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A Thermodynamic Interpretation of the Progression of Historical Processes

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Abstract

This article examines the long-term rise of human civilization in terms of the emergence of socio-physical dissipative structures, including cities, agricultural systems, infrastructure and relevant economic enterprises. The laws of thermodynamics, the Principle of Least Time, and the phenomena of complexity and emergence are briefly reviewed and accepted as assumptions. The concepts of thermodynamic work, power and efficiency are likewise reviewed. Also examined are the emergence of medium-term dissipative structures, such as the rise and fall of dynasties, resource and economic bubbles in terms of thermodynamic theory. The impact of thermodynamic constraints on the emergence and fall of such structures is examined. Particular attention is paid to the interactions between physical resource use and the social progression of those structures. Areas of applicability to World-Systems is discussed.

Keywords: Energy, Power, Dynasties, History, Big History, Complexity, Emergence, Resources, China, Russia

Social philosophy can be seen as a precursor to social science, for they share many of the same subjects and concerns. Today, the social and physical sciences are quite distinct from one another. This distinction seems to have paralleled the separation of natural philosophy from inner philosophy. This separation is still the matter of some dispute:

> With the earliest Greek thinkers, to whom some physical object, or some physical quality, such as hot and cold, might seem to be the most general of all things, there was of course no question of dividing philosophy from science. The two were one. As time went on, and physical science increased, while at the same time men reflected more and more on the operation of their minds, there came to be a tendency to distinguish the two fields of thought and use philosophy only of(for?) the latter. But this restricted use of the word has never gained the consent of mankind. Men still think, and rightly think, of philosophy as the attempt to see things whole, and as the vast mass of things presented to our minds are now the subject-matter of some branch of science, it is theoretically impossible to dissever philosophy from science (Marvin 1936).

The transition from philosophy to social analysis was not surprising. Thomas Aquinas was an important medieval social philosopher who was extremely influential on later thought. Aquinas was a medieval philosopher who attempted to reconcile religious dogma with observations of social inequities and law. Aquinas is best known for Summa Theologica (1265–1273). Social order, for Aquinas, was part of the order of the universe (Fink 1981).

Some of Peter Grimes's work came close to the original thinking in the founding of sociology. For example, early sociologist August Comte was inspired by the success of the physical sciences to develop a science of human society. However, Peter Grimes's ideas and work go beyond the ideas of Comte. This is not surprising, since quantum theory and modern thermodynamics did not exist during the time of Comte or other early sociologists. It is only until the last several decades have social and physical scientists studied and identified the thermodynamic principles that really drive the emergence of life, intelligence and civilization.

In the 1600s, astronomers used a new technology—the telescope—to examine the night sky (Center for History of Physics 2022). They saw that the Moon had craters, that Venus had phases, and that Jupiter had moons, and these observations shook the very foundations of physics and astronomy. In the late twentieth century, social scientists and physicists began using the new, modern understanding of thermodynamics to examine humanity and the nature of life. Peter Grimes was one of a handful of sociologists to do so, and perhaps the only one to apply this new understanding to world-systems theory.

Peter Grimes was nearly unique among sociologists in that he investigated social interactions among living beings such as humans as part of the nature of the physical universe, specifically, that such interactions were matters of thermodynamics. Thermodynamics is literally the physics of life. "It is a law of thermodynamics, the law of the universe, that all life requires energy, and is sustained by using energy to suspend molecules in a state that they would otherwise not naturally be in" (Grimes 2003: 1).

Grimes viewed people as biological organisms that exist in a physical universe and environment. Indeed, people consume physical resources and take physical actions. All interactions between people are ultimately physical, including talking, hearing, facial expressions and projections of power. He was able to show the path and tell the story about how people and society were the product of great cosmological processes and then he applied that story to the very human challenges of our society.

This paper strives to review some of that story and then to show a framework of how it might be applied to medium-term historical processes, with the understanding that there is so much more to be accomplished, especially as regards application to sociological processes and World-Systems theory. This work also attempts to provide a common language across the social and physical sciences, utilizing terminology that readily recognizable by professionals in either group, using the flow of water as an analogy.

The Big Picture

Although people are physical and exist in a physical universe, their reactions to physical phenomena are not simple, straightforward reactions. Evolution has developed a complicated brain and physiology. Information and feelings are stored. The machinery of the brain and the chemistry of the body shape reactions to external stimuli that may individually be decades in the making and as a species millions of years in the making.

If you push an inert object, Newton's Laws of Mechanics suggest that there will be an equal and opposite reaction, that the object will resist and literally push back. However, an intelligent being may push back, run forward, or produce an intellectual discourse on the merits or evils of pushing. While people are subject as physical objects to Newtonian Mechanics, such mechanics are sufficient as constraints upon human behavior, they are poor descriptors of all but the basest of social interactions between humans.

However, the statistical phenomena of thermodynamics as concerns groups of people is a socially more powerful matter. Certain aspects of thermodynamics appear to have been wired into human brains and physiology, for the survival and advancement of the species and lines of individuals. Human society is a stochastic interaction of humans whose brains are the product of surviving the laws of thermodynamics. There is cooperation and competition among humans, and because of our individual differences, a group of humans in a very real sense resembles the semi-random action of clouds of physical particles. The remainder of this article investigates those relations.

Big History, Big Sociology, Wider community

Grimes and his works fit into a small, interdisciplinary school of thought concerning thermodynamics, life and society. The Big History approach is an example of this school of thought as applied to human history by historians David Christian and Fred Spier (Spier 2009).

Some Thermodynamics Theory

It is possible to understand much of the evolution of the cosmos and the evolution of life and the progression of historical processes by knowing just a few principles of thermodynamics. A few general terms are introduced then discussed in terms of thermodynamics. These general terms can be applied to both social and physical phenomena.

Tendencies, Potentials, Flows and Bubbles.

A *tendency* is something with a greater than random likelihood of happening. Forces are tendencies. For example, gravitational force is a tendency for massive objects to accelerate towards each other. The term *force* has a specific meaning in physics, whereas the term tendency is broader and more inclusive. Not all tendencies are forces. For example, the tendency of light to follow the fastest path is not a force. Gravitational attraction is a force. But gravity is also a tendency.

To explain further: a force is a specific concept in physics with specific units, such as kilograms times meters per second squared. Conceivably, all tendencies are ultimately the result of forces, but often so indirectly or in complicated ways. For example, the flow of thermal energy involves the interaction of numerous particles each involving individual force, but is much too complicated to track. The use of the term *tendency* allows us to capture the colloquial idea of force without committing ourselves to the strict physical definition of such. It is a useful shortcut. Such examples can often be described much more succinctly as tendencies with a high statistical probability, such as the high probability that thermal energy will flow from hotter to cooler regions.

Equilibrium represents a state of a system in which tendencies can no longer cause any change. When a system has reached equilibrium, it is literally dead. (In contrast, d*ynamic equilibrium* is when a rate of something remains constant, where tendencies offset each other to produce a steady flow).

Potential represents the ability of a system to achieve something. A potential is typically the result of a system being pulled away from equilibrium with respect to a tendency. For example, when a spring is stretched, it tends to return to its original length. That spring has stored potential energy. If the spring is released, it will move back towards its equilibrium position.

When systems release or consume their potential over time, a *flow* occurs. In some cases, a flow comprises the transport of a physical element such as water or energy. For example, imagine that snow falls on a mountain in winter. The mass of that snow has been raised well above sea level. The material of the snow has gravitational potential. When summer arrives and the snow slowly melts, a steady flow of water will trickle down from the mountains, and travel through rivers back to the sea. As the melted snow water slowly moves downhill, its gravitational potential is consumed. The water has achieved its “goal,” so to speak, of returning to equilibrium with respect to gravity.

Sometimes rivers get blocked, such as from falling trees. Additional flotsam piles up, forming a logjam, blocking the flow of water. More and more water will accumulate behind the logjam, creating increasingly greater force. When the force exceeds that which the logjam can resist, the water will break apart the logjam and flow at an accelerated rate until it transitions back to its usual rate (dynamic equilibrium). This situation is similar to blowing up a balloon with more and more air, until the material is stretched to its breaking point and bursts. These are examples of simple bubbles.

Energy and the First Law

Peter Grimes focused on physical energy. In physics, the term "energy" is somewhat different than common usages of the word. Physicists would say that the following possess energy: moving objects possess *kinetic energy*; if the objects are randomly vibrating atoms and molecules in a solid, liquid or gas, they possess *thermal energy*, and a stretched rubber band would be said to possess *potential energy* that can be converted into either kinetic or thermal energy by un-stretching the rubber band. Or imagine a pendulum swinging back and forth. As the pendulum falls, it goes faster and possesses more kinetic energy and less potential energy. As it rises, it gains potential energy and loses kinetic energy.

The First Law of Thermodynamics states that energy can change forms but never be destroyed. The total amount of energy in an isolated system (energy + potential energy) can never change in quantity, although it can change in form. (Albert Einstein's relativity theory extends this principle, but not in ways that affect our discussion here).

Thermodynamic Tendencies and Drivers. *Thermodynamics* is a branch of physics that concerns the flow of thermal energy (heat) and the ability to convert energy into work. The term statistical mechanics is an applicable, broader term that includes thermodynamics, but this paper shall use the latter term for consistency.

