EVOLUTIONARY DYNAMICS AND THE ECONOMIC ANALYSIS OF LAW

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Regulators and the people that they regulate are engaged in an ever-evolving game of cat-and-mouse. In an attempt to evade regulation, payday lenders have affiliated with national banks and now more recently with Indian tribes, in order to claim immunity from state supervision. Tax shelter promoters have generated a sequence of shelters, each more convoluted than the last, to assist taxpayers in their quest to evade paying taxes. High-frequency traders have actually used federal regulation as bait to lure institutional investors into dark pools where trading algorithms eat them for lunch.

In response to these evasive strategies, regulators have enacted a succession of new laws and regulations, each an attempt to address the latest innovation. Although regulators often move quickly, because innovators often receive advance notice of proposed changes, new legal rules are often already obsolete by the time they are enacted. Even for those regulators that are able to enact effective regulation, the shelf life for such regulation is relatively short, and significant government resources are spent in trying to recapture regulatory power that is lost when lenders discover how to hack existing regulation. These ongoing dynamic interactions have shaped the direction of both regulatory strategy and the strategy of the regulated. We might call this reciprocal relationship the "co-evolutionary" dynamics of resistance.

In fields other than law, mathematical models have proved very useful in understanding and in managing the dynamics of resistance. For example, co-evolutionary models have mapped the dynamics of drug resistance, as bacteria or cancer cells evolve to evade drug intervention. [1] Scholars have drawn from observation and experimental data to construct these mathematical models of resistance, which they have then fit to the data. Drawing on these validated models, researchers have investigated ways to optimize the management of drug treatment, in the search for ways to slow down the evolution of drug-resistant bacteria, and the search for new drugs to replace those to which bacteria have become resistant.

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[1] Yoh Iwasa, Martin A. Nowak and Franziska Michor, Evolution of Resistance During Clonal Expansion, 172 Genetics 2557 (2006); Natalia Komarova and Dominik Wodarz, Drug Resistance in Cancer: Principles of Prevention and Emergence, 102 Proc. Nat'l Acad. Sci. 9714 (2005); Bruce Levin, Sylvain Moineau, Mary Bushman and Rodolphe Barrangou, The Population and Evolutionary Dynamics of Phage and Bacteria with CRISPR-mediated Immunity, 9(3) PLoS Genet. 1 (2013).

Modeling the dynamics of resistance, for example, revealed to public health officials that treatment with chemotherapy that is too early and at too high a dosage actually decreases survival time for cancer patients with certain kinds of tumor, because early high intensity treatment promotes the evolution of resistant cells.[2] Likewise, models have been usefully deployed to develop evolution-proof insecticide for malarial mosquitos.[3]

Could evolutionary dynamic models and corresponding empirical investigation help legal scholars to manage continually evolving law evaders like payday lenders, tax shelter promoters or high-frequency traders? Developing a theoretical model of wrongdoer and regulator dynamics could constitute an important first step in research to optimize the nature, timing and type of regulation. A deeper understanding of these dynamics could be of pivotal importance in devising ways to manage efforts to evade the law.

A number of interdisciplinary scholars have been working to develop evolutionary dynamic models to understand the dynamic relationships that characterize adaptive systems. In evolutionary dynamics, scholars use precise mathematical equations to describe the unfolding patterns of change over time. The abstract Darwinian dynamics that form the core of this approach are based on three central principles: (i) variation (via mistake, experimentation, innovation); (ii) transmission (by copying, adopting, social learning like imitation or payoff comparison) and (iii) selection (as happens during competition, by way of differential survival or via differential reproduction). The dynamics that arise from these principles generate a range of evolutionary outcomes: those include fitness-maximizing equilibrium but also other non-equilibrium outcomes such as oscillations, cycling or other regular patterns of change, and on occasion, chaos.[4]

Although the field of evolutionary dynamics got its start in biology, more recently, the field has expanded its reach to fields as diverse as epidemiology, computer science, sociology, international relations and artificial intelligence.[5] Armed with recent advances in computational power, scholars across the life sciences and social sciences have come to study the unfolding patterns of change not just over time but often across space as well.

[2] Helen Monro and Eamonn Gaffney, Modeling Chemotherapy Resistance in Palliation and Failed Cure, 257(2) J. Theor. Bio 292 (2009).
[3] Andrew F. Read, Penelope A. Lynch and Matthew B. Thomas, How to Make Evolution-Proof Insecticides for Malaria Control, 7(4) PLoS Biol. e1000058 (2009).

[4] Martin A Nowak and Karl Sigmund, Evolutionary Dynamics of Biological Games, 303 Science 793 (2004).

[5] Martin A. Nowak, Evolutionary Dynamics: Exploring the Equations of Life (2006).

Some scholars in the legal academy (a few as it turns out) have begun to use evolutionary dynamics to analyze dynamic patterns of legal change and corresponding changes in social, economic and political behavior of those whom law regulates.[6] Legal scholars have long been interested in applying evolutionary theory to legal change. Indeed, one of the central claims of law and economics from its inception is that legal rules evolve to become more efficient.[7] This chapter on the "evolutionary dynamics of law" discusses the possibilities that an evolutionary dynamics framework might offer for the economic analysis of law, and for understanding the evolutionary trajectories of legal change.

The first part of this chapter discusses in a general way the field of evolutionary dynamics, with illustrative examples from a range of disciplines. Second, the chapter reviews with more specificity the various methodological tools used by evolutionary dynamics that might be useful for the analysis of law. Third, and most importantly, the chapter explores three types of questions about the analysis of law that evolutionary dynamics might provide useful answers.

At the outset, two caveats are in order. First, in this entry, I present a broad review of literature on evolutionary dynamic approaches to biology, to the economy and to social science, but I do not try to systematically survey any genre. Rather, the main purpose here is to present the basic tools of evolutionary dynamic approaches in a range of disciplines, and then to suggest lines of inquiry for the economic analysis of law, so that the general reader can begin to explore the potential usefulness of this tool.

Second, it is also extremely important to note that at present, there is no existing field that one could call the evolutionary dynamics of law. At the moment, there are only a few projects that might be characterized as using evolutionary dynamics to analyze law, at least in the narrower sense that I am describing it. Indeed, those whose projects I describe might not themselves describe what they are doing as evolutionary dynamics. All of this is to say that this chapter is necessarily more speculative about the potential

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[6] In addition to those scholars mentioned infra Part III, see also Paul G. Mahoney and Chris W. Sanchirico, Competing Norms and Social Evolution: Is the Fittest Norm Efficient, 149 U. Pa. L. Rev. 2027 (2001); F.E. Guerra-Pujol, A Stag Hunt Model of the U.S. Constitution, 48 Rev. Der. P. R. 15 (2008); Brett Frischmann, A Dynamic Institutional Theory of International Law, 51 Buff. L. Rev. 679 (2003); John Armour, Simon Deakin, Viviana Mollica and Mathias Siems, Law and Financial Development: What We Are Learning From Time-Series Evidence, 2009 B.Y.U. L. Rev. 1435 (2009).

[7] Richard A. Posner, The Economic Analysis of Law (1973); Paul H. Rubin, Why is the Common Law Efficient, 6 J. Legal Studies 51 (1977); George L. Priest, The Common Law Process and the Selection of Efficient Rules, 6(1) J Legal Studies 65 (1977). For a review of this work, see Todd J Zywicki and Edward P. Stringham, Common Law and Economic Efficiency, Encyclopedia of Law and Economics (2d ed. Francesco Parisi and Richard Posner eds.)

usefulness of evolutionary dynamics for the analysis of law than any worked out version of what might not even yet be a nascent field.

