Toward a New Paradigm for Education, Training and Career Paths in the Natural Sciences

Report on a Meeting held in Strasbourg, France,
November 29-30, 2001
on International Training and Support of Young Investigators
in the Natural Sciences

Introduction

Since the end of the 19th century, science education and training at academic research institutions has been viewed as proceeding along a narrow, unidirectional track, a "pipeline" that produces new research professors within a given scientific discipline. For scientific research in a select group of nations, this traditional model has proven successful in many respects. Yet increasingly there are signs of inadequacies; this model is failing to meet many crucial demands imposed by the complex global, social, and interdisciplinary landscape of 21st century natural sciences[1].

Funding agencies, the primary supporters of science in most countries, are in a unique position to facilitate changes in the culture of research training and support. Thus, the Human Frontier Science Program and the European Science Foundation invited the heads of research funding agencies from Europe, North America and Japan[2] to discuss major problems in current approaches to promoting career opportunities in the natural sciences, with an emphasis on the life sciences. The meeting was convened in Strasbourg in November 2001.

A consensus emerged indicating that a new paradigm for science education and training is needed, one that would be more expansive in its goals and more attuned to the needs both of society and young scientists; one that indicates the rich career opportunities for students having a solid science background. The new organic paradigm, unlike the traditional narrow, unidirectional pipe or hierarchical pyramid models, visualizes science training and careers as a tree with a richly ramifying, highly permeable network of roots and branches reflecting the broad range of inputs into the science pipeline and the wide range of opportunities for those who receive training in science (Fig. 1). This tree has a width equal to its height strengthening the image that the pipeline leads to a wide range of valued careers, some of which are directly involved in scientific research while others may be associated with science in varying degrees and could be found in venues such as industry, schools, administration, government, the media, business and many other domains.

1: The International Training and Support of Young Investigators in the Natural Sciences: Background Report (*see* www.hfsp.org *or* www.esf.org)
2: See appendix for list of participants

Summary

The roots

The role of the roots is to attract the best and brightest students to science and to enhance interactions between Science and citizens. The roots have two aspects: science education at all academic levels below the university level and scientific outreach that supports interactions between scientists and political bodies, business, industry and the general public.

In order to achieve these goals, the participants made the following recommendations:

- Science literacy needs to be strengthened at every educational level. It should instill in citizens early in life an appreciation of and familiarity with scientific language, ideas, and modes of investigation. Concerted efforts are required to introduce young people from all ethnic, cultural, and economic backgrounds to the language and culture of natural science.
- The training of science teachers must receive greater emphasis and good science teachers at all levels must be recognized and appropriately rewarded. Advanced scientific degrees should be required of those teaching science, especially at the secondary school level and above. Web-based teaching aids offer a revolutionary new opportunity to keep teachers abreast of new developments in science, to enhance lesson plans and to enrich student-learning experiences.

The trunk and intermediary branches

The trunk represents all levels of science education and training from the first university degree through graduate and postdoctoral studies. The trunk leads to the intermediate branches that span a wide range of valued careers, only some of which are directly involved in scientific research in academia or industry. Alternatively, an education in science should be seen as excellent preparation for a multitude of diverse careers in which a science education is essential.

The participants agreed that science training and career programs must be redesigned and offered the following recommendations:

- From the outset, students should have the opportunity to explore a wide array of fields and to test where their talents and interests lie through a broadly based scientific curriculum.
- Many universities provide training based on classically defined disciplines. In order to meet new scientific challenges and to better prepare students for a variety of future careers, barriers between departments should be removed. Funding agencies can facilitate this change through the support of cross-disciplinary and inter institutional training programs.
- Students should be exposed to a variety of work settings outside academia and should have opportunities to experience these settings during the course of their education.
- Training programs must be open to all talented individuals, regardless of national origin, race, or minority status. Moreover, programs need to provide mechanisms that enable women scientists to combine scientific careers with family responsibilities.
- The Masters science degree, often viewed merely as a stepping-stone to a Ph.D., should be valued as a legitimate endpoint to formal scientific training providing suitable preparation for a variety of important careers.
- Emphasis should be placed on mentorship and career guidance for students at all levels including newly independent investigators. Students should also be trained in skills outside pure scientific research, such as teaching and personnel and financial management – skills that are useful to the future teacher, administrator and head of laboratory alike.
- Universities have the responsibility to provide guidance for students regarding different career opportunities. Guidelines associated with training programs from government and private funding agencies should clearly support a number of legitimate formal educational endpoints all of which can lead to excellent professional opportunities.
- In the training and employment of doctoral and postdoctoral students, funding agencies should ensure that the highest ethical standards are in place regarding mentorship and authorship. Universities, research institutions, and funding agencies must put in place programs that ensure that training in the ethical conduct of research will be part of all curricula in order to ensure public trust in scientific research.
- In many countries highly trained scientists who remain in the same research positions for prolonged periods are not infrequently treated as long-term temporary workers or "permanent post-docs" with poor remuneration, security, and benefits. There is a need to develop a stronger, more stable, and more ethical career structure to support researchers who are team members, but not in independent, research team leader positions. The Concordat[3] developed by the UK Royal Society could serve as such a model.

Upper branches

The upper branches of the tree represent the various opportunities for scientists after completion of their postdoctoral training. A small proportion of individuals who train in the natural sciences will be able to obtain independent research positions and advance up the academic ladder. The choices of the remaining group may include pursuing research in industry, serving as research team members, or obtaining high-level administrative positions in the private or public sector.

Since in many countries there are limitations in the number of independent research positions, the following recommendations were made to attract and retain the brightest young individuals to careers in research and stimulate innovative research:

- Provide the most talented young investigators with the freedom to direct their own research and support these opportunities by increasing flexibility through development of innovative new programs and changes in hiring practices. Where hiring practices cannot be modified, the creation of internal "mobility and independence" programs should be put in place.
- A substantial, planned effort is needed to provide young scientists with appropriate management skills – not just as the new Group Leader is appointed, but from pre-doctoral training onward.
- Scientists at all levels should be trained in communication to convey effectively their findings to the broader scientific community, to political leaders, and to the general public.
- It is important to ensure that institutional criteria utilized for promotions and the awarding of prizes, stress excellence and originality and not merely quantity of publications. Teaching skills should be more highly valued in promotion evaluations.
- Funding agencies should provide mechanisms to encourage institutions to develop family-friendly infrastructure in order to attract, retain, and support their best talent, especially women.

3: *Concordat to Provide a Framework for the Career Management of Contract Research Staff in Universities & Colleges* 1996 Royal Society, London

International dimension

Science is a global enterprise. It has always been an international endeavor in which individuals have pursued training and collaboration organized around scientific interests and opportunities rather than national boundaries. Further, the meeting made clear that issues related to science training and career development know no geographic boundaries.

- The participants reinforced the need for increased support of international exchange of young scientists at all stages of training. This has been achieved in some countries through the development of portable programs that provide support for training abroad followed by funding for independent positions in the home country. Such programs provide universities and research institutions with opportunities to recruit talent and also induce a need for institutional flexibility. Ideally, the first step should be to provide undergraduate and predoctoral students with greater opportunities for study abroad by institution of additional exchange programs.
- The web provides unprecedented opportunities for communication of scientific advances and information on science-based careers without any geographic restrictions. This medium needs to be further developed and requires institutional and funding agency support.
- Finally, it became apparent during the course of the meeting that there was a paucity of quantitative information about the outcomes of training programs in different countries and the flow of scientifically trained individuals. There is a critical need for databases that assess the mobility of scientific researchers within the tree of science and within disciplines and geographic regions. The participants strongly endorsed the development of adequate databases to track the results of the different funding schemes encouraging governments and private funding agencies to build toward universal tracking system to follow scientifically trained individuals.

Discussion

It is perhaps not coincidental that the pipeline model of science education and training is based on an image that has much in common with the legendary ivory tower. Both pipeline and tower are narrow cylindrical structures that suggest unidirectional internal movement and a stony impermeability to the surrounding world. For a student entering the traditional scientific pipeline, there has been only one honored endpoint: the replication of the student's academic mentor, the research professor heading a laboratory in a well-defined scientific discipline. Those who chose other exit points from the pipeline failed to achieve this outcome and thus did not achieve occupational success. This traditional model reflects the rigid disciplinary divisions that have existed historically within research universities as well as a rigid definition of success.

