Department of Advanced Mathematical Sciences

Mathematical Modeling and Analysis of Phenomena

— In Pursuit of Integration of Science and Engineering —

The essence of science is to derive principles from observations, thereby revealing the simple structures that underlie what appear to be complex phenomena.

Mathematical sciences, in particular, use mathematical approaches to investigate "mathematical models", which are derived through experimentation.

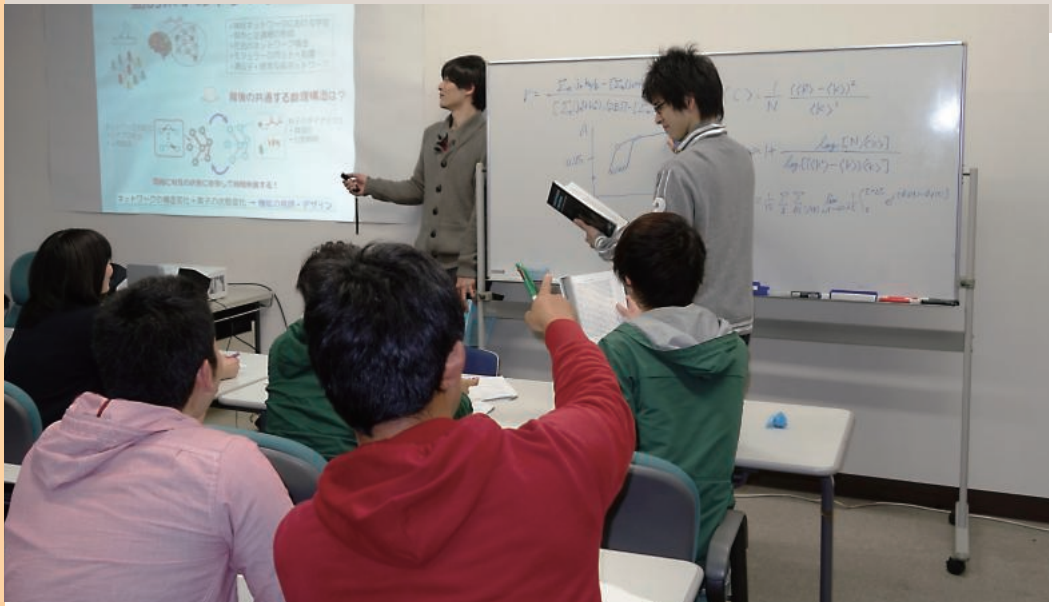
The modern frontier of mathematical sciences considers various new mathematical models, including those for biological and social phenomena, in addition to more traditional models in natural sciences. These models are investigated through analytical approaches as well as numerical simulations in order to understand the phenomena.

The knowledge thus obtained is employed to develop innovative technologies or to predict future developments, and new methodologies are devised for deeper understanding of phenomena.

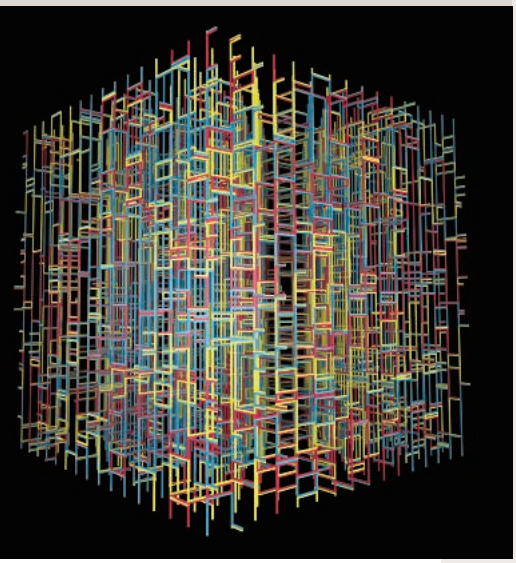
In its research and educational activities, our department pays particular attention to large-scale and/or highly non-linear complex phenomena.

