**Investigations**
**2002**
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## 1. Prolegomenon to a General Biology.

Erwin Schrodinger authored "What is Life" in 1944 which effectively predicted the aperiodic crystaline structure of DNA.

Investigations began with two questions. Could there be a fourth law of thermodynamics for open systems that governs biospheres? What must a physical system be to be an autonomous agent?

**Hypothesis: An autonomous agent is a self-reproducing system able to perform at least one thermodynamic work cycle**.

Kaufman doubts that we can pre-state the configuration of a biosphere because of all of the latent adaption that will only be realized when the environment changes. So the scientific techniques taught since Newton need to be revised.

Statistical fluctuations scale as per the square root of the number of particles. Schrodinger concluded that statistical fluctuations acting on a gene comprising only several hundred atoms would render heritability impossible. The source of order must lie elsewhere.

Humans have about 260 different cell types and each is a different pattern of expression of 80,000-100,000 genes.

An autonomous agent must be displaced from thermodynamic equilibrium as work cycles cannot occur at equilibrium.

**Footprints of Destiny: The Birth of Astrobiology**.
**Molecular Diversity.** We are well positioned to investigate a general biology. There are approx ten trillion different proteins in the biosphere. We generate 10x this number when trying to discover new drugs by sticking the target molecule to agar and then soaking it in a diverse protein wash to find new proteins that match. Oster and Perelson introduced "shape space" to explain how only $10^8$ antibody molecules can match all possible molecular binding sites. A similar concept holds for catalytic task space where $10^{14}$ proteins may be enough to act as a catalyst for every possible reaction.

**Life as an Emergent Collective Behavior of Complex Chemical Networks.** Imagine a molecule catalyzing its own formation from its own components. And then two proteins which are collectively auto-catalytic etc etc. The best current guess is that, as the molecular diversity of a reaction system increases, a critical threshold is reached at which collectively auto-catalytic, self reproducing chemical reaction networks emerge spontaneously.

**The Strange Thing about the Theory of evolution**. Is that everyone thinks that the understand it! Darwins theory of evolution is a theory of descent with modification; it does not explain the genesis of forms. Also, Darwin starts with life already there. Also it is gradualism in that it consists of mostly minor variations. "Evolution must somehow be crafting the very capacity of creatures to evolve." Recombination is said to be a useful search procedure but it is only useful on smooth, highly correlated landscapes. No-free-lunch theorem says that no one search procedure outperforms all others on all fitness landscapes. But mutation, recombination and selection seem to work very well! So then, do organisms, niches and search procedures jointly and self-consistently construct one another?

**Law for a biosphere.** The legal system has developed a rich tapestry based on precedent, interpretation and the resulting ripples. Co-evolutionary assembly must involve co-evolving organisms flexible enough to change but firm enough to resist change. Consider the power Law. "I suspect that autonomous agents co-evolve such that each makes the maximum diversity of reliable discriminations upon which it can act reliably ..... leads to a working hypothesis: Communities of agents will co-evolve to an 'edge of chaos' between over-rigid and over-fluid behavior ..... 2 will suggest that a biosphere gates its way into the adjacent possible at just that rate at which its inhabitants can just manage to make a living, just poised so that selection sifts out useless variations slightly faster than those variations arise." pg 21.

**2. The Origins of Life.**

**The Standard Model of the Origin of Life.** Assumes that life must be based on template replication of double stranded aperiodic solid (DNA). However the current mechanisms of transcription from DNA to RNA and translation of RNA into proteins requires particular proteins or RNA as catalysts. So how then did the process begin? 30 years of attempts to achieve a sequence of DNA or RNA able to line up a set of free nucleotides, ligate them into a complementary strand, melt the two strands apart, then cycle again, to create a self reproducing molecular system have failed. It may be that RNA is the true master molecule of life and there are two different approaches to creating a pure RNA-world-replicating molecular system. Szostak has taken steps towards creating a universal RNA toolbox able to bind to any target approx $10^8$ molecules) and to select RNA molecules capable of catalyzing a chosen reaction. Szostak currently seeks an RNA molecule that is able to serve as a polymerase, able to slide along and copy any arbitrary single stranded RNA molecule (including itself). Kauffman expects that Szostak may succeed but has concerns that 1. a single copying error will progressively taint the population with ever more error prone molecules; 2. the improbability of the system evolving in nature; 3. Cells are an organized whole rather than naked minimal RNA replicators. Cells appear to be of some minimal complexity to function.

