This book is primarily about accounting and change. It is borne out of a belief that our economies are in constant flux; changing dynamically in the short-term with human behavior and evolving over longer time frames in response to technological change and external pressures. Real-world systems, including economies, are messy and chaotic. They do not march orderly from one state to the next.

This is also a book about metaphors and models. We use metaphors to simplify and make sense of the world around us. They influence us as stories told to ourselves. These metaphors inform the mental and empirical models we construct. And, as we collect data (via accounting methods) to assess the validity of those models, our perception of the world is molded and shaped by our accounting, which was informed, in the first place, by the stories we told ourselves about reality. Our models tell us what aspects of the world are important to value (in the literal sense of making measurements), and also, by extension, which parts of the world (literally) have no value. This process has a deeper normative consequence: the aspects of the world to which our models ascribe value are *valuable*, and those ascribed no value become *worthless*. Thus, metaphors inform our thinking about the real world, but consequently, they also constrain our ability to frame reality. We mistake the model-metaphor for reality, and we interact with reality in the same manner as we interact with the objects in our metaphors.[1] Classical physics tells us the universe is *like* clockwork, so we begin to interact with the universe as if it *really were* clockwork. Then, it becomes easy to collect data that confirms the clockwork model, because the model tells us which data to collect. It takes courage to collect data that might be counter-factual and still more courage to modify or let go of our established models and metaphors.

For many decades, the machine metaphor for the economy has conjured images of a *smoothly running*, *well-maintained*, clockwork-like system. But, if we hope to better understand the complex, messy dynamics of real-world economies, if we hope to make sense of real-world events, if we hope to learn where and how economies can go wrong; we had better be counting data that informs *dynamic* models guided by metaphors that tell us *more* than "the world is an orderly place." We need metaphors and models that are able to cope with rapid transience, not just ordered stability.

1 Motivation

> *In developed economies we live the good life for now—with an amazing level of comfort and interest created by our astonishing ability to make and transform materials. We've really only done this at scale in the past 150 years, in which time our use of engineered materials has rocketed, literally. However, if we have some concern about "sustainability" we need to anticipate what effects our use might have on future generations—and we're getting some clear indicators that there's a problem.* [**?** , p. 3]
>
> —Julian Allwood

> The world needs another industrial revolution *in which our sources of energy are affordable, accessible and sustainable. Energy efficiency and conservation, as well as decarbonizing our energy sources, are essential to this revolution.* [**?** , p. 294]
>
> —Steven Chu, US Secretary for Energy

[1] This fallacious process is called *reification*; the making (*facere*, Latin) real of something (*res*, Latin) that is merely an idea. Alfred Whitehead refers to this as *the fallacy of misplaced concreteness*.[**?**]

The motivation for this book is a belief that our global economy is facing an imminent transition; to adequately manage this transition, we need to better understand our economies. What transition are we facing? The twin challenges of climate change and sustainable development require a transition to a low-emission energy system based on non-depletable resources. Given that our energy system currently runs primarily on non-renewable resources (fossil fuels), we need to rebuild our entire energy system as a matter of urgency.

Furthermore, our economies are founded on a fundamental principle; *the moral imperative of economic growth*.[**?**] Growth in production and consumption of goods and services entails the encroachment of the human economy into the biosphere on which it depends. One more table means one less tree. As we increase the scale of the economy, we increase the environmental impact of all of our actions. Unfortunately, there is good reason to believe that the earth is running low on its ability to handle more encroachment.[**?**]

In the face of such concerns, the vision of "dematerialization" has appeared (materialized) [**? ? ?**] with the hope that we can continue to grow our economies while reducing our impact on the environment. Expansion of the frontiers of knowledge and skillful use of technology will, we tell ourselves, allow us to reduce the rate of material consumption when producing our goods and rendering our services. But, if we are to dematerialize, we'll need to change the structure of our economies. Before we do that, however, we need to *understand* the structural elements, not just the flows; to understand the circulatory system, not just the blood. It is only by understanding the structure that we can begin to understand how our economies change. And it is only by understanding how our economies change that we can understand how best to manage the coming transition.

A primer on system theory:

Some concepts of system theory will aid the discussion in the rest of this chapter. Those familiar with thermodynamics or general system theory may skip over the following sections. Systems are generally categorized as isolated, closed, or open systems.

Isolated systems

Isolated systems (Figure 1A) are disconnected from their environment such that neither energy nor material crosses the boundary of the system. Inside the boundary, materials and energy may be exchanged among elements of the system. The isolated system is used often in thermodynamics to represent a perfectly insulated container with no mass or heat exchange with the environment. Within the universe no systems are truly isolated, since all must interact with their environment to at least some degree. The universe itself may be an example of an isolated system.

