

## CHAPTER 1 INTRODUCTION

The seeds of this book were sown back in 1974. At that time the Organisation of Petroleum Exporting Countries had cut oil production and raised the price of crude by a factor of four, from \$3 to \$12 per barrel, significantly affecting the cost of energy. There followed a period of virulent world inflation and then recession, but eventually economic life returned to 'normal' and growth resumed its apparent inexorable path. The early 1980s saw a recurrent bout of oil and price inflation and recession, with oil at one time approaching \$40 per barrel. By 2008, two and a half decades later, oil prices had risen again, this time to over \$140 per barrel, approaching fifty times the level of 1974 but, following the onset of severe recession, prices have again fallen back.

The history of oil and other fossil markets shows that the world economy has become evermore reliant on energy resources to maintain and fuel the economic machine. This has prompted thoughts on the ways of working of economies with respect to energy, and over the last three decades the author began research into the links between energy and economics, with the thought that energy per se is not just a resource input, but that perhaps economic processes themselves reflect the thermodynamic laws governing energy systems.

The nature of the subject of this book requires significant proof for economists and scientists to accept that similarities between thermodynamic and economic phenomena might imply more than just a passing analogy. Indeed relations between the two disciplines have rarely been comfortable, with scientists sometimes having scant regard for the work of economists; and many economists believing that science has little to offer a discipline which, by its nature, can be thought of as anthropocentric rather than eco-centric. In his seminal book *'The Entropy Law and the Economic Process'* Nicholas Georgescu-Roegan (1971) opines that the science of economics is openly and constantly criticised by its own servants as being mechanistic. Thus even within disciplines there can be disagreement and opposing points of view. Trans-disciplinary research therefore is a hard path to tread. Despite these problems, however, similarities between thermodynamic and economic phenomena have caught the attention of a significant band of economists and scientists.

### 1.1 Historical Research

Economist Paul Samuelson, in his book *Foundations of Economic Analysis* (1947), used the analogy of the Le Chatelier Principle and classical thermodynamics to explain the constrained maximisation problem, and acknowledged in his Nobel lecture (1970) that the relationships between pressure and volume in a thermodynamic system bear a striking similarity in terms of differentials to price and volume in an economic system. Other early contributors included Lisman (1949), who saw a similarity between money utility and entropy, Pikler (1954), who highlighted the connections between temperature and the velocity of circulation of money, and Soddy (1934), who suggested that if Marx had substituted the word energy for labour he might have conceived an energy theory rather than a labour theory of value. Perhaps the earliest suggestion of a relationship between the two disciplines was by Irving Fisher (1892), who related marginal utility to force, utility to energy and disutility to work. Fisher himself was mentored by Willard Gibbs, the founder of chemical thermodynamics.

The 1970s saw a rise in interest in the connections between economics and energy/thermodynamics, famously pioneered by Georgescu-Roegan in his book *'The Entropy Law and the Economic Process'* (1971). In a later contribution (1979) he noted that economic systems exchange both energy and matter with their environment and are best represented as open thermodynamic systems. He argued that the entropy law was important. Another strand of work, begun by Odum (1971, 1973), was to try to define the content of a product in energy terms, and he developed the term "*Embodied Energy*" as totalling the energy input into a product. This has met with some resistance within the economic community, because of the variability of the value and utility of money. Hannon (1973) also attempted to define an energy standard of value. The 1970s were also notable for the work of Meadows et al (1972) in *'Limits to Growth'*, a book which, while not concerned with relations between thermodynamics and economics, certainly highlighted the potential links between economic output, resource consumption and pollution.

By the 1980s the position of energy as a contributor to economic output had risen significantly, and Ayres (1984) had begun his work on the impact of energy and exergy consumption on economic output. Costanza (1980) and Hannon (1989) were concerned with the 'mixed units' problem, commensurating dissimilar components. Costanza argued for an embodied energy theory of economic value, similar to Odum. Other researchers at the time included Bryant (1982) on a thermodynamic approach to economics, Proops (1985) on general analogies between thermodynamics and economics, and Grubbeström (1985) on exergy. The decade finished with the work of Mirowski (1989) in his book *'More Heat than Light'*. His was a sustained attack on the foundations of modern neoclassical economics, that economics had copied the reigning physical theorems of the 1870s, with utility being a vector-field corresponding to energy.

