The Evolution of Private Property

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August 13, 2006

Abstract

Experimental studies have shown that subjects exhibit a systematic endowment effect. No acceptable explanation for the existence of this behavior has been offered. This paper shows that the endowment effect can be modeled as respect for private property in the absence of legal institutions ensuring third-party contract enforcement. In this sense, "natural" private property has been observed in many species, in the form of recognition of territorial incumbency. We develop a model loosely based on the Hawk-Dove-Bourgeois game (Maynard Smith & Parker 1976) and the War of Attrition (Maynard Smith & Price 1973) to explain the natural evolution of private property.
Journal of Economic Literature Classification:
   D01—Microeconomic Behavior: Underlying Principles

Keywords: Private Property, Endowment Effect, Evolution

1 Introduction

The *endowment effect* is the notion that people value a good that they possess more highly than the same good when they do not possess it. Experimental studies (see Section 2) have shown that subjects exhibit a systematic endowment effect. The endowment effect can be modeled by amending the standard rational actor model to include an agent's current holdings as a parameter. The endowment effect gives rise to *loss aversion*, according to which agents are more sensitive to losses than to gains. The leading analytical model of loss aversion is *prospect theory* (Kahneman & Tversky 1979). This paper, for the first time, suggests a plausible argument for the existence and importance of the endowment effect and loss aversion.

Carmichael & MacLeod (1999) and Huck et al. (2005) have attempted to explain the endowment effect by showing that agents subject to the endowment effect do better in bargaining than those who have no special attachment to their current holdings. However, the endowment effect appears even when there is no scope for bargaining. Indeed, the effect may disappear in market-like settings (Zeiler & Plott 2004). This paper shows that the endowment effect can be modeled as respect for private property *in the absence of* legal institutions ensuring third-party contract enforcement. In this sense, preinstitutional "natural" private property has been observed in many species, in the form of the recognition of territorial possession. We develop a model loosely based on the Hawk, Dove, Bourgeois game (Maynard Smith & Parker 1976) and the War of Attrition (Maynard Smith & Price 1973) to explain the natural evolution of private property.[1]

We show that if agents in a group exhibit the endowment effect for an indivisible resource, then property rights in that resource can be established on the basis of incumbency, assuming incumbents and those who contest for incumbency are of equal perceived fighting ability.[2] The enforcement of these rights will then be carried out by the agents themselves, so no third-party enforcement is needed. This is because the endowment effect leads the incumbent to be willing to expend more resources to protect his incumbency than an intruder will be willing to expend to expropriate the incumbent. For simplicity, we consider only the case where the marginal benefit of more than one unit of the resource is zero (e.g., a homestead, a spider's web, or a bird's nest).

The model assumes the agents know the present value π_g of incumbency, as well

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[1]Jones (2001) and Stake (2004) have developed analyses of the evolution of private property stressing similar themes.

[2]The assumption of indivisibility is not very restrictive. In some cases it is naturally satisfied, as in a nest, web, dam, or mate who provides for offspring. In others, such as a hunter's kill, a fruit tree, a stretch of beach for an avian scavenger, it is simply the minimum size worth fighting over rather than dividing and sharing.

as the present value π_b of non-incumbency, measured in units of biological fitness. We assume utility and fitness coincide, except for one situation, described below: this situation explicitly involves *loss aversion*, where the disutility of loss exceeds the fitness cost of loss. When an incumbent faces an intruder, the intruder determines the expected value of attempting to seize the resource, and the incumbent determines the expected value of contesting versus ceding incumbency when challenged. These conditions will not be the same, and in plausible cases there is a range of values of π_g/π_b for which the intruder decides not to fight, and the incumbent decides to fight if challenged. We call this a (natural) *private property equilibrium*. In a private property equilibrium, since the potential contestants are of equal power, it must be the case that individuals are *loss averse*, the incumbent being willing to expend more resources to hold the resource than the intruder is to seize it.

Of course, π_g and π_b will generally be endogenous in a fully specified model. Their values will depend on the supply of the resource relative to the number of agents, the intrinsic value of the resource, the ease in finding an unowned unit of the resource, and the like.

Our model of decentralized private property is like the "Bourgeois" equilibrium in the Hawk, Dove, Bourgeois game, in that agents contest for a unit of an indivisible resource, contests may be very costly, and in equilibrium, incumbency determines who holds the resource without costly contests. Our model, however, fills in critical gaps in the Hawk, Dove, Bourgeois game. The central ambiguity of the Hawk, Dove, Bourgeois game is that it treats the cost of contesting as exogenously given and taking on exactly two values, high for Hawk and low for Dove. Clearly, however, these costs are in large part under the control of the agents themselves and should not be considered exogenous. In our model, the level of resources devoted to a contest is endogenously determined, and the contest itself is modeled explicitly as a modified War of Attrition, the probability of winning being a function of the level of resources committed to combat. One critical feature of the War of Attrition is that the initial commitment of a level of resources to a contest must be *behaviorally ensured by the agent*, so that the agent will continue to contest even when the costs of doing so exceed the fitness benefits. Without this pre-commitment, the incumbent's threat of "fighting to the death" would not be credible (i.e., the chosen best response of the agent would not be subgame perfect). From a behavioral point of view, this precommitment can be summarized as the incumbent have a degree of *loss aversion* leading his utility to differ from his fitness.

