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HISTORICAL ROOTS FOR ECOLOGICAL ECONOMICS — BIOPHYSICAL VERSUS ALLOCATIVE APPROACHES

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ABSTRACT

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A number of economists today are aware that the results of their science are more or less at variance with concrete fact and are alive to the necessity of perfecting it. They go wrong, rather, in their choice of means to that end. They try obstinately to get from their science alone the materials they know are needed for a closer approximation to fact, whereas they should resort to other sciences and go into them thoroughly—not just incidentally—for their bearing on the given economic problem. Until economic science is much farther advanced, "economic principles" are less important to the economists than the reciprocal bearings of the results of economics and the results of the other social sciences. Many economists are paying no attention to such interrelations, for mastery of them is a long and fatiguing task requiring an extensive knowledge of facts; whereas anyone with a little imagination, a pen, and a few reams of paper can relieve himself of a chat on "principles" (Pareto, 1935, para. 2022).

INTRODUCTION

Economics has become even more of an axiomatic and deductive science since Pareto's time (with economists asserting that the core theory can be deduced entirely from the principles of rational choice). Criticism of economics as an "armchair science" divorced from any "systematic understanding of a real economic system" has also increased (Leontief, 1982; Simon, 1986). Exploration of the "results of other social sciences" has not been absent, especially by institutional economists and students of economic psychology, but this work has not been enough by itself to constitute an alternative theory of economic activity. What has been missing in all of the various critiques is a reconstruction of the biophysical foundations of economic activity. It is not just the other social sciences which matter for

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economics but the facts and theories of physics, chemistry, biology, and ecology. Modern economic theories have neglected the implications of the basic physical principles governing material and energy use for an economic theory of production, for the operation of a production-based price system, for macro-economic (disequilibrium) dynamics, and for longer run growth processes and prospects.

Why has there been this neglect of basic bio-physical principles? According to Georgescu-Roegen, the mechanistic sins of modern economics (Marxian and neoclassical) can be traced to the Ricardian concept of land "which is expressly defined as a factor immune to any qualitative change (which) we could refer to simply as space" (1971, p. 2). But closer examination of the treatment of natural resources and the physical assumptions of production theory reveal an early attention to the physical side of economic activity in pre-classical, physiocratic, and early nineteenth century classical economics which is absent in modern theories.

Starting from an analogy between the nutrition of living bodies and the provisioning of the economy, early economic writers regarded production in terms of the transformation of materials and food taken from the land. Food and raw materials were *basic* commodities in the Sraffa (1960) sense of inputs entering into the production of all other goods directly or indirectly. Food and materials were used to produce machines and human labor which were employed in turn to extract more materials and food. This materials-processing, proto-energetic approach to production included application of the principle of mass conservation to manufacturing production. It also included an attempt by late classical writers to incorporate energy converters and sources of motive power into production theory.

Parodoxically, the formulation of the laws of thermodynamics in the 1840s and 1850s was not used to extend the classical production approach to include energy and energetic principles or to make a general application of the mass conservation principle. This was certainly due to the fact that the materials/energy foundation underlying classical production (and price) theory was both incomplete and only imperfectly understood. An additional difficulty was that the energy laws were stated exclusively in terms of energy conversion and dissipation in an isolated system. A unified physical understanding of the relation between matter and energy transformations in open systems could have come from physiology (or later from ecology) but economics from the 1860s was increasingly coming under the sway of analytical mechanics.

The adoption of the maximization model from analytical mechanics led to a shift from production dynamics to an analysis of exchange value. The result was a static optimization theory concerned primarily with efficiency and equilibrium which took its inputs (land, labor, and capital) and the tastes, drives, and preferences of consumers as given. Production was treated as an aspect of the allocation and pricing of the "primary" factors of production. Material and energy resources disappeared from theoretical view. If they were considered, it was assumed they could be treated like the other factors of production (i.e., land). Indeed, no essential physical distinction was made between any input. The result was that physical and technical assumptions (marginal productivity) were made about economic activity which were in conflict with the basic physical principles governing material and energy transformations (Georgescu-Roegen, 1971; Ayres, 1978, ch. 3).

Production is a set of sequential activities which feed on low entropy energy and materials. Physical and biological principles suggest the existence of a strong interdependence between material, energy and information flows and the machines and agents which extract, transform, and utilize these flows. Orthodox production theory with its assumption of the separable productivity of independently given primary factors is obviously ill-suited to such interdependence. This suggests the need for an alternative and more systems-based theory of production (and prices).

