What to do with all these bits?

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ABSTRACT

The claim here in is that we can store computational capacity for future generations to use in times of scarcity. The conjecture is that this capacity can be stored in systems through mechanisms related to exchanges of information and associated entropic gradients (and accompanying forces). In this paper we will describe the connections between the thermodynamics of the heat engine and the thermodynamics of information theory in order to postulate a structure through which computational capacity is stored for use in a computationally constrained future. The motivation for this conjecture is rooted in: well-understood and repurposed thermodynamic principles; significant advances in the understanding (via major improvements in data accusation) of complex ecosystems; newly emerging perspectives regarding the relationship between gravity and information exchange; and the need to create mechanistic solutions for problems rooted in complexity science (i.e. climate change.)

An agenda of theoretical and empirical foundations is presented to serve as a guide for the discussion. It provides the context for deeper discussion of topics such as: the relationship between the emergence of thermodynamics and information theory with particular emphasis on the role of entropy; mathematical implementation of these concepts with respect to multi-continuum descriptions of systems and processes; and case studies to describe how this combination of new ideas can be implemented to understand and design complex systems. These case studies are specifically chosen to highlight the multi-scale multi-domain applicability of this unique approach to analysis and design of natural and engineered processes; and to suggest methods through which these systems store computational capacity.

1. Motivation

James Clerk Maxwell (1) roiled generations of scientists when he observed that a clever (and nimble) being- aka Maxwell's Demon- could separate the molecules of a container at uniform temperature into hotter and colder chambers by simply knowing (acquiring and processing information) whether a molecule traveled faster or slower than some cut off value, thereby:

> *" ...without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics.";*

And thus did Maxwell forever tie the thermodynamics of the heat engine to the emerging fields of Information Science. After a century of fruitful study by a who's who list of notable physicists (2-4), Charles Bennett (5-6) cracked the final riddle (although some debate exists still [7]) that saves the second law from the ravages of the demon by calculating the entropic cost of resetting (erasing information) the molecular speedometer. Along with Boltzman himself, Maxwell is rightly heralded as one of the foundational pioneers of Thermodynamics and much like Boltzman appreciated the central role of entropy in the emergence of important phenomena such as diffusion, osmosis, buoyancy and evaporation to name a few (not to mention the concept of an Ideal Gas itself). It has been through control of these phenomena via constructed systems that we have created an industrial society that is increasingly described in terms traditionally reserved for biology; as if an ecosystem of industrial capacity has somehow emerged through processes best understood via analogies to biological agents that acquire, process, transmit, receive and act on information. In a similar vein, ecosystem scientists (8-11) are increasingly recognizing the importance of information exchanges and thermodynamics with regard to ecosystem emergence, function and stability. For example Harte (12) has convincingly postulated that in order for an ecosystem to form and function that the entropy (a measure of information) of the system must drop below certain threshold values and be maintained within limits for optimal performance and resilience. In a related fashion, Ulanowicz (13) argues it is a lack of order (relatively high entropy) in the form of the availability of redundant processes that enable ecosystems to persist. It is also interesting to note that these natural scientists are themselves reaching out to the physical sciences to describe ecosystems in engineering terms such as ductility, fragility, elasticity, plasticity and viscosity. Concurrently, scientists of all stripes are investigating the vast troves of information at large (e.g. deep space telescopes, planetary systems such as NASA GRACE) and small (e.g. National Ecological Observatory Network [USA], SENSE–T [Tasmania]) scales to understand the forces that bind ecosystems into large scale structures that drive global circulation models and small scale structures that control insulin production via microbiomes within the human system.

Verlinde (14) has proposed an intriguing transformational method through which these processes that appear to span many domains can be placed in the context of emergent entropic forces (15) that are the result of gradients associated with information exchanges. Using these methods he has effectively tied the emergence of gravity itself to information exchanges and illuminated a path forward to understanding how other natural systems emerge and function. These methods offer the prospect of devising similar approaches to bridge these ways of knowing through extension of Verlinde's arguments to engineered systems and ecosystems. This approach can provide a framework through which we can understand how to store the computational capacity of the abundant present in systems that can be used in a computationally constrained future.

