MODELS LEARNING CHANGE: CONNECTING THEORETICAL MODELS TO THE NATURAL WORLD OF COMPLEX SYSTEMS

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ABSTRACT: We live in a complex world, made more complex for us by the difficulty of distinguishing between our cultural expectations for how things work and the physical systems we interact with. The environmental systems of nature and the economy are often hard to recognize and constantly change, having behaviors independent of what people think about them. So our rules for systems we come to trust can become highly misleading without notice. That seems to have happened to us, evident in how people still project models of economic growth into the future, and already missing the turning point of timely response to erupting strains, fairly clearly around a century ago. That makes it valuable to know how the laws of physics provide some simple boundary conditions for responding to change in environmental systems, and knowing when you should.

Learning to identify natural systems change and how to respond starts with learning to distinguish between physical systems, as one of our independent realities, and our worlds of information and belief as another. Once you can distinguish our information from its physical subjects you can compare the difference, and plan for change. Telling them apart can be a challenge, however, requiring attention to their distinctly different kinds of energy use, organization and natural limits. Environmental systems often change with their actively learning parts too, for another reason watching them change is more important than having theories of how they worked in the past.

A useful way to find and track change in physical systems is found in how the conservation laws require energy flow and energy transfer processes to begin and end. They need a continuity that can be identified in recorded measures, made useful by raising key questions about irreversible changes precipitated by regular changes in scale. It builds a new bridge of methodology between theoretical and physical systems, introducing a new kind of empirical research.

KEYWORDS: Scientific method, mathematical modeling, physical systems, models, learning, developmental processes, change, foresight

INTRODUCTION

Because natural environmental systems can reorganize and change their behavior over time we need to watch them to see when to respond and update our expectations, but is problematic. The internal workings of a complex natural systems, like organisms or cultures, reveal a complexity quite impossible to understand. The key to studying them is noticing that nature clearly also gives complexity of systems some remarkably simple behaviors, somehow. Finding simple features of how they change as a whole is a simple starting point for understanding their organization and change. It provides solid clues to their regularities, how they work, approaching limits and changes in form.

The basic scientific issues of how our models of change can adapt to real change are discussed here in a conversational style, both for general audiences and the wider community of the systems sciences (Henshaw 2010). The real subject is a new scientific method for raising good original questions, a hypothesis generator, for responding to the local complex systems interacting in our environment. The method is not initially about producing equations, but rather about raising good questions. The basic object is recognizing when nature would soon develop different regularities, and so anticipate that models once relied on will need to change. Discussion of the main conceptual problems, features of natural systems, and an outline of the method, concludes with a conceptual application, defining timely response for approaching natural limits of economic growth.

Our natural problem is that our typical awareness of complex systems includes rather little of how they actually work. We mostly know them only by a name and some cultural metaphors attached to the name. It's not just the problems discussed by J. Sterman (2002) in 'All models are wrong', mostly concerning data collection and interpretation problems of modeling. There's also a more basic problem. How complex physical systems are organized is quite different from how information can be organized. Natural environmental systems are complex changing energy transfer processes between parts with variable connections, and not a set of controlled variables joined by self-consistent rules.

We recognize other people by name and reputation, and may even know them well, but it's not the lack of information that makes what's inside them a void in our minds and impossible to represent. The real problem is that what's going on inside them IS inside them, and not made of information at all, but made of physical processes animated by temporary interactions between distributed parts. It's the same for what is occurring inside the weather, ecologies, economies, businesses, social movements, cultures and even personal relationships. Complex systems have the simple behavior of taking care of themselves and working on their own to responding to their environments, using independent parts that somehow distribute their separate reactions throughout to then act as a whole.

The whole environmental fabric of our world that matters most to us in our daily lives is composed of things working on their own like that, with parts dizzyingly scattered all over the place, working smoothly most often. Still, it means what we can capture of how they work in our minds is not much. We can *only* know them by name and represent them with our own internal language and cultural metaphors. Where we err, it seems though, is in treating our information, ideas and values for them as being their physical processes, causes and effects. The two are different but we have not studied how to tell them apart.

One useful evidence of how nature makes complex systems work simply as a whole can be seen in the most common story of change, starting from small beginnings to lead to small ends, involving growth and decay. Things that use energy take time to assemble and operate the internal processes that do it, but thoughts don't. For physical systems there's no shortcuts. Following the swelling and fading of energy flows for systems is like 'follow the money' for detective work. It helps identify the assembly sequence for the working parts involved. It also serves to define a boundary for the system too, for which one can then outline a basic conservation of energy equations.

Internally a throughput system needs positive net energy, and always have more 'energy producing' than 'energy consuming' processes. At the environmental boundary a system needs to satisfy the basic laws of energy conservation and entropy, but also the law of development. Some of the energy crossing the boundary needs to be used to build the process moving the energy across the boundary, not shortcuts. You know the budget needs these components and that the energy flows need to have continuity as a matter of principle, before knowing how any part of things works (Equation 1). It serves as a starting set of questions treating any event as a map for carefully examining the necessary working parts of the working processes it is part of.

 $\Rightarrow \quad E_{in} = E_{devl} + E_{oper} + E_{loss} \text{ and } E_{devl} > E_{oper}$ (1)

Complex systems develop as individual things, emerging from their individual environment as their 'factory', and not as duplicates of a class of things. Sometimes it matters more than others, but if the exercise is to distinguish between the physical system and your ideas of it, it always matters. That makes the universal laws of physics the most completely secure starting point for studying them. What you can still know about the life cycle of any energy using system emerging from its own environment, built from scratch, is that it has a life cycle, an energy budget, uses energy from its own processes to build and later dismantle itself, E_{devl}.

