An Economic Theory of the Evolutionary Origin of Property Rights

Mukesh Eswaran and Hugh M. Neary

University of British Columbia

ABSTRACT

We model the emergence of an innate, biological sense of property rights where resource scarcity and output contestability reign. Preferences evolve such that, in evolutionarily stable equilibrium, an object is valued more by an individual who possesses it, or has produced it, than if he is neither possessor nor producer. In a distributional contest for the object, the possessor/producer will devote more effort to retaining it than an interloper will to expropriating it. Asymmetry in preferences for an object between possessor/producer and interloper, and consequent asymmetry of efforts defending or expropriating it, constitute our concept of innate property rights.

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

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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 and to be enforced by the legal system. In this paper we contend that legal and philosophical approaches to the specification of property rights—specifically Locke's labor theory and the doctrine of first possession—codify what has been built into human nature by evolution, 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 an innate sense of property rights by showing, in a formal evolutionary model, why effort or labor expended on an object may lead to an innate psychological claim over the object as property. Natural selection hardwires stronger preference for the object in the person who bestowed effort on it than in an interloper who seeks to appropriate it. This hardwiring of asymmetric valuations of the object results in the producer being willing to expend more effort defending his claim relative to the non-producer in a contest between them over the object.

This approach provides a clear evolutionary rationale for Locke's (1689/1967) labor theory of property, which holds that it is the conferring of labor on an object by a person that makes it that person's property.[1]

Similarly, our model can demonstrate that first possession of an object, if first possession provides an incumbency advantage to the possessor, may lead to an evolutionary hardwiring of asymmetric valuations of the object whereby the possessor becomes willing to expend more effort defending his claim relative to the non-possessor in a conflict over the object. Insofar as the

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[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).

first possessor's advantages can be enhanced by the expenditure of labor, first possession and labor expenditure reinforce each other in ownership claims.

Our approach provides a common framework for understanding these two key views in the legal and philosophic literature on how property is acquired — through labor and through first possession. In addition our approach emphasizes the crucial role of enforcement.

The question of enforcement is central to any discussion of property rights. No claim to property can have meaning unless the claim is enforceable, whether by social and legal institutions, or by individual effort in a Hobbesian state of nature. For example, in discussing Locke's approach, Epstein (1979) argues that while property rights confer rights to an individual against the claims of the rest of the world, the latter must respect these rights for them to mean anything. 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." (p. 1228, emphasis added) In other words, if property rights are a mere convention between an individual and the rest of the world, why should we expect them to be respected? Our approach shows why property rights do indeed bind the rest of the world. In the pre-institutional setting of our model, enforceability occurs only through individual effort in a contest setting. 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 effort in claiming it, than those in the rest of the world. This fact means that the rest of the world is forced to grant de facto ownership of property to the former. *This is no mere convention; it is hardwired behavior*. Since the hardwiring of preferences is done at a psychological level, it is manifest in human behavior even in the absence of any laws.[2] 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

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[2]Our paper refers to evolutionary processes taking place in pre-civilized, evolutionary time—probably when humans were hunters and gatherers, for this is the social organization that prevailed during 99% of the evolutionary history of humans. There is no third-party enforcement of the concept of property right here; competing claims to an object can be enforced only by the effort of the individuals involved. Property rights are thus "insecure" in the sense of Gonzalez (2010). 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, they formalize and extend what Nature has already wrought.

that all humans are products of a shared evolution. For this reason, the innate sense of property ownership is universal, too.

Innate enforceability has a number of implications. Nature will not hardwire a sense of ownership of an object that an individual has little or no advantage in securing in the event the claim is contested. What cannot be enforced will not be claimed: such claims would be worthless because costlessly violable, or would be very costly in terms of fitness because they consume energy without commensurate payoff. This answers an objection of Nozick (1974, p. 175) to Locke's labor theory.[3]

Enforceability also resolves the issue known as the Lockean Proviso. Locke added to his labour theory the proviso that while an individual's labor may appropriate part of what originally belonged in common this is so only as long as enough is left over for others.[4] This proviso weakens the concept of private property; see Nozick (1974, Ch. 7) and Epstein (1979). 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. However, as appropriation of the commons proceeds scarcity will emerge eventually and the proviso will then negate the labour theory of property rights. Our interpretation of this conundrum is simple: the Lockean Proviso is not a normative statement about the acceptability of private property, as it has been hitherto interpreted, but rather is a positive one about enforceability, 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

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[3]"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?"

[4]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)

and jointly determined. In this paper, we demonstrate that natural selection simultaneously hardwires a sense of justice and determines what is efficient.

In our model, individuals are identical *ex ante*; scarcity exists because Nature offers production opportunities to some but not to others. If an individual fortunate enough to have received a production opportunity (find a prey animal) invests effort in it (track and capture it) the output will enhance their biological fitness; however, this producer may have his output contested by an interloper who 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. The asymmetry in valuation arises because of the asymmetric role of the contesting individuals in production of the output. Thus there is an innate enforcement mechanism whereby a producer would expend more effort in defense of his output than would an interloper in its attempted appropriation.

