Assessment of the
NASA ASTROBIOLOGY INSTITUTE

Committee on the Review of the NASA Astrobiology Institute

Space Studies Board

Division on Engineering and Physical Sciences

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Preface

In a letter sent to Space Studies Board (SSB) Chair Lennard Fisk on January 11, 2007, Mary Cleave, NASA's associate administrator for the Science Mission Directorate (SMD), requested that the Space Studies Board (SSB) of the National Research Council (NRC) conduct a review to evaluate the progress made by the NASA Astrobiology Institute (NAI) in developing the field of astrobiology, both from the perspective of NAI members and from that of the larger community of NASA-supported scientists. The goal of this review is to help guide NASA in assessing and shaping the future of the NAI, particularly in its preparation of a solicitation issued to help select future teams to carry the NAI into a second decade.

NASA's Astrobiology program is the scientific outgrowth of the public and scientific excitement generated by a series of new results from solar system exploration and astronomical research programs in the mid-1990s, together with parallel advances in the biological sciences. Instituted in 1997, NASA's Astrobiology program focuses on research activities designed to understand the origin, evolution, and distribution of life in the universe. The program consists of four distinct elements: (1) grants programs designed to support individual investigators; (2) technological activities aimed at the development of new scientific instrumentation; (3) technological activities aimed at the field-testing of new scientific instruments; and (4) the NASA Astrobiology Institute, a consortium of geographically dispersed research groups ("lead centers" or "nodes") conducting interdisciplinary research.

The first three elements of the Astrobiology program are quite traditional in that they are designed to fund individual researchers following the peer-review of proposals written in response to annual announcements of opportunity. The NAI, however, was intended to be an experiment in the management of research efforts. The goal behind the creation of the NAI was to broaden and transform NASA's preexisting activities related to the search for life in the universe. The NAI was to promote the formation of interdisciplinary teams that would address cross-cutting questions in novel ways that were deemed not practicable within the constraints of the existing grants program. The NAI was formed to produce the highest-quality research results while ensuring the infusion of astrobiology objectives into NASA missions, to build a coherent astrobiology community, and to provide associated education and outreach efforts to enable public access to and benefit from NASA-supported astrobiology research. Since its founding, the NAI has placed special emphasis on encouraging collaborative research among scientists, as well as providing insights to educators from a variety of different backgrounds.

In response to a mandate contained in Section 314 of the NASA Authorization Act of 2000 and a subsequent request from NASA, the Space Studies Board and the Board on Life Sciences undertook a study in 2001 to assess NASA's Astrobiology program. In particular, the study looked at the relationship between NASA's Astrobiology program and related activities funded by other federal agencies (e.g., the National Science Foundation, the National Institutes of Health, and the Department of Energy) and also research activities conducted by other public and private scientific institutions in the United States and overseas. The resulting report, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology,*[1] gave a generally favorable review of the NASA Astrobiology program. However, the study committee concluded that insufficient time had elapsed to adequately address the key issue of whether or not the scientific contributions of the NAI were greater than the sum of its parts. In other words, did the unique organizational arrangements of the NAI represent a net plus or minus for science relative to what could be achieved if NAI's funding were distributed among more traditional grants programs? The report recommended that "NASA should undertake a comprehensive review of the scientific and educational results of its Astrobiology program in general, and of the NASA Astrobiology Institute (NAI) in particular, at the end of a decade of activity, in order to assess the longer-term effects of the founding of the new program and the new institute on the research area. This review would include analysis of the significant scientific contributions that have arisen from the program. It should be undertaken no later than 2008, when the NAI is a decade old" (p. 3).

Following the receipt of funding from NASA in late-May 2007 to undertake the study requested by Dr. Cleave, the Space Studies Board established the ad hoc Committee on the Review of the NASA Astrobiology Institute in June 2007. The committee's activities began with a conference call held on July 13 and continued at a meeting held in Sunnyvale, California, on July 25-27. Presentations and deliberations continued at a meeting held in Washington, D.C., on August 16-18 and concluded at a third and final meeting held in Costa Mesa, California, on August 31-September 1. In addition to presentations and discussions at its meetings, the committee solicited comments from all of the NAI's current and former principal investigators and from leading astrobiologists at international organizations associated or affiliated with the NAI. In addition, the committee solicited input from past and present NAI postdoctoral fellows.

A draft report was completed during the first week of September and sent to external reviewers for commentary in mid-September. A new draft responding to the reviewers' comments was completed in late October, and the report was approved for release on November 20.

The work of the committee was made easier thanks to the important presentations and comments provided by numerous individuals from a variety of public and private organizations. These include the following: Shige Abe, Marco Boldt, Wendy W. Dolci, David Morrison, Carl B. Pilcher, and Daniella Scalice (NASA Astrobiology Institute); James L. Green, Michael Meyer, and John D. Rummel (NASA, Science Mission Directorate); Jeffrey Bada (University of California, San Diego), John Baross (University of Washington), Baruch Blumberg (Fox Chase Cancer Center), Andre Brack (European Exo/Astrobiologie Network Association), David Des Marais (NASA Ames Research Center), David Deamer (University of California, Santa Cruz), Edna Devore (SETI Institute), Pascale Ehrenfreund (Leiden University), Todd Gary (Tennessee State University), Scott Hubbard (Stanford University), Bruce Jakosky (University of Colorado), Clark Johnson (University of Wisconsin, Madison), Andrew Knoll (Harvard University), Jonathan Lunine (University of Arizona), Rocco Mancinelli (SETI Institute), Michael Manga (University of California, Berkeley), Marcia McNutt (Monterey Bay Aquarium Research Institute), Victoria Meadows (University of Washington), Michael Mumma (NASA Goddard Space Flight Center), Hiroshi Ohmoto (Pennsylvania State University), Tullis C. Onstott (Princeton University), Anatoli Pavlov (Russian Astrobiology Center), John Peters (Montana State University), Francois Raulin (Groupement de Recherche en Exobiologie), Bruce Runnegar (University of California, Los Angeles), Timothy Slater (University of Arizona), Mitchell Sogin (Marine Biological Laboratory), Sean Solomon (Carnegie Institution of Washington), Woodruff T. Sullivan III (University of Washington), Roger Summons (Massachusetts Institute of Technology), Carol Tang (California Academy of Sciences), Catherine Tsairides (Lockheed Martin), Margaret Turnbull (Space Telescope Science Institute), Malcolm Walter (Australian Center for Astrobiology), and Neville J. Woolf (University of Arizona).

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making

[1] National Research Council, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology,* The National Academies Press, Washington, D.C., 2003.

its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

The committee wishes to thank the following individuals for their participation in the review of this report: Sidney Altman (Yale University), Paul Falkowski (Rutgers University), Andrea Ghez (University of California, Los Angeles), Charles Kennel (University of California, San Diego), Eugene Levy (Rice University), H. Jay Melosh (University of Arizona), Kenneth Nealson (University of Southern California), Maxine Singer (Carnegie Institute of Washington), and David Spergel (Princeton University).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Larry L. Smarr (University of California, San Diego). Appointed by the NRC, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Executive Summary

Astrobiology is a scientific discipline devoted to the study of life in the universe—its origins, evolution, distribution, and future. It brings together the physical and biological sciences to address some of the most fundamental questions of the natural world: How do living systems emerge? How do habitable worlds form and how do they evolve? Does life exist on worlds other than Earth? As an endeavor of tremendous breadth and depth, astrobiology requires interdisciplinary investigation in order to be fully appreciated and examined.

As part of a concerted effort to undertake such a challenge, the NASA Astrobiology Institute (NAI) was established in 1998 as an innovative way to develop the field of astrobiology and provide a scientific framework for flight missions. Now that the NAI has been in existence for almost a decade, the time is ripe to assess its achievements.

At the request of NASA's Associate Administrator for the Science Mission Directorate (SMD), the Committee on the Review of the NASA Astrobiology Institute undertook the assignment to determine the progress made by the NAI in developing the field of astrobiology (Appendix A). It must be emphasized that the purpose of this study was not to undertake a review of the scientific accomplishments of NASA's Astrobiology program, in general, or of the NAI, in particular. Rather, the objective of the study is to evaluate the success of the NAI in achieving its stated goals of:

1. Conducting, supporting, and catalyzing collaborative interdisciplinary research;
2. Training the next generation of astrobiology researchers;
3. Providing scientific and technical leadership on astrobiology investigations for current and future space missions;
4. Exploring new approaches, using modern information technology, to conduct interdisciplinary and collaborative research among widely distributed investigators; and
5. Supporting outreach by providing scientific content for use in K-12 education programs, teaching undergraduate classes, and communicating directly with the public.

The committee's assessment of the NAI's progress in these five areas is presented in Chapters 2 to 6, respectively. In evaluating the success of the NAI in achieving these five goals, the committee was requested to address the following considerations:

a. Has the NAI developed, as envisioned, as an evolving experiment in cutting-edge, distributed, collaborative science and education in astrobiology?

b. Does the NAI provide a unique and useful complement to other Astrobiology program support mechanisms (e.g., individual grants to principal investigators), and if improvements need to be made in this area, what are they?

c. Are the research, training, and public educational activities of the NAI appropriately balanced in terms of investments and outcomes, services to NAI members and external partners, and activities that engage and support the wider astrobiology community and the needs of young professionals?

d. What other activities or roles not currently undertaken by the NAI might be appropriate in the future?

The committee's responses to these four criteria can be found in subsections in Chapters 2 to 6. Specific recommendations and suggestions as to how the recommendations might be implemented can be found in the final subsection of each of the same chapters.

Information on the origins of NASA's Astrobiology program and the NAI; a summary of comments on the role, status, and scientific importance of astrobiology from previous NRC reports; and some information on the budgetary history and the impact of recent cuts to the Astrobiology budget can be found in Chapter 1.

FINDINGS AND RECOMMENDATIONS

Overall, the committee is unanimous in finding that the NAI has fulfilled its original mandate. The NAI has played a key role in supporting the development of astrobiology and has positively affected NASA's current and future missions. The committee recommends that the NAI should continue to be supported. Specific findings and recommendations are organized according to the five goals and four criteria listed above

NAI Goal 1—Interdisciplinary Research

Although the committee was not charged to undertake a review of the NAI's scientific contributions, it is difficult to evaluate the NAI's success in conducting, supporting, and catalyzing collaborative interdisciplinary research without some brief mention of the NAI's scientific achievements. Consideration of the NAI's major scientific contributions reveals that some are highly interdisciplinary but that some are not. In the committee's view, interdisciplinarity must be viewed as the orientation and emergent quality of an overall enterprise and not as a requirement or expectation levied on every piece of work produced by that enterprise. Thus, with respect to the goal of conducting, supporting, and catalyzing collaborative interdisciplinary research, the committee finds that the NAI has:

- Successfully promoted interdisciplinary science;
- Stimulated many scientific achievements;
- Successfully integrated life sciences into NASA programs;
- Often effectively leveraged ongoing and new research;
- Contributed to the establishment of new astrobiology programs worldwide; and
- Supported programs that are widely distributed throughout the United States.

The committee makes the following recommendations:

- The NAI should institute better measures of performance and progress to improve the accountability of its nodes in promoting astrobiology as a field of interdisciplinary and collaborative study;
- The NAI should improve the tracking and critical assessment of its publications; and
- The NAI should encourage and cultivate interactions with non-NAI astrobiology teams and organizations throughout the world.

Suggestions as to how these recommendations might be implemented can be found in Chapter 2.

NAI Goal 2—Training the Next Generation of Astrobiologists

The NAI's commendable effort to train the next generation of astrobiologists faces many challenges. The continuation of funding beyond the 5-year lifetime of NAI teams is not guaranteed. Young researchers seeking to establish themselves outside the protective environment of NAI teams face particular challenges when trying to accomplish interdisciplinary research within the highly discipline-oriented organization of research universities. The pool of resources for training new researchers is limited. Nevertheless, with respect to the goal of training the next generation of astrobiology researchers, the committee finds that the NAI has:

- Trained graduates who are now employed in academic and other positions;
- Promoted the establishment of new programs and faculty positions in astrobiology at several universities; and
- Not been sufficiently proactive in countering the negative effects on training and education programs caused by recent cuts to NASA's Astrobiology budget.

The committee recommends that the NAI should work toward developing more consistent educational and training opportunities. In addition, the NAI should ensure more stable support of graduate students and postdoctoral researchers in astrobiology. Suggestions as to how this recommendation might be implemented can be found in Chapter 3.

NAI Goal 3—Leadership for Current and Future Space Missions

Although the NAI has not played a significant role in the selection or execution of NASA missions, the field of astrobiology provides the intellectual and scientific foundation for much if not all of NASA's current robotic solar system exploration missions and many of its astrophysical activities relating to the search for and characterization of extrasolar planets. The NAI's influence has been indirect and has come through the actions of individual scientists affiliated with NAI teams. This is probably the most appropriate vehicle for the NAI's involvement in NASA's flight program. Thus, with respect to the goal of providing scientific and technical leadership on astrobiology investigations for current and future space missions, the committee finds that the NAI has:

- Encouraged astrobiologists to provide needed recommendations and expertise to NASA for mission planning;
- Promoted the participation of astrobiologists in the science teams for current and future missions;
- Organized activities, such as focus groups, that have strongly influenced NASA missions; and
- Identified astrobiology questions that underpin most of NASA's current flight programs.

The committee believes that the NAI must remain clearly focused on supporting NASA's spaceflight missions, and so its highest-priority recommendation is as follows: Because its most critical function is to ensure that its research activities clearly contribute to NASA's current and future spaceflight activities, the NAI should be more proactive in identifying future astrobiology missions. In addition, the NAI should actively encourage a partnership between astrobiologists and their engineering counterparts to help define future NASA missions.

The committee also recommends that in selecting new nodes, the NAI should give more weight to the potential contribution of the proposed research to future NASA missions.

Suggestions as to how these recommendations might be implemented can be found in Chapter 4.

NAI Goal 4—Use of Information Technology

The NAI experience with information technology has been mixed. Those aspects of the application of information technology within the control of NAI Central—e.g., its extensive and informative Web page with its archive of astrobiology seminars and research results—are second to none in NASA. But those aspects of the utilization of information technology outside the direct control of NAI Central—e.g., the use of collaborative work tools by the researchers affiliated with NAI teams—has been less successful. The lack of success most likely results from social rather than technical factors. Thus, with respect to the goal of exploring new approaches using modern information technology to conduct interdisciplinary and collaborative research among widely distributed investigators, the committee finds that:

- The substantial efforts by NAI Central to improve communications among NAI members have achieved some significant successes; and
- The NAI has been less successful in promoting the use of collaborative work tools by the researchers affiliated with its participating teams.

The committee recommends that the NAI should vigorously pursue new approaches using modern information technologies to increase the effectiveness of the NAI nodes. In particular, additional efforts by NAI Central are needed to ensure that new communications tools are used to enhance the effectiveness of interdisciplinary and collaborative research and training. Suggestions as to how this recommendation might be implemented can be found in Chapter 5.

NAI Goal 5—Education and Outreach

The public's interest in the subject matter of astrobiology has enabled the effective leveraging of funds, partnerships, and expertise far greater in scope than those made available by the NAI itself. Thus, with respect to the goal of supporting outreach by providing scientific content for K-12 education programs, teaching undergraduate classes, and communicating directly with the public, the committee finds that the NAI has:

- Successfully promoted astrobiology as a field with broad-based public appeal;
- Developed effective programs for outreach to the general public; and
- Enabled minority educational activities.

The committee makes the following recommendations:

- The NAI should be more strategic in exploiting synergies among nodes in K-12 education, minority education, and teacher training; and
- The NAI should address the specific requirements for teaching astrobiology at the undergraduate level.

Suggestions as to how these recommendations might be implemented can be found in Chapter 6.

1

Introduction

ASTROBIOLOGY AT NASA

In its current usage, the term "astrobiology" is variously defined as the study of the origin, evolution, distribution, and future of life in the universe; the study of life as a planetary phenomenon; the study of the living universe; or the origin and co-evolution of life and habitable environments.[1-3] The term was apparently coined in the 1940s[4] and was used periodically in the 1950s.[5] In about 1960 "astrobiology" appears to have been supplanted by the more restricted term "exobiology" and then independently reinvented in 1995 by Wesley Huntress, NASA's then-associate administrator for space science.[6]

The history of NASA's involvement in astrobiology and its modern precursor, exobiology, can be divided into three periods. The first lasted from the late 1950s to the time of the Viking Mars program in 1976. During this period, NASA's Office of Life Sciences devoted many resources to the study of the origins and evolution of life on Earth and elsewhere in the universe. The second period began after the Viking spacecraft failed to unambiguously detect evidence of life on Mars. This disappointment reduced NASA's eagerness to fund follow-on missions to Mars or other major activities relating to the search for life beyond Earth. In 1996, exobiology experienced revitalization in the aftermath of an announcement claiming the discovery of evidence of past life in the martian meteorite ALH 84001, and the subject of exobiology began its transformation into the current-day field of astrobiology. The revitalization and transformation mark the third historical period.

Beginnings to Viking

NASA's involvement in exo/astrobiology stems from repercussions generated by an international conference focused on studying the origins of life that took place in August 1957 in Moscow. The location of the conference, in conjunction with the Cold War-driven political climate of the time, spread fears among U.S. officials that the Soviet Union had discovered the secret behind the origins of life. Joshua Lederberg, a young Nobel Prize-winning biologist, had recently begun pondering the notion of life on other worlds and was able to use the fears generated by the 1957 conference to persuade the newly formed NASA to devote resources to studying the origin of life. Lederberg argued that NASA would need to understand the origins of life on Earth in order to plan the search for extraterrestrial life. He coined the term "exobiology" to describe studies relating to the origins of life on Earth and the development of instruments and methods to search for signs of life in the cosmos.[7]

In 1960, NASA created the Office of Life Sciences. One function of this office was to award grants for exobiology research. This research included studying life-detection techniques, learning how to prevent forward and back contamination of planetary environments by spacecraft, and studying the origins of life.

After the founding of NASA's Office of Life Sciences, exobiology continued to grow. Many scientists who were unable to achieve funding through agencies, such as the National Science Foundation (NSF) and the National Institutes of Health (NIH), that required that their work fit into a rigidly defined scientific discipline were successfully courted by NASA and encouraged to apply for exobiology grants.

NASA's Office of Life Sciences invested a considerable amount of money in the design and development of life-detection instruments. Three of these instruments were chosen to fly aboard the 1976 Viking mission to Mars. The twin Viking landers were designed to land on the Red Planet and search for the presence of life or organic materials on the surface.

Post-Viking Era

The Viking landers touched down on the surface of Mars in July and September 1976. Although the results were eagerly awaited by many on Earth, scientists were disappointed to find that the data from the landers were ambiguous. While one of the instruments did seem to show a positive detection of life,[8] the other two life-detection instruments did not.[9,10] Moreover, a fourth experiment revealed no sign of organic material in the samples of martian regolith analyzed.[11] Scientists later demonstrated that the positive results from the single experiment likely resulted from abiotic processes related to the highly oxidizing nature of the martian surface material.[12]

In the wake of Viking's failure to unambiguously detect biological activity or, even, organic compounds in the martian soil, the exobiology program experienced a decrease in political support. The public, which had been so enthusiastic about the possibility of life on other planets, became disillusioned by the negative results of Viking. Not only did the prestige of exobiology suffer, but the entire Mars exploration program also experienced a lull in the two decades following Viking.

Although funding did not reach pre-Viking levels in this era, work in the field continued. The scientific community remained interested in studying the origins of life, and internal NASA advisory committees and independent groups continued scientific planning for future endeavors in this area. Many significant discoveries were also made in this time period. Indeed, NASA's strategy of actively seeking out interdisciplinary projects that did not readily find a home in other funding agencies was extremely successful and resulted in the funding of many seminal research activities that proved of lasting value. Examples of important research opportunities funded by the Exobiology program include the following: Lynn Margulis's work on the endosymbiotic origins of eukaryotic cells, Carl Woese's discovery of the Archaea, Luis Alvarez's theory of an asteroid as the cause of the Cretaceous-Tertiary mass extinction, the discovery of microfossils of the earliest life on Earth, and James Lovelock's Gaia hypothesis.[13] This does not mean that other agencies made no contributions to the nurturing of what would later be called astrobiology. NSF, for example, was instrumental in funding many important research activities, including the following: Stanley Miller's work on prebiotic synthesis; the collection of lunar, martian, and other meteorites in Antarctica; and Geoffrey Marcy's search for exoplanets, i.e., planets around other stars.[14]

In 1995, astronomers announced the discovery of an extrasolar planet orbiting the star 51 Pegasi. Although this planet orbits very close to its parent star and is far too hot to harbor life as we know it, this unexpected discovery, taken together with the earlier discovery of planets in orbit around a pulsar, generated enthusiasm for the possibility for countless yet-to-be-discovered planetary systems, some of which could have the potential to sustain life. At about the same time, the Hubble Space Telescope obtained spectacular images of disks around young stars, which were interpreted as possible sites for future formation of planets, perhaps including ones with environmental conditions suitable for life.

Much work was also being done at this time on the existence of life in extreme terrestrial environments, such as deep-sea hydrothermal vents. These new "extreme" life forms expanded the limits of what were once considered to be acceptable conditions for life to develop and proliferate. Finally, observations from the Galileo spacecraft suggested that liquid water existed below Europa's icy surface, raising the tantalizing idea that life could be found elsewhere in the solar system outside the traditional habitable zone.

Transformation and Revitalization

The August 16, 1996, issue of *Science* contained an article that once again ignited interest in the possibility of life beyond Earth. The authors of the article claimed that they had discovered evidence suggesting that ancient fossilized bacteria were present in the meteorite ALH 84001, a piece of Mars collected in Antarctica in 1984.[15] They based this claim on four pieces of evidence: (1) the presence of carbonate globules which had been formed at temperatures favorable for life, (2) the presence of biominerals (magnetites and sulfides) with characteristics nearly identical to those formed by certain bacteria, (3) the presence of indigenous reduced carbon within martian materials, and (4) the presence in the carbonate globules of features similar in morphology to biological structures.

The extraordinary claim of past life from Mars was eagerly reported by the media but received a very skeptical reaction from many researchers. Very little time passed before criticisms of the article were published, sparking a debate over the true nature of the supposed martian “bacteria.” The authors of these opposing articles argued that the putative nanometer-scale microfossils proposed by the discovery team were highly suspect and likely to be of abiotic origin. The formation temperature of the carbonate globules was soon controversial and, in some cases, suggested a value far above the upper limit for life. Some features were very similar to artifacts produced by the application of conductive coatings onto samples during their preparation for study using scanning electron microscopy. In many cases, the supposed biotic features were regarded as too small to support cellular-based metabolisms. It was known that many features resembling morphological and chemical biomarkers are actually formed by abiotic processes. In addition, most of the organic compounds extracted from ALH 84001 showed radiocarbon activity, indicating that they were very young and had been introduced after the meteorite landed on Earth.