This paper argues that some of the tools for a reconstruction of a more ecologically based economics may be found in the older classical tradition. What follows is a consideration of (1) the development and physical assumptions of the classical model of production, (2) the neglect of material and energy resources and production interdependence in early neoclassical theory, (3) the relation of neoclassical price theory to the production model, (4) some theoretical implications of a synthesis of a biophysical model of material and energy flows with the classical production approach, (5) implications of a physically specified approach for macro economic dynamics, and (6) an extension of the classical model of production prices to include reproduction of environmental resources.

THE CLASSICAL PRODUCTION APPROACH

The classical model had its origins in a physiological analogy. Thomas Hobbes (1651) used a Harveian model of the circulation of "nutriments" by the blood as an analogy for the materials foundation of the commonwealth. Materials and foodstuffs extracted from the land and sea were carried via monetary exchanges through various channels of transformation and trade prior to use. Although this original physiological source was soon forgotten, the classical model developed by William Petty, Richard Cantillon (1755), the French Physiocrats, Adam Smith (1776), and their 19th century classical successors continued to embody this materials-based approach to production and prices.

The starting point of the classical approach was a theory of production. Production was a set of sequential activities: the extraction of materials and food preceeded the processing and fabrication of materials. This shaped a sectoral characterization of production inputs: labor, tools or machines, and food (the energy source for labor) were required in each sector. Fertile land or resource-bearing sites were specific to agriculture and mining. Raw materials were the basic input in manufacturing. The capital stock, following Smith (1776, book II, ch. 1) was divided into two broad categories: fixed capital (machines and structures) and the circulating capital (food, fodder, raw materials, working finance, etc.). Physical complementarity existed between fixed and circulating capital. There was no production without appropriate tools, materials, food and fodder.

A crucial distinction was made between land and industrial machinery. The Physiocrats, for example, regarded the land as *productive* because it yielded a *surplus* of output above the material input advanced at the beginning of production: one livre of seed planted yielded five livres of output. Artisan activities, by contrast, were *transformations* of raw materials. Industry buys raw materials from agriculture in order to work them up. Manufacturing gives raw materials a form, but it adds nothing to them materially.

A similar distinction was made by the classical writers. Malthus (1815, 1836) argues that only "the machinery of the land" could produce food and raw materials. This was something no industrial machine could do. The latter only transformed materials from one form to another (when supplied with the appropriate agencies to affect work). Ricardo (1817) similarly writes of the "original and indestructible powers of the soil". This is obviously something more than the mere space which Georgescu-Roegen (1971, p. 2) attributes to him. In an age before a distinction between energy and force had been made, powers referred to those agencies which had the capacity to transform matter (Locke, for example, writes of the power of the sun to melt wax and fire to make lead liquid). Powers were the capacity to bring about change.

Because fertile land was limited in supply, the classicals believed that agricultural output would be subject to diminishing returns. More labor and capital applied to a given plot of land or to a less fertile plot yielded a proportionately smaller return. Industrial machines, although they lacked independent productivity, could be replicated. Thus, given the availability of appropriate raw materials and energy sources, manufacturing output could be extended indefinitely. Manufacturing consequently was characterized by constant or increasing returns. In the absence of an appropriate increase in materials, more labor and capital would not supply more output. This was effectively a "law of zero returns". Manufacturing was subject to the conservation of matter. Double the labor and capital employed on the manufacture of cotton without increasing the quantity of raw materials and "the quantity of manufactured produce could not be sensibly increased" (Senior, 1836, p. 82).

While the classicals correctly recognized the inability of industrial machines to produce without appropriate materials and sources of power, they failed to make the same distinctions about production from the "machinery" of the land (from an engineering point of view, physical structures are passive machines). Of 18th and 19th century writers only the Italian, Pietro Verri, in his critique of the physiocrats, makes it clear that land does not "produce" or create its products any more than industrial machines.

> All the phenomena of the universe, whether they are produced by the hand of man or by the universal laws of physics, are not to be conceived of as an actual *creation* but only as a modification of existing materials.... This is equally the case...whether the earth, air, and water of the fields are transmutted into grain or when by the hand of man the secretions of an insect are transmutted into silk or some metal parts are organized into a repeating watch (Verri, 1773, pp. 21-22).

A specification of the material and energy flows through the land provides a physical basis for the empirically based "law of diminishing returns". Application of successive does of labor and capital to a given plot of land or to new fields of lower fertility can yield positive if diminishing returns because of the availability of extra material and energy resources available in the field: unutilized solar flow, CO_2 in the atmosphere, ground water, available nutrients in the soil, etc. Farming a plot more intensively draws more of these inputs into the production flow. The conservation of mass (as Verri recognized) applies to agricultural production in the same way it applies to manufacturing. For any given technique, there is no increase in output without an increase in material (and energy) input. Marginal products exist in agriculture because of the presence of slack or unutilized resources.