Because this model produces a limited career pathway, bright students may not be choosing scientific careers. There is a need to provide alternative and attractive career pathways, such as those found in industry, administration, and other nontraditional venues. While the vast majority of young people who undergo long periods of education and training in business, engineering, medicine, or law can anticipate obtaining jobs in their chosen field, the same cannot be said for those trained in the natural sciences. In the natural sciences it is common for students to spend more than 10 productive, achievement-filled years as graduate students and postdoctoral fellows without any real prospect of obtaining a fulltime academic research position. This is causing a crisis at the entry-point of the traditional scientific pipeline.

At the November 2001 meeting in Strasbourg, leaders of funding agencies agreed that the natural sciences face an extraordinary new set of challenges in the 21st century. The participants concurred that innovative model programs could serve as catalysts in shaping national science education and support strategies, particularly when research-funding entities acted in partnership with ministries of education, research institutions, and the private sector. It was felt that a tree with roots, trunk and many branches would better illustrate the path and opportunities for the young student prepared to obtain a strong and broad science education than either the traditional narrow pipeline or the hierarchical pyramid models. It would seem logical to discuss the various issues as we move along from the roots to the upper branches.

1 • The Roots: Attracting the Best and Brightest to Science and Enhancing Interactions between Science and Citizens

It is through the early stages of science education that young people may be drawn most effectively into the roots of the scientific tree. Funding organizations, such as the Howard Hughes Medical Institute (HHMI), the Wellcome Trust, the U.S. National Science Foundation (NSF), the U.K. Medical Research Council, as well as many universities and national and local academies have shown great foresight in developing programs for science training and scientific literacy. These wide-ranging pilot programs to develop outstanding science curricula provide students with research experience, train teachers, and educate the public through museum and science exhibits. In addition, experimental programs, currently being developed, work to strengthen science education by creating centers that teach secondary school students cutting-edge science and use up-to-date equipment.

The primary goals of early stage science education should be to introduce the language of science and important features underlying natural phenomena in ways that are vivid and stimulating to young minds. With science literacy in many countries around 10% or lower, there is indeed a great need for improving science education. Ideally, science should be taught as a process of sustained questioning and exploration, not just the accrual of frozen facts by rote. Indeed, science is a supreme exercise of human curiosity, imagination, and accomplishment.

It is encouraging that among scientists in many countries, there is growing interest in assuming greater responsibility in developing formal and informal outreach programs. "If there is one lesson I have taken from this meeting," said Wieland Huttner of the Max Planck Society, "it is the need for scientists to reach out to the community. I will return to my institute and encourage our researchers to interact with students in our community schools."

Indeed, Dr. Huttner's remarks highlight a major resource needed to bridge the culture of science and human culture at large, namely the stories of science as told by scientists themselves. Another way for funding agencies to promote a more expansive, tree-like structure of science education and career paths would be to have scientists who have traveled along the various career paths to share their experiences. The life stories of such scientists could serve as vivid exemplars of the ways in which science draws young people into its roots from diverse backgrounds and interests. These career histories can demonstrate the many ways in which scientific training, scientific disciplines, and jobs branch and interconnect. These stories can also show the ways in which science's advances into the unknown continue to yield new puzzles and answers. For example, web sites such as *Next Wave*[4] are now in use or are being developed which will contain global collections of accounts of these representative paths through science, as well as of experiences of those who pursued scientific training as routes to alternative careers.

