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Seagren, Chad W.

Monterey, California, Naval Postgraduate School

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Agent-Based Modeling and Dynamic Analysis of Accident Law

Chad W. Seagren
Assistant Professor
Operations Research Dept
Naval Postgraduate School
1411 Cunningham Road
Monterey, CA 93943
cwseagre@nps.edu

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Abstract:

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I employ an agent-based computational model to gain insights regarding relationships in accident law that are often overlooked in neoclassical theorizing. I consider 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 may also increase the possibility of an accident. I demonstrate how the agent-based model developed in this paper can be used to answer the questions commonly addressed in the mainstream literature, while also opening up new avenues of investigation. While certain outcomes are consistent with neoclassical theory, I find that agents may elect to be careful even when the neoclassical theory predicts otherwise, and particular negligence rules tend to differ significantly in their ability to rid society of negligent behavior.

[Draft Only – Not For Attribution]

1 Introduction

In the models most neoclassical economists employ to analyze accident law rational agents do not elect to engage in negligent behavior because to employ due care tends to dominate all other strategies. Thus, a puzzle for economists is to explain the findings of negligence that occur rather frequently in the real world. Typical explanations, accompanied by extensions to the models, involve unintentional lapses in the exercise of care, uncertainty in regards to the due care level the courts will declare, and improperly set legal standard of due care [1].

As an alternative, I argue that examining the law through the lens of spontaneous order economics provides insight into this puzzle and illuminates other important characteristics inaccessible to the mainstream neoclassical theorizing. I leverage the notion that many social phenomena are best understood as spontaneous orders and I place this project within the following two threads of analyses. I follow Rizzo [2], who argues there are weaknesses to applying static general equilibrium to analyze a dynamic system constantly in a state of flux. From this perspective, this project is an attempt to imbue the otherwise static neoclassical model with heterogeneous agents and heterogeneous time, in order to allow for out of equilibrium behavior. In addition, I draw from Smith's [3] notions of ecological rationality and explore how the institution of tort law provides otherwise boundedly rational individuals with the appropriate information and incentives to ultimately reduce the social costs of accidents. I explore the extent to which

individuals rely upon the institution for guidance as opposed to their own rational faculties to pursue goals that are privately and socially beneficial.

I present 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 may also increase the possibility of an accident. I demonstrate how an agent-based model of Eggtopian society 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. The analysis within the neoclassical framework revolves around the economic efficiency of various rules given certain extensions and complications.

The power of the evolutionary approach is not simply that it can assist in developing a genetic-causal process as a means for determining the desirability of various liability rules, but it is a tool to examine the mechanism through which the institution of tort law provides individuals with the appropriate information and the incentive to act upon it. In addition, this perspective enables the exploration of population dynamics and a close examination of out of equilibrium behavior and yields insight into such puzzles as why findings of negligence persist in reality and the notion that system level steady state does not necessarily imply agent level steady state.

1.1 Static and Dynamic Analyses of Accident Law in the Literature

Law and economics scholars in the neoclassical tradition, such as Diamond [4] or Landes and Posner [5] typically develop an explicit mathematical equation that describes the social welfare function for actors related to a particular type of accident (see Posner [6], Shavell [1], and Cooter and Ulen [7] for textbook treatments).

Landes and Posner consider a representative injurer and a representative victim to simplify the analysis and delineate the roles of the disputants, while Diamond models a single individual's rational choice in response to $n-1$ other agents, all of whom employ the same strategies in equilibrium. These approaches are consistent with the standard mode of analysis for neoclassical economists that upon selecting a phenomenon for investigation one assumes a system inhabited by rational utility maximizers who have stable preferences and some form of rational expectations regarding their world. 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 optima subject to the theorized constraints.

In this project, I relax the rationality assumption in order to explore the role that the institution of tort law provides individuals with the information and incentives to ultimately conduct themselves appropriately. In keeping with Axtell's [8] notion of the neoclassical sweet spot, relaxing one assumption such as agent rationality necessarily requires one to jettison other assumptions such as agent homogeneity, equilibrium, and

non-interaction. While neoclassical economics does not have much to say about disequilibrium behavior, the agent-based model we employ in the remainder of the article will enable us to maintain tractability of the problem.

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 [9]. 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 [9]. 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.