In the 1990s, concern about the rising use of resources fired the work of Daly (1991, 1992), who posited the ideas of steady state economics and the relevance of entropy to the economics of natural resources. Söllner (1997), however, suggested that there is no direct link between thermodynamic properties and the characteristics of economic systems, and that there had been a failure of most attempts to produce economically interesting results.

The turn of the millennium saw a renewed interest in the connections between thermodynamics, energy and economics, spurred on no doubt by the advent of potential climate change and peak oil/gas. Candea et al (2001) highlight similarities of utility to entropy, as do Smith and Foley (2002, 2004). These conclusions have been reinforced by Sousa and Domingos (2005, 2006), who also cite the Le Chatelier Principle in their work. They conclude that while neo-classical economics is based on the formulation of classical mechanics, economics is actually analogous to equilibrium thermodynamics. Chen (2007) has developed a thermodynamic theory of ecological economics from a biophysical point of view. Martínás (2002, 2005, 2007) stresses that microeconomics and thermodynamics are both based on the idea of exchange, but although irreversibility is a key part of thermodynamic analysis, this is not the case with neoclassical economics. Martínás concludes that microeconomics cannot offer a theory of economic activity. Likewise, Baumgärtner (2002, 2004) believes that the standard irreversibility concept of production theory is too weak to be in accordance with the laws of nature.

A number of researchers have concentrated their efforts in the area of econophysics, in particular, thermodynamic formulations of income and wealth distributions. Among these are Dragulescu & Yakovenko (2001), Ferrero (2004), Purica (2004), Yuqing (2006), Chakraborti & Patriarca (2008) and Chakraborti & Chatterjee.

Ayres & Warr (2002, 2007) have produced several papers confirming the importance of exergy as a determinant of economic output, backed up with empirical research going back 100 years on the USA and UK economies. Ruth (2007) concludes that both conceptual analogies and attempts to quantify material and energy use from a thermodynamic perspective contribute nicely to the ongoing sustainability debate. Bryant (2007, 2008) has researched a thermodynamic theory of economics, with further papers, including empirical research, on monetary economics, peak oil and climate change.

From all of the above it can be seen that there exists a significant body of opinion therefore that acknowledges that links or analogies between thermodynamics and economics can be observed. Moreover the pace is quickening. This book is therefore an attempt to pull together all the above into one process that can be recognised by both economists and scientists. In an effort to make trans-disciplinary research of this kind understandable to people in both disciplines, a simplistic approach is sometimes required. The author therefore requests readers to bear with him if, on occasion, he appears to be preaching to the converted in one discipline or the other, it is not intentional.

Accepting the Darwinian principle of evolution, it is reasonable conclude that the human race is a product of the environment and the biological systems from which it evolved, and the ways in which it develops, including economic interaction, are therefore likely to reflect in some manner the ways in which nature and energy systems have evolved and operate. At the simplest level of the latter, the fundamental principle guiding the kinetics of reactions between chemical substances is the Le Chatelier Principle which states: *"If a change occurs in one of the factors under which a system is equilibrium, then the system will tend to adjust itself so as to annul as far as possible the effects of that change"*. Such reactions obey the laws of thermodynamics, in terms of heat production/consumption and the change in entropy arising.

At a higher level of entity, living organisms are composed of complex chemical compounds that interact with one another, but made up chiefly of molecules of oxygen, hydrogen, nitrogen and carbon, all of which can exist as gases (the last with hydrogen or oxygen). Goldberg et al (1993-1999) have collated thermodynamic data on enzyme-catalysed reactions.

Moving still further upwards, Schneider (1987) has pointed to Schrödinger's 'order from disorder' premise (1944), which was an attempt to link biology with the theorems of thermodynamics, whereby a living organism maintains itself stationary at a fairly high level of orderliness (low level of entropy) by continually sucking orderliness from its environment. Schneider and Kay (1992, 1995) state that life can be viewed as a far-from-equilibrium, dissipative structure, that maintains its local level of organisation at the expense of producing entropy in the environment. Successful species are those that funnel energy into their own production and reproduction and contribute to autocatalytic processes thereby increasing the total dissipation of the ecosystem.

While acknowledging the difficulties concerning the construction of analogues it is, nevertheless, not a far-flung idea to propose that economic principles may have connections with and reflect natural phenomena and the laws of thermodynamics which govern all life, albeit at first sight economics and thermodynamics appear to be very different animals.

