are turning up a number of wide binaries in regions of star formation (H. Zinnecker, University of Wurzburg). It is, however, the use of interferometric methods, sensitive to binaries of intermediate separations, that has so vastly expanded the roster of pre-main sequence binaries, particularly through near infrared-speckle and lunar-occultation techniques. (The use of the near infrared passband allows the detection of companions that are not yet optically visible, being still shrouded in their natal gas and dust). It is among these systems, with separations in the range ten to several hundred astronomical units (the Earth's orbit has a radius of one astronomical unit), that there would appear to be an excess of binaries compared with main-sequence counts, according to reports from three independent groups (A. Ghez, California Institute of Technology; C. Leinert, University of Heidelberg; M. Simon, State University of New York at Stony Brook). With the present sample sizes this result is significant only at the two sigma level. But if it persists in larger samples it poses a number of questions: either a large number of systems are being missed in main-sequence surveys or else many binaries in this separation range are somehow destroyed during their main-sequence lifetimes.

Whatever the outcome of this particular controversy, the discovery of so many pre-main-sequence binaries provides a welcome dataset against which theorists can test their pictures of binary star formation. For instead of having only to produce a correctly finished product, such models have now also to be checked against the appearance of binaries that are still in the late stages of formation — in which, for example, the remnant gas around the young binary can provide a clue as to the initial formation process. Thus numerical models, such as those of A. Boss (Carnegie Institute: see *Nature* **351,** 274; 298–300; 1991) and I. Bonnell (University of Montreal) have now to pass more stringent observational tests than ever before. And this can only hasten the arrival of a consensus about binary formation — and thus, implicitly, about all star formation. □

Cathie Clarke is in the Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK.

EVOLUTIONARY CHEMISTRY

Life in a test tube

Laurence D. Hurst and Richard Dawkins

How many lifes are there? How many lifes could there be? Not lives, lifes. We have experience of only one life, the one on this planet based on DNA as replicator and protein as executor. Is DNA the only molecule with the necessary qualifications? Are there others but vanishingly rare, such that the origin of a life in the Universe is a prodigiously lucky event? Or is there a profusion of alternative biochemistries waiting to be discovered? Work by a group led by Julius Rebek, described in a forthcoming paper[1] and in this week's *Science*[2], suggests that not only can relatively small molecules act as replicators but that it is quite realistic to consider whole otherworlds of chemical replicators.

Rebek's first test-tube replicator had two basic components[3] — an imide ester (which we will call molecule A) and an adenine-containing amine (molecule B). In a solvent the two molecules pair to form a third molecule (molecule C). It is this third molecule that acts as a replicator. Molecule C not only acts as a template on which A and B are guided by hydrogen bonds to line up, but also catalyses the covalent union between A and B. Two identical C molecules then become available to carry on the autocatalysis. Just as a laboratory population of bacteria exponentially grows until it runs out of resources, so growth of the population of C molecules describes the classic sigmoidal form.

As it stands, however, selection (and hence evolution) in this system is impossible as there are no variants. By the incorporation of a variety of B-type molecules which differ only in single side groups, the system can be modified to take account of this[4]. The resulting different C-type molecules have both differing replicating (autocatalytic) capabilities, as well as differing capabilities to catalyse the formation of non-like C-type molecules. A population of two rival variants of C molecules now exists in a state of competition. This variation had to be artificially created, but one of the new B types made the C molecules sensitive to ultraviolet radiation. Exposure to ultraviolet cleaves off part of the B subunit of C, producing a new C-type molecule. This new molecule not only replicates, it actually outcompetes the unmutated molecule and rapidly takes over the system's resources[4]. This then is a replicating system in which new variants are spontaneously generated, albeit in a rather limited fashion.

In their paper in press with *Journal of the American Chemical Society*[1], Rebek *et al.* describe a wholly different chemical replicator. This too has two subunits, D and E, which pair to form a new molecule, F. Like C, F can catalyse the synthesis of more F from D and E. Mutation in this system has yet to be described.

