

XEcon: An Experimental / Evolutionary Model of Economic Growth

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This paper represents the views of the author and does not necessarily reflect the opinions of Statistics Canada

Aussi disponible en français

Abstract

The role of technical innovation in economic growth is both a current matter of keen public policy interest, and active exploration in economic theory. However, formal economic theorizing is often constrained by considerations of mathematical tractability. Evolutionary economic theories which are realized as computerized microsimulation models offer significant promise both for transcending mathematical constraints and addressing fundamental questions in a more realistic and flexible manner. This paper sketches XEcon, a microsimulation model of economic growth in the evolutionary tradition.

Keywords: microsimulation, growth theory, endogenous, technical change, evolutionary economics

Introduction

This paper provides a brief sketch of a new microsimulation model, XEcon, under development at Statistics Canada. Since XEcon is a work in progress, there are no results to report. Also, in contrast to most other microsimulation work in the social sciences, XEcon is intended for theoretical exploration rather than practical empirical application. Since XEcon is relatively unique, the sketch provided here of its broad architecture may be of interest in its own right.

The objectives of XEcon are both substantive and methodological. The substantive objectives at the most general level are the same as much theoretical modeling in economics -- to seek understanding of basic processes and phenomena in real economies, particularly long run economic growth, technical change, individual income inequality, and their inter-relationships. The use of abstract and formal models in this endeavor is helpful to sharpen intuition and to construct logically coherent arguments. The typical style of argument is to posit formally a network of plausible causal pathways, then derive further implications by logical methods (in this case computer simulation), and assess the extent to which these derived implications hold in the real world.¹ Another substantive objective of the theorizing is to inform and guide the development of new measurement systems, such as those of national statistical agencies.

Since theoretical modeling in economics is perhaps overly valued (e.g. Leijonhufved, 1973), XEcon has been conceived with the following criteria in mind. Subject to the inherent complexity of the phenomena under study, the model should be parsimonious and as transparent as possible. The model should rely on at least potentially measurable constructs. One model is “better” than another, *ceteris paribus*, if it can account for a wider diversity of “facts” or empirical patterns. Desirable features of theoretical models are that they address important public policy or social questions; the model structure provides a foundation whereby the model can be extended in the direction of greater realism (e.g. via scenarios, not unconditional forecasts); and the model points to potentially efficacious “policy levers”. Beyond these broader characteristics desired of XEcon, further details of the substantive objectives are outlined in a later section via a plan of simulation experiments.

The methodological objectives respond to concerns that the formalism of much contemporary economic theory, and the associated constraints of mathematical tractability, have excessively limited realism, and engendered an abstract research program increasingly divorced from empirical grounding (e.g. Lipsey, 1993). XEcon shows (proof “by construction”) that many of these concerns can be readily and usefully transcended using modern computer microsimulation

¹ This phrasing is deliberate in order to eschew the more commonly heard descriptions of this process as “writing down a theoretical model in order to explain some phenomenon” and “testing the implications of the model”. “Explain” is inappropriate insofar as it has a connotation of uniqueness when, in fact, many quite different theoretical models can usually be written down which accord at least moderately well with the same “stylized facts”. “Testing” also implies excessive precision for the empirical grounding of the theorizing, certainly in economics.

methods, and that “better” theoretical models (in the sense just defined) become feasible. In other words, there are important benefits from technical change not only in real economies, but also in the art of constructing theoretical economic models, and not just from the application of new mathematical tools.

Background

Neo-classical models dominate the literature on economic growth, and form an essential backdrop to the development of XEcon. Recent work (e.g. Romer, 1990) has emphasized not only the centrality of technical progress, but also the idea that technical progress should be endogenous -- an explicit part of the formal theorizing. The advance of technology should not be seen as some magical process of creative lightning bolts of ideas beyond the scope of economic forces, nor as a given that is appropriately described by the smooth exponential growth in some technical efficiency parameter. Rather technical progress is uneven; it is the result of purposive search activity, and the scale and character of this activity is responsive to economic incentives. This view is not without controversy. For example, Mankiw, Romer and Weill (1992) argue that growth in physical and especially human capital can account for observed national patterns of growth in the post WW II period without requiring technical change as a major explanatory phenomenon. Lucas (1993) emphasizes learning-by-doing as yet another key explanatory factor, coupled with the continuous (and exogenous) introduction of new techniques of production.

Common to many of these recent theoretical growth models are the following components:

- a formal mathematical representation of the technology of production, typically a "smooth" perfectly known aggregate production function, including an abstract but explicit characterization of technical progress;
- a set of agents -- usually one or two kinds of (generally) homogeneous (hence simply aggregated) firms and workers -- who jointly produce output according to the technology;
- a formally specified set of behaviors for the agents -- typically omniscient inter-temporal profit or utility maximization;
- a prose story about the institutional arrangements -- such as perfect or monopolistic competition, and infinitely lived patents; and
- an assumption of steady-state growth equilibrium.

XEcon is similar insofar as it contains many of the same components -- for example a set of agents, formally specified behaviors and descriptions of the technology of production. It is in the evolutionary tradition, however, so that it is not "solved" using formal mathematical deduction. Instead, the model's dynamic trajectory is "revealed" using explicit computer simulation of the behaviors of the myriad micro entities posited in the theoretical economy. Computer simulation approaches have the advantage that mathematical tractability need not be a

constraint in formalizing ideas. Instead, the only constraint is that the formal descriptions of agents, technologies, behaviors, etc. must be well-defined procedures or algorithms.

