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Science and Technology Policy for Promoting Research Cooperation between Mathematics and the Life Sciences in the United States

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1 Introduction

Mathematics has historically played an important role in the development of the life sciences. Especially in post-Mendelian genetics and molecular biology, mathematics and mathematicians have contributed to the development of various theories and models for analyzing and understanding the complexity of life and heredity[1,2].

A recent example of such a mathematician is Eric Lander (Director of the Broad Institute, MIT), a molecular biologist with an educational and research background in mathematics, who made a great contribution to the promotion of the Human Genome Project with his mathematical model for genetic analysis[3].

The U.S. and European countries have traditionally promoted interdisciplinary research or integrated research, and researchers themselves have actively participated in new research areas. For example, it was not geneticists who played the central role in advancing molecular biology; it was researchers with physics backgrounds, who were newcomers to the area of life science[4].

The significance of life science research has increased since the 1990s, based on the belief that progress in this area is a significant driver of the national economy. Consequently, many governments have allocated larger budgets to life science research and placed greater emphasis on policies for development of the field.

The Human Genome Project was not only the first large-scale project but also a turning point in the history of life science; the research style has been shifted from the conventional individual basis to a group basis. Moreover, the project has demonstrated that cooperation with other disciplines to form interdisciplinary or integrated areas can greatly advance life science itself. Since computer science, mathematics and information science contributed significantly to the promotion of the project, the U.S. and European countries have begun to explore a variety of science and technology policies based on the belief that cooperation between life science and these disciplines is necessary for the future development of life science. "Mathematics in Biology" was featured in Science (vol. 3030, No. 5659, 2004), the journal of the American Association for the Advancement of Science (AAAS) in Table 1.

This article surveyed recent developments in the U.S., such as federal support for mathematics research funding, efforts to promote research cooperation between life science and mathematics, and policies for educating life scientists for mathematical competence. The article also discusses measures for promoting research cooperation between life science and mathematics in Japan, which is a necessity for further development of life science in our country.

2 U.S. Budget for Mathematics Research

In order to clarify the current status of federal support for mathematics in the U.S., the dollar amounts of federal research budgets categorized by research field, and of mathematics research funds categorized by agency are presented below.

2-1 U.S. research budgets by research field

As shown in Figure 1, federal support for life science has increased dramatically, especially since 1998. This dramatic increase can be attributed to the 5-year plan for doubling the NIH budget that began in FY 1999. FY 2003 was the final year of the plan, and the budget increase then reached a plateau in FY 2004. Nevertheless, life science continues to enjoy a large share of the entire budget (28.6 billion dollars, approximately 3 trillion yen in FY 2003). By comparison, the Japanese research budget for life science in 2003 was 436.2 billion yen, which was about one-seventh of that in the U.S.

The U.S. research budget for engineering increased in FY 2001 and has remained constant since then. Meanwhile, the research budget for mathematics & computational science has been very low (3.3 billion dollars, approximately 350 billion yen in 2003), corresponding to only one-tenth of that for life science. However, the budget has slowly increased over this decade and is approaching the budget for environmental science[5].

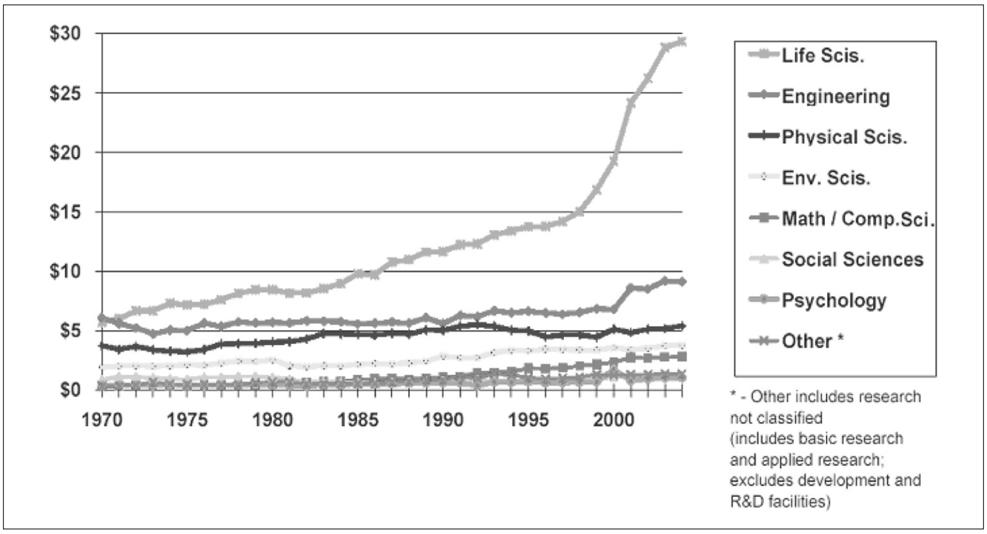
2-2 U.S. federal funding of mathematics research

