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REVIEW

MARK BUCHANAN

Ubiquity. The Science of History . . . Or Why The World is Simpler Than We Think

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Unifying theories have a long history. Ever since antiquity, attempts have been made to explain a seemingly heterogeneous variety of phenomena by a few general principles. One of the most recent attempts in this vein is Self-Organised Criticality (SOC), a new approach to complex systems, which has become one of the important areas of research in physics as well as in many other disciplines during the last decade. SOC has been applied to problems as diverse as earthquakes, forest fires, landscape formation, solar flares, river networks, mountain ranges, volcanic activity, traffic jams, evolutionary processes, plasmas, superconductors, fluctuations in stock markets, brain function, spreading of epidemics, and many more.

In his book *Ubiquity. The Science of History . . . Or Why The World is Simpler Than We Think* (henceforth abbreviated to '*Ubiquity*'), physicist and science writer Mark Buchanan sets out to communicate the basic ideas of SOC to a non-specialist audience. In this well-informed, entertaining and lucidly written book he presents a nice summary of the highlights and the main results of fifteen years of research on SOC. Using concrete examples like the outbreak of the First World War, the 1995 earthquake in Kobe, or the 1987 Wall Street crash, he explains the main ideas of SOC in an intuitive and vivid way, thereby evading the technical aspects of the approach (the book does not contain a single formula).

Over and above being a smooth introduction to SOC, *Ubiquity* vigorously puts forward a daring thesis: SOC is ubiquitous. The strategy of the book is to substantiate this claim by enumerating phenomena from wildly different fields for which SOC can be invoked as an explanation. The introduction of the sand-pile as the paradigm example of a system exhibiting SOC (Ch.1) is followed by an extensive discussion of earthquakes (Chs 2–5), and after an interlude on universality (Ch. 6) Buchanan turns to forest fires (Ch. 7), evolution (Chs 8–9), and economics (Ch. 10). The last chapters of the book are devoted to the discussion of issues from history and sociology: the size of cities (Ch. 11), scientific revolutions (Chs 12, 13), and human history broadly construed (Chs 13, 14). A short postscript (Ch.15) concludes the book. The (implicit) overall conclusion has it that SOC is ubiquitous since it is able to account for all these vastly different phenomena.

Buchanan is not the first to put forward a claim of this kind. Notably Per Bak—one of the founding fathers of SOC—and his disciples have repeatedly voiced similar views, and the prevailing enthusiasm in the physics community to come up with ever more applications of SOC indicates that this indeed seems to be a widespread conviction.

This gives rise to two questions: First, 'ubiquity' is an ambiguous term and to say that SOC is ubiquitous can be understood in different ways. Therefore, what is really being claimed when SOC is said to be ubiquitous? Second, once we have a specific reading of the claim, is it true or not? Is SOC really ubiquitous? The rest of this review is devoted to the discussion of these questions. My conclusion will be rather sober. I will argue that a closer look at how SOC is being put to use renders the claim that it is ubiquitous untenable.

The most obvious interpretation of this claim is to think about SOC as a general theory (like thermodynamics, for instance) at the heart of which lie powerful general principles which turn out to be applicable across different and seemingly unrelated fields. This seems to conform with how scientists tend to think about SOC: Bak entitles his 1997 book on SOC 'How Nature Works', and Blanchard *et al.* ([2000], p. 375) refer to SOC as a 'new paradigm for the explanation of a huge variety of phenomena in nature and social sciences', to mention just a few.

Can this be true? Is SOC a general theory in (roughly) the same way as thermodynamics is? A closer look at how SOC is being applied reveals that this cannot possibly be the case. A remark of Bak's highlights the problem. While writing about earthquake models he notes that the model of evolution can be thought of as an earthquake model 'simply by a change in terminology' ([1997], p. 172). This phrase nicely summarises the way in which SOC is being put to use. Roughly speaking, the general strategy is this: take the sand-pile model (or another well understood SOC model) and reinterpret the terms in its mathematical description so that they refer to the new system. In the case of the earthquake model just mentioned, one reinterprets the mathematical term which stands for fitness in the evolution model so that it refers to the barrier distribution over a fault plane that generates earthquakes (*ibid.*). In this way, we obtain an earthquake model from an evolutionary model almost for free. And this is by no means an untypical example. At the heart of SOC lie a few 'core models' which are 'applied' to different domains by reinterpreting the elements of the model.

And it is this strategy that generates the overwhelming amount of SOC applications.

