



BEYOND PHYSICS: THE EMERGENCE AND EVOLUTION OF LIFE

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1) The historicity of life and its evolution in the non-ergodic universe above the level of atoms: The universe cannot make all possible proteins length 200 amino acids in 10 to 39th times the history of the universe. Most complex things, such as a human heart, will never exist. A fundamental question: Why have hearts come to exist in the universe since the Big Bang? Hearts abet survival, so come to exist in the non-ergodic universe through the emergence and evolution of life. This “becoming” is a non-ergodic, hence historical, process.

2) One way to “get to exist” in the non-ergodic universe, hence historical process, above the level of atoms, is to be a living organism, i.e. a Kantian Whole, where the parts exist for and by means of the whole. Collectively autocatalytic sets of, e.g., peptides, are Kantian Wholes and do this. Living cells are also collectively autocatalytic sets, see next slide.

2b The FUNCTION of a part is its causal role in sustaining the Kantian whole. Functions are SUBSETS of the causal consequences of the part. In a collectively autocatalytic set of peptides, (see next slide), the function of each peptide is to catalyze the formation of a second copy of the “next” peptide in the set. Jiggling water in the petri plate is not the function of that peptide.

2c Thus “functions” are legitimate categories in science in the historical becoming of the non-ergodic universe above the level of atoms.

2d. “Functions” do not exist in physics, which cannot discriminate “functional subsets” of causal consequences.

2e We will see in this presentation that what “gets to exist” in the non-ergodic universe above the level of atoms in the evolving biosphere includes ever new, unprestatable “functions” that abet the survival of the organisms having those functions, e.g . eyes and sight. It will follow that biology cannot be REDUCED to physics.

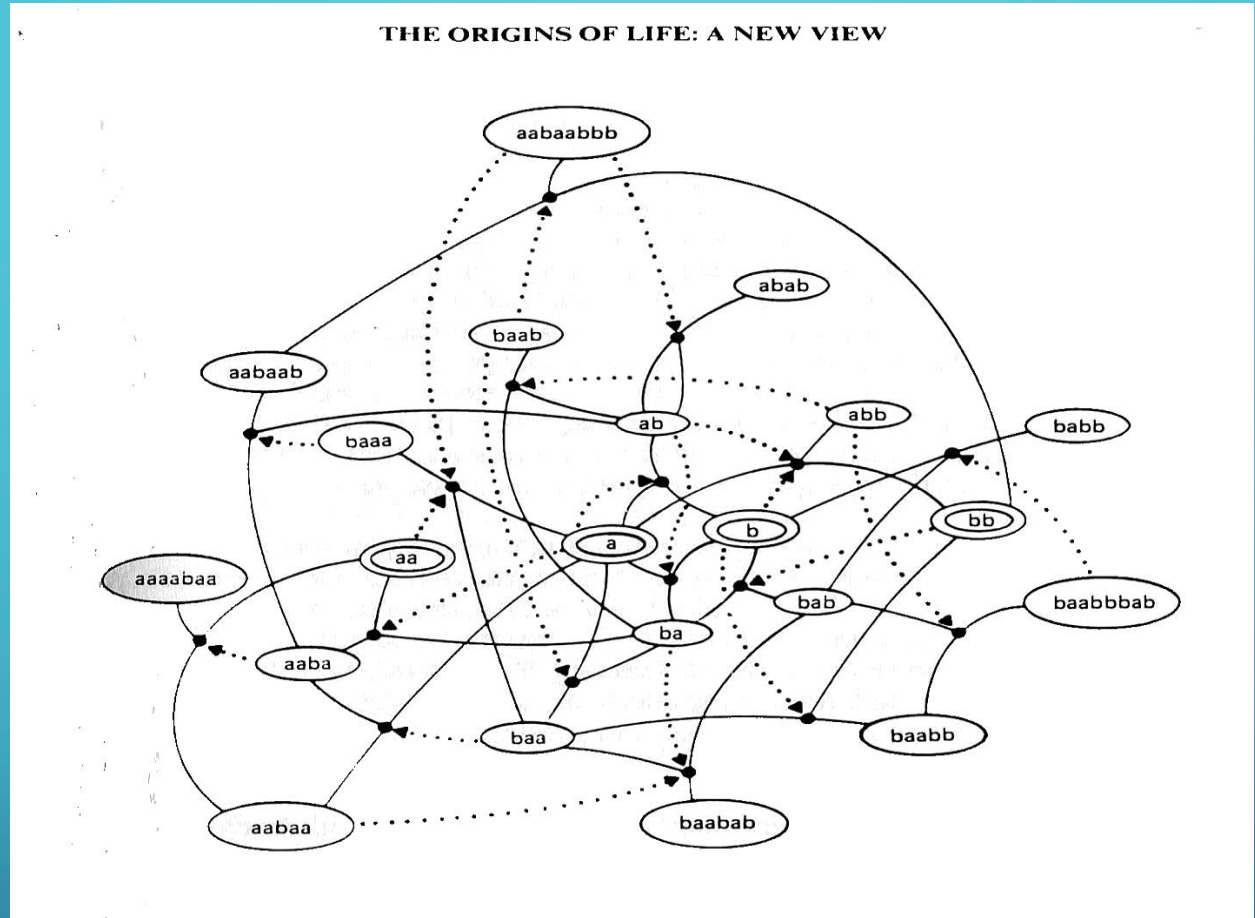


Figure 1. Collectively autocatalytic set. Symbol string are molecules. Dots are reactions. Black arrows go from substrate molecules to reactions to product molecules. Dotted arrows from molecules to reactions show which molecule catalyzes which reaction. Double circles are exogenous food set. The function of a peptide or RNA is catalyzing the reaction forming the next peptide or RNA, not jiggling water in petri plate.

3) MONTEVIL MOSSIO: CONSTRAINT CLOSURE, a fundamental new concept re life i.e. in “autocatalytic sets” and living cells: Links thermodynamic work and constraints on the release of that energy do work to construct its own boundary conditions to build itself. System also does thermodynamic work cycle.

3a Work is force acting through a distance, from $F = MA$

3b, Peter Atkins: work is the constrained release of energy into a few degrees of freedom.

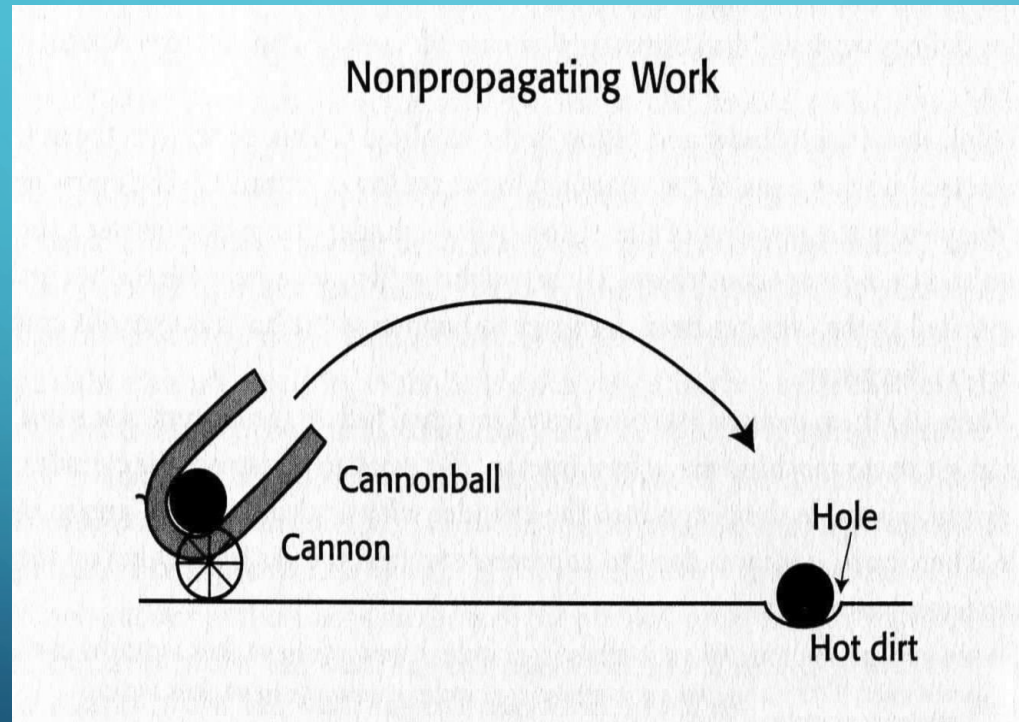


Figure 2. Cannon firing cannon ball, hits ground, hole, hot dirt. = Non Propagating work. KAUFFMAN Investigations OUP 2000

The cannon is the constraint on the release of powder explosion energy into a few degrees of freedom to do work to fire cannon ball out cannon.

