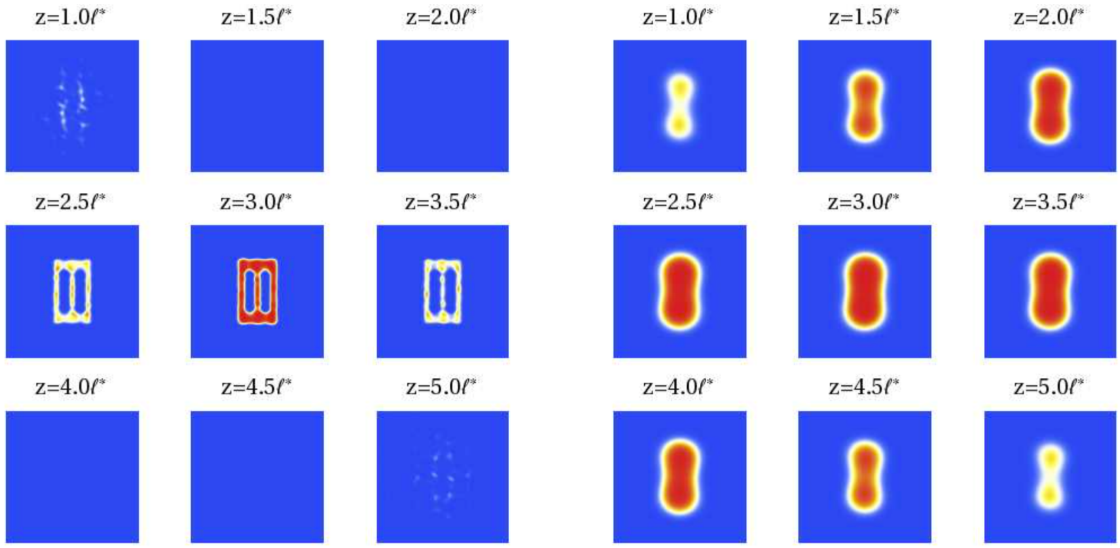
Inverse problems and medical imaging

Graduate School of Mathematical Science,
The University of Tokyo
13 Feb. 2017 - 17 Feb. 2017



Purpose

Inverse problems are rapidly becoming more important in the medical imaging such as electromagnetic mechanical tissue property imaging, the optical tomography. For breakthroughs, we need close international collaboration covering theoretical and clinical, practical aspects. This conference aims at providing wider forum for such collaboration and inspiring graduate students and young post-docs to the wide range of applied inverse problems.

Organizers

Yoko Hoshi	Hamamatsu University School of Medicine
Manabu Machida	Hamamatsu University School of Medicine
Masaaki Uesaka	The University of Toyko
Masahiro Yamamoto	The University of Tokyo

Supports

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- Leading Graduate Course for Frontiers of Mathematical Sciences and Physics;
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Tutorial lectures

(T-1) Overview of near-infrared optical imaging and its clinical applications
Yoko Hoshi (Hamamatsu University School of Medicine)

In 1977, Jöbsis first reported biomedical applications of near-infrared spectroscopy (NIRS); NIRS was originally designed for clinical monitoring, and it has also become a useful tool for neuroimaging studies with the so called functional NIRS (fNIRS). In parallel to these developments, diffuse optical tomography (DOT) using near-infrared (NIR) light has been and is still being developed. DOT is a technique to reconstruct images of optical properties, including the absorption (μ_a) and reduced scattering coefficients (μ_s'), within highly scattering media from measurements of the light propagation at the tissue boundary. Although DOT has great potential for diagnostic optical imaging, its image quality remains far from clinical use. The difficulty in developing DOT is mainly attributed to the fact that unlike X-ray CT, scattered photons are used for image reconstruction. Its image reconstruction algorithm basically consists of two parts: forward and inverse problems. The radiative transfer equation (RTE) accurately describes photon propagation in biological tissue. Because of its high computation load, the diffusion equation (DE) is often used as a forward mode. However, the DE is invalid in the low-scattering and/or highly absorbing regions and near sources. The inverse problem is inherently ill-posed and highly undetermined. The uncertainty of the optical properties of biological tissue also complicates image reconstruction for DOT. To overcome these problems, we have been developing time-domain DOT based on the RTE, and attempting to estimate tissue optical properties. In this lecture, firstly I will summarize NIRS, and then describe various approaches in the efforts to develop accurate and efficient DOT algorithms and present some examples of clinical applications. Finally, I will talk about future prospects of DOT.