Our fuller specification of the behavioral underpinnings of the Hawk, Dove, Bourgeois game allows us to determine the conditions under which a property equilibrium will exist while its corresponding anti-property equilibrium (in which a new arrival rather than the first entrant always assumes incumbency) does not exist. This aspect of our model is of some importance because the inability of the

Hawk, Dove, Bourgeois game to favor private property over anti-private property is a serious and rarely addressed weakness of the model (but see Mesterton-Gibbons 1992).

2   The Endowment Effect and Territoriality

The endowment effect, according to which a good is more highly prized by an agent who is in possession of the good than one who is not, was first documented by the psychologist Daniel Kahneman and his coworkers (Tversky and Kahneman 1991; Kahneman et al. 1991; Thaler 1992).   Thaler describes a typical experimental verification of the phenomenon as follows. Seventy-seven students at Simon Fraser University were randomly assigned to one of three conditions, Seller, Buyer, or Chooser. Sellers were given a mug with the University logo (selling for $6.00 at local stores) and asked whether they would be willing to sell at a series of prices ranging from $0.25 to $9.25. Buyers were asked whether they would be willing to purchase a mug at the same series of prices. Choosers were asked to choose for each price between receiving a mug or that amount of money. The students were informed that a fraction of their choices, randomly chosen by the experimenter, would be carried out, thus giving the students a material incentive to reveal their true preferences. The average Buyer price was $2.87, while the average Seller price was $7.12. Choosers behaved like Buyers, being on average indifferent between the mug and $3.12. The conclusion is that owners of the mug valued the object more than twice as highly as nonowners.

The aspect of the endowment effect that promotes natural private property is known as *loss aversion*: the disutility of giving up something one owns is greater than the utility associated with acquiring it. Indeed, losses are commonly valued at about twice that of gains, so that to induce an individual to accept a lottery that costs $10 when one loses, it must offer a $20 payoff when one wins (Camerer 2003). Assuming that an agent's willingness to combat over possession of an object is increasing in the subjective value of the object, owners will be prepared to fight harder to *retain* possession than non-owners are to *gain* possession. Hence there will be a bias in favor of recognizing private property by virtue of incumbency, even where third-party enforcement institutions are absent.

We say an agent *owns* (is incumbent) something if the agent has exclusive access to it and the benefits that flow from this privileged access. We say ownership (incumbency) is *respected* if it is rarely contested and, when contested, generally results in ownership remaining with the incumbent. The dominant view in Western thought, from Hobbes, Locke, Rousseau, and Marx to the present, is that private property is a human social construction that emerged with the rise of modern civ-

ilization (Schlatter 1973). However, evidence from studies of animal behavior, gathered mostly in the past quarter century, has shown this view to be incorrect. Various territorial claims are recognized in non-human species, including butterflies (Davies 1978), spiders (Riechert 1978), wild horses (Stevens 1988), finches (Senar et al. 1989), wasps (Eason et al. 1985), nonhuman primates (Ellis 1985), lizards (Rand 1967), and many others (Mesterton-Gibbons & Adams 2003). There are, of course, some obvious forms of incumbent advantage that partially explain this phenomenon: the incumbent's investment in the territory may be idiosyncratically more valuable to the incumbent than to a contestant or the incumbent's familiarity with the territory may enhance its ability to fight. However, in the above-cited cases, these forms of incumbent advantage are unlikely to be important. Thus, a more general explanation of territoriality is needed.

In non-human species, that an animal owns a territory is generally established by the fact that the animal has occupied and altered the territory (e.g., by constructing a nest, burrow, hive, dam, or web, or by marking its limits with urine or feces). In humans there are other criteria of ownership, but physical possession and first to occupy remain of great importance. According to John Locke, for example,

> …every man has a property in his own person…The labour of his body, and the work of his hands, we may say, are properly his. Whatsoever then he removes out of the state that nature hath provided, and left it in, he hath mixed his labour with, and joined to it something that is his own, and thereby makes it his property.

> *Second Treatise on Government, §27 (1690)*

Since private property in human society is generally protected by law and enforced by complex institutions (judiciary and police), it is natural to view private property in animals as a categorically distinct phenomenon. In fact, however, decentralized, self-enforcing types of private property, based on behavioral propensities akin to those found in non-human species (e.g., the endowment effect), are important for humans and arguably lay the basis for more institutional forms of property rights. For instance, many developmental studies indicate that toddlers and small children use behavioral rules similar to those of animals is recognizing and defending property rights (Furby 1980).

How respect for ownership has evolved and how it is maintained in an evolutionary context is a challenging puzzle. Why do loss aversion and the endowment effect exist? Why do humans fail to conform to the smoothly differentiable utility function assumed in most versions of the rational actor model? The question is equally challenging for non-humans, although we are so used to the phenomenon that we rarely give it a second thought.

Consider, for instance, the sparrows that built a nest in a vine in my garden. The location is choice, and the couple spent days preparing the structure. The nest is quite as valuable to another sparrow couple. Why does another couple not try to evict the first? If they are equally strong, and both value the territory equally, each has a 50% chance of winning the territorial battle. Why bother investing if one can simply steal (Hirshleifer 1988)? Of course, if stealing were profitable, then there would be no nest building, and hence no sparrows, but that heightens rather than resolves the puzzle.