Total U.S. federal funding of mathematics research is approximately 375 million dollars[6], half of which is funded by the National Science Foundation (NSF) and the rest by the Department of Defense (DOD), the National Institutes of Health (NIH) and the Department of Energy (DOE). In addition, the National Aeronautics and Space Administration (NASA), the Environmental

Table 1 : Science vol.303, No.5659, 2004

Mathematics in Biology
Biology by the numbers : Introduction to the current status and significance of mathematical approaches to biological issues
Life's patterns: No need to spell out? : Simulation of a vast array of biological structures
The new math of clinical trials : Mathematics for integrating past and current data from clinical trials
Making sense of a heart disease gone wild : Mathematics for integrating past and current data from clinical trials
Introductory science and mathematics education for 21st-century biologists : Need for mathematics education for 21st-century biologists
Uses and abuses of mathematics in biology : Recent involvement of mathematics in biology
Evolutionary dynamics of biological games : Analysis of biological evolution based on game theory
Inferring cellular networks using probabilistic graphical models : Analysis of genetic and metabolic pathway networks using mathematics

Figure 1 : Trends in federal research funding by research field ($ billion)



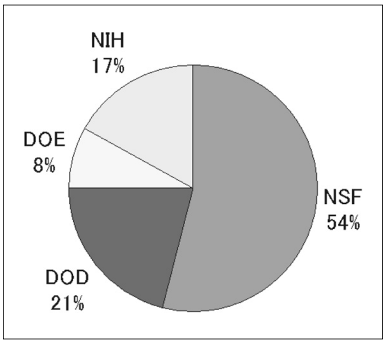
Source: AAAS website

Protection Agency (EPA) and the National Institute of Standards and Technology (NIST) of the Department of Commerce also provide some funding to mathematics research.

Interestingly, the NIH, the largest biomedical research organization in the U.S., has funded 63 million dollars (approximately 6.6 billion yen, 1 dollar = 105 yen).

These research funds are allocated to researchers through the National Institute of General Medical Sciences (NIGMS) and the National Institute for Biomedical Imaging and Bioengineering (NIBIB), both of which are research institutes at the NIH. The main target areas for research support by NIGMS are population biology, systems biology, macromolecular structures and bioinformatics, and those of the NIBIB are computer science, model development and bioinformatics[6].

Figure 2 : Federal funding of mathematics research by agency in FY 2005 (Total of all agencies: 374.5 million dollars)*



*From Message for FY 2005
Source: Prepared by STFC based on reference[6]

3 Efforts to Promote Research Cooperation between Mathematics and Life Science in the U.S.

In recent years, the significance of research cooperation between mathematics and life science has been argued in the U.S. Such argument has been triggered by the fact that the large government budget for life science research has not produced any recognizable social effect. For example, the number of patients with cancer or other lifestyle-related diseases has not decreased. Also, a complete cure for AIDS has not been developed. On a global scale, large-scale epidemics of emerging and reemerging infectious diseases have occurred. Despite progress in life science research, the number of newly developed drugs introduced into the market has actually decreased over this decade.

To improve on this situation, it was recognized that new blood was needed in the life sciences and that integration of the life sciences with other disciplines would achieve this.

Professor Cohen, of Rockefeller and Columbia Universities, expressed his optimism about research cooperation between mathematics and life science thus: “mathematics is biology’s next microscope, and biology is mathematics’ next physics”.

The following section introduces the actual efforts made by U.S. federal agencies for

Table 2 : U.S. federal agencies funding mathematics research (FY 2005)

Governmental agency	Department	Amount (million dollars)
NSF	Division of Mathematical Sciences (DMS)	202.3 (21.2 billion yen)
DOD	AFOSR: Air Force Office of Scientific Research ARO: Army Research Office DARPA: Defense Advanced Research Projects Agency NSA: National Security Agency ONR: Office of Naval Research	30.9 (3.2 billion yen) 10 (1.1 billion yen) 23 (2.4 billion yen) 3.5 (0.4 billion yen) 12.4 (1.3 billion yen)
DOE	Mathematical, Information, and Computational Sciences Division (MICS)	29.3 (3.1 billion yen)
NIH	NIGMS: National Institute of General Medical Sciences NIBIB: National Institute for Biomedical Imaging and Bioengineering	35 (3.7 billion yen) 28.1 (3 billion yen)

1 dollar = 105 yen

Source: Prepared by STFC based on references promoting research cooperation between mathematics and life science.

3-1 Workshop sponsored by U.S. federal agencies

On February 12 and 13, 2003, a joint NSF and NIH symposium on "Accelerating Mathematical-Biological Linkages" was held at the NIH. Attendees at the meeting discussed measures for accelerating research cooperation between mathematics and biology, and the research areas to be targeted.

The prescribed number of participants was 150, but more than 170 researchers, technicians and educators from areas related to life science and mathematics gathered at the meeting[7].