Under the influence of British technical writers such as Smeaton, Babbage and Ure, the post-Ricardian classical economists began to elucidate the importance of power in the new industrial technologies which had established Britain's industrial dominance. In reviews of Babbage and Ure, McCulloch attributed the industrial prosperity of the British nation to its exploitation of coal and coal-using technologies which overcame limited supplies of wood (McCulloch, 1835). The invention of steam engines permitted the draining of coal mines, thus removing a central bottleneck to energy production. Low cost coal was gradually substituted in technological innovations as a fuel in metallurgy and other industrial processes. The low cost production of metals in large quantities lowered the costs of producing machines (including steam engines) and other industrial structures. Low cost fuels permitted low cost and large volume manufacturing, enlarging domestic and international markets.

McCulloch confined himself to emphasizing the commercial importance of coal. The most sustained attempt to incorporate the new prime movers and inanimate sources of power into a theory of physical production was made by his contemporary, Senior (1836). Senior's starting point is a physical classification of production agents. These are labor and skills, natural agents, and abstinence (the source of capital). Capital is divided into fixed and circulating components in order to distinguish tools and instruments of production from the materials which will be embodied in product. Energy resources (food and coal for the laborers and machines) are included with the fixed capital since these are not embodied in output (Senior, 1836, p. 64). Implements, following Babbage and Ure, are further divided into two classes, those which produce power (steam engines, water wheels, etc.) and those which transmit and apply power.

Unfortunately Senior's successors, including Mill (1848), fail to sustain Senior's achievements in establishing a physical taxonomy of production inputs or his explicit linking of production returns in manufacturing to material use via the law of mass conservation. Mill, like Senior, classifies production inputs under three headings: labor, natural agents and capital. Nature provides materials transformed by labor and the (motive) powers which cooperate with and substitute for labor. But instead of maintaining the distinction between materials and motive powers, he subsumes the latter —the coals that drive the steam engine and the food that feeds the worker—under materials in order "to avoid a multiplication of classes (of) no scientific importance". When Senior objected to his inclusion of fuel with materials in an unsigned review (Senior, 1848) on the grounds that only the latter are embodied in materials, Mill replies that although his terminology is not in accord with the physical meaning of the word material such a distinction between materials and fuels is of "almost no importance to political economy" (Mill, 1871, pp. 34–35)! Mill's decision to forego any concern with the development of a scientific terminology appropriate to physical processes obscured the thrust of the materials-energy approach (and it may have influenced Marshall (1920) who explicitly chooses commercial rather than scientific terminology in his discussion of capital).

NEOCLASSICAL PRODUCTION THEORY

Neoclassical economics is distinguished from classical theory by the wholesale shift from a production and growth approach to a static analysis of an exchange economy. Individuals possess initial endowments of various resources (including their own labor) which they trade in markets to maximize their utility. Judgements about the economic value of various goods and services are determined by the subjective tastes and preferences of the individual decision makers (relative to the scarcity of the resources in question). The formation of these tastes, like the endowments of resources, is not examined. Preferences and endowments are simply given.

A full neoclassical theory of production was not formulated until the mid-1890s (by Wicksteed and Wicksell), two decades after the marginal utility approach to prices was established. Even then it was developed not as a theory of production per se but as a theory of the distribution of net output between the contributing factors of production. Each factor, it was assumed, makes a positive, if diminishing contribution to output (the utilization of all other factors is held constant). Conceptually this may be viewed as an attempt to generalize the Ricardian theory of differential rent (based on the differential productivity of land) to labor and capital. Capital is treated analogous to land. But agriculture provides a misleading analogy. Although land acreage was held constant as labor was increased, there was an "invisible" increase in the flows of materials and energy through the land into biomass. In manufacturing, plant and equipment could be held constant as labor was increased but an accounting had to be made of the additional materials and energy—the circulating capital—required to produce another increment of output. Marginal productivity theory presumes the independent productivity of *individual* inputs. This entirely ignores complementarity between inputs within techniques and suppresses materials and energy. If the classical's error was a failure to specify the material and energy resources flowing through the land, the neoclassicals extend this error to manufacturing and the capital stock.

The distorting influence of the marginalist program on the formulation of neoclassical production theory is evident from the beginning. Heterogeneity and complementarity are eliminated and replaced with some version of homogeneity and separability.

In his chapter on "the theory of capital", Jevons (1871) eliminates the distinction between fixed and circulating capital. Fixed capital he says can be considered as a long-lived version of the latter. He then reduces circulating capital to "nothing but" the subsistence of the workers: what they need for food and shelter to engage in long-lived projects (p. 226). Despite his earlier insistence on the importance of coal as the industrial source of power driving British economic growth (Jevons, 1864), he completely ignores machines, raw materials and industrial fuels in his discussion of capital. The marginalist program appears to have created a conceptual blindness in a scientist who well understood the physical significance of energy in production activity.

