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Using Energy Network Science (ENS) to connect resilience with the larger story of systemic health and development

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Abstract

The concept of resilience has become popular in international development circles in recent years, but it is only one of many factors in a larger, integrated, empirical understanding of systemic health and development emerging from the study of energy-flow networks. This article explores how the Energy Network Sciences (ENS) can provide a robust theoretical foundation and effective quantitative measures for resilience and other characteristics that undergird systemic health and development in socio-economic networks. Einstein once said that “theory makes measurement possible.” We believe ENS can provide a more effective theory of economic health, which will open the door to surprisingly precise measures. Our goal is to outline the basic reasoning behind both theory and measures.

How ENS illuminates universal laws and optimal patterns of systemic health

In her 2000 book *The Nature of Economies*, Jane Jacobs suggested that economies are governed by the same rules as nature itself. Jacobs’ actual hypothesis was that living organisms, ecosystems and economies are all types of *energy-flow networks*, and that similar principles of growth and development apply to them all. This thesis was based on empirical research into flow networks, meaning systems whose existence arises from and depends on circulating matter, energy, resources, or information throughout the entirety of their being. Your body, for example, is an integrated network of cells kept healthy by the circulation of nutrients and information. Ecosystems are invisibly connected webs of plants and animals that add to and draw from flows of oxygen, carbon, etc. Economies are networks of interlinked people, communities, businesses and governments that contribute to and draw sustenance from the circulation of goods, services, resources, information, and money (Fig. 1).

Note: Because different systems have different needs, the phrase “energy flow” is merely a placeholder for any kind of flow that matters to the particular system under study. Ecologists, for example, study the flow of carbon and oxygen in the biosphere, while economists study the flow of money, information and resources in economies.

The study of flow networks is often equated with ecosystems or living systems, but the real root metaphor is of metabolic networks[1]. Here, economic networks serve as a society's metabolism: they turn resources and information into the energy and products a society needs to thrive, while constantly distributing these products via a mutually-nourishing, circulatory flow. Here, money is like blood, a vehicle for catalyzing processes, exchanging resources and nourishing economic muscle.

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Fig. 1: An economy, the biosphere and metabolism as flow networks

Where classical economics focused on equilibrium theory, today's expanded energy research studies the behavior of flow networks, systems built around circulating matter, energy and information throughout their entire being.

This simple view of economic processing shifts our focus of *what* makes economies healthy economies from GDP growth to *human networks themselves*. Right now economists tend to view people and the environment as fuel for economic machines that are designed to create monetary profit for owners in a way that grows GDP, but often undermines the health of human networks. ENS says this view is exactly upside down. The flow of money, information and resources should fuel economic networks that support the health and development of human beings and the productive capacity of their networks. Profit-making is part of this but not the central focus.

The study of flow simplifies the study of vitality in such networks by providing a logical basis for systemic behavior. Furthermore, this logic holds regardless of whether the flow-network under study is an economy, an ecosystem or a living organism. For instance, in all the above systems, poor circulation or excessive damage to any part of the circuit will be deadly to the system as a whole because all parts of a flow network depend on robust circulation. In economies, this means that poor monetary-circulation to lower levels of an economy – low wages, few small-scale commercial loans, etc. – results in *economic necrosis*, the dying off of large swaths of economic tissue. As with living organisms, if such necrosis goes on too long, the entire economy may collapse along with the undernourished parts.

Where ecologists taught us to see the biosphere as a web of circuits through whose veins resources like oxygen transverse the globe, the broader science of energy networks explains why similar images apply to living, nonliving and supra-living networks such as economies as well. As Fig. 2 shows, the study of flow makes measurement relatively straightforward because most critical characteristics can be measured by counting the number, diversity and size of nodes and channels, and by mapping the magnitudes of flows and the layout of where they go.

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Fig. 2: Using flow volumes to measure resilience, systemic efficiency

and sustainability

Please note that there is no commonly accepted measure of resilience. This is just one approach.

While ecologists are most famous for using flow-network methods, related research is taking place in many disciplines and under a wide variety of titles[3]. While all such research falls under the related rubrics of systems, networks and complexity, the most rigorous approaches use energy principles (thermodynamics) to explore the rules the cosmos uses to develop healthy networks.

Hence, we use the umbrella term Energy Network Sciences (ENS) to describe all those disciplines that use *energy networks and nature's designs to illuminate universal laws and optimal patterns of health and development*.[4]

Energy Networks: Thermodynamics provides a logical basis for a rigorous, transdisciplinary science because energy principles are known to be both universal and empirical. Energy fuels organization, drives development and creates pressure for change. Because such principles are universal and empirical, they explain why rigorous findings apply as much to economic networks[2,3,4] as to ecosystems[5,6].

Nature's Designs: Scientists have been studying the universal patterns that fill our world for at least 3000 years (Fig. 3). Calling them sacred geometries, the ancient Greeks identified mathematically precise "Golden ratios" like phi over 2500 years ago. In 1490 AD Leonardo da Vinci used these geometries in his Vitruvian Man, and in 1917 Darcy Thompson[7] used them to show why common shapes seen in living and nonliving systems come from physical processes.

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Fig. 3: Sacred Geometries

Mathematically-precise patterns found in complex systems

Today most researchers believe such patterns exist because they support some aspect of systemic health. Lungs, for instance, have a branching structure – with a few, highly-efficient, big conduits on top and successively more numerous, less efficient, smaller conduits on the bottom – because this particular structure optimizes the diffusion of oxygen into the bloodstream. Nowadays we call this pattern a fractal and use new mathematical methods to measure them precisely. Because fractal patterns help optimize many forms of function and flow, they are found in everything from leaves to river deltas.