Thus, XEcon need not and does not make any a priori assumption of equilibrium. Instead, the basic scenario is that of an economy operating in real calendar time, starting at some time t_1 (e.g. 1900) and evolving either continuously or in discrete steps Δt until time t_2 (e.g. 2050). It may turn out that the path followed by the economy is a steady-state growth path, but it is much more likely (and realistic, of course) that the path will involve fluctuations with no clear equilibrium or asymptotic end point. More interestingly, the economy may start out with a relatively simple structure and generally become more complex over time, or new kinds of arrangements or patterns might emerge. This is the essence of evolutionary models, and evolutionary theory.

Another aspect of the computer simulation approach of evolutionary models like XEcon, and the consequential relaxation of the constraints of mathematical tractability, is that many assumptions in neo-classical models become optional. For example, production technology can, but need not, be represented by smooth aggregate production functions. Instead, individual firms can be explicitly represented by heterogeneous techniques of production that evolve over time in a groping "higgledy-piggledy" manner (again arguably more realistic). Other neo-classical assumptions can become impossible in an evolutionary model. The main example is omniscient maximization. The reason is that the optimization problems faced by agents in a formal evolutionary model like XEcon are insoluble. Thus, agents' behavior not only can, but must be described by heuristics or rules of thumb. (These heuristics may adapt or evolve over time.)

Formal evolutionary models in economics are, of course, not new, but they are much less common. The seminal model is that of Nelson and Winter (1982). Their model was designed to give an equally plausible but alternative and decidedly unorthodox account of 20th century technical progress in the US, compared to the account given by the Solow (1957) model, which is the seminal model in the neo-classical growth literature. A brief sketch of the Nelson and Winter model is useful because it provides an initial *point de depart* for XEcon.

The Nelson and Winter model is highly abstract and simplified. It starts with a finite population of firms all of which produce a homogeneous output Q (or GNP). The i -th firm uses two inputs, capital (K_i) and labor (L_i), with fixed coefficient production functions -- a labor productivity coefficient (Q_i/L_i) and a capital intensity coefficient (K_i/L_i). Each firm's output is a "backwards L" function of labor input, with capital on hand providing the upper constraint on output. The firms are heterogeneous because they each can have different fixed coefficients. Each firm's capital is subject to "noisy" exponential depreciation. More importantly, there is an explicit stochastic process of technical change via R&D. Firms search for "better" techniques of production, either incrementally in a local "neighborhood" of their existing technology, or imitatively by trying to copy the technique of a more successful firm.

A simulation of the Nelson and Winter model starts with a handful of firms endowed with technologies randomly distributed around the same 1909 average used in the Solow model. The population of firms then evolves by a random process of innovation according to the stochastic search process just mentioned, and investment of any gross profits in new capital. A principal

conclusion of this unorthodox evolutionary model is that it is equally capable of reproducing the macroeconomic "stylized facts" as the aggregate profit-maximizing parable in the 1957 Solow model. This is not necessarily a very strong test of the relative merits of the two models, nor the two methodological approaches more generally. But it clearly shows some measure of superiority of the evolutionary approach, since the Nelson and Winter model also accounts for the evolving size distribution of firms at the micro level, a feature that is entirely absent in aggregate growth models.

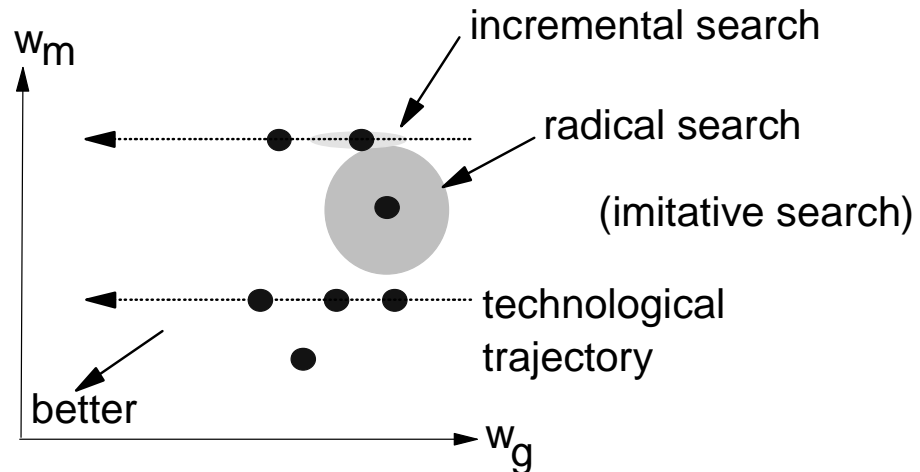
Lane (1993) describes a model under development with Dosi et al which is more general than Nelson and Winter's. This model contributed significantly to the initial conceptualization of XEcon. The Dosi-Lane model has two sectors -- one for producing heterogeneous machines (m), the other producing a homogeneous consumer good (g). In the first sector, "mfirms" make m 's by employing workers; and search for new technologies (new m 's) by employing scientists. In the other consumer goods sector, "gfirms" use m 's and workers to produce g .