But do we apply a theory to a new domain by merely reinterpreting the terms of its calculus? I do not think so. Applying a theory amounts to bringing its general principles to bear on a particular situation. To stick with the example, thermodynamics is applied to a concrete situation by showing that the system's behaviour is an instance of its general physical principles. In the case of SOC, however, things are different. SOC is applied by taking one of the core models, the mathematics of which is then reinterpreted such that its terms refer to features of the new target system. Hence, what lies at the heart of SOC are not physical principles but a few core models, or to be more precise, their mathematical skeleton which is then 'applied' by giving its terms different interpretations.

For this reason, SOC does not seem to be a scientific theory at all. Whatever stance one might take towards scientific theories, it seems to be uncontroversial that an uninterpreted calculus (the mathematical skeleton of a model) is not a part of empirical science at all, let alone a scientific theory. The syntactic view defines theories as a calculus *plus* a specification of the intended empirical interpretation, and the semantic view identifies a theory with a family of models. On both views, a mere calculus is not a theory. To drive the point home, consider the example of linearity. Linear equations are arguably the most widely used mathematical structure in science, but they are not a *theory of* everything they describe; nobody would call linearity a theory of elasticity, the natural rate of unemployment (NAIRU), and learning (linear response theory), just because linear equations are used to describe all these phenomena.

Hence, I conclude that SOC is not a theory at all, at least not in the same sense thermodynamics, or quantum mechanics, for instance, are theories. But what is it then? As I see it, the above discussion of the way SOC is applied suggests that it is best considered as a family of models which are connected to each other by what Mary Hesse ([1963], pp. 75–6.) has called formal analogy. Two objects are related by formal analogy if they bear no similarity other than that of both being interpretations of the same mathematical calculus. This is the situation we find in SOC. What sand-piles, earthquakes and traffic jams have in common is precisely that they are differing interpretations of the same calculus. At the core of SOC lie a few mathematical models which are interpreted in ever different ways in every application, whereby they turn out to be a powerful mathematical tool to tackle a wide range of problems.

On this reading, the claim that SOC is ubiquitous amounts to saying that a variety of different phenomena from various fields can successfully be modelled within the SOC-framework. SOC is seen to provide tools which can be used to build adequate models of vastly different systems. This seems to be a fair construal of what SOC does, and also one with which its proponents can live. Hence the question arises: is it true?

It is undoubtedly the case that SOC models have been constructed for an impressive variety of phenomena, hence the 'numerical' part of the claim is beyond discussion. However, in order to claim that SOC *is* ubiquitous one not only has to come up with a myriad of models for all kinds of things, one also has to show that these models really capture the essential features of the systems modelled, and hence provide a solid account of the processes at work. In what follows I shall argue that this is the problematic bit. Most of the SOC models are so highly idealised that it is, to say the least, an open question whether they really instruct us about what is going on in nature.

As an illustration consider the paradigm sand-pile. In a by now well-know experiment, Frette and his co-workers ([1996]) have set out to check whether a pile of rice exhibits SOC or not. What they found is that the dynamics of the pile reproduces the power-law distribution of the avalanche-size typical for SOC only in the case of very elongated grains, but not in the case of rather roundish ones. The more spherical the grains become, the less SOC-like behaviour the pile exhibits. Hence, SOC is by no means a general pattern of the behaviour of granular piles. And worse, this failure to account for how a host of real piles behave is not just due to 'experimental noise'; rather it is rooted in the simplifying assumptions of the model. The movement of the cubes in the model (the sand-pile model is a cellular automaton model) does not at all correspond to the movement of real grains: cubes move just from one square to the next in axial directions, and they can even jump upwards, whereas the behaviour of real sand shows a variety of slip, slide and roll motions the model cannot account for. A further problem is that the model works under the assumption that the grains move instantaneously from one field to the next and then come to rest. Real grains, however, show inertia (roughly speaking, the tendency to keep moving once set in motion). It takes some time to accelerate them and then it again takes some time until they eventually come to rest. But the SOC model does not take the inertia of the grains into account, and this is another reason why the model fails to capture the dynamics of real piles. And the worst is yet to come: as Dickman *et al.* ([2000], p. 38) point out, the neglect of inertia is necessary to obtain SOC in the first place. When we try to augment the model and build inertia into it, SOC vanishes; and the reason why the model gets things more or less right in the case of elongated grains is that their inertia is extremely small. Hence, there seems to be no way that this model can ever account for how most real piles behave, or in other words, it is not even approximately true. In view of all this, I do not think we are entitled to say that real sand-piles do exhibit SOC.