Because fractals and other universal patterns are measurable and indicate some aspect of systemic health, we can use them to create precise targets for various aspects of health. So, though ENS cannot predict each step of the system, it can predict systemic health by measuring how closely a network approximates the optimal structures seen in the real world. For instance, Nikos Salingaros[8] describes how fractal designs in cities help catalyze critical city processes at multiple scales thereby increasing innovation, empowerment and community cohesion. (Figures 4 and 5; See also Christopher Alexander's *Pattern Language*.)

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Fig. 4: Fractals as Snowflake Science: Unique, universal and measurable

Fractal patterns are particularly apropos of human realities because, like snowflakes, they are both universal and infinitely unique. For example, all trees and lightning bolts have a fractal branching pattern despite the fact that no two trees or lightning bolts are ever exactly the same. The resulting snowflake structures explain why each kind, level and individual manifestation of a system exhibits certain unique properties, while also following certain universal patterns and principles. We can still use these patterns to measure and diagnose health because, as Mandelbrot [9] *and others have demonstrated, underneath uniqueness, the fractal structure of things like trees, lungs and cotton prices on the stock market tell us a great deal about leverage points, breakpoints, and the system's underlying robustness and health.*

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Fig. 5: Fractal designs catalyze processes & optimize flow across all scales

The impossible dream: Predictive theory and precise measures for the social sciences

Fractals provide a concrete example of how we can use energy principles and nature's optimal designs to illuminate *measurable* laws and patterns of health and development, which apply as much to social systems as to ecosystems. Today's researchers are making great strides unveiling these laws and patterns for three main reasons:

- Computers make it possible to organize and explore the data;
- The optimal patterns of organization in complex systems are measurable; and
- Advances in energy theory explain how and why such organization emerges and develops.

This exciting possibility of effective empirical methods for the social sciences, however, has not yet registered on the mainstream mind. We suspect this is largely due to the siloed nature of most academic disciplines and the fog of semantic confusion emerging from various attempts to popularize this work. The concept of resilience provides an example of both these issues.

While the concept of resilience – defined broadly as the capacity to "spring back" – is a relative newcomer to the field of international development, it has a long history in fields as diverse as psychology and engineering. This diversity has naturally blossomed into a variety of definitions and measures of the concept, both within and across disciplines. ENS disciplines, for example, variously define resilience as: a system's ability to tolerate disturbance and reorganize while retaining its function, structure and identity[10],[11], or to adaptively change organizational patterns and learn[12],[13]. In a similar vein, USAID defines resilience as:

> The ability of people, households, communities, countries and systems to mitigate, adapt to, and recover from shocks and stresses in a manner that reduces chronic vulnerability and facilitates inclusive growth.[5]

The USAID definition bears a strong resemblance to ENS definitions because much of resilience's current popularity can be traced back to the Resilience Project, a 5-year interdisciplinary collaboration sponsored by the MacArthur Foundation based primarily on an energy-network analysis of ecosystems. The Resilience Project eventually became the Resilience Alliance, which uses resilience as a unifying hub for all ENS work, and uses the term Panarchy to describe the science itself.

In this way, the field of Resilience is a direct descendant of ENS research in ecosystems. Resilience folks just use different language and have expanded the concept of resilience into a unifying theme. Thus, according to Greg Guest[14], the real excitement about what he calls "the resilience paradigm" comes from belief that it has the potential to provide:

- A unifying, explanatory framework for systemic health and development;
- A powerful set of diagnostic tools and quantitative measures for exploring and assessing issues of resilience, development and systemic health;
- An effective interdisciplinary bridge that connects researchers, practitioners and theorists and helps coordinate knowledge, interventions, and practice.

Ironically, while most ENS researchers see the characteristic of resilience as but one aspect of systemic health, the above list aptly describes the paradigm towards which all ENS disciplines are heading. In fact, a great deal of subtly-connected work is part of a profound shift in scientific vision and abilities that is beginning to fulfill a seemingly impossible dream — the development of predictive theory and precise measures that are effective on human networks including cities, economies and societies. Since the promises of this paradigm are monumental, let me take a moment to provide a little background for why they might come true.

The quest to find effective ways to understand why human systems behave as they do is, of course, ancient. In his seminal 1948 *Scientific American* paper, "Science and Complexity," mathematician Warren Weaver spurred a major 20th-century push to develop more effective *methods* for exploring the human condition by redefining human systems as forms of "*organized complexity*," and then showing why *neither* of science's two mainstay methods – statistics and determinism – were appropriate for such systems.

Weaver explained that precise equations of motion (determinism) work well on “simple systems,” ones dominated by single, main-effects, like the sun’s massive influence on a much smaller planet. Statistics, in turn, works well on what Weaver called “disorganized complexity,” systems with many, disconnected components and loosely-coupled variables.

Weaver noted however that many real-world problems — including those in human systems — involve, “a sizable number of factors which are interrelated into an organic whole.” He called systems built around such interrelated causality, “organized complexity” because they exhibit universal patterns of organization like those studied by the ancient Greeks. For instance, despite their apparent internal chaos, pictures of hurricanes from above show they form a neat spiral swirl — which happens to be a geometrically-identical to spirals seen from the Milky Way to an unfolding fern (Fig. 3).

