Weaving Methodologies:
Research Programmes, Science Studies and Model-Building

The Case of the Leontief Paradox

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Writing this paper with Professor Weintraub has been one of the best experiences we have had at Duke. Through his guidance and inspiration, Professor Weintraub has not only enriched our understanding of both the history and philosophy of economics but proven to us that we could write a serious academic paper. He encouraged us to work together, which has taught both of the stubborn members of this team to meld our minds and come up with a fruitful, cooperative partnership. Largely due to Professor Weintraub, we will be leaving this university with a well-rounded version of economics. No longer are we constrained to mainstream microeconomic and macroeconomic thinking, but we have seen what a truly rich and fascinating field economics has been and continues to be.

When we grow up, we want to be just like Professor Weintraub (except, Sharon doesn't want a mustache).

Only if and when a discipline has reached the state of perfect knowledge will one be able to separate sharply fact from logic, conjecture from proven hypothesis, approximate from exact formulation. Then no territory will be left to conquer; there will be only reviewing grounds where disciplined data will march up and down under the command of completed and universally accepted theory.

W.W. Leontief, 1958

Introduction

Scientific confirmation is a discursive battle. The existence of this 'state of perfect knowledge' remains enigmatic. How are the questions of science conquered on the reviewing grounds? Who decides what is truth and how it should be pursued? Lakatos placed science within organized directions of thought. Latour's actor-network theory (ANT) looks at science in the making—the interaction of scientists with institutions, interest groups, instruments and other scientists. The history of science becomes an ongoing struggle in which actors seek allies inside networks to propel their claims through space and time. A new shift in the philosophy of science places models in the front lines. In their ability to mediate between theory and the world, models are integral to scientific progress.

In earlier studies of the Leontief paradox, there is typically something missing. Historians and economists both have focused on the validity of Heckscher-Ohlin Theory, the importance of research programmes and discrediting Leontief's work. The networks supporting input-output analysis as well as the role of the actual input-output model and Leontief's skill in facilitating empirical study are often overlooked. This paper is an attempt to fill in this gap.

Chronicling the Battlefield

In *Science in Action*, Bruno Latour (1987) probes the 'construction sites of science' rather than 'ready made science' in building his actor network theory, one particular framework of what has become known as 'Science and Technology Studies.' Behind the claims of scientists are not the cognitive processes of ready made science but the papers, laboratories, allies and human and non-human resources of the construction sites of science, or 'science in the making.' ANT examines both the technical and social aspects of technoscience, stressing the mutual support between scientists working in laboratories and those recruiting outside interest. Scientists establish strongholds by enrolling and controlling others so their claims can spread, remaining relatively unchanged. Powerful actors begin constructing and extending networks as they mobilize heterogeneous and distant elements as allies in supporting their claims. A cycle of accumulation begins in which scientists go out of their way to gather these elements, acquiring knowledge and clashing with other ‘societies’ en-route. At the centers of calculation that lie at the heart of these networks, vast collections of elements are unified and the network progresses.

Latour’s ANT presents markedly different interpretations of such concepts as ‘truth,’ ‘society’ and ‘rationality.’ As Latour warns in the introduction to *Science in Action*, “abandon knowledge about knowledge all ye who enter here” (pp. 7). Truth is the result of settled controversies, rather than the cause. While it is easy to attribute truth in hindsight, nature is surprisingly absent from the fighting camps of scientists as they fortify their claims. It is only in the face of disagreement that different ‘societies’ emerge for society is “the set of elements that appear to be tied to a claim in dispute” (pp. 201). Like nature, a stable society is the consequence of concurrence. Analogous to Latour’s interpretation of society, rationality is erroneously conceived by scientists within a network to describe their own knowledge; those outside the network are irrational. Yet this is solely a matter of perception. Rationality is an illusion—there are only individuals inside a network and individuals on the outside (who may be part of some other network).

The result of Latour’s work is an alternative to normative historiographic approaches. By grounding the construction of science in narrow networks, actor network theory provides an outside perch from which to view this construction. With science studies, “lost is the grand vision of revolutionary episodes, theories confronting data, and progress associated with greater and better knowledge about the external world. What replaces such stories are local narratives of laboratory life, of technological innovation, of ideas transformed by argument” (Weintraub, 2002).

In the Trenches between Theory and Data

In the twentieth century, a growing emphasis on logical structure persuaded philosophers of science to acknowledge the importance of models in scientific progress. Even so, descriptions of models have largely focused on models as components, abstractions or interpretations of theory, or simplifications of the empirical domain—in no account does the importance of models stretch beyond the theory or data from which they derive. Yet work by Margaret Morrison and Mary Morgan through the LSE/Amsterdam/Berlin modeling project casts models in an entirely different light. Model building is characterized as an essential ingredient in scientific progress as models play a distinct role in mediating between theory and the world.

This paper focuses on this mediating ability of models. Morrison (1999) identifies three central features of mediating models: they are not derived from theory, nor are they derived from data, and most significantly, they can "replace physical systems as the central object of inquiry" (Suarez 1999, pp. 169). Mediating models can take on a life of their own and hence serve many purposes—building and correcting theory, exploring theoretical implications in the empirical domain, or simply acting as measuring instruments.

The pragmatism of mediating models derives from their partial autonomy from both theory and the empirical realm. This autonomy finds its origins in the construction of models where a creative element independent of both theory and data is introduced. As Boumans (1999, pp. 67) creatively explains, "model building is like baking a cake without a recipe. The ingredients are theoretical ideas, policy views, mathematisations of the cycle, metaphors and empirical facts." While accounts of model construction remain quite varied, a common trend emerges:

> models, by virtue of their construction, embody an element of independence from both theory and data (or phenomena): it is because they are made from a mixture of elements, including those from outside the original domain of investigation, that they maintain this *partially* independent status (Morgan and Morrison, 1999b, pp. 14, emphasis added).

These elements result from the simplification and integration inherent in model construction. Yet of crucial importance is the partial autonomy. As Morrison and Morgan (1999b pp. 17) write, "models must also connect in some way with the theory or the data from the world, otherwise we can say nothing about those domains." This connection takes the form of "a partial representation that either abstracts from, or translates into another form, the real nature of the system" (pp. 27).

It is this partial connection with both theory and the world that allows models to function as instruments of investigation. Morrison and Morgan continue,

> The critical difference between a simple tool and a tool of investigation is that the latter involves some form of representation: models typically represent either some aspect of the world, or some aspect of our theories about the world, or both at once. Hence, the model's representative power allows it to function not just instrumentally, but to teach us something about the thing it represents (1999b pp. 11).

This learning takes place in both the construction and manipulation of models. Building on these ideas, Suarez (pp. 171) characterizes models as “source[s] of mediated knowledge”—it is precisely the application of this local knowledge to either theory or the empirical domain that allows learning to take place.

This view of models as instruments of investigation raises interesting epistemological concerns. If models are completely dependent on theory, whether as interpretations of theory or components of theory, approaches to scientific confirmation are straightforward: an application of models in the empirical domain is analogous to the application of theory. If a model provides accurate descriptions of empirical circumstance and makes successful predictions, so too must theory as the content of the model derives solely from theory. Both realists and constructive empiricists have something to work with.

The partial autonomy of models precludes all scientific confirmation attempts. As the model-theory isomorphism breaks down, the application of models no longer contributes to either the realism or empirical adequacy of theory. As Suarez explains, a successful application of models in the empirical realm only raises our degree of confidence in the theory. Suarez continues,

> *Degree of confidence*, unlike *degree of confirmation*, does not point to the likelihood of the theory to be true; it only points to the reliability of the theory as an instrument in application. The theory is a reliable instrument if it is capable, perhaps when conjoined with good enlightening mediating models, of generating successful applications. And from the fact that the theory is instrumentally successful, the truth of the theory does not follow (Suarez, 1999, pp. 191, emphasis added).

Although Suarez’s characterization of theory as an instrument differs somewhat from the view of models as instruments of investigation, an interesting conclusion remains: the partial autonomy of models with theory erodes both the realist’s and empirical constructivist’s toolkit. The application of models only lends itself to the instrumental reliability of theory.

