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Entrepreneurship, search costs, and ecological rationality in an agent-based economy

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Abstract Since Coase's paper on the firm, transaction costs have occupied much attention as a field of economic inquiry. Yet, with few exceptions, neoclassical theory has failed to integrate transaction costs into its core. The dominant mode of theorizing depends upon Brouwer fixed points which cannot integrate transaction costs in more than a superficial manner. Agent-based modeling presents an opportunity for researchers to investigate the nature of transaction costs and integrate them into the core of economic theory. To the extent that transaction costs reduce economic efficiency, they provide opportunities for entrepreneurs to earn a profit by reducing these costs. We employ an extension of Epstein and Axtell's (1996) Sugarscape to demonstrate this point one type of transaction costs: search costs. When agents do not face the cost of finding a trading partner, the system quickly reaches a steady state with tightly constrained prices regardless of agent production strategies. When search costs are present, entrepreneurs may use competing strategies for production and exchange that allow them to earn higher revenues than they would earn otherwise. These cost reducing innovations tend to promote concatenate coordination (Klein 2012). The agent's production strategies represent technology in the form of mental models (Denzau and North 1994) that shape agent action with regard to the agent's environment. The success of these are dependent on their ability to overcome search costs. The average profit, market rate of return, earned by each of these mental structures tends to equalize as a result of competition.

Keywords Entrepreneurship · Agent-based computational economics · Catallaxy · Ecological rationality · Search costs

JEL classification L26 · C63 · D81 · D83 · D84

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1 Introduction

Over two decades ago, Gode and Sunder (1993), using a simple model of exchange, argued that equilibration in a world of voluntary exchange is dependent on a simple rule: the bid price of a buyer must be greater than the ask price of a seller. The determination of the transaction price leading to execution is of little consequence to the process of equilibration. The only requirement for equilibration is that the transaction price lie between the bid and the ask price. The authors did not leave a role for the entrepreneur as they did not consider the impact of uncertainty and search costs on exchange and equilibration.

Using an extension of the Sugarscape model (Epstein and Axtell 1996; Wilensky 1999), I consider the role of transaction costs in providing opportunities for entrepreneurs to earn profits in a world where each agent acts according to unique mental structures and under different circumstances. They act under conditions of asymmetric information and interpretation (Klein 2012). The existence of costs to finding a trading partner require the agents to adopt and test production and search strategies as well as parameter values that are part of these strategies. These would otherwise be unnecessary in a world absent costs of finding a trading partner. This increases the costs of trade relative to a world where agents can trade with one another without regard to geographic distance. Entrepreneurial agents discover profit opportunities by experimentation (mutation) where they adopt new strategies for production and exchange. These strategies, when they are successful, tend to be reproduced by other agents and thereby guide the market toward a dynamic steady-state that is akin to the static equilibrium of neo-classical theory (Kirzner 1973, 1997).[1]

2 Entrepreneurship and search costs

Despite their lack of recognition in the more common formulations of neo-classical price theory, transaction costs have been well recognized within the field of entrepreneurship.[2] Coase (1937) formulated the firm as a nexus of contracts that helps reduce transaction costs that would otherwise exist without the firm. Economic agents find that they can avoid the costs associated with transactions in the market by participating in this contract nexus. Significantly, search costs are reduced because labor, suppliers, and customers need only contract through a single firm with a limited number of contracts. Demsetz (1988) adds to this by identifying information costs as a component of transaction costs. In our model, search costs are the same as information costs. Agent trade opportunities are limited to Von Neumann neighbors. A search of the landscape for an appropriate trading partner is simply outside the realm of possibility for an agent. Furthermore, because our agent is unable to know the precise actions of other agents in advance, her only means of overcoming the uncertainty concerning the availability of resources and trade opportunities is to adopt particular strategies to guide action *ex ante*.

[1] A steady-state exists when the inflow of commodities over an extended period tend to equal the outflow.

[2] One exception in neo-classical theory includes Franklin Fisher (1983)

In a similar vein as Coase, Williamson (1973) identifies a number of impediments to market efficiency that do not appear in a neo-classical framework that employs systems of linear equations. These include bounded rationality (Simon 1972; Gigerenzer and Gaissmaier 2011) and uncertainty resulting from such rationality. Human agents are not knowledgeable about all circumstances, not even all of those that are of interest to their own welfare. This uncertainty provides incentive for the creation of structures that promote a more efficient flow of information. Strategies that help overcome costs derived from limited knowledge of the agent represent opportunities for efficiency increases, and therefore, profit.

Auswald argues, "transaction costs are the glue that holds together entrepreneurial new combinations (2008, 120)." This is true, whether they are combinations of physical capital or of strategies. Foss and Klein (2012) have presented capital combinations as being integral to the essence of the entrepreneur. They join the entrepreneur to the theory of the firm:

> The reason is simple: firms are bundles of resources and entrepreneurial theory of the firm must be a theory about resources.

The authors see the entrepreneur as an asset owner who bears uncertainty in her search for profit. To the extent that our agents act as asset owning entrepreneurs, they match the description provided by Foss and Klein.

3 Entrepreneurship, knowledge, and overcoming uncertainty

The entrepreneurial type must be considered in light of her relation to knowledge. Kirzner (1973) refers to the entrepreneur's *discovery* of profit opportunities. The entrepreneur has some understanding of the world. She integrates this understanding into her actions (Mises 1949 49, 68; Koppl 2002; Hayek 1962, 248). Understanding is reflected in the knowledge of the agent. To model the entrepreneurial function requires a formulate a theory of knowledge. Many of the pieces of such a theory have already been developed.

Foss and Klein (2012) argue that actions, not opportunities, ought to be the unit of analysis. Entrepreneurs search for possible ends given some means. While entrepreneurs do in fact *discover* profit opportunities, Foss and Klein are correct that these opportunities are themselves created by entrepreneurial action. This systemic creativity, however, is an effect of the second order (Felin et al. 2014; Koppl et al. 2015). Entrepreneurial effectuation implies a relatively open-ended search where agents operate under a one-to-many mapping of reality (Sarasvathy 2001). Agent ends are not given, only the means are. Possible ends are multitudinous. In our model, the determination of agent ends is provided by the rules that govern behavior. Actions are determined by a component of a classifier (Holland 1992) that select from given ends.[3] That end is determined *in light of* given means and environment of the agent. The means is the behavioral rule and any objects that rule may employ. Integrated into its structure are agent abilities.

[3] At the next higher level of abstraction, the market, profit and loss select out unsuccessful strategies and retain strategies that promote success.

The agent relies on understanding, or knowledge, is provided by her mental model (Denzau and North 1994; North 2005). This model is an agent's personal ontology (Nonaka 1994; Cioffi-Revilla 2014). This ontology is comprised of representations of the ecology she helps comprise: objects in the environment, relationships between the objects, and processes that transform those processes (Wagner 2010; Pratten 2015). The agent herself plays a role in this mental model. Objects not only have a relationship with one another, but also may have a relationship with the perceiving agent. An example helps to clarify. An agent in our model may identify sugar on a patch. The agent, by means of her rule of behavior recognizes that she could come to possess that sugar. Further, upon possession, she may transform part or all of the sugar by consuming it. The agent must choose which potential reality to fulfill. The rule not only helps the agent conceptualize the relationship between herself and the sugar, but brings into realization *one* of those potential realities by determining the agent's course of action.

