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PERSPECTIVES: EVOLUTION

# Molecular Origin of Species

### Masatoshi Nei and Jianzhi Zhang

In sexually reproducing organisms, new species originate when a reproductive barrier is established between different groups of organisms. This event, called speciation, is one of the most important biological processes, yet its mechanism remains largely unknown. Reproductive isolation between species can occur either before or after the formation of hybrid zygotes (1). In prezygotic isolation, mating or fertilization is prevented, whereas postzygotic isolation occurs by the sterility or inviability of the hybrid offspring.

The first step in understanding the mechanism of speciation is to identify the genes involved in speciation and to study their effects on molecular aspects of mating or development. Two research groups, one led by Vacquier (2) and the other by Wu (3) (page 1501 of this issue), did just this for prezygotic and postzygotic isolation, respectively. Previously, Vacquier and colleagues had shown that in abalone the fertilization of eggs by sperm is mediated by lysin, a protein that species specifically creates a hole in the egg envelope, and that in evolution this protein undergoes rapid amino acid substitution—apparently as a result of positive Darwinian selection (4). Swanson and Vacquier (2) have now cloned the egg receptor gene for lysin and shown that the receptor protein consists of about 28 repeats of a 153–amino acid sequence motif. The repeat sequences vary among species but are similar within species, apparently because of concerted evolution, which homogenizes the repeat sequences through unequal crossing over or gene conversion.

For many decades, fruitflies (*Drosophila* species) have been favorite organisms for studying speciation, and Wu and his colleagues have now used this organism to clone and characterize a gene involved in speciation. They used a genetic technique to narrow down the chromosomal location of a gene that causes the sterility of male hybrids between *Drosophila mauritiana* and *Drosophila simulans* and cloned it. They found a gene (*OdsH*) containing a 60-codon homeobox that is homologous to the paired-type subfamily of homeobox genes from mice, rats, and nematodes. The real function of this gene is unknown, but

it is likely to control the transcription of a target gene that participates in spermiogenesis.

This homeobox gene has evolved surprisingly rapidly among the four sibling species of *Drosophila* (*mauritiana, simulans, sechellia,* and *melanogaster*), but it is highly conserved in other evolutionary lineages. The extent of sequence divergence among the homeoboxes of the four sibling species is much greater than that between
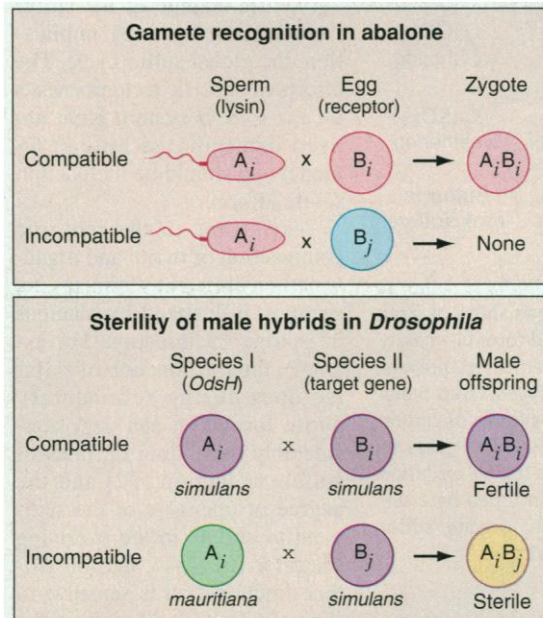


**Making new species, two ways. (Top)** In this example of prezygotic isolation, fertilization is determined by the compatibility of allelic sequences at the lysin and the egg receptor loci (2). (**Bottom**) In postzygotic isolation, the sterility of male hybrids is determined by the compatibility of allelic sequences at the *OdsH* and its target gene loci (3). $A_i$ and $B_i$ are the $i^{th}$ alleles at loci A and B, respectively. The target gene in *Drosophila* has not been identified.

the rodent and nematode homeoboxes. Because the rodent and nematode homeobox homologs are expressed in neural tissue whereas *OdsH* is expressed in the testis, *OdsH* seems to have acquired a new function in spermiogenesis. The rapid evolution of *OdsH* appears to be due to this acquisition of a new function.

