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the molecular scaffolds of the élan vital

paco majic

INTRODUCTION

Life is invention. Evidence of this is all around us, in the endless shapes and behaviors of organisms which with fur, feathers, scales, slime, leaves, and other features have expanded and continue to expand their realm across this planet. But the wonders of biodiversity lie not only in its abundance, but also in how complex lifeforms are, in how well-integrated are many of the processes that permit the subsistence of even the simplest organisms. Such complex integration is at the core of many of the classic controversies surrounding Darwinian evolution that immediately followed the publication of *The Origin of Species* in 1859. After all, it is counterintuitive to think that so well-integrated complex organisms as those alive today might have arisen through a gradual process that is simply based on

the sieving of the outcomes of aleatory aimless changes.

In *Creative Evolution* (1907), Henri Bergson downplayed the importance of chance in the evolution of lifeforms and proposed an *élan vital* or vital impetus as the agent directing biological diversification, innovation and complexification. This *élan vital* is a creative force that is common to all living beings and that propels life forward in time by bringing forth novelty. As it does, it branches and diversifies, thus producing unique separate lineages on which it continues to create independent new forms. An important feature of this impulse is that, although it is embedded in the matter that sustains each living organism, it cannot be decomposed down to the physicochemical properties of that matter – it is a force that transcends a physical mechanicism, and that is exclusive and intrinsic to everything that lives. However, the *élan vital* does interact with matter and, as it pushes life forward on independent lineages, those lineages are constantly encountering material obstacles. Evoking natural selection, some lineages can overcome those obstacles and continue to be thrusted forward creatively on their own branches, while others cannot trespass the obstacles and halt. In Bergson's view, diversification thus relies on two causes, "the resistance life meets from inert matter, and the explosive force—due to an unstable balance of tendencies—which life bears within itself"[1].

As Bergson sees it, the *élan vital* is a finalistic force in evolution. But this is not in the sense of a radical finalism in which the directions life takes are predetermined by a set goal that is to be reached. The finalism Bergson defends is influenced by a creative freedom with which the vital impetus endows organisms. At every instant, organisms face conditions to which they can react based on an internal "psychological" representation of possible actions that can become materialized. In Bergson's own words:

> "The direction of this action is not predetermined; hence the unforeseeable variety of forms which life, in evolving, sows along its path. But this action always presents, to some extent, the character of contingency; it implies at least a rudiment of choice. Now a choice involves the anticipatory idea of several possible actions. Possibilities of action must therefore be marked out for the living being before the action itself."[2]

The possible actions organisms carry with them are the products of the history of their respective lineages and, therefore, the internal "decisions" made by each individual are defined by a singular "organic memory"[3], which tends to be similar

to that of organisms that are more closely related to the individual in question. Each summoning of this organic memory introduces novelty from the present duration, which can then also be incorporated into the memory of eventual representations stemming from a specific one. The *élan vital* in this framework is thus a force that introduces indetermination into matter on the basis of the historical memory of a lineage.

During the scientific developments that have taken place since the publication of *Creative Evolution* there was little room for serious considerations of Bergsonian notions among biologists. First, because Bergson's propositions are not of a scientific nature, as he himself acknowledged[4]. And second, not so much because his concepts were refuted, but rather because they were left aside, bearing the shameful insignia of teleology, vitalism and spirituality. After all, Bergson defended the idea that life has its own singular properties that cannot be reduced to physics, and claimed evolution to be a process ruled by something resembling a spirit, which he defined as a force with the faculty of "pulling out of itself more than what it contains"[5]. Among some of the most influential biologists of the 20th century, Jacques Monod and Ernst Mayr explicitly refused to discuss Bergson's ideas. Monod claimed that Bergson's metaphysical vitalism was "bare of logic but not of poetry"[6] and that he felt incapable of delving into a detailed discussion of Bergsonian notions because he was "a captive of logic and poor in global intuitions"[7]. Mayr on his side wrote that philosophies like that of Bergson "merely replaced the unknown *x* for an unknown, *y* or *z*, for calling an unknown factor *entelechia* or *élan vital* is not an explanation" and that "[e]ven though some of the underlying observations of these conceptual schemes are quite correct, the supernaturalistic conclusions drawn from these observations are altogether misleading"[8].

Unlike Mayr and Monod, I do think that a discussion of Bergson's philosophy of evolution is most welcome. The summoning of an *élan vital* is not merely replacing an unknown *x* for an unknown *y*, but rather, it permitted Bergson to fill conceptual gaps and reconciled his intuition about life with what was known about biological processes at the time. Figuring out the properties of the *élan vital* and how it might work evidence what knowledge is missing and what could be expected to be the properties of those unknowns. As Bergson noted, by taking into account the ideas condensed in the vital impetus "we have an idea full of matter, obtained empirically, capable of guiding our investigations, which will broadly sum up what we know of the vital process and will also bring out what is still unknown" [9]. I take Bergson's dissection of the creative forces of life as an attempt of his method of

intuition to build hypotheses in light of what was yet to be discovered, rather than as a method to provide answers which could deter further explorations.

