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RESEARCH ARTICLE

Hemoglobin Allostery: Resonance Raman Spectroscopy of Kinetic Intermediates 1843
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TECHNICAL COMMENTS

Honeybees and Magnetoreception H. Nichol and M. Locke; J. L. Kirschvink and M. M. Walker; M. H. Nesson; C.-Y. Hsu and C.-W. Li 1888
A Dynamite way to get your data:

Protein-Protein/DNA/RNA interactions
Cooperative Protein-DNA binding studies
DNA-Protein complex formation, immunoprecipitation

Protein-RNA binding assays

DNA binding

Protein-protein interaction, Mapping protein binding sites

Fusion protein binding assays

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Screening for translation-terminating mutations in MDS

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Science in the Stationary Phase

Much of what we know about the mechanisms of catalysis and the regulation of biochemical processes has been learned from study of the growth and survival of microbes. After an interval of rapid growth, microbial cultures respond to impending stringencies in the environment. They sense that the feasting is over and that a major reordering of priorities is needed to survive in what is called the stationary phase. Hundreds of genes are turned on and off, which, along with adaptive mutations, ensures the survival of the colony during the stationary phase and the colony's reemergence under more favorable conditions. What we learn from microbes in the stationary phase will, it seems to me, have profound significance for how we as scientists cope with diminished support for science.

Modern science began in Europe about 300 years ago. As shown in a graph prepared by David Goodstein of the California Institute of Technology, the growth of science (as measured by the number of scientific journals) has been exponential, expanding by a factor of 10 every 50 years. If continued, this trend would extrapolate to 1 million journals by the year 2000, but fortunately it has tapered off to a mere 40,000. However, in the past decade, as more drastic reductions in support for the research enterprise have been made, U.S. science has entered a stationary phase. With sufficient effort, we may produce brief bursts of growth here or there, as microbial cultures do. But to ensure the continued survival of science, we must be resourceful in adapting to the stringencies of the stationary phase.

In the biomedical sciences, we have become increasingly vulnerable to the prospect of severe cuts in federal support. We must not let anyone be deluded into thinking that these cuts will be replaced to any significant extent by private and industrial sources of funding. In the period after World War II, over 90% of the support for the revolutionary advances made in the biomedical sciences came from the National Institutes of Health (NIH). No industrial organization would have invested or ever will invest millions of dollars annually, for decades, in projects that have no direct relevance to marketable products.

We are urged: Do strategic basic research! Do targeted basic research! How can we make clear the oxymoronic nature of these terms? It may seem impractical even to scientists to solve an urgent problem, such as developing treatment for a disease, by pursuing apparently unrelated questions in basic biology or chemistry. Yet it is a fact that throughout the history of medical science the pursuit of basic research has been the most practical and cost-effective route to the development of successful drugs and devices. Investigations that seemed irrelevant to the attainment of any practical objective have yielded most of the major discoveries of medicine. For example, x-rays were discovered by a physicist observing discharges in vacuum tubes; penicillin was isolated during enzyme studies of bacterial lysis; and genetic engineering and recombinant DNA were developed from the study of reagents used to explore DNA biochemistry.

As scientists, we lack the skills to make our case effectively. Universities, research foundations, professional societies, and pharmaceutical companies should band together to organize their resources and employ media professionals to convert to citizens and legislators the essential message that basic research is the linchpin of medicine. If the National Rifle Association can be so effective in delivering its message, why can't we do at least as well with a far better one?

In the face of so much uncertainty, would I recommend a career in science to my grandchildren? Emphatically yes! Science is unique among all human activities—unlike law, business, art, or religion—in its identification with progress. Regarding the means to do science, I think back to 1943 when I was studying rat nutrition at NIH and decided that research was more attractive than the clinical medicine I had chosen as a career. There were no grants then, laboratory resources were meager, and academic jobs were almost nonexistent. Those were not the good old days. But rich or poor, science is great! To frame a question and arrive at an answer that opens a window to yet another question, and to do this in the company of like-minded people with whom one can share the thrill of unanticipated and extended vistas, is what science is all about. That is what we must sustain in us and the days ahead.