At the workshop, various discussions and suggestions were made on (1) institutional action, (2) education action and (3) researcher action.

(1) Institutional action

(i) Foundation of a national institute responsible for the expansion of NSF-NIH linkage (research funds etc.) and research in interdisciplinary areas between mathematics and life science.

(ii) Establishment of a database integrating all kinds of data related to life science, such as genomics and proteomics.

(iii) Establishment of standards to facilitate comparison of data or models published by different researchers.

(iv) Association among academic societies and educational institutions aimed at linking mathematics and life science.

(2) Education action

(i) Establishment of new programs for postdoctoral fellowships in interdisciplinary areas.

(ii) Hosting of workshops targeting deans of mathematics and life science departments for creating international curricula for interdisciplinary undergraduate education.

(iii) Establishment of positions for teachers in the interdisciplinary area between life science and mathematics.

(iv) Establishment of summer educational programs for high school students co-managed by mathematics and life science professionals.

(v) The preparation of teaching materials for elementary and junior high schools regarding the linkage between mathematics and life science.

(3) Researcher actions

(i) Preparation of a list of the ten most challenging tasks in the mathematics-biology interdisciplinary area.

  (a) Establishment of models for systems at various levels, from cellular to human, and extending to the social environment.

  (b) Modeling of complex metabolic and signaling pathways and interactive networks between biological substances.

  (c) Integration of the probability theory for understanding uncertainty and risks.

  (d) Further understanding of computer science - theories established from agent models or computer calculation.

  (e) Understanding of data mining and simultaneous inference (requires a theory that goes beyond Bonferroni's method).

  (f) Analysis of gene and protein structures using graph theory-based approaches.

  (g) Modeling of brain functions.

  (h) Development of computational science-based methods that allow the modeling of life processes with various spatial and temporal sizes.

  (i) Establishment of ecological prediction methods.

  (j) Analysis of the effect of data errors on the understanding of life science (the extent to which erroneous data may affect correct understanding of life science, e.g., missequencing)

(ii) Hosting of domestic meetings related to interdisciplinary areas between life science and mathematics.

(iii) Hosting of meetings and workshops on the education of researchers, providing opportunities for mathematicians to study life science and for life scientists to study mathematics.

(iv) Integration of databases and online journals to promote the publishing of papers in interdisciplinary areas between life science and mathematics.

3-2 Efforts made by funding agencies

(1) Research grants promoting interdisciplinary research between life science and mathematics

Based on the recognition that further research needs to be promoted in interdisciplinary areas between life science and mathematic, NSF and NIH jointly launched a research grant program beginning in 2002. To date, applications have been invited three times, i.e., once a year from 2002 to 2004. The next application deadline is June 30, 2005.

The program was originally titled "Joint DMS/NIGMS Initiative to Support Research in the Area of Mathematical Biology," but was changed to "Joint DMS/BIO/NIGMS Initiative to Support Research in the Area of Mathematical Biology" in 2004, due to the participation of the Directorate for Biological Sciences (BIO) of NSF.

The annual budget for the fund is 6.5 million dollars (680 million yen), of which NSF invests 2.5 million dollars (260 million yen) and NIGMS, acting under the NIH, invests 4 million dollars (420 million yen). The fund is allocated to twenty applicants per year, each receiving 100,000 to 400,000 dollars (10.5 million to 42 million yen) per year for 4-5 years.

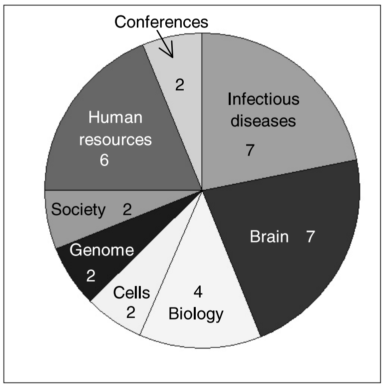
Six program directors (three each with doctors' degrees in life science and mathematics) invite questions from applicants, e.g., whether the suggested project fits the program[8].

(2) Analysis of subjects of life science-related research projects receiving NSF-funding for mathematics

As mentioned earlier, the NSF is responsible for more than half of the U.S. public funding that is invested in mathematics research. The NSF has designated mathematics as a priority area for the years 2000-2006 and aims at increasing the research budgets for mathematics.

In order to examine whether interdisciplinary areas between life science and mathematics have actually been created at the research level, this section analyzes the subjects of research projects adopted by NSF that are related to both mathematics and life science.

Figure 3 : Research areas of Mathematical Biology projects started from 2004



Source: Prepared by STFC

Award search was used to search the NSF grants. First, "*bio* and *math*" were used as keywords to search for standard grant research projects started after 2001. Standard grants are ordinary grants available to researchers on an individual basis. Of 1,000 research projects started after 2001, 417 (more than 40%) were retrieved using the above keywords, which included projects categorized as ecology, mathematical biology, systems biology & biodiversity, population dynamics, computational mathematics, applied mathematics, etc. This indicates that studies in interdisciplinary or integrated areas between various life science-related areas and mathematics are in progress.