An Evolutionary Dynamics Primer

Although evolutionary dynamics is new to legal scholars, the tradition has tremendous depth closer to its points of origin. Biologists who work in evolutionary dynamics trace their rigorous analysis to mathematical principles derived from Darwinian evolution and Mendelian genetics and then more recently to the central investigations of Fisher, Haldane and Wright. In the context of economics, scholars who focus on evolutionary dynamics in the economy draw from a line of argument that goes back hundreds of years, to Smith, Keynes, Schumpeter, Alchian and Hayek, and then more recently, to economists as diverse as Schelling and Ostrom. In the context of sociology and social psychology, evolutionary dynamics scholars trace their beginnings to theorists like Weber and Parsons, and then to the more modern scholarship of Simon (Herbert), Granovetter and Putnam.

What substantively unites these frameworks is a common conceptual foundation. In all these approaches, abstract Darwinian dynamics form the core of mathematical models that describe adaptation and co-evolution in biological and human populations. Evolution is commonly understood to involve progress or improvement, via variation, transmission, and selection. Certain processes in biology and in human activity produce variation in genes, in traits and strategies. Mutations, mistakes, innovations, creativity, generate differences in traits or strategies within a population.

This variation is then is transmitted to or inherited by others in the population. A trait or strategy that confers higher fitness or utility in a particular environment will spread through a population because it is copied more often, whether through genetic reproduction or cultural adoption. So for example, a gene for lactose tolerance is copied more often the gene for intolerance in humans whose diet staples include milk. The strategy of dumping of assets to cover losses might be copied more often in times of financial crisis if it brings with it higher payoffs than other strategies. A common-law exception to a legal rule that reduces litigation frequency and conforms to the relevant precedent might be copied by other states more often than one that does not.

In social science, people transmit strategies or social practices by social learning or imitation; we can think of this transmission as reproduction because it involves copying. Individuals and organizations learn from others by imitating in many ways: following the leader, conforming to the majority, comparing payoffs and switching to another comparative strategy if the payoff differences are great enough. Cultural transmission allows social behavior to diffuse through a population.[8] Those practices

[8] Luigi L Cavailli-Sforza and Marcus Feldman, Cultural Transmission and Evolution: A Quantitative Approach (1981); Martin A. Nowak, Evolutionary Dynamics: Exploring the

that generate a higher fitness (say, social status, or material payoffs) will be "selected" to spread.

If the environment is unchanging, we can picture a "fitness landscape" in which populations are moving up a hill on solid ground, ascending to progressively higher levels of average fitness or utility. Mechanism design techniques are often used to optimize utility or fitness, as are genetic algorithms more recently. These optimization techniques, which have been developed over the last hundred years, push the population towards strategies or traits with more and more optimal fitness, assuming an unchanging environment and a firm fitness landscape.

But when populations interact with each other—when predators rely on prey for food, when cooperators are interacting with defectors, when banks are interacting with borrowers, when firms are interacting with legal regulators—then the populations themselves are part of the environment or fitness landscape on which evolution takes place. This is true as well for individuals within a heterogeneous population: when cooperators and defectors interact in the same population, the utility of their strategies depends on how many other people are deploying the same strategy.

Accordingly, as populations (and individuals in populations) change and move across the landscape, they simultaneously change the fitness landscape for each other. In this way, actors are co-evolving, as they serve as both agent and environment simultaneously. So a host's successful immune response to a virus creates a changed environment in which mutations of the virus that allow it to overcome host immunity will now be copied more frequently. Or to use a legal example, payday lenders' innovation to evade legal regulation creates a changed environment that then exerts "selection pressure" in favor of new regulations that respond to the lender's evasive innovation.

Frequency dependent selection is at work in these examples. Just as the fitness of a trait often depends on its frequency in a population, so too does the utility of a strategy often depend on the frequency of that strategy in the rest of the population, or on the strategy of an interacting population. And because fitness or utility depend on frequencies, and frequencies depend on fitness or utility, systems display dynamics that are often characterized by positive feedback for some portion of time.

Given this interdependency, optimizing techniques are less useful under these circumstances, as are ideas about the inevitability of evolutionary progress or uphill climbing. Here, evolutionary game theory techniques have proved quite useful. Drawing from population biology insights, evolutionary game theory originally developed about fifty years ago in the context of addressing not just biological but also social and

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Equations of Life (2006), Robert Boyd and Pete Richerson, Culture and the Evolutionary Process (1985).

economic problems. More recently, the theory has made its way full circle, back to evolutionary biology.

Evolutionary game theory, and evolutionary dynamics more generally, ask how traits or strategies change endogenously with the patterns that these choices and strategies collectively create. Put a bit less formally, agents react locally to the overall patterns that they themselves have created. And in their reacting to that pattern, they again create patterns, to which the agents further react, and so on. In the context of this dynamic system, the key question that an economist might ask is, "How does this complex system unfold over time? How will the agents react to the patterns of the system? How will their reactions affect the pattern they have created?"

Evolutionary dynamics has generated insight into subjects as diverse as ritual animal conflict, parasite-host interaction, predator-prey interaction, linguistics, signaling, social norms, private property and agricultural contracts, to name just a very few. Adding the dynamic element to traditional game theory enables scholars to study equilibrium formation for dynamics that converge to equilibrium, as well as non-equilibrium dynamics like cycling and oscillations (in predator prey models, for example.)

Some scholars have questioned the usefulness of biological evolutionary dynamics models for the social sciences, which involve human decision making that is less random and error-driven than genetic mutation. But behavioral economists have documented over the past few decades that human decision-making is frequently myopic and boundedly rational, influenced by others through learning, imitation and social pressure. Likewise, human choice often contains elements of experimentation and innovation in conditions of uncertainty that make precise decisions difficult to know in advance, even as we can detect regularities and patterns in that experimentation or innovation.[9]

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[9] In law, for example, see, e.g., Orit Fischman Afori, Reconceptualizing Property in Designs, 25 Cardozo Arts & Ent. L.J. 1105, 1151 (2008) (referring to a statute providing intellectual property protection for vessel hulls as a "legal experiment"); Theodor Meron, Reflections on the Prosecution of War Crimes by International Tribunals, 100 Am. J. Int'l L. 551, 551 (2006) (referring to the Nuremberg and Tokyo war crimes tribunals as "a bold legal experiment"). Scholars sometimes describe approaches to government as analogous to actual experimentation, complete with randomization. See e.g., Michael C. Dorf and Charles F. Sabel, A Constitution of Democratic Experimentalism, 98 Colum. L. Rev. 267, 348 (1998) (noting in a discussion of the experimentalism of democratic government that systems for evaluating experiments "can themselves be benchmarked, and...can be combined with random-assignment experiments and other familiar methods of evaluation.")

And lest we think that humans have a monopoly on rational response, it turns out that some biological agents display less myopic, more targeted or "intelligent" kinds of responses. Some bacteria for example target a virus phage attacker by incorporating a defective version of the virus' DNA into the bacteria's genome, creating immunity (via self-vaccination) against attack. Scholars have begun using those models to investigate human behavior.

It bears repeating that the patterns studied by dynamics scholars can and often do include stable equilibria, in which the dynamics settle into stable rest points. Dynamics scholars can shed great insight into the formation of these points, which may take a long while to form. In addition, those patterns can also include non-equilibrium (disequilibrium) activity (cycling, oscillations) or rest points that are relatively unstable. Both the equilibrium and non-equilibrium patterns of biology, of the economy and of society are of great concern to policymakers, who are often interested in optimizing at particular times and places and under particular conditions.

Indeed, as described above, the questions that evolutionary dynamics scholars ask actually complement those that neoclassical economists ask. At the risk of oversimplification, one can say that neoclassical economics asks a set of questions that represent the mean-field workings of the economy. Generated in the absence of the kind of computational power that we now enjoy, neoclassical theories ask a comprehensive question: "What agent behavior is consistent with, or in equilibrium with, the outcome or pattern that the agents' behavior will cause?"