However, it is not enough just to accept that there may be connections. A thermodynamic representation of economic systems has to reflect the reality of how they operate in practice; all the complex interconnecting systems of stock and flow processes carrying economic value from resources through to production, distribution, consumption and waste; and the feedback mechanisms of births and deaths, investment and depreciation, to replenish parts of the system such as population and capital stock. Such a representation must also have regard for the relationship of economics to resource availability, the environment and ecological systems.

## 1.2 Economics and the Ideal Gas

To connect the world of economics to that of thermodynamics, we turn to the analysis of gas systems. In the physical world, gases can absorb energy from a heat source with a higher temperature level, or by being compressed, raising their internal energy, resulting in a rise in temperature.

It might be argued at this point, that while even a small volume of a gas contains a very large number of molecules, homogenous and at first glance fairly evenly but chaotically dispersed (*Avogadro's or Loschmidt's number indicates  $6 \times 10^{23}$  in just a thimbleful*), some economic systems by contrast can be composed of just a few different items, and unevenly dispersed. Clearly relationships derived from a theory applied to a small system might be significantly clouded by the problems of small-sample statistics. But the counter arguments are that many economic systems and markets are quite large and the problems of small sample statistics would not then apply. Moreover, economics take advantage of a human invention called money, a convenient commodity/medium of exchange with the property of linking non-homogenous economic factors together, so that they effectively work in a homogenous fashion.

To examine the characteristics of gases in more detail, recourse is made to the kinetic theory of an ideal gas. Some might argue that real gases are imperfect, and that their properties can diverge significantly from a model of an ideal gas. However, scientists take account of this fact by modifying the formulae arising from the notion of an ideal gas (*such as the 'compressibility factor' and Van del Waal's equation*) to enable thermodynamic principles to be applied more accurately. Economists also accomplish just the same in their own field, by developing econometric and statistical models encompassing a number of factors to explain the variations in the real world that they see.

The kinetic theory of gases teaches us that, for a closed ideal gas system made up of a number **N** of molecules, which are perfectly elastic and are busy moving about colliding with each other exchanging kinetic energy, the relationship of the system with the outside world is that it is contained in a volume **V** resulting in the gas exerting a pressure **P** on the walls of the system. If, through the application of heat from outside, the gas molecules are made to vibrate and move about faster, they increase their rate of exchange of kinetic energy and the gas accumulates internal energy resulting in a temperature rise **T**,

with pressure and volume potentially increasing too; rather like a sealed balloon being heated and inflated. The relationship between the factors is given by the ideal gas equation:

$$PV = NkT \quad (1.1)$$

Where  $k$  is called the Boltzmann Constant (Ludwig Boltzmann 1844-1906). Temperature  $T$  constitutes a measure of the relative kinetic energy level of the gas; the higher it is, the higher the velocities of the gas molecules, and the shorter the time between collisions of the gas particles with the walls of the system. Physicists utilise the concept of temperature by constructing a *scale* with reference to observable characteristics of physical things, such as the freezing and boiling points of water, the expansion and contraction of fluids and solids, and other phenomena. It provides a base to measure and venture further.

In thermodynamics, distinctions are made between flow and non-flow systems – see figure 1.1. For a non-flow system, such as a balloon or a piston cylinder, generally the number of gas units  $N$  is held constant, with pressure  $P$  and volume  $V$  being a function of temperature  $T$ . For flow systems, such as a pipe or a gas turbine,  $N$  becomes a flow of units per period of time ( $N_t$ ), with a corresponding flow of gas volume  $V_t$  per unit of time; though varying with pressure  $P$  and temperature  $T$ . A distinction is also made between open and closed systems. In a closed system it is only possible for energy in the form of heat to cross the system boundary; matter itself cannot cross the boundary. In an open system, however, both heat and matter can cross the system boundary.