Weaver’s description of *organization* emerges from *tightly-coupled*, *highly-interrelated* wholes —radically revised the standard picture of scientific methods. As Fig. 6 shows, instead of determinism and statistics being our only choices, we now see that these two traditional methodologies are only appropriate for certain types of simple and disorganized systems. The systems we care most about — ecosystems, living systems and human systems — form a broad, middle-range case now made scientifically-approachable by the fact that their complexity is highly organized — measurably so.

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Fig. 6: Organized complexity fills science’s massive missing middle

Weaver argued that understanding today’s world would require a “3rd Great Advance,” a drive to develop effective methods for studying organized complexity. The several next sections provide several examples of how this push is making progress by using energy principles and optimal designs to understand and measure various aspects of systemic health. We begin with measuring resilience and understanding why it must be balanced with efficiency.

Rediscovering the importance of balance while making resilience measurable

Weaver’s description of organization arising from interrelated-causality influenced thinkers from Frederick Hayek’s concept of “spontaneous order of free markets” to Jane Jacobs’ framing of “the kind of problem a city is” in her classic work, *Death and Life of the Great American Cities* (1961). It comes down to us today in fields from meteorology and ecology to cybernetics and urban planning.

Yet, while most economists believe an invisible, ordering hand is at work in free-market economies, most missed Weaver’s core message that this order comes from *interrelated causality* not from *disconnected* agents working solely for their own self-interest. The fact that the invisible hand of order depends largely on *the structure of our relationships* dramatically changes our vision of what makes economies healthy.

At the same time, as we’ve seen, nature’s optimal patterns can provide precise targets for systemic health to guide our understanding. For example, a fractal (power law) balance of small, medium and large conduits is seen in systems as diverse as lungs, lightning bolts, river deltas and the human circulatory system because it helps optimize cross-scale circulation, which in turn improves systemic health and makes the system more likely to be selected. Big, efficient elements (arteries or multinationals) provide the high-volume and speed needed for rapid, cross-level circulation, while the many small elements (capillaries or local contractors) reach every unique nook and cranny. (Fig. 4)

Theoretical ecologist Robert Ulanowicz and his colleagues[15] used the balance of small, medium and large organisms found in nature to identify the optimal balance resilience and efficiency found in healthy systems. In the process, he showed empirically why today's emphasis on increasing efficiency and size is useful *up to a point*, beyond which it is destructive to the economy as a whole.

While there are as yet no commonly-accepted measures of resilience, most researchers agree that the ability to "spring back" depends upon factors such as flexibility, diversity, small size, dense connectivity and multiple options. Ulanowicz noticed that such resilience factors were in opposition to factors which contribute to efficiency, such as streamlining, large size and high capacity. Since efficiency and resilience are both important to systemic health, the inevitable trade-offs between the two means that healthy systems must maintain a proper balance of both.

Ulanowicz[16] demonstrated that actual ecosystems maintain a balance of factors which contribute to *resilience* and those which contribute to *efficiency*. Ulanowicz, *et al*.[17] then used data from these highly-functioning ecosystems and information theoretic measures to identify the range of balance, the "Window of Vitality," within which all healthy systems fell. This range delimits the optimal range of network health/sustainability (Fig. 7).

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Fig. 7: Measuring network health using the balance of resilience and efficiency

Healthy systems maintain a balance of resilience factors (small, diverse, flexible & densely connected) and efficiency factors (big, streamlined & powerful) within a Window of Vitality representing optimal network health.

This work suggests that, because efficiency and resilience are both critical but run in opposite directions, too much or too little of either sets of factors can cause problems. So, while more diversity generally means more resilience, too much diversity creates low-efficiency stagnation. The problem with too much diversity can be seen in a meeting with 20 different people with 20 different opinions where nothing gets done because no one can come to agreement on anything. Conversely, while streamlining and large size generally increase efficiency, too much of either creates brittleness (low resilience) and instability that can lead to collapse.

In other words, this work suggests *resilience is necessary, but not sufficient*. Economies need diversity of options (resilience) to provide choice, competition and fallback options in case a main industry should fail, but economies built almost solely of diverse, small-scale businesses tend toward stagnation because they lack the efficiency, focus and power to generate robust flow.

Similarly, *efficiency is also necessary, but not sufficient*. As we discuss later, economies built primarily of extremely large, highly efficient organizations tend toward concentration, brittleness and loss of resilience because such organizations tend to create "positive feedback cycles", a powerful pull that drains money and resources from the smaller organizations, thus eliminating diversity and making the system more fragile.

The shocking idea that too much efficiency can lead to brittleness led Lietaer, *et al*.[17],[18] to use this work to suggest that the excessive emphasis on efficiency and large size in banking and business contributes to systemic banking and economic crises respectively. Goerner, *et al*.[19] used it to explore implications for free-enterprise theory, policy and practice.