The locus of technical change is in the first sector. Each machine is represented formally by a two element vector (w_m, w_g) , where w_m is the embodied number of FTE (full time equivalent) workers needed to build one m , and w_g is the number of FTEs required to make one physical unit of g using one m . Technical progress then involves reducing either or both w_m and w_g .

Figure 1 gives a graphical representation of this technology. The vertical axis shows the labor required to produce the machine itself (w_m), and the horizontal axis is the labor required to produce one unit of the (homogeneous) consumer good using the machine (w_g). Each point in the graph therefore represents one kind of machine, and in turn the one firm which knows how to manufacture that machine. The multiple dots in the figure reflect the co-existence of various kinds of machines, and hence the realistic coexistence in the economy of a set of heterogeneous firms using quite different techniques to produce the same commodity. Unambiguously "better" machines lie to the south-west (SW) in this figure; moving NW or SE is ambiguous and depends on the relative prices of labor and the consumer good. Somewhat artificially, Dosi-Lane identify westward movements in this space (i.e. holding the labor content of the machine fixed) as technical progress along a "technological trajectory".

Each firm invests in R&D using one of three strategies to search for new technologies in this abstract space -- (1) incremental (westward movements) or (2) imitative (copying "nearby" firms) as in Nelson and Winter, or (3) radical (i.e. 2-d) search possibly moving south as well. Since the model is still under development, no conclusions have been published.

Figure 1 -- Technology and R&D Search in Dosi-Lane



Finally, two macroeconomic models with explicit microsimulation foundations should be noted. One is Eliasson's (e.g. 1986, 1991) micro-to-macro MOSES model. This is much more than a pure theoretical evolutionary model. It is a large empirical model that has been under development since the mid 1970s. It builds on the actual historical behavior of about 150 named large Swedish firms, and has explicitly reconciled their financial attributes with the Swedish national accounts and input / output data. The evolving behavior of these firms is represented by simple but heterogeneous production possibilities, and satisficing rules of thumb. Technological progress is exogenous based on a simple exponential growth trend, though Ballot and Taymaz (1993 **and this volume**) have recently extended MOSES to include an explicit learning process to make technical change substantially endogenous. The other is the Bennett and Bergman "microsimulated transactions model" of the US economy (1986). It is avowedly in the microsimulation tradition, while at the same time explicitly designed to fit 1970s US macro data. It is relatively richly articulated with respect to the myriad kinds of transactions in an economy and its financial sector. However technical progress, as in Eliasson's MOSES, is based on an exogenous exponential growth parameter, albeit with explicit vintage capital.

Given the diversity of these approaches, both within and between the neo-classical and the evolutionary efforts, a central issue in the design of XEcon has been the formal representation of technology. The idea that a technology can be formally represented by a mapping from a set of inputs to a set of outputs seems elemental. At the same time, it would be useful if these "atoms" of technology could be combined and recombined into "molecules" that capture some of the historical evolution of firms -- for example as in Best's (1990) description of historical changes from early 19th century craft shops through the developments of interchangeable parts and

standardization, the specialization and "vertical disintegration" that characterized the emergence of the machine tool industry (Rosenberg, 1976), and the mass production "flow processes" of Ford's production line.

Technology in XEcon

We start in this section to provide a sketch of the structure of XEcon, beginning with the formal representation of technology. The "atom" of production technology assumed in XEcon is a technique for producing one commodity output from a mix of inputs. We assume linear constant returns to scale as in a column vector of a use matrix of an input/output table. (Non-linearity could easily be implemented, but is avoided in the first instance to keep the initial version of XEcon simpler and easier to understand.)

In order to provide a sense of the possibilities opened up by a microsimulation approach rather than a purely mathematical approach, let us describe briefly some further detail of the posited production technology. Each commodity is uniquely identified by an index, say i or j , and it can be produced by one or more techniques. In turn, each technique is represented by a pair of column vectors for the j -th output:

$g(i,j)$ = the amount of commodity i required "to be present" to produce one unit of commodity j

$d(i,j)$ = the amount of i "used up" per unit of input requirement in producing j .

While this two-part linear representation is straightforward, it allows a richer range of production relationships than a single input / output style column vector for each technique, and is much richer than usual neo-classical production functions. For example, if $d(i,j) = 1$, then the input is used up one-for-one in production (e.g. electricity, petrochemical feed stocks). If $d(i,j) = 0$, then the input is an infinitely durable capital good (e.g. a catalyst, or the bit string for a new piece of software) for which there must be at least $g(i,j)$ units present for each unit of output. If $0 < d(i,j) < 1$, then there must be at least $g(i,j)$ units present for each unit of output and $d(i,j) \times g(i,j)$ units will be "used up" in the production of one unit of the j -th output.

This $d(i,j)$ formulation seems more realistic than the usual assumptions regarding durable goods -- the conventional accounting assumption of straight line depreciation, or the standard theoretical assumption of exponential decay. Both conventional assumptions imply a fixed amount of the capital good must be around to "support" any given level of output flow. But unlike the $d(i,j)$ formulation, the rate at which capital is physically used up is a function of the passage of time, rather than having depreciation depend on the intensity with which the asset is actually used. (Depreciation in the sense of technological obsolescence is modeled separately and explicitly as various techniques' profitability's are assessed by firms' management or through market selection -- see below.)