A variant of this model provides a theoretical basis for the first-possession doctrine, which is relevant when no one has a prior claim on an object due to labor already applied. If mere possession of an object confers on the possessor an incumbency advantage in retaining it when ownership is challenged by a contender (a very plausible advantage) then Nature hardwires greater attachment to the object in the possessor than in the contender. Consequently, in a distribution contest to determine ownership the possessor will devote more effort than the contender to securing the object.

We are not the first to adopt an evolutionary approach to understanding property rights.[5] In a first-possession scenario, Maynard Smith (1982) used the Dove-Hawk-Bourgeois game to understand why possessors seem frequently to win contests for ownership 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. Evolutionarily stable strategies are not unique; the anti-Bourgeois strategy "Play Hawk if an interloper and play Dove if an occupant" can also be evolutionarily stable. It then becomes a question of which strategy is adopted *as a convention*; Bourgeois is chosen as an explanation for the role of occupancy in establishing property rights.

Mesterton-Gibbons (1992) has addressed the evolutionary stability of Bourgeois, Anti-bourgeois, Hawk and Dove strategies by characterizing regions in a parameter-space where one or more of them is an ESS. Gintis (2007) also extends the Maynard-Smith model, associating Bourgeois equilibrium with the endowment effect, and seeking to endogenize the levels of effort committed by the incumbent and challenger. To reproduce the Maynard-Smith result we would expect Gintis's Hawk to commit more effort than the Dove, and to rationalize Gintis's references to the endowment effect we would expect the incumbent to commit more effort than the intruder. However, in his model, the agents in fact choose symmetric effort solutions; that is, the incumbent and intruder (and, equally, Hawk and Dove) pick the same efforts. In a later section, he argues that populations that live under the Bourgeois equilibrium will experience a higher average payoff than those that live under the Anti-bourgeois equilibrium, suggesting that Bourgeois populations will come to dominate when resources are scarce. This between-group selection argument complements somewhat Mesterton-Gibbons's within-group selection arguments for the Bourgeois over other strategies.

Our model is complementary to those that follow Maynard-Smith. Rather than pre-specifying particular strategies we allow Nature to evolve preferences that determine actions and outcomes. Asymmetric use of productive labor, or the existence of an incumbency advantage, result in asymmetric preferences for an object, with these asymmetric preferences kicking in depending

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

on whether a person is an interloper or is a producer/occupant.[6] We deduce that the possessor will play more aggressively and the interloper less aggressively in the unique evolutionarily stable outcome; further, our model does not generate an Anti-bourgeois type of equilibrium.

Eaton and Morrison (2003) also have an evolutionary model that speaks obliquely to the issue of property rights. A player can develop an idea that is profitable if and only a second player does not free-ride on it; the original player can retaliate to make any free-riding that occurs unprofitable. There are two weakly-stable equilibria, one in which the first player does not develop the idea, and the second in which he develops the idea but no free-riding occurs because of the threat of retaliation.

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 subsequent subsections we work out the implications of our model; we demonstrate the fundamental asymmetry in the stable preferences between producers and nonproducers, interpreting this as a labor theory of property; then we look at a special case, a noproduction model, for an interpretation of a first possession theory of property; finally we look at some extensions of the production model to evaluate the robustness of the labor theory.

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 a fraction θ of individuals an opportunity to engage in an activity that could enhance their survival.

Fortunate individuals who are offered a productive opportunity have to exert effort K in order to produce fitness-enhancing output. Hunting a hare, for example, requires effort. We refer to engagement in the productive activity as 'production'. Effort, K, produces expected output $q(K)$ according to

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

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

where A is total factor productivity and α is the elasticity of output with respect to effort.

Unlucky individuals who have not received a productive opportunity have two options. They can attempt to extort output from, at most one, producer. Or, if scarcity of producers precludes this possibility, they must fall back on some low fitness activity such as eating roots. We model the challenge of a producer by a non-producer as a distribution contest in which their respective redistribution-effort levels will determine their relative shares of the output. How much productive effort the producers will put into pursuit of their opportunity will depend on their anticipation of the likelihood that they will be subsequently confronted by a non-producer in a distribution contest, and on how aggressive that interloper may be. Throughout the model we refer to the producer as Player 1 and the interloper as Player 2.

Denote by e_1 and e_2 the respective effort levels in the distribution contest. The share[7] that Player 1 retains of his output is s_1 and the share that Player 2 appropriates is s_2. We posit initially that these shares are symmetric in efforts

$$s_1 = \frac{e_1}{e_1 + e_2}; \quad s_2 = \frac{e_2}{e_1 + e_2}.$$

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), Possajennikov (2000), Schaffer (1988, 1989), Eaton and Eswaran (2003), Eswaran and Kot-

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[7]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 might provide a more plausible interpretation in some examples; see for example Gintis (2007). 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.