The debate concerning the validity of the claims about ALH 84001 played a pivotal role in the development of astrobiology.[16] Although the initial suggestions surrounding ALH 84001 have not been sustained, the announcement triggered a political and programmatic reaction out of all proportion to its scientific significance. In response to congressional calls for a space summit—to discuss “the recent evidence that life may have existed on Mars, as well as other significant advances in space science and technology”[17]—the White House’s Office of Science and Technology Policy and NASA requested that the NRC’s Space Studies Board organize a workshop to discuss the implications of ALH 84001 and other recent advances in the space sciences. The resulting workshop was held on October 28-30, 1996, and concluded that the study of the origins of life, planetary systems, stars, galaxies, and the universe is a powerful organizing theme for NASA’s space science activities. A subsequent briefing of the workshop results to Vice President Gore concluded that the recent discoveries—such as those concerning life in extreme environments, planets around other stars, a subsurface ocean on Europa, and the transfer of material from planet (e.g., Mars) to planet (e.g., Earth) in the form of meteorites—“. . . are astonishing returns being reaped from years of investment in many scientific disciplines. Now is the time to leverage that investment and to pursue the quest for origins into the 21st Century.”[18] On February 6, 1997, President Clinton proposed that funds be appropriated for a major new NASA activity—the Origins Initiative—to focus on studying the origins of life in the context of the formation of planets, stars, and galaxies. This initiative included funding for missions to Mars and Europa, several astrophysical projects, and the initiation of a major program in astrobiology.

THE NASA ASTROBIOLOGY INSTITUTE

The planning for NASA’s Astrobiology program built on several parallel activities that had taken place earlier in the 1990s. As is mentioned above, NASA’s long-standing Exobiology program had achieved much success by concentrating on the funding of activities that did not readily fit within the more rigid disciplinary boundaries favored by other funding agencies. Thus, the Exobiology program naturally gravitated to inter- and cross-disciplinary activities. The concept of a virtual institute focusing on interdisciplinary research related to the origin, evolution, and distribution of life in the universe was pioneered in 1992 within the context of a program to establish several so-called NASA Specialized Centers of Research and Training (NSCORTs). An NSCORT focusing on issues relating to the origins and evolution of life, the so-called NSCORT in Exobiology—initially consisting of five principal investigators (PIs) and 20 students divided among the Salk Institute for Biological Studies, Scripps Institution of Oceanography, Scripps Research Institute, and University of California, San Diego—was established soon thereafter. The NSCORT program proved so popular that, a few years later, a second NSCORT—the New York Center for Studies on the Origins of Life—was established, linking researchers and students at Rensselaer Polytechnic Institute, the State University of New York at Albany, and the College of St. Rose. The NSCORTs in New York and California were eventually funded for periods of 5 and 10 years, respectively.

In parallel with the NSCORT activity, scientists at NASA's Ames Research Center drew up plans for a "life in the universe" program that would open up many new scientific possibilities by merging many different research activities underway at the center. The proposal was well received by NASA officials, but the name of the proposed endeavor was changed to astrobiology, thus independently reinventing the term that fell out of usage in the late 1950s. The Ames initative, as well as the subsequent efforts to define astrobiology, laid the foundations of modern astrobiology. Ames was named NASA's Lead Center in Astrobiology by Administrator Dan Goldin in May 1995. Ames personnel soon began holding workshops and meetings to explore models for the best way to perform astrobiology and related multidisciplinary research.

Meanwhile, Gerald Soffen, then the head of University Programs at NASA's Goddard Space Flight Center and formerly the principal scientist on the Viking missions to Mars, independently developed a concept for an institute focusing on astrobiology. Soffen's vision was for an institute having the following characteristics:

- Play a key role in determining the future of astrobiology;
- Be both real and virtual, using modern communications technology;
- Provide access to a continuous council of technical experts;
- Employ an interdisciplinary approach; and
- Recommend research directions, priorities, experiments, missions, and technology developments to NASA management.

The culmination of efforts of both Soffen and researchers at Ames came in May 1998 when 11 geographically dispersed teams of scientists (see Table 1.1) were named as the initial members of the NASA Astrobiology Institute (NAI). The teams, selected on a competitive basis in response to a cooperative-agreement notice (CAN) issued in 1997, were awarded funding of approximately $1 million a year for 5 years. The NAI formally opened for business in July 1998 under the leadership of Interim Director Scott Hubbard. Nobel laureate Baruch S. Blumberg was named the first NAI director in 1999.

From its founding, the NAI has actively nurtured partnerships with international organizations interested in astrobiology. Such partnerships are entered into on the basis of no exchange of funds and have the overall goal of providing collaborative opportunities for NAI researchers via, for example, access to unique scientific facilities and field sites outside the United States. Foreign astrobiology organizations can propose to become either an associate or an affiliate member of the NAI. The former arrangement involves a formal agreement between NASA and a foreign government, and the associated entity has the same status as one of the NAI's domestic nodes, whereas the latter is a much looser arrangement that does not involve a formal government-to-government agreement. The NAI's affiliate and associate members are selected via an application process that considers their organizational nature, the types of scientific activities in which they are engaged and their relationship to NAI objectives, and the likely productivity of the proposed activities. The Centro de Astrobiología in Spain became the first associate member of the NAI in 1999.

A second CAN was issued in 2000 and resulted in the selection of four new NAI teams, bringing the total number of NAI institutions to 15 (see Table 1.1). The Australian Centre for Astrobiology was also established, and it became the second associate member of the NAI.

In 2000, in response to a request from NASA's Office of Space Science, the National Research Council's Committee on the Origins and Evolution of Life (COEL), a joint committee of the Space Studies Board and the Board on Life Sciences, was charged to assess the state of the NASA Astrobiology program. COEL's report, entitled *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, was published in 2002.

In 2003, the 5-year funding period for the 11 original NAI members teams ended. Six of these teams successfully applied for and were awarded funding for an additional period of 5 years. In addition, six new teams were funded (see Table 1.1). Bruce Runnegar, a professor in UCLA's Department of Earth and Space Sciences and the Institute of Geophysics and Planetary Physics, also became the new director of the NAI. In addition, NASA released a revised version of the original 1998 Astrobiology Roadmap outlining the fundamental goals and objectives of astrobiology (Table 1.2).[19]

The year 2004 marked the establishment of the Federation of Astrobiology Organizations (FAO), whose goal is "to create an architecture that can implement cooperative international activities central to the interests of the individual astrobiology networks, associations, institutes, and societies that comprise [the] federation." The federation consists of the NAI as well as groups from Britain, Australia, Mexico, Spain, France, Germany, and Sweden.

Carl Pilcher, the former director of NASA's solar system exploration program, took over as NAI director in 2006. The four teams that received funding in 2001 also completed their 5-year agreements, and membership in the NAI dropped to 12 teams. Because of budgetary restrictions, these four teams were not replaced until 2007.

The NAI currently consists of 16 teams (see Table 1.1) and involves the work of approximately 600 investigators distributed across some 150 institutions. The NAI is administered by its director[20] and a small staff, through an office known as NAI Central,[21] located at the NASA Ames Research Center.

The NAI's teams ("nodes") are supported through cooperative agreements between NASA and the teams' institutions;[22] these agreements involve substantial contributions from NASA and each of the teams. The NAI Handbook outlines the expectations of membership in the institute, emphasizing active participation in realizing all aspects of the NAI's mission.[23]

The principal investigators of each team, together with the NAI director and deputy director, constitute the executive council.[24] Its role is to advise NAI management in matters of institute-wide research, space mission activities, technological development, and external partnerships.

Other aspects of the NAI include the Director's Seminar Series, which brings the community together monthly via videoconference to share scientific progress;[25] focus groups that mobilize expertise within the community on relevant topics;[26] the annual report, which describes the most recent activities of each of the NAI's teams;[27] the online Research Archive, which highlights top scientific discoveries and advances;[28] and the NAI Newsletter, which provides the latest news about activities and opportunities.[29] Special attention to the next generation of astrobiologists is exemplified by the NAI's Postdoctoral Fellowship Program[30] and the Lewis and Clark Fund for Exploration and Field Research.[31] NAI Central also organizes institute-wide workshops, such as the Strategic Impact Workshop,[32] to facilitate collective discussion and planning for the NAI's research.

The NAI continues to adapt and evolve in a changing environment. Most recently, the NAI's 2007 Director's Discretionary Fund competition emphasized a strategic impact on NASA's ability to achieve its goals,[33] especially in the areas of flight missions, cross-program synergies, collaborations with other funding agencies, and external partnerships.

CURRENT STATUS OF NASA'S ASTROBIOLOGY PROGRAM

NASA's Astrobiology program currently resides within the Planetary Science Division of NASA's Science Mission Directorate and consists of four different programmatic elements:

- The NASA Astrobiology Institute (NAI), a consortium of 16 competitively selected, principal investigator-led teams conducting interdisciplinary research at geographically dispersed research institutions. The NAI's budget for fiscal year 2008 is about $16 million.
- The Exobiology and Evolutionary Biology grants programs, which currently fund some 150 individual principal investigators located at U.S. universities, research institutions, federal laboratories, and NASA centers. The combined budget of these two programs in fiscal year 2008 is about $11 million.
- The Astrobiology Science and Technology Instrument Development (ASTID) program, which funds the initial development of new, astrobiology-relevant instruments that may be selected for future flight opportunities. The program currently funds some 49 instrument-development projects at U.S. universities, research institutions, federal laboratories, and NASA centers. The ASTID program budget for fiscal year 2008 is about $9 million.
- The Astrobiology Science and Technology for Exploring Planets (ASTEP) programs, which fund the field-testing of new, astrobiology-relevant instruments in terrestrial settings representative in some way of the extrater-

TABLE 1.1 Members of the NASA Astrobiology Institute, 1998 to Present

Node	Node Name/Theme of Research	Principal Investigator	Selected in Competition for CAN Number	Period of NAI Funding
Arizona State University	Exploring the Living Universe: Origin, Evolution, and Distribution of Life in the Solar System	John Cronin Jack Farmer	1	1998-2003
NASA Ames Research Center	Linking Our Origins to Our Destiny	David Des Marais	1, 3	1998-2008
Carnegie Institution of Washington	Astrobiological Pathways: From the Interstellar Medium, Through Planetary Systems, to the Emergence and Detection of Life	Sean Solomon	1, 3	1998-2008
Harvard University	The Planetary Context of Biological Evolution	Andrew Knoll	1	1998-2003
Jet Propulsion Laboratory	Definition and Detection of Biosignatures	Kenneth Nealson	1	1998-2003
NASA Johnson Space Center	Center for the Study of Biomarkers in Astromaterials	David McKay	1	1998-2003
Marine Biological Laboratory	Marine Biological Laboratory Astrobiology Science Team/Environmental Genomes and Evolution of Complex Systems in Simple Organisms	Mitchell Sogin	1, 3	1998-2008
Pennsylvania State University	Penn State Astrobiology Research Center/Evolution of a Habitable Planet	Hiroshi Ohmoto	1, 3	1998-2008
Scripps Research Institute	Self-Producing Molecular Systems and Darwinian Chemistry	Reza Ghadiri	1	1998-2003
University of California, Los Angeles	From Stars to Genes: An Integrative Study of the Prospects for Life in the Cosmos	Bruce Runnegar Edward Young	1, 3	1998-2008
University of Colorado	University of Colorado Center for Astrobiology	Bruce Jakosky	1, 3	1998-2008
Michigan State University	Center for Genomic and Evolutionary Studies on Microbial Life at Low Temperatures	Michael Tomashow	2	2001-2006

restrial environments in which they may be eventually deployed. The program currently funds six field campaigns and/or two advanced-instrument projects based at U.S. research institutions, universities, and NASA centers. The ASTEP program budget for fiscal year 2008 is about $5 million.

In response to language in the NASA Authorization Act of 2000 and a subsequent request from NASA, the Astrobiology program and related U.S. and international programs relating to the detection of life in the universe were formally reviewed by the National Research Council. The resulting report, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, commented that "remarkable progress has been made over a short period of time in defining the key scientific questions, initiating research and training programs, and developing collaborations on a national and international scale."[34] The report identified five issues that NASA needed to address in the near term to ensure the health of the Astrobiology program:[35]

TABLE 1.1 continued

Node	Node Name/Theme of Research	Principal Investigator	Selected in Competition for CAN Number	Period of NAI Funding
University of Rhode Island	Subsurface Biospheres	Steven D'Hondt	2	2001-2006
University of Washington	Planetary Habitability and Evolution of Biological Complexity	Peter Ward	2	2001-2006
California Institute of Technology	Virtual Planetary Laboratory/Exploring the Habitability and Biosignatures of Extrasolar Terrestrial Planets	Victoria Meadows	2, 4	2001-2006 and 2007-2012
University of California, Berkeley	BioMars/Biospheres of Mars: Ancient and Recent Studies	Jillian Banfield	3	2003-2008
NASA Goddard Space Flight Center	Origin and Evolution of Organics in Planetary Systems	Michael Mumma	3	2003-2008
Indiana University	Indiana-Princeton-Tennessee Astrobiology Institute	Lisa Pratt	3	2003-2008
SETI Institute	SETI Institute NAI Team/Planetary Biology, Evolution and Intelligence	Christopher Chyba Rocco Mancinelli	3	2003-2008
University of Arizona	Life and Planets Astrobiology Center/Astronomical Search for the Essential Ingredients of Life: Placing Our Habitable System in Context	Neville Woolf	3	2003-2008
University of Hawaii, Manoa	Origin, History and Distribution of Water and Its Relation to Life in the Universe	Karen Meech	3	2003-2008
Massachusetts Institute of Technology	Requirements for Development and Maintenance of Multicellular Life	Roger Summons	4	2007-2012
Montana State University	Astrobiology Biocatalysis Research Center	John Peters	4	2007-2012
University of Wisconsin, Madison	Organic and Mineralogical Signatures and Environments of Life on Earth and Other Planetary Bodies	Clark Johnson	4	2007-2012

- *Definition of astrobiology and its goals.* In particular, the perception in some circles at the time the study was undertaken that astrobiology as both an intellectual endeavor and a NASA program is ill-defined.
- *Evaluation of the impact of the NAI on astrobiology.* Has the NAI affected astrobiology in a way that a standard, principal-investigator grants program could not have? The report recommended as essential that a review of the impact of the NAI on astrobiology be conducted.
- *Review/retirement of existing programs.* Should existing NAI nodes be forced to recompete for funds every 5 years or should some other mechanism be devised to ensure the continuation of productive research teams?
- *Insularity of the NAI.* The report expressed concern about the potential tendency to regard astrobiology as a private club whose membership is exclusively confined to those researchers affiliated with the NAI.
- *The "astro" in astrobiology.* Despite considerable overlap in areas of scientific interest, the astronomical community had little involvement in astrobiology at the time the report was drafted.

TABLE 1.2 Astrobiology Roadmap—Fundamental Goals and Objectives of Astrobiology

Goals	Objectives
1.0 Understand the nature and distribution of habitable environments in the universe by determining the potential for habitable planets beyond the solar system, and characterize those that are observable.	1.1 Investigate how solid planets form, acquire liquid water and other volatile species and organic compounds, and how processes in planetary systems and galaxies affect their environments and habitability. Use theoretical and observational studies of the formation and evolution of planetary systems and their habitable zones to predict where water-dependent life is likely to be found in such systems.
	1.2 Conduct astronomical, theoretical, and laboratory spectroscopic investigations to support planning for and interpretation of data from missions to detect and characterize extrasolar planets.
2.0 Explore for past or present habitable environments, prebiotic chemistry and signs of life elsewhere in the solar system by determining any chemical precursors of life and any ancient habitable climates in the solar system, and characterize any extinct life, potential habitats, and any extant life on Mars and in the outer solar system.	2.1 Through orbital and surface missions, explore Mars for potentially habitable environments, as evidenced by water or aqueous minerals. Study martian meteorites to guide future Mars exploration. Develop the methods and supporting technologies for the in situ characterization of aqueous minerals, carbon chemistry and/or life.
	2.2 Conduct basic research, develop instrumentation to support astrobiological exploration and provide scientific guidance for outer solar system missions. Such missions should explore the Galilean moons Europa, Ganymede and Callisto for habitable environments where liquid water could have supported prebiotic chemical evolution or life. Explore Saturn's moon, Titan, for environments favorable for complex prebiotic synthesis or life.
3.0 Understand how life emerges from cosmic and planetary precursors by performing observational, experimental and theoretical investigations to understand the general physical and chemical principles underlying the origins of life.	3.1 Characterize the cosmic and endogenous sources of matter (organic and inorganic) for potentially habitable environments in the solar system and in other planetary and protoplanetary systems.
	3.2 Identify multiple plausible pathways for the condensation of prebiotic monomers into polymers. Identify the potential for creating catalytic and genetic functions, and mechanisms for their assembly into more complex molecular systems having specific properties of the living state. Examine the evolution of artificial chemical systems that model processes of natural selection to understand better the molecular processes associated with prebiological evolution in the universe.
	3.3 Identify prebiotic mechanisms by which available energy can be captured by molecular systems and used to drive primitive metabolism and polymerization reactions.
	3.4 Investigate both the origins of membranous boundaries on the early Earth and the associated properties of energy transduction, transport of nutrients, growth, and division. Investigate the origins and early coordination of key cellular processes such as metabolism, energy transduction, translation and transcription. Without regard to how life actually emerged on Earth, create and study artificial chemical systems that undergo mutation and natural selection in the laboratory.
4.0 Understand how past life on Earth interacted with its changing planetary and solar system environment by investigating the historical relationship between Earth and its biota by integrating evidence from both the geologic and biomolecular records of ancient life and its environments.	4.1 Investigate the development of key biological processes and their environmental consequences during the early history of Earth through molecular, stratigraphic, geochemical, and paleontological studies.
	4.2 Study the origins and evolution of life forms that eventually led to more complex multi-cellular biota that appear in the fossil record or exist today.
	4.3 Examine the records of the response of Earth's biosphere (both the habitable environment and biota) to extraterrestrial events, including asteroid and comet impacts.

TABLE 1.2 continued

Goals	Objectives
5.0 Understand the evolutionary mechanisms and environmental limits of life by determining the molecular, genetic, and biochemical mechanisms that control and limit evolution, metabolic diversity, and acclimatization of life.	5.1 Experimentally investigate and observe the evolution of genes, metabolic pathways, genomes, and microbial species. Experimentally investigate the forces and mechanisms that shape the structure, organization, and plasticity of microbial genomes. Examine how these forces control the genotype-to-phenotype relationship. Conduct environmental perturbation experiments on single microbial species to observe and quantify adaptive evolution to astrobiologically relevant environments.
	5.2 Experimentally examine the metabolic and genetic interactions in microbial communities that have determined major geochemical processes and changes on Earth. Investigate how these interactions shape the evolution and maintenance of metabolic diversity in microbial communities. Investigate how novel microbial species establish and adapt into existing communities.
	5.3 Document life that survives or thrives under the most extreme conditions on Earth. Characterize and elucidate the biochemical capabilities that define the limits for cellular life. Explore the biochemical and evolutionary strategies that push the physical-chemical limits of life by reinforcing, replacing, or repairing critical biomolecules (e.g., spore formation, resting stages, protein replacement rates, or DNA repair). Characterize the structure and metabolic diversity of microbial communities in such extreme environments.
6.0 Understand the principles that will shape the future of life, both on Earth and beyond by elucidating the drivers and effects of ecosystem change as a basis for projecting likely future changes on time scales ranging from decades to millions of years, and explore the potential for microbial life to adapt and evolve in environments beyond its planet of origin.	6.1 [Characterize] [e]nvironmental changes and the cycling of elements by the biota, communities, and ecosystems.
	6.2 Explore the adaptation, survival and evolution of microbial life under environmental conditions that simulate conditions in space or on other potentially habitable planets. Insights into survival strategies will provide a basis for evaluating the potential for interplanetary transfer of viable microbes and also the requirements for effective planetary protection.
7.0 Determine how to recognize signatures of life on other worlds and on early Earth by identifying biosignatures that can reveal and characterize past or present life in ancient samples from Earth, extraterrestrial samples measured in situ, samples returned to Earth, remotely measured planetary atmospheres and surfaces, and other cosmic phenomena.	7.1 Learn how to recognize and interpret biosignatures which, if identified in samples from ancient rocks on Earth or from other planets, can help to detect and/or characterize ancient and/or present-day life.
	7.2 Learn how to measure biosignatures that can reveal the existence of past or present life through remote observations.

SOURCE: Excerpted from revised NASA Astrobiology Roadmap; see http://nai.arc.nasa.gov/roadmap/.

Despite the concerns about these five issues, the report concluded that NASA's Astrobiology program "is well poised to catalyze fundamentally important discoveries concerning the origins of life, its distribution in the cosmos, and the long-term fate of life on Earth."[36] Now, 5 years after *Life in the Universe* was drafted, the first and fifth items above are no longer regarded as issues of general concern. The remaining three items, all focusing on the NAI, are directly or indirectly the subject of this report.

A discussion of the role of astrobiology in the context of a traditional space-science discipline can be found in *Astronomy and Astrophysics in the New Millennium*,[37] the most recent astronomy and astrophysics decadal survey report, which comments that ". . . researchers can recognize the signature of life elsewhere only by understanding better the history of life on Earth over the past 4 billion years and exploring more deeply the possibility that life has also had an independent history on Mars or other planets and moons in our solar system. This study is an essential part of the new synergy between astronomy, planetary science, and biology—what has been called astrobiology" (p. 157). The decadal survey continues by noting (pp. 157-158) that astrobiology has the potential to:

- ". . . encourage collaborations across . . . disciplines in order to address questions that compel the imaginations of scientists and citizens alike."
- ". . . draw together investigators from disciplines that in the past have shared little except a common interest in understanding the natural world."
- ". . . [bring] diverse scientific cultures together at the right moment in time."
- ". . . [generate] extraordinary public interest . . . by [its] attempts to understand our origins and the ubiquity of life in the universe."
- ". . . link the seemingly abstract world of research at the frontiers of knowledge to questions that have excited the human imagination since people first gazed at the heavens."

Another discussion of the role of astrobiology in the context of a traditional space-science activity can be found in *New Frontiers in the Solar System: An Integrated Exploration Strategy*,[38] the first solar system exploration (SSE) decadal survey. That document highlights the role of astrobiology in (p. 158):

- ". . . [providing] a scientific organizational structure that integrates a wide subset of solar system issues and questions that span the origins, evolution, and extinction of life."
- ". . . [allowing] nonexperts to grasp the connections between different component disciplines within planetary science and to do so in a way that most people will appreciate as addressing core themes in human thought."
- ". . . [being] the primary means by which NASA tries to implement one of its prime objectives—understanding life's origins and its distribution in the universe."
- ". . . [becoming] a fundamental part of the solar system exploration strategy."