More specifically, general equilibrium theory asks what prices and quantities produced are consistent with the overall patterns of prices and quantities in the market. Game theory asks what best responses are consistent with the best responses of other players such that no one has the incentive to deviate. Equilibrium analysis identifies those points of convergence.

Dynamic models widen the lens to ask 'How do agents' behavior change in reaction to the pattern that they together create, and how does that then alter this pattern?" This inquiry focuses on the unfolding of patterns over time. So for example, dynamic models can more easily investigate the process of equilibrium formation or selection in a system that features multiple equilibria. Evolutionary dynamics also more easily investigates the empirical regularities that characterize non-equilibrium behavior, like periodic oscillations or other more intricate patterns. Dynamic models can describe novel dynamic structures like endogenous innovation, bubbles, crashes, tipping points and other dynamic structures.

Dynamic models can offer additional insight by relaxing some of the more restrictive assumptions of neoclassical models: evolutionary dynamics investigates multiple heterogeneous agents, often boundedly rational and learning from each other, sometimes out of equilibrium, and often engaging in frequent experimentation and innovation. As law and economics scholars have acknowledged, relaxing these assumptions can add realism and flexibility to models of human decision-making.[10]

The usefulness of evolutionary dynamic models and their ability to supplement existing investigations might usefully be understood by considering the metaphor of traffic. Equilibrium models of traffic focus on the equilibrium conditions that traffic converges to on average, across a range of conditions. Dynamic models describe, in addition, the unfolding of the flow of traffic--traffic jams, including starts and stops, choke points, novelty (accidents) and endogenous change (waves of congestion). Evolutionary dynamic models can help us to explain how a seemingly small event—shutting down a lane for a short time, the entry of a few more cars onto the freeway—can potentially trigger a dramatic phase shift from free-flowing traffic to massive gridlock on the freeways. The dynamics of such change—the patterns of change, their causes and consequences, their frequency--are often of great interest to policymakers.

Evolutionary Dynamics Influences

Evolutionary dynamics is a fundamentally interdisciplinary project, drawing together a core of methods from several disciplines that focus on describing systems of interacting individuals and populations that adapt over time. As such, evolutionary dynamics can be said to draw from four or five key theoretical areas.

First, evolutionary dynamics scholars draw on the study of dynamics, and in particular, the evolutionary dynamics of adaptive systems. Mathematical models are drawn from population genetics, population ecology dynamics, epidemiology, evolutionary biology and sociology. Most models are equation based, and rely on differential equations and their solutions to describe the dynamic patterns that interacting agents create. Some evolutionary dynamics theorists also make use of agent-based models, which numerically simulate the interactions of heterogeneous agents. In an agent-based model, dynamic equations are replaced by rules of interaction, and the dynamics of the system are explored over a range of parameters. Evolutionary dynamics models will be discussed more fully in the following section.

Some evolutionary dynamics scholars in the social sciences also use theoretical tools from the study of information processing to define and describe bounded rationality. In particular, they draw on arguments made by Herbert Simon and others, who show that people operate under conditions of limited information or high uncertainty by making use of effective heuristics—rough and ready rules of thumb—to operate in novel or noisy environments, by social learning and by experimenting.

For example, some evolutionary game theorists use imitation and social learning models that assume that under conditions of uncertainty, market actors will compare their

[10] See Randal C. Picker, Simple Games for a Complex World: A Generative Approach to the Adoption of Norms, 64 U Chi. L. Rev. 1225 (1997).

payoffs with those of others around them—a market leader, their neighbors, the majority, a teacher or mentor—and will switch to the other's strategy with some probability that depends on the difference between their payoffs.[11]

Likewise, evolutionary dynamics scholars (particularly the social scientists) make use of insights offered by social psychology and behavioral economics, having to do with the way in which people interact socially within a group. Scholars incorporate into their models experimental empirical data about the prevalence of altruism, people's pro-social and anti-social reactions to punishment, and the role of gossip and mutual reciprocity.

Economic history and geography play important roles in evolutionary dynamics as well. In the presence of self-reinforcing positive feedback loops, economic outcomes can be path-dependent; small events in history can sometimes strongly influence the evolutionary trajectory of technology markets, for example. This is because many economic processes are self-reinforcing over time. Small events can trigger cascades of change that propagate through a system quickly and with increasing speed, much like an infection sweeping through a population. For example, a choice to locate a firm in one place can generate a labor pool and transportation infrastructure that then draws other firms to locate in the same place, for example.[12]

Evolutionary dynamics scholars also draw insight from network and graph theory. In both biological and social science fields, agents interact in ways that are structured by networks. In an economy, for example, social networks make it more likely that some market actors interact than others, and that people's choices and indeed their very preferences are a function of those around them. In gene-regulatory networks, the architecture of the network directs the cascade of influence from genetic mutations on the regulatory "switches" that control the activation of a gene. In social networks, the network topology can make the difference between the success or failure of cooperation as a social norm. Scholars of cooperation have demonstrated how social network structures can allow cooperation to flourish despite incentives to defect.[13]

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[11] See e.g., Karl Sigmund, Hannelore De Silva, Arne Traulsen and Christoph Hauert, Social Learning Promotes Institutions for Governing the Commons, 466 Nature 861 (2010). For details on the pairwise comparison of payoffs, see Arne Traulsen, Jorge M. Pacheco and Martin A Nowak, Pairwise Comparison and Selection Temperature in Evolutionary Game Dynamics, 246(3) J. Theor. Biol. 522 (2007).

[12] For a review of principles of path dependence and firm colocation, see Paul David, Understanding the Economics of QWERTY: The Necessity of History, in W. Parker (ed.), Economic History and the Modern Economist (1986); W. Brian Arthur, Increasing Returns and Path Dependence in the Economy (1994).

[13] Mark Newman, Networks: An Introduction (2010); Matthew O. Jackson, Social and Economic Networks (2010).

The best evolutionary dynamic scholars (but not all, certainly) link theory to the data—drawing from observation and data to generate theoretical models that capture the essence of a hypothesized set of relationships, and then returning to the data to try to fit it to the theory. For example, scholars who do work on drug resistance generate many of their greatest insights by having to account for the deviation between the data and the theoretical models. In work on the co-evolution of bacterial immunity and virus (phage) targeting of bacteria, researchers began to investigate the possibility of a killer enzyme only after they noted the deviation of data from their theoretical model.[14]

Evolutionary Game Theory Approaches to Evolutionary Dynamics

Evolutionary game theory ("EGT") studies the behavior of large populations of agents who interact over time. Introduced as a way to deal with large populations in biology, John Maynard Smith and George Price developed evolutionary game theory models of animal behavior in the 1970s.[15] Over the last decades, EGT models have come to be used in the social science, economics and biological sciences. In these models, payoffs or utility are synonymous with reproductive fitness. Higher-fitness strategies spread in the population, and less successful strategies diminish or go extinct.

This section will divide the discussion of evolutionary game theory into three subsections: (i) replicator dynamics, and a discussion of the connection to Nash equilibria; (ii) other game dynamics that are more specific about interactions at the micro-level; and (iii) recent extensions and applications of evolutionary dynamics theory.

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[14] Bruce Levin, Sylvaine Moineau, Mary Bushman and Rodolphe Barrangou, Population and Evolutionary Dynamics of Phage and Bacteria with CRISPR-mediated Immumity. 9(3) PLoS Genet e1003312 (2013).

