Pollution in Light of Entropy

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This thesis explores a new approach to understanding contemporary environmental issues. This approach draws on concepts in thermodynamics such as entropy, free energy, and gradient dissipation, and applies them to non-equilibrium settings to provide an alternative view of chemical pollution in the context of ecosystems and human societies. Building on the works of Boltzmann, Gibbs, Schrödinger, E.P. Odum, Prigogine, Georgescu-Roegen, and Kay, this thesis demonstrates the necessity of pollution as a consequence of large scale energy use. First a historical background of thermodynamics and entropy is provided following the description of an "entropy framework" used to analyze various pollution phenomena. This framework is then compared to three traditional academic frameworks commonly used to address pollution and other environmental topics of concern. In this comparison, strengths and weaknesses of each framework are highlighted, revealing both the usefulness and limitations of each. Afterward, implications of the entropy framework are revealed, such as the risks of nuclear energy and geo engineering, and benefits of sustainable gradient reduction. At the end of this paper I provide some recommendations for attaining this goal such as minimizing collective energy use and investing in decentralized social and commercial institutions.

Key words: entropy, free energy, gradients, pollution, mid-line entropy pollutants, end-of-the-line entropy pollutants, entropy framework

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1. Introduction

This thesis was born out of a personal desire to understand two fundamental laws of physics: Newton's third law of motion and the second law of thermodynamics. Respectively, these laws state that for every action there is an equal and opposite reaction that takes place, and the universe is always moving toward maximum entropy. Newton's law is clear and simple, and we can easily observe its consequences in a game of billiards. When we aim our cue ball at 45º against a wall and apply a certain force, we expect the ball to bounce off that wall with the same angle and force that we initially applied. The concept of entropy, however, is not as straightforward. Sometimes, when we hit our cue ball with a certain force, the ball does not seem to meet our expected trajectory. One cause of this incongruity between reality and expectation is simply due to friction. Some of the kinetic energy supplied to the ball by our pool cue is lost as heat due to rolling friction as the cue ball makes contact with the cloth-covered table underneath. This one-way transformation of condensed, organized energy to dispersed, disorganized energy is embedded in the concept of entropy. Ultimately, the universe runs downhill.

The concept of entropy was first introduced to my by my mother, a chemical engineer, who provided a physical argument to convince me why I needed to clean my room. My room, a system, naturally has the tendency to become disordered over time. Yet, if I put work into the system, I could make the room ordered again!

Since that first seed of entropy had been planted in my mind, I have since discovered there is much more to the story. Work, or free energy, supplied by me must come from my environment. In order to have energy to clean my room, I must import nutrients and calories supplied by animals and plants, which is ultimately supplied by the nuclear fusion of hydrogen atoms in the sun. Entropy lowered in the subsystem of my room is only paid for by an increase of entropy in the environment. For every action, there is an equal and opposite reaction. There is no free lunch. For every marginal increase in order, there must be a proportionate increase of disorder taking place somewhere in the universe.

Although this psychological process is an oversimplification of reality, it is this thinking which informs the spirit of this honors thesis. Since the beginning of the industrial revolution, energy use, social order, and population growth have skyrocketed to incredible heights providing us with a quality of life that ancient kings and queens could not have dreamed. Yet there is a price that to be paid for such heavenly heights. Coinciding with this new growth, novel environmental issues of all kind including a sixth mass extinction event and global climate change have begun to be observed all over the world. I believe that these observations are not independent, but connected fundamentally to the two physical laws that I’ve been fascinated with for the past several years.

This thesis is an exploration of the latter, more elusive physical concept; the entropy law. Although, I realize that there are difficulties in being precise with using the term entropy in non-equilibrium settings, I believe that this use is nonetheless warranted for an accurate conceptual understanding of pollution mechanics. Using the second law as a starting point, this thesis attempts to develop a new lens for discussing environmental problems. I refer to this lens as the “entropy framework.” The entropy framework is essentially a new language used to better understand, identify, and communicate issues concerning pollution, environmental degradation, energy use, and human order at every scale. For the sake of brevity, however, the scope of this document will be limited to the issues of chemical pollution and energy use. Unlike most publications in the sciences, this thesis exclusively uses secondary research to make its arguments. To test the validity or at least the utility of this lens, this thesis compares the entropy framework against three already well established lenses. These lenses include the fields of economics, sociology, and biology. To make this comparison the concept of pollution is viewed through each of these lenses and analyzed for simplicity, flexibility, and comprehensibility. Explanations that are the most simple, flexible, and can be applied in the most variety of contexts are often regarded as the most useful ones and become primed for acceptance into the canons of truth and fact. By the end of this paper I hope to convince the reader that pollution is a natural process and a necessary consequence of any sufficiently large, work-producing energy process. Life was made to pollute; however, we *can* learn how to pollute more sustainably. Some advisable principles for living with the entropy law are provided in the *Recommendations* section at the end of this document.

2. Background

2.1 Historical understandings of entropy and the laws of thermodynamics

Sadi Carnot and heat engines

The term entropy finds its root at the origin of classical thermodynamics. The field of thermodynamics developed during the first half of the 19th century with the study of steam engines. Sadi Carnot was the one of the first to study these steam engines in depth, consistently testing and recording the transformation of heat to motive force

(Perrot, 1998). Through his studies, Carnot became aware that heat always moved from hot to cold, never the other way around. Further, Carnot realized that no matter what conditions were present, the amount of work output was never as great as the energy input. Therefore heat engines were rarely, if ever, 100% efficient.

$$e = \frac{W}{Q_H}$$

FIGURE 2.1 Carnot efficiency of a heat engine. Efficiency is the ratio of output (W) to input (Q_H). A maximum efficiency of 100% would demand that (W) be equal to (Q_H).

He also realized that the higher the temperature, the more work he could get out of his engine. Through countless hours of testing and retesting, he eventually came to realize that what mattered for work was not just how hot his heat source was, but equally important, how cold his cold sink was. What really drove movement in an engine was the *gradient* of temperatures, and of the energy available to be used for work, some must always be lost or "wasted" to the cold reservoir.

Clausius and the classical definition of entropy as Q/T

In 1854, Prussian physicist Rudolf Clausius extended the work of Carnot by formalizing both the first and second law of thermodynamics. Realizing that some energy must be wasted, but nevertheless conserved, Clausius realized that the energy not going toward work must be accounted for in another form.

$$Q_H - Q_C = W$$

FIGURE 2.2 First law of thermodynamics. Energy is always conserved. Work (W) must be exactly equal to the difference between the hot reservoir (Q_H) and the cold reservoir (Q_C). By measuring the heat input and the work output, it is possible to deduce Q_C.

The first law of thermodynamics was essentially a reformulation of Newton's law of conservation of momentum applied to energy. The second law introduced a new concept into the world: entropy. Building off of Carnot's results of waste heat and engines, Clausius noted that when total values of heat were divided by temperature, a new value emerged.

$$S = \frac{Q}{T}$$

FIGURE 2.2. Classical definition of entropy. S is entropy, Q is heat transferred, and T is the temperature of the system or reservoir.

This new quantity he called entropy. While it was already assumed that energy could not be created or destroyed, entropy seemed to spontaneously generate from nowhere. In his own words, Clausius, "intentionally formed the word entropy so to be as similar as possible to the word energy, since both quantities, which are known to by these names, are so nearly related to each other in their physical significance that a certain similarity in designation appears to be desirable" (1885). Later on in his studies, Clausius boldly stated that, "the entropy of the universe tends to a maximum," (Wehrl, 1978) and that "no process is possible in which the sole result is the transfer of energy from a cooler to a hotter body." The implications of these statements had devastating effects for the then accepted Newtonian physics due to the introduction of the concept of irreversibility. Up until this point, Newtonian mechanics implied a universe that was totally reversible. The assertion that entropy in sum always increases, however, presented a contradiction in assumptions between the new school of classical thermodynamics and the old school of accepted Newtonian physics.

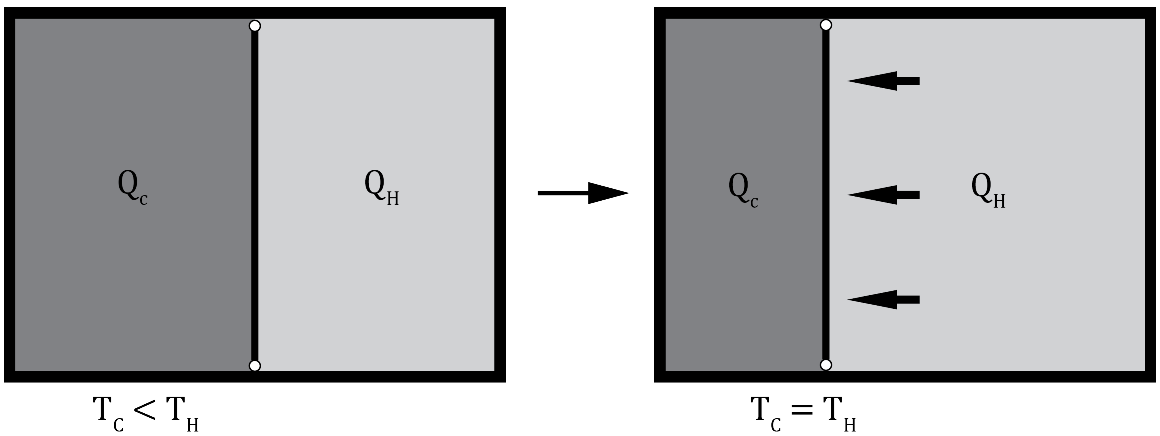

FIGURE 2.3 Closed system maximizes entropy. In this system, two susbsystems are separated by a massless and frictionless moving partition. Subsystem QH initially has a temperature much higher than subsystem QC. Due to this temperature difference, heat spontaneously moves from QH to QC until their temperatures are equal. Because ΔQ is the same for both subsystems, but initial temperatures are different, the total change in entropy (ΔS) is nonzero and positive. $S_{total} = -\frac{\Delta Q}{T_H} + \frac{\Delta Q}{T_C} > 0$

Boltzmann and the kinetic theory of gases

In an attempt to reconcile the apparent conflict between the newly formed field of thermodynamics and classical Newtonian physics, Ludwig Boltzmann, godfather of statistical mechanics, argued that the apparent discrepancy between Newton's physics and Clausius' thermodynamics had to do with the differences between the large numbers of tiny bodies he believed to be atoms, and the relatively small number of large bodies composed of these atoms (Boltzmann, 1974).