The share equations of the distribution game presume, of course, that a player's effort can seriously impinge on his share. Depending of the type of resource under consideration, this may not always be the case. The extent to which this can be done will depend not only on the size of the resource but also on whether part of the resource can be cordoned off from the rest and yet be rendered fruitful. An acre of farmland, for example, can be made exclusive property in this manner. On the other hand, the wild fish resources in a thousand cubic meters of sea water cannot be usefully isolated, for the resource here moves across neighbouring masses of water. To be usefully isolated, a vast amount of the sea has to be appropriated but the cost of enforcing ownership will be that much more difficult. In other words, the enforcement mechanism we are positing depends on the kind of resource in question. For this reason, some resources must always remain common and cannot be appropriated by labor in the manner Locke suggests.

wal (2004)]. We presume that a person's fitness function, $f(c, e)$, is given by:

$$f(c, e) = \ln(c) - (e + K), \tag{1}$$

where c denotes consumption and e and K are efforts. We assume that fitness is logarithmic in consumption for analytic convenience; and, because this functional form severely penalizes low levels of consumption, it captures 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:

$$u(c, e; v) = v \ln(c) - (e + K),$$

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

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[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).]

we construe as ownership rights in an evolutionary sense.

At birth, Nature assigns to an individual a preference pair (v_1, v_2) that they take as given, as part of their genetic makeup. Then Nature randomly assigns productive opportunities to a fraction θ of the individuals. As outlined above, in a stage 1, an individual with an opportunity applies an amount of effort K and bring forth output given by (1). In the distributive stage 2, a player who has not had an opportunity seeks to confront (at most) one of the producers in a distribution contest. The probability, ϕ, that a Player 2 will find a Player 1 whose output to contest depends on the fraction of individuals who have been fortunate, so that $\phi = \min[1, \theta/(1-\theta)]$, depending on whether θ is greater or less than $1/2$. Likewise, the probability, μ, that a Player 1 would find himself in a distribution contest is given by $\mu = \min[1, (1-\theta)/\theta]$. In the event that Player 2 is not successful in locating a productive type to challenge, he has no option but to choose a low-fitness activity that gives him some minimal level of consumption, say $\underline{c}$.

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:

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

Proceeding backward to solve the model, we first need to examine the outcome of the stage 2 distribution game, given Player 1's choice of productive effort in stage 1.

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]

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[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 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

We discuss why the assumption of observability is reasonable in Section 3.

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

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

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

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

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.

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

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

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.

The solution functions are symmetric in (v_1, v_2). However, note that asymmetric values of the utility parameters v_i would result in asymmetric efforts and shares in equilibrium. In particular, if v_1 were larger than v_2 then Player 1 would have a larger equilibrium share of the output, $s_1 > s_2$. 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 also 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.

[Herold and Kuzmics (2009)]. In this arena, the theory is still in a state of development.

2.2   Stage 1: Choice of production effort K

We turn now to the stage-1 choice of effort in production. This will allow articulation of a labor-based theory of property rights, providing an evolutionary underpinning for the principle enunciated by Locke. We suppose that the utility parameter v_1 characterizes Player 1's utility in both stage 2 and stage 1, that is, the v_1 that characterizes utility in the second stage distribution contest also characterizes utility in the first stage where Player 1 chooses K.

Contingent on his prior productive effort K, Player 1 will end up in a distribution contest with probability μ, and will earn Nash equilibrium utility

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

With probability $(1 - \mu)$ Player 1 will be unchallenged, earning utility

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

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

$$\max_K U_1 = [v_1 \ln(q(K)) - K] + \mu[v_1 \ln(s_1^*) - e_1^*]$$

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. The solution to this maximization yields a unique optimum for productive effort, $K^*(v_1)$:

$$K^*(v_1) = \alpha\, v_1. \tag{2}$$

As expected, the productive effort of Player 1 depends on the utility parameter v_1. 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. These parameters will evolve in a way that balances distribution and conflict issues in the distribution contest against production issues in the stage-1 choice of K.

2.3 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 (2), into the fitness function (1) gives players' fitness as functions of (v_1, v_2).

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

$$f_1^*(v_1, v_2) = \ln(s_1^*(v_1, v_2) \, q(K^*(v_1))) - e_1^*(v_1, v_2) - K^*(v_1)$$
$$= \ln(q(K^*(v_1))) - K^*(v_1) + g_1(v_1, v_2)$$

where we use the notation

$$g_i(v_1, v_2) := \ln(s_i^*(v_1, v_2)) - e_i^*(v_1, v_2) \qquad \text{for} \quad i = 1, 2.$$

The functions $g_i(v_1, v_2)$ summarize the impact of the distribution contest on players' fitness functions. When Player 1 is not challenged he retains the entire output and devotes no stage-2 effort to thwarting an interloper; his fitness is

$$f_1^{nc} = \ln(q(K^*(v_1))) - K^*(v_1).$$

Recall that μ is the probability that production is contested; then the expected fitness of an individual in the Player 1 role is

$$\overline{f}_1(v_1, v_2) = [\ln(q(K^*(v_1))) - K^*(v_1)] + \mu g_1(v_1, v_2). \tag{3}$$

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

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

$$f_2^*(v_1, v_2) = \ln(q(K^*(v_1))) + g_2(v_1, v_2).$$

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 $\underline{c}$. Recall that ϕ is 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

$$\overline{f}_2(v_1, v_2) = \phi \ln(q(K^*(v_1))) + (1 - \phi) \ln(\underline{c}) + \phi g_2(v_1, v_2). \tag{4}$$

Note that v_2 enters only the distribution/conflict decisions (last term).

