Emergent Order, Agent-Based Modeling, and Economic Analysis of Accident Law

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Dedication

For Jennifer, to whom I am eternally grateful.

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Abstract

EMERGENT ORDER, AGENT-BASED MODELING, AND ECONOMIC ANALYSIS OF ACCIDENT LAW

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The purpose of this project is to examine the benefits of basing economic analysis of accident law on the notion that individuals form a spontaneous order as they respond to the institution of tort law, each other, and their environment. Furthermore, I examine the efficacy of agent-based modeling as an analytical tool that exploits this realization. I discuss the theoretical implications of the neoclassical analytical perspective and offer an alternative based upon the insights of spontaneous order economics.

I develop an artificial society in which virtual agents pursue productive, though inherently accident prone, activity. The accidents that occur are chance encounters and agents bear a private cost for engaging in behavior that reduces their likelihood. First, I employ empirical techniques based on neoclassical theory and fit regression models to simulation data in order to determine the wealth maximizing behavior under various liability rules. I confirm some of the major theoretical conclusions but I also identify

several common simplifying assumptions that may adversely affect the accuracy of conclusions under certain circumstances.

I contrast the mainstream mode of analysis with an evolutionary approach that uses a computational model comprised of heterogeneous agents that implement satisficing algorithms to select strategies on the basis of their individual experience. The power of this perspective is not simply that it assists in developing a genetic-causal explanation as a means for evaluating the desirability of various liability rules, but it enables the detailed exploration of population dynamics and a close examination of out of equilibrium behavior. I find that for the artificial society under consideration, system level steady-state does not necessarily imply agent equilibrium, agents often elect to be careful even when the neoclassical theory predicts otherwise, and negligence rules differ in their ability to rid society of negligent behavior. Ultimately, I conclude that the emergent approach is complementary to the mainstream neoclassical perspective and holds the promise of opening up new avenues for future research.

Chapter 1: Introduction

I have long argued that cost-benefit analysis in the Kaldor-Hicks sense is both a useful method of evaluating the common law and the implicit method (implicit, for example, in the Learned Hand formula for determining negligence) by which common law cases are in fact decided - and rightly so in my opinion. (Posner, 2000, p.1154)

Precisely because we live outside of general competitive equilibrium and in a world of unpredictable flux, the efficiency case for negligence must fail. In such a world, it is impossible to compare alternative liability systems in terms of judicial cost-benefit analysis or 'fine tuning.' Instead, they must be analyzed in terms of institutional efficiency – the certainty and stability that these rules impart to the social framework. (Rizzo, 1980, p.291)

The single most dominant research question in the field of law and economics concerns the efficiency of the law. That is, the question of whether the common law evolves such that the rulings that judges hand down result in an efficient allocation of resources. The preeminent scholar and advocate of the efficiency of the legal system is Richard Posner, who suggests that the common law legal system is, and ought to be, a wealth maximizing institution (1985). Posner asserts that judges should tailor their decisions through the use of cost-benefit analysis such that human satisfaction, as measured by aggregate consumer willingness to pay, is maximized.

A subordinate strain of this research agenda is the economic analysis of tort law. "The positive economic theory of tort law maintains that the common law of torts is best explained as if judges are trying to promote resource allocation, i.e. maximize efficiency"

(Posner and Parisi, 2002, p.xxiv). This theory considers the cost of accidents, the cost of preventing accidents, and the administrative costs of the judicial system as the relevant variables. The various rules for determining liability found in the realm of tort law have been subject to rigorous economic analysis, to include strict liability and negligence as well as many others (e.g., the above combined with various defenses). The type of accident considered in this paper is limited to chance encounters, which occur between strangers with no prior substantial relationship of any sort, and for whom the costs of transactions necessary to achieve a Coasian solution prior to their dispute are prohibitively high.

The intent of this project is to apply the concepts learned from the study of emergent social orders to the economic analysis of accident law and subsequently demonstrate that agent based simulation is an effective and innovative tool for this pursuit. This paper presents an alternative perspective to the neoclassical law and economics approach that more fully acknowledges the dynamic and complex nature of social interaction. Embracing this alternative perspective will ultimately provide valuable insight into the debate between the relative strengths and weaknesses of the rule of strict liability versus the rule of negligence in tort law, as well as other questions that dominate the law and economics literature. Indeed, a primary feature of this research agenda is that vast new areas of interest are revealed in such an approach. A glimpse of these areas spawn research questions and inspire theoretical analysis that have potential to enhance our current understanding of the social world.

I locate this project firmly within three general threads of research, one that is thoroughly developed and two rather nascent. In the most general sense, the arguments presented in this paper find inspiration in the socialist calculation debate. Ultimately, the Posnerian notion that judges posses the requisite knowledge to rule (as if) they are capable of ruling such that wealth is maximized is vulnerable to a Hayekian knowledge critique (Stringham, 2001). I highlight the difficulties that even a researcher with nearly complete access to necessary information has in identifying the socially optimal rule. If a researcher, or omniscient benevolent dictator, faces a serious knowledge problem collecting the data and effectively identifying the social optimum, then it calls into question the individual judge's ability to engage in the appropriate calculations when presented the facts of a particular case.

A fledging thread of research, though one that certainly has its roots in the Scottish Enlightenment, is the realization that most phenomena studied by social scientists, and certainly the subject of this paper, is better understood as a spontaneous order (Hayek, 1973; Rizzo, 1980; Wagner, 2007). Typical modes of analysis in the public finance, law & economics, and to some extent public choice literatures model government as a monolithic teleological organization. Such a concept holds government as a unitary being separate from the individuals that make up society. Under certain circumstances, this convention is appropriate. However, as Wagner (2007) demonstrates, a conjunctive framework that embraces the notion that individuals tend to coordinate some activities privately and others publicly, can be very fruitful. Such a perspective recognizes the judiciary is not a monolithic institution that stands outside the society and directs its organization with iron-fisted commandments from the bench, for it too is comprised of individuals that pursue their own goals and select the means to accomplish them on the basis of their own subjective evaluations. I ultimately show that individuals subject to accident law respond in a decentralized fashion to the incentives placed before them and form a dynamic spontaneous order.

The final major thread of research that informs this project is the agentization of neoclassical models. In this paper, I analyze the effects of accident law in a particular scenario from both a neoclassical perspective and an agent-based perspective. As forthrightly as possible, I apply neoclassical tools to determine the socially optimal liability rule and illuminate the practical effects of various common assumptions. I contrast this with an analysis that employs an evolutionary agent-based model which highlights the relative strength and weaknesses of these approaches. Ultimately, I conclude that the emergent approach is complementary to the mainstream neoclassical perspective and holds the promise of opening up new avenues for future research.

The second chapter is an expositional outline of the mainstream neoclassical law and economics. In particular, Landes and Posner's (1981) as well as Shavell's (1986; 2004) models are illustrated and their relative strengths are discussed. In addition, the types of research questions that individuals working within the neoclassical tradition are broadly outlined.

In Chapter Three, I make the argument that spontaneous order economics in general, and agent-based simulation in particular, are appropriate and effective tools with which to analyze accident law. I first demonstrate that largely since the legal structure and its affect on individual behavior is not necessarily as teleological as commonly assumed, the individuals subject to tort law select their respective strategies in a decentralized manner and form a spontaneous order. Building upon the work of other researchers who have shown the effectiveness with which agent-based modeling may be applied to the study of spontaneous orders, I argue that the economic analysis of the law would similarly benefit.

Chapter Four introduces the problem faced by the inhabitants of a fictional society known as Eggtopia. These individuals are constantly engaged in a search for highly valuable yet fragile eggs. In the course of their endeavors, they occasionally collide with sufficient force to destroy the eggs they've collected. They face the critical tradeoffs between taking precautions which reduce the chance of accidents and engaging in relatively more productive behavior. It is the problem faced in this society that serves as the target of all subsequent analysis in this dissertation. In order to compare and contrast neoclassical and evolutionary methodologies, the remaining two chapters analyze Eggtopian society. This chapter also introduces the agent-based simulation that is intended to model this society and generate the data necessary to analyze these two divergent approaches.

Chapter Five approaches the analysis of tort rules in Eggtopia from the perspective of a researcher working within the neoclassical framework. I use the agent-based simulation to generate the data necessary to empirically measure the performance of the model. I demonstrate how one would go about answering the research questions commonly posed by theorists in this field and I highlight the effects of certain common assumptions.

The sixth chapter implements a fully dynamic and evolutionary algorithm of agent behavior in the agent-based simulation. The power of the evolutionary approach is not simply that it provides a genetic-causal explanation as a means for adjudicating between various liability rules, it is that the approach enables the exploration of population dynamics and the close examination of out of equilibrium behavior.

The final chapter concludes and maps out a research agenda that builds upon the themes formed in this project. It outlines extensions to the current project which embrace the power of evolutionary thinking more fully. In addition, the general methodology of examining issues from an evolutionary perspective in parallel with the mainstream neoclassical techniques is explored as well.

Chapter 2: General Outline of the Neoclassical Economics of Tort Law

I. Introduction

When an individual is harmed by another outside of a contractual relationship the victim may be entitled to sue the injurer under tort law. A distinguishing feature of such incidents is the existence of prohibitively high transactions costs that preclude individuals from attaining a mutually beneficial agreement prior to the incident and thus achieving a Coasian solution that preemptively avoids the dispute. The Classic Law of Torts requires three elements in order to allow recovery by the plaintiff. They are: (a) the plaintiff must have suffered a harm; (b) the defendant's act or failure to act must have caused the harm; and (c) the defendant's act or failure to act must constitute the breach of a duty owed by the plaintiff to the defendant (Cooter and Ulen, 2007, p.326). It is this general legal structure that is the target for the economic analysis of accident law.

Richard Posner, with occasional coauthor William Landes, has thoroughly developed and prodigiously researched what he has coined the positive theory of tort law (1972; 1981; 2000; 2007). In short, the positive theory of tort law holds that the common law has evolved such that judges, in handing down legal rules through precedents, have acted as if they have been trying to minimize the social costs of accidents. In this case, social cost includes the damage inflicted in the accident, as well as the cost of measures undertaken to prevent the accident. A corollary to the positive theory is the normative theory that states judges should attempt to minimize the costs of accidents through their judicial decision making as such an undertaking would tend to maximize the wealth in society. Posner's theory of tort law fits tightly inside his overarching theory of the common law as a wealth maximizing mechanism (Posner, 2000; 2007).

The neoclassical economic analysis of accident law, which Posner has pioneered, typically applies the same general framework, i.e. rational utility maximization, equilibrium theorizing, etc, as general neoclassical economists apply to the study of the catallaxy. This enables researchers working in this framework to obtain narrow yet definitive conclusions regarding their models. Analytical clarity and tractability are achieved at the price of overlooking certain interesting and possibly critical aspects of reality. In short, the neoclassical analysis of tort law shares many of the same advantages and disadvantages of the more general neoclassical economic paradigm. The primary intent of this chapter is to outline the neoclassical model of tort law to which Posner and others contributed greatly and discuss its advantages.

II. The Neoclassical Analysis of Tort Law

The typical mode of analysis for neoclassical economists upon selecting a phenomenon for investigation is to assume a system inhabited by rational utility maximizers who have stable preferences some form of rational expectations regarding their world. These agents are then imagined to relate in a linear manner, which enables the researcher to choose one or perhaps several representative agents that select strategies to maximize their utilities in response to other agents maximizing their own. Agent behavior in equilibrium is deduced from the basis of these relationships. These assumptions enable the theorist to obtain an explicit closed form mathematical expression of the system which can then be analyzed to determine global or local minima or maxima subject to the theorized constraints.

In the following section, I describe the standard neoclassical treatment of tort law as outlined in Landes and Posner (1981), Shavell (1987; 2003), and Cooter and Ulen (2007). These authors also cite, Calabresi (1970), Brown (1973) and Diamond (1974a; 1974b) as important fundamental influences upon their work as well.

A. Determination of the Social Costs of Accidents

The typical neoclassical analysis proceeds as an attempt to obtain a social welfare function that describes the costs and benefits of agents' activities as it relates to accidents in equilibrium. Once a social welfare function is obtained, global maxima and/or minima are easily identified using differential calculus and individual activity in equilibrium is deduced. Posner then uses the model to explain the evolution of the common law in a positive sense and outlines how such a theory provides a worthy normative goal for jurists as well.

The social welfare function either represents an aggregation of all individuals in society or is normalized to apply to representative agents. There are generally three components to the social welfare functions. A term describing the agents' or agent's income is typically included, as well as the expected costs of accidents, which is the magnitude of damages given an accident occurs discounted by the probability an accident occurs. Finally, a term describing the cost of care taken to avoid accidents is also subtracted from income. The last two terms are usually both functions of the amount of care selected. Taking additional care is costly; however, it does reduce the expected probability of an accident occurring over the appropriate interval. In all cases, the functions are assumed to be continuous, twice differentiable and possess second derivatives of the appropriate sign. Figure 2.1 is a graphical representation of the expected social costs of accidents.

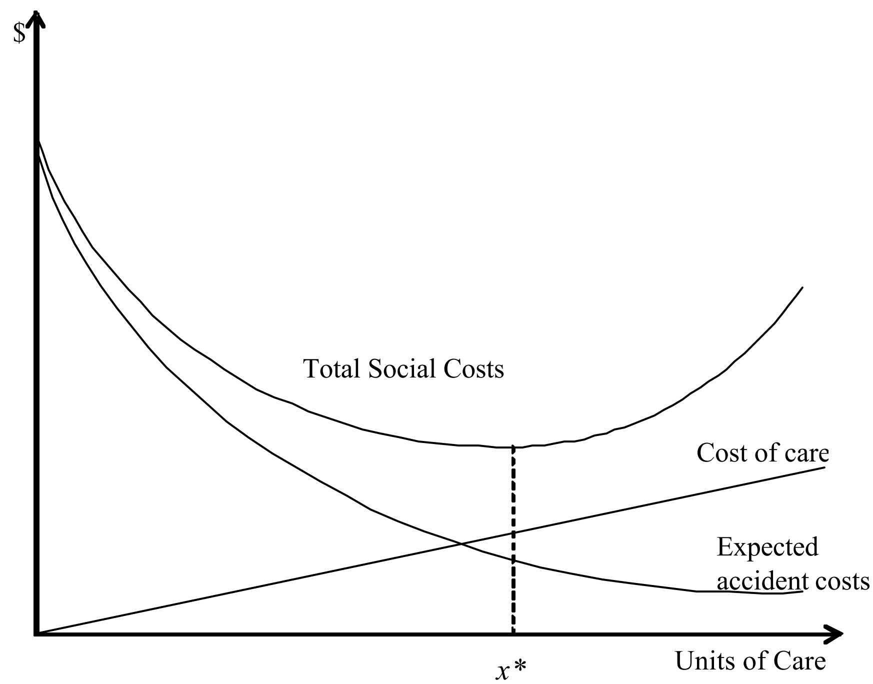

Figure 2.1. Expected Social Costs of Accidents.[1]

As indicated in Figure 2.1, the cost of care and the expected costs of accidents are summed to obtain the total social cost of accidents. In this case, the socially optimal level of care is x^*.

[1] Adapted from Shavell (1987).

The model described in this section is drawn entirely from Landes and Posner (1981). For purposes of consistency and ease of exposition, all discussion of the neoclassical model will be in terms of Landes and Posner's notation to the fullest extent possible. Landes and Posner's (1981) model is populated with a representative victim, denoted A, and a representative injurer, denoted B. Individuals are risk neutral, which also means that they possess linear utility functions. In this case, agent utility functions are given by:

$$U = U(I) \qquad (2.1)$$

where I is income. Placing utility in terms of income has the added benefit of enabling the social welfare function to describe the aggregate wealth of all individuals and simplifies the determination of whether particular legal rules are wealth enhancing because it seemingly sidesteps the complications surrounding aggregating subjective utility.

The rate at which accidents occur is a function of the care that agents take. Let x and y denote the care taken by victims and agents. Then, the following describes the probability of an accident occurring.

$$p = p(x, y) \qquad (2.2)$$

Assume that increasing x or y will reduce p but at a decreasing rate. While taking care reduces the chances of an accident, it is also costly. Let $A(x)$ and $B(y)$ describe the cost of care for victim and injurer, and let D define in terms of wealth the damage inflicted upon the victim in the event of an accident. The following describes the victim's utility function:

$$U^a = p(I^a - D - A(x)) + (1\text{-}p)(I^a - A(x)) = I^a - pD - A(x) \quad (2.3)$$

The following describes the injurer's utility function:

$$U^b = p(I^b - B(y)) + (1\text{-}p)(I^b - B(y)) = I^b - B(y) \quad (2.4)$$

Assuming that all other individual's utilities are independent from that of A and B, maximizing the sum and of A and B's utilities also maximizes social welfare. The social welfare function explicitly describes the total costs of accidents, that is expected damages plus the cost of accident avoidance, as a function of agent activity. Maximizing social welfare is equivalent to minimizing the costs of accidents as described below.

$$L(x, y) = p(x, y)D + A(x) + B(y) \quad (2.5)$$

Thus, $L(x,y)$ is the social cost of accidents. Let $x*$ and $y*$ be the levels of care for victim and injurer that minimizes $L(x, y)$. To obtain optimal care levels, take the partial derivative of $L(x, y)$ with respect to x (or y) and set equal to zero. The following are the first order conditions for optimality:

$$A(x)' = -p_x D \quad (2.6)$$

$$B(y)' = -p_y D \quad (2.7)$$

The optimality conditions indicate that an individual, regardless of her status as injurer or victim, should continue to add inputs of care up to the point where the marginal reduction in expected accident damage is just equal to the marginal cost of care as depicted in Figure 2.2.

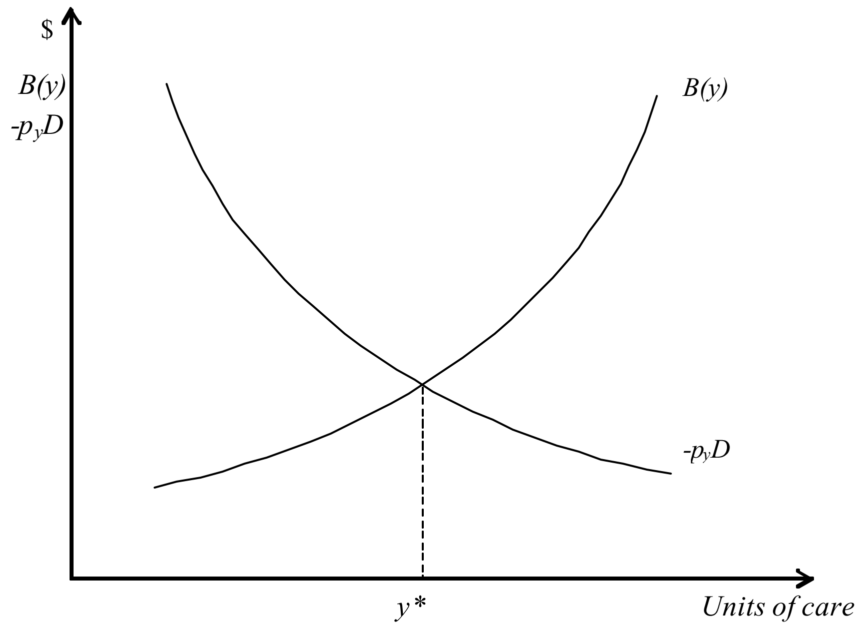

Figure 2.2. Expected Costs of Accidents and Avoidance for Injurers.[2]

As indicated in Figure 2.2, the point at which the marginal cost of care just equals the marginal reduction in expected accidents corresponds with the socially optimal level of care. In the scenario depicted, y^* is the socially optimal level of care for the injurer.

B. Determination of Negligence and the Learned Hand Rule

The landmark case of *United States vs Carroll Towing*, was the first case in which Judge Learned Hand explicitly outlined his widely cited rule for determination of negligence. In it, he suggests that an injurer acts negligently if the expected cost of an accident exceeds the cost of prevention. In his explanation, P is the probability that an accident occurs and L is the magnitude of the damages in the event of an accident. The expected damages are simply given by the product PL. The cost of preventing the

[2] The graph assumes $x = x^*$. Adapted from Posner and Landes (1981, p.542).

accident is given by *B*. Thus, in any particular case that appears before the court if, $PL > B$, or more accurately, if the inequality is true for a "reasonable man", the injurer is found negligent. Alternatively, if $B > PL$, then the costs of accident avoidance exceeds the expected cost of the accident, so efficiency and Judge Hand would dictate that the injurer was not negligent.

While Judge Hand does not explicitly state whether the costs to which he refers are total or marginal, it is clear that within the standard neoclassical framework the costs must be marginal in order to comply with optimality conditions. Brown (1973, pp.332-4) discusses two plausible interpretations of the Hand formula. If the court is privy to complete relevant information, the standard used may be what he terms the full information incremental standard. Under such a regime, the (marginal) Hand formula would be applied for an individual given that the other party in the dispute acted optimally (p.333). Alternatively, if courts are not privy to all underlying information, they may only be able to measure costs in the neighborhood of the courses of action which the disputants selected. Under this limited information incremental standard, the marginal Hand rule would be applied for a party given what the other party actually did. Brown goes on to prove that only under the full information incremental standard is the socially optimal level of care achieved. Posner's positive theory of tort law, around which most neoclassical research is centered, is essentially a more rigorous and formalized version of the Hand Formula which firmly follows Brown's full information incremental standard.

Posner divides accidents into two categories, those of alternative and joint care[3]. In situations of alternative care it is only optimal for one party, either the injurer or victim, to exercise due care in an effort to efficiently avoid the accident. While in joint care situations, both parties must take some measure of precaution in order to efficiently minimize the cost of accidents. Individuals are assumed to respond rationally to private incentives, so the various tort rules are analyzed in an attempt to determine which, if any, effectively provides appropriate incentives for efficient behavior.

The Alternative Care Case

In situations of alternative care, it is optimal for one party to exercise care to minimize social costs. In the event the injurer is the only party which may effectively take precautions to avoid accidents, then it is easily demonstrated that a rule of strict liability will provide sufficient incentive to injurers to exercise the efficient level of care. If injurers are held liable for damages of all accidents they cause, then it will be in their interest to invest in units of care up to the point that the marginal cost of a unit of care just equals the concomitant marginal reduction in expected damages. In terms of the model, $B(y)' = -p_y D$ given that $x^* = 0$. In the event that the only party who may effectively take precaution is the victim, then a rule of no liability provides the appropriate incentives for efficient behavior. The victim will take care up to the point that an additional unit of care just equals an equivalent reduction in expected cost of accidents. In other words, this occurs when $A(x)' = -pxD$ and $y^* = 0$.

[3] Shavell's prefers the terms unilateral and bilateral (1987).

The Joint Care Case

In many situations, action is required on the part of both parties in order to achieve an efficient outcome. In such cases, a rule of strict liability is inefficient because it does not provide the victim with sufficient incentive to exercise precaution. A victim will opt against investing in costly units of care because she can expect full compensation for any accidents experienced regardless of her decision to exercise care. Similarly, under a rule of no liability, the rational injurer will forgo investing in precaution due to the fact that his liability is zero regardless of his decision to exercise care or not.

A rule of negligence will, however, incentivize efficient behavior on the part of both parties. Assuming for the moment that the court is able to define due care at the wealth maximizing level, negligence is defined as exercising less than due care, i.e. selecting $y < y^*$. The rational injurer will select the efficient level of care because selecting a level less than that will result in liability for damages while selecting more than the efficient level would not be worth the cost in terms of reduced liability. In turn, the victim will select the optimal (non-zero) level of due care because knowing that injurers will act non-negligently, they face incentives equivalent to those under no liability and will not expect compensation for the damages they suffer. Thus, they will face sufficient incentives to select the optimal level of precaution.

There are other liability rules to include strict liability with a defense of contributory negligence, negligence with a defense of contributory negligence, and comparative negligence. Strict liability with a defense of contributory negligence holds injurers fully liable for all accidents they cause, unless it is shown that the victim acted negligently. In such a case, the victim would bear liability for all damages if she exercised something less than due care, thus, victims would exercise due care in an effort to avoid liability. The injurer would expect non-negligent behavior on the part of victims and so face the exact same incentives as under the strict liability standard which would lead her to select an optimal level of care. Similarly, the rules of negligence with a defense of contributory negligence and comparative negligence all create incentives for efficient behavior.

C. Extensions and their Effects on Conclusions

Shavell (1980; 1987) outlines a number of different extensions to the standard model. Among the most important is the inclusion of the quantity of activity as an endogenous variable. The decision to exercise a particular level of care when performing an activity is separate from the decision to perform the activity a particular number of times. For example, the decision to exercise care while driving may result in an individual observing the posted speed limit, but this decision is separate from her decision regarding how many miles to drive. Furthermore, there exists an optimal quantity of activity and different tort rules may enjoy varying levels of success incentivizing efficient behavior in this regard.

Let s and t describe the level of activity for that of the injurer and the victim, and $I(s)$ and $I(t)$ be the increase in income that the individuals enjoy as a result of engaging in the activity[4]. The injurer's net utility is given by:

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[4] This section is drawn from Shavell (1987), especially Chapter 2 and its mathematical appendix. However, for the sake of consistency I have translated the mathematics into the notation of Landes and Posner (1981) while maintaining Shavell's assumptions regarding the relationship among variables.

$$U^b = I^b(s) – sp(x,y)D\text{-}sB(y) \quad (2.8)$$

The term $B(y)$ is in units of wealth that are sacrificed in order to obtain y units of care. So if an individual engages in an activity s times, she pays that price s times. Likewise, the expected accident losses are the product of $p(x,y)D$ and s. Thus, the victim's net utility function is given by:

$$U^a = I^a(t) – tp(x,y)D – tA(x) \quad (2.9)$$

The social goal to be achieved is the maximization of society's welfare, thus the sum of A and B's utility is:

$$Usum = I^a(t) + I^b(s) – stp(x,y)D – tA(x)\text{-}sB(y) \quad (2.10)$$

In order to obtain the optimal solution in terms of x^*, y^*, s^*, and t^*, take the partial derivative of $Usum$ with respect to each of these variables and set equal to zero. The following are the first order conditions for these variables:

$$x^*\text{:}\ \ stp_xD – tA_x \quad (2.11)$$

$$y^*\text{:}\ \ stp_xD – sB_y \quad (2.12)$$

$$s^*\text{:}\ \ I^b(s)' – tpD – B(y) \quad (2.13)$$

$$t^*\text{:}\ \ I^a(t)' – spD – A(x) \quad (2.14)$$

While the first two conditions defy a straightforward interpretation, the last two may be summed up as follows. The marginal utility of an increase in the quantity of activity for either the A or B must equal the sum of the cost of care as well as the increase in expected accident losses.

In the alternative care situation, which Shavell refers to as unilateral care, he proves that under a rule of strict liability, injurers will select the socially optimal values of y and s (1987, p.43). However, under the negligence rule, while injurers will select the socially optimal level of care, they will select an activity level that exceeds the social optimum.

He argues that since the concept of "due care" can only be defined on a finite (small) number of margins, then it is possible under a regime of negligence (where individuals are not found liable so long as they exercise due care) for injurers to engage in excessive conduct of potentially dangerous behavior. Suppose a motorist is said to have exercised due care so long as she does not exceed the speed limit. Every driver knows there are clearly more aspects to the exercise of care when driving other than simply speed of travel, i.e. checking mirrors, general attentiveness, even miles driven, etc. But since the motorist will have satisfied the requirements for due care simply by driving the speed limit, she may not have sufficient incentive to exercise care in these other areas. Shavell's contribution is the demonstration of how under a strict liability rule, an individual is incentivized to take appropriate care along all relevant margins.

Shavell identifies an interesting paradox for the joint care case. He proves that there is no such liability rule that will induce both the injurer and victim to select the socially optimal levels of both care and activity (1987, p.44). A rule of strict liability with contributory negligence results in victims selecting a quantity of activity that exceeds the optimum, while a negligence rule results in injurers selecting suboptimally excessive quantity of activity. As a policy prescription he suggests that in situations where it is relatively more important to limit the injurer's quantity of activity then the rule of strict liability should be used, while in situations where it is relatively more important to limit the victim's quantity of activity then the rule of negligence should be in place.

