Cultural life
Theory and empirical testing

Baciu, Dan C.

DOI
10.1016/j.biosystems.2020.104208

Publication date
2020

Document Version
Final published version

Published in
BioSystems

BioSystems 197 (2020) 104208

Contents lists available at ScienceDirect

BioSystems

journal homepage: http://www.elsevier.com/locate/biosystems

Cultural life: Theory and empirical testing

Dan C. Baciu [a,b,c,*]

[a] Delft University of Technology, Department of Architecture, Delft, the Netherlands
[b] University of California Santa Barbara, Department of English, Santa Barbara, CA, 93106, USA
[c] University of California Santa Barbara, Department of History of Art and Architecture, Santa Barbara, CA, 93106, USA

ARTICLE INFO

Keywords:
Variation-selection processes
Homeostatic regulation
Negative entropy
Constructal law
Shannon communication
Quasispecies equation

ABSTRACT

"What is life?" and Erwin Schrödinger's answer, "negative entropy", inspired researchers in the 20th century to unite physics, chemistry, and physiology into a new synthesis that many believe to be an important foundation for life science today. Decades after Schrödinger, life scientists are still fascinated by the riddle that entropy can only accumulate in physical systems, which often leads to biological deterioration and death, but life finds ways to persist and prevail. So to say, life "negates" entropy. Can this fascination and research concept be broadened even further to human culture? Short after Schrödinger's publication, Claude Shannon coined the term "information entropy." Information entropy accumulates when noise interferes during communication. Eventually, all useful information is lost. Yet, from this observation, something surprising can be inferred. Not only biological life but also cultural life has the ability to persist and prevail in spite of the accumulation of entropy. Does this insight mean that cultural life also negates entropy, in Schrödinger's sense? These questions guided me over several years of research during which I developed and tested a new theory of culture based on variation-selection processes and homeostatic regulation. My contribution is to discover that these two processes not only make statements about biological life. They also explain some of the most important phenomena of culture: returning fashions, polarization, diversification, cycles of growth and reform, and the formation of common ethos across entire bodies of knowledge. With access to big data and supercomputing, I tested my theory against hundreds of thousands of news, magazine articles, books, and TV transcripts as well as textual content collected from the social media. Historical, institutional, and geographical information was extracted from these data using a new method; and new interactive tools were created to interpret the results. What should not be missed when reading this article is that the theory proposed here reveals a striking equivalence between nature and culture. The article states this equivalence in mathematical terms, and contextualizes it in the history of science. The mathematical breakthrough is relevant because it aligns the humanities to science while also allowing for live evaluation of what I call "cultural diversification cycles."

1. Introduction

Causal explanation models originating in the life sciences and have entered linguistics and helped advance the field (Nowak, 2000; Nowak et al., 1999). Other causal explanation models from the physical sciences are presently entering the study of social systems and technological evolution (Bejan, 2020a, 2020b, 2020c). My present article expands on earlier work by shifting the focus even further from language and technological evolution to culture. Culture is frequently expressed through language; and it is the integration of all human thought, including technological discoveries.

Despite the slight shift of focus, the main thread of my article remains a question that is fundamental to biology: The systems under consideration have the ability to persist and prevail, but how do they achieve this? Biology is often faced with this question because all biological systems are under pressure to overcome dissipative processes during which entropy accumulates. Homeostasis is the biological response to this latter kind of physical deterioration and death. The study of homeostatic regulation is important in biology, because biology, as the Greek name indicates, is the science of life.

The question, what life is, fascinates not only biologists. Homeostasis was already a well-defined concept when quantum physicist Erwin Schrödinger popularized the idea of negative entropy. For him, life was negative entropy (Schrödinger, 1944). Shortly thereafter, the

* Delft University of Technology, Department of Architecture, Delft, the Netherlands.
E-mail addresses: baciu@ucsb.edu, baciu@ucsb.edu, symposia@yahoo.com.

https://doi.org/10.1016/j.biosystems.2020.104208
Received 5 June 2020; Received in revised form 2 July 2020; Accepted 3 July 2020
Available online 20 July 2020

mathematician Alfred Lotka formulated a third law of thermodynamics in response to the observation that life overcomes the accumulation of entropy (Lotka, 1945). Lotka's formulation was replaced decades later by the constructal law, which states the conditions under which living flow systems persist and prevail (Bejan 2016). Homeostasis, negative entropy, and constructal law could seem almost self-evident and only of practical utility, had they not united biology with physics (Bejan, 2016, 2020a), and would they not yield a potential new answer to the role of the humanities among these sciences.

In this present article, I propose that entire groups of authors and audiences establish variation-selection processes and homeostasis, which, in turn, helps cultural life persist and prevail in spite of dissipative processes. This theory is formulated in words as well as mathematics. In addition, the theory is also contextualized in the history of science, and it is tested against empirical data.

The mathematics employed in the theory is so well known though its applications in biology that it requires little separate attention in this article and is placed in the supplement. This allows me to focus on theory, empirical tests, and historical roots. Over the course of the article, we will encounter important thinkers such as Darwin, Wallace, and Aristotle, but we will also see fashions rise and return; we will see culture diversify and grow; and we will see common ethos spread across entire bodies of knowledge.

Next to the figures printed with this article, there also are interactive interfaces available online. The laboratory under my direction at UC Santa Barbara has helped develop these interactive resources (student names are given in Acknowledgements). Do not miss out on the maps, they add a sense of geographical space that is difficult to render on paper.

What may surprise the theoretical biologist at the end of the day is that my theory makes predictions and explains a broad array of cultural phenomena without breaking out of standard evolutionary reasoning. The clear ties to pre-existent knowledge will make it increasingly easy to evaluate and understand culture live, outside laboratories, and these ties also make me ask: Does the study of cultural life still need to stand apart from life science?

2. Large-scale dissemination: variation-selection processes negate entropy

Information entropy was coined as an analog to what physicists call *entropy principle*. In physics, all useful energy is transformed into heat, in any closed system (Bejan, 2020a). The system eventually reaches physical *dead state*. (No perpetual motion machine will keep moving forever.) During communication, a similar process occurs. When messages are transmitted from senders to receivers, they accumulate information entropy. All useful information is dissipated and disappears behind noise. (The recording of another recording is less good than the original.) This law is not only supported by observation, but, if communication is defined as *exact or approximate reproduction of a message at a new place,* the law can also be logically deduced from the definition. Claude Shannon chose this framework in 1948 (Shannon, 1948).

Broadening Shannon's definition of communication to large-scale dissemination leads us to a surprising, new proposition. When *many messages* are exactly or approximately reproduced *in parallel*, entropy no longer accumulates within the system. The reason is that, under the new circumstances, communication accommodates large-scaled variation-selection processes. The mathematical structure that results from this new definition is equivalent to the *quasispecies equation,* known in physical chemistry to play an important role in the evolution of life (Eigen, 1971). Large-scale communication, as defined here, and quasispecies evolution are mathematically equivalent (Baciu, 2019b).

To fully appreciate the meaning of this mathematical equivalence, one must recognize that not only noise but also human thinking and creativity can be defined as approximate reproduction. In human culture, variants are created through creative processes: Scientists redesign their methods; designers think in variants and alternatives; humanists rethink their evaluation criteria; and even memories are rewritten when they are recalled, which occasionally changes them (Besnard et al., 2012). Rethinking, redesigning, and rewriting are three slightly different actions. Nevertheless, they have the same effect: They create variants. Let us call this phenomenon *variation principle*.

Here again, one must predict that entropy accumulates during isolated acts of creativity. Variation introduces changes, but useful solutions are rare, and they are therefore likely to be lost. Variation dissipates useful information. Anthropologists have described this phenomenon from first-hand observation. In small populations, knowhow is often degraded when it is passed on. People make changes to the techniques that they learn, and those changes more often prove to degrade the initial performance of the techniques in question (Henrich, 2016).

The opposite must be predicted when multiple creative acts occur in parallel, on a sufficiently large scale. At any time, audiences can select between multiple variants that are being disseminated next to each other. There are original, improved, plagiarized, and defective variants, all of which exist in parallel. The audience has the choice—and in the audience, those who make the right choice become most successful.