In summary, the SSE decadal survey report ". . . encourages NASA to continue the integration of astrobiology science objectives with those of other space science disciplines. Astrobiological expertise should be called upon when identifying optimal mission strategies and design requirements for flight-qualified instruments that [will] address key questions in astrobiology and planetary science" (p. 9).

The goals of astrobiology have not only figured prominently in NRC reports. In outlining plans to implement the Vision for Space Exploration—the initiative to return humans to the Moon and, ultimately, to Mars—President George W. Bush charged NASA to conduct robotic exploration of Mars to search for evidence of life; to explore Jupiter's moons, asteroids, and other bodies to search for evidence of life; and to undertake advanced telescopic searches for Earth-like planets and habitable environments around other stars.[39] These fundamental, astrobiology goals, enunciated by President Bush in 2004 as the science component of the Vision, figure prominently in NASA strategy planning documents.[40]

The most recent NRC comments on the role, scope, and status of NASA's Astrobiology program are made in *An Assessment of Balance in NASA's Science Programs*.[41] This document makes the following points (p. 20):

- "The decadal surveys for astrophysics and for solar system exploration both embraced astrobiology as a key component of their programs, with the questions encompassed by astrobiology serving as overarching themes for the programs as a whole."
- "The missions put forward in the solar system exploration survey are all key missions in astrobiology, whether they are labeled as such or not. And issues and missions related to astrobiology represent one of the key areas of interest identified in the astronomy and astrophysics communities."
- "Astrobiology provides the intellectual connections between otherwise disparate enterprises."

The report continues by recognizing that: "NASA's Astrobiology program creates an integrated whole and supports the basic interdisciplinary nature of the field. Further, the Vision [for Space Exploration] is, at its heart,

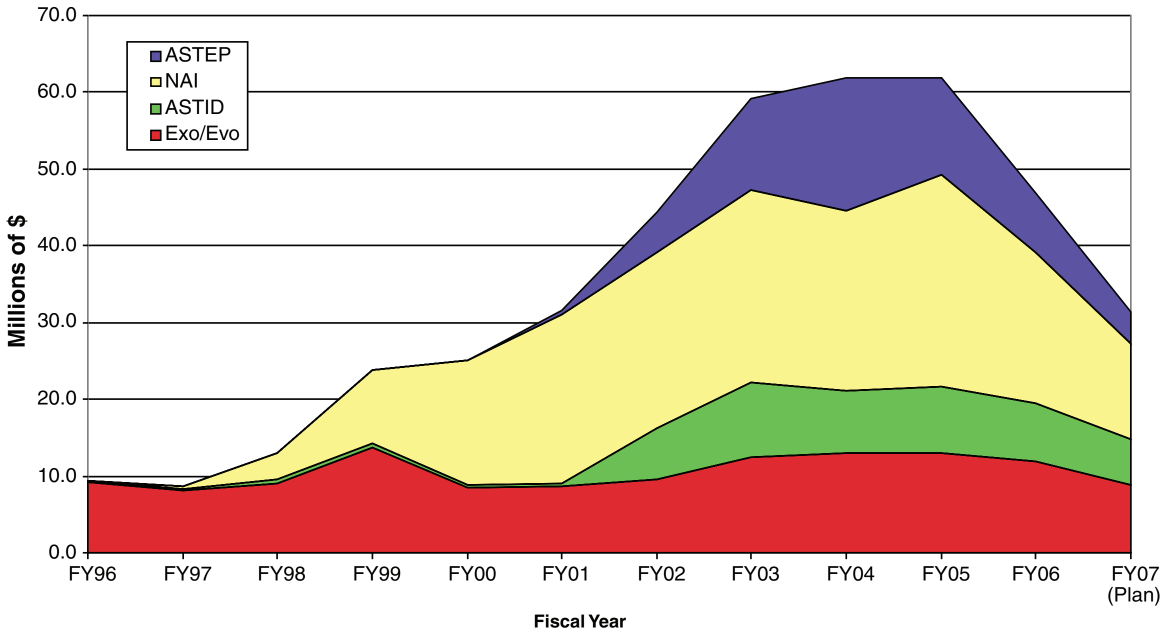

FIGURE 1.1 The budgetary history of the four elements constituting NASA's Astrobiology program. The program is currently operating on an annual budget of approximately $4 million more that the figure indicated for fiscal year 2007. Courtesy of John D. Rummel, NASA Science Mission Directorate.

largely an astrobiology vision with regard to the science emphasis [footnote omitted]. In developing the future of the program, the missions actually feed forward from the basic science. Astrobiology is just beginning the type of synthesis and integration that will allow it to provide science input for future mission development. Without it, the science and the scientific personnel will not be in place to support the missions when they do fly."[42]

Despite favorable reviews by the NRC and almost a decade's worth of steady budget increases (Figure 1.1), the astrobiology community was shocked to learn that NASA's proposed budget for Fiscal Year 2007 included a 50 percent cut for the Astrobiology program. The reason why the program was singled-out for a cut of 50 percent when other programs were only cut by 15 percent has never been explained satisfactorily.

Some slight budgetary relief came in 2007 when approximately $4 million was added back to the program from SMD discretionary funds and a reallocation of resources within SMD's Planetary Science Division. Nevertheless, the current expectation is that NASA's Astrobiology budget will remain at approximately the FY2007-level with annual corrections for inflation. Thus, the Astrobiology program enters its second decade with a major disconnect between the resources allocated to its execution and the important role ascribed to the program in NASA and NRC strategic plans.

NOTES

1. See, for example, S.J. Dick and J.E. Strick, *The Living Universe: NASA and the Development of Astrobiology*, Rutgers University Press, New Brunswick, New Jersey, 2004, pp. 205-213.
2. L.J. Mix et al. (eds.), "The Astrobiology Primer: An Outline of General Knowledge—Version 1, 2006," *Astrobiology* 6: 735-813, 2006. Available at http://www.liebertonline.com/doi/pdfplus/10.1089/ast.2006.6.735.
3. See, for example, http://www.nai.arc.nasa.gov/about/about_nai.cfm#overview.
4. L.J. Lafleur, "Astrobiology," *Astronomical Society of the Pacific Leaflets* 3: 333-340, 1941.
5. See, for example, H. Sturghold, *The Green and Red Planet*, University of New Mexico Press, Albuquerque, New Mexico, 1953; O. Struve, "Life on Other Worlds," *Sky and Telescope* 14: 137-146, 1955; or A.G. Wilson, "Problems Common to the Fields of Astronomy and Biology: A Symposium—Introduction," *Publications of the Astronomical Society of the Pacific* 70: 41-43, 1958.

6. See, for example, S.J. Dick and J.E. Strick, *The Living Universe: NASA and the Development of Astrobiology*, Rutgers University Press, New Brunswick, New Jersey, 2004, pp. 204-205.

7. J.E. Strick, "Creating a Cosmic Discipline: The Crystallization and Consolidation of Exobiology, 1957-1973," *Journal of the History of Biology* 37: 131-180, 2004.

8. V.V. Levin and P.A. Straat, "Recent Results from the Viking Labeled Release Experiment on Mars," *Journal of Geophysical Research* 82: 4663-4667, 1977.

9. N.H. Horowitz, G.L. Hobby, and J.S. Hubbard, "Viking on Mars: The Carbon Assimilation Experiments," *Journal of Geophysical Research* 82: 4659-4662, 1977.

10. V.I. Oyama and B.J. Berdahl, "The Viking Gas Exchange Experiment Results from Chryse and Utopia Surface Samples," *Journal of Geophysical Research* 82: 4669-4676, 1977.

11. K. Biemann, J. Oro, P. Toulmin III, L.E. Orgel, A.O. Nier, D.M. Anderson, D. Flory, A.V. Diaz, D.R. Rushneck, and P.G. Simmonds, "The Search for Organic Substances and Inorganic Volatile Compounds in the Surface of Mars," *Journal of Geophysical Research* 82: 4641-4662, 1977.

12. N.H. Horowitz, *To Utopia and Back: The Search for Life in the Solar System*, Freeman, New York, New York, 1986, pp. 134-136 and 137-138.

13. See, for example, S.J. Dick and J.E. Strick, *The Living Universe: NASA and the Development of Astrobiology*, Rutgers University Press, New Brunswick, New Jersey, 2004.

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2

Interdisciplinary Research

This chapter evaluates the success of the NASA Astrobiology Institute (NAI) in achieving its stated goal of conducting, supporting, and catalyzing collaborative interdisciplinary research.

NAI CONTRIBUTIONS

The NAI has had considerable success in defining key scientific objectives and initiating interdisciplinary research. The NAI has also provided a mechanism for developing collaborations on both a national and an international scale. The NAI has been instrumental in keeping astrobiology a cutting-edge field and fully complements other Astrobiology program elements in NASA's Science Mission Directorate. Although the enormous potential of the NAI for promoting collaborative, distributed, interdisciplinary research has not yet been fully realized, considerable progress has been made.

The NAI has successfully established the infrastructure to promote interdisciplinary research by providing competitive proposal opportunities for major science teams (or nodes) with a geographically distributed membership. These nodes are further facilitated by a central coordinating office—NAI Central—whose small but highly professional staff provides oversight of NAI operations and develops the state-of-the-art Web tools necessary to operate a virtual institute. Strategic decisions are made by NAI leadership in partnership with NASA Headquarters as, for example, in the development of the Director's Discretionary Fund and plans to have NAI Central develop an integrated Web presence for the Astrobiology program as a whole.[1] Additional information on the organization of the NAI can be found in Chapter 1.

The NAI has succeeded in managing proposal competitions that are not biased in favor of NASA centers, demonstrating high scientific standards and fairness. Unfortunately, the NAI's success has been tempered by recent budget cuts that threaten the ability of the NAI to reach its full potential.

Scientific Contributions

Although the committee was not charged to undertake a review of the NAI's scientific contributions, it is not possible to evaluate the NAI's success in conducting, supporting, and catalyzing collaborative interdisciplinary research without some brief mention of the NAI's scientific achievements. Fortunately for the committee, the NAI has compiled a list of what it believes to be its top research accomplishments. Starting with the early Earth and moving outward in time and space, these accomplishments include research aimed at elucidating the following:

- *Early habitability of Earth.* The NAI has supported Stephen Mojzsis (University of Colorado team) and others (e.g., Mark Harrison, University of California, Los Angeles, team) to investigate the oldest rocks and to use ancient zircons to characterize the environment of the young Earth. One result is evidence for an ocean and hydrological cycle in the Hadean Eon, the first 500 million years of Earth's history.[2,3] For additional details see Box 2.1.
- *The rise of oxygen and Earth's "middle age."* NAI support was critical in fostering a new interest in the Archean and Proterozoic Eons, the geological periods from approximately 3.9 billion to 2.5 billion and from 2.5 billion to 542 million years ago, respectively. The NAI sponsored collaborative deep-drilling projects and isotopic studies to document the co-evolution of Earth's biota with the rise of atmospheric oxygen. Findings include new evidence of oxygen before the so-called Great Oxidation Event, improved understanding of the timing of this event, and evidence that this event led to a Proterozoic world unlike what came before or after.[4-8] For additional details see Box 2.2.
- *Snowball Earth*. The NAI supported fieldwork by Paul Hoffman (Harvard University) and his students to provide high-resolution stratigraphic and geochemical data needed to refine the hypothesis that Earth was, at times, completely covered with ice during the period from 850 million to 630 million years ago. Snowball Earth and other extreme events are now considered a natural aspect of Earth's evolution on long timescales. Other NAI investigators at the California Institute of Technology and Arizona State University have investigated the implications of this period for the evolution of life.[9-12] For additional details see Box 2.3.
- *Microbial mat ecology*. In situ studies, led by the NAI team at NASA's Ames Research Center, of the Guerrero Negro hypersaline microbial mats (modern representatives of one of Earth's earliest and most pervasive

BOX 2.1
EARLY HABITABILITY OF EARTH

Direct information concerning the first 500 million years of Earth history—the Hadean Eon, approximately 4.0 billion to 4.5 billion years ago—is very limited, since practically no crustal rocks from that time have survived. Researchers do know that asteroids and comets collided with Earth much more frequently than they do today, and astronomers also tell us that the Sun was about 30 percent fainter then, so that Earth may have been cold, unless there was a large greenhouse effect to trap the Sun's heat and raise surface temperatures above the freezing point. Also of special interest is the apparent fact that life arose on Earth either during or shortly after the Hadean Eon.

Understanding the chemical state of the earliest atmosphere and ocean is critical to any theory of the origins of life on Earth. Stephen Mojzsis (University of Colorado team) and colleagues have been investigating the geological record, including the use of ancient zircons to determine the environment on the earliest Earth. The oldest rocks, found in Australia, Canada, and Greenland, are less than 4.0 billion years old. Some of the zircons they contain are much older; oxygen isotope dating places some of these zircons at ages up to 4.3 billion years. Mojzsis and colleagues conclude that these zircons were formed from magmas containing a significant component of reworked continental crust that formed in the presence of water at Earth's surface. This result is consistent with the presence of a hydrosphere interacting with the crust within only 200 million years of Earth's Moon-forming event.

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BOX 2.2
THE RISE OF OXYGEN AND EARTH'S "MIDDLE AGE"

High-precision studies of sulfur-isotope fractionation reveal that some photochemical reactions can produce isotope variations that do not scale simply with mass. These mass-independent fractionation (MIF) reactions require ultraviolet radiation that is blocked by O_3, and the preservation of their fractionated reaction products requires low atmospheric O_2. Sulfur-MIF studies indicate that Earth's atmosphere became oxygenated (the "Great Oxidation Event") in the early Proterozoic, about 2.3 billion years ago. One possible cause is the development of oxygenic photosynthesis at that epoch; alternatively, the rise of atmospheric O_2 may have been mediated by geological processes.

Access to unweathered and uncontaminated samples of the oldest and least-altered sedimentary rocks is essential for understanding the early history of life on Earth and the environments in which it may have existed. The NAI initiated the Astrobiology Drilling Program (ADP), an outgrowth of the Mission to Early Earth Focus Group, which funded drilling (primarily in Western Australia) to access fresh subsurface samples that are made available to a broad scientific community.

Initial analyses reveal that at least trace amounts of O_2 may have been present hundreds of millions of years before the Great Oxidation Event. Whereas it was once thought that the Proterozoic was a mildly oxygenated version of the modern, it is increasingly believed that the rise of oxygen led, paradoxically, to intensification of anoxia in large parts of the deep ocean. The NAI was instrumental in catalyzing research that tested the broad strokes of this hypothesis as well as research into the possible evolutionary consequences of a billion years of ocean redox stratification.

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ecosystems), combined with greenhouse cultures, reveal a complex layered symbiotic ecology with more than 1,000 species and substantial diurnal fluxes of nutrients and of both reduced and oxidized gases. Ancient mats may have been a significant contributor to long-term atmospheric oxygenation.[13-16] For additional details see Box 2.4.

- *Discovery of the "rare biosphere."* Using novel biotechnology that permits detection of almost all members in a microbial community, the NAI team at the Marine Biological Laboratory have discovered that the microbial diversity in the deep ocean is up to 100 times greater than expected within a population that is more than a million-fold depleted relative to the primary microbiota. This "rare biosphere" gene pool could serve as reserve of genetic diversity for repopulation of a habitat should conditions change dramatically.[17-20] For additional details see Box 2.5.
- *Sub-seafloor life*. NAI investigators from the University of Rhode Island, Woods Hole Oceanographic Institution, and the University of North Carolina led the first ocean-drilling expedition focused on exploration of subsurface life and habitability. Their results demonstrated that deep sub-seafloor communities are metabolically

BOX 2.3
SNOWBALL EARTH

During Snowball Earth events, biological productivity in the oceans collapsed for millions of years due to extensive freezing. The NAI supported much of the fieldwork by Paul Hoffman (Harvard University team) and his students—in Namibia, Spitsbergen, and northwestern Canada—that provided the high-resolution stratigraphic and geochemical data needed to test and refine the snowball hypothesis.The NAI also supported Samuel Bowring's fieldwork that determined strong geochronometric constraints on the timing of Neoproterozoic ice ages. The Snowball Earth topic was an integral part of Harvard University's 1998 NAI proposal, and much of that team's efforts went into developing the concept into a truly multidisciplinary topic of great astrobiological importance. Although the severity of the historical glaciations is debated, theoretical Snowball conditions are associated with the nearly complete shutdown of the hydrological cycle. A recent result by Joseph Kirschvink and colleagues suggests that, during such long and severe glacial intervals, photochemical reactions would give rise to the sustained production of hydrogen peroxide, which is stored in the ice. The peroxide would then be released directly into the ocean and the atmosphere upon melting and could mediate global oxidation events in the aftermath of the Snowball. Low levels of peroxides and molecular oxygen generated during Archean and earliest Proterozoic non-Snowball glacial intervals could have driven the evolution of oxygen-using enzymes and thereby paved the way for the eventual appearance of oxygenic photosynthesis.

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complex and phylogenetically diverse. Microbes in anoxic, deep sub-seafloor sediments respire at rates that are orders of magnitude slower than previously believed necessary to sustain life. Their metabolic pathways include new processes, such as the biological generation of ethane and propane.[21-25] For additional details see Box 2.6.

- *Metal isotope tracers of environment and biology*. Studies of the biological and abiological fractionation of metal isotopes, particularly the redox-sensitive elements molybdenum and iron, were motivated by astrobiology objectives to study Earth's redox evolution and to find new signatures for life. This work has been supported by the NAI from its earliest days (e.g., Kenneth Nealson's team at the Jet Propulsion Laboratory) and is the focus of the new team headed by Clark Johnson (University of Wisconsin). Iron-isotope geochemistry is now being pursued in about 30 laboratories across the globe.[26-31] For additional details see Box 2.7.
- *Life without the Sun*. NAI scientists from Princeton University and Indiana University have discovered deeply buried life in a South Africa gold mine that appears to thrive independent of the familiar surface biosphere, which is powered by sunlight. These microbes draw energy from hydrogen and sulfates produced when the decay of radioactive elements in the rocks disassociates water molecules.[32] For additional details see Box 2.8.
- *Early wet Mars*. NAI astrobiologists such as Jack Farmer (Arizona State University team), David Des Marais (Ames Research Center team), Andrew Knoll (Harvard University team), Mark Allen (JPL team), John Grotzinger (MIT team), and Bruce Jakosky (University of Colorado team) have played major roles in recommending landing sites, defining objectives and spacecraft operations, and interpreting data from current Mars orbiters

BOX 2.4
MICROBIAL MAT ECOLOGY

NAI scientists from the team at the Ames Research Center led an interdisciplinary study of hypersaline cyanobacterial mats that has yielded important insights into the evolution of microbial systems, the role of biology in the chemical evolution of our planet, and the interpretation of biosignatures in Earth's early rock record. As sunlight-dependent systems, microbial mats exhibit dramatic shifts in metabolic, ecological, and biogeochemical function from day to night. The Ames team demonstrated the critical importance of the less-studied dark, anoxic component of this cycle in several areas. Mats were found to deliver fluxes of H_2, CH_4, and CO gases to the atmosphere at rates up to several percent of their gross photosynthetic productivity. Such emissions might have augmented H_2 escape to space and contributed substantially and irreversibly to the oxygenation of the ancient atmosphere. Anaerobic mat processes also produce sulfur-bearing volatile organics that are plausible atmospheric biosignatures. Such processes have been documented in their role as the final filter and ultimate arbiter of organic and carbon- and sulfur-isotopic biomarkers entering the rock record. Through collaborative efforts with the Ames, University of Colorado, Marine Biological Laboratory, and Arizona State University teams, the dynamic geochemistry of these systems has been linked to an enormous underlying microbial diversity.

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and rovers—yielding key chemical and geological evidence for widespread liquid water on Mars in its first billion years. For additional details see Box 2.9.

- *Methane on Mars*. Michael Mumma (principal investigator of the NAI node at NASA's Goddard Space Flight Center) heads one of three teams that have reported detection of methane in the martian atmosphere. Methane, often suggested as a biosignature gas, has a lifetime of only a few centuries under martian conditions, indicating a currently active source. This work thus suggests a line of research that could lead to the first positive evidence for extant life on another planet.[33-36] For additional details see Box 2.10.
- *Comets in space and in the laboratory*. Comets were a major source of biogenic materials on planets. NAI members from the University of Hawaii, Goddard Space Flight Center, Carnegie Institution of Washington, and Ames Research Center teams carry out ground- and space-based research on organics in comets, including development of several state-of-the-art organic astrochemistry laboratories to help interpret the observational data. The Carnegie team and others have probed the molecular structure of organic matter in meteorites, as a complementary approach to understanding the chemical context for the formation of life.[37-42] For additional details see Box 2.11.
- *Exoplanet discovery and analysis*. NAI members, primarily from the team at the Carnegie Institution of Washington, are playing important roles in the search for exoplanets,[43] with particular attention to issues of habitability. They are part of a group that is building several new spectrometers that will accelerate this search, while others are using the Spitzer Space Telescope to study the infrared signatures of atmospheric composition in

BOX 2.5
DISCOVERY OF THE "RARE BIOSPHERE"

A previously unknown "rare biosphere" that co-exists with more familiar life in the deep ocean was discovered by a multi-institution consortium under the leadership of Mitchell Sogin, principal investigator of the NAI team at the Marine Biological Laboratory. These scientists used new genetic analysis tools to sample the much rarer microbes that have previously gone undetected, using samples collected from both normal cold seawater and hydrothermal vents. This new analysis reveals enormous diversity within this rare biosphere. The techniques used do not permit individual organisms to be isolated for study, but they allow statistical estimates of the population. Although the numbers of such microbes are small, there is at least 100 times greater species diversity than had been expected. This rare biosphere is very ancient and may represent a nearly inexhaustible source of genomic innovation. Members of the rare biosphere are highly divergent from each other and, at different times in Earth's history, may have had a profound impact on shaping planetary processes. Perhaps they represent a kind of natural "back-up system" that could repopulate a habitat if environmental conditions were to change in ways that threaten the dominant ecosystem.

Related research from the NAI team at the University of California, Berkeley, has found novel low-abundance archaeal species in biofilms from acidic water at the Richmond Mine in California. These enigmatic microorganisms are ubiquitous at the smallest size level. The Marine Biological Laboratory team, in collaboration with astrobiologists at the Centro de Astrobiología in Madrid, have also discovered high levels of protist diversity in iron-rich acidic environments in the Rio Tinto system in Spain.

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transiting planets. Giovanna Tinetti of the NAI's Virtual Planetary Laboratory team used this approach to discover evidence suggesting the presence of water vapor in the atmosphere of an extrasolar planet.[44] For additional details see Box 2.12.

- *Modeling exoplanet biospheres*. The NAI's Virtual Planetary Laboratory, led by Victoria Meadows, has organized a highly multidisciplinary team to undertake research focusing on habitability, extrasolar terrestrial planets, and biosignatures. This is a fundamentally new effort to develop models for the co-evolution of planets and life, addressed to NASA's requirements for future missions to search for life beyond the solar system.[45-48] For additional details see Box 2.13.