Errors, Uncertainty and Misperceptions

Taken to its logical conclusion, the neoclassical model of behavior under a negligence rule implies that individuals will never be found negligent because they will rationally avoid liability for their accidents merely by exercising due care. In short, rational self-interested actors would simply never select a level of care less than the due care level endorsed by the court because they face greater costs if they were to exercise any other level of care. The fact that in reality injurers are often found negligent for their activities must mean that behavior in reality diverges from the neoclassical model in some crucial manner.

One of the primary ways in which the presented model differs from the real world is the fact that in the model all parties, to include the court, are privy to all necessary information to make appropriate decisions. None of the agents in the model make mistakes regarding any of the pertinent facts of the dispute nor do they err in the execution of any of their intended courses of action. Relaxing this assumption has important implications for the conclusions reported.

Consider the situation where the court makes systematic errors estimating the damages to be paid by the injurer. Under a rule of strict liability, a court that consistently overestimates the damages suffered in cases will incentivize injurers to take excessive precaution while a court that consistently underestimates damages will lead injurers to take insufficient precaution. Under a rule of negligence, however, because injurers are able to avoid compensating victims for harm by exercising care, injurers' level of caution will not respond to errors concerning magnitude of damages. Similarly, even if it is the injurer incorrectly estimating damages, under a rule of negligence the injurer's level of care will remain unchanged. Table 2.1 summarizes how various errors under different liability rules ultimately affect injurer behavior.

Table 2.1. Consequences of Errors of Excess.[5]

Liability Rule	Court's Error	Injurer's Error	Effect on Injurer
Strict Liability	Excessive Damages	overestimates damages	excessive precaution
Negligence	Excessive Damages	overestimates damages	none
Negligence	Excessive Legal Standard	overestimates legal standard	excessive precaution
Strict Liability	Random Error in Damages	random error in damages	none
Negligence	Random Error in Legal Standard	random error in legal standard	excessive precaution

In many situations, individuals commit errors concerning the optimal level of care. For example, an individual may be uncertain as to the level of care that the courts will require. The individual may be ignorant of the relevant case law, the activity in which the individual is engaged may be so new that the court has not had a sufficient number of cases before it to establish a reliable precedent, or the court simply is unable to ascertain the appropriate level of care without systematic error. Regardless of whether the injurer or the court commits the error, bias from either in estimating the optimal level of care leads to errors in actual level of precaution exercised in the same direction.

[5] Adapted from Cooter and Ulen (2007, p.358).

Another source of error results from situations where individuals aim for a particular level of precaution, but fail to achieve it. A driver may be momentarily distracted while changing the radio station or a waiter carrying a tray of hot soup may inadvertently trip. Such temporary departures from due care, or lapses, may result in temporary negligence that ultimately causes an accident. Courts tend to hold defendants liable if their actual level of care is less than due care, regardless of the *intended* level of care. If potential injurers are aware of their likelihood of lapsing, they will select a level of precaution that exceeds the legal requirement by a tolerable enough margin to bring their probability of a lapse that causes negligence to a personally acceptable level.

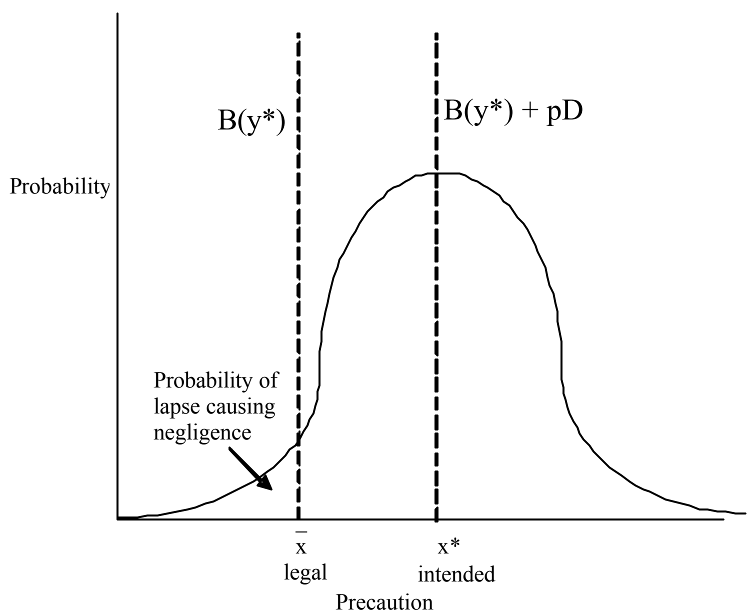

Figure 2.3. Probability of Lapse Causing Excessive Precaution. [6]

[6] Adapted from Cooter and Ulen (2007: 371).

Figure 2.3 shows the probability distribution function of an individual's ability to take precaution. The mean of the distribution is the intended level of care, indicated by x^*. The probability of a lapse causing negligence depends on the margin for error between the intended level of care and that outlined in the legal rule. The higher the margin of error, the smaller the area under the curve where the level of care exercised is less than the due care outlined in the law.

Suppose finally that the due care level selected by the courts is both suboptimal, and known in advance. If the court sets the level of due care below the optimal, then potential injurers will only take due care. If the court sets due care at a level above y^*, but not to exceed $B(y)+pD$, then individuals will still take due care. However, if the court sets the due care level in excess of $B(y)+pD$, which is the sum of the cost of care plus the expected damages, then potential injurers will act optimally and exercise due care.

In each of the above situations, uncertainty is handled in the typical neoclassical fashion where the probability distribution that describes a particular stochastic event is known by the researcher, and usually by the agents in the form of rational expectations as well. Such a framework lends itself to a clear *ex post facto* narrative of events. In other words, looking back at the historical record, it is relatively easy to compute the frequencies of particular categories of events and thus determine the observed objective probabilities of these events. However, such a perspective tends to neglect the uncertainty individuals actually face when planning and executing courses of action in reality. Chapter 6 will address the question why agents may engage in negligent behavior from an alternative, evolutionary perspective.

III. The Neoclassical Assumptions and their Implications

The strict formalism of the neoclassical model is achieved via the selection of several simplifying assumptions. The real world is a place of limitless complexity and as such, human beings consistently make use of abstract mental models in an attempt to make sense of their experience. When constructing such models, a choice must be made as to what elements of the phenomena to include and which to ignore. Include too many, and the model is just as incomprehensible as reality; too few and the model is worthless as a mechanism for explaining the phenomena under consideration.

The neoclassical literature on tort law shares the same good qualities that neoclassical economics exhibits in general. Among the most important qualities is that of syntactic clarity that the mathematical implementation achieves. All variables in the model are explicitly defined and their relationships with other variables are precisely described. The variables are carefully chosen in an effort to reduce the scope of the analysis to the most essential elements. The model is sufficiently abstract to apply to a wide range of situations easily recognizable in the real world, yet is also sufficiently concrete so as to produce policy prescriptions and seemingly testable hypothesis.

The mathematics of the neoclassical model are simple and elegant. Since all terms are continuous and twice differentiable, determination of equilibrium conditions and the locations of global and local maxima and minima are relatively straightforward to attain with the application of differential calculus. In general, neoclassical formulations provide a relatively adequate first-order description of reality. The question of how individuals behave in equilibrium is firmly in the forefront of the narrative, indeed, it is a necessary assumption for the neoclassical methodology, while the activities of individuals when outside of equilibrium are ignored. The models are also consistent with the fundamental insight of economics, which is that people respond to incentives. The model clearly demonstrates how individuals maximize their utility in the face of given constraints. Thus, the models facilitate analysis of the end state achieved but provides little insight in how the individual actually copes with uncertainty and imperfect information to take the steps necessary to better her condition.

The assumptions of rational utility maximization and perfect information tend to simultaneously place notions of time and individual planning in the background of the analysis. The mathematical tools available are well suited for intensive examination of (representative) individual behavior in equilibrium, but the tools with all their power and elegance, provide little insight into the conditions relevant to reality for bringing about an equilibrium condition nor are they capable of effectively describing out of equilibrium behavior. Furthermore, such assumptions tend to reinforce notions of the teleological nature of positive legal analysis. It is tempting to believe that the law provides individuals with perfect incentive to comply with its every aspect. However, individuals are autonomous, they make decisions based on their subjective preferences and their unique knowledge of time and place, and such decisions may often be to pursue courses of action that are in violation of the letter of the law. The assumed presence of equilibrium relegates to the background the fundamental role of the market as a discovery process and the realization that information is ultimately dispersed among individuals (Hayek, 1945). The tacit information that individuals possess of time and place, while critical to the functioning of the price mechanism, are also significant in guiding individuals through non-market processes.

The manner in which Posner utilizes the positive theory of tort law is not unlike the manner in which neoclassical economists uphold the general equilibrium model as a normative benchmark. For example, researchers working in tradition of the Chicago school of economics typically assume that markets clear and that individuals act "as if" they have complete and perfect information and make utility maximizing decisions on the basis of that information. The fact that the global optimum is achieved is less an explanation of how the economy moves from disequilibrium to equilibrium, rather optimization is achieved as it follows logically from the premises.

This equilibrium-always construct vastly simplifies the problem that a theoretical judge faces when deciding how to rule and say, where to draw the line for due care. However, it also assumes away the problem of how, exactly, judges are supposed to accumulate the information necessary to make their rulings (calculations) when such information is dispersed throughout the members of society. To the extent that the problem the judge is required to analyze is not appropriately modeled with General Equilibrium techniques, notions such as "least cost avoider" and "last clear chance" become meaningless (Rizzo, 1980). These concepts will be explored later in this project using a dynamic and evolutionary agent-based model for analysis.

Contrast the Chicago School's use of equilibrium as an assumption with that of researchers working within the Austrian tradition for whom equilibrium is used as an analytical foil. An imaginary construction of a society in "equilibrium," known as the evenly rotating economy, is outlined and all necessary and sufficient conditions are followed to their logical conclusion (see Mises, 1996). In such a scenario, individuals are not merely passive price takers but rather all consumption and production plans dovetail such that all individuals' anticipations are met. As opposed to static general equilibrium, time is a critical component of this construction as time must be allowed to pass in order to enable the appropriateness of the various plans to be revealed. The critical step comes when the imaginary construction is compared with reality, in order to determine the important ways in which reality and the imaginary construction differ, and identify the social institutions that have emerged to deal with the disutopia of reality. For example, in an evenly rotating economy, there is no need for money. That the existence of money differs in reality and in the evenly rotating economy is a clue of its importance and its relevance to the researcher seeking to understand the catallaxy.

I argue in subsequent chapters that an agent based computational model would advance the state of research on tort law by enabling the researcher to implement less restrictive substantive and formative assumptions. Agent based modeling's unique ability to facilitate analysis of models with more relevant variables and greater interacting between agents, while simultaneously maintaining tractability, provides researchers working in this field a powerful tool.

IV. Conclusion

In the last fifty years, many scholars have contributed to the neoclassical model of tort law. Coase (1960) and Calabresi (1970) laid some important ground work while Brown (1973) and Diamond (1974a; 1974b) were among the first to craft formal models that outlined the social costs of accidents in a closed form. Posner (1972; 2000; 2007), Landes (1981), and Shavell (1980; 1987; 2003) extended and refined these models to the point where neoclassical law and economics share many of the same features as neoclassical economics proper.

The models these important scholars have developed are both simple and elegant. They provide clear conclusions that follow logically from their assumptions and have certainly improved our understanding of the economics of the law. However, for as elegant and powerful as the neoclassical paradigm is, there are some potentially important aspects that the framework ultimately overlooks. Among these is a description of the mechanism that enables agents to handle dispersed information and the process through which agents modify their behavior in response to judicial proceedings and other agents. The subsequent chapters are dedicated to demonstrating how the use of agent based computational modeling may be used as a tool to overcome some of the perceived shortcomings of the neoclassical paradigm, as well as open up completely new areas of investigation.

Chapter 3: Agent-Based Modeling as a Tool

I. Introduction

In this chapter I argue that spontaneous order economics in general, and agent-based simulation in particular, are effective methodological tools for economic analysis of the law. A number of different researchers engaged in a wide array of scholarly endeavors influence the arguments presented in this chapter. Scholars of complexity and agent-based computational modeling inform many of the practical arguments presented (Arthur, 2006; Axtell, 2008; Epstein, 2006; Tesfatsion, 2006;), while researchers working within the Austrian tradition inform the discussion concerning spontaneous order economics. These theorists are credited with creating a well developed theory of the market process (see for example Mises 1996; Hayek, 1948; Kirzner, 1973) and spontaneous order (Hayek, 1973) that serves as a methodological alternative to the mainstream neoclassical paradigm. It is the purpose of this project to more fully exploit the insights of spontaneous order economics and apply them to the economic analysis of accident law. Through the course of this endeavor, I examine the suitability of agent based simulation as a tool towards this end.

The typical neoclassical analysis proceeds by imposing equilibrium upon the phenomena under examination and deducing the behavior of the individual actors that sustains that equilibrium (Becker, 1976). Mainstream law and economics analysis proceeds in a similar manner. A social welfare function is constructed that describes agent behavior in equilibrium for a default of no liability and is then used to deduce the behavior of agents under various liability regimes (see Landes and Posner, 1981). I argue that this perspective ultimately relegates critical aspects of the problem, such as the importance of time, uncertainty, and incomplete information to the background. The agent-based approach enables researchers to relax fundamental assumptions of the neoclassical approach and maintain tractability. In one sense, this project is simply an extension of the mainstream effort. In addition, I identify a gap in the Austrian literature on law and I attempt to shore up what has heretofore been overlooked.

As an alternative, I argue that examining the law through the lens of spontaneous order economics gains substantial insight and can illuminate important characteristics that are often omitted in the mainstream neoclassical theorizing. I leverage the notion that many social phenomena are best understood as spontaneous orders. I draw from Wagner (2007) and argue in favor of a conjunctive view of society, as opposed to a more teleological disjunctive perspective. The conjunctive view of the legal world embraces the notion that individuals in society form a spontaneous order in response to legal institutions, each other, and their environment. Thus, every individual, to include judges, disputants, and all potential disputants must cope with the challenges of incomplete information, uncertainty, and the passage of time.

Next I provide a brief overview of the different ways in which other scholars have used agent-based simulation to examine spontaneous orders. Agent-based simulation is capable of illuminating aspects of spontaneous orders that might be neglected or overlooked if using more formalistic and static neoclassical methods. In simulated artificial societies deeply heterogeneous agents interact with one another as they collect local information, take action on the basis of simple rules, and adapt their behavior on the basis of their experiences. Outcomes emerge not as a result of an imposition from above, as in Walrasian theorizing, but from the self-ordering of the agents. Finally, I address the manner in which agent-based modeling is consistent and complementary to Austrian theory and attempt to reconcile any perceived discrepancies.

A search of the literature to find an agent-based simulation model applied to the economic analysis of tort law has proven unsuccessful. Diianni (2007) has applied such techniques to model disputants and the evolution of precedent. See also Yee (2005), and Picker (1997; 2002) for treatments on similar topics. The current project is an attempt to remedy this gap.

II. Critiques of neoclassical and Austrian approaches

What I refer to as Neoclassical Economics in this paper describes the metatheory within which most mainstream economists currently work. Researchers working within this framework generally adhere to the following fundamental assumptions (Weintruab, 2008):

1. People have rational preferences among outcomes.
2. Individuals maximize utility and firms maximize profits.
3. People act independently on the basis of full and relevant information.

In "The Economic Approach to Human Behavior" (1976), Gary Becker states that the "combined assumptions of maximizing behavior, market equilibrium, and stable preferences, used relentlessly and unflinchingly, form the heart of the [neoclassical] economic approach (p.5)." While this approach is firmly embedded as the dominant mainstream paradigm, as other theorists would point out, namely the Austrians, this would come at the price of realism and conceptual clarity (Boettke, 1997). For the purposes of this discussion, we will concentrate on two of these methodological tenets, rational utility maximization and the use of equilibrium analysis.

Do individuals actually maximize utility? Perhaps the more pertinent question is whether models that suggest they do are more useful and insightful than models that make the modest assertion that individuals merely economize between known choices. One could rather easily list at least fifty different items to include in an ice cream sundae (ice cream flavors, toppings, syrups, fruit, etc). Choosing any five ingredients yields approximately 2.1 million different combinations of sundaes. If one were to eat three different sundaes every day, it would take nearly two thousand years to exhaustively test every possibility and decisively determine one's favorite. This combinatoric critique highlights two separate but related limitations of human rationality in that human beings are neither able to collect nor cope with all of the information they are purported to possess and analyze as rational utility maximizers. While the ice cream sundae example is certainly not a devastating critique of Max U, it begins to build the case that it is preferable to select mental models to organize thoughts on the basis of intelligibility as opposed to positivist predictability. To that end, an emergent critique of the hyper-rational utility maximizer is to call into question just how individuals are able to negotiate the maze of nearly infinite combinations of means to effectively achieve the myriad ends they seek. Individuals are only capable of selecting between means of which they are aware. There may be other means that prove more fruitful if only brought to their attention. From this perspective, entrepreneurs are seen as explorers of combinatoric space, providing maps to the previously uncharted universe of means-ends combinations.

Potts' (2000) provides an enlightening critique of the foundations of neoclassic economic theory and attempts to unify the heterodox schools of thought under the umbrella of an evolutionary microeconomics. He argues that:

> Underpinning all neowalrasian economic theory is the concept of the real field: $\mathbf{R}^n$… [I]n mathematics the real field is the generalization of arithmetic and the foundation of integral and differential calculus; one simply cannot do analysis without this concept…. And so from the marginal revolution onwards economics has appropriated this concept and … cemented it into the very foundations of the theoretical edifice. The result is what passes for modern economic orthodoxy is a special application of field theory. (p.11: citation omitted for clarity)

It is the notion of the field that underpins the fundamental assumptions of neoclassical economics. It is ultimately why any recognizable version of choice, competition, and action disappear from general equilibrium theory; it is why time is homogenous and Newtonian in character; and information is always complete or otherwise known as a probability distribution. The field as a concept was borrowed from physics on the notion that it provided economic science with a measure of rigor that was previously missing from the classical theory. While Potts is not the first theorist to identify the ontological and epistemic difference between physics and economics (for example, Mises 2006; Rothbard, 2004), he does provide a graph theoretic foundation as an alternative. He argues that connections or relationships among elements in the economic system are the important evolutionary variables of change, which is a notion that the field construct obscures.

Most importantly, the static nature of general equilibrium theorizing purges all concept of time from the model. Time is a fundamental aspect of the market process as it has a profound effect on how individuals choose and act. Action is unthinkable without time. Since the future is unknowable, all choice – or action, takes place under a fog of uncertainty. Individuals working within the market process constantly adjust their behaviors and strategies as a result of information that becomes revealed in the execution of the plans they have formulated. As the plans of the entrepreneur come to fruition, she is able to measure her profit or loss, thus providing the ultimate criteria against which to measure the success of the plan formulated under the uncertain circumstances of the past.

In a related manner, the general equilibrium framework also purges the notion of causation from consideration. Cowan (1994) notes that the common methodological practice of neoclassical economic proceeds such that "understanding a phenomenon involves finding a model such that the properties of equilibrium can be derived from underlying parameters. On this latter view, there is no place for causation in economics (p.63)." There is no place for causation, because behavior is passive in equilibrium. After all, one definition of a state of equilibrium is the condition in which, given the behavior of all other agents, no agent would opt for an alternative course of action. Such a narrative embodies a quiescent perspective of human behavior. Individuals simply take prices and preferences as given and optimize their behavior consistent with those constraints. A more active narrative would focus on the notion that individuals determine their plans endogenously. Such a narrative would embrace the genetic-causal notions that outcomes that emerge from the catallaxy are the result of the activities of interacting individuals and such phenomena may be traced back to the subjective preferences and expectations of individuals. The outcomes may or may not resemble what scholars might consider an equilibrium, but regardless, the outcome emerged as a result of individuals pursuing goals within their subjective means-ends framework.

Finally, in the neoclassical treatment, methodological individualism takes on a starkly atomistic flavor. While the attempt is made to build equilibrium results on choice-theoretic microfoundations, the real field notion underlying the neoclassical formalism requires individuals to be treated as indivisible and independent. Agents arrayed on a field are fully connected, that is, each agent exerts the same stimuli to all other agents simultaneously, thus reducing any sense of interaction to homogeneous, simultaneous stimulus and response (Potts, 2000, pp.21-30). Lavoie (1994, p.553) reminds us that individuals are not atoms, nor are they "distinct bundles of preferences, but linked participants in the cultural processes. They are shaped and adjusted to one another by the unintended evolution of institutions by which they orient themselves (p.553)."

Law and economics scholars in the neoclassical tradition, such as Landes and Posner (1981) typically develop an explicit mathematical function that describes the social welfare function for actors related to a particular type of accident (see Posner (1985), Shavell (1987), and Cooter and Ulen (2007) for textbook treatments). A representative injurer and a representative victim are selected to simplify the analysis and delineate the roles of the disputants. The social welfare function for a default of no liability is constructed that ultimately embodies the notion that the overall costs of accidents include both the damages that occur as a result of physical accidents, as well as the costs of prevention. The effects of various other liability rules are deduced from manipulations of the social welfare function. Posner asserts that the judiciary should strive to select the liability rule that minimizes these costs for each situation. In fact, his Positive Theory of Tort Law asserts that the common law with regard to tort has evolved through the generations as if judges, through their holdings, have attempted to minimize these accident costs (Landes and Posner, 1981).

B. A critique of Austrian Accident Law and Economics

Rizzo (1980; 1985) calls into question the application of typical neoclassical techniques, such as General Equilibrium analysis, to the realm of accident law due to the framework's inability to appropriately handle the dynamic nature of this facet of society. He demonstrates the hollowness of such doctrinal concepts as least cost avoider and last clear chance, among others. As well he questions the court's ability to calculate the social consequences of certain activity in light of the out-of-equilibrium prices that persist in the market (pp.309-310). While Rizzo's analysis culminates in the determination that the rule of strict liability is superior to the rule of negligence in terms of institutional efficiency, I refrain from judgment on this particular issue at this time. I contend that Rizzo's dissatisfaction for the neoclassical framework ultimately stems from his realization, though implicit, that the static neoclassical analysis is an inappropriate tool for the study of spontaneous orders. A method that does not rely on static, formal mathematical descriptions of behavior and instead embraces the dynamic nature of the system with outcomes that emerge as a result of individuals' decentralized decision making would be superior and perhaps overcome some of Rizzo's criticisms. Agent based computational modeling provides a powerful tool that allows a researcher to relax the general equilibrium assumptions, thus enabling greater realism while maintaining a tractable model. The result is the ability to develop models of interest to social scientists that are recognizable reflections of reality and ultimately capable of enhancing understanding of complex phenomena.

Rothbard (1997, pp.121-170) though an important contribution to the Austrian literature, is essentially an effort to justify a natural rights perspective using praxeological arguments and as such, is largely orthogonal to the discussion in this project. Beginning from his methodological origin of radical subjectivism and an ideological foundation in favor of strict property rights, he notes that intention is crucial in determining liability of an individual in a tort action. He examines the case of *Courvoisier v. Raymond* (1896), wherein a man is threatened by an angry mob. Another man emerges from the crowd and approaches the first. In his anxious state, the first man feels threatened and exercises his right to defend his person by shooting the second, who unfortunately turned out to be a plain-clothed policeman attempting to offer assistance. Rothbard argues that because the policeman's rights to person were violated, the defendant should have been found strictly liable for damages.

Several other contributors from the Austrian School extend Rothbard's arguments (Hoppe, 2004; Kinsella and Tinsley, 2004; Sechrest. 2004). As far as genuine chance encounters are concerned, all tend to argue in favor of the rule of strict liability, for largely normative reasons. However, the moral implications of various liability rules are outside the scope of this project. The model developed in this essay is meant to facilitate theorizing in an attempt to fill this gap with a more consequentialist perspective.

III. Law, Economics, and Spontaneous Order

Numerous researchers have noted that the body of laws that comprise the common law emerged as the result of a spontaneous order (Hayek, 1973; Posner, 1972). These laws have been modified incrementally for countless generations and evolved through an evolutionary process of hierarchical, yet decentralized attempts by various judges attempting to decide various cases on the basis of general principles. These laws also provide the foundation upon which the spontaneous order of society is built. Abstract, purposeless, and equally applicable laws facilitate the generation of order from the bottom up, as individuals are encouraged to use their particular knowledge of time and place to their own advantage. Fehl highlights the dual levels upon which spontaneous order exists:

> To identify the legal and moral framework as an important prerequisite of the spontaneous order is an essential point. As is well known, such 'rules' generate an order in themselves. They enable the individual to make plans involving the interaction with other individuals, insofar as the execution of contracts can, in principle, be expected by the actors. Thus plans can be carried out, even if the goals of the participating individuals are conflicting (Fehl, 1994, p.200).

The institutions of private property and freedom of contract facilitate the spontaneous generation of the market and the emergence of the price mechanism. Individuals refer to prices as guides in pursuit of profits, the existence of which is an indication that they have been successful in satisfying the most urgent demands of consumers, while the lack thereof is an indication of their failure.

While certain institutions of the law enable the emergence of an explicit price mechanism through trade, i.e. certain facets of private property coupled with contract law, other legal institutions serve merely to impose an implicit price for particular behavior such as criminal or tort law. For instance, the fact that the courts enforce a farmer's property rights in his apples, as well as mutually agreed upon contracts that govern their exchange, ultimately enables a market for apples to emerge the outcome of which is a market price for a given quantity and quality of apples. In contrast, the fact that the courts enforce a farmer's property rights in his house by levying a punishment of, say, two years in prison for burglary means that potential burglars face an implicit price for engaging in such behavior. They must weigh their perceived probability of getting caught and punished, by their subjective valuation of the magnitude of the punishment (Becker, 1976). This section examines the characteristics of spontaneous orders that emerge as the result of such non-market decision making.

A. Accident Law and the Emergence of Spontaneous Order

The law as handed down in the rulings of judges ultimately results in the emergence of an implicit price for engaging in risky behavior. Individuals gauge the riskiness of their behavior in terms of damage suffered in the event of an accident, as well as an expectation of how the courts might assign liability. Even if we assume that all participants know the exact liability rule in effect and all of its implications, the ultimate effects of the law upon the individual also depend upon the behavior of every other individual. Even if, say negligence was set at a particular level of care, some individuals may decide upon a behavior whose perceived expected value may result in either greater or less care, simply due to their unique preferences. The process through which individuals measure their perceived expectations with objective reality is highly stochastic due to the variation and interdependence of all other agents and greatly complicates an agent's ability to select behavior that achieves her desired outcome. In this way an implicit price emerges as a result of human action, but not of human design, in a manner parallel to a market price. So, just as the behavior of individuals engaging in market behavior may be considered a complex adaptive system, so may the interaction of individuals engaging in productive, yet accident prone activity.

There are two ways to conceptually frame the relationship between the judicial system and the individuals in society. The first is the more common perspective of the state as a unitary being that stands outside of the market, and intervenes, as necessary to correct deficiencies. Wagner (2007) describes this as the disjunctive perspective. It is disjunctive in the sense that the state is separate from the society of individuals that it governs. In applying these notions to the economic analysis of the law, the implication is that disjunctive analysis treats the judiciary as a monolithic organization that pursues goals with singular focus. The alternative paradigm is a conjunctive perspective, which acknowledges that even the state exhibits the qualities of a spontaneous order as opposed to an organization. "Within the framework of a conjunctive political economy, the state is not a sentient being that intervenes into the market, but rather is an institutionalized process or forum within which people interact with one another (Wagner, 2007, p.14)." In Wagner's analysis, there exists a market square for private transactions, and a public square for collective transactions where private property and residual claimancy is simply absent or attenuated. Individuals who seek to start an enterprise may select either forum to build the necessary relationships. In this view, the courts are simply another institution that resides in the public square.