This process is called a variation-selection process, and it can be modeled with the quasispecies equation. If one were to search for a similar process on a much smaller but more familiar scale, brainstorming can serve as an example. During brainstorming, multiple variants are created and evaluated in parallel.

Would then variation-selection processes be the initial cause for diversification in human culture? Are there any limits? How far can variation-selection processes take us?

2.1. Variation-selection processes across nature and culture, and their limits

"Varieties may indefinitely depart from the original type," this is the observation that inspired Alfred Russel Wallace to formulate the theory of evolution on his hunt of paradise birds in Indonesia (Wallace, 1858). Wallace meant biological varieties, but it might have dawned to him that the same observation can also be made among varieties of thought. His later travelogue dwells on the varieties of names that people and commerce had given to paradise birds: god's birds, dead birds, etc. Next to the biological varieties of birds that Wallace found, there also existed varieties of bird names (Wallace, 1869).

Theoretically, the idea that varieties indefinitely depart from the original type can be broadened from biological varieties to most other types of information stored in digital systems. Genetic sequences are a digital system, but so are letters and words. Variation is open-ended in both cases: One can combine and recombine genetic base pairs to encode for countless proteins, but one can also combine and recombine letters and words to encode for countless bird names.

The bird names mentioned by Wallace are not an isolated case in which multiple variant ideas coexist. Just as one can find variation and speciation in biology, one can also find variation and diversification in human culture. This observation gains additional substance when one recognizes that the systematic thinking that underlies the development of biological taxonomy also underlies the study of human culture, and it has remained largely unchanged for millennia.

In evolutionary biology, Wallace repeatedly revisited the terms *varieties* and *species,* and so did his codiscoverer of evolution, Charles Darwin. Surprisingly, their two pathbreaking articles read at the Linnaean society in 1858 as well as their other evolutionary work (Wallace, 1855, 1858, 1869, 1880; Darwin, 1858, 1859) only reconfirm the Aristotelian roots of Linnaean taxonomy. This historical context strengthens the ties between biology and culture. Two millennia before Linnaeus, Aristotle and his school used *genus and differentia* to define any object or idea, and to develop any system of classification (Aristotle, 2015). In line with these historical roots, we can today speak not only of biological and chemical species; we also know of literary genres. Aristotelian logic is the basis for systematic thinking in many fields of study, ranging from biology to chemistry and to the humanities. Such systematic thinking is now well established, but it might never have become widespread if variation, variants, and diversity had been absent from the fields under consideration.

As we have seen, variation is open-ended and occurs across many fields of study. Nevertheless, variation-selection processes have limitations that have been most conclusively quantified in chemistry (Domingo and Schuster, 2016). The quasispecies equation plays an important role in understanding these limitations.

The term *quasispecies* was first used in biology; although it did not immediately come to fruition there. Francis P. Pascoe, a contemporary of Wallace's, used the term in the heydays of scientific evolutionism. When he sorted out Wallace's and other collections of insects from the Malay Archipelago, he classified the specimens brought to him into species as well as occasional quasispecies (Pascoe, 1866).

Yet, the quasispecies-breakthrough came only a century later, in chemistry, where the concept reached unparalleled simplicity and clarity: One gene is a chemical species; a group of variant genes is a quasispecies. This setup made variation-selection processes most easy to quantify (Domingo and Schuster, 2016).

The strength of the quasispecies equation comes from one main insight: When multiple variants are reproduced in parallel, the result is a distribution in which some variants are more frequent than others. This distribution of frequent versus rare variants depends on both, how fast each variant is reproduced, and how strong variation is.

In absence of variation, only one variant survives, namely the one that is reproduced at the fastest rate. Variation instantly broadens this distribution. In presence of variation, the unit of selection is no longer the isolated variant, but the quasispecies of variants. While the fastest reproduced variants predominate, some other variants are reproduced along with them, simply because they are related. Each quasispecies is comprised of a set of useful genes together with their less prolific but related variants (Nowak, 2006a).

Our proposition, again, is that large-scale dissemination in human culture can be modeled in an equivalent system. Q*uasi*-species literally means *approximately reproduced* species. As already mentioned, approximate reproduction is not limited to genetics. Shannon spoke of approximate reproduction in human communication. Ultimately, approximate reproduction has the same effect in both nature and culture. Regardless of whether approximate reproduction occurs through genetic mutation, recombination, or through human creativity, the effect of approximate reproduction is always the same. It creates variants. Such variants may indefinitely depart from the original type. They may explore unknown possibilities. They coexist, and, they are evaluated next to each other. The logical consequence is a system in which exact and approximate reproduction, together with unequal reproductive rates lead to large-scale accumulation—not of entropy, but of increasingly meaningful variants.

In our case, the quasispecies equation makes multiple additional statements that are important; although they require some initial effort to be understood. A quasispecies is a group of variant ideas. Approximate reproduction interconnects these variants. Together, they are a unit of evolutionary selection. The rate of growth of each variant within one group is equal to the collective rate of growth of the entire group. Thus, if the group grows, all variants grow. In addition, if a new variant grows faster due to new circumstances in the environment, the entire quasispecies will be pulled in that direction. These properties help quasispecies more efficiently explore the open-ended possibilities that culture provides.

While culture in its entirety is open-ended, each quasispecies is a unit of selection, and each quasispecies is finite. No quasispecies will produce all possible variant ideas at any given time. This sets limitations to the directions in which variation alone can search. Each quasispecies must remain a unit of evolutionary selection. It can only search in one direction and with limited resources. There must always remain a variant not tested, a stone not turned, and a road not taken.

These theoretical propositions raise two questions: 1) Can we confirm the existence of groups of ideas as units of evolutionary selection that can be analyzed with the quasispecies equation? 2) If so, will we find only one quasispecies, or do many of them coexist?

If multiple quasispecies coexist, we must consider whether next to variation-selection processes, there also is an additional process of self-regulation. Unaided by other processes, multiple quasispecies can only coexist in the unusual limit of exactly equal growth rates. Biologists easily recognize the problem: Cancer grows only slightly faster than regular tissue, but it grows large enough to kill unless it is checked. (This effect is also known as competitive exclusion.) In healthy organisms, growth rates are controlled by homeostatic regulation. This means that the coexistence of multiple quasispecies can be interpreted as a hint that homeostatic regulation controls the interplay between them. Before we get to this point, let us first test and more intuitively interpret the quasispecies concept.

2.2. Variation-selection processes explain power laws and clustering patterns

The existence of quasispecies of ideas is easily confirmed. The quasispecies equation explains the two most visible empirical laws of human culture: power laws and clustering patterns. These two empirical phenomena cannot be neglected. Countless researchers have studied them, and writers and filmmakers found them fascinating. Some students may recall power laws from their time in high school. Teachers call them pyramids of income, or pyramids of fame. Clustering patterns are even more visible. Everyone experiences clustering on an every-day basis: Speaking of clusters in human culture is simply a more abstract way of speaking about cultural groups and categories. Of course, we know that categories are always blurry. This detail is at once explained with the quasispecies equation. The blur consists of those aforementioned variants that go along because of variation. More importantly however, the quasispecies equation explains why power laws and clusters persist and prevail. Variation-selection processes, as captured by the quasispecies equation, are a basic mechanism that makes these phenomena self-perpetuating. Empirical testing is shown in Figs. 1-3 and is discussed below in brief and in detail in the supplement (Supplement sections 3.2 and 3.3).

Let us discuss power laws and clusters in the order in which they were discovered. Vilfredo Pareto, Alfred Lotka, and George Zipf were among the first to observe that money, culture, and language live in power laws (Pareto, 1896–7; Lotka, 1926; Zipf, 1935).

Towards the end of the 19th century, Pareto evaluated income and found that few winners take most. When he quantified this distribution, he compared it to a pyramid. Pareto's imagery soon entered popular culture, for example through the title sequence of Fritz Lang's silent movie "Metropolis." The sequence features a pyramid of buildings in a city with rampant income disparity.