Many of the gaps in the body of knowledge about evolution that existed in Bergson's time have been at least partially filled with the discoveries made during the past century in the biological sciences, especially in molecular biology. This essay has two aims. First, I will translate some of Bergson's metaphysical concepts relating to biological evolution into the language of contemporary molecular evolutionary theory. After that, I will argue how an actualized Bergsonian viewpoint helps complement the Neo-Darwinian paradigm currently dominating the field of evolutionary biology by emphasizing the importance of a directionality in the evolutionary trajectories that is internal to lineages.

THE GENETIC MATERIAL

By the time Bergson published, *Creative Evolution*, evolutionary transformism and natural selection were well accepted among the community of naturalists. An acceptance that was based mostly on comparative morphology, embryology, natural history and paleontology. However, a cloud of uncertainty still shrouded the principles of heredity and the emergence of variation. This cloud eased the proliferation of different schools subscribing to different hypotheses about these points during that period, which included Neo-Darwinism, Neo-Lamarckism and orthogenesis. Bergson's view of evolution as a process driven by a vital impetus can be regarded as yet another competing hypothesis, in which variation is fostered by the aforementioned internal force that is intrinsic to life, rather than being accidental as defended by Neo-Darwinians, directed by a response to the environment as suggested by Neo-Lamarckians, or defined by underlying physicochemical principles as proposed in the orthogenetic framework.

The ignorance that clouded the understanding of heredity and the origins of biological variation began to be gradually dissipated with the development of genetics. The term "gene" was first used by Johannsen in 1909 to refer to the then abstract agent responsible for heredity. Chromosomes composed of nucleic acids were discovered to be the physical substrate for those abstract genes, and it was only with the description of the structure of DNA by Watson and Crick in 1953 that the set of rules for the maintenance, transmission and mutability of genetic information began to be grasped. This offered an understanding of how new genetic information can emerge based on the strings of nucleotides of four types (Adenine [A], cytosine [C], guanine [G] and thymine [T]) that compose DNA and

how that information can be inherited, or, in Bergsonian terms, it provided a set of rules and material substrate for biological creativity and the persistence of memory.

The molecular revolution that followed the discovery of the structure of DNA also involved the understanding of how cells make use of the information contained in it. A major advancement towards this goal was the deciphering of the genetic code for the production of proteins, which are chains of aminoacids that are responsible for most of the fundamental functions of cells, and the discovery of stretches of DNA that do not code for proteins, but that are responsible for regulating the activity of genes. In both of these cases specific sequences of nucleotides have different effects at the level of cells depending on the proteins they encode or the regulatory activity of a given arrangement of nucleotides. Particularly concerning regulation, the experiments of Monod and François Jacob published in the 60's set the foundation to understand how information that is perpetually present in a cell can be utilized or not depending on the needs or stimuli that a cell might be exposed to. This is a principle that is at the basis of the development of multicellular organisms, where gene regulation allows for different combinations of genes to be active across different cell types or different stages of development. This is of relevance for interpreting some Bergsonian notions under the light of contemporary biological concepts as discussed in the next section.

When *Creative Evolution* was published mutations referred to changes in the traits of organisms, without any mechanistic understanding of what permitted that change. Knowledge on the structure of DNA allowed to elucidate how mutations occur by altering nucleotide sequences and offered significant insight into the basis, frequencies and effects of the different kinds of mutations fueling evolution. Mutations can be classified as neutral, deleterious or adaptive depending on their selective outcomes. Following the study of the occurrence of these different kinds of mutations, some evolutionary trends and processes became prominent in evolutionary theory, such as how if much of the variation is selectively neutral then stochastic population dynamics can be as strong a force in evolution as natural selection, or how much of adaptive genetic variation acts at the level of gene regulation.

Furthermore, more recently there has been a massive development of genome sequencing technologies and other molecular techniques that have provided a great detail about how cells make use of the information encoded in DNA to direct the survival and development of organisms. These techniques also allowed to create

more or less precise reconstructions of the tree of life based on the mutational footprints on the genomes of different organisms, and to understand what kind of biological information and processes were acquired or lost in certain lineages and how the rewiring of gene regulatory networks might have allowed for the arrival of morphological, physiological or behavioral novelty. This understanding has not been limited to interpreting differences in the genomes of different species, it has also made it possible to use molecular tools to direct genetic changes and study how genetic variation can translate into evolutionary novelty in general, or to follow the molecular evolution of experimental populations of model organisms to investigate the underlying causes of the success of certain forms over others.

The knowledge that has been gathered over the past century in the field of molecular biology since the first publication of *Creative Evolution* has substantially altered the way we understand evolutionary processes and the development of organisms.