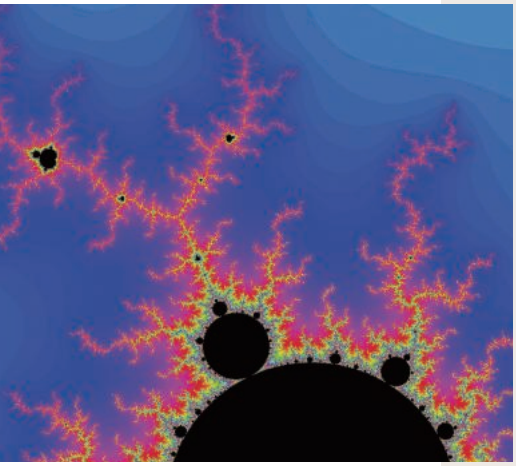
Particularly in education, we aim at providing students with both scientific perspectives, which help them to understand principles, and engineering perspectives which are useful in solving real problems in manufacturing.

This two-pronged approach gives students comprehensive overviews on both science and engineering in mathematical sciences.



Advanced Mathematical Sciences





An Invitation to Mathematical Sciences

In the Graduate School of Informatics, we regard "mathematical modeling and analysis of natural, social and biological phenomena" as an important foundation of what we aim at; i.e., "informatics" in the broad sense of the term, which includes not only traditional computer science but also related disciplines such as mathematical sciences, applied physics, etc. Indeed, we have placed importance on research and education in mathematical sciences since the establishment of our school in 1998 because they are considered to form the academic basis of our disciplines. At the time of inauguration of the school, we considered it appropriate to name ourselves the "Department of Applied Analysis and Complex Dynamical Systems", since "complex dynamical systems" was the phrase that symbolized the advanced mathematical sciences of the time. However, the relentless advancement of mathematical sciences gradually made "complex dynamical systems" not necessarily the best phrase to express what we are. Meanwhile, development of computers and networks has made it possible to deal more easily with so-called “big data,” thus making computers and networks increasingly important in social life as well as in research and education in mathematical modeling and analysis of natural, social and biological phenomena. With these developments in mind, we have decided to change the name of our department to "Department of Advanced Mathematical Sciences," as of April 2017. We believe that the new name reaffirms and clarifies our directions for both education and research.

In the broad research area of "advanced mathematical sciences," we are particularly interested in "mathematical modeling and computer simulations of phenomena," which constitute the basis of our activities. Computer simulations and data analyses are now vitally important in several branches of science and engineering. New applications of computational methods are found in biology, social sciences, etc. and, of course, as more conventional applications in mechanics. These new trends in mathematical modeling of phenomena call for new methodologies, including probabilistic and fractal approaches in addition to classical differential equations and discrete models. New developments in computer simulation include large-scale, high-performance computing, use of new computational environments such as multiple-precision arithmetics, etc. Our department conducts research and education in such new and advanced areas of mathematical sciences.

Traditionally in Japan, fundamental education in mathematical sciences has been carried out in schools of science and more application-oriented education has been provided by engineering schools. However, despite its small size, our department has some faculty members with science backgrounds and others with engineering backgrounds. Our aim is to "integrate science and engineering" and develop students with comprehensive perspectives of advanced mathematical sciences. We also emphasize individualized teaching as well as independent learning by each student, in line with Kyoto University's principle of "self-learning based on dialogue."

TAGUCHI Satoshi

Department of
Advanced Mathematical Sciences

2001: M. Eng. (Aeronautics and Astronautics), Kyoto University, 2004: Dr. Eng. (Aeronautics and Astronautics), Kyoto University, 2004-2005: Mainz University (Germany), 2005-2006: Bordeaux University (France), 2006-2011: Assistant Professor, Kobe University, 2011-2016: Assistant Professor, The University of Electro-Communications, 2016-2017: Associate Professor, The University of Electro-Communications, 2017-2019: Associate Professor, Graduate School of Informatics, Kyoto University, 2019 July-today: Full Professor, Graduate School of Informatics, Kyoto University. Research interest: Fluid Mechanics, Rarefied Gas Dynamics, Numerical Simulation of Fluid Flows. He received the Ryumon-Prize of the Japan Society of Fluid Mechanics in 2015.