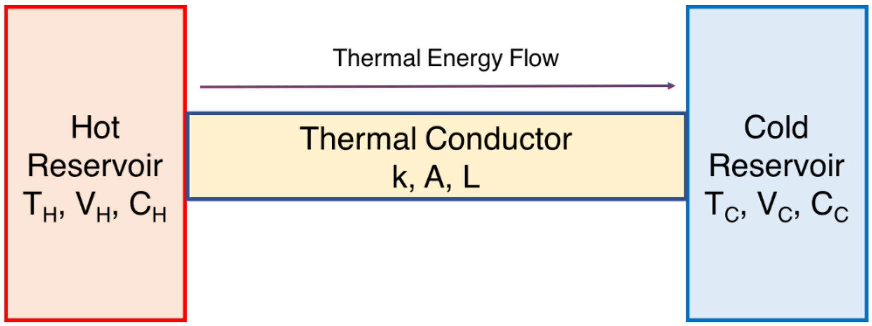
Thermodynamics is extensively used in atmospheric science, biology, chemistry, engineering, and geology. A key motivation for development of thermodynamics as a discipline was to understand how to make engines more efficient, and what could be the maximum efficiency for engines. Another motivation was to express the energy involved in chemical reactions.

There is a tendency in systems for thermal energy to evenly distribute itself in a manner that temperature becomes equal for all regions in a system. When regions in a system differ in temperature, a thermodynamic potential exists. If those regions are bridged by a thermal conductor (Figure 1), then thermal energy will flow from hot to cold regions (Schroeder 2000). For example, thermal energy will flow from a tank of hot water through a copper conductor to a tank of ice water. This tendency is not a force in the same manner as is gravity, but it is a statistical phenomenon with a positive probability of occurring.

As thermal energy flows, potential is consumed. Thermal energy will continue to flow until both regions possess the same temperature. At this point, those regions are said to be in thermal equilibrium and the potential has been exhausted.

Chemical and pressure differences also involve thermodynamic tendencies that can result in flows and the consumption of potential. Humans are biological organisms involving chemical reactions. Humans use engines and other energy-consuming technology. Hence, it should be no surprise that the laws of thermodynamics provide a driver and set of constraints that act upon human systems. Here, *driver* is meant as the cause of a process such as a flow. Here, a *constraint* is something that prevents a process from taking one or more paths. For example, if a river cannot flow through a mountain, then that mountain would act as a constraint upon the path the river takes.

Figure 1. Conductor Bridging a Thermal Difference.



Entropy, Engines, Reproducing Engines and Exponential Growth.

If the total amount of energy in a system cannot change, then why is there all the fuss about "running out of energy" and energy crises? What people really mean is running out of something called *potential entropy*.

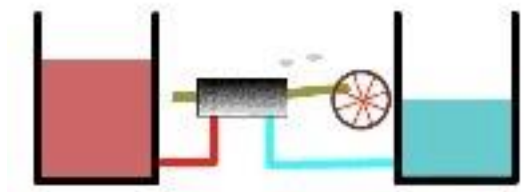
A quantity called *entropy* increases as all real systems progress though time. Entropy is produced when thermodynamic potentials are consumed. Just as energy + potential energy = constant, entropy + potential entropy = constant. Yet here's the catch: energy can change back into potential energy, but entropy cannot typically change back into potential entropy. For example, it is easy to burn coal to create heat and electric power, but it would be difficult and expensive to artificially produce coal. The term potential entropy is seldom used, because most contemporary physics research focuses on energy rather than entropy, and much engineering focuses on specialized areas involving terms such as "horsepower" and "load ratio." However, for the analysis of historical processes, potential entropy is quite apropos.

For example, let us consider a thermal difference bridged by a heat engine rather than a thermal conductor (Figure 2). A heat engine can convert some of the flow of thermal energy from a hot reservoir to a cold reservoir into useful work. However, in addition to work, this process increases entropy.

For systems involving a nonrenewable resource, entropy is the ultimate accounting tool. A real-life system can remain active so long as it can produce entropy. When it can no longer produce entropy, it cannot change in a meaningful way. It is essentially dead. A bubble inherently involves a resource that is nonrenewable within relevant time frames. Therefore, a full accounting of entropy can express the state of the system with regards to how far it is along an irreversible process.

Entropy has a precise definition in physics: it is the log of a quantity called *multiplicity*, multiplied by a constant number (Boltzmann's constant). Operationally, entropy is a measure of how evened-out things are, such as when thermal energy flows to minimize temperature differences. When thermal potential gets consumed by a conductor bridging a thermal difference, the entropy of the system increases.

Figure 2 A Heat Engine Bridging a Thermal Potential



While a system increases its entropy, it is alive, at least in some sense. Once the entropy of a system can no longer increase, it is literally dead. Biological organisms produce entropy, so they are alive, in both this and the traditional sense.

There are colloquial descriptions of entropy that call it "disorder." We all have opinions about disorder, but the term as applied to thermodynamics is typically not useful and even misleading. What has more disorder: a messy room full of yellowing old, wrinkled magazines or a nice, well-kept empty room? A glass full of crushed ice or a glass of homogenous water? A shelf of books organized by author or organized by title? So using the word "disorder" to apply to entropy provides fodder for immensely satisfying or disturbing projections of the state of life and the universe in several trillion years, but has very little practical value for purposes of our analysis.

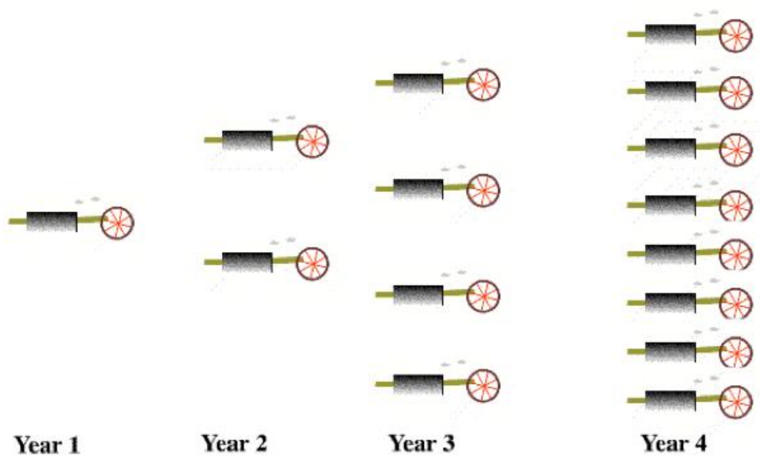
The Principle of Least Time.

It has been proposed that entropy production is subject to the Principle of Least Time (e.g., Anila and Salthe 2010). In other words, systems will tend to be configured in a manner which maximizes the rate of entropy increase with respect to time. An example would be where complexity emerges in a manner in that thermal energy flow increases. This principle has been observed across multiple academic fields. For example, when modeling atmospheres, astrophysicists will tend to choose the form of energy transfer that maximizes heat flow, such as convection versus conduction (Carroll and Ostlie 2007). In chemistry, dissipative structures form that increase entropy production (Prigogine 1967). Psychologist Rod Swenson observed this effect (Swenson 2011), as did Spier (2009). Likewise, some of this thinking is found among physical chemists such as Alfred Lotka (Odum 1996), at least one cosmologist (Eric Chaisson), ecologists such as Howard Odom (Odum 1996), and has been a substantial subject of conferences such as Thermodynamics 2.0 (IAISE 2022).

What if heat engines could reproduce?

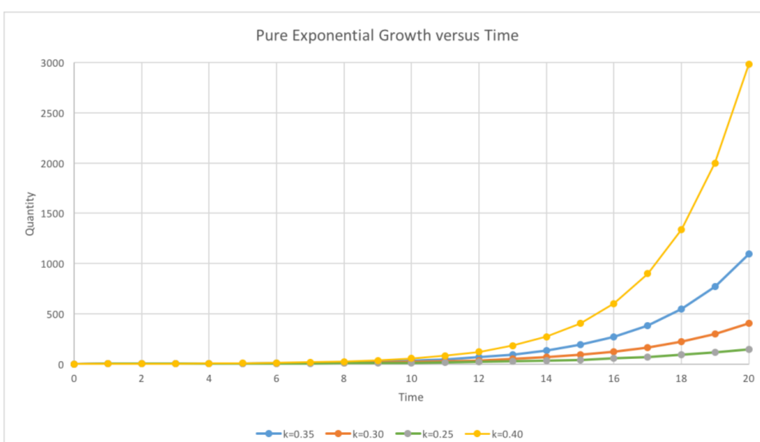
What if the work produced by a heat engine could be used to build additional heat engines (Figure 3)? For example, the heat engine could power machine tools to make the parts for an engine. What if this effect could be generalized to apply to any engine that consumes entropic potential? If so, this would be consistent with the application of the Principle of Least Time to entropy production. This means that systems tend to be configured in a manner that maximizes their rate of entropy production. In fact, we frequently see this phenomenon in nature. For example, fire consumes entropic potential and can easily reproduce. So can bacteria and other forms of life.

Figure 3 Reproducing Heat Engines



In the case of reproducing heat engines, growth would be proportional to the quantity of heat engines. there could be an exponential growth (Figure 4) in both the quantity of heat engines and the rate of entropy increase.

Figure 4 Plot of Exponential Growth for Various Growth Rates



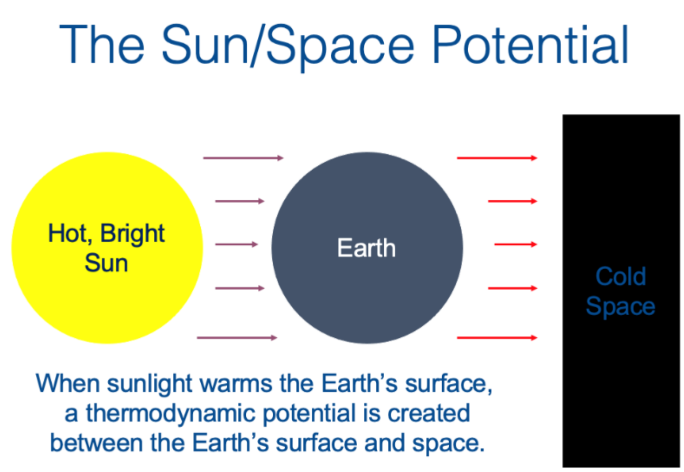
The Formation of the Universe and the Emergence of Life, Intelligence And Civilization

Modern theory proposes that the universe began at a singularity, at which time and space began. This singularity contained all of the energy of the Universe. Then, about 14.3 billion years ago, the universe exploded into time and space in an event known as the Big Bang. The universe then began a great expansion.

