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Models

THE THIRD DIMENSION OF SCIENCE

Edited by

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STANFORD UNIVERSITY PRESS
STANFORD, CALIFORNIA
2004

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CHAPTER THIRTEEN

Secrets Hidden by Two-Dimensionality: The Economy as a Hydraulic Machine

Mary S. Morgan and
Marcel Boumans

> It seems to me that the test of "Do we or do we not understand a particular subject in physics?" is "Can we make a mechanical model of it?" (Lord Kelvin, quoted in Duhem 1954, 71)

> Once upon a time there was a student at the London School of Economics studying for the B.Sc. (Econ), who got into difficulties with his Keynes and his Robertson and . . . with such questions as whether Savings are necessarily equal to Investment and whether the rate of interest is determined by the demand and supply of loanable funds or by the demand and supply for idle money; but he realised that monetary flows and stocks of money could be thought of as flows and tankfuls of water. (James Meade, writing about Bill Phillips in Meade 1951, 10)

A long-standing tradition presents economic activity in terms of the flow of fluids. This metaphor lies behind a small but influential practice of hydraulic modelling in economics. Yet turning the metaphor into a three-dimensional hydraulic model of the economic system entails making numerous and detailed commitments about the analogy between hydraulics and the economy.

The most famous 3-D model in economics is probably the Phillips machine, the central object in this chapter. Made in Britain in the late 1940s, this hydraulic model (shown with its creator Bill Phillips in Fig. 13.1) is 7 × 5 × 3 ft and represents the macroeconomy by flows and stocks of coloured water in a system of perspex tanks and channels. A small number of these machines was made (perhaps 14) and these found their way across the English Channel and the Atlantic, and even to the Antipodes. Though

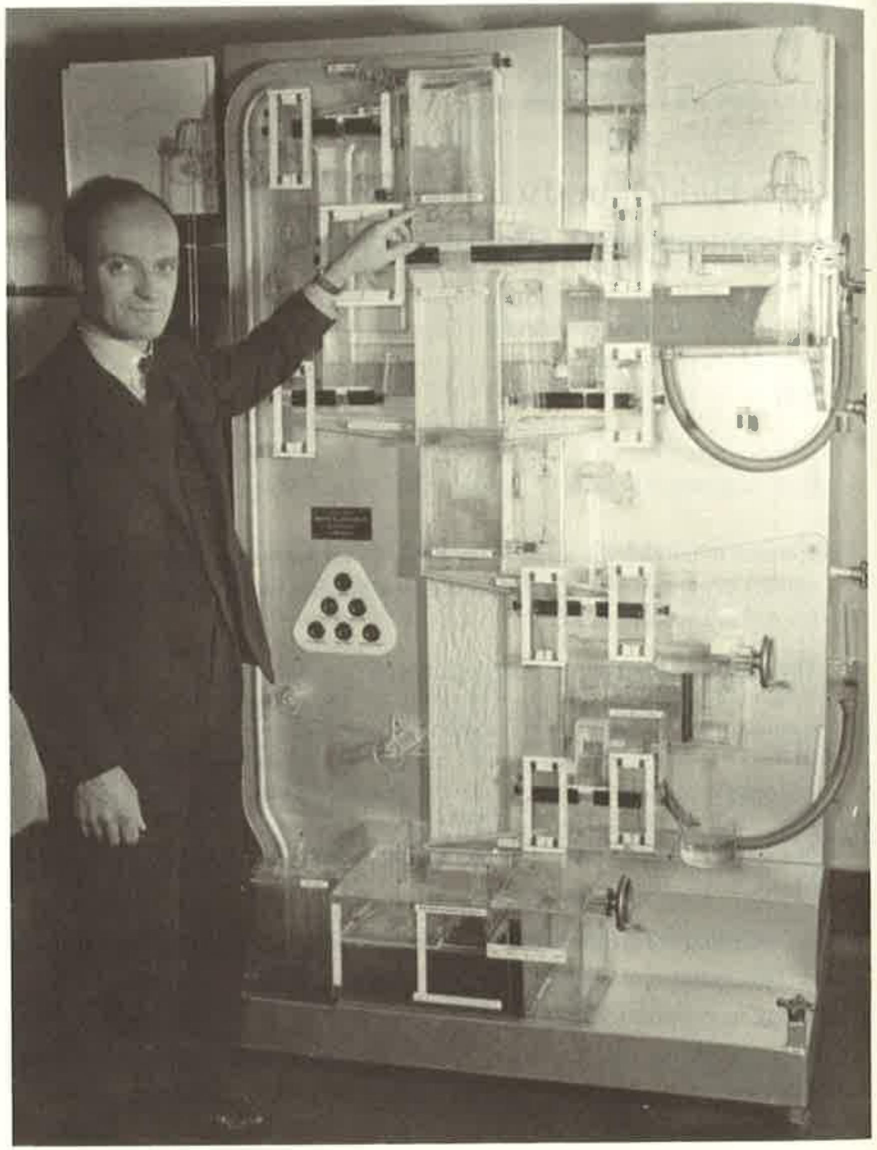


Figure 13.1 Bill Phillips with the hydraulic machine, Mark II. Photograph, probably taken in the 1950s, from the Vrije Universiteit Amsterdam Archive. By permission of the Vrije Universiteit Amsterdam.

used for demonstrations and teaching in the 1950s and early 1960s, these machines fell into disuse by the end of that decade. Recently, several have been restored and have taken on the status of icons, given pride of place in their owning institutions. The Phillips machine remains one of the few 'objects' that the history of economic science can boast, and one of these restored machines has found a prestigious home opposite Charles Babbage's calculating engine in the London Science Museum.[1] Yet mention of the machine in economic circles still usually produces a grin on every face. For economists who saw and worked with the machine, that grin is accompanied by admiration and appreciation of its qualities and those of its creator.

Although economics was not a model-based science in the 1940s, when Phillips made his hydraulic model, it has since become one, with mathematics providing the dominant forms for modelling. Despite the fame of his machine, and recent evaluations of Phillips' work (Leeson 2000), the highly unusual physical form of his model, and its three-dimensionality, have hardly been discussed in the history of economics (but see Barr 1988). This chapter aims to understand the importance of the third dimension in modelling by exploring Phillips' machine and comparing it with metaphors and with some 2-D models in the hydraulic tradition. We portray the issue as one of 'secrets', meaning by this term the elements in modelling which remain unarticulated and so secret or hidden. We treat these secrets at three levels: the secrets which may remain hidden in 2-D models but have to be revealed in 3-D models; those things which may still remain hidden even in the 3-D case; and the kind of hidden knowledge which gets communicated *only by using* the 3-D model.[2]

PHILLIPS AND THE BIRTH OF HIS MACHINE

Alban William (Bill) Housego Phillips (1914–75) was born in Te Rehunga, New Zealand, into a farming family. At the age of 15, he left school and became an apprentice electrician with the Government Public Works Department. Till 1935 he worked at a hydro-electric station. Then a period started in which he took several different kinds of jobs and began studying electrical engineering in the evenings. In early 1937, he decided to go to Britain by way of China and Russia, but the Japanese invasion of China forced him to go via Japan and Siberia. While travelling to Britain he had been taking a correspondence course with the British Institute of Technology.

Shortly after his arrival in London in November 1937, he took examinations of the Institute of Electrical Engineers, becoming a Grad. I.E.E. in early 1938. He was appointed an assistant mains engineer with the County of London Electric Supply Company. Then he joined the Army, being taken prisoner of war by the Japanese (Blyth 1978; 1987; Barr 1988; Leeson 1994). It was only after World War II, at the age of thirty-two, that Phillips started a degree at the London School of Economics (LSE); he took sociology as his major with economics as subsidiary, and received a B.Sc., at a bare pass level, in 1949.

The second quote from the head of our chapter, describing Phillips' difficulties with economics, might be taken as applying to any student going to lectures on macroeconomics in 1949. In Britain, macroeconomics was based around mainly verbal elucidations and extensions of the ideas found in John Maynard Keynes' *General Theory* (Keynes 1936). Economics teaching was, in the 1940s, predominantly non-mathematical (Gilbert 1989, 110), and not just for pedagogical reasons; as a discipline economics was on the cusp between the use of verbal and mathematical language. In the 1930s Keynes' book had actually been regarded as highly mathematical. But it does not seem as if his limited algebra produced clarity, and the immediate response from a number of his contemporaries, both in Cambridge and further afield, had been to build small abstract graphic or algebraic models to clarify what they thought was the meaning of Keynes' system and show how it differed from the older classical system (Darity and Young 1995). Though these little mathematical models were useful, in several ways their media and forms could not represent fully the ideas and conceptions of Keynesian theory. For example, Phillips remembered one problem, the Keynesian identity between savings (S) and investment (I), in the following terms:

> [I]t was my dissatisfaction with [Lerner's] article using the S, I identity to 'prove' that the 'classical' theory was completely fallacious that started me off looking for a technique which would show the process more clearly than is possible with two-dimensional graphs (quoted in Barr 1988, 317–18).[3]

We focus on three particular problems. First, the Keynesian verbal approach presented the economy as a dynamic system, but these little mathematical models tended to be static, so that to understand the system, or show the implications of changes in it, required using 'the method of comparative statics'. This involved comparisons of 'before' and 'after' situations by shifting curves on diagrams or by making a change in one equation and following the causal impact through the series of equations in the system. Proposals to create dynamic mathematical models had already been made during the 1930s by the econometricians who introduced both lags and differential terms into their model equations. But the difficulty of solving these systems of equations and questions of interpretation remained.