[15] John Maynard Smith and George Price developed a concept very much like the Nash equilibrium called the "evolutionarily stable strategy." Assume a large population of players who are randomly paired to play a finite symmetric game with the standard payoff matrix. Assume also that all players play the same pure or mixed strategy. Now assume that a very small number of the population "mutates" and switches to play another strategy. If on average the residents do better than the mutants, the resident strategy is an evolutionarily stable strategy against that mutation. A strategy is evolutionarily stable if it does better on average than all other strategies: its fitness will be driven by competition with other strategies but also by interaction with itself. John Maynard Smith and George R. Price, The Logic of Animal Conflict, 246 Nature 15 (1973). ESS analysis resembles classical game theory far more than does the more dynamics-focused and equation-based replicator dynamics and pairwise comparison adaptive dynamics. See generally Jorgen Weibull, Evolutionary Game Theory (1997); Nowak, Evolutionary Dynamics, supra note 5.

In the interest of accessibility, mathematical notation will be kept to a minimum and I will supply informal descriptions instead.

In replicator dynamics, the central insight (and corresponding equation) is quite simple: the frequency of a strategy increases when the strategy is above average, that is, when its fitness exceeds the average fitness of the population.[16] Consider an infinitely large population of n types; individuals play only pure strategies to correspond with their type. Assume that individuals meet randomly and pair off to play a symmetric game with the standard payoff matrix. Payoffs for each strategy can be calculated by (weightedly) averaging across the different opponent types that each strategy will randomly play. The average payoff for the whole population can also be calculated in a similar way.

Replicator dynamics assumes that a strategy with a fitness higher than the average fitness of the population will grow (will be copied) over time and that best responses (as determined locally in competition) will have the highest long-term growth rate. In particular, replicator dynamics assumes that the per capita growth rate is given by the difference between the payoff of that strategy and the average fitness of the population.

The replicator equation is a differential equation that describes this change over time. This equation can be used to map the long-term behavior of the changing strategies in the population, and can be used to calculate the stability of any rest points. [17] A close relationship exists between the rest points of the replicator dynamics equation and Nash equilibria. (Indeed, an unpublished version of Nash's thesis reveals that he had motivated the Nash equilibrium with both the conventional hyperrational player explanation and a "mass action" explanation that presumed a version of evolutionary game theory.)[18]

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[16] Peter D. Taylor and Leo B. Jonker, Evolutionarily Stable Strategies and Game Dynamics, 40 Mathematical Biosciences 145 (1978).

[17] Deterministic dynamics allows analysts to determine the stability of rest points by linearizing around the equilibria. Rest points are asymptotically stable if after a slight perturbation, the dynamic converges back to the rest point. Unstable rest points move away from the rest point, and neutrally stable points leave the perturbed system at a point near the original rest point. In many cases, the stability of the rest point can be determined by assessing whether the eigenvalue of the Jacobian matrix of the payoff vector field is negative: in essence, this generates a linear approximation around the rest point to determine whether the function is moving toward (stable) or away from the rest point (unstable). See William Sandholm, Population Games and Evolutionary Dynamics (2010).

[18] For each player role (e.g., Row or Column), assume that there are infinitely large populations of players. The game is repeatedly played, each time by players randomly drawn from the appropriate population. Individuals in their respective populations learn from experience to avoid the suboptimal actions. A mixed strategy for a player role

The so-called "folk theorem" of evolutionary game theory specifies that if a population state is (asymptotically) stable or an interior solution trajectory converges under some "selection" process based on the underlying payoffs of the game, then the population state or limit point is a (strict) Nash equilibrium.[19] Beyond the rest points and their stability, replicator dynamics allows us to map the dynamic trajectories of equilibrium formation.

Using replicator dynamics as well as other dynamics, Martin Nowak and Karl Sigmund have analyzed the rock-paper-scissors dynamics[20] in the context of repeated prisoner's dilemma games. Tit-for-Tat is a strategy that famously won several tournaments conducted to search for optimum strategies consistently beating players who play Always Cooperate and Always Defect (and a number of others). But Tit-for-Tat has a vulnerability. Tit-for-Tat players do quite poorly if a player makes a mistake—two mistakes can lead to mutual defection. Generous Tit-for-Tat, in which the first mistake is forgiven, can outcompete Tit-for-Tat.

As Nowak demonstrates, populations playing both regular and generous versions of Tit-for-Tat, as well as Always Cooperate and Always Defect, can cycle from strategy to strategy with no rest point, let alone a stable equilibrium. Individuals playing the strategy of Always Cooperate are outcompeted by those who play Always Defect. Those playing this latter strategy are outcompeted by those playing Tit For Tat, which is in turn bested by Generous Tit For Tat. And in a population in which all play Generous Tit for Tat, Always Cooperate can invade as a "neutral" mutant because its payoffs are essentially the same.[21]

(Row/Column) is just the statistical distribution of the actions available in that role. Nash claimed that if players avoided suboptimal responses, and the population distribution of actions was stable, this distribution was the Nash Equilibrium. See Robert J. Leonard, Reading Cournot, Reading Nash: The Creation and Stabilization of the Nash Equilibrium, 104 The Economic J. 492 (1994).

[19] Josef Hofbauer and Karl Sigmund, Evolutionary Game Dynamics, 40 Bull. Amer. Math Soc. 490, 494 (2003)

[20] In the children's game of rock-paper-scissors, rock beats scissors, scissors beats paper and paper beats rock.

[21] See Martin A. Nowak, Evolutionary Dynamics, supra note 5 at 91; Martin A. Nowak and Karl Sigmund, Oscillations in the Evolution of Reciprocity, 137 J Theor Biol 137 (1) 21-26 (1989); Martin A. Nowak and Karl Sigmund, The Evolution of Stochastic Strategies in the Prisoner's Dilemma, 20(3) Acta Appl Math 247 (1990).

Other evolutionary dynamics techniques allow us to specify the micro-dynamics of how strategies grow or get copied. We can investigate, for example, the dynamics in which each agent learns from or imitates another agent. In pair-wise comparison, in which an agent switches to the strategy of a randomly selected role model, either with some random probability or with some probability proportional to the difference in fitness between the agent and the model. [22] Upgrading the cognitive capabilities of agents, we can specify that in a large population, some small fraction of the players are able to gauge the structure and payoffs of the game and play best response, and can layer a comparison function on to these best-response dynamics.[23]

Evolutionary dynamics approaches also enable us to investigate the role that uncertainty, chance and error plays in real-world interactions. For example, in the dynamics displayed by small finite populations, chance affects the probability that agents will interact, or the probability that all members will come to play the same strategy just by chance, given enough time. More generally, real-world situations are permeated by mistakes or uncertainties. People can misinterpret each other's actions or make mistakes when trying to implement one's own choices. Decision making under uncertainty most often confronts people with a probability distribution of outcomes, rather than an easily discernible best response. Stochastic evolutionary dynamics models allow scholars to study the effects of such errors.[24]

Analytical solutions aren't always possible in evolutionary dynamics analysis. In agent-based simulation models, scholars describe the underlying mechanisms of interaction with simple fixed rules that operate at the level of the individual agent rather than equations that describe population behavior.[25] The dynamics of agent behavior is simulated numerically. For example, an agent-based model depicting the famous Schelling model of segregation would specify that agents should relocate when the fraction of same-race neighbors around them drops below some critical threshold. Such models can generate a wide range of equilibrium and out-of-equilibrium behavior, and

[22] William Sandholm, Deterministic Evolutionary Dynamics, New Palgrave Dictionary of Economics (2d ed. 2008). Although critics complain that the selection of the updating mechanism is arbitrary, updating mechanisms can be roughly grouped into categories—for example, the category of imitation dynamics--and similar mechanisms generate qualitatively similar aggregate behavior. *Id.*

[23] Josef Hofbauer and Karl Sigmund, Evolutionary Game Dynamics, 40 Bull. Amer. Math Soc. 490, 494 (2003).

[24] Nowak, Evolutionary Dynamics, supra note 5.