Since then, there have been two trends of note that continue into the present time. First, as the universe has expanded, its energy has become more diluted; thus overall, it has been cooling down. This is fortunate for humans, as the universe has, overall, become sufficiently cool to support life as we know it. Second, as time passed, the universe has become more heterogeneous. Within local regions, gravity causes matter to condense, heat up and form complex structures such as stars, galaxies and other structures.

Such structures allowed for more rapid increase of overall entropy. Stars allow for sustained nuclear fusion and the release of tremendous amount of potential energy locked into nuclear structures. Likewise, disks of gas and dust formed around stars due to gravitational attraction and dissipated gravitational potential energy. Also, in such disks, planets formed. Although many such planets are giant, hot balls of gas similar to Jupiter, other planets are moderate in size and temperature, such as the Earth. Instead of merely reflecting light back into space, such planets are capable of hosting sophisticated chemical reactions can consume potential entropy from starlight. In the case of the Earth, biological life formed. Initially, such life may have been powered by the Earth's heat and residual energetic chemicals that formed on the Earth due to cosmological and geological processes. Eventually, most life on Earth became powered by Sunlight.

Figure 5 Sun-Earth-Space potential



The Immediate Thermodynamic Environment of Life and Humanity

When it is said that most life on Earth is powered by Sunlight, really, what is meant is that life on Earth is typically powered by the entropic potentials present on the Earth's environment in space. A thermodynamic potential exists between photons emitted by the Sun versus the cold, relative darkness of space (Figure 5). Humans make their living off of this Sun-Earth-Space potential, chiefly from Sunlight driven plant production and related animal production, but also from Sunlight-driven wind and hydro-power. To survive, humans must “go with the flow”, literally with the flow of energy from the Sun to the Earth to space. The sum of social interactions must be consistent with harvesting some of this flow for a human society to endure.

Analyzing History From A Thermodynamic Perspective

Limits on Exponential Growth and Decreasing Efficiency

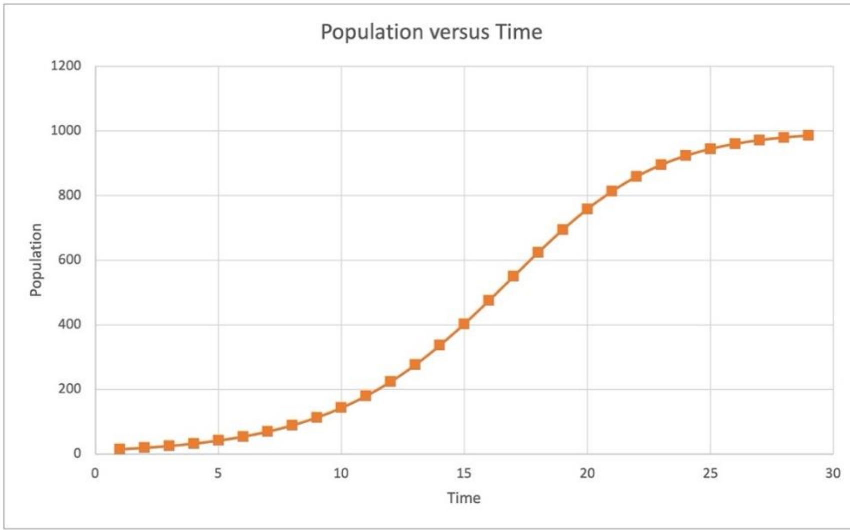
There will always be factors that limit the growth in a system. A regime that experiences exponential growth will eventually begin to experience such limiting factors. Work on system dynamics such as the Club of Rome's *Limits to Growth* (Meadows et al. 1972) involves attempts to better understand these limiting factors. Such factors restrain growth and sometimes stop it altogether. Limiting factors usually exist due to a shortage of some essential resource or an excess of some "negative" resource. Turning to biotechnology, an examination of reproducing cells shows that the chief limiting factors are typically a nutrient limitation or an accumulation of a toxic metabolite (Butler 1996).

We have viewed how exponential expansion is favored by thermodynamics. However, exponential production cannot increase forever. There are limits to available potential. For example, in the Sun-Earth-Space scenario, the Earth receives a limited amount of sunlight per year. Once an area is populated with plants and dependent species of animals and other life, populations cannot generally expand. When life is first introduced, populations will expand exponentially initially, but then level off to approach an equilibrium. This limited growth is called logistical growth, and a plot of such growth is called a logistics curve (Figure 6) or S curve.

Even in an environment that is overall rich in resources, scaling issues result in the decrease of surface area to volume ratio of the organism colony. Lack of oxygen can be a limiting factor for large cell cultures. The organisms often cannot get access to abundant resources because they are crowded out by their neighboring organisms. Multi-cell organisms attempt to overcome the surface area limitation with structures such as veins and folding. Yet this approach itself has limits. An elephant still faces many challenges as compared with an ant, such as expelling sufficient body heat. Human civilization meets a similar surface area challenge with similar structures. The great freeways and road networks in cities and even across the countryside resemble the blood circulation system in our own bodies.

If there is a nonrenewable, built-up potential, such as oil, coal or gold, then generally, the intrinsic efficiency at which each additional unit of consumption is transformed into production decreases. This is expected: we go for the low hanging fruit first, then the slightly higher fruit, and only go for the hard-to-reach fruit at the top of the tree last. There are two chief types of efficiency: intrinsic efficiency and overall efficiency. Intrinsic efficiency is limited by the Second Law of Thermodynamics prohibition on entropy decreasing in an isolated system. Overall efficiency cannot exceed intrinsic efficiency, but it can be much lower. Technical improvements and economies of scale can help improve overall efficiency.

Figure 6 Plot of a Logistics Function



Overall efficiency functions can take several forms, depending on the circumstances involved. For example, for a nonrenewable resource, the efficiency function may decay linearly or exponentially. There are ways of determining the overall efficiency function from actual data or known constraints.

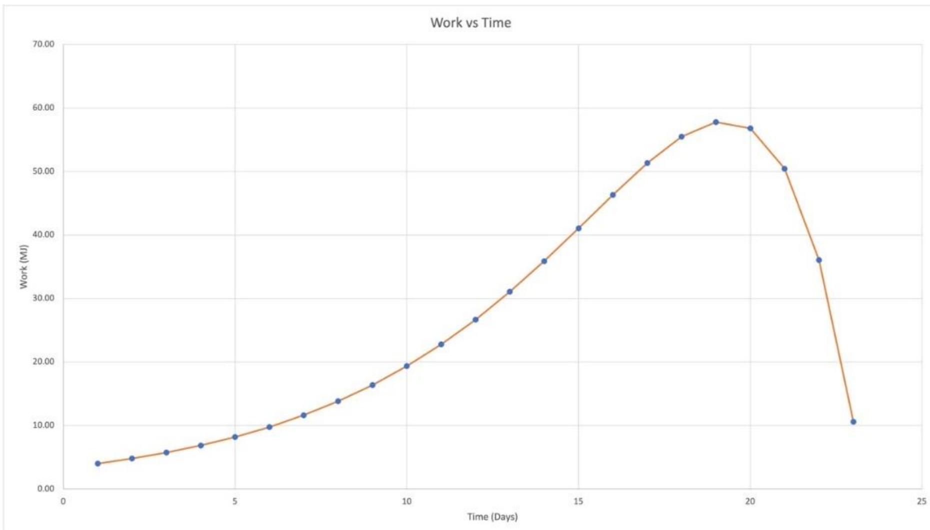
The Rise and Fall of a Bubble

We have seen how the emergence of reproducing dissipative structures can lead to exponential growth. We have discussed how intrinsic efficiency decreases as a nonrenewable resource is consumed. Hence, we now have the conceptual means to understand the lifecycle of a bubble. To be *clear*, *from this point further*, a *bubble* will refer to *a rise-then-fall progression due to the emergence of reproducing, dissipative structures operating upon a limited, nonrenewable resource*.

1. A thermodynamic potential accumulates.
2. A reproducing, dissipative mechanism has emerged to consume the potential.
3. The mechanism reproduces exponentially. Consumption increases exponentially.
4. Growth continues, but intrinsic efficiency decreases.
5. Eventually either all the potential gets consumed, or the efficiency of exploiting it falls below the ability of the mechanism to maintain itself.
6. The progression of the bubble ends.

Since exponential growth is involved, but the transformation of consumption into production must be discounted by efficiency, this approach to bubble modeling is called efficiency-discounted exponential growth (EDEG) (Figure 7).

Figure 7 EDEG Plot



Application to Natural Resources

A bubble can involve physical or social resources. However, it is easier to begin analyzing physical resource bubbles, since there is often more available data and the examples are fairly straightforward.

It is instructive to apply this bubble paradigm to a few cases involving natural resources such as fossil fuels or precious metals. Mining is both a physical and social activity. Deposits of a commercially-demanded substance represent an economic potential (which is ultimately a thermodynamic potential). Mined substances are typically nonrenewable. If you extract a ton of that material, another ton does not form in the ground. Such substances took millions or even billions of years to form and accumulate. Therefore, there is only so much to extract: the mining bubble must eventually end. In other words:

past consumption + future consumption = constant.

Further, since the resource is nonrenewable, the intrinsic efficiency of extracting the potential will tend to decrease over time (according the hypothesis above).

It is preferable to examine a case where there is ample data. Ideally, there should be multiple actors, at least at the beginning, so that individual differences average out to clarify the overall pattern. Multiple actors with significant variation provides a system with a flexible "stochastic" capability to allow the system to adapt and progress.