Outline

Divisions and Groups

Division	Group	Research and Education Topics	Professor
Applied Analysis	Applied Analysis	Inverse and Ill-Posed Problems, Fractal Theory, Nonlinear Differential Equations, Numerical Analysis, Probability	ISO Yuusuke KIGAMI Jun
Nonlinear Physics	Nonlinear Physics	Theoretical Neuroscience, Network Science, Nonequilibrium or Nonlinear Physics, and Computational Condensed Matter Theory	AOYAGI Toshio
Applied Mathematical Sciences	Computational Mechanics	Computational Mechanics	
	Industrial Mathematics	Kinetic theory, Fluid Mechanics	TAGUCHI Satoshi

Graduate Curriculum

Courses for the Master's Program

Applied Analysis A
Applied Analysis B
Nonlinear Physics A
Nonlinear Physics B
Applied Mathematical Sciences A
Applied Mathematical Sciences B
Topics in Differential Equations A
Topics in Differential Equations B
Topics in Nonlinear Analysis A
Topics in Nonlinear Analysis B
Seminar on Applied Analysis I
Seminar on Applied Analysis II
Topics in Applied Analysis I
Topics in Applied Analysis II
Topics in Nonlinear Dynamics A
Topics in Nonlinear Dynamics B
Topics in Nonequilibrium Physics A
Topics in Nonequilibrium Physics B
Seminar in Nonlinear Physics I
Seminar in Nonlinear Physics II
Topics in Nonlinear Physics I
Topics in Nonlinear Physics II
Topics in Computational Mechanics A
Topics in Computational Mechanics B
Topics in Mathematical Sciences A
Topics in Mathematical Sciences B
Seminar in Applied Mathematical Sciences I
Seminar in Applied Mathematical Sciences II
Topics in Applied Mathematical Sciences I
Topics in Applied Mathematical Sciences II
Advanced Study in Mathematical Sciences I
Advanced Study in Mathematical Sciences II

Courses for the Doctoral Program

Seminar on Mathematical Sciences (Advanced)
Seminar on Applied Analysis (Advanced A & B)
Seminar on Nonlinear Physics (Advanced A & B)
Seminar on Applied Mathematical Sciences (Advanced A & B)

Teaching Staff

Professors
ISO Yuusuke; KIGAMI Jun;
AOYAGI Toshio;
TAGUCHI Satoshi
HAYASHI Kazunori

Associate Professors
FUJIWARA Hiroshi;
YOSHIKAWA Hitoshi;
TERAMAE Jun-nosuke;
SHIRAISHI Daisuke

Senior Lecturers
KUBO Masayoshi;
MIYAZAKI Syuji;
DOUGLAS Li

Assistant Professors
TUTU Hiroki;
HARADA Kenji;
NIINO Kazuki;
KAWAGOE Daisuke;
TSUJI Tetsuro

Admission, Curriculum and Other Efforts in Our Department

In study and research of advanced mathematical sciences, one needs both basic mathematical skills as well as knowledge of his/her specialist field. Accordingly, in the entrance exam, all applicants for our Master's course are required to solve basic problems in linear algebra and calculus together with one problem of their choice related to their respective specialties. Final decisions on acceptance are made through interviews with those applicants who score above a certain level in the written exam, since it is not desirable to make such decisions based only on the results of the written exam where one point may be the difference between a pass mark and failure. The interviews will be conducted by all the faculty members in order to determine if applicant's interests match the expertise of our faculties. In the entrance exam for the Ph.D. course, final decisions on acceptance are made based on the achievements of each candidate in his/her research work, which are evaluated in interviews conducted by all the faculty members.

Our curriculum for the Master course consists of both general and specialized subjects. All students are advised to take three general subjects, which help them to develop both scientific and engineering perspectives in mathematical sciences. Research advice is given mainly on a one-to-one basis, taking into account each student's aptitude. For those wishing to go on to Ph.D. courses, we provide Seminar II (for second-year students), which is designed to give students opportunities to learn advanced topics in addition to receiving standard research mentoring. In the Ph.D. course, students can receive mentoring not only from their advisers but also from other professors in our department and affiliated professors from science and engineering schools. This system gives students access to a broader spectrum of state-of-the-art knowledge in the mathematical sciences. Students thus have opportunities to deepen their expertise and to obtain a broad appreciation of mathematical sciences from both scientific and engineering perspectives, which we believe to be a unique feature of the education provided by our department.