Around the time of Metropolis, Alfred Lotka went another, more scientific approach. He counted author names in bibliographies, and he discovered the same distribution as Pareto: Few authors get most citations. Lotka's mathematics led to the development of bibliometrics. A similar idea also entered linguistics: Few words are frequent; many are rare. Power laws in natural language were eventually dubbed Zipf's laws, after George Zipf popularized them at Harvard.

However, evaluating power laws and drawing Pareto plots has an Achilles heel. It requires a researcher to first choose a variable, for example income, and then sort the data by that very same variable. This latter step makes each Pareto plot look like a straight falling line on logarithmic paper (hence the image of a pyramid. The slope of the Pareto plot is imagined as the slope of the pyramid.) However, this sorting procedure also is the reason why Pareto plots are considered statistically incomplete (Piantadosi, 2014). The quasispecies equation replicates the

Pareto plots in a statistically complete setup while also explaining the mechanism behind the Pareto distribution in a broader evolutionary context (Fig. 1 and Supplement section 3.2).

Power laws were first quantified much before clustering, but good theory should be able to explain both phenomena. For example journal impact or the like can be drawn as straight-lined Pareto plots, but, in many instances, journals can also be grouped into clusters of journals that remain hidden on the previous visualization. Theoreticians who attempted to explain the Pareto distribution overlooked this result (Piantadosi, 2014). Those fateful clusters were only later observed, mostly through computer-driven techniques of *dimensionality reduction*.

A social scientist, Pierre Giraud, may have been one of the first who searched for an explanation that united power laws and clusters. He reduced natural language to a handful of units he called *semes* (Giraud, 1968). Later authors spoke of *memes*, while dimensionality reductions independently advanced the development of entire fields of study such as *digital sociology* and *digital humanities*. The word choice *digital* somewhat reflects that the physical meaning of those computer-driven techniques remained hidden despite the continued efforts.

Around the turn of the millennium, Thomas Landauer and Susan Dumais combined a new modeling algorithm with an empirical test to assess model quality, which paved the way towards increasingly better-ranking technical solutions for dimensionality reduction (Landauer Dumais, 1997; Matveeva et al., 2005; Bullinaria Levy, 2012). In most of these approaches, collections of written text were processed into so-called *word co-occurrence matrices*. The matrices were then further processed trough a procedure called *tf-idf*, followed by *eigendecomposition,* or by variants and generalizations thereof. The precise role of these steps was disputed while researchers attempted various ex-post rationalizations. They puzzled: what did the technical solution really solve?

The path that I followed in my research comes the opposite direction and gives a coherent answer. Variation-selection processes led me to the quasispecies equation. To solve the equation, one must first estimate the rates of exact and approximate reproduction, followed by actually simulating the flow of information through the system. Mathematically speaking, one way to estimate rates of exact and approximate reproduction is by collecting text, saving it into matrices, and performing tf-idf. To simulate the flow of information through the system, one must then proceed with eigendecomposition. A step-by-step description and discussion is given in the supplement (Supplement section 3.3). Technically, the procedure developed over the empirical path is equivalent. Of course, this procedure is only one of many possible choices. The new theory opens new paths.

The quasispecies equation was the missing piece of the puzzle between Shannon communication and clustering patterns. The next section intuitively explains important properties of quasispecies, and it tests an additional prediction.

2.3. *Groups of ideas speciate through variation-selection processes*

In our setting, eigendecompositions simulate large-scale dissemination. Students familiar with matrix operations have an easy time understanding the details. They imagine each matrix as a multidimensional space. They also know of the eigenvectors, picturing them as the independent axes of the matrix. Mathematically, performing eigendecomposition on a matrix gives the eigenvectors, and, in our case, each eigenvector is a quasispecies. Conversely, this also means that each quasispecies can be imagined as an independent axis of the matrix.

Take your own hands as an illustrative example. You have ten fingers but only two hands. Within the framework of your body, the fingers on one hand are not independent axes, they often move together. Press your small finger and you'll see the fourth finger move as well. Stretch your arm in one direction, and all fingers go along. In contrast to the fingers, the hands are independent axes. You can stretch them out independently. In this analogy, each finger is an idea, each hand is a quasispecies.

In the case of cultural life, we are using the quasispecies equation to study dissemination. Hence, the eigenvectors can be interpreted as

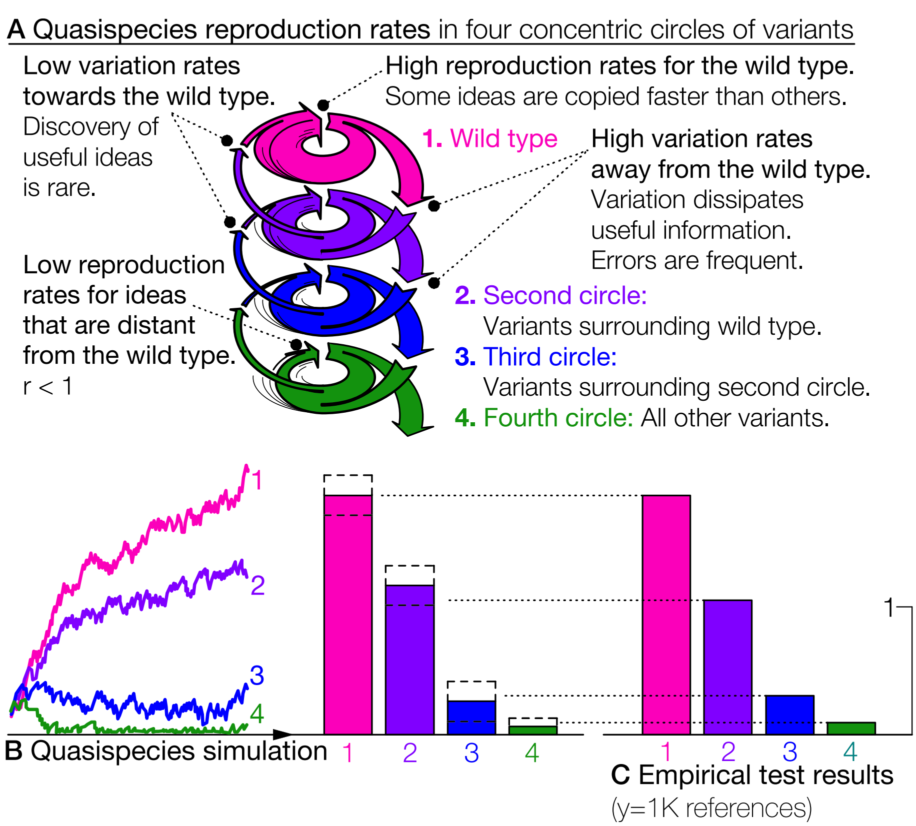

Fig. 1. One quasispecies. The Chicago schools of social science are studied as a quasispecies of ideas. The records that mention these schools are categorized into four concentric circles. The first circle consists solely of the Chicago school of sociology, which is most the frequent school. The schools contained in the second, third, and fourth circles are less and less similar to the Chicago school of sociology. It turns out that they are also less and less frequent, on average. To test the theory of dissemination, the size of each circle is not only measured empirically, but it also is theoretically estimated using the quasispecies equation. The test results are within the expected boundaries. Stochastic refinements were replicated from Bertels et al. (2017). The systematic categorization of Chicago schools follows Baciu (2018, 2019a). **A** Quasispecies evolution visualized as a flow system. **B** Simulation of quasispecies evolution over time (left). Quasispecies distributions, as they result from the simulation (right). **C** Empirically measured distributions for the Chicago schools of social science. **Data:** Chicago school corpus. y = 1K references.

independent *axes of dissemination*. Along each axis, information is exactly or approximately reproduced at an overall distinct pace. Mathematically speaking, each eigenvector has an eigenvalue, which represents the rate at which the axis grows. You can multiply an eigenvector by the matrix, but you really get the same result if you multiply the eigenvector by its growth rate, namely the eigenvalue. This property makes eigenvectors self-perpetuating; which explains why clustering patterns persist and prevail. No matter how the system grows, the variants along one axis grow together. They move together like fingers on one hand. The eigenvalue is the speed with which you stretch out your hand.