**Experimental Auto-catalytic Sets.** Kiedrowski has achieved self reproducing molecular auto-catalytic systems experimentally where a short (6 & 4) single stranded DNA catalyzes a copy of itself and another instance where two single stranded hexamers catalyzed the ligation of each others fragments. So reproduction does not require addition of single nucleotides and collective auto-catylisis is possible. Ghadiri have published a first example of a reproducing protein demonstrating that life might be based on proteins alone.

Life may be based on catalytic closure in an auto-catalytic set and this becomes almost inevitable in sufficiently diverse chemical reaction networks. This inevitability comes about as reactions in a random molecular soup progressively (exponentially) result in a richer variety of components until a critical threshold is passed when the components for an auto-catalytic set will almost certainly exist. In principle it is possible to construct a reaction graph showing the reactions that couple a set of molecules. The path between any two neighboring molecular components on the graph represent a equilibrium in the concentration of the two components. The equilibrium depends on the relative speed of the reaction in each direction which in turn depends on the difference between the energy wells on either side and the height of the activation barrier. A catalyst lowers the activation barrier and speed the approach of the equilibrium point but does not alter the equilibrium point. In an open thermodynamic system there is a flow of energy and components in and out of the system, which displaces the equilibrium. So every member of a set of auto-catalytic molecules must enter the system as “food” or be the end result of one of the catalyzed reactions.

Metabolism is still required to provide the energy to drive these reactions.

The chemical adjacent possible is the set of chemicals just one reaction step away from the currently available chemical components (perhaps a better arrow of time than entropy).

Soon we will be able to experimentally investigate these systems.

### 3. Autonomous Agents

**Hypothesis:** An autonomous agent must be an auto-catalytic system able to reproduce and able to perform one or more thermodynamic work cycles.

**Definitional Jumps and Circles**. Ponciare claimed that Newtons F=MA is a definitional circle as M and A require each other for definition. Wittgenstein initially followed Russell's atomism based on the idea “One might be mistaken in saying that a chair is in the room, but none could hardly be mistaken in reporting bits and pieces of ones own awareness”. Wittgenstein later junked the whole idea in Philosophical Investigations in the realization that concepts at any level typically are formed in co-definitional circles. The problem (briefly) is that there appears to be no finite pre-stateable set of conditions about sense data statements whose truth is logically equivalent to any statement about a real physical chair in the living room. In a legal system “guilt” is defined in the context of many other legal concepts. Useful new concepts (such as F=MA arise in codified clusters – at the center of a wider web of concepts that touches, articulates, discriminates and categorizes the world.

**Autonomous Agents**.

The Carnot work cycle comprises an isothermal expansion, an adiabatic expansion, an isothermal compression and an adiabatic compression and the area of the enclosed area on a PV chart is proportional to the work performed. Key points: it is a cycle, it can operate in both directions, why some reactions are spontaneous (the increase in entropy in the 2$^{nd}$ law is a tendency for systems to flow from less probable to more probable macro-states).

A collectively auto-catalytic set has *catalytic closure* meaning that every reaction that must find a catalyst does find a catalyst. Catalytic closure is a property of the whole system. Each catalyst may catalyze a number of reactions, not all of them critical. “A chemical reaction network with a work cycle will have to link spontaneous, exergonic and non-spontaneous, endogernic reactions into the chemical analogue of a work cycle.” pg 64. Neither Ghadiri's auto-catalytic peptide or Kiedrowski's auto-catalytic hexamer DNA or collectively auto-catalytic set of two DNA hexammers contain a work cycle.

A hypothetical molecular autonomous agent is described which involves three coupled loops 1. Two single stranded DNA trimmers ligating into a DNA hexamer , driven to synthesize DNA heximers by, 2. the exergonic breakdown of pyophosphate into two monophospahtes, and reformed by 3. the energy from an excited electron repeatedly re-excited by the arrival of a photon. This system has two essential features of living systems (self-reproduction and metabolism), it is necessarily a non-equilibrium system, it performs a work cycle, and the cycle is repeatable (and reversible). The autonomous agent has been simulated and demonstrated to work with 13 parameters. The agent reproduces more efficiently with the couplings then without.

These type of systems are unstudied, but should be soon now that we have imagined them. We have to retain the reactants in a confined region (perhaps in a micelle or liposome).

“I have a hunch ..... that the coherent organization of the construction of sets of constraints on the release of energy which constitutes the work by which agents build further constraints on the release of energy that in due course literally build a second copy of the agent itself, is a new concept, the proper formulation of which will be a proper concept of 'organization'”. Pg 72.

Is this definition of an autonomous agent a definition of life? Is it inherently molecular based or could it form in mutually gravitating systems, or photons .....????