Since we are using microsimulation methods, it is straightforward to populate XEcon's artificial or "toy" economy with a myriad heterogeneous firms. They will produce different commodities, and those producing the same commodity will generally use different techniques,

i.e. firms in the same industry will typically have different $g(i,j)$ and $d(i,j)$ coefficients. As a result, even simple versions of this abstract economy can exhibit "economic growth" as the intensity of production shifts among the various available techniques. "Patterns of differential survival and growth in a population of firms can produce change in economic aggregates characterizing that population even if the corresponding characteristics of individual firms are constant" (Nelson and Winter, 1982). Technical progress, i.e. the discovery of new column vectors, is also possible in XEcon and is discussed later.

Agents

XEcon consists of two main kinds of agents -- firms and worker/consumers. In addition, there is a rudimentary finance sector, a government tax/transfer branch, and an information sector. These agents are described briefly in this section.

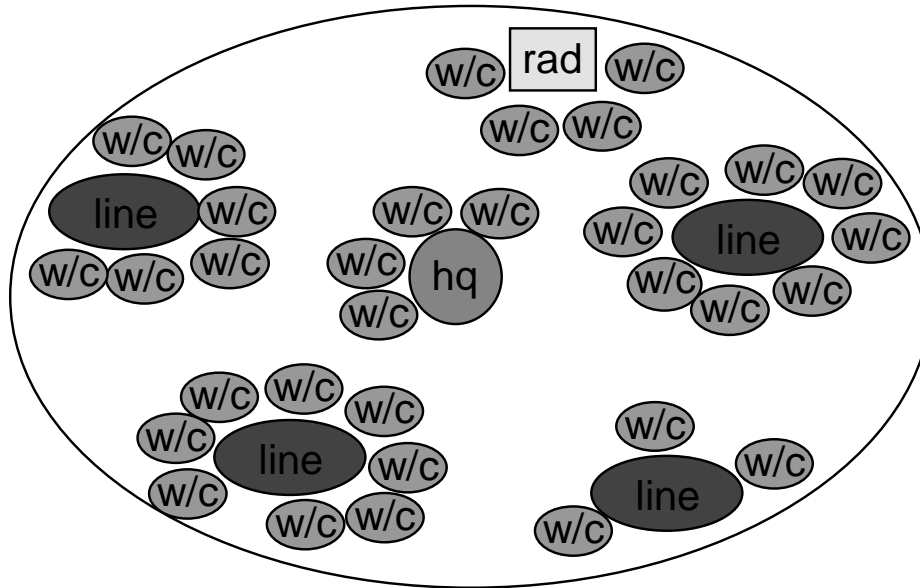
firms

Firms are central in XEcon and have considerable internal structure. They are organized collectivities of individuals engaged in the production of commodities using other commodities as inputs. The basic "atom" of physical production (the transformation of inputs into outputs) is a production line or line of business or "firm-line" for short. Firm-lines need not be identified with explicit industries or sectors; they are identified only by the commodities they produce.

In addition, firms have a "mind and management" which makes strategic decisions with regard to levels and composition of production, human resource policy, financing, investment, pricing, marketing, R&D strategy, etc., denoted "firm-hq" for headquarters. This means that firms are best thought of as "molecules" consisting of one firm-hq and one or more firm-lines.

Firms also tend to search continuously for new more efficient methods of production. This activity is concentrated in one organizational sub-unit in each firm, the research and development department, or "firm-rad" for short. (The R&D search process is typically described by relatively simple rules of thumb.) The internal structure of firms is illustrated in Figure 2.

Figure 2 -- Firm Structure in XEcon



Firms individually can not only grow and decline over time, they can also be born as new entrants, and die or exit via bankruptcy. Growth (and decline) can take several forms. The most straightforward is changes in levels of activity. With explicit R&D, other forms of growth would be the discovery of more efficient techniques for producing commodities the firm is already producing (incremental or imitative R&D, or continuous improvement), and techniques for producing entirely new commodities (radical R&D) -- allowing firms to evolve from uni-cell to multi-cell (i.e. multi-line). A further possibility is the acquisition (takeover) from other firms of their firm-lines.

Firms are assumed to follow similar patterns of behavior -- for example regarding formation of expectations, pricing, and production decisions. Even if a number of firms have identical technologies and formalized behavioral patterns, they will generally be heterogeneous (e.g. numbers of employees, rate of output price adjustment based on (heterogeneous) past experience, and profitability).

To start, XEcon will assume limited heterogeneity in production techniques and nil technical progress, even though the study of technical change is a primary objective of XEcon. The reason is that we must first be able to generate plausible patterns of micro- and macro-level behavior in the simpler case of static technology. Our intuition is that this will *not* be easy, because we shall be departing so radically from the usual neoclassical omniscient maximizing assumptions.

worker / consumers

Individuals in XEcon are considered in two main roles, as workers who supply labor to firms, and as consumers of final outputs. To begin, we assume homogeneous labor with no learning or skill heterogeneity, though such extensions are anticipated. They would allow a more natural representation of learning-by-doing at the level of individual workers rather than it being disembodied at the firm or industry level. (Also, with skills embodied in workers, firm bankruptcy need not imply complete loss of such specialized human capital, insofar as laid off workers are re-employed where they can still use their skills.) Homogeneous behavioral patterns and preferences over consumption goods are also assumed to start. Again, such assumptions are easily relaxed in a microsimulation approach, but are useful not only for debugging the model, but also in coming to understand its properties.

