# Creative Genomic Webs

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Evolutionary progress is generally considered a result of successful accumulation of mistakes in replication of the genetic code. However, Ben-Jacob has proposed that this progress may instead be due to designed creative processes [1]. In this essay, I overview his work.

**Smart bacteria and the "fastest morphology" principle [2]**

Bacteria have generally been viewed as non-interacting passive elements until recently. This notion has been disproved by the studies of "patterning" in bacterial colonies. These colonies have a much richer patterning behavior than non-living systems (where the diffusion field drives the system towards irregular fractal shapes [3]). On creating nutritionally low growth conditions in a petri-dish and growing bacteria, self-organization at a number of levels was seen, indicating cooperative behavior.

It is hypothesized that the bacteria would show transitions from a morphotype (which is a colonial geometric character which can be carried by an individual bacterium) to another faster expanding morphotype, meaning that the colony which can propagate faster on the agar surface to reach food is preferred. Some of these morphotypes are shown in Fig. 1. The chiral morphotype ***C*** is preferred on softer surfaces while the tip-splitting ***T*** morphotype is preferred on harder surfaces. Since the growth velocity is a property of the colony, it seems that some selective pressure is invoked on the colony to undergo such a transformation.

However, the questions that arise from this experiment are twofold. One, how does the colonial pressure reach down to the individual bacteria and cause genetic changes to a new morphotype? The second question arises from the observation that sparse ***C*** morphotype cells scattered among ***T*** cells in a ***T*** colony have no effect on the colonial structure even on a soft surface. Only finite nucleation of these ***C*** cells leads to a "burst" of the ***C*** morphotype. The question is how this nucleation is formed.

These "intelligent" morphotype transitions (along with some experimental findings on adaptive mutagenesis, which we shall not discuss here) have led Ben-Jacob to propose a new cybernetic framework. In this picture, he chooses autonomous genetic agents whose function is regulated by colonial parameters (e.g. growth kinetics, cellular density, level of starvation, etc.) as cybernators, which are the basis for transfer and synchronization of mutations from cell to cell. These cybernators respond to the colonial environment and modify the individual genomes in a way that benefits the colony.

**Genome learning and self-awareness**

Regardless of the mechanism for the morphotype transition, it is clear that the colony has the potential to select the preferred morphotype according to the environmental conditions. The question is, when and where did the genome acquire this potential? Ben-Jacob claims that this is not a result of Darwinian evolution, and that the genome "learns from experience". For this to be true, the bacteria should be (a) exposed to several cycles of alternate environmental conditions, (b) be able to store past information, (c) be aware of their own abilities, and (d) be able to access the stored information in response to the environmental problems they face. Most importantly, these bacterial genomes should have a cybernetic capacity of changing themselves (e.g. reorganizing or restructuring the genes) to adapt to the situation.

Ben-Jacob claims that the genome is a self-aware adaptive cybernetic unit, which means that it is well beyond a universal Turing machine (the Turing machine structure is static and decoupled from the I/O and computation, whereas the genome is a dynamic entity). It is well known that any system that can be described by a closed set of "passive" elements (where the elements' structures are static) cannot be self-aware (i.e. self-referential statements can lead to paradoxes). Therefore, Ben-Jacob replaces "passive" elements by active agents whose identity is not fixed, and that possess internal structure. The set is replaced by a cell, which is no longer closed (due to exchanges with the environment). Finally, these agents have an advanced "language" which permit self-referential statements.

**Godel's theorem**

An understandable version of Godel's theorem from Hofstadter [4] states that "all consistent axiomatic formulations of the number theory include undecidable propositions".

One implication of this theorem is that no fixed axiomatic system, regardless of its complexity, can be used to represent the complexity of the whole numbers. This theorem is only applicable for infinite systems and cannot be applied to the genome directly. However, Ben-Jacob considers the mapping from DNA sequence to proteins, which are a finite set of "words" in an infinite "language" [5] – the functional combination of proteins are the sentences, and their interaction is the grammar. This picture has been supported by linguistic studies of correlations in nucleotide sequences. Now Godel's theorem can be applied.

It has been proposed that the genome can perform self-designed changes. If this were so, then evolution could be explained by the fact that the genome is an adaptive cybernetic unit with self-awareness. However, a lemma of Godel's theorem states that "a system cannot self-design another system more advanced than itself" (However, a system can be improved by successful accumulation of random changes).

