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Research programs, model-building and actor-network-theory: Reassessing the case of the Leontief Paradox[1]

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Abstract Methodology of scientific research programs (MSRP), model-building and actor-network-theory (ANT) are woven together to provide a layered study of the Leontief paradox. Neil De Marchi's Lakatosian account examined the paradox within an Ohlin–Samuelson research program. A model-building approach rather highlights the ability of Leontief's input–output model to mediate between international trade theory and the world by facilitating an empirical application of the Heckscher–Ohlin Theorem. The epistemological implications of this model-building approach provide an alternative explanation of why Samuelson and other prominent economists ignored the paradox. By focusing on the network in which input–output analysis evolved, Bruno Latour's ANT further explains the response of international trade theorists.

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1 REASSESSING THE CASE OF THE LEONTIEF PARADOX

> 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 1958b: 120)

For philosophers and historians of science bent on exploring the empirical application of economic theory, the Leontief paradox has garnered substantial interest. Earlier methodological case studies of the paradox have focused on the validity of Heckscher–Ohlin Theory, the importance of research programs, and the credibility of Leontief's work. In what follows, we adopt a model-building approach (Morgan and Morrison 1999) in reevaluating the paradox, arguing that the role of input–output modeling and Leontief's skill in facilitating empirical study have been under-appreciated, if not overlooked. Our argument will also suggest that the networks of economists and their institutions (Latour 1987) in which input–output models were

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developed, interpreted, refined, and instantiated mattered in the responses to Leontief's apparent refutation of the Heckscher–Ohlin Theorem.

The synthesis of De Marchi's (1976) Lakatosian perspective with model-building and ANT approaches also offers alternative insight into normative elements in historiographies of science. By incorporating three different viewpoints, we demonstrate 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 also show how various methodologies of science all illuminate one or another facet of the development of economic knowledge, thus providing a richer account of this episode in the progression of international trade theory.

2 A METHODOLOGY OF MODELS

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 interpretations or components of theory, or generalizations 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 Mary Morgan and Margaret Morrison 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 an autonomous role in mediating between theory and the world.

Morrison (Suárez 1999: 169) identifies three central features of models: they are not derived from theory, nor are they derived from data, and most significantly, 'they can replace physical systems as the central objects of scientific inquiry' (Suárez: 169). Models can take on a life of their own and hence perform many functions – building and correcting theory, exploring theoretical implications in the empirical domain, applying theories that are otherwise inapplicable, or functioning directly as measuring instruments.

The mediating ability of models derives from their partial autonomy from both theory and the empirical realm. This autonomy originates in the multidisciplinary and multifaceted construction of models where a creative element independent of both theory and data is introduced. As Boumans (1999: 67) creatively explains in his discussion of business-cycle models: '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 up 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: 14)

This 'partially independent status' of models implies both an independence from, and connection to, theory and data. As Morgan and Morrison (1999b: 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 or theory, or one that is capable of embodying only a portion of a system' (p. 27).

It is their capacity for representation that allows models to function as instruments of investigation. Morgan and Morrison write:

> 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: 11)

Learning takes place in both the construction and manipulation of models. Building on these ideas, Morrison (quoted in Suárez: 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.

Where 'mediating models'[2] facilitate the application of theory, the partial autonomy of models with theory precludes scientific confirmation attempts. As models bridging the divide between theory and data retain some independence from theory, the application of theories via mediating models no longer contributes to either the realism or empirical adequacy of theory as theories are only indirectly applied.[3] Suárez explains that a successful application of theory facilitated by mediating models only raises our degree of confidence in the theory:

> *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.
>
> (Suárez 1999: 191 emphasis added)

The theory is an instrument in the classical sense – it acts on the world but this provides no epistemological knowledge. This differs from the instrumentalism prevalent in the Morgan and Morrison modeling account where the ability of models to represent theory, the world, or both, allows models to function as instruments of investigation. While the manipulation of models provides learning opportunities, the application of theory (when driven by mediating models) only lends itself to the instrumental reliability of theory.

3 THE MARCH OF INTERNATIONAL TRADE THEORY

In this section we recapitulate the Leontief paradox. Recall that David Ricardo explained international trade as a result of labor productivity differences between countries – mutual gain resulted if each country specialized in their comparative advantage. The labor theory of value, discredited after 1870, remained useful in international trade theory thus by the twentieth century, modernization of international trade theory was overdue. Eli Heckscher's 1919 paper, 'The effect of foreign trade on the distribution of income' laid the groundwork for the ideas presented in Bertil Ohlin's 1924 doctoral dissertation, 'The theory of trade' and what later became known as Heckscher–Ohlin Theory.