Second, arguments of the day about how the macroeconomy worked often involved reference to both stocks and flows. Although such notions were well worked out in the context of monetary theory before the 1940s, the Keynesian theory dealt in terms of the aggregate national income, and here these notions were sources of confusion and not well represented in the mathematical models.

Third, the macroeconomic breakthrough of Keynesian economics involved the principle of effective demand operating in a continuous circular flow of macroeconomic activity, but this too was not easily represented in the little mathematical models. The circulation of income or goods, conceived as a flow of liquid, goes back at least to François Quesnay's mid-eighteenth-century *Tableau Economique* (Quesnay 1972). In this respect, Keynesian economics joined a long tradition in economics, but one that rarely operated beyond the level of metaphor.

To get a grip on this macroeconomic thinking, and to resolve his own difficulties in understanding, Phillips used his engineering skills to create the famous hydraulic machine. The machine-building began in early 1949 with the help of Walter Newlyn, who had been only a year ahead of Phillips at LSE but was already a lecturer in economics at Leeds University. Newlyn's head of department, Arthur Brown, provided £100 to fund the prototype machine (which is still on display in Leeds). The machine was made and assembled in the garage of friends of Phillips in Croydon, south of London. In engineering the machine, Newlyn was the apprentice, but often, it seems, they had to stop work while Newlyn explained the intricacies of economics to Phillips so that he could decide how to model the next part. By the end of November 1949, Phillips had demonstrated this Phillips/Newlyn prototype (Mark I) machine to the assembled faculty of economics at LSE.

In 1950 Phillips enlisted the help of an engineering firm to construct a more complicated Mark II machine (Fig. 13.1) which incorporated a number of additional features. The engineering innovations were created by Phillips, but now he relied on the economic advice of James Meade, a professor at LSE who had participated in developing small mathematical models of the

Keynesian system. Phillips was soon given a lectureship on the strength of his machine demonstrations and a 1950 article about the machine and its use in the LSE-owned journal, *Economica* (Phillips 1950). In 1950 also, Newlyn published an article in the *Yorkshire Bulletin* (Newlyn 1950), based on his experience using the Leeds prototype.

It seems fairly clear, from the descriptions of the machine-building process, that Phillips did not build his machine by starting from the extant mathematical models and simply translating them, but rather tried to resolve the problems we have indicated above by directly linking the economic ideas with hydraulic ones. This was in part an iterative process in which Phillips began to learn about and understand the macroeconomic system, with the help of Newlyn and then Meade, and embedded this understanding in the machine. The process also involved Phillips incorporating elements he found in various publications. One was Richard Goodwin's 1948 proposal to represent the dynamics of the economic process not by difference equations but by differential equations, in other words, not by discrete steps but as a continuous process (Goodwin 1948). Phillips referred to Goodwin's paper several times in his article and designed the machine's governing relations to incorporate Goodwin's formulations.

The stock-flow conceptualisation of the machine was probably inspired by Kenneth Boulding's *Economic Analysis* of 1948. To clarify how prices regulate production and consumption, he depicted a hydraulic-mechanical device (Boulding 1948, 117) showing economic stocks and flows in terms of a piece of domestic plumbing (Fig. 13.2). Phillips referred to this picture as the analogy on which his machine is based (Phillips 1950, 284), and the right-hand side of the Phillips machine (Fig. 13.3) is clearly an extension of Boulding's diagram.

These two ingredients—Goodwin's dynamics and Boulding's hydraulic design—plus the ideas about economics that Phillips had acquired from Newlyn and Meade, had to be integrated to create the machine.[4] It provided for a circular flow of national income, with the relationships between the elements in the economy to be represented by tanks of liquid with in- and out-flows, and by valves governing the stocks and flows. The machine represented the aggregate economy, and could be set up to model both Keynesian ideas and alternative theses about the economy. A fuller description of the 3-D machine and how it represents the macroeconomy is given below. First,

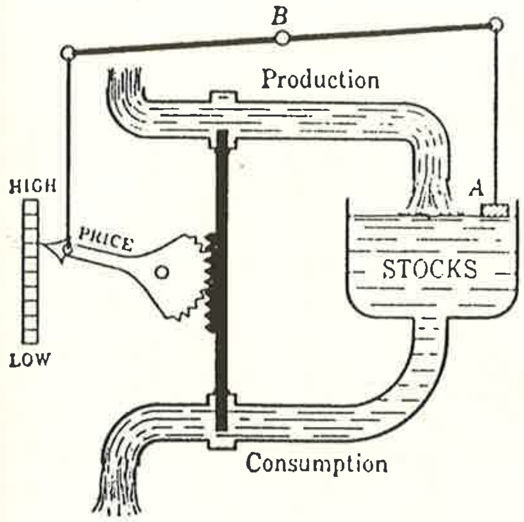


Figure 13.2 "How price regulates production and consumption". The figure shows how the price of a commodity may be compared to a valve, connected to a float *A* and a bar *B*, regulating the flows of production and consumption. Published in Kenneth E. Boulding, *Economic Analysis* (New York, 1948), 117, fig. 9. Source: Kenneth E. Boulding Collection, Box 3, Archives, University of Colorado at Boulder Libraries. By permission of the University of Colorado at Boulder.

though, we pause to discuss secrets, namely those things that are hidden but must be made explicit, even as we move from a metaphor to a 2-D model.

FROM METAPHOR TO 2-D MODEL

As we have noted, there is a long tradition in economics of understanding certain things as behaving like water and the economic system as acting according to the laws of hydraulics. For example, money is often thought of as liquid—it flows through one's fingers and leaks out of one's purse; in times of international financial crises, speculative flows of money or capital are reported daily in our financial newspapers. These figures of speech are usually and accurately referred to as metaphors.[5] Their interpretation is rather flexible and open; their usage restricts very little. The degrees of freedom are large and this encourages original insights. A metaphor might be called a one-dimensional model in the sense that it does not constrain