THE MOLECULAR CONSCIOUSNESS

To start my discussion about how the molecular discoveries of the last century allow to explore the details of Bergson's intuition, I will address his notion of a consciousness that is coextensive with life and that acts as a creative force in evolutionary processes. For this it is important to first consider how organisms develop their characteristics. At the basis of contemporary biological theory is the conceptual distinction between genotypes and phenotypes. The genotype is the hereditary information of an organism and it is mainly contained in its genome composed of the 4-lettered alphabet of DNA. The genotype, not without an influence from the environment, directs the development of phenotypes, which are the observable traits of an organism. A phenotype can be the plumage color of a bird, the shape of a limb, whether an animal has fur or not, the flowering period of a plant, the resistance to antibiotics of a bacterium, etc. In short, the genotype is the hereditary information and the phenotypes is the expression of that information in the material context of an organism.

The mapping of genotypes into phenotypes can be straightforward if the information contained in the genotype directly translates into a specific phenotype. For example, under the set of rules of the genetic code, any combination of nucleotides can map precisely to a specific chain of aminoacids. In a more complex scenario, the presence of a specific gene in a genome can allow an organism to survive on a certain resource, such as if a bacterium has genes involved in pathways used for

the utilization of some sugars. Other phenotypes, like the traits of multicellular organisms, may have a much more intricate codification, with several interacting layers of molecular, cellular, and behavioral processes that integrate the activity of different combinations of thousands of genes. The genotypic blueprints of complex phenotypes include genetic elements that permit genomes to regulate themselves. For example, transcription factors are proteins with arrangements of aminoacids that make up their so-called binding domains, which are portions of the protein that are capable of interacting with specific nucleotide sequences on a strand of DNA. Whenever a sequence is recognized by a transcription factor, it binds to it and it may promote or inhibit the recruitment of other proteins that are responsible for the activation of nearby genes. The genome thus encodes its own regulators and the substrate on which those regulators act, meaning that it holds in itself a diagram of the possibilities of the internal biochemical and physical activities of a cell that define its phenotypes.

Linking back to Bergson, the mapping of genotypes into phenotypes allows to create some parallelisms with his vision of what consciousness is and to understand biologically how "consciousness is coextensive with life"[10] as he defended. Although much of Bergson's discussion about the nature of a consciousness was focused on the mental consciousness of animals and how it is particularly developed in humans, I will now argue that the basic principles ruling this kind of consciousness can be extended to molecular principles that allow genotypes to direct the development of phenotypes. Unlike a mental consciousness, this kind of "molecular consciousness" would apply to all organisms, and therefore helps place consciousness as a fundamental aspect of an élan vital influencing all branches of life – an idea that Bergson proposed, but lacked the molecular knowledge to justify in detail.

At the basis of a Bergsonian consciousness is the idea that "[p]ossibilities of action must [...] be marked out for the living being before the action itself"[11] and that in the living being it is the "representation that precedes the act"[12]. A *representation* here is understood as a pre-figured action, or, in other words, the abstract template for the enactment of an image. In a parallelism with genotypes and phenotypes, the genotype can be seen as a representation of each individual organism and the phenotype as its enactment. The genotypic representation is what passes from germ to germ and permits the reconstitution of an organism in each generation; it is that which Bergson called an "invisible progress [...] on which each visible organism rides during the short interval of time given it to live"[13], and it is related to his idea of an inherited *effort* shared among members of a species:

> "A hereditary change in a definite direction, which continues to accumulate and add to itself so as to build up a more and more complex machine, must certainly be related to some sort of effort, but to an effort of far greater depth than the individual effort, far more independent of circumstances, an effort common to most representatives of the same species, inherent in the germs they bear rather than in their substance alone, an effort thereby assured of being passed on to their descendants."[14]

It is worth remarking that what I am here referring to as a representation is not an outer representation, it is one that is internal to each organism. There is an internal representation of the protein in the sequence of nucleotides that encodes its string of aminoacids, there is an internal representation of pathways to metabolize sugars in a bacterial chromosome, and a single cell can hold on its genome the internal representation for the enactment of an entire animal. Each representation that is contained in every genome of every cell stems from an original representation that has persisted in altered copies of itself since the early stages of life. Yet, the diversity of representations is not the result of an evolutionary trajectory pre-set by that original representation, but rather, "evolution is a trajectory unceasingly renewed"[15] and the material circumstances under which each modified copy of the original representation has existed defined the potential of the representation to be enacted and the success or failure of each individual representation. Therefore, the enactment of the internal potential of each representation together with their material expression defines which are the representations that manage to be thrusted forward in time.