Relaxing the neoclassical sweet spot in this application serves two purposes. The first is that in reality, agents are not intimately familiar with the cost functions of their behaviors, let alone the respective functions for all other individuals engaged in similar activity, yet the model requires an individual to take these factors into consideration and determine a response that is jointly optimal. In fact, individuals must learn these relationships through their experience. Such experience may involve trial and error, observation, imitation, and any number of other modes of learning that humans employ to make sense of their world. This effort is an attempt to examine the role of tort law in guiding individuals in the process of discovery. In other words, we know actual people

are not hyper-rational utility maximizers and according to Smith [3], some of the rationality we see is actually because of institutions that have emerged to provide individuals guidance in making correct decisions. This approach seeks to examine the extent to which the institution of tort law provides individuals guidance in these situations.

The other purpose is to gain a proper understanding of the extent to which the neoclassical model is an adequate description of reality. As George Box famously quipped, “all models are wrong, but some are useful.” The analytical power of the neoclassical paradigm is one reason why it is the mainstream model for scientific thought among economists. It has the strengths of generality, syntactic clarity, and tractability. However, these qualities come at a price of relying on unrealistic assumptions. The use of an agent-based model is an attempt to move towards the more realistic end of the spectrum.

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 [10] applies such techniques to model disputants and the evolution of precedent. See also Yee [11], and Picker [12; 13] for treatments on similar topics. If simulation as a tool is used at all, such as in Katz [14], Hylton[15], Parisi [16] and Hylton and Miceli [17], it typically employed as a computational technique to numerically examine models that otherwise defy a tractable analytical approach, rather than as the focus of effort. This project is an attempt to remedy this gap in the literature as it pertains to tort law.

1.2 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. 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 collide, 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 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 punishment [18]. It is reasonable to believe that individuals subjectively weigh the payoff of risky behavior against the concomitant damage discounted by their estimate of the probability that the destructive event occurs.

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 opts 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 (and now the reader's), no empirical data, case law, or historical record exists that describe in detail the activities of its inhabitants. The agent-based computational model provides the mechanism with which data are generated to test the effectiveness of various approaches to economic analysis of accident law. 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 helps to overcome this challenge.

2 The Model: An Artificial Implementation of Eggtopia

The agent-based model of Eggtopia is implemented in REPAST, a simulation toolkit that uses the Java programming language. The environment is comprised of a two-dimensional torus grid that is populated with heterogeneous agents and eggs. The agents possess various attributes (instance variables), to include egg carrying capacity, visual range, and speed of movement. An agent's vision is the radius of the circle

(centered on the agent), in grid cells within which the agent is capable of viewing and 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 moves in a single timestep.

Agents are always engaged in one of four modes of activity. An agent in *search* mode actively explores 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. The number of cells the agent moves is equal to his speed. 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 which case the agent takes the most direct route to his home cell and drops off his collection of eggs. The eggs are then deposited into a virtual savings account, rendering them invulnerable to damage.

A display of the torus is included as Figure 1. The red rectangles are eggs, while the round objects are agents. Agents are assigned different colors to indicate their mode of activity.

Figure 1 Screen Capture of Model Display

Regardless of the agent's mode, during the *Pre-Step* stage 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. The agent attempting to enter the occupied cell is declared the injurer and the eggs the victim was carrying are destroyed.¹ A tort rule is immediately employed to adjudicate the disputes that arise surrounding the aftermath of these accidents. Figure 2 is a graphical depiction of the general outline of the model.

¹ 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.

Figure 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 agents 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

slower 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 are also functions 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.

It is important to note that there are no exogenous “cost” or fixed “profit” functions related to agent behavior. The consequences to any agent’s behavior are always endogenously determined through their interactions with other agents and the environment. Agents employ a “strategy,” which consists of a choice of vision, capacity and speed. One can easily imagine that a solitary agent’s optimal strategy would be the maximum allowable levels of each parameter. However, such a strategy would likely result in too many destructive accidents if other agents were present. In a social setting with other agents included in the model, causing accidents, suffering from accidents, and ultimately competing with other agents in pursuit of collecting eggs, it is clear that the success an agent enjoys is highly dependent upon the agent’s relationship to (most) other agents in the model. An individual could employ the same strategy and experience highly variable results due entirely to chance, or due to the strategic behavior of other agents.

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 [19] utilized what they termed zero intelligence traders to examine the institutional effects of particular auction rules. See Duffy [20] for a comprehensive survey and assessment of this literature. Ultimately, it highlights the institution's role in guiding behavior, as opposed to relying on notions of rationality or a particular level of intelligence.