A caveat inherent in agent-based modeling must be noted. The agents technically do not have free will. Rather, the human or humans who program the model selects the behavioral rules available to the agents. The rules order the preferred ends of the agent in terms of some valuation and, thus, determine action (Mises 1913; Booker et al. 1989). To this extent, an agent-based model is an extension of the programmer's *will*. The ultimate effects of that *will* are not possible to know *ex ante*. The behavior space is vast (Dennett 2003) and reality is only revealed after the agent acts. Although the agents are, in effect, robots, their action contains some element of human action.[4] As the agents act toward ends determined by some scale of values, this "quasi-action" (Mises 1949, 23–28) represents a manifestation of a category of action that Koppl (2002) identifies under the heading of *acognitive expectations*.

Apart from the fact that in the real world quasi-action occurs within an open system, general form of the logic governing this type of action is not different from that of the automatons programmed into the "game of life" (Beer 2004). In order to make decisions that lead to patterned action, agents must follow clearly defined logic that can be described as knowledge (Hayek 1962). This knowledge exists as a plurality of if-then statements that are executed serially and consider arrangement and values of local objects.

Not all knowledge is useful. Knowledge is only useful to the extent that 1) it helps the agent overcome uncertainty that appears to follow some identifiable pattern. It helps them overcome *ontological uncertainty* (Lane and Maxfield 2005). This type of uncertainty is a component of Knightian risk as it can be identified and overcome with the appropriate knowledge (1921). The system must have some means of selecting rules that promote action that supports agent survival and discarding rules that do not. A rule structure that represents coherent understanding of the objective environment, which includes other agents, represents useful knowledge. It allows agents to increase the chance of survival (Alchian 1950; Gigerenzer 2008; Rosser 1999, 183).

[4] Mises refers to this as "quasi-action":

> We observe two things: first the inherent tendency of a living organism to respond to a stimulus according to a regular pattern, and second the favorable effects of this kind of behavior for the strengthening or preservation of the organism's vital forces. If we were in a position to interpret such behavior as the outcome of purposeful aiming at certain ends, we would call it action and deal with it according to the teleological methods of praxeology.

This combination of behavioral rules and a selection process that tends identify and retain superior rules underlie the core of a self-ordering economy. Just as in biological evolution, competition provides the selection mechanism (Young 1998; Gintis 2009). Unlike in biological evolution, random mutation is not the driving force behind change in the economic system. By her creativity, the entrepreneur provides contributions to knowledge that are tested by competition. In one manner or another, this knowledge is often made public to, and therefore available for use by, other agents. Some agents exhibit knowledge that supports their ability to identify and imitate existing knowledge that promotes agent survival (Hayek 1962; Carayannis et al. 2016; Bikhchandani et al. 1998; Li and Tesfatsion 2012). This process of transmission sometimes occurs with error that may or may not be beneficial to the agent (Earl et al. 2007). By this transmission mechanism, knowledge of beneficial behaviors can spread quickly after its discovery and agents can collectively overcome uncertainty (Lavoie 1986).

This appeal to trial and error is not merely a theoretical assertion. Real world entrepreneurs (for the remainder of this paragraph we refer to the social, as opposed to functional, type of entrepreneur) have identified precisely this mechanism of knowledge generation. Many entrepreneurs practice strategies where they attempt to maximize experimentation among their investments, selecting those innovations that are profitable and discarding those that are not (Kerr et al. 2014). This strategy has become so common that the phrase, "fail fast", has become mantra among many entrepreneurs (Brown 2015). Kerr, Nanda, and Kropf observe that from their sample, 6 % of startups "accounted for about 50 percent of the gross return (Kerr et al. 2014)." This process of experimentation appears to be at the root of skewed wealth structure in society where "a few outliers account for a disproportionate amount of the entire distributions output" as "more than 60 % of all new jobs are created by a mere .03 % of all entrepreneurial start-ups (Aguinis et al. 2015, 697; see also Crawford et al. 2014)." This holds true for our model as the generation agent-firms who use strategies different from the Basic strategy (discussed below) promote a majority of growth for the agent-firm population.

3.1 The Sugarscape economy

Epstein and Axtell's Sugarscape stands as the canonical model for exploration of the capabilities of simulation of societies through agent-based modeling.[5] In *Growing Artificial Societies*, Epstein and Axtell (1996; also see Wilensky 1999) investigate the nature of production and exchange as well as warfare and epidemics. Like Axtell (2005), the authors borrow from neoclassical standard of rationality whereby agents maximize a utility scalar by their decisions that lead to action. While agents do make decisions that they believe will result in the most preferred state of reality (Menger 1976 [1871]), dependence on scalar utility is an artifact that we inherit from the Walrasian paradigm. Advances in the understanding of cognition and decision-making, like those mentioned above, present an opportunity for a new avenue of exploration and understanding.

Perhaps due to the audience receiving their work, Axtell and Epstein did not go on to investigate decision-making rules other than utility maximization. In reflecting on the meaning of their work, Axtell and Epstein recognize this space for development:

[5] As of March 8, 2016, Google Scholar identifies that Epstein and Axtell (1996) has been cited 4240 times.

Table 1 Composition of Possible Strategies

Can also be?:	Basic	Switcher
Basic	–	No
Switcher	No	–
Herder	Yes	Yes
Arbitrageur	Yes	Yes

> . . . Artifical society models permit a more evolutionary outlook: Instead of assuming behavioral rule, there could be a population of rules in society. One might specify this rule population at the outset [Arthur 1994] or have agents invent their own rules using genetic algorithms, genetic programming, or neural networks. But however one generate the rules, some rules enjoy *differential survivability* (emphasis authors') over others – after a long time one observes more agents following rule i than rule j. *This really is all we can operationally mean when we assert that rule i enjoys a selective advantage over, or is 'fitter than,' rule j* (emphasis mine). (162)

The rules employed in this model of Sugarscape draw information from the environment as a guide for agent activity. Agents make prediction according to the observed structure of processes in their environment. This type of strategy is efficient as it reduces the computational requirements of the agent without greatly, if at all, reducing the value of affected outcomes compared to neoclassical utility maximization (Czerlinski et al. 1999). This is significant as, absent assistance from technology, there is an upper limit to the processing power of the human mind (Simon 1974). This formulation of a realistic cognitive framework, often described as ecological rationality (Smith 2003), must remain underappreciated as long as such a mode of operation is not explicitly investigated and implemented with regard to both the individual agent and interactions between multiple agents.

3.2 Agent class

In this rendition of the model, entrepreneurs are treated as firms (Foss and Klein 2012).[6] These agents make decisions according to standards categorized by different classes. There are two primary classes: Basics and Switchers. Each of these can be augmented by the Herder and Arbitrageur classes. The classes are described in Table 1.

3.2.1 Basic

A Basic agent follows a unique instantiation of the original rule used in Wilensky's version of Sugarscape. In it the agent moves to the patch that has the greatest amount sugar. In event of a tie for this measure, he moves to the one of these patches that is closest. In our version of the model, the agent-firm moves to the patch with the greatest amount of resources. Agents can only see as far as one patch away from their location. The agent does not differentiate between resource types.

[6] Thus we should think of the death of an agent as equivalent to the bankruptcy of a firm.