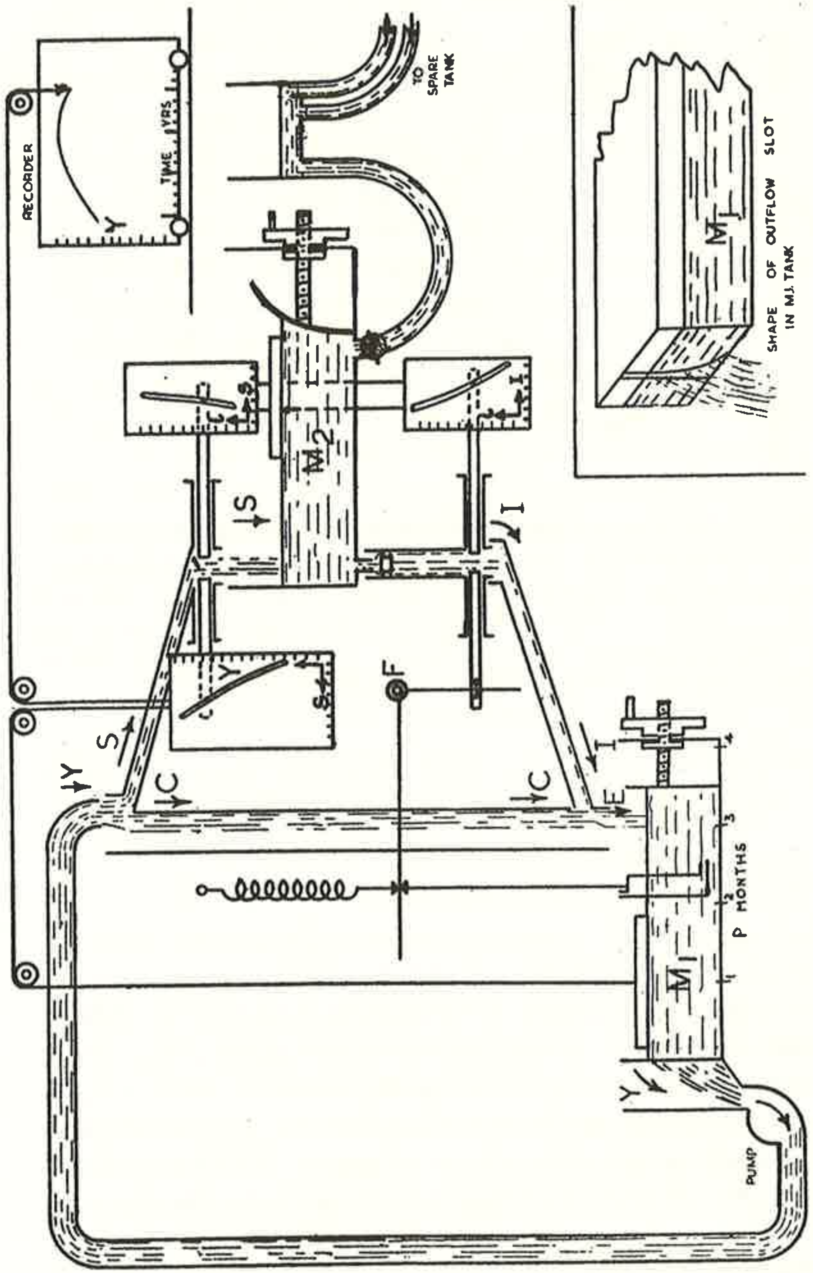


Figure 13.3 A simplified version of the hydraulic model showing an economy without foreign trade or government operations. The inset shows the shape of the outflow slot in the M_1 tank such that the rate of flow is proportional to the height of water in the tank. Source: A. W. Phillips, "Mechanical models in economic dynamics", *Economica* 17 (1950): 290, *fig. 3. By permission of Economica*, the London School of Economics and Political Science, and Blackwell Publishing.

our imagination, but rather gives it free rein even to the point of fantasy. When we come to build a model based on the metaphor, we have to make commitments about exactly what we mean.

First, moving from a metaphor to a model means you have to commit yourself to a particular hydraulic system, but there are several metaphors which do this, and choosing between them has different implications. What kind of an economy is this? And which analogical system would be most appropriate?[6] One possibility would be to think of the income in an economy as like a domestic plumbing system in which water comes out of the tap because of the head of water in the tank in the roof or in the town square. In economic terms this might be thought of as a supply-determined system. At first sight it does not seem quite right for the Keynesian economy, in which the great breakthrough was the idea that what made the economic world go around was the principle of effective demand. But of course, in such a plumbing system, gravity is also involved, and this might provide the analogy for the demand that pulls money or income around the system. Another possible metaphor might be the eighteenth-century view that likened the economic system to a human body with blood flowing around it. This contains the circulation idea Keynes wanted for economics, but we still have a problem with the motive power. The heart pumps blood around the body, but circulation may also depend upon demand elsewhere in the system.

A second aspect of this move from metaphor to model is that just as metaphors do not constrain very much, so they do not stretch very far. For example, in describing two markets as two connected ponds, we do not need to describe the ponds' shape and depth. To understand that the prices equalise, we can suggest several possibilities free of the constraints about how and what flows actually occur: buyers can move, goods can move, and so can money. But, as soon as we move beyond the level of metaphor to a model of such an hydraulic system, we are forced to be specific. We can show this clearly in the work by Irving Fisher, who, earlier in the twentieth century, designed several models on paper to represent the relationship between gold, the money stock, and the general level of prices (Fisher 1911).[7] His purpose was to understand the various different monetary standards that might be appropriate for the dollar, such as the gold standard and bimetallism (Fig. 13.4), which were the subject of considerable political and economic debate at that time.

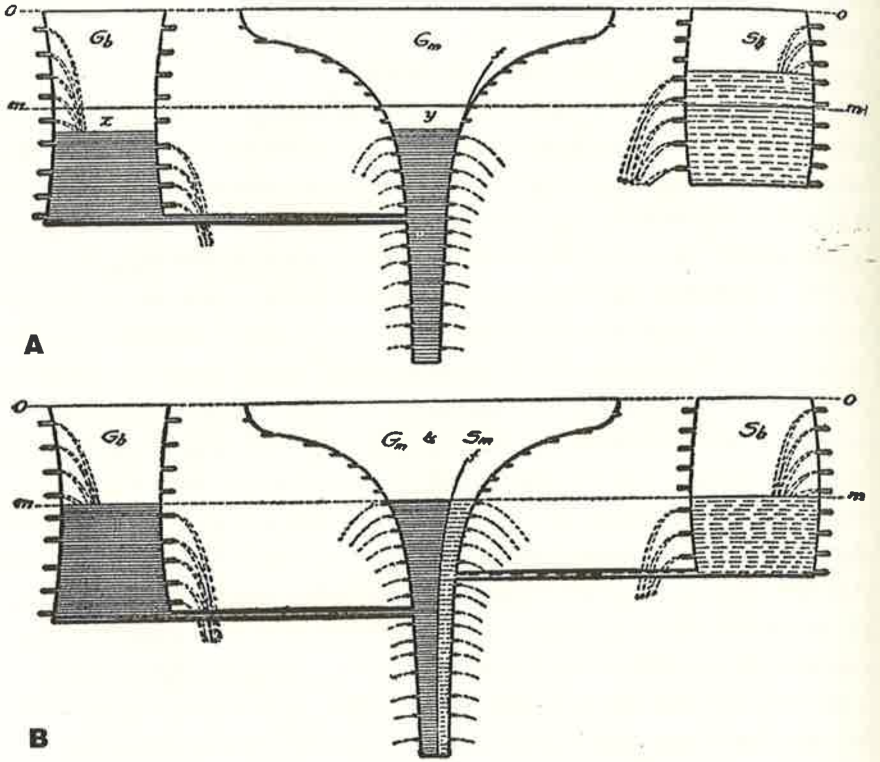


Figure 13.4 Bimetallism demonstrated by Irving Fisher's connecting reservoirs models. The contents of the reservoirs represent the stock of gold bullion (G_b), gold money (G_m), silver money (S_m), and silver bullion (S_b). The waters representing gold and silver money are separated by a movable film (f). Source: Irving Fisher, *The Purchasing Power of Money* (New York, 1911), 119, fig. 7.

In these fairly elaborate 2-D analogical models, Fisher designed a mock-laboratory system involving three vessels containing, from left to right, gold bullion, currency, and silver bullion, all in liquid form, and various inflow, outflow, and connecting tubes. In one respect, he was clever in filling in the space between the metaphor and his model—he was able to specify all the flows and stocks as well as the control valves in economic terms. By portraying various different arrangements of the pieces involved, he could use the model both to demonstrate various propositions in economic theory and to interpret the arrangements and results in terms of the observed monetary systems of the late nineteenth century and earlier times. But his ability to do

all this successfully depended on the amounts of liquids in the vessels, and their shapes, positions, and relations. What were these vessels? Why should they be of any particular shape or arranged in any particular relation to each other? The answer is that Fisher designed their shapes and various arrangements 'just so' in order to make the demonstrations work—by thought experiments using the diagrams (Morgan 1999).

The point to notice is that in this 2-D paper modelling Fisher could fill in the metaphor in such a way that he could buy into the power of the hydraulics analogy when he wanted to, but could also finesse those parts of the system which did not have such a clear or ready-made analogy, or seemed strongly negative in their analogical connotations. He could, in part, choose where to have the hydraulic constraints bite and where he could or would ignore them.[8] This is not possible in a working 3-D model: all the elements in the metaphor have to be filled in for the model to work.

CONSTRAINTS AND COMMITMENTS: FILLING IN THE THIRD DIMENSION

Due to the complexity of Phillips' hydraulic machine, its description and an explanation of how it works are usually introduced with the aid of 2-D diagrams.[9] We shall follow this practice, but will argue later that the importance of the machine is not only its three-dimensionality, but also that in use it shows processes through time and so is, in effect, a 4-D model.