San Juan Mountain Area Mining Region. To apply bubble analysis of a mining region, it is best if the region considered is sufficiently large to initially support many actors, such as mining enterprises. Then in early stages, but after things get started, no individual mine can determine the fate of the entire region. For example, poor management at one mine is offset by effective management at another. The region should be sufficiently isolated so as not to be too influenced by external factors, but there must nevertheless be an internal or external demand for the substance.

The San Juan mountain area (known as the “San Juans”) in southwest Colorado is such a region, and is a suitable physical and social example of a bubble, including the mining society that developed in the region. The San Juans region of Colorado produced gold and silver (Smith 1982) from hundreds of mines, around which towns and communities eventually developed.

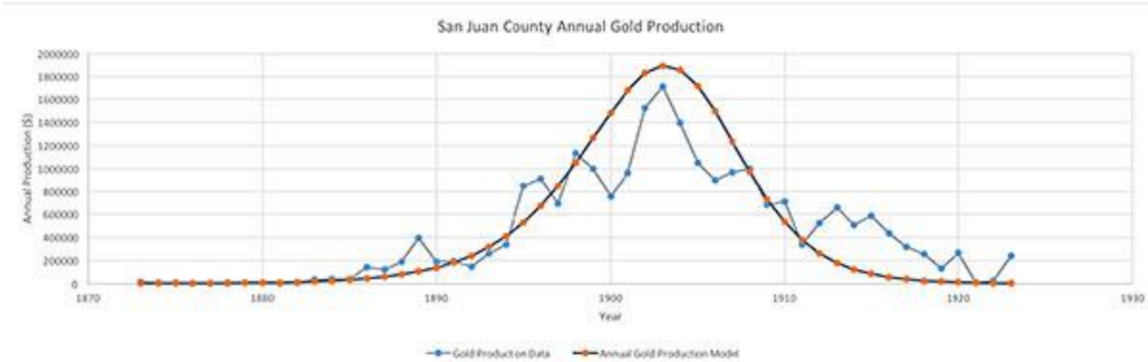
The San Juans were ruled by Spain until 1848, and then by the United States. Spanish gold mining of placer deposits (pieces of nearly pure gold found on the surface) took place between about 1765–1776. Some U.S. mining took place in 1860, but it was interrupted by U.S. Civil War. At this point, “only the smaller deposits of high-grade ore could be mined profitably.” (Smith 1982). Mining slowly started again in 1869. There were 200 miners by 1870. An Indian Treaty was negotiated in 1873, which removed a major obstacle to an increase of mining (Smith 1982; Twitty 2010).

In 1881, a railroad service was established, resulting in a “decline in ore shipping rates.” The regions heydays were between about 1889 and 1900. As the region matured, there was a major consolidation of mining operations as well as significant infrastructure improvements such as rail lines. By 1889, English investors had come to control the major mines. There were also labor troubles. The 1890 production total for San Juans was $1,120,000 in gold; $5,176,000 in silver. The region produced $4,325,000 in gold and $5,377,000 in silver in 1899 (Smith 1982). Note that for mining, production refers to the processed metal rather than mere ore.

By 1900, the region began to take on more of the characteristics of a settled community. There was a movement for more “God” and less “red lights.” By 1909, “the gilt had eroded” (Smith 1982), dilapidation set in and the population decreased. World War I caused production to greatly fall, due to decreased demand from Europe, and the region lost workers. Farming became more important to local economy than mining. Silver and gold mining all but ceased by about 1921. Today, there is again mining in miscellaneous minerals, but not much in gold, which was the primary economic driver for the “great days.” The region is now used primarily for recreation and some agriculture (Smith 1982; Twitty 2010).

An EDEG model was generated for the San Juans region and compared with actual mining data (Figure 8) (Ciotola 2016). Exponential growth was initially facilitated by an increase in the quantity of mines, then later by the growing size of mines. Intrinsic efficiency decline in mining tends to comprise decreasing quality ore. For example, the early-mined placer deposits might comprise 100 percent gold, while late-stage ore might comprise less than one percent gold. The model is somewhat higher than the peak, but parameters were adjusted to provide a better fit with the overall data. Deviations shown in the curve occurred due to both random events, social, economic and logistic "turbulence", business cycles and major external events.

Figure 8 Colorado San Juans Gold Production Versus Model



(data: Henderson, 1926)

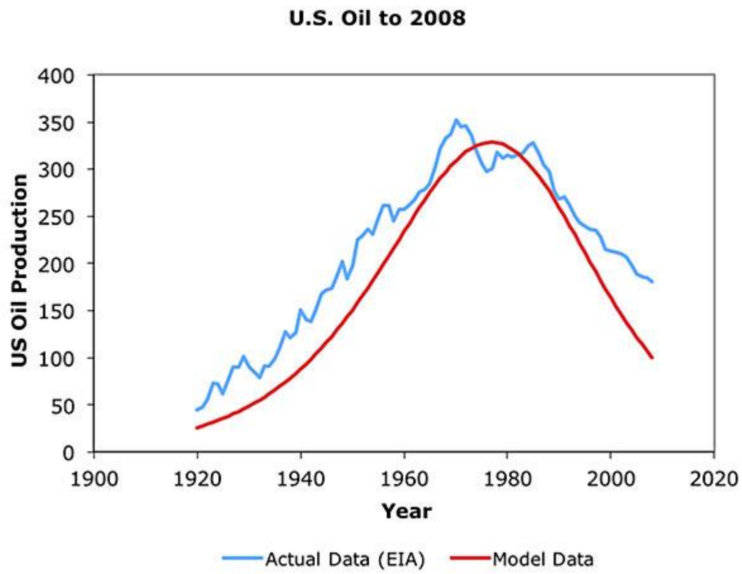
U.S. Petroleum Production. Petroleum (oil) is a mixture of hydrocarbon molecules. The formation of oil is complicated and involves a series of steps and conditions that typically require hundreds of millions of years to complete. First, organic matter from dead plants, animals and plankton falls to the bottom of shallow sea basins. If organic material is deposited at a high rate in large quantities, it will become preserved. Eventually, the deposited matter sinks deeper due to geologic forces as well as the weight of the accumulating matter above it. As the matter sinks thousands of feet under the ground, it becomes hotter and the organic material is literally "cooked." Heat breaks down the organic matter into long hydrocarbon molecules. Eventually oil is formed (Chapman 1983; Deffeyes 2001).

Hewett-Hubbert curves are functions that represent the extraction of minerals or petroleum over time for a large region or country. Such curves apparently originated with Donnel Foster Hewett for European metal mining (Hewett 1929). Such curves were then applied by petroleum geologist M. King Hubbert to U.S. domestic petroleum extraction (Hubbert 1947, 1956). Hewett-Hubbert curves represent statistical distributions regardless of how they are generated; and they generally represent situations where there are a considerable number of actors, such as in the case of regional or national oil or mining production.

Efficiency-discounted exponential growth (EDEG) is an approach to generating a Hewett-Hubbert function (Ciotola 2010). An EDEG model was generated for U.S. domestic petroleum extraction (Figure 9). Actual data exceeds model prior and after peak. Parameters were set to match peak, but could have been adjusted for less error elsewhere at the expense of greater peak error.

As oil became more available, the uses and demand for it multiplied, driving and financing an exponential increase in production. That oil wells have had to be drilled increasingly deeper and in unfavorable areas such as at sea is evidence of decreasing intrinsic efficiency. Some of that decrease has been mitigated by improved exploration and drilling technologies as well as industry consolidation.

Figure 9 EDEG Model for U.S. Petroleum Production up to 2008
Vertical units = 10,000 Barrels.



(data: EIA)

Petroleum extraction represents an especially interesting case, because energy is literally being extracted. For a dynasty (or modern government) substantially dependent upon petroleum for its energy and economy, the rate of net petroleum production versus time *is* its power progression (in physics, power is the rate of energy expended per unit of time). Net production means the total energy extracted less the energy required for production operations.

Emergence and Progression of a Single Dynasty

We will now express historical dynasties as emergent dissipative structures and generate power progression models of dynasties from fundamental principles. In this discussion, the term *dynasty* is used broadly to refer to a continuous ruling group; it could be a related family but not necessarily so. In contrast, the term *society* will refer to a large group of related people, typically of a single or similar group of ethnicities, such as the Han people in China or the Frankish people in France. Dynasties exist within a society, but they can conquer other societies as well. For example, the society of Russian people produced a series of dynasties, and those dynasties sometimes conquered other societies. Dynasties possess properties of both open and closed systems. In this paper, for the sake of simplicity dynasties are considered closed systems (arguably a reasonable approximation for the large, long-lived dynasties), while societies are treated as substantially open systems (again, a reasonable, albeit only partially valid, approximation).

Dynasties as Bubbles. Both physical and social built-up potential can drive the formation of dynasties. Within the context of a civilization progressing over centuries, it is often possible to degrade built-up potential even more quickly with high-level, governing social structures for a society. Hence, dynasties form to accelerate consumption of such potential. Hypothetically, dynasties should result in more rapid degradation of energy than does a more static society.

Each dynasty has a lifecycle. A dynasty is born, matures, endures awhile, then ends. A new dynasty will not necessarily follow an old one, nor might it immediately appear. Yet generally, dynasties continue to form, one after another, so long as there exists built-up potential that cannot be more quickly consumed by other means. The dynastic lifecycle can be described as a march towards equilibrium in terms of nonrenewable resources, and towards dynamic equilibrium in terms of on-going flows such as sunlight and rainfall.

We can consider large, independent, robust dynasties to be bubbles. A new dynasty within a society encounters a built-up potential of physical and social resources (e.g., good will), albeit of limited magnitude. The society governed by the dynasty fills the role of a collection of heat engines, producing both work and entropy. Prosperity expands exponentially, increasing the consumption of potential exponentially. Eventually, it becomes increasingly difficult for the dynasty to rely upon its store of physical and social resources, decreasing its efficiency. As efficiency decreases, the dynasty will experience social crises and will eventually stop functioning.