**Natural Games.** A natural game is a way of making a living in an environment. Search procedures must be tuned to the fitness landscape to be optimized. Most organisms use mutation and recombination as the search procedure but these procedures only do well in relatively smooth. “a biosphere is a self-consistent co-evolutionary construction of autonomous agents and ways of making a living that are themselves self-consistently well searched by the search procedures the agents are using” pg 74. “Ultimately we should be able to build a theory that accounts for the distribution of advantages of trade, the distribution of residence times of energy stored in different forms in an ecosystem, as well as the statistical patterns of linking of exergonic and endergonic reactions in a biosphere as it builds itself and persistently explores novel ways of making a living, the novel niches that permit the success of Darwin's minor variations creating novel species for those niches.” pg 79

**4. Propagating Organization.**

A windmill is a simple device that measures a deviation from an equilibrium and extracts work. Physicists define work as a force acting through a distance. Kauffman defines work as the constrained release of energy (and it required work to construct the constraints). There is a conceptual cluster: the progressive emergence of organization in the universe and a biosphere : the organization involves entities that measure the relevant aspects of non-equilibrium systems to identify sources to extract work : the entities construct constraints and extract work : the work is used to construct more constraints and extract more work.

As symmetries broke in the expanding universe, non-equilibrium situations became available for work extraction. Work cannot be extracted from a system in equilibrium despite it containing energy.

A candidate forth law: As an average trend, biospheres and the universe create novelty and diversity as fast as they can manage to do so without destroying the accumulated propagating organization that is the basis and nexus from which further novelty is discovered and incorporated into the propagating organization.

**Maxwell's Demon**. Maxwell's Demon is a place in physics where matter, energy, information and work come together. Maxwell asks us to consider a box with N particles in it at equilibrium macro-state. The box is divided into two chambers with a flap valve between them. Maxwell's demon is tasked to open the flap valve to allow faster particles to pass to the left and slower particles to pass to the right. So the right side of the box will soon be warmer such that we can use it to extract work. It appears that the actions of the Demon circumvent the 2nd law. However Szilard realized that the demons actions caused the total entropy of the system to decrease a little bit but that the amount of work done by the Demon to discriminate the speed of a gas particle is equal to the entropy decrease so that the 2nd law for the whole system including the demon is preserved. Shanon completed a similar calculation with Information by considering that the receipt of a signal reduced the uncertainty of the nature of the message that had been sent, Sinclair and Zurek have independently considered that as the entropy of the system decreases the demon's information about the system increases and as a result the most compact description of the system also increases (beyond the macro PVT) and that these on average balance.

Consider further the two box system with an identical number of particles in each box but with one side hotter than the other. If the Demon measures the instantaneous position of all of the particles in the system then it will not reveal the potential for work to be extracted at the flap valve. A windmill placed at the flap-valve will make the correct measurement and extract work. Kauffman than asks how does the Demon know which aspect to measure in order to extract work? (see thoughts below)

".. there appears to be some positive relationship between the diversity and complexity of structures or processes and the diversity and complexity of the features of a non-equilibrium system, which can be detected and measured by the detecting structure to identify a source of energy, then couple to the source of energy and actually extract work." pg 95

**Work**. Atkins book on the 2nd law defines work as "the constrained release of energy". It sometimes takes work to construct constraints – but not always.

**Propagating Work**. Autonomous agents (such as cells) carry out linked processes in which spontaneous and non-spontaneous processes are coupled to build constraints on the release of energy.

**Records**. Records are correlated macroscopic states that identify sources of energy that can be tapped to extract work. Interesting features: 1. a useless feature can be recorded 2. errors can be made in recording useful features 3. the record may go out of date 4. the record may be erased and updated. "I suspect that the triad of matter, energy, and information is insufficient .....[and] the missing something concerns organization. " pg 103. "... a molecular autonomous agent achieves two different closures. First it achieves catalytic closure; all the reactions that must be catalyzed are catalyzed by molecular members of the system. Second, it achieves a closure in a set of propagating work tasks by which it completes a construction of a rough copy of itself. ..... the closure in catalytic and work tasks cannot be defined "locally" ..... [and] are typically collective properties of the entire autonomous agent in its environment. .....The propagating closure that is an autonomous agent appears to be a new physical concept that we have not known how to see before." pg 104

Category Theory may be a mathematical concept able to express the concept of propagating organization. Category Theory considers mappings between a domain and a range. An interesting feature of categories is that a category can have the property that the mapping from the domain to the range is specified by the category itself in a recursive way.; the elements of the range determine

the mapping from the domain to the range. This recursive specification comes close to an auto-catalytic set. However it seems necessary to specify ahead of time all the possible domains and ranges and mappings under consideration.