Heckscher's paper broke from classical trade theory by assuming homogeneous production functions across countries, explaining differences in comparative costs as the result of dissimilar factor endowments. Ohlin recognized and publicized the importance of Heckscher's insight, incorporating Heckscher's ideas in a general equilibrium framework and subjecting the new trade theory to a comprehensive analysis. Only later would the next generation of economists, led by Paul Samuelson, distort and expand these ideas into contemporary Heckscher–Ohlin Theory.[4] Heckscher and Ohlin's belief that a country will export goods whose productions are more intensive in its abundant factor was labeled the Heckscher–Ohlin Theorem and recast in the now-standard factor proportions model.

As Ohlin consolidated his ideas in *International and Interregional Trade* (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 an economist does not end with a well thought-out theory, but simply begins there. The economist must then apply his ideas to real economic situations to see if they are reasonably accurate. Leontief's input–output model would be a tool for economists to do just that. Many of Leontief's theoretical input–output equations had been developed before by H.E. Bray in 1922 and again by R. Remak in 1929, but Leontief's most important contribution to economic practice (for which he was awarded the 1973 Nobel Prize in Economics) was his demonstration that the coefficients describing the relationships between the sectors in an economy can be expressed statistically and are stable enough such that they can be used to predict the effects of different economic policies.

In 1953, Leontief published 'Domestic production and foreign trade: the American capital position reexamined,' resulting in the famed Leontief paradox. Using his input–output model, Leontief found that US imports were relatively capital intensive compared to exports. This was a direct contradiction to the widespread belief that the US was a relatively capital-abundant country after World War II and, according to the Heckscher–Ohlin Theorem, should thus export relatively capital-intensive goods. This contradiction is the basis of the following case study.

4 A LAKATOSIAN PERSPECTIVE

Inspiration for our present study lies in De Marchi's MSRP account of the Leontief paradox, presented at the Nafplion Colloquium. In response to Kuhn's view that science evolves in a series of revolutions, each resulting in a different paradigm, Lakatos suggested that scientific inquiry advances through organized progressions of scientific thought, or 'scientific research programs.' Research programs consist of a 'hard core' of irrefutable theory surrounded by a 'protective belt' of auxiliary hypotheses that can be further developed and refuted. A 'positive heuristic' specifies how the research program should advance (Blaug 1976).

Through the lens of Lakatos, the factor proportions model is seen as only a step in a wider Ohlin–Samuelson research program. De Marchi (1976) describes Ohlin's vision of the positive heuristic of this program 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' (p. 117). De Marchi continues,

> The factor proportions model was to be but the first in the 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: 117)

De Marchi's treatment of models is analogous to that witnessed in Ernan McMullin's idealization account of theory-application discussed by Suárez. 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.
>
> (quoted in Suárez 1999: 177)

The parallels between this passage and De Marchi's account are potent. Suárez observes that McMullin uses the term 'model' to describe a 'theoretical description' (p. 177). Similarly, De Marchi sees models as an integral, but not distinct, component of international trade theory. The positive heuristic of the Ohlin–Samuelson research program is almost identical to McMullin's deidealization – the factor proportions model must be modified by slowly dropping its constrictive assumptions. These corrections are made within the context of a '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.

Suárez' criticisms of McMullin's idealisation account can now be extended to the work of De Marchi. As part of the LSE/Amsterdam/Berlin modeling project, Suárez writes, 'despite its intention, McMullin's proposal effectively dispenses with the need for models as mediators because it invariably construes models as approximations to theories' (Suárez 1999: 173). Suárez later continues: 'On the idealisation account the theory does all the work required for its own application by determining, in stages, sets of increasingly *less idealised* representations. These representations, however, may never truly represent anything real at all' (p. 182). Analogously, De Marchi's account of the Leontief paradox ignores the mediating role the input–output model plays in the empirical application of the Heckscher–Ohlin Theorem as his case study solely focuses on the development of models within the Ohlin–Samuelson research program. 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 programs account similarly overlooks how science is actually made. In the Lakatosian metanarrative of progress, science evolves in progressive research programs, rather than the laboratories and offices where scientists work – 'the protagonists are the programs, not the people' (Weintraub 2002: 377). Yet these 'people' should not be ignored. We shall suggest below that Latour's actor-network-theory provides another layer of richness in explaining the responses to Leontief's 1953 paper. Before extending these arguments further, we need to more closely examine the role of both Heckscher–Ohlin Theory and Leontief's input–output model in the development of international trade theory.

