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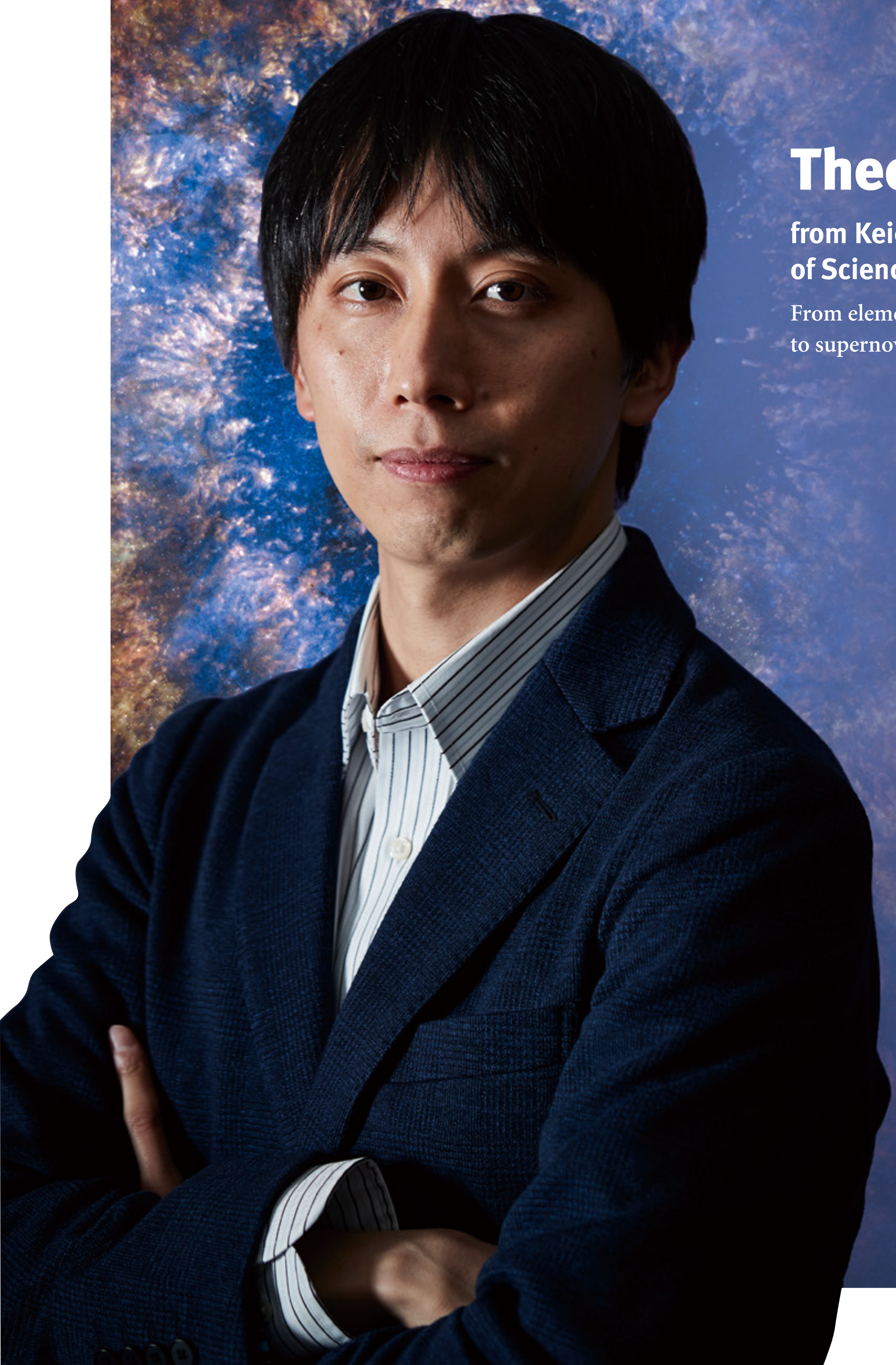


Theoretical Physics

from Keio's the Faculty of Science and Technology

From elementary particles inside atoms
to supernova explosions

Naoki
Yamamoto

Associate Professor
Department of Physics

The star of our current interrogations is Associate Professor Naoki Yamamoto, who is battling the fundamental problem of "the nature of matter" using theoretical physics.

Where are the limits of theoretical physics?