Theoretically, the largest quasispecies must come to predominate. Take the illustrative analogy of the hand again: Although your hands are the same size, one of them, left or right, likely is your dominant hand that you choose to use most. However, empirical results on human culture show that, in human culture, multiple quasispecies coexist. Culture has many hands. Before continuing to the interpretation of this important result, let us use the quasispecies framework to make and test one more prediction.

If the axes of dissemination, as proposed here, result from variation-selection processes, this also means that they are realms of speciation, potentially shaped by geography, history, and institutions. This proposition can be empirically confirmed (Figs. 2 and 3, and Supplement section 4).

Geography is important not only in cultural life but also in biological life. Puzzling geographical distributions of fauna and flora brought Wallace and Darwin's theory of evolution into existence. The Malay Archipelago and the Galapagos Islands offered first sources of insight (Wallace, 1857, 1858, 1869, 1880). Later, island biogeography transformed ecology from descriptive field into theoretical and mathematical science (MacArthur Wilson, 1963).

Biological speciation very often is defined by geographical boundaries such as mountains and waters. Swarms of finches will rarely cross the ocean. The new findings on cultural life suggest that variation-selection processes and speciation in human culture occur in geographical space, as they also do in nature. In addition, they also occur based on collective memory and institutional support. Quite understandably, this sets the stage for a mosaic of cultural diversity. To better comprehend this mosaic, we must next understand the processes through which the growth rates of multiple quasispecies, or, if you wish, multiple axes of dissemination, (or multiple creative swarms of variants,) stay in balance.

3. Large-scale reception: homeostatic regulation

The previous sections laid out the basics of variation-selection processes as applied to cultural life. The main insight is that ideas are disseminated in groups of variants: Each group is a unit of evolutionary selection; each group is a quasispecies. We found that multiple groups coexist, and we interpreted this result as a hint that some sort of self-regulation occurs. The growth rates of all groups must be kept in balance.

Given that we study human culture, the next step is to propose that self-regulation in this context relies on human perception. This setup immediately allows us to specify more details and draw testable conclusions. One can now interpret self-regulation as homeostasis and subdivide it into three sub-processes that are well known in neuroscience: habituation, discrimination, and sensitization. (These three processes tell that: 1., people stop listening to repeated messages; however, 2., they can learn to distinguish between similar messages; and 3., they can regain interest if, based on some new experience, the message seems promising again. Some of these processes are also known in popular culture. For example sensitization is known as the experiment in which a new cow raises a bull's interest in the cows that it already knows.)

This theoretical setup leads us to a system of equations that, once applied to human culture, explains not only the coexistence of multiple quasispecies, it also explains *returning fashions*, *formative periods* at the beginning of trends, *diversity threshold* situations, cycles of *growth and reform*, and the evolution, under certain circumstances, of a *common ethos* that unites entire bodies of knowledge.

The new equations again have equivalent formulations in the life sciences and chemistry. There, they are best known as Lotka-Volterra equations, named after Alfred Lotka and after the mathematician Vito Volterra, a pioneer of mathematical ecology (Lotka, 1910).

The particular formulation of Lotka-Volterra equations that our reception theory leads to, and that, in absence of another name, could be called *diversification equations,* do not stem from Lotka's own hand, but were put to paper at Oxford decades later. They helped develop what is today an entire field of study known as *virus dynamics* (Nowak et al., 1990, 1991; Nowak May 2000; Nowak, 2006a). Some people believe that ideas go viral. Here is a real mathematical equivalence derived from theory and supported by empirical testing.

3.1. Returning fashions are cycles of media activity and audience habituation

Let us begin with the simplest case and add more complexity later. The first step is to model the effects of dissemination and habituation alone. This setup leads to a standard pair of Lotka-Volterra equations, familiar to most scientists. Students use the equations early-on in their education to explain the wavelike wobbling in the sizes of prey and predator populations that consecutively outbalance each other. In our case, the equations are used to predict waves of fashion. Any quasispecies of ideas can serve as prey species; habituation is the predator (Fig. 4A and B and Supplement section 3.4). The interplay between ideas and habituation gives rise to returning fashions.

Habituation not only leads to fashions, but also to diversification. This phenomenon is well known in biology. Thomas Insel showed that a tiny mutation in the chemistry responsible for habituation leads to divergent patterns of behavior and to simple but beautiful adaptations within the animal habitat (Insel and Shapiro, 1992; Insel, 2016). Insel studied prairie and montane voles. In one species, habituation to the animal's sexual mate was faster, and this allowed for more genetic recombination. Hence, habituation supports diversification.

Insel's discoveries also found many practical applications beyond voles and lab mice. Much testing was performed on humans because the related neurochemistry is easily administered through the air. The next section will test whether habituation leads to diversification also in human culture. To achieve this, we must introduce the concepts of discrimination and sensitization. The introduction of these two concepts is necessary because we now study multiple quasispecies that audiences must distinguish.

3.2. From formation periods and rapid turnover to collective breakthrough

Habituation is often found in interplay with discrimination and sensitization. If these three processes are integrated, the above-mentioned diversification equations are obtained (Eqn. 1 in Supplement section 2). These equations explain not only biological but also cultural diversification processes, and they do so in unprecedented clarity.

Consider the event that a fashion becomes popular. In response, habituation is activated and turns people indifferent. This brings about the decline of this previous fashion. However, it is important to remember that people can discriminate. They only become indifferent to the fashion in question, not to life in general. Meanwhile, variation has created variants that escape habituation. From these escape variants, new fashions begin to grow. Where, initially, there was one fashion, now, there are multiple of them.

With multiple fashions coexisting, we must go on and consider the possibility that new fashions make people regain interest in old ones.

