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# Rejuvenated but remembering

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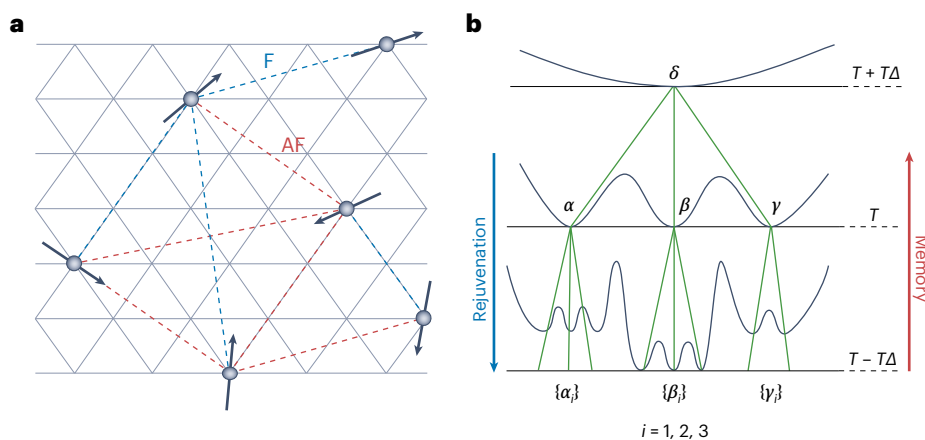
The structure of disordered materials typically ages, but sometimes also rejuvenates, resulting in intriguing memory properties. Progress in numerical simulations of spin glasses has now enabled replication of such phenomena from simple models.

A spin glass is a diluted magnetic material in which the magnetic moments interact randomly, with a huge number of metastable states that prevent reaching equilibrium. It is constantly evolving – the aging phenomenon is well known from, for example, polymers, which get stiffer with time<sup>1</sup>. Experiments on spin glasses have shown that, somewhat counter-intuitively, a ‘rejuvenation’ of the aged state can be observed when lowering the temperature. Yet, during this rejuvenation process, a ‘memory’ of the previous state can be preserved<sup>2</sup>. Due to frustrated interactions, numerical simulations of spin glasses are highly time-consuming. Special-purpose computers have been developed that have led to spectacular progress. While experiments only access macroscopic variables (like magnetization), simulations offer a vision of what is happening at the scale of spins. Recently, Baity-Jesi and co-authors (calling themselves the Janus Collaboration) managed to compare the microscopic correlation length of ‘spin-glass order’ with that obtained in experiments<sup>3</sup>. Now, writing in *Nature Physics*,

Baity-Jesi and co-authors succeeded in observing rejuvenation and memory effects<sup>4</sup>. Thus, we now understand that the basic ingredients of spin-glass models<sup>5</sup> are enough to produce such complex phenomena. The icing on the cake is that ‘temperature chaos’<sup>6</sup> is now identified, together with the different length scales at which it takes place during rejuvenation. (Temperature chaos refers to the notion that typical spin configurations at a given temperature would be very atypical for another temperature.) In this manner, we come to understand how the spins are able to achieve aging, rejuvenation and memory effects at the macroscopic scale.

Magnetic interactions are positive in ferromagnets, tending to align all magnetic moments (or spins), whereas in antiferromagnets they are negative, driving the spins to anti-alignment. In a spin glass, the spin interactions have random signs (Fig. 1a). The first studied spin-glass materials were non-magnetic metals (Au, Ag, Pt, ...) in which a few percent of magnetic atoms (Fe, Mn, ...) were dispersed at random. The random interatomic distances and the spatially oscillatory character of the magnetic interaction in metals produce random sign interactions and a spin-glass state<sup>5</sup>.

In a spin glass, no equilibrium state of simple symmetry exists. The spin glass explores a complex free-energy landscape with a huge number of metastable states, which are separated by barriers of all heights, generating relaxation times spanning from paramagnetic times ( $\sim 10^{-12}$  s) up to astronomical scales. A spin glass is virtually always out of equilibrium, and exhibits slow dynamics with aging effects<sup>7</sup>.