A disjunctive analysis of tort law identifies the presence of externalities and market failure that give rise to disputes, such as the fact that people might drive too fast and impose too high a threat of accidents upon others. They recognize that the existence of transactions costs form a barrier to bargaining between accident disputants *ex ante.* So, it is incumbent upon the judiciary to decide matters such that the efficient outcome obtains and teleologically impose decisions or policy towards that end. Along the spectrum of concepts that range from the teleological to spontaneous, the interaction of the judiciary and those governed does lend itself to a teleological explanation from a certain perspective. An indifferent judge stands outside the case at hand and decides on matters of fact and matters of law that have repercussions to the individuals in society at large. Indeed, in much economic research, the institutions of private property, freedom of contract, and law of torts are assumed to work flawlessly and are relegated to the background. In neoclassical law and economics, the judiciary is seen as an independent body that intervenes as necessary to fine tune the rules governing the interactions of individuals such that society's wealth is maximized.

However, there are some characteristics of the law that are illumined from taking a more conjunctive perspective. The conjunctive view of the legal world embraces the notion that society is not a fully connected graph such that each element is connected to all others. While a single judge might reach a decision and set a precedent, that judge's power to actively change society is limited, because laws as handed down in judicial decisions still require the general consent or adherence of those to whom the law applies. In other words, judges should not expect the decisions they pass down to garner unquestioning obedience from all affected individuals. In a Hayekian sense, a judge's ruling in a case is not a command to an organization in the same way that a military leader commands his subordinates, but rather it helps form the rules of conduct that individuals consider before ultimately deciding upon a course of action suitable to meet their unique goals.

In addition, since judges often must rely on members of the executive branch of government to enforce the ruling, their ability to craft decisions to fully correct the deficiencies they perceive is even more attenuated. Finally, a judge's ruling might also be overturned on appeal; so many judges confine their decisions so as to limit the likelihood of being overturned. A main theme of this paper not only highlights the difficulties judges face when attempting to determine the wealth maximizing liability rule, but also the difficulty in anticipating how the individuals that comprise the complex adaptive system that is society will react to the ruling. This notion is similar to Lucas's famous critique (Lucas, 1976) for macroeconomic policy. When applied to this setting, it suggests that even if judges faced no knowledge problem regarding the determination of the optimal rule given the datum of behavior under the current rule, they still face difficulties in predicting how individuals will react to the new purportedly better rule.

IV. Spontaneous Order Economics and Agent Based Modeling

The modern notion of society and the division of labor as spontaneous order is generally considered to have originated in the writings of the scholars of the Scottish Enlightenment. Adam Smith's metaphor of an invisible hand that leads individuals "to promote an end which was no part of his intention" is a reference to this order (1981). Smith's contemporary, Adam Ferguson, is credited with coining the phrase to describe emergent unintended outcomes as "the result of human action, but not the execution of any human design (1782)." These scholars sought to highlight how the actions of individuals create an order within which individuals cooperate through the division of labor.

Carl Menger's seminal contributions (1994 [1871], 1996 [1883]) provide a foundation upon which much of spontaneous order economics is built. While he is credited, along with Leon Walras and Stanley Jevons, with initiating the marginal revolution, his was a distinctive contribution. His compositive method represented an attempt to trace emergent phenomena back to the actions and preferences of individual actors. A critically important aspect of Menger's methodology and theories he developed is the nearly complete absence of the notion of equilibrium. He begins by examining the choice problem that a single individual faces and subsequently adds additional individuals enabling the emergence of phenomena such as exchange, money, and property, among others. Mises (1996, p.405) cites Menger's description of the origin of money as an irrefutable praxeological theory and offers it as a fundamental example of the praxeological method of research. In this section, I outline how agent based modeling may be employed in the analysis of spontaneous orders and attempt to reconcile the use of this tool with the methodological requirements of Austrian economics.

A. The Application of Agent-Based Modeling

Spontaneous orders are also known as complex adaptive systems in the artificial intelligence and computational economics literatures. Complex systems are composed of interacting agents that exhibit emergent properties (Tesfatsion, 2006, p.836). A system is complex if it is composed of interacting units and exhibits emergent properties that cannot simply be deduced from aggregating the system's components, while emergent properties are those "properties arising from the interactions of the units that are not properties of the individual units themselves (p.836)." Further, a compex adaptive system is "a complex system that includes *goal-directed* units, i.e. units that are reactive and that direct at least some of their reactions towards the achievement of built-in (or evolved) goals (p.837)." Agent-based models, properly constructed, are themselves complex adaptive systems in that goal-directed agents interact to exhibit emergent properties and respond to each other and their environment. The emergent objects, in this case the implicit price of a particular behavior, is the result of the complex process of interactions of individuals. These individuals do not set out to minimize the social costs of accidents, they simply select courses of action on the basis of their subjectively valued ends and their perception of the means available to achieve them. To the extent that certain phenomena exhibit complexity, agent based modeling represents a potential tool to facilitate the development of an invisible hand explanation of such phenomena.

Agent-based simulation is capable of illuminating aspects of spontaneous orders that might be neglected or overlooked if using more formalistic and static neoclassical methods. In simulated artificial societies deeply heterogeneous agents interact with one another as they collect local information, take action on the basis of simple rules, and adapt their behavior on the basis of their experiences. Outcomes emerge not as a result of an imposition from above, as in Walrasian theorizing, but from the self-ordering of the individual agents. Agent-based simulations offer researchers an opportunity to gain insight into how individuals use knowledge, and how institutions guide their interactions.

As Epstein (2006, p.1588) describes, the following are some general features typical of most agent based models:

a. Heterogeneity. Every individual is explicitly represented and their instance variables are allowed to differ in substantial ways in relation to other agents. The manner in which agents are allowed to differ from other agents is limited only in the number of characteristics modeled.

b. Autonomy. There is no leader in charge of agents' behavior. Agents alter their behavior as a result of interactions with other agents and their environment.

c. Explicit space. Events transpire in an explicitly defined environment, which means the notion of "local" is well posed.

d. Local interactions. Agents are allowed to interact with other agents, i.e. neighbors, and their environment on the basis of particular rules of conduct.

e. Bounded rationality. Agents possess neither global information nor infinite computational capacity. While they may be purposive or goal seeking, agents are typically unable to strictly maximize their behavior.

f. Non-equilibrium dynamics. The process through which agents coordinate their activities is the focus of the research, as opposed to the end state.

Agent-based modeling is well suited for studying systems composed of interacting agents which exhibit emergent properties "arising from the interactions of the agents that cannot be deduced simply by aggregating the properties the properties of the agents (Axelrod and Tesfatsion, 2006, p.1649)." Perhaps the most important attribute of agent-based modeling is its ability to model out of equilibrium behavior. Whereas mainstream neoclassical theorizing asks which agents' behavior are consistent with a final equilibrium outcome, ABM [Agent-Based Modeling] facilitates analyzing how agents' behaviors endogenously change with each others' (Arthur, 2006, p.1534). The equilibrium approach lends itself to a closed form analytical solution. With analytical solutions, one achieves generality and syntactic clarity. However, as discussed below, the ability to achieve closed form equations that describe these outcomes often requires the sacrifice of detail and complexity in order to maintain mathematical tractability. The advent of agent-based modeling provides the researcher with a tool that can make the modeling of complex phenomena more tractable while attaining improved levels of realism.

Epstein and Axtell's (1996) Sugarscape model marks a seminal application of agent-based simulation to the study of spontaneous order economics. The authors leverage the capabilities of this technique and eschew common assumptions such as homogeneous agents and equilibrium in an effort to endogenously generate phenomena like trade, culture, disease, and war. In their words:

> The broad aim of this research is *to begin the development of a more unified social science, one that embeds evolutionary processes in a computational environment that simulates demographics, the transmission of culture, conflict, economics, disease, the emergence of groups, and agent coadaptation with an environment, all from the bottom up.* (p.19, emphasis in original)

The present work is an effort to continue this line of research and apply it in the examination of accident law.

Gilbert and Troitzsch (2005) outline a number of reasons why simulation is useful to the social scientist. Chief among these, and the one most consistent with the purposes discussed in this paper, is the ability to gain an understanding of complex social phenomena. The authors review several agent-based simulation studies, Epstein and Axtell (1996), Drogoul and Ferber (1994), Doran *et al* (1994), and Jager *et al* (2001). Additional examples of the successful application of agent-based simulations to the study of spontaneous phenomena abound. Tesfatsion (2006, pp.866-877) generates market behavior through the interactions of decentralized agents and without the aid of a Walrasian auctioneer. Hewitt and Clower (2000) and Axtell (2005) both apply agent-based simulation to market processes in an attempt to make market behavior more intelligible. As well, Vriend (2006) provides a cursory survey of a wide range of agent-based models with special emphasis on those employing assortive interactions. While agent-based modeling literature is relatively new, the previous examples show tremendous potential for future research. Agent-based models can also fruitfully be applied to research problems that are not strictly of an economics nature. Axelrod (1997) contains examples of agent-based models applied to numerous multidisciplinary problems such as variations of the Iterated Prisoners' Dilemma, promoting norms, conflicts and transmitting culture. For an extensive survey of the use of agent-based simulations to examine social dilemmas, see Gotts et al (2003).

While spontaneous orders may achieve any degree of complexity imaginable, those of concern to social science are arguably complex enough to defy exhaustive understanding due to the limitations of human intelligence. Due to the multiplicity of interactions between various individuals all acting on the basis of dispersed knowledge, only (estimates of) global or summary variables might be obtainable by an outside observer, such as the aggregate unemployment rate or the consumer price index as an estimate of inflation. And while certain global variables might display a particular statistical relationship over a period of time, these variables do not "act" on each other, they are not true objects of choice, and the underlying statistical relationship is ultimately transient and bound to change with the underlying conditions.

As Hayek (1964) points out concerning the study of complex phenomena, often the best one can achieve is an explanation of the principle which governs the emergence of outcomes. "[T]he science of complexity is about revealing the principles that govern the ways in which these new properties appear (Vicseck, 2002, p.131)." Simulation facilitates the understanding of the inner workings of complex phenomena and helps to illuminate the process through which outcomes emerge. While simulation begins from a necessarily arbitrary and reductionist foundation, the process of following interconnected chains of causation from the actions of individuals through the macro-level phenomena parallels Menger's methodology.

Mainstream positivist social scientists hold that the true measure of a theory is how well that theory's predictions match the empirical data (Friedman, 1953). Alternatively, Hayek holds that while scientists may obtain an analytical description of simple phenomena which lends itself to empirical falsification, complex phenomena defy such description and the best a scientist may hope to achieve is an explanation of the principle in operation (Caldwell 2002, pp.300-302). As Gilbert and Troitzsch remind us, nonlinear interactions are inherently difficult to predict. "Complexity theory shows us that even if we were to have a complete understanding of the factors affecting individual action, this would still not be sufficient to predict group or institutional behavior (2005, p.11)." An alternative course of action that simulation models enable is to base a theoretical model on relatively more realistic assumptions and through the chain of logical reasoning to deduce the outcome of the models.

As is typical for any scientific method of examination, there exist advantages and weaknesses to any particular means of analysis chosen. As many of the advantages of agent-based modeling were described above, it is important to outline some of the weaknesses. Some have been addressed by earlier scholars while others are still awaiting a conclusive answer.

In what Epstein (2006) describes as “the indictment” of agent-based modeling, he notes the following common objections: agent-based models lack equations, the technique is not deductive, and they lack generality. His responds that agent models are computer programs that could be described by a set of recursive mathematical equations. However, such equations would be incredibly complex and barely intelligible whereas the agent model is immediately recognizable as a model (p.1591). In response to the charge that agent-based models are not deductive, Epstein notes that each realization of an agent-based model is in fact a strict deduction (p.1592). In answering the related charge that because the approach is computational, it does not constitute theory, Arthur (2006, p.1555) notes that “If working out the implications of a set of assumptions is theory, then whether it is done by hand or by computer does not matter. Both methods yield theory.” Finally, against the charge that agent-based modeling lacks generality, Epstein, grants that agent modelers generally do not quantify their models over ranges of variables as wide as standard general equilibrium theory (i.e. the set of all consumers and assuming utility maximization for every agent) but suggests it is the price of empirical progress (p.1599). While these and other similar objections to agent-based modeling may persist, it is important to remember that the ultimate goal of employing such a tool in analysis is greater understanding of social phenomena.

B. Austrian Economics and Agent-Based Modeling

As previously stated, this project is an attempt to show the usefulness of agent-based simulation as a tool for the economic analysis of the law. Researchers working in the fields of Agent-Based Modeling and various facets of simulation study inform the analysis, but it is also heavily influenced by numerous scholars of the Austrian School, and particularly their contributions to the theory of the market process. As such, I attempt to show that agent-based simulation, appropriately applied, can be a useful tool for all scholars who study market and non-market processes.

Boettke and Leeson (2002) offer an outline of the core tenets of how the Austrian school of economics frames its theorizing. While many of the tenets have been (at least superficially) absorbed into neoclassical economics to some degree, taken together, they outline the basic methodology and substance of Austrian economics. The three core methodological tenets are methodological individualism, subjectivism, and the notion of the market as a process (Boettke, 1994). Austrian theorists, perhaps more than many other economists embrace the notion of the market as a process through which the subjective demands of consumers are met with the scarce resources available. The fact that process, individual choice under uncertainty, and subjectivism are in the foreground of their analyses has led the scholars following this tradition to turn their attention to the coordinating effects of entrepreneurship, money, and social institutions that enable individuals to better cope with uncertainty.

Hayek dedicated the vast majority of his life's work elucidating the intricacies of spontaneous order. According to him, order is achieved when the individuals in a society adjust their behavior such that accurate expectations might be formed regarding their future conduct (Hayek, 1973, p.36). The price mechanism is one social institution responsible for enabling individuals to pursue and achieve coordination of consumption and production plans in a decentralized manner. The division of labor is a grown order in which individuals pursue their own goals and are able to coordinate their behavior by sending, receiving, and interpreting price signals communicated as a result of their participation in the market. Alternatively, an organization is a made order, where relationships are formed exogenously and information flows through consciously developed channels (Hayek, 1973, p.37). In organizations, subordinate units carry out the plans of superior units and execute only the tasks assigned them.

The quintessential organization is a military unit. The members of the organization constantly look for guidance from their leader, as they are rarely delegated the authority to make decisions based purely on their local knowledge. Rather, they feed this local knowledge up the chain-of-command so that the commander may make his decision based on the aggregation of all the subordinate knowledge. The nature of organizational decision making and the concomitant limitations of the human mind's ability to process information place significant constraints on the complexity of organizations and their ability to adapt to rapidly changing situations. In an organization, order is maintained by the unitary action of the leader and the alacrity with which his commands are executed.

Order is grown endogenously in a spontaneous order as individuals adhere to rules of conduct on the basis of particular information of time and place (Hayek, 1973, p.37). Outcomes emerge as result of purposive action on the part of agents, rather than the result of the design of any one particular mind. Hayek argues that it is the nature of the rules that govern individual interaction that determine whether order is grown, made, or achieved at all. While the rules that govern an organization tend to be concrete and provide relatively specific instructions to specific individuals with the intent of accomplishing a stated goal of the organization, the rules that govern a spontaneous order are abstract, purposeless in the sense that particular collective outcomes are not pursued, and equally applicable to all individuals. Such rules enable individuals to make the most appropriate use of their specific knowledge of time and place while enabling order to emerge spontaneously.

While agent-based simulation as a method, properly employed, appears capable of complementing the spontaneous order economics of F. A. Hayek, there are certain aspects of the body of Austrian work that may not be as accommodating. For instance, it would appear that the extreme apriorism of praxeology as a method of inquiry should cause Austrians to reject agent-based modeling as too empirically oriented and arbitrary. However, I intend to show that most of the apparent differences can be adequately resolved.

It is difficult to argue that agent-based modeling is as rigorous as the demanding methodological constraints of praxeology. Praxeology begins with the action axiom that states that human beings act to remove a certain felt uneasiness (Mises, 1996; Rothbard, 1997). This axiom is held to be true *a priori.* Any theories deduced from the axiom are held to be true with didactic certainty, as long as the chain of logical reasoning is valid. Certain postulates may also be added, such as the notion that individuals perceive a disutility of labor, which change only the domain under which the resultant theories are operative. Thus, any theories derived from such a postulate are held to be true, but only in those instances where (*ceteris perabis*) leisure is preferred to labor.

Agent-based models are representations of particular sets of assumptions instantiated in computer code. Each simulation run is a realization of the chain of deductions based on the set of assumptions, or as Epstein (2006) notes, every simulation replication is essentially a sufficiency theorem. Upon completion of an experimental design, the researcher uses inductive techniques and statistical analysis to choose among the population of candidate theories that the simulation has produced. While this process of induction is not necessarily of the same character as the scientistic empiricism that Austrians tend to criticize and seek to avoid with aprioristic techniques, it is possible a model may produce competing theories. The criteria developed to select between competing theories would not be immune from the arbitrary opinions of the researcher and thereby limit the theory's universality. However, it does represent a step in the direction of greater realism relative to the neoclassical framework. And, while the conclusions arrived at would not necessarily be true with didactic certainty, the goal of such research is to achieve pattern predictions and explanation of principles rather than universal laws.

A computer model, such as an agent-based simulation, must be built upon much narrower assumptions than the action axiom. As such, it is necessary to make arbitrary decisions regarding the assumptions that govern agents' behavior. For instance, in their Sugarscape model, Epstein and Axtell (1996) found it necessary to make assumptions regarding the particular characteristics of the agents' motivation for collecting and consuming sugar. Among the infinite number of mechanisms to govern agent behavior, one must be chosen and instantiated in the model. So, a critic might argue that the conclusions arrived at in the Sugarscape study are only valid for humans that eat only sugar and have significantly restricted vision, etc. However, that charge misses the point of a simulation study of simply gaining an understanding of the complex mechanism under examination.

Mises developed his methodology to study praxeology in an attempt to craft a universal theory of human action independent of time and place. As such, it was necessary to purge any ad hoc or contingent elements from the framework, since the presence of arbitrary premises would ultimately limit the application of the theory. Arbitrary designs might creep into the development of an agent-based model, and thus limit its application to only that domain in which the peculiar notion is operational. However, it is important to note that there is much more to good economic theorizing than praxeology. After all, as Lavoie (1994) states, "doing economics in an Austrian way is tracing systemic (spontaneous order) patterns of events to the (subjectively) meaningful purposes of (individual) human actors (p.56; parentheticals in the original)." As such, I intend to show that agent-based simulation is consistent with much of *the rest* of Austrian economics.

Mises recognized that the science of human action has a theoretical and a historic aspect (Mises, 2003; 2006). Properly understood, theory is a tool that the student of human action employs in order to make sense of history. The employment of conjectural history, is a technique in which the theorist develops historically contingent theory. When conducting conjectural history, reference is made to specific institutions, policies, or other arrangements that were present in reality at the time.

> Such conjectural histories therefore make use of the ideal-type constructs (these constructs, to be sure, never refer to ideal-typical *people*, but only to ideal-type *objects* or *consequences* of action), although their truth follows apodictically where all the real-life equivalents of the specified ideal-types are present in a given historical circumstances. Causal-genetic or "evolutionary" theories such as Menger's theory of the origin of money fall into this category of conjectural history (Selgin, 1988, p.27; emphasis his).

Theory developed in this manner is highly contingent on the underlying assumptions, but it is indispensable to the analysis of economic phenomena that appear in reality. Agent based simulation can assist researchers in the conduct of conjectural history by facilitating the examination of complex processes. It is capable of employing ideal-types, both agents and institutions, and ultimately assists the researcher in providing a genetic-causal explanation of social phenomena.

In his discussion of the use of ideal types in economics, Koppl (1994a) notes that ideal types are "intelligible" representations of actions or actors (p.72). He goes on to explain that the generality of an argument based on the use of ideal types depends upon the anonymity of the ideal type used. "The anonymity of a personal ideal type is the degree to which it is empty of particular content (p.73)." Thus, the more anonomously the agents inhabiting artificial societies are developed, while remaining recognizable to human beings as actors, the more effective will be their employment as ideal types.

In Cowan (1994) and Cowan and Rizzo (1996), the authors elucidate the importance of the notion of causation in economic analysis. The genetic-causal approach they outline embraces the notion that the cause of an outcome "creates a unidirectional *process* the outcome of which is the effect (1996, p.274)." Purposive human behavior, traced back to the tastes and expectations of individuals, are the endogeneous causes of these outcomes. Typical mainstream equilibrium economics eschews notions of causations. After all, in order for a cause to originate, a change must occur, but change is essentially precluded in the equilibrium framework. Agent-based modeling is uniquely suited to illuminate these complicated chains of causation that result in emergent unintended outcomes. The models are capable of providing researchers with comprehensive information regarding the state of each and every individual agent in the population, which enables the researcher to follow chains of causation from their inception to their ultimate end. However, it should be stressed that such endeavors are truly only fruitful if they lead to greater understanding of actual processes.

Cowen and Rizzo (1996, p.301) borrow what Bunge (1960, p.401) terms as a *poistem*, or "a system of interrelated qualities or variables." They demonstrate that certain mainstream analyses conclude in a poistem, simply because the answer is mathematically derived and lacks any notion of asymmetrical causation. See Chapter 5 below for a more thorough analysis of this concept and how it applies to neoclassical law and economics models. These models may be used to derive optimal agent behavior given a particular liability rule, however, they lack a description of the process by which individual, self interested agents are provided the appropriate incentives that induce socially optimal behavior. If individuals' response functions are sufficiently interdependent, then achieving individual maxima may not achieve the social optimal. I demonstrate in Chapter 6 that an agent-based model that implements an evolutionary algorithm for individual agent strategy selection overcomes this quandary. Such a model embraces the genetic-causal tradition to which Austrians have contributed and I argue that it provides a reasonable example of how an agent-based model may contribute to the Austrian perspective of law and economics.

It is difficult in the extreme to imbue artificial agents with the full character and quality of purposive human action. The inability to capture the open-endedness of how humans manage their subjective means-ends framework is a shortcoming that agent-based simulation as a method may never fully overcome. To the extent that the agents in the model capture relevant characteristics of the action axiom, then the more effective the simulation model is bound to be in illuminating the phenomena under consideration. While it is true that the artificial societies depicted in agent-based models lack the complexity and richness of human society, and the agents that populate these virtual worlds lack the intelligence of human beings, it is also true that the agents' relative ability to act within their society might be comparable (Lavoie, 1994b, p.554). Virtual agents certainly are not as creative or innovative as the individuals they mean to portray, but relative to their world, they could be considered creative as they are capable of learning from experience and adopting courses of actions as a result of trial and error (Lavoie, 1994b, p.554). Thus, artificial agents are subject to the criticism that they are not and perhaps never will be capable of achieving the intelligence and creativity of human beings, but they are capable of innovation relative to the worlds they inhabit.

Mises makes clear that "specific method of economics is the method of imaginary constructions (1996, p.236)." Of course some imaginary constructions are more useful than others when it comes to promoting the understanding of social phenomena. In this section I have argued that agent-based modeling can assist in the development of such imaginary constructions. To date, most Austrians have refrained from exploiting the capabilities inherent in agent-based modeling. However, there have been scholars that have recognized its potential contribution. Lavoie notes that "Agent based simulation may be a useful way to expand the Austrian School's set of expositional tools (Lavoie, 1994b, p.549)." He, correctly I believe, points out that "The theorist might use visualization of dynamic market processes to help think through the logic of the dynamics (p.552)." Agent-based simulation provides the theorist with a means to elucidate the dynamic processes of the target phenomena and lead her to develop a meaningful genetic-causal explanation of its emergence.

V. Discussion

If I have successfully argued the point that the individuals respond to tort law in a decentralized and spontaneous manner and that agent-based modeling is an effective tool with which to analyze such spontaneous orders, then all that is left is to build the model and determine if it enhances our understanding of accident law. The remaining chapters of this dissertation are dedicated to this end.

The application of emergent economic techniques to the analysis of tort law often generates different research questions than those typically addressed with neoclassical analysis. Neoclassical researchers tend to examine the theoretical implications of various notions of efficiency and welfare enhancement of different tort rules. The extensive controversy regarding strict liability versus negligence is one such thread of research. In contrast, the emergent economic perspective is able to highlight the genetic-causal aspects of agent-behavior. That is, the model assists the researcher in tracing the outcomes that emerge back to the preferences and expectations of individual actors. Such a methodology is well suited to answer such questions as how individuals collect the information required to make their decision and the role that institutions play in this process. This perspective embraces the dynamic nature of this complex adaptive system and is able to track changes over time. In addition, its ability to adequately handle numerous heterogeneous agents means that it is possible to pursue questions concerning how various agents interact with one another and realize varying levels of success. These concepts and more will be explored further in Chapter 6.

In this chapter, I have attempted to make the case that individuals form a spontaneous order in response to the institution of tort law, each other, and their environment. I further argue that agent based modeling provides an effective tool with which to examine accident law. Axelrod (2006) declares that agent based modeling facilitates interdisciplinary collaboration, provides a useful multidisciplinary tool when the math is intractable, and can reveal unity across disciplines. When utilizing this method of research, Arthur recommends that "good work here shows an eye for elegance of experiment for the telling, simple, computational model that demonstrates a phenomenon clearly; and for extracting a phenomenon from the jumble of other data that obscure it (Arthur, 2006, p.1555)." In the remaining chapters I attempt to extract certain effects of accident law from the jumble of data that obscure it and chart out a course for further research that exploits this capability.

Chapter 4: An Agent-Based Model to Analyze Accident Law

I. Introduction

The purpose of this project is to explore the notion that the economic analysis of tort law would benefit from the perspective that spontaneous order economics provides. Towards that end, I also examine the capacity for agent-based computational modeling to assist in this endeavor. In order to highlight the relative strengths and weaknesses of the mainstream and the proposed approaches, I analyze the same scenario first applying the techniques of the former, then the latter. This process will not only reveal the relative efficacy of either approach, but perhaps most importantly, it will illustrate the types of questions that each approach tends to generate and ultimately facilitate a discussion of which perspective enhances our understanding of the social world.

The scenario I analyze is the plight of a fictitious society known as Eggtopia whose inhabitants face tradeoffs concerning productive behavior and reducing the costs of accidents. While this world is an abstraction from reality, it is not so abstract that significant features of our own world are unrecognizable within it. In subsequent chapters I will analyze the problem the inhabitants of Eggtopia face, first using a neoclassical framework and then using an emergent framework. In order to overcome the fact that Eggtopia does not actually exist, I develop an agent-based model that represents a computational version of this imagined society. The agent-based model provides an opportunity to conduct a number of productive inquiries. The first is that it provides a laboratory to test the effectiveness with which the neoclassical paradigm leads to the understanding of individual behavior. While law and economics scholars are typically unable to perform systematic experiments to test the effectiveness or efficiency of various tort rules, the agent-based model developed in this chapter may be used that way. In the following chapter I utilize the model to generate a myriad of data to which I apply the tools described in Chapter 2, answer the questions typically addressed in neoclassical analysis and subsequently test the effectiveness of the framework for providing answers to them.

The second inquiry I undertake is to use the model to apply techniques from evolutionary economics to analyze accident law. This approach suggests that the geometry of economic space is best modeled, not as a field, but as a less than fully connected graph (Potts, 2000). It embraces the notion that the process through which individuals learn about their environment and interact with others on the basis of their local knowledge is of primary importance. The advantages of agent-based modeling include the ability to model how heterogeneous agents may alter their behavior using various processes through time. The emergent approach may be used to answer similar questions generated from the neoclassical framework, but the flexibility and the dynamic nature of the model opens up a vast array of interesting threads of research, several of which will be outlined and pursued in this project

II. Eggtopia, a Fictional Society

Imagine a society known as Eggtopia. The inhabitants are human beings, and are just like any other human beings in their ability to use their senses to collect information about their environment, as well as their ability to take action on the basis of that information in conjunction with their subjective valuation of the relative benefits of means and ends. In addition, these individuals possess the same physical attributes as any other human being such as visual acuity, strength, ability to move, etc. The members of Eggtopian society enjoy access to relatively free markets and a moderately liberal order based on private property and freedom of contract. Among other services, there exists a civil court system in which parties resolve private disputes relating to contracts, property, and torts. In many respects, Eggtopian society is indistinguishable from nearly any other in the Western world.

