No obvious environmental benefits accrue from multiple mating (no increase in offspring mass, litter size or total litter mass; nor do females gain higher fertility or lose less body weight during gestation). It could be that 'fit' females simply attract more matings, or that males exert a preference for 'fit' females. Or could the result arise from some ecological effect: perhaps population density (and hence the chance of multiple mating) is higher in 'better' parts of the habitat, with offspring of females in 'poorer' areas suffering adverse effects? The lack of correlation between multiple mating and such features as litter size and mass counts against such ideas, but does not invalidate them — for example 'poor' areas may contain some toxin which results in stillbirths. A further interpretation is that the effect arises through sperm ageing. Multiply mated females may have on average fresher (less defective) sperm than singly mated females.

A final possibility — fitting the authors' hypothesis and even providing a plausible mechanism for it — is that 'fit' males transfer more (rather than more vigorous) sperm. Multiple mating could thus be advantageous to females without any correlation between a sperm's vigour and an offspring's viability. A possible reason for 'fit' males ejaculating more sperm relates to male strategy under sperm competition: sperm expenditure is an evolutionary game in which the best strategy depends on the strategies of other males in the population[8]. Males may even increase sperm numbers if sperm competition is likely[9,10]. The cost of sperm to a 'fit' male may be less than that of an 'unfit' male, and he may therefore ejaculate more sperm[8]. In other words, 'fit' males can buy more tickets and win the raffle more often.

Whatever the exact mechanism underlying their result, if Madsen *et al.* are right that sperm competition allows a female to gain 'better' genes for her offspring we shall have a new reason why some females accept several matings, and a new role for sperm competition. I rather hope it turns out that they are correct. But for the time being judgement must be suspended. □

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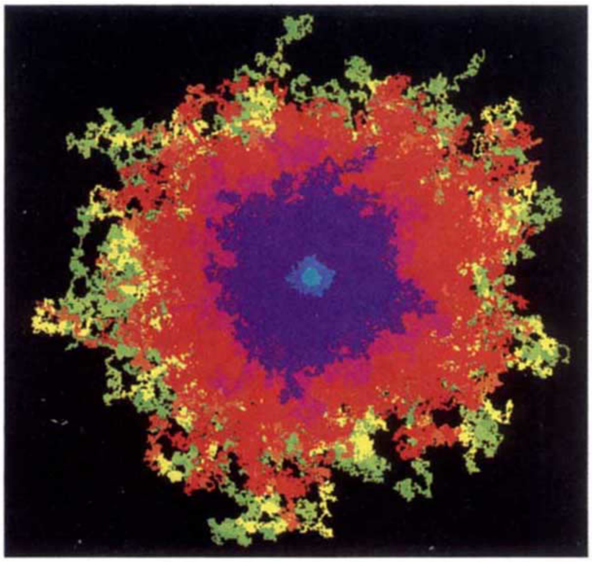
STATISTICAL PHYSICS

New paths for random walkers

Michael F. Shlesinger

A LARGE class of problems involving noise, fluctuations, transport, relaxation and reactions can be cast in the form of a random walk. One area of active investigation[1] in random walks involves calculating the first passage time for a walker to achieve a goal, such as inducing a reaction by reaching a specific site or hitting another walker, and so on. Another active area involves calculating the behaviour of many random walkers. On page 423 of this issue[2] Larralde *et al.* combine both of these themes. They calculate the territory covered by N diffusing random walkers which start nearby each other. New territory is added when a site is visited for the first time. The complication arises that only the first walker to visit a new site counts, so to prevent overcounting one must keep track of the past history of all the walkers.