One common argument, borrowed from Trivers (1972), is that the original couple has more to lose since it has put a good deal of effort already in the improvement of the property. This, however, is a logical error that has come to be known as the *Concorde* or the *sunk cost* fallacy (Dawkins & Brockmann 1980, Arkes & Ayton 1999): to maximize future returns, an agent ought consider only the future payoffs of an entity, not how much the agent has expended on the entity in the past.

The Hawk, Dove, Bourgeois was offered by Maynard Smith & Parker (1976) as a logically sound alternative to the sunk cost argument. In this game Hawks and Doves are phenotypically indistinguishable members of the same species, but they act differently in contesting over ownership rights to a territory. When two Doves contest, they posture for a bit, and then each assumes the territory with equal probability. When a Dove and a Hawk contest, however, the Hawk takes the whole territory. Finally, when two Hawks contest, a terrible battle ensues, and the value of the territory is less than the cost of fighting for the contestants. Maynard Smith showed that, assuming that there is an unambiguous way to determine who first found the territory, there is an evolutionarily stable strategy in which all agents behave like Hawks when they are *first* to find the territory, and like Doves otherwise.

The Hawk, Dove, Bourgeois game is an elegant contribution to explaining the endowment effect, but the cost of contesting for Hawks and the cost of display for Doves cannot plausibly be taken as fixed and exogenously determined. Indeed, it is clear that Doves contest in the same manner as Hawks, except that they devote fewer resources to combat. Similarly, the value of the ownership is taken as exogenous, when in fact it depends on the frequency with which ownership is contested, as well as other factors. As Grafen (1987) stresses, the costs and benefits of possession depend on the state of the population, the density of high-quality territories, the cost of search, and other variables that might well depend on the distribution of strategies in the population.

First, however, it is instructive to consider the evidence for a close association, as Locke suggested in his theory of property rights, between ownership and incumbency (physical contiguity and control) in children and non-human animals.

3 Property Rights in Young Children

Long before they become acquainted with money, markets, bargaining and trade, children exhibit possessive behavior and recognize the property rights of others on the basis of incumbency.[3] In one study (Bakeman & Brownlee 1982), participant observers studied a group of 11 toddlers (12 to 24 months old) and a group of 13 preschoolers (40 to 48 months old) at a day care center. The observers found that each group was organized into a fairly consistent linear dominance hierarchy. They then cataloged *possession episodes*, defined as a situation in which a *holder* touched or held an object and a *taker* touched the object and attempted to remove it from the holder's possession. Possession episodes averaged 11.7 per hour in the toddler group, and 5.4 per hour in the preschool group.

For each possession episode, the observers noted (a) whether the taker had been playing with the object within the previous sixty seconds (prior possession), (b) whether the holder resisted the take attempt (resistance), and (c) whether the take was successful (success). They found that success was strongly and about equally associated with both dominance and prior possession. They also found that resistance was associated mainly with dominance in the toddlers, and with prior possession in the preschoolers. They suggest that toddlers recognize possession as a basis for asserting control rights, but do not respect the same rights in others. The preschoolers, more than twice the age of the toddlers, use physical proximity both to justify their own claims and to respect the claims of others. This study was replicated and extended by Weigel (1984).

4 Respect for Possession in Non-Human Animals

In a famous paper, Maynard Smith and Parker noted that two animals are competing for some resource (e.g., a territory), and if there is some discernible asymmetry (e.g., between an "owner" and a later animal), then it is evolutionarily stable for the asymmetry to settle the contest conventionally, without fighting. Among the many animal behaviorists who put this theory to the test, perhaps none is more elegant and unambiguous than Davies, who studied the speckled wood (*Pararge aegeria*), a butterfly found in the Wytham Woods, near Oxford, England. Territories for this butterfly are shafts of sunlight breaking through the tree canopy. Males occupying these spots enjoyed heightened mating success, and on average only 60% of males occupied the sunlit spots at any one time. A vacant spot was generally occupied within seconds, but an intruder on an already occupied spot was invariably driven away, even if the incumbent had occupied the spot only for a few seconds. When

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[3]See Ellis (1985) for a review and an extensive bibliography of research in this area.

Davies "tricked" two butterflies into thinking each had occupied the sunny patch first, the contest between the two lasted, on average, ten times as long as the brief flurry that occurs when an incumbent chases off an intruder.

Stevens found a similar pattern of behavior for the feral horses occupying the sandy islands of the Rachel Carson Estuarine Sanctuary near Beaufort, North Carolina. In this case, it is fresh water that is scarce. After heavy rains, fresh water accumulates in many small pools in low-lying wooded areas, and bands of horses frequently stop to drink. Stevens found that there were frequent encounters between bands of horses competing for water at these temporary pools. If a band approached a water hole occupied by another band, a conflict ensued. During 76 hours of observation, Stevens observed 233 contests, of which the resident band won 178 (80%). In nearly all cases of usurpation, the intruding band was larger than the resident band. These examples, and many others like them, support the presence of an endowment effect and suggest that incumbents are willing to fight harder to maintain their position than intruders are to usurp the owner.