A significant source of income in the Eggtopian economy is based on the sale of eggs and egg products. These eggs are scarce, extremely fragile, and incredibly valuable, thus a large proportion of Eggtopians are employed in their collection. The eggs are found in the vast Egg Fields, where they lie just below the surface, relatively easy to spot by the trained eye and easily extracted. Individuals search the fields with varying levels of intensity and fill their baskets with the eggs they find. Upon filling their basket to capacity, they return home as expeditiously as possible to store them for later use.

Unfortunately, for all their skill and talent, the process of searching for eggs, extracting them from the ground, and storing them securely is fraught with danger. In their haste to collect as many eggs as possible, accidents between Eggtopians are relatively commonplace. When two individuals attempt to occupy the same location in space, the force of their collision completely destroys the eggs the victim was carrying. Eggtopians face a challenge similar to that of many members of this society. That is, engaging in productive activity also brings with it distinct risk of accidental damage to self or property. Changing behavior along margins that improve productivity, such as speed of travel, also may increase the possibility of an accident occurring.

When an accident occurs, the parties to the accident decide upon how to proceed pursuant to the relevant accident law and pertinent facts of the case at hand. The effect of accident law as an institution is to provide guidance to individuals regarding "appropriate" behavior as it pertains to accidents and duties owed to others. Participants to market exchanges have the luxury of performing economic calculation to determine profit and loss as a means of assisting *ex ante* in decisions regarding considered courses of action and *ex post* evaluating the success of those actions. Price alone is not a reliable guide for the decision to engage in potentially dangerous activity, due to the fact damages that occur as a result of the accidents are not necessarily implied in the market price. A typical analysis of such a decision parallels that of Becker's description of criminal behavior and optimal punishment (1976, pp.39-86). Becker suggests that criminals weigh the payoff of criminal activity versus the cost of getting caught discounted by the probability of being arrested and ultimately prosecuted and found guilty. Thus, an individual would weigh the payoff of risky behavior against the concomitant damage discounted by the probability of the destructive event occurring. Richard Posner, among others, has asserted that the purpose of tort law is to induce efficient behavior via the legal distribution of damages in tort cases (2007).

The fictional Eggtopian society is rather stylized concerning the circumstances surrounding the egg collection and production, but is still recognizable enough to reality to glean insights common to individuals' behaviors regarding accidents. The general keys to analysis of accidents in the virtual world of the model are no different than analyzing accidents in the real word. In reality, accidents typically occur while both parties are engaged in otherwise productive behavior. In the model, agents are constantly in the process of collecting and storing valuable eggs. In the course of evaluating their behavior, individuals may take measures that reduce the likelihood of an accident occurring, however, these activities may simultaneously inhibit productive behavior, i.e. as when the driver of a delivery truck were to maintain a relatively slower speed, it may reduce the probability of an accident, but it also increases the time it takes to transport the goods she is hauling. There is a clear parallel between this line of thinking and say, the accidents that occur between drivers of automobiles. In fact, the idea is so general as to apply to almost any productive, yet risky, endeavor.

The intent of this mental construct is to serve as the target of an economic analysis of accident law. Since Eggtopia is a figment of the author's imagination, no empirical data, case law, or historical record exists that describes in detail the activities of its inhabitants. Part of the reason for the relative dearth of empirical law and economics studies is the difficulty of obtaining data conducive to analysis and testing. In this case, agent-based modeling provides the mechanism to generate data and overcome this challenge.

I begin with the standard neoclassical analysis as a point of departure and draw heavily from Posner, Shavell, and others. Following their lead, I develop a formal mathematical model that describes the social welfare function of representative agents in terms of accident costs and costs of prevention. As faithfully as possible, all relevant assumptions are maintained in the implementation of the model (i.e. only two types of agents, victims suffer damages, risk of accidents varies with level of care selected, etc). I then implement an agent-based computational model as an artificial social laboratory to conduct experiments aimed at generating empirical data and ultimately analyze the data using the neoclassical tools. Not only does this effort provide an opportunity to test how well the neoclassical perspective explains the behavior of Eggtopians in this situation, but it offers insight into the effects of several important assumptions that underlie neoclassical law and economics.

In a subsequent chapter, I dispense with the neoclassical framework and replace it with a more dynamic evolutionary one to further leverage the capabilities of the agent-based approach to solve the same problem. I show that the agent-based approach enables the use of dynamic evolutionary techniques that embrace the spontaneous nature of the extended order of society. Such a framework is easily capable of facilitating vastly more complex relationships among individuals and is not constrained to the extent that formal mathematics constrain the Posnerian model. I argue that the approach ultimately sheds more light on how social institutions guide individuals in their behavior.

III. An Artificial Implementation of Eggtopia

As a point of departure, I develop a model similar to that described in Thébaud and Locatelli (2001), which the authors utilize to examine questions regarding the emergence of property rights. It is implemented in the Java object oriented programming language and makes liberal use of the Recursive Porous Agent-based Simulation Toolkit (REPAST), an agent based simulation package originally developed at the University of Chicago, but is now maintained by REPAST Organization for Architecture and Development (ROAD)[7]. The toolkit consists of a broad library of classes that provides the foundation upon which the simulation model is built. In each of the scenarios described below, an experimental design is implemented and data collected. All data analysis is conducted using the JMP 8.0 statistical analysis application, which is a product of the SAS Corporation[8].

The model of Eggtopia is comprised of a two-dimensional torus grid that is rather densely populated with both heterogeneous agents and eggs. The agents possess various attributes (instance variables), to include egg carrying capacity, visual range, and speed of movement. Upon locating an egg, the agent picks it up and carries it with him while continuing his search for additional eggs. Agents are limited in their ability to simultaneously carry multiple eggs and upon reaching their maximum capacities they must return "home" to unload their collection before resuming their search. Every agent is assigned a unique random location on the grid as home position upon initiation of the

[7] See http://repast.sourceforge.net/ for more information.
[8] See http://www.jmp.com for more information.

model.[9] In the course of maneuvering through their environment, agents occasionally collide with one another. When agents collide, the eggs the victim was carrying are destroyed. A tort rule is immediately employed to adjudicate the disputes the arise surrounding the aftermath of these accidents.

Assume a set of eggs, spread randomly across a two-dimensional torus grid. A set of agents that each possesses attributes of vision, capacity, and speed, inhabits the environment. An agent's vision is the radius of the circle, measured in grid cells, within which it is capable of locating an egg. An agent's capacity is the maximum number of eggs an agent may carry before he must return home and unload his collection, and an agent's speed is the maximum number of grid cells an agent may move in a single timestep. Whenever an agent collects an egg, a new egg immediately appears in a random location on the torus.

[9] For simplicity, the agent's initial position at the beginning of the simulation run is deemed its home position.

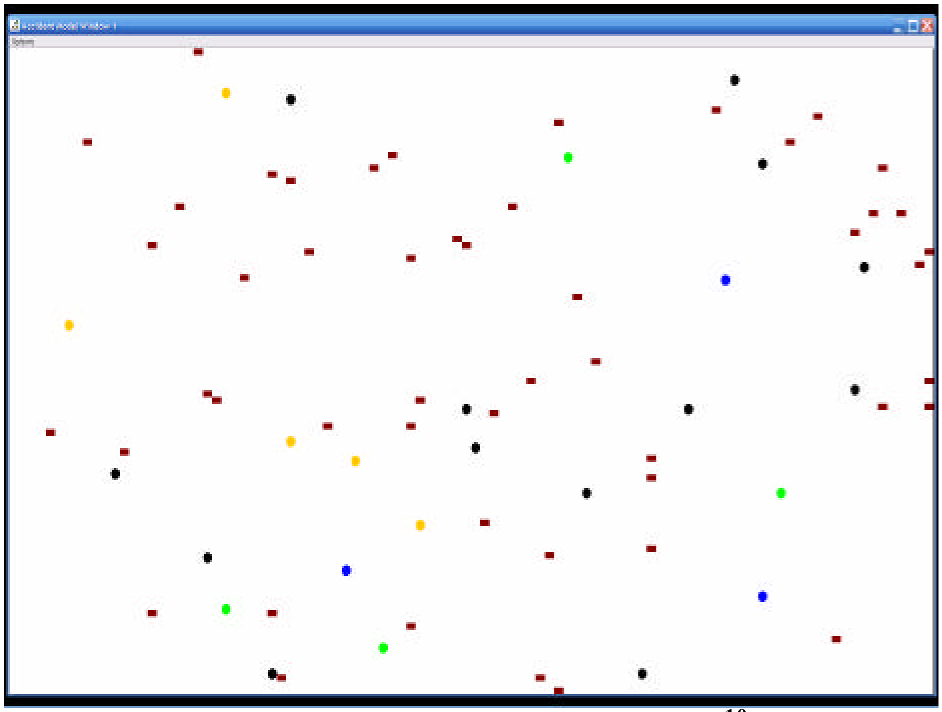

Figure 4.1. Screen Capture of Model Display.[10]

Agents are always in one of four modes of activity. An agent is in *search* mode when it is actively exploring the environment in search of eggs. While searching, the agent randomly selects a heading within ninety degrees of his current heading and moves in that direction. Upon locating an egg, the agent enters *collect* mode and selects the most direct route towards the target egg. When the agent reaches the cell containing the egg, it picks it up and adds it to its collection. The agent returns to *search* mode if there remains excess capacity in his basket. However, if the number of eggs in its collection meets his capacity, the agent enters *return* mode. In this case, the agent takes the most direct route to his home cell and drops off his collection of eggs. The eggs are then

[10] The red rectangles are eggs, while the round objects are agents. The colors of the agents indicate their mode of action: green – search mode; orange – collect mode; blue – return mode; and black – rest.

deposited into a virtual savings account, making them inaccessible to other agents in the model. However, while the eggs are inaccessible, the agent may be required to pay penalties according to the tort rule currently enforced out of his savings. Figure 4.2 is a graphical depiction of the general outline of the model.

The final behavioral mode is *rest*. Under certain configurations, agents are allowed to select their level of activity. This is implemented by enabling agents to rest for a proportion of their time. When an agent is resting it cannot move, but it also cannot be involved in an accident, even if another agent attempts to share its location. The benefit to the agent of resting is the protection from damaging accidents, and the cost is the potential eggs it forgoes as it sits motionless. Agents are assigned a rest parameter between [0,1] as a state variable. During each step, each agent conducts a Bernouli trial to determine whether it will rest. Shavell (1980), Posner (1972), and others have suggested under a rule of strict liability, individuals will tend to limit the quantity of the activity as well as engage in a certain amount of care. Alternatively, under a negligence rule, individuals will tend to exercise due care but not economize on their behavior in other ways.

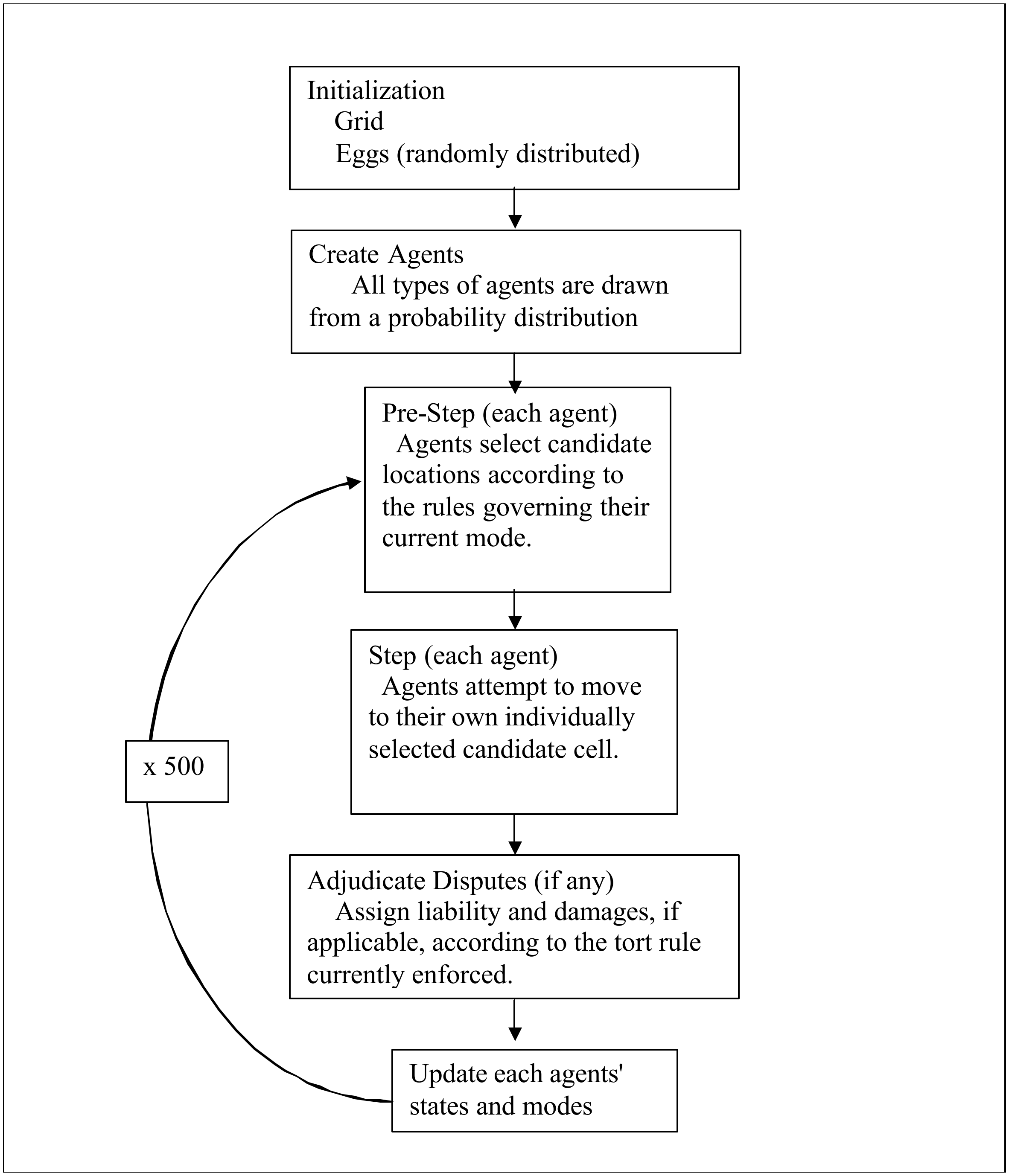

Figure 4.2. Graphical Depiction of the Basic Model.

The process of collecting eggs and bringing them home is a productive endeavor and the efficiency with which a group of agents is able to collect the eggs distributed in the environment is a function of the individual agents' attributes of vision, capacity, and speed. All else equal, agents with greater vision and speed will tend to collect eggs more quickly than their lesser endowed counterparts. An agent's higher capacity allows it to spend more time actively searching for eggs, since agents with lower capacities spend relatively more time returning home delivering their eggs. Like wealth, the number of accidents and the magnitude of accident losses is also a function of agent attributes. An agent with greater speed travels longer paths with each step which increases the probability of interacting with other agents, while agents with a higher capacity are more likely to suffer high losses when involved in an accident.

Note that regardless of the agent's mode, during the *Pre-Step* the agent selects a candidate location on the grid to occupy in that timestep. If another agent lies anywhere on the path to the target cell, an accident occurs between the two agents. If more than one agent lies on the path of the agent in question, only the closest agent is selected for involvement in an accident. The subsequent interaction is governed by whichever liability regime is in effect.

The agents that populate the model single-mindedly pursue the goal of collecting eggs. They possess no explicit choice algorithm nor do they form expectations regarding the future. One might say that if they possess a utility function at all, it is a lexicographic preference for eggs to the exclusion of all other goods, i.e. leisure, safety, etc. Modeling such zero intelligence agents has precedence in the computational and behavioral finance literature. In an influential article, Gode and Sunder (1993) utilized what they termed zero intelligence traders to examine the institutional effects of particular auction rules. See Duffy (2006) for a comprehensive survey and assessment of this literature.

While Gode and Sunder's agents selected their bids randomly, there is no randomness when it comes to an agent's preferred choice in this model. The agent chooses to search for eggs, though there is a stochastic element to the strategy the agent employs to carry out that end. While such an algorithm is perhaps an insufficient description of human action, it does provide a blank slate of sorts to allow for all sorts of behavior that may depart from traditional notions of rationality. This framework allows for "behavioral anomalies" such as loss aversion, where individuals feel that having something they possess taken away is worse than never having it at all. Similarly, individuals may suffer from availability biases. Availability bias occurs when individuals estimate the probability of an event occurring based on the ease with which individuals are able to conjure examples. A citizen of Eggtopia may systematically overestimate the risk of accident since such accidents are particularly devastating and memorable. However, individuals often have difficulty accurately assessing the probability of unlikely events. This particular cognitive dissonance may work in both directions, that is, treating low probability events as if they are zero, or treating low probability events with much more likelihood than they actually are. See Thaler (1994) for a general summary of these and other examples of cognitive dissonance and various departures from the strictures of neoclassical theory regarding *homo economicus*.

This is not to say that the agents in the model possess one or all of these biases, simply that no such assumption concerning their adherence to the rationality paradigm is overtly assumed. The framework is sufficiently flexible to add such explicit assumptions for the conduct of future research. Ultimately, it highlights the institution's role in guiding behavior, as opposed to relying on notions of rationality or a particular level of intelligence.

Accidents and Liability Regimes

In the next chapter, I exclusively implement what I call Posnerian agents. In keeping with the assumptions of the Posnerian framework, agents are broadly categorized into one of two classes, either victims or injurers. Only injurers can cause accidents with victims. If, in the course of the simulation, a victim 'causes' a candidate accident with another victim or injurer (or an injurer causes an accident with another injurer), neither agent will move, but no eggs will be destroyed and no dispute will be adjudicated. It is left to future research to examine completely heterogeneous agents.

The model allows for the implementation and comparison of a number of liability regimes. As accidents occur, they are immediately adjudicated according to the particular liability regime in force at the time. The model provides the researcher with the capacity to examine agent behavior under a regime of no liability and using this information deduce the efficacy of other liability regimes such as strict liability and negligence. It also provides the researcher with the ability to compare the accuracy of these deductions against the 'empirically' generated data of the model actually implementing these regimes. Perhaps more importantly, it affords an opportunity to determine the operational significance of some of the simplifying assumptions that are commonly employed in the neoclassical framework.

Numerous definitions of due care are examined in the subsequent analysis to include various “reasonable” levels of speed, vision, and egg capacity. In reality, if the (perceived) cost of these preventive actions is lower than the expected cost of the accident, a judge may prescribe them in the course of determining a proper definition of "due care." Likewise, various behaviors exhibit varying levels of probabilities of resulting in accidents. Due care may be defined along numerous margins, some of which may not effectively reduce the possibility of an accident. In the model, the speed an agent travels is a significant factor in determining an agent’s productivity. Under certain circumstances, higher speed also contributes to higher accident rates. Thus, the speed at which an agent travels is a potentially excellent margin on which to analyze the intricacies of due care. Consider also, that while the attributes that an agent possesses are obvious to the researcher / programmer, such attributes as visual acuity (attentiveness, intelligence, reflexes) are not necessarily as accessible to the court charged with adjudicating the dispute.

Including Evolutionary Agents

In addition to accommodating heterogeneous agents that employ uniquely different strategies or possess different characteristics, the model also may enable agents to choose their strategies on the basis of information which they alone collect. In the fully evolutionary model, analyzed in detail in Chapter 6 below, agents are allowed to change their strategies in an adaptive fashion on the basis of performance. The algorithm agents employ contains aspects of trial and error, as well as satisficing and hill-climbing methods. Upon completion of a generation, each agent examines the success in terms of wealth of her current strategy. If her current wealth exceeds that from the previous generation, meaning that the incumbent strategy has succeeded again in bettering her condition, it will remain her incumbent strategy and she will employ it in the next time step. This is the satisficing characteristic, in that the agent is satisfied with a relatively well performing strategy and does not seek to "fix what isn't broken."

If the agent's current wealth is less than that observed in her previous generation, that is, if the incumbent strategy does not succeed in improving her condition, she will select a candidate strategy and employ it in the next generation. This is the trial and error portion of the algorithm. Candidate strategies are selected from the set of neighbors of the current strategy with equal probability. At the end of the next generation, candidate strategy's success is measured against the incumbent strategy's latest performance. If the candidate strategy yields greater wealth, it is declared the incumbent strategy and employed in the next generation. If the candidate strategy's performance is less than that of the incumbent's, then the incumbent remains as such and is employed in the next generation.

IV. Discussion and Conclusion

This chapter presents the situation faced by the inhabitants of Eggtopia, a fictitious society whose members search for and collect precious eggs. In the course of their productive efforts they occasionally experience destructive accidents with other individuals. The inhabitants face trade-offs in that engaging in behavior that increases their productivity also increases the possibility of an accident. This scenario is used as the target of both a neoclassical mode of analysis and an evolutionary mode of analysis.

Ultimately, the two approaches are contrasted in subsequent chapters order to determine both their relative efficacy in addressing typical research questions as well as generating new threads of research.

The agent-based model of Eggtopian society developed in this chapter can be used to answer the questions commonly addressed in the mainstream literature. The efficiency of various liability regimes is one such thread of analysis. Other threads include the effects of systematic uncertainty regarding the extant judicial precedent or in the court's ability to obtain the necessary information to appropriately apply the legal rule. The analysis within the neoclassical framework revolves around the economic efficiency of various rules given various extensions and complications.

The model may also be used to address theoretical concerns typically associated with an emergent framework. The evolutionary model illustrates the complicated interactions that impact an agent's ability to find the optimal strategy. An agent's optimal strategy depends on the strategies of every other agent in the population, which are constantly changing in response to the perceived success each agent is able to measure. The evolutionary model facilitates the development of genetic-causal description of the process through which agents cope with each other, the legal institutions, and their environment. Disequilibrium behavior is kept firmly in the foreground, as well as the notion that heterogeneous agents possess unique knowledge of time and place.

Chapter 5: An Empirical Exploration of the Neoclassical Framework

I. Introduction

Landes and Posner (1981) and Shavell (1987) are seminal applications of standard neoclassical theorizing to develop a positive theory of tort law. The typical mode of analysis for most scholars working in the neoclassical tradition is to erect a formal mathematical model which describes individual behavior in an assumed equilibrium, and then draw conclusions regarding the comparison of various deduced equilibrium behaviors. In this chapter, I use these tools to examine the problem faced by the inhabitants of Eggtopia

I utilize the simulation model described in the previous chapter, which is an artificial instantiation of the admittedly imaginary Eggtopian society, to empirically generate the data required to solve the neoclassical optimization problem, namely, those combinations of tort rules and agent strategies that maximize efficiency. This effort is similar to but slightly different from the normal notion of agentization of neoclassical models. In these endeavors, an agent-based model is constructed and the results are compared to what a neoclassical theory would have predicted. For example, see Tesfastion (2006) who creates an artificial market of agents and compares the performance of the market with what a General Equilibrium model would predict. In the present case, the agent-based model serves as an experimental or behavioral laboratory that actually generates data and facilitates pseudo-empirical neoclassical analysis.

Ulen (2003) notes a dearth of empirical work in the law and economics literature, and Landes (2003) discovers that researchers in the law and economic fields publish relatively fewer empirical studies than economists in general. When discussing the challenges facing researchers conducting empirical studies, Ulen states that "in order to assess the deterrent value of exposure to tort liability, we ought to know how many accidents did *not* take place as a result of tort rules (2003, p.22; emphasis his)." Such a number is incredibly difficult to estimate, and would certainly require a well designed experiment. Clearly, fully controlled experiments designed to answer such questions with large segments of the population as subjects are infeasible. Especially absurd is the notion to systematically manipulate tort doctrine in order to measure its effect on behavior. Most researchers must wait for events such as tort reform to occur in isolated geographic areas in order to cobble together a natural experiment.

There have been very few attempts to econometrically determine theoretically crucial concepts such as due care. Shephard (2008) is an attempt to measure the effects of tort reform on accidents, care, and level of activity in reference to the medical profession and malpractice suits. White (1989) uses a neoclassical framework to measure the relative effects of comparative and contributory negligence in driving related suits, but makes little attempt to actually measure the efficient level of care. This chapter may be considered a pseudo-empirical study from a neoclassical perspective. The agent-based simulation allows a unique opportunity to generate vastly more data than the typical applied researcher would ever be able to collect. The greater amount of data not only enables the development of statistically powerful models of agent behavior, but also enables testing the effects of common methodological assumptions.

In the course of this chapter, two themes emerge. The first is that under particular assumptions, the analysis of the agent-based model broadly confirms many of the theoretical conclusions of the neoclassical framework. The other is that even a seemingly simple scenario may actually have significant interdependencies that should not be neglected. As a result of these subtle complexities, the effects of purportedly innocuous simplifying assumptions may be so great as to render misleading conclusions.

This effort fits within the broader themes of this project of the difficulty of socialist calculation and centralized decision making and builds upon the Wagnerian notion of conjunctive modes of analyses. In addition, to a certain extent it demonstrates empirically Rizzo's critique of general equilibrium as applied to tort law. In our case, the simulation model provides the researcher with a nearly complete picture of the effects of liability rules and agent strategies, but I also demonstrate that it is not always possible to reliably identify optimal behavior or shape incentives to achieve it.

II. Theory and Application

The intent of this section is to outline how a researcher working within a traditional neoclassical framework may choose to analyze the economics of tort law as experienced by the inhabitants of Eggtopia. Of course, since Eggtopia is a fictional society, I utilize the agent-based simulation developed in the previous chapter to generate any data required. The simulation allows a unique opportunity to design experiments that systematically and comprehensively vary numerous potentially significant factors in order to determine their influence. In this section I apply the standard neoclassical model to Eggtopian society in order to determine the effects of various liability regimes. Then I test those theories with data generated from the simulation. Admittedly, some of the conclusions reached are peculiar to Eggtopian society, however, the exercise provides insight into the subtleties of mapping neoclassical theory to an empirical target.

As a point of departure, Landes and Posner's (1981) model with several extensions forms the basis of the formal model (see Chapter 2, above). While most of the conceptual relationships are maintained, due to the ability of the agent-based model to provide nearly complete information, some simplifying assumptions that the original authors made are replaced with more realistic ones. In several cases, I am able to isolate the effects these simplifying assumptions have on the conclusions of the analysis.

Agents are assumed to be risk neutral and possess the following utility function:

$$U = I \tag{5.1}$$

Where I is income in eggs. In addition, let aggregate social welfare equal the sum of all utilities. The same caveat applies as Landes and Posner (1972: 869) this convention is not meant as an endorsement of the notion of an actual social welfare function, but is simply a construct in order to be able to define the "social costs of accidents."

Posner's is a representative agent model with a single injurer and a single victim. I scale this to consider how populations of victims may interact with populations of injurers. All injurers and all victims are assumed to select the same levels of care in order to maintain homogeneity.

Time is not a variable explicitly included in the Landes and Posner model. While it is not clear whether the *p(x,y)* term describes the probability of an accident occurring in the next instant, or over some other length of time, I assume it does not matter for the conclusions as long as the same convention is applied across the entire framework. Since time is an integral part of the agent based simulation, it is important to select a convention that is analytically appropriate and remains tractable. Given the fact that any particular agent may be involved in one and only one accident during a timestep and that an agent may be involved in numerous accidents with many different agents during the course of a generation, for our purposes, subsequent equations will apply to expected values for a single timestep.

Following Posner, the probability of an accident occurring in any given timestep is given by:

$$p = p(\mathbf{x}) \tag{5.2}$$

where,

$$\mathbf{x} = [\mathbf{x}_{\mathrm{vic}}, \mathbf{x}_{\mathrm{inj}}] \tag{5.3}$$

and,

$$\mathbf{x}_{\mathrm{vic}} = [vic\_vision,\ vic\_capacity,\ vic\_speed] \tag{5.4}$$

$$\mathbf{x}_{\mathrm{inj}} = [inj\_vision,\ inj\_capacity,\ inj\_speed] \tag{5.5}$$

In other words, the vector **x** contains all of the strategy characteristics or attributes that may vary among agents. These attributes also describe the care that an agent may elect to take, which effects the probability of an accident occurring. The prefix *vic* describes attributes that belong to victim type agents while *inj* describes attributes of injurers. For expositional purposes, it is helpful to distinguish between the strategies, or components of the **x** vector selected by each type of agent.