Early on in his great study, Menger (1871) presents a long discussion of the importance of raw materials and intermediate products in the production of goods of "higher" and "lower" orders (a classification based on distance from the consumer). He also clearly recognizes the existence of fixed proportions between inputs. But his imputation theory of prices requires a theory of substitution in order to assess the difference made by the presence or absence of an individual factor. He thus makes a universal assumption of variable proportions on the basis of the existence of variable proportions in agriculture. Chemical reactions, he says, may be characterized by fixed weights but in economics "the most ordinary experience" teaches that input quantities can be varied (p. 161). More land or more fertilizer can be employed to produce the same output. His mistake (the mistaken analogy with agriculture) is to confuse the possibility of substitution between various techniques of production (each with its individual material, energy, and machine requirements) with a general theory of "variable proportions" (the smooth substitution of one factor for another along an isoquant).

The fundamental step of arguing the independent contribution of individual inputs to output was first made by Walras (1874). Again agriculture is the source of the analogy: capital is put on the same conceptual footing as land. Just as "a field will grow us a crop year after year", he writes, "so machines, instruments, tools... engender incomes in the same way" (p. 213). Items of fixed capital are assumed to yield flows of "producer services" (producer goods) and "income" (consumer) goods. But how does a machine produce physical flows of output independent of material feedstocks and the energy required to do work?

Walras suppresses this question by vertically aggregating manufacturing and agricultural production. There are, he says, two kinds of production. The first kind (agriculture) is a combination of "nothing but" land, labor and capital services:

$$Ta,\ La,\ Ka \rightarrow RM$$

The second case (manufacturing) applies the services of land, labor, and capital to raw materials (p. 237):

$$RM + Tm,\ Lm,\ Km \rightarrow C$$

The second, however, is reduced to the "case of the direct combination of productive services alone" (p. 240):

$$T',\ L',\ K' \rightarrow C$$

where $T' = Ta + Tm$, $L' = La + Lm$, and $K' = Ka + Km$. Final output is produced directly from *primary* factors of production in one step by using larger amounts of the primary factors (the sum of those that would have been applied sequentially). The result of this reduced form equation was the elimination of raw materials and time from the representation of production.

The same neglect of raw materials is found in Marshall (1920) despite his professed sympathy with the classical model and his attempt to preserve the classical distinction between diminishing returns in agriculture and increasing returns in manufacturing. Marshall is well aware of the application of the conservation of matter in production. In his introductory remarks he writes that production "cannot create material things" but only change their form (1920, p. 63). This is repeated when he takes up agricultural production (p. 144). Agricultural crops are linked to the presence of chemical elements in the air, water, and soil (p. 146). But such discussion is entirely absent from his treatment of manufacturing. Nor is the idea of the conservation of materials mentioned here. Indeed, his discussion of this sector (conducted under the heading of capital as an agent of production) lacks any treatment of the physical side of production or even enumeration of the physical inputs of production. Manufacturing is treated solely in organizational terms.

Marshall's hesitancy in speaking about marginal products (and the strategic silence he maintains on raw materials in manufacturing) may stem from an awareness of the significance of materials in production and recognition of their incompatibility with marginalist equilibrium theory. That Marshall knows that marginal products do not exist independently of material flows is apparent in his definition of net product as the additional product obtained by the incremental application of a factor "after allowing for incidental expenses" (p. 432). But materials and fuel are hardly incidental to physical productivity. He affirms the importance of material flows to economic growth in his concluding chapter on production where he states that England's ability to secure the economies of specialized skills and machinery will depend on the future availability of food and other materials on easy terms (pp. 320–322); but these comments are not reflected in a theory of the production process.

The early neoclassicals probably would have disavowed any simple version of the marginal productivity hypothesis, but their neglect of raw materials, energy carriers, and complementarity in production sets the stage for such formulations in the 1890s. This occurred not in the context of a theory of production but as a theory of the distribution of output between the factors of production. "Each factor", Wicksteed (1894) writes, "receives a share of the product regulated by its marginal efficiency as a producer". The "(marginal) significance of each factor", he adds, "is determined by the effect upon the product of a small increment of that factor, all the others remaining constant" (Wicksteed, 1894, pp. 8–9). This, of course, simply assumes that an increase in any input, other inputs being constant, yields a positive increment of product (first partials are taken to be positive). This assumption of the existence of variable proportions in the short run is then extended to provide a general theory of substitutability between inputs. These ideas are advanced without any discussion of relevant physical features of production activity.