How that works is what takes learning to think in new ways. E_{devl} has several parts, some like the 'venture capital' that any business needs to get going, or as any animal needs its egg and egg yolk or a plant needs in its seed with a carbohydrate energy store. It's physically necessary for energy continuity, actually, for things to have a start to get started, and it opens up the new lines of questioning explored here. The three essential types of energy use in systems, organization costs, waste and work, define a basic map. Identifying where necessary functions should be points to gaps in your information you may be able to fill with some effort. It starts only from what's necessary for continuity in beginning and ending any energy flow.

For example, one can account for all the purchased energy used by the world economy and quickly see the simple relationship between energy use and wealth (GDP), a constant ratio over the past 35 years between their rates of growth (Figure 1). That also exposes a telling relations between energy use and amount of wealth energy use creates, or economic energy efficiency, as presented to a recent BioPhysical Economics meeting (Henshaw 2009). The simple evidence indicates 1) the world economy smoothly acts as a whole, and 2) the economy's ability to use energy to create wealth regularly accelerates along with the use of energy. The appearance is that by making energy use more profitable, improving energy efficiency stimulates the use of more not less energy, running quite counter to popular cultural belief.

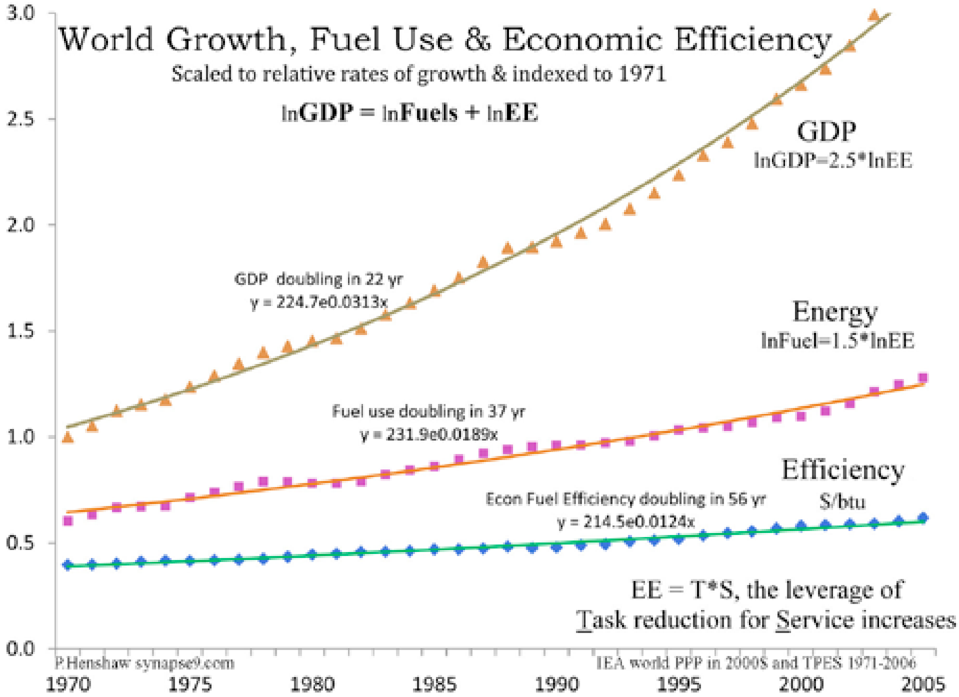


Figure 1. IEA World GDP, energy & economic efficiency scaled to their growth rates

It's a matter of reading the regularities of the data as displaying nature's talent for making complex things work quite simply. Strongly conserved properties of the system can be identified prior to having any theory or equations for them, identifying a particular subject for which you could write conservation equations and explore its instrumental mechanisms. It identifies an unexplained regularity of nature that looks like it could temporarily be trusted as a basis for models, but is of a constantly multiplying scale and pace of change, that cannot. Considering differences between nature's demonstrated regularities and our popular beliefs does not tell you how either originates, but even without other analysis, is very consequential for the questions it raises, given the high dependence our society is putting on both the pattern continuing and on it having the opposite of the evident effect.

What nature demonstrably does simply with complex systems reveals 'things we can know for sure' even when we know very little. This idea of just carefully 'asking the right question' is almost the basic idea of all science. By asking the right question you needn't know everything to at least know some things with high confidence. When studying complex systems what you don't know about them may be more evident, but one can still frame questions that can be answered with high confidence.

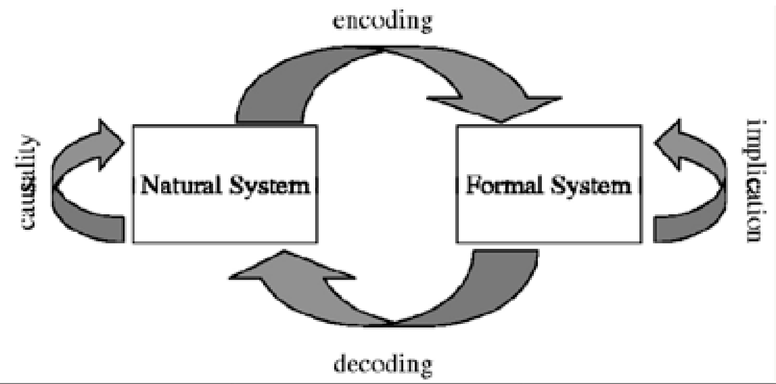
The method outlined below identifies regular progressions of change that are necessarily temporary, and so ask a simple question by predicting their own end. It has to do with the limiting scales of working processes, either too big or small. The interesting problem raised, is that if beginning infinitesimally small for energy continuity, energy flow processes would need to begin at a scale smaller than the working limits of any macroscopic energy transfer process. In the same way energy can't be created or destroyed, the conservation of energy implies energy transfer cannot take place instantly, requiring they have some way to get a start and then develop from small (but not infinitely small) to large scale (Henshaw 2008). Whether we recognize them at first or not, for energy flows to start or stop seems to require temporary smaller scale physical processes building a bridge to the larger scales.