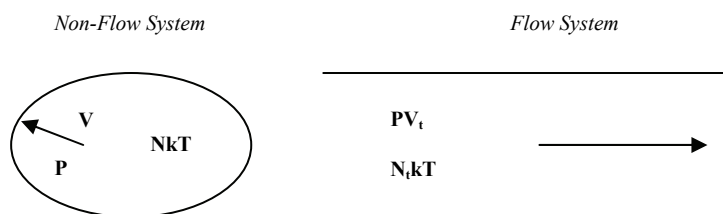


Figure 1.1 Thermodynamic Systems

In thermodynamic flow systems it is common to divide both sides of equation (1.1) by  $N_t$ , as in equation (1.2):

$$Pv = kT \quad (1.2)$$

Where  $v = V_t/N_t$ , is the specific volume per molecule; the inverse of the gas density (*The more usual thermodynamic presentation of this format is to work in terms of the volume per mass of a very large number of molecules, but we will not confuse the issue here*). This arrangement simplifies the kinetics of the analysis of a flow system, as the variable  $v$  becomes independent of time, because volume  $V_t$  and units  $N_t$  are both effectively flow measures per unit of time, with time therefore cancelling out.

Turning now to an economic stock system, an equation with a similar structure to equation (1.1) can be constructed. Imagine a system involving a number  $N$  of 'carriers or holders of value', where each carrier or holder can carry or hold a constant amount of embodied value or productive content  $k$ , *not* dependent on price or volume.

Clearly a concept such as embodied value or productive content might appeal to a scientist who is accustomed to measuring variables against absolute reference points. An economist might argue, however, and with some justification, that economics is not an absolute discipline, but a comparative one where value is not ascertained by deterministic processes used by scientists. It should be strongly emphasised, therefore, that by positing a productive content  $k$ , we are *not* implying that a scale of monetary 'productive content' can be constructed for a currency by reference to a fixed level of value. Economics is very much a comparative discipline, and the value of one currency can and does change compared to another, arising from inflation and international comparisons. But we *are* stating that any non-monetary good or service is made up from a particular mix of non-monetary components that have a very specific productive content, however defined, which are immutable. A particular bolt has mass, is made of steel, which involved a type of energy transfer, and a long line of sub-sources of productive

content. The fact that its price may change by virtue of substitutes or of demand, does not change the shape and content of the bolt in any way. Likewise one could define a currency content as being \$1, £1 or other value based on the confidence of its users, but this does not mean that this will forever have the same equivalence to the productive content of non-monetary goods; however that is measured for each.

A further point to state here with respect to the *nominal* value  $\mathbf{k}$ , is that we are not ascribing a utility value, but a productive content, that is a *physical* value that a unit of economic stock possesses. A bolt still looks like a bolt, and a £1 note still looks like a £1 note. Utility, however, is a notion invented by economists to explain the paradox of say diamonds having much higher and potentially variable *prices* attached to them than can be explained in terms of the cost of their production or their usefulness, compared to say water. The process by which the notion of utility arises in a thermodynamic context will be described at a later chapter, though it should be noted that it has to do with entropy.

With the above in mind, for the time being we will put aside the problem of what standard the constant  $\mathbf{k}$  for a product is to be measured against, i.e. energy, material content, labour man-hours or any other entity that might be regarded as a constituting a scale of reference. It is enough for the moment to assume that the result is acceptable to the parties in an economic system; otherwise they would not willingly trade with each other.

The relationship of the system with the outside world is that the value held by the carriers or holders can be exchanged for goods and services, or the value held by other *different carriers or holders*, at the boundary of the system at price  $\mathbf{P}$  and volume flow  $\mathbf{V}_t$  over a period of time, and vice-versa, according to an *Index (or a degree of a scale) of Trading Value*  $\mathbf{T}_t$  with which they can do this over that period. If they could increase their index of trading value  $\mathbf{T}_t$  over the period, then the number of times the carrying units are re-cycled and used again could go up *and/or* the unit value of exchange of goods (the price) could also increase over the period. Thus the relationship of the variables is given by the ideal economic equation:

$$PV_t = NkT_t \quad (1.3)$$

The above equation corresponds to the acknowledgement by Samuelson concerning the similarities between economic price and volume and thermodynamic pressure and volume, and to Pikler's remarks highlighting of the connections between the velocity of circulation and temperature.

The index of trading value  $\mathbf{T}_t$  has similarities with and is related to turnover, cost and added value, though the distinction is that while turnover, cost and added value can be defined in terms of a scale of value, rising or falling with respect to our index of trading value  $\mathbf{T}_t$ , they are not technically the same as  $\mathbf{T}_t$ , unless they are divided through by  $N\mathbf{k}$ .