Closed systems

A closed system (Figure 1B) can exchange energy, but not materials, with its environment. The earth is often considered to be a closed system. There is little exchange of material—some meteorites and loss of atmospheric gases—but a large incoming flow of solar radiation balanced (according to the Law of Conservation of Energy) by dissipation of (infra-red) radiation. The incoming radiation, at ≈ 5000K, is of much higher quality than the thermal radiation, which leaves at a temperature of ≈ 300K. This degradation in energy quality drives practically all of the biological processes on Earth.

Open systems

Open systems, (Figure 1C), as the name suggests, are open to flows of both energy and materials. The biosphere is a good example of an open system. It exchanges energy and materials with the other systems (atmosphere, hydrosphere, lithosphere) [**?**] of the earth, of which it is a subset.

Feedback and non-linearity

Feedback occurs when elements within a system interact so as to reinforce or diminish some property of the system. For example, when the rate of growth of a population is dependent on the size of that population. If the rate of growth *increases* as population increases, we say that the feedback is *positive* or *reinforcing*. If the rate of growth *decreases* as population increases, we say that the feedback is *negative* or *correcting*. Often feedback systems involve some method of control or intentional regulation, as in self-regulating systems. Systems containing feedback loops will often display non-linear or even chaotic behavior. Such systems may also display *resilience*, even in the face of large changes in external conditions.

Self-regulating systems

Organisms are open systems. They maintain their internal structure by taking in high quality energy and materials from and expending low quality to their environment. This relationship between incoming high quality resources and emission of low quality waste is a general truth for any thermodynamic process but is especially true for open systems operating far from thermodynamic equilibrium (of which every living system is an example). Such systems maintain their internal structure by importing high quality energy and materials (negentropy) and exporting low quality energy and materials (entropy).[**?**] This maintenance requires an ability to regulate internal conditions, such as temperature or chemical composition, known as *self-regulation*. Self-regulation relies on feedback among system elements. Non-living systems may also display self-regulating behavior.

Emergence and hierarchy

Due to the non-linear nature and complexity of natural systems, new *emergent* properties arise which cannot be explained solely in terms of the properties of the elements of which the system is composed. An obvious example is the emergence of life from large molecular structures. Because the properties of the system are *irreducible* to properties of the system elements, we may envision a hierarchy of nested systems. Boulding [**?**] classifies a number of system levels (outlined in Table 1) ranging from simple *structures* (atoms, bridges) up to *transcendental systems* such as religion.

Self-organizing systems

Self-organization involves spontaneous increase in complexity of the internal structure of a system, normally observed in systems far from equilibrium. Examples are the formation of convection cells in heated fluids [**?**] The self-organizing behavior is an emergent property of the system; it cannot be explained in terms of properties of the system elements.

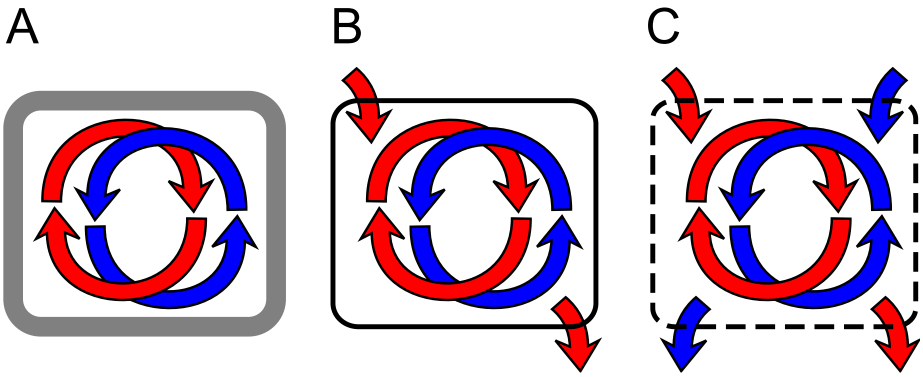

Figure 1: Isolated (A), closed (B) and open (C) systems. Red arrows represent energy flows. Blue arrows represent material flows.

Table 1: Hierarchy of systems.[**?**]

Level	Description	Characteristic	Examples
1	Structures	Static, spatial frameworks	Atom, crystal, bridge
2	Clockworks	Predetermined motion	Solar system, clocks, machines
3	Control	Closed-loop feedback control mechanism	Heater with thermostat
4	Open systems	Structurally self-maintaining	Cells
5	Genetic systems	Community of cells	Plants
6	Animals	Nervous system, self-awareness	Birds and beasts
7	Humans	Self-consciousness, knowledge, language	Human beings
8	Socio-cultural systems	Roles, values, communication	Family, community, society
9	Transcendental systems	Beyond our knowledge	Religion

2 Models for the economy

In the next sections we will explore some of the models and metaphors associated with different views of the economy.