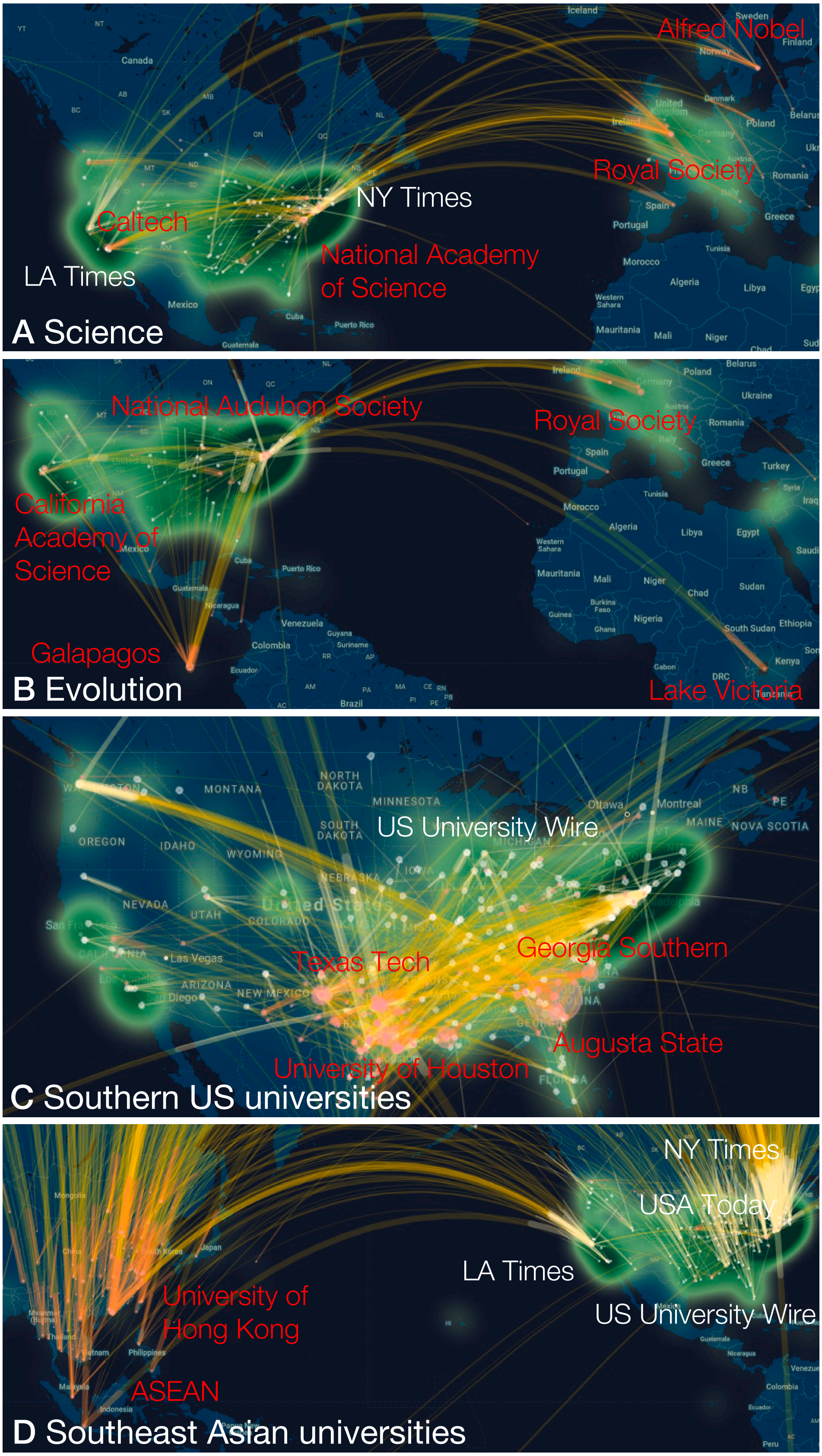

Fig. 2. Multiple quasispecies: variation-selection processes in geographical space. Cultural life renews itself unevenly, which gives rise to regional varieties and to diversification in geographical space. The new theory of cultural life predicted the existence of such geographical diversification, and it helped develop methods to study it. Each map represents a distinct unit of evolutionary selection, or, to use the term coined in section 2.3, a distinct axis of dissemination. **A** This map represents the geographical footprint of science recognition, studied as an axis of dissemination. The National Academy of Science and the Nobel Prize give science recognition an international as well as interdisciplinary appeal. (Dissemination axis S1.11) **B** The Galapagos, Lake Victoria, their birds, the California Academy of Science, and the Audubon and Royal societies dominate the discourse about evolution. This axis is equally international, but stretches across different zones. (Dissemination axis S1.129) **C** In the Southern United States, many universities and their media outlets are tightly interconnected. The ties between these institutions give rise to a distinct variation-selection process. (Dissemination axis S1.80). **D** Southeast Asia is not only a geographical region; it also an axis of dissemination in U.S. American news. (Dissemination axis S1.42). **Legend:** White dots: Publishers. Red dots: Published content. Lines: The yellow lines connect publishers with the content that they published. The lines are tinted white towards the publisher and orange towards the published content. Green haze: Areas frequently covered by news in this corpus. **Data:** U.S. news, science corpus. **Links to online interactive visuals: A** https://doi.org/10.25496/W2RP4H **B** https://doi.org/10.25496/W2MW2K **C** https://doi.org/10.25496/W2H592 **D** https://doi.org/10.25496/W2CC74.

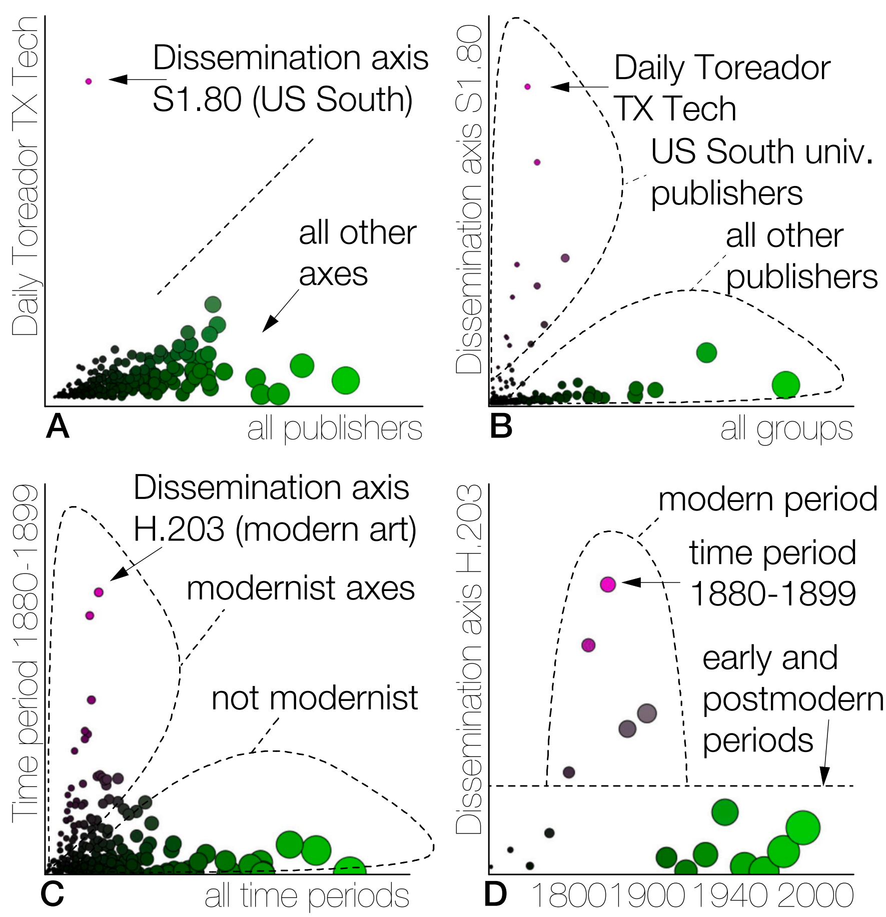

Fig. 3. Multiple quasispecies: variation-selection processes among publishers and in collective memory. Variation-selection processes do not only occur in geographical space. With their mission statements and the like, institutions such as publishers and funding agencies create their own variation-selection processes (A,B). Variation-selection processes may also emerge in the realm of collective memory (C,D). **A,B** These two scatter plots visualize the Southern U.S. network of universities and media outlets mentioned in Fig. 2C. On the left (A), you can see that no other dissemination is as relevant for the "Daily Toreador" at Texas Tech as S1.80. On the right (B), you can have a closer look at the S1.80 axis. You see that, next to the Daily Toreador, several other news outlets at Southern U.S. universities also specialize in this axis. Together, these publishers are part of a variation-selection process that unites them and shapes their joint cultural identity. **C,D** These two scatter plots show how cultural life experiences polarization on the time axis. On the left (C), you can see a clear divide between "modernist" axes that are concerned with the late 19th century, and those that are not. On the right (D), you can more closely inspect the historical profile of one of these axes, H1.203. The axis is centered on 1900, but it spreads out to cover anything from around 1840 to 1940. This historical profile visualizes how the idea of modern art emerges as variation-selection process on the time axis. **Data:** U.S. news, humanities and science corpora. **Links to online interactive visuals: A,B** https://doi.org/10.25496/W2WC7S **C,D** https://doi.org/10.25496/W2159Q

This is a type of sensitization. Let us call it *cross-sensitization.* If such a process takes place, one can use the equations to predict that evolution has two distinct phases, formation and growth. During formation, habituation is active and leads to diversification. The phase of growth sets in when enough diversity is accumulated, such that cross-sensitization disrupts habituation. However, because habituation is disrupted, diversification fails. The equations return to quasispecies behavior. The onset of each of these phases can be predicted from diversity threshold conditions.

These predictions can be tested against empirical data. Here again, the predicted phenomena are not uncommon. To begin with, formative periods are often followed by collective breakthrough. This phenomenon is frequently observed in human culture. Scholars of history already coined the term *formative period.* Now, this phenomenon can be explained as a result of processes that are everywhere at play in human and animal brains. In addition, the diversification equations state that formative periods are periods of diversification, and they also state that the transition from formation to growth occurs after certain diversity threshold conditions are met. These predictions are tested in Fig. 4 (Fig. 4C and D and Supplement section 3.5).