In order to examine research projects for a particular interdisciplinary area between mathematics and life science, research projects in "mathematical biology" were analyzed.

Of the projects started from 2001, 51 were classified as mathematical biology, and more than half (32) were started in 2004.

By research subject, the most common subjects were infectious diseases and brain, particularly infection/ transmission models and neural networks. Projects concerning the development of educational programs for human resources in mathematics-biology interdisciplinary areas also had large shares (Figure 3). For reference, the titles of pure biology- and cell-related research projects are listed in Table 3.

Table 3 : List of titles of projects classified under pure biology- and cell-related research areas among Mathematical Biology projects adopted in 2004

Area	Title	Research institute
Cells	Two-dimensional cell motility model	Worcester Polytechnic Institute
	Dynamic regulation of the cell cycle by the proliferation control (RB) and death control (p53) oncogenes	Virginia Polytechnic Institute and State University
Biology	Dynamical systems in biology	Arizona State University
	Competitive coexistence and life cycle stages	University of Arizona
	Nonlinear dynamics of oscillator networks (Biological clock including the synchronous firing of cardiac pacemaker cells, etc.)	Cornell University
	Spatial Heterogeneity, nonlocal interactions and time delay in epidemiological and biological spread	University of Miami

Source: Prepared by STFC

4 Undergraduate Programs to Educate Life Scientists for Mathematical Competence

For the development of next-generation life scientists capable of using mathematics effectively, educational reforms have been promoted, mainly in undergraduate education.

4-1 Proposal for mathematics education in biology-related departments at universities

Professor Botstein (Department of Molecular Biology, Princeton University) et al. have proposed the need for mathematics education for 21st-century biologists[9]. Students majoring in biology (including those proceeding to medical schools) are generally required to take one or two semesters each of mathematics and physics and two to four semesters of chemistry, but most of the students are not enthusiastic about taking these courses. At the same time, faculty who teach these courses are not as enthusiastic about teaching the biology majors as they are about teaching physics, chemistry or engineering majors. Moreover, the time allocated for these courses differs greatly between curricula for biology majors and physics, chemistry or engineering majors.

Professor Botstein et al. quoted the words of Galileo, "the book of nature is written in the language of mathematics" to express their concern about biology majors being deprived of the natural science education essential for acquiring quantitative thinking, which is necessary for understanding complex systems involving life or organisms.

Professor Botstein has articulated the need for an integrated introductory curriculum (for the first and second years of undergraduate school) in which quantitative thinking for biology students is given significant emphasis. He suggests that, instead of teaching physics, chemistry and mathematics separately as in conventional curricula, they should introduce these disciplines systematically in context with the unsolved biological problems.

4-2 Mathematics education program for biology majors

Professor Gross, a Professor of Ecology and Evolutionary Biology and Mathematics at the University of Tennessee, and the President of The Society for Mathematical Biology, is committed to mathematics education for biology majors.

Professor Gross provides "Resources for Mathematics Education for Biology Students" at his website to enable free browsing and downloading of lectures given to biology students in various universities (some links may be broken).

Professor Gross himself provides an integrated lecture on mathematics and life science to biology majors at the University of Tennessee. For example, he asks his students to go outside and gather data on the size of leaves on trees. Then, he asks them questions such as "is the leaf width correlated with the length, does the relationship differ among species," or "what are the factors affecting leaf size, why do some trees have longer

Table 4 : Example of a mathematics lecture for biology students

University	Lecture title
Florida State University http://www.math.fsu.edu/~mesterto/biocalc.html	Biocalculus
Kennesaw State University http://science.kennesaw.edu/~mburke/modules/	Mathematical Modules in Biology and Chemistry
University of British Columbia (Canada) http://www.zoology.ubc.ca/~bio301/	Biomathematics
University of South Carolina http://www.math.sc.edu/~miller/411/411.html	Mathematical biology
North Shore Long Island Jewish Health System Bio-repository http://www.nslij-genetics.org/bioinfotraining/	On-line List of bioinformatics courses

links confirmed on April 11, 2005

Source: Prepared by STFC based on the above websites

leaves than others," and tells them to set up many hypotheses. Finally, students are asked to evaluate each of the hypotheses by analyzing the gathered data[10].

4-3 The "BIO 2010" report

As a part of the NIH program to reform undergraduate education, The National Research Council completed a report, "Bio 2010: Transforming Undergraduate Education for Future Research Biologists" in 2003[10]. The report was sponsored by the NIH and Howard Hughes Medical Institutes, both of which are known for providing significant funding to medical and biological research[9,10].

The report emphasizes that the future development of life science relies on research cooperation between life science and other disciplines, especially mathematics & computational science, chemistry, physics and engineering. It states that undergraduate curricula need to be revised to include education in interdisciplinary areas between such disciplines and the life sciences.