The March of International Trade Theory

If actor networks and model building are integral parts of scientific progress, any historiography of science should acknowledge their unique roles. The following section provides a casual account of the events surrounding the Leontief paradox. This episode from the history of international trade theory, in particular, lends itself to a reconstruction based on ANT and a model building perspective.

David Ricardo explained international trade as a result of labor productivity differences between countries—mutual gain resulted if each country specialized in their respective comparative advantage. The labor theory of value was discredited after 1870 yet remained in international trade theory so by the twentieth century, modernization of international trade theory was long overdue. Eli Heckscher's 1919 paper, "Effects of Foreign Trade on Distribution of Income" laid the groundwork for the ideas presented in Bertil Ohlin's 1933 *International and Interregional Trade* and its most influential conclusion, The Heckscher-Ohlin Theorem.

The Heckscher-Ohlin Theorem concentrated on the relationship between factor endowments and commodity trade patterns. Instead of basing comparative advantage differences across regions on labor productivity, Ohlin assumed that "the physical conditions of production are everywhere the same" (Ohlin 1933, pp. 15). Every country faces the same basic production functions but price differences arise from the relative scarcity of production factors. Ohlin explained comparative advantage as a result of different factor endowments between countries or regions. Thus, by the Heckscher-Ohlin Theorem, labor-abundant countries would export relatively labor-intensive goods.

As Ohlin was publishing *International and Interregional Trade* in 1933, Wassily W. Leontief began working on a model to assist in observing and measuring economic concepts. Throughout his career Leontief would argue that the task of a theorist does not end with a well thought-out theory, but simply begins there. The theorist must then apply his ideas to real economic situations and test the productions to see if they are reasonably accurate. Leontief's input-output model would be a tool for theorists to do just that.

Leontief began his work on the input-output model around 1933. Many of the equations had been discovered before by H.E. Bray in 1922 and R. Remak in 1929 but Leontief's most important contribution was that the coefficients describing the relationships of the sectors to an economy can be expressed statistically and are stable enough such that they can be used to predict the effect of different economic policies.

In 1953, Leontief published "Domestic Production and Foreign Trade: the American Capital Position Re-examined," resulting in the infamous Leontief paradox. Using his input-output model, Leontief found that U.S. imports were relatively capital intensive compared to exports. This was a direct contradiction of the widespread belief that America was a relatively capital-abundant country, after WWII, and according to the Heckscher-Ohlin theorem should thus export relatively capital intensive goods. This contradiction is the basis of the following case study.

A Lakatosian Perspective

This is not the first case study on the development of international trade theory surrounding the Leontief paradox. Neil de Marchi presented a Lakatosian account at the 1974 Nafplion Colloquium on Research Programmes in Physics and Economics. In response to Kuhn's view that science progressed in a series of revolutions, each resulting in a different paradigm, Lakatos suggested that scientific inquiry progresses through organized progressions of scientific thought or 'scientific research programmes'. Research programmes consist of a 'hard core' of irrefutable theory surrounded by a 'protective belt' of auxiliary hypotheses which can be further developed and refuted. A 'positive heuristic' specifies how the research programme should advance (Blaug 1976).

Through the lens of Lakatos, the factor proportion model is seen as only a step in an Ohlin-Samuelson research programme. De Marchi (1976) describes Ohlin's vision of the positive heuristic of this programme as the construction of "a sequence of models, each designed to illuminate some important aspect or aspects of international economic relations and connected through the 'mutual interdependence' theory of pricing" (pp. 117). De Marchi continues,

> the factor proportions model was to be but the first in a sequence, being modified in the direction of realism by the successive consideration of taxes, tariffs and transport costs, economies of scale, consumer preferences, different conditions of production as between countries, variable factor supply and mobility and imperfections in competition (1976, pp. 117).

De Marchi's treatment of models is analogous to that witnessed in Ernan McMullin's idealisation account of theory-application discussed by Suarez. Given an empirical contradiction to a theory, the theory is deidealised by selecting a theory-driven approximation to the problem-situation. As McMullin writes,

> Theoretical laws […] give an approximate fit with empirical laws reporting on observation. It is precisely this lack of perfect fit that sets in motion the processes of self-correction and imaginative extension described above [i.e. deidealisation]. If the model is a good one, these processes are not ad hoc; they are suggested by the model itself. Where the processes are of an ad hoc sort, the implication is that the model is not a good one; the uncorrect laws derived from it could then be described as 'false' or defective, even if they do give an approximate fit with empirical laws. The reason is that the model

> from which they derive lacks the means for self-correction which is the best testimony of its truth (McMullin, quoted in Suarez, 1999, pp. 177).

The parallels between this passage and De Marchi's account are potent. Suarez observes that McMullin uses the term 'model' to describe a 'theoretical description' (pp. 177). Similarly, De Marchi's account sees models as an integral, but not distinct, component of international trade theory. The positive heuristic of the Ohlin-Samuelson research programme is almost identical to McMullin's deidealisation—the factor proportions model must be modified by slowly dropping its constrictive assumptions. These corrections are made within context of the 'mutual interdependence' theory of pricing, thus keeping with McMullin's essential condition that these corrective processes are not 'ad hoc,' but rather derived or suggested by theory.

Suarez' criticisms of McMullin's idealisation account can now be extended to the work of De Marchi. Clearly influenced by the LSE/Amsterdam/Berlin modeling project, Suarez writes, "despite its intentions, McMullin's proposal effectively dispenses with the need for models as mediators because it invariably construes models as approximations to theories" (Suarez, 1999, pp. 173). Analogously, De Marchi's account of the Leontief paradox effectively ignores the mediating role the input-output model plays as his case study solely focuses on the development of models within the Ohlin-Samuelson research programme. We argue that the heightened importance of Leontief's input-model lies in its ability to mediate between Heckscher-Ohlin Theory and the world.

De Marchi's research programmes account similarily overlooks how science is actually made. In the Lakatosian metanarrative of progress, science is propelled through progressive research programmes, rather than the laboratories and offices where scientists work—"the protagonists are the programs, not the people" (Weintraub 2002, pp. 377). Yet these 'people' should not be ignored—ANT provides a richer account of the Leontief paradox, especially in explaining the responses to Leontief's 1953 paper. Before extending these arguments further, a look at the role of both Heckscher–Ohlin model and Leontief's input-output model in the development of international trade theory seems necessary.

Heckscher-Ohlin Theory

Heckscher-Ohlin Theory examines the element of space in the context of a 'mutual interdependence' theory of pricing. Determinants of commodity prices are demand conditions, factor endowments and physical conditions of production. By casting the former to the side and assuming the latter is the same across regions, the Heckscher-Ohlin Theory identifies differing factor endowments across regions as a central catalyst for divergent relative prices and hence, international trade.

Given the direction of this paper, it seems appropriate to present the particulars of the theory in the common 2x2 factor proportions model (Krugmann 1988). Assume that Countries A and B produce two commodities X and Y with the full employment of two productive factors, labor, L, and capital, K. Ohlin added a capital constraint to Ricardo's labor constraint:

$$a_{LX} Q_X + a_{LY} Q_Y = L$$
$$a_{KX} Q_X + a_{KY} Q_Y = K$$

where the technical coefficient a_{LX} denotes the quantity of labor required to produce a unit of commodity X and so on. It is assumed that the physical conditions of production are identical across countries so technical coefficients are fixed through space. In later models allowing flexible technology, technical coefficients are found by cost minimization where $a_{KX}/a_{LX} = f_x(w,r)$; w is the wage rate and r is the rental price of capital. The assumption of fixed technical coefficients both simplifies the explanation at hand and is consistent with the assumptions pertaining to Leontief's input-output analysis. While there exists perfect mobility of factors of production between sectors in a particular country, factors are considered immobile across countries.

