changes in temperature, but also to changes in moisture, nutrient availability and substrate quality, all of which are also directly or indirectly affected by temperature. For instance, the predicted relationships between soil temperature and soil respiration do not hold when moisture becomes limiting[8–10], or when there is a shift in the composition of the microbial community[11], or when there is a change in substrate quality or quantity[12,13].

The Harvard Forest soil warming experiment in Petersham, Massachusetts, provides a useful example of this latter case. In this study[12], the researchers found that soil respiration increased in response to experimental warming. Soil respiration was 40% greater in warmed plots than in control plots during the first year of the experiment, the rise probably being fuelled by the microbial oxidation of labile (easily decomposed) carbon compounds. The magnitude of the response of soil respiration to experimental warming declined markedly in the second year, however, presumably because the labile carbon supply was depleted. If a Q_{10} value from the first year of data had been used to extrapolate results and predict longer-term respiratory responses to warming, it would have resulted in a large overestimate of the amount of carbon released from the forest soil, and so of the potential feedback to climatic warming.

Luo and colleagues[1] likewise find a decline in the temperature sensitivity of soil respiration with warming: the Q_{10} was 2.70 in the unheated plots compared with 2.43 in the heated plots. As with the Harvard Forest example, the results show that caution should be used in extrapolating results from short-term experiments to predict longer-term responses to environmental perturbations such as warming. The question of how ecosystems might or might not acclimatize to a warmer world bears serious consideration. But as with much research on this topic, longer time series of data will be needed to provide plausible answers. ■

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Ion channels

Swimming with sperm

David L. Garbers

Mice become infertile if they lack the gene encoding a newly discovered sperm-specific ion channel. Sperm are produced in normal quantities, but have trouble moving.

Spermatozoa rely on calcium ions to function. And, like the cells from which they are produced, sperm seem to express several channels that allow calcium ions to enter[1]. But, so far, none of these ion channels has been linked to the regulation of sperm motility. That changes with an impressive paper by Ren and colleagues[2], published on page 603 of this issue. The authors have discovered a channel, which probably allows calcium ions to pass through, that is expressed only in sperm and is needed for them to move normally.

When sperm are first produced in the testes they are immobile (Fig. 1, overleaf). It is only after they are moved to their storage site, the epididymis, that they acquire the ability to swim forwards (progressive motility) — a behaviour that is required for successful fertilization. Sperm do not actually move about in the epididymis, but actively swim forwards after ejaculation or dilution into various media. As they enter the isthmus of the female reproductive tract, sperm slow down once more[3]. They resume their migration when ovulation occurs, eventually reaching the ampulla region of the oviduct, where fertilization takes place.

As well as acquiring the ability to move progressively, sperm must undergo a further maturation process, termed capacitation, before they can fertilize an egg. This occurs while they are in the female reproductive tract, and results in two changes in sperm behaviour. First, they become able to undergo an acrosome reaction in response to the egg's extracellular matrix (zona pellucida), which involves the release of matrix-digesting enzymes. Second, sperm motility is hyperactivated.

Cyclic nucleotides, Ca^{2+} ions and intracellular pH have been all proposed to regulate progressive motility and the events associated with capacitation, including the change to 'whiplash' hyperactivated motility[3]. Spermatozoa express voltage-gated Ca^{2+} channels, cyclic-nucleotide-gated channels and transient receptor potential channels (a different type of putative Ca^{2+} channel)[1,4]. Yet the role of all of these in sperm function has remained elusive, in part because it has not been possible to study sperm by patch-clamping, a central technique for investigating ion channels. Ren *et al.*[2] had similar difficulties with patch-clamping, but a variety of other experiments suggest that the channel they identified — which they dub 'CatSper' — is probably a Ca^{2+}-specific cation channel, and is certainly needed for normal sperm motility.

CatSper is the prototype of a new ion-channel family, described by the authors and by members of my laboratory in another paper[5]. The proteins in this family are something of an oddity. Channels such as the voltage-gated K^+ channels consist of a single subunit, or 'repeat', which comprises six membrane-spanning portions and has a voltage sensor and an ion-selectivity pore. The common voltage-gated Na^+ and Ca^{2+} channels consist of four such repeats. The CatSpers[2,5], by contrast, have a single repeat, but the ion-selectivity pore is similar to that in each repeat of the voltage-gated Ca^{2+} channels. CatSper probably forms part or all of a tetrameric cation channel[2]. Unfortunately, however, the ion selectivity of CatSper remains formally unproven: experimental expression of the protein alone or with other channel subunits resulted in no detectable ion-channel activity[2,5].