Worker/consumers offer their labor to firms based on a reservation wage, which in turn is a function of their previous employment experience. Workers who are already employed will only search for new work if their wage drops by more than a given percentage. Workers who are unemployed lower their reservation wages by another amount at some annual rate, and search for work.

Simple consumer choice could be based on lexicographic preferences (e.g. as in Pasinetti, 1982) over final outputs. For example, worker/consumers allocate all their income to necessities like food until they have met their basic requirements, and then consume as much "luxury" goods (e.g. TV) as they can afford. Such a hierarchical structure of preferences is no less realistic than those implied by conventional "smooth" utility functions, but is virtually impossible to analyze in models using purely mathematical techniques

Even though worker/consumers have homogeneous labor, preferences and behavioral rules of thumb, they will still be heterogeneous in employment, wages, and consumption patterns because they will work for different firms who will likely be heterogeneous in their wage rates, and have the possibility of being unemployed. Also, a more complete description of the XEcon structure would make it clear that the optimization problem for worker / consumers is intractable, so rules of thumb and gradual adaptation to evolving targets will characterize behavior. (Optimization is intractable for firms as well.)

government tax/transfer

Simple income, payroll, profits, value added and retail sales taxes, and demogrant, negative income tax, and unemployment insurance style transfers to worker/consumers, are readily included given the microanalytic foundations for XEcon.

finance

The financial sector is highly simplified and represented by a single monolithic "finance" agent whose deposit-taking and lending (investing, venture capital) policies are parameters of the XEcon model.

Finance has two main groups of actions -- the informational action of setting credit limits and interest rates for firms based on firms' financial performance (or business plans in the case of new entrants); and a set of cash flow actions related to lending money to firms, and taking deposits from firms and worker/consumers.

information

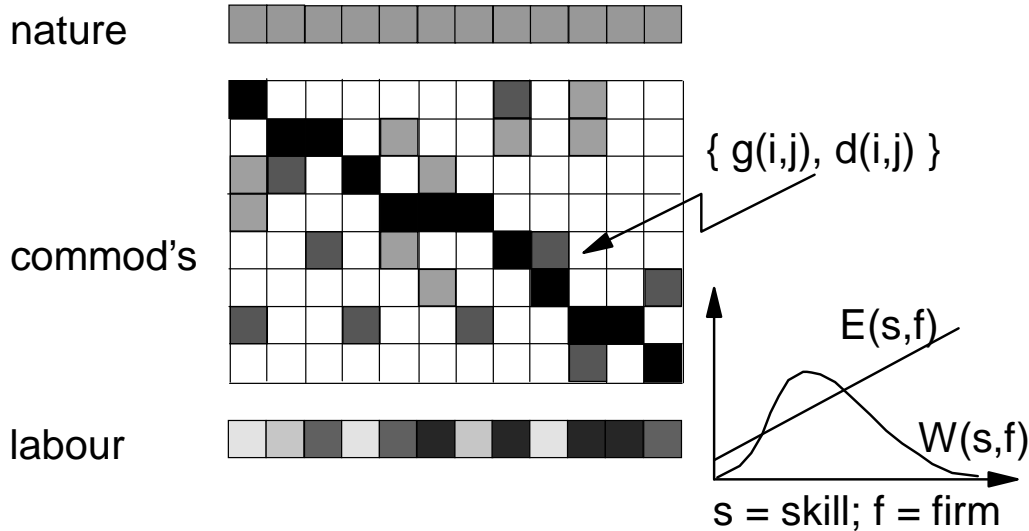
The information sector can be thought of as an amalgam of a national statistical agency and market research firms. For now, it simply produces a set of statistics like price and average wage indices that are instantly and costlessly available to all the agents in XEcon. (See Antonov and Trofimov, 1993, for an interesting analogous analysis using Eliasson's MOSES model.)

Visual Metaphors for Technology and Technical Change

Modeling processes of technical change, including evolving skills amongst workers, is a fundamental objective of XEcon. A central feature of technical change is increasing complexity of the economy, reflected in the growing variety and diversity of commodities and technologies. Thinking in terms of an input/output table, there are growing numbers of distinct inputs and outputs, and thus (at least conceptually) an increasing number of rows and columns over time, and more non-zero cells in the matrix. Labor is also becoming more heterogeneous in many respects -- skill, occupation, education, and tacit firm-specific knowledge.

Figure 3 draws on the concept of an input/output table use matrix as a visual metaphor for representing the technologies formalized in XEcon. Each row indicates a distinct input, and each column represents the output of one firm-line. An empty cell corresponds to zero input requirements; a black cell indicates that the row commodity is the output of the given column vector; otherwise the intensity of shading roughly indicates the physical volume of the given commodity input required per physical unit of output. The diagram shows that there can be many heterogeneous commodities; and that more than one technique for producing each commodity is possible. Recall that each column in the diagram actually has two underlying vectors to describe the technology fully, $\{g(i,j), d(i,j)\}$.