In addition, almost every year, we offer open, public seminars on topical subjects.

Applied Analysis

Applied mathematics seeks to go far beyond mere application of pure mathematics to solution of physical and mechanical problems. Through research into mathematical models of phenomena, applied mathematics creates new mathematics. Our Division teaches and carries out research in applied analysis where there is particular emphasis on analysis in fields of applied mathematics. We seek to improve our understanding of existing analytics and create new analytics for the 21st Century. To give specific examples of the kinds of research we do, we analyze mathematical models of physical and mechanical phenomena by applying mathematical and numerical analysis and stochastic theory to get a better understanding of both the analytical methods and the mathematical structure of the model, and to establish new analytical techniques. In this Division, the key words are “nonlinear analysis” and “inverse problem analysis,” and our staff constantly interacts with one another while they teach and conduct research.

Nonlinear Analysis and Inverse Problem Analysis

Analysis in the 21st Century

Faculty Members and Their Research Interests

■Numerical Analysis of (Partial) Differential Equations, Numerical and Mathematical Analyses
I am interested in both mathematical and numerical analyses in research regarding the determination of unknown coefficients and other inverse problems, as well as boundary value problems and other forward problems with respect to partial differential equations that describe mechanical and physical phenomena. [Professor: ISO Yuusuke]

■Fractal Analysis, Fractal Geometry
I am interested in the mathematical theory of problems concerning heat and wave propagation in fractal concept models –new models for the natural world. [Professor: KIGAMI Jun]

■Statistical Signal Processing, Data Science
I am working on various problems in the fields of data science taking advantage of statistical signal processing, which is a theoretical framework to extract valuable information from raw data. My recent research interest includes underdetermined linear inverse problems with sparse and/or discrete constraints. [Professor: HAYASHI Kazunori]

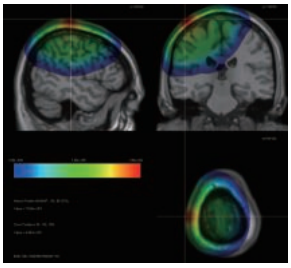
■Numerical Analysis of Ill-posed Problems, Design and Implementation of Multi-precision Arithmetic Environments
I am interested in research concerning regularization methods and numerical analysis of multiple-precision calculations with the aim of solving inverse problems that occur in mechanics and geophysics. [Associate Professor: FUJIWARA Hiroshi]

■Structure of Brownian Motion and Random Walk
How does the trace of Brownian motion look like? What can we say about the structure of random walk trace? Such questions have fascinated probabilists and mathematical physicists for a long time, and they continue to be an unending source of challenging problems. I am interested in the nature of sample paths of these fundamental processes. [Associate Professor: SHIRAISHI Daisuke]

■Inverse Problem Analysis, Numerical Analysis of (Partial) Differential Equations, Partial Differential Equations, Brain Model Mathematical Research
I mathematically analyze partial differential equations that appear in mathematical physics and mathematically and numerically analyze the inverse problems found in these partial differential equations, where the unknown coefficients of these inverse problems are determined by observed data. [Senior Lecturer: KUBO Masayoshi]

■Numerical Analysis of Differential Equations and Data-Driven Science
I am interested in numerical simulations of differential equations and data driven modelling in natural science, technology and social sciences. [Senior Lecturer: DOUGLAS Li]

■Integro-Differential Equations, Spectral Analysis
I study regularity of solutions to integro-differential equations appearing in kinetic theory and optics. Also, I work in spectral analysis on boundary integral operators which are related to the theory of elasticity. [Assistant Professor: KAWAGOE Daisuke]



Numerical Simulation of Light Propagation in a Human Brain (top) and Hardware used in Simulation (bottom).