3.2.2 Switcher

Like the Basic, the Switcher moves to the closest patch with the highest resource value. Unlike the Basic, the Switcher searches for only one type of good at a time. The agent alternates between searching for each good for some period of time drawn from a uniform random distribution.

3.2.3 Herder

The Herder copies the attributes of the richest agent with whom she has come into contact. This assumes that this information is locally available – in other words, agents share information with one another. While this is not always true in reality, it is a useful assumption to employ in order to understand the core dynamics that arise due to the flow of information between agents. The rule might be adjusted so as to set requirements for sharing of information between agents – i.e., only share with friends. The outcome is dependent upon the rule composition of the population within which the herding agent operate.

3.2.4 Arbitrageur

The Arbitrageur remembers past transaction prices. She mines for the good that is, on average, more valuable given her belief in some expected price that she has formed for each good. Unlike other agents, the Arbitrageur integrates information that allows her to immediately respond to the needs of her peers. While it is in the Arbitrageur's interest to mine for the more valuable good, the Arbitrageur also serves the interest of society by doing so. A price that rises above the Arbitrageur's expected price indicates to the Arbitrageur that one commodity is undervalued and incentivizes her to extract that commodity. An individual arbitrageur need not be correct in predicting the market price of the good mined. To the extent that she is wrong, the market will tend to allocate less resources toward that agent.

3.3 Prices and exchange

Agents interact with their environment by means of rules structure associated with each class. Simple interaction with the environment does not necessarily promote coordination. Agent action must be influenced by prices to promote this. These prices are one means by which knowledge is transferred between agents. They comprise a "telecommunication system" (Hayek 1945). An agent's decision to purchase or not to purchase a particular type of good tends to influence the relative price of the good, and thus communicate changes in relative scarcity. This provides a standard for agents to determine which good to produce and incentive to limit their consumption of more scarce goods. It also guides agents' decisions concerning whether or not to produce the good. The change in price in a world of many goods, inasmuch as it represents a change in relative price, will go on to influence the price of complements and substitutes, as well as inputs required for the good's production and outputs for which the good serves as an input (Hayek 1935). Even when agents are not conscious of this change, plans that do not cohere with the price change will tend to be ill-suited for the environment.

In order to interact with prices in a manner that promotes an economic steady-state, agents require at least three basic components. There is a fourth for the Arbitrageur class:

3.3.1 Barter algorithm

Ambiguities arise in regard to agents interacting by means of the pricing mechanism. The first problem arises due to bargaining power. The basic structure for this interaction is adopted from Gode and Sunder (1993). Agents each value a good at a particular price. If the bid-price of the agent demanding the good is higher than the ask-price of the agent selling the good, a random value is chosen within the range supplied by the agents. In our model, the agents are bartering directly. To ensure that the algorithm does not favor either the buyer or the seller, the uniform distribution is chosen from the range of the logged value of prices supplied by the buyer and seller. The value chosen is then converted back to the actual value by un-logging the logged value of the final transaction price.

3.3.2 Target reserve level distribution

Every agent must choose a target reserve level for sugar and water. Random values are selected from a uniform distribution. The target reserve level provides a standard for the agent to adjust the price reflecting their willingness to pay and willingness to accept.

3.3.3 Pricing algorithm

Agents adjust their bid and ask price for sugar according to the algorithm:

$$\Delta p_{s,t} = \alpha\left(\ln\left(T_{s,t-1}/q_{s,t-1}\right) - \ln\left(T_{w,t-1}/q_{w,t-1}\right)\right) \quad (1)$$

Where:

$\Delta p_{s,t}$ Change in the bid/ask price of sugar at time t.
$T_{s,t-1}$ Agent's target level of sugar at time $t-1$.
$T_{w,t-1}$ Agent's target level of water at time $t-1$.
$q_{s,t-1}$ Agent's stock of sugar at time $t-1$.
$q_{w,t-1}$ Agent's stock of water at time $t-1$.
$0 < \alpha \leq 1$.

An agent's willingness to pay for a good increases if the quantity of goods that the agent desires – as defined by the target water and sugar reserve levels – is higher than the quantity of the good possessed by the agent. Likewise, if the agent possesses an excess amount of the good, she will decrease the price that she is willing to accept (or provide) for the good. Under the dynamic pricing rule, the magnitude of the price change increases as the agent's actual stock of goods deviates from the target level. The average amplitude of price changes is moderated by use of the randomly determined scalar, α. As with strategies and other parameters, values that promote agent survival tend to be selected for. One can imagine other rules for setting an agent's bid-ask price. Again, competition would select the appropriate composition of rules on a given landscape.

3.3.4 Expected price (arbitrageur only)

The expected price of sugar (which is the inverse of the expected price of water) guides the Arbitrageur's production decisions. This expected price is chosen from a random distribution. Values that do not promote the survival of the entrepreneur are selected out from the population.

Agents compete with one another by employing particular instantiations of class and pricing strategies. The fitness of these strategies depends not only on the landscape, but on the strategies chosen by other agents. As the environment is often in flux, some strategies may be more fit during some periods of a run than others. Only by the process of trial-and-error are more efficient combinations selected over less efficient ones given some context.

4 Strategy, action, and survival

Agents face a vast array of combinations of decision-making protocol and parameter values. The survivability of each of these combinations can be described in terms of their ability, on average, to lower search costs for the agent who adopts them. For every possible state in the behavior-space, there exists an expected cost for each agent to find a trading partner given their class and parameter values:

$$E(C_T) = (E(d)/v) * (C_s + C_w) \tag{2}$$

Where:

$E(C_T)$	Expected cost of finding a trading partner with the desired good.
$E(d)$	Expected distance traveled.
v	Vision (maximum step length).
C_s	Rate of sugar consumption per period.
C_w	Rate of water consumption per period.

Agent wealth is described as the agent's current stock of goods and the expected stream of goods between period t and period $(t + \tau)$:

$$E\left(W_{t+\tau,0}\right) = q_s + q_w + (E(s + w) - (C_s + C_w)) * E(\tau) \tag{3}$$

Where:

$E(W_{t+\tau,0})$	Expected wealth immediately prior to exchange.
q_s	Agent's stock of sugar at time t.
q_w	Agent's stock of water at time t.
$E(s + w)$	Expected rate of water and sugar inflows per period.
C_s	Rate of sugar consumption per period.
C_w	Rate of water consumption per period.
$E(\tau)$	Expected span of time to find a trading partner.

$$[E(\tau) = (E(d)/v)]$$

We transform the equations, replacing the current quantities and expected flows with expected quantities at time t + τ:

$$E(q_{s,t+\tau,0}) = q_s + (E(s) - (C_s))^*E(\tau) \quad (4a)$$

$$E(q_{w,t+\tau,0}) = q_w + (E(w) - (C_s))^*E(\tau) \quad (4b)$$

$$\text{If } E(q_{s,t+\tau,0}) \leq 0 \rightarrow \text{Agent shuts down operation on average} \quad (5a)$$

$$\text{If } E(q_{w,t+\tau,0}) \leq 0 \rightarrow \text{Agent shuts down operation on average} \quad (5b)$$

Where:

$E(s)$	Expected rate of sugar inflow per period.
$E(w)$	Expected rate of water inflow per period.
$E(q_{s,t+\tau,0})$	Expected stock of sugar immediately before trade.
$E(q_{w,t+\tau,0})$	Expected stock of water immediately before trade.
C_s	Rate of sugar consumption per period.
C_w	Rate of water consumption per period.
$E(\tau)$	Expected span of time to find a trading partner.