NEOCLASSICAL PRICE THEORY

Having reduced all production to a standard model of production from primary "factors", a uniform model of prices for all markets could then be logically justified. Each market exhibits the same opposing forces of downward-sloping demand and upward-sloping supply curves with supply and demand operating entirely independent of each other. The assumption of upward-sloping supply was due to scarcity and diminishing returns. The downward slope of demand curves reflected diminishing marginal utility. It was also assumed that prices were flexible upwards and downwards, thereby establishing equilibrium between supply and demand in each market. Overall equilibrium in the economy as a whole was assured by price flexibility (to eliminate "false" trading at non-equilibrium prices an auctioneer was invoked which established equilibrium in all markets before any exchange took place). Futures markets were similarly assumed to extend this one-period multimarket model to provide equilibrium prices for all future periods.

The basic leitmotif of the exchange model is that market prices of each commodity are derived from the subjective preferences of individual consumers. This is an expression of the methodological individualism of the analytical approach. All explanations relate back to transactions between individual economic agents. Social wholes are built up from the actions of individual agents without feedback from the system or its subsystems to the individual. The essential premise is the given human preferences. There is a remarkable absence of any investigation of how a price system actually works or how preferences are actually formed.

Modern neo-Walrasian theory replaces arguments based on partial derivatives with a programming approach which assumes only that production sets are closed and convex. The starting point of analysis remains the same: the maximizing behavior of individual producers and consumers. Each individual consumer comes into the world with (1) a given initial endowment of resources (including know how and the capacity to labor), and (2) given tastes and preferences which guide consumption decisions. But this a priori conception of resource endowments presents a one-way logic running from given resources (and relative scarcities) to factor prices and from resource prices to factor proportions. It entirely suppresses the dynamic running from technology to resources. We simply do not know the size of existing resource pools and flows, rates of depletion, future discoveries, or the future technologies which will redefine available resources. The purpose of this theory is to demonstrate the existence and stability of an equilibrium set of prices given an initial allocation. It is not an analysis of resource use through time.

It is sometimes held that the transition to the convexity approach eliminates the need for marginal productivity assumptions. "Marginal concepts" Bliss (1975) writes, "are not primary but follow from the basic postulates of maximization". He then asserts that since equilibrium analysis is in no way dependent upon marginal concepts, it "can suffer no crisis on their account". But this ignores the link between maximization and marginalism and the fact that the neoclassical theory of price determination depends on marginal concepts. Bliss quotes, but does not resolve the dilemma posed by Schumpeter:

> ... mere recognition of the element of productivity does not help us much unless it is streamlined by the notion of marginal productivity, exactly as the element of utility will not produce any servicable theory of price unless streamlined by the notion of marginal utility (Schumpeter, 1954, p. 677).

Marginal utility and productivity cannot be dispensed with because they underly the adjustment mechanisms of the theory. Incremental adjustments to incremental changes maintain the story of equilibrated optimal outcomes. Maximization and incremental adjustment together obviate the investigation of physical and informational processes moving in historical time.

According to neoclassical theory, economic values not only are but should be derived from individual preferences. Since there is no way of discerning the preferences of unborn generations, this leaves us with the dictates of the market and the subjective judgements of the present generation as to the values which should be placed on resources and natural environments. While there is undeniably plenty of scope for trying to change those values, there is, from a theoretical standpoint, no way around the autonomy of the subjective judgments of admittedly present-minded individuals. There is nothing in the theory to suggest any intrinsic or internal requirements of environmental or social systems that should shape the process of resource valuation and use. The existence of market failure provides, of course, an argument for recourse to collective action but such action lies outside the bounds of the theory (and runs counter to its normative prescriptions).

A BIO-PHYSICAL APPROACH TO PRODUCTION

In the classical view production, not exchange, provides the starting point of economic theory. A bio-physical perspective extends the classical approach to include the low-entropy energy and materials extracted from environmental systems and eventually returned as waste. Production and exchange in economic systems becomes part of a larger totality of interdependent material, energy, and information exchanges.

Production inputs

From a physical point of view, the basic factors of production are material, energy, and information flows, and the physical and biological structures and agents which convert, transmit or apply materials, energy and information. As Kenneth Boulding (1986) points out, the inputs of traditional theory (land, labor, and capital) are each "hopelessly heterogeneous aggregates". Land is a heterogeneous aggregate of physical structures (storage and staging areas), materials (stocks and flows), and energetic potential. The capital stock is likewise a heterogeneous collection of structures, equipment, intermediate materials, fuels, etc. and requires a physical taxonomy to distinguish between fundamental physical classes. Labor in turn can be viewed as a self-directing (and programmable) cybernetic control mechanism and chemical energy converter. A suggestive physical classification of the inputs in a chemical processing plant has been recently made by Van Gool (1985).

