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Causal models, creativity, and diversity

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Causal models find application in almost all areas of science, and they often support the development of theories that are straightforward and testable. Yet scientists also observe things that surprise them. Fascinated by such observations, they learn to admire the playful aspects of life, as well as its creativity and diversity. Under these circumstances, a compelling question arises: Can causal models explain life's creativity and diversity? Some life scientists say yes. However, other humanities scholars cast doubt, positing that they reached the end of theory. Here, I build on common empirical observations as well as long-accumulated modeling experience, and I develop a unified framework for causal modeling. The framework gives special attention to life's creativity and diversity, and it applies to all sciences including physics, biology, the sciences of the city, and the humanities.

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In 1853, a German refugee—an architect by profession—attempted to explain the evolution of artistic "styles" to a London audience (Mallgrave, 1983–2017; Semper, 1853, 1854, 1855, 1860, 1884). The event took place shortly after a truly large international exhibition that displayed objects of artisanship and industry from around the world. Citizens were faced with a hitherto unknown diversity of artistic expressions and styles Fig. 1. How could one explain such diversity?[1]

Gottfried Semper, the refugee in question, did not have an answer ready, but he believed he knew where to start, and he was willing to share his thoughts. Surprisingly, he formulated his most-cherished idea not in his native German, nor in any other language spoken in haste among visitors at the exhibition. He chose the language of mathematics.

This choice was surprising because Semper had himself experienced difficulties as a student under his famous professor, the preeminent mathematician Carl Friedrich Gauss. Yet not even Gauss was a native speaker of math. Perhaps math could serve as a neutral ground for all art to meet.

Semper's choice of math was motivated by a provocative thought. Admittedly, he sometimes felt overwhelmed by the vast diversity of artistic expressions that the Great Exhibition had brought together. It reminded him of the story of Babel and the confusion of tongues. Nevertheless, he believed that all art had something in common. He trusted that he could study any artwork or any design, and he would always find that there were decisive causes that determined its shape. Any artwork or design—no matter how exotic it seemed—opened the possibility to theorize about the causes that had shaped it.

To illustrate his view, Semper put forward multiple concrete examples. Let us consider the design of a cup. In many early cultures, cups were made of clay, which greatly determined their rounded shapes. Thus, the material that is available for the making of a cup can be interpreted as a cause that determines its shape.

Fig. 1 Impressions from the 1851 Great London Exhibition. The Great Exhibition of 1851 brought together objects of art and industry from around the globe. Typical for the exhibition were the national as well as thematic sections. Making one's way through them, one saw groups of similar-styled objects such as chinaware *above left*, stained glass *below left*, and textiles from Tunis *above right*. Even today, looking at the colorful illustrations that document the exhibition, one can recognize stylistic variants and diversity. For example, the Chinese vases all look quite similar; they are stylistic variants of each other. The same can be said about the stained glass windows. They also look alike, and they can also be taken to be stylistic variants of each other. However, the vases do not look much like the stained glass and vice versa. The difference between vases and stained glass is what we may call stylistic diversity. Today, there are digital tools to analyze styles. One can train the tools to discover stylistic variants and diversity in any collection of objects. These digital tools are borrowed from biology. In biology, there are causal models that explain why the tools work. To explain the workings of the same tools in art, we must develop a causal model that applies to all art, regardless of national or ethnic context. The exhibition was located in a giant glass house built for the purpose. The construction's metal skeleton was visible in most sections of the exhibition. Where it wasn't, one still knew it was there, even if hidden in drapery. The omnipresence of such a skeleton might have helped suggest the idea that there was something universal that held together all styles. Gottfried Semper's role in the exhibition was that of both observer and designer. On the *lower right* is an installation with varieties of wooden planks, designed by Semper. Sources: Dickinson's Comprehensive Pictures of the Great Exhibition of 1851. Artists: Louis Haghe, Joseph Nash, and David Roberts. London, Dickinson, Brothers, Her Majesty's Publishers, 1854. Royal Commission, Descriptive and Illustrated Catalogue of the Great Exhibition. London, Spicer Brothers, 1851. License: public domain.

This example has only become more compelling, with time. Today, many cups are made of plastic; few are porcelain, and it is evident that the availability of plastic can be seen as a factor that has shaped not merely the design of one cup, but the entire history of design.

Of course, even when we study things as simple as the designs of cups, most causes that shaped them remain unknown. Nonetheless, known or unknown, causes are there for us to analyze.

For Semper, the need to analyze unknowns was the point where mathematical models simply had to make their appearance. Mathematics is an excellent way to deal with unknowns. Almost any unknown can be expressed as a variable. Also, would it not be wonderful if mathematics could somehow help us explain artistic styles and creation not only in presence of unknown causes but also in a variety of diverse cultural contexts? With slight revisions, Semper's formula does more than that.

Design is not the only thing that is shaped by causes. Semper was also fascinated by debates about biological evolution. He wrote that they had been his primary source of inspiration. Furthermore, from his former math professor, he learned that Isaac Newton revolutionized physics by developing causal models based on the same type of mathematics that he now had up his sleeve.

Design, biology, physics… Causal thinking seems to apply everywhere. And why should it not? Nobody can possibly reject the proposition that things have causes: Theoretically, causes can always remain unknown. And nobody can reject the proposition that something has one or more unknown causes.

Taking all this into consideration, it must be admitted that one can always state that things have causes. We can invariably say, "Anything new is caused by the past." Let us now formulate this statement in the language of mathematics, and let us graphically render the math as a causal flow model. The result is shown below and in Fig. 2A.

Anything new is caused by the past

$$\dot{x}_i = \varphi_i(x_1, x_2, x_3 \ldots x_n).$$

Causality, in this model, is a function (or relation) that continuously transforms the past into the present. The variables x_1, x_2, $x_3 \ldots x_n$ stand for an indefinite number of past causes. Through a given causal mechanism φ_i, they cause an effect $\dot{x}_i$. According to the model, change takes place continuously. This leaves us with differential equations just like those that Newton developed for his causal models in physics (see also Supplement).

In the real world—the world we live in—we always find that there are many causes x_1, x_2, $x_3 \ldots x_n$. There are also many causal mechanisms φ_1, φ_2, $\varphi_3 \ldots \varphi_n$. And there are many effects $\dot{x}_1$, $\dot{x}_2$, $\dot{x}_3 \ldots \dot{x}_n$. The formula just created applies to any cause, any causal mechanism, and any effect. It is a general formula of causality. Our next step is to take this formula of causality and add detail to it, turning it first into a formula of creativity and then into a formula that explains the emergence of diversity.

+ is for creativity. Although our formula of causality should theoretically help us explain the evolution of artistic styles, it first remains unclear how. Yet it must be possible. The fact is that today there are digital tools to analyze styles in collections of images, text, or music. These digital tools can be used to categorize artworks into groups of similar-styled artworks, and they work with mathematics, after all.

It turns out that our formula puts us on the right track, although we must further develop it. If we now go ahead and rework the formula just a little, we can turn it into a general model of creativity, and we can explain the evolution of artistic styles together with the workings of some of the most advanced digital tools.

Technically speaking, the mathematical reworking that we must perform is easily achieved. It consists of inserting addition signs into the equation.

Consider the statement "Anything new is caused by causes that add up." This statement is a verbal translation of the reworked formula shown below and in Fig. 2B.

Anything new is caused by causes that add up

$$\dot{x}_i = q_{1i}x_1 + q_{2i}x_2 + q_{3i}x_3 + \ldots + q_{ni}x_n.$$

The distinction between the previous and the new equation is that, previously, the various causes x_1, x_2, $x_3 \ldots x_n$ have been separated with commas, whereas now, they are separated with plus signs. Commas stand for anything. Plus signs stand for additions only. Now, the causes only "add up".

Given that causes add up, we can open the brackets and replace φ_i with q_{1i}, q_{2i}, $q_{3i} \ldots q_{ni}$. In our first formula, φ_i symbolized any operation or algorithm. In the new one, the values q_{1i}, q_{2i}, $q_{3i} \ldots q_{ni}$ can often be taken to be constants. They weigh how important each cause is towards a given effect.

Why this reworked formula is a "general formula of creativity", I will now outline.

The formula just obtained is not new. It is the main backbone of perturbation theory, quasispecies evolution (Eigen, 1971), and variation-selection processes, and it has been proposed to be a general formula of creativity in the humanities (Baciu, 2015, 2016, 2017, 2018, 2019, 2020, 2021a, 2021b, 2021c, 2021d, 2021e). The main characteristic of this formula can be easily seen in the flow model. Any given cause x_i can flow away to create an effect x_j. In this way, something entirely new may be "created" from something that had been there before. With this consideration in mind, it makes sense to call this flow model a "general model of creativity". Anything new, anything creative, must emerge from something past, and anything creative must involve at least a small amount of transformation from one thing x_i to something else x_j. The model that we just developed covers any new creation.