We will assume that commodity X is more labor intensive than commodity Y such that $a_{KX}/a_{LX} < a_{KY}/a_{LY}$ —this is reflected in the flatter capital constraint in Figure 1. The result is a biased transformation schedule (the locus ABC) where an increase in the supply of labor (capital) will result in a disproportional production possibilities expansion for commodity X (commodity Y). We also assume Country A has a relative abundance of labor to Country B. While Ohlin defines relative factor abundance in terms of relative factor prices [in this case, $(w/r)_A < (w/r)_B$], we will adopt the definition that if country A has a relative abundance of labor, $(L/K)_A > (L/K)_B$ where L,K denote endowments of labor and capital respectively. Although this is done to keep in line with Leontief's own interpretation of relative factor abundance, it must be noted that differing demand conditions across countries may preclude an isometry from this latter definition to the former (Ohlin 1933). This model assumes that differences in factor endowments dominate variable demand conditions [so $(L/K)_A > (L/K)_B$ implies $(w/r)_A < (w/r)_B$]

yet as Ohlin warns, “we must be careful to remember the qualification which lies in the possible influence of differences in demand conditions” (1933, pp. 17).

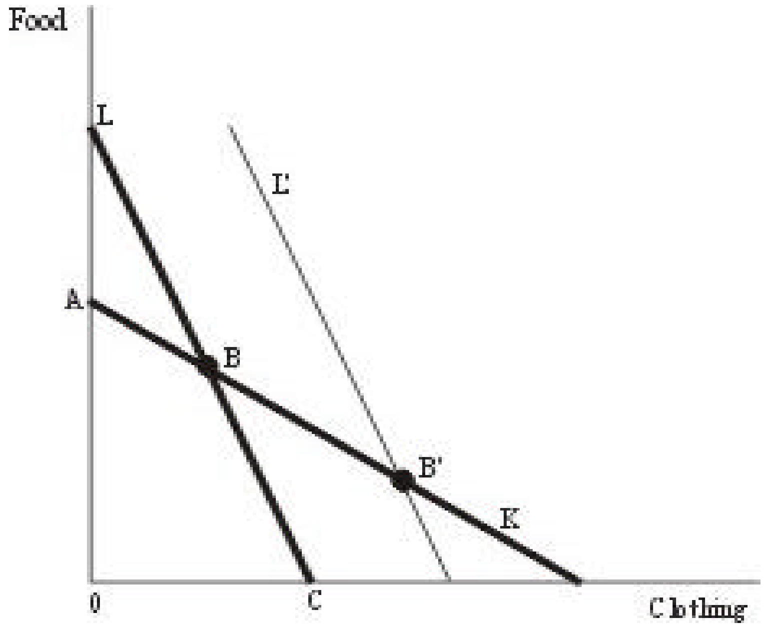

Figure 1: Factor Supply Constraints in a Two Commodity Model (Caves 1999)

The relative labor abundance of Country A is represented in Figure 1 by an outward shift of the labor constraint line—this is equivalent to the $(L/K)_A > (L/K)_B$ condition above. As physical conditions of production are identical between countries, the shift is parallel and Country A will now produce a relatively larger amount of the labor-intensive commodity *X*. One can verify from the conditions above that this implies Country A will export commodity *X*. The assumptions that perfect competition exists in both countries and neither country specializes in the production of either commodity guarantees that:

$$a_{LX}\,w + a_{KX}\,r = P_X$$
$$a_{LY}\,w + a_{KY}\,r = P_Y$$

hold in both countries where P_X, P_Y denote the prices of commodity X and commodity Y respectively. Given these competitive profit equations, the conditions $a_{KX}/a_{LX} < a_{KY}/a_{LY}$ and $(w/r)_A < (w/r)_B$ ensure that $(P_X/P_Y)_A < (P_X/P_Y)_B$ so the Heckscher-Ohlin Theorem is satisfied.

International trade allows both countries to benefit from implicitly trading scarce factors of production. By exporting labor-intensive commodity *X* and importing capital-intensive commodity *Y*, Country A uses its relative abundance of labor to offset its lower capital supply.

Similarly, international trade allows Country B to compensate for its lower labor supply through its relative abundance of capital. As Ohlin writes, "*thus, the mobility of goods to some extent compensates the lack of interregional mobility of the factors*: or (which is really the same thing), trade mitigates the disadvantages of the unsuitable geographical distribution of the productive facilities" (1933 pp. 42).

Of particular importance to this report is the role the factor proportions model has played in the development of international trade theory. Examining the Leontief paradox with Morgan and Morrison in mind, might lead one to believe the anomaly can be explained by examining model-building on the Heckscher-Ohlin side. Yet the factor proportions model is hardly removed from Heckscher-Ohlin Theory. Beginning the appendix to *Interregional and International Trade*, Ohlin acknowledges the ability for mathematical formulae to give, "better than could words, a bird's-eye view of the mutual relationship of prices under somewhat simplified conditions" (1933, pp. 553). The mathematical formulae of the factor proportions model flesh out the assumptions constraining Heckscher-Ohlin Theory and highlight the mechanisms underlying the theory. In this case, the model is so close to theory that there is hardly space for the element of creativity in the model-building process.

We now turn to the other model in our story, Leontief's input-output model. In laying the groundwork for our ANT analysis, the subsequent sections of this paper trace the analysis of interdependence among sectors (markets) through economic thought, from its emergence in French Physiocratic theory to its eventual incorporation into Leontief's input-output model. In eighteenth century France, François Quesnay pioneered the examination of interdependence within economic systems through his famous *Tableau Economique*. A century later, interdependence between markets would catalyze the general equilibrium theory of Léon Walras. Drawing on these past analyses, Wassily W. Leontief would introduce a more pragmatic construct of interdependence in the 1930s, analyzing the flows between economic sectors in his input-output model.

An Empire of Interdependence

Our story begins with the first school of economic thought, the eighteenth century French Physiocrats. While prosperous foreign trade in the British Empire led British economists to chase a theory of exchange, a feudal agricultural system in France shifted French economic thought in the direction of a theory of production. Looking for natural law in production processes, the Physiocrats stressed the eminence of land in that the *produit net*, or surplus, consisted solely of land rents. Published by François Quesnay in 1758, the *Tableau Economique* provided an account, albeit simplified, of the origin of these land rents and the more general reproductive process in the *ancien regime.*

Despite no formal education during his youth, Quesney went to Paris in 1711 to study medicine and would later become an expert on the circulation of the blood and bleeding techniques. Quesnay abandoned his medical writings in the early 1750s to pursue economics, shifting his analysis from the circulation of blood to the interdependence among economic classes. His attention to economics came in a France in which peasants were taxed heavily by both the Church and King. Under the system of the *ferme general*, the right to collect the government *taille* was sold to the *fermiers généraux*, a class of wealthy tax collectors. Having paid the government in advance, the nobles would keep all the tax revenues collected, leading to lower revenues for the King and oppressive tax burdens for the peasants. In the early half of the eighteenth century, agricultural productivity stagnated and famine was not uncommon. Quesnay and the Physiocrats attempted to explain and remedy French economic strife—"they were a group of reformers, who tried to convince the rulers and the sovereign that some changes were needed to make the country more wealthy and politically stronger" (Eatwell 1987, pp. 870).

In 1758, Quesnay published his first edition of the *Tableau Economique*. The following presentation of the *Tableau Economique* largely borrows from Phillips (1955) which reproduces the *Tableau* from Quesnay's "Analyse du Tableau Économique" published in the *Journal d'Agriculture, du Commerce et des Finances*; June, 1766.