The authors' analytical and numerical work for the geometry of the new territory finds three distinct timescales of behaviour, including a fascinating transition in the roughening of the geometry of the sites visited (see figure). Only in the last regime when the walkers have moved far enough apart from each other would the results reduce to those of single-particle statistics scaled by a factor of N. At long times each walker visits new sites proportional to the number of steps taken (in three or higher dimensions). At early times many new sites are visited. After t steps the N walkers (for large N and small t) fill the volume, of radius t, explored around their origin. The number of distinct sites visited initially grows as t^d, where d is the dimension. This growth in the number of new sites visited slows down at intermediate times to $t^{d/2}$ times a dimension-dependent function which has a weaker dependence on t. It is in this intermediate time regime where the geometry of sites visited becomes complex and interesting that the most important applications probably lie.



Territorial army: successive colours show the progress of 1,000 random walkers starting at the origin (centre) as they encroach on new territory over several successive periods. Note how the frontier of the explored territory is initially smooth, but later becomes rough. (Courtesy of Eugene Stanley.)

One might have suspected that Jacob Bernoulli discovered most of the key ideas of random walks way back in the early 1700s. For example, he found that if two gamblers have R coins between them, and one coin is won or lost in each play of a fair game, then the mean number of plays $\langle N\rangle$ before one player runs out of money is given asymptotically by $\langle N\rangle = (1/D)\,R^2$, where D is a constant. This was the 'first' first-passage-time calculation. It took Einstein, 200 years later, to move the brackets from time to space, to invent brownian motion with the mean square displacement of $\langle R^2(N)\rangle = DN$. For the above Bernoulli process, letting R and N be continuous, De Moivre, in 1756, in the 3rd edition of his classic book *The Doctrine of Chances*, derived the first-limit theorem (for what we now call the gaussian probability density) for a player's fortune. So early on much was known about random-walk probabilities, and in principle everything about a random walk can be derived from knowing $P_n(x)$, the probability for being at a site x, after n steps.

The complexity of the many-walker problem studied by Larralde *et al.* is perhaps surprising in that the statistics of each walker are gaussian, and the walkers do not interact (influence one another). The complexity arises through the question which is asked. The authors' question involves a first passage time and a conditional probability for checking that when a walker reaches a new site, it is the first of the walkers to achieve this. It is the infinity of different questions that one can ask, even about simple random processes, that makes probability and statistics such a rich field.

The literature on many-random-walker processes is sparse, but several interesting results have been derived. For example, in one dimension, a single random walker always returns to its origin, but on the average this takes an infinite amount of time. If, however, three walkers begin at the origin the mean time for one of them to return to the origin is finite[3]. For interacting walkers[4] moving along one dimension that annihilate upon meeting, the probability that p walkers starting near the origin all survive for n steps is $n^{-p(p-1)/4}$. Such types of problems are intimately involved with interfacial wetting transitions[4]. But note in particular how involving many walkers naturally generates fractional exponents.

Another example concerns the random walk of entangled chains in a polymer melt. The reptation model[5] freezes all polymer chains but one, and calculates the mean first passage time T for that chain to move away, with snake-like motions, from the chains with which it is entangled. This time T is found to scale with the chain length M as M^3. Experiments, however, yield exponents in the range 3.3–3.4. If one lets all the chains move, some of the entangled neighbours will move in the same direction as the given chain and still be entangled at time M^3. The many-chain calculation gives $M^{10/3}$ for the disentangling time[6,7].

A final example treats many walkers representing mobile defects in a glassy material. The defects can induce a dielectric relaxation upon reaching frozen-in dipoles in the material. For each defect the waiting-time distribution between jumps has such a long tail that the mean jump time is infinite. But when a jump occurs from a finite concentration of defects, not only does the mean time become finite, but the famous stretched exponential law appears as a probability limit distribution which governs the dielectric relaxation[8,9]. The statistics of the minimum jump time from a set are not the same as for a particular member.