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 is relevant. If not he must challenge for a share of a producer's output and if he finds a Player 1 to challenge then v_2 is relevant. If there are not enough Player 1's to allow him a challenge, then 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

$$\max_{v_1} \quad \overline{f}_1(v_1, v_2). \tag{5}$$

That is, 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

$$\max_{v_2} \quad \overline{f}_2(v_1, v_2). \tag{6}$$

Again, v_2 is the best response, $v_2^{br}(v_1)$, to v_1 since it maximizes the expected fitness of individuals

13

in the role of Player 2.

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 $v_2 = v_2^{br}(v_1)$. The pair $(v_1^\dagger, v_2^\dagger)$ constitutes the preferences that Nature would hardwire into humans to allow for their roles as producers and interlopers, respectively. We consider these preferences to be evolutionarily stable in the sense of 'local uninvadability'.[10] No local producer mutant with a parameter different from $v_1^\dagger$ can do better in terms of fitness than other producers in the population; likewise, no local interloper mutant with a parameter different from $v_2^\dagger$ can do better in terms of fitness than other interlopers in the population.

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

Proposition 1 *(i) The best response functions from (5) and (6), $v_1^{br}(v_2)$ 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 locally uninvadable; (iii) the evolutionarily stable preference parameters satisfy the inequalities $v_2^\dagger < v_1^\dagger$; and (iv) $\Pi > 1$.*

Part (*iii*) of the above proposition contains the key result. The asymmetric outcome for the preference parameters, $v_2^\dagger < v_1^\dagger$, indicates that the producer values output more than the nonproducer does. Put slightly differently, an individual values an object that he himself produces at $v_1^\dagger$, while he would value the same object if produced by another at a lesser value $v_2^\dagger$. This suggests the evolutionary hardwiring of a specific conception of property, whereby an individual values what he himself *has produced* more than what another has produced. This asymmetric valuation provides an appropriate underpinning for Locke's labour theory of value.

The evolutionary logic for the asymmetry is as follows. Player 2's expected fitness depends on v_2 only through v_2's impact on the distribution game outcome; the parameter v_1 has a symmetrical importance for Player 1's fitness. These effects are captured by the $g_i(v_1, v_2)$ functions. In addition, however, the parameter v_1 is key to determination of Player 1's production effort and the level of output produced. A symmetric pair of valuations, $v_1 = v_2$, would provide both players with an equal share of output *ex post*. This would provide Player 1 with an insufficient incentive to produce output. Nature contrives an increase in v_1 relative to v_2 so as to provide

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[10]See Definition 3 in Cressman (2009, p. 232). The Maynard Smith concept of an evolutionarily stable strategy (ESS) is defined for a finite strategy space. Generalizing the concept to continuous strategy spaces is complex; see Cressman (2009) and Oechssler and Riedel (2001). We are grateful to an anonymous referee for drawing this point to our attention. Here we take the simplest approach, relying on the notion of local uninvadability.

Player 1 with a larger *ex post* share of output and so a stronger motivation to produce. 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 parameter, α and on the abundance of fitness-enhancing opportunities in the ecological niche, captured by the parameter θ.

Comparative static results can be summarized as:

Proposition 2 *(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 and $v_2^\dagger$ decreasing in α; and (iii) Π is increasing in α.*

When production opportunities are relatively scarce ($\theta \leq 1/2$) both $v_1^\dagger$ and $v_2^\dagger$ are independent of θ: 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: 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, while $v_2^\dagger$ is decreasing: the production function is less constrained by diminishing returns when α 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. Higher α increases the producer's share of the output. This explains parts (*ii*) and (*iii*) of the proposition.

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 promote some extortion.

The problem here can be construed as one of delegation. It is well-known in the literature that in strategic situations a player may benefit by delegating actions through a binding contract to an agent with different preferences and making this information public [see e.g. Fershtman (1985), Vickers (1985)]. Delegation is a way for the principal to commit to behavior with strategic advantages. This is precisely what Nature is doing, albeit through tinkering with the genes.[11]

2.4 First Possession (No Production)

The key to the equilibrium asymmetry in valuation parameters above is the fact that while v_1 has an impact on Player 1's fitness through both production and distribution outcomes ($K^*(v_1)$ and $g_1(v_1, v_2)$ respectively), v_2 only affects Player 2's fitness through distribution ($g_2(v_1, v_2)$). We now look at a simplified model that involves no production, allowing us to comment briefly on the legal doctrine of *first possession*, which holds that first possession of an object confers ownership.[12]

No productive effort K is expended; output is exogenously handed out by Nature to fortunate individuals, who are thereby first possessors. To allow for an incumbency advantage of first possession rewrite the share equations with parameter β (≥ 1):

$$s_1 = \frac{\beta e_1}{\beta e_1 + e_2}; \quad s_2 = \frac{e_2}{\beta e_1 + e_2}.$$

When strictly greater than one the parameter β models an incumbency advantage for Player 1: $s_1 > s_2$ when efforts are equal. It is reasonable to think of an incumbent advantage in this way because the individual possessing the output is generally better positioned to defend it, or hide it, or even simply consume it.