3.3. *Diversity and habituation regulate growth and recession cycles*

Every scientist should become acquainted with the phenomenon of diversification, cross-sensitization, and growth. Let us consider a concrete example of immediate interest: There is physics, biology, geography, etc., but there also are natural sciences, physical science, human science, life sciences, engineering science, climate science, etc. *Science* makes the link between disciplines explicit and interconnects audiences. The result is cross-sensitization by reference to a joint cause. The concept of cross-sensitization is easy to understand: Interest in life science could also spark interest in human science.

With respect to the term *science* it is possible to empirically show that there is more than formation and growth in one single cycle. In science, there are three consecutive cycles of growth and reform. They stretch over three centuries. During this evolution growth leads to diversity loss, while stagnation allows diversity to rebound and to catalyze new growth (Fig. 5 and Supplement section 3.6). As above, the evolutionary model is again identical to the one for virus dynamics (Nowak et al., 1990, 1991; Nowak and May, 2000; Nowak, 2006a, Equation 1 in Supplement section 2).

In absence of another name, I called this type of cooperation *diversity selection.* The five main types of cooperation, (i.e. direct and indirect reciprocity, and spatial, group, and kin selection; see Nowak, 2006b), are thus now complemented by a sixth type of cooperation that is more than a special case of virus dynamics. Even more prominently, the same process is found in human culture.

Diversity selection can occur if the benefit of diversification is larger than its cost. However, are there any benefits that can consistently be gained from diversification? Yes. Diversification helps evolution search in multiple directions. Two hands can do more than one hand with ten fingers. Through diversification, evolution can grab with multiple hands, or it can, at once, take both the road and the road not taken.

3.4. *From creative origins to common ethos*

The diversification equations can be further developed to take into account the distinction between *dissemination drivers* and those colorful attributes, the main role of which is to make the initial ideas appear more novel and diverse. There is a similar distinction in genetics. *Cancer driver genes* drive the growth of tumor and metastases, while many other genes are passed along and mutate, but only indirectly affect the disease.

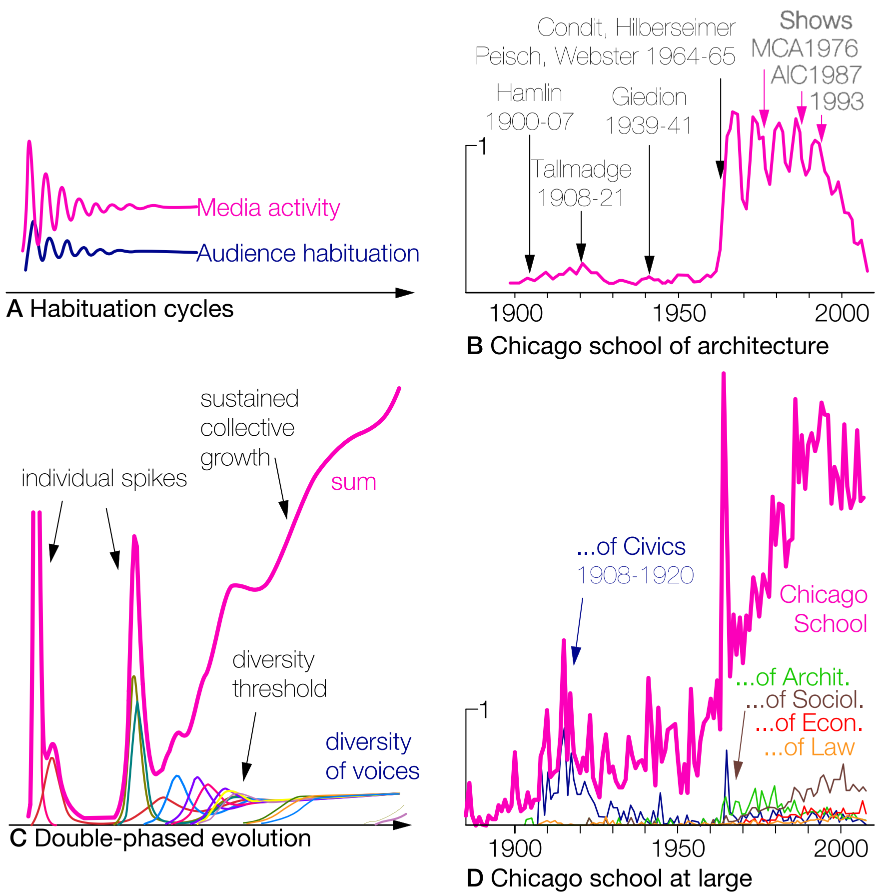

Fig. 4. Habituation, discrimination, and sensitization explain waves of fashion, periods of formation, diversity thresholds, and collective rise to fame.
A Media activity and habituation lead to waves of fashion as modeled with Lotka-Volterra equations. Simulation. **B** Waves of fashion empirically found in the *Chicago school of architecture*. Museum exhibitions ride the waves (Data: Chicago school corpus, 105K periodicals and books, y = 100 references). **C** Habituation, discrimination, and sensitization lead to a double-phased evolution with a diversity threshold between the two phases, as modeled with the diversification equations equivalent to Nowak and May (2000). Note the individual spikes on the left and the collective growth on the right. During formation, ideas do not lie dormant; they diversify. Simulation. **D** Historical data on the *Chicago school* at large confirm the predictions. The peak on the left is dominated by one school. The rise to fame on the right is a collective breakthrough. (Data: Google Books, y = 1/10M words, Online: https://doi.org/10.25496/W27P4V).

New influential work shows that driver genes vary in the original tumor more than in metastases. This insight was recently backed with equations (Reiter et al., 2018); and we also make this type of observation in human culture. There are trendsetters and followers. The first discover and rediscover, while the latter follow. A pair of examples is at hand: When evolutionism gained recognition, Wallace was already moving towards something new; and the type of humanistic endeavor that was called science in early modern English during the scientific revolution is no longer recognized as science. However, this is only anecdotal evidence. In my doctoral thesis, I have confirmed this phenomenon on a large scale for the Chicago school (Baciu, 2016, 2017, 2018, 2019a, 2020).

4. Discussion

One isolated transmission may add noise to a message, and one creative brushstroke may diminish an already finished artwork; however, when entire cultural communities think together, they transform noise and individual creativity into collective strategy. This is *negative entropy* in cultural life. Individuality is on one side of the equations, collective action on the other, and between them are dynamic balances and diversity.

Understanding culture as interplay between individuality and collective action has led us to *large-scale dissemination and reception*, which we formulated as *variation-selection processes* and *cultural homeostasis.* This setup led us to discover creative swarms of ideas that serve as units of evolutionary selection in the open-ended ocean of possibilities provided by human culture. This discovery led us to further observe how entire communities of people *habituate* to information, but we have also seen that they can learn to *discriminate*, and they can be *sensitized* and *cross-sensitized* to certain stimuli.

The physical effects of these processes are many. Among them, we observed that the aforementioned swarms of variants rise along *dissemination axes* with *geographical, historical,* and *institutional profiles* that, if plotted on logarithmic paper, translate into *power laws*. We saw that *formative periods* are phases of diversification and rapid turnover, followed by collective breakthroughs after *diversity threshold conditions* are met. Homeostatic processes over the course of this evolution may lead to *waves of fashion* and to *diversity selection* as a sixth type of cooperation that accommodates cycles of *growth and reform* while a *common ethos* initiated by trendsetters is perpetuated across entire bodies of knowledge. A single logical step sets off an avalanche of consequences.

The present article has not only proposed a theory. The theoretical postulates have been tested using linguistic, institutional, historical, and geographical data. These data were collected from written and spoken language as recorded in news and books, as well as in the social and mass media. In addition, the same theory logically applies to any other type of culture, no matter whether it evolves on large marketplaces or whether it takes shape among professional groups, for example of financiers who buy stock. With access to live data and theory as developed here, it is now possible to evaluate and understand cultural change in real time; and consistent diversity thresholds may occasionally allow for cautionary forecasts.