(T-2) Fundamentals of statistical image reconstruction in Medical X-ray CT, SPECT, and PET
Hiroyuki Kudo (Tsukuba University)

Since 1990s, image reconstruction algorithms based on statistical estimation have been introduced in major tomographic imaging modalities , i.e. X-ray CT, SPECT, and PET. In this field, this class of reconstruction methods is generally called “statistical reconstruction” or “iterative reconstruction”, because it is based on minimizing a cost function designed based on the maximum likelihood (ML) or maximum a posteriori probability (MAP) estimation using various iterative optimization techniques. It is well-known that the statistical reconstruction possesses advantages such as better noise property and possibility of compensating for physical image degradation effects during the reconstruction. In this tutorial lecture, we explain fundamentals of statistical reconstruction for beginners in this field. The lecture roughly consists of the following three parts. In the first part, as an introduction, we explain the basic idea of statistical

reconstruction and show surprising examples which demonstrate higher image quality achieved by the statistical reconstruction. In the second part, we explain mathematical basis of statistical reconstruction, beginning from non-statistical iterative reconstruction algorithms such as ART to ML reconstruction for emission and transmission tomography and MAP reconstruction. In the third part, to introduce new directions of statistical reconstruction, we pickup three conceptually new statistical reconstruction algorithms developed by the authors.

(T-3) Medical imaging techniques using electromagnetic radiations
Jin Keun Seo (Yonsei University)

Medical imaging techniques in science and engineering have evolved to expand our ability to visualize various physical phenomena of interest and their characteristics in detail. We may see inside the body in many different ways since biological tissues manifest different physical and chemical properties. In devising a new imaging tool, we should first consider its uses and significance to diagnosis certain diseases. This tutorial lecture explains recent medical imaging techniques using electromagnetic radiations with various frequencies.

(T-4) Deep Learning for medical image analysis
Jin Keun Seo (Yonsei University)

Machine learning (ML) techniques are increasingly being used in biomedical imaging. The growing demands placed on health care due to the rapid aging of the population over the last three decades have led to the development of numerous biomedical imaging modalities. Numerous mathematical models with differing integrative levels have been developed to solve various medical imaging problems systematically and quantitatively. However, the corresponding problems in many cases are ill posed, with modeling inaccuracies and data uncertainties, which make them difficult to deal with using solely numerical means. ML has the potential to deal with these ill-posed problems using statistical reasoning. This tutorial lecture explains the basics of deep learning techniques in medicine.

(T-5) Nonlinear inverse scattering problem: New approaches
Vadim A. Markel (Aix-Marseille Université)

In this tutorial, I will formulate the nonlinear inverse scattering problem algebraically. I will discuss various ways of discretization of the applicable differential equations; this will lead to the algebraic formulation. Then I will introduce the T-matrix and its various representations. Information content in the scattering data will be discussed next. It will be shown that the nonlinear ISP can be viewed as the problem of completion of T-matrix and is therefore in the general class of matrix completion problems. Several iterative schemes to achieve matrix completion will be discussed. Time permitting, an exactly solvable toy problem will be used to illustrate the underlying mathematics.

(T-6) Reconstruction of nonsmooth refractional index of scattering media by dynamical regularizing scheme
Jijun Liu (Southeast University)

TBA

Conference presentations

(P-1) Optical Tomography for Near-infrared Fluorescence Imaging
Goro Nishimura (Hokkaido University)

Fluorescence imaging technique in biology is one of most common technique to visualize chemical events using specifically designed fluorescence probes. However this technique becomes very hard if the fluorescence is observed in vivo through tissue or body. This is because both excitation and emission lights are strongly scattered and eventually the spatial information of the location of the fluorescence probes is lost. To overcome this problem, the measurements to extract the remained spatial information and the appropriate model to recover the spatial information of the fluorescence probes are required. This imaging method is usually so-called by fluorescence diffuse optical tomography (FDOT) and can be categorized in an inverse problem.
The propagation of these lights can be modeled by a transport process of energy and the radiative transport equations (RTE) or the diffusion equations (DE) is commonly utilized. In this scheme, the transport is characterized by some parameters, scattering coefficient, anisotropy parameter, absorption coefficient, velocity of light, and fluorescence lifetime. These optical parameters are usually heterogeneous in the object and the task is the reconstruction of them. In the targeting of the fluorescence probes, the main interest is the 3D distribution of absorption which is come from the fluorescence probes. Several measurements set on the surface of the object with different injection and detection geometries are usually used for the data set of the reconstruction.
Some numerical simulation researches reveal that quantitative 3D fluorescence images can be yielded with a proper algorithm. However, in practice, there are many problems, such as background, contamination, systematic distortion, etc to be solved and more robust algorithm is actually needed.
In this talk, I will introduce the outline of our approach of FDOT, touch some simulation works and talk on the experimental results.