A physical perspective also challenges the neoclassical conception of primary factors of production. In ecological terms, the primary net input is solar energy:

> Practically everything on the earth can be considered to be a direct or indirect product of past and present solar energy.... Fossil fuels and other natural resources represent millions of years of embodied sunlight. Environmental flows (such as winds, rain, and rivers) represent embodied sunlight of more recent origin (Costanza, 1980, p. 1219).

Since human economies import both materials and energy, the basic or primary inputs can be broadened to include anything not produced within the human system of production: the materials and energy and environmental services which have been produced by biological and geological activity past and present. What is regarded as a primary input is in part a question of the boundaries of the system in question. Also, just as natural resources, structures, and organisms can be regarded as embodied energy, they also represent embodied materials and embodied know-how (genetic and cultural). Indeed, from an economic perspective the latter may be the most important.

Input complementarity

A biophysical perspective also suggests a strong physical interdependence between the inputs employed within production techniques. Materials and energy and the equipment, structures, and agents that process these flows are used together. Machines and other capital equipment are designed with specific engineering characteristics appropriate to given fuels or to specific types of materials. Inputs are *complementary* within an activity. Production is not, therefore, a process that can usefully be described by the mechanistic method of "varying factors one at a time". Successive doses of one input, all others constant, is a methodological-mathematical construct that has little meaningful application to physical processes. Marginal products of individual capital goods simply do not exist.

Sectoral complementarity

Since inputs into one sector are produced by another sector, another aspect of complementarity and interdependence is the coevolution of economic techniques (technologies and organization) between activities and sectors of the economy. Coevolution is the reciprocal adaptive responses of two interacting species: the evolution of flower design and the hummingbird's beak, for example. Norgaard (1984) has applied the idea of coevolution between species to the coevolution of environment and society. The coevolutionary idea can also be directly applied to the evolution of techniques within the economy (an economic technique like a species is a "genetic" mechanism for the extraction and transformation of materials and energy).

Coevolution occurs when positive feedback initiates an ongoing reciprocal process of change between evolving systems or their components (see Norgaard, 1984; Levins and Lewontin, 1985). An example in economics is the emergence of a coal–iron–machine–engineering complex in the British industrial revolution. Another is the decision of Japanese strategic planners to build an industrial economy on the dynamic interdependence between steel, oil refining, petrochemicals, automobiles, industrial machinery and, more recently, electronics. The Taiwanese are considering building an automobile industry in order to develop the technological infrastructure and skills of a machine industry which would supply parts to autos. Marshall's (1920) concept of the internal synergies of an industrial district (economies external to individual firms) is relevant here.

Vertical disaggregation between extraction and manufacture

By presenting production as a one-step process of combining primary factors of production to obtain final products, neoclassical theory ignores both the time pattern of production and important differences in the conditions of resource extraction and resource processing. The extraction of energy and materials prior to processing, fabrication, and use imposes a temporal sequence on production. And differences in the quality, quantity, and timing of resource availability by geographic site impose constraints on primary sector production not present in manufacturing production where materials are purchased.

The high variability of resource availability by geographic site is a result of geological and biological production processes that have unevenly concentrated ores and soil nutrients. Bio-mass production is characterized not only by uneven nutrient availability but also by the condition of geographically dispersed and low intensity energy flow from the sun. Such production is geographically extensive compared to the highly concentrated energy of fossil fuels now employed in minerals extraction, processing and manufacture. High quality resource sites will have lower costs than low quality or low density sites. Extraction sector production, moreover, depletes existing reservoirs of materials which have to be replaced by ongoing climatological and biological cycles in the case of renewable resources, or by the discovery of new sites for exhaustible resources. The timing and extent of resource availability will have important implications not only for the structure of costs but also for price behavior and the dynamics of sector adjustment.

Processing and manufacturing technologies, as Malthus (1836) pointed out, are reproduced by the replication of existing techniques or by the discovery of newer, lower-cost techniques which can in turn be replicated (given necessary materials, energy, skills and so on). Additional production capacity will be obtained at constant or lower unit costs than previously installed capacity (for given input prices). Economies of scale in processing and manufacturing reinforce this cost structure (downward-sloping cost curves). In the presence of economies of scale and available resources, increases in demand lead to lower unit costs in production and set up a positive feedback loop between production and input costs.