Figure 3 -- A "Use" Matrix Visual Metaphor for Commodities and Technology in XEcon



Basic labor requirements are shown as homogeneous (but not of equal intensity) in Figure 3, by virtue of there being only one row. However, these labor inputs could be re-interpreted as efficiency unit input requirements per physical unit of output. In turn, each technique of production or firm-line (i.e. column in the matrix) could have a unique capacity for transforming labor of varying skill levels (s) into efficiency units (according, say, to a simple linear firm-specific function $E(s,f)$, where $W(s,f)$ is the distribution of workers in firm f by skill level s) -- i.e. firm-lines could vary in their abilities to utilize skilled labor. Such variation is essential to exploration of the inter-relationship between technical change and changing patterns of wage inequality from a microanalytic perspective -- another objective of XEcon.

(The "nature" row is a reminder that at some point, use of natural resources should be explicitly considered.)

It may be noted that non-rival goods (Romer, 1990) are easily represented in this visual metaphor, and in the description of technology given above. These are goods which have very low variable inputs; the major cost was in developing the "recipe" (i.e. R&D) or making first copy or making a key ingredient. An example is the original bit string for the DOS 6.0 operating system, which was very costly, versus the shrink-wrapped package on sale at local software retailers. These latter packages are virtually costless in comparison to the original development costs of the software. The production of a commodity like this could be represented in the technology formalism of XEcon by two firm-lines, or two (pairs of) column vectors belonging to the same firm -- one for producing the original "design" which would have very large inputs per (physical) unit of output (an operating system), and one for producing the shrink-wrapped

packages with very small inputs per unit of output, except for the original "design" (the DOS 6.0 bit string) which would have to be around, but would not physically get used up in production.

Non-rival -- though excludable via copyright and legal vigilance, hence private -- commodities such as this are widespread, and can be seen increasingly to be at the heart of much that is considered technical progress. At the same time, they exemplify indivisibilities and hence non-convexities in production possibilities. These in turn cause serious problems for neo-classical theory. The point for now is that such non-convexities and consequential increasing returns to scale are not at all problematic for an evolutionary microsimulation model like XEcon.

The technology representation in XEcon, and the visual metaphor in Figure 3, can also capture other related aspects of technical change. For example, in Rosenberg's (1976) history of the machine tool industry, the story is told that at the beginning of the 19th century, "there was no separately identifiable machine-tool or machinery-producing sector in the American economy. Although machines of varying degrees of complexity were, of course, being used, the production of the machines had not yet become the specialized function of individual firms. ... machinery-producing establishments made their first appearance as adjuncts to factories specializing in the production of a final product. ... (Then, over time) these establishments undertook to produce machines for diverse other industries ... and finally, with the continued growth in demand for an increasing array of specialized machines, machine tool production emerged as a separate industry." (pp 13-15)

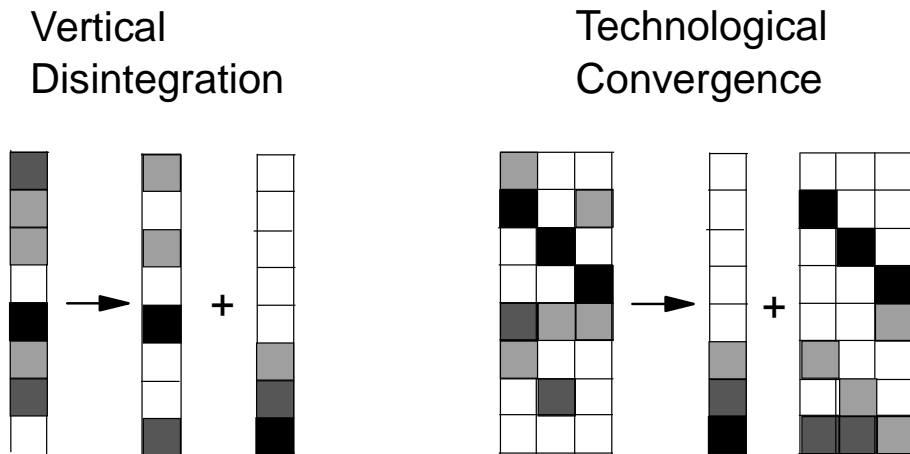
For example, the manufacture of sewing machines needed turned metal inputs. To produce these, manufacturers set aside a back portion of the shop floor to produce lathes for use in the front part of the shop. However, as the general utility of the lathe came to be more widely appreciated, this previously internal and subordinate step in sewing machine manufacture was separated and became a new independent production process in its own right. Rosenberg (following Stigler (1951)) refers to this as "vertical disintegration". Subsequently, many other manufacturers -- e.g. guns and bicycles -- began buying lathes from specialized lathe manufacturers rather than doing without, or making them themselves. This second process was called "technological convergence" by Rosenberg.

This pair of processes -- vertical disintegration and technological convergence -- appear to be general features of technical progress. The basic idea was noted by Adam Smith (1970) in his chapter "That the Division of Labour is Limited by the Extent of the Market". It was emphasized and elaborated by Young (1928) to point out the connection with the increasing returns to scale that are fundamental to economic growth. (Note that these are dynamic economy-wide increasing returns which do not depend at all on increasing returns at the level of individual firms.) Young also connected Smith's insight and increasing returns with the notion of "roundaboutness" in production -- the increasing numbers of inputs and outputs in the economy just mentioned, and the increasingly roundabout paths by which commodities were used to produce final output.