What seems implied for the continuity of energy transfer, then, is for any larger scale energy transfer process to be initiated and completed by others on a smaller scale, some little push to kick it off and conclude it. The odd thing is you can very frequently find just such 'seed events' and 'terminal events' at the beginning and end of larger scale regular processes. Such small events easily go unnoticed, but a car starts and stops with a small lurch generally, even breathing seems to noticeably 'gear up and down' as you begin and complete an individual breath. The same is visible in how a fire starts, with a spark of some kind and ends with a last ember, or how single ideas can result in whole new arts or single inventions may produce whole new industries, always tied to the larger scale by the continuity of the developmental process they trigger. There's also the fertilization of an egg and the moment of death that begin and end a life, the germination of seeds or nucleation of chemical processes or snowflakes. Why the instrumental roles of these beginning and ending events have been neglected, apparently, is for lack of careful study of individual events in general. The pattern is wide enough, though, to support the idea that transitional events at the limits of scale predicted in theory, are what we are actually observing on a regular basis in ordinary events. So, expecting upper and lower limits to the working scale of any process, and need for multiple scales of organization to achieve continuity for developing systems, are used here as the null hypothesis for the study of things nature appears to do simply with complex systems.

To use information to manage tasks on multiple scales of organization generally requires passing control from one information model to another, each defined for each scale by itself. Frequently the languages of interpreting nature on different scales just don't connect. For how we can describe any one scale, the regularity of all other scales of organization are then assumed constant, without being observed. This opens up something like a Pandora's Box of implied hiding places for instrumental complex processes that models would normally leave out. If the observed regularity of nature at one scale happens to be one of regularly changing scale, that alone predicts that the system will cross the limits of its own organizational scale, at some point, and stop following the model it might have followed before. If transitions not predicted in models imply a hole in our information, they are also one of the things nature often just takes care of quite simply somehow, smoothly handing off control of events to unobserved scales of natural processes and organizational scales.

APPROACH TO INFORMATION THEORY

Theoretical models are generally defined as sets of equations idealizing relationships between categories of things, usually to predict real or imaginary physical systems. Models generally don't have environments except their own definitions, and don't change if their physical subjects do in their environments. That view of the relation between model and subject treats information as in Robert Rosen's model of the duality of physical and formal systems (Figure 2). For example, a parent needs to decide when to change their list of their children's clothing sizes as their children grow. To do that they develop a method for learning from their environment to update their formal model if their children as a list of clothing sizes.



Presented complex world	Coordinating information & physical systems	Re-presented abstract world

Figure 2. Natural & Formal Systems - Robert Rosen 1991 (with notes added)

One of Rosen's more disturbing findings, also arrived at independently by two other theoretical biologists, Elsasser and Kauffman, is that all persistent order in the universe would be too improbable to result from the models of statistical physics (Kauffman 2008, Elsasser 1987, Rosen 1993). Here that is also interpreted as meaning that the validity of models relies on natural processes not evident in models.

In questioning the validity of an abstract model one treats the '=' signs as '?' marks. When questioning a model one needs to maintain clear reference to its physical subject and its independent physical organization. The ancient and common way is with just 'pointing', as with how words are often defined without a theory, by pointing to some physical thing. To point to a developmental process one can identify the continuity of energy use during their whole life cycle, as a record of their unique historical continuity of developmental processes. Pointing to your subject independent of your model, though, is not customary in the theoretical sciences. It's more customary in the historical sciences, and done here with a degree of added rigor as in the theoretical sciences.

To distinguish between models and their physical subjects it helps to consider the general differences between information and things. Acting on physical things takes proportional amounts of time and energy, not needed for acting on information. For example, transferring 10 times the furniture takes proportional energy but 10 times the money doesn't. Differences between what's possible conceptually and physically are also seen in how easy it is to imagine an image of your face etched on the surface of an electron. It takes about the same amount of energy to picture that as to have any other simple thought.

What constrains information in a model or theory, once completed, is its own independent network of self-consistent definitions, so treating itself as its environment. Information systems just can't have parts with undefined relations, such as the self-animating and actively learning parts so often found in complex natural systems (Henshaw 2008). Information systems also generally retain their rules as unchanging over time, while physical systems are formed in and change with changing environments, changing continually everywhere within the system at once, as a rule.

Theoretical models of changing scale, such as growth or decay, themselves have no limits of scale and are generally reversible. Being composed of complex physical parts and relationships, physical systems all have 'breaking points' at the operating limits of their parts, and generally change by unique irreversible processes, such as by growth followed by decay. The degree of fit between a model and its subject might be loose as between the weather and weather forecasts, or snug as between hand and glove, but physical things would not have a way to operate without their complexity beyond what anyone could record or describe, and so are implicitly complete in every detail of themselves.

Both physical systems and models display regular processes of addition and subtraction, but they're quite different. For physical systems they're not numerical. From a distance, physical processes of addition may look quite regular and stable as if mathematical, like growth and decay, but growth and decay involve irreversible organizational development. Stable rates of changing scale in physical systems naturally exceed the limits of the working parts that make it stable. That makes the regularity of accumulative systems a predictor of their own instability, and very useful to observe.