Although the genotypic representation is physically encoded in DNA, the representation itself is not physical, but informational[16]. The phenotypic properties it encodes, which are material, are properties that cannot be decomposed down to the physical and chemical attributes of the atoms of the double helix that holds the information. An organism's phenotypes emerge from the material interpretation of the informational representation, from the reading of the message, from the translation of the information from the ACTG-language of DNA into the language of the cell and body. It is through the enactment via the coordination of the organic materials that are at hand for an organism that all the informational pieces of its genome are integrated into a synergic collection of material phenotypes that is the living being. In fact, it is necessary that certain strings of information on a genotype become enacted first in order for other functions encoded in it can become enacted. Consider for example the expression of a transcription factor that would activate the expression of other genes in the genome, or the sequential

differentiation of cell types that create the developmental environments that induce the differentiation of other cell types. Much of the informational representation itself demands a material enactment. Or as Bergson said: "Thought that is but thought, the piece of art that is but design, the poem that is but dream, they are not worthy; it is the material realization of the poem into words, of the artistic conceptualization into statue or painting what demands an effort"[17].

The informational nature of genotypes permits a simultaneous representation of many different potential phenotypes at once on a single physical sequence of DNA. In every genome of every cell, there is an informational potential to produce thousands of proteins and other biochemically functional molecules, each of which can be produced in different amounts depending on their regulatory properties. This means that there is a vast combination of possible cellular states, and that all these combinations coexist virtually in their genomic representation. For example, an animal is composed of numerous different cell types, like neurons, hepatocytes, cardiomyocytes, etc. Yet, within an individual organism those cells tend to mostly share the same genomic information, meaning that each cell has the virtual potential to act as any other cell composing the body of the organism if the material conditions would so allow it. Indeed, it is now a standardized laboratory procedure to dedifferentiate cells of a certain type and then differentiate them into cells of another type[18], a process that is only possible because the representation for both cell types is contained in a single genome.

Because many potential phenotypes could be produced by a single genotype, those phenotypes can be said to be undetermined, at least until there is an enactment. At every instant only one of those possibilities is enacted, and the degrees of freedom that the representational indetermination offers are thus given up in favor of a single phenotype. In such an active surrender of options, it could be said that there is, in Bergson's terms, a consciousness playing a part:

> "(...) consciousness is the light that plays around the zone of possible actions or potential activity which surrounds the action really performed by the living being. It signifies hesitation or choice. Where many equally possible actions are indicated without there being any real action (as in a deliberation that has not come to an end), consciousness is intense. Where the action performed is the only action possible (as in activity of the somnambulistic or more generally automatic kind), consciousness is reduced to nothing. Representation and knowledge exist none the less in the case if we find a whole series of systematized movements the last of

> which is already prefigured in the first, and if, besides, consciousness can flash out of them at the shock of an obstacle. From this point of view, the consciousness of a living being may be defined as an arithmetical difference between potential and real activity. It measures the interval between representation and action."[19]

As mentioned, above, Bergson especially developed these concepts in the framework of a mental consciousness. But the genotypic potential to produce several phenotypes also offers life internal choices, thus, a single cell has a resemblance of a consciousness when it interprets its own genomic information. Evidently, the nature of this "molecular consciousness" is not equal to that of a mental consciousness, mainly because they are grounded on different scales of biological organization. Whereas the representation of a molecular consciousness is on the genome, the mental one is sustained on a network of neuronal activity. Still, mental or molecular, both kinds of consciousness engage in integrating perceptive cues (in the case of the nervous consciousness via sensorial perception, while in the case of a molecular one via molecular receptors), and executing one among many possible represented actions. It is also the case that the mental consciousness has its foundations provided by the molecular one. Each individual neuron that is a unit of the nervous system possesses its own genomic representation, and it is by enacting it that one cell differentiates into a neuron rather than into a muscle cell. It is also by enacting its represented states that a neuron dynamically stretches its dendrites and axons with the molecular machinery of its cytoplasm until it finds a neighboring neuron with which it will engage, thus constructing the network of neural activity that enables a mental consciousness.

This molecular consciousness is compatible with the Bergsonian vision of a consciousness that is coextensive with all of life. Bergson did recognize that the lack of a nervous system does not imply the lack of a consciousness[20], and that "it is consciousness, or rather supra-consciousness, that is at the origin of life"[21]. However, he also suggested that mobility is the ultimate expression of a consciousness, so implying that sessile organisms such as plants had suppressed it[22]. I argue that this emphasis on mobility is misleading. The cell of a plant with its enormous genetic potential has indeed many more molecular options than motile and genetically "simpler" bacteria. Looking at the cellular, developmental and physiological functions of plants, it is evident that in the expression of their phenotypes they are indeed choosing one among many possible actions – these may not be movements, but they are biochemical or developmental choices. This is a form of consciousness, a molecular one, that acts on the same principles as

a mental consciousness. Take for example the recent discovery of the action of a florigen, a protein that at low temperatures is sequestered in the lipid membrane of cells, while at higher temperatures it is released and becomes capable of activating the repertoire of genes triggering blooming[23]. This particular mechanism is one in which there is choice, to bloom or not to bloom, and in which the decision is reached by the own internal mechanisms of the plant.