$C_i =$ Cannon constraint on release of energy



$A \text{ --@--} \rightarrow B =$ constrained non-equilibrium process fires cannon ball and does work on cannon ball, endergonic process.

But it took **WORK** to construct the cannon, and cannon ball, place powder inside and put cannon ball inside the cannon!

No constraints no work. No work no constraints. The W-C cycle!

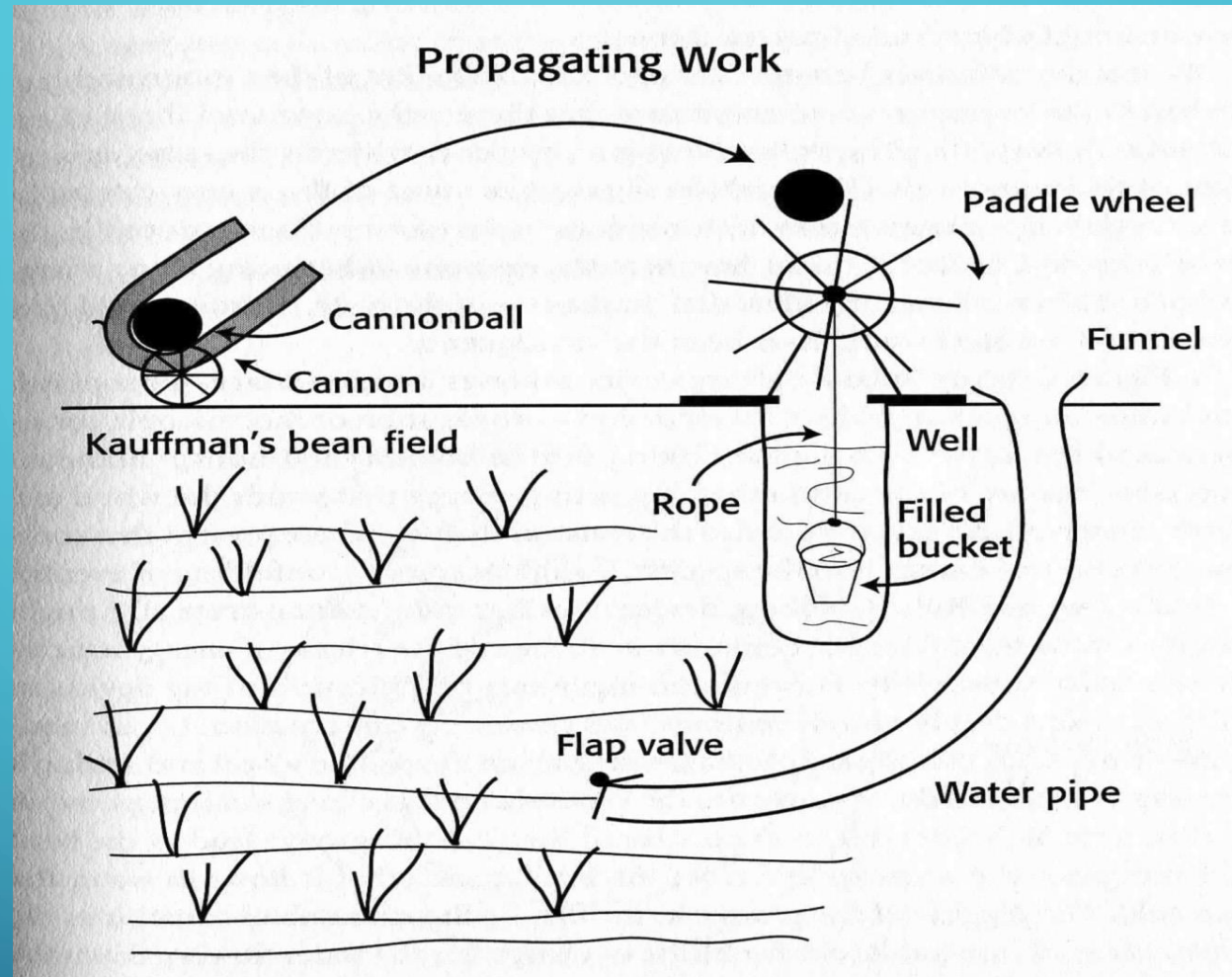


Figure 3. Propagating work. Cannon fires same cannon ball that hits paddle wheel doing work to make it spin, winding up a rope tied to axle and thereby doing work to wind up rope tied to water filled bucket in well, which bucket tips over axle and spills water into a funnel down a pipe to water my bean field. KAUFFMAN investigations Oxford University Press 2000

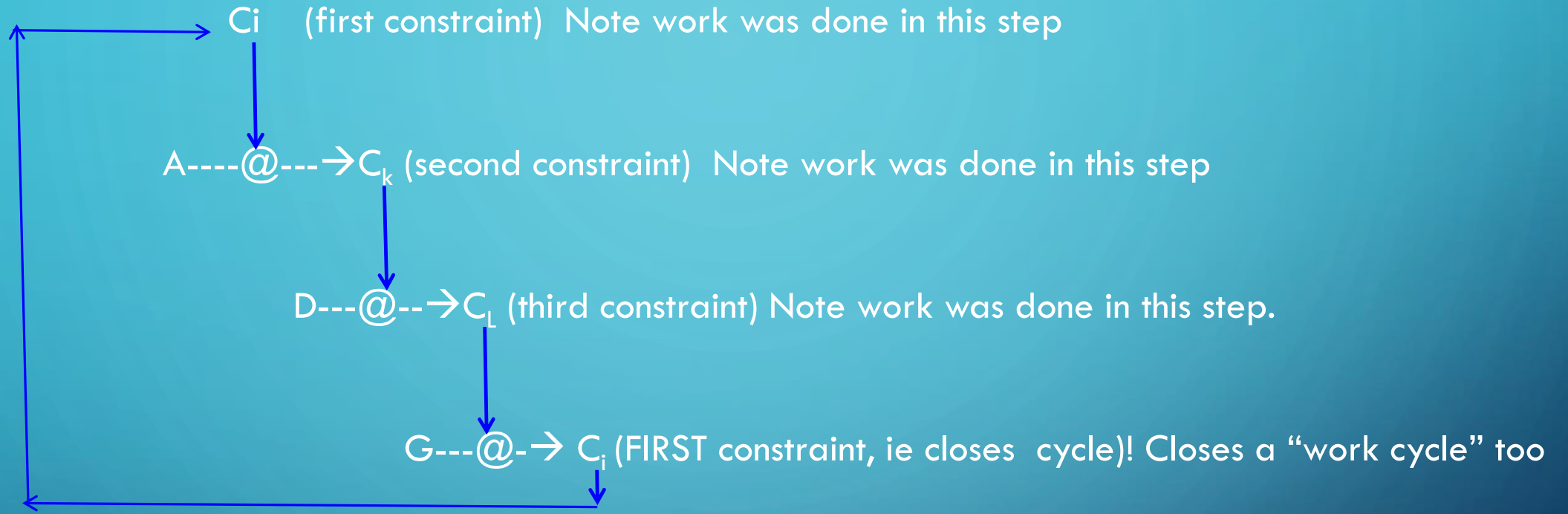
PROPAGATING WORK

C_i C_i ($C_i = \text{cannon}; C_i = \text{paddle wheel}$)
↓ ↓
A-----@----->B -----@----->C (B = fired ball, C spinning wheel) Note: work is done
on cannon ball by exploding powder and on paddle wheel hit by cannon ball