NATURAL COMPLEX SYSTEMS

It seems apparent that natural systems emerge from their own open environments, such as cultures, businesses, species, technologies, social movements, economies, storms, etc., continually changing without a map along regular paths of progression as they go. They always seem to originate with growth, but once given a start growth becomes self-animating and self-steering, using an internally animated complex system, collecting resources to build itself, working simply as a whole. That does not seem to have been studied in generality before. In part the reason seems to be that science has limited itself to repetitious behaviors that have constant explanation. Developmental systems tend to be uniquely individual processes that need ever changing explanations. So they don't fit the usual scientific model. When complex natural systems have been studied scientifically before, the tendency has been, as with economics and ecology, to still represent them with abstract equations. That represents the systems of nature as operating by our information, not their own processes, despite the clear evidence many natural systems are self-animating and independently evolving by their own active environmental learning.

Pointing to natural systems as individual physical subjects does not, of course, turn such references into a better kind of equation. It generates better questions. Well defined references to individual natural systems give you a lead to follow for discovering new information about them, on an as-needed basis. They're a starting point to which you can return, for observing and exploring their natural complexity and development. It greatly improves the value of abstract models to see them in relation to their complex subjects and environments, rather than as replacing them.

The converse is also true, that failing to use models for pointing to their physical subjects removes any guidance to what's missing in the models, perhaps endangering their subject or its environment. The applicability of a model or theory can change dramatically over time, depending on interactions with other things and scales of organization not initially part of the theory or model, like emerging responses from the subject's environment. Resources initially used by just one industry, for example, might begin to be used by another too. That recently contributed to a world food panic as the cost of corn and related commodities were pushed out of reach for people around the world. As industrial farming became used for producing large quantities of automotive fuel as well as food, natural limits kept supplies from responding to demand despite greatly elevated prices. That exposed a serious conceptual error in 20 years of prior government and advocacy group sponsored research on renewable resources.

How one refers to physical systems may vary widely, often starting with just a name and a vague notion of boundaries. One example I studied concerned the crime rates of New York City and the mysterious collapse of the prior 30 year urban crime wave in 1990 (Henshaw 2006). I say 'collapse' as a scientific term for the apparent sudden deflation of what had previously been a very vigorous and resilient crime culture, reflected in steadily intense and variable murder rates for 30 years that then abruptly subsided. Murder rates came to an unprecedented peak in 1990 and then turned to follow a rapid but smooth decay curve, approaching a steady low minimum eight years later. From a systems science view, one does not need to know what changed to see clear indications of nature doing something simply.

A systematic collapse with lasting effect is unavoidably what the simple finality of an active process abruptly changing to a smooth decay curve represents. The collapse of the urban crime wave in New York is a mysterious case, though. Hardly anyone who was involved, the journalists, neighborhood people, politicians or professionals, were aware of the dramatic event that apparently occurred. The collapse started three years before the celebration of dramatically lower crime rates during the Giuliani administration that most people still think of as 'the cause'.

I mention this intriguing case hopefully to share some of the excitement of the hunt for 'wild game' that natural systems science is, as well as the real cultural importance of understanding these great irreversible movements in the shapes of our lives. The data I first had didn't help me understand what was happening, until I found the right way to aggregate it, exposing the different whole parts of the NY street crime culture working independently. I had started with detailed data for 75 police precincts, and tried several ways of viewing it that were misleading. Only when I aggregated it by the five boroughs of New York did I find boundaries for which the street crime cultures each seemed to act as a whole. It now looks like the collapse from an unprecedented peak in 1990 represented the street culture being tested to its own point of 'failure by success' in the crack epidemic, abruptly losing appeal to the whole community. It seems roughly similar to what happened to the even more durable, but also contradictory, institutions of the Soviet Union a few years before too. It's not clear either was predictable from the record, but each definitely did happen.

The approach here for using how nature does complex things simply to help find what's missing from models is for cases where that can be done prospectively, rather than retrospectively. Regularities that signal approaching organizational change are used to signal the need for timely response. It's not for predicting collapses, but responding to the developing conditions before hand, where that is systematic. It prompts the questioning of assumptions while models are still working normally. In that way it's a 'diagnostic' approach to complex systems science. It treats the theoretical behavior of a model and the parallel developmental change of its complex subject as being linked. Regular developmental processes of changing scale raise a 'red flag', indicating the physical system and the model representing it will change form as the system crosses the limits of its own organization. That turns the '=' signs of the equations of a model during the time period into '?' marks. Those '?' marks prompt a focused search for what it is in the system that is systematically changing its way of changing, and what new assumptions will be needed.

THE BASIC METHOD

Models and explanations work by representing some self-consistent set of regularities of more complex physical things, a single dimension. They assume other aspects of the system represented are constant. The usual aim of modeling is to find what regularities can be relied on. The interest here is somewhat the opposite. It's to find common regularities that are certain to become unreliable, processes of escalation and de-escalation. They help point to what parts of a system will change for reasons beyond the information represented by a model. What to look for comes with experience, and tracing how the energy entering the system is used to build , operate and then disassemble a system and scatter its parts (Figure 3). The assembly of a new system begins in a small scale environment, and then through multiplying use of a seed resource gets to then shift orientation to integrating with new relationships and energy sources at its working scale in a new environment. Growth is about starting in one environment to find another environment, using a seed resource as a booster.