In order to account for these differences, Boltzmann introduced a new way of looking at physical bodies: probabilistically. The terms macrostate and microstate were subsequently introduced to model these differences mathematically. A microstate is defined by the microscopic arrangements of molecules and the energies associated with them. A macrostate is a category of microstates that are perceptually the same as each other at the macroscopic level. According to Boltzmann all microstates are equally probable. Macrostates are not. Take for example a deck of cards. In a game of poker, any *specific* hand is as probable as any other; however, categories or groups of hands, such as a junk hand or a straight, are not equally probable. Any *specific* junk hand is just as probable as any *specific* royal flush, but there are a far greater number of combinations for a junk hand than number of combinations for a royal flush. Each *type* of combination, from a straight, to a four of a kind, to a flush, represents a particular macrostate. Each *specific* combination of cards represents a single microstate. While a royal flush is the most desirable poker hand, it is also extremely rare. Out of a possible 2.5 million ways to draw a five-card hand, there are only 4 ways to draw a royal flush. This effectively amounts to a 0.0001% probability of occurring. For a high card junk hand, however, the probability is much higher. Out of the 2.5 million ways to draw, there are roughly 1.3 million combinations that satisfy this macrostate. Chances for drawing a high card junk hand is about a 50% chance.

From this example, it is clear that the macrostate with the largest number of microstates is also the most probable. This is where entropy comes in. The statistical mechanical definition of entropy, defined by Boltzmann is denoted as $S=k\ln\Omega$. Where S is entropy, k is Boltzmann's constant, and Ω is the total number of microstates that satisfy a particular macrostate. Entropy, therefore, is the logarithm of the total number of microstates available to a given macrostate. Using this definition in accordance with Clausius's formalized second law statement predicts that systems that maximize their entropy do so by arriving at the most probable outcome. Reversibility is therefore not impossible, just *highly* improbable. It *is* possible that a cup of coffee will spontaneously get hotter over time, but the number of microstates that correspond to a cooler cup of coffee, with energy spread out evenly in the room, is so overwhelmingly large compared to the hotter cup, that this is the only situation that we ever seem to experience.

2.2 Life, Entropy, Order, and Disorder

Boltzmann's view of entropy as disorder

Aside from defining entropy in the statistical sense, Boltzmann also introduced the idea of entropy as disorder. Picturing atoms as a collection of billiard balls colliding against walls of a box, Boltzmann showed that there were many more microstates in which the atoms were randomly distributed rather than concentrated in a single area. The random distribution of molecules, of which there are many such varieties, also displays a highly disorganized and disordered appearance.

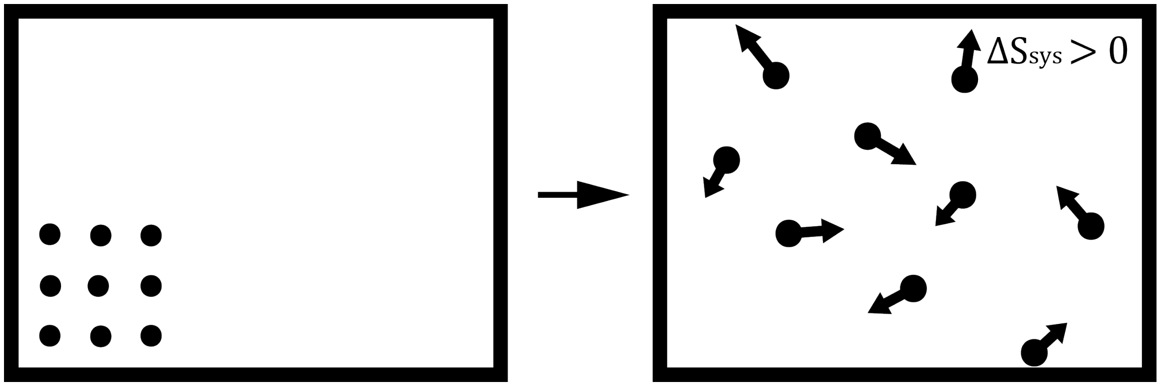

FIGURE 2.4 Disordering of molecules in a closed system. A gas of hydrogen atoms will spontaneously move to fill up the entire volume of an enclosed space in order to move toward their most probable macrostate. Since the number of possible arrangements of ordered molecules on the left is relatively small, the disordered state is the state that is most frequently observed. The probability of finding a disordered state over an ordered one is a difference typically of several orders of magnitude.

If disorder is synonymous with an increase in the total number of microstates, then this definition holds true. Drawing on the results of these analytical predictions, Boltzmann concluded, "if a macrostate has a chaotic structure, it will preserve this structure forever; if it does not have a chaotic structure, it will necessarily tend to it." (Boltzmann 1872).

In many cases, we can observe the validity of this statement. When we put a hot cup of coffee in a room, we find energy that was once concentrated (organized) in the cup, becomes spread out (disorganized) across the room. Predictably, the once hot cup of coffee gets cold. This makes sense statistically since the energy restricted exclusively to the mug has incredibly fewer possible energetic arrangements than the number of arrangements that involve the energy being dispersed more or less evenly across the room. In essence disorganization of energy is overwhelmingly probable in an isolated system. In such a system, entropy, and therefore disorganization, tends to increase over time.

Thermodynamics and Life: "Order from disorder"

In 1790 Kant claimed, "there will never be a Newton of the blade of grass, because human science will never be able to explain how a living being can originate from inanimate matter" (Baeulmer, 1923). To this day there are many people who uphold this assumption, though a few scientists disagree pointing to thermodynamics as a bridge between the living and the dead. Of these individuals, perhaps the most well-known and earliest supporter of the thermodynamic view of life is Erwin Schrödinger. Renowned for his foundational work in quantum theory, Schrödinger suggested the importance of thermodynamics in biology in a series of lectures, which would become the basis of his tiny but far reaching book *What is Life* (1944). In this book Schrödinger provides two main accounts for the existence and persistence of life. The first account he discusses as one of "order from order." Under this account Schrödinger inferred an "aperiodic" molecular structure holding the code of life. This molecule accurately replicated generation after generation came to be discovered as the double-helical DNA through the work of James Watson and Francis Crick, who were both heavily influenced by Schrödinger's inferences.

Schrödinger's second account for the origin of life was described as a paradoxical "order from disorder" (Schrödinger, 1944). This account, which seemed to defy the almighty second law of thermodynamics, was explained through what Schrödinger termed "negentropy." The prevention of life toward the thermal equilibrium is paid for by importing "negentropy" or, in less controversial terminology, free energy. "Thus the device by which an organism maintains itself stationary at a fairly high level of orderliness really consists of continually sucking orderliness from its environment…after utilizing it they return it in a very much degraded form" (Schrödinger, 1944). As Schrödinger colorfully illustrates, by mitigating the thermodynamic tendency to increase entropy, life must consistently import free energy and export entropy to its environment. This finding has been restated and confirmed by many since Schrödinger's time.

During the environmental movement of the 1970s, Eugene Odum, brought concepts of thermodynamics into the field of ecology. He introduced the concept of trophic cascades and showed how roughly 90% of an organisms stored free energy is degraded every time energy moves up a trophic level. For example, of the total light energy emitted by the sun, only ~4% of the light that touches a plant's leaf is converted to biomass (Björn, 1976). The other 96% is degraded to low quality infrared. Similarly, when an herbivore consumes the plant's leaves only 10% of this chemical energy is converted to usable energy for the animal. The rest is lost as heat in the metabolic process. Odum sums up this process saying, "The *second law of thermodynamics* may be stated in several ways, including the following: No process involving an energy transformation will spontaneously occur unless there is a degradation of the energy from a concentrated form into a dispersed form" (Odum, 1971).

In the seminal work *Fundamentals of Ecology* (1971) Odum also states "Organisms, ecosystems and the entire biosphere possess the essential thermodynamic characteristic of being able to create and maintain a high state of internal order, or a condition of low entropy (a measure of disorder or the amount of unavailable energy in a system). Low entropy is achieved by a continual dissipation of energy of high utility (light or food, for example) to energy of low utility (heat, for example). In the ecosystem, 'order' in terms of a complex biomass structure is maintained by the total community respiration which continually 'pumps out disorder.'"

Though neither Schrödinger nor Odum make clear as to what forms this "disorder" takes, it is clear that they believe that disorder is a necessary aspect of the biological process.

Contemporary Musings on Entropy and the Environment

The modern view of thermodynamics in the context of life takes a different angle on entropy. Contemporary thermodynamicists James J. Kay and Eric Schneider stand on the shoulders of the classical giants and turn the concept of entropy maximization into one of gradient minimization. Building on Ilya Prigogine's study of self organization in non-equilibrium systems (1977), Kay suggests that highly ordered systems such as life spontaneously organize to diminish gradients of all kinds (1994). Thus "the second law is a necessary but not sufficient cause for life itself."

While Schrödinger and Odum demonstrate how life is *able* to exist within the constraints of universal thermodynamic law, Kay and Schneider explain *why* life exists by utilizing such constraints. As systems are moved farther away from equilibrium, organization develops as a means to bring the larger system back toward maximum entropy. Although entropy is lowered internally, it is more than compensated by the increase externally. Oddly enough, ordered systems do a much better job of minimizing gradients and maximizing entropy than disorganized alternatives. In the above mentioned document, Bénard cell formation is used to show how N^{23} molecules spontaneously arrange themselves in the form of hexagonal cells to minimize temperature differences between a heat source and cold sink. In this example a viscous fluid lies between two plates, one acting as the heat source and the other as the cold sink. At moderate temperature differences, heat is initially dissipated through disorganized, conductive molecular interactions of the working fluid. Once the thermal gradient becomes steep enough, disorganized conduction makes a transition into highly organized convection visible as Bénard cells. Organization spontaneously occurs to minimize external gradients.