The first point to clarify is how the machine represents the aggregate economy as a circular flow of liquid which distributes itself through the system of pipes and tanks depicted in the rather simple 2-D flow chart shown in Figure 13.5. To imagine a single circulation of the liquid, we begin at the bottom tank, which contains a stock of coloured water representing 'transactions balances' (M_1). (We also give the symbolic names used in Figure 13.6 so that the same circulation can be followed in that more realistic drawing of the machine.) The outflow of water from this tank, that is, 'income' (Y), is pumped up to the top of the machine: this flow of income gushes down through the tanks and channels becoming expenditure (E) in the system and representing the stocks and flows of money in the economy. (Money is conceived as a real command over economic goods: there are no prices in the model.) Taking up the details of the story from the top of the machine, 'taxes' (T) are siphoned off leaving 'disposable income' (Y-T). A

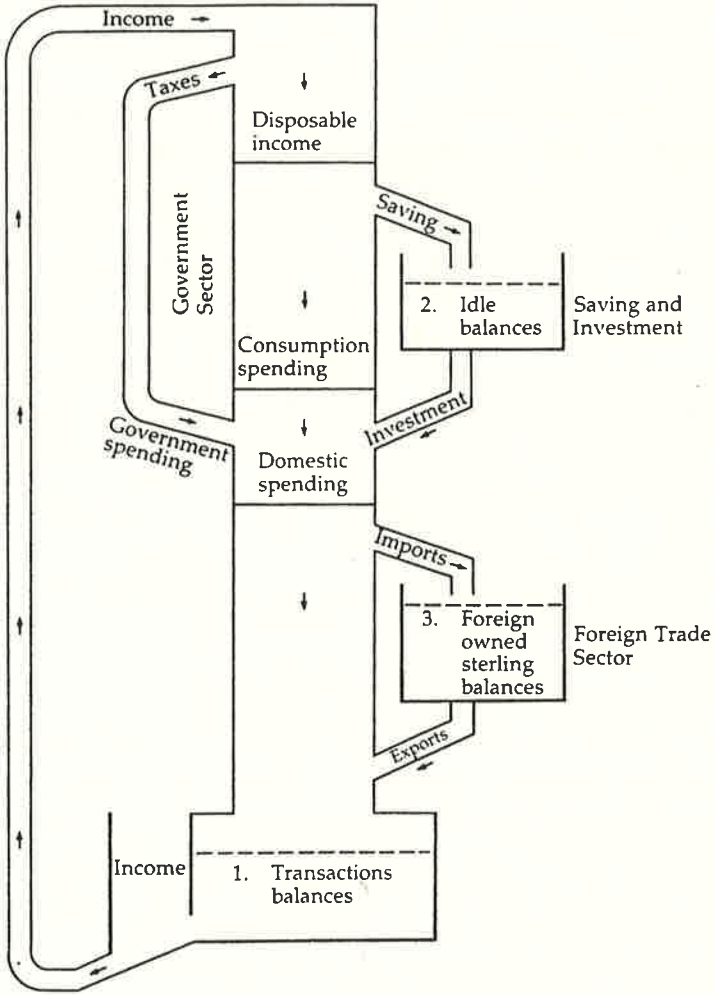


Figure 13.5 "A simplified view of the Phillips machine". Flow chart without control and servo mechanisms. Source: Nicholas Barr, "The Phillips machine", *LSE Quarterly* 2 (1988): 321, fig. 1. By permission of Nicholas Barr, the London School of Economics and Political Science, and Blackwell Publishing.

part of disposable income becomes 'consumption spending' (C) and the rest 'saving' (S). Savings are added to a stock of investments funds, called 'idle balances' (M_2), from which 'investment' (I) is withdrawn. (Figure 13.6 also shows a connecting side channel which allows the government to borrow from these balances, or repay debt to them.) Taxes can also be used by the

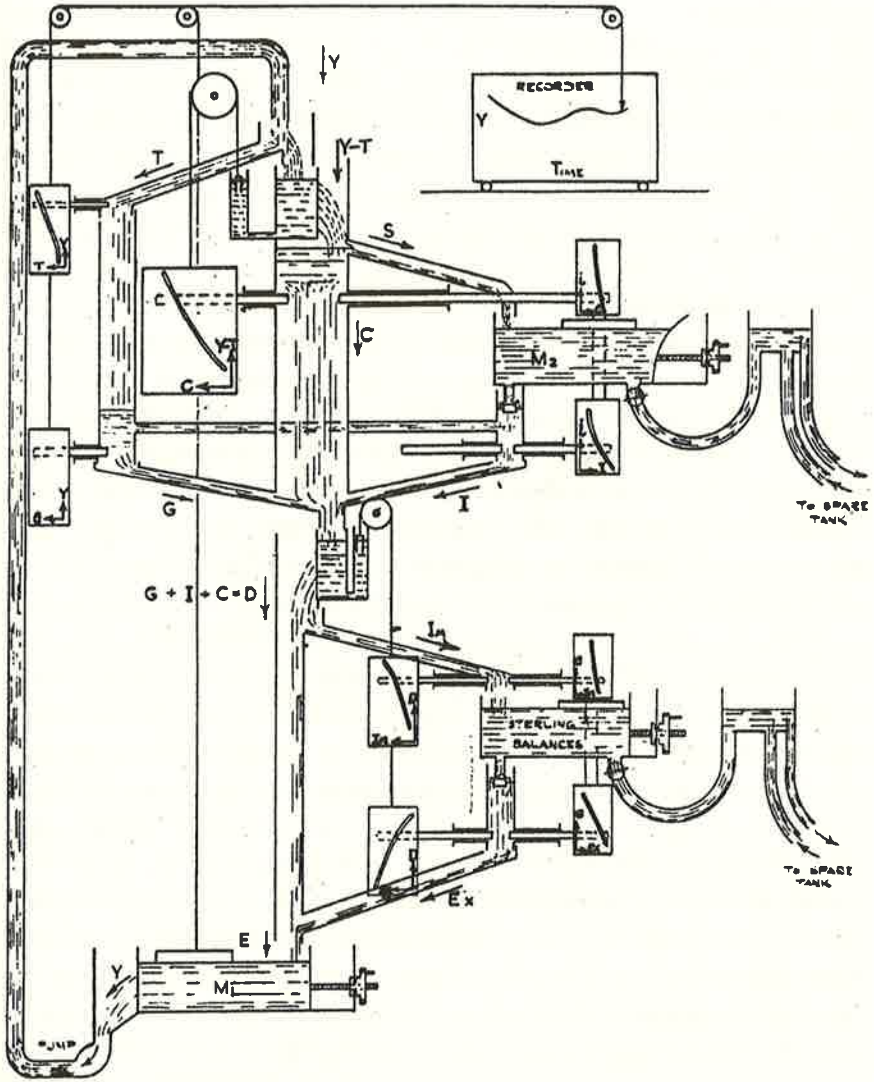


Figure 13.6 A 2-D representation of the Phillips machine, Mark II. Source: A. W. Phillips, "Mechanical models in economic dynamics", *Economica* 17 (1950): 302, fig. 4. By permission of *Economica*, the London School of Economics and Political Science, and Blackwell Publishing.

state in the form of 'government spending' (G). Investment expenditure and government spending are added to the flow of consumption spending to form 'domestic spending' ($D = G + I + C$). 'Imports' (Im) are removed from the stream of domestic expenditure and a flow of 'exports' (Ex) is added to form the flow of national expenditure (E) which enters the transaction balances tank (M_1) at the bottom of the flow chart. The change in the level of that tank, which amounts to the change in income, is registered in the recording device on the top right-hand side (Fig. 13.6).

The second characteristic of the machine that requires description is how it represents the governing economic relationships between the internal flows and stocks. These are shown in the more detailed diagrams in Figures 13.3 and 13.6. The machine has a series of valves that open and close depending on the level of water in the three tanks, and on the flow of water in the relevant part of the system. In some cases a float on the top of one of the tanks is connected to the relevant valve via a cord and a pulley (e.g., in Figure 13.6, the effect of idle balances on savings). In other cases (e.g., in Figure 13.6, the effect of domestic expenditure on imports) a similar effect is achieved by a small float connected to the relevant valve via a servo mechanism, which uses a small motor (at the back) to amplify any downward or upward movement of the float (and may also involve a lag in the adjustment). But the difference between these two float mechanisms says nothing of the economics. The forms of the economic relationships governing the system are found in the cut-out shapes inserted into the square or rectangular perspex slides connected to the other end of each float mechanism. It is these shapes that govern the extent of opening and closing of the valves in response to changes in stocks and flows. Thus, in economic terms, each of the inflows and outflows is governed by a specified economic function (e.g., in Figure 13.6, the consumption function, which relates consumption to income).[10] If you look carefully, first at Figure 13.3, you may get some sense of how these functions work. Figure 13.6 depicts all nine of these relations (look for the rectangular function holders), which together govern the stocks of money in the three tanks and the flows of income and expenditure through various parts of the system.[11] But understanding the diagram is not easy, and a detailed explanation of the economics of the whole machine using such a diagram requires an experienced machine-user and much time and space. It is even more difficult to imagine the ultimate behaviour of the flows of 'money', and changes in them, when the machine is at work.