∨ PROPAGATING WORK CONSRUCTS A CONSTRAINT!, C_k

C_i C_i ($C_i = \text{cannon}; C_i = \text{paddle wheel}$)
↓ ↓
A-----@----->B -----@-----> C_k (C_k is a new constraint. The water dumped from
pail cuts ditch in hill side down to my bean field, can be used rather than the tube)

vi. MONTEVILE AND MOSSIO'S CONSTRAINT CLOSURE

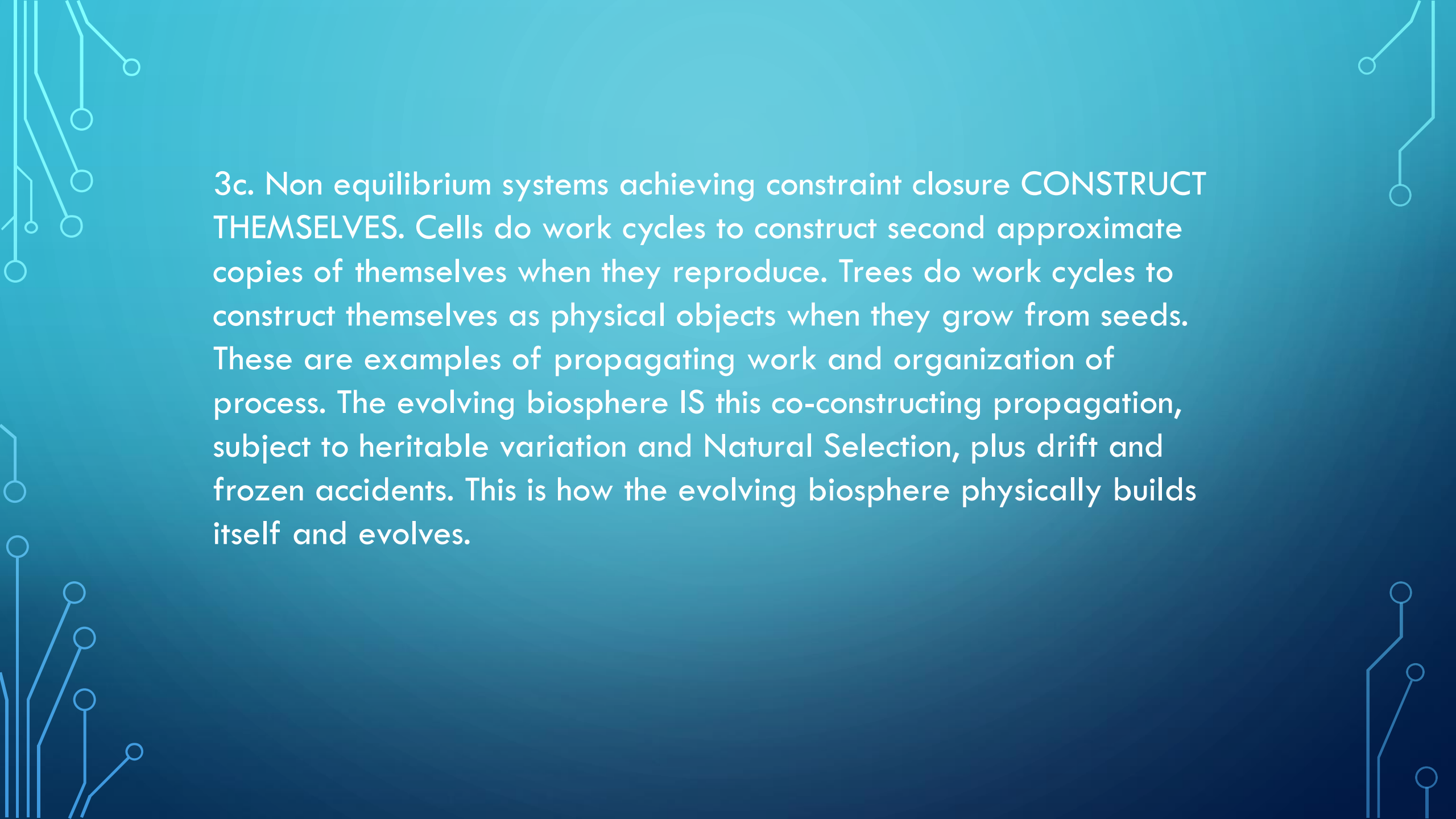


Constraint Closure systems couple a set of non equilibrium processes and the constraints on the releases of energy to do work that constructs the very same constraints, or boundary condition on the same non equilibrium processes. This is a non-equilibrium self constructing system that does a thermodynamic work cycle to construct and assemble its own parts into a working “whole”! IT CAN REPRODUCE ITSELF.

THIS IS A “MACHINE” THAT DOES WORK CYCLE TO BUILD AND ASSEMBLE ITS OWN WORKING PARTS!
CARS DO NOT DO THIS! REPRODUCING CELLS TO THIS!

Life is a fundamentally new linking of non-equilibrium processes and constraints on the release of energy in such processes into a few degrees of freedom that thus is thermodynamic work. But, stunningly, the work done in one such non-equilibrium process as its energy is released can CONSTRUCT constraints on the release of energy in further non-equilibrium processes. In reproducing systems such as cells, a CLOSURE is achieved linking such non-equilibrium processes and constraint construction into an “organization” that closes on itself, so the non-equilibrium work done by the constrained releases of energy constructs the same constraints in a THERMODYNAMIC WORK CYCLE.

Such a system is a “machine” that does work cycle to construct and assemble its working parts. It thus REPRODUCES ITSELF. This concept of “constraint closure” due to Montévil and Mossio, is new and fundamental. It is not matter alone, energy alone, free energy alone, boundary conditions alone, but a new union of these. In Newtonian physics boundary conditions are essential but outside Newton’s laws of motion. We do not know where the boundary conditions come from. Living systems, due to constraint closure, literally do work cycles to co-construct their own specific boundary conditions, for constraints on the release of energy ARE boundary conditions.

The slide features a dark teal background with decorative white circuit-like lines in the corners. These lines consist of vertical and horizontal segments connected by diagonal lines, ending in small circles, resembling a stylized network or data flow diagram.

3c. Non equilibrium systems achieving constraint closure **CONSTRUCT THEMSELVES**. Cells do work cycles to construct second approximate copies of themselves when they reproduce. Trees do work cycles to construct themselves as physical objects when they grow from seeds. These are examples of propagating work and organization of process. The evolving biosphere IS this co-constructing propagation, subject to heritable variation and Natural Selection, plus drift and frozen accidents. This is how the evolving biosphere physically builds itself and evolves.



WE HAVE INSTANTIATED “VITALISM”!

THE ANCIENT AND DISMISSED IDEA OF “VITALISM” IS PRECISLY REALIZED IN NON-EQUILIBRIM SYSTEMS THAT ACHIEVE CONSTRAINT CLOSURE AND SYNTHESIZE THEIR OWN BOUNDARY CONDITIONS ON THE NON-EQUILIBRIUM RELEASES OF ENERGY, IE WORK, BY WHICH THEY HARNESS THE SAME NON-EQUILIBRIM PROCESSES TO CONSTRUCT THEMSELVES.



WE HAVE FOUND THE “LIFE FORCE”

THE ORIGIN OF THE LIFE FORCE

4b. Binary Polymer model: Polymers, Peptides and/or RNA, are binary strings up to length N . Cleavage and Ligation Reactions. Reaction graph among polymers. Each polymer has probability P to catalyze each reaction. Ratio of reactions to polymers scales as N as N increases, ie more reactions than polymers. Given fixed P , for N large enough, each polymer catalyzes at least one reaction and collectively autocatalytic sets emerge as a phase transition similar to random graphs. For two substrate two product reactions with a diversity of species M , the ratio of reactions to molecular species scales as M squared. As the ratio of reactions to molecules, R/M becomes larger as M increases, then for any P , the emergence of autocatalytic sets as a phase transition becomes easier.