Outline

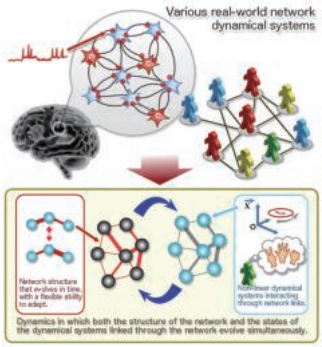
Nonlinear Physics

The dynamic behavior of systems that have a high degree of freedom and engage in nonlinear mutual interactions is both complex and richly diverse; nevertheless, many of these systems share common characteristics, e.g., exhibiting coherent structures and high-level functions, and are fascinating subjects for research. In our division, we use theoretical analysis and computer simulations to gain a better understanding of the complex behaviors and control of these types of dynamic systems and to clarify their universal principles. Our research covers topics in dynamical systems that range from nonlinear and nonequilibrium physics to theories of networks appearing in living and social systems; moreover, our staff members constantly interacts with each other while teaching and conducting research on these subjects.

■From nonlinear physics to theory of networks, as well as living and neural systems

I am particularly interested in systems composed of many simple elements that, through cooperative interactions, come to exhibit complex behavior and high-level functions, such as not only many physical systems, but also biological and social systems. Co-evolution involving the intricate interplay between the dynamics of the network and the elements is a key concept for understanding the self-organized, flexible nature of real-world network systems. I study such cooperative phenomena in systems of this kind, focusing on rhythmic phenomena and chaos from the perspective of nonlinear dynamics.

[Professor: AOYAGI Toshio]



Neural systems and social networks are nonlinear dynamic systems that have a high degree of freedom and develop as their dynamic elements change the structure of their interconnections.

■Nonlinear physics of computation and learning in the brain

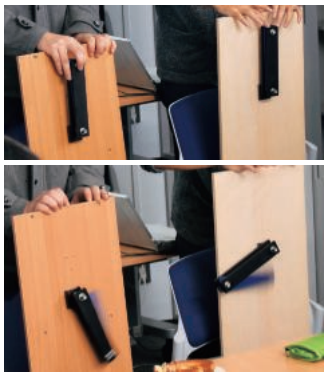
The brain is a highly complex network composed of about 100 billion of neurons. Spike propagation along the network and plasticity of synaptic connection of them cause high-dimensional nonlinear dynamics, which is the nature of neural computation and learning. Central questions, however, still remain elusive. What is intelligence? What is underlying principles of neural computation and learning? Our recent study, for example, reveals significant roles of spontaneous fluctuation in neural computation. By integrating neuroscience, computer science, and nonlinear physics, here we are trying to answer these questions and trying to develop fully brain-inspire AIs.

[Associate Professor: TERAMAE Jun-nosuke]

■Nonequilibrium nonlinear physics, complex networks

I study characteristic temporal fluctuations in the vicinity of various bifurcation points of a chaotic-dynamical system based on the statistical thermodynamic formalism, and I have a keen interest in applications of the projection-operator method used in statistical physics to perform effective calculations of temporal correlations as well as thermodynamic functions. I consider a variety of natural and social phenomena as a complex network from a unified standpoint. I promote cooperation with high schools, and strive to stir young people's interest in natural science by illustrating the abovementioned research fields.

[Senior Lecturer: MIYAZAKI Syuji]



Double pendula showing chaotic motion:
Starting from almost identical initial conditions as shown in the upper figure, we observe quite different time evolution, as shown in the lower figure; thus, we say that the system has a sensitive dependence upon initial conditions.

■Mathematical models for molecular machines

Biological molecular motors are amazing machines that generate useful movement (as a pump or a porter). The relationship between the structures of proteins and their highly efficient energy conversion, even under a fluctuating environment, remains mysterious. I explore the underlying principles of such molecular machines with mathematical models.

[Assistant Professor: TUTU Hiroki]

■Computational condensed matter theory

The new exotic thing emerges even from simple elements and rules. Even if we know them in detail, it is a very difficult, but fascinating task to predict the total property of the system. Base on the computational approach, I focus on such problem. For example, critical phenomena in a quantum matter at zero temperature and nonequilibrium steady state in the autonomous system.

