What is life?

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1 Ubiquitous patterns

Dear Colleagues, welcome to my birthday lecture. I am delighted to have you here interested in what life is. After all, the profound question despite its catching curiosity has not been particularly rewarding as a scientific topic. The riddle, like many other big questions, is mostly regarded only as a philosophical poser. Hence those who nevertheless pursue it, like me, are looked upon – well – if nothing else at least a bit odd. Yet the history of science reveals, strangely enough, that the problem with the big questions is not so much in finding the answers to them, but in meeting expectations for the answers. As John Bahcall said, *what you will discover is not what you were looking for*.

Also the question "What is life?" carries along a strong preconception that there is life. As I doubt the seemingly self-evident fact, you perhaps wonder whether I am gone all insane – and so sorry already at the age of 50. Yet, I only emphasize that there is no demarcation line between living and non-living. In fact we see superb similarity among animate and inanimate. The same patterns are found throughout nature. For example, lengths of genes distribute in the same skewed manner as lengths of words. Animal and plant populations, irrespective of a species, spread out on terrestrial and marine environments in the same manner as economic wealth, irrespective of assets, spreads out in diverse societies. Chemical reactions and economic transactions proceed at times in an oscillatory manner toward stationary cycles such as citric acid cycle and annual cycles of agricultural production. Also a cyclone whirls in a temperature gradient in the same was as a galaxy spirals in the universal density. Moreover, ecological succession proceeds in the same way as technological progress, that is, from one step to another along a sigmoid curve. Production of goods branches out just as phylogenic tree of species fans out. Furthermore, neural activity recorded from cortex displays a power-law pattern just as seismic activity recorded from Earth's mantle. A metabolic network across a cell displays the same degree distribution as the nodes of World Wide Web across the Globe as well as the network of galaxies across the Universe. And so on, and so on.

These ubiquitous patterns urge us to shift from wondering what life is to wonder whether nature in its full entirety as well as in its every detail displays and follows some universal law. If it really does so, could science have missed such a prominent principle? Hardly. *In biology* as Theodosius Dobzhansky said *Nothing makes sense except in the light of evolution*. In physics as Sir Arthur Eddington said *The […] second law of thermodynamics holds the supreme position among the laws of nature*. Therefore, shouldn't the same supreme law allow us also to understand what life is as well as to resolve other prime puzzles?

2 Universal processes

When we wish to speak about everything, we need the most general concepts and the most fundamental notions, not the most exhaustive catalogues of genes or galaxies and not the most detailed charts of metabolic or communication networks. Darwin did not talk specifically about mutations and ensuing expressions as altered protein structures, but in general terms about variation and natural selection irrespective of genetic, metabolic, behavioral or other means that are merely in the service of evolution. Even earlier when natural philosophy had not yet diverged to various branches of science Newton, Leibniz and Maupertuis did not talk about particular particles and certain fields, but about variation in general and about the universal criterion of natural selection irrespective of gravitational, electromagnetic, nuclear or other forces that merely power natural processes.

Darwin was a generalist, but not general enough to acknowledge that evolution entails everything, not only animates. The ubiquitous patters prove processes of life no different by principle from processes of abiotic, technological, economic, social or any other systems. Therefore it is not enough to study living to understand life, but we must place life in a general, cross-disciplinary context to learn what it is all about.

3 The problem of physics

As I speak for physics to provide us with the most general concepts and the most solid logic to make sense of nature, surely some of you doubt whether physics is able to explain life. And you are right in the sense that physics as a discipline the way we know it today, cannot, but physics as we should know it, can.

Let me make my point by reminding you of a law of motion that I believe every one of you will recall, namely, Newton's 2nd law. When I ask physics students what is Newton's 2nd law, I will almost invariably receive that it would be $\mathbf{F} = m\mathbf{a}$. However, it is not. Instead Newton wrote that the force causes a change in momentum, [i.e., $\mathbf{F} = d_t\mathbf{p}$]. Hence the differential [of momentum $\mathbf{p} = m\mathbf{v}$] respect to time yields not one but two terms, namely $\mathbf{F} = m\mathbf{a} + \mathbf{v}d_tm$. The change in mass can be converted to a change in energy by another familiar formula of physics due to Einstein, namely $E = mc^2$. The 2nd term of Newton's law, that I believe your physics teachers all have skipped, should not surprise you because you know that any chemical reaction will either emit heat or absorb heat. *Now let me be clear*: The heat stems from the change in mass. In a nuclear reac-

*Figures: http://prezi.com/k6zbt9iq3kf2/what-is-life/

tion the change in mass is noticeable as is its tremendous output that powers activities of our economy. In a chemical reaction the change in mass per a broken covalent bond is not more than one per mill of the mass of an electron, but it is still ample enough to power processes of life. Since the change in mass is necessary for any reaction to take place, it is also necessary to note it down to understand how nature works.