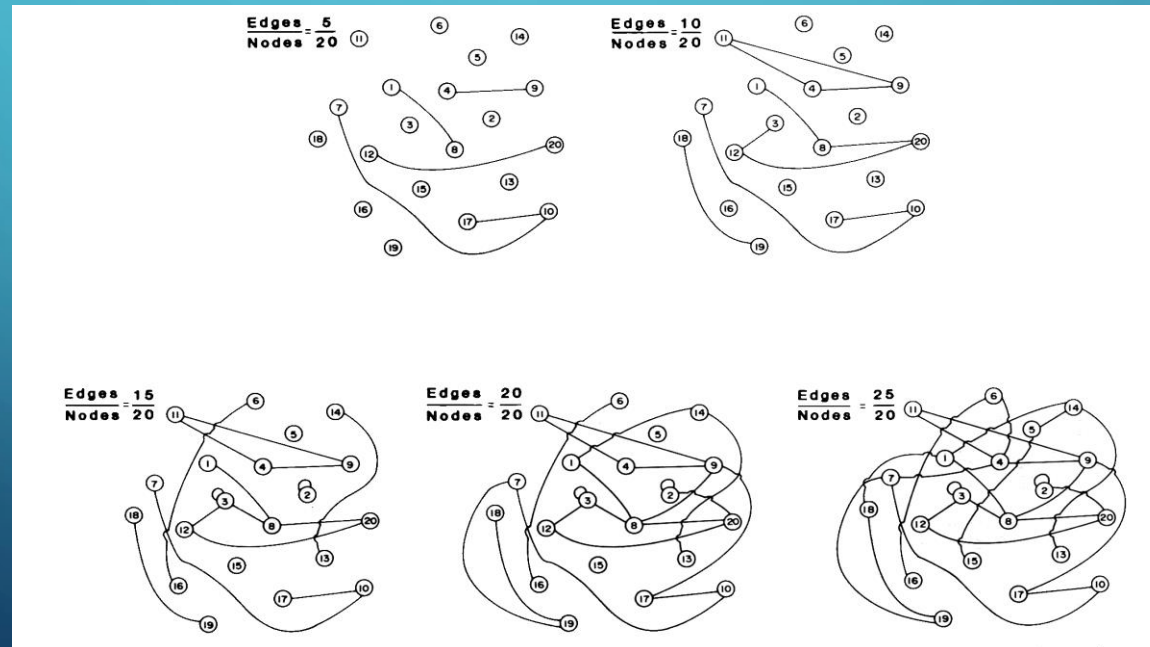
4) The emergence of such constraint closures IS the problem of the origin of life.

4A The Theory of the spontaneous emergence of collectively autocatalytic sets of peptides or RNA systems, their performing of work cycles and achieving constraint closures:

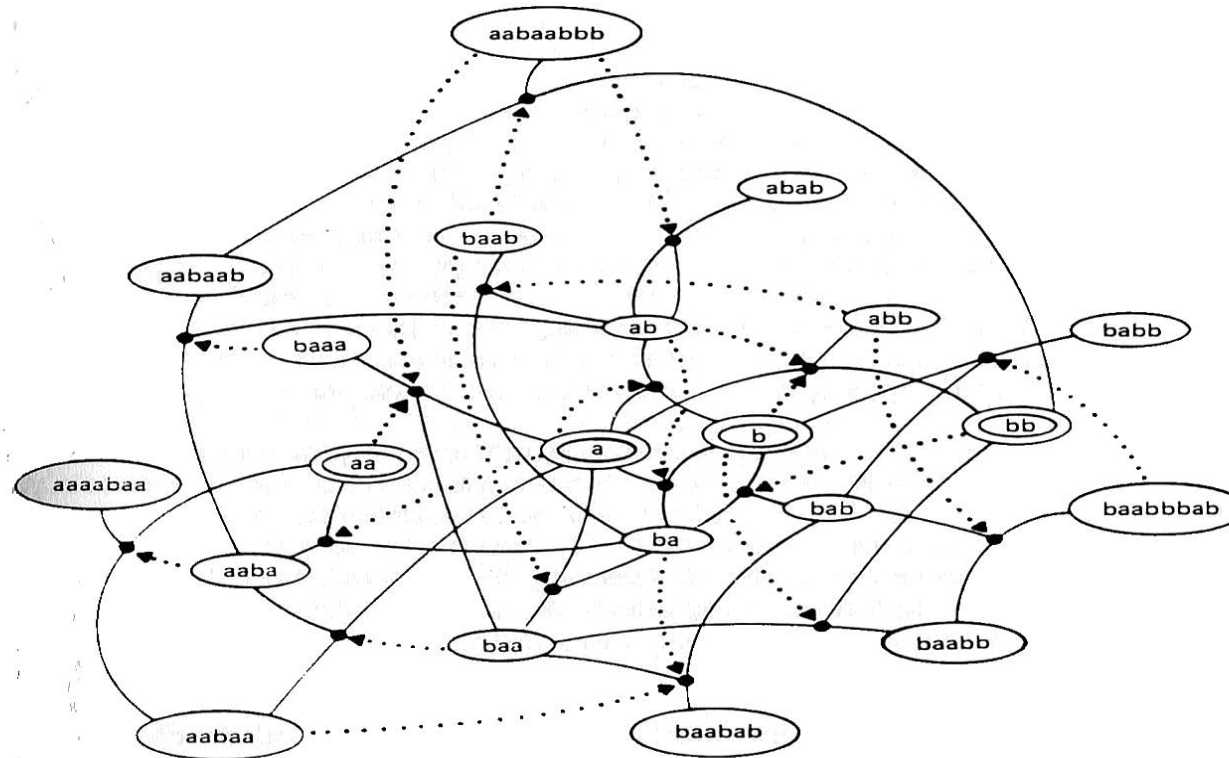
Collectively autocatalytic set, CAS: 1) A set of food molecules and a reaction network such that each member of the set has the last step in its formation catalyzed by at least one member of the set 2) Reactions leading from the food set are catalyzed by members of the CAS. <- (Kauffman 1971, 1986, 1993, RAF, Steel and Hordijk)-> 3) uncatalyzed reactions happen slowly.

4A.I PHASE TRANSITION IN RANDOM GRAPHS

Erdos and Renyi studied the evolution of “random graphs” where N nodes are connected by E edges, as the ratio of Edge to Nodes, E/N , increases. As E/N increases from 0.0 to 1.0 and higher, a “first order phase transition” occurs when $E/N = 0.5$. Before this, small clusters of connected nodes grow in size. At $E/N = 0.5$, suddenly a large connected cluster, or “giant component” forms, with a diversity of “cycles”. As E/N increases further, remaining isolated nodes become tied into the giant component. Figure 4.



THE ORIGINS OF LIFE: A NEW VIEW



Circled binary strings are molecules, dots are reactions, solid lines lead from substrates to reaction dots to products. Dotted lines lead from molecules to the reactions they catalyze. Double circles are around the “food set” molecules supplied exogenously. Thus, non-equilibrium system, achieves constraint closure and work cycle – see below. Function of polymers is to catalyze “next” reaction.

4b.1. Experimental work: Ashkenasy has 9 peptide CAS. Lehman, spontaneous formation of Collectively Autocatalytic Set from halved ribozyme library. Living E. coli metabolism collective autocatalytic set, Szathmáry; Hordijk. Current cells, DNA-RNA-encoded proteins are CAS.

4c. Collectively autocatalytic sets ACHIEVE “Constraint Closure”. Ashkenasy has a nine peptide collectively autocatalytic set. The nine peptides are linked cyclically. Each catalyzes the reaction forming a second copy of the “next” peptide. The next “copy” of each peptide is formed in a reaction among two fragment peptides which, when ligated together, form the new second copy. This reaction remains a non-equilibrium process if the two fragments are supplied exogenously as “food”. Each such reaction is catalyzed by the “prior” peptide in the nine peptide cycle. The catalyzing peptide does thermodynamic work to bind the two fragments forming the next peptide in the cycle, hence catalyzes that ligation reaction by lowering the energy barrier of the reaction. Thus, that reaction energy is released in a constrained way and does work. The whole set does a thermodynamic work cycle.