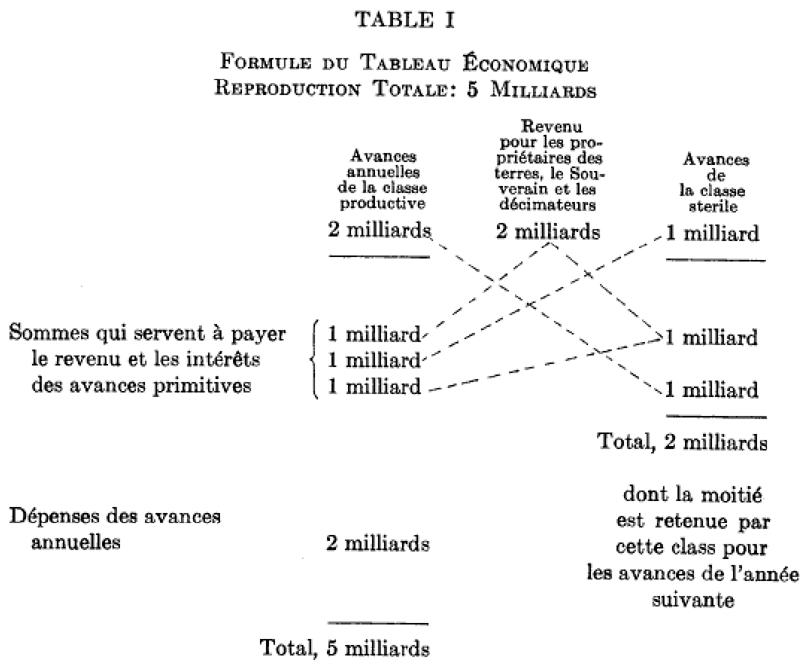

Figure 2: The Tableau Economique (Phillips 1955)

Quesnay divides the economy into proprietor, farmer and artisan classes; A. R. J. Turgot would later add a class of capitalist entrepreneurs. Quesnay's inclusion of an artisan class reflects his own interest in capitalist methods of production, yet only pertaining to agricultural production and not manufacture.

As Phillips explains the above Table,

> In this version, proprietors spent two milliards (two thousand million livres), one milliard on agricultural products and one milliard for the goods of artisans. These are shown in Table I by the dotted lines from the proprietors' two milliards of revenue down to the farmers (*la classe productive*) and artisans (*la classe sterile)* respectively. Artisans spend two milliards also, but all of this is for agricultural products—food and raw materials. The table shows two dotted lines from them to farmers to represent these purchases. Farmers purchase only one milliard of goods, this from the artisans, but they retain two milliards of their own production. Quesnay's total reproduction of five milliards is the sum of agricultural production and is composed of the one milliard purchased by proprietors, the two milliards purchased by artisans and the two milliards retained by farmers. This is the clearest diagram of the *Tableau* that Quesnay provided (pp. 139).

It is precisely the interdependence between classes that drives Quesnay's circular economy—the initial two milliards spent by proprietors sets off a chain of interactions between economic classes, resulting in the generation of an agricultural product of five milliards which is divided among the farmers, proprietors and artisans. While not indicated in Table 1, farmers purchase two milliards of rental services from the proprietors (using one milliard paid to farmers by each of the proprietor and artisan classes) which again sets off the reproduction process.

Yet Quesnay can be credited not just with a pioneer analysis of the interdependence between sectors but also with the construction of a working equilibrium where the inputs and outputs of each sector are equal—a closed system where the interactions between the different sectors are adequate in providing a complete account of an entire economic process. The proprietor class outputs two milliards of rental services in exchange for one milliard of goods from each of the farmer and artisan classes. The output of five milliards by the farmer class, or ‘sum of agricultural production’ is explained above—yet it is in examining the inputs of this class that the *Tableau* is linked to the broader Physiocratic method. Inputs to farmers are two milliards of rental services, one milliard of artisan goods and two milliards in own wages (paid from retained production). Central to Quesnay’s theory, the agricultural product is thus comprised of replacement costs (artisan goods or own wages) and *produit net* which must take the form of the two milliards of rental services. In further accord with Physiocratic theory, the artisan class produces no surplus as the two milliards of production require two milliards of farmer goods. In the closed economy presented by the *Tableau*, only land has value.

In the late half of the eighteenth century, British economists began to adopt their own theory of production. With the arrival of *Wealth of Nations* in 1776, Adam Smith would initiate a shift in the conception of the surplus to consisting of both rents on land and rents on capital, or profits. Smith devoted eight chapters of *Wealth of Nations* to mercantilism but only one to the physiocrats. While Smith respected physiocratic thinkers, he saw serious flaws in their ideas and predicted physiocracy would be short-lived.

Yet even at the turn of the nineteenth century, “it would have been virtually impossible for any British economist to regard Physiocracy as an eccentric, ephemeral and peculiarly French body of thought”(1951, pp.26). As Meek chronicles, these were the years of the great Physiocratic debates. In 1797, John Gray’s *The Essential Principles of the Wealth of Nations* attacked the burden of the proprietor class in its support of Physiocratic principles. Amidst ever-increasing interest in these controversies of production, William Spence’s *Britain Independent of Commerce* in 1807 lent Physiocracy further support, arguing that while industrial surpluses were possible, these arose from the sale of a manufactured good above its cost of production, coming at the expense of the proprietor class and contributing nothing to national wealth. Meanwhile, Daniel Wakefield, Robert Torrens and James Mill enforced Smith's notion of an industrial surplus. In Mill's *Commerce Defended* in 1808, industrial production had already come to be viewed as superior to agriculture.

Tied to this shift from land rents to profits was a shift from the conception of a nominal surplus to a theory of value. Meek explains,

> Whereas the production of a surplus in agriculture could easily enough be visualized in physical terms, it was difficult to visualise a similar process taking place in manufacture, where the elements of input and output usually consisted of entirely different commodities. The production of a surplus in manufacture could be visualized only in terms of *value*, which required quite a considerable development in the use of abstraction in economic analysis (1955, pp. 46).

With the publication of his principles of *Political Economy and Taxation* in 1817, David Ricardo advanced the ideas of profits as a primary income and the surplus as a flow of value. In Ricardo's mature classical outlook, little remained of the physiocratic *produit net.* Earlier conceptions of the surplus as a nominal agricultural product had been replaced by a modern industrial surplus of value, more appropriate for a Britain in the midst of an Industrial Revolution.

Exiled to England in 1849, the last of the great classicist thinkers, Karl Marx used Physiocratic principles in formulating his reproduction schema. Presented in Volume II of *Capital*, a collection of notebooks only published posthumously by Engels in 1885, the schema synthesized the *Tableau* with Classical notions of an industrial surplus, examining the interaction between departments of production and consumption. Marx's ties to Physiocratic thought are evident in what he percieves to be "the real duality of a capitalist economy: material and monetary"(Reuten 1999, pp. 202). Marx attacked capitalism's value analysis of production, stressing the importance of the individual capitals, the inputs of production—Marx's surplus is derived from the extraction of surplus-labor. The continued growth of British industry in the Industrial Revolution would soon prove Physiocracy obsolete yet as this paper implies, "two hundred years later, interest in Physiocracy flourishes considerably higher than the tepid praise of Adam Smith would suggest" (Staley 1989, pp. 31).

At the close of the nineteenth century, the heightened importance of the interdependence between sectors in economic theorizing is apparent in the general equilibrium theory of the French economist, Léon Walras. Both Marx's reproduction schema and Walras' general equilibrium theory build on Quesnay's *Tableau*, constructing explanations of the interdependence between sectors (markets) in economic process. That a normative element enters into these explanations is clear: while Marx attempted to show the inherent instability of growth in capitalist economy, Walras formulated ‘natural laws’ governing this same capitalist economy.

The son of amateur economist Antoine Auguste Walras, the younger Walras was encouraged by his father to study economics and given access to a collection of economic books. Auguste Walras held that economics should be a mathematical science, that value depended upon utility and not the cost of production, that land should be nationalized and that landowners should bear the burden of taxation—all controversial views that kept him out of academia. Leon would later be denied a university position in France by the “closed, semi-official self-recruiting academy” (Hutchinson in Stanley 1989, pp. 170) for pursuing many of the same ideas as his father.

Poor math skills kept Walras from attending the École Polytechnique and so he entered the School of Mines of Paris to study engineering. Walras gradually lost interest in his engineering studies at the School of Mines, preferring instead a Bohemian lifestyle, nurturing an interest in literature, philosophy and social science. Walras’s literary attempts, a short story and a novel, exemplified how economics had ingrained itself into his mind. In one story, the hero fell in love and came to Paris where he terminated the relationship with his lover when “one day he coolly weighed the pleasure his mistress afforded against the loss of time and money she occasioned and discovered there was a net deficit” (Staley 1989, pp. 170).