Veronica Letelier[20] used the dangers of excessive efficiency to explain the negative effects increasing the efficiency of quinoa production had on local communities. Quinoa had been a key staple in Andean countries for centuries where its high protein content supported the nutritional well-being of farmers and local communities. Small farmers raising the crop in small plots kept the price affordable to most poor communities. When an early donor decided to invest in this crop, the initial idea was to increase productivity (efficiency) so that smallholder farmers could increase their incomes. And, indeed, once quinoa became better known in international markets, its high protein content rapidly made it popular among health-conscious buyers in developed countries. This increased demand, however, spurred land grabs and large investors seeking to export the crop to meet international market demand. Eventually increasing efficiency resulted in small farmers being driven out of business; the crop being raised by large conglomerates for export markets; land/resources being used in unsustainable ways; and local quinoa prices becoming unaffordable for poor farmers. As Letelier writes:

> Seeing the quinoa value-chain as linear, focused on bringing in investments to increase productivity/efficiency, ended up harming local communities and farmers, and making the "quinoa system" less resilient. Looking at quinoa not merely as a crop, but as part of a larger network of flows that push and pull each other can help change this. If we had examined all the nodes and flows involved in producing the quinoa — farmers, processors, marketers and business development to credit suppliers *and* the local social networks that were directly affected by growing and consuming this crop — the interventions we made at key nodes might have been able to assure that the quinoa production process developed in a more resilient and mutually beneficial way.

An imbalance towards the big and efficient is particularly dangerous because it generates a positive feedback cycle, a powerful upward pull that drains resources away from the smaller organizations, eliminating diversity and making the system more fragile and vulnerable to collapse. So, while economies dominated by small-scale diversity tend toward stagnation, those dominated by a few extremely large and powerful organizations tend toward instability because the upward pull causes *economic necrosis*, the dying off of large swaths of economic tissue due to weak or lost circulation.

The destructive effects of this upward can be seen the "Walmart Effect", the erosion of local economic networks caused by the overfeeding of giant corporations. Local development officials hoping to bring jobs, taxes and, in Wal-Mart's case, lower prices to town, use taxpayer monies to lure giant organizations like Wal-Mart into town with various forms of subsidies. However, these subsidies plus the giant's existing size allows it to undercut and drive smaller competitors out of business. Local vitality declines as local businesses go out of business and good jobs are replaced with low-paying ones. Lost wages causes demand to fall in the local economy, and less money circulates locally because the giant is funneling money to distant headquarters. Once its smaller competitors are out of business, the giant usually raises its prices to exploit its monopolistic dominance. Meanwhile, taxes go up because the tax base shrinks and because the welfare and healthcare costs shouldered by the local jurisdiction rise as well. In the end, the giant is likely to move to another town when it gets a better lure.

In short, Window of Vitality suggests that many of today's economic problems result from exaggerated ideas about how economies work best by maximizing efficiency, size and profits going to the top, while ignoring harm to the more diverse, more resilient lower levels of the economy. At the same time, the Window also suggests that the solution to our problems does not lie solely in grassroots, "local only" efforts or in resilience factors such as diversity *per se*, but in a proper integration of all levels and factors.

The Goldilocks Rule (Fig. 8) — the idea that each scale needs organizations that are "just right" to meet the needs of the actors and activity at that scale — clarifies why such integration is critical. A corollary to fractal balance, the Goldilocks rule means that, just as ecosystems need fine-grained wetlands to buffer against floods and cities need a proper balance of small, medium, and large pathways to catalyze critical processes at each scale, so proper funding of commercial organizations at each scale requires a proper mix of small, medium and large *banks* because small-scale needs are uneconomic for big banks to handle.

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Fig. 8: The Goldilocks Rule in banking

Energy Theory and Methods for Economics

So, optimal patterns and universal principles such as circulation and positive feedback explain why economies need to maintain a proper balance of diversity & streamlining, flexibility & constraint; resilience & efficiency; and small, medium, and large institutions. The next several sections explore some additional economic applications of today's expanded energy-flow understandings.

Self-feeding return loops: Designing systems to live long and prosper

The most basic characteristic of health — *the ability to endure for long periods of time* — is largely the result of "self-feeding return loops," meaning inputs and outflows that continually channel flow back into maintaining the capacities and processes that support its existence.

So, while many flow-systems, such as tornadoes and lightning bolts, rise up only briefly to diffuse an energy buildup, the systems we care most about – living organisms, ecosystems, and societies – are designed to constantly channel energy into nourishing their internal workings. Your metabolism, for example, is designed to turn the food you eat into the energy you need to maintain your own existence. The circulation of carbon and oxygen in the biosphere similarly serves to maintain the health of plants and animals (Fig. 9).

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Fig. 9: Self-feeding return loops in the biosphere and an economy

Self-feeding return loops mean that the best way to live long and prosper is to channel as many flows as possible back into maintaining productive internal capacities and processes including businesses, schools, roads, utilities, energy, information, healthcare etc. It also suggests that many current economic practices — such as minimizing wages and applying austerity to public services — work against long-term vitality.

Self-feeding arrangements also confirm the basic sustainability rule that systems which want to continue for long periods must maintain *reliable inputs* to fuel local processes and *healthy outputs* that don't destroy other parts of the human or environmental network.

Finding ways to turn waste into constructive products and channeling them back into building local capacities makes a perfect example of how healthy outputs and reliable inputs can be combined. For instance, Frostburg Grows[7], an economic strengthening project in Appalachia, uses local organic waste-matter — yard, cafeteria waste, etc. — that now costs $45 per ton to be dumped into the land fill -to create composting enterprise that turns this waste into soil and soil-improving additives such as organic fertilizer. These products are both exported and also used to grow local food and native trees which also contribute to local sales. The resulting network of environmentally-sound, mutually-reinforcing enterprises increase local jobs, money circulation, resilience and 'durability' all at the same time.