Considerations for Modeling Dynasties. It is simpler to model a sufficiently large, robust, independent dynasty than one that existed merely at the whim of its neighbors, for there are less significant dependencies, and thus it can be approximated as a substantially isolated system. We will examine Russia's Romanov dynasty as an example. Widely accepted start and end dates are 1613 and 1917 (Mazour and Peoples 1975). Peter the Great and Catherine the Great were the two most important rulers of the Romanov dynasty, and the Russian Empire gained much of its most valuable territory by the end of Catherine's reign in 1796. The Romanov dynasty was big, robust, and essentially independent. It fought wars, but generally was not under serious threat of extinction. Even Napoleon could not conquer Russia. This Romanov dynasty was reasonably long-lived, rather than just a quick, "flash-in-the-pan" empire.

By developing a fundamental approach to modeling the rise and fall of dynasties, it is possible to accept or reject models (within a range of uncertainty) based upon both qualitative historical evidence and quantitative historical data. We shall discuss generating models of the rise and fall of power of dynasties versus time and how a single dynasty can be modeled using the efficiency-discounted exponential growth (EDEG) approach (Ciotola 2014). Such an EDEG model of a dynasty can be called a power progression. The models shown should be considered mere first approximations rather than definitive assertions of fact. They are a beginning point of further explorations.

Historical dynasties are consumers of energy and producers of power, so models in terms of such quantities are inherently fundamental in that they can be derived directly from the laws of physics and expressed in physical quantities. Such models are not theories of everything, but rather describe certain aspects of broad macro-historical phenomena rather than the intricate workings of the interactions of individual people.

The term energy is meant in the physical sense here. There are several possible proxies of the physical energy of a dynasty, such as population governed or grain production. Each of these is translatable into physical units of energy. For example, the quantity of people multiplied by the mean calorie diet per person will result in units of energy. These figures can be estimated for most dynasties over their lifespans, albeit with differing degrees of uncertainty. The proportion of that energy that rulers of a dynasty effectively have at their disposal is beyond the scope of this paper, but should be considered for improved accuracy.

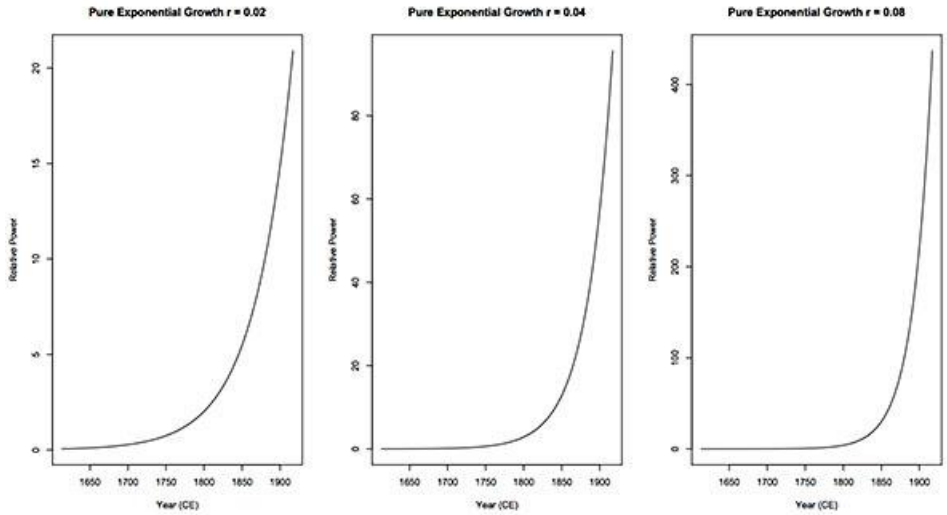
Power is a physical term. It refers to energy expended per unit of time. Yet it also has meaning within social and political contexts, and it will be discussed in both senses. Absolute power would generally be presented in physical units of power such as Watts. However, it is possible to express any type of power in terms of proportions, such as the ratio of power at a dynasty's peak to its start date. Such a ratio can apply to physical, political or even military power. Possibly, the EDEG approach can be utilized to model other types of power, such as political power. In fact, the EDEG approach provides a framework to explore the question of how political and physical power are related.

Exponential Growth of Dynasties. A new dynasty will tend to experience exponential growth. A chief characteristic of exponential growth is that growth feeds even more growth, resulting in an increasing rate of growth. Increases in population and power can become explosive. Nevertheless, the growth rate in early stages tends to be relatively flat, while the growth rate later tends to be relatively steep. The transition between "flat" and "steep" can be surprisingly sudden and disruptive (Meadows et al. 1972).

It will be assumed that dynasties will strive to grow exponentially. (This paper does not attempt to prove this assertion, but rather it is a rebuttable presumption). There is evidence that suggests that it is part of the biological nature of the humans in a dynastic society. Biological organism populations grow as a function of population. Growth that is proportional to population is exponential, mathematically speaking—more people have more children, and hence need more food, more homes. If so, this certainly explains the rise of a dynasty (although not necessarily the initiation of new dynasties, which may be more of a matter of emergence from complexity theory). Sources of growth can include increased agricultural productivity, geographic expansion, and trade expansion.

The Romanov dynasty is shown with various growth rate models (Figure 10). The plot shapes appear similar, except that a greater rate produces a "sharper" corner. Also, notice the range of power values: a greater growth rate produces a disproportionately greater power value at later points of time. The growth rate function can be constrained by the data and an understanding of the growth mechanisms involved.

Figure 10 The Effect of Differing Growth Rates



Limiting Factors and Decreasing Efficiency.

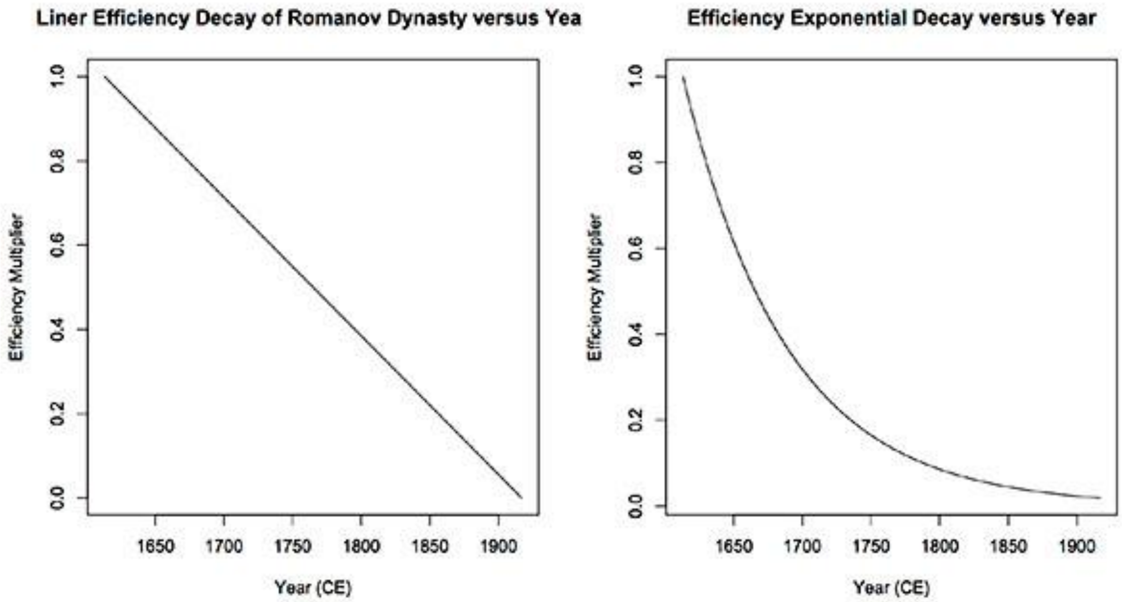
Another source of limiting factors is the increasing cost-per-unit to extract nonrenewable resources such as minerals. Societies attempt to use large-scale social and technical structures to shore up efficiency (e.g., San Juans mining case study), but these structures create additional challenges. There are other examples. In the United States, the “closing” of the western frontier marked a limit of growth to homesteading. In petroleum production, the increasing cost of drilling for oil is a limit to growth. Classical economist Thomas Malthus pointed out limiting factors in the growth of agricultural production (Heilbroner 1980).

A dynasty will typically consume both nonrenewable *and* renewable resources. Yet it is the consumption of one or more critical nonrenewable resources that determines the growth and decline characteristics of the regime. Production in a dynasty is ultimately dependent upon nonrenewable physical and social resources (otherwise dynasties would not typically end). Dynasties inevitably do end, which is typically preceded by a decline in power.

As the dynasty progresses, nonrenewable resources will be consumed, and efficiency will decrease. There will still be production until the end, but there will be a lower return on investment, so to speak. Physical causes of decay can include overuse of agricultural land leading to nutrient depletion, the build-up of toxins in the environment, and the depletion of old growth forests. Social causes can include running low on social goodwill, the increased dependency on expensive, monopolistic, centralized institutions and structures, and the resulting decreased accountability of aristocratic “deadwood.” All such causes may have nonrenewable aspects.

The key impact of limiting factors, whether insufficient positive resources or excessive negative resources, is a decrease in the efficiency of whatever is acting as "heat engines" to do work. There are two types of decay, linear and exponential. Examples are compared (Figure 11). Note that efficiency here is shown as a proportion (multiply by 100 to get a percentage).

Figure 11 Linear vs Decay Efficiency



Exponential decline in an EDEG situation can happen more quickly than exponential growth. However, there are two disadvantages of exponential decay within the context of modeling dynasties. First, it is more difficult to set up. For example, exponential decay has an infinitely long tail. While this allows for mathematical immortality, most of the tail is superfluous in the context of a dynasty of limited lifetime. Second, it may not provide the most consistent models with observations, since there can be multiple sources of efficiency decline with differing functions.