Arthur Kornberg

The author is in the Department of Biochemistry at the Stanford University Medical Center, Stanford, CA.
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Multiple-Use Physics Facilities

The article “Could defense accelerator be a windfall for science?” by Jonathan Weisman (News & Comment, 18 Aug., p. 914), raises an important issue about multiple-use facilities, given their attraction during constrained budget times. Whether or not it is practical to use an Accelerator Production of Tritium (APT) plant both for tritium production for the nuclear weapons stockpile and for neutron beam research is a complex issue that requires careful analysis of the technical, operational, and end user issues.

At present, neither the defense nor the research community believes that its needs can be met if it is forced to coexist with the other. We at Los Alamos believe that there are areas of research and development (R&D) that could be pursued jointly, but currently we are skeptical about a multiple-use facility because of the different operating modes and the tight APT schedule proposed to meet present tritium production requirements.

As Los Alamos APT project leader Paul Lisowski is quoted as saying in the article, accelerator beam power would be adequate both for tritium production and for the neutron beam research if the present tritium supply requirements were significantly reduced. Whether or not the Administration or Congress will settle on a multiple-use facility will depend on an objective analysis of all the pros and cons. We believe that both communities owe the country their best judgment to resolve this question.

A related issue is raised in the article regarding whether defense research (rather than defense production) and basic research can be performed at the same facility. We believe that this issue is less contentious, particularly when the primary purpose of the facility (neutron beam research) is common.

We agree that the performance of the Manuel Lujan Jr. Neutron Scattering Center (MLNSC) at Los Alamos National Laboratory's Neutron Science Center (LANSCE) accelerator facility did not meet user expectations in past years in terms of overall availability. However, in our view, the problems had little to do with the fact that LANSCE engages in both defense research and basic research that uses pulsed neutrons. The problems we encountered at the MLNSC resulted more from the fact that it was an auxiliary activity at the Los Alamos Meson Physics Facility (LAMPF), whose primary mission was nuclear physics, and thus the MLNSC did not enjoy the same priority or amount of resources. LAMPF users, who numbered about 1000 at LAMPF's peak, were apparently happy with the reliability that was provided.

The upshot of this arrangement was predictable—the availability and performance of the MLNSC suffered. This problem paralleled the one suffered by the Stanford Synchrotron Radiation Laboratory when it was an add-on to the Stanford Linear Accelerator. It has little to do with defense research and everything to do with prioritization, planning, and resources. Accelerator research facilities can be designed to provide reliable beams to multiple users, provided the user community is involved early in the planning, operational priorities are properly assigned, and resources are adequate. The European Organization for Nuclear Research (CERN) has successfully demonstrated this type of operation.

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Roger Pynn
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Los Alamos, NM 87544, USA

We would like to remark on the article of Daniel Clery and Andrew Lawler (News & Comment, 17 Feb., p. 952), on that of Weisman, and on the letters of J. Michael Rowe and Louis Ianniello (21 Apr., pp. 349–350). With regard to the dual use of an accelerat-
tor facility for production of tritium, we believe it is unwise to combine neutron scattering capabilities with tritium production functions because such a facility would be costly to run. If the stockpile of tritium-bearing nuclear weapons were to be reduced faster than tritium decays (it has a half-life of 12.3 years), then the need for replacing tritium in the stockpile would disappear. Support of the installation for tritium production would disappear, and the research community would inherit an installation that by present standards would be unaffordable to operate. It also remains unestablished whether tritium producers (which only need volumes of neutrons) and neutron beam sources (which must be compact and, for time-of-flight applications, pulsed) can realistically and productively be fitted together.