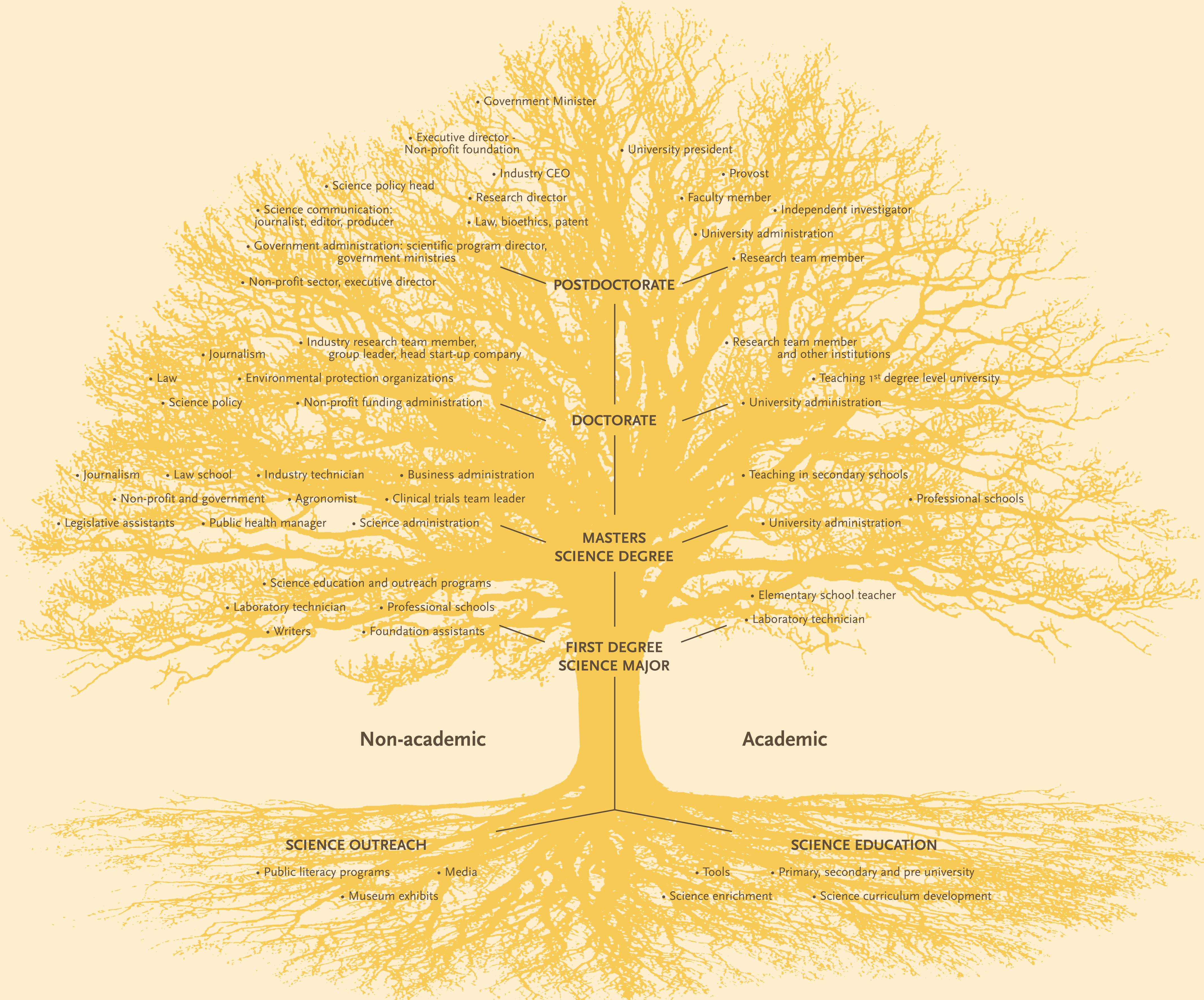
Ultimately, the aim of science education should not only be to attract the most talented and energetic young minds to science as an educational focus and potential career, but to instill in citizens at all ages and from all areas of life an appreciation of and familiarity with scientific language, ideas, and modes of investigation. In our highly technologically driven societies there is a greater need than ever to have a citizenry able to assess the impact of new scientific advances on their society.

2 • The Trunk and Intermediate Branches: Preparing Scientists for a Rich Variety of Career Paths

The trunk and intermediate branches represent the formation of the young scientist. Ideally, this portion of the pathway should be structured in such a way that students receive wide exposure to various disciplines and career opportunities in order to be able to map their talents within the sciences and onto a broader range of professional opportunities than is now common. University training programs should also be structured to attract and recruit students to the natural sciences from all social and ethnic groups within each society.