**Fig. 1 | Spin glasses.** **a**, A spin glass is a diluted magnetic system. The magnetic moments, separated by random distances, interact with random sign (ferro- (F) or antiferromagnetically (AF)). Each moment encounters conflicting interactions (‘frustration’). The equilibrium states are very difficult to find, and have no obvious symmetry. **b**, Schematic representation of the effect of temperature changes on the free-energy landscape of a spin glass. When going from  $T$  to  $T - \Delta T$ , the free-energy valleys subdivide into smaller ones, separated by new barriers, across which rejuvenation processes take place. For large enough  $\Delta T$  (and in the limited experimental time window), the transitions can only take place between the sub-valleys inside the main valleys, in such a way that the

population rates of the main valleys are untouched, keeping the memory of previous aging at  $T$ . Hence the memory can be retrieved when re-heating and going back to the  $T$ -landscape. This hierarchy of states can be transcribed into a hierarchy of length scales<sup>2</sup>. The higher the barrier to be crossed, the larger the length scale over which the spins are reorganized. In spin glasses, there is a strong separation of the time scales that govern the dynamics on different length scales<sup>2</sup>. Changing the temperature changes the length scale at which the system is observed, thereby allowing rejuvenation (concerning short length scales) and memory (stored in long length scales) to coexist. Panel **b** adapted from ref. 7 and references therein.

The Janus Collaboration has performed massive simulations of this slow dynamics. In the present paper<sup>4</sup>, Baity-Jesi and colleagues have simulated a set of  $160^3$  spins interacting with their nearest neighbours through randomly distributed couplings of value  $\pm 1$ . The high computing power, together with the use of clever algorithms, allows exploring up to  $10^{11}$  Monte Carlo steps, which means covering a remarkable time range, from  $10^{-12}$  s up to tenths of a second, thus reaching the shorter time scale of the experiments.

In simulations, a microscopic correlation length  $\xi_{\text{micro}}$  can be defined from a 4-point correlation function, which cannot be assessed in experiments. Starting from a random configuration of the spins, which corresponds to the state of a spin glass cooled from the paramagnetic state, the growth of ‘spin-glass ordered domains’ (correlated domains in which spins flip together) has been characterized by the slow increase of  $\xi_{\text{micro}}$  (ref. 8). On the side of the experiments, macroscopic quantities are measured, like the growing magnetization obtained after cooling in zero magnetic field (that is, the ZFC procedure) and applying a small field after a waiting time  $t_w$ . The derivative of the magnetization with respect to the log of time is bell-shaped, peaking at a characteristic relaxation time  $t_{\text{eff}}$ . Aging has been discovered in the experiments as a dependence of the peak position  $t_{\text{eff}}$  on the waiting time  $t_w$ . Namely,  $t_{\text{eff}}$  is found of the order of  $t_w$  itself, which means that the dynamic properties depend on the ‘age’  $t_w$  (ref. 7). The same aging phenomenon has been known for a long time to exist in the mechanical properties of glassy polymers<sup>1</sup>.

Baity-Jesi and colleagues were able to simulate this experimental procedure, with bell-shaped curves peaking at  $t_{\text{eff}} \approx t_w$ . The breakthrough is that they also observe a rejuvenation effect when the temperature is lowered: the peak is shifted to shorter times, and, after a long aging time at the lower temperature, they find that the memory of the previous age at the higher temperature is retrieved, although rejuvenation has occurred.

Why was it so difficult to observe these effects in simulations<sup>8</sup>, although they have been evidenced in many experiments? To understand this point, we need to consider several length scales. Baity-Jesi and colleagues have simulated some past experiments in which another correlation length,  $\xi_z$ , was made accessible by studying the Zeeman magnetic coupling of the field with the growing spin-glass domains<sup>9</sup>. First, they showed that in a simple aging experiment,  $\xi_z$  and  $\xi_{\text{micro}}$  are similar. This is an important validation of the relevance of  $\xi_z$  as measured in the experiments. Second, they showed that during a rejuvenation experiment  $\xi_z$  is indeed reduced, while  $\xi_{\text{micro}}$  is untouched, keeping the memory of the previous age. Thus, the structure of the spin-glass

domains is highly non-trivial, short-length scales being reshuffled by rejuvenation while large scales are preserved. This points towards a hierarchical organization of different correlation length scales as a function of temperature, as was argued from the early experiments<sup>2</sup> (Fig. 1b). The key point is that the recent simulations can now explore sufficiently large correlation lengths ( $\sim 16$  lattice units), thus making it possible to separately investigate small-scale (from 3–6 lattice units) rejuvenation processes<sup>8</sup>.

Baity-Jesi and colleagues were able to examine the correlations between the spin configurations in the normal aging state, in the rejuvenated state, and in the memorized state. Strong temperature chaos is found when rejuvenation takes place, while it is absent when the same procedures are applied to a simple link-diluted ferromagnetic model. Hence, we can now understand how temperature chaos materializes in aging dynamics. The Janus Collaboration’s simulations open the way to ‘see’ how spins behave during aging, rejuvenation and memory processes. And further progress can be expected from the close collaboration that they have established with experimentalists<sup>10</sup>. Still, the dreamed breakthrough in experiments – access to the spin configurations – seems to remain out of reach despite notable efforts<sup>11</sup>. The progress presently made in simulations is all the more highly appreciable.

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## Competing interests

The author declares no competing interests.