial g^1}{\partial v_1} < 0.$$

The signs in the first four cross-partials above are as in the previous case. In the fifth case $v_1 < 1$ and the sixth follows from the first-order condition for v_1.

The determinant

$$\Delta = \begin{vmatrix} f^1_{11} & f^1_{12} \\ f^2_{21} & f^2_{22} \end{vmatrix} = \mu\phi[\frac{\partial^2 g^1}{\partial v_1^2}\frac{\partial^2 g^2}{\partial v_2^2} - \frac{\partial^2 g^1}{\partial v_1 \partial v_2}\frac{\partial^2 g^2}{\partial v_2 \partial v_1}] - \frac{\alpha\phi}{v_1^2}\frac{\partial^2 g^2}{\partial v_2^2}$$

is again positive for $v_i \leq 1$.

The comparative static expressions are then

$$\frac{dv_1^\dagger}{d\beta} = \frac{1}{\Delta}(-f^1_{1\beta}f^2_{22} + f^2_{2\beta}f^1_{12}) > 0, \qquad \frac{dv_2^\dagger}{d\beta} = \frac{1}{\Delta}(-f^1_{11}f^2_{2\beta} + f^2_{21}f^1_{1\beta}) < 0$$

$$\frac{dv_1^\dagger}{d\mu} = \frac{1}{\Delta}(-f^1_{1\mu}f^2_{22}) < 0, \qquad \frac{dv_2^\dagger}{d\mu} = \frac{1}{\Delta}(f^2_{21}f^1_{1\mu}) > 0$$

$$\frac{dv_1^\dagger}{d\alpha} = \frac{1}{\Delta}(-f^1_{1\alpha}f^2_{22}) > 0, \qquad \frac{dv_2^\dagger}{d\alpha} = \frac{1}{\Delta}(f^2_{21}f^1_{1\alpha}) < 0.$$

The signs of these expressions follow from using the signs of the various cross-partials f^i_{jk}. Since s_1^* is increasing, and s_2^* is decreasing, in α and β it follows that Π is increasing in both these parameters.

Proof of Proposition 5

Substituting $K^* = \alpha V_1$ into the expected fitness functions yields

$$f^1 = \ln(a(\alpha V_1)^\alpha) - \alpha V_1 + \mu g^1(v_1, v_2, \beta)$$
$$f^2 = \phi \ln(a(\alpha V_1)^\alpha) + (1-\phi)\ln(\bar{c}) + \phi g^2(v_1, v_2, \beta).$$

The first-order conditions for maximization of f^1 with respect to V_1 and v_1 are:

$$f^1_{V_1} = \alpha(\frac{1}{V_1} - 1) = 0 \implies V_1 = 1,$$
$$f^1_{v_1} = \mu \frac{\partial g^1}{\partial v_1} = 0.$$

The second-order sufficiency conditions

$$f^1_{V_1 V_1} = \frac{-\alpha}{V_1^2} < 0; \quad f^1_{v_1 v_1} = \mu \frac{\partial^2 g^1}{\partial v_1^2} < 0; \quad f^1_{V_1 V_1} f^1_{v_1 v_1} - [f^1_{V_1 v_1}]^2 > 0$$

also hold.

The result that $V_1 = 1$ maximizes f^1 is independent of anything else in the model. With this solution in hand we can simply solve for equilibrium K and q as $\bar{K} = \alpha$ and $\bar{q} = a\alpha^\alpha$, and then maximizing the respective fitness functions with respect to v_1 and v_2 only.

That is, taking $V_1 = 1$, look for the equilibrium (v_1, v_2) values that solve

$$\max_{v_1} f^1 = \ln(\bar{q}) - \bar{K} + \mu g^1(v_1, v_2, \beta)$$
$$\max_{v_2} f^2 = \phi \ln(\bar{q}) + (1-\phi)\ln(\bar{c}) + \phi g^2(v_1, v_2, \beta).$$

Since this is exactly the model of First Possession considered above, the proof is identical.

Proof of Proposition 6

Here output depends on production effort K

$$q(K) = aK^\alpha.$$

K is chosen by Player 1 to maximize his expected utility

$$U_1 = V_1 \ln(aK^\alpha) - K + \mu[V_1 \ln(s_1^*) - e_1^*].$$

The first order derivative is

$$\frac{\partial U_1}{\partial K} = \frac{\alpha V_1}{K} - 1 + \mu[\frac{V_1}{s_1}\frac{\partial s_1^*}{\partial \beta} - \frac{\partial e_1^*}{\partial \beta}]\frac{\partial \beta}{\partial K}.$$

When Player 1 behaves non-strategically, he takes $\partial\beta/\partial K = 0$ and the first order condition and solution become

$$\frac{\partial U_1}{\partial K} = \frac{\alpha V_1}{K} - 1 = 0 \qquad \Longrightarrow \quad K^* = \alpha V_1.$$