Once the gradient is sufficiently diminished, internal organization begins to decay and the molecules return to more random and chaotic arrangements. Robert Ayers (1997) notes, “Exergy is only non-zero when the system under consideration is distinguishable from its surroundings — the environment.” In another light, when free energy is minimized and entropy is maximized a system become indistinguishable from their environment. This is true for larger systems as well including human societies and ecosystems. I suggest that pollution is one of the natural mechanisms implemented to bring these systems back into equilibrium with the environment.

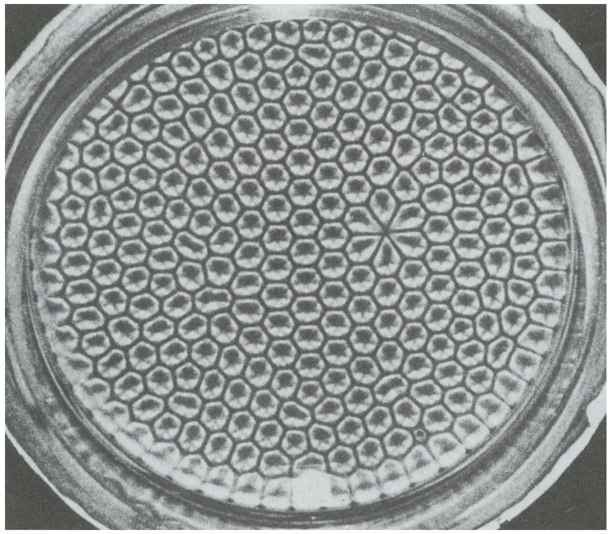

FIGURE 2.5 Rayleigh-Bénard convection of silicon oil on a heated dish. The dish is heated from below and dissipated toward the viewer where cooling is controlled. Initial heating occurs as conductive motion. However, when temperature differences reach a critical level, the convective structure of Bénard cells emerge to increase heat dissipation.

The idea that life exists (at least in part) to diminish gradients puts the idea of entropy maximization into a whole new light. The assured movement toward entropy maximization isn't an unfortunate evil to be avoided—it is actually a major impetus for life's very existence. Life reduces steep gradients imposed from the sun by turning it into work via photosynthesis and basic homeostatic maintenance. Ecosystems like rainforests reduce the thermal gradient between our hot planet and cold space by creating low grade latent heat via evapotranspiration. Old growth forests degrade solar exergy by 90% while quarries at the same latitude only degrade radiation by 62% (Kay & Schneider, 1994). Using satellite infrared monitoring, Kay and Schneider show that the temperature gradient of a mature Douglas Fir forest is reduced by 24K when compared alongside clearcuts receiving an identical solar flux.

This perspective also provides a nice explanation as to why life appears to be so inefficient at storing energy. Most descriptions of efficiency, including classical thermodynamics', define efficiency as a ratio of benefit to cost. If we define the benefit of visible light transformation to be storage in the form of biomass for plants, then efficiencies are extremely low. Yet, if the goal of life is actually to dissipate energy gradients instead of storing it, then we can see that they carry out this function quite effectively.

$$e = \frac{benefit}{cost}$$

$$e = \frac{biomass}{visible\ light} \leq 10\%$$

$$e = \frac{infrared\ and\ latent\ heat}{visible\ light} \geq 90\%$$

FIGURE 2.6 Alternative definitions of photosynthetic efficiency. If the benefit of photosynthesis is conversion of solar radiation into biomass, then efficiency caps around 10%. However, if the benefit of the photosynthetic process is the degradation of visible light to unavailable forms such as low grade infrared and latent heat, then average efficiencies are between 90% and 96%.

Applying this view to human economies and industrial processes, we can make sense of our collective energy use as a natural result of the universal demand for minimization of energy gradients. Life first evolved photosynthetic capabilities to degrade incoming solar radiation to a large degree, though free energy build up in the form of biomass extends the energy gradient into a new dimension. Eventually herbivorous and carnivorous organisms evolved to degrade these new forms culminating in Homo sapiens. Our species not only minimizes gradients on the surface of the planet, but have found ways to degrade free energy buried deep in the Earth's crust by extracting stored plant biomass in the form of oil, coal and natural gas expediting the entropy process at a rate unprecedented on Earth. Since our first attempts at fossil fuel degradation, coinciding with the first studies in thermodynamics, we have also begun to experience pollution on a scale previously unimaginable.

The Entropy Law and the Economic Process

Romanian Mathematician and economist Nicholas Georgescu-Roegen imported the implications of thermodynamics to economics in his most famous work *The Entropy Law and the Economic Process* (1971). Georgescu-Roegen's work was originally built on of Prigogine's, describing economies as large-scale dissipative structures that degrade raw material principally through the industrial economic process. In the text Georgescu-Roegen states "the economic process consists of transformation of low entropy to high entropy, that is into *irrevocable waste* or, with a topical term into pollution" (1971). Up until this point, none of the famous works in thermodynamics have explicitly stated what forms entropy as "disorder" takes. Georgescu-Roegen is the first to suggest that entropy takes the form of pollution as a direct consequence of physical law.

In his eyes, the refinement of raw materials and the manufacture of low entropy products such as cars, roads, paper, and computers, is paid for only through creation high-entropy waste. For example, during the refinement of copper ore, a large amount of free energy in the form of coal is irreversibly transformed to "sort" the ore into pure copper. This "sorting" from high-entropy, well-mixed ore to low-entropy, pure copper demands an import of free energy and an export of entropy. The free energy comes from chemical bonds embedded in the coal. Once the activation energies of these bonds are overcome through the chain reaction of burning, heat is released allowing the copper metal to separate from the ore eventually producing the metal sheet desired. Although the entropy of the ore and copper products are lowered as a result of the coal burning process, total entropy is increased. This is due to the large amount of heat released in the process. Additionally, coal burning also produces carbon dioxide, sulfur oxides, nitrogen oxides, and volatile organic compounds. To resolve these wastes, they must either be allowed to give up their remaining free energy by reacting with the environment, or more free energy must be supplied to alter them to more benign forms. Ultimately, increased economic activity and wealth will only lead to increasingly cumbersome high entropy waste products in the form of refuse and pollution.

2.3 Historical understandings of pollution

Pollution wasn't formally defined until Dr. Johnson's sixth edition of *A Dictionary of the English Language* (1783), which, at the time, was the foremost authority of English until the first Oxford dictionary was published nearly one hundred years later. In the text, the verb, polluting, is defined as "the act of defiling" or "the contrary of consecration." At the time of this statement, the industrial revolution had just been established and was well underway in the United Kingdom. The first industrial revolution was punctuated by innovations in coal fired steam engines, iron forging, and textile machinery. From the direct works of Carnot and the other first thermodynamicists, steam engine efficiency increased significantly at this time by as much as a factor of ten (Landes, 2003). Such rapid changes in technology made steam power streamlined enough for industrial use, taking off at full swing at the turn of the 19th century. One direct consequence of these advances was an intense increase of airborne pollutants such as soot, sulfur dioxides, fluorine compounds and hydrochloric acid eventually culminating in the London's worst pollution event in history, the Great Smog of 1952 (metoffice.gov.uk, 2015). However, as Markham (1994) points out, "air pollution in Britain has been a political issue for almost 800 years. When Queen Eleanor of Provence visited Nottingham Castle in 1257, the fouled atmosphere, full of heavy coal smoke forced her to move to Tutbury Castle." On the topic of coal use in London, Markham also notes, "the coal itself, burning in every factory, foundry and household gate, cased the worst concentrations of air pollution the world had known."

Van Nostrand's Scientific Encyclopedia describes the present lay understanding of air pollution below:

> Air pollution is a broad term applied to any chemical, physical (particulate matter) or biological agent that modifies the natural characteristics of the atmosphere. These substances are generally contaminants that substantially alter or degrade the quality of the atmosphere. This term is often used to identify undesirable substances produced by human activity, that is anthropogenic air pollution. Air pollution adversely affects human health, animals, and plants; deteriorates structures; interferes with commerce; or interferes with the enjoyment of life.

Nostrand's encyclopedia cite increases in combustion, human population, and economic activity, and energy consumption as the primary sources of contemporary pollution. Interestingly, Precambrian oxygen is also included as a pollutant, contributing to the mass extinction of the anaerobic life forms present during this time period. However, other types of pollution like plastics and CO_2 go unmentioned. In the entropy framework described below, I attempt to include these materials into descriptions of pollution with a physical basis.

3. Analysis of Contemporary Academic Frameworks

To demonstrate the merits of an entropic perspective in environmental contexts, a brief comparison of this framework alongside three other well established frameworks is provided below. The disciplines of choice for this comparison are referred to as the social framework, based on the field of environmental sociology; the economic framework, based on the field of environmental economics; and the chemical framework, based on the field of chemistry. Each of these disciplines are extremely broad in scope and, therefore, any summary offered will be necessarily incomplete. In addition, every scholar in these fields has a slightly different take on what their field means in the larger academic context. The goal of this comparison is not to apply any strict limitations to any of these fields, but hopefully to explore and expand the current language available for discussing global environmental issues.

Provided below is an outline of the entropy framework and its basic applications within the context of pollution and environmental studies. Next an overview of the comparison frameworks are provided along with each field's definition of pollution and the possible solutions that are informed by these definitions. In the analysis section, I compare each framework for simplicity, flexibility and comprehensivity by looking at the strengths and weaknesses of each.

3.1 Contemporary frameworks for understanding and addressing pollution

The social framework

The social framework encompasses the lens of environmental sociology. Sociology is "above all else, a way of viewing and understanding the social world." (Auriffeille and King, 2013) It is broader in scope than the economic lens and admits a value-laden perspective. To be able to cover a greater variety of topics, however, the scope of this lens is necessarily larger than that of economics and much larger than that of "hard" sciences like physics and chemistry. For this reason, well developed theories in the sociology are much harder to verify empirically, though theories gain flexibility in exchange.

The modern sociological perspective is typically a blend of "realist" vs. "constructivist" perspectives (Metzner-Szigeth, 2009). This perspective acknowledges that while environmental problems do have material presence, perception and understanding of these phenomena as problems are ultimately constructed and relayed through science, media, and culture. Still, the social lens tends to favor the constructivist approach since sociology largely explores the plasticity of shared human understanding.