Figure 4 extends the visual metaphor in Figure 3 to show how these fundamental ideas and processes can be readily included in XEcon, once radical innovation -- the creation of entirely new commodities -- is allowed. The first column can be thought of as a sewing-machine manufacturing process, and the bottom row is the commodity "lathes". Since the lathe is initially

an intermediate step in the production of sewing machines, it is "invisible" outside the firm (and to the national accountant constructing this column of the input/output table). However, once this commodity is "invented" and becomes the output of a distinct industry (the third column), it can be combined with the other sewing machine inputs in a new and presumably more efficient manner (the second column). Greater efficiency in this visual metaphor is indicated by more lightly shaded inputs in the pair of column vectors where lathes are explicit. Moreover, in line with Young's analysis, the second method by virtue of involving two industries rather than one illustrates the idea of increasing roundaboutness.

Figure 4 -- Two Processes of Innovation



Correspondingly, the right hand process in Figure 4 illustrates Rosenberg's idea of technological convergence. The first three columns here can be thought of as bicycle, gun and sewing machine manufacturing before the development of an independent lathe-making industry. However, with readily available high quality lathes, they too innovate and develop more efficient techniques of production which now use purchased lathes as inputs, represented by the three rightmost columns.

Running an XEcon Simulation

XEcon, given a population of firms with these kinds of technologies as well as a population of workers, has the potential to become quite complex. Thus, it is important that other researchers, not just the authors, should find the simulation model easy to run and use for experiments. One requirement is that the software should be modular; a second is that each module or component should itself be relatively simple and transparent; and a third is that the

model should be open -- a "glass box" rather than a black box. This combination of characteristics, where overall complexity results mainly from the interactions amongst a large number of modules, each of which is relatively simple and easily understood, seems to have led to the widespread acceptance of simulation models in other fields like cosmology.

Another consideration for wider use is the user interface. This section sets out ideas for the user interface, and an image of what it should be like to run / play with XEcon. The computer games of Maxis Software like SimCity and SimLife provide relevant images.

The first step in running XEcon is setting parameters. To make this convenient, it would be best if all the parameters were grouped (e.g. technology, tax/transfer, firm-line price formation, credit limits, ...). Then for each parameter group, one or more already constructed default scenarios would be available. The user could then mix and match various existing parameter scenarios, or choose to over-ride one or more of these defaults and create a custom scenario. The management of this process of selecting scenarios and making selected modifications could be similar to Statistics Canada's just developed CEPHID user interface (1993); indeed much of that software will likely be reused for this purpose.

The real power and interest of XEcon comes in the ability to view simulation results -- in Lane's (1993) sense, the properties of the artificial world -- as they unfold. It is therefore very important to have a variety of easy-to-use intuitive graphical displays. The image is a researcher sitting at a PC with a Windows or equivalent operating system. Then, while XEcon is executing, the user can "click" between a variety of views of the dynamic economy as it is evolving, as in SimCity and SimLife. (If the computer is fast enough, the user would instead explore the artificial world as an economic historian, albeit one who could assure that any data desired could be found in the archives.) The views of the economy could include the following graphs:

labor input by sector -- numbers of employed workers by production sector, and unemployed over time

factor incomes -- profits of the bottom 50% of firms, top 50% of firms, wages of bottom 50% of worker/consumers, wages of top 50% (totals 100% of factor income) all over time (Note that the difference between the bottom and top 50% is a quick indicator of skewness hence inequality of the underlying distributions.)

firm size distribution -- a 2-d scatter plot of firms' total sales against number of employees at a given point in time, and a histogram plot of value added per worker by firms sorted by this variable, with the width of each bar proportional to the firm's total employment (Eliasson refers to this as a "Salter Curve" after Salter, 1969) -- where both plots will evolve through time

firm micro-dynamics and volatility -- 3-d scatter plot of (1) each firm's average market share (i.e. sales as a percent of total sales), (2) trend in market share (represented by a slope coefficient from a simple linear regression), and (3) coefficient of variation of market share around trend -- all defined over an arbitrary time interval t_1 to t_2 (Note that viewing such a scatter plot requires some sort of point cloud rotation or scatter plot matrix as found, for example, in the S statistical graphics language, Becker et al, 1988.)

alternative views of productivity -- ingredients in typical aggregate total factor productivity calculations: wage and profit shares, index of labor inputs, index of capital inputs, and the "Solow" residual, all against time; and the difference between actual GDP and "microanalytic" potential GDP based on a linear programming style convex hull of the population of firms' actual techniques, capital, labor and inventories on hand, all over time

financial sector -- total loans out, total deposits, interest payments and receipts, interest rates, debt-to-equity ratios by size group of firm, all over time

basic SNA statistics -- components of the basic national income identity $Y = C + I + G$; also inventory versus capital investment, gross and net, all over time

aggregate welfare measures -- GDP per capita, average wages, average disposable income, average "utility" (given explicit underlying utility functions posited for worker/consumers), all over time

distributional patterns -- quintile shares, polarization shares for wages, incomes, and utility, all against time as well as Gini, and other summary inequality and polarization measures (Wolfson, 1994) over time