The more choices a genotypic representation offers, the more intense is the consciousness that chooses the action. In the example of protein production based on a genetic code, consciousness is dim, since there are few degrees of freedom for a cell when a sequence of three nucleotides translates into a specific aminoacid. But if more complex phenotypes are taken into account, such as the bacterial sugar pathways or the development of a multicellular organisms, there is a larger "arithmetical difference", as written by Bergson, between the representation and the action than for simpler phenotypes. The more branches a molecular pathway has, or the more nodes and edges making up the dynamic gene regulatory networks, the more phenotypic options for an organism to develop, the more intense is the consciousness that derives actions from representations. Given this diversity in degrees of consciousness, we can then agree with Bergson that when it comes to living organisms "the group must not be defined by the possession of certain characters, but by its tendency to emphasize them"[24].

The point of interpreting a Bergsonian idea of a consciousness in molecular terms is not to endow psychological attributes to basic cellular functions, but rather to bring under the spotlight three notions that speak of the organismal potential for self-determination. These notions being: 1) the influence of an internal choice in the development of phenotypes given a material placement of genotypes, 2) the existence of a virtual representation that the materialisation renounces, and 3) how over evolutionary time some lineages can repress or exalt developmental choices of individuals, thus enhancing or restricting their plasticity. Even if the reader may have an opinion on whether calling this a consciousness is wise, the important argument is not the psychological nomenclature, but the idea of an active surrender of options that a genomic interpretation carries with it.

THE MOLECULAR MEMORY

In the lifetime of organisms there are two kinds of sources of biological indetermination. The first kind is the one to which I referred to above and it is the one that is found in the representation before it is enacted, when the genotype

gets materialized into a phenotype. The second kind is when there is genetic novelty arising as the product of mutations, or, in other words, when there is a heritable change that alters the genotypic representation itself. This second kind is one that transcends generations and that links to another fundamental concept of Bergson's philosophy, memory.

Mutations that alter genotype *A* and turn it into genotype *B* are simply a modification or rearrangement of the sequence of nucleotides on a molecule of DNA. If one considers that the genotype – and therefore the representation – is written in combinations of the four types of bases A, C, T and G, then the mutational history of lineages can be considered to be an exploratory process among possibilities of those combinations. These combinations can be conceptualized into a theoretical space of all possible genotypes as a *genotype network*[25]. Each node of that network is a unique sequence that is interconnected to all other possible sequences that are a single mutational step away from it. For example, if an organism has a genotype AT, it will be neighboring genotypes AG, AC, AA, TA, CA and GA. Whenever a mutation occurs on a representation, said representation will be displaced from its current genotype to a neighboring one in the network. Any mutation would then move the representation of an organism into a new mutational neighborhood, thus opening up a whole new context of potential mutational pathways. If our exemplary genotype AT mutated into AG, now the mutational neighborhood will be composed of AC, AT, AA, TG, CG and GG.

Because the common ancestor of all known life likely had a representation that was a point in the genotype space of possible combinations of A, C, T and G, it can be simplistically considered that the much of the history of life on earth has been an exploration of this space. During this exploration there has been, for each genotypic representation, a phenotypic enactment. Since the new change needs to be coherent with the rest of the representation, it is implicit that the change will also be coherent with the historical memory of its ancestry. An organism with a given genotypic representation (a point in the space of all possible sequences) develops according to the materialization of that representation. Whenever a mutation tempers with the enactment, that mutation can either be neutral, deleterious or beneficial. Those phenotypic materializations that prevailed and managed to reproduce, permitted mutated versions of their own representations to try their chances in their own enactment. In this way, mutational neighborhoods of the space of representations continued to be sampled, expressed and selected across generations, tracing behind them a trail of the history of explored portions of the space of genotypes.

Because in each generation the substrate that is mutated is a memory of the genotypic representation that has had a successful enactment, and because the mutational steps tend to not take the representation too far from its mutational neighborhood (this is because a sequence of several bases will unlikely change the nucleotide in many of its positions at once), then the history that has brought a representation to a specific point in the space of genotypes becomes a key player in the channeling of evolutionary paths. The diffusion of organismal representations across a genotype network thus allows to visualize perhaps one of the most important aspects of Bergson's view of life, which is the importance of memory and historical contingency, the fact that "[e]volution implies a real persistence of the past into the present, a duration which is, as it were, a hyphen, a connecting link"[26].

According to Bergson, the existence of this memory is one of the aspects that separates the world of life from the world of the mathematics, which is a "world that dies and is reborn at every instant"[27]. Biological memory offers continuity in the shape of imperfect copies of parental genotypes that carry with them traces of the history of generations. But this continuity is not only in the persistence of the representation but also in that of the phenotype, since not only is the representation inherited, but many of the external material circumstances that allow for a viable enactment also remain relatively stable across generations. There is therefore continuity in both, representation and enactment. In spite of this continuity, of this persistence of memory, in each replication of the representation and in each enactment of it there is a creative impetus that sprouts out of that memory.

