or proteins which bind to this domain might therefore uncover novel regulators of cell survival.

The physiological roles of this ligand and receptor remain enigmatic. The key to their immunological function surely lies in the unusual population of non-dividing T cells that enlarges the lymph nodes of *lpr* and *gld* mice. This disorder was initially attributed to a breakdown in the thymic purging of immature self-reactive T cells[9]. However, despite the expression of Fas/Apo-1 by most thymocytes[13], it now appears that thymic selection remains intact in *lpr* and *gld* mice, and opinion is growing that their lymphadenopathy reflects the accumulation of terminally differentiated T cells. If so, a major role of Fas/Apo-1 may be to limit the amplitude and duration of the immune response.

Because Fas/Apo-1 is expressed in liver, ovary, heart and lung, it may regulate homeostasis or stress responses in these tissues. Indeed, wild-type (but not *lpr*) mice injected with an antimouse Fas monoclonal antibody died within eight hours, with wholesale destruction of the liver[13]. Clearly, increased understanding of the physiology of cell suicide is necessary before apoptosis can be harnessed for tumour therapy.

Finally, by analogy with the pleiotropic effects of TNF, the biological responses triggered by the Fas/Apo-1 ligand may not be confined to apoptosis. In certain cell types, or in combination with other signals, the Fas/Apo-1 receptor may in fact promote activation[14] and thereby favour life over death. ☐

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PATTERN FORMATION

Spirals and chaos

J. P. Gollub

SPIRALS crop up as the dominant type of pattern in a remarkable variety of physical, chemical and biological systems. Recent developments include unexpected spiral patterns in thermal convection[1], and a possible explanation for the sudden onset of ventricular fibrillation[2]. On page 345 of this issue, Assenheimer and Steinberg describe novel observations of spirals in thermal convection near the critical point of a fluid[3]. These examples show that studies of pattern formation in spatially extended nonlinear systems continue to reveal surprises, especially where chaos is involved.

Remarkable observations of nearly perfect spiral patterns in thermal convection were first made by Bodenschatz *et al.*[1] in 1991. Their work was based on measurements in high-pressure carbon dioxide gas, which allows systems very much larger than the basic scale of the pattern to be conveniently studied. Strikingly perfect hexagonal patterns also occur when the fluid properties vary significantly across the layer.

Last year, Morris, Bodenschatz and collaborators discovered a new form of spatiotemporal chaos composed of a disordered array of rotating spirals[4]. This work is noteworthy for its contribution to the problem of describing spatially extended chaos quantitatively, rather than qualitatively. On measuring the characteristic domain size or correlation length of the patterns, Morris *et al.* found a clear power law for the dependence of this length on the temperature difference measured from the convective onset. They were able to demonstrate that the band of wavenumbers found in the spiral pattern lay almost entirely within the band for which stability theory predicts stable straight rolls. This apparent contradiction between theory and experiment is puzzling; the authors speculate that the straight roll pattern predicted by theory has a small basin of attraction, so that it is hard to reach from the initial and boundary conditions of a real experiment for temperature differences significantly above the onset of convection.

The work of Assenheimer and Steinberg in this issue explores patterns in Rayleigh–Bénard convection near the thermodynamic critical point, T_c, of SF$_6$. They take advantage of the fact that the fluid properties vary strongly with temperature near T_c, so that very thin layers only 130 μm thick can be used, and the two important fluid parameters can be easily varied. (These are the Prandtl number P, which is related to the viscosity, and a parameter Q that specifies how strongly the fluid properties vary across the fluid layer.) They add a new twist to previous work on spirals by showing that spiral patterns dominate for $P<3.5$, whereas target patterns dominate for larger values. Furthermore, they are able to investigate the precise mechanisms by which one pattern is converted to the other through interaction with defects in the patterns.

The role of defects in non-equilibrium patterns is itself a challenge to work out. The situation is much like that in the physics of solids, where the dynamics of defects often controls the mechanical and thermal properties of crystalline matter. Many investigators have proposed that the key to understanding non-equilibrium patterns lies in achieving a better understanding of defect nucleation, propagation and interaction. But this hope has been only partially realized (the interested reader is referred to a wide-ranging review by Cross and Hohenberg[5]).

How spatially disordered patterns or spatiotemporal chaos are generated is now one of the main themes of nonlinear science. Its possible importance is underlined by theoretical work[2] on the mechanism by which spiral patterns of excitation in cardiac tissue might become disorganized, possibly leading to fibrillation. Karma's work[2] is based on numerical simulations of the Noble model originally adapted from the classic Hodgkin–Huxley equations. The model has many of the properties seen experimentally in studies of cardiac tissue by imaging methods[6]. A particular oscillatory pulse instability of these equations can lead to the breakup of a large isolated spiral wave into a more complex pattern of many spirals with randomly distributed centres. The breakup of spiral waves has also been studied in other model systems relevant to excitable media. Of course, the adequacy of models based on a homogeneous medium remains to be established[5].

Spirals are only one of the possible basic elements of spatiotemporal chaos in non-equilibrium systems. By now a host of examples is known, with manifold variations on both the basic patterns and the transitional mechanisms. An adequate classification scheme does not yet exist, much less a general explanation of the phenomena.

Although the term 'chaos' is frequently heard in connection with deterministic nonlinear phenomena in extended systems, the standard methods of low-dimensional nonlinear analysis are very difficult to apply to extended systems. Worse still, the methods used for characterizing and distinguishing the different forms of spatiotemporal chaos seem inadequate. Although statistical methods are clearly needed, some of the more obvious candidates do not reveal the coherent structures (such as spirals and hexagons) that are visible even to the eye. This subject remains as murky as the turbulence it attempts to describe. ☐

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