If expected costs of finding a trading partner are less than the sum of present income and expected income flows, the agent will not survive on average. If expected costs are less than these, then the agent will become wealthier on average. Over many runs, if one particular class of agents tends to perform better than others, the agent class, given their discovery of profitable arrays of parameter values, is more fit than other according to the logic of these equations. Successful strategies will tend to reduce the costs borne by agents who follow the respective strategy. To the extent that the strategy produces profits (TR > TC), the strategy will be duplicated by reproduction by the agent. If it generates a greater level of success than that of competing agents, the strategy will tend to be duplicated by trading partners of the herder class.

Agents trade goods. Thus far, equations have included the costs of finding a trading partner without including the price associated with a trade. All executed exchanges are subject to some price that is set between the bid and ask prices of each agent. The equations below include expected transaction price. Equations 6a and 6b represent cases where the agent has enough of one good to match the stock of the good in which she is deficient to the target level. Equations 7a and 7b represent the case where an agent has excess of one good, but not enough to move the stock of the other good to its target level. In the last case (Eq. 8) trade will not occur until the agent accumulates excess of one good:[7]

[7] One could imagine arrangement where an agent attempts to match the ratio of target reserve levels to consumption ratios or any number of other strategies. This represents an unexploited profit opportunity that I invite others to explore.

$$\text{If } T_w - E(q_{w,t+\tau,0}) \le (q_{s,t+\tau,0} - T_s)/p_w : E(q_{w,t+\tau,1}) = E(q_{s,t+\tau,0}) - (p_w) * (T_w - q_{w,t+\tau,0}) \tag{6a}$$

$$\text{If } T_s - E(q_{s,t+\tau,0}) \le (q_{w,t+\tau,0} - T_w)/p_s : E(q_{s,t+\tau,1}) = E(q_{w,t+\tau,0}) - (p_s) * (T_s - q_{s,t+\tau,0}) \tag{6b}$$

$$\text{If } T_w - E(q_{w,t+\tau,0}) > (q_{s,t+\tau,0} - T_s)/p_w : E(q_{w,t+\tau,1}) = E(q_{s,t+\tau,0}) - (p_w) * (T_w - q_{w,t+\tau,0}) \tag{7a}$$

$$\text{If } T_s - E(q_{s,t+\tau,0}) > (q_{w,t+\tau,0} - T_w)/p_s : E(q_{s,t+\tau,1}) = E(q_{w,t+\tau,0}) - (p_s) * (T_s - q_{s,t+\tau,0}) \tag{7b}$$

$$\text{If } T_s - E(q_{s,t+\tau,0}) > 0 \text{ and } T_s - E(q_{s,t+\tau,0}) > 0\text{: No trade expected} \tag{8}$$

Where:

T_s	Target stock of sugar.
T_w	Target stock of water.
$E(s)$	Expected rate of sugar inflow per period.
$E(w)$	Expected rate of water inflow per period.
$E(q_{s,\ t+\tau,0})$	Expected stock of sugar immediately before trade.
$E(q_{w,\ t+\tau,0})$	Expected stock of water immediately before trade.
C_s	Rate of sugar consumption per period.
C_w	Rate of water consumption per period.
p_s	Price of sugar in units of water.
p_w	Price of water in units of sugar.

The reader should note that in the above exposition, we treat expectation differently than it is has traditionally been used in economics (Muth 1961; Fama 1970; Sargent 2014). Expectation in Eqs. 1–8 represent a Bayesian interpretation where agents need not be aware of the expected value of a strategy that occurs at the system level. The rate of survivorship indicates whether the expected value of a combination of strategy and parameters are positive given some state of the model. Expectations of the agent herself are implied by her strategy and parameter combination.

5 Results

To observe the effect of cost-reducing technology, model runs are divided into three separate cases (Table 2). In the first case agents trade locally and use only Basic strategy. Agents may only trade with Von-Neumann neighbors. In the second case agents trade globally and use only Basic strategy. Agents are paired automatically with another agent who has surplus of the desired good. In the third case, agents face costs of

Table 2 Simulation Cases

	Agent Class	Global or Local Trade
Case 1	Basic	Local
Case 2	Basic	Global
Case 3	All Classes	Local

finding a trading partner and can use any combination of strategies and parameters described above. The first and second cases represent the bounds of the experiment, against which the third case is compared.

For each case there is taken the average value of a given parameters and variables at period 15,000. These represent approximations of long-run conditions, and therefore equilibrium values, in the model. Results are presented in the form of heat maps where each square represents the average value of a variable that is endogenously determined across 10 different runs. The x and y axes represent the consumption rates of water and sugar respectively. Tables include the values of population (Figs. 1, 2 and 3), the price of sugar[8] and its variance (Figs. 4, 5, 6, 7, 8 and 9), class population reported as proportion of the entire population (Figs. 10, 11, 12 and 13), and wealth per capita of the entire population as well as among class populations (Figs. 14, 15, 16, 17, 18, 19 and 20).

5.1 Population as welfare measure

The clearest indicator of economic health in each set of experiments is the population of agents.[9] The welfare level of the system, as reflected by population tend to be highest in the case where each agent is automatically paired with a trading partner regardless of her geographic positions (Fig. 2). Likewise, welfare levels are their lowest when agents face these costs and use only Basic strategy (Fig. 1). The integration of new strategies into agent decision-making increase welfare across the behavior space. Under most circumstances, population levels are either as high or nearly as high as in the case where there are no trading costs (Fig. 3). Given objective conditions faced by the agents, i.e., the needs of each agent as represented by consumption rates, the level of population is dependent upon the ability of that population to maintain minimal flows to each agent. In a dynamic equilibrium, inflows of goods into the economy tend to equal outflows. Thus, an increase in the long-run level of population is equivalent to an increase in the flows of these resources.

A pattern emerges across each of the three cases. As either consumption rate increases, the equilibrium level of population falls. That is, population falls as the costs of action increase. The number of agents that employ these goods falls as the price of either input rises just as the number of firms in an industry to decrease when input prices increase.

[8] The price of water is the inverse of the price of sugar

[9] In the real world, the best indicator is cambiodiversity which is "diversity in the things traded (Koppl et al. 2015)." The model here includes only two goods."