2.1 Traditional mechanistic view of economy

The classical school of economics flourished during the Enlightenment when Newton's clockwork universe was ticking along nicely, physicists were beginning to build an understanding of energy and its conservation, and physicians and biologists were beginning to understand the workings of the human body, in particular the circulatory system.[2] Most cultures were agrarian, depending largely on land for food and muscle power to get things done. Agriculture was subject to the whims of nature and a sense of stewardship was still largely prevalent. Economists were largely preoccupied with delineating the main factors of production (land, labor, and capital) and their influence on economic output.

The neo-classical school of economics was born out of the fire of the Industrial Revolution. Thermodynamicists were outlining theories on heat cycles and equilibrium processes allowing the development of more efficient engines. Machines were changing everything. For the first time in history, nature could be bent to the will of humans. New vistas of experience (and riches) were opening up in the New World. The bounties of nature were there for the taking.

Figure 2 depicts the neoclassical model of the economy, represented in mainstream *Principles of Economics* texts. Goods and services flow from the production sector to the household sector (consumption) in exchange for payments. The factors of production (labor, capital) flow from the household sector to the production sector in exchange for wages and rents. Attention is primarily focused on the circular flow of money (dashed line) which is is often described in reference to the "circular" flow of blood around the body. Hence we often speak of money as the "lifeblood" of the economy.

This traditional model of the economy is unashamedly mechanistic. General equilibrium models of the economy [**? ?**] borrowed directly from classical physics' models of mechanical equilibrium.[**?**] Markets specifically, and the economy more generally, are seen as being in "balance."

Additionally, the traditional view of the economy (as depicted in Figure 2), in much the same fashion as our naive picture of the circulatory system, is represented as separate from its environment. "Blood" circulates around the economy with no need to interact with the rest of the universe. Although we show the biosphere in Figure 2, it is rarely represented in mainstream economic texts. In mainstream economics, the economy is implicitly and figuratively separate from the material world within which it operates. The traditional economic model is presented as an *isolated* system, independent from flows of materials and energy to and from the biosphere. All of the necessary factors to keep the economy running exist within its confines. If growing the economy can be shown to have any societal benefits whatever, we pursue the moral imperative for economic growth. This moral imperative for economic growth combined with the expansionist vision of the pioneers leads to the "cowboy economy" where everything is up for grabs.[**?**]

The next section will explore some problems with this optimistic view.

[2] William Harvey is normally credited with the first anatomically accurate description of the circulatory system, published in 1628.[**?**]

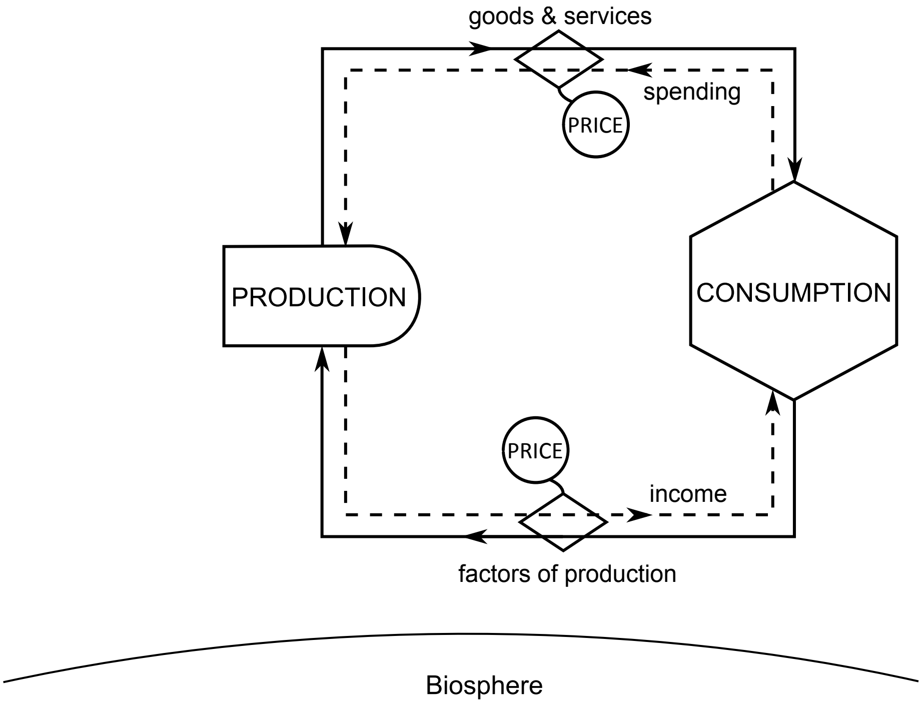

Figure 2: The economy is represented as a circular flow of goods and services between two sectors. The producers manufacture goods and services by taking in labor and capital. Consumers exchange labor for wages which are used to purchase the goods and services of the producers.

