Towards Modeling Economic Ecosystems: an Initial Model and Preliminary Validation

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Abstract. We introduce an approach to modeling economies that focuses on the interconnectedness of economic agents. This ecosystem-based approach allows us to enhance our understanding of economic growth by accounting for how the interactions of one agent directly impacts the local neighborhood and indirectly impacts the global system. The specific approach that we take to modeling economic ecosystems emphasizes technology and innovation in an attempt to account for gaps in the current literature on economic growth.

1 Introduction

Innovation is recognized as a core component of economic growth. In recent decades, the level of innovation due to cooperation among multiple entities has soared, but as a consequence, so has the chance of failure. When multiple entities are involved in a process, a successful outcome depends not only on the leading entity, but everyone else involved. In an economic environment, the success of an innovation depends not only on the cooperating entities, but also the suppliers and consumers associated with that innovation; these environments are called *innovation ecosystems* [2–4]. How then, does one model these interdependencies and their effect on economic growth?

To answer this question, we create an agent-based model of innovation ecosystems that allows us to study the role, impact, and limits of innovation on economic growth through the lens of ecology. Ecology studies how organisms interact with each other and their environment. Economic entities such as firms, households, and governments can be viewed as organisms living in an environment. Innovation can be viewed as an ecological process similar to niche creation and habitat formation.

Previous research [9,13] has approached modeling economics as an ecosystem by considering technology as a transformation process and showing that networks

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can be used to model the structure of technology in an artificial economy. The structure of these "transformation networks" is correlated with the economic performance of the associated artificial economy when trade networks are static. More interesting, however, is that these "transformation networks" are similar to ecological networks.

We extend the work of Hollander [13] and Garibay [9] by including speciation based on technology and modeling the relationship between species as an ecological network. Furthermore, we embed each economic agents in a spatial environment and allow them to move across that environment. As agents move, trade networks are formed between spatially local neighbors. These extensions result in a spatially embedded artificial economy that can be used to investigate the role of innovation on economic growth.

This paper describes our extended model.

2 General Concepts

It is well known, and accepted, that innovation and technology diffusion are critical components of economic growth [1, 6, 20]. The existing research on innovation and technology diffusion can be broken up into three broad areas: research that investigates the nature of innovation and how to encourage it, research that explores the methods and patterns of technology diffusion and adoption, and research that incorporates innovation and diffusion into models of economic growth. Our research focuses on the last area.

Economic growth models that account for innovation and technology diffusion are modeled with either a neoclassical approach, including DSGE models [6, 7]; an evolutionary approach [19]; econometrics [16]; or more recently, a computational agent-based approach [8]. These approaches differ primarily by their expressive power: the level of nuance allowed to the modeler when representing various economic behaviors and structure. With respect to modeling the role of innovation in economic growth, we believe that an agent-based approach [5, 15, 21] offers flexibility and is a natural fit to the stochastic and non-linear nature of innovation. Agent-based modeling also lets us represent knowledge in ways that are mathematically intractable. Our approach, however, is more than just a standard approach to agent-based modeling (e.g. agent-based computational economics). We do not merely embody economic theory and behavior "as is" in computational agents – our model views an economy as an ecosystem. For example: agents are treated as components in an ecological network, technology is represented by a structure similar to a food web, resources "flow" in much the same way as energy, innovation is viewed as creating new niches, and local economies form habitats.

The primary concept that we use from ecology is that of an ecological network [10, 12, 22]. The purpose of an ecological network is to model the flow of energy within an ecosystem. To accomplish this, each species is modeled as a simple input/output system. A species may have multiple inputs and multiple outputs. Species may receive input from either the environment or other species. Likewise, the output of a species may be transfered to either the environment or other species. Two species are connected by a directed link if the output of one is the input of another. The resulting structure is a directed graph (figure 1). We

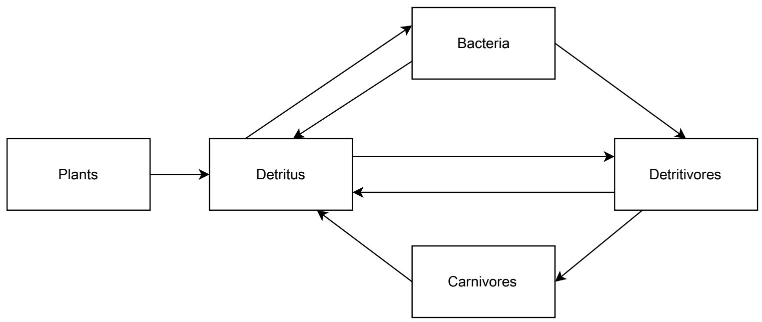

Fig. 1. A simplified example of an ecological network. This particular network is based on the Cone Springs diagram from Hirata [12]

model the flow of resources through an economy. Each species represents the set of firms with a particular technology that is used for production. Two species are connected if the output of one production process is the input to another (i.e. one technology depends on another).