The lens of environmental sociology predictably characterizes pollution and environmental degradation as a social problem with social solutions. The dubbing of these harmful chemicals as "pollution" and the fact that many of these issues are in our collective awareness may be credited to the socialization of the environment. This phenomena of bringing objective experience into common understanding through culture and language is know known as social constructionism. Hannigan uses the example of the ozone “hole” to show that our understanding is aided by a socially constructed concept of the real phenomena, which we cannot experience directly. “There really is no ozone hole as such but rather a thinning in concentration; the image of the hole was scientifically constructed to make the situation more dramatic and understandable” (1995).

Allan Schaiberg (1980) describes pollution as a direct result of the “treadmill of production.” The treadmill of production is a lens within sociology and political economy that views pollution as a consequence of political capitalism. In political capitalism, economic elites and political elites act as mutual stepping stones for one another to elevate each other’s status through government regulation, subsidy, and taxes (Holcombe, 2015). Ultimately this form of capitalism shorts the majority of its constituents by demanding prodigious quantities of labor and resources for the promise of economic growth. Profits tend to accumulate in the top tiers of society instead of being distributed equitably among what Marx referred to as the proletariat (1939). The carrot of economic wealth effectively lures the working class into continued labor and resource exploitation while providing little in return. This model is commonly used in political economy as well, with political economy of the environment expanding Marx’s view of the exploited worker to non-human ecologies and the environment (Robbins & Hintz, 2010).

Perhaps the most popular recent characterization of pollution in sociology has to do with the notion of environmental justice. Environmental justice, defined by the EPA, is “the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies" (epa.gov, 2015). This means that when the criteria for environmental justice are met, all peoples ought to share in harms and benefits wrought by the environment equally. Most commonly, however, harms associated with pollution are borne by the marginalized groups in society without receiving any of the benefits that are gained by producing pollution. These groups consist of low-income and often black and Latino populations, which are situated in high risk locations such as flood zone areas or close proximity to power plants and other heavy industry. Social justice attempts to bring these often overlooked and unintended issues into public awareness through media and activism.

The economic

The economic study of pollution generally operates under the subfield of environmental economics. This discipline uses econometrics to determine how to balance environmental harms such as pollution, in order to come up with the most efficient allocation of resources. Pollution is seen as a cost, typically borne by the public who see none of the benefits associated with pollution. This framing is reminiscent of social justice, but applies economic solutions to deal with these problems. By internalizing the negative externality of pollution via assignment of property rights, or through taxes and subsidies, environmental economics asserts that we can reach the most efficient outcome for a given situation, therefore maximizing total net benefit for society as a whole.

Air pollution represents an externality that is produced by firms at a cost to society and the environment. While some amount of pollution is warranted for benefits associated with energy production and other socially valued goods, inefficiencies arise when privately optimal levels of pollution differ from the socially optimal levels.

One strategy for removing this difference is to tax pollution emitted, so that the cost of emissions made by firms is exactly equal to the social costs of pollution borne by society. Tax revenues can then be reinvested into cleanup efforts, or research for better control technologies, or any number of benefits toward pollution reduction. One potential downside to the taxation approach is that all firms must equally bear the effects of taxation, but individually may have different control costs. For example, a newer firm may have easier access to new technologies and their implementation than old firms.

An alternative to the taxation approach that allows firms to minimize control costs at acceptable pollution levels is the “cap-and-trade” system. Under cap-and-trade a set quantity pollution is determined representing the entire market’s cap for a specific type of pollution such as SO_2 or CO_2. Permits authorizing a standard quantity of pollution are then handed out or auctioned to firms to be traded for at market value. Some firms will be able to reduce pollution at a cheaper cost and therefore may need less permits. Other firms who have high costs associated with limiting pollution may buy permits from firms who can reduce their pollution cheaply. While some firms will produce more pollution than others, the number of tradable permits available limits the total amount of pollution that can be produced.

Environmental economics also has its own definition and criteria for sustainability. The main sustainability criterion that most economists agree upon, including Tom Tietenberg, author of Environmental Economics and Policy (1998) is that “future generations should be left no worse off than current generations.” He goes on to say that “one of the implications of this definition of sustainability is that resources (even depletable resources) may be used—as long as the interests of future generations are protected.” Net benefits as well as costs of future generations, in the sustainable model, should be exactly equal to net benefits and costs in the present. Through the application of accurate discounting rates the economic framework is able to balance shorter term benefits against long term costs.

The chemical framework

Pollution is viewed through the lens of chemistry in much academic discourse. This lens will be referred to as the “chemical framework,” which primarily addresses the “how” of pollution processes. Chemistry is a branch of the physical sciences. Its scope, however, is different than physics, which focuses on scales ranging from as large as the universe, to the microscopic quanta of atoms, photons, and quarks. In contrast, chemistry focuses on a scope somewhere in the middle avoiding quarks and generalizations that hinge on the simplified structure of the hydrogen atom. Instead this lens takes a more detailed approach to atoms, investigating a multitude of molecular compositions and their emergent properties. In Silberg & Amateis’ college text *Chemistry: The Molecular Nature of Matter and Change 7e* (2015), chemistry is described as “the study of matter and its properties, the changes that matter undergoes and the energy associated with those changes.” They also go on to say that “macroscopic-scale properties and behavior, those we can see, are the result of atomic-scale properties and behaviors that we cannot see.” By understanding the microscopic properties and interactions of arrangements of atoms, we can make sense of the macroscopic effects of pollution. Chemistry focuses on these details to help us get an in depth understanding of the macro scale and find tangible ways of dealing with it.

The chemical framework addresses the mechanics of pollution, at the very minimum discussing inputs and outputs of chemical reactions at any two points in time. Pollution under this model is often understood as a negative byproduct of a favorable chemical reaction. Managing pollution in this model generally consists of utilizing those chemical reactions which have fewer or less-harmful negative effects. Although many chemists accept that nearly every chemical reaction will produce some waste products, this lens does not explicitly address *why* wastes must exist. Instead, chemistry tends to focus on how wastes form and what types of wastes emerge from a given reaction through experimental research. The below example illustrates the basic chemistry of sulfurous coal burned and the resulting sulfuric acid—the primary component of acid rain:

$$S + O_2 + M \rightarrow SO_2 + M$$

$$SO_2 + OH + M \rightarrow HSO_3 + M$$

$$HSO_3 + O_2 \rightarrow HO_2 + SO_3$$

$$SO_3 + 2\ H_2O \rightarrow H_2SO_4 + H_2O$$

Figure 3.1 Sulfuric acid formation. Sulfur in coal goes through two tertiary reactions to form HSO_3, which in turn reacts with oxygen to form SO_3, the precursor to acid rain.

Although this example is a shallow characterization of the chemical view of pollution, it does highlight the general view of chemical framework. For instance, emergence of the pollutant H_2SO_4 is made possible only through the presence of oxygen and hydroxide in the atmosphere. Furthermore, acid rain in this form is only possible when sulfur is available most commonly in sulfurous coal. In order for specific pollutants to form, the right concentration of specific molecules and thermodynamic conditions must be present. In the chemical framework if one were to alter the inputs to remove sulfur using flue scrubbers, for example, the negative product of this process can be avoided.

Chemistry shares significant overlap with thermodynamics. Chemists often use thermodynamic to determine whether a process is possible or not. Unless free energy is provided from the outside, reactions that increase the reactant's entropy are the only types of reactions that may take place. Therefore reactions that increase entropy or lower enthalpy are thermodynamically favorable to reactions that increase enthalpy or lower entropy. These processes are known as exothermic reactions, which are defined by a resulting release of heat. Conversely endothermic reactions require heat and subsequently lower the entropy for the reactants.

Brady & Holum, authors of the general chemistry text *Chemistry: The Study of Matter and Its Changes* (1993), are some of the few proponents of the chemical framework that link chemical pollution to thermodynamics on a broad level. When discussing pollution and the second law they note that "whenever we create order somewhere, our activities must generate an even greater disorder in our surroundings." They go on to discuss the types of order they refer saying "whenever we clean up our desks and put out the garbage, mow the lawn and rake leaves in the autumn…the increased order that we create for ourselves has to be balanced by an even larger increase in disorder somewhere in our surroundings—the environment…We must simply face the fact that we can never avoid pollution entirely."

3.2 The Entropy Framework

The entropy framework defined below takes an alternative approach to pollution and its solutions. Following Brady and Holum, this lens shows that pollution is never entirely avoidable, though it can be minimized with the right approaches. There is no such thing as truly "green technology" when conversion of energy is involved. In the following sections the entropy framework is described in detail, applying the concepts of entropy and free energy to more generalized systems including ecosystems and human societies. In the last section, pollution is described in the context of the entropy framework as a consequence of the increasingly heavy demands of the new equilibrium created by intensive energy use.

Entropy as Macroscopic Disorder

The "entropy framework" defines entropy as a measure of disorder, not only microscopically, but at the macro level as well. But how ought we define disorder? The definition of disorder I will refer to stems from J. Willard Gibbs' description of entropy as a measure of "mixed-up-ness" (Rock, 2013). In this definition, as systems increase their entropy they become more disordered as their molecules begin to mix with each other. Low entropy systems have a high degree of order and a low degree of mixing. Conversely, high entropy systems have a low degree of order and a high degree of mixing. Human systems, both biologically and societally, are inherently low entropy due to highly-regulated and minimized mixing of materials. Biologically, when mixing begins to occur, such as when organs rupture, or when an excess bodily fluids such as blood are lost to the environment, entropy increases. Once entropy increases enough to the point of death, molecules mix freely with the environment and become indistinguishable from the larger system.

Entropy as disorder, in aggregate, is always increasing in the universe. However, within this gigantic system, entropy increases and decreases within various subsystems that we can observe. This often occurs when free energy is transported from one system to another. For example, a refrigerator lowers its temperature, and subsequently its entropy, by using electricity imported from an outside source. Consequently, however, to balance this entropy loss, an entropy gain must be had by its surroundings. The heat pump that keeps the refrigerator cool does so by dumping heat into its environment. By importing electricity used to do work, the refrigerator transfers its own internal heat to a fluid, which is subsequently dumped to the surrounding environment.