5 THE HECKSCHER–OHLIN THEOREM

Heckscher–Ohlin Theory examines the element of space in the context of a mutual interdependence theory of pricing. Commodity prices are determined by demand conditions, factor endowments and physical conditions of production. By casting demand conditions to the side and assuming production processes are the same across regions, Heckscher–Ohlin Theory isolates 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 Heckscher–Ohlin Theorem in the standard 2×2 factor proportions model (Krugman 1988). Assume that Countries A and B produce two homogeneous 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 therefore technical coefficients are fixed through space. The assumption of fixed technical coefficients both simplifies the explanation at hand and is consistent with Leontief's input–output analysis where input–output coefficients also remain fixed. 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 $a_{KX}/a_{LX} < a_{KY}/a_{LY}$. 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, $(w/r)_A < (w/r)_B$, where w is the wage rate and r is the rental price of capital], we will adopt the same definition as Leontief – that if Country A has a relative abundance of labor, $(L/K)_A > (L/K)_B$. 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: 17).

The assumptions that perfect competition exists in both countries and neither country specializes in the production of either commodity guarantees that:

$$a_{LX}w + a_{KY}r = P_X$$

$$a_{LX}w + a_{KY}r = P_Y$$

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 $(P_X/P_Y)_A < (P_X/P_Y)_B$ therefore Country A has a comparative advantage in the production of commodity X – Country A will thus export the labor-intensive commodity X 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: 42).

We now turn to the other model in our story, Leontief's input–output model.

6 AN INPUT–OUTPUT FORTRESS[5]

Exhibiting an early empirical disposition, Leontief first conceived of input–output analysis while working as a research economist at the University of Kiel from 1927–30. Only after moving to Harvard in 1932 did Leontief actually begin compiling input–output tables for the American economy. Four years later, Leontief presented the first input–output table 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' (p. 105).

Leontief's input–output technique condensed economic activity into the revenue and expenditure accounts of business and household entities using a double-entry system of accounting. As Leontief bluntly explained,

> It follows from the obvious nature of economic transactions that each revenue item . . . of an enterprise or household must reappear as an outlay item 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.
>
> (p. 106)

This table is presented in Figure 1. 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		$\sum_a^e D_i$
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 1 Leontief's input–output table (Leontief 1936: 106)

Leontief's 1919 table had 44 sectors: 41 industrial sectors and international, household and 'Undistributed' sectors – the latter serving as an accounting balance 'which reflected a lack of income-expenditure accounts for wholesale and retail trade, banking and finance, and nonrail transportation, as well as federal, state, and local governments' (Kohli: 194). This early model included capital outlays in the expenditure account, avoiding complications from explicitly introducing investment.

In 1937, Leontief began developing an algebraic formulation of input–output analysis to provide both a theoretical foundation for his closed input–output model and a general method of abstract reasoning by which the model could be further explored:

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

where X_i is production (output) of sector i and x_{ij} is the amount of product i absorbed (inputted) by sector j. Added to these was a set of equations ensuring that the value of each sector's inputs and outputs were equal. 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) which were held constant, a controversial assumption given analyses of factor substitution. Yet Leontief believed coefficients should be arithmetically measured directly from data, not via statistical inference procedures. As Kohli writes:

> He did not deny that as a matter of fact some production technologies allowed for substitution. Instead, lacking direct observations of alternative technologies, he shaped his theoretical scheme according to his judgement about the reliable measurement of the parameters.
>
> (p. 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 American Economy, 1919–1929* which met 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: 191) Lubin petitioned Congress to fund an economic analysis of demobilization, especially concerning postwar employment. Drawn to the pragmatism of Leontief's input–output model and undaunted by his use of fixed technical coefficients, the Bureau of Labor Statistics (BLS) 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 a domestic private investment column and depreciation row. 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 an autonomous sector which consumes, but does not produce. With final demands now determined outside the endogenous sectors, Leontief could examine the effects of exogenous government spending with his input–output model.

