saltatory locomotion in the adult but also provides space for reproductive organs. Because of the extreme morphological differences between the tadpole and the frog, anuran species that retain a larval stage are mechanically obligated to metamorphose.

Both ecologically and morphologically, a paedogenetic tadpole is evolutionarily implausible. Presumably, in jointly perfecting the suspension-feeding, herbivorous tadpole and the saltatory, carnivorous frog, canalization has made the paedogenetic tadpole genetically unlikely.

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Wassersug raises the obvious and interesting question why there are no paedogenetic anurans. We chose to restrict our discussion to models useful in explaining the observed diversity of amphibian life cycles. Wassersug attempts to define the limits of diversity possible for anuran evolution, a far more ambitious task. I do not believe it is possible to determine the limits of evolutionary change, except for restrictions imposed by the laws of the physical sciences. The essence of evolution is the attainment of the intuitively improbable; consider the remarkable convergence in function yet difference in phylogeny of the vertebrate and cephalopod eyes. Haldane once commented that the universe is not only queerer than we suppose, but queerer than we can suppose.

Wassersug seeks an answer to his question in morphological arguments. Although it may not be easy to visualize how maturation of the gonads might be completed in the larval state, elongation of the ilial bars or morphological specializations for suspension feeding can hardly be constraints on the evolutionary possibilities for anurans. Sex differentiation occurs before metamorphosis and the gonads begin to develop within the body cavity of the growing tadpole (*1*).

The fossil record does not add insights. The earliest known frogs are from the Jurassic and, except for having ribs, are not very different morphologically from modern frogs of the families Ascaphidae and Discoglossidae. Estes and Reig (*2*) point out that elongation of the ilium and tarsal elements are present in several primitive Paleozoic amphibians as an adaptation for swimming and are only incidentally a preadaptation for saltation. *Triadobatrachus* from the Early Triassic of Madagascar is the only clue to the possible proanuran condition. This form has a tail and elongate hind limb elements. It presumably was an aquatic form and the fossil specimen is probably a young animal, but it is difficult to ascertain if it had a metamorphosis as complete as in later anurans.

Clearly frogs have been committed for a long time to a complex life cycle in which temporary aquatic habitats are exploited by a larval form specialized for rapid growth. Some anuran lines have shortened the larval stage as an adaptation to terrestriality and have direct development. Other lines have become aquatic, not by becoming paedogenetic but by retaining the adult form, which is a very suitable design for the aquatic mode of living. Paedogenetic frogs as well as viviparous turtles and birds are perhaps evolutionary possibilities but ecological impracticalities.

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## A Chondrule: Evidence of Energetic Impact Unlikely

Lange and Larimer (*1*) conclude that the morphology and mineralogy of an unusual chondrule from the Ngawi meteorite are the results of a highly energetic impact within the solar nebula. Enclosed within the chondrule's fragmented olivine crust is an embedded magnetite grain which, according to their calculations, impacted with a velocity between 1 and 10 km/sec. The lower and upper velocity limits are determined by the possible range of chondrule temperatures at the time of impact and the melting temperature of glass and sulfide.

The evidence given for an energetic collision is inconsistent with laboratory impact data. In an experiment simulating the destruction in space of tektites by micrometeoroid impact, Gault and Wedekind (*2*) found that 1 joule/g of projectile kinetic energy per unit mass of a spherical target completely ruptures the sphere and less than 0.1 joule/g results in a crater. Spallation, caused by the reflection of shock waves from the surface, generates about as much damage in the antipodal region as around the impact site on the sphere. From the values given for the mass ratio of the magnetite grain to the remainder of the chondrule of 1/50 and the calculated range of impact velocities of 1 to 10 km/sec (*1*), the kinetic energy per unit mass values are 10 to 1000 joule/g, far in excess of the amount required to completely disintegrate the chondrule. Moreover, for the upper limit, complete melting of the magnetite grain would occur. Even if it had not shattered, there are no fractures about the magnetite grain or near the opposite surface that are characteristic of the spallation process. A velocity of 0.1 km/sec would correspond to the kinetic energy per unit mass required for cratering. Although this velocity is below the experimental range of velocities, noticeable damage should still occur. Lange and Larimer propose a cushioning effect by the outer layer of the chondrule as a mechanism to preserve the chondrule from shattering. Experiments on a centimeter scale (*3*) and micrometer scale (*4*) show that thin, less cohesive layers attenuate the effects on a massive substrate but that the protective layer is cleared away over an area large relative to the projectile size. Vedder (*4*) has also shown that an irregular pit forms in a substrate covered by a layer comparable in thickness to the projectile diameter. The attenuation of the effects on the substrate is small in this case. In contrast, the chondrule's crust covers the magnetite grain; and the contact surface under the grain appears smooth. An energetic impact would remove most of the crust and would drive some of it into the chondrule.