This brief description of the economics and hydraulics of the 3-D model of Phillips shows how the gap between metaphor and model might be, and in another sense has to be, filled in. Phillips was required to specify the economic elements and relations of the macroeconomy in terms of the following physical elements:

(a) the flows and stocks in the system;
(b) the size, shape, and relative positions of the tanks (containing the stocks);
(c) how the flows go between different stocks including feedback loops;
(d) the nature of the connections between flows and stocks: valves, sluices, plugs, springs;
(e) the motive power(s) and their positions in the system;
(f) the viscosity of the fluid;
(g) the shape of the outflow slots in the tanks;
(h) the devices to maintain a constant head of water over the valves;
(i) measuring devices so that flows can be monitored (for which they are transformed into stocks) to regulate the valves via floats or servo mechanisms; and
(j) registration devices to see the effects of manipulations (which can sometimes be compared with non-machine calculations).

Items (a) to (c) in this long list involve commitments which already had to be made in the case of the 2-D models, as we can see from the detailed diagrams of the machine. Items (d) to (i) are in effect elements that might remain secret or hidden in the 2-D model, either because they can be more easily omitted or because they do not really have to 'work'. To put it another way, the list is a pile of boxes, each and all of which have to be opened and filled to make the 3-D machine work. All the hydraulic elements in the list, namely (a) to (i), are required to be specified fully, rather than partially as Fisher had done, for if the machine does not work successfully as a hydraulic system, it cannot function as a 3-D model.

But three points should be made about this process. First, there were various ways to make the model work. This points to implicit assumptions or decisions about the details of the economic equivalences, for the choices can be made to represent one or another interpretation of the relations thought to occur in the economy. Thus, the 3-D model that Phillips built was constrained not only by the laws of hydraulics, but also by the modeller's commitments to his account of the economic world being modelled.[12] The second point is that, although all the bits in the machine must be specified, not all the things in the economy must be specified in the machine. With the help of Newlyn and Meade, Phillips made his model to represent a set of elements and their economic relations, along with a set of controls and regulators, all built in line with economic theories of the day; he did not make a model to represent everything in the economy. Finally, as we shall discuss in the next section, not everything specified in the machine will necessarily have an economic meaning.

Choosing to model the economy as a 3-D hydraulic machine involves both a great many constraints imposed from the physical side and a whole lot of commitments about how the economics is physically represented. But these are not separate steps: each modelling decision involves both a physical constraint and an economic commitment at the same time. To make commitments about the analogue to the economy at the same time as working within the physical constraints requires tremendous creativity. Phillips demonstrated such creativity both in the craft skill he brought to bear in building the machine,[13] and also in the design choices he made so that the machine could be used to demonstrate many different (but by no means all) aspects of the macroeconomic thinking of his day.

WHAT STILL LIES HIDDEN IN THE MACHINE?

The constraints and commitments of 3-D modelling will reveal to the machine-builder elements which remain secret or hidden in 2-D models; such discoveries are inherent in the adventure of model-building. But to the onlooker, important elements are still hidden in the Phillips machine, and these we explore in this section. Even if we stand with the machine working in front of us, there remain invisible elements in the model as well as things hidden behind the model (Fig. 13.7); and, last but not least, there is tacit knowledge embedded in the modelling.

In Phillips' machine, two elements create the circular flow of liquid: an electric motor hidden at the back of the machine (Fig. 13.7), which has to be switched on to force the water to go upwards, and subsequently gravity which draws the water downwards through the system. One of the most important characteristics of 3-D physical objects is that they are subject to gravity. Gravity is the invisible hand that keeps our physical world together, and we become immediately aware of this characteristic if we want to use 3-D

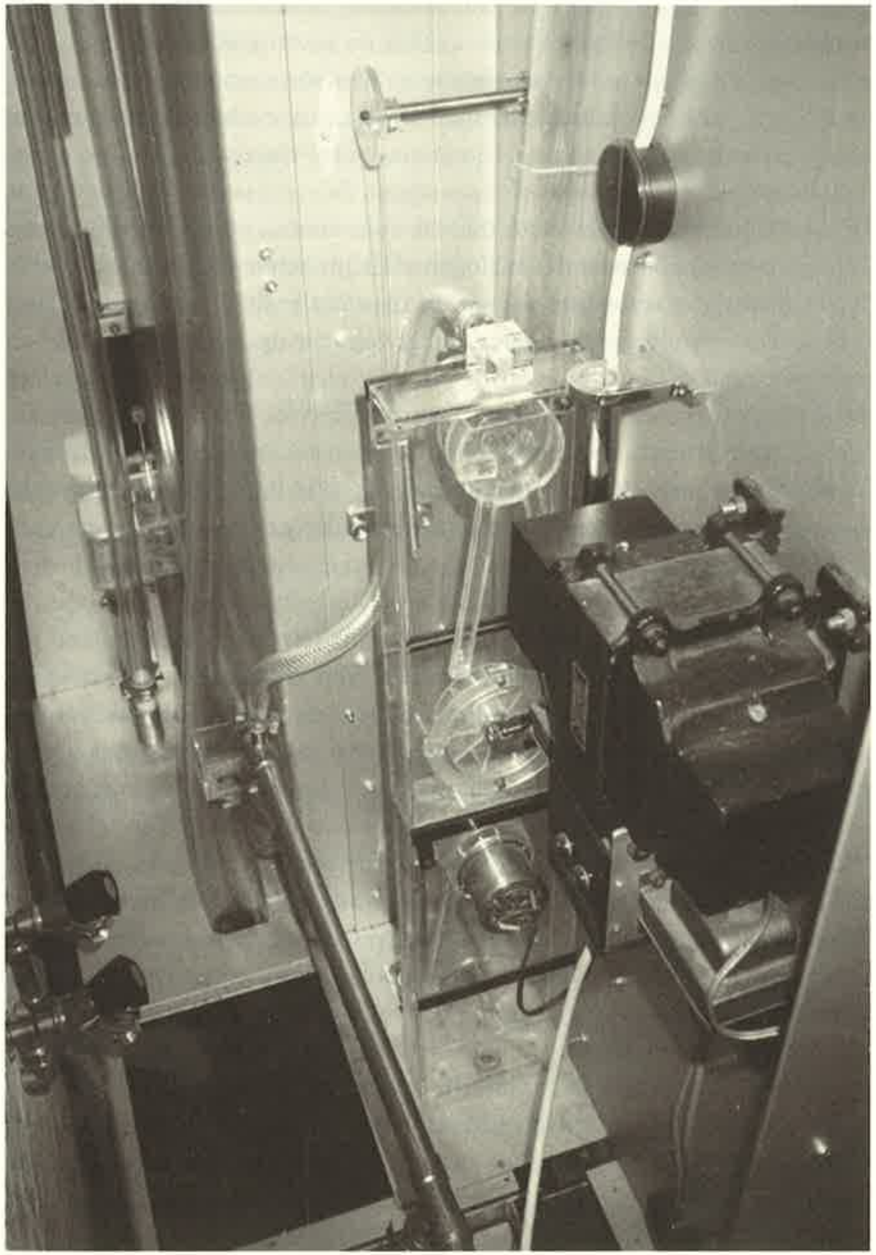


Figure 13.7 Behind the Phillips machine exhibited at the Erasmus University Rotterdam. Photo by Marcel Boumans.

objects as analogical models for understanding economics. Then we see that sometimes these 3-D objects work as they do because of this hidden force. One example where gravity works naturally in the economic model can be found in another of Fisher's 2-D models, where a mechanical balance and its dependence on gravity act as an analogue for the equation of exchange between money and goods (Morgan 1999). In contrast to the Fisher case, in the Phillips machine it seems there is no economic equivalent of gravity. It might be thought to be the analogue of the principle of effective demand, but that would be to negate the idea of the circular flow of the economy in which there should be no separation between the upstream (dependent on the electric motor) and the downstream (dependent on gravity). We therefore interpret gravity as an invisible element required for the machine to work, and the electric motor required to pump the water round as a hidden element.

Hidden elements may also be indicated by the bits of the machines the restorers did not understand. This was particularly true of the various connections between the elements and the system of sensors: "The facts behind these features were painstakingly deduced, though it would have been an impossible task without our comparison of the existing machines and the advice of those, particularly James Meade, who remembered operating the machine or helping when he first tackled these problems" (Moghadam and Carter 1989, 25). For Phillips, the back of the machine was just as important as the front, and we know that it posed the restorers an even greater challenge, perhaps because it was less well documented and its economic meaning remained unclear. This indicates further secret elements. The tacit knowledge hidden in, and behind, the machine was clearly immense, and had to be somehow reassembled by those rebuilding these machines.

In this list of 'secret' elements we should not forget that we also need a person to fill up the tanks, empty the overflow tanks (also hidden around the back), and turn the motor on. In fact, most times that the machines were used, they also needed an engineer in attendance, for they did not always work properly and often deposited red water on the floor.[14] If Phillips was there, all was well and good. But as the machines got older, getting them to work was increasingly difficult. Without Phillips' enormous tacit knowledge of engineering and of his machine, it was difficult to keep the machine alive.