While Gode and Sunder's agents selected their bids randomly, there is no randomness when it comes to an agent's choice in this model. That the agent pursues the collection of eggs is given, however, agents do select the strategy to carry out that end. While such an algorithm is perhaps an unambitious description of human action, it emphasizes the institution's role in guiding behavior, as opposed to relying on notions of rationality or a particular level of intelligence.

2.1 Accidents and Liability Regimes

The three classes of liability regimes we consider are no liability, strict liability, and simple negligence. Under a regime of no liability, the parties to the accident simply have no recourse to adjudicate their dispute and the losses fall where they may. A strict liability rule requires the injurer to fully compensate the victim of the accident for all of his lost eggs. Finally, the negligence rule requires the injurer to compensate the victim if the injurer was not exercising due care, and relieves the injurer from liability for losses if

he was exercising due care. 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 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.

2.2 Evolutionary Agents

Let the term, strategy, refer to a particular combination of *vision*, *capacity*, and *speed* levels. Parameter values may range from 1 to 33. The parameters *vision* and *speed*

are measured in cells, while *capacity* is measured in eggs. Thus, to say that an agent's *speed* = 9 is to say that such an agent takes "steps" 9 cells in length each timestep.²

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 have exactly 33^3 or 35,937 strategies from which to choose. Their choice is based on the perceived effectiveness of their current strategy and 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 [21] provides an analysis of the shortcomings inherent in basing a model of individual decision-making on a mathematical field and illustrates how it ultimately assumes an impossible level of knowledge concerning the state of the world on the part of the individual. He 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 3 is a

²Agents take their maximum step size in all cases except when it is necessary to take a smaller step to pick up an egg or to occupy their home cell.

graph theoretic representation of the strategy component for any given agent. The connected elements represent the strategy the agent currently employs. The elements outlined with dotted lines are outside of the agent's present strategy neighborhood, and are thus inaccessible at the present timestep.

Figure 3 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. Because the agent is faced with such ignorance and uncertainty, this framework should be a good test to see how well the tort law as an institution and the rules therein help to teach agents the appropriate behavior.

2.3 The Satisficing Algorithm

Agents are allowed to change their strategies upon completion of each generation lasting 500 timesteps³. The evolutionary algorithm the agents employ contain both satisficing and hill-climbing aspects. Assume the agent employed a particular strategy. If her current wealth exceeds her performance from the previous generation, meaning that the current (incumbent) strategy has succeeded again in bettering her condition, it remains her incumbent strategy and she employs 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 [22] for a description

³ Initial strategies are randomly assigned, though they need not be.

of satisficing strategies, and see Nelson and Winter [23] 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 selects a candidate strategy to employ in the next generation. Candidate strategies are selected with equal probability 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.

Figure 4 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 employed in the next generation. Thus, the upper level of the model is a classic evolutionary process in which the agents adapt their strategies or attributes according to the strategies and attributes that have exhibited success in that particular generation, or stage, of the model.

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 dependent upon the strategies employed by the other agents, it is impossible for an agent 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.

3 Results

Consistent with typical neoclassical analysis, this more dynamic evolutionary approach is capable of differentiating among any of several liability rules and identifying the superior performing rule. In the present case the measure of effectiveness is aggregate wealth, but alternative metrics are imaginable. 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 only analyzing the effects of a rule of no-liability and deducing the effects of subsequent rules. A number of other questions concerning the distribution of wealth, the distribution of strategies, individuals' steady state behavior, and transient behavior is examined as well.

In the following section, the scenario where Eggtopia is inhabited by 100 agents in search of 1,000 eggs is presented. Each scenario is tested 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 various outcomes.

The agents in the model form a complex adaptive system with many characteristics that maintain a state of flux. Aggregate wealth, that is, the sum of the wealth of all agents, exhibits transient behavior before settling into a steady-state. Each replication is run for 800 generations, or 400,000 timesteps, but only data after 350,000 timesteps is considered for analysis of steady-state variables. All data is considered for the analysis of transient variables, such as the trajectory of agent's strategy choices through time. In order to economize on time and computer space, only the results of every 10th generation are output and thus available for analysis.