A good understanding of this general model of creativity is gained from a basic version that is gradually expanded. Let us begin with only two variables x_1 and x_2. The resulting model is shown in Fig. 2C. It serves us as a simplified and, in this sense, a basic model of creativity. As you can see in the visual, x_1 can create x_2, while x_2 can create x_1. We have already described such creative flows. Now, it is time to say something more about them.

Clearly, changes in x_1 will immediately affect x_2 and vice versa. The creative flows make the two items appear to be "related" or "close"; they link x_1 and x_2 together (Hume, 1739, p. 88, corollary 5 already obtained a similar result).

If we now expand the model by adding more variables and additional plus signs between them, we see that multiple variables begin to cluster in groups that are held together by creative flows. Each group consists of many variables that are tightly linked by creative flows and therefore appear to be interrelated. This idea is graphically explained in the video abstract https://doi.org/10.25496/W2KW28. Mathematical analysis reveals that the groups[2] can be taken to represent units of evolutionary selection. The survival of a group depends on its ability to channel causal flows towards itself as well as to keep the flows inside the group. Given that the groups are held together by creative flows, let me call them "creative groups".

At first, the idea that creativity leads to the emergence of "creative groups" may sound abstract and remote. When reading this article for the first time, you will be surprised to learn that you already know of many different types of creative groups—and

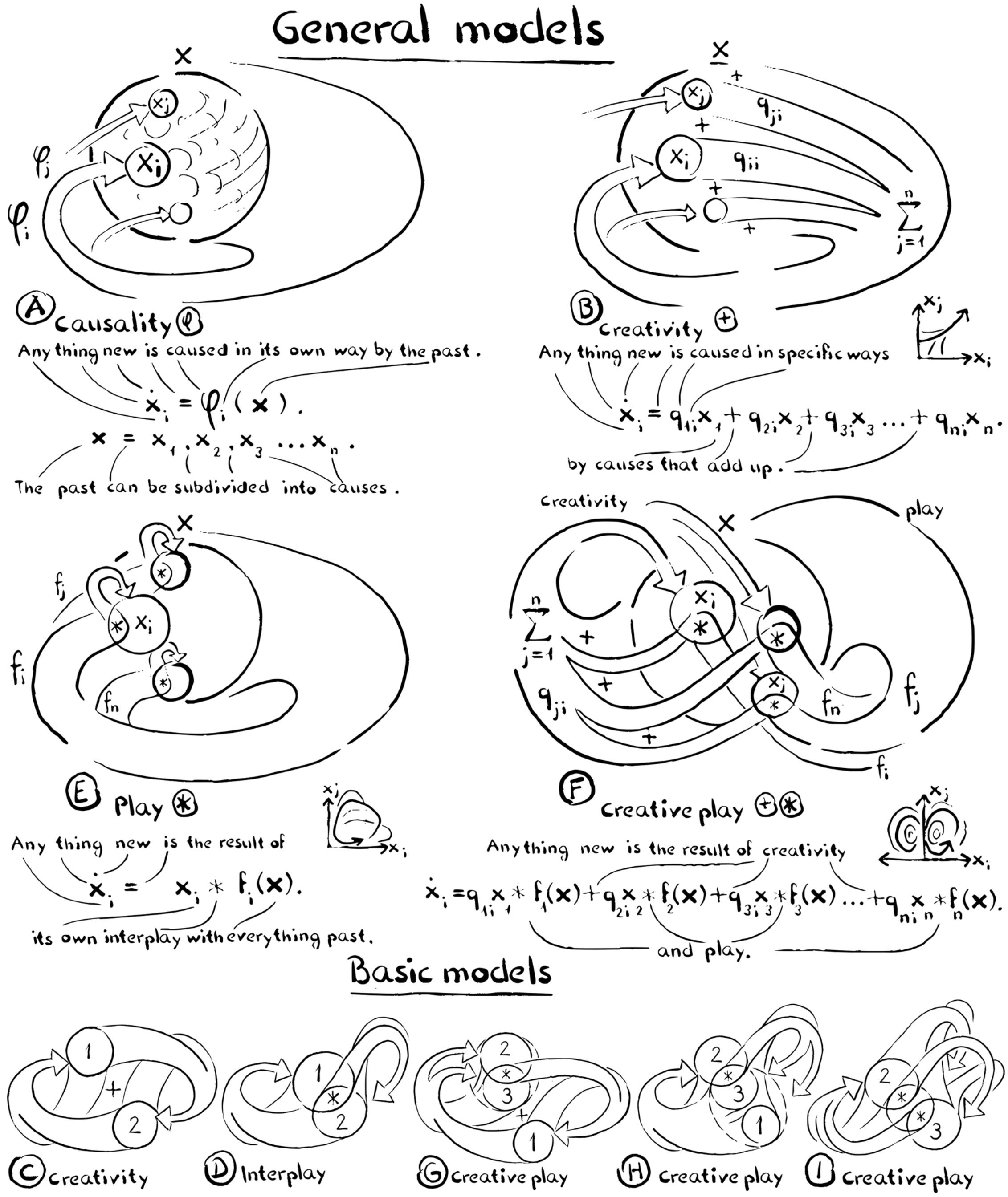

Fig. 2 Framework for causal modeling. Sketch of a unified framework for causal modeling. On the upper left is the most general description of causation, which is split into two special cases by introducing additions in B and multiplications in E. These two separate cases represent creativity and play, respectively. They are also reunited into a model of creative play, shown in F. Below are several basic (low dimensional) models useful for analysis. **A** Universally applicable model of causality according to which anything new is caused by the past. Causation is continuous change, which gives differential equations. $\boldsymbol{x}$ represents the past. $\dot{x}$ represents change that has presently occurred. **B** General model of creativity. Causes simply add up. The insertion of additions splits the world into different causes and allows for causal flows between them. These flows make causes related. This is the backbone of perturbation theory, quasispecies evolution, as well as a general model of creativity in human culture. It also serves as architecture for the layers of Neural Networks used in Artificial Intelligence. **C** Basic model of creativity. The larger a flow is that links a cause and an effect, the more it makes them related. **D** Basic model of interplay. Variables are multiplied. This leads to equations of the Lotka–Volterra type. They are a basic model for ecology, virology, and diversification in human culture. Perhaps the drawing reminds you of a Venn diagram. The intersection between circles stays for AND, which computers use to calculate multiplications. **E** General model of interplay. This is also the backbone of game theory and compartmental models in all fields of study. It is also known as generalized Lotka-Volterra or replicator equation. **F** General model of creative play. This is the replicator-mutator-equation used across many disciplines. It unites models B and E. **G**–**I** Basic models of creative play. They behave once like creativity, once like interplay: Within G, there are two groups connected by creativity. Within H, there are two groups connected by interplay. I is the Lorenz system (Lorenz, 1963), known in popular literature for the "butterfly effect". The equations of these latter models are found in the section "Equations". Source: Dan C. Baciu. License: CC-BY.

you know them under many names. Artists and architects speak of "styles", each style being a group of closely interrelated artistic expressions. Literature professors teach that there are "literary genres", and they imagine each genre as a group of similar literary works. Historians of science like placing their historical heroes in "lineages" of researchers who all developed similar scientific concepts. Sociologists have described the existence of "social axes and fields" that make room for groups of similar human attitudes and activities. Linguistics students learn that language consists of groups of similar words. Researchers of memory know that closely associated memories group together. Geneticists analyze "mutant swarms" which are groups of similar genetic variants. Even more broadly, cluster analysts speak of "clusters" that consist of similar items that can be grouped together.

The examples seem countless. Depending on your field of study, you probably recognize one or more of these creative groups, or you know one of your own.

What one calls "similarity" in all of these groups is an effect of creativity. In some cases, we deal with human creativity of one or another kind. In other cases we are witnessing the creativity of the genetic machinery of viruses, cells, and bacteria. What remains the same in all examples is that some creative steps are made more frequently than others. Because these steps are made frequently, they appear to be small and easily achievable steps between seemingly close items. Of course, creative steps frequently made in one context may be rare in others: Human creativity has evolved to support creative steps that are useful in human society. By contrast, the genetic machinery of viruses has evolved to facilitate mutations that are more valuable for the viruses.

The model of creativity that we have developed is useful. It makes the logical connection between creativity and relatedness. The model tells us that creativity leads to the emergence of creative groups, which are made up of closely interrelated things. Suddenly, understanding creativity means understanding relatedness, and vice versa.

The applications of such knowledge are many. In genetics, the relatedness between two or more genetic variants can be determined through genetic analysis. Once relatedness is determined, it can go into a flow model, and one can use the model to predict how the genetic variants will spread and what creative groups they will form (Eigen, 1971; Domingo and Schuster, 2016). Thus, by knowing the variants and how they are interrelated, one can say something about their creative potential. For example, developing the present multidrug HIV medication meant understanding the creative potential of HIV variants in any given patient, and it meant challenging this viral creativity. (It is too great for any single antiviral, but certain combinations of multiple drugs can check it.)

In the humanities, the opposite situation is more frequent. It is often difficult to say how closely interrelated two ideas are. Yet public media can serve as a record of human creativity that tells how the ideas under consideration have spread over time. One can take this record and calculate backward how closely any two ideas must have been related to each other to spread the way they did. Online search engines routinely perform such computations to determine the meaning of online content. The same computations are also performed in the study of styles that I mentioned earlier.