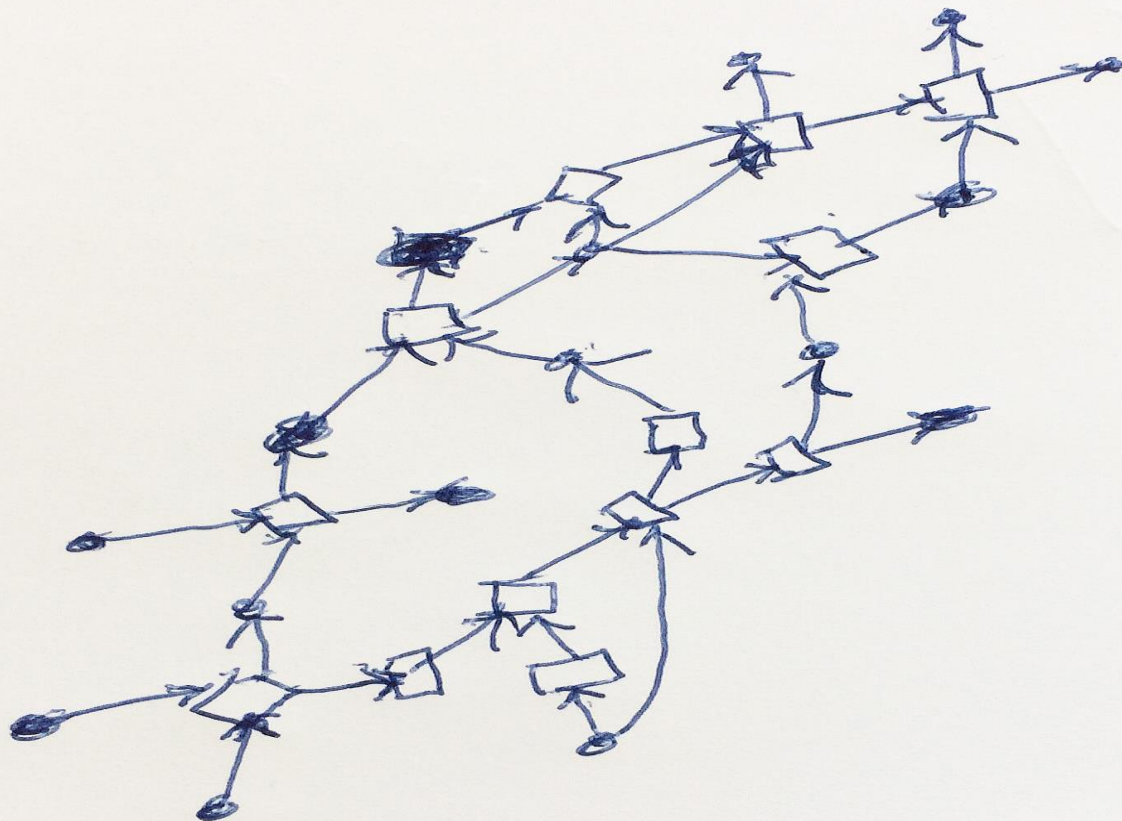
4d. Emergence of a connected catalyzed metabolism whose reactions are catalyzed by the CAS. Chapter 9, Origins of Order 1993. Propose that metabolism can synthesize lipids endergonically to form bilipid liposome housing collectively autocatalytic set and supporting metabolism (see below) -> PROTOCELL.

CHEMICAL REACTION GRAPH: DOTS = MOLECULES, BOXES = REACTIONS.



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Dots = molecules
□ = reactions