Maximum power and efficiency

In energetically open systems, those species and economic technologies which get the most energy and use it the most effectively in competition with other systems will reproduce at a differentially higher rate (Lotka's Principle). Under conditions of limited (renewable) resources, equilibrium population levels may be established for non-evolutionary time scales. The shift from a largely renewable resource base to the exploitation of large stocks of coal and petroleum changes the possibilities for growth. Resources are used to produce machines which are used to extract more materials and energy, produce more machines, etc. This sets up a positive feedback (autocatalytic) loop. The new technology generates a larger surplus which is reinvested, the adoption of new technology is a function of the rate of investment, and the system grows at an exponential rate.

Obviously there are limits to such growth. Bacteria in a petrie dish can reproduce at an exponential rate as long as they have food and space. Most economists have dismissed concerns about resource scarcity by noting that resource prices have not risen faster than prices in general (and by assuming that should resource scarcity appear that technological change will create "new" resources). But this fundamentally misreads a historical record where growth and technological change have been based on the exploitation of large but not unlimited supplies of coal and oil. It is certainly possible that new virtually unlimited supplies of energy may be developed in the future. It is also not certain. In any case the major difficulty of the future may not be scarcity of resource "inputs" but the increasing problem presented by the inability of natural systems to absorb increasing levels of material and toxic wastes. The inconsistency of maximum power behavior with environmental limits indicates the need for control mechanisms to keep the economic subsystems in balance with environmental systems.

CLASSICAL/POST-KEYNESIAN PRODUCTION PRICES

The theoretical implications of a bio-physical approach to production extend beyond consideration of environment–economy interactions. They require a reformulation of the theory of interactions within the economy. This includes a sector-based model of prices and a short-run macro model of price and quantity dynamics which offers an explanation of the output, productivity, and inflationary effects of primary commodity price shocks unexplained by conventional theory.

A sectoral model of asymmetric price behavior was partially developed by classical theorists. Petty, Cantillon, the Physiocrats, and Smith formulated manufacturing prices in terms of the costs of raw materials and labor employed in production plus profit earned on the value of capital advanced. Longfield (1833) observed that manufactories used inventory and quantity adjustments to maintain equality between demand and supply. Prices were determined by costs of production. Agriculture and raw material prices were determined by demand and supply and were highly variable. Mill (1848) treated prices under two categories: demand and supply pricing when there is some constraint on supply; and cost of production prices when output can be increased without limit (but he does not make this distinction by sector and he reduces costs to direct and indirect labor).

Modern empirical work (Hall and Hitch, 1939; Wilson and Andrews, 1951; Wiles, 1963) has emphasised the ubiquity of a materials or prime-cost pricing model (also known as full-cost and mark-up pricing) in industrial sectors of the economy. Several Post-Keynesians, notably Kaldor (1979) and Sylos-Labini (1985) have combined a mark-up model for industrial sectors with a recognition that markets for agricultural products and industrial raw materials are sensitive to changes in short-run supply and demand (and to expectations). But the underlying physical conditions which shape this difference between "flex" and "fix" prices have not been considered.

The behavior of extraction sector and agricultural prices is shaped by the high variability in the quality and extent of resources by geographic site. When production cost conditions vary significantly by site, there is no firm cost-floor under prices (there would be, rather, a more steeply upward slanting floor). Under conditions of low demand, lowest cost producers may still be able to produce at a profit or even earn economic rents. But low prices dissuade new exploration and investment (setting the stage for a future escalation of prices as demand is restored). Increased demand and higher prices permit production from high-cost sites. Prices are sensitive to changes in demand and supply and exhibit significant instability. The instability of primary commodity prices has been widely noted (O.E.C.D., 1980).

Processing and manufacturing sectors with significant variable costs are characterized by cost-plus pricing behavior. Prices are set to cover the throughflow of materials, fuel, and the hire of labor plus a markup for overhead and profit on capital. These sectors have a floor under prices determined by costs (with economies of scale this is a downward-sloping floor). Costs (and prices) change when the costs of labor, raw materials, energy and other intermediate goods change; but prices are less sensitive to changes in demand. Faced with a fall in demand for its product, a firm cannot make any substantial cut in its prices until the prices of its inputs are cut. It lays off workers, reduces purchases of materials and fuel, etc. Quantity adjustments preceed price adjustments. A materials- and energy-based, cost-plus pricing model provides a theoretical rationale for the quantity adjustments of Keynesian theory.

Given cost-plus pricing in manufacturing sectors, the behavior of primary sector prices will have important effects on macro economic behavior. Low commodity prices and availability of resources set the conditions for a sustained economic expansion. Increases in demand lead to increases in output at stable prices. The existence of economies of scale lead to lower unit costs, increasing productivity and moderating price pressure. Low energy prices reduce the costs of extracting raw materials, transportation costs, and the costs of manufacturing including the costs of capital goods. They also contribute to rapid technical progress since mass-production technologies substitute cheaply produced machines and large energy supplies for labor.