Nevertheless, the fact that CatSper is expressed only in male germ cells — specifically, in the tails of mature sperm — was a strong hint that it is involved in regulating sperm motility. Indeed, Ren *et al.* show that CatSper is required for normal progressive motility, and that its absence renders mice infertile. This represents a step towards understanding how ion channels regulate sperm motility. It also provides an opportunity to test the role of different forms of motility in fertilization. Sperm from CatSper-deficient mice swim with a progressive velocity about one-third that of normal. They can fertilize eggs whose extracellular matrix has been removed but not those with an intact matrix, so it seems that the reduction in progressive motility is sufficient to block penetration of the zona pellucida. Alternatively, the sperm might also fail to acquire the hyperactivated form of motility (a possibility that has not yet been tested).

The molecular details of how CatSper works remain unknown. Animals lacking CatSper produce normal quantities of morphologically normal sperm, so it probably

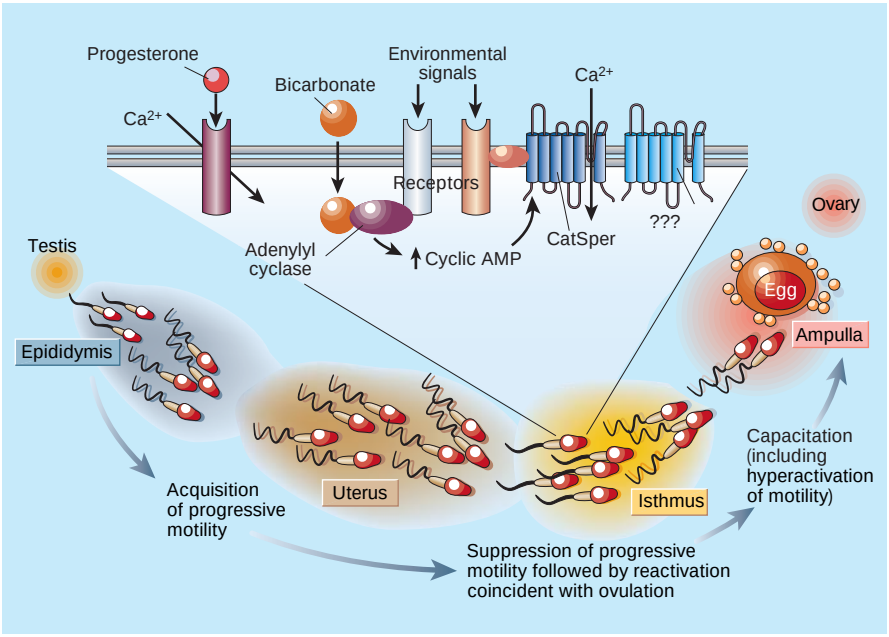

Figure 1 **Changes in sperm motility, from production to fertilization. Spermatozoa are produced in the testis and acquire the ability to swim progressively (forwards) in the epididymis. In many species, after entering the female the speed of progressive motility is slowed in the isthmus of the oviduct. Later, often when ovulation occurs, sperm regain active motility and move to the ampulla, where fertilization occurs. While in the female, sperm cells gain the ability to fertilize the egg — a process known as capacitation. Part of this process is the induction of a whiplash form of motility (hyperactivated motility). Ren *et al.*'s results[2] suggest that a newly discovered ion channel, CatSper, is essential for sperm motility. Top, CatSper, in combination with partner subunits that have yet to be identified, might be a Ca^{2+} channel that is positively regulated by cyclic AMP. Concentrations of cyclic AMP in sperm are regulated by direct stimulation of the enzyme adenylyl cyclase by bicarbonate (HCO_3^-), or by environmental factors that act through an adenylyl-cyclase-coupled receptor. CatSper might also be directly regulated by a receptor that responds to environmental signals. Progesterone, possibly through a receptor similar to that for the neurotransmitter GABA[11], also causes an influx of Ca^{2+}, but this is independent of CatSper[2].**

does not affect sperm development. But one could envisage that this channel is a central gateway through which different signalling pathways feed in information from the environment to regulate motility (Fig. 1). For example, sea-urchin sperm have a cell-surface receptor protein that binds to the egg's extracellular matrix[6]; activating this receptor leads to Ca^{2+} influx and induces the acrosome reaction. The receptor on sea-urchin sperm is similar to a human protein, PKD1, which might also be a receptor. (Mutations in PKD1 are associated with the kidney disorder autosomal dominant polycystic kidney disease.) PKD1 has been proposed[7] to interact with and regulate an ion channel, PKD2. So it is plausible that a protein like the sea-urchin receptor could similarly interact with CatSper.