The *varieties equations*, as I would like to collectively call the equations employed in this article, are not only about individualism and collectivism, but also about diversity and inclusion. Individualism and collectivism have sometimes been held to mutually exclude each other because of an unsettling *uncertainty relation*: At different scales, data may invite divergent interpretations that cannot be pursued all at the same time. Edward Simpson, whose diversity measure is employed in Fig. 5, is only one of many who formulated this principle. Small data may point

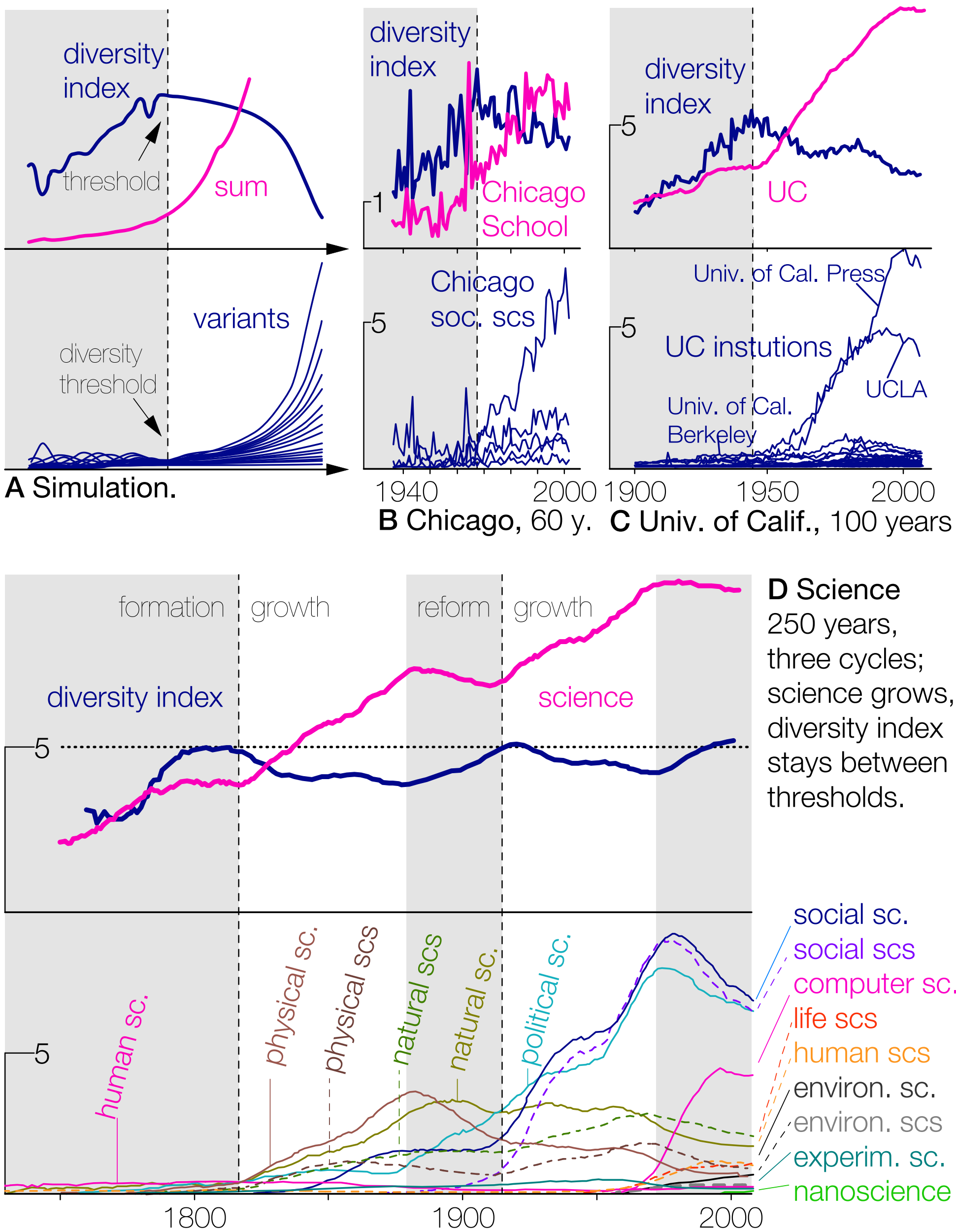

Fig. 5. Growth and stagnation as diversification cycles. Diversity leads to growth. However, growth reduces diversity. In absence of diversity, growth eventually comes to a halt. At this point, diversification may restart. These predictions are confirmed by measuring growth and Simpson's diversity index. Growth and diversity index move against each other in both simulation and empirical data. Diversity index stays between thresholds over three centuries of "science."
A Diversity and growth delimit each other. Simulation by Nowak et al., (1991), initially developed for a different application. **B** Diversification in Chicago schools of social science. (Above: "Chicago School"/"Chicago" y = 1/1M words; diversity index y = 1/D. Below: Chicago schools of social science y = 1/1 M words.) **C** Diversification in institutions of the University of California. (Above: "University of California"/"California" y = 2/100 words; Diversity index y = 1/D. Below: Institution names y = 1/1M words.) **D** Science and science branches during three cycles of diversification and growth. (Above: "Science" y = 2/10 K words; Diversity index y = 1/D. Below: Science branches y = 1/1M words.) **Data:** Google Books.

one way; aggregated data, may point the other.

This unity-diversity uncertainty is deeply rooted in the human mind (Baciu, 1982). It is the etymological source for something as vast as the uni-verse and as intellectually fulfilling as uni-versity (with presently renewed concerns about diversity and inclusion). The same uncertainty may have left behind divergent interpretations for the Tower of Babel. Was the tower a symbol of growth and greatness, or did its builders begin to babble, loosing their common basis of communication?

The modern world may still face this problem of uncertainty. Globalization unites an increasing number of people while the seemingly opposite process, individualization, advances among them: Serial mass production has become individualized; and mass media have given way to social media. Globalization has legitimized global economical institutions. Individualization has inspired postmodernism with its multitude of incompatible realities.

However, what is the precise relationship between the two processes? The varieties equations substantiate that diversification is the very source of sustainable collective growth. Individuals and diverse sociocultural groups are not alone; they need each other in order to grow. Diversity is most meaningful in the presence of inclusion.

After so many considerations, we must admit that our inquiries suggest that humans are not alone in yet another sense. Nature and culture are very much alike. Variation-selection processes and homeostasis unite physics, nature, and culture.

This also means that humanities research does not need to be separated from the other sciences, which has become silent reality over the last centuries. Science refers to any empirical or theoretical system of knowledge. On the other hand, humanities refer to the study of human culture. Science is a method, the scientific method. Humanities are a field of study. Method and field of study can go together. The study of human culture, as practiced in this present article, is theoretical and empirical; it is a type of science.

You may say that there also exists other scholarship in the humanities, and you are right. Nevertheless, while observing how categories of STEM and GLAM evolve through variation-selection processes and homeostasis, we must recognize that the study of life unites researchers under a broader umbrella. Researchers and scholars are diverse, but not alone. They jointly expand our understanding of life in many directions both in nature and culture.

Note

This article is an outcome of the research grant that the author obtained from the Swiss National Science Foundation in the academic year 2017–2018. The article was composed in Chicago, Santa Barbara, at Lake Tahoe, in the Grand Canyon, and at Lake Navajo.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

D. Baciu, I. Matveeva, B. Capitanu, E. Dickson, D. Roth, N. Khedekar, S. Pande, A. Paturi, K. Kilari, S. Jagirdar, K. Bhatiya, A. Sharma, S.S. Murthy, S. Guhathakurta, P. Castro, C. Kumar, M. Kadam, D. Ghiurco, S. Naik, M. Tunga, S. Kashyap, K.L. Rajakumar, B. Subramani, R. Sukhadia, H.K. Shivappa. **Grants** HathiTrust Research Center, scientific support and data, recipient D.C.Baciu; Swiss American Society, recipient D.C. Baciu; Swiss National Science Foundation, grant nr. P1SKP1_174883, recipient D.C. Baciu; The Fulbright Program, recipient D.C. Baciu; Swiss-American Society, recipient D.C. Baciu; Illinois Institute of Technology, recipient D.C. Baciu; Mellon Foundation, recipient A.Y. Liu. **Interactive visuals by Interpretation Laboratory** D.C. Baciu, director of lab, research concept and supervision, design and coding; S. Park, GeoD and 7D (design); X. Kang, GeoD (design); Y. Li, GeoD (design), 7D (coding); J. Sun, wikification of text data; A. Sunku, Z. Zhao, S.P. Kajarekar, semantic testing, 7D and GeoD (coding). **Data and materials availability:** Data, code, and interfaces upon publication released under creative commons license. Corpora: HathiTrust Research Center (Chicago school corpus); University of California Santa Barbara, Department of English, WE1S Project (science and humanities corpora); Google Books (Google Books data)

Appendix A. Supplementary data

Supplementary material to this article is available online and contains: equation 1, corpus and model specifications with accessibility descriptions for all figures, discussion of methods and testing as called out in the article, and other material. The author's project page can be found online at https://doi.org/10.17605/OSF.IO/QDGY8

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystems.2020.104208.