At first glance, these two studies of the molecular mechanisms of speciation might look unrelated, but in fact they show that the two different phases of speciation apparently have a similar genetic basis. In abalone the fertilization of eggs by sperm occurs only when the lysin and the receptor sequences are compatible (see the figure,

top panel). Similarly, the male offspring from a mating in *Drosophila* are fertile only when the sequences of *OdsH* and its target genes are compatible (see the figure, lower panel). In general, reproductive isolation between different species appears to be caused by the incompatibility of alleles at two or more loci that control mating, spermiogenesis, and development. The new findings in abalone and *Drosophila*, as well as a similar finding about the genes controlling the binding of sperm to eggs in sea urchins (5, 6), are consistent with this view.

If reproductive isolation is caused by the incompatibility of multiple alleles at different loci, what is the evolutionary mechanism of reproductive isolation? This is a difficult question to answer. Suppose that an abalone species has alleles $A_i$ and $B_i$ at the lysin and the receptor loci, respectively, and a new lysin mutation, $A_{i+1}$, appears in a population. If this mutant allele is incompatible with the receptor allele $B_i$, it will never be fixed in the population. Theoretically, it is possible that $B_i$ also mutates to $B_{i+1}$ in the same population so that $A_{i+1}$ and $B_{i+1}$ become compatible. However, the chance of the $A_{i+1}$ sperm meeting with the $B_{i+1}$ egg would be vanishingly small in a large population. One way to avoid this problem is to assume that there are intermediate alleles between $A_i$ and $A_{i+1}$ (or $B_i$ and $B_{i+1}$) and that these alleles are compatible either with $B_i$ or $B_{i+1}$ (or $A_i$ and $A_{i+1}$). Mathematical models based on this idea indicate that the evolution of reproductive isolation can be developed by the incompatibility of multi-allelic loci (7). Some of the empirical observations (5) are compatible with this model.

The results from abalone, however, are not easy to explain with this model. In this organism the rate of amino acid substitution in lysin is about four times higher than that in the egg receptor. Swanson and Vacquier (2) suggest that the accelerated substitution in lysin is driven by concerted evolution. But concerted evolution is merely a process of homogenizing repeat sequences and cannot enhance the evolutionary rate of lysin. Theoretically, it is possible to modify the model proposed in (7) to enhance the evolutionary rate of locus A (lysin) by considering sperm competition, but this will also enhance the evolutionary rate of locus B (egg receptor). Because the egg receptor has evolved much slower than lysin, additional factors must be

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involved. One possibility is that to attain optimal binding between lysin and the receptor several amino acid changes are required in lysin when one change occurs in the receptor. This problem will probably be resolved if the three-dimensional structure of the egg receptor is clarified.

The molecular study of speciation has just begun. Although it has given us a glimpse into the complex nature of gene interactions in the evolution of reproductive isolation, most problems remain untouched (8). As molecular biologists foray into this area, more surprising properties of gene interactions may be revealed.

### References
1. T. Dobzhansky, Genetics and the Origin of Species (Columbia Univ. Press, New York, 1937).
2. W. J. Swanson and V. D. Vacquier, Science 281, 710 (1998).
3. C.-T. Ting, S.-C. Tsaur, M.-L. Wu, C.-I Wu, ibid. 282, 1501 (1998).
4. Y.-H. Lee and V. D. Vacquier, Biol. Bull. 182, 97 (1992).
5. E. C. Metz and S. R. Palumbi, Mol. Biol. Evol. 13, 397 (1996).
6. R. A. Cameron, T. S. Walkup, K. Rood, J. G. Moore, E. H. Davidson, Dev. Biol. 180, 348 (1996).
7. M. Nei, T. Maruyama, C.-I Wu, Genetics 103, 557 (1983).
8. V. D. Vacquier, Science 281, 1995 (1998).

## PERSPECTIVES: QUANTUM DOTS

# Controlling Artificial Atoms

François H. Julien and Antigoni Alexandrou

Semiconductor quantum dots are fascinating objects. They contain up to a few hundred thousand atoms yet behave in many ways like one single gigantic atom. Their unique optical and transport properties are just being explored, but they already offer great promise for the development of extremely low threshold laser diodes, single-electron logic devices, or optical computing quantum units. As reported on page 1473 of this issue, Bonadeo et al. (1) have now achieved a remarkable degree of control of the quantum states of individual "artificial atoms."