If understood in terms of order and disorder, as the temperature of the refrigerator is lowered, the molecules within this system move at a slower rate. Since the excited states of molecules within the refrigerator are fewer than those of molecules outside, fewer spontaneous reactions take place and the contents of the refrigerator maintain a relatively ordered state. Even rubber bands and batteries last longer in the refrigerator as a consequence of these thermodynamic properties. Outside of the refrigerator high energy foods oxidize or become easily metabolized by bacteria and molds, which further disorder foods until molecular structures become simple, mixed-up, and stable.

On Earth, order gained is only paid for by disorder gained on the Sun. As Rock (1983) notes, “the spontaneous radiation production by the sun is accompanied by a tremendous entropy production." The sun burns intensely through atomic fusion of hydrogen atoms at a temperature of 5,778 K. As a consequence, visible radiation is exported to Earth driving the complexity and order of life's processes. The burning sun stacks free energy, in the form of visible radiation, like dominoes on Earth's landscape. One after the other the dominoes are stacked, though randomly and dispersed. The standing dominoes represent free energy gradients begging to fall to thermal equilibrium and entropy maximization. Each domino falls in time, promoting the prerogative of entropy generation by converting visible light to sensible heat. Yet eventually these standing dominos become so numerous that when one falls, it topples over another, and a chain reaction begins to take place. Through the trial and error of evolution, living systems find that if the dominos are aligned in such a way that more dominoes fall, not only is an interesting process allowed to continue, but more entropy is produced as well.

This simplified analogy of the evolutionary process leaves us with a few lessons. Domino felling is a necessary and interesting fact of life. However, if dominos fall at a rate faster than they are lined up, eventually the domino effect must come to a stop. Similarly, if a life process generates entropy beyond both the sun's ability to "stack dominoes" and life's ability to line those dominos up, the life process must ultimately come to an end.

This basic relationship of order, disorder, and energy is the foundation of the entropy framework that I will use to describe humankind's relationship with its environment. Systems can only increase order and complexity at the expense of energy and disorder paid for by an exterior system.

Entropy and various open systems

The observable world is decidedly an open system. Both energy and matter are exchanged between most systems that we observe and their surroundings. When this is the case, entropy changes associated with a particular system may actually be minimized instead of maximized, contrary to what we would expect in a closed system. As energy is transferred from an outer system to one of its subsystems, the entropy of the subsystem is subsequently lowered. However, in order for this to occur, the entropy lost by the subsystem must be sufficiently compensated by the entropy gained by the surroundings in order to satisfy the second law.

$$\Delta S_{tot} > 0$$

$$\Delta S_{tot} = \Delta S_{sys} + \Delta S_{sur}$$

If $\Delta S_{sys} < 0$, then $\Delta S_{sur} \gg 0$

FIGURE 3.2 Entropy balance of open system. Total entropy in the universe must always increase. Total entropy is equal to the sum of the entropy changes associated with the system and its surroundings. Therefore, if a particular system lowers its entropy, the magnitude entropy change of the surroundings must be larger than that of the system.

In his book, *Chemical Thermodynamics*, Peter Rock (1983) states that “all living systems build themselves up at the expense of their environment.” This idea is not altogether new, though explanation of these points have been minimal over the years. Erwin Schrödinger also marveled at life’s ability to seemingly defy the second law of thermodynamics, but eventually concluded that life is only able to maintain its inner order by exporting energy and materials to the environment in “a very much degraded form" (1944). Schrödinger, however, does not go on to describe what these forms are. The most obvious and quantifiable of these forms is sensible heat. After consuming low entropy free energy in the form of food, we metabolize the food and assimilate it with our own biological structure. In the process, heat is generated and exported to the environment as a measurable form of entropy. This author believes that other forms ought be considered as well. Some of these would include feces and urea. The forms themselves are no longer useful to the human body and allowing them to mix with internal biology moves the body toward death and thermal equilibrium.

Once excreted from the body, human waste is higher in entropy than the food that it originated from yet this matter can still be degraded further. Decomposing bacteria and fungi further break down this waste, squeezing the last bit of free energy out of this matter until it is as close to equilibrium as possible. At this point, without the aid of an external energy source, the cycle ends. However, with the aid of sunlight, plants can, through photosynthesis, reintroduce once "dead" matter back into the cycle of life. Plants degrade visible sunlight to low-grade sensible heat and lower-grade latent heat. Biomass and structures are built up and then degraded by herbivorous heterotrophs, which are eaten by carnivorous organism, all of which are degraded by decomposers.

The reaches of entropy are not just limited to biological structures, but pervade and dictate all physical structures including industrial scale energy systems, chemical manufacturing facilities, and cities. While all of these undoubtedly produce entropy as a consequence of free energy dissipation, perhaps the most obvious and least controversial of these examples is the coal burning power plant. With the aid of the steam turbine, a coal power plant generates highly usable free energy by converting chemical energy to heat to kinetic energy finally to the electrical energy we use to power our lights, electric stoves, washing machines and other household appliances. Along the way, at every step of the conversion process, some energy is necessarily "wasted" and entropy is produced. The heat produced and exported to the environment is one obvious form of entropy created, but the entropy framework suggests that there may be other forms as well.

Pollution Defined in the Entropy Framework

The entropy framework essentially characterizes chemical pollution phenomena as a natural consequence of high rates of free energy consumption, or, conversely, high rates of entropy production. Much of this perspective's development is owed to the contributions of the late thermodynamicist James J. Kay. Kay and his colleague Eric Schneider reformulate the second law to state that, "as systems are moved away from equilibrium, they will take advantage of all available means to resist externally applied gradients" (1994). Far from equilibrium systems like planet Earth paradoxically develop complex intermediary systems, including life and tornadoes, to reduce energy gradients applied by our Sun. Life is both entropy driven and entropy driving depending on one's perspective.

This conclusion is largely the extent of contemporary non-equilibrium thermodynamics' understanding with respect to life. However, there are many other implications to consider. Internal entropy lowering processes like life are the exception to the universe—not the rule. Far-from-equilibrium systems such as life are anomalies that must constantly battle their own internal entropy maximization, while facilitating entropy increase externally. When the environment maintains a relatively low level of entropy and high levels of free energy, life, so to speak, is good. When entropy in the environment is high and free energy levels are low, life is difficult. When external gradients are sufficiently reduced, life ceases to function altogether. The obvious implication is that when energy runs out, we die. Yet this alone does not directly explain the common experience of pollution. So what is pollution exactly?

Pollution, in the traditional sense, is not an end to entropy maximization itself, but rather a means to facilitate the equilibrium process. In this framework pollution is the necessary result of extreme gradient reduction. Pollution can be further broken down into two main categories. These categories will be referred to as, 1. Mid-line entropy pollutants, and; 2. End-of-the-line entropy pollutants.

Mid-line entropy pollutants are chemical byproducts imbued with free energy and released into the environment. These chemical pollutants are harmful (or useful) due to their natural instability. Some of these mid-line pollutants include NO_X, SO_X, CO, and even free oxygen. What makes these chemicals harmful to living systems is their stored free energy which seeks any available means to reach equilibrium with its environment. These chemicals, once stable in coal fired furnaces, automobile engines, or lithium-ion batteries, become dangerous when released into environments much closer to ground state. In pursuit of energetic equilibrium, these newly emigrant molecules react with anything they can. Far-from-equilibrium systems such as life are a prime choice of host for these reactants since these systems are already thermodynamically unstable and beg to be degraded from an entropic perspective. One thing to note is that these compounds actually have the potential to be degraded further by humans for producing work if the technology is available. However, more commonly, these compounds give up their free energy by “working” on ecosystems and human populations to break us down and expedite entropic maximum for the environment. By reacting with these products, our low entropy systems are pushed closer to thermal equilibrium and ultimately toward death.

End-of-the-line entropy pollutants are exactly what their name implies: they are compounds that have no more free energy to give up (or have high activation energies), and have reached entropic maximum with their surroundings. This category of pollutants includes plastics, carbon dioxide, and CFCs. End-of-the-line pollutants are a nuisance outside of their original systems specifically because they are so stable. Most plastics take at least a hundred years to break down. Carbon dioxide sequestration typically demands free energy inputs from the sun to drive photosynthesis. CFCs are extremely stable in the troposphere, but react catalytically with ozone in the troposphere with the aid of photon energy. All of these types of pollutants require energy input from outside sources, most typically from the sun. Humans may be able to engineer technologies to essentially synthetically bring free energy to convert these types of pollutants back into degradable substances, but unless that free energy use is less than the sun's rate of harness-able input, we can expect that we will see some other type of pollution or degradation in place of the end-of-the-line entropy pollutant we were trying to get rid of in the first place.

At this point, the reader might be asking, "what distinguishes a pollutant from any other substance in the universe? Aren't all substances products of free energy changes?" While this is certainly true, the main difference between pollutants and non-pollutants has to do with the *rate* of free energy transfer. Pollutants are born out of extreme rates of free energy consumption beyond the rates of exergy (free energy) production provided by our sun. When energy gradients are reduced in larger quantities than, or within shorter time spans than the sun’s ability to buffer gradients, pollution accumulates. An ecosystem’s resilience is essentially a function of this solar buffering, the chemical resources available (like water), and time.

An important point to note is that pollution isn’t harmful to the environment itself. A pollutant is significant because it threatens to increase the internal entropy of observable systems of interest. What makes these systems of interest is generally that they are far from equilibrium and can therefore be harmed by bringing them close to equilibrium with their environment. These systems are typically ecosystems and human populations. The “environment” itself has no interests of its own and therefore can only be altered—not harmed. What environmentalists really mean when they talk about the environment is ecosystems and resources. Mid-line and end-of-the-line entropy pollutants inhibit our ability to maintain far-from-equilibrium status and are harmful for this reason.