The 1940s were a productive decade for input–output analysis. In 1944, the Office of Strategic Services commissioned a German input–output table to facilitate its attack on the German economy. Of particular importance, this enabled a test of Leontief's fixed technical coefficients, which were fairly consistent with earlier US estimates. The next year, the Office of War Mobilization and Reconversion wanted an examination of postwar demand for capital goods, and in 1947, the BLS 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 percent. 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 for SCOOP soared. Evans and Hoffenberg (1952) wrote,

> 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. (p. 97)

The product of this heightened interest was a massive 500 sector 1947 table, completed by 1951 and later used in the Leontief paradox.

In his influential 1953 paper 'Domestic Production and Foreign Trade: The American Capital Position Reexamined,' Leontief centered his study on a 200 industry version of the 1947 table. Competitive imports were now subtracted from the final demands of their rival domestic sectors, while non-competitive imports had a separate row. The classification of competitive imports by industry allowed Leontief to measure the requisite intersectoral flows for meeting the demand for these imports domestically. Applying statistical data of capital and labor requirements for each industry, Leontief concluded that contrary to what a synthesis of widespread belief about US 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 reproduced in Table 1.

Table 1 Capital and labor requirements for exported and imported goods (Leontief 1953: 81)

	Exports	Import Replacements
Capital *(dollars in 1947 prices)*	2,550,780	3,091,339
Labor *(man-years)*	182.313	170.004

As the capital-labor requirement ratio for imported goods exceeded that for exports, Leontief concluded:

> America's participation in the international division of labor is based on its 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: 81)

In explaining this paradox, Leontief suggested that American labor is more productive than foreign labor, and that the US labor force should be multiplied by three. By exaggerating the productivity of American labor, Leontief argued that the US was actually labor-intensive compared to many other countries and thus reconciled his findings with the predictions of the Heckscher–Ohlin Theorem.

In 1954, Leontief's relationship with the Bureau temporarily ended. Secretary of Defense Charles Wilson halted Department of Defense funding for input–output work. While the construction of tables at the BLS ceased, work continued to reconcile the 1947 table with the national income and product accounts. Strong 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.
>
> (Kohli: 210)

Input–output tables are still found in US national account statistics.

7 MEDIATING BETWEEN HECKSCHER–OHLIN AND THE WORLD

What has been consistently underplayed in accounts of the Leontief paradox is the ability of the input–output model to mediate between Heckscher–Ohlin Theory and the world. Examining the model in the context of Leontief's 1953 study reveals an intricate system capable of merging heterogeneous elements to provide quantitative representations of economic activity. The input–output model (in its various forms) for the 1947 American economy is not simply a data-ordering mechanism but rather a collection of theoretical concepts, accounting principles, statistical techniques, empirical data, methodological considerations, policy views and laboratory resources.

These ingredients are blended together in the model's construction process which entails a compromise between a theoretical ideal and empirical measurement limitations. The ideal is a complete and consistent double-entry system of accounting where every household and business entity is included as separate accounting units whose expenditure and revenue accounts (and thus the expenditure and revenue accounts for the entire system) equate. Yet financial and methodological constraints preclude the construction of this perfect model. In actuality, the input–output model must incorporate significant simplifications including: the aggregation of the American economy into only 500 sectors (recall that Leontief's 1953 study uses a 200 sector version), the collapse of all foreign economic activity into a single unit, the assumption of fixed technical coefficients of production and the exclusion of natural resources. Despite enhanced detail over earlier models, the input–output model remains a fairly general approximation of the US capitalist economy.

Integrated in this compromise are strategic choices made by Leontief and other members of the BLS to facilitate their use of the model for empirical study. By building a model for the national economy rather than other potential economic systems, Leontief ensures further empirical work will have a macro-economic focus. While necessitated by financial constraints, the breakdown of the economy into sectors also involves tactical decisions. In grouping accounts, Leontief must determine which double-counted items are irrelevant, as grouping any two accounts removes their mutual economic interaction from the accounting system. Of particular importance to Leontief's 1953 study, the reclassification of competitive imports by rival domestic industries rather than by inputting sectors also allows Leontief to trace changes in exogenous demand for these imports through the model.