This list, like all such lists, raises multiple questions: Are these contributions really important? Will they stand the test of time? What fraction of these contributions was influenced by or due directly to the NAI? Do they represent unique contributions that would not have been made absent the NAI? Are they the result of a dispassionate assessment or do they represent the most favorable interpretations of NAI research results? However, the committee was not charged to answer such specific questions. Rather, it was asked to evaluate the NAI's success in conducting, supporting, and catalyzing collaborative interdisciplinary research. While it will be very interesting to look back in another decade and see which of these contributions have flowered into major discoveries, and

BOX 2.6
SUB-SEAFLOOR LIFE

NAI-supported investigators from the University of Rhode Island, Woods Hole Oceanographic Institution, and the University of North Carolina have investigated life deep beneath Earth's seafloor. Their results from Ocean Drilling Program Leg 201 demonstrated that deep sub-seafloor communities are metabolically complex. Mutualistic interactions sustain these communities for millions of years with extremely little ongoing input of organic matter. In many aspects, these communities serve as a model for possible life on other worlds. These aspects include their extraordinarily low rates of maintenance activity, their complexity of energetic interactions, and their generation of compounds not previously known to be biomarkers (i.e., ethane and propane).

Collaborations involving the NAI teams at the Marine Biological Laboratory, University of Rhode Island, and Pennsylvania State University have helped to advance understanding of microbial diversity in this remote environment. In pursuit of this research, NAI investigators have developed many tools that can also be applied to the study of life in other extreme environments and on other worlds: these include an assay for quantifying extremely low levels of fundamental enzymatic activity (hydrogenase), refined techniques for quantification of microbial contamination, and a simple technique for quantifying concentrations of dissolved volatile metabolites (such as methane).

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which are ascribed to the NAI, the committee does not have that luxury. Without commenting on the specifics of any of NAI's self-selected scientific contributions, the committee believes that taken together they do represent a substantial body of scientific results.

An important question then is, since some of the NAI's scientific contributions listed above are more interdisciplinary than others, should the NAI only take credit for research that is truly interdisciplinary? The answer must be no. Research that is predominantly the domain of a single discipline (e.g., the search for and characterization of exoplanets) is a necessary precursor to more interdisciplinary activities (e.g., modeling exoplanet biospheres). Thus, interdisciplinarity must be viewed as the orientation and emergent quality of an overall enterprise and not as a requirement or expectation levied on every piece of work produced by that enterprise. Too great an emphasis on what is and is not interdisciplinary science could potentially lead to an overly bureaucratic emphasis on proxy measures of intellectual achievements such as counts of the relative number of papers with multiple authors from different disciplines. Progress in addressing interdisciplinary science goals can be made by independent experts working singly or in concert with colleagues from other disciplines. Since it is the result that counts, and not the

BOX 2.7
METAL ISOTOPE TRACERS OF ENVIRONMENT AND BIOLOGY

Isotopic variations among the transition metals and other heavy elements permit tracing the redox cycling of metals and hence environmental redox change. Some of the largest isotopic fractionations are produced by microbially mediated redox changes, such as the fractionation in $^{34}S/^{32}S$ ratios that occurs upon bacterial reduction of SO_4^{2-} to S^{2-}. Significant isotopic fractionations may also be found among the transition metals that have multiple redox states. The greatest focus has been on Fe because it is a major element in the crust and serves as an electron donor for anaerobic photosynthesis and an electron acceptor for metabolic Fe reduction. Studies of the coupled C-S-Fe system provide insights into the co-evolution of photosynthetic and heterotrophic respiration pathways.

Molybdenum (Mo) provides another useful probe of global ocean conditions. NAI-sponsored research has shown that the Mo isotope composition of the oceans reflects the extent of seafloor oxygenation. Under oxidized conditions, Mo exists as MoO_4^{2-} in the oceans, and significant fractionations in $^{97}Mo/^{95}Mo$ ratios occur upon sorption to Fe-Mn oxides. Under reduced conditions, Mo (present as MoS_4^{2-}) is relatively insoluble and would be expected to have isotopic compositions reflecting bulk continental crust. This area of research is just beginning to be fully explored.

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methodology chosen to achieve it, the committee determined that the NAI has been successful in conducting, supporting, and catalyzing collaborative interdisciplinary research.

RELATIONSHIP TO OTHER ASTROBIOLOGY PROGRAMS

NAI programs appear to complement the other elements of NASA’s Science Mission Directorate Astrobiology program: i.e., the Exobiology and Evolutionary Biology grants to individual scientists, the technology development activities of the Astrobiology Science and Technology Instrument Development (ASTID) program, and field-testing activities supported by the Astrobiology Science and Technology for Exploring Planets (ASTEP) program.

BALANCE OF NAI ACTIVITIES

Interdisciplinary, collaborative research is a requirement for NAI funding. As a result, proposals that address questions best answered using interdisciplinary and collaborative approaches are favored. The effectiveness of the NAI’s strategy can, therefore, be judged, in part, by its success in advancing interdisciplinary science. This work ranges from purely theoretical studies to observational science based on field expeditions. The NAI researchers

BOX 2.8
LIFE WITHOUT THE SUN

Potentially among the most important recent discoveries in astrobiology is the finding of specific examples of deeply buried life forms that appear to thrive independent of the familiar surface biosphere, which is powered by sunlight. These particular microbes, discovered by scientists from the NAI's Indiana-Princeton-Tennessee team, live in hot groundwater 2.8 km below the surface in a South African gold mine.[1] They ultimately draw their energy from the slow decay of radioactive elements in the rocks. The radiation dissociates water, and the resulting oxygen reacts with pyrite to form iron sulfate. This iron sulfate, in turn, is utilized along with hydrogen from the dissociated water to support microbial metabolism. The existence of such a deep subsurface microbial community on Earth suggests that similar isolated biospheres could persist on other planets, such as Mars, in spite of hostile conditions on their surfaces.

Using modern genetic analysis tools, the NAI team was able to compare the microbes with other anaerobic microbial communities that derive their energy from sulfate reduction. A detailed study of the water chemistry from this environment indicates that there is sufficient naturally produced sulfate and hydrogen to sustain life indefinitely. The base of the food chain is a sulfate reducer belonging to the phylum called Firmicutes, and other microbes in the community may subsist on products from this primary producer. The water itself was dated at approximately 10 million years, during which time it has had no physical or chemical contact with the familiar world far above.

[1]L-H. Lin, P-L. Wang, D. Rumble, J. Lippmann-Pipke, E. Boice, L.M. Pratt, B. Sherwood Lollar, E.L. Brodie, T.C. Hazen, G.L. Andersen, T.Z. DeSantis, D.P. Moser, D. Kershaw, and T.C. Onstott, "Long-Term Sustainability of a High-Energy, Low-Diversity Crustal Biome," *Science* 314: 479-482, 2006.

who spoke to the committee—including those from the Marine Biological Laboratory, the California Institute of Technology, the University of Washington, Pennsylvania State University, and the Ames Research Center—believe that many of these efforts would not have been conceived and brought to fruition without the unique interdisciplinary focus supported by the NAI. Examples of specific efforts catalyzed by involvement in the NAI are described in Boxes 2.2 (Pennsylvania State University), 2.4 (Ames Research Center), 2.5 (Marine Biological Laboratory), and 2.13 (California Institute of Technology and University of Washington).

Also significant are the international relationships that the NAI has nurtured through the systematic definition and promotion of astrobiology goals, the free exchange of information, and a general willingness to cooperate with both individual scientists and research organizations outside the United States. The creation of astrobiology research centers and scientific organizations in Europe (e.g., Spain's Centro de Astrobiología,[49] France's Groupement de Recherche en Exobiologie,[50] the Astrobiology Society of Britain,[51] the Russian Astrobiology Center,[52] and the European Exo/Astrobiology Network Association[53]), Australia (e.g., the Australian Center for Astrobiology[54]), the Middle East (e.g., the Israel Society for Astrobiology and the Study of the Origin of Life[55]), and Latin America (e.g., the Red Mexicana de Astrobiología[56]) would not have been realized without the catalytic role of the NAI in prompting a tightly knitted international community of astrobiologists with similar scientific goals.

The level of distributed, collaborative, interdisciplinary research performed by active NAI science teams varies, ranging from some truly interdisciplinary work that demands expertise, collaboration, and contributions from the many fields within astrobiology, to cases that are best described as multidisciplinary, performed by groups of researchers with limited collaborative interactions among members of the same node or with other NAI nodes.

The committee notes that competition for NAI funding can discourage collaboration among teams by inhibiting the free exchange of ideas and data between the competing teams. To offset this tendency, the NAI established the Director's Discretionary Fund (DDF). The establishment of the DDF was agreed to at the NAI's January 2007 Strategic Impact Workshop. The principal investigators of the NAI teams agreed to take a somewhat larger

BOX 2.9
EARLY WET MARS

From its inception, the NAI provided a multidisciplinary forum (e.g., in the NAI Mars Focus Group, as well as topical workshops, the NAI General Meeting, and so on) for ideas concerning the habitability of Mars. These discussions and interactions have played a significant role in recent and ongoing Mars missions that are transforming current understanding of the planet and reviving interest in the possibility of extant life there. Two of the most important recent discoveries on Mars were “gullies” that indicate relatively recent surface flows, less than a million years old, and the evidence from the Mars Exploration Rovers on the surface that shallow ponds or seas of salty water once covered much of the surface, although they may have been transient. The rover *Opportunity*, which was targeted toward a region where hematite had been discovered, has repeatedly surprised and delighted astrobiologists with its measurements of sedimentary rocks exposed in crater walls that provide convincing chemical and physical evidence of past water. These discoveries are the result of an astrobiology-inspired strategy for Mars exploration called “follow the water.” This focus on issues of past and present habitability is the logical prelude to resuming the search for life itself.

One metric of NAI influence on Mars-mission science is the participation of NAI members in the competitively selected mission teams:

- Mars Exploration Rover—David Des Marais, Andrew Knoll, Ronald Greeley, John Grotzinger, Phillip Christensen, and Jack Farmer;
- Mars Reconnaissance Orbiter—David Des Marais and John Grotzinger;
- Mars Science Laboratory—Paul Mahaffy, Wesley Huntress, James Scott, Andrew Steele, Edward Vicenzi, John Grotzinger, and David Blake; and
- Mars Atmosphere and Volatile Evolution (Mars Scout Proposal)—Bruce Jakosky.

percentage cut to their individual budgets than was called for in the Administration’s budget for the 2007 fiscal year. The resulting savings were pooled to create a $1.8 million fund for strategic investments addressing the following goals:

- Advancing the science of astrobiology,
- Demonstrating impact on NASA’s spaceflight programs or its broader science activities, and/or
- Contributing to NASA’s role as a federal research and development agency through the development of strategic partnerships.

Proposals to the DDF were solicited and were required to be cross-nodal and to address strategic astrobiology goals, and they could involve researchers not affiliated with the NAI. In April 2007, 18 DDF proposals were selected for funding. Approximately half were for research projects; the other half were for workshops or conferences. The research projects ranged from development of Mars-related instrument concepts, to an inter-laboratory cross-calibration of sample-analysis instruments, to a geomicrobiology study of an Arctic ice-sulfur spring ecosystem as a testbed for Europa exploration technology. The DDF awards are an important mechanism for addressing strategic issues and for promoting interdisciplinary research.

Perhaps the most important metric of the success of the NAI is the publication record of its members, past and present. Unfortunately, the extent to which the publications of the NAI are interdisciplinary is very much subject to interpretation. Some of the papers are truly interdisciplinary. But there also appears to be a large body of work arising from NAI-funded research that contributes only to specialized fields, i.e., activities than could be

BOX 2.10
METHANE ON MARS

Three research teams reported detecting the gas methane in the martian atmosphere, at the low concentration of 10-50 parts per billion. Most methane on Earth is produced in biological processes, both contemporary production by microbes and as underground natural gas formed by earlier generations of microbial life. Since methane is relatively short-lived once it is released into the atmospheres of either Earth or Mars, its presence has long been considered a biomarker. Identification of a biomarker on Mars would qualify as one of the most important discoveries of astrobiology and space exploration. The three reported detections of methane were all made spectroscopically, by one team led by Michael Mumma (principal investigator of the NAI team at NASA's Goddard Space Flight Center), by other astronomers led by V. Krasnopolsky of Catholic University of America, and from the Planetary Fourier Spectrometer instrument on the European Space Agency's Mars Express spacecraft (Vittorio Formisano, principal investigator). Both biological and non-biological possibilities are being pursued, for example in recent work by members of the NAI team at the University of California, Berkeley, on hydrate dissociation. The amount of methane detected on Mars is about a factor of 100 less than the amount that would result if martian methane production were equal to Earth's non-biological production.

A timely NAI contribution to this important debate was the workshop "Methane on Mars" conducted on May 18, 2005, shortly after the first detections were presented. The NAI used its video and Internet-based communications network to link participants at a number of sites. A workshop report was published in *EOS* in 2006.

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described as "business as usual." Of course, not all contributions addressing interdisciplinary science goals need to be made in an interdisciplinary manner.

Nevertheless, it is the committee's assessment that a growing number of publications being produced by some of the NAI nodes report truly interdisciplinary work. For example, many of the research contributions outlined above (and in Boxes 2.1-2.13) involved collaborations between individuals who categorize themselves primarily as Earth scientists and life scientists (e.g., the work on microbial mats, metal isotopes, and subsurface biospheres) or as Earth scientists and physicists (e.g., the work on Snowball Earth). Other contributions involved more complex collaborations between researchers who call themselves Earth scientists, planetary scientists, astronomers, and chemists (e.g., studies of cometary materials) or Earth scientists, life scientists, planetary scientists, astronomers, and physicists (e.g., modeling of exoplanet biospheres).[57]

Moreover, the publications that result from these multidisciplinary collaborations are generally of a high quality. This is attested to by the fact that 60 percent of the papers referenced above in the list of the NAI's most significant scientific contributions (see also Boxes 2.1-2.13) were published in high-impact, general science journals such as *Nature* (13 percent), *Proceedings of the National Academy of Sciences* (15 percent), and *Science* (32

BOX 2.11
COMETS IN SPACE AND IN THE LABORATORY

Construction at NASA's Goddard Space Flight Center (GSFC) and Ames Research Center (ARC) of premier organic analytical laboratories for astrobiology permits analysis of returned samples from the Stardust mission (Donald Brownlee, a member of the NAI team at the University of Washington team and the principal investigator of the Stardust mission) and simulations of organic synthesis that takes place in the interstellar material and on the surfaces of icy bodies.

The GSFC team's study of Stardust samples has provided identification of specific cometary organic compounds (i.e., methylamine and ethylamine). Laboratory work has led to the discovery that the reaction mechanism for the formation of amino acids from ultraviolet photolyzed ices varies by amino acid. The laboratory study at ARC of the properties of polycyclic aromatic hydrocarbons has led to the identification of this ubiquitous compound in many solar system bodies and as an important reservoir of carbon throughout this (and other) galaxies.

Astronomical observations of comets—undertaken by the NAI teams at GSFC and the University of Hawaii—have shown that Kuiper Belt and Oort cloud reservoirs both contain compositionally-distinct comets formed in diverse nebular regions, with both organics-normal and organics-depleted comets found in both reservoirs. These results support the emerging new paradigm in which icy planetesimals from diverse regions of the protoplanetary disk are injected into each reservoir, albeit in different fractions.

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percent). Of the remaining papers referenced, a significant number were published in high-impact, specialized journals such as the *Astrophysical Journal* (9 percent).

Entrepreneurial researchers within nodes use NAI resources effectively to leverage funding from their home institutions, other federal agencies (e.g., the National Science Foundation, the National Oceanic and Atmospheric Administration, the National Institutes of Health, and the Department of Energy), and private sources. This appears to be critical to the success of NAI nodes, and it is not clear that any of the nodes could accomplish their research goals without these additional funds. Two NAI teams, those based at Harvard University and the Scripps Research Institute, decided to forgo re-competing for additional NAI funds when their 5-year funding term expired and obtained more substantial funding from other sources. Former members of the Harvard team and others are now developing a major origins-of-life initiative independent of NAI funding.[58] Other nodes reported the attrition of researchers when available resources dwindled to levels that could not sustain effective collaborations.

An example of the effective leveraging of NASA funds is given by the NAI's Astrobiology Drilling Program (ADP), which has given researchers unprecedented access to pristine rock cores obtained from stratigraphic intervals that encompass critical periods in Earth's biogeological history. The ADP consisted of two separate but

BOX 2.12
EXOPLANET DISCOVERY AND ANALYSIS

The NAI has contributed to perhaps the most astronomical aspect of astrobiology, the discovery of extrasolar planetary systems. The majority of the 250 known exoplanets have been discovered by Paul Butler (Carnegie Institution of Washington team), Geoffrey Marcy (University of California, Berkeley, team), and their colleagues in the California-Carnegie Planet Search. Marcy, Butler, and their colleagues are conducting long-term precision Doppler surveys with the Keck 10-m, Magellan 6.5-m, Lick 3-m, and Anglo-Australian 3.9-m telescopes. These surveys have found about 140 planets over the past 12 years. This group (partially sponsored by the NAI) is nearing completion of a Planet Hunting Spectrometer for the Carnegie team's Magellan 6.5-m telescope, a 2.4-m robotic planet-finding telescope at the Lick Observatory, and two 80-cm robotic photometry telescopes at the Carnegie team's Las Campanas Observatory in Chile. The Lick Robotic Telescope should allow the team to detect the small-amplitude signals of Earth-mass planets by searching every night. Carnegie astronomers Alan Boss and Alycia Weinberger are searching for gas giant planets around nearby low-mass stars using their new astrometric camera on the du Pont 2.5-m telescope at Las Campanas. While a habitable Earth has not yet been found, the astronomers of the NAI's Carnegie team are working toward this ultimate goal. Astronomers from the NAI's Virtual Planetary Laboratory team are using the Spitzer Space Telescope to study the atmospheric composition of giant planets from their transit signals, including the tantalizing possibility of the discovery of water vapor in the atmosphere of a hot giant planet.

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related drilling campaigns in Western Australia. The first, the Archean Biosphere Drilling Project, involved an international collaboration linking Japan's Kagoshima University, the Geological Survey of Western Australia, the University of Western Australia, and the NAI team at Pennsylvania State University. The second, the Deep Time Drilling Project, was an NAI-wide activity involving members of the NAI teams at the University of Washington, University of Colorado, and Harvard University. The cores extracted in both campaigns have been archived and a sample-distribution process defined that involves the submission of a proposal to a scientific review committee. Anyone in the scientific community can apply to receive samples for analysis, and the analytical results are archived and made available to the entire community. This has been an effective means for stimulating research in critical areas.

Other examples of leveraging involve international cooperative activities that have provided U.S. astrobiologists with access to field sites that might not otherwise be readily accessible. Notable examples of such activities include the 2006 NAI-Russian Expedition to Klyuchevsky Volcano in Kamchatka and the cooperative development with Spanish astrobiologists of Rio Tinto of southwestern Spain as an analogue site for studies relating to habitable zones on early Mars.

RECOMMENDATIONS FOR FUTURE NAI ACTIVITIES

With respect to the goal of conducting, supporting, and catalyzing collaborative interdisciplinary research, the committee finds that the NAI has:

BOX 2.13
MODELING EXOPLANET BIOSPHERES

The NAI's Virtual Planetary Laboratory, led by Victoria Meadows, has organized a highly multidisciplinary team to undertake research on habitability, extrasolar terrestrial planets, and biosignatures. This is a fundamentally new effort to develop models for the co-evolution of planets and life, addressed to NASA's requirements for future missions to search for life beyond the solar system.

The NAI's Virtual Planetary Laboratory (VPL) has undertaken a broadly based theoretical effort to understand the co-evolution of terrestrial-type planets and their biospheres. At a time when direct observations of extrasolar terrestrial planets are not yet possible, theoretical research has been used to constrain the likely prevalence of habitable planets and the nature and detectability of biosignatures. Working with NAI colleagues on the Pennsylvania State University, University of Colorado, University of Arizona, Ames, Arizona State University, and University of Washington teams, the VPL's highly interdisciplinary team used planet formation models to understand the likelihood of habitability and water content for terrestrial planets around M stars, or those formed in the wake of a migrating Jupiter. Climate-chemistry and radiative transfer models were used to constrain the surface habitability of model planets. Other studies by the VPL team included the formation and detectability of gaseous photosynthetic byproducts, and the discovery of the enhanced detectability of known and new biosignatures and photosynthetic pigments for planets around stars that are hotter and cooler than our Sun.

The VPL has received its primary support from the NAI, and it exemplifies a new kind of multidisciplinary research organization focused on a single class of problems. Disciplines represented by the VPL team include atmospheric chemistry, planetary science, biochemistry, computational geoscience, infrared astronomy, atmospheric physics, ecosystems, astrophysics, astrochemistry, biometeorology, planetary dynamics, biogeochemistry, high-energy radiation, oceanography, bioinformatics, geophysics, heliophysics, chemical physics, and astrobiology.

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- *Successfully promoted interdisciplinary science.* This is evidenced by the publication record and feedback from the NAI's principal investigators and the establishment of two new scientific journals, *Astrobiology* and *The International Journal of Astrobiology,* specializing in the publication of interdisciplinary results. Although the publications are somewhat difficult to analyze in their entirety, they do indicate that a significant amount of interdisciplinary and collaborative research has been accomplished.
- *Stimulated many scientific achievements*. The field of astrobiology has grown tremendously in the past decade. A partial indication of the NAI's contributions to this growth is given in the NAI's list of its top research contributions (see Boxes 2.1-2.13). Particularly notable are important contributions to the developing field of metagenomics—the application of the techniques of genomic analysis to the study of entire communities of microorganisms[59]—undertaken by several NAI teams as highlighted, for example, by the activities relating to the ecology of microbial mats (see Box 2.4) and the unexpected diversity of marine microbial communities (see Box 2.5).

- *Successfully integrated life sciences into NASA programs*. There is much evidence of successful collaboration between biologists and non-biologists in the context of NASA activities, as evidenced by many of the NAI contributions highlighted in Boxes 2.1-2.13.
- *Often effectively leveraged ongoing and new research*. To be productive, some of the successful astrobiology programs, especially those at various universities, have required funding and other support from non-NASA sources. The NAI's programs have facilitated these relationships. A prime example of leveraging of funds is recounted in the discussion above concerning sub-seafloor life (see Box 2.6): a relatively small NAI contribution was more than matched by significant contributions in the form of infrastructure and operating costs borne by the Ocean Drilling Program. Similarly, the NAI support for the laboratory analysis of cometary materials (see Box 2.11) was an insignificant addition to the cost borne by NASA's Planetary Science Division for the design, construction, launch, and operation of the Stardust spacecraft that actually collected the cometary samples and returned them to Earth. Finally, the Astrobiology Drilling Program could not have been undertaken without significant foreign contributions.
- *Contributed to the establishment of new astrobiology programs worldwide*. There are now astrobiology institutes, centers, and programs in many countries. Most, if not all, trace their origins to the encouragement and inspiration provided by the NASA program.
- *Supported programs that are widely distributed throughout the United States*. The universities and research institutions currently engaged in research in astrobiology are located throughout the United States, which will facilitate the continued growth of the field.