3.1 Identifying the Wealth Maximizing Rule

I examine the rules of strict liability, no liability, and negligence, where due care is defined in terms of various levels of each strategy parameter. Table 1 provides an overall comparison of the best performing tort rules⁴. For each of five liability rules, agents' per capita wealth is measured over the course of a generation. The negligence rules shown are the best rules for each parameter. For example, the best performing negligence rule on the basis of speed is one where due care is defined as *speed* > 9.⁵ The rule of no liability achieves the highest per capita wealth, while strict liability performs relatively poorly. The difference between strict liability and all other rules is not only highly statistically significant, but is of practical significance as well. Per capita losses and accidents are also shown for each rule as well as compensation and strategy changes.

⁴ Differences between all pairs are statistically significant with the exception of the negligence rules for vision and capacity. Metrics shown are per capita averaged over all replications.

⁵ Rules where due care is defined in terms of *speed* > 17 and > 25, as well as *speed* < 9, < 17, < 25 were considered.

Per capita compensation is the average amount of wealth each agent transfers as a result of a dispute over the course of a generation.

Table 1 Overall Comparison of Tort Rules
(100 , 1000)

	Liability		Negligence due care in terms of		
	None	Strict	Vision	Capacity	Speed
due care	n/a	n/a	< 25	< 25	> 9
avg wealth	223.9	36.8	217.7	217.7	220.5
avg losses	128.4	256.3	133.3	124.3	131.5
avg accidents	40.3	26.0	38.4	42.9	42.1
avg compensation	0.0	256.3	4.0	1.8	0.5
avg strategy changes	161.96	172.32	153.38	157.70	160.58

The evolutionary perspective provides a rich description 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. 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. Agent interaction tends to drive social wealth asymptotically to the vicinity of the maximum achievable for a given liability rule and is an unintended, though seemingly beneficial, consequence of agent behavior.

These results, namely that strict liability performs poorly relative to other negligence rules and even no liability rule would seem to militate against Rizzo's argument that in a world of flux, the rule of strict liability is superior. However, Rizzo's thesis is that given an uncertain world of flux, the rule of strict liability provides an institutionally efficient rule by reducing uncertainty as to how the courts will handle disputes. Given the relative *ex ante* certainty of the rule of strict liability, individuals are better able to plan their activities and assess the consequences of risky behavior. This effect is magnified in a world of technological change that affects relationships in unimaginable ways and where people make subjective predictions on the basis of local knowledge. Since the present version of the model includes neither agent expectations nor a mechanism for technological change, these results should serve to simply inform this debate rather than provide weight to either side. In this stage of its development, the model may be considered a useful foil. Simply adding time and process to the analysis is not sufficient to conclude that strict liability is superior to negligence rule in a dynamic society.

3.2 Macro-Steady State, Micro-Turbulence

The previous section 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 the entire

distribution of agents. While the macro-level outcome of time-invariant aggregate wealth is the result of the interaction of heterogeneous agents and their environment, it is not obvious what individual behavior is necessary to achieve it. Agent based modeling enables us to answer this question.

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 or around 350,000 timesteps. Figure 5 is a graph of average agent strategy changes through time, with separate lines depicting the effects of a number of different liability regimes. As the graph indicates, there is no reduction in the frequency of strategy selection upon entering steady state since the slopes of the lines remain unchanged. That is, agents do not seem to settle on a particular strategy that is a robust response to the strategies employed by all of the other agents. Agents continue to grope for strategies as a means to improve upon the outcomes they currently experience.

Figure 5 Agents' Average Cumulative Strategy Changes Through Time

While we establish 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 affects the agents' outcomes that ultimately obtain. Figure 6 outlines the how widely agents' outcomes in terms of wealth vary during steady state.

Figure 6 Comparison of Average Agent Mobility Among Wealth Quintiles in Steady State

If agents' outcomes achieved in steady-state were commensurate with that of the macro-level steady state, we would expect that 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, between 70% and 96% of agents appear in three or more quintiles throughout steady state, depending upon the liability rule in effect. The most variable outcomes result under the rule of strict liability, where approximately 96% of agents experience significant fluctuations in their success relative to other agents even while the system is in steady state. This result is counterintuitive in that one would expect that

individual stability or “equilibrium” would be a necessary condition for system level stability.

It is fortunate that the model achieves a steady state in terms of an important aggregate variable such as total wealth and enables a straight-forward method to compare different liability regimes. Whether this system we have created would behave in this manner was a question that could only be answered empirically. Furthermore, while the aggregate system may achieve a pattern of steady state behavior, this section demonstrates that the agents do not exhibit behavior recognizable as individual equilibrium.