As mentioned above, cyclic nucleotides, such as cyclic AMP, have been reported to activate sperm motility. Ren *et al.*'s results[2] point to the idea that these molecules, too, might work through CatSper: sperm lacking CatSper did not respond to analogues of cyclic nucleotides by increasing their Ca^{2+} influx as usual. Cyclic AMP is generated by the enzyme adenylyl cyclase, which in sperm is connected to the environment through bicarbonate[8] or receptors that detect extracellular signals. Bicarbonate, present in genital fluids, has long been known to alter sperm function in mammals[9], and signals from the egg that increase cyclic-nucleotide levels and sperm motility are also well known, at least in invertebrates[10]. Cyclic nucleotides might bind CatSper to affect its opening and closing directly, or they might be needed by enzymes that phosphorylate CatSper. The lack of a consensus cyclic-nucleotide-binding motif in CatSper supports the phosphorylation idea, but other data do not[2], so it remains unclear how cyclic nucleotides control CatSper.

Progesterone has also been reported to activate sperm motility, so it will be interesting to see what effect both progesterone and cyclic nucleotides have on the motility of sperm from CatSper-deficient mice. For example, if these molecules accelerate progressive motility, will fertility be restored? Or will that depend on the induction of hyperactivated motility? The results may show that the regulation of CatSper is critical to fertilization. This ion channel has a human counterpart[2], so it is already an attractive target for new contraceptives. It will become even more so if it proves to be

100 YEARS AGO

I should say a university is a place of higher education for those who are qualified by nature to profit by it. And I say that deliberately, holding the opinion as I do that it is not advisable to give more than elementary education to everybody, nor to encourage young people indiscriminately to enter upon a university course. An enormous amount of educational power is now wasted in trying to give a training to intellectual faculties which do not exist, for Providence has not given brains equally to everyone, and many a boy and girl now forced by parents or circumstances to the study of books would be much happier and more useful members of the community if they were taught to lay bricks and to sew and cook and wash, and do these necessary things well which are now done badly. This, of course, is not the business of a university, but if the university can so arrange its tests, whether by examination, or in some other way yet to be devised, as to prevent any large number of weaklings from entering upon the university curriculum, it will be doing a kindness to the rejected and a service to the rest of the world.

From *Nature* 10 October 1901.

50 YEARS AGO

When physics is regarded as the study of the external world, and the world is regarded as a distribution of matter in time and space, there is little room left for anything else except illusions…When I am asked whether I believe in the existence of the external world, I promise to reply when I am told precisely what is meant by the external world and its existence. I have not yet been called upon to redeem the promise. The fundamental question is: What exactly is it that physicists are doing? That can be answered satisfactorily only in terms of experience, not of the external world. It is in any event undeniable that all we can know of any world at all must come from our experience of it—not necessarily sense experience alone, but experience taken as a whole. If then we describe the task of science in terms of experience we shall describe it more directly than is possible in terms of an investigation of a postulated world. That might have been realized long ago; the physics of the past century has made its realization inescapable.

From *Nature* 13 October 1951.

a central node for processing extracellular information in sperm cells. ■

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Materials science

Melting from within

Robert W. Cahn

For many years there has been uncertainty about the processes that trigger melting in solids. A new simulation manages to tie several threads together.

Melting has been a playground for theorists for almost a century. The problem is in understanding how and why a crystalline solid melts, and what determines the temperature at which this happens. Many theoretical criteria for melting have been advanced, of which two stand out: the Lindemann criterion[1] (1910) and the Born criterion[2] (1939). A paper by Jin *et al.*[3] in *Physical Review Letters* has now addressed the question of whether the Lindemann and Born criteria predict the same melting temperature for an idealized crystal without surfaces. The new study, an international collaboration between China, Germany and the United States, is a highly sophisticated molecular-dynamics simulation, and shows that, as the crystal is 'heated', melting is triggered by instabilities governed simultaneously by the Lindemann and Born criteria.

Lindemann proposed that melting is caused by a vibrational instability in the crystal lattice when the root-mean-square displacement of the atoms reaches a critical fraction (δ_L) of the distance between them. Lindemann originally conceived δ_L as applying to the interior of the crystal , but in a later version it was applied to events at the surface, where the amplitude of atomic vibrations is larger than in the interior. Born, on the other hand, proposed that a 'rigidity catastrophe' occurs — caused by a vanishing elastic shear modulus — that determines the melting temperature within the bulk crystal. In other words, the crystal no longer has sufficient rigidity to withstand melting, so this process is often referred to as 'mechanical melting'. These two distinct theories have each accumulated an extensive literature.