**Horizontal changes and vertical leaps**

Ben-Jacob uses a metaphor for the advancement of scientific ideas to explain his evolutionary theory further. Two types of scientific progress are identified here: the first is the "normal science" or "horizontal change" which arise by solving problems within a well-defined conceptual plane; the problems in this case are also in the conceptual plane. The second kind – the “scientific revolutions” or “vertical leaps” – are initiated in response to a paradox (a problem that cannot be solved in the boundaries of the current paradigm), and entail the creation of new paradigms, with an enlarged conceptual space.

In the case of living organisms, problems are difficulties or hazards that can be solved using the tools available to the genome. An example is the exposure to an antibiotic for which the bacterium needs to activate a silent gene. An example of a paradox, however, is a difficulty to which the genome cannot find a solution using its own tools, and a new genome has to be created. For example, the emergence of sporulating bacteria is a “vertical genomic leap”. The decision to “sporulate” is a collective decision based on the prediction that the conditions will become lethal. The paradox in this case may have been the need to learn from lethal conditions.

Unfortunately however, a good definition for the plane of the organism has not been provided, and Ben-Jacob intends to use Godel’s approach to reach one.

**Colonial wisdom**

According to the lemma of Godel’s theorem, the genome can perform horizontal changes but not vertical leaps. A possible solution is that the horizontal changes are designed while the vertical leaps are the outcome of random mistakes. However, Ben-Jacob proposes a solution to the dilemma by assuming cooperative behavior.

In a stressed colony, some bacteria break open and deposit their genetic material in the media while others make their membranes more permeable to the genetic material. This, along with the direct and indirect physical and chemical connections 9and long-range chemical signaling) formed between the bacteria, lead the bacteria to form a network. This (along with the assumption that the bacteria activate or produce special cybernators enhancing the genome communication), lead to a “super-genome” relative to the individual genomes. It should be noted that the creation of such webs requires a good deal of self-awareness; the environment should lead the bacteria to give up their awareness as individual entities.

This picture has a conceptual difficulty. The colonies of bacteria formed after a vertical leap seem to be more advanced than what they were originally, in contradiction to the lemma of Godel’s theorem (if we consider the colony as a multicellular organism). This contradiction is explained away by saying that the colonies are only improved horizontally, and not made more complex. In other words, the vertical leap in this case is at the genomic level, and one would need a web of colonies to create more complexity at the colonial level.

This bacterial picture can also be extended to eukaryotic cells, and to multicellular eukaryotic organisms. In this case, the state of the eukaryote can directly affect changes in the individual cells. In this case, however, a more developed control mechanism will be needed for communication between different levels. Also, it is expected that there is a strong coupling between genetic webs of different species which are functionally related, and this may cause induction effects in genetic changes.

## Discussion

Ben-Jacob's work is interesting because it provides a mathematical framework for complexity of systems, and emphasizes the importance of networks in bacterial communication (This framework is contradictory to the claims of some artificial life researchers, who claim that there exist systems that can design more complex ones than themselves). However, the arguments are not convincing enough because they are not backed up by more rigorous definitions. The existence of cybernators is yet to be proved experimentally. However, if communication is really the key to the intelligence of bacteria, then novel approaches may be used to control bacterial resistance. Bacteria develop resistance to antibiotics really quickly, and new strategies may be needed for treatment. If the strength of these bacteria lies in colonies and communication, then jamming their communication channels (instead of disabling the individual bacteria) may be an effective way to control their resistance.

## References


[1] E. Ben-Jacob, *Bacterial Wisdom, Godel's Theorem and Creative Genomic Webs*, Physica A, **248** (1998), pg. 57, and references therein.

[2] E. Ben-Jacob, I. Cohen, A Czirok, *Smart bacterial colonies in : Physics of biological systems: from molecules to species*, Lecture Notes in Physics, Springer, Berlin, 1997, pg. 307.

[3] E. Ben-Jacob, H. Levine, Pattern: The Artistry of Nature, Nature, 409 (6823), 2001, pg. 985.

[4] D. Hofstadter, *Godel, Escher, Bach : an Eternal Golden Braid*, Basic Books, New York, 1979.