We as a society are today faced with some very nasty choices regarding the use of resources in the context of supporting 9-10

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billion people (projected peak human population) on a planet whose most populated and productive zones are predicted to be subject to destructive flooding (e.g. coastal regions-Southern California) or subject to severe drought (e.g. central California). Thinking ahead to these awkwardly long range scenarios (50-200 years) poses some rather difficult problems with respect to the design of engineered systems such as sea walls, bridges, and water storage (i.e. civil engineered society) which are typically designed for maximum life times that are far short of the lifespans needed to address these scenarios. For example, it may be more economical and practical to expend natural and computational resources now to design and build the massive amount of sea walls needed to protect critical segments of our coastal communities (e.g. estuaries, port facilities, transportation corridors). We are however in a conundrum since it is through access to vast amounts of computational resources (to manage supply chain logistics, high throughput material processing, design against some pretty uncertain futures, etc.) that we are able to conceive of and execute infrastructure programs on these scales. Unfortunately we have currently accepted design practices that result in infrastructures with around a 50-75 year lifespan that will likely fall well short of the time frames for which we seek solutions. In order to adapt to these constraints we should contemplate design principles that in some way regenerate the processes under which the original infrastructure is constructed. An intriguing candidate from which to draw inspiration for these design principals is the abundance (for now) of diverse ecosystems and the mechanisms through which these complex systems are bound and function. And so we come to the conundrum identified by Fenner (16) when he noted that a central problem of sustainability science is to develop mechanistic solutions to problems rooted in complexity science. Guided by these motivations, a roadmap is presented in Section 2 that will describe methods through which ecosystem function can be understood in a mechanistic framework. This roadmap introduces, in broad strokes, thermodynamic concepts that form the basis for modern industrial society and points to important relationships between these concepts and information exchange within complex systems; it points to important aspects of the continuum description of processes that form the basis for most of the methods through which engineers model the world and produce simulations of future states upon which designs are based; and it provides an overview of applications of these new approaches to ecosystems and the infrastructures that are engineered to support human activity within these ecosystems.

2. Agenda

It is a central thesis of this paper that information theoretical approaches to thermodynamics can provide insight into the mechanics of ecosystems that can form the basis for design of sustainable infrastructures. We will begin to lay this approach out in the following sections.

In section three we discuss in parallel the history of the relationship between the thermodynamics of the heat engine and the thermodynamics of information theory; as well the emergence of thermodynamic measures of ecosystem function. The connections between information and thermodynamics go back to nearly the beginning of thermodynamics as if one emerged along side the other. We will discuss how the reasoning that leads to the development of the Kinetic Theory of Gases also emerges to lay down fundamental concepts of Information Theory. This reasoning will be placed then in the context of Verlinde's surprising perspective on the emergence of gravity in the early universe. The parallels between the development of the Kinetic Theory and this perspective will form the basis for extending Verlinde's construct into continuum mechanics in a fashion that can enable engineers to reliably design systems that can evolve/adapt to environmental fluctuations, as do ecosystems.

In section four we develop extensions of these transformational methods to continuum mechanics in the context of describing the mechanics of ecosystem form and function. The starting point will be the adoption of a multiphase continuum mechanics definition of a continuum point at which multiple constituents exist and interact through supply terms associated with mass, momentum, energy and entropy. It is through these supply terms that constituents exchange information and through which forces that bind and lend properties to the overall continuum emerge. This serves as a natural framework through which familiar mechanics parameters (e.g. velocity, acceleration, viscosity, conductance, etc.) can be placed in the context of information exchanges between the constituents of a multiphase continuum.

In section five we will describe how the proposed information theoretical mechanics can describe ecosystem form and function. We will discuss how these insights can be used to create tools through which scientists and engineers design sustainable infrastructures that can store computational capacity for future generations to use in times of scarcity. This discussion will focus on three case studies: one each from ecosystem science, water resource engineering and civil engineering. For the ecosystem science case study we will utilize well-known approaches from engineering mechanics, now grounded in information theoretical mechanics, to describe ecosystem sustainability relative to material science concepts such as ductility and brittleness. For a water resource case study we examine the Colorado River system relative to the role that policy related information creates scenarios that push water from the rivers watershed hundreds of miles to urban areas. For a civil engineering case study we examine principals rooted in new information theoretical perspectives to design and deploy infrastructure needed in a hotter and wetter climate where-in many scientist predict that tropical storms, like Hurricane Katrina, would likely be more numerous.