For quite some time, mathematical models in the humanities and social sciences were borrowed from other disciplines, and parameters were set arbitrarily or on the basis of empirical testing results. Digital humanists "knew" that the tools worked, yet they had no causal models to explain what they knew. The situation was complicated. Some scholars straightaway rejected the proposition that causal models could be developed. Other researchers developed causal models, but those models were creations of their own, sometimes without precedents to the 21st century. Maybe people needed complex ways to explain observations in the humanities. Let me take a different path and coin the term "humanities mechanics" for a more mechanistic way of thinking —a way of thinking that is rooted in causal models. Insert additions into the causal models, and you will see creativity in nearly endless forms and variations.

× is for diversity. While our models of creativity (Fig. 2B and C) can explain many phenomena of creativity and relatedness, they must be further developed to simulate how diversity emerges.

Diversity can be quantified for example with Simpson's diversity index. This index has found application in anything from physics to biology, and from the sciences of the city to the humanities (Fisher et al., 1943; Yule, 1944; Simpson, 1949; Hirschman, 1945; Nowak et al., 1990; Baciu, 2020; Baciu et al., 2022). Diversity is studied in all areas of science, and Simpson's index has proved to be useful in quantifying it.

Mathematically, Simpson's index estimates the probability that different things meet. The most basic way to estimate this probability is to measure how large any two things are and to multiply their sizes: the larger two things are, the likelier it is that they meet.

Take the example of two rare species that share an ecosystem. You measure the size of each species by counting how many individuals it has. As time goes by, the sizes of the species may change. The larger each rare species becomes, the likelier it is that the two species meet, and the higher becomes the diversity of the ecosystem.

In technical terms, the size of each species represents the probability that it is encountered somewhere in its ecosystem. The multiplication represents the conjoint probability that the two species are encountered together.

When we look at Simpson's index, we begin to understand that diversity might have something to do with things that meet, which we model as multiplication (Annex 1).

When we developed our models of creativity, we inserted plus signs into the equations. This insertion brought us the concepts of creativity and relatedness. Inspired by Simpson's index, let us now insert multiplications and test step-by-step whether we receive meetings and diversification.

In our basic model of creativity (Fig. 2C), let us replace the causal flow from x_1 to x_2 with a flow from $x_1 \times x_2$ to x_2. Thus, we insert a multiplication between x_1 and x_2. We intend to model that these two things meet. The resulting formula is graphically rendered in Fig. 2D. (The figure is rendered in the style of a Venn diagram. x_1 and x_2 are circles, and their meeting is the intersection between the two circles. Perhaps you can recognize the concept of logical conjunction or the AND operator. They are equivalents of multiplications.) Let us call this model a "basic model of interplay". We intend to use it to study what can happen when two things meet.

Famously, the history of this model goes back to Alfred Lotka and the Lotka-Volterra equations that have become a basic model for ecology and virology, as well as viral news and diversification in human culture (Nowak and May, 2000; Baciu, 2015, 2016, 2017, 2018, 2019, 2020, 2021a, 2021b, 2021c, 2021d, 2021e).

At first, a closer look into Lotka's work brings us on a small detour. Yet this detour is almost unavoidable and provides us with connections to additional empirical observations that belong together.

The empirical phenomenon that Lotka initially studied is not the emergence of diversity. Instead, he looked at a set of growth curves. Notably, these growth curves are difficult to explain with our initial model of creativity.

If we had chosen to stay with our model of creativity, not making the step to the present section, the growth curves that we'd be able to predict are exponential. However, common empirical observations demonstrate that exponential growth rarely lasts. While it is true that many growth curves do start with an exponential push upwards, this initial push mostly ends sooner or later. The curves are generally bent down into s-shapes (Lotka, 1910; Baciu, 2021c; Bejan, 2019; Bejan and Lorente, 2012a).

Given this observation, it is evident that, next to creativity, there must be another process at work that bends down the curves. Already in the 1830s and 1840s, Adolphe Quetelet and Pierre-François Verhulst brought up the idea that there must be a process that bends down exponential growth curves. Verhulst called this unknown process $\varphi(x)$, using a notation similar to the one Semper later chose for his formula of style in the 1850s. Based on empirical observations, Verhulst suggested that the unknown $\varphi(x)$ could be set to be the known function x^2. If we now write x^2 as $x_1 \times x_2$, we proceed roughly as Lotka did in the 1910s, and we are back at our basic model of interplay. Could it be that this model of interplay can help us explain both the emergence of diversity and the complex phenomena of growth?

Of particular interest to Lotka was a growth curve that displayed an undulating upwards trend, as if two s-curves followed one at the other's heels. The growth he saw is best described as slow–fast–slow–fast–slow. It looked like a wave.

The story that Lotka's (and our) mathematical model tells us goes something like this: In a first step, resources build up, and their abundance grows exponentially. Yet in the presence of abundant resources, consumers can make their appearance in groups that grow larger and larger, too. Suddenly, there are many resources and consumers, all at the same time. This means that consumers can come across resources with increasing ease, and they can rapidly consume and deplete them. In many cases, the resources end up being depleted faster than they can replenish themselves. Eventually, this depletion of resources brings the growth of the consumers to a halt. The number of consumers in the system may even go down until the resources are once again replenished or otherwise recycled. Thus, the interplay between consumers and consumed leads to growth curves with wavelike ups and downs.

Such wavelike growth curves are common, and they are known under many names: In epidemiology, they are called "epidemics", among fashion designers, "fashions", and among trend scientists, "trends" (Anderson and May, 1991). Epidemics, fashions, and trends come and go in waves, and the waves can return. The workings of causality are the same in all of these contexts. Everywhere, the waves emerge out of the interplay between consumers and consumed.

In epidemics, viruses are the consumers. The resources that they consume are living organisms, which can be us, humans. We like living in dense cities, and viruses can take advantage of this circumstance to multiply their population. Luckily, we can mostly respond with social distancing or by becoming immune. This makes us less available to the viruses. In consequence, most epidemics eventually ebb out—although, they can return when our immunity is lost and we are once again susceptible. In this manner, the interplay between viruses and people leads to waves of infections.

The study of human culture offers another, perhaps even more interesting empirical example in which humans can take both roles; they can be both creators of resources and consumers thereof. For example, when artists create new styles, their audiences and followers go after what has been created, and they consume and get bored with it. Boredom can turn any style into something irrelevant and commonplace that is unsuited for further consumption and therefore abandoned. Most styles have fallen out of fashion at least once. Eventually, appreciation returns when people forget that they were bored and find renewed interest in the same or similar material. On this basis, fashions can be in and out, and in–out–in–out–in, etc. (Baciu, 2018–2020).

The same pattern is also found in zoology: In ecosystems, the predators take the role of consumers. They go after the prey and consume it. Through this activity, entire populations of predators and prey consecutively outbalance each other.

In all of these fields of study, the waves come and go because consumers rarely get started before there is much to find and consume, and they are hard to stop as long as there is something left. Going repeatedly from nothing to much and then back to almost nothing makes the wave. It is a wave of interplay between opposite forces.

We have now explained the growth curves that attracted our attention. To do this, we have modeled the effects of meetings and interplay between consumers and consumed. Yet how is such interplay related to diversification?

Interplay of this kind does not necessarily lead to diversification, but it can. Take this example: In ecosystems, predators are often most successful when they prey on the most abundant prey species. This circumstance gives rare species a chance to recover, and recovery is a first step toward diversification. The opposite of recovery is extinction. Thus, as a consequence of predation on large species, we see large populations shrink, while small populations grow. In this manner, the growth curves of multiple species are adjusted to each other, which allows for coexistence and diversity.

In addition, diversification can continue when predators force their prey to escape not only in physical but also in evolutionary space. Animals may escape in evolutionary space by developing different skills and acquiring different adaptations. Nature has many examples to illustrate this process.

The examples are most intuitive to follow when you think of physical space first. In physical space, imagine a pride of lions chasing a herd of antelopes. The antelopes might end up running in different directions, which will result in their breaking up into multiple separate groups.

A similar process occurs in evolutionary space. Chased by predators, the ancestors of the antelopes developed different fighting styles, and evolution brought them different shapes of horns suited to baffling the opponent in different ways (Caro et al., 2003). As another perhaps even clearer example, think of rodents who escape predation. One good way to escape may be to hide in underground tunnels, while another way may consist of developing a running style that benefits from the evolution of long hind legs. However, the long legs do not fit well in tunnels. This latter example illustrates that adaptations can be incompatible with each other. As a result of incompatibility, separate species begin to be formed, each with its own adaptations.

Empirically, such diversification is found not only in ecosystems. Let us turn our attention to virology and briefly consider the pathogenesis of HIV, for example. HIV viruses are chased by a person's immune system. Like all viruses, HIV escapes the immune response of one person by infecting new people. In this manner, the viruses escape in physical space. In addition, those viruses that remain in the same body escape in evolutionary space and diversify. These escapades make HIV very hard to beat and very dangerous (Nowak et al., 1991).