5 Status of the Linkage between Life Science and Mathematics in Japan

This chapter analyzes the current status of "research cooperation between life science and mathematics" and "education of life scientists for competence in mathematics" in Japan.

5-1 Views of life scientists on interdisciplinary integration

Are Japanese life scientists willing to cooperate with mathematics or any other scientific fields?

The attitudes of researchers toward interdisciplinary studies were surveyed in "FY 2003 Survey of the Actual State of Research Activities in Japan" conducted by the Research and Coordination Division, Science and Technology Policy Bureau of the Ministry of Education, Culture, Sports, Science and Technology[11].

The results showed that more than 60% of the researchers are interested in interdisciplinary studies (Figure 4). By discipline, the proportion of researchers who expressed interest was lower in life science compared to that in information & communication, environment, energy or material & nanotechnology.

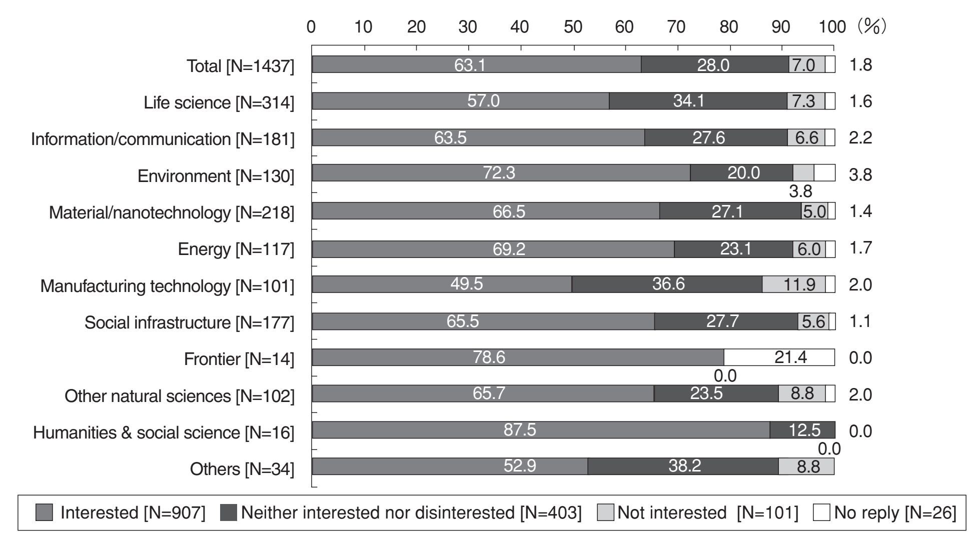
Those who had replied they were "interested" were further asked why they were interested. The most common answer was "because it is necessary to promote studies responding to social needs," and the second was "because it is necessary for the creation of new disciplines".

5-2 Is there any movement for promoting the integration of life science and mathematics?

In Japan, governmental agencies or funding agencies have not implemented any policy to promote the integration of life science and mathematics.

Among the projects that were allocated science

Figure 4 : Researchers' interest in the integration of humanities and science, and interdisciplinary research (by scientific field)



Source: Reference[11]

Table 5 : Projects categorized under life science-mathematics interdisciplinary research that received science and technology-related budgets in FY 2004

Project title	Governmental agency	Responsible organization
Cell/Biodynamics Simulation Project	Ministry of Education, Culture, Sports, Science and Technology	Keio University etc.
Institute for Bioinformatics Research and Development	Ministry of Education, Culture, Sports, Science and Technology	Japan Science and Technology Agency (JST)
Bioinformatics Infrastructure Development	Ministry of Economy, Trade and Industry	Japan Biological Informatics Consortium
Development of Analytical Methods for Intracellular Network Structures	Ministry of Economy, Trade and Industry	New Energy and Industrial Technology Development Organization (NEDO)

Source: Prepared by STFC

and technology-related budgets in FY 2004, four could be categorized as integrated research between life science and mathematics (Table 5). However, these projects focused mainly on bioinformatics and computer simulation, and none of them aimed at promoting the integration of life science and mathematics.

Moreover, among the research projects conducted under Exploratory Research for Advanced Technology (ERATO) of the JST, three could be categorized as integrated research between mathematics and life science: the "Kitano Symbiotic Systems Project (1998-2003)", a systems biology study concerning interpretation of each biological phenomenon as a system and its analysis by computational science, the "Aihara Complexity Modelling Project (2003-2008)", a study of the application of computation to complexity, including the establishment of dynamic data processing principles for a bioinformatics network, and the "Shimojo Implicit Brain Functions Project (2004-2009)", a brain science study concerning the learning mechanism. In addition, the Center for Developmental Biology at RIKEN has a research team working on "Systems Biology" under its Creative Research Promoting Program.

However, these projects are all based on the ideas of individual researchers. In the U.S., science and technology policies established by public organizations have promoted the integration of mathematics and life science, but Japan still lacks such a policy.