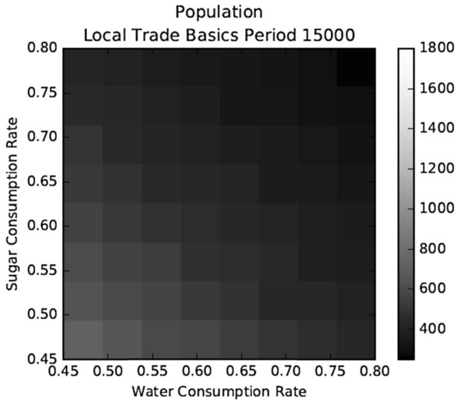

Fig. 1 Population - Local Trade – Basics

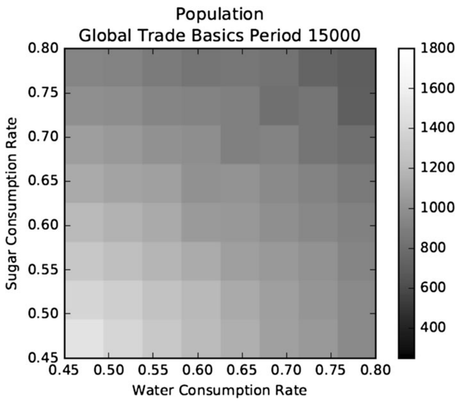

Fig. 2 Population - Global Trade – Basics

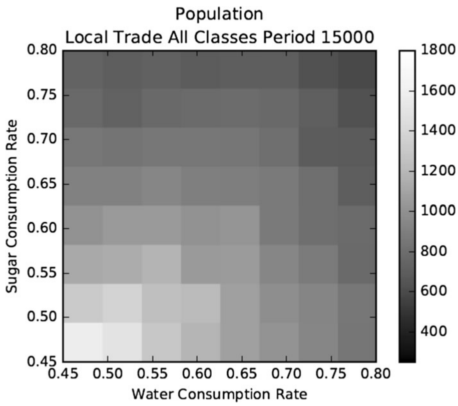

Fig. 3 Population - Local Trade - All Classes

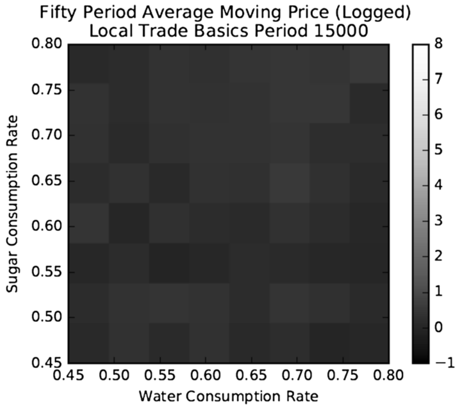

Fig. 4 Average Prices - Local Trade – Basics

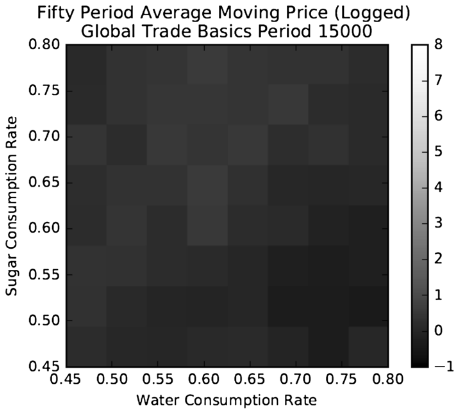

Fig. 5 Average Prices - Global Trade – Basics

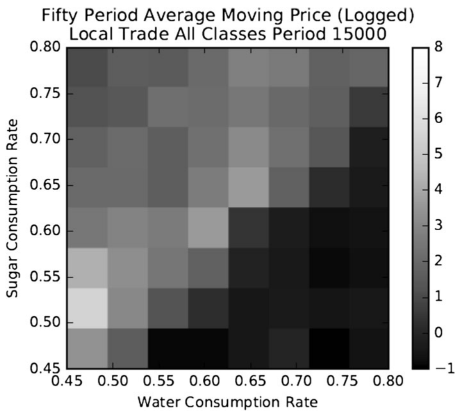

Fig. 6 Average Prices - Local Trade - All Classes

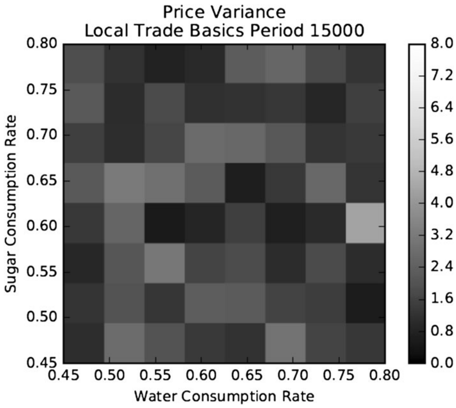

Fig. 7 Price Variance - Local Trade – Basics

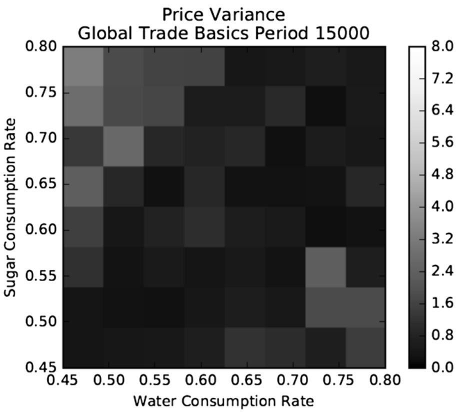

Fig. 8 Price Variance - Global Trade – Basics

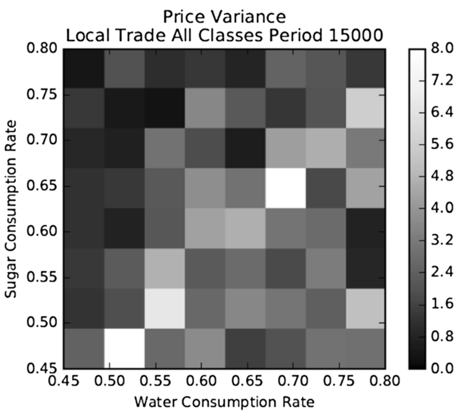

Fig. 9 Price Variance - Local Trade - All Classes

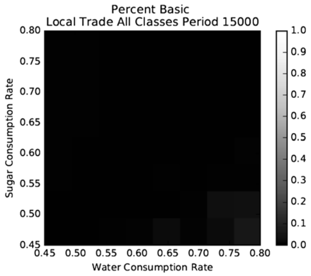

Fig. 10 Percent Agents Basic - Local Trade - All Classes

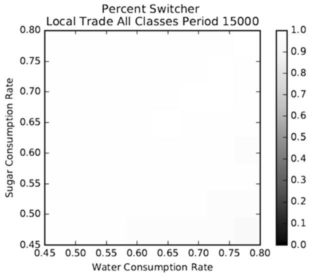

Fig. 11 Percent Agents Switcher - Local Trade - All Classes

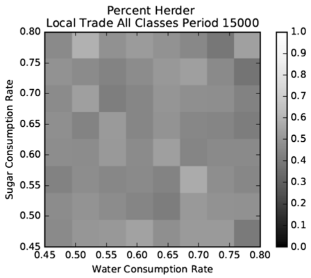

Fig. 12 Percent Agents Herder - Local Trade - All Classes

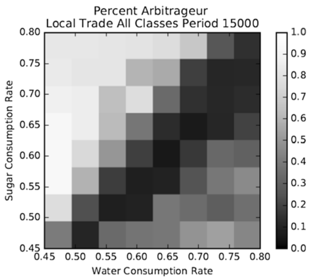

Fig. 13 Percent Agents Arbitrageur - Local Trade - All Classes

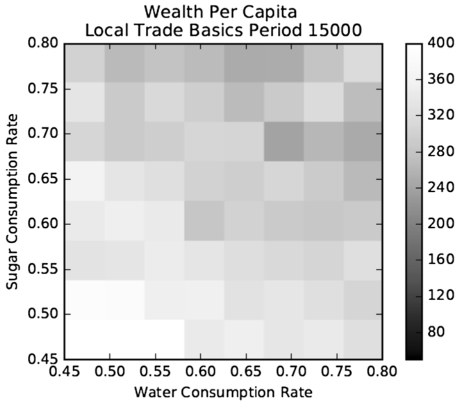

Fig. 14 Overall Wealth Per Capita - Local Trade – Basics

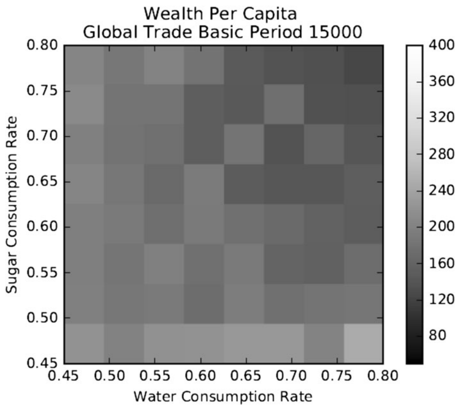

Fig. 15 Overall Wealth Per Capita - Global Trade – Basics

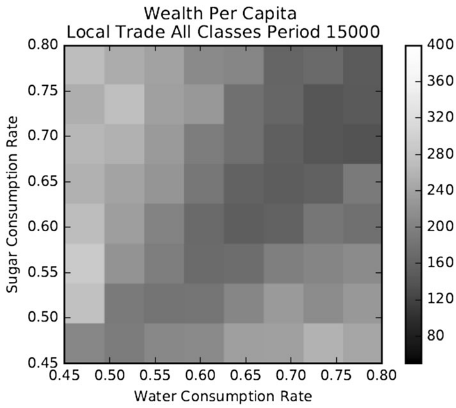

Fig. 16 Overall Wealth Per Capita - Local Trade - All Classes

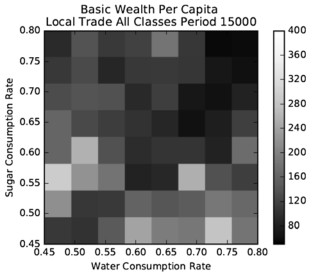

Fig. 17 Basic Wealth Per Capita - Local Trade - All Classes

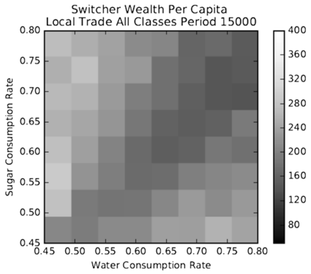

Fig. 18 Switcher Wealth Per Capita - Local Trade - All Classes

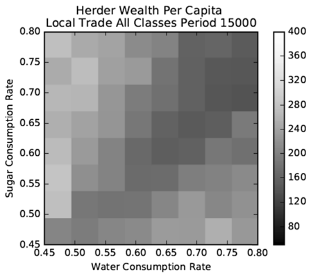

Fig. 19 Herder Wealth Per Capita - Local Trade - All Classes

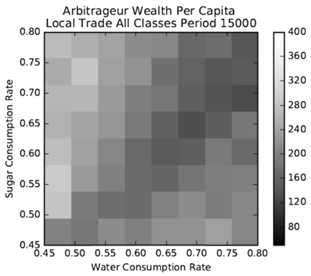

Fig. 20 Arbitrageur Wealth Per Capita - Local Trade - All Classes

5.2 Prices, profit and entrepreneurial niches

Figures 4, 5 and 6 compare the mean prices that emerge for each case. Prices in both the local and global cases that include only Basic agents are more tightly constrained than in the remaining case where agents use diverse strategies. The increase in variance occurs when consumption rates tend to be more similar as multiple strategies are present on the landscape (Figs. 6 and 9). There is much less variance in the runs that lack diverse strategies (Figs. 4, 5, 7, and 8).

As conditions change, different classes of agents fill niches that emerge, leading to a variety of types of outcomes across the behavior space. When consumption ratios are more similar, prices play a less significant role in coordination than in cases where consumption rates for each good are less similar. Both the Basic and Switcher strategies, when not augmented by the arbitrageur strategy, tend to promote rates of harvesting for each good that are similar. Thus Arbitrageurs tend to perform poorly compared to non-Arbitrageurs in this class of scenario (Figs. 11, 12 and 13). As consumption rates deviate from one another, however, the society requires an increase in the flow of the good that is consumed at a higher rate. Arbitrageurs promote this outcome as reflected by a strong correlation between the presence of arbitrageurs and decrease in price variance (compare Figs. 9 and 13). Arbitrageurs respond to prices. Those that survive tend to gather the good that is scarcer.

5.3 Population and wealth per capita