(P-2) A new scheme for the time-domain fluorescence imaging of a semi-infinite turbid medium: Monte Carlo evaluation
Kernel Prieto (Hokkaido University)

We investigated the feasibility of a two-step scheme for reconstruction of a fluorophore target embedded in a semi-infinite medium. In this scheme, we neglected the presence of the fluorophore target for the excitation light and used an analytical solution of the timedependent radiative transfer equation (RTE) for the excitation light in a homogeneous semi-infinite media instead of solving the RTE numerically in the forward calculation. In the first step of this reconstruction scheme, we implemented a pixel-based reconstruction using the Landweber method. The second step uses this result as an initial guess for solving the shape and contrast value reconstruction problem using the level set method. Numerical experiments using Monte Carlo data measurements, show that the proposed scheme provides reconstructions of shape, location and contrast value of the target with rather good accuracy. The computation times of the solution of the forward problem and the whole reconstruction process were reduced by about forty and fifteen percent, respectively.

(P-3) Algebraic reconstruction of moving monopolar wave sources from boundary measurements

Takashi Ohe (Okayama University of Science)

Inverse source problem for wave equation is an important mathematical model of many problems in seismic science, acoustic science, and so on, and widely discussed in various fields. Here, we consider the problem for moving monopolar wave sources in a three dimensional domain, and discuss an algebraic reconstruction method from measurements on the boundary. As algebraic reconstruction schemes of monopolar or dipolar wave sources, various methods are proposed based on the reciprocity gap technique, or the path-integral method [16]. However, in these methods, sources are assumed to be fixed, or only one source is assumed to be exists. In this talk, we extend the reconstruction method in [5] for multiple moving monopolar wave sources, and show some numerical experiments for the new procedure.

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(P-4) Inverse boundary value problems for the heat equation

Haibing Wang (Southeast University)

TBA

(P-5) Inverse estimation of environmental properties by using a non-Gaussian probe

Hisao Hayakawa (Kyoto University)

We often use a thermometer as a probe to measure the temperature of the environment we consider. If we know the details of environmental properties, we can estimate the temperature and some other properties of the environment in terms of solving its basic equation. Then, we can evaluate how the probe behaves as the result of the environmental fluctuation. Nevertheless, we often encounter the situation when we do not know the details of environmental properties. In this case, we should infer the properties of the environment from the reaction of the probe under the interaction with the environment. Therefore, we need a general method to estimate environmental properties from the reaction of the probe. In this talk, we demonstrate that the construction of the inverse estimation of the environmental properties is possible if the probe is a mechanical object activated by non-Gaussian Poisson noise or the probe is randomly hit by mechanical objects. This is related to a mathematical problem on the stochastic thermodynamics by non-Gaussian noise [1]. In this talk I will show you some examples of physics and its application of non-Gaussian noise as well as how to estimate the environmental properties from the response of the probe [2]. As an example of the application of the inverse estimation, by using the motion of a rotor in vibrating granular bed, I will plain how to estimate the environmental properties from the motion of the probe [3]. If I have time, I will extend the inverse estimation to a quantum setup [4] and demonstrate the relevancy of the non-Gaussian noise for the glass transition [5].

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(P-6) Transport-based optical tomography algorithms by rotated reference frames

Manabu Machida (Hamamatsu University School of Medicine)

In this talk, numerical algorithms for optical tomography will be presented. Since the inverse problem is formulated using the Green's function for the radiative transport equation, our focus is on how to efficiently compute the Green's function. The technique of rotated reference frames provides different efficient numerical schemes for the three-dimensional radiative transport equation. We will develop and compare two numerical algorithms which make use of rotated reference frames.