[25] Scott Page, Agent Based Models in New Palgrave Dictionary of Economics (2d ed. 2008).

can illustrate quite graphically processes of equilibrium formation or selection in systems that produce multiple equilibria.

Evolutionary game theory is well positioned to easily model public goods games, which are a version of the classic Prisoner's Dilemma but with interaction groups of large size. In a public goods game, agents have the opportunity to invest at cost into a common pool or to defect and contribute nothing. The common pool total is then multiplied by some factor and afterwards, divided evenly among all participants whether or not they contributed to the pool. Evolutionary game theory can map the effect of various factors—for example the effect of giving players an option to abstain from either contributing *or* receiving the benefits of the common pool (which turns out to facilitate cooperation.)

Public goods games are very useful for studying the co-evolutionary dynamics of legal punishment, not just by individual agents but also by centralized agents like "the State."[26] Most "public goods with punishment" games punish an agent by imposing a fine, at some cost to the punisher. The impact of the fine changes the payoff structure for the choice of whether to contribute, and the cost of punishment shapes the choice of whether or not to punish. Evolutionary dynamics can easily model the administration of such a punishment scheme by a centralized state, to observe what features of centralized punishment might facilitate cooperation.

Critics have objected in particular to agent-based models, in which scholars simulate the dynamics of interacting agents, rather than deploying analytical tools. Here, the critics argue that replacing analytical solutions with numerical simulations that are worked out computationally makes the method far less rigorous, and far more subject to confusion about what drives outcomes. But practitioners point out that equation-based methods often require assumptions and abstractions that are highly unrealistic, to make the method tractable.[27] Agent-based modeling supplements such tools, with an eye towards improving both the realism of the assumptions and of the outcomes.

The Evolutionary Dynamics Analysis of Law

So what might an evolutionary dynamics approach to law look like, and how might it interact with neoclassical and post-neoclassical law and economics? Let us begin with a deliberately (and likely grossly) oversimplified account of modern law and economics as a point of departure. Contemporary law and economics studies legal rules

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[26] Daria Roithmayr, Alexander Isakov and David Rand, Should Law Keep Pace with Society (unpublished manuscript under review).

[27] For the basic arguments of this debate, see W. Brian Arthur, Out of Equilibrium Economics and Agent-Based Modeling, in 2 Handbook of Computational Economics (Judd and Tesfatsion eds. 2005).

and institutions using economic theory and econometric methods. [28] The engine that powers this investigation is the insight that legal sanctions or rewards affect behavior in much the same way that prices affect behavior in economic theory—by affecting the payoffs of behavioral strategies.

Seen through the lens of economic theory, legal rules work by changing the payoff structure of alternative decisions. Legal fines or criminal penalties lower the payoffs of certain choices. Legal subsidies or rewards raise the payoffs of other strategies. And in a rational expectations model, people respond to those incentives rationally, just as they respond to price. Normatively, the discipline focuses on generating legal rules that produce an "efficient" equilibrium outcome.

To use the traffic metaphor, the neoclassical incarnation of law and economics asks a set of questions about the relationship between law and behavior in equilibrium. How would a change in the traffic rules about whether motorcycles can share lanes affect the equilibrium speed of car traffic? Or, to use a more law-and-economics example, how would a change in liability rules for motorcycles from comparative negligence to all-or-nothing rules change the equilibrium level of precautionary care-taking by the driver? Neoclassical approaches assume, as a useful shortcut, that both traffic and care-taking reaches some equilibrium, and that changing legal rules shift these equilibria by changing payoffs.

Evolutionary dynamics allows us to ask an additional set of questions. In particular, the evolutionary dynamics of law might help us to ask and answer three categories of questions:

<u>First</u>, how does a change in legal rules affect the unfolding patterns of interactions (and not just the timeless equilibrium interactions) among people? For example, how would a change in property rules from collective ownership to individual ownership affect the dynamic trajectories of cooperation, individual investment and punishment? As the following discussion will elaborate, recent work shows that simple rule changes can produce unexpectedly intricate patterns of equilibrium formation.

<u>Second</u>, how does law itself construct the field of interaction on which patterns unfold? Law often shapes the world that it regulates by structuring the networks and institutions that mediate interaction—compelling some agents to interact and prevent others from doing so. In the world of telecommunications for example, the overall flow of traffic on a telecommunication network emerges in unpredictable ways from the interaction of individual nodes and links. As the following discussion demonstrates, regulatory requirements that compel interaction can have unexpectedly negative effects.

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[28] See Ejan McKaay, History of Law and Economics in Encyclopedia of Law and Economics (0200) in Boudewijn, Bouckaert and Gerrit de Geest (ed.), Encyclopedia of Law and Economics, Edward Elgar 2000 (http://encyclo.findlaw.com/0200book.pdf.)

Third, and finally, how does law evolve, endogenously and in tandem, with the behavior it regulates? It is well accepted that social behavior and norms evolve over time as practices diffuse across populations and people experiment with new practices; the same can be said for law. What's more, just as law shapes and structures the unfolding patterns of regulated behavior, so too is law shaped by those patterns. As the introduction adverts to, law and society are often engaged in a game of cat and mouse. Congress adaptively revises its tax rules in response to innovative tax shelters created by taxpayers who in turn are seeking to adapt to current legal rules. State (and soon federal) regulators are constantly scrambling to keep up with payday lenders. What is the nature of this co-evolutionary relationship between law and society?

Evolutionary dynamics might also shed light on the broader questions of legal and social change. Law enables the collective to commit to stable legal rules, and this commitment to conservatism and slow change has important implications for the co-evolutionary relationship of law and behavior. How does law's slower rate of change affect its ability to subordinate individual interests to the collective? Is it an advantage, a liability or both? The following discussion considers each of these three categories of inquiry in turn.

1. How does law affect the unfolding patterns of behavior that law regulates?

Traffic (like the economy, like our political system, like our social networks) spends much of its time out of equilibrium. Micro-interactions among cars produce regular and intricate patterns—for example, as a few more cars enter the freeway, the traffic exhibits a very dramatic phase-shift between free-moving traffic and jammed traffic. Likewise, micro-interactions among social actors and legal rules can also give us insight into the complex dynamics of equilibrium formation.

Evolutionary dynamics might allow us to investigate the relationship between legal rules and those more intricate patterns. In a recent paper, Samuel Bowles and Jung-Kyoo Choi have investigated the evolutionary relationship between property rights and the non-equilibrium unfolding of the transition between hunter gathering and farming around 12,000 years ago.[29] Bowles and Choi argue that property rights co-evolved with new farming technology, the institution and the technology unable to advance on its own, but the emergence of each making the other possible. We will have more to say below about a co-evolutionary model of the relationship between law and regulated behavior. But for the moment, let us focus on the part of their paper that investigates the relationship between the legal rules of private property and the dynamics of equilibrium formation.

[29] Samuel Bowles and Jung-Kyoo Choi, Coevolution of Farming and Private Property During the Early Holocene, 110 Proc. Nat'l Acad. Sci 8830 (2013).

Bowles and Choi use a computational agent-based model that numerically simulates agent interactions according to simple rules of engagement. In their model, agents first decide whether to forage or farm. They then decide whether to share the fruits of their labor and afterward, and whether to collectively punish those who do not share. Thus, for both the farmers and the hunters, agents can choose one of three strategies: to share their profits ("Sharers"), to keep their profits for themselves ("Bourgeois") and to both share and collectively punish those who don't share ("Civics."). After each round of play, agents compare payoffs with another randomly selected agent in the group, and switch (probabilistically) to their partner's strategy if her payoffs are higher.[30] In this model, law operates both in the rules of private property that enable the Bourgeois to keep the profits for themselves without the punishment involved in the Civics, and in the rules of punishment that the Civics might adopt to discipline the Bourgeois.