2.2 Economic models that include resource inputs

Thermodynamics tells us that all physical processes require a transfer of energy. Because Figure 2 has no flow of energy to the economy, we may consider it a perpetual motion machine of the *first kind*: it produces work without the input of energy and thus violates the First Law of Thermodynamics—the law of conservation of energy.[**?**] The real circulatory system is connected to the lungs, from where it takes in oxygen, and to the digestive system, where it takes in processed food, which are passed to the cells throughout the body. This is a major function of the blood: to act as an intermediary between the input of energy and material resources, the food we eat and air we breathe, and the internal working of the body. The circulatory system is necessarily connected to its environment and circulates energy and materials that have been extracted from it.

The economy as an isolated system represents a "perpetual motion machine," seemingly able to operate indefinitely with no binding constraints. Because these physical elements of the biosphere are absent from economic models, the physical constraint they place on the allocation of resources, distribution of outputs, and scale of an economy are outside the scope of neoclassical economic discussion.

Current economic models assume continued economic growth is possible, necessary, and good. Thus, questions about the appropriate scale for the economy are not asked. Even if they were, those questions could not be answered because the required data are not collected. As the population of the world grows, will we be able to create enough cars to satisfy the growing demand? Can we meet the increasing demand for steel, rubber, glass, and fuel without considering the consequences? Will there be enough energy to power the automobile factories as well as the increasing number of cars? Will the environment be able to assimilate an ever-increasing amount of pollution?

The mainstream response to those questions has been to assume that over a long enough time period, economies are not bound by physical limits because of *factor substitutability*. A particular energy resource (oil) may be in short supply, but our technological expertise—which expands as the economy grows—will allow us to substitute another resource (coal) for it. Substitution may continue indefinitely thus, so goes the story, the only limiting resource is human ingenuity.[**? ?**]

This assumption was thrown into stark relief following the oil shocks of the Seventies. Suddenly the global economy was thrown into reverse for lack of one fundamental resource. The necessity of including, at the very least, energy resources into the economic picture spurred the efforts of early (net) energy analysts.[**? ?**] Figure 3 depicts the traditional economic model updated to account for energy flows from the biosphere into the economy. The economy has changed from an *isolated* system into an *closed* system, since only energy inputs have been accounted.

The metaphor for such a model is still very much a mechanistic one. This mechanistic description lends itself to a view of the economy, much like the engines of the Industrial Revolution, as well-behaved and amenable to control. Machine metaphors abound in our economic discussions. We speak of the "fueling" the "economic engine" lest it should "stall." [**?**] Like an engine, the economy is assumed to be resilient to small and even quite large perturbations. It can either self-correct, or be corrected with adjustments to a few predictable policy levers. Additionally, the biosphere is relegated to the position of a provider of resources; the larder of the economy.[**?**]

2.3 The metabolic economy

The cowboy economy soon depletes resources. The consumption of resources also leads to wastes. The question arises as to "what to do with these wastes?" The neoclassical economic view sees these wastes as anomalous to the normal functioning of the economy.[**?**] Thermodynamics takes a different stance.

According to the Second Law of Thermodynamics, all real-world processes involve the degradation of material and especially energy resources and the creation of entropy. High quality (low entropy) material and energy come in, low quality (high entropy) material and energy go out. The depiction in Figure 3 can be classified as a perpetual motion machine of the *second kind*: it perfectly converts energy resources into work (useful services) without generating any entropy, in violation of the Second Law of Thermodynamics. Since the generation of high entropy (low quality) output is a *necessary* feature of *all* processes (including economic processes) then the generation of wastes is a *normal* feature of economic processes, not an anomaly. Within a closed system, such as the earth, these wastes soon accumulate, necessitating the change to a "spaceship" economy, wherein account is made of the waste outflows of the economy.

Figure 4 has been updated to include energy resources. In addition, the production and consumption sectors both produce waste flows which must be assimilated by the biosphere. Similarly, our circulatory systems 'waste' carbon dioxide (from the consumption of food-fuel with oxygen) and urea (from protein catabolism) to the environment.