**5. The Physics of Semantics.**

“If the concept of autonomous agents were something like useful .... definition of life itself, then autonomous agents span the gap from the merely physical to that new realm of the merely physical where 'purpose' is ascribed by all of us to one another” pg 110

**Know-how**. Philosophers distinguish between know-how and know-that. Know-how predates know-that. Know-how is just the doings of autonomous agents..

**Semantics**. C.S.Pierce defines the semiotic triad : sign, signified and significans. It is clear that mere chemistry in an autonomous agent can harbor symbols and signs in the full sense of the words (eg RNA). Nowhere in the core of Shannon's work concerning the encoding and decoding of transmission of information does the meaning, or semantics, of the information enter. Shannon does hold a view that the semantic resides in the decoder but Kauffman disagrees unless the decoder is an autonomous agent. The definition of an autonomous agent is circular in that it is an entity with a purpose.

**Knowing.** Daniel Dennett's book *“Darwins Dangerous Idea”* advances a hierarchy of forms of knowing. Darwinian creatures evolve without behavioral learning. Pavlovian creatures has a nervous system and is capable of stimulus-response learning. Popperian creatures (vertebrates) have “internal models” of their world and can “run the internal model” with the clutch disengaged. Gregorian creatures (humans) utilize tools to enlarge our shared world of facts and processes – creating more know-how and know-that. Kauffman thinks that a lot of this hierarchy would find molecular realizations. “It is not much of a stretch to think of the immune system as a conditioned stimulus and response system” pg 116.

**Ethics**. Hume told us that we cannot distinguish 'ought' from 'is'. Rawls argued that human notions of fairness derive from what we would all contractually agree to, were we to know before birth that we would all be born with differing abilities and endowments. The foundation of Ethics requires first an ability to act and also a responsibility for those actions.

**6. Emergence and Story – Beyond Newton, Einstein and Bohr.**

**Hierarchies of Autonomous Agents.** There appears to be an indefinite hierarchy of autonomous agents – prokaryotes (single cell without a nuclei, e.g. E.coli) to eukaryotes (single cell with nuclei and mitochondria, e.g. Yeast) to multicellular organisms. Eukaryotes contain mitochondria and pant cells contain plastids with chlorophyll. Euaryotes are probably the symbiosis of two separate autonomous agents.

McCaskill attempted to create a computer soup of Turing machines which operated on one another. Wlater invented algorithmic chemistry using lisp and which allowed expressions to operate on one-another and found coppiers (type 1) and collectively auto-catalytic sets of expressions (type 2) but no further. Perhaps the limitation is that the collective properties of ordered sets of lisp expressions are not recognized and acted upon as collective objects. Tom Ray created Tierra where computer strings in live memory core reproduce and fight for space in the core.

“I will suggest that if we cannot pre-state the configuration space of a universe then “time” is real and necessary, and that the way a universe constructs itself may have analogies to a way a biosphere constructs itself.” pg 123

“physics is used to distinguish the initial and boundary conditions from the laws but in the evolution of a biosphere, the emergence of systems such as the genetic code and meiosis seems rather like the emergence of new laws.” pg 125

**The Furniture of the Universe.** Philosophers have struggled with the troublesome questions of emergence and reductionism. A strong form of reductionism states “x is nothing but y”. There seems to be no pre-stateable set of statements about physical events that is jointly necessary and sufficient for the truth of the statement. Concepts are defined in webs. Every word in the dictionary is defined in terms of other words. Are legal systems and human actions parts of the furniture of the universe or somehow above the locations and motions of atoms? A weaker form of reductionism casts an account of a higher level object, concept or phenomenon in terms of a sufficient but not necessary and sufficient set of conditions at a lower level. But what does this suffice for? Gold is a yellow malleable metal but nowhere in the quantum description are these macroscopic properties found. So then autonomous agents are parts of the ontological furniture of the universe and are more than the sum of their parts. But it is hard to walk away from the strong form of reductionism where causality is seen as only running upwards. Kauffman distrusts this as it makes the “decisions” of autonomous agents had to embrace.