3. Heat Engines: Thermodynamics and Information

It is not the intent of this section to provide a comprehensive description of the development of the Kinetic Theory of Gases (KTOG). The goal is to highlight some of the key KTOG developments that led to the emergence of Information Theory in a fashion that suggests a path to understanding how information exchange influences the forces that drive complex systems. It was Carnot that lit the fire that would propel the world into the industrial age when he formally identified the primary mechanism through which work is generated by steam engines, as the transfer of heat from a higher temperature to a lower temperature by means of a working fluid. He also seems to have been one of the first to recognize the limitations placed on systems by what came to be known as the second law of thermodynamics and by noting that it was through creation of a temperature gradient (and associated entropy gradient) that forces are generated from which work can be extracted.

Contemporary to these findings was the building consensus that matter was composed of atoms, which combined to form molecules. Clasius, Boltzman , Maxwell and others built upon this perspective to describe the behavior of gases as the response of a large collection of molecules that exchange momentum (representing information about the available energy) through collisions in the same manner as perfectly elastic hard spheres on a pool table. The resulting theory worked well with respect to the measurement tools available at the time but was subsequently modified to account for forces that emerge due to volume exclusion principles (e.g. Van der Walls forces) which, like temperature differences, can be represented as entropic gradients; which in this case are associated with a boundary that defines the inside and outside of a container. Other paradoxes were resolved by adopting a fundamentally statistical model with respect to the mean free path of individual molecules as they travel within a gas and importantly a statistical model for the distribution of molecular velocities about some mean speed that came to be recognized as the temperature of the gas. It was the latter that led Maxwell to propose that an intelligent being (a Demon) could partition the molecules of a gas (at uniform temperature) based upon their velocities relative to the mean velocity described by this distribution into two chambers (one with low temperature "slow" molecules and one with high temperature "fast" molecules) from which work could then be extracted in violation of the second law of thermodynamics.

Although it is likely that Maxwell himself posed the Demon paradox simply to describe the statistical nature of the KTOG, the saving the second law from the paradox presented a formidable challenge for over a century. This discussion laid the foundation for the Information Theory that pervades nearly every aspect of our technological society. For example, the very concept of a bit, seems to have it's root in the yes/no decision that the Demon must make as it observes the speed of a molecule to determine if it is slow or fast (relative to the mean). Similarly when Claude Shannon set out to quantify the resource requirements for the emerging telephone networks (and create the mathematical basis of Information Theory) of the early 1900's, he leaned heavily on the work of Weiner (17) and a host of other contributors to the Demon paradox but rather surprisingly does not appear to have formally weighed in himself. The paradox has largely been put to rest by Charles Bennett who noted that in order for the demon to conduct it's business it must produce "at least one bit" of entropy in order to collapse two possible states (left or right…fast or slow) into one-"no measurement has been taken". This led Bennett and others to expand upon the notions of computational reversibility and introduce a concept that could be useful in describing how complex systems bind together, logical depth. Logical Depth and its cousin Thermodynamic Depth arose out of the need to find a rational, measurable definition for complexity on the way to describing how it is that complex systems self organize (18). It refers to the amount of time for a universal Turing machine to reproduce a system from random inputs. Similarly, Thermodynamic Depth is the amount of information that has been discarded (and subsequent entropy production) while a system evolves from simple initial states to its current condition. During this evolution entropy production results from forces that do work that dissipate energy as a system experiments with various configurations to arrive at an optimal (at least in a local sense) set of processes that determines its function and its ability to make the calculations necessary for it to persist.

So we see from the KTOG that after a significant number of information exchanges via collisions transferring momentum throughout the gas, that a macroscopically measureable force, the gas pressure, emerges as a state variable to a gas system. At this macroscopic level we see that forces emerge that are capable of doing work (a force times a distance through which it acts) in the presence of temperature gradients that are fundamentally equivalent to entropy gradients as in the Carnot Engine. In addition we see that in order to harmonize the original formulation of the KTOG with experimental observations it was discovered that volume exclusion effects (and associated entropy production constraints) result in forces (Van Der Walls) that bind the molecules of a gas together as the volume decreases. We see similar entropic effects when calculating surface tension, osmotic pressure, buoyancy and other well understood phenomena from thermodynamics, hydrodynamics, and multi-phase continuum mechanics. And so it seems that the notion of information exchanges (and associated entropic gradients) are important (if not central) to the Newtonian response of physical systems. The challenge then is to understand the mechanisms through which these phenomena are manifested so that we can better understand how natural and man-made systems emerge and function.