Environmental Economics, as a sub-discipline, expands neoclassical economic models by recognizing the valuable role played by the environment in supporting

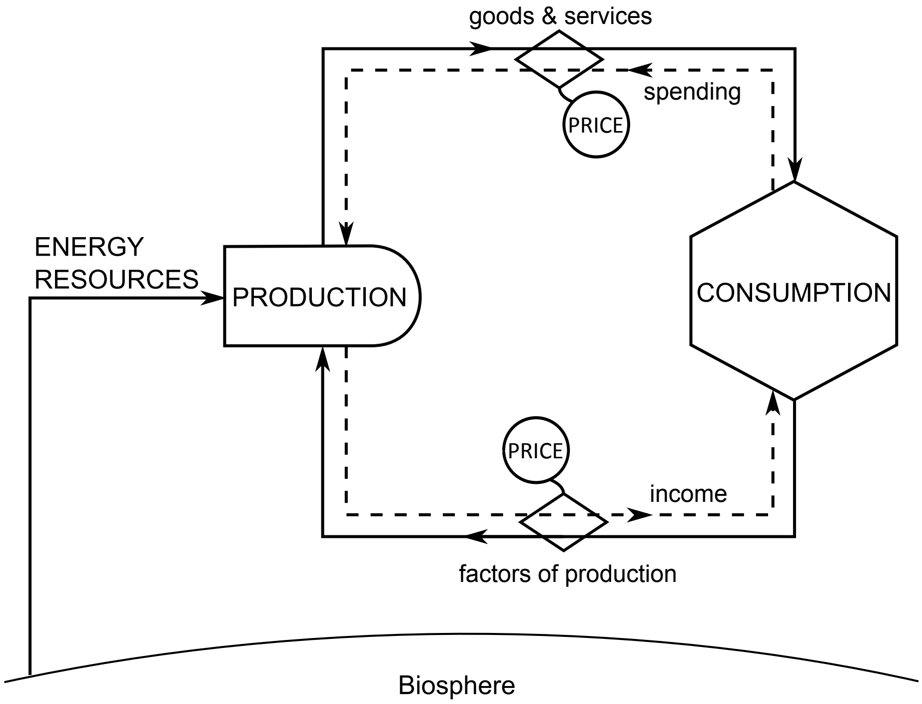

Figure 3: Energy input output analysis has included the flows into the economy from the environment. This may be considered a perpetual motion machine of the second kind.

the economy and attempting to place value in those services. However, even with this expanded model, the simplifying metaphor, that of an engine, remains intact. Predominantly linear relationships of inputs and outputs rule the day. Successful management of local pollution such as SO_2 (acid rain) through environmental legislation is a positive result of this expanded model. However, systemic events resulting from reinforcing feedback loops or from events occurring outside historical experience cannot be modeled and are not predictable. The 2008 global financial crisis is an example of one such systemic event.[**?**] The 1930's dust bowl is an example of another systemic event. It was one of the greatest man-made environmental disasters, arising from unexpected, non-linear results of widely accepted traditional farming practices, implemented in a new, and unknown ecosystem.[**?**]

Ecological economists, in the tradition of Herman Daly, have begun to update the neoclassical models.[**?**] In ecological economics texts, the economy is represented as an *open* system. The guiding metaphor for this kind of economic model is a *metabolism*.[3] The blood serves a self-regulatory, homeostatic role by transporting hormones. Like an organism, the economy metabolizes energy and materials that it receives from natural resources into forms usable for human purposes. The economy's behavior is non-linear and chaotic, but also self-regulating. Models and accounting frameworks are being developed to describe "society's metabolism." [**? ? ? ? ? ? ?**]

Empirical measurements are necessary to support (or dispute) scientific theory and models. Accounting frameworks and methodologies are necessary to facilitate measurement. The following sections outline attempts to account flows of economic

[3]The Greek root of metabolism (*metabolē*) means "change."

factors through the economy. The first (Section 3.1), looks at traditional input-output analysis methods, that assume the economy is an isolated system and track only flows of money. The second (Section 3.2), looks at the development of the energy input-output methodology (an extension of the traditional method), which assumes that the economy is open to inputs of energy. The third (Section 3.3), looks at further extension of the input-output methodology to include other material extractions from the biosphere and also to track discharges from the economy back into the biosphere. In the fourth (Section 3.4), we give a justification for a further extension of the input-output method to include, not only flows (of physical materials and money), but also *accumulations* of these items in economic sectors.