[5] S. Jones, *The Language of The Genes*, Flaming, Glasgow, 1993.

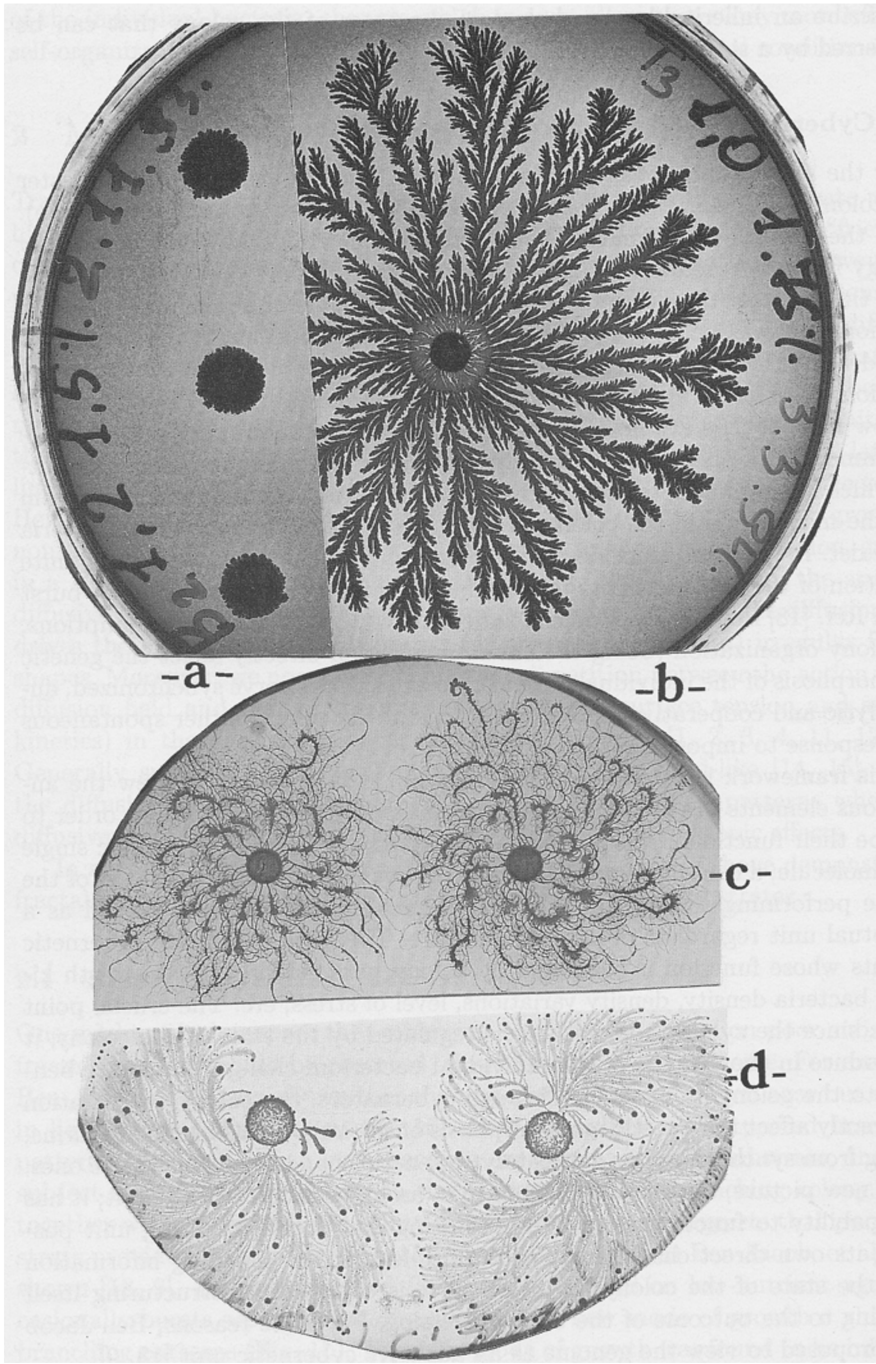


Fig.1 (from [2] )

Examples of the four morphotypes:
(a), (b), (c), (d) are for ***B***, ***T***, ***C***, and ***V*** morphotypes respectively.