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Thresholds, tipping points, and random events in dynamic economic systems

Traditional concavity assumptions in dynamic economic models suggest that small changes in economic conditions should generate small changes in economic outcomes. But it has become increasingly observed in a wide variety of economic phenomena that small changes, in certain circumstances, can produce relatively large or abrupt effects. At the individual or firm level, tipping point and threshold behavior can arise where discontinuous actions are triggered by small changes in economic conditions. For example, prices may cross a threshold that triggers adoption of a new technology or entry/exit in a market. At a more aggregate level, tipping point phenomena may arise where behaviors become reinforcing once a threshold is crossed. Disease outbreaks, fads, and poverty traps are all characterized by drastic changes in economic outcomes that originate from minor changes in behavior or economic conditions. Economists have long been interested in events that lead to reinforcing behaviors. For example, Leibenstein's (1950) work on fads and fashions describes situations where an individual's demand increases with the number of others also buying the good. Schelling's (1971) dynamic models of neighborhood segregation identified the conditions that could lead to thresholds in the racial composition of a neighborhood. While a precise definition of a tipping point does not exist, it is clear that tipping points require a threshold but not all thresholds constitute a tipping point.

In economics, threshold behavior is most commonly observed in the literature related to dynamic economic systems with multiple equilibria (Dasgupta and Mäler, 2003; Deissenberg et al., 2004). In these systems, tipping point phenomena arise when variables cross a threshold in the state space that represents the boundary of two different basins of attraction. Crossing this boundary triggers a shift from one long run outcome to another. Thresholds of this type have been investigated in growth theory (Skiba, 1978), development (Azariadis and Drazen, 1990), labor (Diamond, 1982), trade (Krugman, 1991), environmental (Tahvonen and Salo, 1996), and natural resources (Lewis and Schmalensee, 1977). Initial conditions and economic shocks take on increased importance in such systems as initial conditions may determine the optimality of a given equilibrium and random events can cause a system to unexpectedly tip causing lock-in to undesirable long run outcomes. Multiple equilibria most commonly arise due to convex production technologies but may also arise in concave systems (Wirl and Feichtinger, 2005). The thresholds in the multiple equilibria systems are usually called Skiba thresholds or points though all thresholds in these models are not Skiba thresholds.

In 2005, a special issue of *the Journal of Economic Behavior & Organization* (JEBO) was devoted to thresholds and multiple equilibria (Semmler, 2005). Since that time, economic research in this area has extended in five main areas:

1 Greater attention devoted to the interaction between uncertainty, thresholds, and tipping points (see Lemoine and Traeger in this volume). Traditional conclusions concerning risk/ambiguity aversion and precautionary behavior are being questioned in the presence of thresholds and tipping points (Dannenberg et al., 2015; Pindyck, 2007). There has also been an increased usage of adaptive management frameworks and Markov decision processes to investigate the optimal way to learn about the location and implications of thresholds and tipping points (Boettiger et al., 2015; Crépin et al., 2012).

2 Development of coupled human-natural models that more fully mesh social and natural science perspectives on thresholds and tipping points (see Sims, Finnoff, and ORegan in this volume). Economic decisions are often made in the context of natural systems that have a history of or are thought to exhibit thresholds and tipping points. For example, epidemiologists have long known disease dynamics are governed by prevalence thresholds above which the disease outbreaks and below which eradication is achieved (Allen and Lahodny Jr., 2012). Ecologists are aware of regime shifts in natural systems whereby ecological processes flip as seen in the eutrophication of shallow lakes (Carpenter et al., 1999). Climatologists