From elementary particles inside atoms to supernova explosions

From elementary particles inside atoms to supernova explosions, all things that exist in this world are compelled by particular "laws of physics," all of which are subjects for research within "theoretical physics." Dr. Yamamoto from the Department of Physics is steadily expanding his research scope in the vast field of "theoretical physics," propelled by the dictates of his curiosity and intuition. This piece will introduce one thread of the research of a young theoretical physicist.

Deduction of a nontrivial phenomenon from a simple theory

Dr. Yamamoto of the Department of Physics at the Faculty of Science and Technology, Keio University is a theoretical physicist engaged in a wide range of research from "nuclear and particle physics" on the quarks and neutrinos at the micro scale through to "astrophysics" at the macro scale.

Paper and pen remain the fundamental tools at his disposal for such dynamic research. "Well, I may have recently replaced these with an iPad and Apple Pen. It may appear that I am simply staring into space during my research," says Yamamoto, reflecting on how he may appear when researching. Nevertheless, a huge amount of mental turnover on Yamamoto's part is required to clarify a non-trivial phenomenon based on a simple theory during these ruminations. The ultimate result may be "a theoretical prediction of a previously overlooked physical phenomenon" or "a new theory to supersede a fundamentally flawed conventional theory."

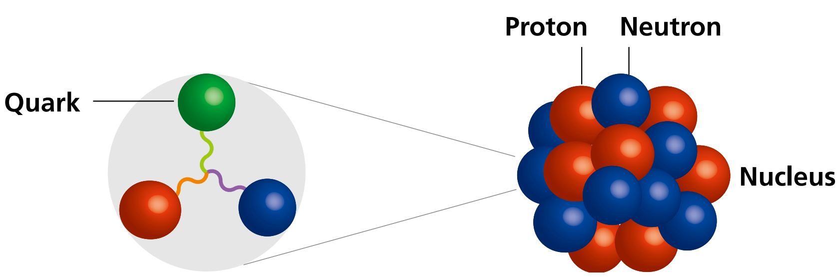
My life's work of "quark confinement"

"Quark confinement"— the original problem which inspired Yamamoto's incursion into theoretical physics (Fig. 1). This is also related to one of seven others in mathematics identified in 2000 as Millennium Prize Problems, with a million-dollar prize being offered to the person who can solve it. However, it remains unsolved today and is one vein of Yamamoto's life's work. But just why is this problem so dastardly difficult? To learn the answer to this, we must familiarize ourselves with the very constituents of matter.

"All matter is made up of atoms"— this is common knowledge to anyone over junior high school age. While atoms were originally thought to be the smallest components of matter, it is now known that they are made up of a "nucleus" surrounded by "electrons." Further, these nuclei are made up of nucleons such as protons and neutrons, with such nucleons in turn comprised of still smaller particles called "quarks." Although yet smaller components may remain to be discovered in the future, quarks, neutrinos, electrons, and their compatriots are currently the smallest known units of matter, and referred to as "elementary particles." The presence of quarks within nucleons has been confirmed in experiments conducted using large accelerators.

In everyday life, just as the movement of matter conforms to the rules of

The problem of "the strong force"



- Quark confinement
- The origin of the mass of matter

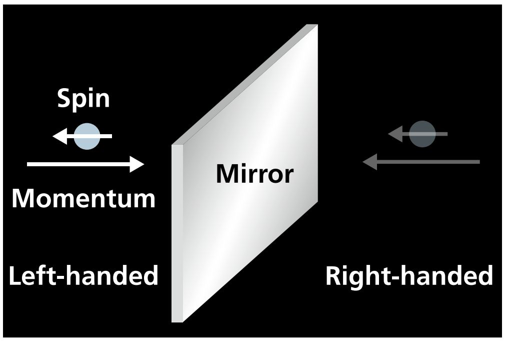
$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G^{a}_{\mu\nu} G^{\mu\nu}_{a} + \bar{q}\gamma^{\mu}(i\partial_{\mu} - g t^{a} A^{a}_{\mu})q - m\bar{q}q$$

- One unsolved problem in the Standard Model of particle physics
- Millennium Prize Problem in mathematics

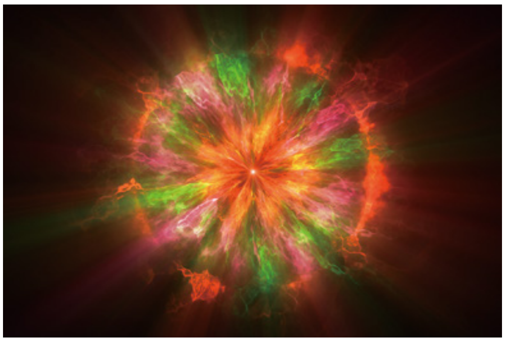
Fig.1 Constituent elements of nuclei and QCD. Three quarks are confined in nucleons such as protons or neutrons.
The dynamics of quarks is described by QCD (equation).

