Emergence and Decline of Scientific Paradigms

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Scientific paradigms have a tendency to rise fast and decline slowly. This asymmetry reflects the difficulty in developing a truly original idea, compared to the ease at which a concept can be eroded by numerous modifications. Here we formulate a model for the emergence and spread of ideas which deals with this asymmetry by constraining the ability of agents to return to already abandoned concepts. The model exhibits a fairly regular pattern of global paradigm shifts, where older paradigms are eroded and subsequently replaced by new ones. The model sets the theme for a new class of pattern formation models, where local dynamics breaks the detailed balance in a way that prevents old states from defending themselves against new nucleating or invading states. The model allows for frozen events in terms of the coexistence of multiple metastable states.

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Human history contains a number of epochs, each dominated by certain themes. Themes are often centered around scientific ideas, which each become so dominating on a large scale that nearly everybody is affected and influenced by their prevalence in the ongoing human communication and thinking [1]. In science these themes are often centered around single words or concepts, with recent examples such as, nano, climate change, chaos, string theory, systems biology, and high-T_C superconductivity. These phenomena have a real basis—but also include a large social factor associated with people communicating with each other. Typical for such phenomena is a relatively sharp initiation, a rapid growth up to near-global awareness level, followed by a slow decline where the ability to sustain interest is weakened by new ideas. Sometimes, scientific concepts even escape the scientific community to the global public, and become common themes that influence the frame for future cultural development. Examples of the latter include nanotechnology and the concept of climate change.

In social system modeling, there exist models to deal with consensus formation [2,3] and opinion formation [4–10]. In these models, agents can take one of a certain number of opinions, and opinion spreads by allowing agents to influence each other. The simplest opinion formation model [3] would be to consider agents on a 2-d lattice, each taking one of two opinions, say A or B. Minimal dynamics would be to take one agent and then update it to the same state as a random neighbor. At any time where both opinions are present, there is an equal chance for increasing or decreasing the number of agents with a particular state. Thus, the number of these agents perform a random walk, until the system reaches one of the absorbing states where one opinion is extinct. The next simplest opinion formation model includes noise, where at each time-step there is a probability α to change the state of a random agent. For finite values of α, consensus is never reached permanently, and the system fluctuates randomly while taking opinion values anywhere between the extremes.

In social systems it is believed that opinion formation is governed by cooperative effects [11] in the sense that two persons provide much stronger convincing ability than one person. Such cooperativity contrasts simple infectious epidemics, where spreading occurs from one person to the next. Cooperativity could be included in a model by taking two persons, and only allowing them to exert influence when they are of the same opinion [6–8]. If this is implemented in the above model with a certain level of noise, one obtains a bistable system, provided that the noise level is sufficiently low. In that case one of the opinions will dominate for a period, interrupted by an abrupt switching to the other opinion.

We here consider spreading of ideas, concepts, or in general orientations that are open-ended in the sense that there is an infinity of varieties. Furthermore, we consider these ideas to have a small probability α for being initiated. In fact we assume that each new idea appears spontaneously only once. Finally, and most importantly, we assume that each agent can only hold any particular idea only once. When changing to a new idea, the agent never returns to any of the ideas that he has had in earlier times.

We believe that suppression of ability to revert to previous concepts reflects part of cultural or scientific activity, where people are on an ongoing hunt for new ideas and ideally never return to exactly their old positions. In reality people may return to positions that are close to their previous idea, but we will assume that whatever they return to, this can be viewed as an entirely new state. The model is defined on a 2-d square lattice with $N = L^2$ agents. Each agent i is assigned a number r_i which can take any integer value. This number plays the role of a particular idea or concept. At any time step one random agent i is selected, and the following two actions are attempted: (i) One of the nearest neighbors j to the agent i is selected. Denoting by n_j the total number of agents with integer value equal to that of j, we with probability n_j/N let the agent i change its integer value to that of its neighbor j, provided that i never assumed that particular integer value before. In case it had, then no update is made. (ii) With probability α another random agent k is assigned a new random integer which does not appear anywhere else in the system. Thus α represents the ''innovation'' rate.