In 1858, Walras realized his true interest laid in the social sciences and immersed himself in economics once more at the request of his father. In 1860, as a struggling journalist, Walras answered a challenge put forth by the Council of State of the Vaud Canton in Switzerland for the best essay answering the question: “Within the present social order, what system of taxation would achieve the most equitable possible distribution of the burden on taxpayers or taxable commodities?” (Jaffé 1965 in Jaffé 1975, pp. 810). While Walras did not win the first place, he was invited to read his memoir at the 1860 International Congress on Taxation in Lausanne where he drew the attention of a Swiss politician who would later procure a professorship for Walras at the Academy of Lausanne in Switzerland. For the next eight years, at a time when “economics on the Continent was hardly a scientific pursuit but rather a mixture of normative prescriptions, classical theories expressed alongside protectionist doctrines, and commercial law," (Staley 1989 pp. 171). Walras would have a personal period of intense creativity during which he developed many of the foundations for his equilibrium theory.

Walras presented his general equilibrium theory in *Elements d'Economie Politiqué Pure* (1874, 1877) and four subsequent editions. The following mathematical exposition borrows from Kuenne (1955) whose presentation provides a useful guide for exploring the interdependence between markets in a Walrasian economy. Kuenne's work is adapted from Walras' definitive edition. While this fifth edition was published in 1926, it was for all practical purposes the same as the 1900 fourth edition so Kuenne's analysis is relevant to general equilibrium theory at the turn of the twentieth century.

In the household sector, x_i individuals are located in an economy with perfect competition and no transportation costs. Each individual is given an endowment q_{iu} of money Q_u and an endowment q_{iz_j} of factor services z_j used in the production of y_k goods (both consumer goods and intermediate industrial materials) or the reproduction or sale of a corresponding capital good Z_j. With the clear influence of Quesnay, members of the household sector include workers, landlords, and capitalists acting in their role as consumers, each with marginal utility functions $r_{iy_k} = R_{iy_k}(q_{iy_k})$ for each good y_k which are independent of the quantity of every other good consumed (similar marginal utility functions exist for capital goods Z_j, investment E and inventory services) and facing the budget constraint:

$$\sum \overline{X}_{iz_j} p_{z_j} + \sum \overline{X}_{iy'_k} p_{y'_k} + \overline{X}_{iu} p_{u'} = \sum X_{iy_k} p_{y_k} + X_{ie} p_e$$

where $\sum \overline{X}_{iz_j} p_{z_j}$, $\sum \overline{X}_{iy'_k} p_{y'_k}$ and $\overline{X}_{iu} p_{u'}$ represent the values of an individual's supply of factor services z_j, inventory services y'_k (where inventory held as goods) and money services (as $p_{u'}$ is the price of the service of money, or the price at which the money market reaches equilibrium), $\sum X_{iy_k} p_{y_k}$ denotes the value of consumed goods y_k and $X_{ie}p_e$ denotes the value of investment in securities, where the marginal utilities of goods demanded and supplied are proportional to prices. In the market for productive services, individuals in the household sector provide services to entrepreneurs and receive income $Y_i = \sum \overline{X}_{iz_j} p_{z_j} + \sum \overline{X}_{iy'_k} p_{y'_k} + \overline{X}_{iu} p_{u'}$, which it either consumes on goods y_k or saves. In the aggregate, $X_e p_e = X_{z_j} p_{z_j} + X_{y'_k} p_{y'_k}$, so individuals invest in both capital goods Z_j and new inventories y'_k.

In the entrepreneurial sector, Walras developed the technological production functions for the production of goods y_k and capital goods Z_j respectively:

$$\overline{X}_{y_k} = f_{y_k}(a_{z_j y_k}, a_{y_k y_k}, a_{y'_k y_k}, a_{u y_k}, \overline{X}_{y_k})$$
$$\overline{X}_{Z_j} = f_{Z_j}(a_{z_j Z_j}, a_{y_k Z_j}, a_{y'_k Z_j}, a_{u Z_j}, \overline{X}_{Z_j})$$

Given the production functions, entrepreneurs maximize utility through maximizing profits in the consumer (and intermediate) goods and capital-goods markets. While the technical coefficients of production a_{ij} represent the *average* amount of productive services or intermediate goods *i e {z_j,y_k,y'_k,u)* required for the production of good *j e {y_k,Z_j)*, Walras had originally fixed his *coefficients de fabrication* in his early general equilibrium theory. Total demand for goods y_k is given by:

$$_t X_{y_k} = X_{y_k} + X_{y'_k} + \sum_K a_{y_k y_K} X_{y_k} + \sum a_{y_k Z_j} X_{Z_j}$$

and thus consists of consumer demand X_{y_k}, inventory (or investment) demand $X_{y'_k}$ and entrepreneurial demand $\sum_K a_{y_k y_K} X_{y_k} + \sum a_{y_k Z_j} X_{Z_j}$. Demand for capital goods Z_j is X_{Z_j} as above and is derived entirely from investment.

Perfect competition eliminates all economic surpluses so Walras introduces the no profit conditions:

$$\sum a_{z_j y_k} \overline{X}_{y_k} p_{z_j} + \sum_K a_{y_k y_K} \overline{X}_{y_k} p_{y_K} + \sum_K a_{y'_K y_k} \overline{X}_{y_k} p_{y'_K} + a_{u y_k} \overline{X}_{y_k} p_{u'} = \overline{X}_{y_k} p_{y_k}$$
$$\sum a_{z_j Z_j} \overline{X}_{Z_j} p_{z_j} + \sum_K a_{y_K Z_j} \overline{X}_{Z_j} p_{y_K} + \sum_K a_{y'_K Z_j} \overline{X}_{Z_j} p_{y'_K} + a_{u Z_j} \overline{X}_{Z_j} p_{u'} = \overline{X}_{Z_j} p_{Z_j}$$

In Walrasian equilibrium, supply and demand are equal in both the consumer and capital goods markets, so equating the above conditions with the demand equations for goods y_k and capital goods Z_j (in value terms):

$$\sum a_{z_j y_k} \overline{X}_{y_k} p_{z_j} + \sum_K a_{y_K y_k} \overline{X}_{y_k} p_{y_K} + \sum_K a_{y'_K y_k} \overline{X}_{y_k} p_{y'_K} + a_{u y_k} \overline{X}_{y_k} p_{u'} =$$
$$X_{y_k} p_{y_k} + X_{y'_k} p_{y_k} + \sum_K a_{y_k y_K} X_{y_k} p_{y_k} + \sum a_{y_k Z_j} X_{Z_j} p_{y_k}$$
$$\sum a_{z_j Z_j} \overline{X}_{Z_j} p_{z_j} + \sum_K a_{y_K Z_j} \overline{X}_{Z_j} p_{y_K} + \sum_K a_{y'_K Z_j} \overline{X}_{Z_j} p_{y'_K} + a_{u Z_j} \overline{X}_{Z_j} p_{u'} = X_{Z_j} p_{Z_j}$$

In the entrepreneurial sector, the productive services purchased by entrepreneurs are converted into the consumer and capital goods required to meet demand in the consumer (and intermediate) goods and capital-goods markets. By the above equations, the value of inputs $Y = \sum \overline{X}_{z_j} p_{z_j} + \sum \overline{X}_{y'_k} p_{y'_k} + \overline{X}_u p_{u'}$ (where $\sum \overline{X}_{z_j} p_{z_j} = \sum a_{z_j y_k} \overline{X}_{y_k} p_{z_j} + \sum a_{z_j Z_j} \overline{X}_{Z_j} p_{z_j}$ etc.) equals the value of output $Y = \sum X_{y_k} p_{y_k} + X_e p_e$ (where $X_e p_e = X_{Z_j} p_{Z_j} + X_{y'_k} p_{y'_k}$) in the entrepreneurial sector. The same is not true for the household sector when investment is perceived as a separate sector. While households output services $Y = \sum \overline{X}_{z_j} p_{z_j} + \sum \overline{X}_{y'_k} p_{y'_k} + \overline{X}_u p_{u'}$, their only input is consumer goods $\sum X_{y_k} p_{y_k}$—the difference ($X_e p_e = Y - \sum X_{y_k} p_{y_k}$ by household budget constraint) is imputed into the investment sector.