The model's results illuminate the more complex dynamics that evolutionary dynamics models can highlight. For the forager economy, the dynamics converge to two stationary points, one convergently stable and the other "neutrally stable," meaning stationary but nearby points are neither converging nor diverging.[31]

More specifically, in the forager economy, the population will converge to a state consisting of no Civics, and a mix of Sharers/Bourgeois. Civics cannot invade the population because they must pay the cost of punishing Bourgeois players, which none of the other strategies must pay. Bourgeois and Sharers exist in a sort of mutual détente. Bourgeois cannot take over Sharers because they face a significant liability when there are too many in the population—they bear the cost of conflict among them, because possession of the goods is always contested when two Bourgeois meet. Sharers cannot take over Bourgeois because the former must give up some of their goods to the others, which Bourgeois do not do.

More remarkably, another stationary state is neutrally stable, and forms an alternative pathway to the formation of the Sharers/Bourgeois equilibrium. This neutrally stable state is the state in which the population is all Civics. A population of all Civics resists the invasion of Bourgeois because the Civics collectively punish any Bourgeois

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[30] Interestingly, the authors tried to approximate the parameters and payoffs to accord with available data on the benefits of hunting and farming, and amazingly, the weather conditions during the relevant periods. *Id.*

[31] In evolutionary dynamics, rest points are classified as being in one of three categories. Stable rest points (we could call them "convergently stable") are those to which a dynamic system returns after the system is pushed a short distance from the rest point (a perturbation.) Unstable points see the system move away from the rest point when perturbed. Neutrally stable points remain at or near the point of perturbation. See Sarah P. Otto and Troy Day, A Biologist's Guide to Mathematical Modeling in Ecology and Evolution (2007).

mutant who arises to threaten the group. But Sharers can invade. Because there are so few Bourgeois, the Civics rarely bear the costs of such punishment and so the Sharers are become equivalent to Civics in terms of fitness.

The system might remain here for some time. The mix of Sharers and Civics will remain in place so long as a sufficient number of Civics are available to punish the occasional Bourgeois effectively. But if the number of Civics drops below that critical point as a matter of random chance, then the mix becomes vulnerable to Bourgeois agents. The system now slides toward the first stable point described above, which is a mix of Sharers and Bourgeois. Thus, in a forager economy, bourgeois property rights gain a small foothold but cannot outcompete sharing conventions or rules.

In the farmer groups, bourgeois property rights can now emerge to outcompete rules that require sharing. In a farmer economy, the population converges to a state in which all players are Bourgeois. With private property rights to settle disputes exist, no conflict between the Bourgeois arises and they can outcompete the Sharers. But as before, there is also a neutrally stable point—a population that is all Civics—which is stable in the same way as in the forager groups, and for the same reasons. That is, a population of all Civics is stable but vulnerable at some critical point to invasion by Sharers, and then at some critical point to a slide towards all Bourgeois. This alternative pathway to equilibrium formation explains why a farmer society might remain a sharing economy for some time before it converges to one in which property rights dominate.

Bowles and Choi's work shows the co-evolution of property rights and farming: property rights likely could not emerge until foraging gave way to farming, and that property rights made such a transition possible. But more importantly for our purposes, Bowles and Choi's agent-based model illustrates the dynamic trajectory of equilibrium formation on the path to property rights. In their model, the system can spend some significant amount of time at the neutrally stable point of all Civics, and then as a matter of random chance, tip towards a convergently stable point, either a mix of Sharers and Bourgeois in the forager groups or the all-Bourgeois populations in the farmer groups. Descriptions of the neutrally stable point of all-Civics, and of the pathway to equilibrium formation, are the central focus in models that allow for dynamic change.

In a different vein, Eric Posner and Richard McAdams have used evolutionary game theory to argue that when law acts as a focal point, to coordinate cooperation or reduce conflict, the magnitude of its effect will depend very much on existing informal norms or conventions. Posner studies the relationship between Supreme Court decisions and existing social conventions that reduce conflict by specifying rules of engagement—so for example, the rule finders, keepers reduces conflict by specifying the owner of abandoned property.[32]

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[32] Eric Posner, Constitutional Possibility and Constitutional Evolution, in Law, Economics and Evolutionary Theory (Zumbansen and Calliess eds. 2011).

Drawing from evolutionary game theory, Posner argues that the impact of the Supreme Court's rulings will depend on the interaction between (i) the opinion's relationship to existing conventions (confirming them or invalidating them) and (ii) the "desirability" of those conventions (e.g., whether they produce relatively higher payoffs or lower payoffs). When society has already adopted a desirable high-payoff convention, like say racial equality, the Court's decisions have relatively little effect on such a convention, except that a ruling might aid in the dynamic spread of such a convention if it has become weakened. Again, given where society is, even rulings that strike down a desirable high-payoff convention likely have little effect on the convention--one could read Bowers v. Hardwick as being little more than a speed bump in the massive shift in public opinion towards equality. But rulings that validate a lower payoff convention (e.g., racial segregation) have more effect—they can weaken the legitimacy of the Court (think of Plessy v. Ferguson), or trigger a significant shift in behavior via a new focal point if the decision strikes down the undesirable convention (like Brown v. Board of Education).

Likewise, McAdams draws on a study of repeated games to argue that law often works by filling the gaps and ambiguities of existing conventions.[33] For example, adjudication can clarify a question about whether the first to kill or the first to chase the fox get possession of it. Going forward, such clarifying rulings will affect the expectations of parties other than the litigants. As repeated game analysis makes clear, precedent will shape the evolutionary trajectory of third parties. For both Posner and McAdams, law has potentially its greatest impact when social conventions have yet to settle or converge. More generally, their use of evolutionary frameworks illuminates the law's effects on social dynamics: its ability to shift social conventions towards a higher payoff outcome or to change the future trajectory of social interaction by clarifying what the social convention is.

2. How does law structure the very field of interaction on which the dynamic patterns of regulated behavior unfold?

At a deeper level, evolutionary dynamics can highlight the way in which law actually constructs the field of interaction that give rise to dynamic patterns. In the most foundational sense, law generates the rules that govern local interaction among agents, in addition to markets, kinship and social networks. Legal rules often determine the architecture of social interaction. Legal rules prohibit some people from interacting even though they might want to. Other rules require some people to interact, or interact in certain ways, whether or not they want to voluntarily. For example, law often requires the disclosure of certain kinds of information between a buyer and seller, where the parties

[33] Richard H. McAdams, The Expressive Power of Adjudication in an Evolutionary Context, in Law, Economics and Evolutionary Theory (Zumbansen and Calliess eds. 2011); see also Richard H. McAdams, The Expressive Power of Law: Theories and Limits (2015).

might not ordinarily be inclined to share such information. Antitrust law prohibits certain kinds of interaction or sharing in the market.

More subtly, legal rules often determine the probabilities of who interacts with whom in a complex adaptive system. Interaction among people is far from random. Institutional and social networks are structures that make interaction among certain people who are linked by network connections far more likely than people who are not linked. Law structures those network connections: for example, the relationships among courts of appeal and trial courts form a hierarchical connected network.

But as evolutionary network theory makes clear, where networks are involved, often we cannot predict the effect on the market over time of changes to those network-constructing legal rules. Because a change to the network often produces cascades or ripples that affect the entire network configuration, the overall pattern of network flow cannot be reduced to or predicted from the behavior of network elements in isolation. Small changes in the individual elements might produce unexpected larger-scale effects—bottlenecks, congestion, traffic jams and so on.