The product of this construction process is an input–output table for the 1947 American economy which 'describes the actual flow of commodities and services among all the different parts of the American economy' (Leontief 1953: 67). Entries in the table are the exchanges between sectors. As Leontief manipulates the input–output model in his international trade study, he alters both the physical structure of the model and how the model represents the world. From the initial US input–output table, Leontief derives a matrix of technical coefficients which isolates the underlying relationships between sectors. With the model in this form, economic activity is characterized by the structure, rather than the magnitude, of intersectoral flows. By then taking the inverse of this structural matrix, Leontief traces economic relationships through the entire system as entries in the inverse indicate the overall (direct and indirect) effect of a change in the final demand of a particular sector on the output of another sector. This offers a more dynamic representation of the economy as the inverse's coefficients can be perceived as the potential economic flows resulting from changes in demand. Leontief then multiplies the inverse of the structural matrix by the factor requirements of each industry, depicting the economy as a dynamic mechanism in which capital and labor drive the production processes of integrated industries. Once the input–output model represents the American economy in this way, Leontief can apply foreign-trade statistics to measure the factor requirements for US international trade.

In providing this measurement, the input–output model mediates between Heckscher–Ohlin Theory and the world. While the Heckscher–Ohlin Theorem suggests that a capital-abundant American economy will export capital-intensive goods, international trade theory provides no mechanism to assess this conclusion. Nevertheless, Leontief's input–output model 'enables us to narrow the frustrating gap between theory and observation' (Leontief 1953: 67) by facilitating an empirical test of the Heckscher–Ohlin Theorem. The established connection between the input–output model and Hecksher–Ohlin Theory 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: 75)

While able to mediate between theory and the world, the input–output model remains partially autonomous from both domains. Although the model connects with Heckscher–Ohlin Theory for its applicability, both the model's construction process and its manipulation in Leontief's 1953 study proceed largely outside the realm of international trade theory. Despite the model's ability to represent the American economy, the input–output model also retains much independence from the world. By characterizing the economy in terms of an input–output model, Leontief 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: 106). Incorporating such non-empirical elements as accounting principles, strategic choices and methodological simplifications in the hybrid structure of his input–output model, Leontief quantifies American economic activity only by constructing a system capable of merging data with his own unique conception of the economy.

The input–output model's partial independence from the world is further revealed in the model's ability to supplant the actual US economy as the central object of scientific inquiry in Leontief's study. Once data has been arranged in the initial input–output table, Leontief's analysis proceeds by manipulating the model rather than exploring the empirical realm. By 'using the matrix of technical coefficients, A, as a central storage bin for the basic factual information used again and again in various computations' (Leontief 1967: 41), Leontief sequentially shifts how the model represents the world, relying on only factor requirements and foreign trade data from the empirical domain. Yet while the study advances in the model world, the input–output model's connection with both theory and data allows Leontief to learn about both domains: on an empirical level, Leontief's study concludes that America exports relatively labor-intensive goods and imports relatively capital-intensive goods compared to the rest of the world; on a theoretical level, the study concludes that given the apparent capital-abundance of the American economy, the Heckscher–Ohlin Theorem cannot adequately explain US trade relations with other countries.

It is left to explore the explanatory power of both this model-building approach and Latour's ANT in relation to the multitude of responses surrounding the Leontief paradox.

8 RESPONSES TO THE PARADOX

De Marchi presents a 'four-way classification of responses' to the Leontief paradox (1976: 114–23). There are those who criticized Leontief, either through his method (exclusion of natural resources, human capital and non-competitive resources, etc.) or his data (1947 was an atypical year). A second group worked on specifying conditions under which the Heckscher–Ohlin Theorem held while a third group tried to develop a new model of international trade. 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")' (pp. 109–10). As recounted above, De Marchi argues that the Heckscher–Ohlin Theorem was an initial stage of a wider Ohlin–Samuelson research program. Despite the factor proportions model's empirical inadequacy in Leontief's 1953 study, the model was nonetheless 'a potentially fruitful point of entry into the general network of interdependent relations operating to determine competitive prices' (pp. 115–16). From this 'network' emerged Samuelson's analyses of factor-price equalization, as well as continued efforts to expand the basic factor proportions model by relaxing its restrictive assumptions. Given the progressiveness of the Ohlin–Samuelson research program, 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' (p. 124).