[Assistant Professor: HARADA Kenji]

Applied Mathematical Sciences

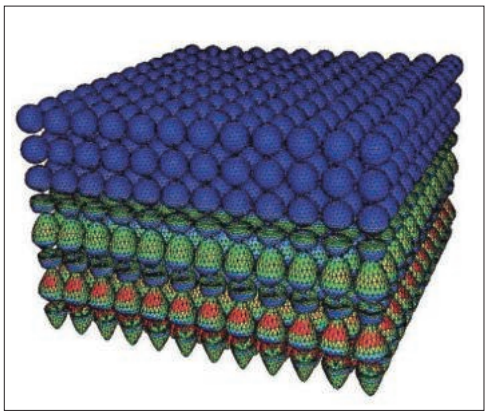
Many of objects that we study in mechanics are large and complex, and often exhibit behavior that is uncertain and difficult to predict. Although the most important issue for us is to accurately predict this behavior and control it, this is generally not easy to do. It is essential to establish sophisticated mathematical models of physical systems and to develop high-speed and accurate simulation techniques to analyse them. Numerical simulation techniques are particularly important in nano-scale and/or global phenomena where experimental approaches are extremely difficult. This division investigates mathematical modeling and simulation techniques and their applications from the viewpoints of applied mathematical sciences.

Computational Mechanics

Computer simulations: development of fast BIEMs and their applications to engineering problems

Numerical simulations provide powerful tools for solving various problems in science and engineering. Computational mechanics, together with theoretical and experimental mechanics, is an effective method of investigating mechanical phenomena in engineering based on numerical simulations. Our group specializes in Boundary Integral Equation Methods (BIEM) which are among major techniques in computational mechanics. BIEMs are particularly effective in wave and fracture problems. We focus on fast BIEMs and their applications to large-scale problems with special interest in electromagnetic wave propagations in periodic structures, which have many applications in optics. Other topics of interest include shape optimization problems, eigenvalue problems and inverse problems.

[Associate Professor: YOSHIKAWA Hitoshi,
Assistant Professor: NIINO Kazuki]



Example of analysis using a time domain fast multipole boundary integral equation method

Industrial Mathematics

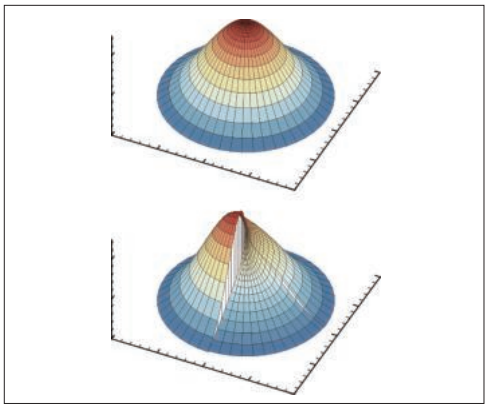
Toward new fluid mechanics for non-equilibrium flows

In our group we investigate the behavior of non-equilibrium flows based on kinetic theory describing the collective behavior of innumerable particles. We aim at understanding mechanical and/or thermodynamic properties of non-equilibrium flows both theoretically and numerically. We also aim at elaborating continuum theory and applying it to non-equilibrium flows, by deriving suitable mathematical models for non-equilibrium flows.

[Professor: TAGUCHI Satoshi]

Recent advances in micro/nanoscale technologies require the understanding of transport phenomena in micro/nanoscale and their control. For this reason there is a growing interest in the research of non-equilibrium flows. In particular, we aim at investigating moving boundary problems for non-equilibrium flows and the motion of tiny materials (or particles) driven by non-equilibrium effects from the view point of mathematical sciences and from experimental view points. We also aim at integrating them in industrial applications.

[Assistant Professor: TSUJI Tetsuro]



Example of velocity distribution function of gas molecules. Local equilibrium state (top) and locally non-equilibrium state (bottom). The conventional continuum theory is applicable only to the situation where the local equilibrium is satisfied everywhere in the fluid. We develop and elaborate a new framework of fluid mechanics applicable to a wider class of flows, including non-equilibrium flows.