An example from telecommunications is most instructive in this regard. In a telecommunications market, private companies interact with consumers and suppliers of complementary services to produce the market. Network providers "supply" the architecture of the market by designing it, by choosing when and with whom to cooperate contractually to extend the network, and by investing in network facilities. Consumers shape the network by way of their choice of services, and suppliers of complementary services also shape network structure via their choices.[34] These market actors shape the evolution of the network and the market, as more profitable choices spread in the market and other strategies are outcompeted. In connection with such choices, competitors decide where to access the network on the basis of price.

In an effort to promote open access and competition, the 1996 Telecommunications Act required that an incumbent network operator's emerging competitors have access to the network, on terms that the competitor was largely free to decide. Daniel Spulber and Christopher Yoo have modeled the way in which competitor access, even to links in the network that appear to have sufficient capacity, can unexpectedly reduce the capacity of the entire network, and render pricing schemes incoherent. What's more, such reduction is accompanied by inefficient equilibrium prices, as market actors compete on prices that do not reflect the impact of their entry on capacity.

Required competitor access can diminish network performance by affecting a set of critical links through which all traffic must flow, like the bridges to Manhattan across

[34] Daniel F. Spulber and Christopher S. Yoo, Networks in Telecommunications: Economics and Law (2009).

which everyone must drive to get off the island.[35] A network's point of vulnerability is its set of smallest bridges or weakest links through which all traffic must flow. If a competitor accesses capacity on a link that is already one of the weakest links, or if access on a link actually now pushes that link into that weakest link set, then the overall performance of the network may be reduced.

In compelled access rules, incumbent network operators are not allowed to decide where on the network competitors gain access; the law specifies that the competitors can choose their point of access at any technically feasible point. In addition, compelled access rules only require price to be calculated on the basis of the local impact of access, and not on impact on overall network performance.

Graph theory shows us how changing capacity at any one of the links in the network can have unexpected effects on the dynamics of traffic flow in the entire network by affecting that set of weakest links. For some links, at some particular point in time, competitor access will diminish performance. For other links, or the same link at other times, competitor access will have no effect or actually improve performance.[36] Pricing access by looking only at the link to which the competitor gains access bears no relation to the actual costs of that access. Thus, compelled access and local pricing disconnects the link between the costs of a competitor's strategy to other strategies and reduces capacity for all involved.

The authors argue that just as transportation policymakers must take into account the dynamic effects of adding a new on or off-ramp to traffic patterns on the entire network, so to should policymakers require pricing to reflect the effect of permitting competitor access on the entire network. Because legal rules are in effect the rules that structure the interaction of market participants, they shape the evolutionary dynamics of the market.

In addition, to structuring the rules of interaction, law can also endogenously shape the emergence of preferences or cognitive biases in a population. Work by Oren Bar-Gill uses replicator dynamics (described above) to map the relationship between legal rules and the evolutionary spread of cautious optimism in the context of litigation.[37]

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[35] Daniel F. Spulber and Christopher S. Yoo, On the Regulation of Networks as Complex Systems: A Graph Theory Approach, 99 Nw. U L. Rev. 1687 (2005).

[36] *Id.* at 1710.

[37] Oren Bar-Gill, The Evolution and Persistence of Optimism in Litigation, 22 J. Law Econ. and Org. 490 (2006). See also Steffen Huck, Jeorg Oechssler and Georg Kirchsteiger, Learning to Like What You Have- Explaining the Endowment Effect, 115 Econ. J. 689 (2005) (similar analysis on the evolutionary diffusion of a moderate endowment effect in bargaining); Oren Bar-Gill and Chaim Fershtman, The Limit of Public Policy: Endogenous Preferences, 7(5) J. Public Economic Theory 841 (2005)

Optimism confers a benefit to a person in bargaining, by acting as a commitment device to affect an individual's threat point during in negotiation and shift the settlement range available to that person. Optimism also has a negative effect because it distorts negotiation's equilibrium points by affecting a person's discount rate in calculating her acceptable range of settlement. Too much optimism forces the other partner out of the range of settlement and derails the possibility of reaching agreement. Thus, cautious optimism outcompetes unbridled optimism.

Bar-Gill uses replicator dynamics to show that legal rules can endogenously affect the levels of optimism that spread to dominate a population. In litigation, the British rule (in which the loser pays) induces a lower population level of optimism than under the American rule. This is because, under the British rule, the stakes are higher. As a result, under the British rule, optimism has a greater negative effect on the probability of settlement, and a greater positive effect on the settlement terms for the optimist relative to the American rule. Bar-Gill's work illustrates the way in which law serves to shape the very field of interaction on which law operates, by shaping the levels of cognitive bias in a population, even as those cognitive preferences will shape the operation of law in return.

4. How does law evolve, endogenously and in tandem, with the behavior it regulates?

Perhaps most noteworthy, evolutionary dynamics might give us the tools to investigate not just how law structures the evolutionary dynamics of regulated behavior, but also how law itself evolves in tandem ("co-evolves") with the behavior it regulates. Biologists study the co-evolutionary relationship among species that evolve in response to each other. For example, scientists recently have discovered that a species of poisonous newt has evolved in some localities very high levels of poison in response to selective pressure created by a predator snake. And the same species of snake has evolved in those same localities almost perfect immunity to newt poison.[38] Mathematical biologists refer to the predator-prey models that explain these corresponding high levels of immunity and toxicity as arms-race models.

Co-evolutionary models specify two sources of selective pressure that drive the evolutionary arms race dynamics. First, as between the species, each species creates selective pressure that influences the evolution of the other. For example, the snake that develops greater immunity will eat more newts, and this predatory strategy will be

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(investigating crowding out as the extinction of a behavioral concern for social status in the population in response to a subsidy available to agents playing a public goods game).

[38] These co-evolutionary dynamics are not inevitable. Indeed, the research demonstrates that for some localities, traits between the species are so mismatched that either the snakes or the newts win decisively, and the arms race never gets off the ground. Charles T. Hanifin, Edmund D. Brodie, Jr. and Edmund D. Brodie III. Phenotypic Mismatches Reveal Escape from Arms-Race Coevolution, 6 PLoS Biology 471 (2008).

reproduced more frequently in subsequent generations. At the same time, more poisonous newts will evade capture, and their reproductive strategy will appear with greater frequency within the species. Immunity and poison give the species comparative advantage against each other. Second, within the species, individuals compete for limited resources and that internal competition creates selective pressure. For example, immunity and poison give individual newts and snakes comparative reproductive advantage against each other.

Co-evolutionary models of this sort might help policymakers to understand the evolutionary dynamics of legal innovation. In the interaction between legal rules and regulated behavior, legal rules can evolve in response to adaptive innovation in regulated behavior. For example, in tax policy or financial regulation, taxpayers and financial players often innovate to produce the next new "legal" tax shelter or new complex financial product with astonishing speed.

In turn, at the level of competition within legal rules and within regulated behavior, legal rules will compete against each other, as will the strategies of those who are regulated. For example, in the area of tort liability and corporate governance regulation, states frequently compete with each other to attract business and tax revenue. States frequently copy each others' regulatory approaches, corporate governance law, tort law and civil procedure codes. These bodies of law affect a state's ability to attract business and citizens, among other things.

A co-evolutionary model can usefully describe the processes of innovation and competition among legal rules, and the way in which those processes are directed and shaped by competition from (and between) those who are regulated. Like those who are regulated, regulatory actors operate in the face of uncertainty by experimenting, exploring a wide range of "search space" among legal rule prototypes, copying from successful jurisdictions and then adapting the rules to better fit the local environment. Like the strategies of those who are regulated, legal rules evolve endogenously in the ecology of rule and regulated; the fitness of legal rules is determined by how well they address the latest innovation from the regulated, and the fitness of regulated strategies is determined by how well they work around (or with) legal rules.