Examples from non-human primates exhibit behavioral patterns in the respect for property rights much closer to that of humans. In general, the taking of an object held by another individual is a rare event in primate societies (Torii 1974). A reasonable test of the respect for property in primates with a strong dominance hierarchy is the likelihood of a dominant individual refraining from taking an attractive object from a lower-ranking individual. In a study of hamadryas baboons (*Papio hamadryas*), for instance, Sigg & Falett (1985) hand a food-can to a subordinate who was allowed to manipulate and eat from it for five minutes before a dominant individual who had been watching from an adjacent cage was allowed to enter the subordinate's cage. A "takeover" was defined as the rival taking possession of the can before thirty minutes had elapsed. They found that (a) males never took the food-can from other males; (b) dominant males took the can from subordinate females 2/3 of the time; and (c) dominant females took the can from subordinate females 1/2 of the time. With females, closer inspection showed that when the difference in rank was one or two, females showed respect for the property of other females, but when the rank difference was three or greater, takeovers tended to occur.

Kummer & Cords (1991) studied the role of proximity in respect for property in long-tailed macaques (*Macaca fascicularis*). As in the Sigg and Falett study, they assigned ownership to a subordinate and recorded the behavior of a dominant individual. The valuable object in all cases was a plastic tube stuffed with raisins. In one experiment, the tube was fixed to an object in half the trials and completely mobile in the other half. They found that with the fixed object, the dominant rival took possession in all cases and very quickly (median one minute), whereas in the mobile condition, the dominant took possession in only 10% of cases, and then only

after a median delay of 18 minutes. The experiment took place in an enclosed area, so the relative success of the incumbent was not likely due to the ability to flee or hide. In a second experiment, the object was either mobile or attached to a fixed object by a stout two meter or four meter rope. The results were similar. A third case, in which the non-mobile object was attached to a long dragline that permitted free movement by the owner, produced the following results. Pairs of subjects were studied under two conditions, one where the rope attached to the dragline was 2 meters in length, and a second where the rope was 4 meters in length. In 23 of 40 trials, the subordinate maintained ownership with both rope lengths, and in 6 trials the dominant rival took possession with both rope lengths. In the remaining 11 trials, the rival respected the subordinate's property in the short rope case, but took possession in the long rope case. The experimenters observed that when a dominant attempts to usurp a subordinate when other group members are around, the subordinate will scream, drawing the attention of third parties, who frequently force the dominant individual to desist.

In *Wild Minds* (2000), Marc Hauser relates an experiment run by Kummer and his colleagues concerning mate property, using four hamadryas baboons, Joe, Betty, Sam, and Sue. Sam was let into Betty's cage, while Joe looked on from an adjacent cage. Sam immediately began following Betty around and grooming her. When Joe was allowed entrance to the cage, Joe kept his distance, leaving Sam uncontested. The same experiment was repeated with Joe allowed into Sue's cage. Joe behaved as Sam had in the previous experiment, and when Sam was let into the cage, he failed to challenge Joe's proprietary rights with respect to Sue.

No primate experiment, to my knowledge, has attempted to determine the probability that an incumbent will be contested for ownership by a rival who is, or could easily become, closely proximate to the desired object. This probability is likely very low in most natural settings, so the contests described in the papers cited in this section are probably rather rare in practice. At any rate, in the model of respect for property developed in the next section, we will make informational assumptions that render the probability of contestation equal to zero in equilibrium.

5   Conditions for Private Property Equilibrium

Suppose that two agents, prior to fighting over possession, simultaneously pre-commit to expending a certain level of resources to the contest. As in the War of Attrition (Bishop & Cannings 1975), a higher level of resource commitment entails a higher fitness cost, but increases the probability of winning the contest. We assume throughout this paper that the two contestants, an incumbent and an intruder, are *ex ante* equally capable contestants in that the costs and benefits of battle are symmetric

in the resource commitments s_o and s_u of the incumbent and intruder, respectively and $s_o, s_u \in [0, 1]$. To satisfy this requirement, we let $p_u = s_u^n/(s_u^n + s_o^n)$ be the probability that the intruder wins, where $n > 1$. Note that larger n implies resource commitments are more decisive in determining victory. We assume that combat leads to injury $\beta \in (0, 1]$ to the losing party with probability $p_d = (s_o + s_u)/2$, so $s = \beta p_d$ is the expected cost of combat for both parties.[4]

This paper uses a territorial analogy throughout, some agents being incumbents and others being migrants in search of either empty territories or occupied territories that they may be able to occupy by displacing current incumbents. Let π_g be the present value of being a currently uncontested incumbent, and let π_b be the present value of being a migrant searching for a territory. We assume throughout that $\pi_g > \pi_b > 0$. Suppose a migrant comes upon an occupied territory. Should the migrant contest, the condition under which it pays an incumbent to fight back is then given by

$$
\begin{aligned}
\pi_c \equiv\ & p_d(1 - p_u)\pi_g + p_d p_u(1 - \beta)(1 - c)\pi_b + \\
& (1 - p_d)(1 - p_u)\pi_g + (1 - p_d)p_u\pi_b(1 - c) > \pi_b(1 - c).
\end{aligned}
$$