5-3 *Is there any movement to educate life scientists for mathematical competence?*

Japanese universities are not planning to initiate any undergraduate programs to provide life science majors with math abilities. However, there are some efforts to develop human resources specialized in bioinformatics, an interdisciplinary area between life science and information science.

The "University of Tokyo - Undergraduate Program for Bioinformatics and Systems Biology (UPBSB)" started in 2001, with the support of Special Coordination Funds for Promoting Science and Technology of the Ministry of Education, Culture, Sports, Science and Technology. This program aims at providing an undergraduate education appropriate for developing human resources in bioinformatics with strong support from faculty specialized in the information and life sciences. They consider that bioinformatics education requires a balance among (i) professional education in bioinformatics, (ii) basic education in information science and (iii) basic education in life science, which is reflected in the curriculum. Meanwhile, Special Coordination Funds for Promoting Science and Technology has also supported the Education and Research Organization for Genome Information Science to start the Bioinformatics Education Program from 2002 at Bioinformatics Center, Institute for Chemical Research, Kyoto University.

A research cluster devoted to "bioinformatics" at Keio University's Shonan Fujisawa Campus aims at clarifying life phenomena by simulating genes, genomes and cells in silico and works on research projects such as bioinformatics, the E-Cell Project and the E-Neuron Project.

6 Difference between Japan and the U.S. in Science and Technology Policies

This chapter explores the difference between Japan and the U.S. in science and technology policies related to cooperative research involving both the life sciences and mathematics, and discusses what we should do in the future.

6-1 Paths to accelerate research cooperation between life science and mathematics in U.S. and Japan

The U.S. and Japan are going in completely different directions to accelerate cooperative research between life science and mathematics. The U.S. aims at (i) educating life scientists to be competent in mathematics as well by changing the undergraduate curriculum and (ii) helping researchers expand their research areas by establishing programs that can provide knowledge of mathematics or life science to postdoctoral fellows or those who already have become life scientists or mathematicians, and attempts to (iii) attract researchers into new areas by funding research projects in interdisciplinary areas between mathematics and life science. These measures cover researchers from any field, so more and more researchers are likely to enter this new area in the future.

Meanwhile, Japan emphasizes the education of a limited number of elite researchers specialized in bioinformatics and systems biology, both of which are interdisciplinary areas positioned between life science and information science or computational science. In recent years, the importance of systems biology research has been emphasized worldwide[12]. Japan has taken the initiative in these areas but we may lose our preeminence at any moment. In the U.S., Harvard Medical School has founded the world's first department of systems biology, and the NIGMS of the NIH, which promotes the linkage between mathematics and life science, also supports systems biology. To date, the U.S. has more than ten public and private organizations serving as central bases of research programs related to systems biology[13]. Such a swift move by the U.S. can be attributed to its long history of science and technology policies promoting the linkage between mathematics and other research fields.

6-2 Research cooperation between life science and mathematics in Japan in the future

Considering these circumstances, it is necessary to change our direction from the education of a few elite researchers to the fostering of many capable researchers who can conduct research in new interdisciplinary areas between the life sciences and mathematics. These researchers are expected to play important roles not only in bioinformatics and systems biology but also in the creation and development of other new research areas based on mathematics.

Progress in a new area cannot be achieved without recruiting a certain number of researchers into that area. In order to ensure the critical mass, it is necessary to establish a program targeting a large number of researchers or students to develop life scientists capable of doing mathematics.

Japanese universities or academic societies are not very active in proposing research cooperation between life science and other disciplines. This may be due to the fact that life scientists in Japan have little interest in integration with other disciplines. Japanese mathematicians are also reluctant to cooperate with other disciplines or conduct studies in applied mathematics. Therefore, we must reform the attitudes of the researchers themselves. Such reform may be implemented through an accumulation of small, pilot projects responding to industry needs and requiring cooperation between mathematicians and life scientists for their success.

Moreover, the education of next-generation life scientists requires the enrichment of mathematics education for students at all levels from the elementary grades through high school, by means such as a cooperative education program between mathematics and the life sciences.