Another common fallacy, found here and perhaps permissible in order-of-magnitude calculations, is that of equating the projectile kinetic energy to the heat generated by impact (*5*). Calculations supported by experimental results show that less than 25 percent of the projectile kinetic energy is converted into heat in the target for iron or aluminum projectiles impacting basalt (*6*). The energy partition should be little different for the chondrule and would more than double the velocities calculated by Lange and Larimer (*1*) for melting.

We do not believe that this chondrule shows evidence of high relative velocities in the solar nebula. Furthermore, arguments against chondrule production by impact on planetary surfaces on the basis of ejection velocities (*7*) are not supported by laboratory experiments, since spherules are found within the debris in craters (*6*) and must have had negligible velocities to remain in place.

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There are numerous features in the chondrule found in the Ngawi meteorite that seem to indicate a highly energetic collision. They include the following: extensive fractures in the chondrule; granulation of the olivine rim, particularly in the pronounced bulge over the magnetite grain; and extensive melting coupled with reorientation of the olivine bars immediately beneath the grain (*1*). Vedder and Gault (*2*) offer no explanation for these features. Instead they argue that the impact velocity estimated is too high and that certain other features characteristic of shock damage are not observed.

We estimated the relative velocity of the two freely moving particles by merely assuming conservation of energy and momentum; any heat produced is equivalent to the difference between the kinetic energy before and after impact. Since both the composition and the physical properties of the two particles are known reasonably well, the calculation is straightforward. Of the reported impact experiments, those of Gault and Wedekind (*3*) seemed to most closely simulate such a system. But there are so many dissimilarities that we were, and still are, reluctant to draw direct comparisons. In these experiments, targets of homogeneous strained or unstrained silica-rich glass, 10 cm in diameter, held stationary, were impacted with Pyrex and aluminum projectiles. Clearly, the scale, physics, chemistry, and physical properties do not resemble the characteristics of the proposed collision between chondrule and magnetite grain. Furthermore, the experimental results are not without ambiguity. Of ten or so experiments in which the projectile kinetic energy per unit mass of target approximated 1 joule/g, two, or about 20 percent, of the targets did not rupture completely. Interestingly, Gault and Wedekind attributed this effect to the use of carefully annealed glass targets, and hence the materials in these experiments may more closely resemble a mixture of crystals and glass than any of the others. Gault and Wedekind also point out that collisions at high angles significantly lessen damage. The angular relationship between chondrule and magnetite grain at the time of impact is completely unknown.

With regard to this last point, it should be recalled that the chondrule was found in a thin section which limits observations to two dimensions. Lacking a three-dimensional view, one cannot know the extent of spallation, the size or any other characteristic of the crater, the direction of the antipodal region, or how much damage or mass loss occurred there. Moreover, there are no apparent features in the small amount of magnetite remaining that rule out partial or complete melting; in fact, it may have partially vaporized. All of these features pointed out by Vedder and Gault should certainly be sought in future studies of chondrules and chondrule fragments.

The last point raised by Vedder and Gault, that chondrules could be produced on planetary surfaces during cratering events, is arguable. It cannot be disputed that chondrule-like spherules are associated with both natural and experimental craters. In both cases, however, the amount of such material is negligible, as is to be expected from simple calculations (*4*). This negligible amount of material in no way corresponds to chondritic meteorites where chondrules commonly comprise more than 70 percent of the mass.

Finally, I cannot resist mentioning that other chondrules bearing characteristics very similar to those of the Ngawi chondrule have now been found (*5*). Experiments such as those discussed by Vedder and Gault (*2*) will be useful in delimiting the physical conditions under which all these objects formed.

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