Technology enables the flow of resources between firms by defining the production capabilities of a firm. The core component of Hollander and Garibay's original model, and our extension, is the treatment of technology as the transformation of products and resources. Products are heterogeneous and can interact and compete with one another. Because technology is a transformation process, it connects products and resources to one another. The resulting structure is a directed network that is similar to recent results from Hidalgo and Hausmann [11], where products are associated with countries. A directed network where technology links products and resources together is a "transformation network." Transformation networks are useful because they summarize the technological structure (and production capabilities) of an economy. Furthermore, there is a correlation between the structure of a transformation network and the economic performance of the associated economy [13, 17, 18].

Mathematically, transformation networks are directed hypergraphs, $H = (V, E)$, such that V is the resource space and E is the technology space: a set of "hyper" edges that connect all resources used in a production process (i.e. each edge encodes a specific technology available to the population). The resource space of an economy is the set of resources used for production and consumption. These resources can be natural (e.g. trees), manufactured (e.g. tables), or intangible (e.g. labor). Each edge in the technology space is associated with a positive weight that denotes the number of companies capable of the associated production process. Firms with the same production processes are all part of the same species. As firms enter and leave the economy, the weights associated with E will change. Edges with a weight of 0 are removed from E and added back when their weight becomes greater than 0. Thus, the transformation network of an economy changes with the production capabilities of the population. An example transformation network from our extended model is displayed in figure 2. For this particular example, there are 12 resources with technology restricted to one-to-one transformations. The weight of each edge denotes the total number of agents with the corresponding technology, and the number of agents employing that technology in the current time step. (There are 112 agents in the economy.)

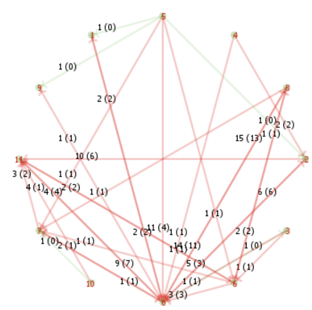

Fig. 2. An example transformation network. Red edges represent technologies being used in the current time step. Green edges represent technologies not being used in the current time step.

3 The Model

We construct an agent-based model of innovation ecosystems using Netlogo [23]. Agents exist in a spatial environment and are driven by simple economic behaviors. The interactions between agents produce network structures. Aggregating the individual agent states produces macroeconomic measures such as GDP and employment.

3.1 Agents

In our model, we take the view that every economic entity can be abstracted as a "resource transformer". Under this assumption, firms, households, and banks all have the same structure; though different functionality. Accounting for the difference in functionality, we specify three types of agents in our current model:

sources, *adaptive resource transformers*, and *sinks*. We also make use of an abstract "government" agent to account for money and an abstract "environment" agent to account for resources.

A diagram of the relationship between all agents in our model is given in figure 3. Resources flow from the environment into source agents, where they are

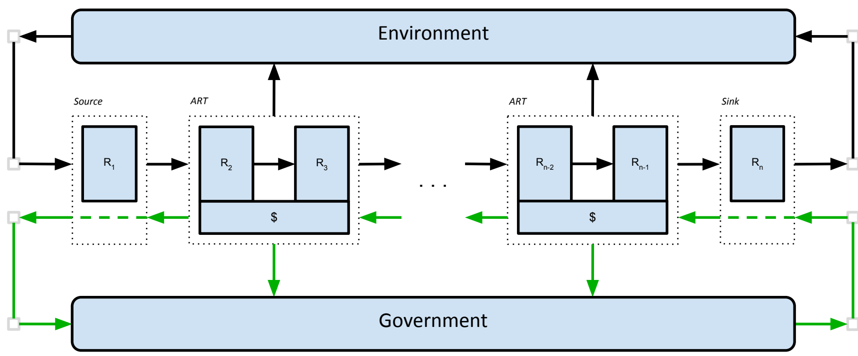

Fig. 3. A One Source One Sink (OSOS) Economic Ecology. Green arrows represent the flow of money, black arrows represent the flow of resources.

then bought by adaptive resource transformers and transformed into products. These products are then bought by other adaptive resource transformers and sink agents. Resources bought by sink agents are given back to the environment. Similarly, money flows from the government to the sink agents. Sink agents use their money to buy up resources from adaptive resource transformers. Adaptive resource transformers then use that money to buy resources from other adaptive resource transformers and source agents. Money traded to source agents in exchange for resources is given back to the government. This model of alternating flow between resources and money forms the basis of our economic model and gives rise to ecological structure.