The Walrasian economy is now complete. In the productive services market, households provide services to entrepreneurs and earn the national income. Acting in their unique roles as intermediaries, entrepreneurs convert these services into consumer and capital goods, which are then sold to households acting in their roles as consumers and investors in the consumer and capital-goods markets respectively. Regarding Walras' exclusion of government and foreign trade sectors, Kuenne provides a ready explanation, "the need for simplicity and the interferences of institutional barriers are sufficient grounds for excluding the international trade sector. The failure of governments to follow traditional economic motivation provides the theoretical grounds for the exclusion of their transactions from the model" (pp. 349).

French thought had come a long way since Quesnay. While Quesnay can be credited with the recognition that interdependence between sectors lies at the heart of economic activity, Walras illuminated the true explanatory power of this interdependence. In his comprehensive general equilibrium theory, Walras suggests that all economic activity can be explained through an analysis of the interdependence between sectors, or markets, that comprise the economy.

The Walrasian model has clear limitations. A combination of restrictive assumptions and idealisations leave Walras' general equilibrium theory in a rather abstract realm. Yet empirical adequacy can be left for Leontief—Walras rather shows the potential for mathematical analyses of the interdependence between economic sectors. As Kuenne writes,

Granted that as a device to describe to a close approximation the processes in an advanced economy it is seriously deficient, the Walrasian type of system remains, nevertheless, the best approach to a study of the nature of the complex interrelationships on a detailed basis in such an economy. Both as pedagogical and analytical tools, the Walrasian 'vision' of the mutual interdependence of variables within the economic universe as a whole, as well as the breadth of his structure without sacrifice to detail, remain valuable" (Kuene pp. 324).

We agree.

The Fortress

While Walras' contributions were coming to an end in France, across the Atlantic Ocean, mathematical economics was under attack. In the 1920s, econometric studies had centered around business cycle research, later discredited by the unforecasted Great Depression in 1929. The arrival of Keynes' 1936 *General Theory of Employment, Interest and Money* "consumed the passion and interest of economists with a taste for theory" (Weintraub 1985, pp. 81). Wassily W. Leontief's input-output analysis was born in a climate bent in favor of theoretical economics.

Trained as a 'Learned Economist' at the University of Leningrad, Leontief later received his PhD from the University of Berlin in 1928. Showing an empirical disposition early in his career, input-output analysis was first conceived while Leontief worked as a research economist at the University of Kiev for the next three years. In 1931 Leontief moved to American to work as a research assistant at the National Bureau of Economic Research but soon moved to Harvard in 1932, the same year the Cowles Commission for Research in Economics was established in Colorado.

Leontief's input-output model was first introduced in his 1936 paper "Quantitative Input and Output Relations in the Economic System" of the United States as "a *Tableau Economique* of the United States for the year 1919" (pp. 105). With clear influences from both Quesnay and Walras in focusing on the interdependence between different sectors in the economy, the input-output model allocates expenditure and revenue amounts across pairs of sectors—as Leontief bluntly explained,

> It follows from the obvious nature of economic transactions that each revenue item of an enterprise or household must reappear in the account of some other enterprise or household. This consideration makes it possible to present the whole system of interconnected accounts in a single two-way table (pp. 106).

This table is presented in Figure 3. With A,B,C,D,E representing business and household units, rows break down the revenue items for a particular sector across all other sectors; columns break down expenditure items across all other sectors. Accounts are often grouped for simplification purposes.

Distribution of Outlays (Input)	Distribution of Output (Revenue)					
	A	B	C	D	E	Total
A		A_b	A_c	A_d	A_e	$\sum_a^e A_i$
B	B_a		B_c	B_d	B_e	$\sum_a^e B_i$
C	C_a	C_b		C_d	C_e	$\sum_a^e C_i$
D	D_a	D_b	D_c		D_e	$\sum_a^e D_i$
E	E_a	E_b	E_c	E_d		$\sum_a^e E_i$
Total	$\sum_A^E i_a$	$\sum_A^E i_b$	$\sum_A^E i_c$	$\sum_A^E i_d$	$\sum_A^E i_d$	S

Figure 3: Leontief's input-output table (Leontief 1936)

Leontief's 1919 table has 44 sectors: 41 industrial sectors and international, household and 'Undistributed' sectors, the latter serving as an accounting balance. This early model includes capital outlays as expenditures, escaping complications from introducing investment. Ties to Quesnay are evident in Leontief's initial use of a closed system.

In 1937, Leontief began developing the theoretical scheme behind the closed input-output model:

$$
\begin{array}{ccccc}
(1-x_{11})X_1 & -x_{12}- & \cdots & -x_{1n} & =0 \\
-x_{21} & +(1-x_{22})X_2- & \cdots & -x_{2n} & =0 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
-x_{n1} & -x_{n2}- & \cdots & +(1-x_{nn})X_n & =0
\end{array}
$$

where X_i is production (output) of sector i and x_{ij} is the amount of product i consumed (inputed) by sector j. With further influence from Quesnay, added to these was a set of equations ensuring that the inputs of each sector equal that sector's outputs. Drawing on the technological production functions of Walras' general equilibrium theory, Leontief also introduced the technical coefficients a_{ij} where $x_{ij} = a_{ij}X_j$, so a_{ij} represents the amount of good i required in the production of one unit of good j. As in Walras' early theory, the technical coefficients were held constant, a controversial assumption given analyses of factor substitution. Yet Leontief believed coefficients should be measured from data and not statistical inference. As Kohli (2001) writes, "He did not deny that as a matter of fact some technologies allowed for substitution. Instead, lacking direct observations of alternative technologies, he reshaped his theoretical scheme according to his judgement about the reliable measurement of the parameters" (pp. 197).

A later 1929 table was published by the Industrial Committee of the National Resources Committee in 1939, introducing Leontief's work to committee member and commissioner of Labor Statistics, Isador Lubin. In 1941, Harvard University Press published much of Leontief's work in *The Structure of the American Economy, 1919-1929* which met with a weak response in academia, largely due to criticisms regarding fixed technical coefficients. The political arena was more enthusiastic. At a time when "the imperative of waging war led to a further expansion, building on the New Deal, of both federal intervention in the economy and of innovations in federal efforts to measure economic activities," (Kohli, pp. 191) Lubin requested $96,500 from Congress to fund a study of the economic effects of demobilization, especially concerning postwar employment. Drawn to the pragmatism of Leontief's input-output model and undaunted by the fixed technical coefficients, the Bureau of Labor Statistics hired Leontief and opened an office of its Post-War Division in Cambridge.

Leontief immediately began work on a 95-sector table for 1939, later published in 1944. Thanks largely to the work of Marvin Hoffenberg, the Bureau's expert on national accounts, the new table distinguished between current account and capital account expenditures by introducing an investment sector whose columns were domestic private investment and rows were depreciation. This progression of the input-output model shows a striking similarity to the evolution of the *Tableau* to general equilibrium theory—while Quesnay practically ignores investment (farmers purchase one milliards of artisan goods to replace those used during the reproduction process), household investment demand is integral to Walras' theory. Not surprisingly, a government sector was now present. Leontief also revised his theoretical scheme to an open system:

$$\begin{array}{ccccc}
(1-a_{11})X_1 & -a_{12}X_2 - & \ldots & -a_{1n}X_n & = Y_1 \\
-X_{21} & +(1-a_{22})X_2 - & \ldots & -a_{2n}X_n & = Y_2 \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
-a_{n1}X_1 & -a_{n2}X_2 - & \ldots & +(1-a_{nn})X_n & = Y_n
\end{array}$$

where Y_i are final demands in autonomous sector which consumes, but does not produce. With exogenous final demands now determined outside the interdependence between sectors, Leontief could examine the effects of government spending with his input-output model.

The 1940s were a productive decade for input-output analysis. In 1944, the Office of Strategic Services wanted a German input-output table to facilitate its attack on the German economy. Of particular importance, this facilitated a test of Leontief's fixed technical coefficients, which were fairly consistent with US figures. The next year, the Office of War Mobilization and Reconversion wanted an examination of postwar demand for capital goods, and in 1947, the Bureau used the 1939 table to forecast 1950 employment. In 1948, the Harvard Economics Research Project was established, here Leontief would serve as director for the next 25 years.

