the resistance R at temperature T is then cancelled by the feedback loop just as other error signals would be cancelled in a more conventional application. A current of heat flows from R to R_f and is dissipated there. Under operating conditions ($T >> T_f$), the heat current or cooling power is $\dot{q} = kT\Delta f$, where kT is the thermal energy of the electrons in R and Δf is the bandwidth of frequencies over which R and R_f communicate. Practically speaking, Δf cannot be much greater than 10 gigahertz (GHz), which means that $\dot{q}$ will not exceed 10^{-12} watts (W), and it is likely to be much smaller. The typical cooling powers from dilution refrigeration or demagnetization are orders of magnitude greater (in the microwatt range) but at concomitantly higher base temperatures[3].

To obtain the lowest electron temperatures, one must employ an amplifier with very low intrinsic noise in making R_f. The best candidate is the superconducting quantum interference device (SQUID) comprising a loop of superconducting material broken at two points by tunnel barriers, especially the double-interferometer or direct-current SQUID. The amplifier works by phase-locking the wavefunctions of 'Cooper' pairs of electrons (which are the basis of superconductivity) across the tunnel barriers. In this case the feedback circuit (operated typically at 4 K) is likely to limit the base effective noise temperature of R_f, but this is quite small in some amplifiers — as low as $T_f \leqslant 1$ μK (ref. 5) — and the fundamental limit is lower. The output noise from the feedback amplifier could be coupled (very weakly) to another SQUID and be read as an indicator of the electron temperature in the wire. The usefulness of the technique depends on surmounting the two design problems (which Price acknowledges) of reducing the heat flow into the sample below the cooling power of the refrigerator and of making a suitable coupling circuit between the passive resistor and R_f.

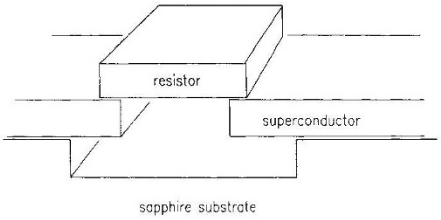


Fig. 2 A possible realization of the refrigerator that thermally isolates the resistor.

To imbed a thermally isolated resistor into the circuit, Price suggests the use of superconducting contacts. This might be accomplished as in Fig. 2 where the metal wire forms a bridge between the superconductors, which in turn are connected to the rest of the feedback refrigerator. The sapphire substrate is a strong enough thermal conductor to allow a conventional refrigerator to lower the temperature of the whole circuit into the millikelvin range. The feedback refrigerator would then have to surmount the heat leaks shown in Fig. 3. The greatest heat leak into the wire is through the thermal conductance of the superconductors, and at temperatures far below the 'energy gap' of the superconductor this leak is typically[3] (although not always[6]) quite small. At such temperatures, essentially all of the electrons in the superconductor are bound up in Cooper pairs that carry no heat at all.

The only remaining thermal conductance is through vibrations of the lattice (phonons) of the superconductor to the lattice of the wire, and then into the bath of normal electrons in the wire. Again the low temperatures reduce this drastically; the thermal conductivity of the phonons in the lattice falls as the cube of the temperature. The coupling of the energy from the phonons to the electrons in the metal also falls as a power law in the temperature. So overall, at very low temperatures, the electrons are likely to be largely decoupled from the lattice temperature (see Fig. 3).