The probability that an accident occurs in any given timestep is given by $p(\mathbf{x})$. The cost of care for the victim is given by $A(\mathbf{x})$, while the cost of care for a representative injurer is given by $B(\mathbf{x})$. It is commonly assumed that damages and income are not dependant upon the level care **x** exercised on the part of either injurers or victims (Landes and Posner, 1982; Shavell 1987). However, even casual consideration of the Eggtopian society reveals that it is entirely possible that an agent's income is highly dependant both on their own levels of care and that of the other agents. I reject this assumption in favor of a richer depiction of agent income and damages as potentially being highly interdependent on various individual strategies. Thus, expected damage inflicted as a result of an accident is $D(x)$ and income is $I^a(\mathbf{x})$ and $I^b(\mathbf{x})$. A representative victim's expected utility in any given timestep is given by:

$$U^a = p(I^a(\mathbf{x}) - D(\mathbf{x}) - A(\mathbf{x})) + (1\text{-}p)(I^a - A(\mathbf{x})) = I^a\,(\mathbf{x}) - pD(\mathbf{x}) - A(\mathbf{x}) \qquad (5.6)$$

While a representative injurer's expected utility is given by:

$$U^b = p(I^b\,(\mathbf{x}) - B(\mathbf{x})) + (1\text{-}p)(I^b - B(\mathbf{x})) = I^b\,(\mathbf{x}) - B(\mathbf{x}) \qquad (5.7)$$

Notice that in Landes and Posner's (1982) model, which is generally outlined in Chapter 2, the victim's (injurer's) cost of care is a function of only the victim's (injurer's) level of care. This is another characteristic that might very well be dependant upon *both* agents' level of care. Thus, in this model, every component is ultimately a function of **x** the vector that contains the levels of care selected by both injurers and victims.

The complex nature of the interactions among the inhabitants of Eggtopia is apparent when one considers that an individual's decision to change her behavior simultaneously effects not only the probability of an accident, but her productivity and the damage expected in the case of an accident. If the cost of care is the difference in income between exercising a particular level of care and not exercising care (while neglecting the effects of the accidents on income), it is difficult even from the perspective of a modeler with access to most information contained in the model. In other words, the prospect of collecting the appropriate information is nontrivial, even for a researcher who has the power to modify the model to operate as desired, let alone a judge who only has access to information presented in the court room and his own perception of society. The agent-based modeling framework is beneficial in this sense as well, since it forces (allows) the researcher to be the custodian of all knowledge contained in the model. And it is through decisions concerning how to model the communication of such information that the knowledge problem is highlighted.

It is not possible to directly observe Eggtopian society and questions concerning the effects of behavior on the probabilities of accidents occurring and the damage incurred are empirical questions that cannot be answered *a priori*. In order to make determinations regarding the relative advantages and disadvantages of various liability regimes I must turn to the simulation of Eggtopian society developed here to craft estimates of the terms necessary for the above analysis. The simulation is analyzed using a systematic experimental design with data collected on response variables of interest. Ordinary Least Squares (OLS) multivariate regression models are then constructed as a means to estimate the response variables at various points in the domain. Owing to the interdependence of various components on either type agents' strategies, the regression models are then aggregated into a system of equations, or metamodel, that is used to ascertain optimal behavior under various conditions.

Experimental Design and Implementation

If we were to consider only two types of agents, each with three attributes that vary between levels of 1 to 33, the inherent combinatoric problem would cause a full factorial experimental design to explode. For example, a 2^6 full factorial design would result in 64 design points (Box, Hunter, & Hunter, 1978, p.348). In such a design, only the corners of the hypercube are observed and such a sparsely fitted hypercube would almost certainly overlook possibly important interactions. A full factorial design of 6 factors each with just 4 levels would require 4096 design points, which when considering the necessity to replicate design points to accurately measure variance, rapidly becomes intractable.

The Nearly Orthogonal Latin Hypercube experimental design offers an attractive alternative for surveying a domain of many factors (Cioppa, 2002; Sanchez and Lucas, 2002). Such designs maintain the benefits of orthogonality, which helps ensure independence of estimates of variables, while achieving enhanced analytical performance as a result of the space filling properties that facilitate comprehensive exploration of the model (Cioppa, 2002). An added benefit is that such efficiencies are gained with far fewer design points relative to the factorial design. I implement a O_{33}^{11} experimental design as outlined in Cioppa (2002, p.105) which contains the factors and levels listed in Table 5.1[11]. This particular design is for experiments with greater than 7 but less than 12 factors. The intent of the wide sweep is to identify the most interesting regions of the variable space and determine the most important factors responsible for differences in the response variables. Ultimately, I develop numerous regression models to determine the appropriate estimates of the necessary components to the social cost function. The levels selected for each factor are shown in Table 1.

Table 5.1. Factor Descriptions and Levels for Initial Full Factorial Experimental Design.

Factor	Description	Levels
numAgents	number of agents	[100,500] by ~13
numEggs	number of eggs	[100,1000] by ~28
vic_vision	victim visual range	[1,33] by 1
vic_capacity	victim maximum capacity	[1,33] by 1
vic_speed	victim speed	[1,33] by 1
inj_vision	injurer visual range	[1,33] by 1
inj_capacity	injurer maximum capacity	[1,33] by 1
inj_speed	injurer speed	[1,33] by 1

This design requires only 33 design points which also corresponds to the 33 levels of each factor. For the initial experimental designs, each design point is replicated 30 times for a total of 990 simulation runs. The relatively high number of replications are an effort to mitigate the effects of any multicolinearity that might emerge in the metamodel,

[11] In Cioppa's (2002) notation, the 11 indicates the number of factors considered and the 33 refers to the number of design points (which is also the number of levels for each factor).

especially due to the fact that the OLS regression models include polynomial factors. In this chapter and throughout most of the project a simulation run consists of 500 timesteps.

The explanatory variables or factors included in the experimental design are of three types. The first type are comprised of completely arbitrary, though possibly significant, model parameters. The two considered in this design are the number of agents and the number of eggs available in the environment. Other variables of this type include the number of timesteps in each generation and the dimensions of the two-dimensional torus environment. In the abstract figment of our imagination that is Eggtopia, the levels selected for these variables are entirely arbitrary, however, it is important to gain an understanding of these effects, so as to differentiate the effects of more substantive variables. Another type of variable are those that are actual attributes of agent behavior, defined above as consisting of an agent's strategy. The final type includes the rules that are intended to parallel the legal rules that govern agent behavior.

Common Random Numbers are utilized in the experimental design whenever feasible, in an effort to reduce variance between design points (Law and Kelton, 2003, pp.582-598). This technique provides at least a small amount of protection against the possibility that variation observed in the output is due to an artifact of the pseudo-random numbers generated through the course of the simulation. The seeds for random number generators that determine the placement of the eggs as well as the initial placement of agents in the environment for each i^{th} replication of every design point are identical. This also ensures that as eggs are collected, the subsequent eggs also appear in the same places. Essentially, this allows each design point to be compared within the same "environment" with respect to eggs and their locations.

Achieving Common Random Numbers for agent behavior is significantly more difficult. During the initialization of every model run, each agent is assigned its own random number generator that governs its random search behavior. Every j^{th} agent in replication i of any particular design point is initialized with the same seed. However, due to the complexity of the model and the cascading ramifications of the localized decisions that each agent makes, it is impossible to ensure complete commonality persists across replications.

In order to fully examine the scenarios using the neoclassical tools, it is necessary to collect the appropriate data from the output of the model. Table 5.2 outlines a few of the primary response variables that are collected for every simulation run in an experimental scenario:

Table 5.2 Primary Response Variables for Experimental Design.

Variable	Description	Definition
vic_caprate_wealth	per capita productivity rate	vic_wealth / [time*vic_total]
vic_caprate_loss	per capita loss rate	vic_loss / [time*vic_total]
vic_caprate_acc	per capita accident rate	vic_acc / [time*vic_total]
inj_caprate_wealth	per capita productivity rate	inj_wealth / [time*inj_total]
inj_caprate_loss	per capita loss rate	inj_loss / [time*inj_total]
inj_caprate_acc	per capita accident rate	inj_acc / [time*inj_total]

The primary response variables are aggregate wealth among victims *vic_wealth,* aggregate losses among victims *vic_loss,* and the total number of accidents *vic_acc,* as well as the corresponding variables for injurers. These primary variables are then combined with other parameters to obtain the response variables of interest. The variable *cap_rate_wealth* is an estimate of the average number of eggs an agent collects each timestep. The variables *cap_rate_loss* and *cap_rate_acc* are simply the estimated magnitude of losses and the number of accidents that the representative agent expects each timestep. Throughout this project, variables whose name contains the word *cap* are the per capita average of that variable and variables whose name contains *rate* captures the average change in the magnitude of that variable per timestep.

Using the Metamodel to Identify Optimal Strategies

I now develop empirical estimates of the components of the equation that describes the social costs of accidents. In keeping with the typical course of discussion, the social welfare function under a tort regime of no liability is first constructed. I then deduce agent behavior under alternative regimes using the social welfare function and making the appropriate adjustment for the effects of compensatory payments and assumptions regarding strategic behavior. In this case, the simulation model provides us the luxury to actually test those suppositions against the agent's actual behavior in subsequent simulation runs under those regimes.

In the initial implementation, Ordinary Least Squares regression models are crafted to explain the response surfaces for the following dependant variables: *vic_cap_rate_wealth*, *vic_cap_rate_loss,* and *inj_cap_rate_wealth.* Obtaining a mathematical description of the effect of agent behavior on these three variables under a regime of no liability will allow us to deduce the effects of any subsequent liability regime with a minimum of additional information. Using standard optimization techniques, it is possible to identify the levels of care that achieve particular optima.

The metamodel is a mathematical representation of the behavior of the simulation model, which enables us to effectively explore the response surface without resorting to additional simulation runs. Since prediction within the domain of the variables is of primary concern, we are concerned less with erroneously including irrelevant variables or with the magnitude of various effects.

$$E[\,vic\_cap\_rate\_wealth\,] = f(\mathbf{x}) \qquad (5.9)$$

$$E[\,inj\_cap\_rate\_wealth\,] = h(\mathbf{x}) \qquad (5.10)$$

The two regression regression models, Equations (5.9 and 5.10), are then inserted into the social welfare function, which becomes the objective function for the following optimization formulation:

$$\max_{\mathbf{x}} \; vic\_cap\_rate\_wealth + inj\_cap\_rate\_wealth \qquad (5.11)$$

subject to: $\mathbf{x}_{\mathbf{min}} < \mathbf{x} < \mathbf{x}_{\mathbf{max}}$

Where $\mathbf{x}_{min}$ and $\mathbf{x}_{max}$ are vectors containing the minimum and maximum factor levels previously indicated in Table 1 above.

The metamodel is implemented in Windows Excel, where the **x** vector is manipulated and the simultaneous effect on the response variables is calculated. The maximization of Equation 5.11 is solved using the Solver Add-In, which uses a

Generalized Reduced Gradient algorithm to perform nonlinear optimization[12]. The response surfaces for most of the variables are highly irregular and each contain a myriad of local maxima. This characteristic often makes the Solver solution highly dependant upon the starting values for the **x** vector. I employ a macro that offers Solver numerous random starting points with which to initialize the optimization and provides reasonable assurance that the optimum obtained is indeed in the neighborhood of the global optima.

III. An Empirical Analysis of the Model

The primary outcome of applying neoclassical analysis to accident law is the understanding that tort rules are an attempt to minimize the cost of accidents. The costs of accidents include the actual damages incurred in the accidents, as well as the costs of prevention. The rule of no liability is examined in the first stages of most neoclassical analyses presumably because determining damages and identifying the costs of prevention are easier when compensation is neglected. In order to analyze other rules, the mathematical model is then manipulated to implement particular suppositions deduced from a game theoretic analysis of agent behavior under the rule in question. For example, assuming that the courts employ a simple negligence rule and set the level of due care at the socially optimal level, then for the injurer, acting in a non-negligent manner is a strictly dominant strategy. Knowing this, the victim will always select the socially optimal level of care. While the payoff to the victim's strategy is dependant on the injurer's strategy of whether to exercise due care, any additional level of dependence

[12] For more information on Solver, see http://www.solver.com/ , as well as the Microsoft Help and Support website: http://support.microsoft.com/kb/214115

as examined above is typically neglected. The agent-based implementation facilitates the examination of these often overlooked interdependencies.

Our first task is to compare the effects of the various simple liability rules. For several agent and egg combinations, metamodels are constructed that describe behavior under the liability rules of interest. As for the negligence rule, each of the three margins for the definition of care is considered, namely injurer vision, capacity, and speed. While in most sources the level of care is determined by applying the Hand Rule to the components of the social welfare function (Cooter & Ulen, 2007), in our case the simulation model provides sufficient flexibility in that we need not solve for the individual components of the Hand Rule, but simply select the level of care that maximizes aggregate wealth.

Table 5.3 outlines the results for the scenario in which there are 200 agents in the population and 2,000 eggs in the environment. In this case, the highest social total is achievable under the rule of strict liability. The other liability rules are not vastly different, but result in different distributions of wealth between victims and injurers. Also of note is the way in which the tort rules influence the components of agent's strategies. Both victims and injurers' optimal speed is 33 for all rules. In contrast, the liability rule in effect greatly effects their choice of capacity.

Table 5.3. Comparison of Liability Rules for 200 agents and 2000 eggs.[13]

(200 , 2000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
vic_vision	**25**	**20**	**22**	**22**	**23**
vic_capacity	**33**	**15**	**23**	**22**	**23**
vic_speed	**33**	**33**	**33**	**33**	**33**
inj_vision	**20**	**19**	**21**	**20**	**21**
inj_capacity	**19**	**33**	**25**	**24**	**24**
inj_speed	**33**	**33**	**33**	**33**	**33**
social total	**1.50**	**1.55**	**1.48**	**1.49**	**1.48**
vic_total	**0.64**	**0.76**	**0.67**	**0.68**	**0.68**
inj_total	**0.86**	**0.79**	**0.81**	**0.81**	**0.80**

Table 5.4 outlines the corresponding results for the scenario in which 100 agents inhabit an environment with 1,000 available eggs. In this case, a rule of negligence based on a definition of due care of *vision* equal to 23 is the optimal rule. However, agents' vision is a characteristic that would presumably be very difficult for a court to determine. This case very much demonstrates the difficulties inherent in crafting a rule that both achieves the optimal outcome and is realistically possible to implement in practice. The next best rule is another negligence rule, based instead on capacity.

[13] In this case, the highest social total is achievable under a rule of strict liability. Totals are in terms of eggs per agent per timestep and the highlighted values indicate the efficient level of care for each negligence rule.

Table 5.4. Comparison of Liability Rules for 100 agents and 1000 eggs.[14]

(100 , 1000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
vic_vision	**27**	**22**	**21**	**21**	**24**
vic_capacity	**33**	**17**	**19**	**19**	**22**
vic_speed	**30**	**33**	**33**	**31**	**33**
inj_vision	**23**	**19**	**23**	**22**	**25**
inj_capacity	**20**	**33**	**33**	**33**	**23**
inj_speed	**26**	**33**	**33**	**33**	**33**
social total	**1.51**	**1.47**	**1.77**	**1.71**	**1.48**
vic_total	**0.64**	**0.74**	**0.89**	**0.88**	**0.75**
inj_total	**0.86**	**0.73**	**0.88**	**0.84**	**0.74**

Shavell (1980) points out that if a class of accidents are governed by a negligence rule, then individuals would have an incentive to exercise due care, but may still engage in an inefficiently high quantity of the activity. One reason for this is the fact that there is a finite number of margins one may define (and measure, detect, confirm, etc) due care. Another reason is that since exercising due care shields them from any liability, individuals will have no incentive to economize on this behavior, relative to the accidents and the concomitant losses they cause. However, under a regime of strict liability, since an individual is liable for any and all accidents caused while engaged in a particular behavior, they have the incentive to limit their behavior to the point where the marginal benefit of the activity equals the marginal damage caused by the activity.

Preliminary analyses of results are consistent with the notion that under strict liability, individuals will reduce the quantity of activity, if it is beneficial to do so. Under

[14] In this case, the highest social total is achievable under a rule of negligence. Totals are in terms of eggs per agent per timestep and the highlighted values indicate the efficient level of care for each negligence rule.

negligence rules, which only hold an individual liable if she is not exercising due care, agents find it much less beneficial to reduce their quantity of activity, since it does nothing to reduce their liability while simultaneously makes them less productive.

Table 5.5 outlines the results for the scenario in which 200 agents inhabit an environment with 2,000 available eggs. In this scenario, the regime of no liability yields the highest expected social wealth, with strict liability and negligence following closely behind. It is evident that in most cases, victims are the ones who find it optimal to rest, while this is not the case for injurers.

Table 5.5 Comparison of Liability Rules for 200 agents and 2000 eggs with rest.[15]

(200 , 2000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
vic_vision	**22**	**21**	**22**	**22**	**22**
vic_capacity	**33**	**33**	**33**	**33**	**33**
vic_speed	**19**	**19**	**19**	**19**	**19**
vic_rest	**0.0**	**22.6**	**12.6**	**13.4**	**13.2**
inj_vision	**17**	**16**	**15**	**16**	**16**
inj_capacity	**33**	**33**	**33**	**33**	**33**
inj_speed	**23**	**14**	**1**	**33**	**33**
inj_rest	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
social total	**1.72**	**1.69**	**1.64**	**1.68**	**1.68**
vic_total	**0.85**	**1.04**	**0.97**	**0.84**	**0.84**
inj_total	**0.87**	**0.65**	**0.67**	**0.85**	**0.84**

It is of interest to note that the regression models indicate that agents who rest are capable of achieving greater levels of wealth. Table 5.6 shows the results of the scenario

[15] In this case, the no liability rule achieves the greatest social total. Totals are in terms of eggs per agent per timestep and the highlighted values indicate the efficient level of care for each negligence rule.

for 100 agents and 1,000 eggs. In this case both no liability and strict liability appear superior to any of the negligence rules.

Table 5.6. Comparison of Liability Rules for 100 agents and 1000 eggs with rest.[16]

(100 , 1000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
vic_vision	**23**	**22**	**22**	**23**	**22**
vic_capacity	**32**	**33**	**33**	**33**	**33**
vic_speed	**19**	**19**	**20**	**19**	**19**
vic_rest	**0.0**	**17.4**	**9.6**	**9.4**	**9.9**
inj_vision	**18**	**18**	**19**	**17**	**17**
inj_capacity	**33**	**33**	**26**	**33**	**33**
inj_speed	**33**	**33**	**19**	**24**	**31**
inj_rest	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
social total	**1.79**	**1.76**	**1.47**	**1.52**	**1.54**
vic_total	**0.79**	**0.97**	**0.88**	**0.88**	**0.86**
inj_total	**1.00**	**0.79**	**0.59**	**0.64**	**0.68**

Interestingly, again in most circumstances it is socially optimal for the victim to engage in a nonzero level of rest. This tends to be contrary to the Shavellian notion that under strict liability the victim need not limit her quantity of activity because she does not pay the price in terms of the additional risk of damage incurred.

Shavell (1987) argues that since the rule of strict liability encourages the injurer to internalize the expected costs of the accidents he causes and ultimately to take care along all relevant margins, the victim is left with an incentive to exercise due care, but no corresponding incentive is present for him to select the optimal level of activity. The preceding analysis is simply intended to demonstrate the typical types of questions asked

[16] In this case, the no liability rule achieves the highest social total. Totals are in terms of eggs per agent per timestep and the highlighted values indicate the efficient level of care for each negligence rule.

within the neoclassical framework. The agent-based simulation provides nearly complete information concerning the behavior of agents within the artificial society and provides a unique opportunity to conduct a comprehensive empirical analysis.

IV. Matters for Concern

The previous section demonstrated how agent-based modeling and simulation that loosely maintain certain assumptions may be used to generally confirm some of the major theoretical conclusions of the neoclassical framework. The agent-based model supported the pursuit of the traditional neoclassical threads of research. The model as an artificial social laboratory is capable of providing the researcher (or judge) with nearly any desired information. As such, it is possible to examine the effects of assumptions or methodological techniques common to neoclassical analyses.

Indeterminateness of Optimal Behavior

As outlined above, standard procedure among researchers working within the neoclassical school is to develop a model that describes the behavior of individuals in equilibrium. Typically a system of equations is devised which describes the behavior of representative agents and a constrained maximization is performed in order to determine optimal behavior. The task in the previous section was to identify the respective strategies of injurers and victims, which when implemented under a particular liability rule would yield the highest possible aggregate wealth among the members of society. In actual practice, this meant that a system of multivariate linear regression models describing the components of aggregate wealth was optimized.

For example, according to Table 5.5 above, in the scenario with 200 agents and 2,000 eggs, the socially optimal outcome is achievable under a rule of no liability. However, from a genetic-causal perspective, it is by no means clear that a population of individual agents who are each striving to maximize their own wealth will arrive at that outcome under any given liability rule, or a single victim and single injurer for that matter. The neoclassical model does not describe how the rule of no liability provides the necessary incentives to cause agents in disequilibrium to discover and implement the socially optimal strategy.

The information depicted in Table 5.7 is the result of various kinds of optimizing behavior for several (agent, egg) scenarios, all under the rule of no liability. The neoclassical brand of methodological individualism would suggest that each injurer and victim could individually pursue its personally maximizing strategy. The individual agents have no knowledge of the social welfare function and either party's optimal behavior may depend on the other agents' strategies. We may consider individual behavior to be efficient to the extent that such behavior coincides with social maximizing behavior. However, in most cases both the requisite strategies for either to achieve their own optima differ from the strategies that achieve the socially optimal. Because of this difference, it is unclear how, in practice, the rule of no liability will provide the appropriate incentives for the inhabitants of Eggtopia to achieve the purported social optimal under this liability regime.

Table 5.7. Comparison of Socially and Individually Maximizing Strategies of Various (agent, egg) Combinations Under No Liability.

(100,1000)				(200,2000)			
	Maximize				Maximize		
	Social	Victim	Injurer		Social	Victim	Injurer
vic_vision	**27**	**27**	**1**	vic_vision	**25**	**26**	**1**
vic_capacity	**33**	**22**	**33**	vic_capacity	**33**	**33**	**33**
vic_speed	**30**	**33**	**18**	vic_speed	**33**	**33**	**17**
inj_vision	**23**	**1**	**22**	inj_vision	**20**	**1**	**20**
inj_capacity	**20**	**15**	**32**	inj_capacity	**19**	**13**	**31**
inj_speed	**26**	**1**	**26**	inj_speed	**33**	**1**	**30**
social total	**1.51**	**0.84**	**0.96**	social total	**1.50**	**0.84**	**0.94**
vic_total	**0.64**	**0.84**	**0.00**	vic_total	**0.64**	**0.84**	**0.00**
inj_total	**0.86**	**0.00**	**0.96**	inj_total	**0.86**	**0.00**	**0.94**
(200,1200)				(500,1500)			
	Maximize				Maximize		
	Social	Victim	Injurer		Social	Victim	Injurer
vic_vision	**27**	**27**	**1**	vic_vision	**20**	**21**	**16**
vic_capacity	**33**	**1**	**33**	vic_capacity	**12**	**6**	**33**
vic_speed	**31**	**33**	**17**	vic_speed	**25**	**33**	**16**
inj_vision	**26**	**1**	**22**	inj_vision	**20**	**1**	**20**
inj_capacity	**18**	**13**	**31**	inj_capacity	**33**	**1**	**33**
inj_speed	**33**	**1**	**27**	inj_speed	**33**	**1**	**33**
social total	**1.33**	**0.86**	**0.90**	social total	**1.13**	**0.86**	**0.97**
vic_total	**0.53**	**0.86**	**0.00**	vic_total	**0.36**	**0.86**	**0.13**
inj_total	**0.80**	**0.00**	**0.90**	inj_total	**0.77**	**0.00**	**0.84**

Recall that the typical analysis concludes that since the victim bears the entire cost of the accident, she will opt to exercise the socially optimal level of care, while since the injurer escapes liability, he has no incentive to exercise care (Landes and Posner, 1981). Take for instance, the scenario with 200 agents and 2000 eggs, summarized in the upper right panel of Table 5.7. The socially optimal $\mathbf{x}_{vic}$ coincides nearly exactly with that which maximizes the victim's wealth. Thus, to the extent that victims are led to behavior achieves maximum wealth, such action is likely to lead to socially optimal behavior on the part of victims. However, the wealth maximizing level of activity for the injurer is much lower than that which would appear to maximize the injurer's wealth.

The scenario with 500 agents and 1500 eggs, summarized in the lower right panel of Table 5.7, reveals the inverse situation. The socially optimal level of $\mathbf{x}_{inj}$ coincides with the *inj_wealth* maximizing level. However, the corresponding values of $\mathbf{x}_{\mathbf{vic}}$ are much different. In fact, if the victim were to exercise due care, she could expect a wealth level of 0.36 per timestep, compared with her own wealth maximizing behavior of 0.86. Thus, it appears possible to lead the injurer to efficient behavior under the no liability rule, but not the victim in this case.

The problem of possible incongruity between socially optimal levels of activity and those that maximize wealth for a particular individual are heightened when we consider marginal activity. Consider the case with 200 agents and 2000 eggs, where the injurer must decide upon a carrying capacity. Assuming her other attributes are fixed, and assuming that the victim selects the socially optimal strategy, then the effects of the injurers choice is illustrated in Figure 5.1.

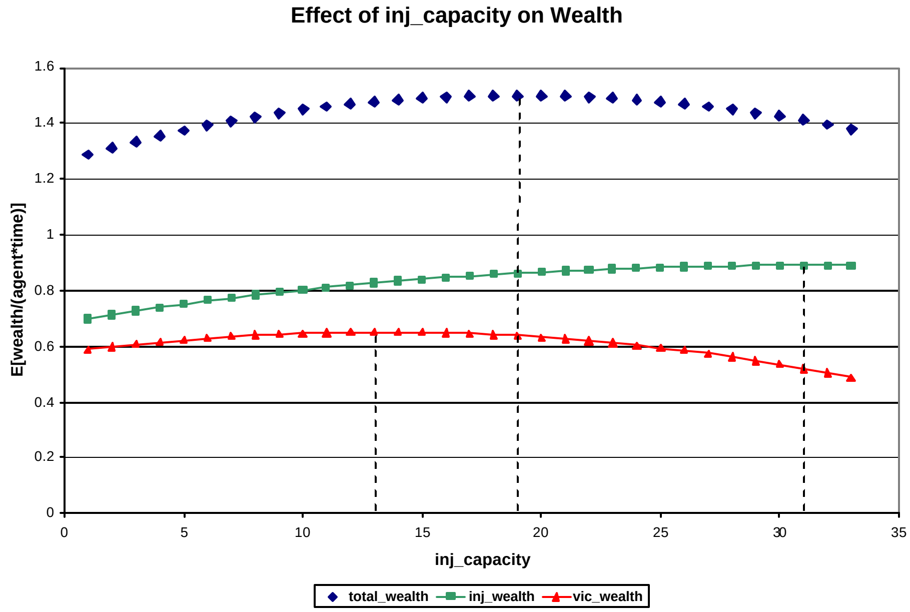

Figure 5.1. Effect of inj_capacity on Wealth. [17]

If the victim were able to make the choice of *inj_capacity* for the injurers, she would choose a capacity of 13, because that is the value that maximizes her wealth. The proverbial benevolent despot would compel the injurer to select a level of 19, as that is the level that maximizes social welfare. Likewise, an omniscient judge who purportedly wishes to maximize social welfare would likely set a rule of negligence that defines due care as capacity less than 20. However, to the extent that the injurer is allowed to select his own carrying capacity, he would opt for a level of 31, as that is the level that maximizes his wealth.