Capacities, circuits, and the ability to do work

The image of economies as metabolic networks which convert resources and information into the products and energy a society needs to thrive, also suggests several other key aspects of health:

- ***Capacities***: Because, as Ben Cohen founder of Ben & Jerry's Ice Cream puts it, economies are "organized systems of human effort that produce *work*," metabolic vitality begins with *capacities*, or as Amartya Sen [21] puts it, have, "the ability to transform resources into valuable activities." Economic capacities must include all forms of "capital," including human, social, cultural, intellectual, financial, spiritual, material and environmental.
- ***Circuits***: For a metabolism to work, capacities must be connected in circuits that support both processing and circulation. The core economic circuit is the one formed by workers and business. Workers get money to buy goods, and businesses get workers that produce and buy their products. Like all good circuits, both sides flourish when they work together, and both sides suffer if either side of the circuit is damaged.
- ***Circulation***: Robust cross scale circulation is critical because economic metabolisms only work when all their internal parts and processes are well-nourished and highly developed.

In *The Nature of Economies*, Jacobs[22] notes that economic vitality depends on the number and diversity of circuits and capacities because: “The more different means a system possesses for recapturing, using and passing around energy before its discharge from the system, the larger are the cumulative consequences of the energy it receives.” Allenby and Richards 23 use this observation to create a typology of network durability based on how many flows are rechanneled inward.

In this typology, an Appalachia coal town that survives primarily on outside organizations extracting resources exemplifies a “through-flow” network (Type I), one with such poor internal recirculation that it has little capacity to maintain its own long-term health beyond the extraction process. In contrast, New York City’s meshwork of mutually-reinforcing businesses and abundant capacities exemplifies the power of self-sustaining economic engines to draw in flows and channel them into ever-expanding internal vitality (Fig. 10).

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Fig. 10: Network durability: Through-flow, recirculation, and self-sustaining systems

*Allenby and Richards*23 *categorize network durability/sustainability using the degree of through-flow vs. internal recycling of inputs and outputs. The more internal circulation and circuitry a system has, the greater its efficiency, resilience, durability and self-sustainability*.

While supporting schools and roads is the most obvious ways to build internal capacities, Jacobs’s24 exploration of “import substitution” extends the concept to business networks in general by showing how gradually replacing imports with locally-created substitutes can recapture outward monetary flows and channel them back into internal regenerative processes. Using the example of how the Japanese auto industry grew out of import substitution of hard to find bicycle parts following World War II, Jacobs describes how substitution gradually builds networks as follows. Since bicycles were scarce but in demand, some local entrepreneurs learned to repair bikes. Next, some repair shops learned to make certain parts and some began assembling whole bikes from local parts. Eventually, some learned to add motors to the bicycles (motorcycles) — automobile manufacturing followed on the heels of motorcycles. At each step of the process, the local network not only built more circuits, it also developed more capacities such as local expertise, infrastructure and a network of trusted relationships that allowed them to “transform resources into valuable activities.”

Intricacy: Growing strong, fast, flexible social fabric

Seen in the way embryos develop, a universal pattern we call “intricacy” creates a concrete picture of how nature builds systems that are strong, fast and flexible at the same time.

Intricacy refers to the lace like networks of small, interconnected, synergetic circles that the cosmos uses to weave smaller elements into larger wholes. Molecules are built of atoms which are built of subatomic particles. Your body is built of organs and tissues that are built of individual cells. Armies are built of divisions, regiments, brigades and platoons. This pattern is common because the organizational fabric arranged this way is strong, fast and resilient at the same time. The basic rubric is “small and connected = strength and speed.”

Scientists attribute this developmental pattern to an energy rule called the Surface Volume Law. Seen in the way embryo develops from a single cell, this law says that, as a system grows, the bonds holding it together becomes stretched until they reach a literal breaking point. At this point, the flow-structure must find a way to restore small, tight circles and link them synergistically or risk fragmentation and collapse (Fig. 11).

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Fig. 11: Increasing intricacy and development in an embryo and an economy

The same intricacy seen in a growing embryo also clarifies the difference between a bubble, with weak internal structure and poor circulation, and an intricate economic network with robust internal circulation.

Happening over and over again, this pattern of development explains why everywhere you look, big things are built of intricately-entwined smaller things. It also explains differentiation. As the embryo’s cells grow, divide and reconnect, they slowly change from clumps of undifferentiated cells to differentiated organs and integrated organ systems naturally arrange to circulate energy, information and resources throughout the entirety of its being.

This fine-grained weave is ubiquitous because it creates an organizational fabric that is strong, fast, resilient and flexible at the same time. Small tight teams work better than big bulky ones, but linking small, teams in a close, synergistic weave works best of all because they have the combined benefits of size, distributed intelligence and rapid, effective action.

Charles Sabel’s[25] descriptions of flexible manufacturing networks “in the innumerable small firms in the great cluster of small industrial cities in north-eastern Italy” shows the power of human intricacy – systems of small, synergetic, interconnected businesses and individuals – in circulating ideas, meeting needs and creating innovative services and well-being for its members. Also seen in similar clusters from Silicon Valley in the US to Asian motors in Japan such networks achieve both rapid innovation and tremendous economies of scale, not within the framework of huge organizations as conventionally assumed, but through symbiotic networks of small enterprises, most with but 5 to 50 workers a few with 100 to 200.