THE MOLECULAR CREATIVITY

Creativity is the core essence of the *élan vital*. In Bergson's view, life is unceasing creation because it is a reality that is "productive of effects in which it expands and transcends its own being"[28]. Whenever there is an act of creation life escapes repetition. Be it the development of a new organism or in the inheritance of imperfect copies of a parental genotype, differences, even if minute, create new and unique individuals. This creative aspect is what makes matter influenced by the *élan vital* unpredictable and indetermined, constrained but not defined by the clockwork mathematical precision of physics:

> "The impetus of life consists in a need of creation. It cannot create absolutely, because it is confronted with matter, that is to say with the movement that is the inverse of its own. But it seizes upon this matter,

> which is necessity itself, and strives to introduce into it the largest possible amount of indetermination and liberty."[29]

In the biological terms discussed in this text, the "indetermination and liberty" involved in creativity can be considered form the point of view of the development of phenotypes and the mutational process that allows populations to navigate the network of genotypes. Concerning the first of these points, creativity arises as the direct result of the reduction of the genotypic indetermination under the material circumstances in which an individual develops. As mentioned above, phenotypes are not just the expression of a genotype that is predesigned and that is directly mapped into a material arrangement, but rather, when a genotype is expressed, the information it contains is exposed to the singular material circumstances of the developing organism. The interaction of the representation and its unique circumstances is what defines a unique phenotypic product showcasing the creative originality of each individual. The enactment of a representation is therefore not a simple unfolding of predesigned possibilities as could be considered within the paradigm of orthogenesis, it is not a process that simply selects one among many options, but rather it is a process that implies creation along the material lines of choice. The virtual representation that underlies each enactment is mostly common to that of other closely related organisms sharing a common ancestry as noted by Bergson, but the originality is expressed when that virtuality is enacted in a material singular way of being-in-the-world.

When it comes to considering mutations as a creative agent, the nucleotide change that moves the representation from genotype *A* to genotype *B* is hardly creative since what it is doing is merely explore the pre-existing space of possible genotypes. The true creative power of mutations comes rather from the placement of a given representation in a specific material and historical context in which it is to be enacted. As explained above, there is a creative expression in the enactment of the virtual that is unique to the space and time of each individual. It is this unique material enactment that determines the success that the new representation may have and whether the mutational step is a step in false or a step that will be foundational for a new lineage. Mutations explore a "potential" by producing one out of many possible genotypes, but mutations are also a creative force when they enable the encounter of some genotypes with a particular set of circumstances with which they will interact, and with which they will craft the historical paths life treads on.

Both of these forms of biological creativity, that is the mutational pathways and

the action of the molecular consciousness, are therefore based on the historical and circumstantial placement of a genotypic representation. This historical singularity of biological individuals is what makes, according to Bergson, evolutionary predictions a challenge:

> "That the appearance of a vegetable or animal species is due to specific causes, nobody will gainsay. But this can only mean that if, after the fact, we could know these causes in detail, we could explain by them the form that has been produced; foreseeing the form is out of the question. It may perhaps be said that the form could be foreseen if we could know, in all their details, the conditions under which it will be produced. But these conditions are built up into it and are part and parcel of its being; they are peculiar to that phase of its history in which life finds itself at the moment of producing the form: how could we know beforehand a situation that is unique of its kind, that has never yet occurred and will never occur again?"[30]

Thus, an organism inherits genetic information that has been channeled over generations and then as that information is enacted, the internal and external accidents (which is a way of describing the uniqueness of the historical moment in which the organism is enacted) shape a new unique shape or behavior, or even produce a new representation. Biological creativity can thus be understood to arise from the internal and external historical circumstances of everything that lives.

THE INTERNAL TENDENCIES

The Bergsonian vision of evolution is one that underlines the role of historical contingency as a creative agent, and this point is what makes Bergson's view of life a relevant alternative to Neo-Darwinism, orthogenesis and Neo-Lamarckism still to this day. During the past century the paradigm defining the community of evolutionary biologists has been dominated by the Neo-Darwinism, where chance and necessity are considered the primary forces in evolution. Briefly, under this vision mutations are the creative driver of evolution and they are chance events relative to the adaptive potential of the new genotype. This random variation is then filtered by selection, which is an expression of the necessity of a lineage of changing into specific directions in order to adjust to the environmental pressures it faces. Classically, the sole determinism that comes from mutations is the selective process that filters them, the ecological mold into which each organism tries to fit,

or as Monod wrote, “drawn out of the realm of pure chance, the accident enters into that of necessity, of the most implacable certainties”[31].