This conclusion regarding selection of capacity was only achievable with the assumption that the rest of the **x** vector was fixed. This is not likely to be the problem

[17] All else constant, the choices of *inj_capacity* that maximizes social, injurer and victims wealth are all different. Maxima are indicated by the dotted lines. (agents=200; eggs=2000; x_vic=[25,33,33]; *inj_vision*=20; *inj_speed*=33).

that the typical Eggtopian faces. In reality, individuals constantly change their behavior in their inexorable pursuit of a better life. Thus, a strategy that treats other agents' behavior as fixed and then selects an optimal, may be disappointed when it is revealed that the strategy is no longer optimal given the new datum of individuals behavior. One way to marginally simplify this problem is to assume that victims' strategies do not effect injurers' payoffs and vice-versa, an assumption that I call the non-interdependence assumption. The neoclassical paradigm has trouble coping with such complex dynamics, which is why equilibrium behavior is assumed at the outset. The potentially deleterious effect of the non-interdependence assumption is explored in a subsequent section.

As demonstrated above, it is possible to optimize the system of equations to determine the maximum point on the objective function that satisfies the constraints. This is not a causal determination but a mathematical one. This difficulty arises since the Posnerian model amounts to a poistem (Bunge, 1960; Cowan and Rizzo, 1996). A poistem is simply a "system of interrelated qualities or variables (Bunge 1960, p.401)." In short, the Posnerian model lacks any notion of asymmetrical causation or process. Without a genetic-causal description of how agents in disequilibrium ever arrive at the optimum, there is no reason to necessarily believe that the optimum is even achievable, or that it is even an equilibrium outcome. One can easily solve the optimization problem using any one of the several objective functions discussed, but there is no way to link it back to the behavior of individual agents. We will explore how spontaneous order economics in general and agent based modeling in particular may offer a solution in the next chapter.

Endogenous Effects of Regimes – Strict Liability Example

Typically, upon developing a model that describes the costs of accidents that injurers and victims face under a rule of no liability, the effects of subsequent liability rules are deduced from the expected effects of the rule in question. For example, to examine the effects of strict liability, one need only manipulate the system of equations such that injurer's wealth is reduced by the magnitude of damages they cause and victims are made whole. It is further assumed that the tort rule in question will have no other effect upon agent behavior. The intent of this section is to determine the validity of that assumption.

A regression model (Equation 5.12) is developed that estimates the effect of **x** on *vic_cap_rate_loss.*

$$E\,[\,vic\_cap\_rate\_loss\,] = g\,(\mathbf{x}) \qquad (5.12)$$

The estimate of the effect of this rule on agent behavior is obtained by adjusting the wealth functions from the metamodels obtained in the previous section as follows:

$$vic\_adj\_caprate\_wealth = vic\_caprate\_wealth + vic\_caprate\_loss \qquad (5.13)$$

$$inj\_adj\_caprate\_wealth = inj\_caprate\_wealth - vic\_caprate\_loss \qquad (5.14)$$

Thus, the estimate of aggregate victim wealth is the sum of observed wealth and observed losses, because under a rule of strict liability they would be fully compensated for these losses. Likewise, the estimate of aggregate injurer wealth is observed wealth minus observed victim losses, due to the fact that under the rule of strict liability, they would pay an amount equal to victim losses in compensation to the victims.

Since social scientists are rarely given the opportunity to perform controlled experiments regarding accident law rules on the general public, most analyses end at the point where the effects of a particular rule are estimated. Researches model particular behavior given the data at hand, and the model either confirms the rule in place for the scenario is the appropriate one, or the model suggests an alternative rule would be superior. The agent-based model of our artificial society provides an opportunity to test the effectiveness of these estimates.

Table 5.8. Comparison of Calculated and Observed Levels of Agent Strategies Under Strict Liability.[18]

	(100, 1000)		(500, 1500)		(200, 2000)	
	Calculated	Observed	Calculated	Observed	Calculated	Observed
vic_vision	**27**	**22**	**20**	**22**	**25**	**20**
vic_capacity	**33**	**17**	**12**	**9**	**33**	**15**
vic_speed	**30**	**33**	**25**	**33**	**33**	**33**
inj_vision	**23**	**19**	**20**	**12**	**20**	**19**
inj_capacity	**20**	**33**	**33**	**33**	**19**	**33**
inj_speed	**26**	**33**	**33**	**1**	**33**	**33**
social total	**1.51**	**1.47**	**1.13**	**1.27**	**1.50**	**1.55**
vic_total	**0.94**	**0.74**	**0.92**	**0.73**	**1.03**	**0.76**
inj_total	**0.57**	**0.73**	**0.21**	**0.54**	**0.47**	**0.79**

Table 5.8 compares the "calculated" results, with the results of the metamodels developed from actual instantiations of the rule of strict liability. It brings into relief the problem that emerges from the seemingly benign assumption that simply transferring the losses experienced by the victims to the injurers in the mathematical model is an adequate

[18] Calculated levels are those deduced from the analysis of the no liability rule while Observed levels are developed from analyzing the metamodel yielded from the model actually implementing the strict liability rule.

representation of conducting that transfer at the agent level at the time of the accident. None of the cases presented (or otherwise analyzed) achieved an estimated optimal strategy that was close to the actual optimal strategy under strict liability.

Admittedly, a component of the error is due to the error inherent in the use of the linear regression models under the hood of the metamodel. However, it is also possible that a significant portion of the difference is a result of the fact of an endogenous relationship between the liability regime and the agents' behavior in carrying out their respective strategies. It is clear from both theoretical and empirical perspectives that various tort rules have different implications for wealth distribution. If it is the case that an agent's probability of being in an accident is greater when searching than when returning home, then those agents that are consistently compensated for the damages they suffer would spend marginally more time returning than searching. This subtle effect is a possible explanation for the endogenous interaction of liability regimes. In such a case, estimating agent behavior under a rule of strict liability simply by increasing victim wealth by the amount of their losses and decrementing injurer's wealth by that amount would overlook an important aspect and likely reach erroneous conclusions. Similarly, it is possible that applying this technique to analyze scenarios in reality is subject to the same subtle dangers.

The Non-Interdependence Assumption

The assumption that simplifies the microeconomic analysis of the pursuit of individual optima is that of independence of agent behavior on the other agent's payoffs.

While Posner and Landes do model the probability of an accident as a function of the care exercised on behalf of both the injurer and the victim, *p(y,x)* in their notation, and their model is generic enough to accommodate extensions in this area, the admission that p_{xy} may be nonzero and thus there exist a different $\boldsymbol{x}^*$ for each and every value of $\boldsymbol{y}$ (and vice versa) is relegated to a footnote (1982, p.870).

Table 5.9 outlines a potentially adverse effect of this assumption on a researcher or judge's ability to estimate a socially optimal level of care. The column marked "Independent" on the left displays the socially optimal strategies for a metamodel which is based on a regression in which the independence assumption is implemented. In other words, *vic_caprate_wealth* is only regressed upon $\mathbf{x}_{\text{vic}}$, which renders all metrics independent of the behavior of the opposite type agent and likewise for *inj_caprate_wealth.* The column marked "Dependent" is for the metamodel which is based on a regression that contains the entire **x** vector as a factor. This results in the measures of *vic_caprate_wealth* and *inj_caprate_wealth* being dependant upon both the behavior of victims and injurers.

Table 5.9. Comparison of Dependence Assumption For Negligence.[19]

(200, 2000)		
Negligence: Due Care in terms of Capacity		
	Independent	Dependent
vic_vision	**22**	**22**
vic_capacity	**21**	**22**
vic_speed	**26**	**33**
inj_vision	**20**	**20**
inj_capacity	**33**	**24**
inj_speed	**33**	**33**
negligent	**no**	**no**
social total	**1.65**	**1.49**
vic_total	**0.72**	**0.68**
inj_total	**0.93**	**0.81**

So, an omniscient benevolent dictator would presumably be able to detect the interdependence of agents' strategies and implement the dependent model which would yield for him a due care *capacity* level of 24. In contrast, a neoclassical researcher who elects to make the simplifying assumption of strategy independence will erroneously arrive at a suboptimal level of *capacity*, not to mention potentially significant differences in $\mathbf{x}_{\mathbf{vic}}$.

That same researcher, if he was able to avail himself of all the data for independent models for the various liability regimes would likely arrive at the solutions illustrated in Table 5.10.

[19] In this case, there are 200 agents in the population and 2000 eggs in the environment. The assumption of independence causes model to suggest that a capacity of no more than 24 is efficient.

Table 5.10. Comparison of Liability Rules for Independent Models.[20]

(200 , 2000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
vic_vision	**22**	**21**	**22**	**22**	**22**
vic_capacity	**18**	**23**	**21**	**21**	**21**
vic_speed	**25**	**28**	**26**	**26**	**26**
inj_vision	**20**	**19**	**21**	**20**	**20**
inj_capacity	**33**	**33**	**33**	**33**	**33**
inj_speed	**33**	**33**	**33**	**33**	**33**
social total	**1.52**	**1.58**	**1.65**	**1.65**	**1.66**
vic_total	**0.65**	**0.87**	**0.72**	**0.72**	**0.72**
inj_total	**0.87**	**0.71**	**0.94**	**0.93**	**0.94**

Table 5.10 indicates that the socially optimal liability rule under the non-interdependence assumption is a negligence rule. While defining due care in terms of *speed* technically results in the greatest social wealth, the other negligence rules are very close as well, and all exceed that achievable under other liability rules. Unfortunately, according to Table 5.3 – the results for the interdependent model - the socially optimal liability rule is that of strict liability. So, even in our rather simple Eggtopian example, the assumption of independent strategies has led to not only a minor quantitative error – that of selecting the wrong level of care, but a major qualitative error of wrongly concluding that a particular liability rule was optimal when the fuller model revealed that it was not. The fact that this seemingly innocuous simplifying assumption can be significant in such a simple model of behavior leads one to wonder if other such instances exist.

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[20] In this case, there are 200 agents and 2000 eggs. The results of this analysis would lead a researcher (or judge) to believe that any negligence rule would be superior to strict liability.

V. Limitations and Concluding Remarks

In this chapter, I attempt to analyze the effects of Eggtopian tort law from a neoclassical perspective. I am fortunate in that the artificial society instantiated in the agent-based simulation is capable of generating copious amounts of data with which many questions may be answered. In general, many of the major conclusions of mainstream economics of tort law are confirmed.

As the opportunities arose, certain tradeoffs that are the result of simplifying assumptions are challenged and the implications are examined. For instance, even in the very simple example presented in this paper, it is clear that the assumption of strategic non-interdependence is inappropriate. The victim's choice of strategy most definitely affects the payoffs and incentives that injurers face and vice versa. In those cases, attempts were made to demonstrate how the capabilities of the agent-based simulation provide an opportunity to avoid such assumptions or at least mitigate their effects. As well, I demonstrated that in the present case, to neglect the endogenous interaction between agents' behavior, social welfare, and the liability regime in force would be a risky assumption. The fact that the neoclassical model is devoid of notions of causation is the source of some confusion concerning how exactly agents would arrive at the theoretically possible socially optimal behavior. To be sure, these minor faults are by no means intended to completely undermine all the progress that neoclassical economists have made in their analysis of accident law, though they tend to be the result of methodological processes that neglect out of equilibrium behavior, consider time in only Newtonian terms, and purge genetic-causal notions from the analyses.

In addition, this chapter borrows several analytical techniques from the Operations Research modeling and simulation literature which have heretofore gone unexploited in the economics agent-based modeling literature. Metamodel construction and analysis is outlined in Law and Kelton (2003) and provides a mechanism with which to optimize a simulation model without reverting to additional simulation runs. The metamodels are constructed using response surfaces generated from a Nearly Orthogonal Latin Hypercube design (Cioppa, 2002). The use of common random numbers as a variance reduction technique (Law and Kelton, 2003) is also implemented in order to produce more powerful statistical tests.

Ultimately, this chapter provides the main thrust of the agentization theme of the overall project. Agentizing the Posnerian model in this manner also contributes to the other themes of this project in the following manner. First, it provides a useful standard to compare against the evolutionary model of the next chapter. The thesis I defend is that the economic analysis of accident law would greatly benefit from a spontaneous order economic perspective, so it is crucial to compare that to the mainstream benchmark. Secondly, the analysis in this chapter highlights the major informational challenges judges face if they are to effectively adjudicate cases in terms of wealth maximization. Indeed, it is by no means clear how a Posnerian judge with comprehensive access to similar data would be able to successfully determine the wealth maximizing legal ruling for any particular case, let alone all cases over a particular period of time.

Chapter 6: The Evolutionary Model and the Neoclassical Sweet Spot

I. Introduction

In this section, I relax certain assumptions that provide the foundation for neoclassical economic models which Axtell (2008, pp.106-108) characterizes as the neoclassical "sweet spot." The sweet spot consists of assumptions of agent rationality and homogeneity, as well as non-interaction and equilibrium, which are necessary to achieve the researchers' desired model performance in terms of formality, generality, and tractability. Neoclassical theory is one attempt to make sense of the spontaneous order that individuals collectively form when interacting with tort law as an institution, interacting with other agents, and interacting with their environment. Spontaneous order economics in general and agent-based computational modeling in particular is another framework available to examine these spontaneous orders, but from an alternative perspective. This approach embraces the dynamic nature of these orders and allows the researcher to trace emergent macro-level phenomena back through the genetic-causal chain of interactions to its origin in individual behavior.

In the previous chapter, I utilized a computational model of an imagined society known as Eggtopia as an analytical target to examine the effectiveness with which the Posnerian model facilitates understanding and analysis of accident law. While the computer model itself actually dispensed with three-fourths of the sweet spot (homogeneity was left largely intact) in the workings of the model, the analysis of the data was consistent with applied neoclassical technique in that regression models were built to fit a Posnerian model that described aggregate behavior. In Potts (2000) terminology, the analysis still relied on the assumption of the existence of an underlying field. In this chapter, I again utilize the simulation model outlined in Chapter 4, however, I extend it to enable agent behavior to evolve in response to individual experience and thus generate a spontaneous order.

The methodology adopted in this project of applying agent-based simulation to the study of social science is of the mold of Epstein and Axtell's Sugarscape model they employed in their seminal work "Growing Artificial Societies" (1996). The authors develop a world inhabited by artificial agents. They begin with simple agents that follow simple rules and attempt to generate macro-level outcomes such as migration and distribution of wealth. At each successive stage, the authors add greater complexity to the model in a continuous attempt to generate outcomes recognizable as phenomena observed in human societies, i.e. trade, culture, war, etc. Epstein (2006) calls this generative social science, and it is an attempt to leverage the unique capabilities of agent-based simulation to gain insight into spontaneous orders that humans form in society. Similarly, I start with relatively simple implementation of rules and agents and successively add additional rules or relax particular assumptions to analyze their effect on the outcomes that emerge. The traditional comparative static approach tends to obscure the outcomes that emerge as a result of agent interaction and behavior.

Posner's positive theory of tort law posits the common law evolved such that judges attempted to settle disputes so as maximize wealth (Posner 1972; Landes and Posner, 1981). Most theoretical research revolves around questions concerning which tort rules (i.e. strict liability, negligence, etc) succeed in maximizing wealth under particular circumstances, (i.e. joint care, alternative care, etc) (Shavell, 1987). Indeed, the evolutionary model depicted in this chapter provides insight into this question as well; admittedly from a slightly different perspective. However, the true power of this tool is the *additional* research questions that such an approach is capable of illuminating. Unraveling the sweet spot enables careful analysis of the distribution of wealth, how agents employing various strategies interact with each other, and how emergent behavior changes through time. This methodology provides a major contribution in the form of a narrative of how individuals ultimately cause the emergent outcomes we observe and it begins to illuminate the manner in which tort law as an institution guides individuals in their interactions with other agents and their environment.

A search of the literature to find an agent-based simulation model applied to this aspect of economic analysis of tort law has proven unsuccessful. Diianni (2007) has applied such techniques to model disputants and the evolution of precedent. See also Yee (2005), and Picker (1997; 2002) for treatments on similar topics. The current project is an attempt to utilize agent based simulation and generative social science techniques to shed light on how accident law as upheld by judges affects the behavior of individuals in society.

II. A Dynamic Model of Individual Behavior

As a point of departure, I begin with the agent-based computational model fully described in Chapter 4. Like most agent-based models, it already encompasses the notions of individual interaction and disequilibrium dynamics. In this chapter, I extend the model to enable agents to change their strategies in response to their experience by means of a modest evolutionary algorithm. This enhancement necessarily requires agents to be heterogeneous in their characteristics and to implement a decision-making process that is much less ambitious than neoclassical rationality. Modeling agent behavior in this manner embraces the realization that Eggtopians confront a significant challenge concerning how to best employ their skills in pursuit of egg collection since, contrary to neoclassical agents, they lack the information required to systematically identify and implement an unambiguous globally optimal strategy. I maintain the final vestige of the Posnerian framework and continue to differentiate between victims and injurers in order to facilitate comparisons between various conclusions of the two threads of analysis. This artificial distinction is easily jettisoned for future research.

A. Evolutionary Agents

Just as outlined in Table 5.1, victims and injurers select from a wide array of parameter combinations, as all of their individual attributes may vary between 1 and 33. The task placed before each agent is daunting. Individuals must select the strategy that, given all other agents' strategies and behavior, will improve or at least maintain their current level of income over the course of a generation. However, they each have exactly 33^3 or 35,937 strategies from which to choose. Their choice is based on a comparison of the perceived effectiveness of their current strategy and that of their most recent reasonably successful strategy. As opposed to the elegant continuous, twice differentiable field upon which neoclassical agents are assumed to maximize their utility, these agents are, more realistically, confronted with an enormous combinatoric problem.

Potts (2000) analyzes of the shortcomings of the neoclassical method of applying the mathematical field to social phenomena and ultimately provides a framework for overcoming certain weaknesses of this approach. A problem with basing a model of individual decision-making on a mathematical field is that it ultimately assumes an impossible level of knowledge concerning the state of the world on the part of the individual. The interconnectedness of the elements of the field, i.e. the continuous function in **R** space, implies that the individual has at his disposal a complete understanding of the world and is easily able to identify and implement an optimal response. Potts argues that the economic space upon which individuals operate is better perceived as a less than fully connected set of elements. The individual's task is to explore this space by experimenting with various combinations of elements in order to discover the means which best serve her ends. This combinatoric problem goes beyond the largely artificial necessity of only choosing integer values for strategy parameters, rather it implies massive amounts of uncertainty in the agent's choice due to a paucity of information concerning the relative values of various strategic choices.

Figure 6.1 is a graph theoretic representation of the strategy component for any given agent. The connected elements represent the strategy, $\mathbf{x}_{\mathbf{vic}}$ or $\mathbf{x}_{\mathbf{inj}}$, the agent currently employs. The elements outlined with dotted lines are outside of the agent's present strategy neighborhood, and are thus inaccessible.

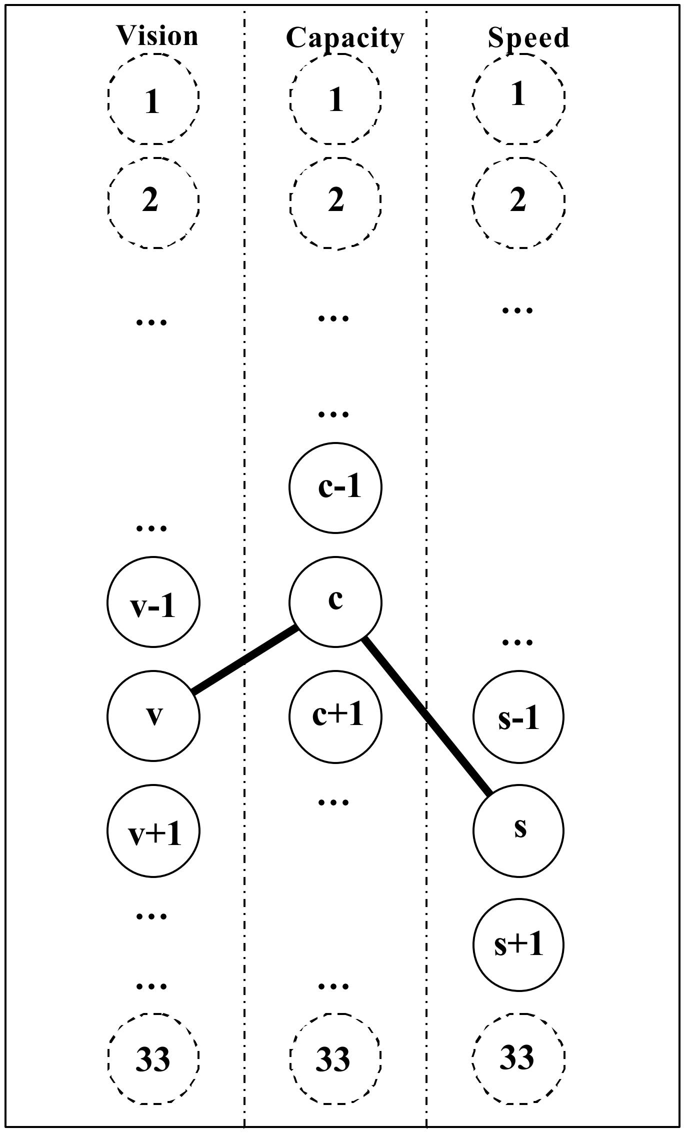

Figure 6.1. Agent Strategy Choice as Combinatoric Problem.

An agent may only select a candidate strategy from its neighborhood, that is, those levels that are within two elements from the agent's incumbent strategy. (Note: For clarity, only one level is shown for the neighborhood in the figure.) Those elements that are omitted from the figure or otherwise outlined with dotted lines reside outside the neighborhood and are only reachable after multiple iterations of the evolutionary algorithm.

The agent is not just a strategy however. Consistent with Potts (2000), the agents in this model are properly construed as systems of systems. They are also comprised of an algorithm for selecting among strategies which is described in greater detail below, as well as various other endowment elements such as their egg savings and instance variables necessary for the operation of the model. They exhibit system-element duality in that not only are they economic systems, but they are elements in the higher inter-agent level system as well.

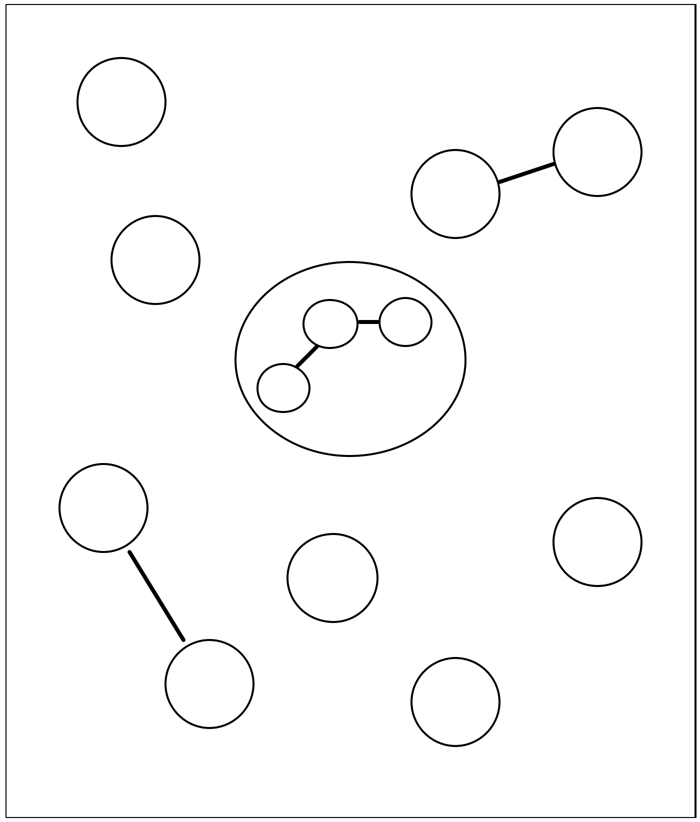

Figure 6.2. Graph of System Element Duality of Agents.[21]

The elements of change in an evolutionary microeconomic system are the connections (Potts, 2000) between the elements of the system. I have already described the nature of connections in terms of agent strategic decision making. At the inter-agent level, connections only occur when agents experience accidents with other agents, and are only operable during those timesteps. As depicted in Figure 6.2, the graph of the relationships among members of the population of Eggtopia tends to be very sparsely connected.

[21] The between-agent connections formed are those that form as a result of an accident. The graph also shows that agents are themselves comprised of various nodes.

The implications from complexity theory for the performance characteristics of such a sparsely connected graph is that such systems would reside towards the "order" axis on the spectrum of coordination from order to chaos (Potts, 2000, pp.85-6). Since the elements lack connections, the amount by which an agent's experience is influenced by others is muted, which tends to enable the system to maintain a stable order. In our case, it is also true that for the agents in question, accidents are a shockingly damaging experience that can significantly affect the success of the agent. Thus, where accidents do occur, the result is of such a non-linear nature that it may not reasonable to model it as a linear relationship.

B. Evolution of Behavior

In the full model, agents are allowed to change their strategies at particular intervals. The algorithm employed contains aspects of trial and error, as well as hill-climbing and satisficing. From a practicality perspective, the complexity of the model precludes a straightforward hill-climbing or similar optimization algorithm, due to the fact that it is impossible to "test" the expected success of the candidate strategy prior to employing it. For example, in the classic hill-climbing algorithm, the agent selects a candidate strategy in the neighborhood of his current strategy. Given the current strategies of the other agents, and a *known* function that relates individual agent strategies to the response variable of interest, the agent tests the candidate strategy to determine an expected value of the strategy. The agent then employs the strategy with the greatest expected value among a short list of candidates. There are two aspects of the current model that render such a straight-forward choice algorithm impossible. The first is that since an agent's performance is dependant upon the strategies employed by the other agents, it is impossible for an agent – or an algorithm – to practically and effectively predict the success of a particular candidate strategy, because as it is employed, a nontrivial number of agents are likewise changing their strategies in preparation for the next generation. The second is that the strategy space itself is so broad and sparsely populated, it is impractical to even learn about successful strategies from other agents. The domain is so large, that many strategies are never even employed by any agent through the course of entire replications.

Upon completion of a generation of 500 timesteps, each agent examines the success of her current strategy in terms of wealth accumulated. Let us assume that the agent has employed her incumbent strategy, which simply means that strategy which has proven successful in the recent past. If her current wealth exceeds that from the previous generation, meaning that the incumbent strategy has succeeded again in bettering her condition, it will remain her incumbent strategy and she will employ it in the next generation. This is the satisficing characteristic, in that the agent is satisfied with a relatively well performing strategy and does not seek to "fix what is not broken." See Brenner (2006, pp.913-4) for a description of satisficing strategies, and see Nelson and Winter (1976) for a well known and successful implementation in terms profit seeking firms.

If the agent's current wealth is less than that observed in her previous generation, that is, if the incumbent strategy does not succeed in improving her condition, she will select a candidate strategy and employ it in the next generation. This is the hill-climbing and the trial and error portions of the algorithm. Candidate strategies are selected from the set of neighbors of the current strategy. In the current implementation, neighbors are all strategies whose parameters are no more than +/- 2 levels from the current one. This means that most strategies have 5^3 or 125 neighbors, including itself. However, strategies at the edge of the strategy space, say with *vision* = 1, do not have a full set of 125 neighbors. In order to economize on computer time, an array containing the neighbors for every enumerated type of agent is uploaded at the beginning of the model and referred to as necessary. The agent chooses among the set of neighbors with equal probability assigned to each member.