However, other models seem to be better off since they, unlike the sand-pile model, actually do yield the right predictions. The evolutionary model, for instance, posits a power law distribution for the extinction of individual species, and this is exactly what palaeontologists found when they went through their fossil extinction records. The latter is certainly a remarkable finding, but is it sufficient to establish that evolution exhibits SOC? I do not think so. Power laws and SOC states are two different things; the finding of a power law can be, but need not be, a footprint of an underlying SOC structure (here the well-known problem of alternative hypotheses crops up). There might be other, yet unknown, mechanisms for generating the same power law. Therefore, further evidence is needed to establish the claim that evolution really is a SOC process; in particular, one has to show that the model captures the essence of the phenomenon. At this point, however, one may have one's doubts. One cannot help having the feeling that this model is constructed simply to do what it does. 'Real' evolution does not have much in common with a game based on the static replacement of one species by another whose fitness is chosen by a random number generator, and a closer look at the set-up of the model reveals that it does not seem to capture what is really going on in this enormously complex process we call evolution.

Hence, neither in the case of sand-piles nor in evolution do the present models warrant the conclusion that the real systems exhibit SOC. And these examples are by no means exceptions. Although there are cases where a SOC model can be considered an adequate description of the system's behaviour (traffic jams or the movement of domain walls in type II superconductors, for instance), similar provisos apply in almost all cases. In the bulk of the concrete applications, one has, in order to use the SOC machinery, to distort the phenomena to an extent that the model misses out essential features of what is really going on.

To some degree, Buchanan is aware of this difficulty and he aims to overcome it by appeal to a technical concept called 'universality': vastly different systems can exhibit the same behaviour at the critical point if they fall into the same 'universality class'. Roughly speaking this means that the details of the system do not matter. Buchanan now invokes universality to justify the validity of the models in light of the gross oversimplifications made. This is certainly an interesting suggestion, but given the present state of knowledge, it is merely speculative. A general theory of universality is available only for equilibrium systems. But SOC systems are far away from equilibrium, and no one has yet figured out what a general theory of universality for such systems might look like. Hence, universality arguments have no force in the present case. Moreover, it is even doubtful whether a future theory of universality will be able to do the job Buchanan wants it to do: to show that the model and the real system belong to the same universality class and that it is therefore legitimate to omit all kind of 'details' without losing track of what is really going on—as we have seen in the case of the sand-pile, some omitted details actually do matter.

For these reasons, I conclude that the present SOC models do not provide sufficient grounds to sustain the claim that a vast class of real-world systems exhibit SOC. If at all, this is true only in a few special cases; to have a SOC model for some process and to show that this process really does exhibit SOC are two very different issues.

In the last chapters of the book, Buchanan leaves the field of natural science and sets out to discuss sociological and historical issues. He starts off with the observation that the size of cities and the distribution of wealth both follow a power law, and takes this to be evidence that they are the product of a SOC process. Then, a detailed discussion of scientific revolutions aims at establishing that they, too, result from a process governed by SOC. Buchanan finds evidence for this in the fact that the number of citations of research papers follows a power law distribution. And last but not least, he extends these ideas to human history in general: war, music, fashion, art, or whatever you like is organised into a SOC state. The witness for this claim is again of a statistical nature: the number of people killed in deadly conflicts obeys a power law.

It goes without saying that the provisos I have voiced above bear on these cases. It is certainly a remarkable empirical finding that the number of people killed or the number of citations of research papers follow a power law distribution, but this does not warrant the conclusion that history and scientific research work in a SOC state. Here Buchanan has just got carried away with SOC. Even if one grants that an analogy can be established between the sand-pile and history, it is certainly pushing the argument too far to conclude that since the sand-pile exhibits SOC history does as well; an analogical inference of this kind just does not provide anything like a sufficient justification to accept its conclusion. Given Buchanan's premises, there is no way to establish the claim that history and other social phenomena really *are* SOC processes.

However, adopting a less committed reading, the claim would be that we can learn interesting things about history if we do look at it as if it were a SOC process; that is, if we took the sand-pile as a metaphor for history. Construed in this way, the suggestion is certainly worth pursuing and can lead to a valuable cross-disciplinary transfer. As a metaphor, the sand-pile could suggest a new way of thinking about historical and social processes, and it could be taken as an antipode function to stagnant assumptions like the view that there are recurring law-like patterns in history. It could help to de-familiarise deeply entrenched styles of reasoning and thereby open new paths for thinking about these issues. Thus understood, the sand-pile could be useful to social scientists and historians alike.

To sum up, I have argued that Buchanan fails to establish the claim that SOC is ubiquitous. Neither is SOC a general theory that applies to a wide range of phenomena, nor are most SOC models adequate descriptions of real processes as they happen in nature. Nevertheless, *Ubiquity* is a well-written and interesting book about SOC, and it will serve as an entertaining and smooth introduction to everyone interested in this discipline.

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