The same type of diversification process is also found in human culture—here with positive effects. When audiences consume culture, their boredom attacks mainstreams first, but then the mainstreams rarely fade away without escaping in physical space to attract the interest of new people in new countries. In parallel, fading mainstreams can also escape in

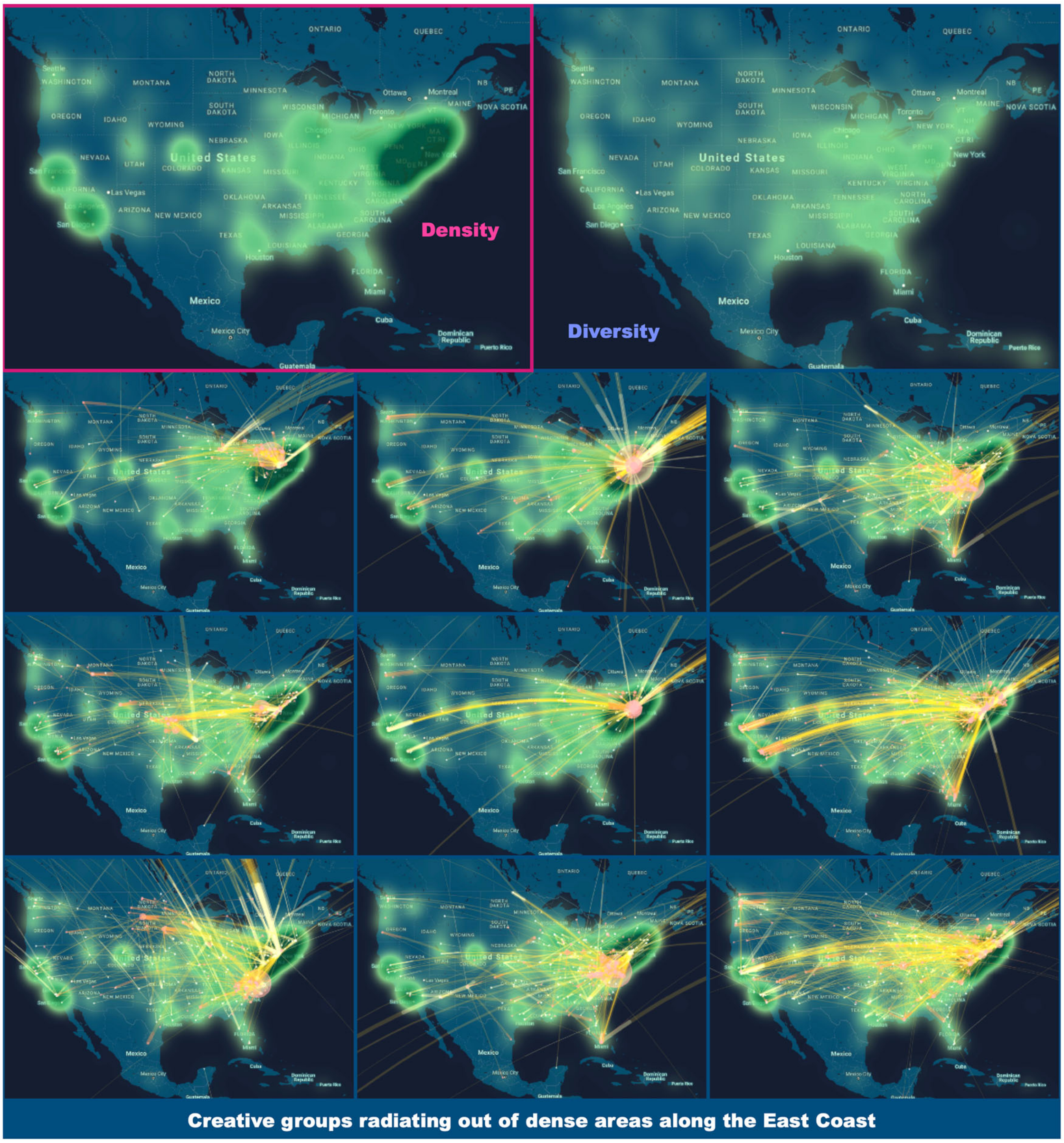

Fig. 3 Diversity radiates out of centers of density in urban environments. The heat map on the top left—framed pink and labeled **Density**—represents the geographical coverage of US-news that contains the term "science". In such "science-news", journalists most frequently write about institutions, infrastructures, and places that are located along the East Coast (most prominently around New York). Hence, high density is found there. Almost equally featured in the science-news are the metropolitan areas of Los Angeles and San Francisco. The data used in the density map can be analyzed and split into multiple creative groups of news. A sample set of nine such groups is displayed below, labeled **Creative groups**. These particular nine groups were chosen among 300 as examples of creative groups that radiate out of the dense zone along the East Coast. The map labeled **Diversity** is a diversity map created by calculating Simpson's diversity index on all 300 creative groups. The highest levels of diversity are found in the centers of density located along the East Coast as well as along the West Coast between Los Angeles and San Francisco. Sources: Baciu (2020), Baciu et al. (2022). Interactive visuals are available online. Source: Dan C. Baciu. License: CC-BY.

evolutionary space. They can inspire the evolution of new and more eccentric ideas that can start new cultural streams of their own. These new cultural streams evade boredom in distinct ways. In response to boredom, culture diversifies. This diversification makes it powerful. It makes it interesting and resilient (Baciu, 2018, 2019, 2020).

Interplay explains not only how diversity forms but also where. Where there is much life, there is much to consume, and where there is much to consume, there is diversification. This is true for ecosystems (Jenkins et al., 2013) and also for cities. In cities, diversity radiates out of centers of density. This is shown in Fig. 3—and it also matches our own life experience.

All of these conclusions about meetings, escapes, and diversification can be drawn from basic models of interplay as just developed, but these models can also be generalized.

A general model of play is obtained by imagining that all benefits or losses of x_i are a result of its interplay with multiple other things such as x_1, x_2, or x_n. Let us formulate this idea as follows: "Anything new is the result of its own interplay with all past things." The multiplication sign that symbolizes interplay is now between x_i and all past things as shown below and in Fig. 2E.

Anything new is the result of its interplay with all past things

$$\dot{x}_i = x_i \times f_i(x_1, x_2, x_3 \dots x_n).$$

Notably, this model goes back to Ronald Ross and his 1911 "Theory of Happenings" (Ross, 1911; Smith et al., 2012). It is also known as "generalized Lotka–Volterra equation". Today, the model is a backbone for game theory and all compartmental models used in fields such as epidemiology, ecology, urbanism, or humanities (Hofbauer and Sigmund, 1998; Brauer et al., 2019; Hastings and Gross, 2012; Baciu et al., 2022; Baciu and Della Pietra, 2021; Bejan and Lorente, 2012b; Baciu, 2018). For example, when epidemiologists attempt to forecast how an epidemic will spread, they likely use one or another version of this model.

We have thus developed both a basic and a general model of interplay. The meaning of the mathematical operations that we used remains the same in both cases: Insert multiplication signs into the causal models, and you see play in countless forms and variations. It can give rise to wavy growth curves and numerous phenomena of diversification.

+ and × are for creativity and diversity. Play can also be reunited with creativity, which results in one big and, this time, more complex model. Verhulst's work mentioned in the previous section already went in this direction in the nineteenth century, and some versions of the quasispecies equation have expanded on this work in the 1970s and 1980s. Yet the idea can also be generalized. Consider the statement "Anything new is the product of all past play and creativity." This statement is best turned into mathematics by coupling the model of interplay with that of creativity—shown in Fig. 2F.

Multiple scientists who attempted to unite perturbation theory with game theory obtained this same model in the 1980s, 1990s, and early 2000s (Hadeler, 1981; Bomze and Burger, 1995; Page and Nowak, 2002). Since then, the model has been applied across a broad range of disciplines (Kauhanen, 2020; Safarzynska and van den Bergh, 2011; Garcia and Traulsen, 2012; Alfaro and Veruete, 2020; Baciu, 2018, 2019, 2020, 2021a, 2021b, 2021c, 2021d, 2021e; Baciu et al., 2022; Baciu and Della Pietra, 2021).

This model of "creative play", as I call it, behaves once like creativity, once like interplay. This conclusion can be reached for example by analyzing simplified worlds such as those represented in Fig. 2G–I. In these simplified worlds, we can see groups of causes that engage in interplay, or they are creative, or both.

Imagine now that life passed through such a complex model of creative play (maybe a mill of causality). Theoretically, we would have some three options to describe what we see. The first option is basic, yet it is important because all others build on it. The easiest way to pass through the causal model is to remain unchanged. If something remains unchanged, it simply stays.

Such things that stay unchanged are not only a matter of imagination and theory, they are also found in the real world. When we model phenomena in the real world, we see that we can use the option "stay unchanged" to describe what happens to atomic nucleons, genetic nucleotides, or binary digits in computer memory. They stay what they had been: nucleons, nucleotides, or bits.