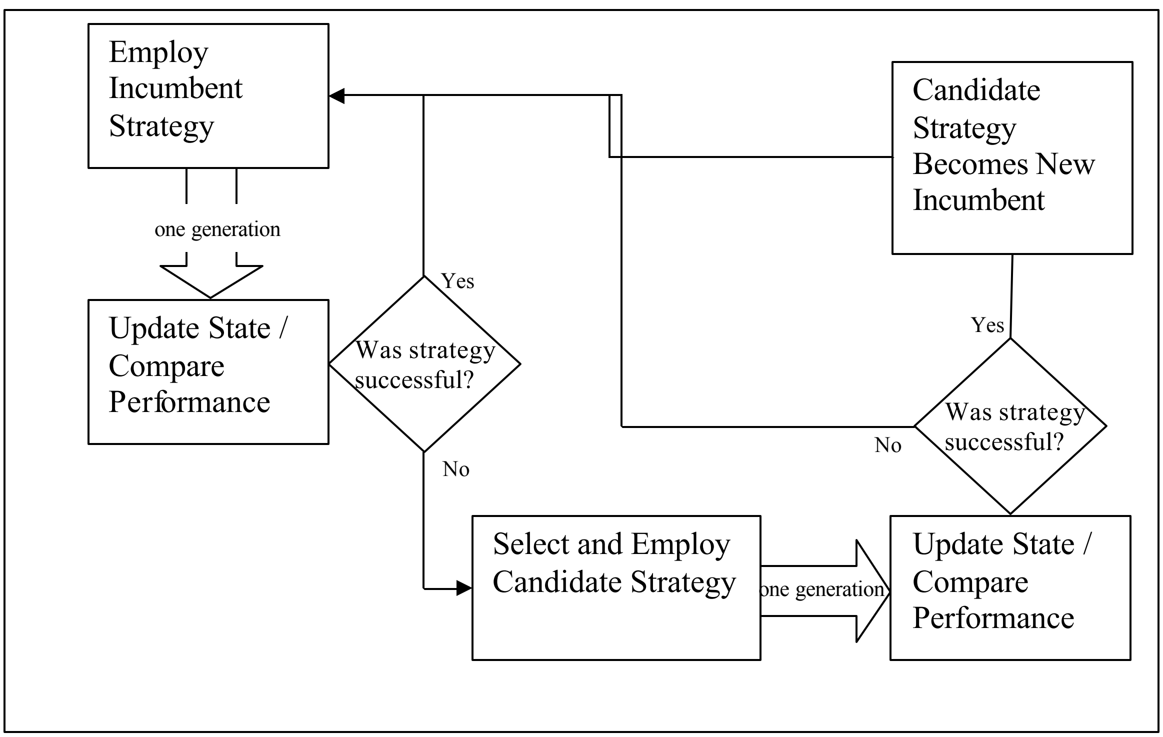

Figure 6.3. Flow Chart Depicting Agent Level Evolutionary Algorithm.

At the end of the next generation, the candidate strategy's success is measured against the level of wealth the incumbent strategy garnered the last time it was employed. If the candidate strategy yields greater wealth, it is deemed the new incumbent strategy and employed in the next generation. If the candidate strategy's performance is less than that of the incumbent, then the incumbent remains as such and is retried in the next generation.

C. Transient and Steady State Behavior

The agents in the model form a complex adaptive system with many characteristics that maintain a state of flux. While the primary response variables listed in Table 4.2, as well as their *injurer* counterparts, are still of interest, for the determination of transient and steady states we are mainly concerned with the measure of aggregate wealth, because it is the primary metric with which to compare the effectiveness of different liability rules. Aggregate wealth exhibits a transient state for a period of time before settling into a steady state for most scenarios (see Figure 6.4). In Law and Kelton's (2003, p.502) terminology, this is a nonterminating simulation and aggregate wealth is an appropriate steady state parameter. As such, a run time must be selected of sufficient length for the system to not only enter steady state, but to collect a sufficient sample of steady state data as well.

Figure 6.5 is a graph of *total_wealth* over time for N = 30 replications with 100 agents in an environment of 1,000 eggs and under a rule of no liability.

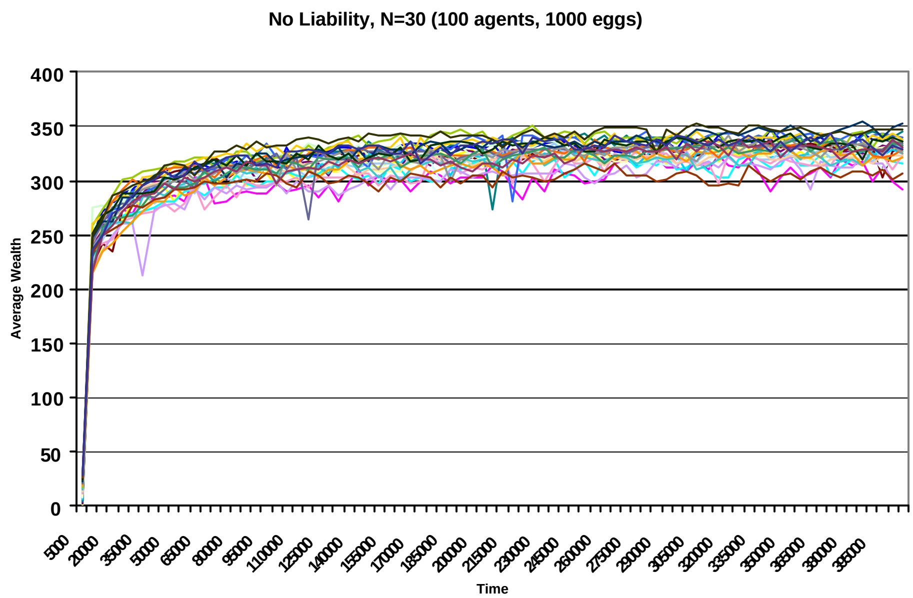

Figure 6.4. Aggregate Wealth Versus Time Under No Liability Rule (100, 1000).[22]

As the figure illustrates, there is an unmistakable transient period before this particular response variable settles down into a steady state, which appears to be some time after time = 300,000. However, the individual runs are highly variable, so it is not possible to conclusively determine through casual observation when the system enters a steady-state.

I use Welch's Method to determine when steady state is achieved (Law and Kelton, 2004, pp.520-525). Essentially, the method makes use of rolling averages of various dimensions in order to eliminate the short run variance in the output and reveal the underlying long run (steady state) behavior.

[22] Contains all (n=30) replications.

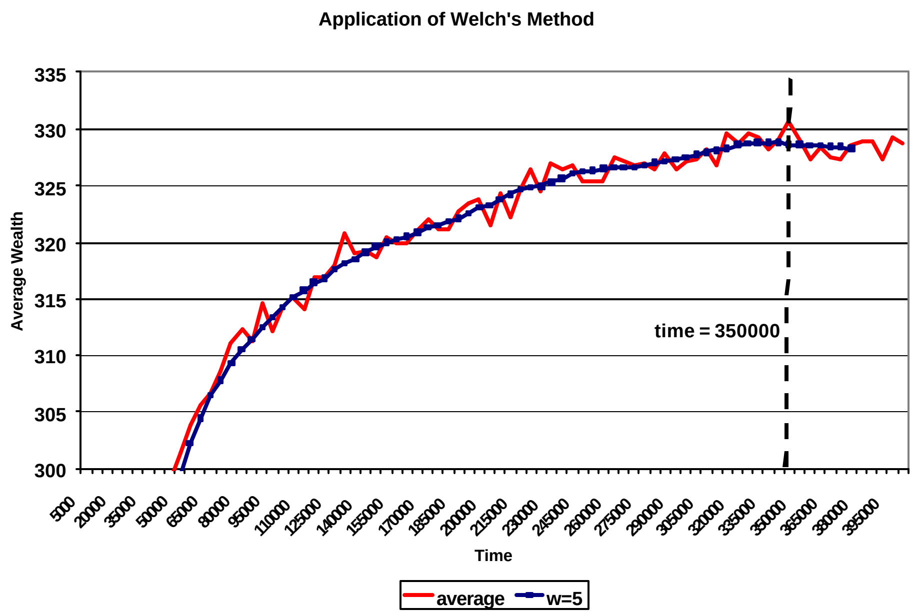

Figure 6.5. Welch's Method to Determine Steady State.[23]

According to the method, for the scenarios considered, all settle into a sufficiently ordered steady state by 350,000 timesteps. This result appears robust across all relevant variables as well. Figure 6.5 is an example of applying the method to the present scenario. Using a value of w=5 for the window span removes much of the short run variance from the average line. The smoothed line clearly "settles" at or around 350,000 timesteps. So, I use the replication/deletion method (Law and Kelton, 2004, pp.525-6) to measure the level of steady state variables of interest. In order to economize on time and computer space, only the results of every 10th generation are output and thus included in the analysis.

[23] Scenario considered is 100 agents, 1000 eggs and the rule of no liability.

III. Results, Comparison and Discussion

Consistent with typical neoclassical analysis, the evolutionary approach is capable of differentiating among any of several liability rules and identifying the rule that achieves the expected optimal. In the present case the measure of effectiveness is aggregate wealth, but alternative metrics could be used as well. The framework allows for the researcher to actually employ the various liability rules in artificial societies to examine the rules' effects directly, as opposed to explicitly analyzing the effects of a rule of no-liability and simply deducing the effects of other rules. A number of other questions concerning the distribution of wealth, the distribution of strategies, individuals' steady state behavior, and transient behavior are examined as well.

A. Identifying the Wealth Maximizing Rule

In this chapter, the scenario where Eggtopia is inhabited by 100 agents in search of 1,000 eggs is examined. Recall that Welch's method determined that the system tends to achieve steady state no later than 350,000 timesteps. As such, steady state parameters are estimated from the samples taken between time = 350,000 to 400,000. Each scenario is run between 10 to 30 replications each in order to shrink confidence intervals sufficiently to approach statistically significant results. However, throughout the analysis emphasis is placed on the practical significance of outcomes.

Table 6.1. Comparing Steady State Effects of Liability Rules.[24]

(100 , 1000)		
	Liability	
population mean	None	Strict
vic_vision	**21.7**	**25.7**
vic_capacity	**13.2**	**24.5**
vic_speed	**24.4**	**27.3**
inj_vision	**25.5**	**17.7**
inj_capacity	**24.1**	**17.1**
inj_speed	**27.1**	**18.0**
social total	**1.31**	**0.93**
vic_total	**0.52**	**0.81**
inj_total	**0.79**	**0.12**

Table 6.1 contains the summary results for a comparison of the rules of strict liability and no liability. The difference in the estimated aggregate wealth for either rule is both highly statistically and practically significant. As in the previous section (see Table 5.4), no liability is deemed superior to strict liability in terms of expected wealth, though there are some qualitative differences. For instance, the applied neoclassical method estimates that under strict liability, victims and injurers' portion of the social total is approximately even (see Table 5.4), whereas the evolutionary method estimates that victims will account for a vastly larger proportion of wealth. Similarly, the evolutionary method estimates that the average strategy sets for victims under strict liability and injurers under no liability are nearly identical, while the neoclassical method does not identify any such relationship.

[24] The strategies shown are the steady state population means for those parameters. Each scenario consists of n=30 replications and the difference in expected wealth is highly statistically and practically significant.

Table 6.2. The Rule of Negligence, Due Care Defined in Terms of inj_speed[25].

(100 , 1000)										
	Negligence due care in terms of Speed			Negligence due care in terms of Speed						
care	< 9	<17	<25	> 5	> 9	> 13	> 17	> 21	> 25	> 29
vic_vision	23.6	22.5	22.1	21.9	21.9	22.0	22.0	22.0	22.2	22.5
vic_capacity	18.5	15.3	14.0	13.3	13.5	13.5	13.6	14.2	14.9	16.3
vic_speed	25.0	24.0	24.7	24.3	24.5	24.4	24.3	24.5	24.4	24.6
inj_vision	20.0	23.5	24.9	25.7	25.7	25.5	25.5	25.1	24.4	23.6
inj_capacity	19.8	22.1	23.9	24.1	24.3	23.9	23.7	23.5	22.9	21.8
inj_speed	15.5	17.4	22.0	27.1	27.1	27.0	27.0	27.4	26.6	25.9
social total	1.07	1.20	1.28	1.31	1.31	1.31	1.30	1.30	1.27	1.22
vic_total	0.66	0.56	0.52	0.52	0.52	0.52	0.52	0.52	0.54	0.57
inj_total	0.41	0.64	0.75	0.79	0.79	0.79	0.79	0.78	0.73	0.65

Ten negligence rules where due care is defined in terms of various levels of speed are displayed in Table 6.2. The negligence rules that are significantly different from the other, higher performing rules are lightly shaded. The rules where due care is defined in terms of *speed* greater than 5, 9, 13, 17, and 21 achieve the highest expected aggregate wealth total. Where due care is defined as *speed* greater than 13 achieves the greatest wealth, however, the difference is neither statistically nor practically significant from the other non-shaded rules. Negligence rules in terms of vision and capacity were also thoroughly examined and the results are displayed in Table 6.3.

[25] The strategies shown are the estimates of steady state behavior.

Table 6.3. Overall Comparison of Tort Rules.[26]

(100 , 1000)					
	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
care	**n/a**	**n/a**	**> 5**	**> 9**	**> 13**
vic_vision	**21.7**	**25.7**	**21.6**	**21.7**	**22.0**
vic_capacity	**13.2**	**24.5**	**13.3**	**13.7**	**13.5**
vic_speed	**24.4**	**27.3**	**24.6**	**24.2**	**24.4**
inj_vision	**25.5**	**17.7**	**25.5**	**25.5**	**25.5**
inj_capacity	**24.1**	**17.1**	**24.2**	**24.1**	**23.9**
inj_speed	**27.1**	**18.0**	**27.1**	**27.2**	**27.0**
social total	**1.31**	**0.93**	**1.31**	**1.31**	**1.31**
vic_total	**0.52**	**0.81**	**0.52**	**0.51**	**0.52**
inj_total	**0.79**	**0.12**	**0.79**	**0.79**	**0.79**

Table 6.3 provides an overall comparison of the best performing tort rules. Various definitions of due care in terms of *inj_vision* were tested and, of those tested, the optimal was due care as defined as *vision* > 5. Similarly, the leading rules for capacity and speed were determined as well. Note, however, the 'optimal' rules illustrated in this table may not differ statistically nor practically from several other liability rules defined in terms of their respective parameters as described above. It is theoretically possible to replicate the scenarios a sufficient number of times to determine which rule results in the greatest expected social wealth with a desired level of statistical significance. However, such an endeavor would not likely bring us closer to understanding what, if any, practically significant difference any of these rules provides. The essential point is that there are a large set of rules that generate similar expected values of various measures of

26 Only Strict Liability is different than the others.

effectiveness. In contrast, Table 5.4 unequivocally declared that the rule of negligence, where due care is defined as *vision* less than 23, as the optimal liability rule.

The evolutionary perspective provides a richer understanding of the complexities of Eggtopian society because, as we have shown, it is possible to demonstrate from a genetic-causal standpoint the process through which a system generates particular steady-state outcomes. There is no confusion regarding whether it is appropriate to optimize individual, or social, outcomes, as it is when employing the poistem that is the neoclassical model[27]. Unraveling the sweet spot and enabling heterogeneous agents to pursue their own interests on the basis of their local knowledge is sufficient to achieve a steady state condition for each of the liability rules under investigation. The agents employ a simple satisficing algorithm with limited neighborhood search in pursuit of their own well-being, to the exclusion of all other concerns. The fact that such agent interaction tends to drive social wealth asymptotically to the vicinity of the maximum achievable for a given liability rule is an unintended, though beneficial, consequence of agent behavior.

B. Macro-Steady State, Micro-Turbulence

In the previous section, I outlined the relative performance of various liability regimes in terms of average wealth achieved during steady state as a measure of effectiveness. Steady-state is determined to have arrived when aggregate wealth ceases to vary significantly with time. One of the benefits of the agent-based modeling approach to the analysis of the current problem is the ability to examine the behavior of

[27] See above, Chapter 5.

the entire distribution of agents. While the aggregate outcome of time-invariant aggregate wealth is the result of the interaction heterogeneous agents and their environment, the individual behavior required to achieve this state is not obvious.

If it were the case that individual equilibrium is a necessary condition for system level steady-state, we would expect that agents would decrease the frequency with which they change their strategies as the system achieves equilibrium, at approximately 350k timesteps. Figure 6.6 is a graph of average agent strategy changes through time, with separate lines depicting the effects of several selected liability regimes. As the graph indicates, there is no apparent reduction in the frequency of strategy selection. That is, agents do not seem to settle on a particular strategy provides a robust response to the strategies employed by all of the other agents. Agents continue to grope around for strategies that improve upon the outcomes they currently experience.

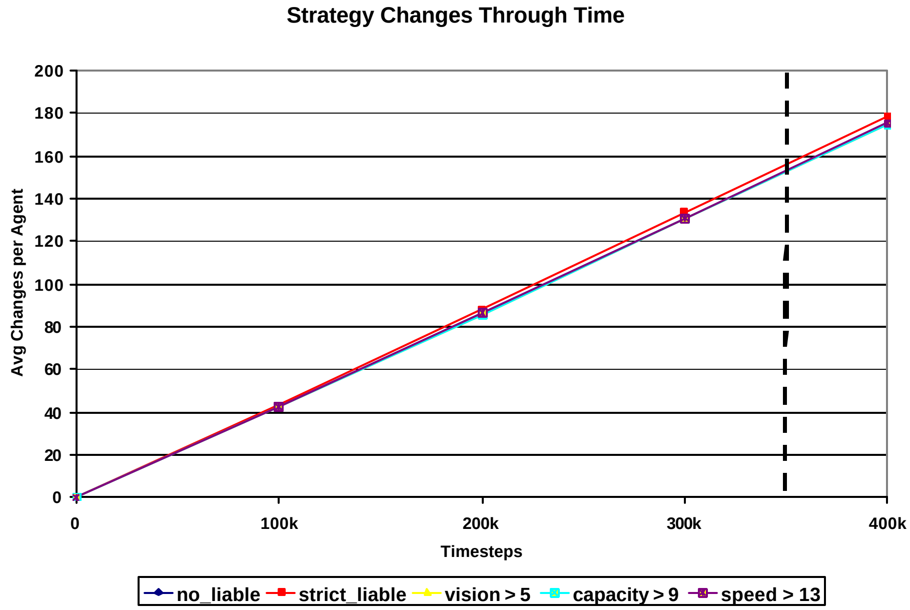

Figure 6.6. Agents' Average Cumulative Strategy Changes Through Time.[28]

While we established that agents continue to change their strategies in light of their attempt to respond to an ever changing world, it is not clear whether this flux also effects the agents' outcomes that ultimately obtain. Figure 6.7 outlines the how widely agents' outcomes in terms of wealth vary during steady state. Recall that steady state is achieved at approximately 350k timesteps. Every 10 generations from the onset of steady state to 400k timesteps is sampled, and the agents are divided first into injurers and victims, and then sorted into quintiles on the basis of wealth.

[28] The onset of system-level steady state appears to have no effect on the rate at which individual agents change their strategies.

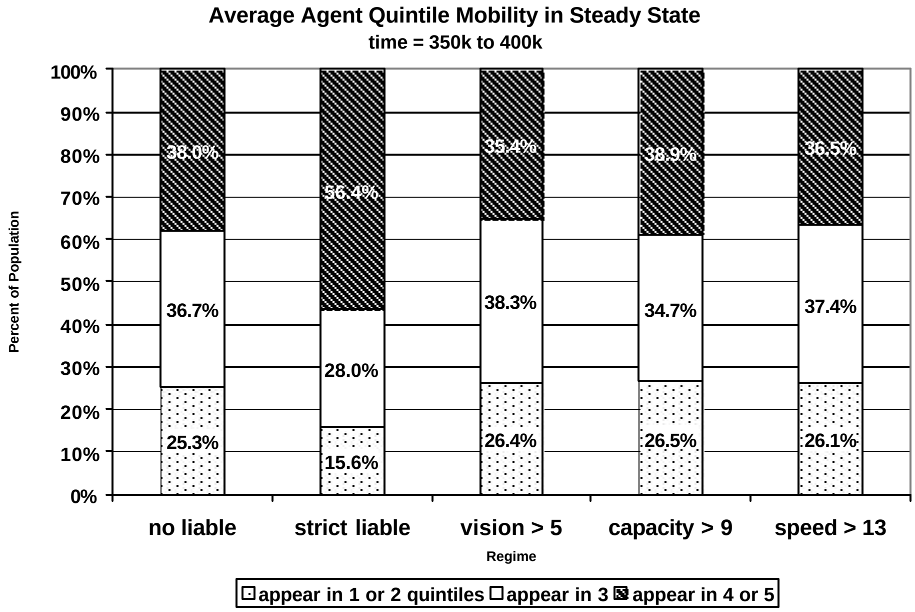

Figure 6.7. Comparison of Average Agent Mobility Among Wealth Quintiles in Steady State.[29]

If agents' outcomes achieved steady-state commensurate with that of the macro-level steady state, we would expect agents that appear in a given quintile at the onset of steady state would remain there throughout. Indeed, a charitable expectation would be for most agents to appear in no more than two different quintiles. However, as the figure indicates, approximately three-fourths of agents appear in three or more quintiles throughout steady state. The most variable outcomes result under the rule of strict liability, where approximately 85% of agents experience significant fluctuations in their success relative to other agents even while the system is in steady state. This result is

[29] Once system-level steady state is achieved, the vast majority of agents still experience significant variance in the success of their selected strategies, as evidenced by the fact that they may find themselves in three or more different income quintiles during the given timeframe. As indicated, this result is robust across liability rules.

counterintuitive in that one would expect individual stability or "equilibrium" would be a necessary condition for system level stability.

C. Examining Population Distributions

A drawback of representative agent theorizing is that it is not at all clear how the behavior of a representative agent 'scales' up to describing the actions of a population of heterogeneous individuals capable of diverse perceptions and opinions. Such an endeavor is subject to untold error via expected value propagation and is blind to the effects of interactions between different agents, especially those who find themselves in the tails of their distributions. The more diverse the population under investigation, the more their individual subjectivist views differ in light of their local knowledge of time and place, the more problematic is a representative agent approach. Indeed, one of the most compelling aspects of agent-based modeling and its ability to enable the researcher to unravel the neoclassical sweet spot is that it provides visibility on the entire population of agents, rather than reducing all behavior and all interactions into the activities of a single representative agent.

Tables 6.1 to 6.3 above outlined the results of various measures of effectiveness for particular liability rules, and as is typical, presented averages (expected values) of various strategy parameters for the population. In contrast, Figures 6.8 and 6.9 depict the distributions of agent strategies. For each of the graphs presented below, agents were first sorted into victims and injurers, and ultimately into quintiles based on the wealth acquired per generation. Again, only the results for timesteps 350k to 400k are considered. (The second and fourth quintiles are omitted for clarity.) The modified boxplots show the 25th, 50th, and 75th percentiles, thus, the vertical length of the box is the interquartile range.

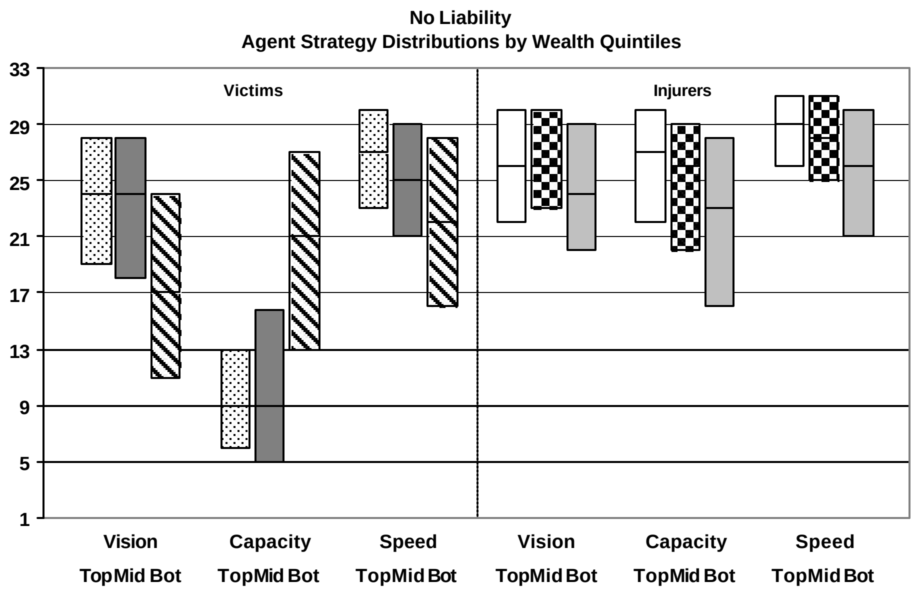

Figure 6.8. Agent Strategy Distributions by Wealth Quintiles for No Liability.[30]

[30] Note: for clarity, only results for the top, middle, and bottom wealth quintiles are depicted.

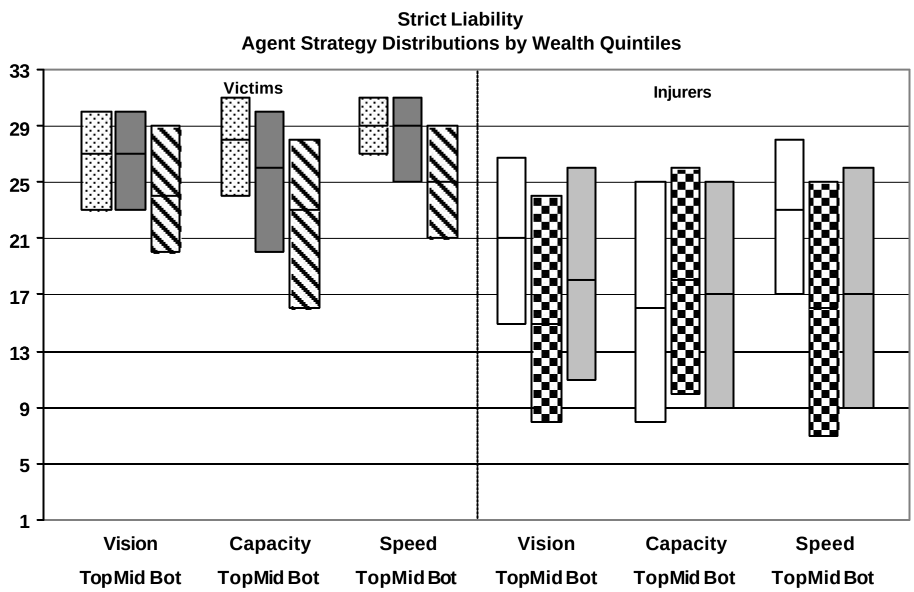

Figure 6.9. Agent Strategy Distributions by Wealth Quintiles for Strict Liability. [31]

Figures 6.8 and 6.9 illustrate agent strategy distributions by wealth quintile for the rules of no liability and strict liability. Note that the category of agents that are the residual bearers of the cost of accidental harm (victims under no liability and injurers under strict liability) exhibit a significantly larger interquartile range in their strategy parameters than their counterparts under the same rule. Interestingly, the distributions of strategies of victims under strict liability are remarkably similar to those of injurers under no liability. One hypothesis is relieving a particular class of agents of liability for any accidents in which they participate tends to reduce the variance in their income and thus simplifies their process of seeking out the appropriate, institutionally contingent, wealth-enhancing strategies. Conversely, placing liability on a particular class of agents

[31] Note: for clarity, only results for the top, middle, and bottom wealth quintiles are depicted.

increases the variance in their incomes and inhibits their ability to identify the most satisfactory strategies through time. While there appears to be substantial overlap for most strategy parameters among the quintiles, in most cases the means (and medians) are significantly different at a 0.10 level of significance. However, that does not necessarily imply practical significance.

A major theoretical conclusion of neoclassical analysis is that in cases of joint care, that is when it is efficient for both the injurer and victim to exercise some level of care, neither the rules of no liability nor strict liability are efficient. Under no liability, since injurers are not forced to internalize the damage from the accidents they cause, they engage in an insufficiently low level of care. Similarly, under strict liability, victims are relieved from responsibility for their actions and know that they will be fully compensated for any losses they may suffer in any accident, no matter the circumstances, so they too will engage in insufficiently low levels of care (Shavell, 1987). It is not necessarily obvious how this conclusion regarding inefficient behavior scales up to a large population of heterogeneous agents. It may be the case that in the aggregate, injurers under a rule of no liability select lower levels of care and thus reduce the overall wealth in society by destroying an inefficiently large amount in accidents. Are the wealthiest (most successful) injurers those that cast caution to the wind and charge around Eggtopia in search of eggs, without regard to the accidents they are causing and the wealth they are destroying? Do victims under a rule of strict liability respond to their unaccountable status with similar disregard for the (social) consequences of their actions?