All this is very trivial and therefore also very important. Newton's law says, for example, that a bacterium is forced to swim up along a concentration gradient of sugar and to metabolize the associated free energy. If the second term were omitted, that description would be without metabolism, that is, without changes of any kind. But biology is all about changes; about evolution, development, differentiation, proliferation, adaptation, learning and so on. Therefore physics, the way it was taught to you, cannot account for life, but the way Newton knew physics, it may well account for everything.

You must be now somewhat puzzled by the thought that if the change in mass is so vital, as I argue, why it is then omitted from teaching physics. The reason is simple but selfish. Namely, the equation of motion including the change in mass cannot be solved. For example, when the bug is consuming sugar molecules, undeniably the motivating sugar gradient is diminishing. When the motion itself is consuming its motive force, there is no way to solve Newton's law or for that matter any other equation.

It is obvious to any biologist that a growing population will invariably cause changes in its surrounding ecosystem, just as it is evident to any economist that an expanding enterprise will inescapably put competitors in plight. Yet many a physicists does prefer to ignore these indisputable consequences imposed by an evolving system on its housing surroundings to keep his equations computable. It seems that the intellectual challenge to calculate supersedes common sense. So, do not think too highly of a physicist, think yourself.

Newton's law of motion in its original complete form provides us with the proper physical portrayal of nature. It is not weird and mysterious but familiar to us and consistent with our everyday experience. On the contrary to prevailing impressions quandaries of quantum mechanics do not conceal secrets of life in some subatomic uncertainty and the curved space-time of general relativity does not wrap up the origin of life in Cosmos to an intangible weft. Many eerie ideas of modern physics merely articulate our own aspirations about a computable nature rather than expressing true comprehension of an evolving nature.

4 Intractable nature

I am not only blaming contemporary physics for lack of common sense, I am also claiming that modern biology pronounces more like our own wishes about a tractable nature than provides us with apprehension of true nature. Too often we wish to establish definite causal scenarios, not knowing that one-to-one sequential mapping of events cannot be made. And too often we work to unveil common origins, not knowing that diversification is an intractable process. Over and over again we make mathematical models to mimic data, but a good fit as such is no explanation for the phenomenon that underlies the data.

Despite our extreme efforts to elucidate ever finer details of ever larger systems, we know too well by now that we will never gain the certainty we wish to have. The trouble is not that we would not know enough, the trouble is, as the late Stephen Jay Gould said, the assumption we wish so much to be true is false. Namely, when changing one aspect, all other things would remain equal, but they never do. *Ceteris paribus* principle does not hold. Courses of nature are inherently intractable because everything depends on everything else. It is not only that *we* cannot solve Newton's equation in its complete, correct form – nobody can. Nature varies its courses too. Only by trial and error it will make the natural selection for the least-time free energy consumption.

Yet we should not mistake non-determinism for indeterminism. Paths of evolution just as paths of development and differentiation do vary, but the tracks are not all arbitrary. The natural bias toward the least-time processes gives rise to the rules and regularities, but too often we mistake these trends and patterns as outcomes of some special mechanisms or as consequences of some discipline specific doctrines whereas in fact they are manifestations of the supreme law that spans across all schools and scales.

5 The universal incentive

We make sense of the world we face by looking for causes of changes. *Let me be clear:* It is always the superior surroundings that has the say whether a system will change or not. For example, a protein will not fold when being cooked. A cell does not differentiate when not given a stimulus for it. A child will not learn to read when not given a book. A society will not develop when unable to exploit surrounding resources.