Another important factor in categorizing a substance as a pollutant has to do with the rate at which entropy is produced relative to the rate at which systems of interest are able to reduce their own internal entropy. As in the primary example of the industrial revolution, entropy has been generated more quickly at this point in time on Earth, than we have been able to account for in the rest of geologic history. Yet this high rate is only an issue because it exceeds many organisms and ecosystems’ entropy lowering capacities. If either solar flux were somehow increased, or evolutionary processes developed stronger resilience capacities, it may be reasonable to believe that high entropy wastes would have less of an effect. However, given our current circumstances it is probably unsound advice to hope for either.

4. Comparison and Results

4.1 Comparing each of the frameworks in the context of pollution

The chemical framework:

The chemical framework excels in providing the necessary details for having a comprehensive understanding of chemical pollution. It's hard to overstate the importance of these details, yet there are also clear limitations to this perspective. It takes a tremendous amount of processing power to understand systems holistically while taking every detail into consideration. In order to understand the world we must simplify it to some degree. In simplifying the world we make generalizations and leave out information that appears to be irrelevant to our scope of study. We draw connections, make patterns and leave out nonessential data to make sense of a particular area of interest. Out of all of the physical sciences, chemistry arguably does the least simplification, and therefore must narrow its scope when conducting primary research. Although broadly-scoped fields such as metaphysics and economics may inform the direction of inquiry in the chemical framework, they are generally not considered when research is taking place. The scope of individual research in the field of chemistry may be small, yet the collective knowledge assembled paints a picture of the physical world in high definition. Chemistry may therefore be considered a fine-grain lens in the broader category of academics.

Unlike chemistry, thermodynamics, statistical mechanics, and philosophy are coarse-grain disciplines that generalize and make assumptions in exchange for larger sample size and scope. In statistical mechanics atoms of all kinds are often reduced to simple harmonic oscillators (SHO) in exchange for the ability to discuss large and very large numbers of atoms in the range of N^{23}. In making such generalizations, physics and its subfields are able to make powerful estimations when considering distant planets and galaxies.

When it comes to discussing pollution, chemistry is absolutely necessary for precisely identifying physical problems and engineering tangible solutions. The risk of giving all of the responsibility of environmental solutions to chemistry is that the big picture, both spatially and temporally, may be compromised. For example, since the early 20th century, chemistry had a major role in its contributions toward the green revolution (Evenson and Gollin, 2003). The Haber-Bosch process, developed for industrial use by 1910 (Hager, 2008), uses natural gas and atmospheric nitrogen to create ammonia for nitrogen fertilizers. These fertilizers were manufactured and used to support growing populations all across the globe and helped the U.S. make the transition from a farmer to consumer ratio of 3:1 in 1930 to 100:1 today (Lobao and Meyer, 2001).

While the petrochemicals developed during the green revolution provided an incredible boon to the average citizen in the United States and Europe, the negative unintended consequences associated with these benefits are quite obvious today. Overuse of nitrogen and phosphate fertilizers is known to cause oceanic dead zones due to eutrophication. Massive human induced algal blooms have led to hypoxia, killing off millions of sessile aquatic organisms in areas greater than 20,000 km^2 in the Gulf of Mexico (noaa.gov, 2015). Rachel Carson's best selling work *Silent Spring* (1962) documents the decline of several bird populations due to the overuse of DDT on crops. Chemical solutions such as pesticides and fertilizers have had the indisputable benefits of increased crop yield, but subsequently higher population sizes and unprecedented ecological harms force us to question whether the benefits of such solutions outweigh their costs.

The entropy framework ought to help steer us away from the types of solutions that create problems further down the line. The issue with some of the solutions put forth within the chemical framework alone is that they often make use of steep thermal gradients to meet their ends. In doing so these solutions create volatile conditions that put us at risk of dealing with larger unforeseen costs further in the future. The issue with relying on the entropy framework on its own is that many details are left out, leaving a large gap between the theoretical and the tangible. However, if the chemical framework and the entropy framework are able to inform each other, many of these issues can be avoided. For example, we can use chemical thermodynamics to gain some understanding of pollution kinetics such as in the high temperature environments of coal fired furnaces or nuclear reactors. When high-energy state compounds are transferred from previously thermodynamically stable environments to environments near ground state conditions, the molecule will take whatever avenue available to reach equilibrium with its environment. Although thermodynamics tells us that we can expect some type of reaction to occur, the exact path is determined exclusively by chemistry. However, if we change or remove the pathway for pollution synthesis, but leave the original thermodynamic conditions unchanged, we may expect novel pathways to give us an analogous result.

In the case of carbon monoxide production, this deadly pollutant can be avoided in the coal burning process if by burning coal more completely at higher temperatures with increased presence of oxygen. However, though the path is altered by the presence of oxygen to minimize CO production, the higher temperatures, and subsequently steeper thermal grade establishes the conditions for NO_X production to occur in CO's stead. Although NO_X, and its derivative compounds, nitric acid, nitrous acid and ozone, are substantially different from carbon monoxide in molecular form, a similar process is taking place. These compounds with either high free energy values, low activation energy levels, or both, are more reactive with both living and non-living systems. By reacting with, and subsequently altering the molecular composition of these systems, compounds such as CO, NO_X, HNO_2, HNO_3, and O_3 expedite the race toward thermal equilibrium.

Luckily, many contemporary researchers and engineers using the chemical framework have learned from previous oversight and have developed new intuitions to deal with the law of unintended consequences. This new intuition uses fewer energy inputs and keeps in mind the long run, bringing us closer to the prospect of long term sustainability.

The economic framework

The economic framework is one of the most pragmatic lenses for creating tangible solutions in our modern word. Our increasingly global society operates under the language of capital making the economic framework the primary academic authority. Economic forces are one of the main drivers of public policy regarding industry regulations making environmental economics a key player in the realm of environmental policy. By recognizing that clean air, clean water, and pristine wilderness have monetary value, environmental economics is able to manage these goods and services by balancing their public benefits against private costs through taxes, permits, property rights, and government regulation. The appeal of the economic framework is that it is already tailored to the our current social system. Solutions in this framework typically maximize economic efficiency, providing the maximum cumulative benefit to its constituents

One proposed economic solution for dealing with pollution involves internalizing negative externalities such as carbon through a Pigouvian tax. This method directly controls the cost of carbon by taxing it at some value per ton in an attempt to balance the social, or "true," cost borne by society. Currently, the EPA values the social cost of carbon and thus the carbon tax at $36/ton based on current and future carbon damage costs at a 3% discount rate (epa.gov, 2015). Taxation is the preferred method used by economists since it deals with set costs. In theory, if the marginal private cost of carbon for firms is equal to the marginal social cost, an efficient quantity of carbon is yielded. Ideally benefits gained through industrial activity are equal to the costs of pollution associated with production, both in the present and into the future. However, determining the real social cost of pollution can be very difficult and inaccurate, making effective policies hard to come by.

Another proposed solution for dealing with pollutants like CO_2 is to implement a cap and trade system. This solution has worked remarkably well for regulating SO_X emissions from coal, but has yet to be adopted for carbon. Essentially, a fixed number of permits are distributed to producers, determining the maximum quantity of pollution that can be produced per year. Some producers will naturally be able to reduce their levels of pollution at a lower cost than others and therefore may sell their permits to producers until the marginal cost of controlling pollution is equal to the social cost of bearing pollution. This method of regulation relies on "natural" market forces, thus avoiding the difficulties that taxation runs into of assigning monetary value to the true costs of pollution.

One issue that plagues the economic framework is known as Jevon's paradox. This concept shows that as efficiency increases in technology and economies, a rebound effect occurs expediting energy use on a larger scale. Essentially when efficiency effectively lowers the costs of resource use, more use tends to occur rather than less. Kenneth Small and Kurt Van Dender (2005) show that as fuel efficiencies increased over a 35-year period, demand for fuel has increased roughly 20% to counteract expanses in fuel saving technology. Harry D. Saunders (1992) more generally claims that increased economic efficiency increases overall energy consumption. Saunders' argument essentially posits that increased energy efficiency lowers the cost of resources providing users with more capital to invest in other sectors of the economy thereby increasing economic growth rate and further resource use. From this perspective, without applying proper regulation to energy use on a societal scale, improvements in economic efficiency will be fall short from environmental goals, at times solving one problem only to create another.

Another drawback of this framework is the assumption that antiquated limitations are solved by innovations in new forms capital created through human innovation. Tietenberg (1998) conveys this widespread view held by many economists, saying:

> "capital has broken down the barriers imposed by human limitations. With the advent of bulldozers, earth moving, once limited by the strength and endurance is limited no more. The size of the market, once limited by the time and effort required to transport commodities in a horse and buggy, expanded with the advent of the railroad, the truck, and the airplane. Limits on corporate controllability imposed by the size and competence of record-keeping staffs—as they attempted

> to stay on top of the information and paper flows—have been expanded in the face of computers that can provide instant access to important information compiled in the most useful format"

Urban pollution caused by horses before the 1900s was a major limiting factor for New Yorkers and even the Romans (Morris, 2007). During these times costs of this form of pollution were very high; however, with the advent of the horseless carriage, a new form of capital was able to effectively solve such limitations. The transition to the automobile removed the need to address urban horse manures, though today we are faced with a new challenge that has escalated from local to global scales. To address Tietenberg's statement, capital may solve some physical limitations of human physiology, but these solutions certainly aren't paid for by human ingenuity alone. Bulldozers and trucks require diesel, airplanes require jet fuel, and computers require electricity, all of which currently require large amounts of fuel and resources extracted at the expense of ecosystems and the environment.

A relatively new brand of economics called ecological economics attempts to resolve this predicament by integrating other fields of study including environmental ethics, feminist economics and thermodynamics. In contrast to classical and neoclassical economics, which values goods strictly based on the market forces of supply and demand (Solow, 1974, 1993), ecological economics attempts to elevate the status of natural capital over human capital, citing the fact that once natural capital is transformed into other forms, the process cannot be reversed without additional inputs. This outlook, informed directly by the work of Georgescu-Roegen (1971) shows that natural capital and human capital are rarely perfect substitutes. However, through more accurate valuation techniques that place human economies into the larger context of the global ecosystem, ecological economics has the potential provide solutions which can be understood and adopted readily by government institutions seeking to maximize economic welfare. Unfortunately, ecological economics is largely prescriptive rather than descriptive making adoption of this framework challenging on a broad scale. The traditional economic framework, on the other hand, portrays itself as largely descriptive and is alluring to institutions hoping for increased economic wealth. However, this lens ultimately oversimplifies the human/environment relationship and cannot be solely responsible for providing solutions to contemporary environmental issues.