Epitomizing the idea that ‘small & connected = strength & speed,’ these small, cooperative, enterprises produce very sophisticated, high quality work while simultaneously supporting the kind of community resilience not seen in massive corporations. Innovation is high because improvisation is a central theme. Quality is high because craftsmanship is still important. Craftsmanship is important and well-being is well-distributed because human ties still bind. Hence, here people pursue quality and integrity, as well as profit.

Quality and creativity are also high because workers and ideas circulate. Such circulation builds expertise, breadth of experience and an invisible chain of valued human connections. Breakaway enterprises spring up easily and often as workers from older enterprises move out to start firms of their own. Such spin-offs often collaborate with the older establishments because they share history and have related work. People, information and expertise cycle easily, and members prosper in a synergetic way (not zero-sum) because advances anywhere tend to stimulate benefits everywhere. Goerner, *et al*.[26] describes such human intricacy as:

> Intricate webs of human expertise, material infrastructure, behavioral patterns, and cultural systems that have grown up together such that all elements play mutually-supportive roles in the well-being of all members and the long-term health of the social, economic and environmental whole.

Intricacy validates with the recent push to develop fine-grained local networks by increasing small-scale circulation and funding. The Grameen bank, for example, increases the success of its borrowers and its loans by organizing its borrowers into loan circles that provided mutual support, basic training in business and ethics, seed capital, etc. Stacy Mitchell of the Institute for Local Self-Reliance[8] encourages independent businesses to band together to create purchasing and marketing cooperatives, with a common system for e-commerce and collective strategies for incentivizing local shopping.

More recently, *re*organizing efforts are attempting to restore networks that have collapsed by reconnecting and nourishing now dormant capacities. Cotton of the Carolinas, for example, is rebuilding an organic version of the textile industry in North Carolina by harnessing dormant capacities in the textile value-chain, now with an organic bent: (organic) cotton farmers, weavers, (non-toxic) dye companies, tee-shirt manufacturers, etc. Similar attempts are being made to harness existing capacities to restore industries decimated by policies such as NAFTA from boat-building and furniture-making to steel-making.

From an energy perspective, nature prefers intricate arrangements because they increase the *speed and thoroughness of internal circulation* while maintaining network strength and flexibility. Thus, small, tight cells circulate energy rapidly, while close-knit connections expand the area reached. The resulting fast, flexible social fabric enhances network health by providing rapid, thorough distribution of all the things we need – money, resources, information, etc.

Physicist Eric Chaisson27 uses the relationship between intricacy and internal circulation to measure development itself. Internal circulation corresponds to increasing "development" because each increase in intricacy is accompanied by an increase in internal circulation. Figures 12 and 13 show how Chaisson's measure of internal circulation speed, flux density, corresponds to developmental stages in ecosystems and human economies respectively.

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Fig. 12: Succession of in ecosystems

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Fig. 13: Succession in Economic Systems

In both ecosystems and human systems, increasing complexity and development are accompanied by increasing speed of internal circulation which can be measured using Flux Density (F = ergs/sec^{-1} *gm*$^{-1}$*).*

The connection between development and internal circulation explains why existing measures of internal circulation such as the Multiplier Effect can help assess systemic health. The Multiplier Effect tracks how much money circulates *within* the local economy, as opposed to being channeled away to a distant region where it is less likely to create local jobs or purchasing power. The idea is that, when companies source work or materials locally, they stimulate local businesses, which are themselves more likely to spend a portion of that money locally. In this way, locally-sourced purchases *multiply* the local circulation and the local benefits of money because money is spent multiple times locally — a process which increases local jobs and purchasing power.

Such measures suggest that intricately-woven networks that circulate money robustly within the local economy are better for local economic health than corporate giants who siphon money off to distant headquarters. A 2003 study of Midcoast Maine[10], for example, showed that local businesses spent 54% of their revenue within Maine (on professional services, wages, goods, etc.), while big-box retailers returned just 14.1% of their revenue, mostly in the form of payroll. A 2002 study[11] in Austin, Texas, similarly showed that for every $100 local consumers spent at a national bookstore, the local economy received only $13, whereas the same amount spent at local bookstores yielded $45.

Healthy hierarchies: Why healthy systems require coordination from the top to

Still, while intricacy is important, hierarchical structures that coordinate, facilitate and maintain unity across scales are also critical for groups beyond a certain size.

In an ENS view, hierarchies were most likely driven into being by the same process of growing apart and needing to stay connected seen in the development of intricacy. So, while small, circles can grow horizontally for some time, eventually the bonds holding groups together break, individuals and groups become disconnected, and communication, efficiency and unity breakdown down. The ensuing unity problems create powerful make-or-break pressures. Some systems collapse; some find a niche and cease to grow; and some develop innovative ways to say whole. Nervous systems serve this connective purpose in biological organisms, while media, government and organizational hierarchies do the same in human networks.

Fig. 14 shows how this need to stay connected drove the development of a hierarchical (fractal) structures in the nervous system and human societies, here serving as form of connective tissue that supported the communication and coordination across increasingly vast, unwieldy and disjoint wholes. The Occupy movement exemplifies how problems of communication, coordination and focus plague large groups attempting to use a flat organizational structure.

