

NONLINEAR DYNAMICS

Universal clues in noisy skews

Crackling noise emitted in systems as diverse as candy wrappers and earthquakes show strikingly similar behaviour, but how it is influenced by the details of these systems is unclear. A study that identifies the microscopic origin of unexplained asymmetries in the noise emitted by a magnet could provide some answers.

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Crackling noise is a familiar phenomenon that arises when a system responds to slowly changing external conditions with the emission of a series of sudden avalanche-like pulses, and displays many universal characteristics over a wide range of time and length scales and in a diverse range of contexts¹. So the crackle of a candy wrapper as it is crumpled, the crackle of a tree as it is felled and the crackle of the Earth as it quakes under the movement of tectonic plates, all follow similar laws. Remarkably, most of the essential elements of this behaviour are successfully predicted by simple, cartoon-like models of the systems in which it occurs. Yet despite their success, the basic nature of these models, which either neglect or make crude approximations of the complex microscopic details of the systems they describe, means our understanding of the subtler aspects of crackling noise is incomplete. On page 46 of this issue², Zapperi and colleagues identify a microscopic origin for the previously enigmatic asymmetric shape of the noise pulses emitted by a magnet when its magnetization is reversed by an external field. Not only does this resolve a leading deviation between theory and experiment, it could have significant implications for other crackling-noise systems.

Central to the universal behaviour of crackling noise is the notion of self-similarity. A system is said to be self-similar when its behaviour is independent of the scale on which it is observed — a property that is illustrated by the behaviour of a simple magnet. When the magnetization of a magnet is reversed by an external field, the interaction of the magnetic domain walls (that are created and set in motion by this field) and inhomogeneities in the magnet (such as impurities or crystal grains) causes a sequence of individual avalanche-like reversal events that generate crackling noise in a suitable experimental setup — a phenomenon known as the Barkhausen effect. The self-similarity of this effect is demonstrated in Fig. 1,

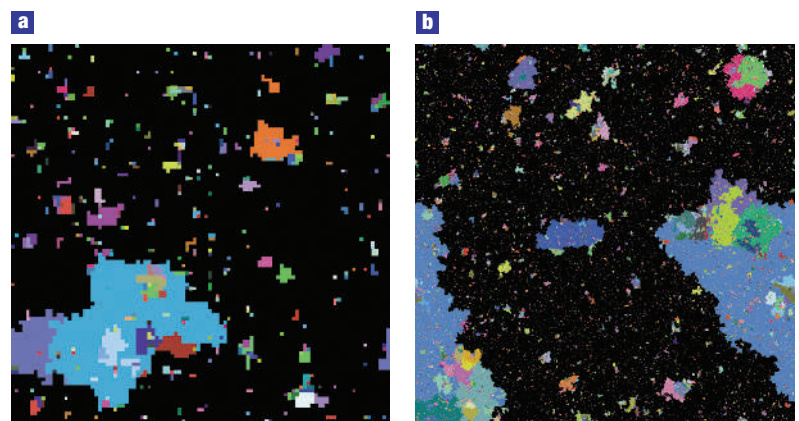


Figure 1 Self-similarity. Cross-section of magnetization avalanches in a model with a power-law avalanche size distribution. Different avalanches are drawn in different colours. **a**, Cross-section of a system with 100^3 magnetic domains. **b**, Cross-section of a system with $1,000^3$ domains, rescaled. Apart from the resolution of the two images, the general shape and distribution of the avalanche events depicted in both is the same. Reprinted from ref. 1.

which depicts the occurrence and spatial distribution of magnetization avalanches exhibited by simulations of a simple model magnet¹. The two parts of this figure were obtained from simulations carried out at two different magnifications (Fig. 1a being taken at ten times the magnification of Fig. 1b), yet, apart from the obvious difference in resolution, both images are visually similar — which reflects the fact that the statistical distribution of magnitude and extent of the avalanches in both is the same.

The scale-independent nature of self-similarity is common throughout nature. Moreover, at long length scales, universal parameters such as the power-law exponents and scaling functions that characterize the statistics of crackling noise are not only scale-invariant but have been shown to be independent of the microscopic details of the systems in which it occurs¹. That is, different magnets respond to an applied external field with the same power-law distribution of magnetization avalanches, regardless of their specific composition, grain size or microscopic

structure. Some models predict the same universal quantities³ even for earthquakes^{4–6}. The reason that such vastly different systems can be described by the same universal quantities is that they only depend on a few fundamental properties of a system. This is the reason for the predictive success of many theoretical models to describe this behaviour despite their crude simplicity¹.

Yet there is a subtle but crucial difference in the universal features of the noise predicted by models compared with those exhibited by real magnets. The average avalanche profile characterizes the evolution of the noise pulses emitted in a given avalanche obtained by averaging over many events of the same duration. Average profiles for different durations obtained from experiments on real magnets can be rescaled to lie on a single curve. Similarly, the data obtained from simulations of the Barkhausen effect also can be made to lie on a single universal plot^{7,8}. However, comparison of the two reveals that these supposedly universal curves do not overlay^{1,8}. Theory predicts¹ that the avalanches associated with Barkhausen noise grow and subsequently decay at the same rate — resulting in a symmetric universal time profile — whereas experiments show that in fact these avalanches grow more quickly than they decay, resulting in an asymmetric or skewed time profile. The reason why theory should be so singularly unable to model the asymmetry in this scaling function whilst being so very successful in quantitatively predicting the many other universal features of Barkhausen noise has until now been a mystery^{1,8}.

Zapperi *et al.*² resolve this contradiction by taking greater account of a microscopic detail that had been neglected by previous models — namely the influence of eddy currents. Eddy currents are transient current loops that arise in conducting magnets in response to the reorientation of a magnetic domain. These currents temporarily prevent neighbouring domains from being triggered to realign in the same direction in an avalanche of domain reversals. Moreover, finite electrical resistance causes the eddy currents to dissipate in a characteristic time, τ , which represents an effective microscopic delay for avalanches to be triggered in neighbouring domains, and slows the movement of domain walls through the material

by enough to account for the asymmetry seen in the experimental scaling function. The authors also show that for larger avalanches of longer duration, the asymmetry decreases as τ becomes small in comparison to the avalanche duration. The authors thus identified this prominent deviation between theory and experiment, which otherwise agree exceptionally well, as an unusually large effect of microscopic details that would be negligible on much larger scales. This implies that the asymmetry observed in experiments is not universal, but dependent on the material details and on the duration of the experimental avalanches.

This result not only resolves the mystery of the asymmetry in Barkhausen noise but has potential implications for the broader class of crackling systems, particularly those for which the corresponding scaling function is yet to be measured. Intriguingly, similar asymmetric behaviour was recently identified in earthquakes^{6,9}. It has been suggested that triggering delays — arising from an increase in the failure threshold during the formation of new cracks in the earth and subsequent weakening as rock damage increases — could be responsible for aftershocks that often follow large earthquakes. On a long timescale a large mainshock with smaller aftershocks reflects a similar asymmetry to that seen in the magnets, possibly with a similar explanation. The slip-time profiles of individual large earthquakes also seem to reflect this asymmetry. Given this and the many other features that are common in the crackling noise of magnets, earthquakes and related phenomena, the new avenues for future studies opened up by the present work are promising indeed.

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