A linear approach is simpler to set up. Importantly, it also provides some reflection of overall efficiencies achieved through centralization and economies of scale as the dynasty progresses. Centralization can produce economies of scale that can boost net efficiency, but when a centralized system eventually goes bad, its collapse can happen quickly. Failed central institutions can bring a dynasty crashing down quickly. This is an example of an irreversible process.

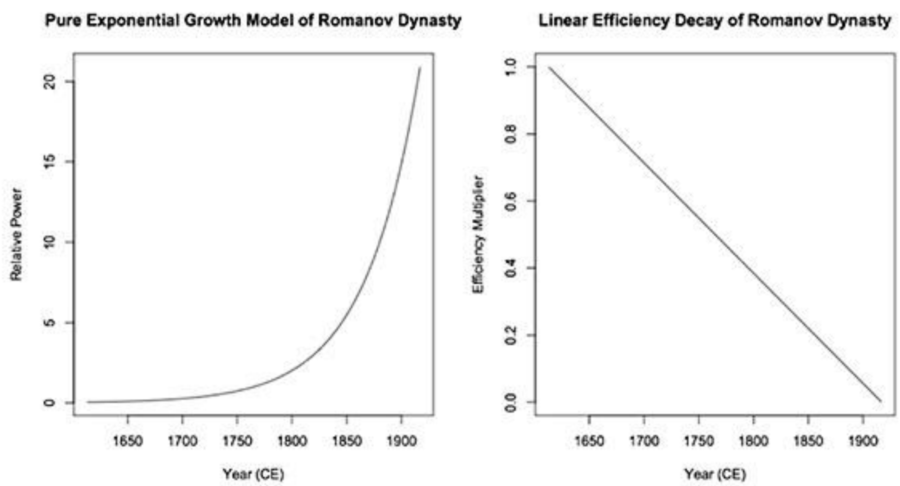
A linear approach has unambiguous beginning and end points. Efficiency cannot be greater than 100 percent, and it is typically not lower than zero. Therefore, as a first approximation, one can set the overall efficiency to 100 percent at the start date of the dynasty and zero percent at the end year—although the math is simpler if the value one is used for 100 percent. While physical efficiency is typically lower than 100 percent for real life heat engines, one provides an easy starting point that also produces the correct shape of curve; which can be adjusted based on the nature of the power source. Using a value of zero for ending efficiency ensures that the dynasty ends by its historical end date. It is possible to use a value other than zero for the ending efficiency, but then some other factor must be used to end the dynasty. The following is an example of linear decay function:

$$\text{efficiency} = 1 - \left((\text{year} - \text{start year}) / (\text{end year} - \text{start year}) \right).$$

As the year increases, efficiency will decrease. Using a lower initial efficiency reduces the magnitude of production increase for the dynasty compared to its initial production. It also flattens out the curve.

Generating A Dynastic Power Progression. We now bring exponential growth and declining efficiency together (Figure 12).

Figure 12: Exponential Growth and Linear Decay.



Growth will not only slow down but often will start to reverse. Such growth and decline can be represented by an EDEG function, where the area under the curve represents either the total production or consumption of a conserved resource over time. Note that the critical resource becomes more expensive as each successive unit of it is utilized. In the case of petroleum or a precious ore, the least expensive deposits are extracted first. Then the next least expensive deposits are extracted and so on. The following is an example of an EDEG equation:

y = efficiency function * exponential growth function.

Here is a simple way to generate a quantitative model for a dynasty. It is simplistic, but it generally produces qualitatively correct results. Assume exponential growth:

$$P_t = P_0 e^{kt},$$

where P is power, P_0 is initial power, t is time and k is a growth factor.

Assume that a nonrenewable resource is being consumed that cannot be replaced within the lifetime of the dynasty. Then assume the efficiency of each subsequent unit of resource consumed produces power as a decreasing efficiency. Using the simple linear efficiency decay function from above:

$$e = 1 – (\text{year - start year of dynasty}) / (\text{end year of dynasty - start year of dynasty}),$$

where e is efficiency. Then the efficiency-discounted power is:

$$P = e * P_0 e^{kt}.$$

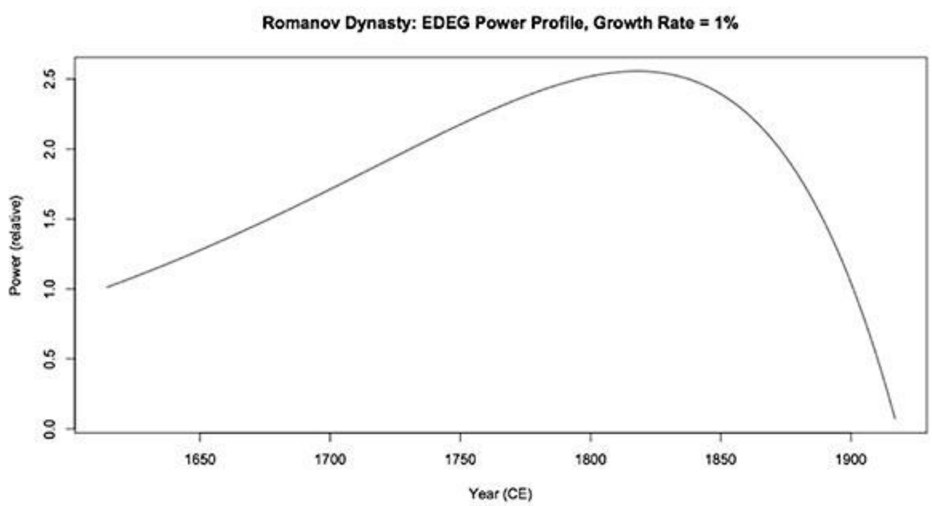
Substituting in our functions (utilizing linear decay):

$$Y = (1 - ((\text{year - start year}) / (\text{end year - start year}))) * P_0 * e^{k(\text{year - start year})}.$$

This produces a steady rise, a level period and a slightly faster decay. By discounting exponential growth by decreasing efficiency, we then have a rise and fall pattern that is consistent with the rise and fall of a dynasty (Figure 13).

Let us assume a conservative one percent growth rate for the Romanov dynasty. Let us further assume linear decay from 100 percent to zero percent efficiency. A simulation has been written in the Ruby programming language. This language is mathematically robust, yet it involves code that is relatively easy to read and understand. The dynasty is run through the Ruby simulator, using the above parameters. The R program was utilized to generate a plot of the results (Figure 13).

Figure 13 Efficiency-Discounted Exponential Growth (EDEG).



Here the peak is close to 1820. Napoleon had been conquered, and the dynasty had achieved much of its geographic expansion by then. Yet by this time, social unrest began to shake the Romanov dynasty. Also, note how the dynasty power begins at a level of one and ends at a level of zero. This is conceptually appropriate, since the dynasty had to begin from something, but typically ends in nothing—actual power quantities can be used, but their explanation is beyond the scope of this paper. For example, the ancestors of the Romanovs existed before 1613, but the entire immediate family was killed during the Russian revolution. The peak occurs at a relative power value of height of 2.6, which indicates that the dynasty was over twice as powerful at its peak as it its beginning. Remember, this model is merely a hypothesis that is either valid or not for a particular level of uncertainty.

Note that utilizing a higher growth rate results in a later peak. Also, the total peak to initial power ratio skyrockets as the growth rate is increased. Additional factors can be imposed as adjustment functions. One-time events (such as a rare but large natural disaster) can be superimposed as an event "mask."

It may be of further interest to tie the rise and fall to patterns concerning the production and consumption of resources, to determine what correspondence, if any, there is between physical and political power. This can be explored by utilizing actual physical energy data to produce a model of physical power, and then comparing that model with evidence of political power over time. With the wealth of historical data being gathered in anthropological data warehouses, and other "big data" facilities, this may be accomplished with increasing validity.

Narrative Description of Generic Dynastic Progression. We can use the EDEG approach to describe anecdotally the lifecycle of a major dynasty (e.g., China, France, West Africa). It would typically begin with a daring, competent, often unpolished leader, but with effective power loosely distributed. Chaos becomes order and economic production rises. Yet, future generations of rulers will become increasingly desirous of luxurious living, "trophies" such as palaces, major public works, or optional conquests. This will stress the resources of that society, and the dynasty will experience financial difficulty. Initially, centralization will be used to increase overall efficiency, but at the expense of decreasing individual initiative and decreased ruling class accountability. Eventually, taxes will need to be increased. Bureaucracy will need to be greatly expanded to collect increased taxes. Internal dissatisfaction will increase, so greater internal military effort will be required to suppress rebellions. Dynasty rulers will become increasingly dependent upon their military to maintain internal order and to enforce tax collection.

Meanwhile, the rulers will tend to become increasingly occupied with court etiquette and pursuit of "civilized" activities as art and scholarship; but they will become less competent at governance and further removed from the realities of the population they govern. A large, hungry population and bureaucracy has formed that cannot be downsized without considerable disruption (overshoot). Eventually competing figures from within the society will challenge the rulers. These initial challenges will be put down often brutally, further increasing discontent, and destroying much of the social structure and institutions required for the effective maintenance and defense of the society and its economy.

Due to the chaos and decreasing magnitude of economic activity, the population and its strain on natural resources will decline, allowing for some recovery of productive capabilities and once again the build-up of potential. Nevertheless, it is too late for the dynasty. Further challenges from either within or without the society will replace the dynasty, and a new dynasty will form. Must a dynasty have a life cycle? Could it not last forever, or at least indefinitely? Societies, religions and some other institutions can last much longer than dynasties. It is conceivable that a dynasty could be managed in a sustainable manner, but this is not what we typically observe in history.