CATALYZED REACTION SUBGRAPH IS "RED". THE DOTTED ARROW FROM EACH CATALYST, C_i , GOES TO THE REACTION IT CATALYZES

Add Random Catalysts C_i

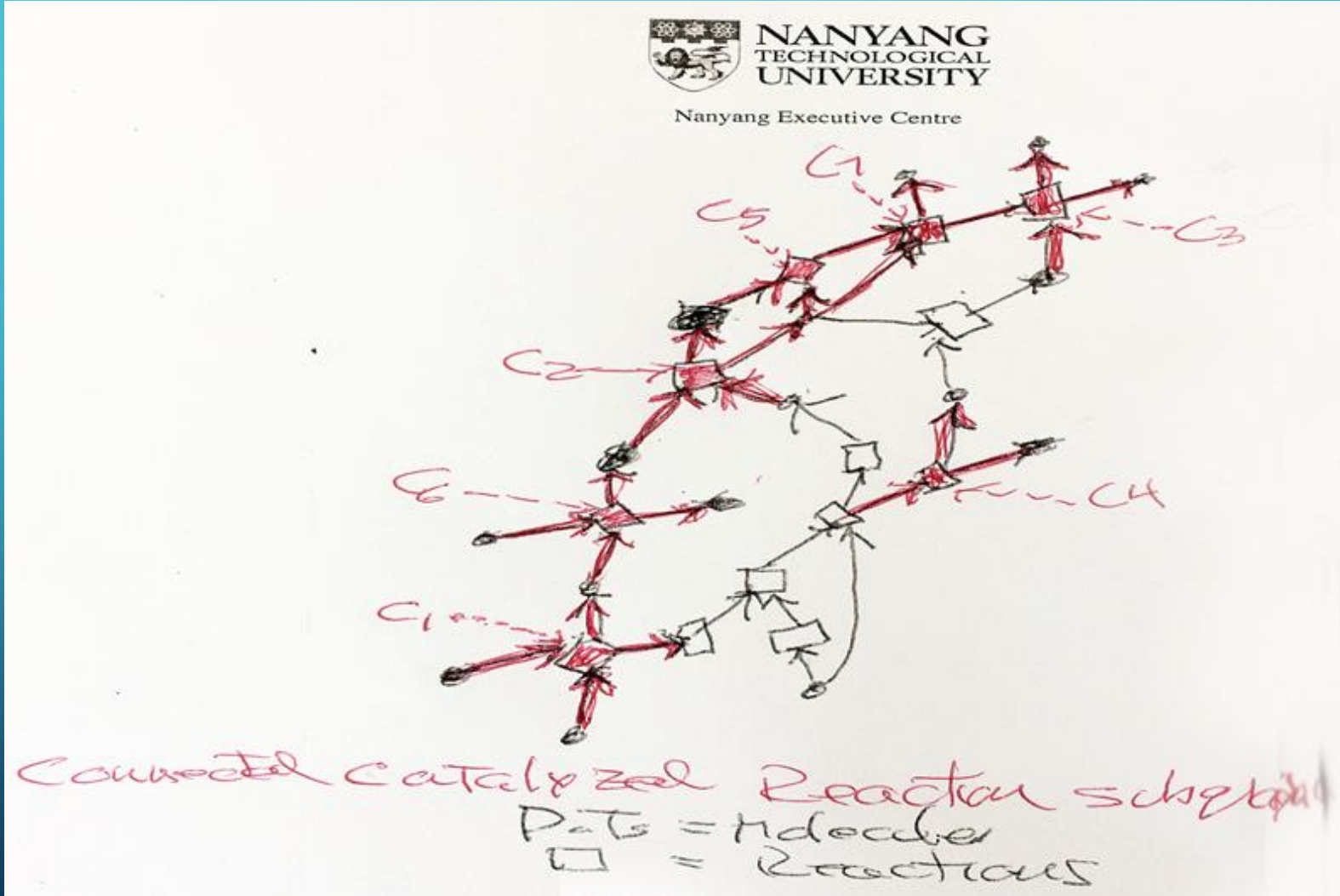


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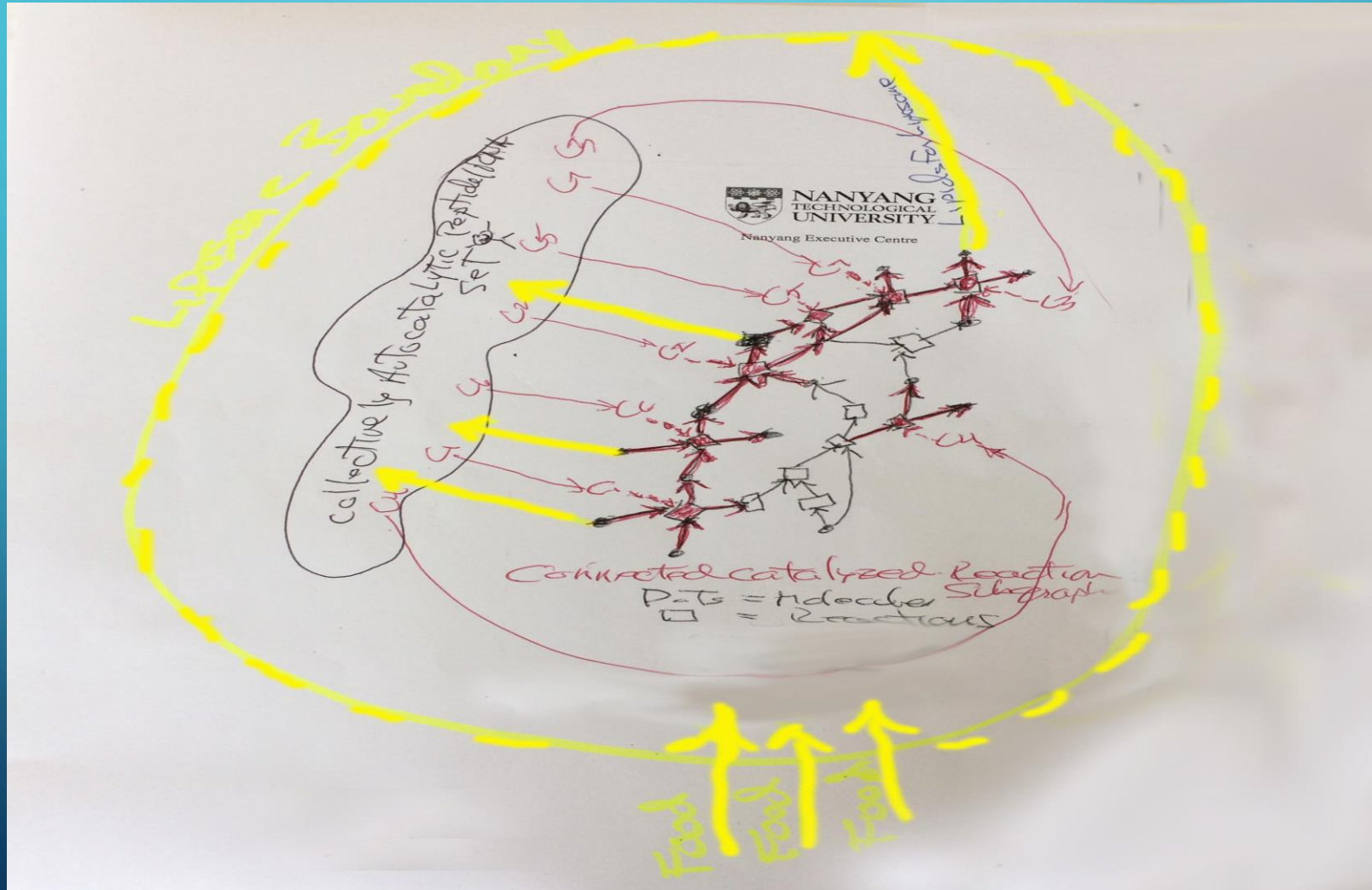


 CATALYZED REACTION subgraph
Pats = nodes
 \square = reactions

AS MORE REACTIONS ARE CATALYZED, A CONNECTED "RED" CATALYZED REACTION SUBGRAPH EMERGES AS A PHASE TRANSITION LIKE ERDOS AND RENYI GRAPHS. THIS CAN BE ORIGIN OF A CONNECTED CATALYZED METABOLISM IN A PROTOCELL AT THE ORIGIN OF LIFE. THIS PREDICTED PHASE TRANSITION IS TESTABLE



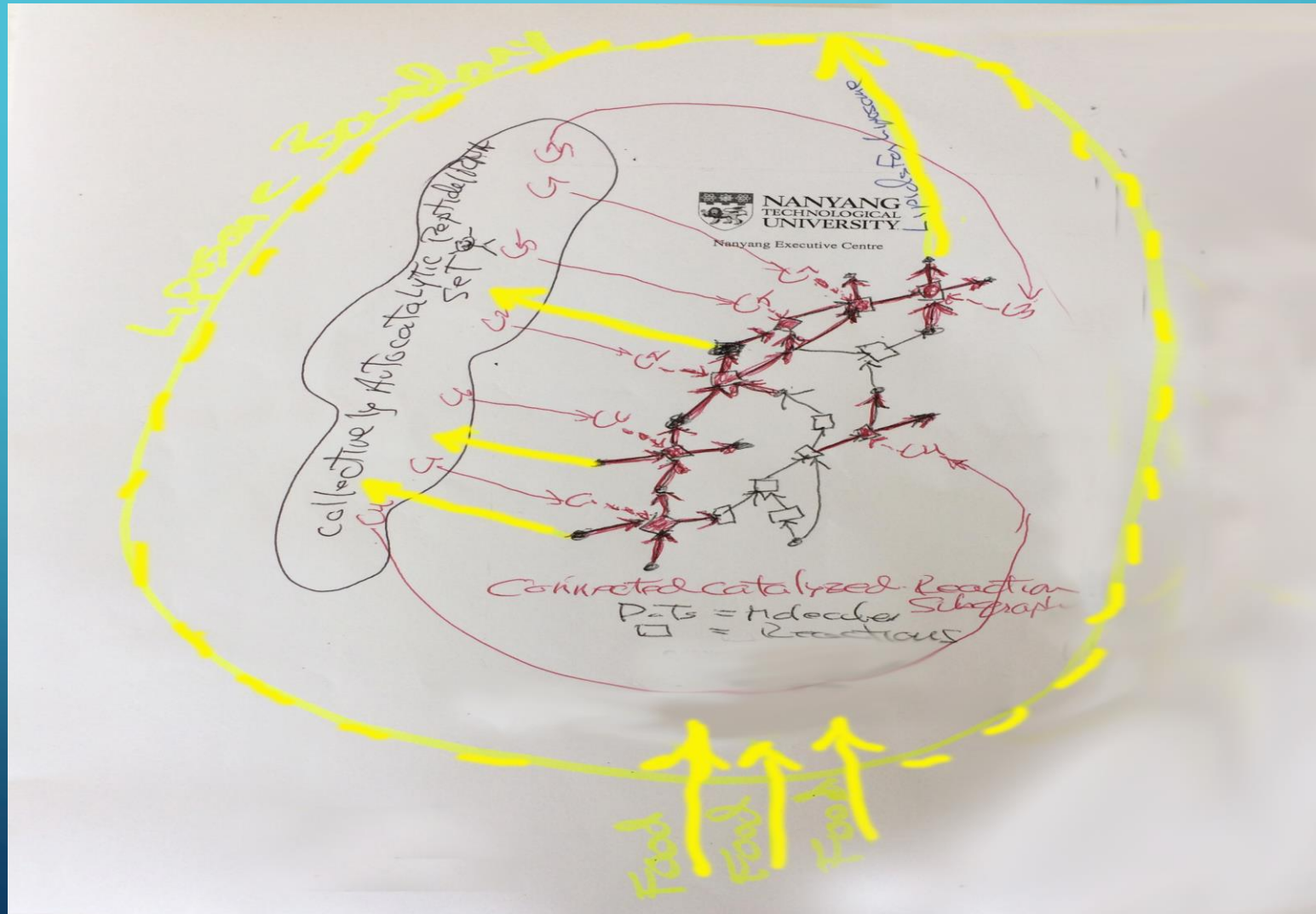
THE POSSIBLE EMERGENCE OF PROTOCELLS: THE PEPTIDES OR RNA IN THE COLLECTIVELY AUTOCATALYTIC SET INCLUDES MEMBERS THAT CATALYZE THE NOW CATALYZED CONNECTED METBOLISM. IN TURN THE CONNECTED CATALYZED METABOLISM MAKES SMALL MOLECULES THAT SUPPORT THE REPRODUCING COLLECTIVE AUTOCATALYTIC SET, AND ALSO LIPIDS TO FORM THE BUDDING LIPOSOME BOUNDARY THAT HOUSES THE "CAS "AND METABOLISM. THE WHOLE IS A PROTOCELL



4d Further recent work on prebiotic chemical evolution: Damer and Deamer - Large population of “progenote” multilamellar liposomes holding diversity of peptide, RNA sequences, or both. Wet dry cycles drive cleavage and random re-ligation, so combinatorial synthesis and shuffling of polymer sequences in each “progenote”. This yields heritable variation WITHOUT constraint closure and clear reproduction. The large population of “progenotes” dry on a surface, say clay, near one another, each spilling out its diversity of polymers. Many of these are absorbed by spatially neighboring dried “progenotes”. Upon rehydration there is now a new population of progenotes, “similar” in sharing overlapping sets of absorbed polymers in each progenote. Selection occurs over many “generations” among these evolving progenotes for Dynamic Kinetic Stability, Pross. Thus lipid compositions and polymers included in these progenotes that increase their dynamic kinetic stability will be selected. This is a form of heritable variation and selection BEFORE the emergence of constraint closure and true reproduction.