The next move was to attempt to make hybrids[2] and to investigate whether A with D or B with E would make a replicator. The team comment that "at first glance both recombinants might be expected to replicate. They both bear self-complementary recognition surfaces, and can gather their respective reaction components in termolecular complexes". Duly, one of the hybrids did replicate, and in no insignificant terms. It was in fact the most efficient replicator found to date. Conversely, the other was sterile. The difference between the two was simply a question of the orientations of the respective recognition surfaces. The successful hybrid had the recognition surfaces in parallel whereas the other hybrid was either C shaped or S shaped. In neither the C nor S form could the stable intermediate structure be formed.

What does this elegant system tell us about evolution and the origin of life? At the very least it shows that DNA and RNA are not the only possible replicators. However, Rebek's work might have another importance. Short of travelling the Galaxy, it is hard for us to know which features of life are particular, which general. We can surmise that some form of darwinian selection is universal for all lifes[5] but beyond that we cannot say what chemical properties would be necessary. Rebek's work allows us to approach the question of which chemical and structural aspects of replicators are necessary, and which are details. We can for instance start to ask whether some types of structures are inherently more or less likely to become replicators, and whether there are general properties of all of the chemical structures which can replicate. The new studies show that replicators need not be particularly large molecules and that simple replicators could have the potential to mutate. Life could have relatively modest beginnings. Similarly, the fact that the C- and S-form hybrid molecules were sterile is significant in that it goes some way to defining necessary structural characteristics which replicators must have. Furthermore, Rebek's chemicals and DNA share a number of properties: they are organic, use hydrogen bonding as structural information and covalent bonds to maintain structural integrity. But until we have a larger compendium of replicators we will not know if these are necessary characteristics or simply characteristics which happen to be shared by these two systems.

Although Rebek's system is unique in employing synthetic chemicals, analogous systems of replicating molecules have been set up using biological chemicals[6]. Whereas these biological replicators can be seen as attempts to understand what actually occurred at the origin of life, Rebek's system, like Thomas Ray's replicatory computer world[7,8], can be seen as a different, but parallel, replicating kingdom. Ray's work might best be thought of as being complementary to that of Rebek. Where Rebek's programme attempts to investigate the conditions necessary for the initial evolution of a life, Ray's replicating 'information sets' are defined with the ability to replicate and hence permit study of the consequences of mutation and selection in a population of simple replicators. The revealing aspect of Ray's work is that a diverse population can evolve from such an initial population of simple replicators. For instance, the tendency for parasites (replicators which use another's replicatory machinery) to invade and persist means that parasitism might be an unavoidable aspect of all lifes.

There might however be a fruitful connection between the two approaches. Just as we can ask whether particular types of 'information sets' differ in their evolutionary potential, so we can now ask whether different systems of chemical replicators differ in their capacity to evolve, and if so why. Where Rebek's system (and probably protein replicators[9,10] as well) falls short is that these replicators, unlike DNA, do not encode much information. This must surely limit their evolutionary potential. But it is probable that in early evolution DNA (or whatever the early replicator was) didn't encode much information either. Could strings of Rebek-type chemicals evolve to encode more than their own replication? If so, would we want to think of this as a life in a test tube? □

Laurence D. Hurst and Richard Dawkins are in the Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK.

1. Park, T. K., Feng, Q. & Rebek, J., Jr *J. Am. chem. Soc.* (in the press).
2. Feng, Q., Park, T. K. & Rebek, J., Jr *Science* **254**, 1179–1180 (1992).
3. Nowick, J., Feng, Q., Tijivikua, T., Ballester, P. & Rebek, J., Jr *J. Am. chem. Soc.* **113**, 8831–8839 (1991).
4. Hong, J.-I., Feng, Q., Rotello, V. & Rebek, J., Jr *Science* **255**, 848–850 (1992).
5. Dawkins, R. *The Selfish Gene* (Oxford University Press, 1989).
6. Zielinski, W. S. & Orgel, L. E. *Nature* **327**, 346–347 (1987).
7. Ray, T. S. in *Artificial Life II*, Santa Fe Inst. Studies in the Sciences of Complexity, Vol XI (eds Langton, C. G., Taylor, C., Farmer, J. D. & Rasmussen, S.) 371–408 (Addison-Wesley, Redwood City, California, 1991).
8. Maynard Smith, J. *Nature* **355**, 772–773 (1992).
9. Hurst, L. D. & Haig, D. *Nature* **351**, 21 (1991).
10. Cheng, M. Y., Hartl, F.-U. & Horwich, A. L. *Nature* **348**, 455–458 (1990).