Series of Dynasties

A society can be modeled as a series of dynasties or EDEG bubbles. Each bubble would typically represent a dynasty for a traditional historic monarchy. Robust, traditional, monarchical, agricultural-based regimes have historically tended to endure for roughly 300 years. This is an empirical observation and not based upon theory. Not all regimes last for about 300 years. Yet the 300 year pattern has appeared frequently in history from France to China to West Africa. We will focus on dynasties that endure for about that time.

A common error would be to assume that the series of EDEG curves represents a periodic function. It's not. Dynasties might not follow immediately one after another. Not all dynasties last the same amount of time. Or there could be some overlap between older and newer regimes.

Dynasties in major historical civilizations are typically easy to identify. In a sense, dynasties are what fill the pages of historical textbooks. A series of power progression models of Russian dynasties is plotted (Figure 14). Although the plots are each set to a maximum power of one, actual power would vary among dynasties.

Figure 14 Series of Russian Dynasties

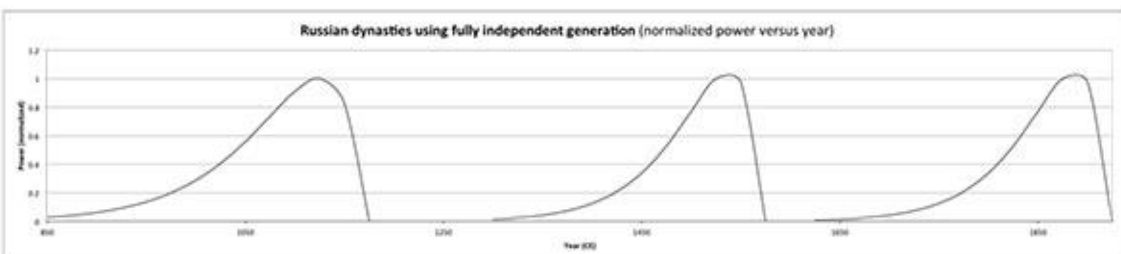


Table 1 presents a chronological list of French dynasties, along with duration data. The real picture is not quite as neat as the table suggests, but there were several distinct dynasties. Clearly, dynasties are not precisely periodic, as their length somewhat varies. Dynasty start and end dates are typically from Mazour and Peoples (1975). The results are plotted (Figure 15).

TABLE 1: Dynasty Series for France

Dates (CE)	Regime	Duration
481–751 CE	Merovingian dynasty	270 years
754–987 CE	Carolingian dynasty	233 years
987–1328 CE	Capetian dynasty	341 years
1429–1588 CE	Period of relative discontinuity	
1589–1791 CE	Bourbon dynasty	202 years

Figure 15 French Dynasties 500–1850 CE

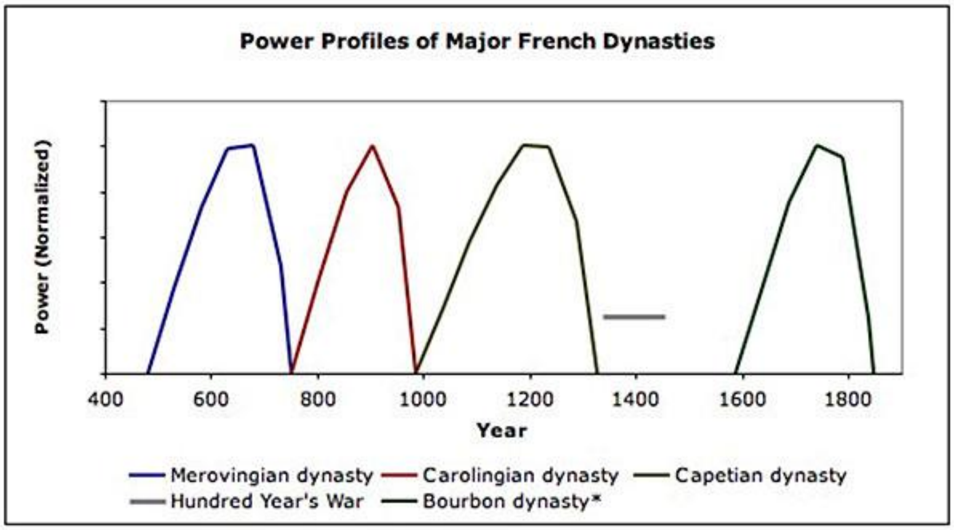
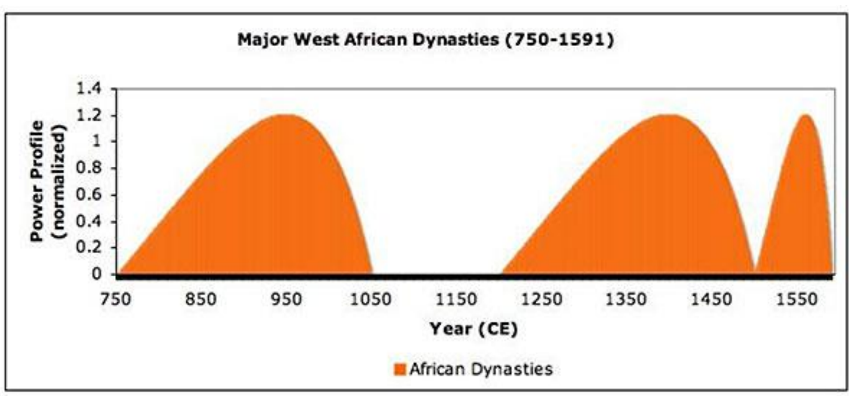


Table 2 shows a chronological list of several major West African dynasties, along the Niger River, from 750 CE to 1591 CE.

TABLE 2: Dynasty Series for West Africa Niger River Region

Dates (CE)	**Regime**	**Duration**
750–1050 CE	Kingdom of Ghana	300 years
1200–1500 CE	Kingdom of Ghana II	300 years
1500–1591 CE	Kingdom of Songhai	91 years

Figure 16 Selected Major West African Dynasties, 750–1591 CE



Power progressions for them have been plotted (Figure 16). The lack of periodicity is more obvious. Although the geographic locations were all in West Africa, the exact locations varied. There was less territorial overlap than in the French dynasties presented.

The longest series of dynasties for a single region and people is that of the Han people in China, shown in Table 3.

TABLE 3: Major Traditional Regime Series for China

Dates (CE)		**Regime Duration**
2000–1500 BCE	Hsia	500 years
1500–1028 BCE	Shang	472 years
1028–642[1] BCE	Chou 1	386 years
642–256 BCE	Chou 2	386 years
202 BCE–220 CE	Han	422 years
618–906 CE	Tang	288 years
960–1279 CE	Sung	319 years
1368-1644 CE	Ming	276 years

The duration of major Chinese dynasties versus their midpoint dates has been plotted (Figure 17). There might have been an exponential decay trend in the duration of major Chinese dynasties over time.[2]

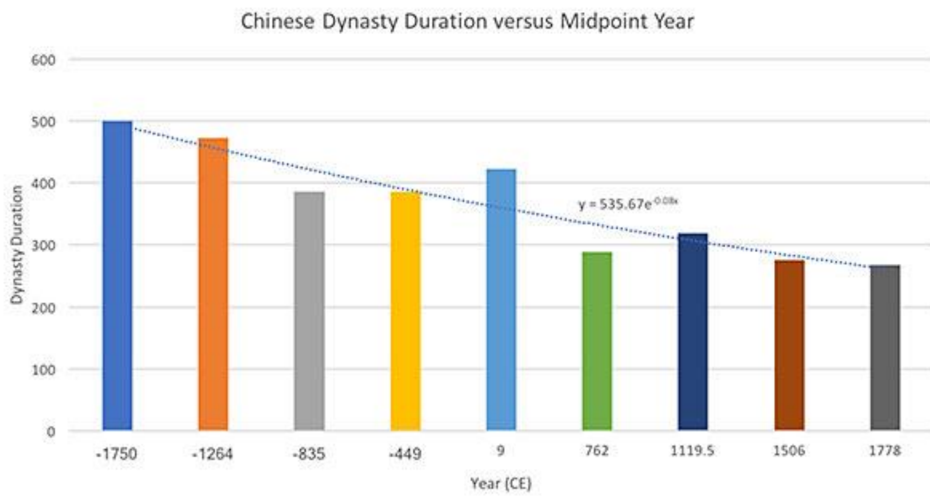
There are two main approaches to generating a series of dynasties. One approach is to generate a model for each dynasty separately, and then combine the simulation results for a combined period. A second, more insightful approach is to model potential as an ongoing flow versus a resisting tendency, so that a series of logjams and bubbles are created. This allows for some resource replenishment. The challenge is to do so with as few parameters as possible. While the second approach has been tested, only the first approach is used in this paper.

The power progressions shown were normalized. However, one dynasty in a series might be more powerful than another. There are several ways to express changing power. For example, later dynasties might have more power than preceding ones due to greater population or energy technologies (animals, windmills, agricultural improvements). However, the relative power of a series of dynasties compared to nearby dynasties could vary as well. A society may face differing levels of competition from neighbors.

[1] Chou dynasty became essentially symbolic by about 700 BC, and China was chiefly ruled by small states during this symbolic "second" Chou dynasty.

[2] Disclaimer: this example only applies to history preceding 1911. Regimes since 1911 may have fundamental characteristics that are different from those of traditional regimes. This same disclaimer could apply to most other contemporary societies as well.

Figure 17 Duration of Chinese Dynasties over Time



(data from Table 3)

Interacting Dynasties

A EDEG function can be a robust entity, but it can still be affected by simultaneous or co-existing dynasties or even overwhelmed. Potentials can exist between dynasties (generalized as *regimes* here), such as in the case where one regime has a persistent trade surplus with a co-existing regime.