The recent work of Verlinde (14) describes an intriguing approach that sheds significant light on the problem by proposing that the gravitational force itself is emergent from the exchange of information associated with the location and magnitude of mass. The approach requires some somewhat controversial assumptions regarding the organization of the universe. In particular it requires the assumption of a holographic universe in which all the information describing the world is stored on holographic screens separating points in space. For the purpose of this article we will assume that this is the case and leave it to others to litigate the validity of this assumption. Suffice it to say that there are convincing arguments supporting this view but at a minimum the approach represents an effective transform method to connect the thermodynamics of the heat engine and Newtonian mechanics to the thermodynamics of Information Theory.

Beyond the assumption of a holographic description and the general concept of the "course graining" effect of entropy production, Verlinde's approach additionally assumes that there are a finite number of degrees of freedom (possible states) that are proportional to the area of the holographic screen and that the energy of a system is evenly distributed over these degrees of freedom. With these assumptions in hand it can be shown that the change in entropy of a screen due to the approach of a mass **m** at a distance Δx is given by**:**

$$\Delta S = 2\pi k_B \frac{mc}{h} \Delta x.$$

By noting that energy is related to mass via $E = mc^2$ and noting that the area of a sphere represents the holographic screen associated with the degrees of freedom in that region of space, Newton's gravitational law emerges. We have quite obviously skipped over a fair amount of details in this exposition of Verlinde's work and interested readers are encouraged to study the elegant and detailed presentation of these arguments. The main point is to note that there is a deep connection between Newtonian mechanics and entropy (which for many applications is the same whether we are viewing an information system or a physical system.) We will further argue that the forces that emerge in the presence of entropy gradients can be characterized relative to the information exchanges that occur in a wide variety of systems and (as Verlinde argues) can be characterized in the absence of knowledge of the underlying microscopic mechanics. All that is required is to have knowledge of the information exchanges that occur within the system.

4. Multi-Continuum and Information Mechanics

Continuum mechanics is an idealized mathematical description of material systems- solids, fluids and gases. The assumption is that materials have a continuous distribution of mass that extends to a mathematical point. For example, to determine the density of a material in a given volume, $\rho_1 = \frac{dm_1}{dv_1}$, we would count the number of molecules in that volume, multiply by the mass of the molecules and divide by that volume. This exercise is repeated until after looking at successively larger volumes (and larger numbers of molecules) the density, $\rho_n = \frac{dm_n}{dv_n}$, of the n^{th} volume is not appreciably different than the $(n-1)^{th}$ density. The assumption then is that this density represents the density at a mathematical point. No cracks, no gaps, no space between molecules or atoms… only a continuous material whose density is $\rho = \rho_n$. This is not how real materials exist and necessarily restricts the applicability of continuum mechanics to scales at which the molecular nature of the material is not apparent. In spite of this restriction, continuum mechanics is at the core of most methods for analyzing the behavior of solids, liquids and gases. Multiphase continuum mechanics generalizes this notion to allow for multiple materials to exist at a continuum/mathematical point. Quantities such as density are calculated using the same course graining technique as with a single phase continuum with the added complexity of having to count multiple types of molecules until the density of the constituents, ρ_α, for the n^{th} volume is not appreciably different than the $(n-1)^{th}$ density as before. Once again these finite volume densities are assumed to represent the density of the material at a continuum point, which has a vanishingly small volume but now consists of multiple phases at each point. This of course further restricts the applicability to scales at which the multiple constituents are not distinguishable. The practical result is that calculated constituent entities like stress represent an average of the stress associated with individual constituent particles that comprised the finite volume from which the density was calculated prior to condensing to a continuum point.

The balance equations for a multiphase continuum look much like those of single-phase continuum but importantly include supply terms that represent interactions between the constituents that exist at a point. For example (19) the balance of mass, momentum, and energy for constituent α are written as:

$$\dot{\rho}_\alpha + \rho_\alpha \underline{\vec{\nabla}} \cdot \underline{\dot{x}_\alpha} = \hat{c}_\alpha,$$

$$\rho_\alpha \underline{b}_\alpha + \underline{\vec{\nabla}} \cdot \underline{\underline{T_\alpha}} + \underline{\hat{p}}_\alpha = \rho_\alpha \underline{\ddot{x}}_\alpha,$$

$$\underline{\underline{T_\alpha}} : \underline{\underline{L}}_\alpha^T - \underline{\vec{\nabla}} \cdot \underline{q_\alpha} + \rho_\alpha r_\alpha + \hat{e}_\alpha = \rho_\alpha \dot{e}_\alpha.$$