The second option is to be creative. Creativity recombines digits, nucleotides, or nucleons. The combinations that are formed during this process are subject to change, yet they can persist if they form creative groups. In the real world, such creativity is found in styles, genres, cultural lineages, social fields, mutant swarms, industrial clusters, etc. Creativity gives rise to groups of similar things that can adapt and evolve.

Finally, there is a third option that builds on the previous two. It is to engage in interplay. During interplay, one creative group can pursue another, chasing it in both physical and evolutionary space. At this high level of complexity, the system is entirely unstable. Existing hierarchies are frequently overthrown. In a sense, we have now moved from evolution to revolution. There can be sudden upheavals and threats, but we can also feel the thrill of playful, rapid escapes. We are now at the scale of entire ecosystems, cities, or cultures. Or we look deep into brains that alternate between creativity, boredom, and fast, delightful rethinking.

Together, these three options to describe our observations give a multi-level architecture to our theoretical understanding of life: basic building blocks of life (nucleons, nucleotides, digits, nerve signals) are creatively combined and recombined into larger creative groups, and the creative groups engage in interplay with each other.

This multi-level architecture is empirically found in physics, biology, and urbanism, as well as in the humanities. In physics, nucleons are combined into atoms; the atoms are combined into chemicals; and the chemicals form complex physical systems, such as a living cell, for example. In biology, nucleotides are combined into DNA, which is translated into proteins and into entire competing proteomes that, finally, make for complex ecosystems (Wilkins, 2009). In human culture, computer digits are combined into letters, which are then combined into words and stories (Nowak and Komarova, 2001). Share the stories, and you get cultural life.

Everywhere, the same pattern reappears. First, there are basic building blocks that pass unchanged through the causal model. Then, there are creative groups. Then, there is play. Along the way that leads from stable building blocks to play, life becomes increasingly unstable, but this also means that it gains increasing access to the energy that passes through it. Today, this principle is recognized in the "constructal law" (Bejan, 1996). Alfred Lotka proposed something similar when he wrote that time lets the wheel of life spin at ever-greater speed (Lotka, 1945).

The idea was not completely new. Even earlier, in 1914, Italian artist Umberto Boccioni proposed that architecture and art followed one common equation: Necessity = Speed. In turn, Boccioni's work was likely directly or indirectly inspired by Semper and his keen interest in laws of necessity that shaped all art and design (Boccioni, 1914; Baciu, 2011).

Equations

This section presents the equations for the basic models. It is for readers who are more dedicated, and can be skipped otherwise.

The following notation is chosen: q_i are coefficients, though they can be interpreted as functions to generalize. For convenience, I number them in the order in which they occur in the equations. In general, every causal flow in these models can be interpreted as cooperation. If the q value is positive, we have active cooperation. If it is zero, the cooperation is absent; we can speak of defection. If it is negative, we speak of consumption. x_i, y_i, and z are variables. The equations are differential equations. Annotated versions are found in Baciu (2021e).

Some readers looking at the equations will observe that there are multiplications not only between variables but also between variables and coefficients. These readers may then ask whether the meaning of these two types of multiplication is the same. The answer is yes. Every variable exists in an environment that it is in interplay with. This interplay is expressed as a multiplication. If one assumes that the interplay does not change the environment,

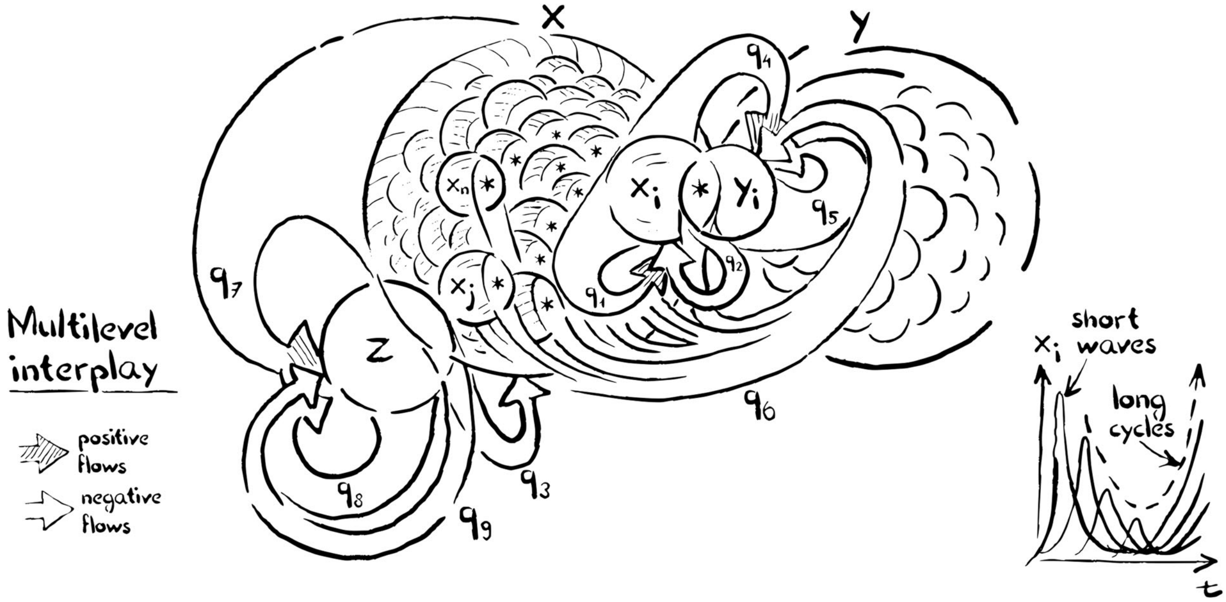

Fig. 4 Multi-level interplay. In human culture, small sub-categories often cluster into larger, overarching categories. This hierarchy is taken into account in multi-level models that predict short growth waves as well as longer cycles of growth and reform. $\boldsymbol{x}$ represents an overarching category (science at large). $x_1, x_2, x_3, \ldots x_n$ are the subcategories of $\boldsymbol{x}$ (the various scientific fields of study). $y_1, y_2, y_3, \ldots y_n$ are habituation (boredom) against each of the subcategories separately. z is habituation against the overarching category $\boldsymbol{x}$ in its entirety. The equations are given in the section "Equations" as well as in Baciu (2021e). Source: Dan C. Baciu. License: CC-BY.

it means that the environment is not a variable in the system, and one can use a constant or coefficient rather than another variable to stand in for the environment. This assumption often simplifies a model, but it is mostly only applicable within certain bounds. For example, in the general model of creativity, we assume that the environment is invariable. Interplay, if it takes place at all, is between each variable and an invariable environment. Assuming this, we focus as much as possible on creativity. If, on the other hand, we insert a variable for the environment, we give more attention to play, and we receive our general model of creative play of Fig. 2F.

Figures 1C and 9 left:

$$\dot{x}_{1,2} = q_{1,2}x_1 + q_{3,4}x_2.$$

Figures 1D and 9 right:

$$\dot{x}_1 = q_1x_1 + q_2x_2,$$

$$\dot{x}_2 = q_3x_1 + q_4x_1x_2.$$

Figure 1G:

$$\dot{x}_1 = q_1x_1 + q_2x_2x_3,$$

$$\dot{x}_{2,3} = q_{3,4}x_1 + q_{5,6}x_{2,3} + q_{7,8}x_{3,2}.$$

Figure 1H:

$$\dot{x}_{1,3} = q_{1,2}x_{1,3} + q_{3,4}x_{3,1} + q_{5,6}x_2x_3,$$

$$\dot{x}_2 = q_7x_1 + q_8x_2 + q_9x_3.$$

Figure 1I:

$$\dot{x}_1 = q_1x_1 + q_2x_3,$$

$$\dot{x}_2 = q_3x_1 + q_4x_1x_3 + q_5x_2,$$

$$\dot{x}_3 = q_6x_1x_2 + q_7x_3.$$

Figure 4:

$$\dot{x}_i = q_1x_i + q_2x_iy_i + q_3x_iz,$$

$$\dot{y}_i = q_4x_i + q_5y_i + q_6y_ix,$$

$$\dot{z} = q_7x + q_8z + q_9xz.$$

$$x = x_1 + x_2 + x_3 + \ldots + x_n$$

Cycles of creativity and diversification

The insight that there are multiple levels of complexity motivates one additional model that has long fascinated me.

I have worked in different fields of science. I know that there is physical science, and there are social sciences, life sciences, computer science, etc. Each science is special in its own way, and yet all sciences are part of science at large. These sciences fascinate me most when they stand together—and I am not alone.

Evidently, scientists find interest in each other's work. The success of pan-disciplinary journals such as *Nature* and *Science* documents this interest: One can get bored and drown in one's own small field, but then comes the safety ring from the other sciences. One can regain interest because science at large does so many different and inspiring things.

This process of regaining interest in the sight of a broader and more diverse cultural outlook is very common. It applies to most culture that we consume. We can get bored of anything, yet oftentimes, this "anything" is part of a broader context that can surprise us. This process of interplay on small and large scales is graphically rendered in Fig. 4 (Baciu, 2018, 2019, 2020).