(P-7) Uniqueness in inverse acoustic medium scattering problems
Guanghui Hu (Beijing Computational Science Research Centre)

TBA

(P-8) Monte Carlo simulation of near-infrared light propagation in head models
Eiji Okada (Keio University)

Accurate forward modeling to predict light propagation in tissue is important to image reconstruction of near-infrared spectroscopy data. The light travels considerably farther through tissue than the geometrical length between the source and detector probes because of multiple scattering.
Various models have been developed to calculate light propagation in tissue and Monte Carlo simulation is a stochastic technique that is arguably related to the physics of the photon propagation. It has the advantages of being conceptually simple and permitting direct handling of complex geometries and optical heterogeneity. The propagation of photon packets in the tissue is determined with the scattering coefficient, phase function and random numbers. The weight of the photon packets, which relates to the fluence of light, is calculated from the absorption coefficient and optical path length. The disadvantage of the Monte Carlo simulation is that it requires long computation time to obtain well converged results because the statistical errors in the results decrease with an increase in the number of detected photons.
In brain activation imaging by near-infrared spectroscopy, it is important to obtain the volume of tissue interrogated with a particular source-detector pair. The heterogeneity of the optical properties in the head affects light propagation in the brain and the model is typically segmented into several regions such as the scalp, skull, cerebrospinal fluid, grey matter and white matter. The geometry of the head model is based on structural magnetic resonance images of the human head.
In this talk, I will present the Monte Carlo simulation of light propagation in tissue and the construction of head models for the optical image reconstruction of brain activation.

(P-9) Novel challenge for radiative transfer solver in astrophysics
Masayuki Umemura (University of Tsukuba)

TBA

(P-10) Numerical solver of the 3D radiative transfer equation in turbid media with anisotropic scattering based on the discrete ordinates method
Hiroyuki Fujii (Hokkaido University)

Diffuse optical tomography (DOT) has a potential for a non-invasive hemodynamic evaluation and cancer detection in a wide range of organs and tissue volumes such as brain and breast by reconstructing a spatial distribution of the optical properties (absorption and scattering coefficients). DOT uses near-infrared light in a wavelength range from 700 to 1000 nm because near-infrared light can penetrate inside biological tissue compared to light in other wavelengths but with multiple scattering. Due to the multiple light scattering, an image reconstruction algorithm for other computed tomography (CT) such as X-ray CT is not directly applied to DOT, where absorption of X-ray is dominant over scattering X-ray. Hence, DOT requires a mathematical model to describe light propagation with multiple scattering in the organs and tissue volumes. It is widely accepted that the radiative transfer equation (RTE) can provide the accurate description of light propagation in turbid media like biological tissue. However, it is quite difficult to solve the RTE analytically and numerically because it is an integro-differential equation with many independent variables: position, angular direction, and time. For mathematical simplification and reduction of computation loads, usually DOT utilizes the diffusion equation (DE) by the diffusion approximation to the RTE. Nevertheless, its applicability is limited to long source- detector distance and highly scattering media. As far as forward model, one needs a fast and efficient solver the RTE in three dimensions for further development of optical tomography. Although analytical solutions of the RTE have been extensively derived in simple geometries, derivations of the analytical solutions for complex tissue volumes are unreasonable. Hence, the RTE is usually solved numerically by discretization of the space, angular direction, and time. In discretization of angular direction, spherical-harmonic expansion and simplified spherical-harmonic expansion are widely used because these methods can reduce computation loads. However, these methods cannot treat anisotropy of scattering well. Biological tissue is known as a highly forward-peaked scattering medium, so that for numerical calculation of the RTE to biological tissue, the discrete ordinate method (DOM) is used instead. The DOM approximates the integral term in the RTE over the unit sphere with respect to the angular direction to numerical sum with the discretized angular directions. Although the DOM can treat anisotropy with sufficient number of the discretized angular directions, the large number of the angular directions results in high computation loads. In this presentation, we develop accurate and efficient DOM solver by renormalizing the phase function based on the double exponential formula. Accuracy and efficiency of the developed scheme are tested by comparing to conventional renormalization approach.

(P-11) Probabilistic image reconstruction algorithm of diffuse optical tomography for human functional brain imaging

Okito Yamashita (Advanced Telecommunications Research Institute International)