The second law of thermodynamics is not required to hold for an individual constituent but can be written for the entire continuum as the summation of the constituent terms and is given by:

$$\sum_\alpha (\rho_\alpha \dot{s}_\alpha + \underline{\vec{\nabla}} \cdot \underline{q}_\alpha/\theta - {\rho_\alpha r_\alpha}/_{\theta} - (\hat{c}_\alpha s_\alpha + \rho_\alpha \hat{s}_\alpha)) \geq 0.$$

In the above equations $\rho, b, T, L, q, and\ r$ are the density, body force (e.g. gravity), stress tensor, the spatial gradient of the local velocity, heat flux and specific internal heat source respectively. θ is the temperature and $\underline{\dot{x}}, \underline{\ddot{x}}, and\ e$ are the velocity, acceleration and specific energy of the constituent (subscripts implied for brevity). $\hat{c}_\alpha, \underline{\hat{p}}_\alpha, \hat{e}_\alpha, and\ \hat{s}_\alpha$ are the mass, momentum, energy and entropy supplied to constituent α due to interactions with all other constituents at the continuum point. It is these supply terms that are of particular interest with regard to how systems exchange information and produce emergent phenomena as discussed in section three. For example, in Maxwell's description of the KTOG the momentum supplied to constituent α by interaction with constituent β that drives the diffusion of a binary mixture of gases is given by:

$$\underline{\hat{p}}_\alpha = K \rho_\alpha \rho_\beta (\underline{\dot{x_\alpha}} - \underline{\dot{x_\beta}}).$$

For gas mixtures like these, the constituent velocities are functions of the probability distribution of the molecules that comprise the individual gas species and so the velocities can be written in terms of these probabilities. It should come as no surprise then that the entropy change of the resulting mixture is related to the information exchanged through these collisions and can be written as (15):

$$\Delta S = -T_0 R \sum_1^n x_i \ln x_i.$$

Where $T_0, R, and\ x_i$ are the reference temperature, gas constant and the mole fraction of the i^{th} constituent respectively (which is equivalent to the probability of finding that constituent at a particular location). Further insight into the relationship between these supply terms and the emergence of forces within a multiphase continuum are illustrated in the entropy balance equation where we see a coupling between the mass supply term and the entropy supply term, i.e. $(\hat{c}_\alpha s_\alpha + \rho_\alpha \hat{s}_\alpha)$. Much like the emergence of pressure through momentum exchange driven supply terms like $\underline{\hat{p}}_\alpha$, it is through coupling of the information exchanges represented by these supply terms that forces emerge that can drive the behavior of complex systems.

The beauty of what Verlinde has suggested is that it is through the exchange of information (and attendant entropy gradients) that fundamental forces like gravity emerge to drive system behavior. In addition, he has shown that these emergent forces can be computed without knowledge of the underlying mechanics through which these information exchanges manifest themselves. All that matters is that the entropy can be calculated from a rational accounting of the information exchanges that occur within a system. This is a particularly useful result when placed in the context of multi-continuum mechanics presented in this section through which we can see how entropy changes can be accounted for via supply terms that influence the overall mechanics (velocities, forces, accelerations, etc.) of systems that can be represented as a continuum.

5. Applications

<u>*Ecosystem Science*</u>

"To meet the needs of the present without compromising the ability of future generations to meet their own needs" (20) is a call to arms to understand how coupled human and natural systems can be modeled, simulated and designed in the face of global climate change that will impact virtually every aspect of modern society. The challenge is to understand how the ecosystems that surround us are bound together and it is the contention of this discussion that forces that emerge in the presence of entropy gradients can serve as useful guides to understanding the role that computation plays in this process. The health of ecosystems are commonly measured relative to indicators that generally fall within a Pressure-State-Response Framework in order to relate pressures such as GHG emissions to state variables such as global temperatures (21). Increasingly scientists are also looking to information theoretical approaches to characterize ecosystem health. For example, Shannon Entropy has become a relatively standard method for measuring resilience based upon evidence that more diverse ecosystems are better able to withstand perturbations that might otherwise significantly reduce function (22.) In addition it is interesting to note that May (23) built upon the work of Gardner and Ashby (24) to

demonstrate that large complex systems fail to persist once they become too diverse (too many species and/or too much or too strong connectance.) The result is that ecosystems in general display a “goldilocks” principle in that the entropy must be low enough for the system to exist and high enough for the system to persist.