The model-building approach suggests an alternative explanation. Under Suárez's epistemological account raised above, the Leontief paradox simply lowered economists' confidence in the factor proportions model as the empirical application of the Heckscher–Ohlin Theorem was facilitated by a mediating model. In the context of Leontief's 1953 study, Heckscher–Ohlin

Theory was only an instrument, relying on the input–output model to indirectly connect theory with the world. As the input–output model remained partially autonomous from Heckscher–Ohlin Theory, the study only concluded that the Heckscher–Ohlin Theorem was instrumentally unreliable but carried no epistemological weight.

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 was readily apparent. Yet many economists in the Samuelson–Ohlin research program also realized the lack of realism in the factor proportions model. They saw Heckscher–Ohlin Theory as only a first step in an accurate theoretical description of international trade. De Marchi writes: 'Now neither Ohlin nor Samuelson was under any illusion about the realism of the factor proportions model. . . .Both were aware that this starting model, even in its fullest theoretical development, was bound to be replaced in the effort to secure closer approximation to reality' (p. 118). 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.

9 AN ACTOR-NETWORK-THEORY EXPLANATION

Latour's actor-network-theory provides a different interpretation of the Samuelson group's indifference to the Leontief paradox. In his 1987 *Science in Action*, Latour probes the 'construction sites of science' rather than 'ready made science' in building his ANT, one particular framework of 'Economic Science Studies.' Latour wants to know 'when someone utters a statement, what happens when the others believe it or don't believe it' (p. 21). This he says is critical in establishing what becomes accepted fact as: 'Fact construction is so much a collective process that an isolated person builds only dreams, claims and feelings, not facts' (p. 41). Behind the claims of scientists are not the cognitive processes of ready-made science but the papers, laboratories, allies and other human and non-human resources of 'science in the making.'

The result of Latour's work is an alternative to normative historiographies. 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 technical innovation, of ideas transformed by argument' (Weintraub 2002: 268).

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 programs and actor-networks are 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 network supporting input–output analysis provides a more engaging answer: the Samuelson group ignored the Leontief paradox because they could not challenge this input–output network, and abandoning Heckscher–Ohlin Theory has already been shown unreasonable by both the Lakatosian and model-building arguments.

ANT examines both the technical and social aspects of scientific progress. Scientific arguments begin as claims in literature, where authors rely on numerous rhetorical strategies to make their argument as impenetrable as possible to dissenters. Scientists enlist powerful allies, or construct ancestors, by referencing previous texts and tacit knowledge within a field. In his 1936 paper, Leontief introduced the input–output model as a *Tableau Economique* – a direct reference to the early macroeconomic modeling of the French physiocrat, Francois Quesnay.

Arguments take place in literature, but to arrive at and support their claims, scientists must step into a laboratory. Inside laboratories, scientists assemble instruments that provide the graphs, displays and other visual aids used to build the claims presented in scientific texts. Leontief used a particularly expensive instrument, the Bureau of Labor Statistics with its machinery of mathematicians, economists, statisticians, pollsters, computers and other resources focused on measuring the economy. By harnessing the power of the BLS, Leontief quantified economic activity within his input–output framework, establishing himself as a spokesperson for the economy.

Rounding up academic allies is necessary for claims to spread, but financial allies are also needed to pay for science. Finding financiers requires that scientists market their work to nonscientists as important and potentially useful. It often involves altering the direction of the research to accommodate the goals of the financial backer. Leontief had to convince not only other scientists of input–output's importance, but also those with the resources to support his research. Although Leontief's *The Structure of the American Economy, 1919–1929* had presented a compelling argument, he did not convince enough readers that his work was important. Fortunately for Leontief's work, the US government was more responsive. While input–output was not initially suited to analyze policy decisions, Leontief was able to translate his interest into something the government could use. To make his original input–output model satisfy the needs of his financiers, Leontief published a transactions table for 1939 that included both government and investment sectors, and shifted to an open model which facilitated the model's use for public policy, securing a steady input of human and non-human resources.

Input–output analysis quickly aligned with the powerful actors and acquired the vast resources necessary to establish a strong network. In addition to the Bureau of Labor Statistics, the Air Force was 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' (p. 121).

Leontief's Harvard Economic Research Project became a center of calculation for a much wider network linking economists, statisticians, computer scientists, policy makers, corporations, government bureaus, universities and past economists. 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 in a theoretical scheme, Leontief further consolidated the power of the Harvard Economics Research Project by creating a common framework from which input–output analysis could be extended.