The social framework

The social framework both studies and facilitates the transmission of scientific knowledge to public awareness. This framework adopts the role of the technical writer who translates the engineer's enigmatic vision to the people at home reading the manual to figure out how to operate their new toaster. Without a solid understanding of public perceptions, many important topics studied by the scientific community such as global warming would remain accessible only to those within the special club of research and academics. For this reason social theory is essential for building the bridge for widespread understanding and solutions in the environmental sciences.

The translation of scientific knowledge into the public spheres can work both for and against the views held widely by the scientific community. Fossil fuel lobbyists have quite successfully convinced the public that there is still a large degree of scientific uncertainty regarding the case of global warming. However, without the aid of this framework, which encompasses media, activism, and social theorists, the issue of global warming would likely go unheard altogether. Very few of us, including myself, have done the research to provide any insight into CO_2's contribution to atmospheric warming. Although we all perceive weather, few of us can bridge the connection between moderate changes in weather patterns and the larger climate which encompasses them. Social theory helps sift through the "statistical fuzziness" (Dispensa & Bulle, 2003) inherent in scientific research and simplifies this knowledge into digestible issues that both the public and policy actors can use to make substantial changes.

One potential risk of reliance on a social lens of pollution is that there is often a bias for a 'constructivist' perspective over a 'realist perspective. Often neglected in the social framework are the physical details that underpin constructed issues of pollution. When comparing the social lens against the entropy framework on the issue of human induced global warming, the social lens frequently pegs responsibility on neoliberalism and corporations and political actors with bad intentions. The entropy framework, on the other hand, suggests that global pollution issues such as global warming have strong physical impulse for their occurrence. This focus on physical causes may avoids some issues of blame and intention allowing for greater collective action to address pollution and other environmental concerns.

The social framework is at best a middleman for pollution issues. It does not carry out its own epistemological research directly, but helps frame this research in a way that the public can understand. Theories involving pollution are inherently more flexible than many other fields of study, but for this reason also face challenges of being taken seriously in the hard sciences. In order to implement the wisdom of experts on a wide scale, however, the social framework must work in conjunction with both the physical and economic frameworks if we hope to see lasting change.

5. Discussion

In the entropy framework pollution is a natural step in the entropy process. The difference between wastes that humans produce and wastes that animals and plants produce is simply a difference in scale. Even photosynthesizing organisms create harmful wastes. For example, 2.3 billion years ago, the first known mass extinction event occurred now known as the Great Oxygenation event. Interestingly enough, this great mass extinction event was evidently self inflicted. Photosynthesizing cyanobacteria slowly transformed the Earth's atmosphere by producing free oxygen as a waste product (Pinti, 2011). Once natural sinks, such as iron deposits became saturated, energy rich O_2 built up in the atmosphere with toxic effect to the obligatory anaerobic organisms that were present during this time. Eventually, from the survivors, complex aerobic organisms evolved making effective use of the newly available energy supplied by free oxygen. Yet at the time of the Great Oxygenation Event, oxygen would have been considered a volatile mid-line entropy pollutant. This perspective posits interesting implications.

Today oxygen is essential for respiration of all aerobic organisms. It's volatile and toxic role the historic context of the GOE has switched to one of usefulness and growth for the vast majority of organisms now present on this planet. In principle the volatility of other mid-line entropy pollutants could potentially be used for human benefit. With the right conditions in place, passive systems engineered could potentially manage these pollutants to do work *for us* rather than letting them do work *on us*. These chemicals are harmful, or conversely useful, due to their free energy content relative to the environment. Although the viability of this prospect is very exciting, there are still likely to be negative consequences of unregulated gradient reduction. If only end processes are altered and the root causes are left unchanged, the new result would only be the conversion of mid-line pollutants to end-of-the-line pollutants. If gradient reduction is occurring faster than the Earth's ability to recycle these end-of-the-line pollutants using incoming solar flux, a steady build-up of stable, hard-to-get-rid-of pollutants is sure to ensue. These types of pollutants are much more cumbersome to deal with since they actually require free energy to "unmake" them. This is the main reason why carbon dioxide is such a difficult pollutant to regulate. Carbon dioxide's high activation energy make its use fairly prohibitive in its atmospheric environment. Photosynthesizing organisms like plants are clearly able to make use of CO_2, though they only do so with the aid of free energy supplied by sunshine. For humans, there are viable ways of dealing with CO_2 such as carbon sequestration, but these methods require prodigious amounts of energy and are economically unfeasible. For a coal fired power plant, roughly 25%-45% more energy would be needed to capture and store carbon emitted (Smith, 2016). Additionally, use of amine solvents in carbon capture techniques poses pollution risks as well. The solvents themselves, such as monoethanolamine (MEA), diethanolamine (DEA), and methyldiethanolamine (MDEA) have properties similar to ammonia and are harmful in high concentrations (Haszeldine, 2009). Heating these solvents at high temperatures can also produce toxic byproducts.

Energy use

The entropy framework has some major implications for the ways that we use energy and responses to proposed alternatives to a fossil fuel economy. In principle any form of unregulated energy use will lead to what Jeremy Rifkin calls an "entropy watershed" (1981). This concept states that as we exploit resources at a higher and higher rate, eventually social, economic, and pollution problems mount to the point of civilization collapse. As far back as 3500 BC, the problem of the entropy watershed has had devastating effects on civilizations. Markham notes "Pollution of agricultural salinization dates back to Sumerian times thinning out the population from 3500 to 1800 (1994). In this example, even when energy was still available, pollution caused by large scale resource extraction via agricultural irrigation techniques prevented an entire civilization's ability to continue its existence. Although we've become more clever in our ability grow crops and extract resources, issues like global climate change are threatening to alter our collective existence on a scale larger than we've ever experienced. At this time it's clear that we're not in danger of running out of fossil fuels within at least the next hundred years, yet loss of biodiversity and the threat of a much hotter planet still indicate that we must alter our energy use even before this energy is gone. Under the entropy framework, energy or technology switching will not solve this issue. We must fundamentally change both the ways in which we view technology and the ways we use energy.

With this in mind there are a few conclusions that can be made using this outlook. For one thing, nuclear is probably not the answer to our problems. Although we may have the ability to use nuclear as a viable energy source for the next hundred to several hundred years (Lovelock, 2004), the risk associated with this use is extremely precarious. The most obvious issue that must be dealt with is that of nuclear waste . A single nuclear plant generates about 20 metric tons of radioactive waste each year (nei.org, 2015). Although some of this fuel can be recycled for further power generation eventually all of it is converted into high-level radio active waste which must be disposed of. Currently the amount of waste produced by the nuclear sector is close to 240,000 metric tons globally (world-nuclear.org, 2015). Although this number is much smaller than that of toxic wastes produced by other industrial sectors, nuclear waste is much more problematic to deal with. High-level radioactive wastes produce radiation at a rate of 10,000 rem/hr even 10 years after removal from a reactor. Only 500 rem is necessary for a fatal dose in humans. For isotopes like plutonium-239, radioactive decay half life is 24,000 years. Additionally, more reliance on nuclear will guarantee more events like the Chernobyl and Fukushima meltdowns on a statistical basis alone.

For a similar reason, most geoengineering is also unadvisable from an entropic perspective. Geoengineering is defined as "the deliberate large-scale intervention in the Earth's natural systems to counteract climate change" (geoengineering.ox.ac.uk, 2016). Some techniques proposed by geoengineers include: ocean fertilization to increase carbon sequestration by phytoplankton; ocean alkalinity enhancement to combat ocean acidification; and stratospheric aerosol dispersal to increase atmospheric albedo. Large scale iron fertilization was first proposed by J.H. Martin in 1988 and implemented shortly after by oceanographers in small quantities in the open ocean. One experiment of small periodic additions of iron in the ocean resulted in a 20 to 30 fold increase of phytoplankton biomass (Coale, et al, 1996). Sallie Chisolm and her colleagues (2001) predict that large scale ocean fertilization will most likely lead to hypoxic effects similar to agricultural eutrophication, as well as heavy metal accumulation in fish, and a potential increase of microorganisms that produce methane and nitrous oxide wastes. Ocean alkalinity enhancement and stratospheric aerosol will also likely alter the biosphere in unpredictable ways creating harmful unintended effects that will need to be addressed further down the road. However, some non-energy or chemically intensive geoengineering techniques, like afforestation, may be warranted.

Solar flux away from equilibrium

Whether we like it or not (we like it) the sun will keep on shining, preventing Earth from reaching maximum entropy and thermal equilibrium. Although future conditions will doubtless be very different from today's, it's likely that at least for the foreseeable future, life will continue to degrade. The prospect of a global warming catastrophe is, of course, a great detriment to many of the living organisms currently residing on planet Earth, but this catastrophe is, above all else, a threat to our own species' existence. As Schneider and Sagan aptly note, "many organisms would survive on a hotter planet. Microbes survive scalding sulfur springs and grow on the side of nuclear reactors. Unique and clever as we are, human beings are not going to destroy the biosphere…the 'environmental crisis is not one of the environment, but of ourselves" (2004).

Through all of the local turmoil present on Earth, one condition will remain unchanged: the sun will shine on. Incoming solar radiation will continue to swell the gap of energy gradients, begging for some process to find a way to snap Earth back toward equilibrium. If humans are not around to do the job, something else will surely fill in to do the work. It may take some time, and it may not be a living process that attends to this business, but the need for degradation will assuredly continue in some form or another. If our species goes extinct it is most likely that some other form of life will evolve to make use of the gradients provided by the sun. We do a pretty good job at reducing our externally applied gradients, but if we reduce these gradients too quickly, we won't be around to reduce them in the future.