To understand the mechanics of this effect consider the effect of causal entropic forces described in (25) and given by:

$$\underline{F}(\underline{X}_o) = T\underline{\nabla}S(\underline{X})$$

Where $\underline{F}(\underline{X}_o)$ is a force that emerges due to constraints that produce an entropy gradient $\underline{\nabla}S(\underline{X})$ (T is the temperature) and $\underline{X}_o$ is the current macrostate $\underline{X}$ (e.g. a spatial coordinate.) In the absence of a gradient, the probabilities of all interactions (or abundance of species) are equivalent but when the entropy is reduced producing a gradient, forces emerge to bind the system together. If the entropy gradients are relatively large, these forces are themselves relatively large and the system can become stiff (prone to large response associated with relatively small perturbations) and brittle (if the total entropy becomes relatively small). Conversely, for relatively shallow gradients the binding forces themselves are relatively small and the system is less stiff and with higher diversity will exhibit a ductile response. The internal mechanics of these forces can manifest themselves in many forms. For example the exchange of chemical information between a pollinator and a flower essentially produces a force that propels the pollinator through space to the flower. Similarly the ants that crawl across our counter tops leave trace chemicals for their little pals to read which again result in forces that propel them to food sources. Recall that Verlinde has shown us by pulling Newton’s gravitational law out of the morass of information residing on holographic screens that while the underlying mechanics of the screen (or the pollinators or the ants on our counters) might be very interesting and useful, it is not necessary to understand the details of these mechanics so long as the information associated with the resulting interactions is available in a form that allows us to calculate the entropy (and entropy gradients.) This line of reasoning opens up an approach to characterizing ecosystem function that is at the same time novel and familiar. It is familiar to talk of ecosystems with terms like resilience, brittleness, fracture and collapse as though they are structural systems resisting gravity and impacts. It is also familiar to describe sociologic phenomena with rhetorical flourish that use terms typically reserved for engineered systems: such as ‘the compulsion of the European settlers to move the mechanisms of western society into the Americas as though drawn by the force of the idea of open lands unconstrained by the boundaries of past lives.’ It is also novel to open the conversation to the notion that these are not necessarily or exclusively metaphors of the Newtonian systems that have produced modern industrial society. Verlinde has shown us that from information the most fundamental of Newtonian systems can emerge. If we accept that, then it is not so large a leap to consider that information exchanges can produce other forces that shape our environment in equally fundamental ways.

Water Resource Engineering

Consider for an example the role of policy and politics that have shaped the riverine system that slices through the American west from Wyoming to the Gulf of California, the Colorado River.

“ An act to secure homesteads to actual settlers on the public domain…that any person owning or residing on land…one hundred and sixty acres.” (the Homestead Act of 1862).

These words, this policy (and related acts) and the information contained therein would doom the great American river that had flowed for millennia to carve the Grand Canyon. In just over a hundred years later, the gates of Glenn Canyon dam slammed shut to form Lake Powell ironically named after the great John Wesley Powell who fought to save the mighty river. Unfortunately, as Marc Reisner wrote in Cadillac Desert, *“…in the west water flows uphill toward money*.” (26)

Physics dictates of course that water flows downward with respect to the potential of gravity. But if gravity itself is emergent from information and associated entropic gradients why then would not the material effected by gravity also be subject to forces emergent from entropic gradients created from information exchange. We present an argument for discussion that the homestead act and related legislation (such as those to create the borders of the states) represent information exchange that produce entropy gradients in the landscape that after a sufficient number of interactions (much like the molecules of a gas) produces forces that cause water to literally flow uphill (e.g. the pumps and siphons of the Central Arizona Project). Parceling the landscape into 160 acre plots via the Homestead Act at relatively small scales and the formation of state boundaries at larger scales disrupts the natural entropy production of the existing ecosystems and produces tremendous new forces that, in defiance of gravity, quite literally expanded the watershed of the Colorado river to include places like Phoenix and the Imperial Valley of California. This new watershed is held together in an arguably brittle configuration (re: the modern Salton Sea was formed through the sudden catastrophic failure of systems engineered and constructed to produce the forces- and associated entropy gradients- needed to divert Colorado river water.) It seems clear then that we need to either expand our perception of a watershed or expand our perception of gravity (maybe both.)