A key difference from previous models of opinion spreading is the rule that, in our model, old ideas are never repeated. Practically, one could of course repeat a particular integer in the simulation, provided that it does not exist anywhere in the system. This is because an integer that is not on the lattice would not be differentiated from a new number by the model. Another feature of the above model is the factor n_j/N, which implies that a minority concept has more difficulty in spreading than a more widespread idea. This particular feature represents cooperative effects in social systems [11], and is nearly the same as just selecting two agents for influencing one. This is included in a way that we (1) allow cooperativity to act on long distance but at the same time restrict propagation to spreading on a 2-d plane, (2) avoid discussion of detailed neighborhood updates related to where the two agents are located, and (3) allow a single idea to nucleate from one person (with probability $1/N$). The collective effects associated to the cooperative coupling lead to globally coherent states, that sometimes are replaced by new coherent states through a system sweeping ''avalanche dynamics.'' Figure 1 shows 12 subsequent states of a system driven by the model. The snapshots reflect states of the simulation shown in Fig. 2(b), starting at time $t = 62\,000$. The first picture shows the system a little after a new idea has swept the system, leaving the system in a coherent state dominated by this particular state (black color). A few agents have different colors, representing the effect of a finite innovation rate α over the short time interval after the dominating state took over. The second and third panels show the system closer to the next transition (at $t \sim 68\,000$), where several states have nucleated some sizable clusters of coherent colors. Panels 4–5 correspond to the spike at $t \sim 68\,000$ which subsequently leaves the system with two mutually coexisting coherent states that persist until they are erased by a new ''avalanche'' in panels 8–9. Finally, panels 9–12 show the dominance,

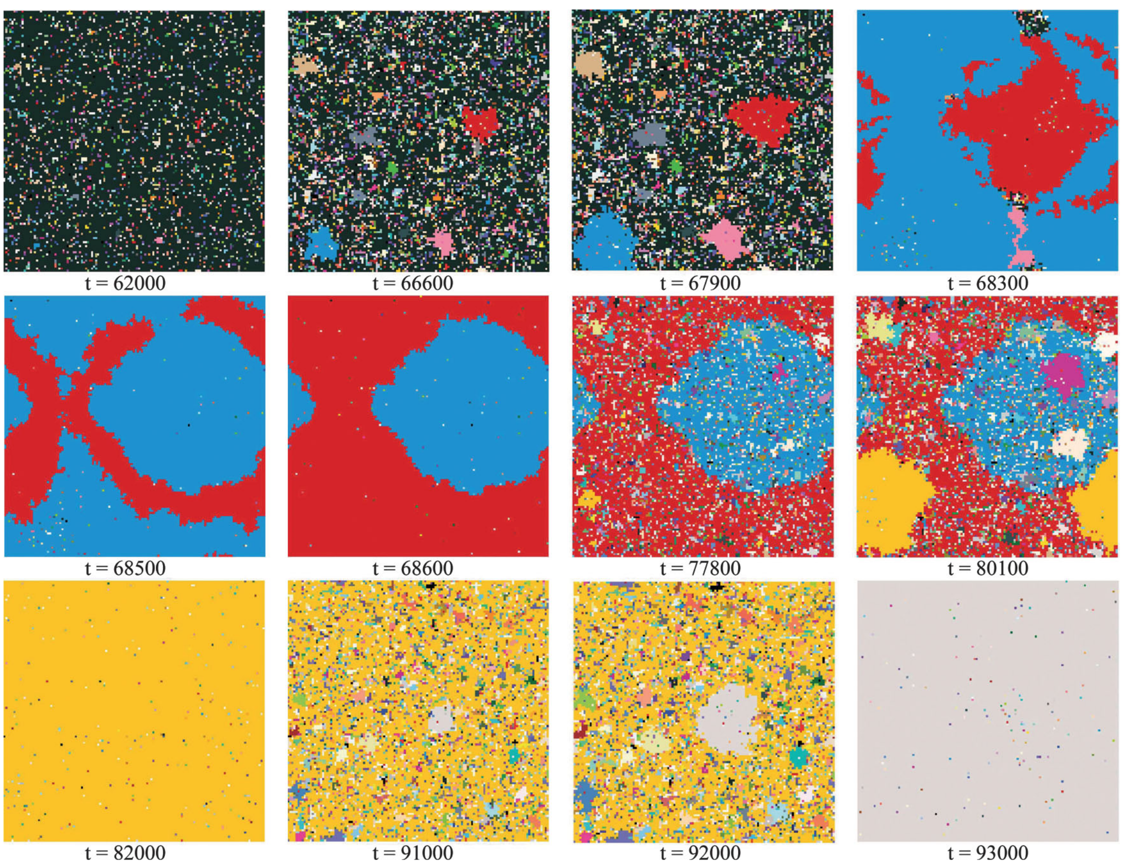

FIG. 1 (color). Twelve consecutive snapshots of a $N = 128 \times 128$ system with $\alpha = 25 \times 10^{-6}$. The time intervals between the pictures are not equidistant, as can be seen from the times given for each panel [times correspond to Fig. 2(b)]. Time is measured in units of full sweeps, i.e., one update for each agent.