Concerning a 5-megawatt pulsed spallation source (30 times the power of ISIS in the United Kingdom) most knowledgeable people believe that it can eventually be done. The Kohn panel (I) noted that if the Advanced Neutron Source (ANS) were not built, a 5-megawatt pulsed source would be needed. However, no one has yet clearly seen a particularly good way of accomplishing the 5-megawatt source or estimated what its cost might be, and it will take considerable time to work these problems out. Meanwhile, feasible concepts for a 1-megawatt, short-pulse source, the most versatile type, have already been developed and documented, with defensible estimates of costs and schedules. Such a source would exceed the capabilities of ISIS by a factor of six and in many ways exceed those of the Institute Laue-Langevin and cost about 25% as much as ANS. Proposals that a smaller source be built so as to be upgradable to 5 megawatts are attractive in principle but weak because the vision of the 5-megawatt upgrade is so dim. Moreover, the 30-fold jump, when existing experience already reveals engineering problems, calls for an intermediate step. It gives one pause to recall the many steps that lay between the Wright Flyer and the Concorde, which flies about 30 times faster.

Rowe properly calls attention to the upgrade of neutron facilities at the National Institute of Standards and Technology (NIST), which Clery and Lawler did not acknowledge. Great credit is due the NIST team for their accomplishment. But such upgrades represent at best a catching-up to the versatility and performance of the best reactor instruments, and not new capabilities on a world scale.

Ianniello observes that techniques other than neutron beam methods represent alternative ways to perform cutting-edge research. Yes, to some extent, but leaving off or putting off the neutron option surely means foregoing access to a hugely important range of information. So far, whatever shadow the new photon sources may cast on the fields where neutrons now hold sway is narrow; what more may yet be overshadowed is conjectural and the list is not exhaustive. Committees fully acknowledging the prospects for the photon sources endorse the construction of new, more powerful neutron sources because of their broad-ranging and still unique capabilities. The U.S. scientific community has waited a long time for a much-needed new, more powerful neutron source. A 1-megawatt pulsed source can be built now.

John M. Carpenter
Intense Pulsed Neutron Source, Argonne National Laboratory, Argonne, IL 60439-4814, USA
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References and Notes

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I am concerned about a comment attributed by Weisman to Walter Kohn to the effect that the experience of LANSCE shows that dual use of a major accelerator is not feasible. My own experience, as director of LAMPF from its beginning until 1985, is quite the opposite. We found multiple use to be efficient, stimulating, and cost effective. We often operated more than 10 channels simultaneously, with negligible interference, even with the weapons neutron research facility, which received all the beam it could use, as does LANSCE today. Design and scheduling conflicts that Kohn mentions did not materialize.

The only requirement, as far as I can see, is that the operators and researchers (many hundreds from scores of institutions, in the case of LAMPF) be motivated, competent, and reasonable, and that management be enthusiastic about incorporating user needs and advice in the decision-making process.

At the moment, LAMPF is providing high-quality, high-intensity beam to LANSCE without interference from other experiments. One hopes that the neutron scattering community will take full advantage of the capabilities already available.

**Louis Rosen**  
Los Alamos National Laboratory,  
Los Alamos, NM 87544, USA

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**The Endangered Species Act**

I represent 138 biomedical research scientists in areas such as drug development for AIDS, cancer, cardiovascular disease, pain relief, and the study of basic chemical and biochemical processes of health and disease. We believe that the progress of biomedical research and disease treatment depends on the maintenance of the greatest possible biological diversity in nature. Rather than allowing legislation currently before Congress to weaken one of our nation’s most important laws, we implore the President and Congress of the United States to support reauthorization of a strong and effective Endangered Species Act.

Plants and their attendant microorganisms have provided an armamentarium for cancer chemotherapy: Doxorubicin is used to treat acute leukemia, Hodgkin’s disease, other lymphomas, Wilms tumor, and several other cancers; bleomycin is used for the palliative treatment of squamous cell carcinomas; etoposide is valuable in combination chemotherapy against small cell lung cancer; vinblastine is one of the most effective single agents against Hodgkin’s disease; vincristine is used in combination therapy against acute leukemia, where 90% remission can be achieved in children; and taxol provides a therapy for ovarian cancer.