While the index  $\mathbf{T}_t$  is most readily equated to the velocity of circulation of a currency, there is no reason why it should not be compared also with the velocity of circulation of other items of exchange, such as the turnover of a producer stock, or depreciation of capital stock. Even a labour force can be regarded as a stock, with new entrants coming from births through education, and retirals at the end of a working life. It is just that the lifetime comparisons are very different, from almost instantaneous for electronic money, to forty or fifty years for a member of the labour force; and much longer for some resources, if not noticeably depleted, and for some waste stocks, if not recycled back into the ecosystem. In addition to velocity, however, the index  $\mathbf{T}_t$  also carries a connection to the value of exchange (price  $\mathbf{P}$ ) compared to the productive content  $\mathbf{k}$ .

Thus, by way of example, a producer may have a stock of finished items, which leave at a volume rate of  $\mathbf{V}_t$  per unit of time at price  $\mathbf{P}$ , with an equal and opposite flow of money from a customer to purchase the stock flow. The money flow represents a turnover of the money stock used to finance the operation, and likewise the value flow leaving the producer stock represents a turnover or velocity of circulation of the producer stock.

The 3-dimensional plot of price  $\mathbf{P}$  versus volume flow  $\mathbf{V}_t$  and index of trading value  $\mathbf{T}_t$  at figure 1.2 indicates that for a given index of trading value  $\mathbf{T}_t$  the carriers could carry more or less products with lower or higher prices, and a change in the index of trading value  $\mathbf{T}_t$  can give rise to a change in volume flow  $\mathbf{V}_t$ , a change in price  $\mathbf{P}$  or both.

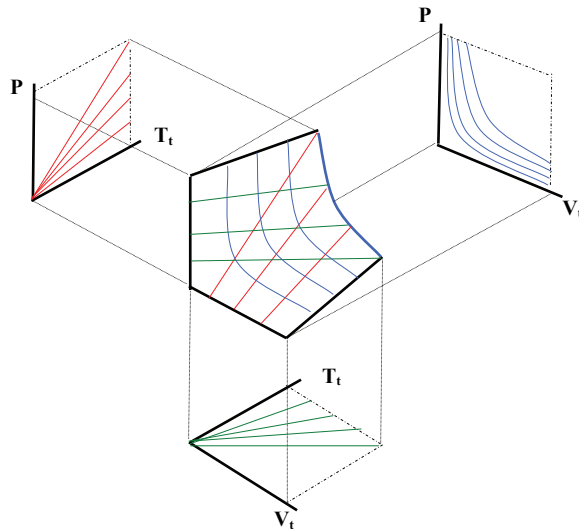


Figure 1.2 Price, volume flow and the index of trading value

It is important to stress that the index of trading value  $T_t$  so described here is one based on value, and not volume. If value flow, equal to price  $P$  multiplied by volume flow  $V_t$ , can vary on one side of the equation then on the other side of the equation value must be able to vary as well. Of the factors on the other side, the embodied value/productive content  $k$  that can be carried or held by a carrier, although inherently a value, is a *nominal value* and is deemed to be constant. It is the same whether trading occurs or not. A £ of currency is still a £ of currency. A grain of wheat is still a grain of wheat, whether or not it is traded. Likewise, a barrel of a particular type of oil has weight, energy content and other properties which might be regarded as constant. As it is possible that the number  $N$  of carriers of value in a particular system configuration may be fixed (e.g. shares in issue), then the index of trading value  $T_t$  must be able to embody both changes in volume *and price* in order to make both sides of the equation compatible with one another.

The structure of the ideal economic equation can be clarified further by reference to dimensional analysis. In a thermodynamic system, at the boundary, pressure  $P$  is measured by force  $F$  per unit of area (length x length =  $L^2$ ) on which it acts (i.e.  $F \times L^{-2}$ ), and energy  $J$  is a product of force x distance moved (i.e.  $F \times L$ ). Thus pressure  $P$  is equivalent to energy  $J$  per unit of volume (i.e.  $J \times L^{-3}$ ). The Boltzmann constant  $k$  is defined as energy ( $J$ ) per molecule per degree of temperature ( $T$ ). Therefore restating equation (1.1) in simplified dimensional terms we have:

$$\left(\frac{J}{L^3}\right) \times (L^3) = N \times \left(\frac{J}{NT}\right) \times T \quad (1.4)$$

Similarly for an economic system, at the boundary, in dimensional terms, price  $P$  is measured as value  $J$  per volume flow  $V_t$  of items, and the embodied value or productive content  $k$  is measured as value  $J$  per carrier per index (or degree) of trading value  $T_t$ . Hence re-stating equation (1.3) we have a similar dimensional presentation:

$$\left(\frac{J}{V_t}\right) \times (V_t) = N \times \left(\frac{J}{NT_t}\right) \times T_t \quad (1.5)$$

There are two main differences between to the two systems.