Sustainable entropy production generates the highest total entropy. Schneider and Sagan observe this in another way. They note that organisms, directed by the second law, maximize entropy through gradual gradient reduction. "Healthy organisms exhibit a kind of natural wisdom. They conserve their resources, preserving their long-term ability to reduce the gradients on which they depend" (2004). If gradient reduction happens too quickly, the organism uses up all of its resources and perishes, halting further gradient reduction and entropy production. However, in addition to the loss of resource availability, organisms also bear the risk of harmful consequences associated with high rates of entropy production. As Sagan and Schneider note:

> In the sick organism or ecosystem, gradient reduction may have temporarily increased. But the increase is not sustainable. It is a function of the inability to maintain the superior, long-lasting means of gradient reduction achieved by the healthy adult or mature ecosystem…**organisms operating in their comfort zones do not produce entropy and heat so much as the ability to continue to do so**; biology walks a thin line between gradient reduction and survival. On the one hand, without energy life does no work…On the other hand, maximal entropy reduction as seen in overheating excessive exercise, and too rapid population growth can fatally compromise life's systems of gradient reduction. Neither to burn out nor fade away —that is the mandate for life, a kind of genetic fire.

6. Recommendations

If the entropy framework is an accurate model, then the problem isn't that we pollute, it's that we do it at an unsustainable rate. From a universal perspective, there isn't any problem at all. Entropy will be maximized with or without us. If we choose to maximize gradient reduction as quickly as possible in a "short, but fiery, exciting and extravagant life rather than a long, uneventful and vegetative existence," as Georgescu-

Roegen (1971) puts it, “let other species—the amoebas for example, which have no spiritual ambitions inherit an earth still bathed in plenty of sunshine.” Total entropy of the universe will always increase. There are no two ways about it. But while we’re here, we might as well be the ones to minimize externally applied gradients rather than letting some other process, living or otherwise, claim all the glory. It is clear that if we want to be able to continue to live and reduce gradients of all kinds, we must do things differently.

Minimizing energy use

Our best bet for avoiding an “entropy watershed” as Jeremy Rifkin (1981) puts it, is to minimize our collective energy use thereby minimizing the unmanageable effects of the entropy process. What is the optimal level of gradient reduction? This thesis suggests that balancing reduction rates against solar production rates should provide us with manageable consequences. On average, the sun provides roughly 3.6 $kWhm^2$ over an 8 hour period, which is roughly equal to 0.1 gallons of gas. For an area the size of a rooftop (roughly 100 m^2) the amount of incoming solar radiation would equal 10 gallons of gas per day. Although this amount seems plentiful, much of this energy is degraded in the conversion process even before it can be used by us. The current world record for solar cell efficiency is 46% (ise.fraunhofer.de, 2014) though average efficiencies are much closer to 15%. In 2011, the average American consumed 251 kWh of energy every day (eia.gov, 2014). If we did no more building and kept our consumption rate constant, North Americans would still be consuming more than 5 times the amount of energy provided for an area of an average household.

We must not only lower our consumption rates for the clear implications that running out of energy would have, but also for the unmanageable pollution consequences that we face. Under the entropy framework, carbon dioxide, the world's leading greenhouse gas, is considered a pollutant due to the inordinately high rate of which we degrade energy. Although animals produce CO_2 during natural respiration, what makes CO_2 a pollutant for humans is the high rate of entropy production associated with industrial scale gradient reduction processes. Industrial processes may be considered natural in a descriptive sense, but it certainly doesn't justify extreme gradient reduction in prescriptive terms if our goal is to facilitate human existence into perpetuity.

Minimize energy processing

There are many strategies available to us for managing our global entropy balance. The first is to fundamentally use less energy. The second, is to reduce the amount of processing we do with the energy available to us. Gasoline may be a highly concentrated form of available energy, just as beef is, yet the amount of energetic processing required to create these goods is inordinately high. To produce gasoline, first crude oil must be extracted from the ground requiring energy intensive heavy machinery; then the oil is distilled, cracked, and treated producing 12 gallons of gasoline from a single barrel (42 gallons) of crude oil (eia.gov, 2015). At each step of the process, large quantities of energy provided by fossil fuels are used to produce the usable energy we seek from gasoline for our cars, to natural gas to heat our homes, and electricity for everything else. If we can reduce the number of steps needed to create the energy forms that we use on a day-to-day basis, we can both increase overall energy efficiency and reduce rates of entropy production and the harmful associated consequences.

Energy conversion processes like wind turbine power and solar PV are the top choices for both minimizing energy use, and minimizing the number of steps between initial and final energy forms. Since these processes rely directly on daily solar flux there are already embedded limitations to the amount of energy that can be used for work. Yet these forms have an additional advantage of reduced processing as well. Traditional electrical production converts large quantities of stored solar energy in the form of fossil fuels from chemical energy, to heat energy, to mechanical energy, and finally to electrical energy. For solar PV, visible light is directly converted to direct current electrical energy through the use of crystalline silicon or thin-film technologies. For wind, air currents driven by atmospheric thermal gradients are converted from one type of mechanical energy into another, ultimately being converted to electrical energy through the same electromagnetic turbine technology that is used by natural gas and coal powered utilities. The difference between these types of technologies and fossil fuel technologies is not that one is clean and the other isn't but that solar and wind technologies simply do less free energy processing and can therefore bypass some of the negative effects of these demanding new equilibriums.

Unfortunately, with the state of solar and wind energy as it is today, the electrical process uses a few more steps than the ideal described above. Once kinetic or visible radiation energy is transformed into direct current electricity after which it is typically stored in chemical form using battery technology and then converted to AC for domestic use. Although DC to AC conversion is fairly efficient, there is some loss (about 5%) and some entropy generated in the process (Rodriguez, et al, 2002). This waste, however, comes primarily in the form of fairly benign sensible heat and not much is produced. The more serious conversion process has to do with the batteries needed to store electrical energy for later use. Both lead-acid and lithium-ion batteries have problems with efficiency, storage, and pollution. Lead-acid technology is roughly 85% efficient at low charge and 50% efficient at full charge (Stevens & Corey, 1996). Lifetime for most batteries are from 3 to 10 years, after which they must be disposed of or recycled. Lead-acid batteries contain both lead, a toxic heavy metal, and highly corrosive sulfuric acid. Lithium-ion is more expensive to produce than lead-acid, but is more efficient overall (~90%), and has similar environmental costs. Zackrisson et al. (2010) show that during the lifecycle of a 10 kWh PHEV battery, 1660 kg of CO_2 is produced along with impacts on photochemical smog, acidification, and ozone depletion. Yet even though these impacts are significant, they are still much smaller in magnitude than high level fossil fuel use. In bypassing several of the steps of converting solar radiation to usable electricity, we are able to reduce the magnitude of entropy demanded by such processing, and sidestep many of the pollution effects we experience on the large scale.

Decentralization and generalization

On a societal scale, our best bet for sustainable gradient reduction would involve the transition from large centralized social and commercial institutions to smaller decentralized systems. Large scale organization demands huge quantities of energy and create proportionately large quantities of entropy at rates that are currently unsustainable. By minimizing the size of organization through tactics like residential energy production and permaculture we can mitigate some of the effects wrought by industrial agriculture and energy production. Smaller scale institutions demand that its members are less specialized and have a wider variety of skills to compensate. These smaller systems may not be as efficient, and we may not be able to buy mangos whenever we desire, yet the payoff may help circumvent the negative aspects of wage labor and unmitigated pollution. Decreased specialization increases our odds of survival as a species and allows us to step off the "treadmill of production" thereby allowing us to take fate into our own hands. If this and the above methods are adopted, we are guaranteed a much better chance at sustainable living.

7. Conclusion

With an entropic understanding of the universe it becomes easier to view pollution as a 'natural' facet of human existence. This view avoids the need to point fingers at individual actors within the larger socio-economic system we're all apart of. This 'natural' view may allow some to interpret pollution issues with apathy or endorsement, but this jump from positivist explanations to normative judgments is inherently fallacious. However, as a global community that generally agrees that preservation of the human species is a goal worthy of political and economic investment, through a physical understanding of pollution, we can share responsibility more equitably and learn how to work better with important political actors and corporate entities rather than making them out as eternal foes.

As a newly global society, there is no longer an environment outside of ourselves. System and environment increasingly converge to become one and the same. When we export entropy or mid-line wastes, we do it in our own backyards. There is no away. While we may be fulfilling an important universal prerogative by using up energy quickly, we are certainly not helping ourselves continue to do so in the future. It is doubtless that the universe will find some other means to carry out its bidding, but I, for one, would prefer it if humanity had a role in this larger cosmic play. Perhaps our destiny is to simply be a prototype for sustainable entropy maximization, but I don’t think that conclusion is obvious at this point.

I believe that much of our universal experience follows a pattern similar to the function, sin(x)/x. As we move forward in time we can observe what appears to be a dampening oscillation: like a pendulum swinging back and forth, our path makes incrementally smaller crests through the experience of friction. We swing from one extreme to another, making mistakes in the process, but learning from them as well. With new knowledge gained from collective experience, we swing less and less wildly, getting ever closer to the asymptotic equilibrium of “truth.” Periodically we touch this equilibrium, though we never stay for long. During the rare times that we do touch equilibrium, however, we get a glimpse of the long view, like peering across several vestibuled train cars after a long bend in the rails. During these glimpses we see present, future, and past with a clarity rarely experienced in everyday living. When we swing wildly this clarity is short lived, yet with knowledge and wisdom we can dampen our oscillations to a path that allows an extended vision through time. The closer we get to the truth, the farther our ability to see and the longer we are able to maintain this clarity.

There will never be a “future perfect” for limited identities like humanity or life, but the more we are “in balance” with the universe, the greater the quality of life these forms will can achieve. In sum the universe is always in balance. However, individual components within the universe may swing wildly in a chaotic manner. The closer we are to the universe’s fulcrums, the greater the chance of success at living happy lives into perpetuity. By understanding universal constants and tendencies through truth seeking institutions like academics, we can approximate these fulcrums better and develop principles to use them in the most effective ways. These principles allow us to ride the wave toward equilibrium rather than getting tossed around in the surf. The entropy framework is but one attempt at guiding our steps on the fulcrums that allow for long and happy living. Clearly much work still needs to be done to develop this framework further, but through continued research and the sharing of information we can extend our collective ride on the path toward universal truth. Sustainable chaos for sustainable order.

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