At all scales nature is in evolution by consuming energy differences of any kind in the least time. A chemical reaction, proliferation, development, differentiation or any other process did happen in the past and will happen also in future to abolish energy differences between the system and its surroundings. For example, biota appeared and covered the Earth by diverse species to consume the free energy con-

*Figures: http://prezi.com/k6zbt9iq3kf2/what-is-life/

tained in the hot sunlight relative to the cold space. Likewise economies emerged and are now enveloping the Globe to consume energy differences between rich natural resources and the cold space by many means, mines, factories, stores and other industrial machinery. Also galaxies housing stars and other powerful mechanisms of combustion formed and spread across the Universe to consume energy differences between matter and the cold radiation of space.

It would take me many more words to exemplify further the universal principle, but only Newton's equation to state it. When using mathematical formalism, it is not only about being concise, but about being precise. Mathematics will keep a perfect record so that nothing gets created from nothing and nothing gets lost for nothing. The book keeping of numerous transactions will ensure that our answer to the profound question what is life as well as our resolutions of other prime puzzles are not missing anything, not even a single build block of nature, that is, violating the conservation of quanta, and are not subject to a logical error. In this way ascertained apprehension cannot be undervalued as another opinion.

6 Flows of energy

When Newton's equation is multiplied with velocity, it displays explicitly the least-time flows of energy. This form, given first by Maupertuis, is known as the principle of least action. It sums all changes as changes in kinetic energy. The term does not only denote, for instance, that a zebra will ran faster after inheriting a beneficial mutation, but the term compiles also accompanying increase in its metabolism, and importantly also consequences in its surroundings, for example, that few lions will be left high and dry.

In thermodynamic terms the change in kinetic energy is equal to the change in entropy. It is financed by energy that is bound, for example, in numerous chemical potentials of food as well as by energy that is in free propagation, that is, light which is needed, for example, to raise fodder for the zebras. It is only a trivial mathematical task to show that the equation accounts for the ubiquitous patterns, skewed distributions with long tails which sum up along sigmoid curves which on log-log scale follow mostly straight lines, that is, comply with power laws. A like analysis reveals that logarithmic spirals and branching trees and networks are natural consequences of least-time energy dispersal.

Energy differences of various kinds are consumed in changes of various kinds. Diverse mechanisms merely channel flows of energy when proteins fold, cells differentiate and plants grow, or when inventions are made, products are sold and business is flourishing, or when stars shine, galaxies mature and the Universe is expanding.

Natural processes despite their many names do not differ from each other by principle, only by their mechanisms. In economics the universal principle can be recognized in the law of supply and demand as well as in the law of diminishing returns. In physics the irreversible evolution is also known as the second law of thermodynamics and the principle of increasing entropy. Curiously in mathematics irreversible processes are labeled by attributes such as non-holonomic, non-Abelian and non-computable. The prefix "non" reflects dislike, the mathematical impossibility to solve the equation, that is, to make precise predictions. Also many forms of modern physics prefer precise calculations over perfect comprehension.

7 Resolutions

Now let me exemplify what we can comprehend by this universal law.

To begin with, life is an inseparable process from any other natural process in the Universe. Admittedly the vital machinery has perfected itself over the eons in the free energy consumption, so that today it may seem rather different from pioneering abiotic mechanisms, but the operational principle is still the same. Likewise a modern integrated circuit on a semiconductor chip may appear rather different from its ancestral thermionic triode in a vacuum tube, but the operational principle to consume free energy is still the same.

Since there is no qualitative difference between animate and inanimate, it is also meaningless to ask how life originated. This resolution, however, does not relinquish all reasoning of abiogenesis futile. Metabolism first hypothesis makes sense, but first when it includes breeze of wind stirring a warm pond and other seemingly abiotic processes. Also the advocated role of RNA is justified, but not solely by its hereditary properties but primarily by its ability to absorb light. From this perspective it is no coincidence that nucleic acids are energetically expensive molecules. They were initially recruited to the free energy consumption due to their energetic value as such and only later became to embody free energy in a form of information. Likewise, our alphabet evolved from pictorial presentations of those things that were already vital to our early existence. For example the letter A stands for an ox and the letter B for a house and only later they became to embody the free energy in the form of information.

From the supreme viewpoint the origin of chirality consensus we see among natural amino acids and sugar moieties of nucleic acids is no mystery, but also a result of natural selection for the least-time free energy consumption. Molecular standardization facilitates energy transduction in the same way as, for example, the transportation convention to drive on the right hand side. Of course the mirror-image standard would be equally good, but you know it is best to settle for one or the other to keep moving and consuming.