First, the gas system is defined by the volume containing the energy of the gas,  $L^3$  in dimensional terms. It is spatial and 3-dimensional. In an economic system, however, volume flow  $V_t$  does not have a dimensional configuration, and the value contained by the economic unit can be said to act at a 'point' with no spatial dimensional format. It may be a pin, a bank note or a power station, but it is still considered to be acting at a 'point'. This aspect does not matter, however, as the economic value  $J$  is likewise defined as per item 'point', and not per spatial volume as in a gas system, and therefore  $L^3$  and

$L^{-3}$  at equation (1.4) effectively cancel each other out for the economic system. The first difference of the two systems is illustrated at figure 1.3.

The second difference is that of throughput flow and time. In a gas *flow* system, throughput flow is defined by reference to volume flow  $V_t$  per unit of time on the left-hand side of the equation, and flow of molecules  $N_t$  per unit of time on the other side. The same time dimension occurs on both sides of the equation and is of the same measure, that is  $V_t$  and  $N_t$  proceed in tandem together. In a non-flow gas system, on the other hand, time does not enter into consideration, and the number  $N$  of molecules remains the same; and though the volume  $V$  can change through expansion and compression, it is not flowing in the sense of continually changing in content. Thus the ratios  $V_t/N_t = v$  and  $V/N = v$  retain the same relationship to each other via the specific volume and density, which relates to the volume  $L^3$  format as in equation (1.2)  $Pv = kT$ .

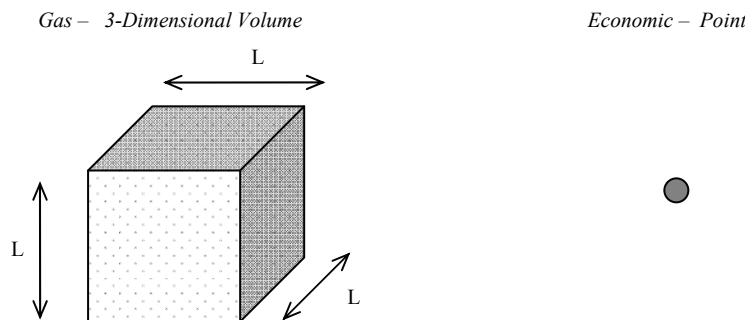


Figure 1.3 Gas and Economic Formats

Economic systems, however, have elements of *both* flow and non-flow processes. Thus on the left hand side of the equation we might envisage a volume flow throughput  $V_t$ , retaining the same time relationship (items per transaction time – a year etc) as that of a thermodynamic flow process, such as production inputs and outputs from a stock. But on the other side of the equation the stock quantity  $N$  is ordinarily not flowing. It can of course change in size, according to the differences between inputs and outputs, but otherwise it stays where it is. On the right hand side of the equation therefore, the notion of flow is transferred to the index of trading value  $T_t$ , which becomes a velocity of circulation relative to the central stock  $N$ , and is related to both the *lifetime* of a stock item and the *price* of exchange. By re-arranging equation (1.3) we have:

$$P \left( \frac{V_t}{N} \right) = kT_t \quad (1.6)$$

$$Pv_t = kT_t \quad (1.7)$$

$$T_t = \left( \frac{Pv_t}{k} \right) \quad (1.8)$$

Where the volume throughput rate per unit of stock per unit of time  $v_t = V_t/N$  is inversely related to the lifetime  $t_L$  of an economic item. It will be noted that a change in the index of trading value  $T_t$  can be occasioned by a change in price  $P$  and/or a change in the volume throughput rate per unit of stock per unit of time  $v_t$ .

Figure 1.4 illustrates the lifetime principle. Two economic items are presented with different lifetimes:  $t_{L1}$  and  $t_{L2}$ . The first for example might represent money, having a shorter lifetime than a transaction time  $t_t$  of a year. Thus money gets turned over perhaps several times in a year. The second entity might represent some form of capital stock, with a lifetime of several years. Thus the volume flow in a transaction year will represent only a proportion of the lifetime of the economic entity, the depreciation or consumption rate.