Program of Experiments

Given a working version of XEcon, including the kinds of graphical "views" just described, the research program with a theoretical microsimulation model consists of a series of simulation experiments. These experiments should start very simply -- to assure that the model is functioning as intended -- and will likely be drawn from the following:

reproducing equilibrium -- As a first set of "debugging" experiments, note that XEcon's input/output technology can be specified such that there is an "equilibrium" steady-state path for the economy (with a zero growth rate). One test of the model would be to give it a set of initial conditions at this equilibrium, and check that it endures.

disequilibrium dynamics -- Once an equilibrium path is demonstrated, it would then be interesting to explore what happens to the economy when it is started at various points away from equilibrium. Our conjecture (based on discussion with Eliasson) is that in the absence of any intervention, the economy could spend long periods far away from equilibrium. In other words, there is no reason to believe that XEcon (or a real economy like Russia) has any tendencies to approach an equilibrium quickly or asymptotically when it is started with a highly distorted price vector .

conventional statistics versus "unobservables" -- Conventional statistics like GDP and disposable income per capita are readily computed for this artificial economy. So is an input/output table, and several measures of total factor productivity. At the same time, "unobservable" items like potential output and aggregate utility can also be computed, as indicated in the proposed graphical outputs above. An obvious conjecture is that observable

measured growth need not correspond well with growth in otherwise unobservable indicators of social welfare.

robustness and path dependence -- One question about an evolutionary path for an economy is its robustness. This can be assessed directly with XEcon by running several simulations with exactly identical inputs, save for the starting point (seed) for the (pseudo) random number generator. A robust economy would then be one with small variance over such replicates. Non-robustness, or a high degree of path dependence, would correspond to high variance over replicates.

role of adaptive expectations -- The stability properties of XEcon probably depend critically on the rules of thumb used by firms and worker/consumers to adjust to faulty expectations, whether pessimistic or optimistic. This can be explored by trying various adjustment rules, for example the rates at which wages, prices, and production are adjusted to evolving circumstances. One conjecture is that slower adjustments will give more short term volatility, but greater long term stability.

role of finance -- The finance sector sets interest rates and credit limits. One obvious question is the role of interest rates in economic growth. Recent macro policy in Canada suggests that high interest rates have had serious depressing effects, while Romer's (1990) model suggests the contrary.

alternative market forms -- The microanalytic foundations of XEcon offer the possibility of exploring decidedly non-neoclassical but more realistic kinds of market structures, for example abandoning the pervasive "law of one price" (Smith and Williams, 1992), and assuming that firms follow "posted offer pricing" with transactions continually occurring at a variety of posted prices. One question is how much difference these markets make, in comparison, say, to the conventional textbook Walrasian markets.

Keynesian automatic stabilizers -- One conjecture is that XEcon, without redistributive government taxes and transfers, is more likely to enter a vicious spiral of rising unemployment and falling GDP per capita -- a conjecture that can easily be explored with a series of simulations.

patterns of income inequality -- Income inequality in XEcon derives in part from heterogeneity in the wages paid by firms. One question is the feedback from macro level policies like demand stabilization to income inequality. Another question is whether tough credit limits which drive weak firms out quickly will have a beneficial impact on inequality.

firm dynamics -- Dosi et al (1993) suggest, and Canadian longitudinal microdata support the view, that firm dynamics are characterized by the following "stylized facts": (1) The overall size distribution of firms is positively skewed and has a relatively stable shape (e.g. Pareto or lognormal). (2) Nevertheless, within the population of firms there is a high and persistent degree of turbulence. (3) Part of this turbulence is high rates of new entry and death. (4) The turbulence, however, is not entirely random as in Brownian motion; many firms have persistently above- or below-average performance (i.e. their annual growth rates are autocorrelated). (5) Even though the overall size distribution has a stable and characteristic shape, this shape is not

reproduced within sectoral sub-populations (e.g. energy versus retailing). Formal mathematical models have been constructed which can generate one or other of these properties, but not all together. Dosi et al's (1993) simulation model does. XEcon should similarly be able to account simultaneously for these patterns.

role of new firm entrants -- Dosi et al (1993) also explore the importance of entry to economic growth. In particular, they experiment with the extent to which new technology is introduced only by new entrants rather than incumbents. Similar experiments would be possible with XEcon. Another set of experiments could relate the financing of new entrants to their birth and success rates. Jointly, these two sets of experiments might give some insight of the relative importance of venture financing to the overall pace of technical progress.

tax incidence in an evolutionary world -- The incidence of the corporate profits tax is a continuing subject of debate, depending for example on alternative assumptions regarding capital mobility. However, this debate is still largely framed within a static neo-classical framework. It is likely that in XEcon, imposition of such a tax will have widespread, complex and subtle effects that will vary with initial conditions and behavioral assumptions. Experiments to explore these impacts should have a salutary impact on the arguably simplistic analyses that dominate this literature.

Concluding Comment

As stated at the outset, XEcon is a work in progress. This paper has provided a sketch of the structure of the model, and illustrative simulation experiments.. Work is currently focused on developing an appropriate software environment along the lines sketched in Gribble and Wolfson (1992). The actual writing of code to implement XEcon is awaiting this new software environment.

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