There is now widespread recognition that many scientific research paths, particularly in the life sciences, transcend conventional disciplinary boundaries. This means that research training requires a broader didactic base and experiences beyond a single laboratory or department. Increasingly, the traditional model of science education and training seems outmoded in that many universities provide training based on classically defined disciplines. Emphasis on more than one discipline and a breakdown of department barriers would make it easier for students to be exposed to more than one scientific field and to move

4: *http://nextwave.sciencemag.org/*


• Government Minister
• Executive director - Non-profit foundation
• University president
• Industry CEO
• Provost
• Science policy head
• Research director
• Faculty member
• Science communication: journalist, editor, producer
• Law, bioethics, patent
• Independent investigator
• University administration
• Government administration: scientific program director, government ministries
• Research team member
• Non-profit sector, executive director
POSTDOCTORATE
• Industry research team member, group leader, head start-up company
• Journalism
• Research team member and other institutions
• Law
• Environmental protection organizations
• Teaching 1st degree level university
• Science policy
• Non-profit funding administration
• University administration
DOCTORATE
• Journalism
• Law school
• Industry technician
• Business administration
• Teaching in secondary schools
• Non-profit and government
• Agronomist
• Clinical trials team leader
• Professional schools
• Legislative assistants
• Public health manager
• Science administration
• University administration
MASTERS SCIENCE DEGREE
• Science education and outreach programs
• Elementary school teacher
• Laboratory technician
• Professional schools
• Laboratory technician
• Writers
• Foundation assistants
FIRST DEGREE SCIENCE MAJOR
Non-academic
Academic
SCIENCE OUTREACH
• Public literacy programs
• Media
• Museum exhibits
SCIENCE EDUCATION
• Tools
• Primary, secondary and pre university
• Science enrichment
• Science curriculum development

from one field to another. The current revolution in the life sciences has to a large degree been driven by the availability of new tools developed in physics, chemistry, informatics and engineering. Importantly, with the current convergence of the natural sciences on biology, there is a real need for scientists trained beyond the traditional disciplines.

A number of funding agencies have established model programs that provide interdisciplinary training by faculty from different departments, and also offer experiences in a variety of research venues, including industrial settings. These programs have also begun to address an urgently needed change in the culture of the life sciences, which has been the training of students to become independent investigators rather than members of collaborative teams. With the growth of proteomics, genomics, and other large-scale approaches in the life sciences there is an increase in the number of large, interdisciplinary groups that collaboratively probe many aspects of complex biological systems. This new large-scale, interdisciplinary approach to problems in the life sciences – an approach that has long been a feature of research in the physical sciences – is already part of a few model programs and should be made a stronger component of training options available to students in the life sciences. Programs that bring together different disciplines and institutions in training and experience, such as the NSF IGERT Program and the Max Planck International Research Schools have successfully attracted high quality students and foster a new interdisciplinary culture. The success of such programs and the new paradigm for science training presented in this report should stimulate a dialogue that, in due time, will lead to the restructuring of science education in different programs.

Over the past 20 years, there has been a concerted effort to strengthen and structure science-training programs, to provide exposure to fields outside science, and to improve mentoring and support mechanisms. Over the same period, the world has been increasingly driven by scientific and technological innovations and opportunities. Never before has there been a greater need for individuals with strong education in the sciences to meet the needs in industry business, government, administration, teaching, journalism, and a host of other fields. Some funding agencies support training programs that include training in administration, teaching, and ethics as ways of enhancing the scientific research enterprise and laying the groundwork for alternative careers. Yet such broad training is not the norm in most universities and national research systems. Training programs should provide students with research and training experience outside the academic environment, preferably at an early stage of their education. These programs should also provide students with career mentoring and ensure that the Master of Science degree, often viewed as a stepping-stone to a Ph.D., should be valued in itself as a legitimate endpoint in the spectrum of formal scientific training as it can lead to a variety of important careers, such as teaching, administration, and industrial operations.