From this multi-level model, an important conclusion can be drawn: At first, interplay between many small sub-categories leads to short growth waves such as those previously referred to as "fashions". Yet once larger, overarching categories are introduced into the system of equations, and once these large categories are connected to the smaller sub-categories (causal flow

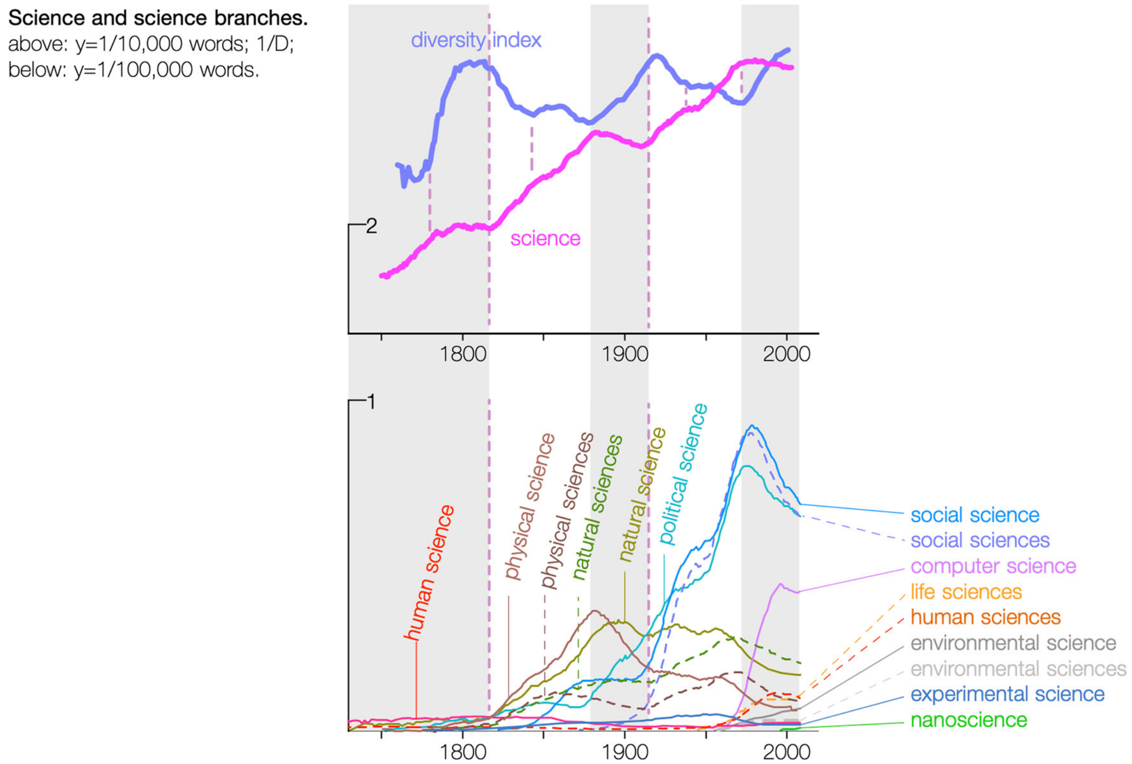

Fig. 5 Cycles of diversification in science and scientific fields. Culture goes through century-long cycles of growth and reform. This phenomenon can be observed for example in "science" and different scientific fields. The cycles of growth and reform can also be thought of as cycles of diversification: diversity decays during growth, but it rebounds during reform. Source: Baciu (2020). License: CC-BY.

q_6 in Fig. 4), something new happens. The short waves are overrun by much longer cycles. You know these longer cycles as repeated periods of "growth and reform". In human societies, they can take up to centuries to pass.

Empirical evidence for such long cycles of growth and reform is found for example in the study of science and science branches. Over three centuries of historical record, there were three cycles of scientific growth and reform, as illustrated in Fig. 5. (In the figure, the gray phases are reform, while the white ones are growth.)

A characteristic of the cycles of growth and reform is that diversity goes down during growth. We intuitively understand this phenomenon in the context of economic bubbles. When a bubble grows, market diversity goes down: the bubble is so successful—so creative—that it outcompetes all else. This competitive exclusion may go on until the market crashes. Then, the bubble shrinks and diversity has space to return.

Cycles of growth and reform are ubiquitous. They can also be found in large institutions (Baciu, 2020), in the previous example of HIV pathogenesis (Nowak et al., 1990; Nowak and May, 2000[3]), in Holling's figure-8 model of ecosystems, in the paleontological record (Haeckel, 1866), and in the uneven growth of cities, as illustrated in Fig. 6. Next to economic bubbles, there are urban, cultural, scientific, and institutional bubbles.

Insert multiple levels of creativity and play into the causal models, and you receive multi-level phenomena of creativity and diversification.

Conclusion

Causality applies to everything that we can explain (Bejan, 2000; Hofbauer and Sigmund, 1998; Nowak, 2006; Blalock, 1985; Ryall and Bramson, 2013; Ried, 2016; Nowak and May, 2000). When we begin our explanations, we can always state, "The object that is presently under consideration must have been caused by the past." We can then go on and turn such and similar statements into causal models with solid mathematical foundations. In these models, causality is interpreted as a function (or relation) that continuously transforms the past into the present. In this context, any change from something past to something present can be studied with differential equations, which makes these equations a general framework of causality.

This general framework of causality can be applied to model anything one observes. One can model many different causes that, through many different causal mechanisms, have many different effects. The framework is universally applicable to any cause, any causal mechanism, and any effect. Nevertheless, most situations that we encounter can be studied with two main types of causal models: When causes simply add up, models of creativity are obtained. By contrast, when the same causes are better multiplied, we obtain models of interplay.

The models are not new. Looking at this or that model means looking at a history of more than a century of thinking, and it means looking at empirical observations that are key to the people who make them: The models of creativity explain what artists and architects call styles, what geneticists call mutant swarms, what social scientists call social fields, or what cluster analysts call clusters. The models of interplay explain what epidemiologists call epidemics, what fashion designers call fashions, or what trend scientists call trends.

In addition, the models of creativity and interplay can be reunited to explain how life proceeds from basic building blocks to diversity. Life combines and recombines basic building blocks into larger creative groups, which together form complex ecological, urban, and cultural systems Fig. 7. In such living systems, we theorize that there are basic building blocks that stay, creative groups that adapt, and diversity that radiates out of centers of density. Occasionally, in situations in which multiple levels of complexity