The study of random walks has maintained its vitality over three centuries since the pioneering work of Jacob Bernoulli. New processes, new questions and new applications ensure a never-ending richness to be mined. The work of Larralde *et al.*[2] opens up a host of further possibilities — of using interacting walkers, of working in fractal spaces, of space–time coupling of trajectory lengths with velocities (as in turbulence), and so on. These would find applications in fields as diverse as physics and ecology. □

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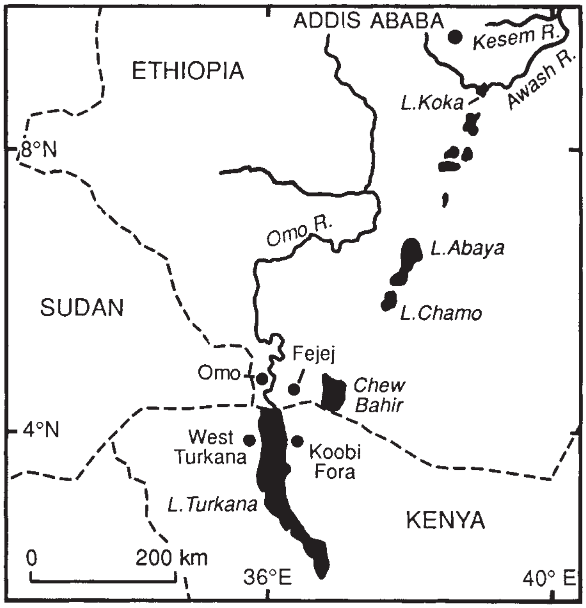
PALAEOANTHROPOLOGY

A remote sense for fossils

Bernard Wood

THE latest discoveries[1] of early hominid remains in Ethiopia owe a great deal to the successful application of space-age technology in palaeontology. That technology, remote sensing, holds the promise of helping to deliver further and richer finds both within and beyond East Africa.



Sketch map of the principal sites discussed in this article. (Modified from ref. 1.)

The eastern arm of the African Rift valley has furnished much of the evidence for human evolution, sites such as Olduvai, Koobi Fora, Omo and Hadar being especially rich sources of the fossilized remains of early hominids. The remains range from those of the earliest known hominid species, *Australopithecus afarensis*, to material which has been allocated to *Homo erectus*. Although research at the sites themselves has become increasingly rigorous, knowledge of their existence has been obtained in a haphazard fashion. Some were pinpointed when explorers and travellers noted finding 'fossil bones', others by extrapolating from regional geological knowledge and looking where sediments 'ought to be'. Field surveys are notoriously hit-and-miss unless controlled by detailed aerial photographs, however, yet the expense of such photographs cannot be justified unless the area is known to be rich in fossils.

The impasse was broken with the report[2] of the results of a much more systematic survey designed to locate potential fossil sites. From 1988, Berhane Asfaw has been co-ordinating the innovatory Palaeoanthropological Inventory of Ethiopia in Addis Ababa. The survey harnesses the powerful techniques of remote sensing. Two modalities, thematic mapping and large-format camera images, were used by the team, which included members from NASA–Goddard, Los Alamos, the University of California, Berkeley, and the University of Tokyo.

Thematic mapping data are derived from satellite-based radiometers which measure the intensity of reflected sunlight. Whereas earlier Landsat scanners generated spectral data in only four wavebands, with a 76-m resolution and with the range of intensity expressed on a 64-digit scale, the newer equipment provides measures of intensity in six wavebands, with a seventh thematic infrared radiation band, at an increased resolution of 30 m and with an intensity specified on a 256-digit scale. The Ethiopian project drew upon data enhanced by high-frequency spatial filters and made manifest as composite colour images. The modifications were used to highlight vegetational changes and the occurrence of tephra, and to emphasize fault structures and exposures of sedimentary strata. The large-format camera system images were taken aboard the shuttle *Challenger* in 1984. Substantially larger (23 cm × 46 cm) negatives and more precise optics provided particularly high-resolution photographs which can sustain enlargement to 1:50,000 (the thematic-mapping system cannot practically exceed 1:75,000).

From the data, both major regional geological structures and more local basin topography could be identified.