The first term in π_c is the product of the probabilities that the intruder loses $(1 - p_u)$ and sustains an injury (p_d), times the value π_g of incumbency, which the incumbent then retains. The second term is the product of the probabilities that the incumbent loses (p_u), sustains an injury (p_d), survives the injury $(1 - \beta)$, and survives the passage to migrant status $(1 - c)$, times the present value π_b of being a migrant. The third and fourth terms are the parallel calculations when no injury is sustained. This inequality simplifies to

$$
\frac{\pi_g}{\pi_b(1 - c)} - 1 > \frac{s_u^n}{s_o^n}s. \tag{1}
$$

The condition for a migrant refusing to contest for the territory, assuming the incumbent will contest if the migrant does, is

$$
\begin{aligned}
\pi_u \equiv\ & p_d(p_u\pi_g + (1 - p_u)(1 - \beta)(1 - c)\pi_b) + \hspace{3em} (2) \\
& (1 - p_d)(p_u\pi_g + (1 - p_u)\pi_b(1 - c)) < \pi_b(1 - c). \hspace{1.5em} (3)
\end{aligned}
$$

This inequality reduces to

$$
\frac{s_o^n}{s_u^n}s > \frac{\pi_g}{\pi_b(1 - c)} - 1. \tag{4}
$$

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[4] Section 9 supplies a list of variables used in this paper.

A private property equilibrium occurs when both inequalities obtain

$$\frac{s_o^n}{s_u^n}s > \frac{\pi_g}{\pi_b(1-c)} - 1 > \frac{s_u^n}{s_o^n}s. \tag{5}$$

An incumbent who is challenged will choose s_o to maximize π_c, and then contest if and only if the resulting $\pi_c^* > \pi_b(1-c)$, since the latter is the value of simply leaving the territory. It is easy to check that $\partial\pi_c/\partial s_o$ has the same sign as

$$\frac{\pi_g}{\pi_b(1-c)} - \left(\frac{s_o\beta}{2n(1-p_u)} + 1 - s\right).$$

The derivative of this expression with respect to s_o has the same sign as $(n-1)\beta\pi_b/(1-p_u)$, which is positive. Moreover, when $s_o = 0$, $\partial\pi_c/\partial s_o$ has the same sign as

$$\frac{\pi_g}{\pi_b(1-c)} - 1 + \frac{s_u\beta(1-c)}{2},$$

which is positive. Therefore, $\partial\pi_c/\partial s_o$ is always strictly positive, so $s_o = 1$ maximizes π_c.

In deciding whether or not to contest, the migrant chooses s_u to maximize π_u, and then contests if this expression exceeds $\pi_b(1-c)$. But $\partial\pi_u/\partial s_u$ has the same sign as

$$\frac{\pi_g}{\pi_b(1-c)} - \left(s - 1 + \frac{s_u\beta}{2np_u}\right),$$

which is increasing in s_u and is positive when $s_u = 0$, so the optimal $s_u = 1$. The condition for not contesting the incumbent is then

$$\frac{\pi_g}{\pi_b(1-c)} - 1 < \beta. \tag{6}$$

In this case, the condition (4) for the incumbent contesting is the same as (6) with the inequality sign reversed.

By an *anti-private property* equilibrium we mean a situation where intruders always contest, and incumbents always relinquish their possessions without a fight.

Theorem 1. *If $\pi_g > (1+\beta)\pi_b(1-c)$ there is a unique equilibrium in which an migrant always fights for possession and an incumbent always contests. When the reverse inequality holds, there exists both a private property equilibrium and an anti-private property equilibrium.*

Theorem 1 implies that private property is more likely to exist when combatants are capable of inflicting great harm on one another, so β is close to its maximum of unity, or when migration costs are very high, so c is close to unity.

Theorem 1 may apply to a classic problem in the study of hunter-gatherer societies, which are important not only in their own right, but because our ancestors lived uniquely in such societies until about 10,000 years ago, and hence their social practices have doubtless been a major environmental condition to which the human genome has adapted (Cosmides & Tooby 1992). One strong uniformity across current-day hunter-gatherer societies is that low-value foodstuffs (e.g., fruits and small game) are consumed by the families that produced them, but high-value foodstuffs (e.g., large game and honey) are meticulously shared among all group members. The standard argument is that high-value foodstuffs exhibit a high variance, and sharing is a means of reducing individual variance. But an alternative with much empirical support is the *tolerated theft* theory that holds that high-value foodstuffs are worth fighting for (i.e., the inequality in Theorem 1 is satisfied), and the sharing rule is a means of reducing the mayhem that would inevitably result from the absence of secure property rights in high-value foodstuffs (Hawkes 1993, Blurton Jones 1987, Betzig 1997, Bliege Bird & Bird 1997, Wilson 1998).[5]

The only part of Theorem 1 that remains to be proved is the existence of an anti-private property equilibrium. To see this, note that such an equilibrium exists when $\pi_c < \pi_b(1-c)$ and $\pi_u > \pi_b(1-c)$, which, by the same reasoning as above, occurs when

$$\frac{s_u^n}{s_o^n} > \frac{\pi_g}{\pi_b(1-c)} - 1 > \frac{s_o^n}{s_u^n}s. \tag{7}$$

It is easy to show that if the incumbent contests, then both parties will set $s_u = s_o = 1$, in which case the condition for the incumbent to do better by not contesting is exactly what it is in the private property equilibrium.