Wealth per capita is highest in the most impoverished case: local trade with only Basic strategy (Fig. 14). This does not reflect that the society that practices only Basic strategy under conditions of local trade has the highest level of general welfare. Recall that a lower level of population reflects diminished flows of goods relative to circumstances with a higher level of population. The impoverished society represented by the case of local trade with only Basic strategy reflects an inability for poorer agents to trade with wealthier agents for goods necessary to their survival.

Similar results hold for the cases of global trade with only Basic strategy and local trade with all strategies present (Figs. 15 and 16). There exist discrepancies between these two cases when consumption rates for each good tend to diverge. Where there exists no cost to transporting goods between trading partners, this divergence has little effect on the level of wealth per capita. When consumption rates diverge, population levels (Fig. 2) and wealth per capita tend to be higher in the case of global trade with only Basic strategy relative to a society with local trade and all strategies. Finally, these results suggest that competition in combination with innovation tends to flatten discrepancies in wealth. Failure to reduce the costs of economic activity promote the opposite effect. Lower levels of population are associated with higher costs of activity and impoverishment of those agents who fail to survive. An increase in the costs of economic activity not offset by cost-reducing technologies promotes higher levels of wealth concentration *and* impoverishment.

5.4 Macrostability and microvolatility

The process of equilibration itself requires guidance from disequilibrium conditions as disequilibrium represents a profit opportunity; it represents an available niche in the market (Kirzner 1973; Fisher 1983). Entrepreneurs attempt to discover and exploit these. Whatever niche is to be filled, those capable of filling it are retained to fill the niche by their earning above-normal rates of profit. One might be surprised to see the term "normal profit" in reference to a model that does not assume equilibrium conditions. However, the model does generate equilibrium conditions as defined by the average rate of return for a given strategy. The patterns of returns that emerge support the equimarginal principal as an *ex post* outcome generated by the system, consistent with a general discussion of emergence in economics by Harper and Lewis (2012, 331; also see Miller and Page 2007, 44–53). This does not suggest that, *ex ante*, all agents optimize in correspondence with this principle. The system selects for agents who use strategies that efficiently exploit the landscape.

There emerges from the model nearly identical levels of wealth per capita across classes and combinations of consumption rates that result from a process of trial, error, and strategic duplication of strategies by agents (Figs. 18, 19 and 20). When the system is in stasis, agent classes that successfully sustain substantial population levels exhibit market rates of return as defined by wealth per capita. Basic agents do not exhibit this tendency when competing against Switcher agents. In the long run this population is practically non-existent across cases and parameter sets. This also appears to be true within a given run. Figure 23 shows that the average wealth per capita within the Switcher class broadly defined[10] tends to equalize once the system has reached a stasis.