**Adaptations, Exaptions, and the Impossibility to Finitely Pre-state the Configuration Space of a Biosphere.** A heart is to pump blood but it also makes sounds. We cannot know the functions of parts except in the context of the whole autonomous agent in the environment. Darwin pre-adaptions and Gould's exaptions express the notion that in an appropriate environment a causal consequence of a part of an organism that had not been of selective significance might come to be significant and hence be selected for. Is there a finitely pre-statable set of all possible potential biological functions? No! Newtonian science cannot be the whole story. Biologists tells stories about what happened and its semantic import. We do not deduce our lives – we live them.

**Forever Creative**. Kandal believes that a biosphere is profoundly generative – but why? The halting problem is an example of the impossibility of stating ahead of time what an algorithm will do. However, our capacity to pre-state the configuration space of a biosphere is not the failure to pre-state the primitives themselves. Godel's theorem proved that in every set of axiomatic system richer than arithmetic there would be statements that are true but unprovably so. Exaptions in evolution seem rather like the emergence of novel primitives. “Changing the biological laws in evolution seems rather like the generation of a novel axiom from which new consequences can be derived.” pg 137. However this alignment with Godel's theorem is not convincing. “My best bet guess is that the incapacity to finitely pre-state the configuration space of a biosphere is deeply related to the incapacity to enumerate and predict all the possible detailed dynamics of coupled molecular systems by any computational system in the universe.” pg 139

**7. The Nonergodic Universe – The Possibility of New Laws.**

The aim of this chapter is to explore the profound failure, on the scale of a sufficiently large closed thermodynamic system and, a fortiori, the open system of the biosphere, to come close to equilibrium on vastly long time scales with respect to the lifetime of the universe.

**The Actual and the Adjacent Possible**. The adjacent possible consists of all those molecular species that are not members of the actual, but are one reaction step away from the actual. In the last 4.8 billion years the biosphere has veritably exploded. Because the substrates are present in the actual and the products only exist in the adjacent possible there is a disequilibrium driving towards the adjacent possible. The total chemical potential from the actual to the adjacent possible is difficult to estimate but not small.

**The Nonergodicity of the Universe**. The universe, at levels of complexity of complex organic molecules is vastly nonergodic. There can only have been $10^{193}$ reactions since the big-bang but there are $10^{260}$ possible proteins of length 200 hence it would take $10^{67}$ times the current age of the universe for all to be possibly explored. And the situation is getting rapidly worse with no obvious upper bound. But this is driving in the opposite direction to the eventual heat-death of the universe when all heat difference required for the Carnot cycle are equalized. (see thoughts below)

**Formalizing the Adjacent Possible**. The dimensionality of the adjacent possible for the whole earth is between 0 and 2 to the power $10^{41}$. Heisenberg's uncertainty principle states where at the quantum level the current micro-state can have an aptitude to flow to many of the adjacent micro-states (rather than just the one in classical physics).

**Historical Expansion to the Adjacent Possible and Hints of a Law**. The adjacent possible of the earths biosphere has increased dramatically in the last 4.8 billion years. It is interesting to note that living cells do straddle the quantum classical boundary in that one photon hitting a visual pigment molecule can beget a classical neural response. “More, at the risk of saying something that might be related to consciousness, the persistent de-coherence of persistently propagating superpositions of quantum possibility amplitudes such that the de-coherent alternative becomes actualized as the now classical choice does have at least the feel of mind acting on matter.” pg 150. (see notes)

**Bounds on the Growth of the Biosphere's Adjacent Possible**. There are two schools of thought on extinctions: the catastrophists (ie a meteorite hit the dinosaurs) and the endogenists (who note the power law distribution of the size of extinction events). If we took all the currently available molecules in the biosphere and blended them then the result would be supercritical with every different reaction finding 100 different protein catalysts. But individual cells are not supercritical as the addition of a single random protein has between a 0.1 and 0.0001 chance of catalyzing a reaction. If cells were supercritical they would forever generate internal molecular diversity and many of the novel molecules would poison the cell. Cells and cells in communities must remain sub-critical to survive. The isolation of the chemical constituents of a cell is what separates the sub-critical cell from the potentially supercritical blended biosphere. “The inverse argument allows the diversity of the community to increase by immigration or mutation of current members. This suggests a possible tendency of local communities to move towards the subcritical-supracritical boundary.” pg 154. “Eigen and Schuster elegantly relate the known mutation rates of viruses to the sizes of their genomes and show that viruses are close to but below the error threshold where selection can still overcome the melting [of a local fitness peak and spread across the fitness landscape]” pg 155. “All this suggests the hypothesis that a biosphere expands to the adjacent possible, about as fast as it can get away with such exploration, subject to the requirement that selection must on average be strong enough and fast enough to slightly more than offset the rate of exploration of novelty.” pg 155 Morowitz has calculated that the average energy per unit volume of the biosphere of the earth is near the temperature where the number of stable extending bonds (like C=C) are at a maximum in relation to the stable terminating bonds (like -OH).