Using morphine as a model, medicinal chemists have made alterations to the drug that have produced a variety of other medicines including methadone, used in the treatment of heroin addiction, and dextromethorphan, a common constituent of cough syrups. Moreover, the scientific study of morphine (derived from the poppy) and its chemical relatives has led to the discovery of opiate receptors in the brain and to novel approaches to pain relief and narcotics addiction.

The plant products digoxin and digitoxin are routine medications for heart failure, and ouabain is used in the emergency treatment of potentially fatal heart rhythm disorders. Another botanical product, quinidine, is prescribed for the control of certain heart rhythm abnormalities.

Animals provide indispensable models for the study of the origins and therapy of human diseases such as leprosy (armadillo), late-onset diabetes (monkfish), and injured heart muscle (Mexican salamander, an endangered species).

Discoveries are made regularly of novel, natural products that contribute to new drug design and advance our understanding of health and disease. A Chinese plant, *Artemisia annua*, for example, provides arte-
misinin, a promising new therapy for chloroquine-resistant malaria.

For each beneficial discovery, a large variety of species must be examined. Thus, scientific success in natural product drug discovery depends on biological diversity, which represents nature's myriad solutions to challenges of species survival. A strong, effective, and well-funded Endangered Species Act provides a safety net for the diversity of life on Earth and so ensures that biomedical science will be able to continue to learn from nature.

Michael Clegg (Chair of the Committee on Scientific Issues in the Endangered Species Act of the National Research Council of the National Academy of Sciences) has written (1, p. 3; 2) that

The ultimate goal of the Endangered Species Act is to ensure the long-term survival of a species...the current rate of extinction is among the highest in the entire fossil record, in large part due to human activity. The introduction of non-native species and especially the degradation and loss of habitat are causing extinctions at a rate that many scientists consider a crisis.

Congress should accept the 1995 findings and recommendations of the National Research Council of the National Academy of Sciences in its reauthorization of the Endangered Species Act. This independent scientific body found (1, p. 3; 2) that "There has been a good match between science and the Endangered Species Act," and has emphasized that habitat protection on both federal and private lands is required for effective species protection.

A healthy future for humans depends on a healthy future for the species with which we share the Earth.

Paul F. Torrence
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References

Garlic and Mosquitoes

The report that marigold toxins kill mosquito larvae (1) (Random Samples, 12 May, p. 809) is not necessarily unique. S. V. Aman and others previously reported (2) that diallyl disulfide, a major component of garlic that contributes a large share of its odor and flavor, readily kills mosquito larvae. I believe I have observed such an effect. In 1989, the severity of onion and garlic white rot disease was so great in a standing garlic field in central Oregon that the crop was a total loss, even though half or more of the plants remained alive in mid-June. To prevent further increase in the inoculum, to reduce the population of the fungal pathogen Sclerotium cepivorum, and to kill off the remaining garlic (which would become a weed in subsequent crops), we flooded the field continuously between June and November. I waded weekly through the field collecting soil samples to monitor pathogen and garlic survival (3). No mosquitoes materialized in the field during these months, nor did the farmer who lived adjacent to the field notice any mosquitoes that summer. There were, however, many other insects and other invertebrates present in abundance. A slight garlic odor suggested that diallyl disulfide was leaking from the decaying garlic.

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References

"Not-Even-a-Draft?"

The headline of a Science Scope item (18 Aug., p. 911) declares, "Major EMF report warns of health risks." There is no report. This is acknowledged in the text that follows, but the implication is that it's just a matter of time. It is more likely that the not-even-a-draft was leaked by its authors precisely because they knew its prospects for adoption by the National Council on Radiation Protection and Measurements (NCRP) lie somewhere between slim and zero. It is based on information that other agencies, including the American Physical Society (APS), have dismissed as inconclusive or worse.