Figure 6.10 displays the average per generation accident rates for agents in steady-state and separated by wealth quintile. A distinct inverse relationship between wealth quintile and accident rate is clearly discernable. Under the rule of strict liability, victims are actually involved in fewer accidents in all but the very poorest quintiles. Similarly, under no liability rule, the most successful injurers are also the most careful.

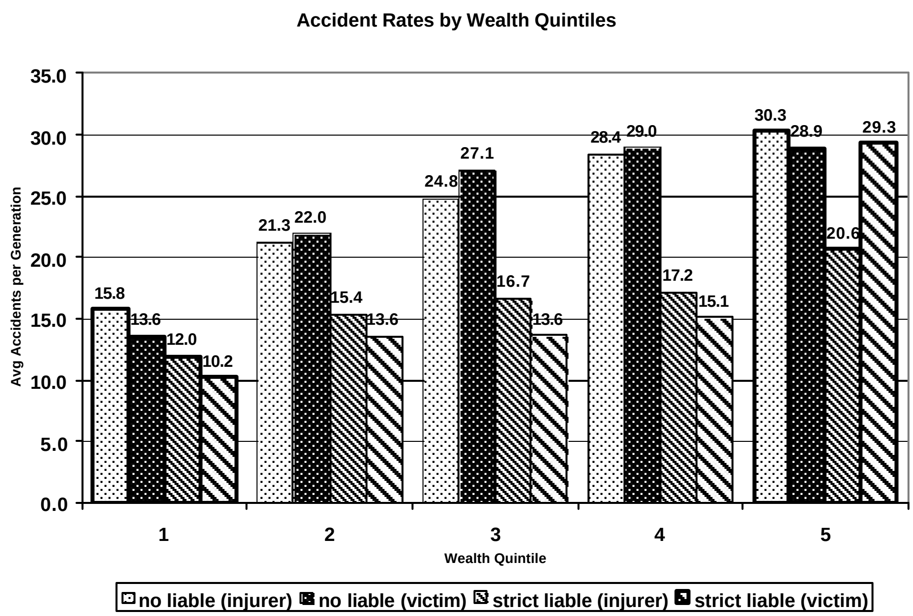

Figure 6.10. Accident Rates by Wealth Quintiles.[32]

Thus, the agent based approach enables us to unravel the sweet spot and examine questions with which static equilibrium methods are unable to deal appropriately. Under either liability rule, it appears that the wealthiest agents are not the wealthiest because they successfully take advantage of the fact that the rule relieves them of financial

[32] Notice how not only does the rule of strict liability tend to result in fewer accidents across members of all quintiles, but that under both liability rules, the top income earners are actually involved in fewer accidents.

responsibility of their actions, rather they are wealthy because they select those strategies that are most productive. This is another example of how this particular approach opens new doors for examining social phenomena more closely and inspires new questions to pursue.

D. Out of Equilibrium Dynamics

Another powerful feature of the evolutionary approach is the ability to analyze out of equilibrium behavior. Rather than assert the existence of equilibrium and then deduce the conditions that must be present in order to sustain it, this approach begins from non-equilibrium conditions and enables analysis of the process through which agents achieve equilibrium – or rather a steady-state, if at all.

We have already demonstrated that under all liability regimes considered, the system achieves a steady state in terms of aggregate wealth on or before time = 350k. Figures 6.11 and 6.12 illustrate how the wealth that injurers and victims accumulate changes through time in under the rules of no liability and strict liability.

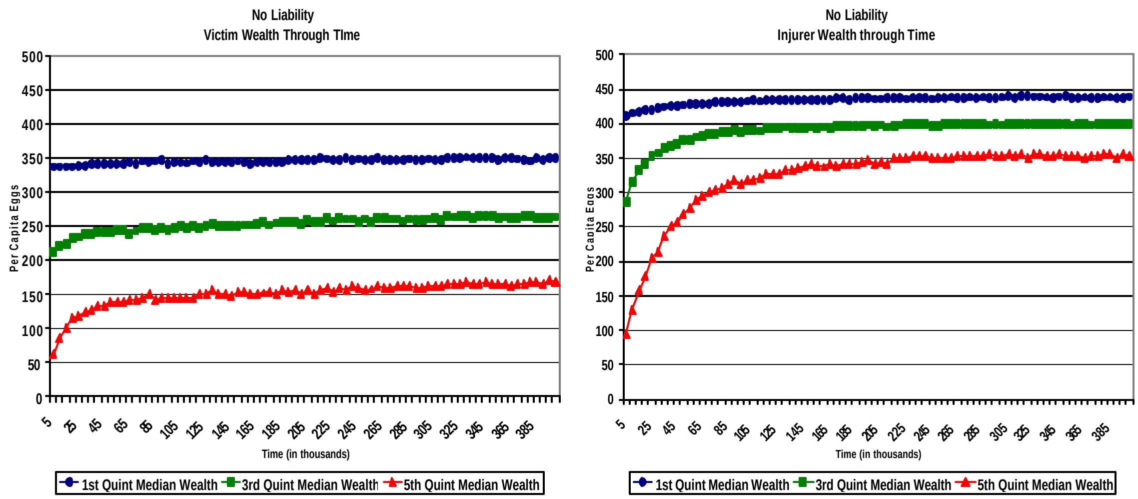

Figure 16.11. Victim and Injurer Wealth through Time Under No Liability Rule.[33]

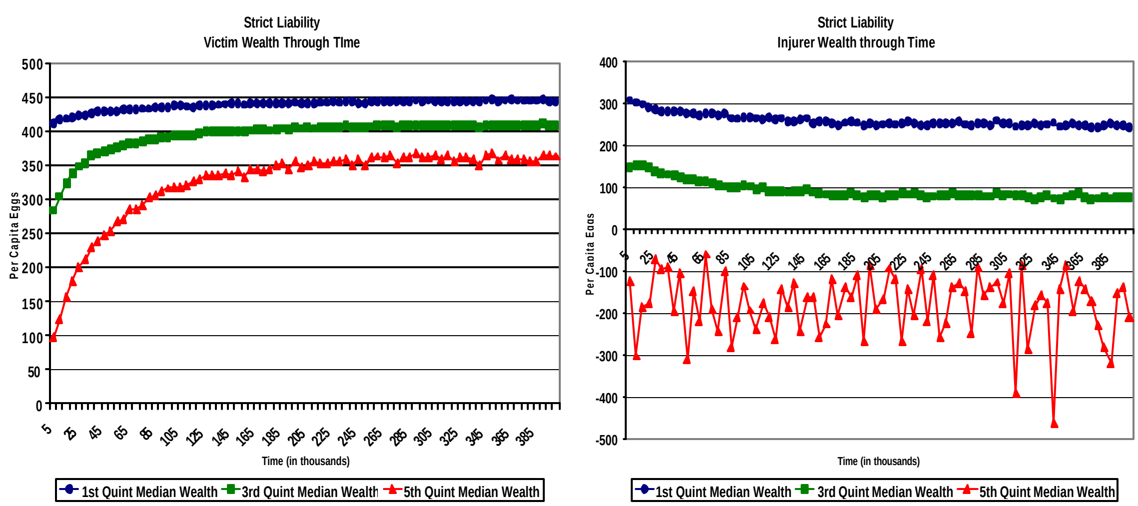

Figure 6.12.Victim and Injurer Wealth through Time Under Strict Liability Rule[32]**.**

Under both liability rules the agents required to bear the burden of accidents, victims under no liability and injurers under strict liability, experience greater variance in their

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[33] The three lines in each graph correspond to the mean wealth accumulated each generation by agents in the 1, 3, and 5 quintiles.

wealth and less convergence among quintiles. These same agents experience significantly less convergence in wealth among their counterparts in different quintiles as well. Interestingly, in each case the initial level of wealth is closest to the steady state level for the first quintile. This is consistent with the possibility that successful agents are such merely because they were lucky enough to be assigned a productive initial strategy at or near the most productive region of the strategy space. However, the fact that the vast majority of agents bounce around among the different quintiles does militate against the possibility that this is an important factor.

Figure 6.13 illustrates the manner in which agent behavior changes through time under three alternative liability regimes. The first liability rule is that of no liability, then strict liability and finally negligence, where due care is defined as *speed* in excess of 25. The left-hand panels are the results for victims and the right-hand are injurers. The average median value for each strategy parameter are drawn for agents that make up the top and bottom income quintiles. Note that the liability regimes that achieve wealth levels that are statistically "similar" to that of no liability have remarkably similar graphs. For this reason, a negligence rule that achieves a substantially different result from the top rules was chosen.

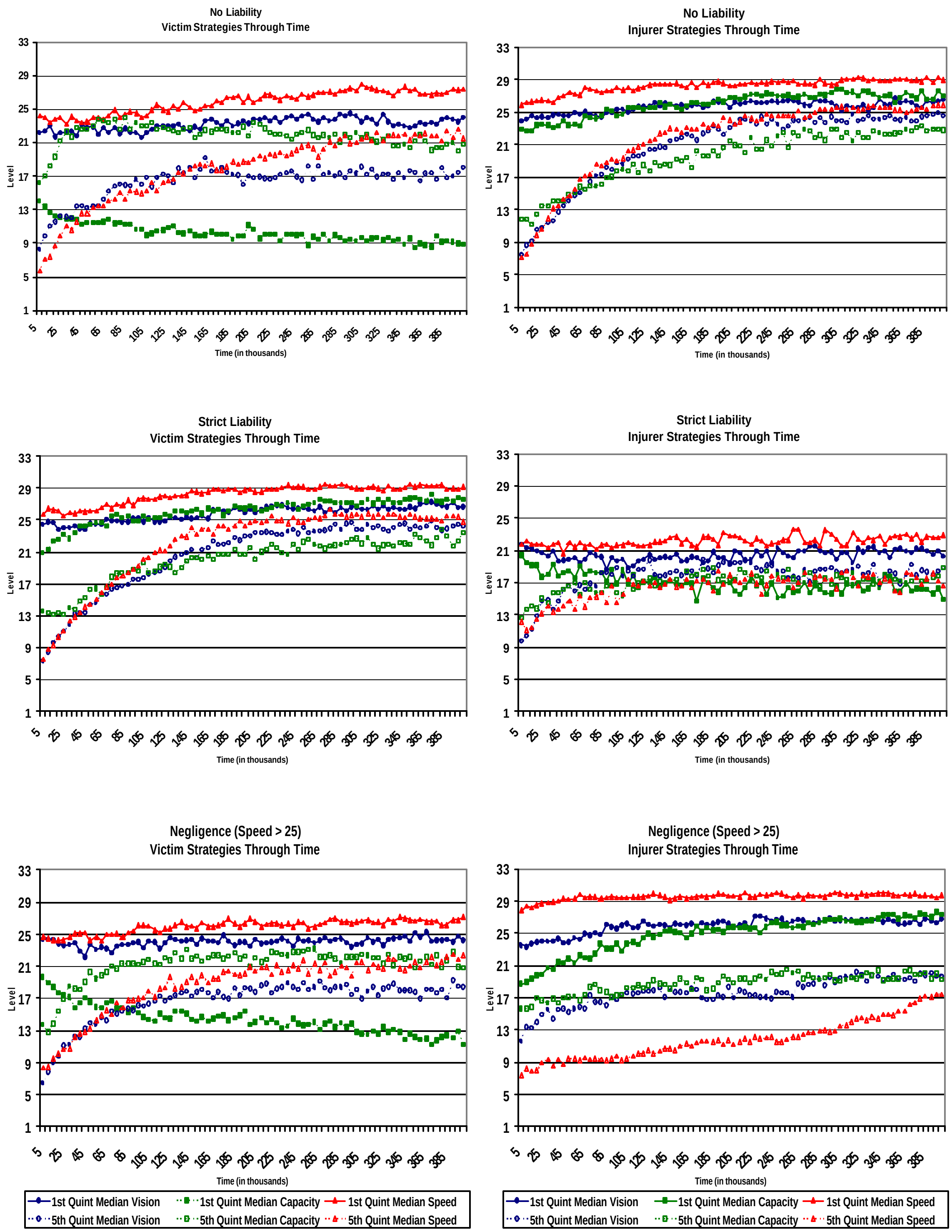

Figure 6.13. Agent Strategies through Time.

Casual observation of Figure 6.13 confirms the relationship victims under strict liability and injurers under no liability share that was discovered above. A similarity between victims under negligence and victims under no liability is present as well. This seems reasonable, given that the charts for the top performing liability are all similar, and this particular negligence rule, while statistically different, is not wildly different. It would seem that the difference in outcome is due particularly to the ability, or inability, of the injurers to determine the most appropriate strategies. For example, the trajectory of levels for all strategy parameters for injurers under strict liability all hover around 17, which is the center of the parameter domain and what you would expect if agents were selecting strategies randomly.

In contrast, consider the top quintile of injurers under the negligence rule. Their strategies, while not as tightly bound, are similar to that of the top quintile of injurers under no liability. This is consistent with the notion that the most successful agents – even under sub-optimal liability regimes, avoid liability by acting non-negligently. However, the bottom quintile fails to converge to the same non-negligent strategy set, as the median level of speed hovers between 17 and 20 for the majority of the time. This raises the question of what is preventing these agents from successfully identifying and selecting non-negligent behavior. Given the fact that these agents reside in the bottom quintile, it is unlikely they have settled in this region of the domain space because it is their true global optimum.

The persistent presence of negligent injurers may be indicative of an institutional failure to provide appropriate incentives to agents to engage in non-negligent behavior.

However, it could also mean that individuals select negligent strategies because it is profitable for them to do so despite bearing liability for accidents. Figure 6.14 is a graph of the expected number of negligent agents through time for the negligence rules in terms of speed. The top five rules (where due care is defined as speed greater than 5, 9, 13, 17 and 21) tend to guide all agents to attain non-negligent strategies. The other regimes considered fail to rid society of negligent behavior. Whether some negligent agents are present in the wealth maximizing scenario is an empirical matter, but one that Figure 6.14 begins to address.

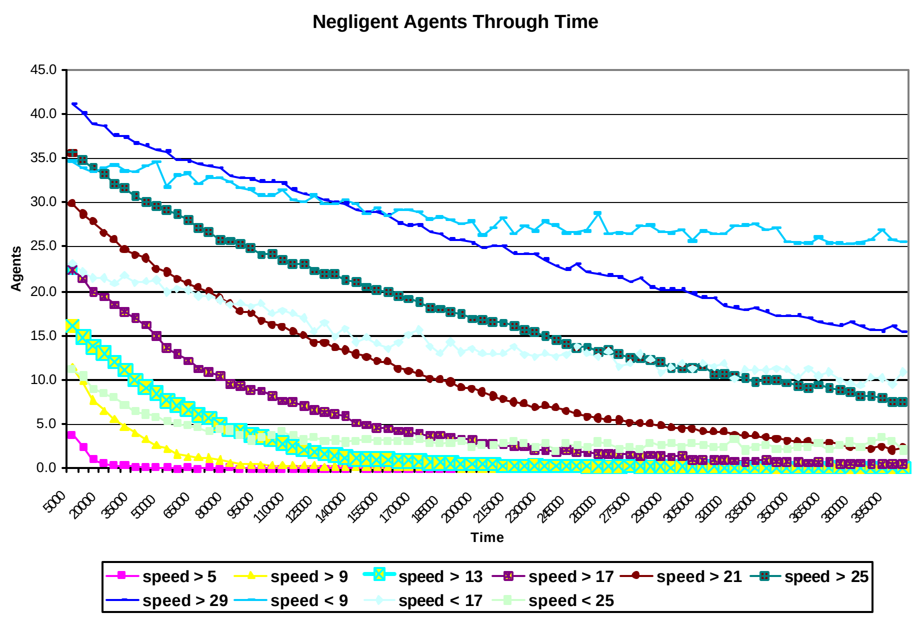

Figure 6.14. Average Number of Negligent Agents Through Time

More information is required before we can determine if the suboptimal negligence rules are so due to their inability to provide agents with sufficient incentives to behave safely.

Figure 6.14 demonstrates that under certain liability rules, the number of negligent agents either diminishes or continues indefinitely, and it raises the question of how these agents' behavior effects the number of accidents observed. Figure 6.15 illustrates the effect of negligent agents on the number of accidents. The first, third, and fifth quintiles are divided between negligent and non-negligent agents and the number of accidents cause by each group is plotted through the course of the simulation.

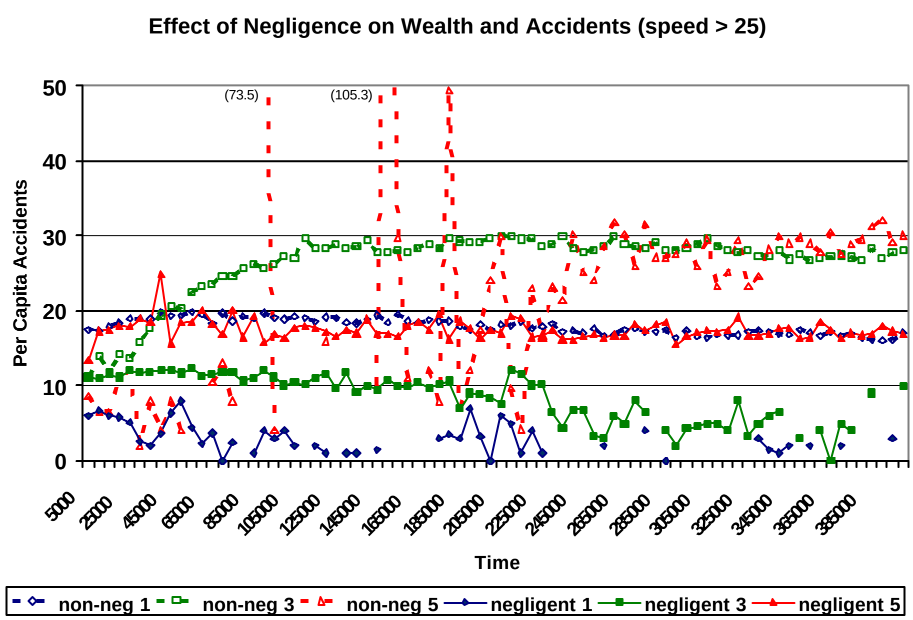

Figure 6.15. The Effects of Negligent Agents on Accidents. .[34]

The graph illustrates that agents deemed negligent are actually involved in fewer accidents than non-negligent agents. The relevant comparisons are among the lines with the same colors/shapes, which denote the same income quintile. Negligent agents in both

[34] Note: the numerals in the series titles (i.e. negligent 1) denote the wealth quintile. So, "non-neg 1" refers to the non-negligent agents in the first quintile.

the first and third quintiles experience far fewer accidents per capita. The line for non-negligent agents of the fifth quintile is highly variable, which is also a result of there being few non-negligent agents in that quintile during that period of time. Note that by the time steady state is achieved, all lines settled down with the relative positions among the quintiles still holding. While the graph depicts the results for an "inefficient" negligence rule, similar results obtain for higher performing rules as well.

IV. Limitations

This project represents an initial effort to utilize agent-based modeling and evolutionary methods as a tool for the economic analysis of accident law. While I hope to convince the reader that it shows much promise in its as yet nascent state, there remain limitations that bear addressing. First, I model the agents as possessing lexicographical preferences for eggs to the exclusion of all other possible goods, i.e. leisure, security from accidents, etc. These agents do not participate in markets and thus are not motivated by the price mechanism or profit and loss in the pursuit of egg collection. If agents' decision to collect eggs were influenced by market decisions, it would add a needed aspect of realism. Similarly, it is difficult for a model to capture all the salient factors of liability and the incentives to take care if insurance is omitted from the analysis.

The fact I assume the existence of a costless, perfectly operating judiciary is a simplifying assumption that could bear on certain conclusions. There is no uncertainty regarding the court's decision for any disputes, nor is there any uncertainty regarding any of the relevant facts of the case. While there is no uncertainty as it pertains to legal rules the approach does allow for shirkers, i.e. individuals who know what the due care level is and act negligently anyway.

Another limitation of this particular simulation model in its present form is the substantial computer time required to achieve steady state for most of the scenarios. The algorithm of agent choice is very simple and only gently drives the agents to their optimal regions of the domain.

V. Conclusion

In this chapter, I have demonstrated that the agent-based modeling approach is able to adjudicate between numerous liability rules and determine the rule or set of rules that achieve a particular performance standard in regards to any number of effectiveness measures. The evolutionary choice algorithm that agents employ to select their strategies drives the complex adaptive system that is the artificial society to eventually achieve an institutionally contingent social wealth maximizing steady state. The individual agent behavior also ultimately assists in the development of a genetic-causal explanation for the observed macro-phenomena. Agents, in diligent pursuit of ever more eggs, gradually identify, change, and employ strategies that tend to result in higher egg production and pushes the system to achieve a steady state level that is in the neighborhood of the highest achievable under that liability rule. So, an unintended consequence of the agents' quest for improving their state in life is to raise the aggregate level of wealth in society.

The power of the evolutionary approach is not simply that it provides a genetic-causal explanation as a means for adjudicating between various liability rules, it is that the approach enables the exploration of population dynamics and the close examination of out of equilibrium behavior. Among the realizations this framework yields is the notion that for Eggopians, the aggregate system appears to achieve a relatively stable level, the components of the system, continue to furiously grope around the domain in search of wealth enhancing strategies. Agents' continued search for alternatives tends to cause varied outcomes such that even in steady state, agents tend to jump around between income quintiles with alacrity.

The agent-based model provides insight into the manner in which the tort rule influences the entire distribution of agents. For example, it appears that the agents who are assigned to bear the residual costs of the accidents tend to have more widely varied strategy distributions, as well as greater differences in wealth quintiles. In contrast, those agents absolved from responsibility of accident costs experience more tightly distributed strategy distributions and more stable wealth distributions as well. It would appear that bearing responsibility for all accidents tends to increase variance of outcomes in terms of wealth and thus complicate the agents' ability to identify the strategy choices that lead to higher income.

In a related manner, the carefulness of various agents is easily examined in this framework. We find that typically the most successful agents are also the most careful and are not the ones necessarily 'getting lucky' and taking advantage of their fellow agents by engaging in risky behavior when they are shielded from liability. The outcome for negligence rules is not as simple. While the same relationship holds between high wealth and low accident rate, when negligence is considered, it appears that negligent agents tend to cause fewer accidents. However, when the level of due care is incorrectly set, then negligent behavior may not actually be unsafe.

The discussion and analysis in this chapter touches upon all three overarching themes of this project. This chapter represented the final step of the agentization of the neoclassical framework. Unraveling the neoclassical sweet spot and analyzing an identical target in parallel with the analysis of Chapter 5 brings the major differences between the two approaches into sharp relief, but also reveals them to be largely complementary. And consistent with the second theme of the project, the analysis in this chapter fully embraced the notion that individuals in society form a spontaneous order as they individually respond to particular institutions, each other, and their environment.

Finally, this chapter also highlights the knowledge problem inherent in the pursuit of economic efficiency of judicial decision making. The fact that this approach arguably provided a relatively more consistent and coherent model for the theoretical determination of superior liability rules than did the neoclassical effort of the previous chapter should not be construed as an endorsement of the notion that judges should employ agent-based simulation studies to aid their decision making. In fact, this analysis only serves to highlight the enormous informational requirement such pursuits place upon judges. "Optimal" rules only emerged after systematic enumeration and experimentation of the rules considered. Indeed, only a relatively small proportion of all possible rules were even considered. For example, due care could be defined in terms of various intervals along the strategy space, or even in terms of combinations of attributes. Such a realization would tend to militate against Posner's objective version of judges leading the common law to efficiency through their concerted effort to select the wealth maximizing ruling.

Chapter 7: Conclusion

I. Discussion

This project is best understood as an attempt to locate a metaphorical trailhead that leads the economic analysis of the law on a path that more effectively leverages the insights of spontaneous order economics and utilizes agent based modeling to gain greater understanding of complex phenomena. As such, it is far from the final word on the matter and it certainly suffers from a number of deficiencies which I hope to resolve in the future.

First and foremost, the final distinction between injurers and victims should be discarded. It was maintained throughout in order to facilitate comparisons between the results for Chapters 5 and 6. However, it is an entirely artificial division whose removal would add an element of realism in that individuals do not always know *a priori* what their roles will be in an upcoming dispute.

Until this point, the judicial mechanism implemented in the model differs from actual judges in a number of important ways. The pertinent facts of the case are known with certainty to the "judge", which is actually just an algorithm that deterministically applies the predetermined liability regime. Secondly, the judge in the model works completely within the confines of the liability rule in effect. In the current construct, the judges may not exercise discretion and must comply with *stare decisis.* A potentially fruitful refinement would be to create a mechanism whereby the judge collects information, in addition to having the ability to decide on the basis of a potentially changing or evolving rule. The cost of judicial proceedings, particularly in terms of the distribution of agents' labor, would also be beneficial to model. Rather than model judiciary as a costless and faceless algorithm, the judiciary would employ agents as judges. Rules that generate more judicial activity might encourage more agents to become judges rather than egg collectors and vice versa. More judges mean fewer agents available to collect eggs, thus capturing the social costs of judicial institutions in a unique and dynamic fashion.

A slightly more significant modification is to allow more than one jurisdiction for agents to reside, and allow purposeful emigration between them. This would facilitate the comparison of various regimes directly and the examination of the effects of competition and congestion. Agents in more sparsely populated areas are likely to thrive relative to the alternative jurisdiction due to the reduced probability of wealth destroying accidents. As more agents move there, however, the likelihood of accidents will increase, until the advantage of that jurisdiction is reduced.

One avenue that may prove fruitful would be to model the common law judicial process itself, and allow the different tort rules to evolve endogenously. Multiple jurisdictions with each attempting to select the appropriate rules would allow for much more complex relationships to be discovered. Different mechanisms for collecting relevant information might also be compared, i.e. one where the "judge" is privy to all global information that may be of use for composing a ruling intended to maximize wealth, and the other algorithm would also try to maximize wealth, but it would only be privy to the facts of the case at hand (and perhaps some sampling of other pertinent information). Such a framework could shed light on the practicality and practicability of the concept of wealth maximization for judicial decision making.

II. Areas for Further Research

A careful examination of the neoclassical paradigm developed by eminent scholars such as Posner and Shavell shows an underlying mathematical model, elegant in its simplicity that effectively employs the framework to achieve certain definitive conclusions. However, in the course of attempting to make sense of reality we may ultimately acknowledge that individuals, in responding to the institution of tort law, other individuals, and their environment form a spontaneous order. It is the purpose of this project to exploit this fact and demonstrate that the tools of spontaneous order economics and agent-based modeling in particular may be applied in a manner that enhances our understanding of accident law.

There are a number of fields of economic research that could benefit from the injection of the spontaneous order approach in a similar fashion. For example, theoretical analysis in the field of public choice generally relies heavily on equilibrium analysis. In particular, the Chicago School of public choice is essentially the canonical neoclassical framework applied to politics. Agentizing public choice models, particularly those that model the transmission of voter preferences into government or legislative action might enhance our understanding of the dynamic nature of politics or the influence of individuals with particular distributions of preferences.

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Curriculum Vitae

Chad W. Seagren was born on 6 January 1976 in Marion, Iowa and graduated from Marion High School in 1994. He received his bachelor of science from the United States Naval Academy at Annapolis, Maryland in 1998 where he majored in Systems Engineering. Upon graduation, he accepted a commission as an officer in the United States Marine Corps. Chad began attending the Naval Postgraduate School in Monterey, California in 2001. In 2003, he graduated with a master of science in Operations Research and was subsequently assigned as an operations analyst to Headquarters Marine Corps in Quantico, Virginia. In the fall of 2004, he began pursuing graduate studies in economics at George Mason University. He is currently the Aviation Supply Officer for Marine Aviation Logistics Squadron 29, in Jacksonville, North Carolina.