Among other things, engineers principally design mechanisms and processes to enforce the boundary conditions associated with the known solutions to differential equations that are presumed to govern the mechanics of the world. Setting aside the argument of governance vs. description, what is meant here is that as it is currently practiced (as described design codes), the profession of engineering is bound by what structural engineers jokingly describe as the “force of habit”- the force that keeps most buildings standing. While this paradigm has served us quite well with regard to technological development, it has done so at a considerable price that we are just now starting to pay. Entirely predictable events such as Deep Water Horizon, Hurricane Katrina and Enron point to a fragility/brittleness of an over constrained system. These events are not so much about being in the wrong place at the wrong time. It is more the case that our approach to engineering creates ever more complex systems whose state variables are often combinatorially in the wrong place and by increasing the overall entropy of the planet, the wrong time is all but certain to come along. The challenge then is to expand our mechanistic design principals so that the systems we create are inherently ductile from both a material science perspective and a complex systems perspective.

From the perspective of material science the ductility of a material is proportional to the area under the stress (force over area) vs. strain (ratio of the displacement to the original length) curve resulting from a standard tensile test conducted on a standard specimen. From a complexity science perspective the ductility of a system is not as clearly defined; at least in a way that is compatible with engineers mechanistic use of the term. This is central to overcoming the challenges Fenner et. al. [16] identified.

The proposal for discussion in this paper is that we can use informational theoretical concepts to calculate sustainability properties of ecosystems with respect to emergent entropic forces that are compatible with engineering design principles. This will allow for the rational inclusion of sustainability principles in system design and deployment.

Civil Engineering

Hurricane Katrina made landfall 50 miles SSE of New Orleans on August 29, 2005 as a Category 3 (down from the CAT 5 that it had grown to.) Although it actually missed New Orleans the reverberations of its impact are still felt today, 10 years later. It is well within the capabilities of modern engineering science to calculate (with reasonable accuracy) the magnitude and direction of the forces that need to be resisted in the likely event of a CAT 4-5 pouncing right on New Orleans. Similarly, the amount of energy needed to construct and deploy conventional systems (concrete/earthen barriers, pumps, pipes, electric grids etc.) to generate the necessary constraints to resist these forces is well within these computational capabilities. One difficulty is the need for these designs to be maintainable over timescales for which current designs methods offer little guidance (other than maxims like "rust never sleeps"); and cost is likely to be very high. As an alternate to this heavy handed approach (which has largely put us in this situation) we should consider the cost of developing engineered systems that compliment existing natural processes to rebuild and fortify the Delta.

To see how this might be done, let's to return to the original proposition of this case, which is to design a system to protect a coastal city like New Orleans from the devastating effects of direct landfall of a CAT 4-5 hurricane. Physics essentially requires that a certain amount of mass be placed in the path of the storm to absorb energy by momentum transfer (e.g. storm surges impacting sea walls) and heat transfer (i.e. act as a heat sink to extract thermal energy from the storm). As previously noted the energy cost for deploying conventional (in the sense that this is what we usually do) methods is a relatively straightforward calculation. There are of course numerous complications to this approach including the open question of: from where will this mass come and how will it be transported? An unconventional answer to this question that can be grounded in the methods described in this paper is: the Mississippi River system and Gravity respectively. The processes that comprise the Mississippi watershed ecosystem are the result of a millennia of calculation through which information has been processed and discarded resulting in entropy production as system states collapse and a complex, logically (and thermodynamically) deep system emerges. The resulting system, held together by the entropic forces generated through these information exchanges, has potential, like a coiled spring, to do the computations and work necessary for transporting the required mass to the Delta. The system of dams, dikes, levies and pipelines that currently constrain these processes in the service of commerce and industry have starved the delta of the raw materials from which its natural ecosystem can construct the necessary structures to resist the force of these large storms. These systems can be redesigned (or removed) to engage in a computational process to rebuild the Delta and dampen the impact of rising sea levels on coastal communities like New Orleans.