Rising prices of primary commodities and energy are, likewise, passed on in manufacturing costs. An increase in energy prices, for example, increases the cost of production in extraction sectors; it increases the cost of manufacturing directly and indirectly via the higher cost of raw materials; and the higher cost of capital goods has a further effect on prices. This is a "price multiplier". There is also an important recessionary effect as higher commodity prices reduce the demand available for manufacturing goods leading to layoffs, loss of economies of scale, lower productivity growth, etc. Seven of the eight recessions since World War II were preceeded by a significant increase in the price of crude oil (Hamilton, 1983).

The connection between rising primary commodity prices, especially energy, and inflation is obvious in the historical record but has been difficult to explain in conventional models. According to the primary factor model of orthodox theory, an increase in energy prices has only a small inflationary effect. If energy costs are 5% of GNP, for example, then a doubling of energy prices would increase prices by 10% and only if there was *no* substitution away from energy. According to neoclassical theory, the energy price shocks of the 1970s explain only a small part of the price escalation of the mid and late 1970s. But as Robert Fri of Resources for the Future observes:

> Neither energy's share of GNP nor the slow rate at which energy consumption patterns change accounts for the sharp changes in production, productivity, unemployment, or inflation that occurred in 1974 and 1979. It appears that something amplifies the effect of oil price swings (Fri, 1987, p. 40).

ENVIRONMENTAL RESOURCES AND REPRODUCTION PRICES

A materials and energy approach to prices also indicates the incompleteness of the price system. Environmental resources are, in general, valued at the margin at costs of extraction (not reproduction). The effects of economic production on natural environments and the global system is likewise valued at costs of dumping or dispersal. Although orthodox theory recognizes the existence of such externalities in the divergence between private and social cost, any calculation of social costs is ordinarily made in terms of current market prices which themselves do not reflect the full cost of the use of resources or environmental systems.

The production prices of the classical model (Sraffa, 1960) provide one methodology for extending the range of price calculations. These are ostensibly *reproduction* prices. That is, they are formulated to ensure the replication of the components of the social-economic system through time. They have, therefore, an intrinsic determination shaped by the internal physical requirements of replacing commodities and services used up in production and consumption.

But this model of reproduction has been formulated in terms of produced commodities alone. The continued flow of necessary materials and sources of energy from natural systems has been taken as given. There is no calculation of the environmental costs of production of the resources taken from natural systems apart from their economic costs of extraction. Reproduction of the larger bio-social system through time suggests an extension of the concept of production prices from produced commodities to environmental resources and services. Most resources are not, of course, reproducible except on a geological time scale and their production requires the use of other resources (and non-reproducible energy). In a reproduction approach, exhaustible fuels, for example, would be priced either at the cost of renewable sources of power or in terms of the cost of exploiting alternative fuels whose supply is sufficiently large to avoid near-term exhaustion. Materials, likewise, would be priced in terms of the costs of recycling or in terms of the cost of substitutes. This would in effect reverse Marx's famous transformation of values into prices. Current prices would be recalculated to reflect reproduction "values" for critical environmental resources and services.

Prices alone, of course, are insufficient. The goal is the long-term viability of the environmental-economic system. Markets and prices are important social tools. They are one type of regulatory regime, but they have their limits. As Georgescu-Roegen suggested:

> The market mechanism has never been able to deal with bioeconomic ills. Whenever communities have been concerned with conserving resources—forests, fish, or game—or a healthy environment, they had to introduce legal quantitative restrictions (1981, p. 73).

The interdependence between economy and environmental resources (and potential long-term damage of industrial pollutants) suggests the need for quantity signals, physical limits and non-market regulatory systems. The physical underpinning of the classical model with its potential emphasis on the interconnectedness of social life and nature provides a rather different policy emphasis than the *laissez-faire, laissez-passer* dictum drawn by the Physiocrats and Adam Smith.

CONCLUSION

Classical economic theory provides a physical, materials-flow and proto-energetic approach to production and prices which had its origin in a provisioning metaphor drawn from physiology. Extension of this approach via the insights of modern physical and ecological science provides an alternative theoretical viewpoint to the equilibrium assumptions and marginalist adjustment mechanisms underlying neoclassical theory. It also provides an alternative conception of the internal physical and social reproduction requirements of a price (and regulatory) system which is absent from the marginalist approach and its emphasis on the subjective preferences of the present generation. Ecological and socio-economic systems are highly interdependent and a theory is needed which reflects that interdependence at the physical level. Obviously, the ideas of classical theory are only a beginning but they provide a possible starting point for developing a more ecologically (and socially) informed economic theory.

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