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Quantum dots can be fabricated by colloidal chemistry techniques; by patterning, etching, electrostatic confinement, or monolayer fluctuations in thin semiconductor layers; and by controlling self-ordering mechanisms during epitaxial growth of strained semiconductor films (2). Although much progress has been made toward achieving large densities of uniform dots, the size fluctuations usually lead to an inhomogeneous broadening of the spectral features when observations are performed on an ensemble of dots. Some optical or transport properties associated with a single quantum dot have been reported by the use of nanoluminescence techniques or by fabricating single-electron transistors. This includes observations of extremely sharp luminescence lines (3), Coulomb-blockade effects in the one-by-one electron charging of the dots (4), or the Kondo effect (5). Bonadeo et al. (1) have achieved even deeper insight into the atomlike nature of semiconductor quantum dots by demonstrating

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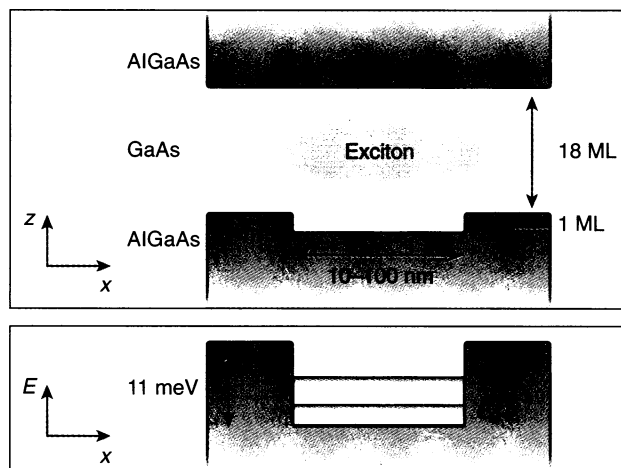
the manipulation of the confined state wave functions of a single dot.

The quantum dots investigated in their study are formed by thickness fluctuations in a quantum well made of a thin layer of GaAs embedded in AlGaAs (6). If the quantum well is sufficiently thin (10 nm or less), a single monolayer increase of the well thickness causes large changes in confinement energy, and excitons can be local-



**Artificial atom. (Top)** A schematic diagram of a semiconductor quantum dot formed by a one-monolayer (ML)–high island in a narrow GaAs quantum well. **(Bottom)** The resulting energy diagram of the dot. Excitons are formed by the Coulombic interaction between one electron and one hole. They are analogous to a gigantic hydrogenic system with spatial extension on the order of tens of nanometers. One exciton can be trapped in the dot by the lateral confinement potential created by the monolayer-high island.

ized in the three directions of space instead of just one in a perfectly flat interface quantum well. The formation of single-monolayer–high islands with lateral dimensions of 10 to 100 nm is achieved through epitaxial growth interruption by allowing surface migration of the atoms to their lower energy position at island edges. The size and shape are not really controlled, but the islands tend to be elongated and aligned along the [$\bar{1}$10] crystal axis. The interface quality is excellent, and extremely sharp lines have

been observed by exciting and detecting the dot luminescence through micrometer-sized apertures in an aluminum mask. This masking technique allows selection of a few quantum dots within the broad distribution of dots. By combining spatial and spectral resolutions, it becomes possible to excite and probe only one individual quantum dot.

Bonadeo et al. (1) used a sequence of two laser pulses with a stabilized phase difference to coherently control the excitation state of these quantum dots. The interaction of light with a semiconductor creates a polarization in the material with a phase related to the phase of the exciting laser field. As long as this phase relation is preserved, the system is referred to as coherent. If a second pulse arrives with a well-defined phase difference (that is, a time delay $\tau$) with respect to the first pulse, it generates a polarization that will interfere with the polarization created by the first pulse. Controlling the phase difference between the two pulses results in control of the interference between the two polarizations and thus control of the excitation state (namely, the wave function) of the system, hence the term coherent control. Although coherent control was first implemented in atomic and molecular physics, its application in semiconductor physics is very promising. A very simple demonstration of coherent control involving a single pulse was provided by the emission of terahertz (7) and midinfrared (8) radiation from semiconductor quantum wells: A broadband femtosecond pulse creates a coherent superposition of two states that results in a coherent charge oscillation emitting radiation at the difference fre-