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[11] The more recent literature on delegation [e.g. Katz (2006), and Polo and Tedeschi (2000)] are somewhat less relevant here. In these papers the delegation is such that a principal's contract with an agent is contingent on the contract offered by the rival principal to his agent. Nature, which operates in a mechanical manner in natural selection, cannot design such contingent contracts that require self-conscious deliberation.

[12] See Epstein (1979) and Rose (1985). A landmark case is *Pierson v. Post* (see Section 3 below).

Rewrite the $g_i(\cdot)$ functions as

$$g_i(v_1, v_2, \beta) := \ln(s_i^*(v_1, v_2, \beta)) - e_i^*(v_1, v_2, \beta) \qquad \text{for} \quad i = 1, 2.$$

As before, these functions summarize the impact of the distribution contest on players' fitness.

Adding the specification that output is exogenously given as $\bar{q}$, and $K \equiv 0$, to the expected fitness functions (3) and (4) respectively, the expected fitness of an individual in the Player 1 and Player 2 roles is given by

$$\overline{f}_1(v_1, v_2, \beta) = \ln(\bar{q}) + \mu \, g_1(v_1, v_2, \beta);$$
$$\overline{f}_2(v_1, v_2, \beta) = \phi \ln(\bar{q}) + (1 - \phi) \ln(\underline{c}) + \phi \, g_2(v_1, v_2, \beta).$$

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

$$\max_{v_1} \ \overline{f}_1(v_1, v_2, \beta) \qquad \text{and} \qquad \max_{v_2} \ \overline{f}_2(v_1, v_2, \beta). \tag{7}$$

The following result is immediate:

Proposition 3 *(i) The best response functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$, derived from (7), 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 locally un-invadable; (iii) the evolutionarily stable preference parameters satisfy the inequalities $v_1^\dagger(\beta) > v_2^\dagger(\beta)$ for $\beta > 1$; and (iv) $\Pi > 1$ for $\beta > 1$.*

Part *(iii)* of the proposition contains the key result. The asymmetric outcome, $v_1^\dagger > v_2^\dagger$, occurs if and only if there is a strict incumbency advantage associated with first-possession. In the presence of an incumbency advantage 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—will occur.

The evolutionary logic is as follows. Unlike the production case, the valuation parameters now enter the fitness functions symmetrically through the $g_i(v_1, v_2, \beta)$ functions. The only asymmetry that can occur in the system is $\beta > 1$, which reflects an incumbency advantage to Player

1. In this case, even when $v_1 = v_2$, Player 1 gets 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 $v_1^{\dagger} > v_2^{\dagger}$. When there is no incumbent advantage the equilibrium valuations will coincide. 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.

In this no-production case the equilibrium values for the preference parameters are functions of the single parameter β. Comparative static analysis shows that $v_1^{\dagger}$ is increasing and $v_2^{\dagger}$ is decreasing in β. The greater the incumbent advantage of first possession the stronger will be the first possessor's claim relative to the interloper's.

2.5 Robustness of the Labor Theory Outcome

The valuation parameter results of the production model examined above follow because the same parameter v_1 determines both production and distribution decisions, resulting in $v_1^{\dagger} > v_2^{\dagger}$. We now consider the possibility of Nature breaking the link between production and distribution decisions. One can envisage Player 1's utility valuation differing between the consumption and the production of output, with a utility parameter, v_1, applied to utility in stage 2, as above, but with a potentially different parameter, V_1, applied to utility in stage 1. The presence of this additional preference might act to break the specific link between production and distribution that was key in the labor theory section. Nature selects both V_1 and v_1. In the presence of this production-specific utility parameter Player 1 at stage 1 chooses K to maximize

$$U_1 = V_1 \ln(q(K)) - K + \mu[V_1 \ln(s_1^*(v_1, v_2, \beta)) - e_1^*(v_1, v_2, \beta)]. \tag{8}$$

The solution parallels that of the previous model:

$$K^*(V_1) = \alpha\, V_1.$$

Now productive effort is independent of the values (v_1, v_2), severing the connection between the distribution contest and production effort. It can be shown that natural selection 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, as in the first possession case, v_1 is selected greater than v_2 if and only if there is an incumbent advantage ($\beta > 1$). To summarize:

Proposition 4 *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 $\beta \geq 1$.*

Thus, introduction of the utility parameter V_1 might seem to nullify the labor theory interpretation of property rights. We counter this observation in two ways. First, is the matter of functional form. The separation of production and distribution that the introduction of V_1 allows, 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 parameter V_1. This brings back asymmetry of the v_i's, even when $\beta = 1$.[13]

Second, in the log model there may be alternative channels linking production and distribution that affect the evolution of the preference parameters. It is plausible, for example, that the magnitude of the incumbency advantage in the distribution contest is endogenous to the productive effort applied in stage 1. That is, K may be interpreted partly as productive effort but partly as defensive effort to help secure output from interlopers. If production effort helps to secure output by raising β this will typically affect the equilibrium values of v_1 and v_2.