7 Conclusions and Suggestions

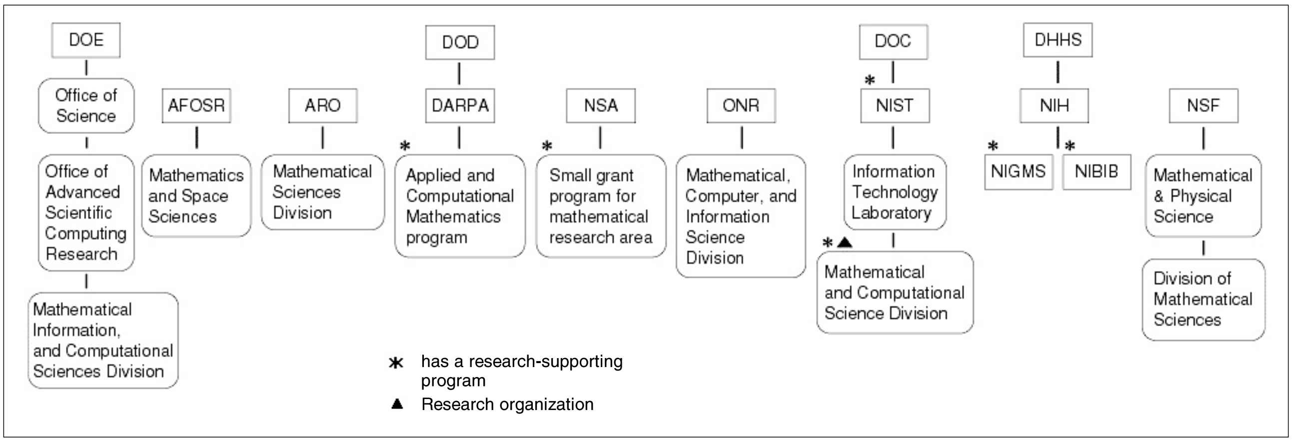
The following activities are suggested for promoting a linkage between life science and mathematics in Japan.

(1) Establishment of divisions responsible for promoting and supporting mathematics within governmental agencies

The U.S. government has many divisions that support research in mathematics, including the Division of Mathematical, Information, and Computational Sciences of DOE, Division of Mathematical Sciences of the NSF, the Mathematical and Computational Sciences Division of the Information Technology Laboratory of the NIST, the AFOSR (Air Force Office of Scientific Research), ARO (Army Research Office) and DARPA (Defense Advanced Research Projects Agency) (Figure 5). With the aim of supporting cooperative research between life science and mathematics, the U.S. government has established a cross-agency funding system represented by the linkage between the NIH and NSF, rather than the conventional vertically divided funding systems.

Meanwhile, the Japanese government has no division responsible for supporting mathematics research similar to those in the U.S., nor any system for planning science and technology policies related to mathematics. In order to develop interdisciplinary areas between mathematics and life science, divisions responsible for supporting mathematics must be established within governmental agencies. Additionally, we must increase competitive research funds supporting interdisciplinary areas between mathematics and life science, and take

Figure 5 : U.S. public organizations and divisions supporting mathematics-related research



Source: Prepared by STFC

measures to attract researchers to these new areas.

(2) Enrichment of mathematics education for life science majors

Mathematics education for life science majors is essential to promote linkage between life science and mathematics. In addition to conventional mathematics courses as part of the basic curriculum, multidisciplinary educational programs should be established, such as the analysis of life science issues using mathematics.

It is also important to establish opportunities for mathematics majors to acquire knowledge of life science.

If such educational programs cannot be established or implemented due to shortage of staff, overseas faculty can be recruited.

(3) Creation of opportunities (research institutes) for cooperative research between life scientists and mathematicians

New research areas cannot be created without an intense exchange of ideas among researchers from different disciplines. Therefore, we must provide life scientists and mathematicians with opportunities to conduct joint research.

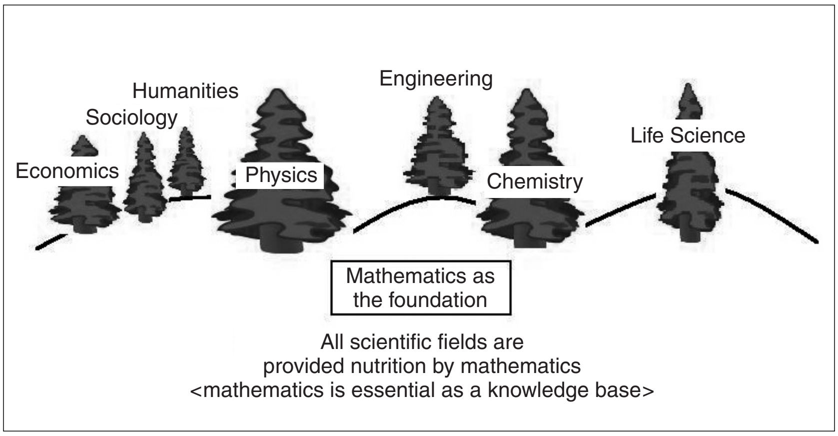
One effective approach could be to establish a research funding system for joint research that would allow mathematicians to participate at existing life science research institutes or life scientists at mathematics research institutes.

In the U.S., there are many mathematics research institutes that meet international standards; these institutes are actively engaged in applied mathematics research, i.e., joint research between mathematics and life science or many other scientific fields. In the U.K., a research institute named CoMPLEX (Centre for Mathematics and Physics in the Life Sciences and Experimental Biology) was founded recently, where life scientists or medical researchers tackle the challenging tasks of life science or medicine in cooperation with mathematicians, physicists, computational scientists or engineers. This institute also serves as an educational institute and started a doctoral course in 2004.