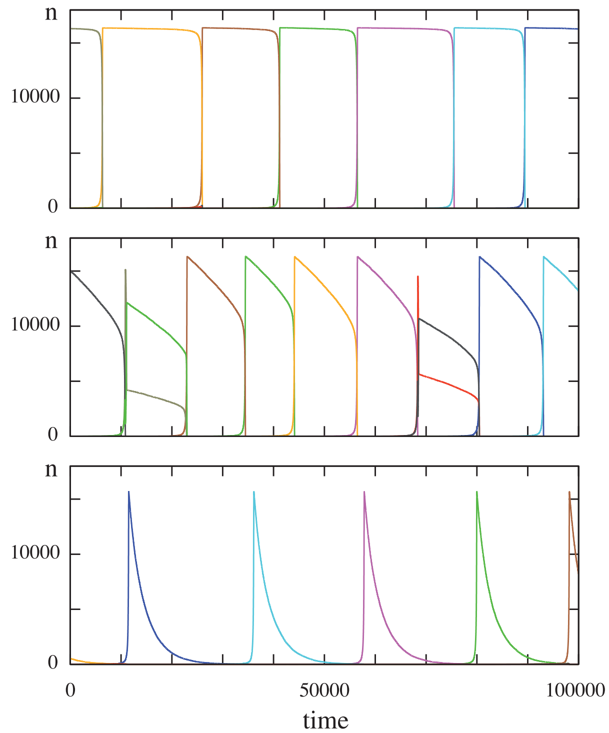

FIG. 2 (color). Three time series of the sizes of the dominant states of the system, at $\alpha = 0.4 \times 10^{-6}$, $\alpha = 25 \times 10^{-6}$, and $\alpha = 400 \times 10^{-6}$, respectively. Time is measured in units of sweeps (updates per agent). Notice that the length of each period does not change substantially with α, and in fact becomes more regular with larger α.

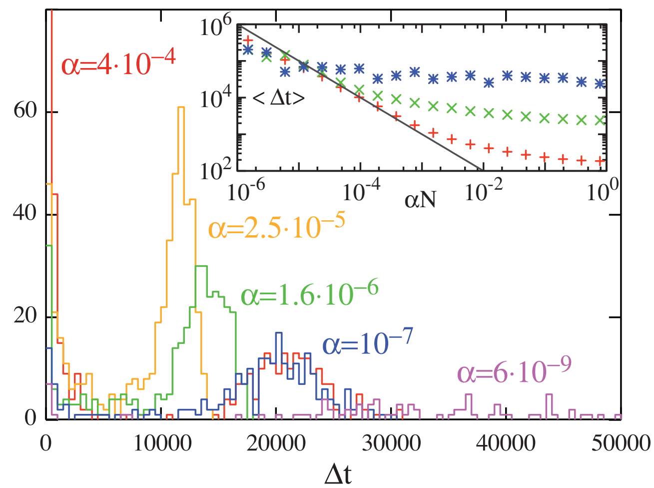

FIG. 3 (color). Distribution of waiting times between shifts of the dominant state for a $N = 128 \times 128$ system at different values of innovation rate α. Inset: Average waiting time vs αN for different system sizes $N = 16^2$ ($+$), $N = 64^2$ ($\times$), and $N = 256^2$ (*). The diagonal line measures the time between individual innovations $t = 1/\alpha N$. For small innovation rates, waiting time is close to this line, independently of system size N. For large innovation rates, waiting times become insensitive to αN, while strongly increasing with N.

erosion, and subsequent replacement of one state with another between times $t = 82\,000$ and $t = 93\,000$.

Figure 2 shows three time series for the subsequent rise and fall of leading communities, illustrating the behavior at low, intermediate, and high values of the innovation rate α. In all cases one observes a sharp growth of the dominating community, followed by a slower decline. Remarkably, the length of domination periods are quite insensitive to α. However, as seen from Figs. 2(a)–2(c), the nature of the decline of the dominating state depends on α: (i) For low α the dominating state nearly remains intact until it is replaced by a rare single nucleating event that suddenly replaces the old state with a new one. As a consequence, low noise only rarely leads to situations where more than one state nucleates at the same time. (ii) At intermediate α the decline is substantial and many nucleating states are competing. Sometimes two nucleating states grow and interfere which subsequently result in a period where there are two frozen states [as in panels 6–8 in Fig. 1]. This reflects events where one of the major communities was defeated in some part of the system by another community, and therefore cannot reinvade that region again. Thereby a substantial minority community can remain protected by its immunity to the prevailing majority. (iii) Large α results in a complete erosion of the dominating state, before a new nucleating state can grow. This growth will be in an environment where it also has to compete with ongoing erosion from other nucleating states. Because the winner is the result of many events, the distribution of time intervals between global state changes becomes more regular than for lower noise. At even higher α, the ongoing activity prevents nucleation, thereby leaving the system in a permanently noisy state with multiple small domains that are constantly generated and replaced.