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Fig. 14: How the need to stay connected drove the evolution of nerves

& civilization

So, while many activists call for localism and flat organizational structures, from an ENS perspective, hierarchies are ubiquitous because they too play a critical role. Still, unlike the exploitative hierarchies often found in human organizations today, nature invariably evolves servant hierarchies with highly-distributed intelligence and empowerment. There are two main reasons for this. First, complex systems like your body are too complex to be run from the top down. Instead, nature operates on the “subsidiarity principle,” that is, decisions are made at the lowest level possible because that is where they are most appropriate. Secondly, because flow networks are circulation systems, everyone’s health depends on the health of the whole including all its parts. In such systems, fitness depends on people acting in ways that serve the health of the whole, as well as themselves.

In sum, hierarchies are absolutely essential to societies beyond a certain size, but if not properly balanced and focused, they can do more harm than good. Here too, the challenge of health lies in effective integration of top & bottom, local & global with equitable distribution and thorough circulation for all.

Self-organization: Succession, S-curve cycles, and quantitative measures of development

Perhaps the most important of today’s expanded understandings, self-organization theory provides an energy-driven explanation of cycles of development and the long observed evolutionary movement towards increasing levels of complexity and intelligence. As its discoverer Illya Prigogine[28] puts it, self-organization illuminates the process of “*becoming*” not just “*being*.” Seen in everything from boiling water to stages of societal development, self-organization occurs when: 1) energy build-ups (gradients/demand) that create pressure for change; 2) link up with naturally-occurring *diversity* — say an innovative idea or invention capable of solving a critical problem that serve as seed crystals of new ways; and, 3) open a new pathway for more effective flow (Fig. 15)

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Fig. 15: Self-organization and S-curve development

Energy’s penchant for driving recurring cycles of development can be seen in the process of boiling water: 1) ***Pressure:*** *adding heat drives water molecules to move faster and faster until they literally cannot go any faster in the pattern of random collisions. 2)* ***Opportunity:*** *Once this limit is reached, continued pressure makes the system unstable and ripe for change. 3)* ***Diversity serves as seed crystals for new ways:*** *Little pockets of relatively hot molecules that have been coming together and moving apart all along, have a new effect. Because hot molecules are lighter and more buoyant than their cooler surroundings, they form bubbles that begin to float upward. 4)* ***A new pattern of organization emerges:*** *Eventually, one pocket rises all the way to the top; loses its heat; and sinks back down pulling other molecules in its wake. The system “self-organizes” into circular rolls. 5)* ***On-going cycles of development follow an S-shaped curve:*** *If the pressure (heat) continues, the process will repeat. The new pattern moves energy faster, which causes the circular rolls to grow. Heat pushes the new rolls to move faster until they too reach their limit. Instability sets in again; new bits of diversity seed a new pattern; and the system reorganizes into a yet faster pattern, something like a figure ‘8’. 6)* ***Success is not guaranteed:*** *if any of the above factors — pressure, opportunity or diversity — is missing, then* *the system will not self-organize into a more effective pattern. Super-purified fluids show what happens if the pressure is on but diversity is missing. Having removed all impurities, super-purified fluids don't reorganize under pressure; they explode because a better flow-path never opens up. The human equivalent is societal collapse*.

Self-organizing processes repeating at all levels provide an energy-driven explanation of the long-observed *succession* of increasingly complex forms. In ecosystems, succession is seen as the progression from grasslands to pine forests to oak forests. In business, it is seen in organizational stages as companies grow from 10 to 50 to 150 to 500 employees. In human organizations, it is seen in the succession from foraging hominids to the information age.

Gunderson and Holling[29] use the S-curve cycle of self-organization to outline a four-stage Adaptive Cycle seen in human and natural systems (Fig. 16). Table 1 describes each stage and the problems commonly encountered entering and exiting it.

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Fig. 16: Holling's adaptive cycle

Table 1.

The Adaptive Cycle (after [34])

Description of Stage	Problems Entering the Stage	Problems Inside the Stage
a-FORMATION /TRANSFORMATION A new system emerges or an existing system reorganizes & renews itself.	A sense of impotence or victimization from last stage blocks the need to come together.	Lack of direction; inability to find a new orientation
r-PIONEER New organization takes shape and grows rapidly by tapping into readily available energy.	Insufficient innovation or activation energy (the poverty trap); inadequate organizational scaling	Relentless resource acquisition (overshoot)
K-MATURITY New organization is well established and resources are locked up; change occurs more slowly	Lack of sufficiently complex internal structure: inadequate diversity, organization and/or connectivity.	Maintain status quo by cannibalizing productive process.

Description of Stage	Problems Entering the Stage	Problems Inside the Stage
O-CLIMAX, DECLINE & RELEASE. Limits are reached, boundaries become fragile & energies are released; Innovation is more possible but may be lost in the struggle to survive.	Subsidizing and buttressing rigid, out of touch systems makes progress difficult.	Rigidity trap, loss of connection to outside; Inability to innovate or let go.

Business provides a familiar example of the adaptive cycle. *In the formation phase*, some bit of diversity links up with pressure (an energy buildup) in the environment to power the emergence of a new organization or the reorganization of an existing one. In the business world, if a new invention taps unmet demand and manages to create a “whole path” — a circuit that aligns people to develop, produce, market, distribute, etc. the new product — then economic energy will pour into that organization, making it grow.

In the Pioneer stage, innovators reap the rapid-growth rewards of previously untapped demand. But, as the system matures, established structures become entrenched, markets become saturated, growth slows, and focus changes to increasing efficiency and new variations on old cash-cow themes. Increasing efficiency, however, increases the system’s rigidity and revolutionary change becomes increasingly difficult.

