films[10] which alters the conducting network (as shown with CTAB in phosphatidylethanolamine), in agreement with the results on reconstituted bacteriorhodopsin[2–4].

It is clear that a thermodynamic barrier prevents free proton movement from the surface to the bulk, as proposed 10 years ago[11] and confirmed by the studies on purple membranes[2–4].

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SCHERRER REPLIES —Teissié refers to earlier work on a phospholipid monolayer system. The interpretation and the model proposed for diffusion of protons along the membrane surface are basically in agreement with our data from the bacteriorhodopsin–lipid–detergent system[3] and data from the purple membrane system[2,4].

The experiment I proposed[5] to obtain direct experimental evidence for lateral movement of protons requires a proton source on the membrane surface, proton detectors in well-defined positions on the membrane surface (at the proton source and a defined distance away), and a proton indicator in the aqueous bulk medium. In the experiment referred to by Teissié the proton source was in the bulk medium and the proton indicator in the monolayer, and so that system does not meet these requirements.

In addition, in our studies on bacteriorhodopsin–lipid–detergent micelles[3], we showed direct experimental evidence for the effect of the pK_a of lipid headgroups on the lateral transfer of protons, and for the delayed proton transfer from surface to bulk. The conclusion drawn from previous studies on the dissociation rate constants of the lipid headgroups against a retarded proton transfer from membrane surface to bulk[6,7] does indeed not agree with our experimental data. However, this conclusion was based on data obtained in a model system that again did not allow the defined placement of the proton source and proton indicators.

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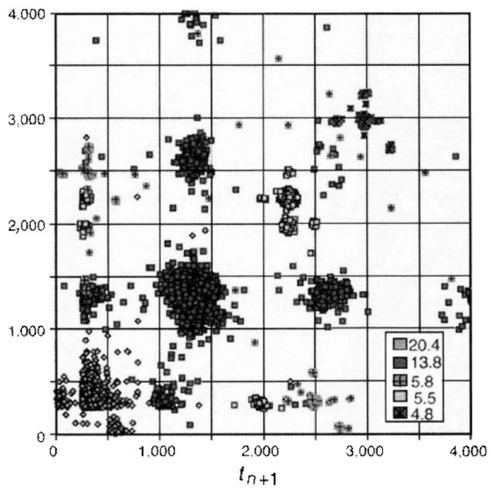
Scientific Correspondence

Scientific Correspondence is intended to provide a forum in which readers may raise points of a scientific character. Priority will be given to letters of fewer than 500 words.

Chaos in the classroom

SIR — It is said that many universities in the UK struggle to fill undergraduate science places, asking lower entry grades than other subjects. *The Independent* newspaper recently suggested that sciences are "considered intellectually difficult and not always well taught in schools"[1]. Could school science be failing to fire students' enthusiasm? I recently completed my secondary school science education in an excellent tertiary college, but found parts unimaginative and too focused on factual recall. Nuffield A-level physics, however, offered real opportunities in course work to escape the well-worn and mundane if one wished. Here I present my work, based on the dripping tap as a model chaotic system, to illustrate possibilities inherent in simple experimental investigations for inspiring students to study science.

A system of three plastic header tanks, rubber tubing (donated by The Leyland Rubber Company) and a small pond pump provided a constant but variable pressure, isolated from vibration. Water dripped through a capillary tube, and drops were detected using a light-dependent diode (LDD), allowing measurement of the time gaps between each successive drop. Observation of the relationships between these time gaps revealed a number of potentially chaotic behaviours with different head heights (see figure). As would be expected, with increasing water pressure the average time between drips decreases, but not in a linear manner.



Return maps (plots of *n*th against (*n*–1)th time between drips) of five different types of behaviour observed at different head heights. More than 12,000 data points were recorded, many superimposed, so that the 'noise' is less than appears at first glance. The 4.8-cm data had a single period with subgroups, the 5.5-cm data show short and long time periods, while the 5.8-cm data are dipolar (that is, for example, short, long, short). The 13.8-cm data have four time periods (a further bifurcation doubling) and had the greatest number of definite time periods found, whereas the 20.4-cm data have progressed to a more independently random system (with the square left-hand corner to the main group showing the definite end of phase space) which has only two obvious time periods.

Statistical analysis was simplified because the system is discrete. Tests of randomness[2] showed that all times related to previous times. Shaw defined "information stored in a system" as the difference in its expected randomness with and without knowledge of its past[3]. In tests for this, Markov chain χ^2 analysis of the 5.8-cm data proved very significant for first-order relationships (strong evidence for long/short dipolarity, a relatively long gap being followed by a relatively short gap) and quite significant for second-order relationships (gaps affect the next but one gap). Serial autocorrelation[2] of the data turned up many other strange relationships; for example, in the 4.8-cm data, gaps appeared unrelated to the immediately preceding gap but were related to all previous gaps; in the 5.8-cm data, an autoregressive process[4] showed that there was a large jump in stored information with the tenth preceding gap.

Far more data were produced than could be analysed in the three weeks allowed for the project. But the innovation involved in solving the problems of experimental design and data analysis (thereby acquiring skills from computer programming and electronics to surface tension and plumbing) was similar to 'real' research. Experimental investigations are the bedrock of all scientific discovery; surely there must be many students, like myself, in all branches of science, whose imaginations would be fired by encouraging them to do less 'well-worn' and more innovative work?

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2. Kendall, M.G. & Ord, K. *Time Series* (Edward Arnold, London, 1990).
3. Shaw, R.S. *The Dripping Fawcet as a Model Chaotic System* (Ariel, Santa Cruz, 1984).
4. Chatfield, C. *The Analysis of Time Series* (Chapman & Hall, London, 1989).