Stability in one average statistic does not imply stability at all levels of the system (Wagner 2010, 2012). There can exist macro level stability that coincides with orderly chaos within the economy. As long as entrepreneurs continually exploit profit opportunities generated as second order effects of action by other agents with the system, this macro stability may be maintained (Koppl et al. 2015). The composition of the population as defined by class affiliation is almost always in flux within the model as new profit opportunities attract entrepreneurs suited to exploit them, and thus earn supernormal profit as long as the niche remains available (Figs. 21, 22 and 23). We observe strong correlations between different classes of agents. Successful entrepreneurs correctly predict the oversupply and undersupply of goods that result from the systematic behavior of others in this society. These correlations are by no means permanent in character. They do indicate changes in the composition of niches available for exploitation by entrepreneurial agents.

Finally, Figs. 21, 22, 23 and 24 do not show all information pertaining to agent-firms. Agents not only adopt 1 of 8 possible strategy combinations, but must also choose from parameters governing their switching rate, the nature of their response to prices, the rate at which agents adjust bid and ask prices, and so forth. Even reduced to a lower level of dimensionality defined only by the strategy used, changes in strategy composition alone suggest strong endogenous

[10] This includes non-augmented Switchers, Switcher Herders, Switcher Arbitrageurs, and Switcher Herder Arbitrageurs.

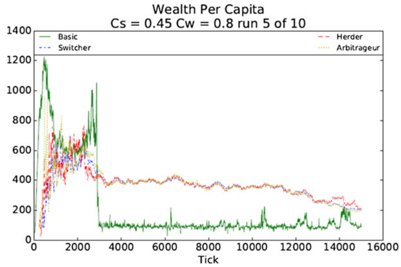

Fig. 21 Wealth Per Capita (Primary and Secondary Classes)

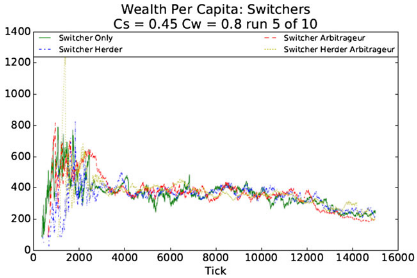

Fig. 22 Wealth Per Capita (Switcher Classes)

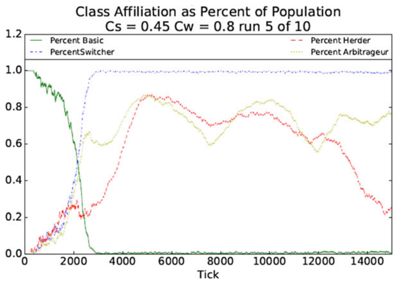

Fig. 23 Class Affiliation as Percent of Population (Primary and Secondary Classes)

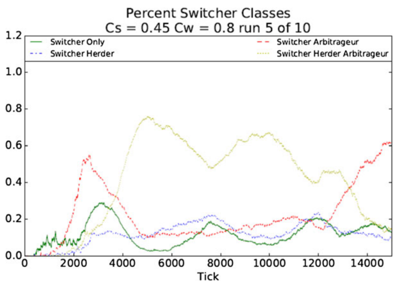

Fig. 24 Class Affiliation as Percent of Population (Switcher Classes)

interaction between agent strategies as well as between those strategies and the environment.

6 Implications

Competition between agents employing different strategies and parameter sets tends to promote patterns of action that overcome search costs and efficiently exploit gains from the landscape given the knowledge available to agents. The addition of entrepreneurs with different class strategies tends to increase the efficiency of production and exchange and more tightly constrain price variance. This is confirmed by comparison of economic activity in the case where agents use only Basic strategy against the case of local trade and competing technologies. The introduction of additional strategies increases the carrying capacity by allowing agents to more efficiently gather and trade resources. The composition of strategies on the landscape are determined by the rate of return associated with the strategy. The population of a class tends to increase until the average rate of return of the class meets the market rate of return. Agents using them can better predict changes in the landscape and thus act in a manner that promotes their survival. Further, under conditions where prices that fail to reflect scarcity reduce the welfare of the system, there exists profit opportunities for Arbitrageurs, agents who use strategies that might exploit the imbalance for gain. This simultaneously results in an improvement in system performance, and the welfare of the system as reflected by population levels.

Put simply, agents must target goods that are, at the present state, undersupplied. The strategy of Basic agents is especially inefficient in accomplishing this as compared to other classes of agents. Basic agents fail to directly respond to prices and fail to find another means to systematically target resources that are most highly valued. For this reason, they are outcompeted in the presence of Switcher and Arbitrageur agents. Switcher agents, by virtue of collecting both water and sugar target the scarcer resource half of the time. Arbitrageur agents respond to price. They accomplish the task with greater efficiency than Switcher agents under conditions where consumption rates diverge. As Yang and Chandra (2013) as well as Koppl et al. (2015) argue, the agent's environment includes other agents. Therefore, the success of an agent and the agent's nature itself is dependent upon the nature of other agents in the environment against whom they compete. The strategy of an entrepreneur may promote success under certain conditions and failure under others. Consistent with a systems level interpretation of the equimarginal principle, super-normal profits are competed away as one entrepreneur's niche might be displaced by the innovation of a competing strategy.

7 Conclusion

This paper makes several contributions. It presents a framework for modeling entrepreneurial decision-making and, therefore, entrepreneurial action that is ecologically rational. Such a model has allowed for investigation of an aspect of entrepreneurship which, to this time, could not be satisfactorily investigated using analysis dependent upon systems of linear equations. This model provides means to investigate the relationship between cost and the structure of entrepreneurial strategy. In overcoming these costs entrepreneurs profit and improve the welfare of the system. One need not assume equilibrium as economic teleology. A stable equilibrium is a phenomenon that emerges in particular domains of observation. It is a phenomenon that emerges due to the interaction of agents and the environment under conditions of disequilibrium. I hope that this construction and its results might encourage economists to employ their creative energies to model what, to this time, could not be formalized.

References

Aguinis, H., Lichtenstein, B. B., Davidsson, P., & Mckelvey, B. (2015). Power law distributions in entrepreneurship: implications for theory and research. *Journal of Business Venturing, 30*, 696–713.

Alchian, A. (1950). Uncertainty, evolution, and economic theory. *Journal of Political Economy, 58*, 211–221.

Auerswald, P. E. (2008). Entrepreneurship in the theory of the firm. *Small Business Economics, 30*, 111–126.

Axtell, R. (2005). The complexity of exchange*. *The Economic Journal, 115*(504), F193–F210.

Beer, R. D. (2004). Autopoiesis and cognition in the game of life. *Artificial Life, 10*, 309–326.

Bikhchandani, S., Hirshleifer, D., & Welch, I. (1998). Learning from the behavior of others: conformity, fads, and informational cascades. *Journal of Economic Perspectives, 12*, 151–170.

Booker, L. B., Goldberg, D. E., & Holland, J. H. (1989). Classifier systems and genetic algorithms. *Artificial Intelligence, 40*, 235–282.

Brown, D. (2015). “Here’s What ‘Fail Fast’ Really Means.” *Venture Beat*: http://venturebeat.com/2015/03/15/heres-what-fail-fast-really-means/.