Sources Source agents represent naturally occurring resources. Structurally, they are composed of a single compartment for output resources. A diagrammatic representation of source agents as simple input/output entities is displayed in figure 4. Each source agent is responsible for the distribution of a single resource. A source is able to hold up to c_{source} resources at any given time. Source agents receive resources from the environment at a rate of r_{source} resources per step, with

$$r_{source} = \min\left(\max(c_{source} - R_{source}, 0), R_{government}\right) \tag{1}$$

where R_{source} is the current quantity of resources in the source agent and $R_{government}$ is the quantity of resources in the government agent. There is no

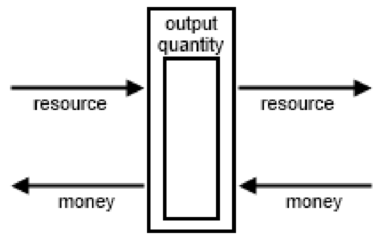

Fig. 4. The structure of a source agent.

immediate cost associated with the transfer of resources from the environment to a source agent.

Resources leave a source agent when they are purchased by an adaptive resource transformer. Each source associates a unit price with its associated resource. This price can either be fixed, or it can change over time in response to the success or failure of trade activities. In exchange for resources, adaptive resource transformers transfer money to the source. When a trade occurs, the source immediately passes any and all money received directly to the government. Source agents do not store money.

Adaptive Resource Transformers Adaptive resource transformers (ART) represent firms. Structurally, they are composed of a compartment for input resources, a compartment for output resources, and a compartment for money. A diagrammatic representation of adaptive resource transformers as simple input/output entities is displayed in figure 5. Adaptive resource transformers are

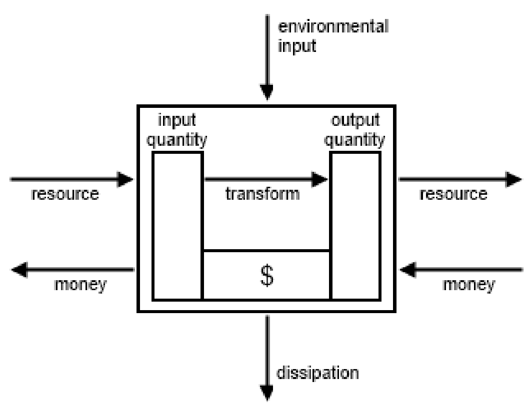

Fig. 5. The structural representation of an adaptive resource transformer.

driven by production. Each adaptive resource transformer contains a single transformation rule, denoted ($R \rightarrow P$), that represents the technology required to transform a *resource*, R, into a *product*, P.

Production requires input resources. Input resources (*resources*) are obtained by trading with other adaptive resource transformers and source agents. Once obtained, production converts input resources to output resources. These output resources (*products*) are then traded to other adaptive resource transformers and sink agents. Money enters and leaves an adaptive resource transformer as a side effect of trading; however, resources and money can also leave an adaptive resource transformer through the stochastic process of dissipation. In economic terms, dissipation can be interpreted as the indirect costs of production and resource decay. If an adaptive resource transformer ever runs out of both money and resources, it "dies" and is removed from the spatial environment. To counter this death process, adaptive resource transformers have a probability to reproduce each time one of their resources is bought (i.e. successful firms are those that are able to sell their output resources).

Resource Acquisition Adaptive resource transformers acquire resources through trade with other adaptive resource transformers and sources. They continually search their local environment for agents that contain output resources that correspond to the input resource specified by their transformation rule (i.e. an agent with the rule $1 \rightarrow 2$ searches for the resource "1"). If the desired resource is found in another agent, the adaptive resource transformer buys as much of the resource as possible − limited by either its money, or the seller's quantity. The newly acquired resource is stored in the buyer's input resource compartment and the money spent to acquire the resource is removed from the buyer's money compartment and transferred to the seller's. If no agent is found with the desired resource, then the adaptive resource transformer moves to a new location in the spatial environment.