The result that there exists an anti-private property equilibrium exactly when there is a private property equilibrium is quite unrealistic since few, if any, anti-private property equilibria have been observed. Our model of course shares this anomaly with the Hawk, Dove, Bourgeois model, for which this weakness have never been analytically resolved. In our case, however, when we expand our model to determine π_g and π_g, the anti-private property equilibrium will generally disappear. The problem with the above argument is that we cannot expect π_g and π_b to have the same values in a private and an anti-private property equilibrium.

6 Property and Anti-Property Equilibria

To determine π_g and π_b, we must flesh out the above model of incumbents and migrants. Consider a field with many patches, each of which is indivisible, and

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[5]For Theorem 1 to apply, the resource in question must be indivisible. In this case, the "territory" is the foodstuff that delivers benefits over many meals, and the individuals who partake of its are temporary occupiers of the territory.

hence can have only one owner. In each time period, a fertile patch yields a benefit $b > 0$ to the owner, and dies with probability $p > 0$, forcing its owner (should it have one) to migrate elsewhere in search of a fertile patch. Dead patches regain their fertility after a period of time, leaving the fraction of patches that are fertile constant from period to period. An agent who encounters an empty fertile patch invests an amount $v \geq 0$ in preparing the patch for use and occupies the patch. An agent suffers a fitness cost $c > 0$ each period he is in the state of searching for a fertile patch. An agent who encounters an occupied patch may contest for ownership of the patch, according to the War of Attrition structure analyzed in the previous section.

Suppose there are n_p patches and n_a agents. Let r be the probability of finding a fertile patch, and let w be the probability of finding a fertile unoccupied patch. If the rate at which dead patches become fertile is q, which we assume for simplicity does not depend on how long a patch has been dead, then the equilibrium fraction f of patches that are fertile must satisfy $n_p f p = n_p (1 - f) q$, so $f = q/(p + q)$. Assuming that a migrant finds a new patch with probability ρ, we then have $r = f\rho$. If ϕ is the fraction of agents who are incumbents, then writing $\alpha = n_a/n_p$, we have

$$w = r(1 - \alpha\phi). \tag{8}$$

Assuming the system is in equilibrium, the number of incumbents whose patch dies must be equal to the number of migrants who find empty patches, or $n_a\phi(1 - p) = n_a(1 - \phi)w$. Solving this equation gives ϕ, which is given by

$$\alpha r\phi^2 - (1 - p + r(1 + \alpha))\phi + r = 0. \tag{9}$$

It is easy to show that this equation has two positive roots, exactly one lying in the interval $(0, 1)$.

In a private property equilibrium, we have

$$\pi_g = b + (1 - p)\pi_g + p\pi_b(1 - c), \tag{10}$$

and

$$\pi_b = w\pi_g(1 - v) + (1 - w)\pi_b(1 - c). \tag{11}$$

Note that the cost v of investing and c of migrating are interpreted as fitness costs, and hence as probabilities of death. Thus, the probability of a migrant becoming an incumbent in the next period is $w(1 - v)$, and the probability of remaining a migrant is $(1 - w)$. This explains (11). Solving these two equations simultaneously gives equilibrium values of incumbency and non-incumbency:

$$\pi_g^* = \frac{b(c(1 - w) + w)}{p(c(1 - vw) + vw)} \quad \text{and} \tag{12}$$

$$\pi_b^* = \frac{b(1 - v)w}{p(c(1 - vw) + vw)}. \tag{13}$$

Note that $\pi_g, \pi_b > 0$, and

$$\frac{\pi_g^*}{\pi_b^*} - 1 = \frac{c(1-w)+wv}{w(1-v)}. \tag{14}$$

By Theorem 1, the assumption that this is a private property equilibrium is satisfied if and only if this expression is less than β, or

$$\frac{c(1-w)+wv}{w(1-v)} < \beta. \tag{15}$$

This inequality shows that, in addition to our previous result, that low fighting cost and high migration cost undermine the private property equilibrium, a high probability w that a migrant encounters an incumbent undermines the private property equilibrium, and a high investment v has the same effect.

Suppose, however, that the system is in an anti-private property equilibrium. In this case, letting q_u be the probability that an incumbent is challenged by an intruder. we have

$$\pi_g = b + (1-p)(1-q_u)\pi_g + (p(1-q_u)+q_u)\pi_b(1-c) \tag{16}$$

and

$$\pi_b = w\pi_g(1-v) + (r-w)\pi_g + (1-r)\pi_b(1-c). \tag{17}$$

Solving these equations simultaneously gives

$$\pi_g^* = \frac{b(c(1-r)+r)}{((p(1-q_u)+q_u))(vw+c(1-vw))} \tag{18}$$

$$\pi_b^* = \frac{b(r-vw)}{(((p(1-q_u)+q_u))(vw+c(1-vw)))}. \tag{19}$$

Also, $\pi_g, \pi_b > 0$, and

$$\frac{\pi_g^*}{\pi_b^*} - 1 = \frac{c(1-r)+vw}{r-vw}. \tag{20}$$

Note that $r - vw = r(1 - v(1-\alpha\phi)) > 0$. We must check whether a non-incumbent mutant who never invests, and hence passes up empty, fertile patches, would be better off. In this case, the present value of the mutant, π_m, satisfies

$$\pi_m - \pi_b^* = (r-w)\pi_g^* + (1-r+w)\pi_b^*(1-c) - \pi_b^*$$
$$= \frac{bw(v(r-w) - c(1-v(1-r+2)))}{(p(1-q_u)+q_u)(vw+c(1-vw))}.$$