Students undertaking doctoral research represent one of science's and society's most valuable resources. Too often students labor on funded research projects where broader educational goals are largely displaced by the fulfillment of an advisor's research objectives that may not be in the students' best long-term benefit. Universities should have in place guidance on mentoring and career development for students pursuing scientific careers that clearly state that there could be a number of legitimate formal educational endpoints, all of which can lead to excellent professional opportunities. Students, as well as all personnel associated with the scientific enterprise, should be trained in the ethical conduct of research to ensure public confidence in science. The reduced number of individuals going into science emphasizes the importance of ensuring that scientific careers must be open to all talented individuals, regardless of national origin or gender. Moreover, programs need to provide mechanisms that enable both female and male scientists to combine scientific careers with family responsibilities.

A period of postdoctoral training has become an essential part of the preparation of scientists (especially those in the life sciences) before they are ready to assume independent research positions. This is a critical period for broadening research experiences, learning new techniques and skills, and becoming acquainted with new scientific perspectives and approaches. It is generally during postdoctoral fellowships that young scientists have the best opportunity to prove their mettle and sow the seeds of a successful independent career. Too frequently, however, postdoctoral fellows are treated as highly skilled and hard-working technical assistants rather than scientific minds in training. Moreover, the academic mechanisms to monitor doctoral candidates' progress are rarely accompanied by equivalent mechanisms to guide postdoctoral fellows. Student-centered training environments for postdocs as well as graduate students are urgently needed for the health of the scientific enterprise. Development of special postdoctoral mentoring programs, such as the one at the University of Pennsylvania[5], by a number of institutions fill an important need and can be easily adapted through web-based technologies. Funding agencies should require that all institutions receiving support to provide the kind of mentoring and training outlined in a recent report from the U.S. National Academy of Sciences[6].

The web is largely still an untapped resource in science education and mentoring. Web sites provide opportunities for individuals to exchange experiences and for institutions and organizations, including funding agencies, to provide online mentoring for those on the research-training ladder. Sites sponsored by Professional Associations and Funding Agencies such as *Next Wave* or those supported through student and fellow groups such as the Marie Curie Fellowship Association[7] serve as important resources on a global level providing young scientists with instant access to enormous resources.

3 • Upper Branches: Promoting Independent Research Careers for Outstanding Young Scientists

The upper branches of the tree correspond to numerous endpoints of the traditional scientific pipeline. On these branches are outstanding young scientists who have completed their postdoctoral training and risen to independent positions in which they lead their own research laboratories. Once established, the professional life of a scientist normally reaches beyond the area of pure research into the teaching of students at various levels within the university, the training of graduate and postdoctoral students, and often various administrative responsibilities such as department chair or head of an institution. In recent years the challenges in industry have attracted outstanding scientists and it is expected that in the future collaboration between academy and industry will be still more an integral part of the research community. It should also not be forgotten that the leaders in science serve the government as advisors, for example through the national academies of science, and often hold important positions within governmental agencies and as elected members of their governments. Finally, scientists at all levels of the tree structure can move to other careers such as journalism or law.

It is primarily on the upper branches that science makes its major advances. Only a small proportion of students who train in the natural sciences will attain positions as independent investigators or scientific group leaders. Yet, organizational policies in many countries exacerbate the problem. Countries that structure the scientific enterprise around a large group that is financially and scientifically dependent on a single departmental leader produce fewer independent investigators. Thus, even the best and the brightest young scientists – those who successfully complete postdoctoral fellowships or their equivalent and who demonstrate resourcefulness, technical skill, intellectual acuity, originality, and imagination – find it difficult to obtain independent positions. Not only does this waste innovative talent, but it also fuels "brain drain", causing a nation's vital talent to immigrate to other countries that provide these superb young scientists with opportunities to determine their own research paths and to build their own scientific teams.

This problem is generally recognized. Indeed, all of the countries represented at the Strasbourg meeting have begun to address this issue by establishing innovative programs to facilitate the transition to independence for their most promising investigators. Such awards are often coupled with a period of training in a foreign country before repatriation. These newly established young investigators have been given the opportunity not only to learn new skills and explore new areas of science but also to establish important personal contacts needed to forge trans-national collaborations.