Some of these secret elements need not have been hidden. There is no reason why the electric motor could not have been visible, for example. Nor is it the case that such elements are found only in 3-D models; they may equally appear in 2-D models. These elements, whether hidden or not, seem to have in common that we cannot easily give them an economic interpretation, yet they are critical to the working of the machine. But it would be wrong to see these elements as necessarily undermining the potential demonstrative power of the machine. Consider, as a comparison, the planetary-motion models of earlier times, for these bear the same kind of relation to the universe as Phillips' machine does to the economy. The planetary models were built with particular attention to the relationships between the parts that they were designed to understand and demonstrate. But neither the physical way the elements were joined up, nor the control systems which regulated their use, were necessarily particularly representative of the beliefs of the period about how the planets moved and why. Such models did not rely on the law of gravity, nor did their makers believe that the planets were made of wood or papier mâché and linked by metal rods. Similarly, economists did not believe that the economy consisted of perspex tanks and plastic tubes with red ink circulating around, but they did take seriously the notion that the main elements of the national income in the aggregate economy were rather liquid and that the stocks and flows thus conceived obeyed, in some ways or to some degree, the laws of liquids. For economists, this was more than a metaphor; it was an informative and substantive analogy.

Modelling is a process in which we try to represent some aspect of the world. We do not expect our model to represent the entire world, nor do we expect every part of the model to be represented. There are always some things, which are likely to be untranslatable or just plain wrong. But these elements do not necessarily cause difficulties in learning from the model—we willingly suspend disbelief in order to focus on the demonstrative power of those parts which do represent.

UNDERSTANDING THROUGH THE MIND'S EYE

Moving from one to two and finally to three dimensions involves an increase in commitments and constraints and ought to have some kind of pay-off in understanding. For what is the purpose of building such machines unless there are further insights to be gained? Does it alter the kind of knowledge we have? What are the secrets of understanding revealed by the 3-D machine that are not to be found in the 2-D diagram? We argue here that building and using such machines provides insights that are closely related to an engineer's way of understanding.

In *Engineering and the Mind's Eye*, Eugene Ferguson argues that good engineering is as much a matter of intuition and nonverbal thinking as of equations and computation. In nonverbal thinking, a special role is assigned to the "mind's eye", "the organ in which a lifetime of sensory information—visual, tactile, muscular, visceral, aural, olfactory, and gustatory—is stored, interconnected, and interrelated" (Ferguson 1992, 42). The mind's eye is that part of our memory built up by all the sensory information that we use in our efforts to understand the world. Because visualisations appeal to this memory, visual language is the *lingua franca* of the engineers: "It is the language that permits 'readers' of technologically explicit and detailed drawings to visualize the forms, the proportions, and the interrelationships of the elements that make up the object depicted" (Ferguson 1992, 41–42). As such, visualisations can function as an alternative for using the mathematical language, and they are particularly useful in helping understand complex systems. But, since a 2-D analogue is in principle a sufficient means of visualisation, it is still not clear why 3-D machines are built.

An engineer learns to understand the world through the "eyes and fingers", which are according to James Nasmyth "the two principal inlets to trustworthy knowledge in all the materials and operations which the engineer has to deal with" (quoted in Ferguson 1992, 50). There are many anecdotes of Phillips reminding us of his engineering approach to life:

> James Meade . . . recalled that Phillips stayed one summer with the Meade family in a cottage which contained a broken-down, out-of-tune piano: "We moaned what a pity it was so out of tune that we really couldn't use it. Bill went to the car, fetched his spanner and set to work tuning the piano . . . this anecdote shows how directly he was prepared to tackle any problem" (Leeson 1994, 606n).

Being an engineer, Phillips built the machine to learn and understand economics through his eyes and fingers rather than through mathematics and words. The quote from Kelvin which began our chapter gets at a similar kind of understanding: understanding the principles of something means being able to make a model of it, and, we would emphasise, 'a working model'.[15] But if Phillips built a model only for his own interest, an electronic

analogue machine might have been a more obvious choice, because he was, after all, an electrical engineer. And in fact, in the same period as Phillips developed his machine, other 'electric analogues' were being built and used for economic investigations. The Aeracom analogue machine for studying oscillations was used to investigate inventory oscillations (Morehouse, Strotz, and Horwitz 1950). A simple electronic circuit for determining prices and exports in spatially distinct markets was used by Stephen Enke in 1951 (Enke 1951).[16]

We can think of the Phillips machine as an analogue computer but it is clear that Phillips' interest was not only (or primarily) in computer processing power and calculation, but also in how best to represent a macroeconomy so that its activities could be displayed and understood as a process (Swade 1995, 17).

> Fundamentally, the problem is to design and build a machine the operations of which can be described by a particular system of equations which it may be found useful to set up as the hypotheses of a mathematical model, in other words, a calculating machine for solving differential equations. Since, however, the machines are intended for exposition rather than accurate calculation, a second requirement is that the whole of the operations should be clearly visible and comprehensible to an onlooker. For this reason hydraulic methods have been used in preference to electronic ones which might have given greater accuracy and flexibility, the machines being made of transparent plastic ('perspex') tanks and tubes, through which is pumped coloured water (Phillips 1950, 283–84).

The mathematical model (like a computer) could be used to calculate solutions, but only for a restricted type of relations (those which could be easily solved). The mathematical models could, by the use of comparative statics, show certain steps in a dynamic process, but at the cost of missing much of the story. The analogue computer that Phillips built was both unrestrictive about the form of relations (any shapes could be cut into the governing slides) and it showed the full interactive and dynamic process, how things worked, directly.[17]

It is particularly important that Phillips aligned himself not with the mathematicians, but with gaining knowledge of the economy through the mind's eye, Ferguson's engineering mode of comprehension. Because of the inadequacies of words and mathematics to represent complex systems like the economy, models or machines are built to study both processes and outcomes. Because the machine involved a reasonably complex set of interconnected components and relationships, neither the processes nor the final outcomes were obvious. Using the hydraulic machine model makes these processes and outcomes evident and enables us to understand complexities of the economy through our eyes and fingers.

All the records show that the demonstrative power of the Phillips machine made a deep impression. Seeing the machine working is different from seeing pictures of it, as those who have seen the Philips machine working readily attest. Spectators could not only see the red water streaming through the pipes, but also hear the bubbling and splashing as it ran through the machine. They were able to see not a 2-D picture or system of equations, or even a static 3-D representation, but the kind of interrelated and dynamic cause–effect changes over time that economists suppose to happen in the circular flow of the aggregate economy. The working machine was a 4-D representation.

The Phillips machine was used to answer various questions about the dynamic economy it modelled.[18] As we have seen, the machine had valves that could be simply opened and shut manually. But they could also be controlled via the set of 'slides', each of which embodied a particular functional relationship between the relevant variables and could be changed. In principle, the relationships could be, and sometimes were, non-linear.[19] Once set going, the machine was used by changing the positions of one or more of the valves, and/or their governing relations. The user could then follow what happened and see the sequence of effects of such a change as they worked through the whole system, and thus understand how the immediate changes were transformed into longer-term effects as the circulations of income and expenditure continued. In this way, unlike the comparative statics of the mathematical demonstrations, the machine demonstrated a true dynamics. The effect of a change in policy or behaviour on national income could be 'measured' on a calibrated scale, and sceptics or those wishing to check the system could compare the result with arithmetical calculations using the mathematical relations expressed in the governing slides.[20] At first, it was also expected that the machine could be adjusted to represent the real timescale of changes, as we see in the bottom tank calibrations in Figure 13.3, but this seems to have been difficult to achieve. Finally, the flexibility and complexity of the machine offered many different options: by altering the governing slides, the machine could be set up and used as an experimental

instrument to investigate various different theories about, and institutional arrangements of, the economy.

Phillips' faith in the ability of his machine to produce comprehension out of confusion proved correct. The machine as a large physical 'inscription' created 'optical consistency' in the sense Bruno Latour has defined: all the theoretical elements and institutional arrangements were made homogeneous in space in such a way "that allows you to change scale, to make them presentable, and to combine them at will" (Latour 1986, 7–8). The first time the prototype machine was demonstrated at LSE, in the weekly seminar for faculty and graduate students, has become the subject of folklore. The seminar was convened by Lionel Robbins, head of the economics department, who was sceptical about Phillips' hydraulic machine: "all sorts of people", he said, "had invented machines to demonstrate propositions which really didn't require machines to explain them" (Barr 1988, 310). From Robbins' and others' recollections, we learn that Phillips began by giving a lecture on the Keynesian system:

> They all sat round gazing in some wonder at this thing [the machine] in the middle of the room. Phillips, chain-smoking, paced back and forth and explained it in a heavy N.Z. drawl. Then he switched it on. And it worked! "There was income dividing itself into saving and consumption ...." He really had created a machine which simplified the problems and arguments economists had been having for years. "Keynes and Robertson need never have quarrelled if they had the Phillips machine before them".[21]

The demonstration convinced the participants that the on-going argument about the relative merits of the theories of Keynes and Dennis Robertson over the determination of the interest rate was settled. Previous arguments had claimed that these were alternative (rival) theories; or that they were essentially the same. According to the Phillips machine, they were to be understood as complementary claims about the stock of idle balances (the tank labelled M_2) and the liquidity preference function (represented in the side panel of the tank) and the flow of savings and investment funds (the I and S flows). Further, the continuous circular flow of the machine was able to demonstrate the initial changes, the chain of further changes, and their effects on the final equilibrium values.[22] The machine clarified, and sometimes 'settled', some of the endless arguments that arose from the verbal treatment of Keynesian economics and for which the available mathematical treatments seemed insufficient.