**8. Candidate Laws for the Co-construction of a Biosphere.**

**Candidate Law 1: The Dynamical Edge of Chaos**
**Boolean networks.** can be constructed as an idealization of the DNA activities in a cell. Consider that the human genome has about N=80,000 genes, each either on or off. The state of each gene is regulated by the state of some of the other genes. There are $2^{80,000}$ possible states of the network so clearly only a small fraction of these states is actually sampled. In a deterministic system each state has only one successor state. Some states will be transient and others will be part of a recurring loop of one or more states (an attractor).

**Order, Chaos, and the Edge of Chaos**. Genes in the ordered regime are those which rarely if ever change while those in the chaotic regime change very frequently. Regions of chaotic and order can coexist in a fairly stable manner within a system. There is evidence that in the ordered regime near the phase transition to chaos, the number of states on a state cycle scales as the square root of the number of genes (ie $80{,}0000^{.5}$=270 states). The scaling is polynomial in the ordered regime and exponential in the chaotic regime. In fact it takes 1-10 minutes for a eukarotic cell to turn a gene on or off which translates to a state cycle of 5-48 hours. A plot of median cell cycle times vs total DNA per cell is close to a square root function from bacteria to human cells. If a single gene is disrupted (changed from 0 to 1 or vise versa) then the knock on effect spreads very broadly in the chaotic region but the extent of the propagation in the ordered region obeys a power law (many of small extent and a few of large extent). If the chaotic regions are islands within the ordered regions then disruption in a chaotic region is contained by the ordered surrounds. If the disruption is in the chaotic region but near the phase transition then the filaments of ordered area can contain disruption. The Hamming distance between state 1 and state 2 is the number of binary variables by which the two states differ (divide by the number of variables for normalized Hamming distance). The system is increasingly chaotic if the hamming distance increases from one time to the next. Three parameters tune the stability of the system. First, if the number of inputs per gene K>2 then the Hamming distance is increasing. Second, P is the number of instances of the majority value over the full set of cases (ie P=5 for 10101011 and P = 6 for 00011000). Third, canalizing boolean functions have at least one input with at least one value that suffices to guarantee the next state of the regulated gene, regardless of the value of the other inputs. A sufficient bias towards a high fraction of genes with a sufficiently high number of canalizing inputs will drive a system towards being ordered. Phase transitions occur as a function of K, P and C.

**The Biology**. "Being autonomous agents, cells must, as individuals living in communities, make the maximum number of reliable discriminations possible and act on them reliably without 'trembling hands'. ..... slightly convergent flow in state space allows classification, for when two states converge on a single successor state, those two states have been classified as 'equivalent' by the network. Slightly convergent flow would seem to allow the maximum number of reliable classifications in the face of a noisy environment." pg 177 Real regulated genes show a dramatic excess of cases where K=3, C=3 and where K=4, C=4. Furthermore, this result is even stronger within P classes. If the operation of cells lies in the ordered regime then each state cycle attractor corresponds to a cell type (liver, kidney, etc). The ordered region (frozen core) corresponds to the core set of genes shared by all cell types with the differences making up only a few percent. Cellular differences correspond to the perturbation that moves the network from one attractor to another – and a succession of perturbations differentiates along branching development pathways to a large number of cells types. The best location for real cells in phase space may be close to but a little back from the phase transition to provide a buffer from disruptions from the chaotic region.

**Candidate Law 2: Community Assembly Reaches a Self-Organized Critical State**. Work by Pimm and Post in the late 1970's made use of the Lotka-Volterra equations which say for any species, what other species it eats, how readily it turns the eaten prey into an extra copy of itself , and how fast it reproduces on its own without eating. They found that when random species were added to a uniform environment that after each addition the ecology would settle down into a stable balance of surviving species but there came a point where the number of surviving species could not be increased despite additions. The Ksat problem involves boolean expressions with multiple variables and three operators: and, or and). There is a phase change between expressions which are easily satisfied and those which are very difficult to satisfy where the ratio of Clauses to Variables exceeds ln 2 x 2K where K=C/V. This can be related to previous example with each variable corresponding to a species and the expression corresponding to which species eats each other in the environment.