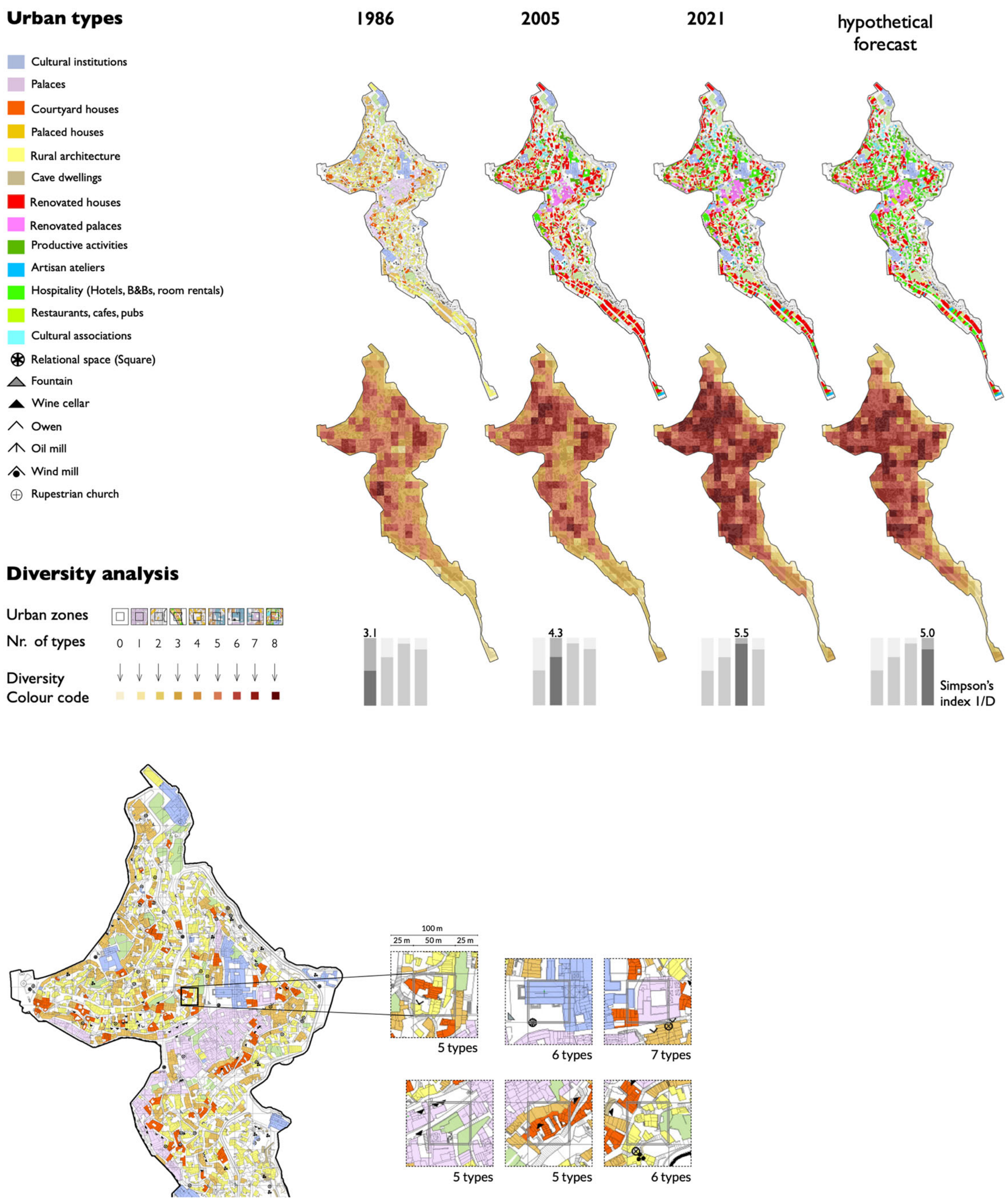

Fig. 6 Cycles of diversification in urban space. Life is diverse. Yet, diversity is not stable; it comes and goes. As shown earlier (Fig. 4), entire cycles of diversification can be observed in science and scientific fields. The cycles can also be observed in urban environments, for example in Sassi di Matera, a UNESCO world heritage site in Italy. The four maps above show how buildings have been used over the course of the last several decades. The four maps below are diversity maps created with the method shown in the lower left. Simpson index is displayed below each diversity map. Note how the diversity index goes up and down. The cycles are very common. They are traditionally termed "gentrification cycles". Source: Baciu and Della Pietra (2021). License: CC-BY.

create rich forms of interplay, there are short growth waves overrun by long cycles of growth and reform. Certainly, modeling things that are at the heart of life and that are so important to the people who study them is valuable and requires much care.

In this context of being careful, Semper's historical example offers a precedent that might be interesting, especially to scholars working in the humanities and social sciences.

Semper studied mathematics under Carl Friedrich Gauss, a mathematician well known for the eponymous "Gauss function" or "bell-shaped curve". In Semper's time, Gauss was probably even better known for his success in astronomy, which might have attracted Semper as one of many students whom Gauss, lacking sufficient empathy, thoughtlessly failed.

Semper, for one, never lost his fascination with stars. He began his major book on style by comparing the life and death of stars and galaxies with that of human societies and cultures. Entire systems of stars were born and decayed, and explanations could be attempted. Societies and cultures were born, too.

Occasionally, on calm nights at sea, one can look up at the night sky, and one can look at nearby cities, and it could seem

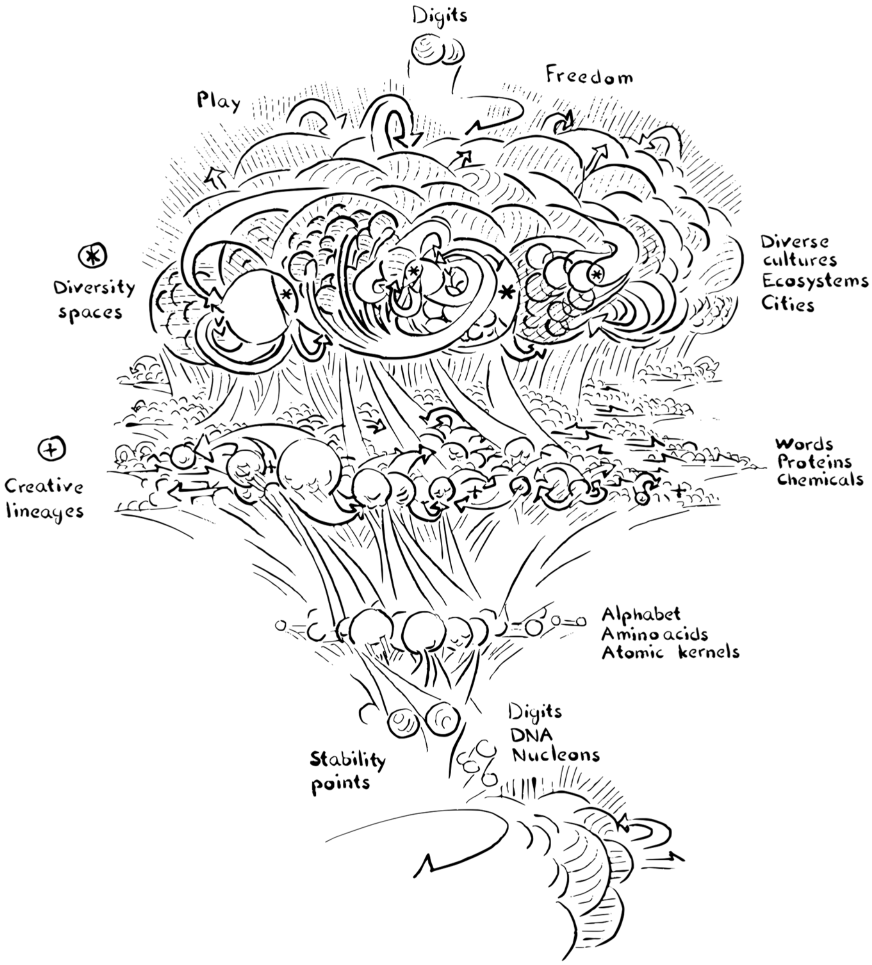

Fig. 7 From digits to diversity. Life repeatedly goes from basic building blocks to diversity. This progression can be traced over distinct levels of creativity and diversification. Source: Dan C. Baciu. License: CC-BY.

that the stars and bright planets, at least in our imagination, might be able to move from their place to come down and shine as city lights. Certainly, this is just a vision, but does it inspire something? Would formulas used to calculate the orbits of planets also work for human culture? When Semper reached London, first galaxies had been sighted. They might have suggested the idea that the physical universe was no less complex than life more broadly. As for the universe, it could be described with laws that were mathematically expressed as functions. Would the same type of mathematics also apply for culture?

As a German speaker in London, Semper savored the universality of mathematics. He used functions to calculate all kinds of things, and he might have just then realized that almost anything could be expressed with functions. Along the way, a transition occurred from using math to calculate orbits, curves, and geometries to using it in the study of style and human creativity (Annex 3).

It remains unlikely that Semper fully understood where his ideas could lead, but he was aware that he had to be careful. He wrote that some of his thoughts were "a very dangerous matter" to consider (Semper, 1853, Ms. 122, p. 14), and he specified that he did not wish his "general formula of style" to replace genius or good taste. Mathematics should not replace artists. Semper had taken a bold step, but he was not boasting, he was excusing himself for it.

Today, almost two centuries later, similar apologetic words are formulated again when mathematical tools are developed that have the potential of automating creative work that would otherwise be done by designers (Ramesh et al., 2021). Although such "apologizing", as Semper originally called it, has experienced continued practice, it is nonetheless amazing to see how much has meanwhile been achieved.

Semper reached London after being part of a political revolution that was lost, but he was part of a cultural revolution that is ongoing. The mathematics that he employed is increasingly well understood—it is asymptotically approaching reality. The switch from using the math to calculate geometries to applying it in the study of human culture can be explained easily.

The idea, specifically, that makes the subtitles of this article, namely that $+$ is for creativity while $\times$ is for diversity already makes sense when these mathematical operations are interpreted in their most basic geometric terms.

Additions are linear operations. In geometry, when you add a line to another line, you get a longer line. No matter how long this line becomes, you stay with a line. By contrast, multiplications are used to express multidimensionality. When you multiply two or more lines, you get areas and volumes. The lines do not remain lines. They begin to span planes and spaces. Each multiplication adds a dimension Fig. 8.

The same distinction between additions and multiplications is maintained in more advanced modeling. Additions are for creativity. They are used to model how varieties depart further and further away from the original type. Small creative steps add up to

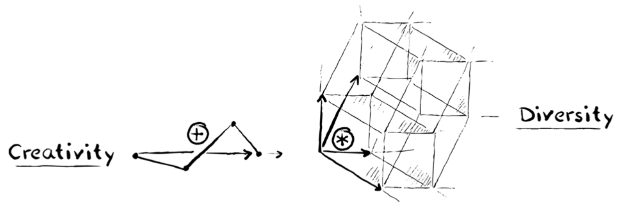

Fig. 8 + is for creativity, × is for diversity. Additions are linear operations. In geometry, additions extend things. They add line to line and create longer lines. By contrast, multiplications are used to express multidimensionality. They unite multiple lines, turning the lines into planes and spaces. The same distinction is found again in more advanced modeling. Additions are used to model creativity. In human culture, they are used to model how individuals or groups of people extend their creativity, forming lineages that stretch further and further out into the unknown. By contrast, multiplications are used to model diversity. They are used to model the interplay between lineages. Every multiplication adds a new lineage; it adds a new dimension. On this topic, review also the video abstract for this article available at https://doi.org/10.25496/W2KW28
Source: Dan C. Baciu. License: CC-BY.