Recommendation: The NAI should institute better measures of performance and progress to improve the accountability of its nodes in promoting astrobiology as a field of interdisciplinary and collaborative study. The committee suggests the following actions to implement this recommendation:

- The NAI could consider conducting thorough, unbiased reviews of its nodes to ensure that they continue to nurture the NAI's original intent to promote astrobiology as a field of interdisciplinary and collaborative study. These reviews could assess the extent to which the NAI strategy has promoted new approaches resulting in science or discoveries that would not have been pursued by traditional programs.
- An iterative schedule of review, evaluation, and response during the active period of each award might serve to increase attention to facilitating interdisciplinary collaborations within nodes. The nodes could be required to demonstrate their collaborative, interdisciplinary activities through annual reporting that explicitly documents what is truly interdisciplinary. Site visits (virtual or actual) approximately midway through a node's 5-year funding period could be instituted, and these visits could focus on evaluation of interdisciplinary, collaborative accomplishments.
- Nodes submitting re-competition proposals could be required to show evidence of sustained and productive interdisciplinary interactions, specifically peer-reviewed papers by authors in different fields.
- Interdisciplinary, collaborative research could be encouraged throughout all aspects of NAI activities. Proposals that clearly target questions that can only be addressed using interdisciplinary approaches could be favored, even if this means fewer nodes for a given announcement of opportunity. This is especially important if there is not sufficient funding to adequately support the desired number of nodes.
- The NAI could seek ways to increase communication between nodes and reduce competitiveness between teams by offering incentives to promote interteam collaborative interactions. One simple incentive-based approach might be to institute a yearly award to recognize a team or teams that have been particularly successful in collaborative research.
- NAI Central could continue to balance the number of nodes with projects funded by the DDF, so that all astrobiology activities in the NAI roadmap are represented. The DDF could be retained and could serve as a predictable and effective funding instrument. The majority of the DDF could be reserved for projects that explicitly support the NAI's goal of conducting, supporting, and catalyzing collaborative interdisciplinary research.

Recommendation: The NAI should improve the tracking and critical assessment of its publications. The committee suggests the following actions to implement this recommendation:

- NAI Central could consider carrying out a detailed review of publications by NAI-funded teams on an annual basis. To enable this review, NAI Central could develop and maintain a single unified database of the NAI publications. Furthermore, NAI Central could develop and maintain the procedures and tools needed to analyze the impact, relevance to astrobiology, originality, and interdisciplinary character of publications, with feedback to individual NAI members, individual NAI nodes, and the NAI as a whole. Although computerized techniques and the expertise of information-technology specialists will play an essential role in this effort, scientists with broad experience must be involved in the evaluation of individual publications. The NAI director could have a role in the evaluation of papers, and self-evaluation by the principal investigators of the individual NAI nodes could be useful.
- The details of how the database is organized and how the evaluation is carried out are the responsibility of the NAI. However, the committee offers the following suggestions: (1) The individual nodes could include a detailed bibliography of the papers actually published during the reporting period as part of their annual reports; (2) papers in preparation would not be included; (3) the bibliographies could include complete citations, including titles and abstracts or links to abstracts; (4) the analysis would only consider papers in refereed journals or books; (5) duplicate entries in the master database would be avoided; (6) the disciplines and NAI node affiliations of each author could be part of the database and could be available for analysis; (7) measures of impact, relevance to astrobiology, and originality could be part of the database and available for analysis; and (8) only papers that acknowledge the NAI explicitly, either for support or for inspiration, would be included in the analysis. The committee recognizes that the details of the database will require additional thought and consideration beyond that which was feasible within the context of this study. To successfully accomplish item 7, for example, requires a determination of how to measure such things as impact, relevance, and so on. Similarly, determining the criteria for item 8 may require the adoption of a policy concerning the leveraging of NAI funds with those from other sources.

Recommendation: The NAI should encourage and cultivate interactions with non-NAI astrobiology teams and organizations throughout the world. The committee suggests the following actions to implement this recommendation:

- Care should be taken to ensure that the NAI promotes an open program that engages the entire astrobiology community and scientists in related fields of endeavor to avoid the perception that it and its activities are exclusive privileges of NAI membership.
- The NAI could continue its efforts to develop astrobiology at the international level through co-sponsored educational activities (e.g., the Pilbara field conference with the Australian Center of Astrobiology) and public outreach (e.g., sessions at international conferences such as those of the International Society for the Study of the Origin of Life and the IAU-sponsored Bioastronomy meetings).
- The NAI could make its existing Web site a more effective portal for astrobiology by promoting access to it by all interested parties (not just NAI members) and by more inclusive coverage of pertinent astrobiology science, sources, and non-NASA sites.

NOTES

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3

Training the Next Generation of Astrobiologists

This chapter evaluates the success of the NASA Astrobiology Institute (NAI) in training the next generation of astrobiology researchers.

NAI CONTRIBUTIONS

University-based training of astrobiology students located at NAI nodes is an important activity that has historically included a broad range of undertakings, including the following:

- Students complete a dissertation in a traditional field such as astronomy, microbiology, geology, and so on.
- Students take additional coursework in a field outside their major concentration; for example, astronomers take a course in microbiology, or vice versa. Some universities require that students spend a semester or summer doing a research rotation in a laboratory not directly related to their primary field of study.
- Most universities with NAI programs offer a survey course, or at the very least a seminar, on astrobiology. In these courses students typically give presentations in their area of expertise for the rest of the class or are exposed to NAI-funded faculty members who co-teach the course.
- Some of the NAI teams also have student-run journal clubs to which faculty members are specifically not invited.
- The Astrobiology Graduate Conferences, a series of conferences held annually since 2004 and organized by graduate students to foster peer-to-peer communication within the broad community of students interested in astrobiology, give junior researchers the opportunity to practice speaking about their work in a collegial atmosphere.[1]
- Students can contribute to the drafting of the student-written "Astrobiology Primer," a general introduction to and summary of basic concepts in the traditional scientific disciples relevant to astrobiology.[2]

At present, no university offers a stand-alone degree in astrobiology. Students are currently awarded a degree in a traditional discipline with a certificate or a minor in astrobiology, indicating cross-disciplinary training beyond that required for the major discipline. Pennsylvania State University, for example, has already graduated students with undergraduate degrees in a traditional scientific discipline and a minor in astrobiology.[3] It also offers a dual-title graduate program that awards a Ph.D. in a traditional science discipline and astrobiology.[4] At the University of Washington, astrobiology graduates are awarded a Ph.D. in a traditional discipline and a graduate certificate in astrobiology.[5] However, most of the students who have graduated from these programs have not been formally employed as astrobiologists and are filling positions in traditional disciplines. Former NAI postdoctoral fellows reported to the committee, however, that although astrobiology was not specified in the title for the position they filled, during the interview process their interdisciplinary training and astrobiology background were seen as a plus and served to set them apart from other candidates. In short, anecdotal evidence suggests that the interdisciplinary training of students in astrobiology is producing a new generation of scientists whose education has encouraged them to see the world in a broader context, although validating such a claim in a quantitative manner is beyond the scope of this study.

Most astrobiology students remain active in the broader community, continuing to bring creative research ideas to the field and making efforts to foster collaborations with other departments and successfully tap into new sources of research funding.

It is too soon to gauge the full impact of the NAI's training efforts. Simply counting the number of graduates currently employed as astrobiologists not only is misleading but also glosses over important issues that are key to the continued growth and eventual acceptance of astrobiology as a formal science discipline. At this time, most scientists categorized as being "astrobiologists" are in faculty or other senior positions (e.g., in the civil service, and so on) not usually filled by newly minted Ph.D.s. The fact that some graduates continue on in their traditional discipline, and that many NAI postdoctoral positions are filled by people with no prior association with astrobiology or the NAI, is consistent with the early stages of a developing field. Recent graduates bring astrobiology into their home discipline, and up-and-coming researchers from traditional disciplines bring their expertise into the astrobiology community and the NAI specifically. This kind of interchange between fields is integral to the development of astrobiology as a science.

A better approach to measuring the NAI's success in training the next generation of astrobiologists is to follow these recent graduates through their postdoctoral years to see if they are publishing significant papers on astrobiology-related issues in major scientific journals, collaborating with a wide variety of scientists in other disciplines, successfully applying for astrobiology grants, winning awards (Table 3.1), attending astrobiology conferences, teaching astrobiology classes, and, in general, contributing to the field of astrobiology.

The first astrobiology graduates are only just now reaching the point in their careers where they are obtaining faculty jobs (Table 3.2), principal investigator (PI) status on their own grants, and/or stable positions as research scientists. It is not unusual for a new Ph.D. to spend 5 years or more in postdoctoral positions before obtaining a permanent position.

It is important to note the particular challenges young researchers face when trying to conduct interdisciplinary research within the highly discipline-oriented organization of research universities but outside the bounds of an existing astrobiology group.[6] Graduate students and new assistant professors, for example, who need to impress the faculty in their home departments, can be under intense pressure to prove their competence in the departmental discipline, and this constraint can influence the way research is carried out and published. The particular challenges posed by undertaking interdisciplinary research include the following:

- Communications and cultural barriers that reflect the ways in which different scientific disciplines regard each other, use different vocabularies to describe common concepts, and have different ways of doing things.[7]
- Organization of research and structuring of teaching activities around discipline-based departments—frequently mirroring the organization of funding organizations, professional societies, and scientific journals—in ways that affect decisions relating to hiring, promotion, tenure, and allocation of research resources (e.g., laboratory space).[8]
- Requirements for additional training and/or for undertaking the research activities (e.g., field studies) necessary to be proficient in multiple disciplines, which can cut down on apparent research productivity and harm careers.[9]
- The difficulties posed by the evaluation of interdisciplinary activities within the context of a single-discipline departmental culture.[10]

TABLE 3.1 Examples of Awards Won by NAI-Affiliated Researchers

Year of Award	Award	Recipient	NAI Affiliation	Current Affiliation
2000	AAS Annie J. Cannon Award in Astronomy	Alycia J. Weinberger	University of California, Los Angeles	Carnegie Institution of Washington
2004	Sloan Research Fellowship	Colin Nuckolls	Scripps Research Institute	Columbia University
2004	Sloan Research Fellowship	Brad Hansen	University of California, Los Angeles	University of California, Los Angeles
2004	Presidential Early Career Awards	Sarah Stewart-Mukhopadhyay	Carnegie Institution of Washington	Harvard University
2004	Sloan Research Fellowship	Andrew Roger	University of California, Los Angeles	Dalhousie University
2004	Sloan Research Fellowship	Dustin Trail	University of Colorado	Rensselaer Polytechnic Institute
2005	Sloan Research Fellowship	Michael Liu	University of Hawaii	University of Hawaii
2006	NASA Haskin Early Career Fellowship	Michelle Minitti	Arizona State University	Arizona State University
2007	Howard Hughes Medical Institute Biomedical Research Institutions Initiative	Seth Bordenstein	Marine Biological Laboratory	Marine Biological Laboratory
2007	L'Oréal USA Fellowship for Women in Science	Julie Huber	Marine Biological Laboratory	Marine Biological Laboratory

TABLE 3.2 Examples of NAI-Trained Researchers Who Have Obtained Faculty Positions

Name	NAI Affiliation	NAI Role	Current Faculty Position
Charles Boyce	Harvard University	NAI Postdoctoral Fellow	University of Chicago
Seth Bordenstein	Marine Biological Laboratory	NAI Postdoctoral Fellow	Marine Biological Laboratory
James Farquhar	Carnegie Institution of Washington and University of California, Los Angeles	Postdoctoral Fellow	University of Maryland
Shannon Hinsa	Michigan State University	NAI Postdoctoral Fellow	Grinnell College
Julie Huber	Marine Biological Laboratory	NAI Postdoctoral Fellow	Marine Biological Laboratory
Matthew Hurtgen	Harvard University	NAI Postdoctoral Fellow	Northwestern University
Marc Kramer	Ames Research Center	NAI Postdoctoral Fellow	University of California, Santa Cruz
Michelle Minitti	Arizona State University	NAI Postdoctoral Fellow	Arizona State University
Stephen Mojzsis	University of California, Los Angeles	Postdoctoral Fellow	University of Colorado
Shuhei Ono	Carnegie Institution of Washington	Postdoctoral Fellow	Harvard University
Alexander Pavlov	University of Colorado	NAI Postdoctoral Fellow	University of Arizona
Susannah Porter	University of California, Los Angeles	NAI Postdoctoral Fellow	University of California, Santa Barbara
Henry Scott	Carnegie Institution of Washington	NAI Postdoctoral Fellow	Indiana University
Yanan Shen	Harvard University	NAI Postdoctoral Fellow	University of Quebec, Montreal
Margaret Turnbull	Carnegie Institution of Washington	NAI Postdoctoral Fellow	Space Telescope Science Institute

An important influence of astrobiology can be seen in a gradual diminishing of departmental barriers, although overcoming such barriers will likely be a long and challenging enterprise. Some useful lessons can be drawn from the history of the development of molecular biology. The movement to join biochemistry and genetics began with some forward-looking scientists in the early 1940s. But actual programs and departments in molecular biology took decades to establish even though individuals in the separate disciplines already thought of themselves as colleagues and collaborators. Among the most successful of the catalytic activities in this regard were the summer, laboratory-based courses for researchers, postdoctoral fellows, and graduate students at the Cold Spring Harbor Laboratory. Similarly, existing activities such as the Josep Comas i Sola International Summer School in Astrobiology (see Chapter 6) may represent an important foundation for a more expanded future program.

RELATIONSHIP TO OTHER ASTROBIOLOGY PROGRAMS

Traditionally, scientists are trained at the graduate level by taking a variety of courses in their disciplines and then focusing their research on a specific subdiscipline. Graduate students in existing NAI-supported astrobiology programs must do coursework in their home discipline and also gain interdisciplinary training primarily by being involved in research, by taking astrobiology courses (where available) or cross-bridging courses in other disciplines, or conducting a short research project outside their primary discipline. Although focused research is usually an important element of astrobiology training, it is not a substitute for the knowledge and experience gained by completing a formal curriculum. If astrobiology is to grow into a recognized discipline with associated degrees and sustained careers, formal curriculum development will be necessary.

Two factors mitigate against the NAI achieving its goals of educating the next generation of astrobiologists. First, the relative impermanence of the NAI nodes is not consistent with the long-term stability needed to nurture a new generation of researchers. Second, the resources at the NAI's disposal may be insufficient to the task, especially as compared to the case for another interdisciplinary field, oceanography, which has long-term commitments of funds that dwarf those available to astrobiology. The NAI is being asked to do what the oceanography community has done, but with only a few percentage of the funding for oceanography. Some observers might argue that if NASA thinks it is important to develop astrobiology into a stand-alone scientific discipline similar to oceanography, the agency needs to make the kind of funding commitments that will lead to success.

The research-based approach to training currently emphasized by the NAI should be regarded as a transitional step along the way as the discipline is becoming established. However, such an approach, which varies broadly in its implementation across past and present NAI nodes, will not be entirely successful in allowing a new generation of young scientists to emerge as fully trained astrobiologists who understand the language, culture, and conceptual interfaces between the sciences that make up astrobiology. Yet it is clear to the committee that NASA's experiment to establish the field has succeeded and that astrobiology is here to stay. To develop astrobiology properly into a new science discipline will require the establishment of formal educational and training programs to support the evolution and transformation of this nascent field. The NAI could play an active role in this evolution by promoting the establishment of integrated education programs at its partner institutions. However, such an effort requires commitments that extend beyond 5 years, a level of permanence that is currently difficult to assure.

While some alumni members of the NAI at U.S. universities have made commitments to establish astrobiology programs on the basis of NAI 5-year funding contracts, longer-term commitments involving the establishment of research centers, targeted faculty hires, and commitment of faculty to develop curricula and supporting degree and certificate programs have been much harder to achieve. In the absence of a formal renewal process for NAI nodes at the conclusion of their 5-year funding period, university programs established, in part, using NAI funds have been discontinued because the host universities were not prepared to provide the resources needed to sustain the development of these programs. In other words, the organizational structure of the NAI is hindering the development of academic programs in astrobiology.

The two educational and training programs that have been successfully established within the NAI to date (i.e., at Pennsylvania State University and the University of Washington) have succeeded because support for those programs extended beyond 5 years. In fact, the NAI can claim full credit for the establishment of only one of these programs, because funding to initiate the activities at the University of Washington was obtained from

NSF's Integrative Graduate Education and Research Traineeship (IGERT) program in 1998, 3 years before the University of Washington's involvement with the NAI. The committee was told, however, that the NAI funds were important to the development of the University of Washington's astrobiology program because the IGERT grant principally supported student salaries and provided very little for student travel or research. The NAI funds were used to support the research undertaken by the IGERT graduate students.[11] Such sustained funding is critical for gaining the cooperation and support of university administrators, who must concern themselves with the long-term value of a program to the educational institution and the university's ability to sustain students entering the field. The NAI's recently instituted Director's Discretionary Fund (DDF) grant program has been an effective tool for providing opportunities for the NAI to provide continuity of support for students who lose funding during the course of completing their degree.

BALANCE OF NAI ACTIVITIES

The training of young scientists by the NAI has been accomplished mainly through postdoctoral positions funded by the individual NAI teams. A minority of postdoctoral fellows (approximately 10 percent) are funded via a highly competitive NAI-wide postdoctoral fellowship program, which has provided full support (salary, benefits, and travel) for approximately six new junior scientists each year. Fellowships are renewable annually for a maximum of 3 years, during which fellows typically spend time at two or more NAI nodes, thus broadening their research experience. Statistics maintained by NAI Central indicate that most if not all former-NAI postdoctoral fellows have successfully moved into academic and research positions in the field.[12] However, the postdoctoral program currently appears to be underfunded and overly competitive. Six new NAI postdoctoral fellows were selected each year between 2000 and 2005, except in 2003 and 2004 when five and seven were selected, respectively. However, only four fellows were selected in 2006, and only one was selected in 2007.[13] Clearly, the budget cuts experienced by the Astrobiology program in 2006 have had a severe impact on the recruitment of junior scientists.

As noted previously, graduate training efforts by the NAI have been promoted primarily through activities at the member nodes, although NAI Central has provided grants to support graduate student travel to meetings and occasional field seminars. Modest support for graduate student fieldwork has also been provided each year, for example, through the Lewis and Clark Fund for Exploration and Fieldwork, a program jointly sponsored by the NAI and the American Philosophical Society.

Graduate-level education and training have been implemented primarily through student involvement in research activities at the various NAI nodes. However, many academic departments around the country and at several NAI nodes have now established graduate and undergraduate courses in astrobiology, which is evidence of the impact of the field on university education. Such courses are currently supported by a half dozen textbooks published since the NAI was established, several of which have been written by scientists affiliated with the NAI. However, formal NAI-supported training programs, enhanced by organized curricula that could lead to the chance to earn minor degrees or certificates attached to traditional disciplines, have so far been successfully established only by the NAI team at Pennsylvania State University. This particular program appears to have been possible because of the longer period of commitment afforded by NAI's award of funding for a second 5-year term.

RECOMMENDATIONS FOR FUTURE NAI ACTIVITIES

With respect to the goal of training the next generation of astrobiology researchers, the committee finds that the NAI has:

- *Trained graduates who are now employed in academic and other positions*. Former NAI postdoctoral fellows who contacted the committee reported that they had been very successful in obtaining employment in their fields, although they are not always engaged solely in astrobiology. This anecdotal evidence is backed up by statistics compiled by the NAI showing that most, if not all, of its former postdoctoral fellows have moved on to academic positions or other research appointments.[14] However, the training of graduate and undergraduate students in astrobiology has been hampered to some extent by a scarcity of formal educational programs. If the field is to continue to grow within the United States, it will be necessary to provide broader opportunities for formal training of the next generation of students by developing integrated curricula and programs of study at leading educational institutions.

- *Promoted the establishment of new programs and faculty positions in astrobiology at several universities*. There are not many faculty appointments in astrobiology, but the breadth of training does appear to help graduates obtain positions in related departments, according to comments provided to the committee by former NAI postdoctoral fellows and NAI PIs. Success in establishing new university education programs in astrobiology comes with special requirements, including assembling a critical mass of university faculty who collectively represent the major subdisciplines of astrobiology, providing reasonable breadth in the curriculum and research environment, and supplying sustained support that allows programs to grow to a steady state including the capacity to confer formal degrees.
- *Not been sufficiently proactive in countering the negative effects on training and education programs caused by recent cuts to NASA's Astrobiology budget*. The instability created by these cuts has had an adverse effect on the growth of graduate training programs, interrupted student research programs, and discouraged many students from entering the field. Stability in training and education programs will remain a key requirement for the continued success of the NAI.

Recommendation: The NAI should work toward developing more consistent educational and training opportunities. In addition, the NAI should ensure more stable support of graduate students and postdoctoral researchers in astrobiology. The committee suggests the following actions to implement this recommendation:

- The NAI Fellowship program could continue to be supported at a level commensurate with the number of NAI nodes and used to provide more stable support for graduate researchers. In addition, to promote the growth of interdisciplinary interactions, fellows could be encouraged to pursue science projects that cross-link the expertise at two or more NAI nodes.
- One route to developing formal curricula would be to encourage the establishment of one or more member nodes in astrobiology that emphasize the synergy between research and the training of undergraduates, graduate students, and postdoctoral fellows. NASA Specialized Centers for Research and Training (NSCORT)—e.g., the NSCORT in Exobiology at the University of California, San Diego or the New York Center on Studies of the Origins of Life—provide a potential model for how such nodes might be established. An external review of the two NSCORTs issued in early 2002 attested to the quality of the two programs and commented that "the NSCORTs have served to enhance greatly the education of the next generation of astrobiologists, breaking down barriers between fields, and enhancing multidisciplinary research. The result is a remarkable cohort of young scientists who are creatively addressing questions in the field of astrobiology or who are bringing these abilities to more traditional fields. The breadth and depth of knowledge that the students obtain and the excitement they continue to display for astrobiology research is a direct result of the NSCORTs."[15] Given that most NAI nodes lack the resources to establish such programs and that their growth requires commitments longer than 5 years, such training programs could be sustained by an NSCORT-like program within the NAI that runs in parallel with more research-oriented activities.
- The NAI could consider continuing its policy of the selective use of the DDF to stabilize student funding levels and to protect them against future cuts. It is important for NASA to recognize that continuity for the training of the next generation of astrobiologists is essential for the development of astrobiology as a credible field of science.