As the Korean War approached, the Truman Administration trimmed the Bureau's budget by 20%. Wanting to update the 1939 table, W. Duane Evans, then responsible for the Bureau's input-output work, allied with the Air Force on an interagency project SCOOP (Scientific Computation of Optimum Programs). When the Korean War began, funding soared. Evans and Hoffenberg write in 1952, "Topics stemming from the pioneer work of Leontief are engaging the attention of research groups at the Bureau of Labor Statistics, the Air Force, Army, and Navy, the Bureau of the Budget, Bureau of Mines, Department of Commerce, RAND Corporation, the Harvard, Chicago, Washington (at St. Louis), Princeton, Rice, Pennsylvania, and John Hopkins universities, and elsewhere. Other groups are at work in the United Kingdom, Canada, France, Holland, Italy, Israel, and Norway" (pp. 97). The product of this heightened interest was a massive 500-sector 1947 table, completed by 1951 and later used in the infamous 'Leontief paradox.'

In his influential 1953 paper, Leontief centered his study around a 200 industry breakdown model for the U.S. economy, or rather the table's inverse whose entries "indicate by how much the total output of each sector would be raised to satisfy the total, i.e., direct and indirect, requirements corresponding to, say, one million dollars' worth of additional deliveries to final demand" (pp. 391). Coupled with statistical data of capital and labor requirements for each industry and 1947 trade accounts, Leontief was able to conclude that contrary to what a synthesis of widespread belief about U.S. capital abundance and the Heckscher-Ohlin theorem would indicate, America imports relatively capital-intensive goods and exports relatively labor-intensive goods. Calculations of capital and labor requirements for exported and imported goods are shown in Figure 4.

	Exports	*Import replacements*
Capital (dollars, in 1947 prices)	2,550,780	3,091,339
Labor (man-years)	182•313	170•004

Figure 4: Capital and Labor Requirements for Exported and Imported Goods (Leontief 1953)

As the capital-labor requirement ratio for imported goods exceeds that for exports, Leontief concludes, "America's participation in the international division of labor is based on the specialization on labor intensive, rather than capital intensive, lines of production. In other words, this country resorts to foreign trade in order to economize its capital and dispose of its surplus labor, rather than vice versa" (1953, pp. 126). In explaining this paradox, Leontief suggests that American labor is more productive than foreign labor, and that the U.S. labor force should be multiplied by three. By exaggerating the productivity of American labor, Leontief argued that the U.S. was actually labor-intensive and thus reconciled his findings with the predictions of the Heckscher-Ohlin model.

In 1954, Leontief's relationship with the Bureau of Labor Statistics temporarily ended. With the advent of the Cold War, a fear of programming swept into Washington, halting federal support for input-output analysis. Yet while the construction of tables ceased, work continued to reconcile the 1947 table with the national income and product accounts. Government financial assistance soon returned—

> what was once a wartime imperative became a peacetime routine, as the Budget Bureau recognized in 1955 when it made the national income and product accounts the central framework for federal statistics. Because the Bureau of Labor Statistics had demonstrated the value of Leontief's tableaux in measuring these aggregates accurately, the Budget Bureau was able, once the Kennedy Administration took office, to establish the making of input-output tables as an integral part of the government's measuring activities (pp. 210).

Almost two centuries after Quesnay, interdependence remained embedded in economic study. While Walras had explored interdependence in high level theory, "Professor Wassily Leontief, of Harvard University, had the insight to recognize in these ideas not simply a tool for the theoretician but a practical instrument for attacking some of the most complex and perplexing real problems of our modern industrial economic environment" (Evans and Hoffenberg 1952, pp. 97). With a new pragmatism offered by input-output analysis, the interdependence between sectors catalyzed empirical studies of economics.

Mediating between Heckscher-Ohlin and the World

What has been consistently underplayed in accounts of this paradox is the ability of Leontief's input-output model to mediate between Heckscher-Ohlin Theory and the world. As Leontief himself explains,

> hypothetical production and consumption equations gain explicit meaning as soon as the symbolic algebraic signs are replaced by observed numerical values. Once an empirical foundation is thus established, the vague generalities of abstract theoretical statements will acquire concrete empirical significance (1936, pp. 116).

Before discussing the epsitomological implications of this 'concrete empirical significance,' it remains to be shown that the input-output model is partially autonomous from theory and the world and can replace both domains as the central object of inquiry.

The independence of the input-output model from Heckscher-Ohlin Theory is obvious. While the latter is an explicit account of how differing factors of production affect international trade patterns, the former is simply a data ordering mechanism—a powerful accounting tool. In another apparent break from theory, with the Leontief paradox, the input-output model only involved a single country while Heckscher-Ohlin Theory is usually presented in a two-country framework.

Yet this result of data limitations actually sparks the connection between the input-output model and Heckscher-Ohlin Theory. In drawing international trade conclusions from only the input-output model for the U.S. economy, Leontief must make the strong assumptions shared by the simple version of the Heckscher-Ohlin Theorem; specifically, identical tastes and methods of production across countries. Excluding his manipulation of the U.S. labor supply, Leontief reasons that as the U.S. exports relatively labor intensive commodities, then America must have a relative abundance of labor to its combined trading partners. This is simply the converse of the argument presented above in the factor proportions model. As each step is reversible, Leontief's conclusion is valid—Leontief must thus make all the assumptions articulated in the factor proportions account, adding to his strong assumptions such requirements as perfect competition in all relevant markets and the immobility of production factors across regions.

The established connection between the input-output model and Hecksher-Ohlin is lauded by Kindleberger: "Leontief's technique was appropriate as a test of the Heckscher-Ohlin theorem, which assumes that production techniques are the same the world over and that they allow little room for factor substitution. What he proves is not that the United States is capital-scarce and labor-abundant, but that the Heckscher-Ohlin theorem is wrong" (1962, pp. 75).

Both the actual input-output model and its role in Leontief's greater study exhibit an independence from data and the world. By characterizing the American economy in terms of an input-output model, Leontief essentially views the economy in a very specific way: "the economic activity of the whole country is visualized as if it were covered by one huge accounting system"(1936, pp. 106). Such realistic features as tariffs or differences in productivity are ignored. By synthesizing the U.S. input-output model with factor requirements and trade data in his study, Leontief manages to connect the input-output model with American trade relations with other countries—this is clearly not necessitated by the data. Rather, Leontief's skill in intertwining data furnishes an empirical test of the factor proportions model, despite apparent data limitations.

In Leontief's 1956 study "Factor Proportions and the Structure of American Trade: Further Theoretical and Empirical Analysis," the capacity of the input-output to act as a separate object of inquiry is revealed. In finding additional support for his 1953 study, Leontief learns from both the construction and manipulation of the input-output model. In regards to model construction, Leontief further refines his statistical method by constructing replacement coefficients to account for the depreciation of the capital stock. In addressing his earlier suggestion that the American labor force is more productive than abroad, Leontief also breaks down labor requirements by skill levels concluding, as expected, that American exports use higher-skilled labor than imported goods. As this break-down incorporates the input-output model, the model essentially serves as a tool in investigating the role of human capital in international trade patterns—an inquiry raised by the input-output model's own earlier use.

Although partially autonomous from both Heckscher-Ohlin Theory and the empirical domain, the input-output model mediates successfully between both domains. By utilizing its points of intersection with both the Heckscher-Ohlin Theory (through its assumptions) and the U.S. economy, the input-output model drives a fruitful application of the theory. Leontief's input-output model also replaces both domains as a central object of inquiry, highlighting the strong human capital element of American production. It is left to explore the explanatory power of both this model-building approach and ANT in relation to the multitude of responses surrounding the Leontief paradox.

The Battle Cry

De Marchi presents a ‘four-way classification of responses’ to the Leontief paradox (1976, pp. 114). There are those who criticize Leontief, either through his methods (exclusion of natural resources, human capital, etc.) or his data (1947 was an atypical year). A second group worked on producing specific conditions under which the Heckscher-Ohlin model held while a third tried to develop a new model of international trade to replace the Heckscher-Ohlin theory. The fourth group, led by Samuelson, simply ignored the Leontief paradox.