References

Aristotle, 2015. 5. Definitions. In: The Organon (Reprinted in University of Adelaide. Adelaide.
Baciu, D., 1982. thesis. University of Medicine and Pharmacy, Cluj-Napoca.
Baciu, D.C., 2016. "Sigfried Giedion: Historiography and History of Reception on a Global Stage." Ar(t)chitecture. Technion Israel Institute of Technology, Haifa.
Baciu, D.C., 2017. The Chicago School: Evolving Systems of Value, Report for the Advanced Collaborative Support Project 06.2016-03.2017 at the Hathi Trust Research Center ([This report develops a theory of dissemination via quasispecies equation; it tests the theoy; and it explains some methods and applications.]).
Baciu, D.C., 2018. From Everything Called Chicago School to the Theory of Varieties,. Doctoral Dissertation. Illinois Institute of Technology ([This thesis develops the theory of varieties as a theory of dissemination and reception with quasispecies and Lotka-Volterra equations. The thesis gives testing results on the Chicago school and develops and discusses methods in detail.]).
Baciu, D.C. (Ed.), 2019a. Chicago Schools: Authors, Audiences, and History, Prometheus, 2 (IIT) ([This article introduces the idea that human culture must persist in spite of dissipative processes; and it makes the connection between Shannon's definition of communication and negative entropy via variation-selection processes. The article also gives mathematics and testing with empirical data on the Chicago school.]).
Baciu, D.C., 2019b. Chicago schools: Large-scale dissemination and reception. Prometheus 2, 20–43.
Baciu, D.C., 2020. Sigfried Giedion's Chicago School: A Midpoint in 150 Years of History. https://doi.org/10.31219/osf.io/fh2gj. OSF Preprints.
Bejan, A., 2016. The Physics of Life. St.Martin's, New York, NY.
Bejan, A., 2020c. Freedom and Evolution: Hierarchy in Nature, Society and Science. Springer, Basel.
Bejan, A., 2020a. Freedom and evolution in the dynamics of social systems. BioSystems in print. https://doi.org/10.1016/j.biosystems.2020.104148.
Bejan, A., 2020b. Human evolution is biological & technological evolution. BioSystems in print. https://doi.org/10.1016/j.biosystems.2020.104156.
Bertels, F., Gokhale, C.S., Traulsen, A., 2017. Discovering complete quasispecies in bacterial genomes. Genetics 206, 2149–2157.
Besnard, A., Caboche, J., Laroche, S., 2012. Reconsolidation of memory. Prog. Neurobiol. 99, 61–80.
Bullinaria, J.A., Levy, J.P., 2012. Extracting semantic representations from word co-occurrence statistics. Behav. Res. Methods 44, 890–907.
Darwin, C., 1858. On the perpetuation of varieties and species by natural means of selection. Linnean Soc. Zool. J. 3, 46–53.
Darwin, C., 1859. On the Origin of Species by Means of Natural Selection. Murray, London.
Domingo, E., Schuster, P., 2016. Quasispecies. Springer, Basel, pp. 1–22.
Eigen, M., 1971. Self-organization of matter and the evolution of biological macromolecules. Naturwissenschaften 58, 465–523.
Giraud, P., 1968. The semic matrices of meaning. Soc. Sci. Inf. 7, 131–139.
Henrich, J., 2016. The Secret of Our Success. Princeton, Princeton, NY.
Insel, T.R., 2016. Translating oxytocin neuroscience to the clinic: a national Institute of mental health perspective. Biol. Psychiatr. 79, 153–154.
Insel, T.R., Shapiro, L.E., 1992. Oxytocin receptor distribution reflects social organization in monogamous and polygamous voles. Proc. Natl. Acad. Sci. Unit. States Am. 89, 5981–5985.
Landauer, T.K., Dumais, S.T., 1997. A solution to Plato's problem. Psychol. Rev. 104, 211–240.
Lotka, A.J., 1910. Contribution to the theory of periodic reactions. J. Phys. Chem. 14, 271–274.
Lotka, A.J., 1926. The frequency distribution of scientific productivity. J. Wash. Acad. Sci. 16, 317–323.
Lotka, A.J., 1945. The law of evolution as maximal principle. Hum. Biol. 17, 167–194.
MacArthur, R.H., Wilson, E.O., 1963. An equilibrium theory of insular zoogeography. Evolution 17, 373–387.
Matveeva, I., Levow, G., Farahat, A., Royer, C., 2005. Term Representation with Generalized Latent Semantic Analysis. Recent Advances in Natural Language Processing.
Nowak, M.A., 2006a. Five rules for the evolution of cooperation. Science 314, 1560–1563.
Nowak, M.A., 2000. The basic reproductive ratio of a word, the maximum size of a lexicon. J. Theor. Biol. 204, 179–189.
Nowak, M.A., 2006b. Evolutionary Dynamics: Exploring the Equations of Life. Belknap, Cambridge Ma.
Nowak, M.A., May, R.M., 2000. Virus Dynamics. Oxford University, Oxford.
Nowak, M.A., May, R.M., Anderson, R.M., 1990. The evolutionary dynamics of HIV-1 quasispecies and the development of immunodeficiency disease. AIDS 4, 1095–1103.
Nowak, M.A., Anderson, R.M., McLean, A.R., Wolfs, T.F.W., Goudsmit, J., May, R.M., 1991. Antigenic diversity thresholds and the development of AIDS. Science 254, 963–969.
Nowak, M.A., Plotkin, J.B., Krakauer, D.C., 1999. The evolutionary language game. J. Theor. Biol. 200, 147–162.
Pareto V., Cours D'Économie Politique (Rouge, Lausanne, 1896-7).
Piantadosi, S.T., 2014. Zipf's word frequency law in natural language. Psychonomic Bulletin 21, 1112–1130.
Pascoe, F.P., 1866. On the coleoptera of Penang. Proc. Zool. Soc. London 8, 222–267.
Reiter, J.G., Makohon-Moore, A.P., Gerold, J.M., Heyde, A., Attiyeh, M.A., Kohutek, Z.A., Tohkeim, C.J., Brown, A., DeBlasio, R.M., Niyazov, J., Zucker, A., Karchin, R., Kinzler, K.W., Iacobuzio-Donahue, C.A., Vogelstein, B., Nowak, M.A., 2018. Minimal functional driver gene heterogeneity among untreated metastases. Science 361, 1033–1037.
Schrödinger, E., 1944. What Is Life? Cambridge University, Cambridge.
Shannon, C., 1948. A mathematical theory of communication. Bell Sys. Tech. J. 27, 379–423.
Wallace, A.R., 1855. On the law which has regulated the introduction of new species. Ann. Mag. Nat. Hist. 16, 184–196.
Wallace, A.R., 1858. On the tendency of varieties to depart indefinitely from the original type. Linnean Soc. Zool. J. 3, 53–62.
Wallace, A.R., 1880. Island Life. Macmillan, London.
Wallace, A.R., 1869. The Malay Archipelago. Macmillan, London.
Wallace, A.R., 1857. On the natural history of the Aru Islands. Annals of Natural History 20, 473–477.
Zipf, G.K., 1935. The Psycho-Biology of Language. MIT, Cambridge, MA.