Functional near-infrared spectroscopy (functional NIRS or fNIRS) is a noninvasive optical imaging technique that measures the changes in oxygenated and deoxygenated hemoglobin concentrations (hemodynamic changes) in response to changes in neuronal activity. fNIRS is sensitive to hemodynamic responses analogous to the blood-oxygenation-level-dependent (BOLD) signals found in functional MRI (fMRI), yet offers the advantages of low cost, easy portability, and the possibility of extending brain measurements to include such subjects as babies, elderly people, and patients with an implanted electronic device. It also permits measurements to be made in ambient envi-

ronments.
However lack of ability to specify activity location on brain anatomy and contamination of scalp blood flows are big issues to interpret spatial patterns of fNIRS measurement. Diffuse optical tomography (DOT) is an emerging technology for improving the spatial resolution and spatial specificity of conventional multi-channel NIRS. The hemodynamics changes in two distinct anatomical layers, the scalp and the cortex, are known as the main contributor of NIRS measurement. Although any DOT algorithm has the ability to reconstruct scalp and cortical hemodynamics changes in their respective layers, no DOT algorithm has used a model characterizing the distinct nature of scalp and cortical hemodynamics changes to achieve accurate separation. We propose probabilistic image reconstruction algorithm based on a hierarchical Bayesian model in which distinct prior distributions for the scalp and the cortical hemodynamics changes are assumed. We verified the reconstruction performance with a phantom experiment, a computer simulation using a real human head model and real human experimental data. Results suggest our method enables accurate simultaneous reconstruction of both scalp and cortical hemodynamics changes. By extending the advantages of NIRS such as low running cost and portability with our DOT method, it might be possible to advance brain research in a real environment.