Robert L. Park
American Physical Society, 529 14th Street, NW, Suite 1050, Washington, DC 20045, USA

Response: Park correctly points out that the information on which the NCRP panel based its draft report has been dismissed by others, including Park's own organization. We should have stated that explicitly. However, Park oversteps the mark. In a widely disseminated electronic newsletter, Park said the draft report "hasn't even been approved by the panel itself," and in his letter he calls it "not-even-a-draft." That's news to the panel members with whom we spoke and the executive director of the NCRP, who all told Science that the draft has been approved by the panel and sent on to the NCRP for review. As our item pointed out, it now faces an extensive and vigorous review process, standard practice for NCRP reports.—Editors

Pioneering Work

In the introduction of their Research Article reporting the total nucleotide sequence of the Haemophilus influenzae genome (R. D. Fleischmann et al., 28 July, p. 496), J. Craig Venter and his colleagues write that bacteriophage \( \Phi X174 \) was the first viral or organelar genome to be completely sequenced in 1977 by F. Sanger and his colleagues. May I point out that, although this is true for DNA molecules, the first viral genome to be completely sequenced was that of the RNA bacteriophage MS2 (1).

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References

Response: We wish to add to our Research Article acknowledgment of the pioneering work of Fiers and his colleagues and that of Joachim Messing and his colleagues. Fiers completed the publication of the sequence of the 3569 base pair (bp) RNA bacteriophage MS2 in April 1976 with the sequence of the third gene (replicase gene) from bacteriophage MS2. Messing's contributions of a set of M13-derived vectors, his pioneering work in the development of shotgun sequencing strategies, and the sequencing of the 8031-bp cauliflower mosaic virus in 1981 (1) are lasting contributions that we continue to build on today.

J. Craig Venter
Institute for Genomic Research, 9712 Medical Center Drive, Rockville, MD 20850, USA

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second-order recombination (intermediate U) converts the molecules to the R state at pH 7.4; the remaining deoxy chain produces a R_{deoxy} UVRR difference spectrum. At pH 5.8, however, the tri-ligated molecules probably remain in the T quaternary structure and produce a positive W3 UVRR difference band for the interior tryptophan residues.

The most interesting conclusion to emerge from this study is that the allosteric reaction coordinate is not unidirectional, but instead proceeds by reciprocating tertiary and quaternary motions. Although the force generated by ligand dissociation is initially felt at the proximal His residue, the first large-scale protein motion (20 ns) involves the E helix, on the distal side of the heme. The next step (0.5 μs) is dimer rotation and the initial formation of the quaternary H bonds. The last step (17 μs) completes the circuit, locking the quaternary contacts into place and shifting the proximal F helix to its deoxy Hb position, thereby straining the Fe-His bond.

This strain is critical to cooperative ligand binding because it is responsible for lowering the affinity in the I state. The oxygen affinity has been directly linked to the Fe-His stretching frequency in various Hb's (32) as has the activation energy for CO rebinding (13, 26). Likewise, Gibson's transition from fast to slow recombining Hb (5) is shown by the present work to be a transition (S→T') from a relaxed to a strained Fe-His bond. This transition establishes the coupling of the ligation free energy to protein structure change, but it is mainly a tertiary, not a quaternary motion, in that the interdimer rotation has already occurred in S.

REFERENCES AND NOTES

33. We thank Professors Gary Ackers and Philip Anfinrud for helpful discussions and Beth Villafane for creating Fig. 7. Supported by NII grant GM 25156.
34. 20 December 1994; accepted 21 August 1995.
English he draws on are also problematic as sources, such as David Bergamini's sensationalistic Japan's Imperial Conspiracy (Morrow, 1971) and Edward Behr's impressionistic Hirohito: Behind the Myth (Villard, 1989).