3.3 Examining Population Distributions

A drawback of representative agent theorizing is that it 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 a population, the more their individualized 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 is that it enables analysis of the entire population of agents, rather than distilling all behavior, and all interactions, into the activities of a single representative agent.

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 [1].

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 on average and thus reduce the overall wealth in society by destroying an inefficiently large amount in accidents. Under no liability rule, 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 7 displays the steady state average accident rates (per generation) for each of several liability regimes separated by wealth quintile. A general inverse relationship between wealth quintile and accident rate is clearly discernable. In fact, agents in the highest wealth quintile cause the fewest accidents for each of the liability regimes considered. This effect is both statistically and practically significant for the rule of no liability, as well as the others.

Figure 7 Accident Rates by Wealth Quintiles

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

3.4 Out of Equilibrium Dynamics

Another compelling feature of the evolutionary approach is that it provides the researcher with 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 out of equilibrium conditions and enables analysis of the process through which agents achieve equilibrium – or a steady-state, if at all.

Figure 8 Transient Behavior for No Liability and Strict Liability

Figure 8 is a depiction of the transient behavior of the system for both no liability (upper panels) and strict liability (lower panels). The panels on the left-hand side show the average wealth of agents in the 1st, 3rd, and 5th quintiles, and the panels on the right

show the strategy changes over time for the top and bottom quintiles. The effect of the different rules on the relative wealth of the different quintiles is startling. While the average wealth levels for the different quintiles under no liability simultaneously approach their asymptotes, under strict liability, the bottom quintile is highly variable and is always negative.

A possible explanation of this behavior is evident upon examining the right-hand panels. Under the no liability rule, agents in the top quintile locate the productive regions of the strategy space within approximately 400 generations, or 200,000 timesteps. In contrast, all of the agents under strict liability seem to be concentrated around the middle of the strategy space, which is consistent with the notion that the agents are unable to reliably ascertain the correct strategy selection from their experiences.

In the neoclassical framework, agent rationality rules out negligent behavior by definition under most negligence rules. Agents know that if they fail to exercise care they will bear the full costs of accidents they cause, so it is rational to exercise the level of care that meets the legal standard and nothing more. The persistent presence of negligent injurers is 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 5 is a graph of the average number of negligent agents through time for several negligence rules where due care is defined in terms of

speed. The top three speed based rules (spd_nlt_09, spd_nlt_17, and spd_NMT_25)⁶ according to average wealth also tend to guide agents to attain non-negligent strategies. The other regimes considered fail to rid society of negligent behavior. Whether some number of negligent agents are present in the wealth maximizing scenario is an empirical matter, but one that Figure 9 begins to address.

Figure 9 Average Number of Negligent Agents Through Time

It appears the suboptimal negligence rules are possibly so due to their inability to provide agents with sufficient incentives to behave non-negligently. In cases where due care is

⁶ The convention is neg_spd_nlt_09 identifies a negligence rule where due care is defined as speed not less than 9. Likewise, neg_spd_NMT_25 identifies a negligence rule where due care is defined as speed not more than 25.

improperly set, the incentives seem to be such that some agents are not guided to engage in non-negligent behavior.

4 Conclusion

In this paper, we demonstrate 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 of this artificial society to eventually achieve an institutionally contingent social wealth maximizing steady state. The individual behavior also ultimately provides a genetic-causal explanation for the observed macro-phenomena. Agents, in diligent pursuit of ever more eggs, search for strategies that tend to result in higher egg production, and gradually push the system to achieve a steady state level that is in the neighborhood of the highest achievable under that liability rule.

The power of the evolutionary approach is not simply that it provides a genetic-causal explanation as a means for differentiating 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 while 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. In addition, agents may elect to be careful even when the

neoclassical theory predicts otherwise, and particular negligence rules tend to differ significantly in their ability to rid society of negligent behavior.

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Captions

Table 2 Overall Comparison of Tort Rules

Figure 1 Screen Capture of Model Display

Figure 2 Graphical Depiction of the Basic Model

Figure 3 Agent Strategy Choice as Combinatoric Problem

Figure 4 Flow Chart Depicting Agent Level Evolutionary Algorithm

Figure 5 Agents' Average Cumulative Strategy Changes Through Time

Figure 6 Comparison of Average Agent Mobility Among Wealth Quintiles in Steady State

Figure 7 Accident Rates by Wealth Quintiles

Figure 8 Transient Behavior for No Liability and Strict Liability

Figure 9 Average Number of Negligent Agents Through Time