Only something out of a science fiction movie could have eliminated either the Roman Empire or the Chinese Tang dynasty at their heights. The power profiles for the very largest human regimes in history will be largely independent of each other. Many smaller regimes are still powerful enough to be fairly robust. However, regimes of small states are highly affected by their neighbors. Likewise, new or dying regimes of larger states lie along portions of their power progressions that are not as robust as middle portions. Such vulnerable regimes may have power profiles that are abruptly terminated rather than gradually terminated. The remaining critical resource of the regime must either be considered to have been discarded or must be consolidated into the power progression of a conquering regime.

Regimes often interact with each other. Therefore, one regime can impact another. This interaction can become quite complicated, especially for smaller regimes. However, the largest, most durable regimes often provide more available data and tend to be somewhat less affected by other regimes, so that the effects are less discernable.

To study a system of interacting regimes, it is best to study the greatest series of regimes. China has historically described itself as the central kingdom. Have other historic regimes "orbited" about China as do the planets circle around the Sun in a heliocentric system of astronomy? Is a Sinocentric sociology valid? Yes, but to a limited degree. The social "mass" of China is generally historically larger than that of other societies, but not by such a high proportion, and at times other empires have eclipsed or absorbed China's social "mass." Yet to the extent that there has been *any* solar equivalent in history, it would be China. Further, the Han people of China have exhibited a series of traditional regimes for a much longer period than any other single society, so it could be argued that it is the closest thing that exists to a historical "clock." Yet perhaps an argument could be made for central Asia being such a clock, since its invasions have frequently affected societies in the continents of Asia, Europe and Africa. What drives the waves of invasions in history of central Asia? Is it a social cause or the build-up of a resource-driven potential? The answer to this question is not well known.

When China is ruled by a regime during the strong part of its lifecycle, does this block the Central Asiatic invaders so that their only outset is India, the Middle-East, or Europe? The answer to this question depends upon several factors and changes depending on the state of those factors at a given time.

Table 4 shows several strong traditional regimes in China and corresponding waves of invasions in Europe. This list is not complete, but is suggestive for several regimes. Dynasty start and end, as well as invasion, dates are typically from Mazour and Peoples (1975).

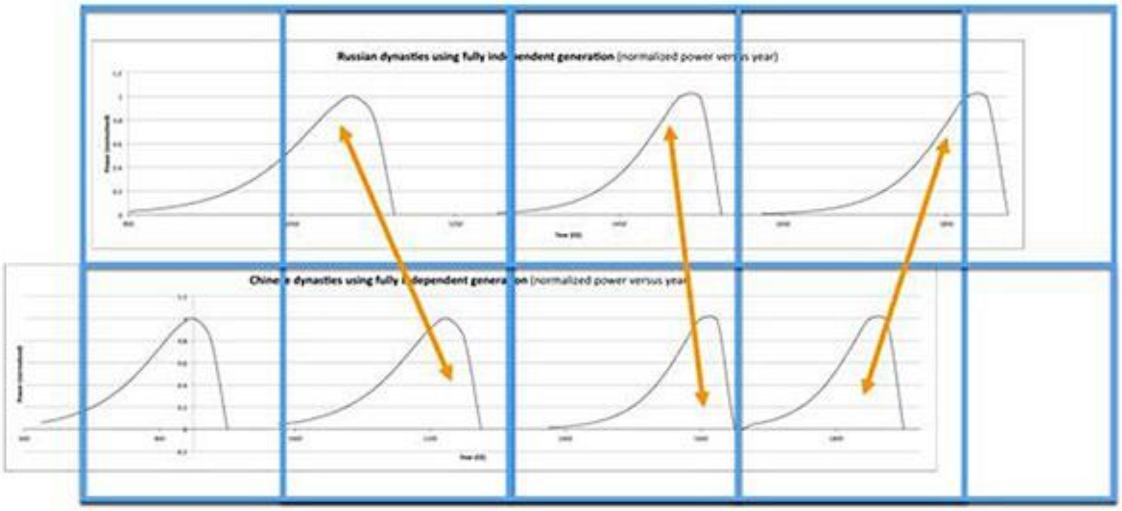
TABLE 4: Asiatic Invasions in European During Selected China Dynasties (CE)

Dates	**Regime**	**Duration**	**Invasion**
618–906	Tang	288 years	Lombards & Avars
960–1279	Sung	319 years	Slavs & Magyars
1368–1644	Ming	276 years	Ottoman Turks

Yet there are exceptions. The Huns, and later the Mongols, overwhelmed both China and much of the West. Conversely, a strong Roman empire might have pushed the Huns eastward before they went westward, for the Huns attacked China in 317, while they did not invade western Europe until the mid-400s. It could be that the coincidence of strong empires in both the East and the West bottled-up potential in central Asia up to the point that the Huns became extremely potent. That both Russia and China were both relatively strong during the time of the Sung dynasty may have contributed to a build-up of potential in central Asia that helped the Mongols become so powerful. Such speculation should not detract from the achievements of the Mongols such as their innovative battle tactics.

Russia is the closest major dynasty-producing region to China. Most barbarian invasions of Europe tended to come through lands at one time ruled by Russia. Therefore, if the rise and fall of Chinese dynasties affects Europe, then Russia (and nearby territories) would be the bridge for these interactions. Are there any patterns between rise and fall patterns in China and Russia? This is examined in "matrix" (Figure 18). Initially Chinese dynasties lag Russian dynasties in their peak. However, the Chinese dynasties are shorter, so the Chinese series finally "jumps" ahead of the Russian series.

Figure 18 Possible Interdependence between Chinese and Russian Dynasties.



Discussion and Future Directions

This discussion of the EDEG approach is more of a barebones beginning than a complete end. It raises more questions than it answers, but it enables a broad framework to answer these questions. This framework acts as a unifying skeleton to link the humanistic elements of history with the quantitative constraints of the physical universe.

The power of such a framework should not be underestimated. It is possible to gather quantitative data (or quantify qualitative evidence), perform statistical analysis and accept or reject hypotheses. Yet individually such results, while often important, are merely empirical. They are often hard to use to constrain or illustrate each other. In a unified framework, all results act to constrain all other results. When we learn about one thing, we necessarily learn something about everything else. This is where the physical sciences have derived much of their strength.

There are many immediately apparent enhancements to improve the value of the EDEG approach. One improvement would be to better understand efficiency decay. Another improvement would be to start using actual data of physical energy, to the extent such data is available. Another improvement will be to separate the power level of the underlying society from that of the dynasty. For example, Russia did not disappear upon the death of the Romanov dynasty. On the contrary, it is still one of the most powerful societies on Earth. The brings up the need to be able to model the emergence of a series of dynasties in a way that connects and constrains each dynasty, such as concerning relative strength and timing of emergence. Further, there needs to be a way to compare co-existing dynasties and model their interaction within this framework. While the EDEG approach suggests possible means, the devil will be in the details.

A Thermodynamic Approach To World-Systems

How would this sort of thermodynamic approach be applied to world-systems? Peter Grimes had several ideas about this, and he would have expressed them more fully had he lived longer. He was actively working on writing up his ideas into a comprehensive book before his passing. I will use an approach that Grimes would have understood, although it is neither as sophisticated nor aspirational concerning world-systems as was the work of Grimes.

Typical historical analysis is broken up into a multidimensional matrix: nation-state, century, sub-topic. This balkanization of historical analysis is substantially due to the necessity to specialize in an area to such a degree so as to produce novel, yet highly scholarly research. Unlike most other fields, there has been about 2500 years of work by historians, hence the pressure to drill down, and produce analysis that is a literal inch wide and a mile deep. The world-systems approach takes a much different approach. In the development of world-systems theory, "the whole system was the proper unit of analysis, not national societies" (Chase-Dunn et al. 2020).

In a world-system, of the "central mechanisms by which the network of production permit the endless accumulation of capital" is the "unequal exchange between core and periphery" (Wallerstein 1995). In the language of this article, this mechanism is possible due to the presence of a potential, and the term "endless" suggests the magnitude of such potential is large.

Is it appropriate to use the terminology of this article to suggest the analogy in nature where the flow of water accumulates behind a logjam? Is there an "activation energy" or a thermodynamics exponential growth mechanism that might overcome the logjam? Possibly yes. "There are ceilings to … these trends. Technical change often relies on energy sources that are not infinite while producing effluents that are deadly" (Chase-Dunn and Grimes 1995). As social and physical technology progresses, the foundations that drive and support that change are continually consumed at the expense of both intrinsic efficiency and future progress. Using the thermodynamic and ecological mindsets that Grimes explored provides a rich opportunity to further explore and analyze world-systems concepts and relationships between the core and periphery and provide further quantitative and physical evidence of inequalities, as well as the sustainability and endurance of those systems.

Certain differences between societies could in some cases represent potentials. Although such cases would ultimately be entropic potentials, it is possible to consider them in more abstract but accessible ways. Both the exact nature of the resources and the power dynamic between those societies would further influence the nature of this relationship. A simple case is where two societies each had resources of value that the other wanted. There could be simple trade activity to consume that potential. Such would be the case where the two societies had roughly equal bargaining power.

Of course, such is often not the case. In other cases, the potential might be unidirectional, in that perhaps one society had a resource demanded by another society but not vice versa. In that case, the resource might be achieved through a trade deficit, conquest or other predatory means. Where one society has more power than another, it often uses that power to gain advantageous terms. We can use thermodynamics to analyze power differences in trade and conquest. Most transactions, including the transfer of gold, can be "priced" in terms of grain, which can be used to express the trade in terms of energy, efficiency, work, and other concepts discussed above. However, disadvantageous arrangements typically last for limited, even if long, periods of time. If so, they can be expressed as the consumption of a nonrenewable entropic potential.

The distribution of energy and potential entropy among different classes, such as rulers, soldiers and agricultural workers can shed light upon the relative power of socio-economic classes in an objective and quantitative way. The concentration of control of production can be expressed thermodynamically and compared between core and periphery societies. Such expressions can be used to constrain hypothesis and improve upon the work of cliometricians, who also use quantitative approaches, but in a more empirical rather than fundamental manner.

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