*Figures: http://prezi.com/k6zbt9iq3kf2/what-is-life/

Accordingly it is no surprise that cellular metabolism and synthesis revolve around with a comparatively small number of conceivable organic molecules, just as modern manufacturing consumes comparatively few components. The standardized production is simply more effective in consuming free energy than manufacturing unique items. Biota's high-degree of standardization reflects a high-degree of global integration, just as the on-going standardization of goods and procedures reflects an increasing economic integration.

Moreover, the fact that our genomes contain genes only in a small fraction is not a bigger puzzle than the fact that our computer disks house valuable documents only in a small fraction. Just as we keep old versions in numerous copies, drafts, memos, rejected manuscripts and other failures as well as pieces of information we have unintentionally obtained in interactions, our genomes keep elements that are not of prime but eventually of some value. As long as maintenance costs are low, also inefficient information will be kept just in case. When it comes to computers, I guess expenses are about to be unbearable. Soon we will shift for cloud services that can be centrally administered, that is to say, documents can be purged against our will.

Moreover, redundancy and multiplicity that we see in cellular metabolic and communication networks is by principle no different from overlapping and backup systems in our societies. We simply need all that to sustain the free energy consumption under various and even unexpected conditions. We may wish to have deterministic control, but deterministic systems are not viable. They are simply unnatural. It is well known in traffic planning that only one track does not guarantee reliable operation as well as that when a network suffers from two or more blocks, there is no way to predict how traffic will reroute, but it will. For the same reason we fail to anticipate consequences of introduced mutations, yet we witness remarkable resolutions for survival.

The simple principle sheds light also on our complicated cognitive operations. Neural pathways are literarily the least-time paths for flows of energy as electric signals. We learn by building new paths and recall by running along established pathways. Conversely, when one ought to revise ascertained impressions, energetic costs will be greatly higher than when acquiring accurate understanding in the first place. It is these costs that we sense as aversion toward unconventional thinking, for example, that evolution would entail everything and that natural selection for the fittest would in fact be selection for the least-time free energy consumption. Also the cognitive cost of absorbing Newton's law in its original complete form [$\mathbf{F} = d_t\mathbf{p}$] goes up the higher a physicist has already invested in appending the incomplete form [$\mathbf{F} = m\mathbf{a}$]. The aversion of a scholar does not only amount from building new and blocking old neural pathways, but also from the demolished conceptual framework that provides the scholarly living.

8 Implications

Certainly there are many more matters to be exemplified and examined by the universal principle, but my address today, of what life is, should contain also some implications for our ways to live and to interact with each other.

Although I keep referring to the principle as the supreme law, the law is not a compelling commander rather a guiding counselor. It refutes the idea of superior knowledge, but approves trial and error. See, for natural selection to act there must be variation from which to choose. Hence we should come up with alternatives rather than imaging that there is no option. Accordingly we should cultivate characters, just as we should care for characters of organizations, not eradicate them, since complementary differences provide us with most resources from surroundings. So we should engage us more with intriguing disparity and adhere less to comfortable company. Ideas, even when opposing, serve as markers of our path.

The supreme law sets the arrow of time. Thus, to progress we should experiment, not cement the present status where in fact we are already stalling. We should evaluate the product in sight, not discard the prototype we have at hands. We should foster sensitivity toward strength, not cast creativity for customary. In short the supreme law reminds us of responsibility to make the best out of resources in our command. As you see, the legacy of the law parallels old wisdoms.

Dear Colleagues, some ten years ago, when I sought for the professorship in biophysics, I thought that had Darwin's theory been written as a theory of physics, it would grant us with an unparalleled understanding of nature. Today I know that the evolutionary theory had in fact already been written as a theory of physics a long time ago providing us with unprecedented explanatory power. It arches over and far beyond all my anticipation. Apparently [Maupertuis'] early insights were as breath-taking as they are today, but the holistic enlightenment did not match expectations for reductionist resolutions of that time. Hence it fell in a struggle for survival. It seems that the old easy explanation does not meet expectations for complicated compilations of our time. Hence it faces yet a struggle for revival. Despite the natural bias toward effective comprehension, it is still up to us to understand, in fact, it is the inspiring and enjoyable assignment that we have been given to accomplish.

Thank you for your interest.

[*] Figures: http://prezi.com/k6zbt9iq3kf2/what-is-life/