**Candidate Law 3: Co-evolutionary Tuning of Fitness Landscapes and Organisms to a Self-Organized Critical State**. Darwin Evolution progresses by gradual selection where most mutations are of minor effect but how did it arrive at this. If you create a computer program and randomly

change one symbol then the effect is typically disastrous. A computer program with all of the redundancy taken out is indistinguishable from a random string of bits and a change to one bit (hamming distance = 1) is almost always devastating. Now evolutionary processes use recombination and mutation but no search procedure works equally well on all landscapes so there are some complex systems which cannot be constructed by evolutionary processes. “Organisms are not solving arbitrary problems. We are solving the kinds of problems we can solve given our solution procedures. How could it be otherwise?”.

**A Sojourn to Co-evolution in the NK Model**. The NK model is a toy world in which organism has N genes with two alleles (0 and 1). The fitness of an organism depends on the contribution from each gene which depends on its value and the value of K other epistatic genes. The 2N combinations of alleles of the N genes are located on the vertices's of an N-dimensional hypercube. The NK model creates a fitness landscape over the N-dimensional boolean hypercube. Choose N and K and assign alleles and fitness values randomly. When K=0 all genes are independent and it is a basic hill-climb. When K=max then the landscape is random with an exponential number of random peaks. When organisms co-evolve, a change to one organisms fitness will also change the fitness of the the co-evolving organisms – the fitness landscape heaves and deforms. In general these systems operate in the ordered or chaotic regime. In the chaotic regime the landscape changes faster than each organism can adapt to a local peak. If by chance the tuned landscape structure is advantageous to all then then it tends to persist and tune the fitness landscapes (for instance to a landscape which is advantageous to the search procedures in use by all). The organisms and the environment co-evolve.

**Candidate Law 4: Expanding the Adjacent Possible in a Self-Organized Critical Way**. “ ..if the community is super-critical, the novel cascading molecular species will kill off some of the microbal species, thereby lowering the community to the sub-critical regime. On the other hand, mutation and immigration should drive the community towards the supercritical regime.” pg 207. “We broach the adjacent possible by those exaptions that are not, I hold, finitely describable beforehand and do so at a rate that manages to work. We gate our entry into the adjacent possible.” pg 208

**Chapter 9. The Persistently Innovative Econosphere.**

Economics has considered itself the science of the allocation of scarce resources. However, current economic theory has no account of the persistent secular explosion of the diversity of goods, services and ways of making a living.

**General Competitive Equilibrium and its Limitations**. Conceptual general equilibrium grows out of a conceptual framework in which the core question is how prices form such that markets clear. For a single good, markets clear where the supply and demand curves intersect. However, two goods such as bread and butter have dependent supply and demand curves. Furthermore these curves change over time and are contingent on many other possible futures such as the quality of the wheat crop. In the Arrow-Debreu theory, we are to imagine an auctioneer, who at a defined beginning of time holds an auction covering all possible dated contingent goods., with values calculated under different future hypothesis. It fundamentally depends on a fixed-point. Economists distinguish between normal uncertainty and knightian uncertainty (where the possible outcomes are unknown). Arrow-Debreu is impressive but fundamentally flawed. Growth in wealth per capita is deeply related to the growth in the diversity of the economy.

**Rational Expectations and its Limitations**. An extension of the theorem to Rational Expectations was an attempt to understand trading on the stock exchange. However, it is another fixed-point theorem. It assumes a set of economic agents with beliefs about how the economy is working that act on those beliefs. However it may not be stable under minor changes in beliefs and demands excessive rationality to fit real human agents.

**Natural Rationality is bounded**. Vince Darley as Harvard prepared a thesis that endeavored to find a natural bound to infinite rationality and a natural sense of satisficing. Typically, optimum prediction of price is achieved by fitting limited historical data with 4-5 Fourier modes. Agents who have theories of one-another and act selfishly based on those theories will typically create a persistently changing pattern of action. As the system of agents and actions settles down to some repeatable behavior an increasingly wide range of complex theories, simple and very complex fit the same data. But the complex theories attempt to predict fine details, and as a result become more fragile to the inevitable minor disturbance. At this point theories and actions can change radically but often settle down to a point not far from the originally stable behavior.