Figure 3 shows the distribution of waiting time intervals between subsequent changes of the dominant state. Over a wide range of innovation rates α one observes a typical time scale for these paradigm shifts. At lower innovation rates, the shifts are dominated by single rare nucleation events, making the switching time given by a pure exponential process. This can also be seen in the inset, where this mode is shown as a diagonal line $\Delta t = 1/\alpha N$ measuring the time between individual innovation events. Anything above this line quantifies how much individual innovations are replacing themselves before a system-wide sweep takes over. We observe a strong system size dependence for large values of αN. Innovative people in the model observe a much higher turnover rate of dominating ideas in small isolated systems (think of a small country, company, etc.) than in big systems. For less innovative people, however, a small system will have as frequent sweeps as a big one. In summary, with respect to innovation, the model shows how a small system can be more dynamic than a big one. This is, for example, reminiscent

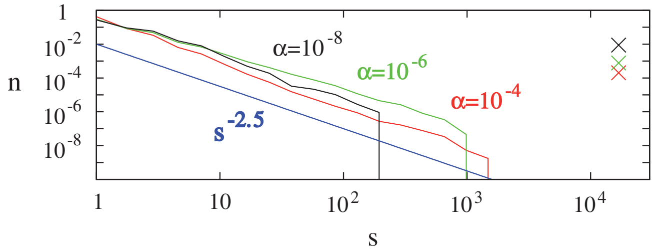

FIG. 4 (color). Distribution of the number of sites s that a particular idea visits during its life span for different values of α. Scaling $\sim 1/s^{2.5}$ for comparison (blue line). Note the gap between the main part of the distribution and the bins counting the ideas with system-wide sweeps (crosses). System size is $N = 128 \times 128$.

of the frequent acquisition of startup firms as a viable source of innovation for large companies.

The key aspect of the model, compared to previous opinion spreading models, is the infinite space of ideas and, in particular, the repression of previously rejected ideas. In case one removes this constraint and allows old ideas to reinvade the same site again, one still obtains a multistable system for low levels of the innovation rate. The nucleation process will be a rare process, the winner will take all and there will never be a metastable state with more than one prevailing state. During times where one state prevails, new ideas are constantly created (with rate α) and typically removed quickly by the cooperative reinvasion of the dominating idea. Such a simple system has no memory of all these small "noise events," in contrast to the memory that is inherent in human inventions.

Such memory is present in our model where also the nondominant ideas can obtain a sizeable spread. Figure 4 shows the distribution of the number of sites s that a particular idea visits during its life span. Remarkably, the distributions of this spread s scale as $\sim 1/s^{2.5\pm0.3}$ for a wide range of α values. Furthermore, the distribution shows a characteristic gap separating the distribution of "small" ideas from the system-sweeping, dominant idea plotted as crosses in Fig. 4. This gap is strongly dependent on α. The remarkably steep exponent resembles the distribution of small events when integrating the behavior of an extended system that approaches a critical breakdown (the global event) [12].

Viewing our cooperative model in terms of paradigm shifts in science or society, one should be aware of limitations of a geometry defined by homogeneous 2-d space. In the real world there are predefined subcommunities that often are hierarchically organized: there is the community at large; there is science; there is the subdiscipline physics, which again is subdivided into high energy physics, solid state physics, astrophysics, biophysics, etc. Each of these communities is again subdivided, making it possible to spread one particular idea to dominate a subcommunity completely without having any noticeable impact on the remaining world. Examples are high T_C superconductivity, which had large impact in the solid state community, but essentially none outside that field. On the other hand, a subject like global warming has effects on a global scale.

Overall our model provides a new frame for understanding the interplay between dominance of prevailing concepts supported by a large number of followers, and the striking inability of these concepts to defend themselves against new ideas when the situation is prone to takeover. The increased vulnerability of a dominating idea or paradigm with age is in our model seen in the steady increase in the number of competing ideas, and a parallel decrease in its support. For intermediate or large innovation rates, the takeover is a chaotic process with multiple new states competing on short time scale. The final takeover is on a much shorter time scale than the decline. Existing paradigms are eroded in a preparadigm phase for the next paradigm (as perhaps visible at present for the paradigm of global warming) much as envisioned by Kuhn [1]. The new paradigms are born fast, ideally aggregating in a real scientific competition between the many random ideas that emerge in the preparadigm phase.

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