However, there are a few observations and conceptualizations that need to be acknowledged when it comes to assessing how aleatory mutations actually are. First of all, mutations can in many ways not be strictly random, but they can be biased or facilitated. For example, it is much more frequent that an C will change to a T than any other type of single-nucleotide mutation[32], and some genomic regions have higher mutation rates than others[33]. Secondly, evolution has followed trajectories in which chance has been tamed to a certain extent. The portion of the genotype space where most organisms are includes the codification for proteins that are responsible for repairing copying errors, which can result in relatively low mutation rates[34], thus dampening the importance of chance. Additionally, phenotypes will tend to evolve robustness to mutations once they are selected and continue to be selected - this means that the genotype space can be explored without immediate selective repercussions. Thirdly, and more importantly, the history of a lineage has in many ways defined the set of mutations that are possible. If we consider genotype ATG, it is much more likely that a mutational event will take this genotype to ACG than it will take it to GCA, since there are fewer mutational steps needed to reach the first of these two genotypes. The paths on which a lineage has treaded as it explored the space of possible genotypes strongly restricts subsequent evolutionary possibilities and limits what chance can achieve. Mutations might be, to the best of our knowledge, mostly chance events when it comes to their occurrence, but they are biased chance events that happen in a historical substrate that is the genome of the organism. In other words, what changes are likely to occur at each moment is determined by the sequence that is being mutated, which means that the history that has crafted and selected a given genomic sequence over generations is what delineates which are the potential novelties of an evolutionary lineage. Chance is therefore channeled by history.

Although Bergson strongly criticized the emphasis on the accidental nature of change as proposed by Neo-Darwinians of his time, this mutational view of chance is one that Bergson would not have had an issue with, having claimed that although the variation itself may be accidental, what he thinks is fundamental is that the *tendency of the change* is not[35]. Whatever change takes place within the realm of all possible mutational steps, it is a change that, in order to prevail, needs to be integrated into the pre-selected informational representations. This means that a mutation disrupting basic vital functions that help shape phenotypes that have thrived in the past like metabolic or developmental pathways is unlikely to

produce a viable lineage, and that the new variation that arises needs to construct new forms on the foundations of pre-existing information. In this way it can be said that the tendency of the change is internal to a lineage and that the direction of the creative potential is drawn by the lineage itself, rather than it being dominated by the authority of necessity or the anarchy of chance. Thus, contingency outlines how it is that the creative push and its directions are internal to life itself like Bergson suggested, not only at the level of phenotypic developments as mentioned above, but also at the level of intergenerational change.

In spite of the dominance of chance and necessity in evolutionary explanations over the past century, historical contingency has not escaped debate among biologists. Among the interpretations of contingency discussed are the ones popularized by Stephen Jay Gould when he presented his "replaying life's tape" thought experiment[36] or by Jacob when he defended that evolutionary processes resemble tinkering, where new forms are crafted on the basis of pre-existing materials[37]. Furthermore, some biologists have tried to define whether chance, contingency or necessity have a higher impact in defining evolutionary trajectories. For example, some experimental efforts have explicitly tried to tackle the question of the relevance of contingency relative to chance and selection in evolving bacterial communities[38] and in reconstructed ancestral proteins[39]. Although these conceptual developments and experiments are key to remark that a contingency like the one implied by Bergson needs to be accounted for in evolutionary studies, separating chance, necessity and contingency is an attempt at carving evolution apart in pieces, trying to emphasize one principle over other. But in a very Bergsonian way, life is holistic; chance, necessity and contingency are intertwined in the evolution of each lineage that is following an unstopping tendency that is creative and internal. The direction of the tendency of the change as well as the possible paths forward are drawn by the memory of a lineage, on which chancy mutations occur. Memory points the direction, chance explores possibilities following it and then necessity filters this exploration. Evolution is not ruled by chance, nor by necessity, but by their interplay with the internal memory and potential which each unique lifeform itself crafts.

CONCLUSION

Overall, features of Bergson's élan vital can be interpreted in a context where molecular creativity is the interplay between mutations, genetic information and ecological and developmental conditions. More importantly, this Bergsonian interpretation of molecular evolution is one that emphasizes the internal

potential of organisms in developing their phenotypes and of lineages in defining their evolutionary trajectories. This is a vision that reinforces lines of study in evolution that are alternative to the dominating paradigms and which could lead to discoveries that are closed off from exclusively considering a Neo-Darwinian framework. Considering a Bergsonian take on evolution goes beyond seeing organisms as simple vehicles for genes and lineages as passive consequences of chance and selection, but rather considering them as active agents tracing their evolutionary fates. In this alternative paradigm, each cell division is a bifurcation in the trail of memory and each new cell is but a small step on a landscape of possibilities that is unique and unrepeatable. This is so, firstly, because of the uniqueness of the historical path that has resulted in the enactment of this cell, the impulse that carries with it this ever-expanding memory, and secondly, because of the external circumstances in which it is embedded, the material opportunities and obstacles that this individual cell encounters. This view of life is one in which there is a constant creation that is intrinsically defined by each individual living being as it encounters its material circumstances. This is, furthermore, a view of life that is compatible with the scientific knowledge that we have developed since we began to understand the double helix of memory and creativity.