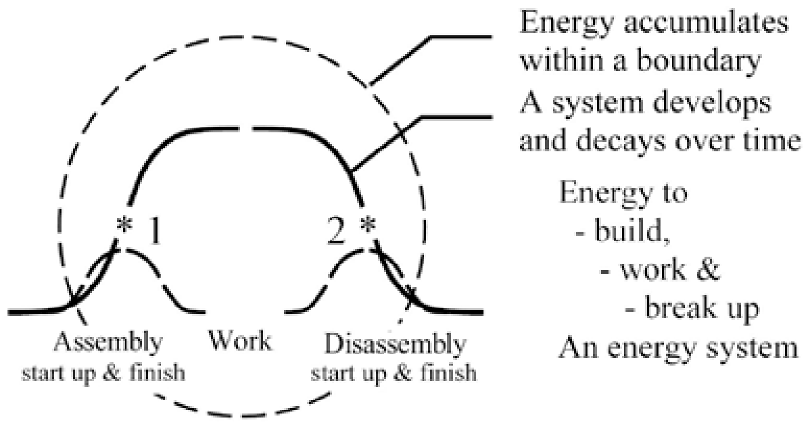


Figure 3. Conceptual diagram of a local system's energy accumulation and dispersal from a ground state. The energy for assembly and disassembly switches at inflection points 1 & 2 from multiplying use of a seed from the past to finding new relationships in the next environment

Because models would never change to follow change in the environment by themselves, indications that the system they refer to will change form prompts reconsideration of the model. When a set of regularities and a useful model are found the question changes to when might they change. It's hard to find a subject of science not involving natural complex systems prone to change according to changing circumstances. Monitoring what they refer to also exposes new levels of organization in them, new opportunities to relate to them differently, making them fascinating as well as helping avoid unexpected conflict with them or their environments.

If one can identify systems that are naturally temporary it raises the question of how the observed regularity began and will end. Beginning events like the germination of a seed, a handshake between people cementing a deal, or a spark that turns to flame, are events on a minute scale that would not normally have any relevance to events on a larger scale. Something about the environment's simultaneous readiness to respond also seems essential for their magnified effects. Process ending events are similarly different from the processes they end. They include the slight jerk that occurs as the breaks of a car grab as it stops, the 'finishing touch' that completes a task, the garnish on the plate being served perhaps, or the mysterious event of death for organisms.

How regular processes of changing scale result in changes in the form of natural systems does not seem to have been studied as a general subject before. Some research on the granularity of nature has been part of the scientific discussion for a long time, though, with recent interest in the limits of fractal scale in theoretical quantum physics (Schulman 2002), for example. It seems to give more support to the logic and evidence that all granular models and physical processes with their granular parts have natural limits of organizational scale, and exist independent of their models. Uninterrupted processes of continually changing scale would naturally cross those limits of scale, then. The use of that principle as a tool for understanding environmental systems and prompting a search for new assumptions for models also does not appear to be explicitly discussed elsewhere. It's been a philosophical issue since the Greeks, though, as displayed in the related riddles about changing scales raised by Zeno's paradoxes.

The empirical confirmation of the theory is in finding the seed events initiating and terminating the regular processes of changing scale seen in data or in models, and identifying some of the auto-catalytic processes of growth or decay by which they work. That makes the four directions of auto-catalytic development and regular proportional change, with the steady state periods between them, the principle questions used here to direct attention to physical systems (Figure 4).

Figure 4 Directions of regular proportional change that may indicate auto-catalytic processes altering their own environment to bring about their own end.

The words used for the four characteristic progressions of change and stability may vary with context. For example in music the growth period of a musical note is called 'attack' and its stabilization leading to the note's 'sustain' is called 'decay'. Each progression of changing scale represents a positive or negative feedback, interpreted according to the subject in question. Watching for these kinds of regular progressions leads one's questions beyond the information available, to discover unexplained but connected processes and relationships. Being certain to change themselves, due to events on another scale of behavior, they define a path of inquiry for finding hidden information. To begin the search you would trace the conserved resources and locate the developmental processes, survey the environment for what else uses the same things. One looks at environmental indicators such as for declining stress or increasing conflict, for example, or things like responsiveness, diversity or efficiency. Patterns that indicate change developing on other scales include unusual periods of calm or processes that are usually self-correcting but display some new resilience or 'stickiness'. When strained product markets no longer quickly respond to demand, for example, a whole system limit may be prompting reorganization.

To check if an apparent period of regularly changing scale indicates the presence of a system or not there are a variety of mathematical tests for data continuity. They help verify whether statistically ambiguous patterns of regular proportional change display real continuity and probably an underlying regular process or not (Henshaw 1999, 2007). As with any search for otherwise hidden information, what you find depends on the combination of what is actually there and how quickly one is able to recognize it. As a careful detailed study of individual events it also represents a new way of considering time, as a one-way ladder of accumulative change, explored by locating some of the rungs, rather than treated as a variable in an equation with no direction. The equations of a model themselves might imply either continual growth or decay for a physical system, or an inflection from growth to stabilization. Having that raise questions about implied missing organizational changes, inserts '?' marks at information gaps, often exposing how the model actually refers to a succession of systems, rather than one. In each case once you've identified a process likely to change it leads to changing the model at some point to correspond.

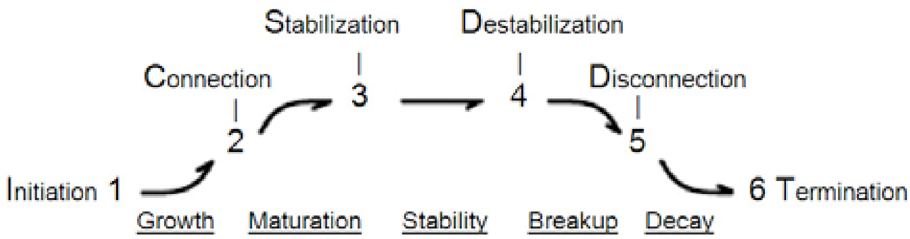


Figure 5. A system model as a continuous chain of local processes. Six punctuating smaller scale events and five periods of regular proportional change. Showing one possible naming convention for the natural sequence of developmental processes (Henshaw1985, Salthe 1993)

Chained together with their transitions as they occur in nature, the four kinds of regular irreversible processes of proportional change are a general map of good questions to ask about 'how things come and go'. It is 'a typical life story' of developmental processes punctuated with smaller scale events of change, events 1-6 with periods 1-5, perhaps plus periods 0 & 7 for before and after (Figure 5).