To consider the possibilities we specify $\beta = 1 + \gamma K$, for $\gamma \geq 0$. The outcome of the distribution contest now will depend on the value of production effort K through the endogenous β. Different scenarios are possible. Suppose Player 1 does not take the strategic effect of K on the distribution-

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[13]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 the evolutionary stable preference parameters (V_1, v_1, v_2) invariably satisfy $V_1^\dagger = 1$, $v_1^\dagger > v_2^\dagger$, and $\Pi > 1$ for $\beta \geq 1$.

contest equilibrium into account when choosing K; maximization of (8) with respect to K again gives the solution $K^* = \alpha V_1$, which is independent of the distribution-game parameters (v_1, v_2).

Whereas 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 involve only the distribution game. These equations are symmetric and yield $v_1^\dagger \geq v_2^\dagger$ if and only if $\beta \geq 1$. However, in equilibrium $\beta = 1 + \gamma K^* > 1$; as a result, $v_1^\dagger > v_2^\dagger$ and $\Pi > 1$.

Proposition 5 *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, then $\beta = 1 + \gamma K^* > 1$, and the evolutionary stable equilibrium values of the preference parameters, $(V^\dagger, v_1^\dagger, v_2^\dagger)$, exhibit $V_1^\dagger > 1$, $v_1^\dagger > v_2^\dagger$, and $\Pi > 1$.*

In summary, by making β endogenous to the choice of K, or by using a non-log functional form where equilibrium distribution-game efforts depends naturally on K, we can see that the labour theory result holds robustly in the event of an additional utility parameter V_1, even when there is no exogenous incumbent advantage.

3   Discussion

Our analytical results provide the essential basis of our claim that humans are programmed by Nature to exercise property rights when they either have bestowed labor on an object or have first possession of it. The incumbency advantage conferred by possession or the incentive requirements of effort in production 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 expends more effort in defending claims than

do interlopers in making them, though they may desire the object. Property rights, as instilled by Nature, bind the rest of the world to this extent. This answers Nozick's (1974) and Epstein's (1979) objection to Locke's labor theory of property.

We contend that the law formalizes the innate sense of ownership by granting property rights both to first possession and to the product of one's labor. For example, in *Pierson v. Post*, a landmark case in legal history, the law conferred ownership of a fox on Post based on the doctrine of first possession. In a later case, *Swift v. Gifford*, the courts granted ownership of a wounded whale to the whaler that had first harpooned it, arguing that the harpoon had brought the mammal within the grasp of the whaler; in our interpretation, the whaler's labor in harpooning the whale conferred ownership. In an evolutionary setting first possession and production through labor have created a stronger sense of property rights in the possessor/producer than in an interloper. The court's ruling in these landmark cases was consistent with the implications of this 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 producer of an object, the law serves justice *and* also efficiency. Our theory provides a theoretical underpinning for 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 explains how property rights get assigned, and it 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.

The asymmetric valuation of the consumption good by the possessor/producer and the interloper derived in the previous section is reminiscent of the "endowment effect" that is well documented in the psychology literature [Kahneman et al (1980)] and referred to 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. We can 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 the object.

Our theory finds confirmation in recent experimental findings. In dictator games where unearned sums of money are 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 the endowment is determined by the recipient, who is rewarded according to performance in a skill-testing exercise or, as a benchmark, rewarded randomly through a coin toss. Ruffle found that dictators rewarded recipients who did well (resp. badly) in the skill-test relatively better than (resp. worse than) recipients who received the same amount 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 allocated by them. Here 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 value it more highly than if it is unearned. Further, Oxoby and Spraggon (2008) recently found that, while legitimizing 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 recog-

nize the property rights of others over what they (others) have earned. This is consistent with our theoretical result that natural selection has evolved preferences in a way that binds humans into respecting the property rights of others.

Finally, the labor theory model predicts behavior that may appear to be governed by the sunk cost fallacy. Nature has found reason to cause an individual who has bestowed labor on an object to therefore 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)].