For the Russian dimension, Harris draws on the readily available translated postwar Khabarovsk trial record. This transcript, however, does not shed much light on the single most direct combat confrontation between the Japanese and the Soviet Union, the small war waged at Nomonhan (Khalkhin Gol) between the Kwantung Army and the Red Army two years before Pearl Harbor. For this case history, Harris has consulted this reviewer's massive study, *Nomonhan: Japan Against Russia 1939* (Stanford University Press, 1986). There was a definite potential for the use of biological or chemical weapons at Nomonhan, but in the course of this reviewer's decades of research and interviews with 400 Japanese respondents, the unanimous testimony was that Ishii's unit only handled water-purification and epidemic-prevention measures at the front. Harris is acquainted with these missions (p. 74), but he is convinced that "Ishii viewed the outbreak of fighting at Nomonhan as a golden opportunity to test the possibilities of BW on a large scale" and that the Kwantung Army Commander finally gave him permission to do so by July 1939 (pp. 74–75). Harris also asserts that this reviewer "appears to believe that the fuss about BW use in the [Nomonhan] war was based on 'pseudonymous sources'" (p. 253).

A peripatetic scholar as tenacious as Harris might have exploited the proximity of Northbridge to San Diego to ascertain the basis for such contentions at first hand. He would have learned that once-classified Japanese archives reveal very real Japanese suspicions that it was the Russians who were contaminating the river at Nomonhan. As for Japanese culpability, Ishii later told the Kwantung Army chief of staff, in utmost secrecy, that the Japanese central authorities had authorized use of biological weapons but that he had declined to do so because countermeasures were not ready. As for the unconvincing pseudonymous leftist accusers, this reviewer expended much effort to trace them in Japan but could not determine their identities.

The first 10 chapters of Harris's book are devoted to Ishii (reputedly "a womanizer, a night owl, and a heavy drinker," as well as a big spender at places of amusement; p. 15) and to the various death factories in Manchuria and China. The last six chapters address the postwar cover-up involving American scientists and soldiers. An important appendix provides detailed data from the Chinese side concerning chemical weapons discovered abandoned in China by "a certain foreign state" (pp. 235–238).

Though his special anguish for the Chinese "martyrs" is apparent throughout, Harris has sifted through the evidence available to him with care and restraint. He has broken new ground with his exploration of the grisly subject of Japanese testing and field use of anthrax, typhus, and dysentery germs. He has provided biographical and chronological information and a "road map" for studying the cruel Japanese facilities and the resort to human guinea pigs—the so-called manua, or "logs"—at Bei-yinhe, Ping Fan, Changchun, and Nanking. Perhaps such publicity underlies the Japanese government's belated decision in 1995 to send military and chemical experts to...
China to seal 30 decaying poison gas shells and three vats of mustard gas located by the Chinese authorities. The Japanese had already dispatched teams to China to check on possible soil contamination, but this is the first effort to neutralize some of the 2 million Japanese gas shells that reportedly remain buried in northeast China.

The physical apparatus of the factories of death was demolished by the Japanese 50 years ago. Regrettably, the legacy of psychological scars inflicted by the "certain foreign state" can never be eradicated from the pages of Sino-Japanese history.