In addressing this latter group, de Marchi heeds Lakatos’ claim that “it is rational to adhere to an apparently refuted theory, so long as the research programme of which it forms a part is consistently predicting novel facts (is progressive)” (1976, pp. 109-110). Arguing that this is the case, de Marchi concludes that “under the wider theoretical perspective adopted by Samuelson it was entirely proper that Leontief’s finding did not determine the direction of research” (pp. 124).

The model-building approach suggests an alternative explanation. Under Suarez’s epistomological account raised above, the Leontief paradox simply lowers the degree of confidence in the factor proportions model. Concerning both the group attempting to specify the requisite assumptions for the Heckscher-Ohlin model and those who looked toward new models of international trade, this lowered confidence is readily apparent. Yet many economists in the Samuelson-Ohlin research programme already realized the lack of realism in the factors proportions model. Rather, they saw Heckscher-Ohlin Theory as only a first step in an accurate theoretical description of international trade. Thus in regards to the Samuelson group, the Leontief paradox did not appear to lower economists’ degree of confidence in Heckscher-Ohlin theory but rather confirmed an already existent lack of confidence in the theory.

Sibling Rivalry

Latour’s actor network theory provides a different interpretation of the Samuelson group’s indifference to the Leontief paradox. A possible ANT approach places Ricardo, Heckscher, Ohlin, Samuelson and other actors integral to the development of twentieth century international trade in a larger network, examining the support structures capable of withstanding Leontief’s assault on Heckscher-Ohlin theory. Yet the de Marchi account already presents a good argument to this effect. While the differences between research programmes and networks is profound, the Lakatosian perspective nonetheless provides a reasonable explanation of why, in light of the evolving structure of international trade, the Leontief paradox was ignored. Shifting our science studies focus to the powerful networks supporting input-output analysis provides a more engaging answer: the Samuelson group ignored the Leontief paradox because they could not challenge these networks, and abandoning Heckscher-Ohlin theory has already been shown unreasonable by both the Lakatosian and model-building arguments.

Leontief's Harvard Economic Research Project was the center of calculation of a much wider network linking economists, statisticians, computer scientists, policy makers, corporations, government bureaus, universities and past economic thinkers. The strengthening of this network was apparent, as the works of input-output economists, especially Leontief, became more technical and the number of sectors in input-output tables multiplied as resources accumulated. With the formalization of input-output analysis, Leontief further consolidated the power of the Harvard Economics Research Project by creating a common framework from which input-output analysis could be extended.

Support for this input-output network can be characterized by two principal domains: 'laboratory resources' and the annals of past economic thought. In the former domain, government organizations such as the Bureau of Labor Statistics and the Air Force were driving tax dollars into input-output research. Statisticians such as W. Duane Evans and Marvin Hoffenberg advanced both the construction and application of input-output tables. John B. Wilbur, and later Howard Aiken, designed powerful computers capable of calculating the large inverses of Leontief's matrices—the 1947 table used 50,000 punch cards. As Dorfman writes in 1954, "there can hardly be an economist who has not watched with amazement that nova of economics, input-output. Into a science characterized by individual research, piddling grants, and hand-me-down data, it brought large, well-financed research teams and fresh resources of statistical material" (pp. 121).

These laboratory resources were instruments that allowed Leontief to become a spokesperson for the economy. To make a meaningful challenge to the Leontief paradox, the Samuelson group would have needed these same statisticians, computers and government support. Science is expensive.

The second source of support for input-output analysis was links to past economic thought. Leontief's input-output model built on earlier analyses of interdependence, reaching back into a network connecting Quesnay, Marx, Walras and other actors pivotal to the incorporation of interdependence in economic study. While the *Tableau* provided a blueprint, Walras' general equilibrium theory was arguably the leading inspiration for input-output analysis, demonstrating the explanatory power of interdependence in an economy.

Just as Quesnay and Walras' work provided support for input-output, Leontief's continued success bolstered these past works. Nowhere is this more striking than in the works of Phillips (1955), Maital (1972), Lange (1959) and Kuenne (1954) who reconstruct Quesnay's *Tableau*, Marx's Reproduction schema and Walras' general equilibrium theory as input-output schemes. Leontief's work on input-output extended a larger network, a network advancing economic knowledge through examinations of interdependence. International trade theory was attached to this same network. While Quesnay and Walras explored the interdependence between sectors, Heckscher-Ohlin Theory examined the interdependence between countries. International trade theory also built on Walras' marginal utility theory, exemplified in Leontief's 1933 early theoretical work, "The Use of Indifference Curves in the Analysis of Foreign Trade," in which indifference curves "are used in such a way as to enable us to disclose the intimate connection between the 'national' and the 'international' elements of economic equilibrium" (Leontief 1933, pp. 21).

A powerful conclusion emerges: both input-output analysis and international trade theory allied with a mutual network of interdependence. By challenging Leontief's input-output model, the Samuelson group would have attacked the same foundations on which their own theories evolved. This can be pushed further. The Leontief paradox illustrates the power of this larger network of interdependence—inconsistencies within the network are effectively disregarded.

Further Discussion

Accepting ANT and model-building perspectives does not preclude the Lakatosian notion of research programmes. One can accept Lakatos' idea that scientific progress proceeds through research programmes while still incorporating this paper's argument. De Marchi's account indicates that research programmes are driven by confidence. The Ohlin-Samuelson research programme was driven by the belief that in relaxing the assumptions of the factor proportions model, a high degree of realism would result. In cases where mediating models facilitate theory-application, models either raise or lower our degree of confidence in a theory. In this sense, mediating models can catalyze the progression of research programmes. While networks and research programmes diverge, they are not mutually exclusive concepts. Research programmes can be used to grasp the progression of theory in a fairly abstract light; ANT can be used to grasp the intricate connections driving the making of science. When examining the Leontief paradox, one realizes that de Marchi's account is not wrong, but limited. Instead of focusing on one particular methodology, we have chosen to weave in the importance of actor networks and model building with the explanatory power of research programmes.

The models account differs from both ANT and the Lakatosian argument in that it carries a strong normative tone. ANT and research programme are purely descriptive; absent is any proposal on how to conduct scientific inquiry. As Hands (2001, pp. 295) writes, "The bottom line is that if one wants MSRP [methodology of scientific research programmes] to serve demarcationist ends – to provide strict methodological rules for demarcating good/scientific economics from bad/unscientific economics – then it fails in this task." While the models perspective does not fully delineate 'methodological rules,' it suggests that the construction of effective mediating models is integral to "good/scientific economics.' Mediating models do not provide scientific confirmation but where confirmation attempts are unavailable, models give scientists something to work with.

In accepting this methodology of models, an examination of its implications on theorizing is necessary. What are these implications? Leontief provides an interesting answer:

> If we want generality, anyone possessing mathematical dexterity, knowledge of economic writing, and, last but not least, a liking for that kind of exercise can easily construct a theory of international trade far more general than either of these. Such a theory—only formally—would take into account continous and discontinous production functions of all imaginable shapes, external economies, independent tastes, and everything else conceivable. Lacking specific observation and measurement of these factors and relationships, that all-inclusive theory would have little, if any, explicatory value. Neither would it guide the drawing up of concrete and useful plans for factual research. A less general, more simple theory is needed; one which could be made more complicated in step with the systematic progress of the empirical analysis (1958, pp. 120).

This suggests a 'sophisticated' models approach in which the construction of mediating models is coupled with well-specified theories that draw up 'concrete and useful plans for factual research.' Yet recognizing the ability for mediating models to facilitate empirical examination where theories are otherwise inapplicable, this sophisticated approach is unnecessary. Even in cases where theory is not applicable to the real world, the true skill in mediating models is in bridging the gap between theory and data. No change in economic theorizing is necessary; rather scientists should focus on mediating models as a useful tool in the battle for scientific progress.

By incorporating three different historiographic viewpoints, we have shown how a particular case study can support multiple readings and interpretations. Our case study of the Leontief paradox undermines any theorization that 'economic science develops in this or that particular fashion'. Nevertheless, we have also shown how the various theorizations of ''science'' –Lakatos's research programmes, Latour's ANT, Morgan and Morrison's mediating models—all illuminate one or another facet of the development of economic knowledge, thus providing a richer account.

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