NOTES

1. For more information about the conference series see http://abgradcon.arc.nasa.gov/index.php?fuseaction=home.home.
2. L.J. Mix et al. (eds.), "The Astrobiology Primer: An Outline of General Knowledge—Version 1, 2006," *Astrobiology* 6: 735-813, 2006. Available at http://www.liebertonline.com/doi/pdfplus/10.1089/ast.2006.6.735.
3. For more information see http://www.geosc.psu.edu/undergrads/minors/astrobiology.php.
4. For more information see http://www.psu.edu/bulletins/whitebook/programs/abiol.htm.

5. For more information see http://depts.washington.edu/astrobio/certificate/.

6. See, for example, National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2005.

7. National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2005, pp. 1 and 68.

8. National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2005, pp. 1-2 and 69-79.

9. National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2005, p. 68.

10. National Research Council, *Facilitating Interdisciplinary Research*, The National Academies Press, Washington, D.C., 2005, pp. 73 and 75.

11. Personal communication, John Baross, University of Washington, October 4, 2007.

12. Personal communication, Daniella Scalice, NASA Astrobiology Institute, July 26, 2007.

13. Personal communication, Daniella Scalice, NASA Astrobiology Institute, July 26, 2007.

14. Personal communication, Daniella Scalice, NASA Astrobiology Institute, July 26, 2007.

15. S. Solomon, M. Bernstein, C. Cavanaugh, J. Dasch, D. Deamer, C. Pilcher, J. Pratt, M. Meyer, and W. Berger, "Review of the Astrobiology NSCORT Review Panel," unpublished report chartered by NASA's Office of Space Science, February 18, 2002.

4

Leadership for Current and Future Space Missions

This chapter evaluates the success of the NASA Astrobiology Institute (NAI) in achieving its stated goal of providing scientific and technical leadership on astrobiology investigations for current and future space missions.

NAI CONTRIBUTIONS

As pointed out in Chapter 1, the field of astrobiology provides the intellectual and scientific foundation for much if not all of NASA's current robotic solar system exploration missions[1] and many of its astrophysical activities relating to the search for and characterization of extrasolar planets (exoplanets).[2] Understanding how life arose on Earth and how it evolved helps to define the scientific rationale for recognizing life elsewhere in the solar system and beyond. These questions are also central to many of the science goals enunciated in the Vision for Space Exploration.[3]

The current NASA strategy of "follow the water" for exploring Mars[4] and, by extension, the rest of the solar system and beyond forms the basis for future missions that will focus on specific astrobiology themes. The presence of past and recent-present water on Mars has almost certainly been established (e.g., by the Mars Exploration Rovers and the Mars Reconnaissance Orbiter),[5] and the existence of subsurface ice is expected to be confirmed with the recently launched Mars Phoenix mission. As a result, the NAI has a unique opportunity to begin preparing for missions that will critically assess the question of life beyond Earth. Astrobiology also has been and will likely remain the major driver in the exploration of the outer solar system, influencing planning for missions to the Galilean satellites of Jupiter and to Saturn's moons, Titan and Enceladus.

Astrobiology also has influenced and will continue to influence NASA's astrophysical investigations, such as those that use the Hubble Space Telescope, the Spitzer Space Telescope, and, eventually, the Kepler mission and the James Webb Space Telescope in the search for and characterization of Earth-sized planets orbiting other stars. It would be appropriate for the astrobiology community to help define a mission that highlights the search for life in the universe, a compelling question that provides intellectual connections to the search for Earth-like planets and investigations of their potential habitability.

Although the NASA Astrobiology Institute has been in existence for almost 10 years, as an institution it has not played a dramatically significant role in NASA's current and future strategy to explore the solar system and beyond. This does not mean that the NAI and, in particular, members of NAI teams have not played a central role in determining NASA's plans for current and future missions. The NAI regards the following particular activities as its principal contributions to NASA's flight program:

- *Mars landing sites and exploration strategy.* The NAI Mars Focus Group, initially chaired by Jack Farmer (principal investigator of the NAI team at Arizona State University), provided key recommendations on Mars landing sites. Subsequently, the NAI has contributed several chairs to NASA's Mars Exploration Program Analysis Group (MEPAG), the group developing Mars exploration strategy. In addition to Farmer, NAI members who have chaired MEPAG include Ronald Greeley (Arizona State University team), Bruce Jakosky (PI of the NAI team at the University of Colorado), and Jack Mustard (Marine Biological Laboratory team), providing continuing input to NASA mission planners. See Box 4.1 for more information.
- *Future Mars missions.* NAI member Mark Allen (Jet Propulsion Laboratory) developed a proposed Mars Scout, the Mars Volcanic Emission and Life (MARVEL) mission to measure atmospheric composition and loss mechanisms, that has led to the selection of these objectives for the Mars Science Orbiter proposed for launch in 2013. The NAI also provided a context for development of the current Mars Atmosphere and Volatile Evolution

BOX 4.1
MARS LANDING SITES AND EXPLORATION STRATEGY

The many recent discoveries about the past and present habitability of Mars are linked to an astrobiology-inspired strategy for Mars exploration called "follow the water." The NAI played a key role in recommendations for landing sites for the Mars Exploration Rovers (MERs), which were presented by the focus group chair (Jack Farmer, principal investigator [PI] of the NAI team at Arizona State University) at community-wide landing-site workshops. Based on inputs from these workshops, the MER Landing Sites Steering Committee developed a short list of approximately 10 sites, half of them on the NAI list of recommendations. Both of the final landing site selections (*Opportunity*'s landing site on Meridiani Planum and *Spirit*'s landing site in Gusev Crater) had been given a high priority for astrobiology by the NAI Mars Focus Group. On the question of landing site selection, interactions between the NAI and NASA's Mars Exploration Program Analysis Group (MEPAG) were promoted through several NAI-sponsored videoconferences organized by the chair of the Mars Focus Group. So effective were these contributions that when Jack Farmer was appointed to lead MEPAG, much of the NAI focus group activity simply merged with the NASA-wide advisory system.

Another indication of NAI influence can be drawn from the fact that roughly 70 percent of the authors of recent MEPAG reports are members of past or present NAI teams. These individuals include the following:

- Ames Research Center team—David Des Marais (PI), Christopher McKay, and Allan Treiman;
- Arizona State University team—Phillip Christensen, James Elser, Jack Farmer (PI), Ronald Greeley, and Ferran Garcia-Pichel;
- Carnegie Institution of Washington team—Nora Noffke and Andrew Steele;
- Goddard Space Flight Center team—Paul Mahaffy;
- Jet Propulsion Laboratory team—Kenneth Nealson (PI);
- Johnson Space Center team—Thomas Kieft;
- Marine Biological Laboratory team—James Head and Mitchell Sogin (PI);
- Massachusetts Institute of Technology team—Roger Summons (PI);
- Pennsylvania State University team—Christopher House;
- SETI Institute team—Rocco Mancinelli (PI);
- University of Arizona team—John Baross;
- University of Colorado team—Bruce Jakosky (PI) and Stephen Mojzsis;
- University of Hawaii team—Jeffrey Taylor; and
- University of Washington team—John Baross and Jody Deming.

BOX 4.2
FUTURE MARS MISSIONS

Mark Allen (Jet Propulsion Laboratory) was stimulated by his membership in the NAI to adapt techniques for studying terrestrial photochemistry to the detection of trace gases in the martian atmosphere, and he was first author of the report "Is Mars Alive?" from the NAI Virtual Workshop on Methane on Mars held in March 2005.[1] Allen's Mars Scout (MARVEL) proposal was not selected for flight, but his instrument approach combined with excitement about the possible detection of methane on Mars (NAI Goddard Space Flight Center team and others) led to the selection by NASA of a trace gas science payload for the proposed 2013 Mars Science Orbiter. The MAVEN Mars Scout candidate mission (Bruce Jakosky, PI of the NAI team at the University of Colorado) also emerged from the interdisciplinary environment fostered by the NAI.

[1]M. Allen, B. Sherwood Lollar, B. Runnegar, D.Z. Oehlar, J.R. Lyons, C.E. Manning, and M.E. Summers, "Is Mars Alive?" *EOS* 87: 433-448, 2006.

(MAVEN) Scout proposal led by Bruce Jakosky, the PI of the NAI team at the University of Colorado. See Box 4.2 for more information.

- *Astrobiology in the NRC's solar system exploration decadal survey report.* Recognizing the increasing importance of astrobiology in planetary science, the NAI provided formal input to the NRC's solar system exploration decadal survey, including a rationale for recognizing astrobiology as a central component, ways in which astrobiology interacts with the rest of solar system exploration, and a ranking of key missions. See Box 4.3 for more information.

BOX 4.3
ASTROBIOLOGY IN THE NRC'S SOLAR SYSTEM EXPLORATION DECADAL SURVEY REPORT

At the request of the National Research Council's (NRC's) Committee on the Origins and Evolution of Life, the NAI provided input on astrobiology to the NRC's solar system exploration (SSE) decadal survey committee. Astrobiologists discussed the role of astrobiology in solar system exploration and the nature of flight missions that would contribute simultaneously to addressing the goals and objectives of solar system exploration and astrobiology. The SSE decadal survey committee took the input to heart and, in its report, described the importance of astrobiology as one of the fundamental underpinnings of solar system exploration.[1] This embracing of astrobiology was consistent with the increased visibility that astrobiology was receiving as the intellectual centerpiece of the planetary exploration program. As put forward by the NAI, the highest-priority missions lined up remarkably well with those missions that were considered as having the highest priority for solar system exploration independent of the role of astrobiology. This correspondence can be seen as evidence of the numerous ways in which astrobiology science goals mesh with non-astrobiology goals designed to elucidate the formation and evolution of our planetary system. Thus the list of priority missions recommended by the NRC agreed closely with those put forward for astrobiology by the NAI.

[1]National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

BOX 4.4
PALE BLUE DOT

From its inception, the NAI has recognized the importance of astronomical biosignatures, evidence for life that could be detected on exoplanets by instruments such as NASA's proposed Terrestrial Planet Finder mission. Since for the foreseeable future such terrestrial exoplanets will only be seen as single pixels (i.e., pale blue dots), biosignatures must be global, detectable in the spectra of such planets. The challenge is highly interdisciplinary, involving planetary science and geoscience (to understand the range of expected surfaces and atmospheres of terrestrial exoplanets), biology (to understand the influence of microbes and possibly other life forms on the composition of the atmosphere and the reflectance of the surface), and astronomy (to determine which spectral regions might carry spectral biosignatures and to design instruments that could detect them). It is desired, of course, to distinguish planets that are habitable (capable of supporting life) from those where life exists and has imposed a detectable biosignature on the spectrum. Over the past decade, the NAI has cosponsored three community-wide "Pale Blue Dot" conferences in which NAI PIs David Des Marais (Ames Research Center) and Victoria Meadows (California Institute of Technology, now at the University of Washington) played leading roles as organizers. Meadows leads the NAI's Virtual Planetary Laboratory, which has focused on a broadly based theoretical effort to understand the co-evolution of terrestrial-type planets and their biospheres.

- *Pale blue dot.* Three NAI-sponsored conferences have focused on defining astronomical biosignatures, examining the coupling of biotic activity, planetary environmental conditions, and the parent star. The work of the NAI's Virtual Planetary Laboratory has provided much of the scientific underpinning for these conferences. See Box 4.4 for more information.
- *M Stars and habitability.* The NAI team at the SETI Institute led a workshop as part of a multidisciplinary re-examination of the likely habitability of M-star planets. The positive outcome of this work has more than doubled the range of potential target planets that might support life. See Box 4.5 for more information.
- *Astrobiology and the James Webb Space Telescope.* The NAI Astronomy Focus Group made recommendations to NASA for astrobiology programs that could be accomplished with the James Webb Space Telescope, which will be a powerful asset for studying the processes by which planets form and acquire essential ingredients for life, and for investigating faint comets and exoplanets. See Box 4.6 for more information.

BOX 4.5
M STARS AND HABITABILITY

In the summer of 2006, Rocco Mancinelli (the principal investigator of the NAI team at the SETI Institute) co-organized and hosted a workshop to examine the prospect that planets orbiting dwarf M stars are habitable for either microscopic or complex life. Some 30 scientists from 19 institutions in the United States and the United Kingdom participated, with 13 of the participants representing 6 other NAI teams. A paper summarizing some of the material presented at the workshop, together with other results relating to the habitability of M stars, was published in the February 2007 issue of *Astrobiology*.[1] The consensus of these activities was that there is no reason to preclude the possibility of life on a planet orbiting a dwarf M star. Since the number of M dwarfs is approximately 10 times greater than the number of Sun-like G stars, this conclusion will have important implications for searches for life.

[1] J. Scalo et al., "M Stars as Targets for Terrestrial Exoplanet Searches and Biosignature Detection," *Astrobiology* 7: 85-166, 2007; and "Special Collection of Papers: M Star Habitability," *Astrobiology* 7: 27-274, 2007.

BOX 4.6
ASTROBIOLOGY AND THE JAMES WEBB SPACE TELESCOPE

The NAI formed the Astronomy Focus Group in 2003. Its first task was to consider the role of the James Webb Space Telescope (JWST) in contributing to astrobiology. The focus group was chaired by Sara Seager (Carnegie Institution of Washington, now at the Massachusetts Institute of Technology) and Jonathan Lunine (University of Arizona). A workshop held by the group led to recommendations for realizing many "nascent capabilities" of JWST for astrobiology.[1] These recommendations included developing comet-tracking software, allowing high-cadence observations of bright sources, improving stray-light rejection and the stability of the point-spread function to allow observations of faint planets near bright stars, and enhancing coronagraphic capability with careful control of scattered light. Many of the recommendations were implemented, leading to an expectation of greatly improved astrobiological capability for this mission.

[1]S. Seager and J.I. Lunine (eds.), "Astrobiology and JWST: A Report to NASA Recommending Additional or Optimization of the James Webb Space Telescope Capabilities to Maximize Astrobiology Science Return," unpublished white paper available at http://www.dtm.ciw.edu/seager/NAIAFG/JWST.pdf.

- *Lunar astrobiology.* In response to the plan enunciated by the Vision for Space Exploration to return astronauts to the Moon, the NAI organized a workshop and developed a white paper on lunar astrobiology. Recommendations included using the Moon to understand the environment on ancient Earth and making integrated observations of Earth from the Moon to calibrate potential astronomical biosignatures for exoplanets. Many of these recommendations were subsequently included in the NRC report *Scientific Context for Exploration of the Moon.*[6] See Box 4.7 for more information.

BOX 4.7
LUNAR ASTROBIOLOGY

In July 2004 the NAI prepared a white paper for NASA headquarters titled "Astrobiology Science Goals and Lunar Exploration" with Bruce Jakosky (principal investigator [PI] of the NAI team at University of Colorado) as primary author.[1] The white paper noted that the Moon preserves unique information about the habitability of the Earth-Moon system, particularly from early eras for which Earth's record is largely missing. The NAI suggested study of two specific issues concerning the early solar system: the history of impacts and the history of exposure to radiation. The Moon is expected to provide the data for a quantitative investigation of these issues. Each of these problems can be addressed in a step-wise manner by a NASA lunar science program that includes orbital imaging and remote sensing, in situ analysis from landed spacecraft, robotic sample-return missions, and human exploration missions. More recent discussion within the NAI (led by Neville Wolff, PI of the NAI team at the University of Arizona) has identified an additional opportunity, using the Moon as a platform for low-spatial-resolution (single-pixel) observations of the whole Earth, as a function of phase, to demonstrate and calibrate approaches to the "pale blue dot" challenge of detecting biosignatures on exoplanets.

[1]B.M. Jakosky, A. Anbar, G.J. Taylor, and P. Lucey, "Astrobiology Science Goals and Lunar Exploration: NASA Astrobiology Institute White Paper," unpublished white paper available at http://nai.arc.nasa.gov/library/downloads/lunar_astrobiology.pdf.

The main conclusion to be drawn from this list is that the NAI's influence on missions has been indirect and has come principally through the actions of individual scientists affiliated with NAI teams. This is probably the most appropriate vehicle for the NAI's involvement in NASA's flight program. The committee agrees with the NRC's 2003 review of NASA's Astrobiology program that considered the appropriateness of the NAI's involvement in the development or selection of missions and cautioned NASA "against attempting to force the NASA Astrobiology Institute . . . into an artificially focused role of trying to design specific 'astrobiology missions'."[7] While the 2003 report encouraged individual NAI team members to propose instrument or entire PI-class missions (e.g., Discovery, Mars Scout, or Explorers), the direct involvement of the NAI as an entity was worrisome because it might appear to bias NASA's well-understood and time-tested peer-review selection process in favor of a small group of NAI insiders.

To fully integrate astrobiology into NASA's strategy for future missions while precluding the NAI from becoming too directly involved in their design or selection, the astrobiology community itself (both NAI members and others) must take responsibility for providing scientific and technical leadership on astrobiology investigations for current and future space missions. Therefore, the role of the NAI is to provide the astrobiology community with the tools necessary to take that leadership role.

The NAI performs this function through its support of focus groups (i.e., forums where like-minded astrobiologists can discuss issues of mutual interest) that address a variety of specific issues associated with flight missions. Particularly notable are the activities of the focus groups concerned with defining strategies for exploring Mars (1999-2003), Europa (2001 to present), astro/cometary materials (2002-2003), and Titan (2003-present, now called the Icy Worlds focus group). The recent reinvigoration of the NAI's Mars focus group has already made significant contributions to NASA's Mars Next-Decade group, which is looking at Mars exploration activities beyond the Mars Science Laboratory program. This is an important step toward establishing a more strategic role for astrobiology in future mission planning.

RELATIONSHIP TO OTHER ASTROBIOLOGY PROGRAMS

There are several programs complementary to the NAI that are supported by the Science Mission Directorate: the Exobiology and Evolutionary Biology grants programs, the Astrobiology Science and Technology Instrument Development (ASTID) program, and the Astrobiology Science and Technology for Exploring Planets (ASTEP) program. These programs each contribute to NASA planning of flight opportunities, and there is good synergy among the various activities.

The NAI and the scientists it supports have contributed directly to the National Research Council's decadal survey process. Indeed, as is mentioned in Chapter 1, the astronomy and astrophysics decadal survey and the solar system exploration decadal survey include language highly supportive of the scientific goals of astrobiology. Both surveys and at least one more recent NRC report[8] point to the close alignment between specific missions of interest to astronomers (e.g., the search for and characterization of exoplanets) and planetary scientists (e.g., the exploration of Mars, Europa, and Titan) and the activities of direct interest to astrobiologists. So, although the Astrobiology program has no missions entirely of its own, it has proxy ownership of missions belonging to other NASA science programs. Indeed, this alignment of interest between astrobiology and other NASA programs, for which NAI rightfully deserves credit, represents a very effective leveraging of astrobiology funds.[9,10] In keeping with the close alignment between subjects of interest to astrobiology and the planetary science community, NAI members regularly serve on science definition teams for missions to Mars and Europa and are members of the science teams of the Mars Exploration Rovers, the Mars Reconnaissance Orbiter, the Mars Science Laboratory, and the Mars Phoenix missions.

BALANCE OF NAI ACTIVITIES

The focus groups provide an appropriate mechanism for the NAI and, more importantly, the wider astrobiology community to play an important strategic role in defining NASA's future missions. Participation in the focus groups is open to all interested parties and not just the scientists supported by the NAI or by other NASA programs.

A model for how the focus groups could play an even more strategic role in the future is given by MEPAG and its emulators,[11] the Outer Planets Analysis Group (OPAG),[12] the Venus Exploration Analysis Group (VEXAG),[13] and the Lunar Exploration Analysis Group (LEAG).[14] Through the drafting and promotion of timely white papers and, more importantly, the systematic documentation of key scientific goals and objectives, and by defining investigations and priorities for their respective areas of interest,[15] the "AGs" have played an important role in NASA's strategic planning exercises. Moreover, such groups provide a forum at which scientists can interact with their engineering counterparts and form the partnerships essential to the design of future spacecraft missions.

The NAI could further promote the astrobiology community's contribution to planned and future missions by building on the present missions that include some astrobiology goals, for example the Mars Science Laboratory (MSL), scheduled for launch in September 2009. One of the key questions to be addressed by MSL is the critical astrobiology objective to investigate the past and present habitability of Mars (i.e., the planet's potential for supporting life of any kind). To perform this task the MSL payload includes several instruments that will assess the biological potential of several special regions on Mars, characterize the geology and geochemistry of those regions, investigate the planetary processes that influence habitability, and measure the surface radiation environment. The NAI should actively promote one or more focus groups to build on MSL's habitability strategy by helping to define the scientific requirements and goals for a follow-up mission—such as the proposed Astrobiology Field Laboratory—that has the principal goal of determining if life has ever developed on Mars. A similar approach can be adopted for other potential missions that will contribute to achieving the scientific goals outlined in the Astrobiology Roadmap.

RECOMMENDATIONS FOR FUTURE NAI ACTIVITIES

With respect to the goal of providing scientific and technical leadership on astrobiology investigations for current and future space missions, the committee finds that the NAI has:

- *Encouraged astrobiologists to provide needed recommendations and expertise to NASA for mission planning.*
- *Promoted the participation of astrobiologists in the science teams for current and future missions*. This has been an effective mechanism for involving life scientists and others in NASA programs.
- *Organized activities, such as focus groups, that have strongly influenced NASA missions*. There are many factors that help determine a NASA mission, but this is an important way to ensure that the science is as relevant as possible.
- *Identified astrobiology questions that underpin most of NASA's current flight programs*. The potential discovery of the existence of life on worlds other than Earth is certainly one of the most important reasons for many NASA missions. But it must be remembered that the goals of astrobiology go beyond the search for life and encompass a far richer and broader set of questions relating to the origin and co-evolution of life and habitable environments. This breadth of goals gives astrobiology great resilience in the face of short-term programmatic changes.

The NRC's 2003 review of NASA's Astrobiology program recommended that "an important operational goal of astrobiology is to inform NASA missions with respect to the techniques and targets for the search for life elsewhere, and the search for clues to the steps leading to the origin of life on Earth."[16] The committee endorses this recommendation and suggests that the most critical function of the NAI is to remain central to NASA spaceflight programs.