4e. Damer Deamer system leads to spontaneous emergence of collectively autocatalytic sets housed in liposomes and reproducing -> true reproducing Protocells

THE POSSIBLE EMERGENCE OF PROTOCELLS: THE PEPTIDES OR RNA IN THE COLLECTIVELY AUTOCATALYTIC SET INCLUDES MEMBERS THAT CATALYZE THE NOW CATALYZED CONNECTED METBOLISM. IN TURN THE CONNECTED CATALYZED METABOLISM MAKES SMALL MOLECULES THAT SUPPORT THE REPRODUCING COLLECTIVE AUTOCATALYTIC SET, AND ALSO LIPIDS TO FORM THE BUDDING LIPOSOME BOUNDARY THAT HOUSES THE "CAS "AND METABOLISM. THE WHOLE IS A PROTOCELL



4f INANIMATE TO ANIMATE WORLD: ONSET OF AGENCY

Molecular Autonomous Agent is a system that can reproduce itself and do at least one thermodynamic work cycle. (Kauffman Investigations, 2000)

Ashkenasy's nine peptide collectively autocatalytic set is already a minimal autonomous agent.

Housed in a liposome as protocell with connected metabolism and reproducing doing work cycles IS a minimal Molecular Autonomous Agent.

Stronger: Molecular Autonomous Agent can "sense" world, evaluate Yuck vs Yum for "me", make a "choice" and "act". (Clayton Kauffman 2002; Peil 2014) Selectively highly advantageous.

e.g.

Emergence of SELF MOVING: Protocell able to e.g. control internal sol - gel transition e.g. by chemosmotic pumps and move like amoeba = one form of "act". This requires a work cycle.

For Plato and the "ancients" self moving is one sign of "soul".

WE HAVE "VITAL LIVING FORCE" AND PLATO'S "SOUL"
THIS IS THE TRANSITION FROM INANIMATE TO ANIMATE WORLD

5) THE BECOMING OF THE ANIMATE WORLD IN EVOLUTION

Evolution requires Darwin's heritable variation and natural selection. The physical bases of these are wider than DNA and encoded protein synthesis which could not have been present *ab initio*. Collectively autocatalytic sets achieving constraint closure, so constructing themselves, can evolve without a genome, and if contained in systems that divide, such as budding lipid vesicles, can evolve as protocells to some extent eg Vasas et al., Serra).

6). Evolving protocells constitute “for whoms” there can be “contexts” that constitute “opportunities” that can be “seized” by heritable variation and natural selection:

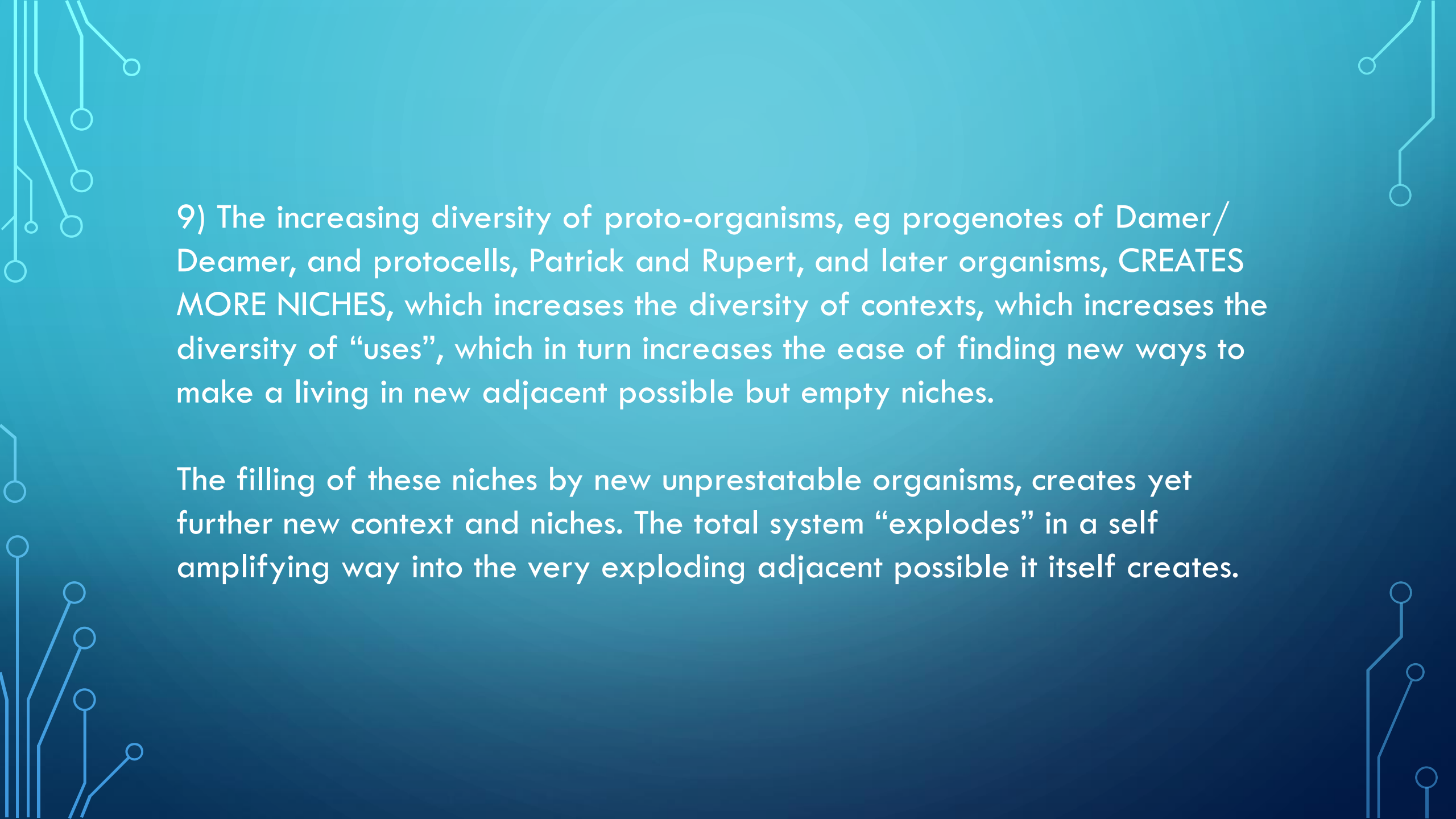
6.a The Surprising True Story of Patrick the First, Rupert, Sly and Gus Protocells. These protocells evolve and emerge in the Lagoon, similar to Damer/Deamer, as Darwinian preadaptations. They are floating in the lagoon with slowly flowing “stuff” they eat. Patrick happens to stick to a rock, and so gets more food per unit time, and so evolves to become the very first “sessile feeder” in the universe. The rock is Patrick’s opportunity, and Patrick is “for whom” there can be an opportunity, “seized” by heritable variation and natural selection. There cannot be an “Opportunity” without a For Whom it is an Opportunity. This “story” needs to be a narrative, and cannot be derived by equations. The becoming is not derivable by entailing law, for we can write no such laws of motion, as we do not know the relevant variables prior to their emergence in evolution. Patrick, Rupert, Sly, and Gus have context dependent “information” about one another, created by their own becoming and “making a living” with one another. This information increases in diversity as more “species” come to exist.

7) Such evolving early forms have the astonishing property that each such life form, by coming into existence, often constitutes new “contexts” that afford opportunities that do not cause but “enable” further life forms, “species”, to come into existence. Patrick constitutes the empty niche into which Rupert becomes. Rupert and Patrick constitute the empty niche into which Sly comes into existence. Each can constitute a new niche enabling yet other life forms to come into existence in ways that “depend upon” the prior existing “species. The increasing diversity of organism and niches, increases the diversity of “contexts”, that in turn afford yet more “opportunities” for yet further “species” to emerge. In turn, this creates yet more “context” and affords yet more “opportunities”.