ELECTRONICS

Single atoms as transistors

Sean Washburn

As the drive to gigabit computer memory chips accelerates, requiring smaller and smaller transistors, one might ask what the limits are to making transistors smaller. Recent experiments indicate that the limit might be reached only at the level of single atoms. Three independent groups of researchers now show[1–3] that electrical current can be controlled by the configuration of an individual atom's quantum-mechanical state and that the state itself can be switched on and off.

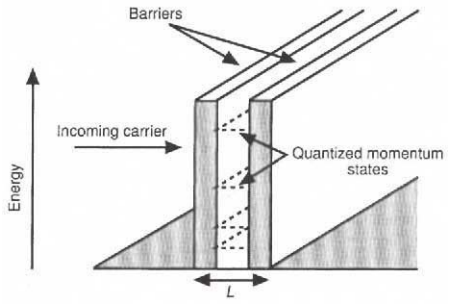

FIG. 1 Resonance tunnelling: a pair of barriers separate off a slice of semiconductor, a quantum well, inside which only discrete momentum states (broken lines) are possible. Charge carriers impinging from the left will be reflected unless their momentum is aligned with one of the allowed states in the well. Carriers in the well are free to move parallel to the plane.

The transistor of Dellow *et al.*[1], from the Universities of Nottingham and Glasgow, is based on the process of resonant tunnelling, which has been used for many years[4], but never on so small a scale. Current through such a device is controlled by the existence of discrete quantum levels in a thin confined layer through which it must pass, whose energies can be adjusted externally (Fig. 1). Charge carriers entering from one side of the device cannot be transported across the barriers unless one of these levels in the quantum is tuned into resonance with the carriers' energy. To attain the quantum-well states, it is not necessary to restrict the charge-carriers' motion in all three directions. It is sufficient for the barriers to confine the motion along only the current direction on a scale of length which is short compared with the carriers' characteristic lengths, such as the wavelengths of their wavefunctions (a few nanometres in the GaAs semiconductor used by Dellow *et al.*[1]).

So earlier work on resonant tunnelling concentrated on planar systems with motion free in the plane but confined across it[5], or on tunnelling through localized carrier states in disordered insulators[6]. If the motion is confined along other directions, the quantum effects can be more dramatic[7]. This drama occurs when the size w of the tunnelling region (Fig. 2*a*) is also comparable with the important characteristic length. Dellow *et al.* have used a constricting ring to squeeze the tunnelling area down to less than 0.1 μm^2, inside which only a few donor atoms are active. The conduction region is schematically drawn in Fig. 2*a*, which shows that the carriers are confined to flow from the top through a small port of dimension w containing the two tunnel barriers to the bottom. Depending on the voltage settings on the transistor, most of the carriers are funnelled through only a single donor. By changing the voltage settings, the authors can cause the carriers to flow through one or another of the donors or study the voltage dependence of the donors' states. As the donors move through the resonance, peaks appear in the transistor's current–voltage curve. The peaks mark the energy spectrum of the donors.

Gregory, of Bellcore, has also studied tunnelling of electrons through a single atom between two wires that nearly touch[2]. His ingenious technique is to bring the two thin tungsten wires very close to each other magnetically, by passing a current through one in an applied field, and to cement them in place with the van der Waals forces between helium atoms adsorbed onto their surfaces. In such a configuration, the electrons tunnel from wire to wire preferentially through the nearest two points (as the tunnelling probability is exponentially smaller elsewhere). Again, a single impurity atom can be the funnel point, just as a particular donor was in the device of Dellow *et al.* (Fig. 2*b*).

Gregory used this technique to study tunnelling through magnetic impurities. Sometimes there is a magnetic inclusion in the asperity where tunnelling occurs. This leaves a specific signature in the current–voltage curve, and, because the interaction with the carriers is magnetic, the signature can be altered by a magnetic field. The signature is a 'zero-bias-anomaly' similar to those studied for several decades[8,9]. Tunnelling experi-

Correction

It has been pointed out that increased error estimates, mentioned in a Résumé item (*Nature* **356**, 288; 1992) on the latest γ-ray burster statistics from the Compton Gamma Ray Observatory, are attributable to the inclusion of an estimate of the positional uncertainty in burst locations, and do not indicate deteriorating results.