Eventually, the organization reaches its climax point (limits) and faces a choice: cling to old ways and decline, or release resources and open the door to a new revolutionary transformation. You can see this pressure for transformation in the fossil fuel industry today. Over the last 300 years, Western civilization has moved from wood to coal to oil and is now facing pressure for highly-distributed clean, green renewables to power the accelerating development of the information age. No matter how much it tries to hold on to its climax control, the fossil fuel industry cannot avoid the choice of decline or transform any more than medieval Europe could avoid the crisis that came from consuming all their forests. Especially when it comes to energy sources, the choice is always adapt or die.

Succession and the Adaptive Cycle teach us to appreciate context, timing, pressures and an individual or organization’s place a developmental progression. Furthermore, while the rules of network development are universal, each network is nevertheless unique. This means developing self-sustaining individuals, organizations and networks takes time, creativity, appreciation of place, and lots of local involvement at every level.

Human factors: Reciprocity, inclusive growth, stewardship and common cause

The metabolic story of health and development emerging from of ENS is at once practical, logical and measurable. In stark contrast to neoliberalism’s prized “amorality,” it also validates many of the moral foundations and human factors essential to economic health that many of today’s economic reformers are seeking to restore. The paradoxical result is that, while ENS’ approach is new, its picture of healthy relationships and culture is ancient.

For example, as mentioned, *fitness* in flow networks depends on most people behaving in ways that serve the health of the whole as well as the health of the individual. This type of fitness rediscovers the concepts of stewardship and common cause, and extends them from environmental protection to maintaining the health of all levels our societal and economic whole.

The concept of intricacy also provides a new twist to the age-old tug-of-war between individual and community. For instance, the embryo's first step, dividing (individuating/ separating), explains the origins of specialization, diversification and distinct individuals. Yet, the embryo's second step, reconnecting in community, confirms that power and productivity come more from many hands operating synergistically than from lone-wolves operating separately. The combination explains why healthy social fabric must combine *strong selves and strong bonds*.

This need for strong selves and strong bonds also confirms *reciprocity's* well-documented role in societal health and economic functioning. For example, Nobel prize-winning sociologist, Elinor Ostrom[30] shows that balanced give-and-take arrangements — that include shunning freeloaders and requiring commitment to the greater good — are essential to proper management of commons. Fath[31] uses network analysis methods to show quantitatively that network health requires a preponderance of positive valence (win-win) relationships.

Such examples suggest that healthy networks:

- *Thrive on mutual benefit and common-cause relationships*
- *Depend on social capital and community-serving institutions*
- *Must be integrated and inclusive*. Societies are multi-scaled and multi-dimensional networks that provide all the things individuals need to thrive. This system must be integrated because processing and circulation only works when these network forms a whole circuit, a complete path from farm to fork, raw materials to finished product and all points in between. Developing the abilities of all members is also important because, like water molecules in a vortex, damaging effects tend to ripple across the network as a whole.
- *Are part of an iterative learning process aimed at self-sustaining vitality*. Self-organizing systems are learning systems in that they are driven to organize and reorganize in response to changing pressures in their environment. Diversity's role in adaptive cycles clarifies why effective societal learning depends on what Marc Granovetter's[32] calls, "The Strength of Weak Ties," meaning mavericks willing to go against standard rules.
- *Require both human empowerment and environmental sustainability*: The importance of input flows explains the need for environmental sustainability, and the importance of collective capacities explains the importance of human empowerment. Consequently, economies that want to thrive for long periods must pour money, information resources and energy into empowerment-building processes such as education and healthcare while also taking care of environmental health.

How do you build a sustainably vibrant economy?

While the story that emerges from ENS is reasonable, it is also strikingly different from today's dominant economic views. Here, for example, lasting economic vitality centers on:

- *Nourishing human capacities and networks* by channeling money and resources into building all forms of capital from material infrastructure and business networks to empowering education and public-serving governance systems.
- *Robust circulation* of money, resources and information that every nook and cranny. Because GDP only measures of the volume of money exchanged, not where it goes, GDP growth often masks economic necrosis caused by draining money from lower levels of the economy.
- *Balance*, particularly of efficiency & resilience, flexibility & constraint, diversity & unity and small, medium & large organization. None of these characteristics are panaceas, and too much or too little of any of them causes problems.
- *Building intricate social fabric* that increases strength, resilience, flexibility and circulation, while integrating them with hierarchies that coordinate, facilitate and protect the health of the whole.
- *Maintaining effective organizational and societal learning* now that we know that there are no final, perfect economic arrangements, and that the goal of learning must be to maximize the health of the whole system, not the wealth of a few people.

To these relatively obvious insights, ENS also adds the following unexpected addition:

- We can use energy principles and optimal patterns to measure development and a number of characteristics that under-gird systemic health in human systems.

The broader story of development

While the study of organized complexity is just beginning and many questions remain, a growing number of researchers believe that applying energy principles to the study of health and development in real-world flow-networks has the potential to provide:

-

A unifying, explanatory framework for systemic health and healthy development;

- A potentially powerful set of diagnostic tools and quantitative measures for exploring and assessing issues of resilience, development and systemic health;
- An effective interdisciplinary bridge that connects researchers, practitioners and theorists and helps coordinate knowledge, interventions, and practice.

Regardless of the names used, in the end, all ENS disciplines are pursuing the same, apparently possible dream: an effective transdisciplinary, empirical approach to understanding and measuring systemic health and development in human networks.

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