Production The transformation rule of an adaptive resource transformer determines its production capabilities. Production is possible only when there are resources in the input compartment. The quantity of output resources produced by agent a is determined by a Cobb-Douglas production function with the form

$$R_a^{out} = \min\left(\left\lceil (1+\$_a)^{0.5} * {R_a^{in}}^{0.5} \right\rceil, R_a^{in}\right) \tag{2}$$

where R_a^{out} is the quantity of products produced by agent a, $\$_a$ is agent a's current quantity of money, and R_a^{in} is the current quantity of resources possessed by agent a. For each output resource products, one input resource is consumed. Functionally, production is realized as the transfer of resources from the output resource compartment to the output resource compartment.

Resource Pricing Each adaptive resource transformer associates a unit price with its output resources. Agents adjust their prices over time based on the success or failure of trades. Agents increase the unit price demanded for their resource if they experience a series of consecutive successful trades. Agents lower the unit price if they experience a consecutive series of failed trades (i.e. they meet buyers who cannot afford to buy even one resource.) The number of successes or failures required to trigger a price change, and the amount that the price will change by, are specified as parameters to the model.

Reproduction Each time an adaptive resource transformer has one of its output resources bought, there is a parameterized probability that the agent will reproduce. When an agent reproduces, it creates a near-perfect copy of its child; the only difference that may occur is in the transformation rule of the child. Each time an agent reproduces, there is a probability of mutation for both the input and output component of the transformation rule. Each act of reproduction alters the transformation network. If the mutation produces an edge that already exists, then the weight of that edge is increased. *Innovations* are reflected by the creation of new edges in the associated network. An innovation can produce either a new edge between two resources currently in use by others, or a new edge between a resource currently being used and a resource that is not currently being used. It is also possible to create an innovation that uses two unused resources, but these innovations are not immediately economically viable. The new adaptive resource transformers created by the reproduction process are placed in the same spatial location as their parents.

Sinks Sink agents represent households. Structurally, they are composed of a single compartment for input resources. A diagrammatic representation of sink agents as simple input/output entities is displayed in figure 6. Each sink agent is

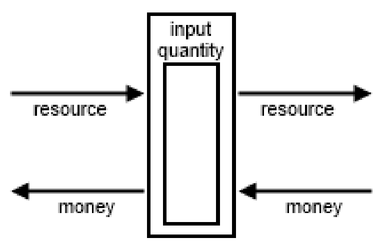

Fig. 6. The structure of a sink agent.

responsible for the distribution of money. A sink is able to hold up to c_{sink} units of money at any given time. Sink agents receive money from the government at a rate of r_{sink} units of money per step, with

$$r_{sink} = \min\left(\max(c_{sink} - \$_{sink}, 0), \$_{government}\right) \quad (3)$$

where $\$_{sink}$ is the current quantity of money in the sink agent and $\$_{government}$ is the quantity of money in the government agent. Sinks do not need to immediately exchange resources with the environment in exchange for money from the government.

Money leaves a sink agent when the agent purchases resources from an adaptive resource transformer. When buying resources, sinks follow the same trade rule as adaptive resource transformers – buy from the agent that allows you to acquire the most resources. When a trade occurs, the source immediately passes any and all resources received directly to the environment. Sink agents do not store resources.

The Government The government agent in our model is an abstract entity that closes the monetary supply so that there is a fixed amount of money in the economy. Money enters the government from source nodes, who transfer funds that are obtained through trade with adaptive resource transformers. Money also enters the government as "dissipation" from adaptive resource transformers. Money leaves the government as payment to sinks. The government agent is capable of implementing monetary policy by creating money "from thin air" or altering the flow of money given to sinks in response to macroeconomic measures, but the current simulation does not use this capability.

The Environment The environment agent in our model is an abstract entity that closes the resource supply so that there is a fixed amount of resources in the economy. Resources enter the environment from sink nodes, who transfer resources that are obtained through trade with adaptive resource transformers. Resources also enter the environment as "dissipation" from adaptive resource transformers. Resources leaves the environment as payment to sources. The environment agent is capable of creating additional resources "from thin air" or altering the flow of resources to source agents in response to macroeconomic measures, but the current simulation does not use this capability.

3.2 The Spatial Environment

Sources, adaptive resource transformers, and sinks exist in a spatial environment. The environment and government agents are ethereal. The structure of the spatial environment is a two dimensional grid that allows multiple agents to occupy the same space. Sources are stationary, but adaptive resource transformers and sink are able to move around the grid and "see" other agents within a circle of v units, centered on the observing agent. The *vision radius*, v, plays an important role in agent decision making by bounding the observable world and defining the local neighborhood of each agent. Agents can only interact with other agents less than v units away.