Carayannis, E. G., Provance, M., & Grigoroudis, E. (2016). Entrepreneurship ecosystems: an agent-based simulation approach. *The Journal of Technology Transfer, 41*, 631–653 http://link.springer.com/article/10.1007/s10961-016-9466-7.

Cioffi-Revilla, C. (2014). *Introduction to computational social science: Principles and applications*. London: Springer.

Coase, R. H. (1937). The nature of the firm. *Economica, 4*, 386–405.

Crawford, G. C., McKelvey, B., & Lichtenstein, B. (2014). The empirical reality of entrepreneurship: how power law distribute outcomes call for new theory and method. *Journal of Business Venturing Insights, 1*, 3–7.

Czerlinski, J., Gigerenzer, G., & Goldstein, D. G. (1999). How good are simple Heuristics? In G. Gigerenzer & P. Todd (Eds.), *Simple Heuristics that make us smart*. New York: Oxford University Press.

Demsetz, H. (1988). The theory of the firm revisited. *Journal of Law, Economics, and Organization, 4*, 141–161.

Dennett, D. (2003). *Freedom evolves*. New York: Penguin Books.

Denzau, A. T., & North, D. (1994). Shared mental models: ideologies and institutions. *Kyklos*, *47*(1), 3–31.

Earl, P. E., Peng, T., & Potts, J. (2007). Decision-rule cascades and the dynamics of speculative bubbles. *Journal of Economic Psychology, 28*, 351–364.

Epstein, J., & Axtell, R. (1996). *Growing artificial societies: Social science from the bottom up*. Cambridge: MIT Press.

Fama, E. (1970). Efficient capital markets: a review of theory and empirical work. *Journal of Finance, 25*, 383–417.

Felin, T., Kauffman, S., Koppl, R., & Long, G. (2014). Economic opportunity and evolution: beyond landscapes and bounded rationality. *Strategic Entrepreneurship Journal, 8*, 269–282.

Fisher, F. (1983). *Disequilibrium foundations of equilibrium economics*. Cambridge: Cambridge University Press.

Foss, N. J., & Klein, P. G. (2012). *Organizing entrepreneurial judgment: A new approach to the firm*. Cambridge: Cambridge University Press.

Gigerenzer, G. (2008). *Rationality for morals: How people cope with uncertainty*. Oxford: Oxford University Press.

Gigerenzer, G., & Gaissmaier, W. (2011). Heuristic decision making. *Annual Review of Psychology, 65*, 451–482.

Gintis, H. (2009). *Game theory evolving: A problem-centered introduction to modeling strategic interaction*. Princeton: Princeton University Press.

Gode, D. K., & Sunder, S. (1993). Allocative efficiency of markets with zero-intelligence traders: market as a partial substitute for individual rationality. *The Journal of Political Economy, 101*(1), 119–137.

Harper, D., & Lewis, P. (2012). New perspectives on emergence in economics. *Journal of Economic Behavior and Organization, 82*, 329–337.
Hayek, F. A. (1935). *Prices and production* (2nd ed.). London: Routledge and Kegan Paul.
Hayek, F. A. (1945). The use of knowledge in society. *The American Economic Review*, 519–530.
Hayek, F. A. (1962). Rules, perception, and intelligibility. In *The market and other orders*. Chicago: University of Chicago Press.
Holland, T. (1992). Genetic algorithms: computer programs that "evolve" in ways that resemble natural selection can solve complex problems even their creators do not fully understand. *The Scientific American, 267*, 66–72.
Kerr, W. R., Nanda, R., & Rhodes-Kropf, M. (2014). Entrepreneurship as experimentation. *Journal of Economic Perspectives, 28*, 25–48.
Kirzner, I. (1973). *Competition and entrepreneurship*. Chicago: University of Chicago Press.
Kirzner, I. (1997). Entrepreneurial discovery and the competitive market process: an Austrian approach. *Journal of Economic Literature, 35*, 60–85.
Klein, D. (2012). *Knowledge and coordination: A liberal interpretation*. Oxford: Oxford University Press.
Knight, F. H. (1921). *Risk, uncertainty, and profit*. Boston: Houghton Mifflin.
Koppl, R. (2002). *Big players and the economic theory of expectations*. New York: Palgrave Macmillan.
Koppl, R., Kauffman, S., Felin, T., & Longo, G. (2015). Economics for a creative world. *Journal of Institutional Economics, 11*, 1–31.
Lane, D., & Maxfield, R. (2005). Ontological uncertainty and innovation. *Journal of Evolutionary Economics, 15*(1), 3–50.
Lavoie, D. (1986). The market as a procedure for the discovery and conveyance of inarticulate knowledge. In D. L. Prychitko (Ed.), *Individuals, institutions, interpretations: Hermeneutics applied to economics*. Aldershot: Avebury Publishers.
Li, H., & Tesfatsion, L. (2012). Co-learning patterns as emergent market phenomena: an electricity market illustration. *Journal of Economic Behavior and Organization, 82*, 395–419.
Menger, C. (1976 [1871]). *Principles of economics*. Grove City: Libertarian Press, Inc.
Miller, J. H., & Page, S. E. (2007). *Complex adaptive systems: An introduction to computational models of social life*. Princeton: Princeton University Press.
Mises, L. (1953 [1913]). *The theory of money and credit*. New Haven: Yale University Press.
Mises, L. (1996 [1949]). *Human action*. Indianapolis: Liberty Fund, Inc.
Muth, J. F. (1961). Rational expectations and the theory of price movements. *Econometrica, 29*, 315–335.
Nonaka, I. (1994). A dynamic theory of organizational knowledge creation. *Organization Science, 5*(1), 14–37.
North, D. (2005). *Understanding the process of economic change*. Princeton: Princeton University Press.
Pratten, S. (2015). *Social ontology and modern economics*. New York: Routledge.
Rosser, J. B. (1999). On the complexities of complex economic dynamics. *The Journal of Economic Perspectives, 13*, 169–192.
Sarasvathy, S. D. (2001). Causation and effectuation: toward a theoretical shift from economic inevitability to entrepreneurial Contigency. *Academy of Management Review, 26*, 243–263.
Sargent, T. J. (2014). Rational expectations and ambiguity. *Financial Analysts Journal, 70*, 14–19.
Simon, H. A. (1972). Theories of bounded rationality. In C. B. McGuire & R. Radner (Eds.), *Decision and organization*. New York: American Elsevier Publishing Company.
Simon, H. A. (1974). How big is a chunk? *Science, 183*(4124), 482–488.
Smith, V. (2003). Constructivist and ecological rationality in economics. *The American Economic Review, 93*, 465–508.
Wagner, R. (2010). *Mind society and human action: Time and knowledge in a theory of social economy.* London: Routledge.
Wagner, R. E. (2012). A macro economy as an ecology of plans. *Journal of Economic Behavior and Organization, 82*, 433–444.
Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.
Williamson, O. E. (1973). Markets and hierarchies: some elementary considerations. *Organizational Forms and Internal Efficiency, 63*, 316–325.
Yang, S. S., & Chandra, Y. (2013). Growing artificial entrepreneurs: advancing entrepreneurship research using agent-based simulation approach. *International Journal of Entrepreneurial Behavior and Research, 19*, 210–237.
Young, H. P. (1998). *Individual strategy and social order: An evolutionary theory of institutions*. Princeton: Princeton University Press.