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are increasingly concerned about potentially irreversible climate tipping points (Lenton et al., 2008). This integration has caused economists to more carefully differentiate between thresholds and regime shifts. A threshold is a boundary in the state space that causes a discontinuous change in economic outcomes but leaves the dynamic economic system unchanged. The dynamic systems models with multiple equilibria discussed above are all examples. In contrast, a regime shift is an event that triggers a discrete change in the dynamics of the system (see Baggio and Fackler in this volume). This integration has also led to a greater focus on whether thresholds and tipping point phenomena have economic or ecological origins (see Fenichel and Horan in this volume).
3 Use of agent-based and network models to investigate how individual- or firm-level behavior manifests as tipping point phenomena at an aggregate level (see Wood, Mason and Finnoff in this volume). Agent-based models allow for the study of macro phenomena without making assumptions at the macro level (Lengnick, 2013). This approach has been used to uncover unexpected triggers for abrupt change in the macroeconomy. For example, something seemingly benign such as an asymmetry between the rate of hiring and firing has been shown to induce a transition from an economy with low unemployment to one with high unemployment (Gualdi et al., 2015). Agent-based models have also been used to investigate the factors that trigger cooperation in a common pool resource problem (Janssen and Rollins, 2012).
4 Adoption of recent advances in the econometrics literature on the well-known identification problem to differentiate systems with thresholds and tipping points from those that simply produce identical empirical patterns (see Chavas, Grainger and Hudson in this volume). Many dynamical processes that have little to do with tipping points produce identical empirical patterns (Brock, 2006). The recent popularity of identification techniques have allowed economists to separate true tipping point dynamics that produce punctuated equilibria from exogenous dynamics of unobserved variables (Durlauf and Young, 2004).
5 Quantifying the economic impacts of thresholds and tipping points (see Heutel, Moreno-Cruz, and Shayegh in this volume). Traditionally, economic models are developed to explain observed threshold behavior and tipping point phenomena and suggest possible avenues to avoid them. As computable general equilibrium models have advanced, greater attention has been devoted to linking dynamic models with models of the larger economy to more carefully articulate the implications of crossing a threshold or tipping point. This is particularly evident in the growth of integrated assessment models in climate change economics (Lenton and Ciscar, 2013).

This special issue of *JEBO* on “Thresholds, tipping points, and random events in dynamic economic systems” showcases some of the leading research in these areas as well as new directions that extend the concept of thresholds and tipping points beyond the multiple equilibria context. The included articles were part of a workshop in July 2015 generously hosted by the Howard H. Baker Jr. Center for Public Policy at the University of Tennessee. The Baker Center was established to honor the legacy of Senator Baker who worked with Democrats and Republicans on the Clean Air Act of 1970, Watergate, the Panama Canal Treaty, and the 1978 Amendments to the Endangered Species Act which allowed for economic considerations in the designation of critical habitat. Since its establishment in 2003, the Baker Center has developed a research and policy outreach agenda focused on global security, energy, and the environment. The workshop attracted papers that provide policy-relevant insights consistent with this agenda. We thank Matthew Murray, the Director of the Baker Center, along with the Baker Center staff, for their help in making the workshop such a success.

Several studies focus on climate change and two of them utilize integrated assessment models (IAM). Dereck Lemoine and Christian Trager show how aversion to Knightian uncertainty about a climate tipping point affects the optimal tax on carbon emissions. Knightian uncertainty is thought to be key to formulating climate policy since climate tipping points have rarely been observed in history. Using a numeric application based on a reformulation of the DICE IAM as an infinite-horizon dynamic programming problem, they show that aversion to Knightian uncertainty about climate tipping points does increase the optimal tax on carbon emissions but only by a small amount. Garth Heutel, Juan Moreno-Cruz, and Soheil Shayegh also use a variant of DICE to study the effect of climate tipping points on the optimal usage of CO_2 emission reduction policies and solar geoengineering. They compare results for three types of tipping points: one where the tipping point causes a direct economic loss but no change to the dynamics of the system and two regime switches where the tipping point triggers a change in the system dynamics. Solar geoengineering is shown to be most effective at dealing with regime-switching style tipping points. Yacov Tsur and Amos Zemel consider the tradeoffs between long-term policies of adaptation and mitigation in the face of uncertain, discrete catastrophic climate events. Optimizing across steady states with multiple state variables, they are able to analytically identify a unique interior steady state that is determined by the interactions between adaptation and mitigation responses to catastrophic risk. The final climate change paper takes an econometric approach. Jean-Paul Chavas, Corbett Grainger, and Nicholas Hudson use 400,000 years of paleoclimate ice core data and a threshold quantile autoregressive econometric approach to present evidence of tipping points in CO_2 dynamics. Determining when climate tipping points have been crossed in the past can help current policy makers better understand when the costs and benefits of climate policies my abruptly shift. Unfortunately, identifying the presence of climate tipping points from CO_2 data is an enormous empirical challenge because lag effects in CO_2 concentrations can vary with previous concentration levels. This can undermine the usage of more traditional quantile autoregressive models. They find evidence of reversible tipping points but not irreversible tipping points.

Two studies focus on energy. The first uses evolutionary game theory and agent-based modeling to investigate a regime shift from one carTel.: to another in world oil markets Aaron Wood, Charles Mason, and David Finnoff consider the historical interval where world oil market dominance shifted from seven major oil firms to OPEC They are particularly interested in