Programs that have promoted the transition to independence and have supported group leader positions, such as those established by the Markey Trust, the Max Planck Society, EMBL, and VolkswagenStiftung, have produced a generation of leading independent investigators throughout Europe and North America. Such programs are now being replicated in other countries. In addition, where administrative structures have limited new positions and constricted mobility, new programs, such as L'Avenir in France, have been designed to bypass these barriers.

Successful leadership of a research team depends not only on research skills but also competence to manage substantial financial and human resources. Running such an enterprise requires many of the same management skills needed to run a small company, such as planning, finance, human resource development, negotiation, liaison and cooperation with outside organizations. Meeting participants called for a substantial, planned effort to provide young scientists with appropriate management training. Such training, as already mentioned, should not wait until the new Group Leader is appointed, but rather should begin in pre-doctoral training and continue throughout career development. In addition, scientists

5: *www.uphs.upenn.edu/postdoc/*
6: *Enhancing the Postdoctoral Experiences for Scientists and Engineers* 2000 COSEPUP, NAS
7: *http://www.mariecurie.org/*

at all levels should receive training in communication skills to ensure that they can convey their findings effectively to the broader scientific community, political leaders, and the general public.

Advancement in academic research is based on a number of measures, including the number of publications, grants, and other awards. While these measures are quantifiable, they may fail to assess fully the quality and originality of scientific thought, which is the most important gauge of research achievement. Moreover, measures of achievement may discriminate against family life and primary caregivers, particularly women. It is important to ensure that criteria utilized by institutions for promotions and awarding prizes stress excellence and originality, not merely the number of publications. Through funding guidelines, agencies can also encourage institutions to develop family-friendly infrastructure to attract, retain, and support their best talent.

Teaching is important in all phases of scientific career development and is a key component of life within a university community. As such it should be more highly valued in promotions and evaluations. In many countries teaching is a primary function of university faculty, while often the best scientists are associated with research institutions where they may not come into contact with students, particularly those beginning their university training. The consequence of such dissociation is that students may not be exposed to the best science, a fact that may be reflected in the decreased number of individuals pursuing advanced science degrees. A solution that is increasingly being recognized by funding agencies is exemplified by HHMI whose Investigators are provided with salaries and research support but remain part of the university environment, thus ensuring that students are in contact with the best scientists.

The International Dimension

Though most national funding agencies are mandated to support scientific research for the benefit of their citizens, science is by its very nature a global not a national affair. Scientists from different cultures and backgrounds pose different research questions and use different techniques to answer them. Creativity often arises at the intersection between disciplines and cultures, and many important scientific advances have resulted from young scientists open to new ideas being challenged in a new environment. Programs such as the Human Frontier Science Program, EMBO, Japan Society for the Promotion of Science (JSPS), and the European Commission Marie Curie Fellowship Program facilitate international exchange for students early in research careers. For those who are establishing their own independent groups, programs to promote repatriation and international collaborations among young researchers have been developed by the HFSP, the Wellcome Trust, the EU Framework Program, DFG and most of the other participating agencies contributing to increased opportunities for young scientists who have spent time abroad. These reinsertion programs can serve as important drivers in increasing institutional flexibility. The participants reinforced the need for increased support of international mobility for scientists and the value of international exchange for young scientists. They particularly emphasized providing opportunities for predoctoral students for short visits to study abroad, as once students become mobile early in their training they are more likely to have a broad range of contacts and to continue international interactions.

Many of the recommendations emerging from the meeting are at various stages of implementation in the participating countries. By agreeing on basic principles and a concerted set of actions and by working together rather than in isolation, common goals are more likely to be achieved. As Mary Clutter of the U.S. National Science Foundation so nicely summarized: "How much more powerful, if we joined forces."

These stories from the tree of science would surely have humanistic value as well. The Open Society described by the philosopher Karl Popper, in which ideas are subject to passionate yet peaceful test and debate, was modeled on the ethos of the scientific enterprise. Popper liked to summarize this ethos with the maxim: "I may be wrong, and you may be right, and by an effort we may get nearer to the truth." The lives of scientists in their collective represent a quest to understand the inner workings of nature and exemplify human qualities, which should be given the widest possible currency.

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