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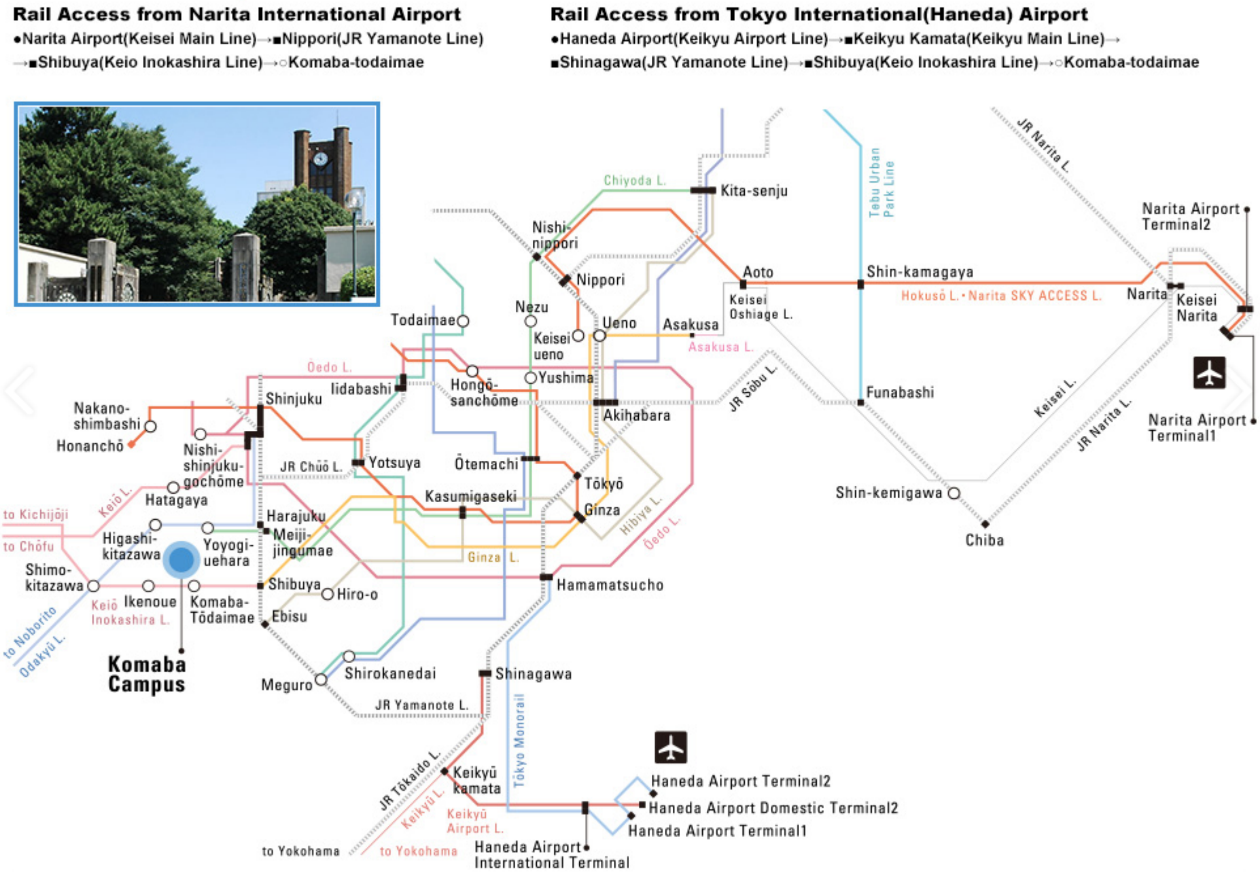
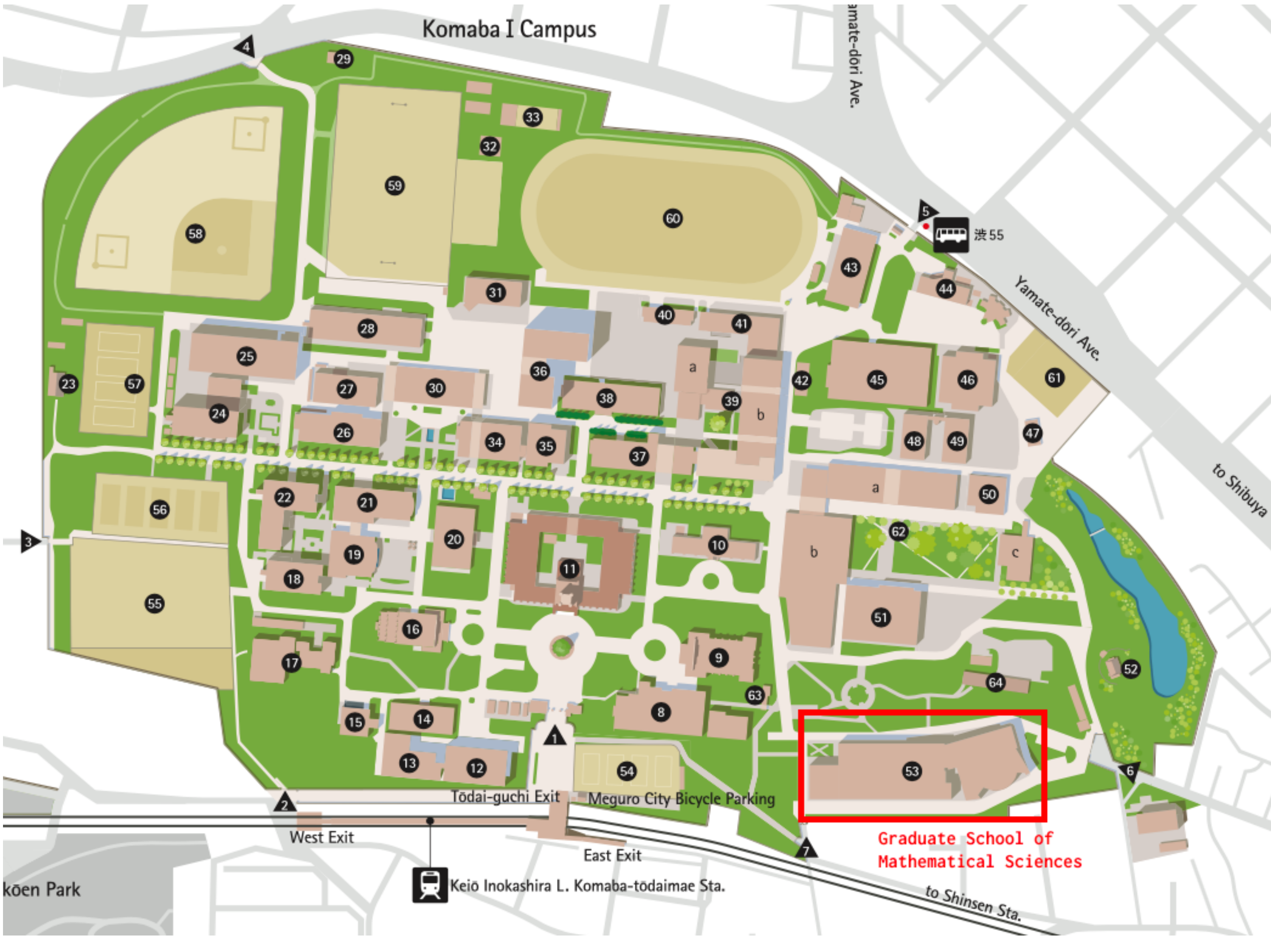
Maps

Access to Komaba Campus



Location of Graduate School of Mathematical Sciences



Location of the main lecture room and tea room