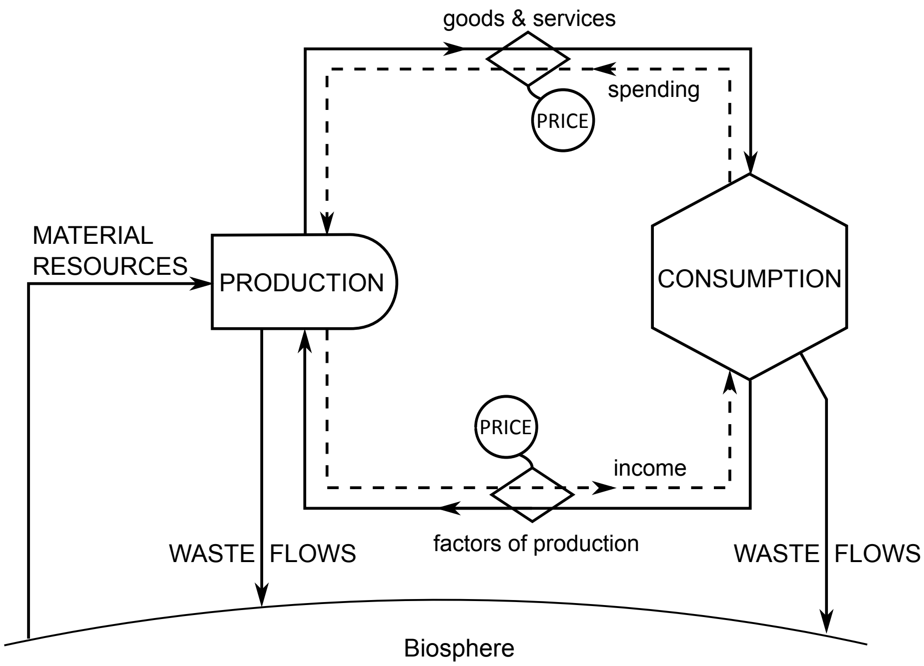

Figure 4: A comprehensive model of the economy, fully consistent with the laws of thermodynamics must include degraded resources (waste) expelled to the environment as a necessary consequence of economic activity.

3 Brief history of input-output (I-O) analysis

Input-Output (I-O) analysis, developed by Wassilly Leontief in the 1930s as an extension to the work of Quesnay and Walras [**?**], is of primary importance in national accounting. The method allows determination of the flows of value through an economy as well as, among other things, calculation of a nation's gross domestic product (GDP), today's prevailing measure of economic activity.

3.1 Basic I-O method

The basic premise of the I-O method, as depicted in Figure 5A, is that each economic sector takes in factors of production from other sectors (and possibly itself) to produce an economic good at some rate. For example, the automotive sector takes in steel, rubber, glass, etc. and produces a number of cars per year. In contrast to high-level economic growth models that include only a few factors of production (such as land, capital, and labor), the I-O analysis technique allows many differentiated factors of production and raw material feedstocks.[**?**] In I-O methods, each factor of production is considered to be a output from a sector of the economy. As will be discussed later, the traditional primary factors of production (land, capital, and labor) are not *flows* into the production processes. Rather, they are *stocks* that, when present, allow factors of production (steel, rubber, and glass) to be transformed into final products (automobiles). The quantity and quality of these stocks determine the quantity and quality of their flow of productive services.