In the same way as locating the boundary of a system gives you an energy budget to study and opens up diverse new perspectives on how the identified system works, this typical sequence of events also identifies a whole system, but in time, and exposes its diverse interactions with its environment over time. That prompts further questions about internal processes and environmental responses, as well as where in any given model one might need to replace '=' signs with '?' marks.

CONCEPTUAL APPLICATION & DISCUSSION

Keeping with the conversational format, the sample application discusses alternative paths for a process of responding to the approach of natural limits to a system's scale (Figure 6). The change symbolized is that of switching from acting as a whole to multiply to acting as a whole to approaching a natural limit. The options for switching from multiplying patterns of the past (growth) to adapting to the new environment of the future (maturation), range from too early to much too late. That switch in orientation of the system's use of its environment also corresponds to the switch in orientation at the inflection point (figure 3). The system's net energy used first to multiply its net energy from a non-renewable seed resources is then applied to obtaining net energy from its environment of the future and integrate with systems on the scale of the new environment.

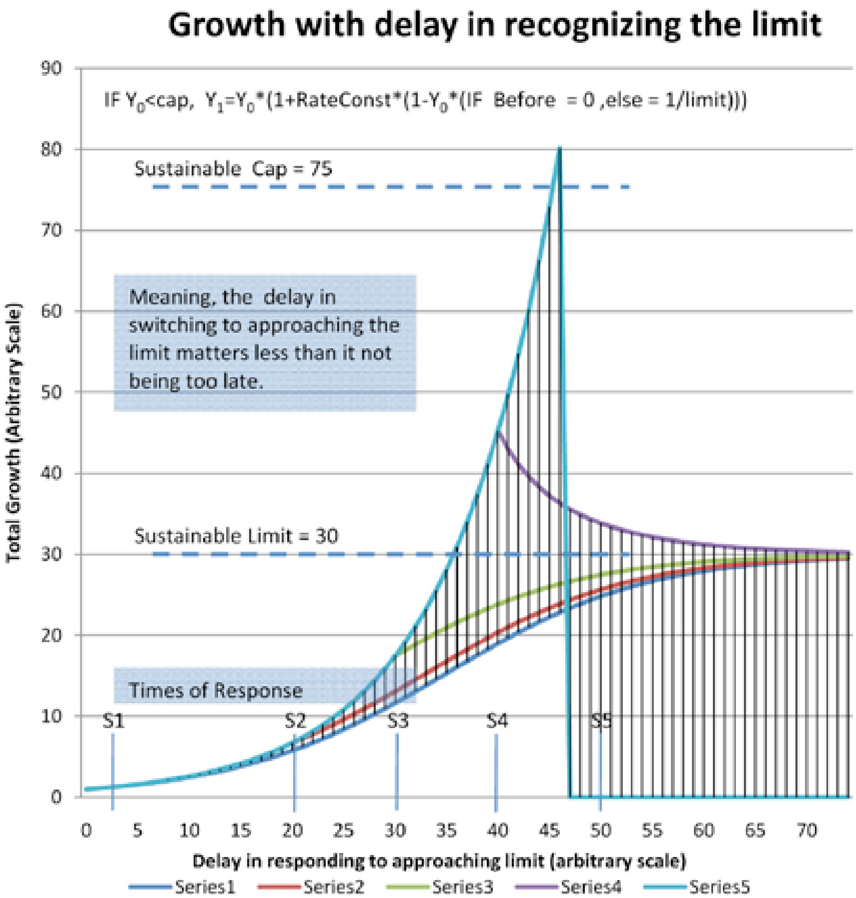


Figure 6. Growth toward a limit with delay in recognizing the limit: IFYo<cap,Y1=Yo*(1+R ateConst*(1Yo*(IF Before=0,else=1/limit)))0

At the 'time of response' the equation of the model switches from expanding by regular proportional change in relation to its scale of the past to expanding by the same regular proportional rate to toward its scale in the future (Figure 6). Each of the curves shows the exact same equation. The difference is the point in time when it's responses switch from, implicitly, using its net energy resource from multiplying to stabilizing as it enters its new environment at the limits of its new scale. The timing of the choice tests the system's own response to its internal and external environments and ability to switch modes of change. In the equation the same response rate, representing its 'learning speed', is used before and after.

It is almost self-explanatory that delayed responses result in disruptive change and timely response in smooth change, but it helps to see it visually too. If you're 'asleep at the wheel' and start a turn in your car too late, your own as well as the vehicle's responsiveness may easily be exceeded, leading to fishtailing or worse. The equation for Figure 6 uses arbitrary units and the response rate of 10% is used for both the positive and negative feedback learning rates. An arbitrary point of failure (Cap = 75) is set at 2.5 times the arbitrary 'sustainable limit' set at 30. What varies is the time when switching from multiplying to stabilizing occurs.

The model represents any growth system that matures, as it takes off from its seed, and then switches to its own maturation and integrating with its environment. The question asked is how does it affect the system if the switch in the direction of response occurs early or late, with the time of the choice to switch marked for each series. The clear implication is that switching early has little effect on the future and switching late has a very large effect. One need not know anything more to acknowledge the general principle, that in environments presenting a need to respond to new conditions the window of opportunity for responding successfully gets shorter and shorter. The important recognition is that system response problems are invariably about how systems start *without* information on what response will be needed. The practical benefit of noticing that a system is exhibiting a period of regular proportional change is the simple information that events on another scale will end that regularity, and timely information on how to respond will be needed. The model shows generally how the timing of beginning that response determines whether it will be made gracefully or not.