The machine showed things economists already thought they 'knew' via reasoning with words or with mathematics, but, to an extent (doubtless variable with different people) the understanding of that knowledge had remained both hidden and limited. From the demonstration of the machine, they really came to know and understand in their mind's eye the knowledge implicit in the macroeconomic thinking of the day. Thus, though neither mobile nor flat like Latour's 2-D inscriptions, the Phillips machine functioned in those same overlapping domains of visualisation and cognition which Latour ascribed to representation devices such as maps and diagrams (Latour 1986).

Richard Lipsey, who arrived as a student at the LSE soon after this demonstration, remembers how, from demonstrations with the Phillips machine, they immediately understood the notion of a model and how it could be used. The verbal reasoning and the comparative statics of mathematics and geometry were replaced by the real, not mathematical, dynamics. You could really see the economic process at work, you could see and understand the individual relations and the interactions between them in a way not available before.[23]

To understand why this machine use was so important in the 1950s, it helps to know something more about the design context. At that time, the Keynesian analysis was believed, at least in Britain, to offer governments a kind of instrumental control over the macroeconomic system via their ability to influence effective demand for goods and services. Keynes' success in managing the British war economy gave added credibility to this programme of macroeconomist as engineer. After the war, 'fine-tuning' government fiscal policy (by spending more or taxing more) was used to create multiplier effects in demand elsewhere in the economy. By such tuning, it was thought that the business cycles of the interwar economy could be mitigated, and the economy kept on a growth path. During the mid-1950s particularly, a stronger systems-control idea grew up in economic circles. Although such control-engineering notions of the use of Keynesian economics were relatively short-lived, they were particularly compatible with Phillips' background, and his work through the 1950s continued in this vein.[24]

The machine suggests the possibility of control, but at the same time it demonstrated the vulnerability of the relations and hence the dangers of such a project. James Meade regularly used the machine to demonstrate such policies in his teaching at LSE during the 1950s. One of his most enjoyable demonstrations was to appoint one student Chancellor of the Exchequer and another Governor of the Bank of England, and have them attempt to get the economy back to equilibrium, each using their own instrument of control to achieve a set target of national income. The usual outcome was confusion and leakages—from which students really understood the difficulties of fine-tuning and the importance of policy coordination.[25] The complicated dependencies in the machine (even if simpler than those of the real economy) showed just how difficult it was to co-ordinate or control the system.

WHEN VISUALISATIONS ARE ILLUSIONS

As we have seen, visualisations can lead to better understanding. But the opposite is also possible. If a visualisation contradicts the sensory information stored in our memory, it will lead to confusion, disorientation, or astonishment. Sometimes this is for aesthetic reasons, like the optical illusions in Escher etchings, or sometimes just for fun, like the Tom and Jerry cartoons. But water that streams upwards by itself never leads to a better understanding of either hydraulic or of economic principles. This was a little bit of a problem for the Phillips machine (remember the hidden pump). The problems are more clearly evident in FYSIOEN, a computer animation of a hydraulic system representing a macroeconomic model developed for PC usage, dating from the late 1980s.

FYSIOEN, a Dutch acronym for Physical–Visual Operational Economic Model for the Netherlands, represents a number of the most important mechanisms of the macroeconometric model (MORKMON) used in the Nederlandsche Bank (the Dutch Central Bank).[26] FYSIOEN was designed to help users gain understanding of the complex mathematical model by translating it into the visual domain: "The visual model affords more rapid and better insight—to more advanced model users as well—than a set of mathematical equations with explanatory notes" (Kramer et al. 1990, 159).

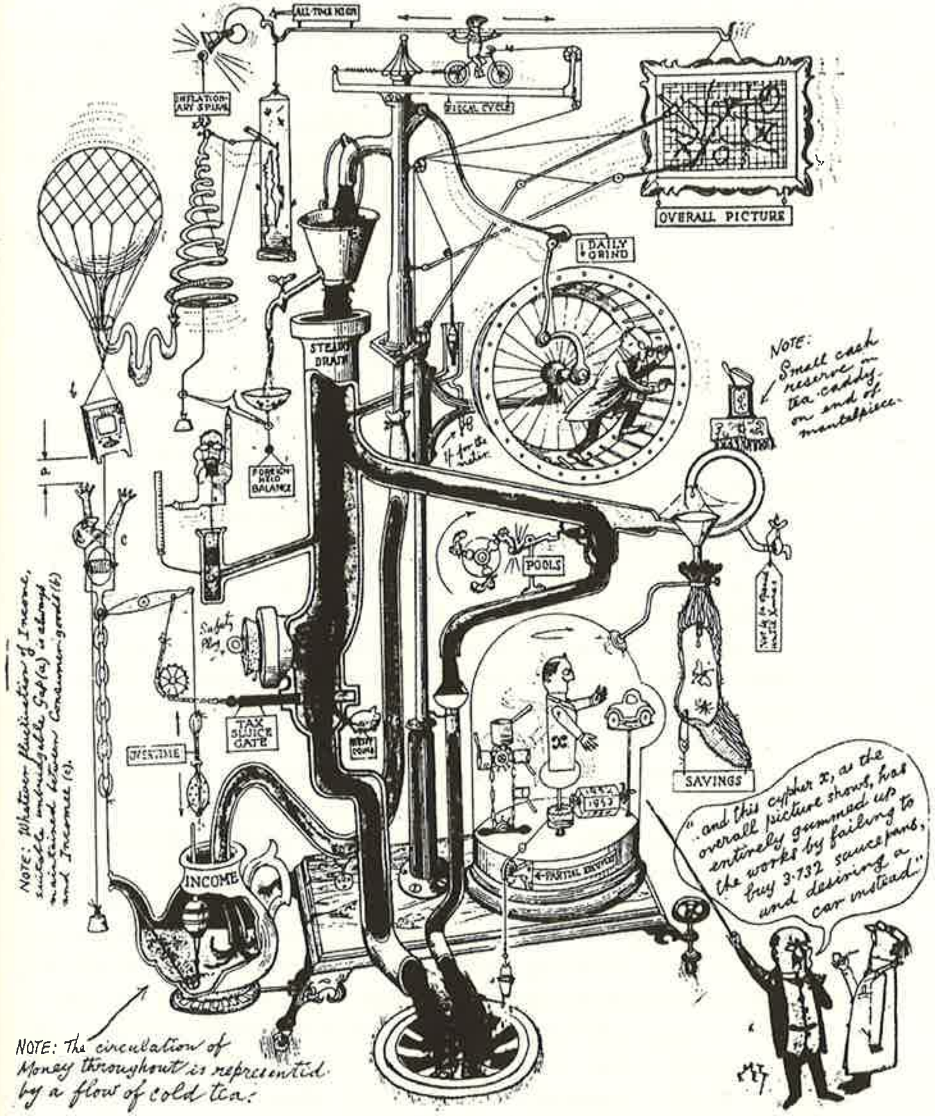
But there were problems in developing FYSIOEN. Although it required no motor to force the water round the system, what you saw in the computer animation were only coloured areas increasing or decreasing. You did not see a streaming of liquid, you heard no noise or splashing of running water. During the development of FYSIOEN several improvements to the animation, intended to make the 2-D visualisation behave more like a 3-D system such as the Phillips machine, were suggested (Reus 1987, 6–7). For example, the addition of noise and of arrows to show directions of flow, and the possibility of users manipulating the visual model. The PC computing technology of the time limited the possibilities. Some of these improvements were made, but even if all of the suggestions had been incorporated into FYSIOEN, the visualisation remained an illusion. For example, there were occasions when a cistern might fill up without the tap being opened. The equations of the economic model guiding the motion of the pictures were translated by a physics graphics package which interpreted them in terms of colours and sizes of predetermined shapes. The unfamiliar mathematics was translated into an animated representation that seemed to be in the more familiar language of hydraulics, yet it did not work according to the laws of hydraulics. Not every visualisation necessarily increases our understanding.[27]

Experience of such computer modelling suggests that more can be learnt from a 3-D model than a 2-D representation of a 3-D machine. Two points seem important. First, there appear to be certain aspects critical to the demonstrative success of 3-D models which remain hidden in various 2-D representations. Second, there are cognitive differences between using non-physical models (including computer-generated designs) and physical versions of the hydraulic model. At stake here are issues not just of dimensionality, but also of the familiarity of the representations.