It has been established experimentally that melting begins preferentially at a surface, and that superheating a crystal beyond the melting point set by the surface melting requires this process to be impeded. For example, coating the surface with a metallic layer that has a higher melting point can suppress surface melting[4] and retain the solid phase to bulk temperatures well above the equilibrium melting point, T_E. (This is the temperature at which both solid and liquid forms of a material can exist in thermodynamic equilibrium.)

Jin *et al.*[3] set out to discover whether the Lindemann and Born criteria yield the same answer when both are applied to the bulk instead of a surface — that is, in the case of superheating. The authors considered a molecular-dynamics simulation of an array of about 7,000 particles obeying Lennard–Jones interatomic forces, arranged on a face-centred cubic lattice, and heated using a step-by-step procedure. They also applied a set of three-dimensional boundary conditions to the simulation, which have the effect of making the surface of the crystal disappear. (This technique was pioneered in this context by Phillpot *et al.*[5], who showed that, in the absence of an effective surface, a simulated silicon crystal can be superheated by hundreds of kelvin to a point at which mechanical melting occurs.)

In their simulation, Jin *et al.* first examined the validity of the Born criterion. They found that the idealized crystal could be superheated by about 20% (in terms of absolute temperatures); melting occurred when the elastic shear modulus of the crystal lattice came very close to zero. Mechanical melting was identified by a sudden change in the atomic volume.

Jin *et al.* then checked the Lindemann criterion. At the normal equilibrium melting temperature, T_E, the Lindemann parameter δ_L averages 0.12–0.13, which is consistent with Lindemann's original value for melting in the crystal interior; but at the much higher temperature T_M, required for mechanical melting, $\delta_L \approx 0.22$. This value is almost 80% larger than the value at T_E, but is similar to previous values found for surface melting at the equilibrium melting point. So $\delta_L \approx 0.22$ clearly has physical significance in both bulk and surface melting.

The last stage of the analysis is the most original. As the authors point out, the ability of the molecular-dynamics procedure to track "the physical properties of the atoms not only as global averages but also locally"

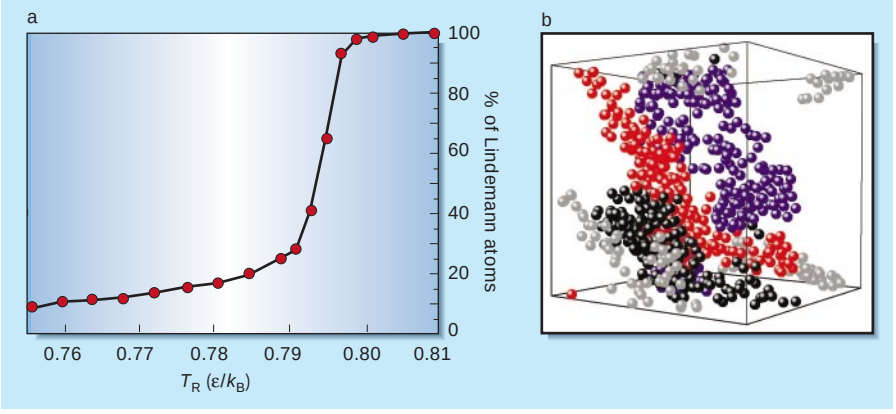

Figure 1 **Heating without melting.** a, **The computed percentage of 'Lindemann atoms' in a crystal as a function of reduced temperature, T_R. A Lindemann atom is one for which $\delta_L > 0.22$, where δ_L is the root-mean-square displacement of the atom divided by the interatomic distance. In their simulation, Jin *et al.*[3] show that the maximum temperature at which a crystal can be superheated (beyond its usual melting point, T_E) is $T_M = 0.79$. This is almost 20% higher than the normal equilibrium melting point ($T_E = 0.66$). (Reduced temperatures are given in units of ϵ/k_B, where ϵ is the depth of the potential well of the Lennard–Jones particles in the molecular-dynamics simulation, and k_B is the Boltzmann constant.)** b, **Snapshot of the positions of the Lindemann atoms in a three-dimensional idealized crystal without surfaces at $T_M = 0.79$. If the distance between a pair of Lindemann atoms is smaller than a critical value then they belong to the same cluster. In this region there are three large clusters with 219 (red), 214 (purple) and 187 (black) atoms. Jin *et al.*[3] suggest that these clusters play a similar role to crystal surfaces in initiating melting.**