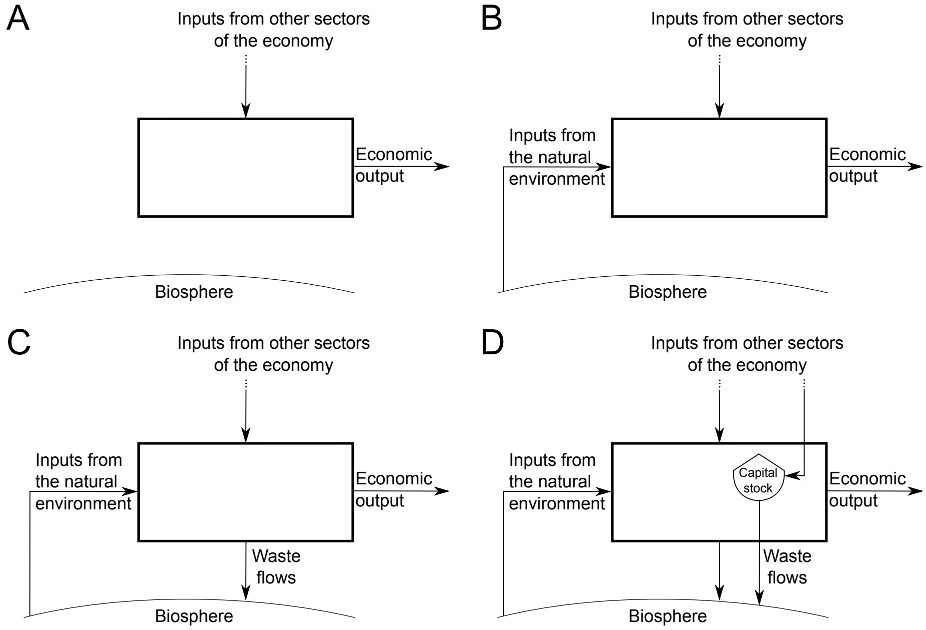

Figure 5: The basic unit of input-output analysis: **A** the standard economic approach includes only transactions among sectors of the economy; **B** the Energy Input-Output (EI-O) method allows inputs from the natural environment to be factors of production; **C** including waste flows to the environment makes the model physically consistent; and **D** the framework developed and presented herein accounts also for accumulation in capital stock (K) of embodied energy within materials in economic sectors.

3.2 I-O method including inputs from the biosphere

The oil shocks of the 1970's spurred great interest in the important role of energy in economic production. In addition to the productive services provided by flows of capital and labor, a flow of energy[4] is required for economic activity. These energy flows originate from the natural environment, recognition of which provoked researchers from fields of net energy analysis (NEA) to extend the traditional Leontief input-output method to include important energy flows from the environment, developing an Energy

[4]Or, more precisely, the degradation of an exergetic gradient/destruction of exergy.

Input-Output (EI-O) method as depicted in Figure 5B.[? ? ? ? ? ? ? ?] While the Leontief input-output method relies exclusively on monetary units to represent value flows among sectors of an economy, the key insight of the EI-O method is to rely upon physical units (especially energy units of joules) to represent some of the flows among economic sectors. In doing so, energy intensities of monetary flows can be estimated.

However, as we discussed above, resource inputs are only one side of the coin. According to thermodynamics, all acts of production (requiring inputs from the biosphere) are simultaneously acts of consumption, degrading high quality inputs into wastes to be discharged back into the biosphere.

3.3 I-O methods including resource inputs and waste flows

Now that the global economy is experiencing the pressure of physical constraints, the necessity for a more comprehensive model, and collection of data to estimate it, is emerging. A number of disciplines including material flow analysis (MFA), industrial ecology (IE), and life-cycle assessment (LCA) have developed further extensions of the EI-O framework to account for energy, material and waste flows between the economy and the biosphere. Motivated by concerns over environmental impacts (especially climate change), the primary focus of such efforts has been on tracking flows of materials (especially greenhouse gases) into the biosphere rather than on resource depletion.[? ? ? ? ? ?] This extended method is depicted in Figure 5C.

The making industries related to extraction, refining, and utilities mark the entry point for materials extracted from the biosphere into the economy. These three industries (extraction, refining, and utilities) are the first three industries listed in the North American Industry Classification System (NAICS) that the Bureau of Economic Analysis (BEA) uses to track economic information. [? , Table B, p. 25] Conversely, consumption, with associated waste discharge, occur from all sectors of the economy. But why do we have consumption? Boulding tells us that consumption is the real cost of living in a physical world; that there is,

> no particular virtue in consumption. It is, unfortunately, a necessary incident in the business of living. We cannot eat without destroying food; we cannot walk without destroying shoes; we cannot drive without destroying gasoline, tires, and cars; and so on.[? , p.2]

In a sense then, it is the existence of physical objects within our economies (and their subsequent degradation) that is the driver of consumption. As such, to truly understand our economies and the flows of materials through them, we must account the physical stocks within them.

3.4 An I-O method for dynamic (transient) economic analysis

Both the original Leontief input-output method and the extensions cited in Sections 3.1-3.3 assume steady-state conditions in an economy, i.e., flows of value and material into and out of each economic sector are in balance. Dynamic or transient behavior of the economic system is not considered. Thus, there is no accumulation of economic factors or embodied energy within any of the sectors. The analysis techniques provide "snapshots" of economic activity at an instant in time.

Assuming no accumulation of materials, within economic sectors or society itself, is tantamount to assuming that *all* material flows through the economy are directed toward the production of non-durable goods. However, evidence of the durability of goods and the accumulation of materials surrounds us. Furthermore, energy was required to both fabricate and emplace the durable goods and infrastructure of modern economies. (The energy it took to create the durable goods and infrastructure can be considered "embodied" within the built environment, a point to which we will return in detail later). As Georgescu-Roegen notes, "in the everyday world one cannot possibly cross a river only on the flow of maintenance materials of a non-existent bridge." [**?**]

Analysis methods that neglect the accumulation of materials and embodied energy in the durable goods and infrastructure of the everyday world lack explanatory power. Such models can tell us at what rates materials and energy are required to *use* our built environment. But, such models cannot tell us *how* the built environment came to be (and how much energy was required to construct it) or *why* flows of resources are needed to maintain it. To use Georgescu-Roegen's imagery, models that neglect accumulation fail to explain why we need any material flows to maintain a non-existent bridge. Stocks of accumulated materials (capital, appliances, even people) are drivers of demand. It is to service their needs and wants that we put the economy to work.