ECONOMICS: THE RULES GOVERNING THE HOUSEHOLD

Hydraulic systems seem to be particularly important in analogical modelling just because we are all familiar with our domestic plumbing: this point is central to a *Punch* cartoon of 1953 by Rowland Emett in which the British public is invited to understand the Phillips machine through a vision of a domestic economy running on the circulation of cold tea around a Heath-Robinson kind of machine (Fig. 13.8).

Phillips' own childhood memories must have involved something like living inside a Phillips machine. His sister's description of their domestic economy tells how their mother first designed a system to provide running water in the house, and their father then adapted another water flow to provide electricity first in the milking shed, and then for lighting inside the house.[28] It was a kind of set-up rather like the *Punch* cartoon, in which



MACHINE DESIGNED TO SHOW THE WORKING OF THE ECONOMIC SYSTEM

Figure 13.8 "Machine designed to show the working of the economic system". Cartoon by Emett. Source: *Punch*, 15 April 1953, 456, from the Punch Library. By permission of Punch Ltd.

the luxuries denied to their neighbours, electric power, running water, etc., were all hooked up together via his parents' ingenuity. With this experience of domestic economy, and 'the rules governing the household', hydraulics was surely the obvious way for Phillips to reach an understanding of the macroeconomic system. By seeing his machine at work, other economists came to share some of that way of understanding the economy.

NOTES

We thank Roger Backhouse, P. A. Cornelisse, Peter van Els, Martin Fase, Francesco Guala, Dan Hausman, Kevin Hoover, Judy Klein, Richard Lipsey, Terry McDonough, Hans Martensen, and Doron Swade; seminar participants in Europe and America, and the editors and referees of this volume for all their questions and suggestions. We are grateful to the Science Museum, London; the STICERD Archive and the Library at the LSE; De Nederlandsche Bank; Delft University of Technology; and the Free University of Amsterdam for allowing us access to their archive collections.

1. The Science Museum model is unique. It was made at the request of James Meade (a future Nobel laureate for his work on international economics), as a 'mirror image machine' (configured the opposite way around from that in Figure 13.1) so that he could demonstrate propositions in his field by having two machines linked to show the interconnections between economies.

2. We understand a model as a scientific tool useful for learning about the world and/or about theories. This general approach to the role of models as a technology of investigation is discussed in Morrison and Morgan 1999 and in other chapters in Morgan and Morrison 1999.

3. The essay to which Phillips refers was probably Lerner's contribution to the so-called Savings–Investment Discussion in the *Quarterly Journal of Economics* in 1937–39 (Lerner 1938). Ironically, one of the reasons Lerner gave why people do not see the savings–investment equality is that they confuse stocks and flows. No such confusion arises in the hydraulic Phillips machine where stocks and flows are clearly differentiated and savings only equal investment in equilibrium.

4. We use the terms 'ingredients' and 'integration' advisedly, drawing on Boumans' account of how models are formed from the integration of many different kinds of elements (Boumans 1999).

5. Klamer and Leonard 1994 offers an insightful analysis of metaphors in economics.

6. The kind of analogies discussed in this chapter are substantive analogies, in contrast with formal analogies (Nagel 1961, 110). In the former, a system of elements possessing certain already familiar properties, assumed to be related in known ways, is taken as a recipe for the construction of a theory or model for some second system. In the latter, the system that serves as the recipe is some familiar structure of mathematical relations.

7. On these 2-D models, see Morgan 1999. Fisher also had a working 3-D hydraulic model of the market system built for him, which is not discussed here.

8. The treatment here draws on Mary Hesse's classic work on models as analogies, but further suggests that negative analogies need to be taken seriously in analysing the way analogical models are used (Hesse 1966; see also Morgan 1997). Hesse actually refers to "hydraulic models of economic supply and demand" consisting of "pipes carrying colored fluids", clearly having the Phillips machine in mind (Hesse 1967, 354).

9. There are several different 2-D diagrams that we could have used for explanation, ranging from rather abstract illustrations (as in Figure 13.5) to rather realistic drawings. The most realistic one we found (in the STICERD Archive, LSE) is a detailed drawing labelled "Hydraulic Analogue of U.S. Money Flow by Phillips & Newlyn" (exact date and provenance unknown, but likely to be early 1950s given that Newlyn is still credited) in which you see the water whirl and splash; unfortunately the detail would not reproduce here. The best one we could reproduce is Figure 13.6.

10. These relations can also be represented in mathematical form, such as in the small mathematical model found in Phillips' 1950 essay. But that model does not provide a full mathematical description of the machine or of the flow of water around the machine, which would be no easy task for an hydraulic engineer.

11. Beside these functions there is also an ingenious mechanical connection between investment and the rate of change of income, the 'accelerator' seen in Figure 13.3 as the connection attached to the float with the curly spring.

12. Some of these differences in belief are reflected in Newlyn's discussion of the economic labelling of the three tanks and the flows in terms of Keynes' definitions, Robertson's definitions, and the definitions found in the National Income Accounts (see Newlyn 1950, 115–17).

13. The Phillips machine was beautifully engineered, a point on which technicians involved in restoration always insist.

14. This created amusement amongst students and faculty alike, but economists had a ready interpretation for this: everyone knows that money leaks from the regular economy into the black economy!

15. Francoeur and Segal's chapter in this volume discusses physical molecular models in a similar way. The importance of these physical models and the Phillips machine lies not just in their enhanced qualities of visualisation, but also in their manipulability compared to some of the other 3-D models discussed in this book.

16. Morris Copeland designed (but did not build) electric circuit models to represent the circulation of money in preference to hydraulic designs on the grounds that the latter involved a slow circulation with lags and delays (as appropriate for income circulation) (Copeland 1952).

17. The Eniac was already operational by the end of 1945, and the Edsac came into service at the University of Cambridge, England in June 1949 (Swade 1995), but both were digital computers and analogue computing still had such advantages as its ability to deal with non-linear equations (Gilbert 1989, 111–12).

18. A good description of the machine's working is given in Swade 1995.

19. Goodwin claims that he used the machine for non-linear formulae: "I spent years using it for teaching both linear and non-linear dynamics" (Goodwin 1992, 13).

20. It is probably this calculation to which the Phillips machine literature refers as giving an accuracy of ± 2% according to the manufacturers (Moghadam and Carter 1989, 25), but Phillips claimed only ± 4% (Phillips 1950, 284).

21. Robbins' recollections recorded by Shirley Chapman: "Some notes on Bill Phillips and his machine . . . from a conversation with Lord Robbins, 1 Dec. 72", STICERD Archive, LSE, box 3.

22. This long-running debate is connected with the savings–investment debate referred to earlier. That late 1930s discussion was closed by F. A. Lutz with two sentences noteworthy in respect of Phillips' later demonstrations: "Those who think of things as happening in a certain order of time, and therefore try to link the future with the past (because they feel the desire to *visualize* the economic process step by step), will prefer Robertson's concepts. Those who think of things, not in process of happening but after the event, will favour Keynes' terminology" (Lutz 1939, 631).

23. Interview by Mary Morgan with Richard Lipsey on the topic of the Phillips machine, University of Bergamo, 15–17 October 1998.

24. See Phillips 1954 and 1957, in which electrical engineering diagrams replaced the hydraulic ones; and Allen 1954.

25. With the two linked machines (see note 1), the exercise involved the appointment of the two matching officials from the US system, and further confusion.

26. MORKMON is a 164-equation econometric model, meaning that the mathematical model has had its parameters estimated using statistical data and techniques. FYSIOEN was developed as a joint research project of the Bank's Econometric Research and Special Studies Department (P. Kramer, T. J. Mourik, and M. M. G. Fase) and the Control Engineering Laboratory of the Delft University of Technology (P. P. J. van den Bosch and H. R. van Nauta Lemke). Its dynamics however are based on MINIMORK, a simplified version of MORKMON.

27. Our discussion of FYSIOEN is necessarily incomplete and does not do justice to the ways in which the animation is helpful in understanding the mathematical model. Many of the problems we found might be overcome with the technical developments in computer animation of the last 15 years.

28. Carol Phillips, "A. W. H. Phillips, M.B.E.; 1914–1975, A.M.I.E.E.; A.I.L.; Ph.D. Econ., Professor Emeritus; Sibling Memories, Press Cuttings, Selected Biographical Notes" (undated), STICERD Archives, LSE, box 7, file 6.

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