PACO MAJIC obtained his degree in Biology from Universidad de la República (Montevideo, Uruguay) specializing in Genetics and Evolution and with a strong focus on zoology and natural history. He carried out his Master's degree studies in the University of Tokyo, Japan. There he worked in the field of developmental biology investigating the regeneration of echinoderms from a molecular perspective. Since 2017, Paco Majic is a doctoral candidate in the Computational Biology group in the Institute of Integrative Biology at ETH Zurich in Switzerland. During his Ph.D, Paco has worked on the de novo origins of protein coding genes, the evolution of gene regulatory complexity and the potential for non-heritable genetic variation to drive adaptive evolutionary trajectories. Associated with Swiss Institute of Bioinformatics, Lausanne, Switzerland.

NOTES

1.Henri Bergson. *Creative Evolution*. Trans. A. Mitchell. London: Macmillan, 1911, 103. https://archive.org/details/in.ernet.dli.2015.94170/page/n5

2. Ibid. 102

3. Ibid. 20

4. Ibid. 89

5. Henri Bergson. *La conscience et la vie*. Trans. F. Worms. Third edition. Paris: PUF, 2016, 17. "Et par où la force spirituelle, si elle existe, se distinguerait-elle des autres, sinon par la faculté de tirer d'elle-même plus qu'elle ne contient?"

6. Jacques Monod. *Chance and Necessity.* Trans. A. Wainhouse. New York: Vintage Books, 1972, 26

7. Ibid. 27

8. Ernst Mayr. "Cause and effect in biology." *Science* 134, no. 3489 (1961): 1501-1506.

9. Henri Bergson. 1935. *The Two Sources of Morality and Religion*. Trans. R. Ashley Audra and C. Brereton. New York: Henry Holt, 193, 105. https://archive.org/details/in.ernet.dli.2015.191246

10. Bergson, *La conscience et la vie,* 13. "la conscience est coextensive à la vie."

11. Bergson, *Creative Evolution*, 102.

12. Bergson, *La conscience et la vie*, 15. "(...) la représentation qui precede l'acte (...)".

13. Bergson, *Creative Evolution*, 28-29.

14. Ibid. 92.

15. Ibid. 108.

16. See Daniel Dennet. *Darwin's Dangerous Idea*. Simon & Schuster, 1995, 59 and David Haig. *From Darwin to Derrida*. MIT Press, 2020, 104 for discussions on the informational or virtual definition of a gene that is distinct from material molecules. It is worth pointing out that the information theoretical approach to biological questions is not without detractors, see for example the arguments put forth by Giuseppe Longo, P-A. Miquel, Carlos Sonnenschein, and Ana M. Soto. "Is information a proper observable for biological organization?." *Progress in Biophysics and Molecular biology*109, no. 3 (2012): 108-114.

17. Bergson, *La conscience et la vie,* 22. "La pensée qui n'est que pensé, l'oeuvre d'art qui n'esta que conçue, le poeme qui n'est que rêvé, ne coûtent pas encore de la peine ; c'est la réalisation materielle du poeme en mots, de la conception artistique en statue ou tableau, qui demande un effort."

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19. Bergson, *Creative Evolution*, 152.

20. Ibid. 116

21. Ibid. 275

22. Ibid. 117

23. Hendry Susila, Snježana Jurić, Lu Liu, Katarzyna Gawarecka, Kyung Sook Chung, Suhyun Jin, Soo-Jin Kim et al. "Florigen sequestration in cellular membranes modulates temperature-responsive flowering." *Science* 373, no. 6559 (2021): 1137-1142.

24. Bergson, *Creative Evolution*, 111.

25. Joshua L. Payne and Andreas Wagner. "The robustness and evolvability of transcription factor binding sites." *Science* 343, no. 6173 (2014): 875-877.

26. Bergson, *Creative Evolution*, 24.

27. Ibid. 23
28. Ibid. 55
29. Ibid. 265
30. Ibid. 29
31. Monod, *Chance and Necessity*, 118.
32. Ruth Hershberg and Dmitri A. Petrov. "Evidence that mutation is universally biased towards AT in bacteria." *PLoS genetics* 6, no. 9 (2010): e1001115.
33. Alan Hodgkinson and Adam Eyre-Walker. "Variation in the mutation rate across mammalian genomes." *Nature reviews genetics* 12, no. 11 (2011): 756-766.
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35. Bergson, *Creative Evolution*, 90.
36. Stephen Jay Gould. *Wonderful Life: The Burgess Shale and the Nature of History.* New York: Norton, 1989, 48.
37. François Jacob. "Evolution and tinkering." *Science* 196, no. 4295 (1977): 1161-1166.
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