The expected fitness functions are

$$\begin{aligned} f^1 &= \ln(a(\alpha V_1)^\alpha) - \alpha V_1 + \mu g^1(v_1, v_2, \beta_0 + \gamma\alpha V_1) \\ f^2 &= \phi \ln(a(\alpha V_1)^\alpha) + (1-\phi)\ln(\bar{c}) + \phi g^2(v_1, v_2, \beta_0 + \gamma\alpha V_1). \end{aligned}$$

The first-order conditions for maximization of f^1 with respect to V_1 and v_1 are:

$$\begin{aligned} f^1_{V_1} &= \alpha(\frac{1}{V_1} - 1) + \mu\gamma\alpha\frac{\partial g^1}{\partial \beta} = 0 \\ f^1_{v_1} &= \mu\frac{\partial g^1}{\partial v_1} = 0. \end{aligned} \tag{A.19}$$

Note that because $\partial g^1/\partial\beta > 0$ by (A.5), it follows that the solution value of V_1 must satisfy $V_1^\dagger > 1$.

Sufficient second-order conditions for the maximization of f^1 with respect to V_1 and v_1, are

$$f^1_{V_1V_1} = \frac{-\alpha}{V_1^2} + \mu(\alpha\gamma)^2\frac{\partial^2 g^1}{\partial\beta^2} < 0; \qquad f^1_{v_1v_1} = \mu\frac{\partial^2 g^1}{\partial v_1^2} < 0$$

where the signs are given in (A.8) and (A.6), and

$$f^1_{V_1V_1}\, f^1_{v_1v_1} - f^1_{V_1v_1} f^1_{v_1V_1} > 0$$

where

$$f^1_{V_1v_1} = \mu\alpha\gamma\frac{\partial^2 g^1}{\partial\beta\partial v_1} > 0$$

signed in (A.10). The latter condition can be rewritten as

$$f^1_{V_1V_1}\, f^1_{v_1v_1} - f^1_{V_1v_1} f^1_{v_1V_1} = \frac{-\alpha\mu}{V_1^2}\frac{\partial^2 g^1}{\partial v_1^2} + (\alpha\gamma\mu)^2[\frac{\partial^2 g^1}{\partial\beta^2}\frac{\partial^2 g^1}{\partial v_1^2} - (\frac{\partial^2 g^1}{\partial\beta\partial v_1})^2]$$
$$= \frac{-\alpha\mu}{V_1^2}\frac{\partial^2 g^1}{\partial v_1^2} +$$
$$(\alpha\gamma\mu)^2 v_2[\frac{(\beta v_1)^{3/2}(2 + 2v_1 - v_1^2) + v_2^{3/2} + \sqrt{\beta v_1 v_2}(\sqrt{\beta v_1}(5 + v_1 - 3v_1^2) + \sqrt{v_2}(4 - v_1))}{(2\beta v_1)^2(\sqrt{\beta v_1} + \sqrt{v_2})^5}] > 0$$

where the sign follows from (A.6), and for $v_1 \leq 1$. We will see shortly that the first-order conditions require $v_i < 1$.

The first-order condition for maximization of f^2 with respect to v_2 is:

$$f^2_{v_2} = \phi\frac{\partial g^2}{\partial v_2} = 0 \tag{A.20}$$

The second-order condition,

$$f^2_{v_2v_2} = \phi\frac{\partial^2 g^2}{\partial v_2^2} < 0$$

is satisfied from (A.7).

Since both f^1 and f^2 are strictly concave functions of their arguments for values $v_i \leq 1$, any Nash equilibrium with solutions $v_i < 1$ must be unique.

Conditions (A.19) and (A.20) imply that, in any equilibrium, $(v_1^\dagger, v_2^\dagger)$ are each less than 1. That is, using (A.4), these first-order conditions show that any equilibrium values of v_1 and v_2

must satisfy

$$(1 - v_1^\dagger - e_1^*) = 0 = (1 - v_2^\dagger - e_2^*). \tag{A.21}$$

It is immediate that

$$v_i^\dagger = 1 - e_i^* < 1.$$

Furthermore, for any given value of V_1, which fixes the equilibrium value of $\beta = \beta_0 + \gamma\alpha V_1$, the equilibrium values of (v_1, v_2) are determined completely by the equations

$$\frac{\partial g^1}{\partial v_1} = 0 = \frac{\partial g^2}{\partial v_2}.$$

The structure of the relationship between v_1 and v_2 is therefore exactly the same as in the First Possession case treated above. In particular the equilibrium values of (v_1, v_2) depend directly only on the value of β. Specifically, $v_1^\dagger \geq v_2^\dagger$ iff $\beta \geq 1$; and $v_1^\dagger$ is increasing, and $v_2^\dagger$ is decreasing, in β.

Since the equilibrium value of β is endogenous, with $\beta = \beta_0 + \gamma\alpha V_1$, a sufficient condition for $v_1^\dagger > v_2^\dagger$ in equilibrium is that $\beta_0 + \gamma\alpha V_1 > 1$. Thus, even when there is no exogenous incumbent advantage, $\beta_0 = 1$, the fact that the producer of output can create an incumbent advantage through his production effort results in the evolution of private property parameters, that is, a value of v_1 greater than v_2. In this case, it follows from reasoning familiar by now that $\Pi > 1$.