Georgescu-Roegen distinguishes two types of economic inputs: *flows* which are the resources (such as cloth and thread) to be transformed into final products (shirts) and *funds*—stocks (such as needles) that must be present in order to facilitate the transformation. Confusing the two categories could lead to some painful consequences! [**?**] Daly makes a similar distinction between *material* and *efficient causes*.[**?**] A full model of the economy must account the stocks (funds, efficient causes) that give rise to the flows (material causes). In car production, for example, we must consider not only the flows of inputs required, but also the stocks of factories, machines, and robots that must be in place to meet the growing demand.

Because economic activity requires energy, we need to understand the way energy flows through economies. The steady-state I-O techniques of Bullard, Herendeen, and others [**? ?**] offer a means to that end. We contend, however, that these techniques need to be extended and modified to include transient effects that arise when durability of goods and infrastructure (and associated embodied energy) are considered. When accumulation is not accounted for, the assumption is that all flows in and out balance instantaneously. Imagine a bath tub where the water flowing in through the tap is exactly balanced by the water flowing out the plughole. The state of the system (the amount of water within the bath) is fixed—therefore we say the system is in steady-state. Or, imagine a growing baby. The inputs of food and other materials, though small compared to an adult, exceed the output of excreta (gas, solid, and liquid). While this may be hard for new parents to believe (how can there be possibly be more going in than is coming out!), it is simply this imbalance that induces the growth of the baby. Materials accumulate within the baby's body. Obviously, this imbalance (and the subsequent growth induced) slows as the child grows up to adulthood. Nevertheless, adults still maintain the ability to accumulate materials. We can gain (or lose) weight; a fact to which any yo-yo dieter will readily attest.

Steady-state systems are unable to change their internal state. Real systems are rarely in steady state. As such, our economic models, analysis methods, and associated accounting frameworks need to be able to deal with dynamic systems that are not in steady-state—they must be able to account accumulation within the economy. During the Great Recession, for example, the demand for new cars dropped precipitously, a large percentage of emplaced capital (and workers) stood idle, and a strong secondary car market blossomed.

In this manuscript, we develop a physical input-output, matrix-based analysis method and accounting framework for modeling multi-sector economies, in the tradition of

Table 2: Examples used throughout this book.

Example	Sector 0	Sector 1	Sector 2	Sector 3
A	Biosphere	Society	NA	NA
B	Biosphere	Final Consumption	Production	NA
C	Biosphere	Final Consumption	Energy	Goods & Services

Georgescu-Roegen's "flow-fund" model.[**? ?**] The method presented takes a decidedly thermodynamic approach to extend the techniques of Bullard, Herendeen, and others to account for accumulation of goods and embodied energy. This framework allows us to see how energy and materials flow through the economy, as well as where embodied energy accumulates in the economy. Real economies, much like babies, grow and develop. Their internal structures are dynamic, undergoing change and transitions. We need to be able to understand these developments by understanding the underlying structural changes. This book addresses that need.

4 Structure of the book

The remainder of this book is organized as follows. Part **??** models flows of physical matter and energy through the economy. Chapter **??** presents a discussion of material flows. Flows of direct energy are discussed in Chapter **??**, and a rigorous, thermodynamics-based definition of and accounting for embodied energy is presented in Chapter **??**. In Part **??** we turn to non-physical flows through the economy. Flows of economic value are discussed in Chapter **??**. In Chapter **??** we combine the results from Chapters **??** and **??** to calculate the energy intensity of economic production. Part **??** gives context to the framework developed in Parts **??** and **??**. Chapter **??** draws out some of the direct implications of the results. Chapter **??** looks at unfinished business: practical, conceptual, and theoretical issues that arise in the development of this framework. We finish off the book with a summary in Chapter **??**.

Throughout the methodological chapters (**??**–**??**), the framework is developed through a series of increasingly-disaggregated models of the economy (Table 2). In addition, we use the US auto industry as a running example for application and discussion. We choose the auto industry, because it remains a large portion of many industrialized economies, because is very resource intensive, because it has been used in the literature [**?**] to illustrate input-output analysis methods, because its links with energy are obvious, because its health is sensitive to disruptions in energy supplies, and because it shows evidence of post-industrial decline (shrinking profit margins, etc.).