Throughout the progress of science, claims often come under attack from fellow scientists. The dissenter claims that the world is not as the author claims; that nature and truth are not on the author's side. It is now the job of the dissenter to re-enact everything that went into building the original claim. To make a meaningful challenge, the dissenter requires the same heterogeneous assortment of resources used by the claim's presenter. As Latour puts it, '*arguing is costly*' (p. 69).

For the Samuelson group to deconstruct the results of the Leontief paradox, they would have had to challenge Leontief's position as a spokesperson for the economy. International trade theorists would have required a similar network to collect, analyze and interpret data – '*everything else being equal*, the winner is the one with the bigger laboratory or the better article' (Latour p. 103).

Mobilizing the support of the BLS strengthened Leontief's work. Without parallel statisticians, computers and government support, the Samuelson group would have been unable to successfully challenge Leontief's input–output network, essential to disputing his 1953 results. Facing this costly obstacle, it was not surprising that the Samuelson group simply ignored the paradox. Science is expensive.

10 CONCLUSION

In writing a historiography of science, the historian must inherently adopt a normative view on how science progresses. This view impacts both the selection of facts upon which the historical account is built, as well as the framework in which these facts are presented. We hope that by weaving together three separate methodologies of science, we have demonstrated that the historian's normative stance need not be as limited as the distinct methodologies offered by philosophers of science. Rather, each viewpoint illuminates different facets of scientific inquiry.

The synthesis of model-building, research programs and ANT provides an intricate narrative of the Leontief paradox. Differences between the approaches drive alternative historical reconstructions of the same episode in the development of international trade theory. De Marchi's Lakatosian account highlights the evolution of twentieth-century international trade theory within an Ohlin–Samuelson research program. The ANT perspective adopted in this paper explores the myriad of human and non-human catalysts of the powerful network supporting input–output analysis. A model-building approach focuses on the ability of Leontief's input–output model to mediate between Heckscher–Ohlin Theory and the empirical realm. Yet despite the differences in the methodologies and their respective historical concentrations, all three viewpoints present relevant insight into Leontief's 1953 study and suggest plausible explanations of why prominent international trade theorists ignored the paradox.

The methodologies also complement each other by building on the alternative approaches. While model-building stresses the autonomous role of the input–output model in scientific progress, both Lakatosian and ANT perspectives provide further insight by examining the context in which Leontief's model mediates and the factors underlying the model's construction and manipulation. Placing the input–output model in an Ohlin–Samuelson research program presents a backdrop to Leontief's 1953 study and isolates the model's connection with international trade theory. Examining the actors and resources integral to input–output modeling reveals the real world in which the model originates and exists – a world which facilitates and constrains how the model evolves. Taken together, the incorporation of the input–output model in both MSRP and ANT frameworks supplies relevant details that the model-building account overlooks.

Similarly, model-building enriches the other methodological stances. Although the ANT approach provides a detailed account of the development of the input–output model within a network, it largely disregards the model's actual role in scientific practice. De Marchi focuses on the progression of international trade theory within a research program but ultimately ignores the empirical application of theory. It is left to the model-building account to fill in these gaps by illustrating how the input–output network created a powerful system capable of mediating between international trade theory and the world.

Despite their symbiotic relationship, the different methodological viewpoints carry strong, distinct conclusions. The MSRP account presumes that science advances through research programs and advocates retaining empirically refuted theories that are part of progressive research programs. The model-building approach suggests that 'models should no longer be treated as subordinate to theory and data in the production of knowledge. Models join with measuring instruments, experiments, theories and data as one of the essential ingredients in the practice of science' (Morgan and Morrison 1999b: 36). Actor-network-theory rather stresses that analyses of science should encompass both the technical and social aspects of scientific practice. By intertwining these different viewpoints, we have attempted to show that these conclusions are not mutually exclusive. All warrant consideration in historiographies of science and when combined, contribute to a more thorough understanding of scientific progress.

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NOTES

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2 'Mediating models' are not one special class of models, like mathematical models, econometric models, green models, etc. Instead it is best, linguistically, to think of 'mediating models' = 'all models are mediators.'
3 For a more detailed argument, see Suárez (1999: 192–4).
4 A thorough account of the differences between contemporary Heckscher–Ohlin Theory and the original writings of the Swedish economists is documented in Flam and Flanders (1991: 25–9).
5 We are indebted to M. Kohli (2001) for his detailed account of Leontief's collaboration with the Bureau of Labor Statistics from 1941–54. Much of the historical content of this section derives from Kohli's work.

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