It follows that if

$$v \le \frac{c}{(r-w)(1-c)+c}, \tag{21}$$

then the mutant behavior (not investing) cannot invade, and we indeed have an anti-property equilibrium. Note that (21) has a simple interpretation. The denominator in the fraction is the probability that search ends either in death or finding an empty patch. The right side is therefore the expected cost of searching for an occupied patch. If the cost v of investing in a empty patch is greater than the expected cost of waiting to usurp an already productive (fertile and invested in) patch, no agent will invest.

However, if (21) is violated, then migrants will refuse to invest in an empty fertile patch. Then (9), which implicitly assumed that a migrant would always occupy a vacant fertile patch, is violated. We argue as follows. Assume the system is in the anti-property equilibrium as described above and, noting the failure of (21), migrants begin refusing to occupy vacant fertile patches. Then, as incumbents migrate from newly dead patches, ϕ will fall, and hence w will rise. This will continue until (21) is satisfied as an equality. Thus, we must redefine an anti-property equilibrium as one in which (9) is satisfied when (21) is satisfied; otherwise (21) is satisfied as an equality and (9) is no longer satisfied. Note that in the latter case the equilibrium value of ϕ will be strictly less than in the private property equilibrium.

Theorem 2. *Suppose (21) is violated when ϕ is determined by (9). Then the anti-private property equilibrium exhibits a lower average payoff than the private property equilibrium.*

The reason is simply that the equilibrium value of ϕ will be lower in the anti-property equilibrium than in the property equilibrium, so there will be on average more migrants and fewer incumbents in the anti-property equilibrium. But incumbents earn positive return b per period, while migrants suffer positive costs c per period.

Theorem 2 helps to explain why we rarely see anti-property equilibria in the real world, If two groups differ only in that one plays the private property equilibrium and the other plays the anti-private property equilibrium, the former will grow faster and hence displace the latter, provided that there is some scarcity of resources leading to a limitation on the combined size of the two groups.

This argument does not account for private property equilibria in which there is virtually no investment by the incumbent. This includes the butterfly (Davies) and feral horse (Stevens) examples, among others. In such cases, the property and anti-property equilibria differ in only one way: the identity of the patch owner changes in the latter more rapidly than in the former. It is quite reasonable to add to the model a small cost δ of ownership change, for instance, because the intruder must physically approach the patch and engage in some sort of display before the change in incumbency can be effected. With this assumption, the anti-private property equilibrium again has a lower average payoff that the private property equilibrium, so it will be disadvantaged in a competitive struggle for existence.

The next section shows that if we respecify the ecology of the model appropriately, the unique equilibrium is precisely the anti-private property equilibrium.

7   An Anti-Private Property Equilibrium

Consider a situation in which agents die unless they have access to a fertile patch at least once every n days. While having access, they reproduce at rate b per period. A agent who comes upon a fertile patch that is already owned may value the patch considerably more than the current owner, since the intruder will have, on average, less time to find another fertile patch than the current owner, who has a full n days. In this situation, the current owner may have no incentive to put up a sustained battle for the patch, whereas the intruder may. The newcomer may thus acquire the patch without a battle. Thus there is a plausible anti-private property equilibrium.

To assess the plausibility of such a scenario, note that if π_g is the fitness of the owner of a fertile patch, and $\pi_b(k)$ is the fitness of a nonowner who has k periods to find and exploit a fertile patch before dying, then we have the recursion equations

$$\pi_b(0) = 0 \tag{22}$$

$$\pi_b(k) = w\pi_g + (1-w)\pi_b(k-1) \quad \text{for } k = 1, \ldots, n, \tag{23}$$

where r is the probability that a nonowner becomes owner of a fertile patch, either because it is not owned or the intruder costlessly evicts the owner. We can solve this, giving

$$\pi_b(k) = \pi_g(1 - (1-r)^k) \quad \text{for } k = 0, 1, \ldots n. \tag{24}$$

Note that the larger k and the larger r, the greater the fitness of a intruder. We also have the equation

$$\pi_g = b + (1-p)\pi_g + p\pi_g(n), \tag{25}$$

where p is the probability the patch dies or the owner is costlessly evicted by an intruder. We can solve this equation, giving

$$\pi_g = \frac{b}{p(1-r)^n}. \tag{26}$$

Note that the larger b, the smaller p, the larger r, and the larger n, the greater the fitness of an owner.

As in the previous model, assume the intruder devotes resources $s_u \in [0, 1]$ and the incumbent devotes resources $s_o \in [0, 1]$ to combat. With the same notation as above, we assume a fraction f_o of incumbents are contesters, and we derive the conditions for an incumbent and an intruder who has discovered the owner's fertile

patch to conform to the anti-private property equilibrium. When these conditions hold, we will have $f_o = 0$.