An objection to our analysis is the assumption of observability of type in the distribution game. We assume that each player's facial expression and body language in a confrontation reveals the value that they place on the object of contention. We justify observability by appealing to an argument of Darwin, and to recent work on the psychology of deception. In his *Expression of Emotions in Man and Animals*, Darwin argued that facial expressions cannot be manipulated at will and so betray true information about emotions. Humans betray their feelings because of what is dubbed "emotional leakage".[14] Recent literature in psychology confirms Darwin's view. 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; he further shows 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. In an experimental setting, Porter

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[14]"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)].

and Brinke (2008) recently found that participants asked to conceal or fake emotions invariably exhibited expressions that were inconsistent with the emotion.[15] This was particularly true of the negative emotions. A case can be made that Nature may not have eliminated observability of valuation as revealed through facial expression and body language in a confrontation. Finally, Tullock (1972) has argued that the irrational loss of temper may be a means through which property rights can be protected. If two men of unequal strength are bargaining, there are limits to the stronger man's predation because loss of temper by the weaker may inflict a high cost on the former. The greater effort that Player 1 would apply relative to the interloper in the distribution game is precisely the formal analogue of anger.

4 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 subject to natural selection evolutionarily stable valuations are generated in which the producer/possessor values the object more highly than does an interloper. This model provides an evolutionary basis for both the doctrine of first possession and Locke's labour theory of property rights, which are crucial ingredients of the philosophical and legal approaches to property rights. We have also seen that the model has implications for a number of

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[15]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)].

topics in the property rights and experimental literatures.

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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

$$s_1^* = \frac{\sqrt{\beta}v_1}{\sqrt{\beta}v_1 + \sqrt{v_2}}; \qquad s_2^* = 1 - s_1^*. \tag{A-2}$$

Note that s_1^* is increasing in β and v_1 and decreasing in v_2; and conversely for s_2^*.

For $\beta \geq 1$ 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 the results of the paper. The derivatives $\partial g^i/\partial v_i$ have the sign of $1 - v_i - e_i^*$ for $i = 1, 2$. We will see that in equilibrium $v_i < 1$ for $i = 1, 2$. The second order derivatives $\partial^2 g^i/\partial v_i^2$ are negative for $v_i \leq 5/3$ so each of the functions is strictly concave in the "own" variable in equilibrium. The cross-partial derivatives $\partial^2 g^i/\partial v_i \partial v_j$ have the sign of $1 - v_i - 2e_i^*$, which is negative in equilibrium, for $i = 1, 2$. The determinant of the second-order cross partial matrix, $(\partial^2 g^1/\partial v_1^2)(\partial^2 g^2/\partial v_2^2) - (\partial^2 g^1/\partial v_1 \partial v_2)(\partial^2 g^2/\partial v_2 \partial v_1)$, is positive for $v_i < 1$.

Proof of Proposition 1

The expected fitness functions are in equations (3) and (4). $\bar{f}^1$ is strictly concave in v_1 if $v_1 \leq 5/3$; $\bar{f}^2$ is strictly concave in v_2 if $v_2 \leq 5/3$. The first-order conditions for maximization of $\bar{f}^1$ and

$\bar{f}^2$ are respectively:

$$\bar{f}_{v_1}^1 = \alpha\left(\frac{1}{v_1} - 1\right) + \mu\frac{\partial g^1}{\partial v_1} = 0 \qquad \text{and} \qquad \bar{f}_{v_2}^2 = \phi\frac{\partial g^2}{\partial v_2} = 0. \tag{A-4}$$

The second condition implies that $(1 - v_2^\dagger - e_2^*) = 0$ in equilibrium and hence that $v_2^\dagger$ is less than 1 in the solution. The first condition evaluated at $v_1 = 1$ implies $\bar{f}_1^1 = \mu(\partial g^1/\partial v_1) < 0$. Given strict concavity of $\bar{f}^1$ in v_1 for $v_1 \leq 5/3$, this implies that $v_1^\dagger$ must be less than 1 in the solution.

Since $v_i^\dagger < 1$ in the solution, the fitness functions are strictly concave wherever the first-order conditions hold; the best response functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$ defined in the text are locally unique and the Nash equilibrium $(v_1^\dagger, v_2^\dagger)$ is unique. Since the concept of local uninvadability merely requires $(v_1^\dagger, v_2^\dagger)$ to be a neighborhood strict Nash equilibrium [see Cressman (2009)], it follows that $(v_1^\dagger, v_2^\dagger)$ is locally uninvadable.

Equilibrium $v_1^\dagger < 1$ implies $\alpha\left(\frac{1}{v_1^\dagger} - 1\right) > 0$ and hence $\partial g^1/\partial v_1 < 0$, so that the first order conditions imply respectively

$$1 - v_1^\dagger - e_1^* < 0 \qquad \text{and} \qquad 1 - v_2^\dagger - e_2^* = 0. \tag{A-5}$$

Suppose now that $v_2^\dagger \geq v_1^\dagger$ in the solution. The inequalities in (A-5) can be combined with (e_1^*, e_2^*):

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

the last inequality because $v_2^\dagger \geq v_1^\dagger$ by supposition. However the inequality

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

implies that $v_1^\dagger > v_2^\dagger$ and thus contradicts the original supposition. Hence it must be that $v_1^\dagger > v_2^\dagger$ in the solution. Since $s_1^* > s_2^*$, it follows that $\Pi > 1$ for all θ.