The contradiction implied is that systems growing independent of their future constraints need to 'encode and decode' information about a complex world of relationships they will become part of, well before they develop familiarity with it. They need to use some rather simple kind of information. Nature is full of systems that come to remarkably graceful limits of development just this way, though. So there must be something they are responding to other than pre-adapting to an unfamiliar complex place. One possible working hypothesis is that responsive growth systems are sensitive to the stresses of their own processes as their parts multiply. So, as multiplying stops getting easier for their own design it may signal them to respond by acting to reduce their growing internal stress.

A plant's growth begins with the germination of its seed, and the end of its explosive auto-catalytic growth comes as that seed resource is used up. A seedling apparently responds to its own internal stresses as its multiplying use its non-renewable resource comes to an abrupt end, as a slender and fragile sprout. That leaves it momentarily very vulnerable to disturbance, drought and infection. That stopping point seems to be what prompts it to harden and switch to seasonal growth, though, and using the resources its roots and leaves can find in the gaps between other things as it begins to mature and begin its full growth, by the reverse regular proportional change pattern. It's germ cell may have expanded by a million times to leave it then quite helpless, having a million times the appetite and no real access to resources. Later it will only double a few more times as it matures, but the changes as it matures are arguably the larger part of what it becomes as it reaches its full size and its peak vitality.

The end of growth for complex natural systems seems to be the natural time for them to shift their responses from self-replication to yielding to and becoming part of their environments. It's the end of multiplying from a seed and the beginning of completing their task of remaking their environments to fit their own image. For systems that become self-sustaining what takes over as the swell of their tasks then subsides is the other principle of natural growth, successively reducing the tasks. They mature toward a peak of health and vitality as they find new images of themselves in partnership with the other things of their new worlds.

The trick of making a graceful and relatively effortless response to limits seems to be to start the turn before you really need to. Otherwise the time needed runs out very quickly. That natural 'fine line' between too early and too late is one of main features of many sports and games. As with most any steering task, for example, in paddling a canoe on a winding river you quickly discover that taking the last possible opportunity to turn risks capsizing and spoiling the trip. So in canoeing the earliest opportunity that is not premature is the one to choose. Starting a turn at just the right moment takes two steps, preparation at the earliest time available and then waiting for the perfect time to do it.

DISCUSSION

Our economic system faces a choice of this kind, changing established practices of adding to things by accumulating %'s, long part of our culture and institutions. Whether there is even a question of needing to end the institution of endless growth and its ever multiplying 'free lunch' is not yet even discussed in public though. It's strange. So naturally we have no ready response either, despite the time to have switched the direction of our response perhaps having long past. As a world system we seem likely to be following a path like series 3, 4 or 5. The increasingly noticeable emergence of growing global environmental conflicts of many kinds, resource strains, basic problems with the manageability of regulations, and unending economic disruptions, all seem to be clear evidence that the period of unfettered growth is well past, so clearly already too late to climax smoothly without all that.

For people one of the biggest confusions is how the apparent limits themselves had for so long always seemed moveable. Using our creativity to eliminate barriers to using up ever more of the earth's resources seemed to reveal ever more resources to use up for so long. That pattern itself is clear evidence of a system of regularly changing scale, though, that will come to an end at its own hand, however. Just seeing the pattern signaled the need to preparing to enter a new environment. So the question of limits is not 'whether' but 'what' and 'when', same as with climate change.

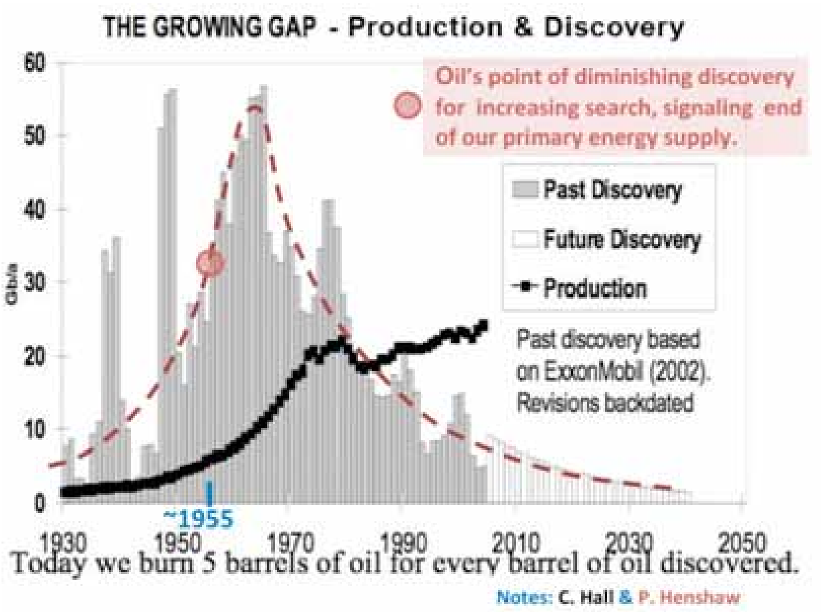


Figure 7. Petroleum discoveries by year since 1930 from ExxonMobile 2002. Initial inflection point to diminishing rates of discovery in ~1955

If it is understood to be advantageous to discover limits in a timely way, the purpose in denying them switches to a need to substantiate them. In our case we might have responded to any number of things a century ago, but surely should have responded to the end of our making ever bigger resource discoveries as for oil in the 1950's (Figure 7), along with clear evidence of biodiversity collapse, climate change and various other unsustainable trends.

It's reasonable that businesses seeking only short term investor profit would simply use up resources as fast as possible. Somehow our society was open to believing that running out of oil would just be a stepping stone to 'electricity too cheap to meter' and such things, as many people in the 1950's were encouraged to believe. In the time since, though, no affordable substitute has been found, and the world economy has only become ever more dependent on oil. That dependency itself has become ever more of a threat to the climate, ecosystems around the world and the economy itself.