The relative rates of regulatory and behavioral innovation likely play a crucial role in determining how effective law can be in generating sustained compliance. Recently, Roithmayr, Isakov and Rand have investigated the effect that varying this relative rate of innovation might have on citizen compliance.[39] Typically, legal rules evolve or "update" more slowly than the behavior that the rules regulate. The US Constitution evolves very slowly, requiring constitutional conventions or ratifications by states to adopt an amendment. Even faster evolving legal rules—like administrative regulations—frequently are outpaced by the speed with which those who are regulated can shift their strategies.

[39] Roithmayr et al., supra note 26.

Recent research in biology reveals that in some circumstances, a more slowly-evolving species can obtain a comparative advantage over a cooperating species by "committing" to a strategy, that is, by evolving relatively more slowly than the partner species. At the same time, in more antagonistic relationships, evolving more quickly produces a comparative advantage by "outrunning" the competing species.

The Roithmayr team's model simulates a public goods game with punishment to investigate the rate at which legal punishment rules evolve relative to the evolution of citizen contribution behavior. In the real world, the investigation might focus, for example, on the rate at which tax law evolves relative to the rate at which citizens generate new tax shelters.

In the Roithmayr et al. agent-based model, citizens play a public goods game with centralized State punishment. Citizens decide how much to contribute to the State's tax coffers. Their contributions are multiplied and then divided pro rata among all citizens, regardless of how much the citizen contributes (which creates the incentive to free-ride, in the absence of punishment.) States punish the non-contributors at varying levels.

Citizens compete with each other and learn from each other. States also compete with and learn from each other. States face budget constraints--the State's ability to punish depended on how effectively citizens contributed to the public good. In turn, citizen's level of cooperation in contributing depends on the State's ability to punish effectively.

Numerical simulations reveal that States can maximize citizen cooperation when the rate at which their legal rules evolve hits a critical rate. This critical update rate is sufficiently slow relative to citizens that the citizens are forced to adapt to their State's legal rule. By adopting a relatively slow rate, states effectively tie their hands and commit to costly punishment. But the critical rate of legal evolution must also be sufficiently fast that states can stay ahead or outrun their citizens and prevent widespread and contagious defection. A rate that is both slow enough to create commitment but fast enough to respond to citizen mass defections appears to be the most effective at maximizing compliance under a budget constraint.

Empirical data seems to provide some suggestion of the existence of a "Goldilocks" rate of relative evolution. Analysis that plots the rate of amendment against the longevity of national Constitutions shows a non-monotonic inverted U-shaped curve: constitutions that are either easily amended or very hard to amend do far less well than constitutions whose amendment rate lies somewhere in the middle. India, whose constitution contains a mix of various amendment rates that apply differentially to certain provisions, appears to enjoy the greatest longevity relative to others.[40]

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[40] Zachary Elkins, Tom Ginsburg and James Melton, The Endurance of National Constitutions (2009).

This co-evolutionary model constitutes an initial step towards developing a more robust and useful co-evolutionary model of legal rules and citizen strategic behavior. First, the model usefully illuminates the way in which, against the backdrop of bounded rationality, citizens experiment to figure out how to maximize their profit while minimizing the burden of legal punishment. The federal government has recently ended a string of prosecutions of tax shelter promoters who used a succession of tax shelters seeking to artificially step up the basis of claimed tax losses; we might consider those to be real-world examples of such experimentation.

Likewise, the model highlights the way in which legal regulators themselves also experiment with an eye towards maximizing compliance and minimizing cost, particularly in times of budget crisis. Under the pressure of budget constraints, for example, the state of California has recently revamped its sentencing provisions to reduce punishments for low-level crimes.

Most importantly, the model demonstrates the way in which legal rules and the behavior of those whom the law regulates co-evolve in tandem, each shaping the direction of the other, to produce patterns that are hard to predict without the benefit of a co-evolutionary framework. Future research is needed to investigate the meta-question of how governments might go about choosing the relative rates of evolution for various legal provisions, with agency regulations updating far more frequently say than Constitutional provisions, and statutes somewhere in the middle.

Conclusion

Evolutionary dynamics offer a range of flexible tools that scholars interested in a dynamic analysis of law can use. Evolutionary dynamics can help to describe equilibrium formation. Evolutionary dynamics models make room for non-linear dynamics, with endogenously generated events. And this tool also can describe co-evolutionary systems that spend large amounts of time out of equilibrium. The dynamic approach intrinsic to such a model is particularly apt to describe heterogeneous behavior, in both lawmaking and the decision-making of those who are regulated by law.

The agents in evolutionary dynamics models can display realistic limits on their rationality. They can use heuristics to navigate their way through uncertainty. They can learn from each other and from experience, over time. Most notably, the evolutionary dynamics framework allows us to see agents react to the patterns they create, and then to create new patterns or recreate the old ones. For policymakers, who usually work at a scale in which history and time matter, the ability to describe the dynamics of law and society is quite useful. Recall the possibility, for example, that evolutionary dynamic approaches might provide insight to those who regulate the ever-evolving tax shelter.

More generally, these dynamic models offer scholars the ability to describe the relationship between law and regulated behavior. Such models can potentially incorporate both the way in which legal rules and regulatory regimes compete with each other and affect citizen behavior, which in turn affects the creation of legal rules themselves.

Importantly, evolutionary dynamics might give legal scholars a framework for studying innovation. Innovation is not imposed from the outside but endogenously generated. New legal rules generate new unmet legal needs ("How do we price competitor entry into a network?" "How do we evade payday lending rules?") that then give rise to new strategies and new legal technologies to meet those needs, and so on. Innovators tweak old legal rules and recombine their parts with other parts of other rules (using a disability framework to analyze discrimination, for example.)

Evolutionary dynamics enables observers of legal evolution to say things about the patterns of co-evolution that are in formation, by drawing on regulatory and behavioral history and constructing models of legal change that explain observed patterns. Richard Posner, Anthony Niblett and Andrei Shleifer recently published a paper in which they conducted an empirical review of the economic loss rule over a period of fifty years to investigate the long-standing hypothesis that the common law evolved to efficiency.[41] The authors found no evidence that the states converged on the efficient version of the economic loss rule (either a general rule with no exceptions, or a general rule with well-accepted or statutory exceptions). But they did find a pattern over time: states converged towards the efficient versions of the rule until 1995, and then states began to adopt a range of idiosyncratic exceptions, many having to do with independent (non-statutory) duties for builders and architects that permitted (in theory, and in fact) plaintiffs to recover outside contract causes of action.

Evolutionary dynamics might give us a framework with which to investigate this evolutionary pattern. A closer reading of the cases before and after 1995 (and then more broadly) might provide sufficient information to construct a model, and then try to fit the model to the data, to discern the trajectory and origins of this pattern. Social learning might be at work: states adjacent to those with statutory exceptions might have adopted non-statutory exceptions.

Alternatively, the early diverging exceptions might be understood as innovative experiment or mutant mistake, which might end up being outcompeted over time by the better accepted exceptions, as states decide whether to copy the new idiosyncratic exceptions. Recall that equilibrium formation can often take quite a bit of time, as the Bowles and Choi model makes clear. Whatever the actual explanation, a dynamic model might be well positioned to make sense of the pattern that Niblett et al. observed (and again for emphasis, the data reveals a pattern).

More broadly, evolutionary dynamics methods offers legal scholars the opportunity to draw useful insights not just from their colleagues in economics and the

[41] Richard A. Posner, Anthony Niblett and Andrei Shleifer, The Evolution of a Legal Rule, 39 J. Legal Studies 325 (2010).

social sciences but also from a wide range of other bodies of knowledge like biology and epidemiology. As the earlier discussion makes clear, evolutionary dynamics draws from the sciences and from the social sciences--history, information theory, economic geography, economic sociology, political theory and many other disciplinary traditions. Legal scholars in general, and law and economics scholars in particular, have much to gain from such collaboration.