**Technology Graphs and Economic Webs**. Kauffman founded Bios Group Inc with Ernst and Young. Boeing wondered how to design and build airplanes in one year rather than seven. Kauffman bought a Leggo kit. A set of primitive parts and the transformation of those parts into other objects is a technology graph. An economic web is a set of goods and services in an economy, linked by red lies between substitutes and green lines between compliments. As the diversity of objects increases the diversity of prospective niches for goods and services increases even faster (i.e. a major driver of economic growth). Economic growth in a city is correlated with economic diversity. Micro-financing of a linked diversity of cottage businesses in the third and first world seems to be achieving local economic growth more than massive efforts at education and infrastructure. The Java object library is another example of a rich and increasing library of primitives may be very powerful if coupled with search engines to discover compliments and substitutes. Military operations is another example. "Technology graphs concern objects and actions, things and objectives, products and processes in a single framework." pg 228

**Robust Constructibility.** A construction pathway is more robust if there is multiple possible construction pathways. Increasing the number of construction steps from the minimum may significantly increase the available pathways. When making sub-assemblies it makes sense to hold stock of sub-assemblies that have multiple possible future pathway rather than stopping at points where the lack of a single part or process will block the only (few) available manufacturing pathways.

**A Phase Transition in Problem Solvablity.** Consider that you are on a fitness landscape and the tide is rising and/or the landscape itself is heaving and changing. It makes sense to stay on the most connected portion of the landscape above tide level rather than simply hill climbing. There is a survival phase transition as a system moves from connected ridges to isolated peaks above the tide line. One measure is the Hausdorff dimensionality which measures how rapidly the points of acceptable (equal or better) fitness are growing. The Hausdorff dimensionality is the ratio of the logarithm of the fitness of acceptable 2-mutant neighbors with the logarithm of the fitness of the acceptable 1-mutant neighbors. In the survivable regime the Hausdorff dimension is on average greater then 1. Typically, every time a fitter 1-mutant neighbor is found, the fraction of 1-mutant neighbors falls by a constant fraction (known as the learning curve). We can control the statistical structure of the search space such that a solution is more readily solvable. Unilever report that plants that manufacture multiple products do well until the number of products reaches 27 then they fail. This can be considered as a Ksat problem that crosses the phase transition boundary from solvable to insolvable. However, if Unilever could lower the number of conflicting constraints by storing poly-functional sub-assemblies then they could drive the plant back into the solvable regime. "Thus, by use of the technology graph to design both products and processes, we can choose a family of products and construction pathways with highly redundant intermediate objects. That choice makes the problem space easy to solve rather than hard to solve. We have thereby tuned the statistical structure of our problem space into a survivable regime. Furthermore, we can test whether our choice of construction pathways to the house and/or house with a chimney is robustly survivable or in the living dead—isolated peaks regime. We need merely use the technology graph to test for percolating sets of i-mutant neighboring pathways of construction of the same objects and the average Hausdorff dimension of such pathways. No need to operate in the isolated peaks regime. Indeed, if you face loss of parts and machines, you had best locate back from the phase transition, deep enough into the survivable regime to survive. And if you are a military force fighting against an enemy whose strategy changes persistently deform your payoff landscape and whose efforts are to destroy your capacity to fight, you had best operate even further back from the phase transition in the survivable regime." pg 237. "Ways of making a living that cannot be well searched by an organism and their mutation recombination search procedures will not be well populated." pg 239.

**Chapter 10: A Co-constructing Cosmos?**

The Universe has become enormously more complex and we do not know why. General relativity and quantum mechanics have both been verified to 11 decimal places but remain isolated from each other and Darwin's theory of evolution.

**The Complexity of the Universe.** Smolin notes that the physical constants in the universe are very finely tuned to allow the complexity that we see.

**Quantum Mechanics and Classisity**. Feynman notes that there is no way in classical physics to explain the two-slit experiment where a single light source at a single frequency causes a diffraction pattern through two-slits but a Gaussian pattern through one slit. Quantum mechanics explains this behavior but the transition from quantum possible events to classical actual events remains difficult. Feynman's approach is to take the sum over all possible trajectories or histories but it assumes a continuous background space and time (which has problems) and it only gives a maximum amplitude rather than actually counting photons arrivals. De-coherence is an alternative approach requires that literally all the propagating possible pathways in Feynman's sum over histories that are to arrive at each point on the photon-counter surface do in fact arrive at that point. De-coherence, affords a way that phase information can be lost thereby collapsing the wave function in a non-mysterious way.

**An Outsiders Doubts**.

And at this point it all became very technical.....and I lost interest.....

**Further Reading**

- Erwin Schrodinger authored "What is Life" in 1944
- Wittgenstein, Philosophical Investigations
- McCaskill at Santa Fe Institute attempted to create a computer soup of Turing machines which operated on one another.
- Walter algorithmic chemistry
- Vince Darley, Harvard thesis
- boolean networks at the beginning of chapter 8
- read about technology graphs on pg 228
- John Welsh
- Glass, L. & Hill, C. (1998) *Ordered and disordered dynamics in random networks.* epl