The cross-partial derivatives $\bar{f}_{12}^1$ and $\bar{f}_{21}^2$ have the sign of $1 - v_1 - 2e_1^*$ and $1 - v_2 - 2e_1^*$ respectively. In equilibrium $1 - v_i^\dagger - e_i^* \leq 0$ implies $1 - v_i^\dagger - 2e_i^* < 0$. It follows that the best-response

2

functions $v_1^{br}(v_2)$ and $v_2^{br}(v_1)$ defined in the text are downward-sloping.

Proof of Proposition 2

In (A-4) the first-order condition for v_2 is multiplicative in $\phi = \theta/(1-\theta)$ and so $v_2^\dagger$ does not depend directly on θ; $\mu = 1$ 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 $\mu = (1-\theta)/\theta < 1$. Standard comparative static analysis on (A-4) shows that $v_1^\dagger$ is increasing in θ (decreasing in μ) and is increasing in α; $v_2^\dagger$ is decreasing in both θ and α.

Finally, since s_1^* is increasing in v_1 and decreasing in v_2, and conversely for s_2^*, it follows that Π is increasing in both α and $\theta > 1/2$.

Proof of Proposition 3

The proof closely follows that of Proposition 1. The first-order conditions for the game in (7) are

$$\bar{f}_1^1 = \mu\frac{\partial g^1}{\partial v_1} = 0 \qquad \text{and} \qquad \bar{f}_2^2 = \phi\frac{\partial g^2}{\partial v_2} = 0. \tag{A-6}$$

These conditions require that in equilibrium

$$(1 - v_1^\dagger - e_1^*) = 0 = (1 - v_2^\dagger - e_2^*). \tag{A-7}$$

and so $v_i^\dagger < 1$ for $i = 1, 2$. In turn this ensures that the fitness functions are strictly concave where the first-order conditions hold; the Nash equilibrium $(v_1^\dagger, v_2^\dagger)$ is unique and locally uninvadable. As in Proposition 1 the best-response functions are downward sloping.

The above equalities can be rewritten as

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

Suppose now that $v_2^\dagger > v_1^\dagger$ in the solution. This combined with $\beta \geq 1$ implies $\sqrt{v_1^\dagger}/(\sqrt{\beta}\sqrt{v_2^\dagger}) < 1$ which implies $(1 - v_1^\dagger)/(1 - v_2^\dagger) < 1$ which implies $v_1^\dagger > v_2^\dagger$, a contradiction. Hence it must be

3

that $v_1^\dagger \geq v_2^\dagger$ in the solution. Specifically, $v_1^\dagger = v_2^\dagger$ if and only if $\beta = 1$; $v_1^\dagger > v_2^\dagger$ if and only if $\beta > 1$. Since $s_1^* > s_2^*$, it follows that $\Pi > 1$ for all θ.

The solution values depend only on β. Comparative static analysis of (A-6) shows that $v_1^\dagger$ is increasing and $v_2^\dagger$ is decreasing in β. The greater the incumbency advantage is the stronger will be the relative sense of ownership.

Proof of Proposition 4

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

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

The first-order maximization conditions with respect to V_1 and (v_1, v_2) are

$$\bar{f}_{V_1}^1 = \alpha\left(\frac{1}{V_1} - 1\right) = 0; \qquad \bar{f}_{v_1}^1 = \mu\frac{\partial g^1}{\partial v_1} = 0; \qquad \bar{f}_{v_2}^2 = \phi\frac{\partial g^2}{\partial v_2} = 0.$$

The first condition is solved by $V_1^\dagger = 1$ independently of anything else in the model. The second and third conditions, which are independent of V_1, determine $(v_1^\dagger, v_2^\dagger)$ entirely within the distribution game. These conditions are exactly those of the previous proposition and yield the same outcomes.

Proof of Proposition 5

When Player 1 behaves non-strategically with respect to choice of K he takes $\partial\beta/\partial K = 0$ and the solution is $K^* = \alpha V_1$. Substituting into the expected fitness functions gives

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

The first-order maximization conditions with respect to V_1 and (v_1, v_2) are

$$\bar{f}^1_{V_1} = \alpha\left(\frac{1}{V_1} - 1\right) + \mu\gamma\alpha\frac{\partial g^1}{\partial \beta} = 0; \qquad \bar{f}^1_{v_1} = \mu\frac{\partial g^1}{\partial v_1} = 0; \qquad \bar{f}^2_{v_2} = \phi\frac{\partial g^2}{\partial v_2} = 0.$$

Because $\partial g^1/\partial \beta > 0$ it follows that the solution value of V_1 must satisfy $V_1^\dagger > 1$. The second and third conditions determine $(v_1^\dagger, v_2^\dagger)$ entirely within the distribution game and independently of V_1. These conditions are exactly those of the previous two propositions and yield the same outcomes. Since the equilibrium value of β is endogenous, with $\beta = 1 + \gamma\alpha V_1 > 1$, it follows that $v_1^\dagger > v_2^\dagger$ in equilibrium. Finally, it follows from familiar reasoning that $\Pi > 1$.