The Biosphere explodes in diversity.

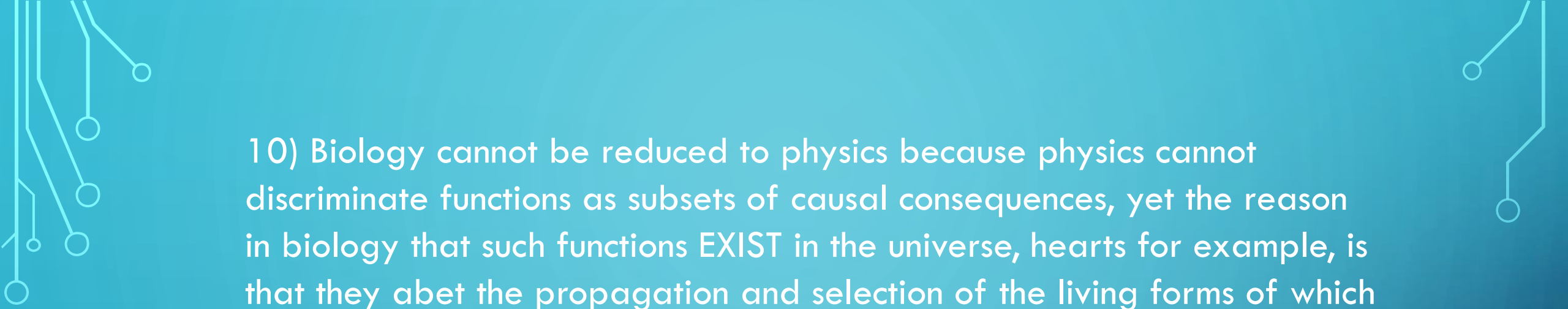
8) The “function” of a part of such a life system is that subset of its causal consequences by which it abets the reproduction of the Kantian whole. The becoming of the biosphere is in large part the becoming of new, unprestatable functions.

8.a, The screw drive argument. Conclusions: 1) The number of uses of a screw driver cannot be algorithmically enumerated, nor can new uses of screw drivers be derived algorithmically. Such new uses or functions are unprestatable. 2) Evolution of new functions in the biosphere is often the unprestatable evolution of such new functions, as in Darwinian preadaptations. 3) The number of uses of a screw driver depends upon the diversity of the context. Few uses in space, many in New York.

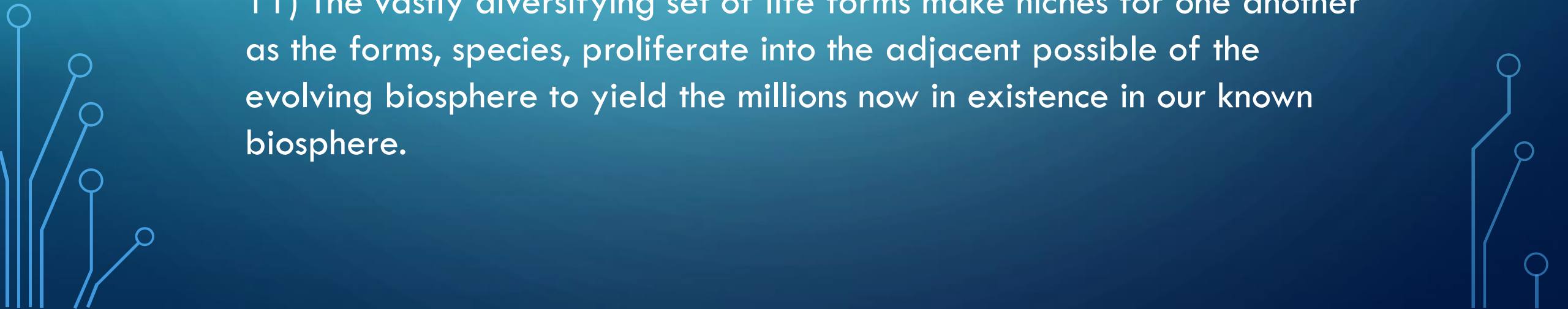


9) The increasing diversity of proto-organisms, eg progenotes of Damer/Deamer, and protocells, Patrick and Rupert, and later organisms, **CREATES MORE NICHES**, which increases the diversity of contexts, which increases the diversity of “uses”, which in turn increases the ease of finding new ways to make a living in new adjacent possible but empty niches.

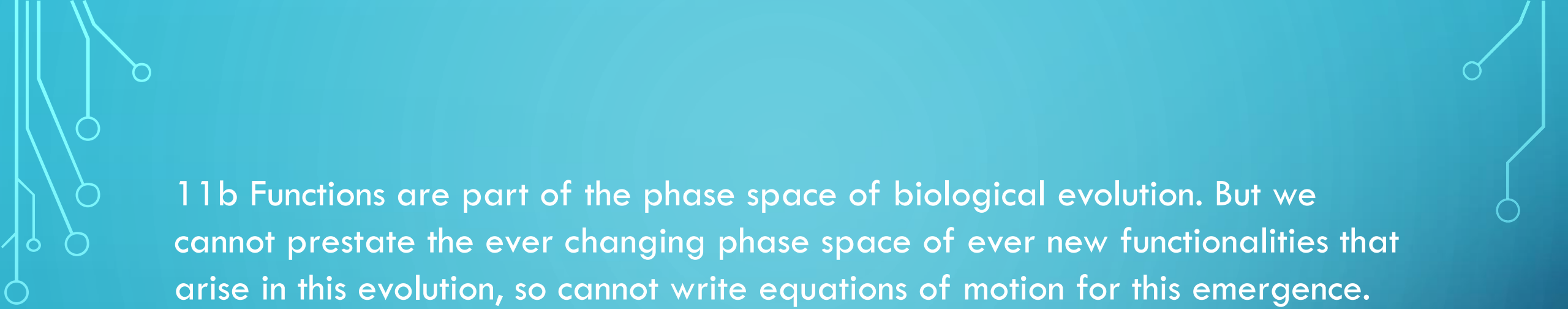
The filling of these niches by new unprestatable organisms, creates yet further new context and niches. The total system “explodes” in a self amplifying way into the very exploding adjacent possible it itself creates.



10) Biology cannot be reduced to physics because physics cannot discriminate functions as subsets of causal consequences, yet the reason in biology that such functions EXIST in the universe, hearts for example, is that they abet the propagation and selection of the living forms of which they are parts. Hearts exist in the non-ergodic universe above the level of atoms because they are selected for the function of pumping blood. We cannot deduce ab initio 3.7 billion years ago that hearts will emerge.




11) The vastly diversifying set of life forms make niches for one another as the forms, species, proliferate into the adjacent possible of the evolving biosphere to yield the millions now in existence in our known biosphere.



1 1 b Functions are part of the phase space of biological evolution. But we cannot prestate the ever changing phase space of ever new functionalities that arise in this evolution, so cannot write equations of motion for this emergence. Then we cannot integrate the equations we do not have to yield entailed laws.

1 1 c. Thus: NO LAWS entail the becoming of our biosphere, nor others.

1 1 d. Since the highly complex evolving biosphere is part of the universe, reductionism, the dream of a final theory that ENTAILS all that comes to exist, is FALSE.



11 e. Yet we can hope for and find “statistical laws”:

i. Strogatz Letto Modified Polya Urn model for exploration of unprestatable Adjacent Possible yields Zipf’s and Heap’s laws.

ii. Self Organized Criticality, Bak, Teng, Weisenfield, Kauffman, yields power law distribution of extinction and speciation events.

iii. Species life time distribution.

iv. Power law distribution of species per genus, genera per family.

12) This vast emergent becoming is beyond physics, yet based on it. This is life literally co-constructing itself and enabling its own vast evolutionary diversification, here and on any biosphere in the universe.

12a. If, among the 100 billion solar systems estimated to exist, life is common, this self constructing becoming is “rife” in the universe, is beyond physics, and may be as huge as physics in the emerging, growing complexity of the evolving universe as a whole.

13) This is: Beyond Physics: The Emergence and Evolution of Life in the Universe.

THANK YOU