Movement Adaptive resource transformers and sinks are mobile agents. Movement through the spatial environment is governed by an agent's vision radius and the desired resource. Adaptive resource transformers look at every other adaptive resource transformer and source agent in their local neighborhood and identify the agent that they can buy the most resources from. Sink agents conduct the same process, but only considering adaptive resource transformers –

not source agents. Once a "trade partner" has been identified, the agent moves along a straight line until it is adjacent to it.

3.3 Network Structures

The core factor that distinguishes our approach to modeling economics from many others is our focus on the network structures between agents. Networks can be used to identify the relationship between entities and help explain individual behavior and emergent phenomenon. The three types of networks that we are primarily interested in modeling are: interactions networks, species networks, and transformation networks.

Interaction Networks All agents within the local neighborhood of one another form an "interaction network". This network is dynamic and is restructured at every time step as adaptive resource transformers and sink agents move through the environment.

The interaction network at time t contains multiple subgraphs. The two that we are primarily interested in for analysis purposes are the resource flow network – a directed graph between local neighbors that indicates who might be interested in buying a resource – and the trade network – a directed graph between the agents that actually traded during the current step.

Ecological Networks Adaptive resource transformers can be grouped by their transformation rules, with group being thought of as a species. Connections can be made between species to show how one technology depends on another by matching the output of one species to the input of another. The resulting structure is an ecological network that illustrates how resources flow through a population. This network structure is useful because it identifies bottlenecks and points of weakness within the economy.

Transformation Networks The ecological network between species can be abstracted to construct a transformation network that encodes the resource and technology space of the economy into a single structure. In a transformation network, two resources (nodes) are connected by a technology (edge) if one resource can be transformed into another through a technological process. As with the species network, a transformation network identifies bottlenecks and points of weakness within the economy. For example, a transformation network displays "keystone" resources in the system, whose removal would cripple the production of many products.

3.4 Macroeconomic Measurements

Our model produces data on the GDP, distribution of wealth, population, production level, product prices, distribution of technology, and structure of the transformation network. The GDP, distribution of wealth, population, production level, and product prices yield traditional macroeconomic data that give a summary on the general health of the economy. The distribution of technology and structure of the transformation network yield information about the innovation activity and technological state of the economy. One benefit of collecting data related to innovation and technology is that we can observe the process of Schumpeterian creative destruction [14]. More importantly, however, we can use data related to the innovation and technological structure of the economy to augment our understanding of economic growth and test new policies that encourage economic development.

4 Preliminary Validation

We have validated the initial version of our model (using a Netlogo simulation) against a small set of basic stylized facts from economics. The front end of this simulation is depicted in figure 7. The age of adaptive resource transformers at

Fig. 7. The front end of our Netlogo implementation for the economic ecosystems model.

an arbitrary time step is exponentially distributed, and may follow a power-law. The combined money and resources of an adaptive resource transformers also appears to be power-law distrusted. We also observe the process of creative destruction as a shift between dominate technologies (i.e. the distribution of species undergoes a radical change) and observe cyclic behavior in the macroeconomic output variables that suggest the presence of business cycles. All of these observations occur over a wide range of parameter settings.

As a further step towards validation, we have repeated two previous experiments conducted on a model similar to the model discussed in this paper. As with the initial work by Hollander and Garibay [13] on transformation networks, we investigated the relationship between the GDP of the underlying economy associated with an innovation ecosystem and the structure of its transformation network. We found that that 1) there is a positive correlation between the density of the transformation network and the GDP ($\rho = 0.77$); and 2) this relationship holds when money or resources are exogenously injected into the economy ($\rho = 0.75$). We also replicated the results of Garibay and Hollander [9] and found that an exogenous injection of money or resources produces a long-term change in the density of the transformation network and GDP of the underlying economy.

5 Summary

In this paper, we introduce an approaching to modeling economies that focuses on the interconnectedness of economic agents. This ecosystem-based approach allows us to enhance our understanding of economic growth by accounting for how the interactions of one agent directly impacts the local neighborhood and indirectly impacts the global system.

The specific approach that we take to modeling economic ecosystems emphasizes technology and innovation in an attempt to account for gaps in the current literature on economic growth. We treat economic entities as "adaptive resource transformers" – simple agents that encapsulate a technology which allows them to transform a resource into a product. These agents live in a spatial environment and are only aware of their local geographic area. Their interactions (via resource trading) with spatially local neighbors results in economic activity that can be aggregated to form a macroeconomic picture of the population.

Our initial model displays interesting and insightful results, but we are still in the process of tuning our model and conducting parameter sweeping and validation. Once complete, our approach to constructing economic models could potentially lead to a deeper understanding of the microeconomic and network dynamics that lead to commonly observed macroeconomic patterns.

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