There's an opportunity cost in all that, that today's investment decisions are not factoring in. It does make clear, though, that the time we should have switched from expanding ever faster to limiting our internal and external was apparently over 50 years ago. So, one of the features of the basic Keynesian growth model that implicitly has to change is the previously automatic use of investment as the system building resource for maintaining growth, now multiplying strains and conflicts, to being used for reducing our strains and conflict. Considering how difficult it would be to change cultural habits, even if the genuine necessity is perceived, seem it might add large delays to the response time.

Nature is also full of examples of developmental processes that switch from growth to stabilization a the very last possible moment it seems, as if to figuratively 'turn on a dime', successfully making a rather hazardous but quick turnaround. It's not just seedlings as described above that end their exponential growth in a most vulnerable state, and prone to wilt. The birth of organisms generally marks the end of their exponential growth too, and emergence into new environments to become virtually helpless for a period. Human newborns have gone from a single cell to approaching a hundred billion cells in a period of nine months, and then spend much longer struggling to master the practical task of caring for themselves. There's far less change of scale to the age of 18 when humans reach a their peak of physical health and vitality , but there certainly is quite considerable change in kind. It's the same for lots of things that begin with complex system growth, that the best of life is long after the end of compound growth is done.

For our present situation, though, the standing world plan for economic stability is to continue multiplying the scale of the economies and our rate or reorganizing the earth, creating ever more complex, and unmanageable, solutions to do so. All our institutions are organized for that, and have included in their budgets a reliance on the projected multiplying future earnings expected from it. If, say, today were the first moment the real necessity of doing something else was noticed, the rational response would be to think of it as steering. First it's to ask how to prepare and then ask when to do it. That two part sequence in responding to system change wouldn't change, even if it might seem already too late to do it smoothly.

One often discovers what other things exist in a new environment by how they respond, such as with the collision between the low income world and the rich world when food resources started needing to be used for fueling supplies. That kind of surprising response from others sharing the environment is quite good evidence that they exist. To understand the other cultures and systems we share the planet with you start with discovering the names for some of them, identifying how they work by how they work as a whole, just as you would in graduating enter and become part of any new world of relationships . Some you could identify boundaries for and energy budgets, and where they are in their history of development, and start to understand the networks they are part of. What we discard is not things worth keeping, but what's become a dangerous pipe dream, really, the hope that spending our energy and money would somehow make an ever more complex and conflicted path of development manageable. Both using energy to ever multiply energy and using money to multiply money display the basic features of regular proportional change, and so pose the question of how to end them. Responsive steering would mean being prepared to end them in a constructive way at the right time, to avoid having them end disruptively.

CONCLUSION

Where this general method for investigating natural systems too complex to explain first came from was noticing that every run of any experiment somewhat misbehaved, and then closely watching simple individual events to see how they individually developed. When you organize and complete a project, even just making dinner, the work proceeds with a swell of larger tasks leading to completion in successively smaller ones, with each generally setting the stage and handing off to the next in sequence. These complex developmental processes take on either a simple or complex life of their own, and seeing that as a pattern then helped generalize an image of how they worked, and the way to refer to use the boundary conditions of physics to direct attention to their instrumental processes.

Being able to distinguish between information and things allows natural and formal systems to be considered separately, and to make what we learn from each independently useful. Recognizing that regular proportional change often points to complex systems that would cross the limits of their own scale of organization, when new organization would appear, not only gives a sense of awe for how nature actually works for individual systems. It also permits locating their boundaries to construct rudimentary energy equations along with a rudimentary life cycle narrative that assist in exploring them. Seeing one of the periods of regular proportional change in a model or the environment then helps locate it's physical system subject and point to where information on how the system is likely to change can be found, and by finding it, confirm the value of the question and the method. It permits using how nature makes complex things simple, for telegraphing the approach of some of nature's most eventful changes, helping observers indentify things they can know with confidence without needing to know all that much.

Science seems to not often discuss the differences between its models and its subjects. Language has long allowed discussing independent things we can only point to as having organization of their own, without theories, just as easily as discussing theories as having organization of their own, without associated physical things. So learning how to refer to the physical systems beyond our information and how long our models will fit, may not take as much rethinking as it might first appear. One can even make an argument that most of the words of language, from nouns like 'swarm' or 'process' to concepts like 'breaking point' or 'individual', themselves are terms culled from direct observation of complex systems, largely self-defined by reference to familiar features of our complex world and experience.

The harder part may be learning to hesitate in describing natural systems, recognizing them as voids in our information to explore, rather than as puzzle pieces of our own invented cultural 'world views' and images. Referring to natural systems as physical things, about which observers naturally remain largely in the dark, does not seem to be what we normally do. It's a switch away from treating them as objects of social agreement determined by what stories are found acceptable to others. That ability to recognize the difference between cultural and physical reality doesn't seem to a matter of having the right image. It seems to be more about noticing gaps in your information, and posing questions that send you back to the physical subject for answers. It's about looking for or noticing regular proportional change in things, and finding what that continuity comes from and how to respond to its limits.

It's that trip back and forth from image to subject that confirms the physical subject as a source of information that an image can't contain. In the tale of the 'six blind men' struggling to explain an elephant, but failing to connect the parts, what's missing from their information seems to be the question of how the different elephant parts are connected. The key seems to be whether one can acknowledge that things too complex to really understand must necessarily exist independent of one's explanations. That's what makes it possible to tell whether discussions are of different views of a common subject all can consider independently, or about private images of our own that others can't actually share.

Science would seem to clearly need to enter into an exploration of individual complex systems and how their developmental processes work, at least. The difference in perception allowed by perceiving physical systems as subjects people can consider in common, and independently refer to for filling in the gaps in our models, provides an avenue for discovering their connections too. That may be needed for our survival, and for our arts, values and relationships.

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