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Evolution by Reticulation


Corals in Space and Time is a monumental synthesis of the evolution of corals in which the author challenges Charles Darwin head on. Veron argues that, instead of evolving dichotomously along discrete lineages as a result of natural selection as proposed by Darwin, coral species perpetually fuse (by hybridization) or separate (by isolation and genetic drift), giving rise to a reticulate pattern of evolution. Veron's theory of reticulate evolution initially grew out of his observation of the abundance of intergrades between species. He describes his early years of separating and classifying corals, in fact, as "a failure." In the last decade, three discoveries have bolstered Veron's theory with regard to corals. First, it has been established that about three-quarters of all coral species are spawners, releasing their gametes into the water column, where external fertilization takes place. The second discovery is the synchronous mass-spawning events on the Great Barrier Reef of Australia, where many dozens of coral species spawn (within a few days of each other) at the same time of the year, producing a rich soup of reproductive material that can lead to frequent hybridization. The third discovery is an increasing list of species that can produce viable hybrids at least at the F1 generation. From all this Veron has concluded that coral intergrades are in fact hybrids, some viable but sterile, some viable and reproductive, some fusing back to the parent generation, some diverging, but together forming a species complex of races and subspecies—a large genetic pool of interconnected populations that he calls a syngameon. Such a species is not discrete; its boundaries are fuzzy, and it represents a continuum of variation. At opposite ends of the continuum species may appear different, but all varieties along the continuum are interfertile. The species complex may also include sterile hybrids, which can be ecological dominants, that is, species that may not themselves reproduce but that play a dominant role in the ecosystem and are continually reproduced over time by hybridizing parental populations.

The syngameon is an interconnected net of populations (races, subspecies, and species) that either converge or diverge in space and time depending on gene flow. Their connectivity in turn depends on the strength and direction of currents. Veron does not deny that natural selection is embedded within the process, but he sees connectivity, or the lack of it, as more important in species evolution. In this regard, this analysis is in agreement with neo-Darwinists Ernst Mayr, Niles Eldredge, and Stephen J. Gould. Veron sees ocean currents, a physical process, as being the dominant control over evolution in corals. He also invokes reticulate evolution to explain why biodiversity in corals is not higher. Hybridization and reproductive connectivity favor fusion and damp separation (speciation). Most coral reefs in the Indo-West-Pacific...
are characterized by less than 10 percent endemicity. This also helps to explain the very long average age (10 million years) of coral species in the fossil record.

Veron does not overlook the fact that low coral biodiversity can also be a consequence of low habitat diversity; reef-building corals occur only in the eutrophic zone and in the tropics. Veron explains similarities in species composition as due to similarities in habitat. Reefs characterized by large differences in physical habitat though separated by a few miles may be more different than reefs with similar habitat on western and eastern coastlines of Australia, a separation of over 1000 miles. Herein may lie a limitation to Veron’s argument. If corals need to retain genetic specialization (for example, habitat specificity), they must avoid hybridizing with species occupying very different but nearby habitats. Veron does not discuss this problem, but then he does not claim that reticulate evolution applies to all corals any more than it applies to all species in nature.

Thus Veron does not argue either-or regarding dichotomous or reticulate evolution; rather, he offers the latter as a significant process to explain the evolution of those species that can successfully hybridize. The hypothesis of reticulate evolution is not new regarding plants, but it has been given little consideration in animal systematics. Veron suggests that reticulate evolution may be a major mechanism in the evolution of many marine invertebrates (among them crustaceans, mollusks, polychaetes, and echinoderms) and some vertebrates, notably Amphibia, in which fertilization is external. This is the major contribution of the book, and it should usher in a plethora of new research to test the generality of the hypothesis. If it occurs broadly, reticulate evolution should wreak havoc on traditional cladists. Ultimately, the overall importance of reticulate evolution may be proved or disproved by molecular genetics. Thus the book represents a challenge for future research.

Having focused on the positives, I would be remiss not to mention some shortcomings. Perhaps the most bothersome to me is Veron’s use of the term “vicariance circulation” to explain both separation and connectivity. Clearly circulation (ocean currents) can cause both, but the term “vicariance” refers to separation only. Other bits of jargon, such as “connectivity ratchets” are distracting, although Veron’s meaning is clear. The references in some chapters are rather spotty, and some types need correcting, such as the latitude of Clipperton Atoll (10 degrees north, not south). The writing in places is somewhat nebulous, but this is more than offset by the numerous summaries of main points and conclusions. It may take a decade of research to verify reticulate evolution as a major evolutionary process. If it proves to be such, history could well place Veron’s Corals in Space and Time on the shelf alongside the works of Darwin, Mayr, Eldredge, and Gould.

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