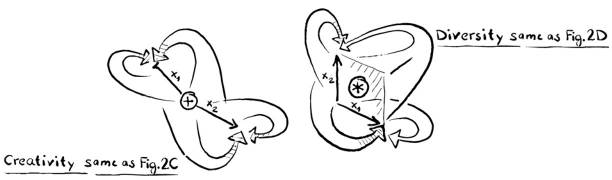

Fig. 9 Models of creativity and diversification visualized in a graphical language inspired from geometry. The causal models that we have developed in this article can be visualized in a graphical language inspired from geometry. The model of creativity then becomes a model in which creative steps are lines that add up to stretch further and further out into the unknown *left*. By contrast, the model used to study diversification becomes a model in which opposite forces act like axes that span planes and spaces *right*. In mathematical terms, the two models shown here are the same as those of Fig. 2C and D. Each graphical style has its merit. The present lines-planes representation is better at illustrating mathematical aspects, while the previous causal Venn diagram better illustrates aspects of logic. The workings of the model on the right are also explained in my video available online at https://doi.org/10.25496/W2QP46.
Source: Dan C. Baciu. License: CC-BY.

become big steps. In this way, creativity stretches further and further out into the unknown, yet after all of this creative exploration, you simply remain with new variants that continue their lineage. By contrast, multiplications are used to express diversity Fig. 9. When diversity is studied, for example in diverse social fields and spaces, one has to study interplay, which is modeled with multiplications. Here again, each multiplication adds a new dimension Fig. 10, or a connection between different dimensions Fig. 11. And intuitively, we do imagine culture and society as well as ecosystems—even the entire cosmos—as spaces with many dimensions that interact.

Next to additions and multiplications, the broader idea that differential equations—expressed for example as $\varphi(x)$—can stand for causal mechanisms also has a more basic geometric interpretation. In geometry, you use functions to transform spaces. The variables inside each function are introduced to stand in for things that change, while the functions themselves are there to express the unchanging rules that you must apply to effectuate the change.

In causal modeling, the variables and functions that you employ take on the same role. The variables are used for entities

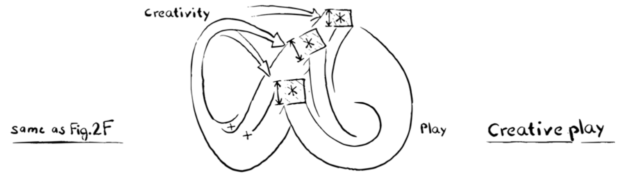

Fig. 10 The model of creative play of Fig. 2F visualized in lines-planes style. Like all other models, the model of creative play can also be visualized in a graphical language inspired from geometry. Play is multidimensional; it creates planes. Each act of interplay is rendered here as a rectangle. The rectangle's height represents the value of x_i. Its length represents the value of $f_i(x)$. Creativity is linear in that it influences only the height of the rectangles. If you look carefully at this model, you can recognize in it the general models of creativity and play of Fig. 2B and E.
Source: Dan C. Baciu. License: CC-BY.

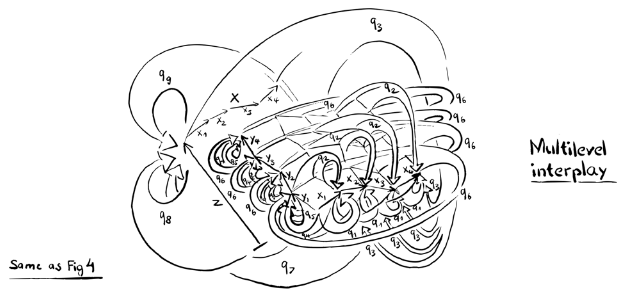

Fig. 11 The model of multi-level interplay of Fig. 4 visualized in lines-planes style. To prove that it is possible, I have added here a lines-planes representation of the model of Fig. 4. This is for the most advanced readers only. The model shows interplay that takes place between overarching categories and subcategories. Easily recognizable are the flows q_2 along the diagonal of the matrix. They are a result of interplay between any given subcategory x_i and its matching pair y_i. By contrast the flows q_6 are a result from interplay between any given subcategory y_i and the entire overarching category x, with $x = x_1 + x_2 + x_3 + x_4$. Evidently, these latter flows include all interplay that takes place not only along the diagonal but also off the diagonal of the matrix. We have applied this model to explain cycles of diversification. The present visual is helpful in this respect because it makes evident that the model works like a machine that computes diversity. If the sum of $q_2 x_i y_i$ values along the diagonal of the matrix is high, diversity is low, and the x_i values are held in check, whereas if the sum of all pairwise $q_6 x_i y_j$ values that include all interplay that takes place off the diagonal are high, diversity is high, and the x_i values are not held in check (Simpson's index is calculated by dividing the first set of values by the latter, which is why diversity is low in the previous and high in the latter situation. See also Fig. 12 in Annex 2) If this model is only studied in terms of the diversity of x and y, it can be simplified to yield a formula for cycles of diversification equivalent to the basic model of interplay of Fig. 2D; (Annex 2).
Source: Dan C. Baciu. License: CC-BY.

that change, while the functions represent laws of necessity that effectuate the change. Newton expressed the law of universal gravitation as a function that was at work everywhere in the universe. He used it to calculate the changing forces that acted on planets and other celestial bodies.

The same distinction between the role of functions and that of variables is maintained in the life and human sciences. Life often is about change—it is about moving on and getting somewhere. Yet, living beings are searching not only for new places to reach but also for the unfailing operations that can help them to get there.[4]

Taken together, causality is a great, unified theory of life. It applies to everything that we can study. As soon as we have brains, we can think. And as soon as we think, we can start searching for causes in anything that we observe, and in any discipline that we work in. By and by, causality becomes a way of thinking that can unite all sciences from physics to the humanities and beyond. Certainly, nobody can stop us from looking at observations and searching for causes. And, nobody can reject causal thinking altogether: Causal thinking allows for unknown causes. There is no shame in saying that an effect is caused by an unknown cause through an unknown causal mechanism. This also means that anything unknown can be part of the equation, and it means that anything, no matter how incomprehensible it may first seem, can always be described in terms of causality, and with equations that feature functions and variables (Supplement).

And, as if this pan-scientific success of causal thinking were not already sufficient, there is something more that adds a unique appeal. Creativity and diversification are not standalone processes. They are two distinct faces of causality; they are universal aspects of it.

When you model causality with functions, you will likely end up inserting additions and multiplications. You can use the additions to express creativity and the multiplications express the emergence of diversity.

Together, causality and its two faces—creativity and diversification—can be your key to any science at any time.

Data availability

Author's project page for this article: https://doi.org/10.17605/OSF.IO/2EJXC. The data for Fig. 5 is available at: https://storage.googleapis.com/books/ngrams/books/datasetsv3.html English, version 20120701 Code is available from the author on request. The preprint of this article (October 12, 2021) is located at https://doi.org/10.31219/osf.io/byndg An expanded, earlier version of the article (September 20, 2021) in which each causal model is individually presented with its own flow diagram and system of equations is found in my preprint "10 Causal Models for Life" https://doi.org/10.31219/osf.io/8uyc3 This latter document also contains annotated equations for the models shown in Figs. 2C, D, G–I and 4. Methods for mapping urban diversity and applications of these methods in mapping historical cycles of urban diversification are found in Baciu et al. (2022) and Baciu and Della Pietra (2021). For more detail, read these articles and the methods paper related to them. For the UNESCO world heritage site of Sassi di Matera, the data are provided as a separate dataset of Baciu and Della Pietra. Additional cycles of diversification in human culture are discussed in detail in my articles of 2019, 2020, and 2021. The data are provided there.

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Notes

1 A video abstract for this article is online accessible here https://doi.org/10.25496/W2KW28

2 In matrix representation seen as eigenvectors and eigenvalues

3 The model led to the understanding that HIV diversifies during the asymptomatic period as a reaction to a patient's immune response

4 The present framework applies across all sciences as well as both mathematics and logic. The framework is also compatible with many more artistic perspectives than I had space to present here. For example, the idea that the world around us can be imagined to have more than three dimensions eventually took root in architectural history. In the 1910s, the American architect Claude Bragdon developed an entire system of ornamentation based on two-dimensional projections of four-dimensional objects. For him, multidimensionality was reflective of what he called a multidimensional, mathematical "world order". Other artists and designers retook Semper's fascination with functions. The architect and Harvard dropout Buckminster Fuller wrote, "I am not a thing—a noun. I seem to be a verb, an evolutionary process—an integral function of the universe." This statement brings to bear that we perceive our identities as something that stays with us while all else is changing. This is also true for functions. They can be used to express laws that remain unchanged while everything around them is changing. Here again, the present framework is compatible with many different perspectives and world views. Newton spoke of "fluxions" when he used functions and their derivatives to study dynamics in the physical sciences. We can now speak of "cultural fluxions" when we do the same in the humanities. Theories and tools can work across disciplines.

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