Figure 1.4 Lifetime of an economic good compared to the transaction time

Thus instead of a specific volume  $v$  with dimensions of  $L^3$ , as posited for a gas system (equation (1.2)), an economic system has a volume throughput rate  $v_t$  per unit of stock per unit of time, with no spatial dimensions, but with a time dimension (equations (1.7) and (1.8)). To this is added the effect of price  $P$  relative to the productive content  $k$ .

The description of the variable  $v_t$  ‘volume throughput rate per unit of stock per unit of time’ is rather long, and for the rest of this book we will refer to it as the *Specific Volume Rate*  $v$ , being equal to volume flow  $V$  divided by stock quantity  $N$ . We will also drop the subscript  $t$  from the variables volume flow  $V$ , specific volume rate  $v$ , and index of trading value  $T$ , as these are automatically associated with a flow of volume per unit of time.

From all of the above analysis it can be seen that the formats of the ideal gas equation and the ideal economic equation outlined so far are similar, with a defined equivalence; pressure  $P$  with price per unit, volume  $V$  with units of output/consumption per unit of time, the number of molecules of gas  $N$  with the number of carriers or holders of value in a stock, temperature  $T$  with the index of trading value, and the Boltzmann constant  $k$  with the embodied value/productive content per unit of carrier and index (*degree*) of trading value. In both gas and economic systems time is balanced out on both sides of the equation. The analogy suggests that value in an economic system might have some equivalence to heat content in a thermodynamic system. Figure 1.5 further illustrates the principle of economic systems.

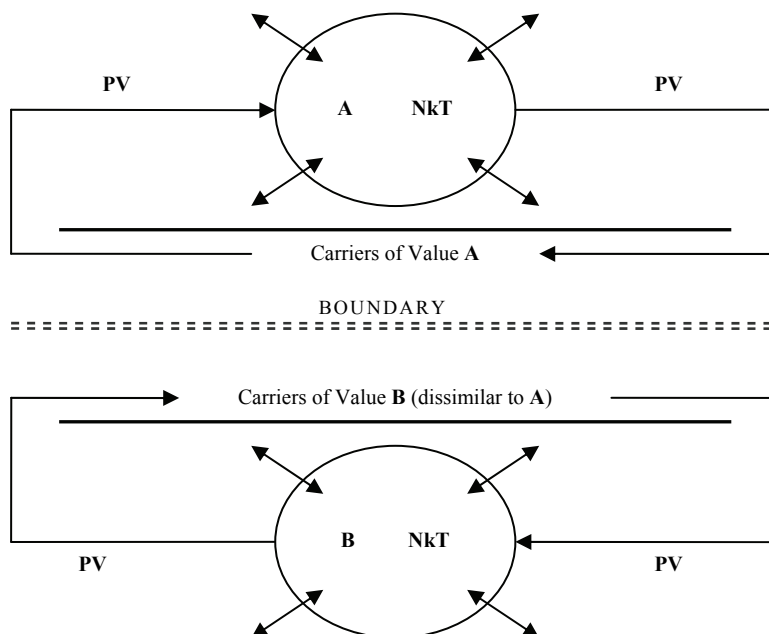


Figure 1.5 Economic System

The definition of open or closed systems changes with how the boundary is conceived. An economist might argue that a producer trading with customers and suppliers is an open system, but an economy that does not trade with any other economy might be regarded as a closed system. Following this argument, the world economy could be described as a closed system, as net trading would be zero. A scientist, on the other hand, would argue that all economic systems derive their benefit from the

productive content found in the ground, sea and air, from the living things that grow and inhabit the earth, and from the energy supplied free from the sun. From a scientific point of view, no economic system can be regarded as being closed.

Irrespective of being open or closed, the real size of an economic system (net of inflation) is determined by the flow of volume and real value per unit of time.

It should be emphasised that if two sets of carriers of value are different in nature (e.g. money versus product output) then neither can cross the system boundary and they flow in the opposite direction to each other, though, as with thermodynamic systems, value can be exchanged between them. If, however, the carriers of value and the input/outputs are *one and the same* (such as a flow of products into a finished stock and then outputted to customers), then there is no boundary and they all flow in the same direction and are part of the same stock.

We now turn to consideration of the structure of economic stock and flow processes.