Let π_c be the fitness value of contesting rather than simply abandoning the patch. Then we have

$$\pi_c = s(1 - p_u)\pi_g + (1 - s)((1 - p_u)\pi_g + p_u\pi_b(n)) - \pi_b(n),$$

which reduces to

$$\pi_c = \frac{\pi_g}{2}\left(\frac{s_u^2 + s_o(2 + s_u)}{s_o + s_u}(1 - r)^n - s_u\right). \tag{27}$$

Moreover, π_c is increasing in s_o, so if the owner contests, he will set $\sigma_o = 1$, in which case the condition for contesting being fitness-enhancing for the owner then becomes

$$\frac{s_u + 2/s_u + 1}{1 + s_u}(1 - r)^n > 1. \tag{28}$$

Now let $\pi_u(k)$ be the fitness of a nonowner who must own a patch before k periods have elapsed and who comes upon an owned, fertile patch. The agent's fitness value of usurping is

$$\pi_u(k) = (1 - f)\pi_g + f(sp_u\pi_g + (1 - s)(p_u\pi_g + (1 - p_u)\pi_b(k - 1))) - \pi_b(k - 1).$$

The first term in this equation is the probability the owner does not contest times the intruder's gain if this occurs. The second term is the probability the owner does contest times the gain if the owner does contest, and the final term is the fitness value of not usurping. We can simplify this equation to

$$\pi_u(k) = \pi_g\frac{s_o(1 - f) + s_u}{s_o + s_u}. \tag{29}$$

This expression is always positive and is increasing in s_u and decreasing in s_o, provided $f_o > 0$. Thus, the intruder will always set $s_u = 1$. Also, as one might expect, if $f_o = 0$, the migrant usurps with probability 1, so $\pi_u(k) = \pi_g$. At any rate, the migrant always contests, whatever the value of f_o. The condition (28) for not contesting, and hence for there to be a globally stable anti-private property equilibrium, becomes

$$2(1 - r)^n < 1, \tag{30}$$

which will be the case if either r or n is sufficiently large. When (30) does not hold, there will be an anti-private property equilibrium.

The anti-private property equilibrium is not often entertained in the literature, although Maynard Smith (1982) describes the case of the spider *Oecibus civitas*,

where intruders virtually always displace owners without a fight. More informally, I observe the model in action every summer's day at my bird feeders and bathers. A bird will arrive, eat or bathe for a while, and if the feeder or bath is crowded, then will be displaced, without protest, by another bird, and so on. It appears that, after having eaten or bathed for a while, it simply is not worth the energy to defend the territory.

8 Conclusion

Humans share with many other species a predisposition to recognize private property. This takes the form of *loss aversion*: an incumbent is prepared to commit more vital resources to defending his property, *ceteris paribus*, than an intruder is willing to commit to taking the property. The major proviso is that if the property is sufficiently valuable, a private property equilibrium will not exist (Theorem 1).

History is written as though private property is a product of modern civilization, a construction that exists only to the extent that it is defined and protected by judicial institutions operating according to legal notions of ownership. However, it is likely that private property in the fruits of one's labor existed for as long as humans lived in small hunter-gatherer clans, unless the equality in Theorem 1 holds, as might plausibly be the case for big game. The true value of modern private property, if the argument in this paper is valid, is fostering the accumulation property even when $\pi_g > (1 + \beta)\pi_b(1 - c)$. It is in this sense only that Thomas Hobbes may have been correct in asserting that life in an unregulated state of nature is "solitary, poor, nasty, brutish, and short." But even so, it must be recognized that modern notions of property are built on human behavioral propensities that we share with many species of nonhuman animals. Doubtless, an alien species with a genetic organization akin to our ants or termites would find our notions of individuality and privacy curious at best, and probably incomprehensible.

9   List of Symbols

$\beta \in (0, 1]$ Amount of injury from combat

$\phi \in (0, 1]$ Fraction of agents who are incumbents

π_g Present value of being a currently uncontested incumbent

π_b Present value of being a migrant searching for a territory

$\rho \in (0, 1]$ Probability migrant locates a patch

b Benefit from incumbency

$c \in (0, 1]$ Fitness cost associated with territorial search

$f \in (0, 1]$ Fraction of patches that are fertile

$f_o \in (0, 1]$ Fraction of incumbents who contest

n Number of days agent can live without incumbency

n_p Number of patches

n_a Number of agents

$p \in (0, 1]$ Probability of patch death

$q \in (0, 1]$ Probability of dead patch become fertile

$q_u \in (0, 1]$ Probability incumbency is challenged by intruder

$r \in (0, 1]$ Probability of finding a fertile patch

$v \in (0, 1]$ Cost of investing in newly fertile patch

$w \in (0, 1]$ Probability of finding a fertile unoccupied patch

$p_d \in (0, 1]$ Probability of combat leading to injury

$p_u \in (0, 1]$ Probability intruder wins contest

$s =\in (0, 1]$ Expected injury from combat

$s_o \in (0, 1]$ Resources committed to combat by incumbent

$s_u \in (0, 1]$ Resources committed to combat by intruder

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