Meanwhile, Japan has only one mathematics research institute meeting international standards, i.e., the Kyoto University Research Institute for Mathematical Sciences. However, the institute mainly focuses on pure mathematics research, so Japan actually has no research institute that focuses on applied mathematics or interdisciplinary areas involving mathematics and other disciplines. Thus, it is important to establish research institutes intended for applied mathematics, where interdisciplinary research between mathematics and life science or many other areas can be conducted for promoting the future development of science and technology in Japan.

Furthermore, the following activities are also important for the advancement of mathematics.

Figure 6 : Mathematics as the foundation



Source: Prepared by STFC

(4) Reinforcement of research cooperation between companies and universities

We must reinforce research cooperation between companies and universities and establish a system that encourages industrial issues to be effectively addressed by facilitating cooperation between mathematicians and company-employed researchers in other areas. This should promote the industrial application of mathematics and the creation of new research fields.

(5) Improvement of the public understanding of mathematics

We must establish a nationwide policy that brings students in all areas, and the public, to recognize the importance and significance of studying mathematics. Such a policy is essential to establishing a knowledge and industrial base for the application of mathematics to a wide variety of areas and its linkage and integration with other disciplines (Figure 6).

References

[1] "What mathematics can do - Why is it important for science and technology, how can we make effective use of it-". Ministry of Education, Culture, Sports, Science and Technology, National Institute of Science and Technology Policy lecture No.147: November 2004. (in Japanese)

[2] Malkevitch, J., Feature Column Archive, "Mathematics and Genome" (American Mathematical Society): www.ams.org/new-in-math/cover/genome1.html

[3] Eric Lander, Unraveling the Threads of Life, p80-81, TIME Magazine April, 2004

[4] Jonathan Weiner, "Time, Love, Memory: A Great Biologist and his quest for the origins of behavior," Knopf, 1999.

[5] Kei Koizumi, An Update on R&D in the FY2005 Budget for the ASTRA Board of Directors. November 23, 2004.: http://www.aaas.org/spp/rd/present.htm (as of April 11, 2005), http://www.aaas.org/spp/rd/prastra1104.pdf (as of April 11, 2005)

[6] AAAS Report XXIX: Research and Development FY2005, Mathematical Sciences in the FY2005 Budget: http://www.aaas.org/spp/rd/rd05main.htm (as of April 11, 2005), http://www.aaas.org/spp/rd/05pch23.htm (as of April 11, 2005)

[7] Accelerating mathematical-biological linkages: Report of a joint NSF-NIH workshop: http://www.palmerlab.umd.edu/report.pdf (as of April 11, 2005)

[8] Joint DMS/BIO/NIGMS Initiative to Support Research in the Area of Mathematical Biology: www.nsf.gov/pubs/2004/nsf04572/nsf04572.htm (as of April 11, 2005)

[9] Bialek, W. and Botstein, D., Introductory Science and Mathematics Education for 21st-Century Biologists. Science, Vol. 303, 788 790, 2004

[10] BIO2010: Transforming undergraduate education for future research biologists, The National Academies: http://books.nap.edu/catalog/10497.html (as of April 11, 2005)

[11] "FY 2003 Survey of the Actual State of Research Activities in Japan"s. Research and Coordination Division, Science and Technology Policy Bureau of the Ministry of Education, Culture, Sports, Science and Technology (in Japanese)

[12] Hood, L., Heath, J.R., Phelps, M.E., and Lin, B., Systems biology and new technologies enable predictive and preventative medicine. Science, Vol. 306, 640-643, 2004

[13] Research institutes and projects related to systems biology in the U.S.: Genomes to Life (DOE): http://doegenomestolife.org/ (as of April 11, 2005), Microbial Cell Project (DOE): http://microbialcellproject.org (as of April 11, 2005), Complex Biological Systems Initiatives (NIGMS): www.nigms.nih.gov/funding/complex_systems.html (as of April 11, 2005), MIT Computational and Systems Biology Initiative: http://csbi.mit.edu/ (as of April 11, 2005), Bio-X, Stanford University: http://biox.stanford.edu/index.html (as of April 11, 2005), Pacific Northwest National Laboratory: www.sysbio.org/ (as of April 11, 2005), Department of Systems Biology, Harvard Medical School: http://sysbio.med.harvard.edu/ (as of April 11, 2005), Lewis-Sigler Institute for Integrative Genomics, Princeton University: http://genomics.princeton.edu/ (as of April 11,

2005), IBM Research: www.research.ibm.com/FunGen (as of April 11, 2005), The Molecular Science Institute, Berkeley: www.molsci.org/welcome.shtml (as of April 11, 2005), Institute for Systems Biology, Seattle: www.systemsbiology.org (as of April 11, 2005), Alliance for Cellular Signaling, www.cellularsignaling.org (as of April 11, 2005), Cell Systems Initiative, Seattle: http://csi.washington.edu/about/ (as of April 11, 2005)

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