Recommendation: Because its most critical function is to ensure that its research activities clearly contribute to NASA's current and future spaceflight activities, the NAI should be more proactive in identifying future astrobiology missions. In addition, the NAI should actively encourage a partnership between astrobiologists and their engineering counterparts to help define future NASA missions. Although the committee has not, in general, prioritized its recommendations, it believes that this one is of the highest importance. The committee suggests the following actions to implement this recommendation:

- The NAI focus groups have suffered from a lack of stable leadership and sustained activity, despite their demonstrated value as open community forums for the exchange of ideas and as venues whereby the NAI can take a leadership role within the larger space science community. The creation and continued support of focus groups should be strongly promoted and their performance critically evaluated at periodic intervals by NAI Central and the NAI Executive Council in strategic areas, especially those related to NASA missions and the scientific goals outlined in the Astrobiology Roadmap, to make sure that they remain responsive to NASA needs.
- Securing a tie to NASA flight programs is critical to the future of the field of astrobiology because the public is very interested in following NASA missions, and making the latest measurements and information widely available in a timely fashion allows the public to share in the discoveries and perhaps help determine the future directions NASA should pursue. In this context, the NAI should continue to promote a vigorous outreach program.
- The NAI should provide scientific recommendations in areas of mission strategy to NASA. It is critical that the exploration of the Moon and of Mars have a very firm scientific justification, and the astrobiology community, through the NAI, should take the lead in providing roadmaps outlining scientific goals, objectives, investigations, and priorities for these endeavors. As progress is made in addressing the key questions in astrobiology, important information such as improvements in scientific understanding of how life evolved on Earth should be factored into specific strategies for how to explore other planets. A continuous updating of the state-of-the-art knowledge founded on ground-based results, improved theories, and the latest astrobiology thinking as it relates to the details of planned missions would help ensure that NASA missions are as productive as possible. The focus groups are an appropriate mechanism for undertaking such activities.
- The NAI director has an important role to play as the de facto point of contact between the astrobiology community and relevant NASA flight programs. As such, the director should consult with the teams responsible for current and future flight programs and help to identify the most appropriate sources of astrobiological advice for their respective activities. Similarly, the NAI director should actively encourage NAI and non-NAI astrobiologists to serve on mission planning activities, focus groups, and mission science teams.

Recommendation: In selecting new nodes, the NAI should give more weight to the potential contribution of the proposed research to future NASA missions. Specifically, in the evaluation of proposals for new nodes, the NAI should require the proposed research program to demonstrate relevance to potential NASA missions that, if successful, would provide insight that can be translated into enhanced mission activities.

NOTES

1. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003, pp. 157-158.
2. National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001, pp. 157-158.
3. National Aeronautics and Space Administration, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004, pp. 4-13.
4. See, for example, D.J. McCleese and the Mars Advanced Planning Group 2006, *Robotic Mars Exploration Strategy 2007-2016*, JPL-400-1276, Jet Propulsion Laboratory, Pasadena, California, 2006, pp. 7-9. Also see, D.W. Beaty, M.A. Meyer, and the Mars Advanced Planning Group 2006, *2006 Update to Robotic Mars Exploration Strategy 2007-2016*, unpublished white paper, posted November 2006 by the Mars Exploration Program Analysis Group at http://mepag.jpl.nasa.gov/reports/index.html.
5. See, for example, National Research Council, *Assessment of NASA's Mars Architecture 2007-2016*, The National Academies Press, Washington, D.C., 2006, pp. 11-12.
6. National Research Council, *The Scientific Context for Exploration of the Moon*, The National Academies Press, Washington, D.C., 2007.

7. National Research Council, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, The National Academies Press, Washington, D.C., 2003, pp. 5 and 28.

8. National Research Program, *An Assessment of Balance in NASA's Science Programs*, The National Academies Press, Washington, D.C., 2006, pp. 20-21.

9. National Research Council, *Astronomy and Astrophysics in the New Millennium*, National Academy Press, Washington, D.C., 2001.

10. National Research Council, *New Frontiers in the Solar System: An Integrated Exploration Strategy*, The National Academies Press, Washington, D.C., 2003.

11. For more information about MEPAG see http://mepag.jpl.nasa.gov/.

12. For more information about OPAG see http://www.lpi.usra.edu/opag/.

13. For more information about VEXAG see http://www.lpi.usra.edu/vexag/.

14. For more information about LEAG see http://www.lpi.usra.edu/leag/.

15. For more information about, for example, MEPAG's *Mars Scientific Goals, Objectives, Investigations, and Priorities* document, see http://mepag.jpl.nasa.gov/reports/MEPAG%20Goals_2-10-2006.pdf.

16. National Research Council, *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology*, The National Academies Press, Washington, D.C., 2003, pp. 2 and 13.

5

Use of Information Technology

This chapter evaluates the success of the NASA Astrobiology Institute (NAI) in exploring new approaches, using modern information technology, to conduct interdisciplinary and collaborative research among widely distributed investigators.

NAI CONTRIBUTIONS

Applications of information technology within the NAI have been focused in two major areas: improving communications among widely distributed research teams to enhance interdisciplinary research and cross-disciplinary training of graduate student researchers and improving communications with the public to enhance education and public outreach. The NAI has achieved significant progress in both these areas.

Electronic communications such as e-mail and information posted on Web sites have been essential for the successful operation of NAI nodes and for effective communication between the nodes and NAI Central. In particular, the Web site developed and maintained by NAI Central and the associated Web-based tools for communicating with NAI Central are viewed as important developments.[1] The NAI newsletter published regularly on the NAI Web site and the archive of webcast/podcast seminars are praised as being especially effective for keeping NAI members informed about current scientific and other developments.[2]

The NAI has made significant efforts to take advantage of new communications technologies such as videoconferencing and WebEx tools for sharing presentations in real time. In the case of WebEx, the NAI played something of a pioneering role in the application of this technology. The principal investigators (PIs) of various past and present NAI nodes and foreign affiliates/associates who provided input to the committee reported, however, that the effectiveness of these new technologies was poor (see Box 5.1). But it is difficult to assess these comments because only 9 responses were received from some 30 individuals contacted. What is clear from both written and verbal input to the committee is that some of the nodes embraced the new technologies and learned how to use them effectively, but other nodes were slow to take full advantage of them.

The Director's Seminar Series, which is active during the academic year, is a monthly webcast aimed at a broad scientific audience.[3] Seminars cover a wide range of astrobiology research topics, provide basic introductions to the subdisciplines of astrobiology, give updates of NAI-sponsored research, and offer opportunities for interactive participation of NAI members through moderated question-answer and discussion periods. This seminar series appears to have been an effective tool for connecting NAI nodes to the broad range of NAI-sponsored research,

BOX 5.1
SELECTED COMMENTS ON NAI INFORMATION TECNOLOGIES

Baruch Blumberg (Fox Chase Cancer Center and founding director of the NASA Astrobiology Institute):

Each team received videoconferencing equipment. To assist with the conferencing sessions "producer directors" were appointed at each of the sites, and they met periodically by video and in person to facilitate the videoconferencing. Our video communication capabilities improved over the time I was Director and I understand are even better now. The NAI Web site was established as a mechanism for frequent communication of papers, newsletters, notices, educational material, administrative matters and also for nonhierarchal peer-to-peer communications. It was also a major part of the public outreach effort. We realized that electronic means alone were insufficient to establish good collaboration, and we instituted other methods for abetting interaction and collaboration. The Executive Council met monthly by video and in person three or more times a year. The entire membership was invited to multiday meetings at one of the team sites every other year, and on alternate years they would meet at the Astrobiology Science Conference. We also encouraged participation in field trips. Funding was available for members of one team to join field trips organized by another in order to increase interaction. Additional funding was made available for joint research projects that would bring people from different teams together. There was a remarkable amount of personal connections established between members of the different teams and, I believe, it did lead to the coherence of the organization and increased collaboration.

David Des Marais (principal investigator, NASA Ames Research Center):

The initial efforts to develop novel approaches in information technology were neither very successful nor were they truly novel. However, in recent years the NAI has very successfully employed mainstream applications such as WebEx. Also, the NAI-supported Web-based seminar series have typically been excellent. I cannot cite hard evidence, but I suspect that these seminars have fostered several interdisciplinary collaborations.

Bruce Jakosky (principal investigator, University of Colorado):

Not very, to be honest, but then nobody has figured out how to do this. The NAI pioneered the (somewhat) effective use of videoconferencing, video seminars, and WebEx, but I would hope that modern approaches to collaborative work would go farther than this. Of course, if I had any good ideas as to how to enhance these, I would put them forward.

Andrew Knoll (former principal investigator, Harvard University):

The NAI certainly made it possible for me to conduct collaborative research at Rio Tinto with Spanish colleagues, and for this I am most appreciative. NAI-driven technological innovation played little role in this collaboration. E-mail, the Internet, wiki-sites, etc. go a long way toward facilitating collaborative research. I don't know to what extent NAI has developed resources above and beyond these readily available facilitators.

Rocco Mancinelli (principal investigator, SETI Institute):

With the use of WebEx and videoconferencing capabilities the NAI has successfully conducted meetings (e.g., the NAI Executive Council monthly meetings, informational workshops) and presented colloquia. These have provided us the opportunity to interact more regularly than we otherwise could.

Hiroshi Ohmoto (principal investigator, Pennsylvania State University):

During the early stage of the NAI, we talked about creating a common Astrobiology Laboratory in Moffett Field (Ames), which would house (1) biological experimental facilities and (2) large state-of-the-art analytical instruments. Experiments and analyses were to be carried out remotely using modern technology, such as the technology used in Mars exploration, and the data were to be shared by all NAI-related investigators via advanced IT network. It would have been great if such a laboratory had been built. But unfortunately, such a grand vision was lost when Dr. Blumberg left the NAI.

BOX 5.1 (continued)

Mitchell Sogin (principal investigator, Marine Biological Laboratory):

I think the NAI needs to require the PIs to spend more time interacting at meetings, and that would extend into videoconference activities that are more productive. Currently and historically the multiteam videoconferences have been technologically superb but all too often lack substance.

Sean Solomon (principal investigator, Carnegie Institution of Washington):

The NAI has been a leader in the exploration of new approaches to cross-team communication. Not all approaches have proven successful, but negative outcomes are to be expected in the pursuit of novel methods for conducting collaborative research among geographically dispersed participants. It is difficult to improve on face-to-face meetings among potential collaborators with shared interests and complementary expertise as a basis for the most successful collaborations.

Roger Summons (principal investigator, Massachusetts Institute of Technology):

NAI has certainly explored this successfully and in numerous ways. However, I think the outcomes are modest. Science works best when people engage one-on-one. Personally, I don't see an easy way around this and think that the scientific meetings and field exercises have been the linchpin in bringing widely distributed investigators together.

Malcolm Walter (director, Australian Center for Astrobiology):

From my point of view it has failed. My group's interaction with its collaborators in the NAI has not been enhanced by the NAI's use of "modern information technology."

Neville Woolf (principal investigator, University of Arizona):

This does not work very well. We do indeed use it as a substitute for face-to-face meetings because any meeting is better than no meeting. But face-to-face is still needed. It is likely that some of the difficulties result from the loss of nonverbal signals. Other difficulties arise from the rigid time constraints of Web meetings. Some of the difficulties are inherent in time zone differences around the globe.

thereby promoting interdisciplinary interactions, although there appears to be little consistency of participation across all of the NAI nodes.

The staff at NAI Central identified a variety of factors that have posed challenges to effective electronic interactions between disciplines and between NAI nodes. Social factors included the difficulty of finding times for video conferences that fit into the busy schedules of NAI members; lack of enthusiasm on the part of some NAI members for virtual collaborations; and differences in member abilities to master new technologies. Technical factors included platform incompatibilities, differences in Internet connection speeds, lack of local information technology expertise and support at some nodes, and coping with security policies at some sites.

NAI Central's response to these challenges has been well balanced in terms of the responsiveness to solving hardware and software problems and in keeping up with the latest advances in technology to improve interactions between NAI members. The social factors have been far less tractable, although on-site training in the use of communication tools by the staff of NAI Central proved to be fairly successful in overcoming some of these issues during the formative years of the NAI.

Software developments by the NAI to manage virtual collaborations through secure, shared Web interfaces among researchers at different nodes (e.g., sharing of data and products in real time) have been part of an experimental effort that may have promise for improving interdisciplinary interactions.

The staff of NAI Central has given much thought to potential future activities and undertakings that will enhance the NAI's role as a virtual institute. Examples of recent developments include the following:

- *Reconstituting the NAI's Information Technology Working Group.* This group, with members drawn from the NAI teams, is responsible for addressing collaborative technology issues and implementing continual improvements. Although the group ceased operation following the recent NAI budget cuts, it was reestablished in 2007 and is now meeting regularly.
- *Developing stronger ties with information/collaborative technology developers in the Silicon Valley area.* The NAI team at the Ames Research Center, for example, is already undertaking a Google-funded project relating to the tracking of sea-level rise and climate change. NAI Central submitted a proposal to Google to explore virtual environments for science collaboration, but it was not selected for funding.
- *Upgrading of NAI's video- and teleconferencing technologies.* As a parallel and lower-cost option to upgrading its collaborative tools, NAI Central recently purchased a Codian Multipoint Control Unit. This device employs a user-driven interface to establish up to 30 simultaneous videoconferencing connections. It will allow NAI teams and team members to independently schedule videoconferences without the involvement of NAI Central. In addition, the Ames Research Center—with NAI encouragement—is considering the acquisition of a Cisco TelePresence system, which provides a highly elaborate and comprehensive videoconferencing and collaborative work environment.
- *Exploring social networking, user-driven content, and virtual world systems to enhance interactions between astrobiologists.* NAI has currently made only tentative forays in these directions. NAI-sponsored astrobiology students have established a presence in Facebook, and there is a nascent astrobiology presence on Nature Network. NAI Central is looking at the potential of wiki software to enhance online collaborations. In addition, the NAI is considering establishing an "Astrobiology Island" in Second Life, a three-dimensional virtual world where users can meet and interact. The NAI's long-term hope is that a combination of these new information technology concepts and existing videoconferencing tools can be harnessed to create a new generation of virtual meetings and workshops. To this end, it is notable that the NAI was the host of a NASA Science Mission Directorate Web workshop held in November 2007 and organized a session on the use of social networking to promote scientific collaborations.

RELATIONSHIP TO OTHER ASTROBIOLOGY PROGRAMS

The use of modern information technology to enhance interdisciplinary and collaborative research among widely distributed investigators is a characteristic of the NAI that sets it apart from the other components of NASA's Astrobiology program.

BALANCE OF NAI ACTIVITIES

The Web site developed and maintained by NAI Central has been an effective tool for communicating with the public, serving a very large volume of individuals and downloads in the United States and around the world. The committee notes and welcomes the fact that the NAI is developing an integrated Web presence for the Astrobiology program as a whole, drawing on the capabilities and tools developed to support the NAI Web site.

RECOMMENDATIONS FOR FUTURE NAI ACTIVITIES

With respect to the goal of exploring new approaches and using modern information technology to conduct interdisciplinary and collaborative research among widely distributed investigators, the committee finds that:

- *The substantial efforts by NAI Central to improve communications among NAI members have achieved some significant successes.*

- The NAI has been less successful in promoting the use of collaborative work tools by the researchers affiliated with its participating teams. NAI's results are uneven because there is inherent resistance to adopting new technologies.

Recommendation: The NAI should vigorously pursue new approaches using modern information technologies to increase the effectiveness of the NAI nodes. In particular, additional efforts by NAI Central are needed to ensure that new communications tools are used to enhance the effectiveness of interdisciplinary and collaborative research and training. The committee suggests the following actions to implement this recommendation:

- The NAI should initiate an in-depth study of the use of technology for communication, collaboration, and training with the goal of understanding why so many NAI participants believe that success to date has been mixed.
- The NAI might consider methods to increase its emphasis on enabling the exchange of interdisciplinary ideas and research. This enhanced effort would continue to be coordinated and perhaps funded by NAI Central, supported by information-technology specialists on staff at NAI Central as needed. Particular attention might be paid to the social challenges of incorporating new information technology tools into the NAI's daily activities.
- To help teams of scientists with the task of figuring out collaborative technology, the NAI should take advantage of the multidecade-long research literature developed by social scientists and other experts on collaborative activities concerning the success and failure modes for virtual teams.
- The NAI might consider continuing the Director's Seminar Series, which has been an effective tool for enhancing interactions among NAI members, on a regular basis and encouraging broad participation by all members of the astrobiology community.
- The NAI might consider accelerating the use of the expertise and the Web tools developed at NAI Central to support other segments of NASA's Astrobiology program.
- The NAI could set up an external review team, composed of national leaders in collaborative technologies from university and industry, to examine the NAI teams' use of collaboration technology tools. This approach not only would give NAI objective advice about how to improve its support of virtual teams but also might help to identify opportunities for future joint work.
- NAI Central is encouraged to continue its current efforts to develop strategic alliances with Silicon Valley companies in the collaboration/information technology sector.
- NAI Central could also consider partnering with one of the university-based research groups working to develop collaborative technologies that are much more advanced than commercially available systems. Moreover, what computer scientists interested in collaboration research need most is a tightly knit scientific community with which to experiment. NAI Central could persuade one or more NAI teams to act as testbeds for other groups whose primary research mission is scientific collaboration, thereby gaining a research and development capability financed with non-NAI funds.
- Funding agencies such as NSF and DOE are increasingly interested in funding projects relating to "e-science" and "cyberinfrastructure." NAI Central could issue requests for proposals that would allow certain NAI teams to partner with collaboration researchers seeking NSF or DOE funds and thereby prototype leading-edge systems for the NAI as a whole.
- The NAI could turn its scientists who are reluctant to engage in the use of collaboration technology into an asset by asking these reluctant adopters to suggest specific improvements that would attract them to use the improved technology and then use that information to develop a research agenda for NAI collaboration research partners.
- The NAI is encouraged to continue its current efforts to explore the possibility of harnessing some of the new software tools developed to facilitate social networks and virtual worlds to support astrobiology research.

NOTES

1. The NAI Web site can be found at http://www.nai.arc.nasa.gov.

2. The NAI Newsletter is archived at http://www.nai.arc.nasa.gov/newsletter/past_issues.cfm. The Web casts are archived at http://www.nai.arc.nasa.gov/seminars/indexall.cfm#2.

3. NAI seminars are archived at http://www.nai.arc.nasa.gov/seminars/indexall.cfm#4.

6

Education and Outreach

This chapter evaluates the success of the NASA Astrobiology Institute (NAI) in supporting outreach by providing scientific content for use in K-12 education programs, teaching undergraduate classes, and communicating directly with the public.

NAI CONTRIBUTIONS

Astrobiology addresses scientific topics that attract wide interest from the public: the origins and evolution of life, space exploration, and the possibility of life on Mars or elsewhere in the solar system and beyond. NASA legitimized and took ownership of these topics through its support of astrobiology. The education and public outreach (EPO) component of the NAI is essentially NASA's vehicle to deliver its discoveries to the public.

NAI member scientists and EPO professionals have capitalized on the broad appeal of astrobiology by making substantial contributions to the public's general understanding of science. The close interaction between EPO professionals and NAI scientists is the key to the impressive list of the NAI's EPO accomplishments. In many cases, the scientists themselves play active roles in education and outreach by giving public lectures, leading field trips, and teaching college courses at all levels. These EPO efforts have been extremely well received by their intended audiences. There is extensive evidence that the products of NAI EPO are being incorporated into mainstream science education at all levels. Astrobiology courses that comply with National Science Education Standards (NSES) are being taught in high schools. Astrobiology courses are now offered at most of the NAI principal investigators' (PIs') and co-investigators' (CoIs') home universities, in addition to many universities not directly affiliated with the NAI (see Chapter 3). And the NAI's EPO effort is a highly effective mechanism for providing the public with information on the latest discoveries, many of which have been made by NAI teams, regarding evolution, the origins of life, and our cosmic origins.

Overall the NAI has been highly successful in integrating cutting-edge research into educational products. In fact, the interdisciplinarity of the science (and of the NAI members themselves) has been a major factor in the success of the NAI's EPO efforts. NAI scientists are adept at communicating with colleagues in various disciplines, and by so doing make the information accessible to a wider audience, including science teachers and the public.

Although interdisciplinary scientific research is the major mission of the NAI, it has since its inception in 1998 set very high goals for education and public outreach. Examples of the NAI's EPO achievements include the following:

- Elementary-school science activities that directly address educational standards;
- A high-school-level astrobiology textbook and curriculum that address educational standards;
- A number of college-level textbooks for general education,[1] undergraduate-,[2] and graduate-level[3] courses authored by NAI members;
- Workshops and field trips for teachers, science journalists, and students, organized by both EPO professionals and scientists;
- Well-attended public lectures given by leading NAI scientists; and
- Interactive Web sites, teacher training activities, workshops, field trips, and museum and national park displays whose science content is provided by NAI scientists.

The NAI has effectively used its visibility to leverage funds, partnerships, and expertise. With assistance from NAI Central, NAI researchers and educators together have developed an extensive array of activities in multiple formats. Collaborating with organizations that provide major or supplemental funding has produced high-profile, high-quality products. Examples include the following:

- *Origins—14 Billion Years of Cosmic Evolution*—a Public Broadcasting Service (PBS) television broadcast in the Nova series.[4]
- *Looking for Life*—a NASA/PBS program on astrobiology.[5] The NAI expanded public distribution of this program by producing 4,000 DVDs, which were distributed within the NAI EPO community for use in local public outreach events such as Astrofest, Space Day, science fair judging, Girl Scout programs, and so on.
- *Aliens of the Deep*—an IMAX film produced by the Disney Corporation.[6]
- *Are We Alone?*—a weekly hour-long radio program focusing on a wide range of topics relevant to astrobiology. Initiated by the SETI Institute with its endowment fund but currently supported in part by the NAI,[7] the series is broadcast on the National Public Radio satellite channel and is available as a podcast.[8] The podcasts present the latest developments in astrobiology to approximately 50,000 listeners per program.

NAI Central and members of NAI teams assisted as consultants in all of these productions and provided coordination and support for companion Web sites and other accompanying educational materials. The Nova series identified above features NAI scientists at work. The NAI node at NASA's Ames Research Center is engaged in several cooperative endeavors that reach large audiences. Examples include contributions to the *Yellowstone Resources and Issues Handbook*,[9] training lectures given to park and interpretative rangers, and the Park Kids Program (Astrobiology Educator Guide). Yellowstone is one of the most visited parks in the United States, hosting some 3 million visitors a year. The NAI team at the Ames Research Center also assisted in developing displays at the museums of the California Academy of Sciences[10] and the New York Hall of Science.[11] To further promote the interpretation of science to the public, the NAI team at the University of Colorado has organized a series of workshops designed specifically to explain the science of astrobiology to journalists and thus enhance their ability to accurately inform the public.[12]

To inspire a future scientist takes an ongoing effort that continues from middle school, through high school, to college and into graduate school. Early capture of students' interest depends on inspired teaching of science in the early grades. Embracing this concept, the NAI has made teacher professional development a major cornerstone of its EPO activities. NAI teams have instituted and maintained a host of effective teacher training programs. With earlier NAI support and currently as a member of the NAI, the SETI Institute offers both curriculum and teacher development programs. *Voyages Through Time*,[13] a 9th and 10th grade high-school curriculum, is taught in more than 400 schools around the United States and is supported by an active network of more than 90 teachers who have been trained in the SETI Institute's Astrobiology Summer Science Experience for Teachers (ASSET) program.[14] Teachers attending ASSET can obtain continuing education unit credits at San Francisco State University, a major educator-training university in the San Francisco Bay area. NAI Central works toward creating a cadre of "master astrobiology teachers" who can bring their knowledge back to local communities and share their work with their peers. This initiative has created an effective national network of astrobiology teachers across the United States. In addition, the University of Arizona presents semester-long Internet courses entitled "Astrobiology for Teachers" and "Advanced Astrobiology for Teachers 1+2."[15] A total of some 250 teachers have enrolled in this program in the 7 years it has been offered.[16]

Another element of the NAI's EPO program is serving diverse populations. A collaborative NAI project drafted, field tested, and finalized a workbook with six hands-on activities and a short film weaving together astrobiology and origins science with Navajo Indian cultural knowledge. The workbook—*So' Ba Hane', Story of the Stars*—and the film were internally distributed to approximately 300 schools on the Navajo Reservation.[17] The project has been presented by Navajo partners at Indian education conferences, and the companion film was screened at the 31st American Indian Film Festival, held in San Francisco in 2006.