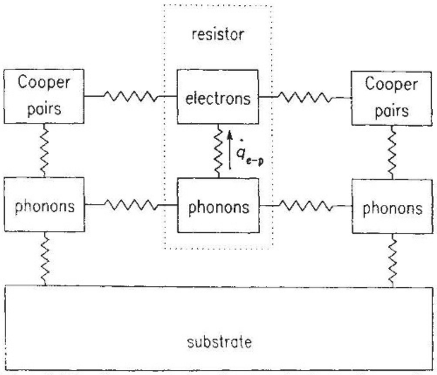


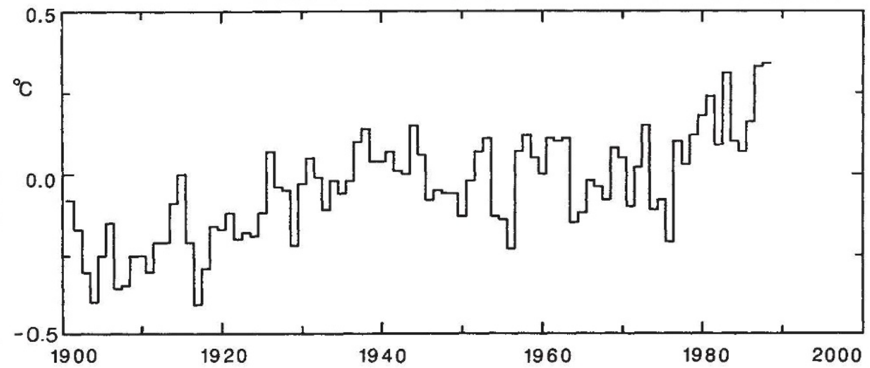
Fig. 3 The heat conduction paths into the resistor in Fig. 2. The circuit elements indicate thermal baths and thermal conductances among them. Measurements[7] indicate that the coupling between the electrons and the lattices is poor even at temperatures $\gtrsim 10$ mK. Typically the heat leak from the lattice to the electrons is $\dot{q} = \alpha V T^z$ (V, volume). Because the coupling strength α is rather small[7,8] and the exponent z is large (3–5; ref. 8), this heat leak should be small, so that cooling of the electrons separately from the lattice should be possible.

The problem of the coupling between the passive and active resistors is thorny. It must limit the bandwidth of frequencies between which R and R_f communicate to the range in which R_f exhibits low noise and is capable of cooling, but it must dissipate no energy. Any dissipation in the coupling is noise (increased temperature) that can be dissipated in R. The coupling must therefore comprise purely reactive elements linked by superconducting wires. This in turn causes further complications. The use of superconducting contacts requires that a magnetic field be applied to quench any proximity-effect superconductivity in the resistor. And the magnetic flux in the superconducting elements can lead to dissipation providing a further heat leak.

Assuming that the difficulties in the connecting circuitry can be overcome, Price shows that for reasonable values of resistor size and phonon temperature a conservatively specified direct-current SQUID (noise levels far in excess of the best yet obtained[5]) should be able to cool the electrons in, say, a thin copper film to less than 1 mK. For extreme design criteria, the base temperature might be orders of magnitude lower. ☐

1. Strutt, M.J.O. & van der Ziel, A. *Physica* **9**, 513–527 (1942).
2. Price, J.C. *Phys. Lett.* **134**A, 380–382 (1989).
3. Lounasmaa, O.V. *Experimental Principles and Methods below 1K* (Academic, London, 1974).
4. Richardson, R.C. & Smith, E.N. *Experimental Techniques In Condensed Matter Physics at Low Temperatures* (Addison Wesley, Menlo Park, 1988).
5. Awschalom, D.D. *et al. Appl. Phys. Lett.* **53**, 2108 (1988).
6. Sharma, J.K.N. *Cryogenics* **7**, 195–199 (1967).
7. Roukes, M.L. *et al. Phys. Rev. Lett.* **55**, 422–425 (1986).
8. Rammer, J. & Schmid, A. *Phys. Rev. B***34**, 1352 (1986).

Sean Washburn is at the IBM T.J. Watson Research Center, PO Box 218, Yorktown Heights, New York 10598, USA.



LAST year was the warmest year since records began. Global temperature records analysed at the UK Meteorological Office and the University of East Anglia show that the global average temperature for 1988 was 0.34 °C above the long-term (1950–1979) average and that eight of the nine warmest years this century have occured in the 1980s. Whether this apparent warming trend is a consequence of the 'greenhouse effect' is moot; as variations ranging from the daily changes in weather to the long-term glaciations show, global temperatures fluctuate considerably owing to natural causes. But the observed warming is consistent with model predictions of the greenhouse effect.

Philippa Lloyd