To see how the methods suggested in this paper can inform the redesign of these systems we focus on the materials from which these systems will be constructed. The structural materials and the processes for making them are well understood after decades of research. The relatively recent nexus of high performance computing and precision sensing has driven the development of processes through which structural systems can be effectively engineered from the nanoscale on up (not always economically or practically). Those calculations have been done and the detailed information of sub-scale mechanics have been course grained into process parameters that can reliably produce the large-scale behavior we desire. The complicated response of these multi-phase multi-scale materials is mediated through the exchange of information via mechanisms that can be modeled with multi-phase continuum mechanics (e.g. mass, momentum, energy and entropy supply terms). The framework that has been presented offers some intriguing clues as to how we might take advantage of the logical depth of these materials. For example we have previously discussed the role of ecosystem diversity (i.e. entropy) in maintaining function over extremely long time periods. As a purely hypothetical proposition, we could then design structures to "bridge" channels in the Delta that are constructed to be specifically multi-scale at the structural system level (e.g. on the scale of meters) and hierarchically multi-scale at the material level (i.e. microns to mm) so as to encourage natural processes that will ultimately take over the long term maintenance of the system function. This hierarchical approach to design can be specifically grounded in the information theoretical constructs previously described in order to provide an environment for the emergence of forces that encourage organic colonization, beneficial sediment transport and other sustainable process that can rebuild and maintain a boisterous Delta. At the larger scale, design of these systems could incorporate the impact of a particular design on system performance by superimposing the pipeline network on a GIS representation of the Delta. The entropic changes and associated gradients could be calculated based on, for example, satellite images and corresponding forces could be calculated to predict important system properties like sediment transport.

As previously noted natural systems (like the Delta ecosystem) have done experiments over millennia to arrive at processes that similarly course grain sub-scale mechanics into parameters that we can measure with the advent of multi-scale sensing and computation. What Verlinde, Maxwell and his demon slayers have shown is that we don't necessarily need the precise details of the mechanics through which these natural forces emerge. If we understand well the correlations between the information that we can measure (whether it is semantic like the text of a policy or numeric like the distribution of a species in a watershed) and the forces that emerge from these interactions; we can, in a deterministic way, create systems now that autonomously reproduce over time, the calculations needed to maintain desired function.

6. Summary

In summary let's return to the initial claim that we can store computational capacity in the abundant present for use in a computationally constrained future and summarize the main ideas that support the claim. Maxwell and the thermodynamics originalists made the earliest connections between heat and information transfer when they concluded that the temperature of a gas represents the average speed of the molecules comprising the gas as they exchange information related to their relative energy through the transfer of momentum during collisions imagined to be like perfectly elastic spheres. The concept of entropy was introduced to formally account for this information exchange and the attendant statistical nature of the information exchange. Conceptually this leads directly to the definition of pressure as an emergent force resulting from the entropy gradient produced by constraining the location of the gas with the walls of a container.

The statistical nature of these processes led many notable physicists to ponder the paradox of an intelligent being (Maxwell's Demon) that could extract useful work from a gas at uniform temperature through acquisition of knowledge of the relative speed of individual molecules; thus laying the foundations upon which Shannon built Information Theory. Bennett and others convincingly demonstrated that the Demons engine could not function without discarding information and producing enough entropy to avoid violating the Second Law of Thermodynamics. In the process they introduced the useful concept of logical depth (the amount of entropy produced through state transitions as systems evolve) to characterize complexity in dynamical systems. As these systems evolve some states persist while others die out to produce a complex network of emergent entropic forces. Verlinde has added to this an important perspective on the fundamental relationship between information exchange, entropy production and the emergence of Newton's gravitational law showing the deep connection between information and Newtonian mechanics. Importantly he has shown that this connection is agnostic as to the internal dynamics of a particular system and is only dependent upon course-grained information in the form of probability distributions describing the systems overall state.

By combining these ideas, a framework for describing the mechanics of how the evolution of complex socio-ecological systems like the watersheds of the Colorado and Mississippi rivers leads to forces that bind these systems together like the grains of sand are bound to produce glass. And like glass, these systems have wondrous and complex properties (e.g. transparency in glass) but are also vulnerable to catastrophic events that can shatter cohesion. It is through the relationship between information exchange and entropic forces that these systems store the capacity to produce the calculations necessary to persist and evolve. This framework also suggests approaches to engineering design that can produce the mechanistic solutions to problems rooted in deeply complex processes that have evolved over millennia and are now threatened by the pressures of a hotter more entropic future.

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