The NAI team at NASA's Goddard Space Flight Center (GSFC) has initiated the Minority Institution Astrobiology Collaborative (MIAC), which involves secondary school teachers and faculty from historically black colleges and universities (HBCUs).[18] A 2-year curriculum was developed and field tested at GSFC and at South Carolina State University. Under this program, 10 middle-school teachers received training each year and 20 middle-school students were engaged in science projects. This pilot project moved to Tennessee State University, where a 3-year program to train teachers is ongoing. This MIAC project is now the recipient of a newly funded National Science Foundation grant for education research.

Tennessee State University has also become part of the Minority Institution Research Support (MIRS) project that successfully involves researchers from HBCUs, Hispanic-serving institutes (HSI), and tribal colleges (TC).[19] Tennessee State University not only has embraced the minority teacher training program but also has initiated an effective undergraduate program in astrobiology. Astrobiology has generated considerable interest at Tennessee State in part because it is viewed as a "pioneer" field of science, and the students entering perceive increased opportunities for making significant discoveries as compared to the more traditional fields of science.

There are many successful NAI education and public outreach projects in addition to those cited here. The NAI contribution to undergraduate and graduate courses and their accompanying educational materials is discussed in Chapter 3. Curricula and several excellent astrobiology textbooks have been developed by NAI members for use in high schools and middle schools. Examples include the following:

- *Astrobiology in Your Classroom*—a NASA educator resource guide for grades 5-8,[20]
- *Astrobiology*—a new book for middle-school students by Fred Bortz,[21] and
- *Astrobiology: An Integrated Science Approach*—a high-school textbook by Jodi E. Asbell-Clarke et al.[22]

The NAI is also providing an astrobiology framework for the national Science Technology, Engineering and Math (STEM) education initiative and actively encourages collaboration among EPO practitioners. A large component of the University of Washington's EPO effort has been to expand the very successful Project Astro—a nationwide program in which astronomers are paired with local school teachers to bring astronomy into K-12 classrooms[23]—into Project AstroBio.[24] Starting with the 2002-2003 school year, the University of Washington's Project AstroBio has annually paired 20-25 teachers from the Puget Sound region with volunteer astronomers or biologists. Each teacher-scientist partnership participates in a training workshop, receives resource materials, and develops a strategy for working together in and out of the classroom. The teachers participating in Project AstroBio subsequently guide students in grades 3 to 12 through inquiry-based, hands-on activities relevant to astrobiology. These activities are rigorously designed to meet national and state education standards. The partnering scientists each commit to a minimum of five classroom visits per school year. In its years of operation (i.e., prior to the termination of the University of Washington's NAI funding in 2006), Project AstroBio had a direct impact on some 150 teachers and almost 4700 students.

The NASA Astrobiology Institute's overarching mission, to search for clues to the origins of life on Earth and to search for life on other planets, clearly resonates with the public. This is attested to by statistics on visits to the NAI Central Web site,[25] which in May 2007 logged more than 46,000 visits from more than 29,000 unique visitors. At first sight, these numbers do not appear large when compared to, for example, the 3,952,000 visits to the main NASA Web site in the same period.[26] However, the significance of the NAI's 29,000 visits becomes apparent when they are normalized by the ratio of the total NASA budget to the NAI budget (i.e., approximately

1,000:1). NAI Central created and maintains the Web site that serves members by posting a newsletter, an events calendar, funding opportunities, team Web sites, a seminar series archive, collaborative tools, and a handbook. It also communicates the activities and accomplishments of the NAI to the astrobiology community at large and to the public.

In summary, the NAI's EPO activities and products are a profitable return on the investment, and there has been a very successful synergistic relationship between the NAI researchers and the EPO staff of the individual teams.

RELATIONSHIP TO OTHER ASTROBIOLOGY PROGRAMS

The NAI provides a unique and useful complement to other EPO activities associated with PI-driven programs within the Astrobiology program (e.g., the Exobiology grants program). While EPO activities are associated with some of these grants, there are few examples of scientists being as actively involved in the EPO activities as NAI scientists are, and also few other instances where the scientific results of the project are the focus of the EPO products. For example, the NAI's Virtual Planetary Laboratory (VPL) EPO team has developed an interactive Web site where visitors can "meet" the individual scientists and learn about planet formation from the scientists themselves, via pre-recorded interviews. They can also build their own planet online and see if it is likely to support life.

An example of NAI scientists who become intimately involved with EPO efforts and of EPO professionals who acquire a high level of understanding of the science is evident in the NASA Ames NAI team's contribution to the public understanding of life in extreme environments in Yellowstone National Park.[27] The study of hyperthermophiles is an important focus of the research of the Ames team, and its scientists were actively involved in providing technical content for eight new trail signs that relate the unique geophysical phenomena at these locations to astrobiology.

BALANCE OF NAI ACTIVITIES

The NAI's EPO efforts have been highly successful at transforming the science and discoveries of astrobiology into K-12 educational products, curricula, and standards. However laudable the NAI's efforts in EPO are, can they have an impact on a national scale? The short answer must be no; the expenditures are too small. Indeed, if the entire NAI budget were devoted to EPO activities, NAI EPO would still be too small an effort to have a sustained national impact. The NAI is not going to solve the nation's educational woes. Nevertheless, the NAI has demonstrated that limited public outreach activities can have a major local impact. A sufficient number of parallel local efforts, be they by the NAI or other NASA activities, may create a cascade with sufficient momentum to be important on the national scale. Unfortunately, it is not evident that other NASA programs, even the non-NAI Astrobiology programs, are taking full advantage of the EPO activities of the NAI. They could do so to great advantage.

In the educational arena, although there are many NAI scientists who also are faculty members and demonstrate their commitment to EPO by giving public talks or leading field trips, they do not stray far from their home discipline with regard to teaching a course on astrobiology for science majors. The result is that "astrobiology" courses at the college level tend to be taught by several instructors or to be narrowly focused on a traditional field, which sends the wrong message about the interdisciplinary nature of astrobiology.

More support could be given to NAI faculty members who offer truly interdisciplinary astrobiology courses for undergraduate science majors. This support could be in the following forms:

- Curriculum materials, similar to those produced for K-12, but adapted to the college undergraduate level;
- Release time, before or during the semester that an astrobiology course is being taught, to allow researchers to host workshops for current and future astrobiology educators;
- Initiation of a focus group on astrobiology education at the undergraduate science-major level; and
- Summer courses in astrobiology for undergraduates.

In 2006, for example, the Vatican Observatory Summer School hosted a course on astrobiology inspired and supported by George Coyne S.J., the former director of the Vatican Observatory and ardent supporter of science education. Members of the University of Washington's NAI team and colleagues from the University of Arizona team played a major role in this course and reported that the international cadre of students was very enthusiastic and benefited greatly from the experience. A similar, but continuing, activity is the Josep Comas i Sola International Summer School in Astrobiology jointly sponsored by the NAI, its Spanish associate, the Centro de Astrobiología, and the Universidad Internacional Menéndez Pelayo Palacio de Magdalena. Support for such activities would help bridge the gap between K-12 education and Ph.D. programs.

Several general-education textbooks on astrobiology have been published for introductory courses whose target audiences are nonscience majors, and several upper-level textbooks have appeared recently. Various universities offer general-education astrobiology courses. However, there has not been much progress in offering advanced undergraduate astrobiology courses for science majors. This is an issue that the NAI could address to prevent a disconnect between success in inspiring schoolchildren and success in developing Ph.D. candidates in astrobiology. In the near future, faculty positions will be held by instructors who have had formal astrobiology training, and undergraduate educational opportunities will increase accordingly. In the interim, however, attention should be paid to this gap in undergraduate education.

RECOMMENDATIONS FOR FUTURE NAI ACTIVITIES

With respect to the goal of supporting outreach by providing scientific content for K-12 education programs, teaching undergraduate classes, and communicating directly with the public, the committee finds that the NAI has:

- Successfully promoted astrobiology as a field with broad-based public appeal;
- Developed effective programs for outreach to the general public; and
- Enabled minority educational activities.

Recommendation: The NAI should be more strategic in exploiting synergies among nodes in K-12 education, minority education, and teacher training. Because the current NAI teams are at various stages in their tenures, their EPO activities are in various stages of development. To avoid duplication of effort and wasted resources, the committee suggests that when new NAI teams are selected, NAI Central could facilitate connections between the existing EPO teams and the new arrivals.

Recommendation: The NAI should address the specific requirements for teaching astrobiology at the undergraduate level. The committee suggests the following actions to implement this recommendation:

- The NAI could support development of educational products (other than textbooks) at the undergraduate level similar to those available for K-12 education;
- NAI faculty could be encouraged to take courses outside their areas of expertise (e.g., through release time, and so on);
- Workshops could specifically target undergraduates interested in astrobiology (most workshops have been conducted for graduate students);
- Programs similar in scope to the NSF's Research Experience for Undergraduates (REU) could be developed;
- A focus group should be formed that is specifically dedicated to issues related to teaching astrobiology at the undergraduate level. Care should be taken to ensure that its membership includes individuals who teach undergraduates and are familiar with the disciplinary pressures, rather than individuals whose experience with undergraduate education is restricted to their own undergraduate days; and
- High-achieving undergraduates could be supported to attend the NAI-sponsored astrobiology summer school in Spain, for example, or other similar events and conferences.

NOTES

1. See, for example, Bruce M. Jakosky, *The Search for Life on Other Planets*, Cambridge University Press, New York, 1998.
2. See, for example, Jonathan I. Lunine, *Astrobiology: A Multi-Disciplinary Approach*, Benjamin Cummings, 2004.
3. See, for example, Woodruff T. Sullivan III and John A. Baross (eds.), *Planets and Life: The Emerging Science of Astrobiology*, Cambridge University Press, New York, 2007.
4. For more information see http://www.pbs.org/wgbh/nova/origins/.
5. For more information see http://passporttoknowledge.com/life/.
6. For more information see http://en.wikipedia.org/wiki/Aliens_of_the_Deep.
7. For more information see http://radio.seti.org/index.php.
8. For more information about the podcasts see http://podcast.seti.org/.
9. See, for example, Chapter 4 of the 2007 edition of the National Park Service's *Yellowstone Resources and Issues Handbook*, available at http://www.nps.gov/yell/planyourvisit/yellowstone-resources-and-issues-handbook.htm.
10. For more information see http://www.calacademy.org/.
11. For more information see http://www.nyscience.org/home.
12. For more information see http://lasp.colorado.edu/education/journalists/index.htm.
13. For more information see http://www.voyagesthroughtime.org.
14. For more information see http://www.seti.org/epo/asset/.
15. E.E. Prather and T.F. Slater, "An Online Astrobiology Course for Teachers," *Astrobiology* 2: 215-223, 2002.
16. Personal communication, Timothy F. Slater, University of Arizona, October 11, 2007.
17. For more information see http://nai.nasa.gov/storyofthestars/.
18. For more information about MAIC see http://miacnetwork.org/index.html.
19. For more information about MIRS see http://www.nai-mirs.org/.
20. For more information see http://teachspacescience.org/cgi-bin/search.plex?catid=10000406&mode=full.
21. Fred Bortz, *Astrobiology*, Lerner Publications, Minneapolis, Minnesota, 2007.
22. Jodie E. Asbell-Clarke, Daniel W. Barstow, Teon E. Edwards, and James L. Larsen, *Astrobiology: An Integrated Science Approach*, Technical Education Research Center, Cambridge, Massachusetts, 2005.
23. For more information about Project Astro see http://www.astrosociety.org/education/astro/project_astro.html.
24. For more information about Project AstroBio see http://www.astro.washington.edu/projastrobio/index.html.
25. The NAI Web site can be found at http://www.nai.arc.nasa.gov.
26. E.R. Hedman, "The Fragility and Resilience of NASA," *The Space Review*, August 6, 2007. Available at http://www.thespacereview.com/article/924/1.
27. See, for example, Chapter 4 of the 2007 edition of the National Park Service's *Yellowstone Resources and Issues Handbook*, available at http://www.nps.gov/yell/planyourvisit/yellowstone-resources-and-issues-handbook.htm.

Appendixes

A

Letter Requesting This Study

January 11, 2007

Dr. Lennard A. Fisk, Chair
Space Studies Board
National Research Council
500 Fifth Street, NW
Washington, DC 20001

Dear Dr. Fisk:

When the NASA Astrobiology Institute (NAI) was formed in 1998, it was intended to be an experiment in the management of research efforts aimed at broadening and transforming NASA's historical program in exobiology into the newly christened field of astrobiology—the study of the origin, evolution, and distribution of life in the universe. The creation of the NAI was considered an innovative approach to extend and broaden the multidisciplinary nature that had long characterized exobiology—requiring the formation of interdisciplinary teams that would address cross-cutting questions in novel ways which were deemed not practicable within the constraints of the existing grants program. The NAI was formed to produce the highest quality research results while ensuring the infusion of astrobiology objectives into NASA missions, to build a coherent astrobiology community, and to provide associated education and outreach efforts to enable public access and benefit from NASA-supported astrobiology research. Since its founding, the NAI has placed special emphasis on encouraging collaborative research among scientists and providing insights to educators from a variety of different backgrounds.

As a management experiment, the NAI was established as a "collaboratory" or "institute without walls," which was intended to stimulate cooperation and collaboration across the members' home institutional and geographic boundaries. The NAI members were selected under a cooperative agreement notice that provided grants to institute members under a flexible format that allowed full participation across Government/non-Government lines. A central office, with an NAI Director, was established at NASA Ames Research Center and several rounds of competition were held over the years, resulting in today's 12 member institutions (from a peak of 16). At the time of the NAI's founding, it was envisioned that a decadal review would be held to examine the results of this management experiment in the context of NASA's overall space and Earth science responsibilities.

I would like to request that the Space Studies Board (SSB) conduct a review to evaluate the NAI's progress in developing the field of astrobiology, both from the perspective of NAI members and that of the larger community of NASA-supported scientists—both within the NASA Astrobiology Program and outside of it. It is hoped that the results of this review can help guide NASA in assessing and shaping the future of the NAI, particularly in its preparation of a solicitation that would be issued to help select future teams to can lead the NAI into a second decade.

This review should evaluate the success of the NAI in achieving its stated goals of:

- Conducting, supporting, and catalyzing collaborative interdisciplinary research;
- Training the next generation of astrobiology researchers;
- Providing scientific and technical leadership on astrobiology investigations for current and future space missions;
- Exploring new approaches, using modem information technology, to conduct interdisciplinary and collaborative research amongst widely-distributed investigators; and
- Supporting outreach by providing scientific content for K-12 education programs, teaching undergraduate classes, and communicating directly with the public.

In evaluating the NAl's success, the SSB should address the following broad questions:

- Has the NAI developed, as envisioned, as an evolving experiment in cutting-edge, distributed, collaborative science and education in astrobiology?
- Does the NAI provide a unique and useful complement to other Astrobiology Program support mechanisms (e.g., individual grants to principal investigators), and if improvements need to be made in this area, what are they?
- Are the research, training, and public educational activities of the NAI appropriately balanced in terms of investments and outcomes, services to NAI members and external partners, and activities that engage and support the wider astrobiology community and the needs of young professionals?
- What other activities/roles not currently undertaken by the NAI might be appropriate in future?

I would like to request that the National Research Council submit a proposal for the execution of the proposed review. In order for the conclusions of the review to be available in sufficient time to be incorporated into the next-scheduled solicitation for NAI member-institutions, the final report of this review committee should be available no later than October 1, 2007. The technical point of contact for this activity will be Dr. John D. Rummel, who can be reached at 202-358-0702.

Sincerely,

Mary L. Cleave
Associate Administrator for
Science Mission Directorate

cc:
Science Mission Directorate/Dr. Hartman
- Dr. Hertz
- Dr. Al1en
- Ms. Hol1and

SMD/Planetary Science Division/Dr. Green
- Dr. Rummel

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Committee Biographies

JOHN M. KLINEBERG (*Chair*), an independent aerospace consultant, is the retired president of Space Systems/Loral (SS/L). Before assuming the presidency of SS/L, Dr. Klineberg served as executive vice president for Loral's Globalstar program, where he successfully led the development, production, and deployment of the Globalstar satellite constellation used for telephone services. Prior to joining Loral in 1995, Dr. Klineberg spent 25 years at NASA, where he served in a variety of management and technical positions. He was the director of the Goddard Space Flight Center, director of the Lewis (now Glenn) Research Center, deputy associate administrator for Aeronautics and Space Technology at NASA headquarters, and a research scientist at the Ames Research Center. Before beginning his career at NASA, he conducted fundamental studies in fluid dynamics at the California Institute of Technology and worked at the Douglas Aircraft Company and the Grumman Aircraft Company. He is currently a member of the National Research Council's (NRC's) Aeronautics and Space Engineering Board, and he served on the Committee on Assessment of Options for Extending the Life of the Hubble Space Telescope.

LUANN BECKER is an associate researcher in the Institute for Crustal Studies at the University of California, Santa Barbara. Her primary research areas cover the study of Permian-Triassic rocks and the search for life on Mars. Dr. Becker participated in an expedition to Antarctica in search of clues that can confirm activity of past life on Earth. Her current interests focus on the development of the Mars Organic Molecule Analyzer, an instrument selected for inclusion in the payload of the European Space Agency's ExoMars, a rover/lander mission scheduled for launch to Mars in 2013. She is best known for her work showing that fullerenes are present in meteorites and for studies evaluating the source of the organic material found in the martian meteorite ALH 84001. In addition to serving on the NRC committee that authored the report *Life in the Universe: An Assessment of U.S. and International Programs in Astrobiology* (2003), Dr. Becker's NRC experience includes membership on the Committee on Exploring Organic Environments in the Solar System.

YVONNE C. BRILL is an independent consultant whose primary focus is aerospace technology and policy issues. Her specific research interests include liquid- and solid-propellant rocket motors, launch vehicles for space applications, and spacecraft (on-board) propulsion systems. She began her career with Douglas Aircraft as a rocket propellant chemist on a project at Douglas to design and launch an unmanned, Earth-orbiting satellite. Later at RCA Astro-Electronics, she developed the concept for a new rocket engine—an electrothermal hydrazine thruster. Ms. Brill is a member of the National Academy of Engineering (NAE) and a fellow of the American Institute of Aeronautics and Astronautics and the Society of Women Engineers. She has served on numerous NRC and NAE committees, including the Committee to Evaluate the International Science and Technology Center and the Committee on International Organizations and Programs.

JACK D. FARMER is a professor in the Department of Geological Sciences at Arizona State University. His research covers microbial biosedimentology and paleontology, early biosphere evolution, and astrobiology, specifically focused on understanding the factors that control biosignature preservation and how that knowledge can be translated into a strategy for exploration of Mars. Dr. Farmer previously worked as a research scientist in the Exobiology branch of NASA's Ames Research Center. He was a member of NASA's 2003 Landing Site Steering Committee and was involved with landing site selection for the Mars Pathfinder. Dr. Farmer was also a member of the science definition teams for the Mars 2001 and 2005 missions, and he has participated in the recent revamping of the Mars Program architecture as chair of the Life Subgroup for NASA's Mars Exploration Program Analysis Group. He is a former member of the NRC Space Studies Board and of NASA's Space Sciences Advisory Committee.

MONIKA E. KRESS is an assistant professor in the Department of Physics at San Jose State University (SJSU). Dr. Kress joined SJSU in 2004 after serving as a research associate with the Center for Astrobiology and Early Evolution at the University of Washington (UW). Prior to her position at UW, she was an NRC postdoctoral research associate at NASA Ames Research Center. Her research interests include life in hyperarid planetary environments, early solar system evolution, the formation of habitable planets, and meteorites.

DAVID W. LATHAM is a senior astronomer at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. His current research interests focus on the study of extrasolar planets, especially transiting planets. Dr. Latham's work also includes the construction of large telescopes and observing facilities, the development of astronomical instruments and detectors for large telescopes, and the development of computer hardware and software systems for astronomy applications. He is co-chair of the joint NASA/ESA Transiting Planet Archive Working Group. Dr. Latham is a co-investigator on the Kepler Mission and also a co-investigator on one of the key projects for the Space Interferometry Mission (SIM). He is a member of the Harvard Origins of Life Initiative.

ANTONIO LAZCANO is a biology researcher and professor at the National Autonomous University of Mexico in Mexico City. He is considered to be among the 10 most distinguished Latin American scientists; he has studied the origins and early evolution of life for more than 30 years. His research focuses on the study of the deepest branches of the tree of life, with particular interest in the last common ancestor of extant life forms and the origins and development of metabolic pathways. Dr. Lazcano has been professor-in-residence or visiting scientist in France, Spain, Cuba, Switzerland, Russia, and the United States. He has written several books in Spanish, including the best-seller *The Origin of Life* (1984). Additionally, he has served on many advisory, editorial, and review boards, and he has organized several scientific meetings in Mexico, the United States, and Europe.

CINDY L. VAN DOVER is the director of the Duke University Marine Laboratory. Prior to her appointment at Duke, Dr. Van Dover was associate professor of marine biology at the College of William & Mary. She is a deep-sea biologist who began work in this field in 1982 as a member of the first biological expedition to hydrothermal vents on the East Pacific Rise. Her basic research focuses on the study of biodiversity and biogeography of fauna living in the extreme physical and chemical environments associated with deep-sea vents. In 1989, she described a novel photoreceptor in a vent invertebrate, which in turn led to discovery and characterization of a geothermal source of light at vents and investigations of its biological significance. Also, in 1989 she joined the team that operates the deep-diving submersible ALVIN. Her work with ALVIN has taken her to most of the known vent fields in the Atlantic and Pacific, as well as to deep-water seamounts, seeps, and other significant seafloor features. Dr. Van Dover has published more than 60 articles in peer-reviewed journals and has written several books.