The problem of "the weak force"

Mystery of the neutrino



Mystery of supernova explosions



Supernova = System with the largest violation of the left-right symmetry in the universe

Fig.2 Supernova explosion (right) and the neutrino property with the potentially important role (left)
Neutrinos are left-handed only, and mirror image right-handed neutrinos do not exist, resulting in the violation of the left-right symmetry.

"Newtonian Mechanics," the miniscule world of quarks is animated by the rules of "Quantum Chromodynamics (QCD)." This is not to say that quarks have actual "colors."Rather, the three primary colors of light are paralleled to the three degrees of freedom which quarks have.

"It is not possible to extract a single quark from a nucleon. It's certainly a puzzler," says Yamamoto. This is the "quark confinement" problem. While it is expounded that "quarks are connected by the strong force," to date no one has been able to offer analytical proof of this based on QCD.

I wish to learn "the nature of matter"

"Unless we solve the problem of 'quark confinement,' we will never truly understand the matter in which quarks are contained. There are any number of fundamental things which we have yet to explain about matter, not confined to this particular problem." Yamamoto's theoretical research is simultaneously oriented towards clarification of "the nature of matter" and the pursuit of the challenge of "quark confinement."

So, just how does he go about approaching these objectives?

"Theoretical physics often presupposes extreme states. For example, these quarks which now cannot be isolated from the nucleon earlier existed in a disjointed plasma state in the extremely high temperatures which directly followed the Big Bang, known as 'quark-gluon plasma.' What then, conversely happens when this matter is compressed into an ultra-high-density state? It is thought that quarks ultimately assume superconducting and superfluid states. For now, though, our attention is on the nature of the states they go through before reaching this point." This is the way that Yamamoto is seeking to clarify "the nature of matter."

Can "Chiral Transport Theory" clarify the mystery of supernova explosions?

Yamamoto's recent research focus has been on supernova explosions. Elements which are formed in stars are scattered throughout space in the massive explosion which marks the end of a heavy star. Supernova explosions are thus the source of everything — as these elements are the constituents of the matter and biological life which surround us. However, explosions do not readily arise under the conventional theory. We may be able to find the solution to this problem by applying the "Chiral Transport Theory."

Chiral Transport Theory, presented in a paper by Yamamoto in 2012, offers a theoretical description of the transport phenomena with their roots in the nature of elementary particles referred to as "chirality."

One familiar transport phenomenon is Ohm's Law, which states that a current will flow when an electrical field is applied. However, in this case heat is generated with the current and energy is lost. Meanwhile, the nature of chirality is such that particle transport without energy loss not normally seen in regular matter becomes possible.

Under conventional supernova theory, there is the issue of the elementary particles known as neutrinos being expelled without having imparted enough energy to the surrounding matter to cause an explosion. However, this overlooks the property that "only left-handed chirality is found in the neutrino, causing the left-right symmetry to be violated" (Fig. 2). Since Chiral Transport Theory also accounts for the phenomena of transport without energy loss, due to the property of neutrinos, it is suggesting and elaborating new directions in research to explore the mysteries of the supernova explosion.

"This world" chock full of things we don't understand

The diligently research-driven Yamamoto meanwhile recounts that, "There are many things that I wish to unravel, with over 50 problems which I have yet to turn my hand to still in my 'jottings book.'" Among these, he says, are those which require vast calculations and years to figure out before the full picture is revealed. This includes research into the supernova explosion. Meanwhile, there are also those which would take around a week to turn into a paper if the right ideas were to make themselves known. Whatever the problem, if solved these will result in a "new world" revealing itself. I am getting more and more excited at the prospect of the worlds Dr. Yamamoto has yet to reveal to us.

(Interview and text writer: Akiko Ikeda)

Theoretical physics to transcend time and space and travel to far off places

"There were times at graduate school when I oscillated between becoming a physicist or choosing another path," Yamamoto tells us. His embarkation on a physics path, his choice of ballroom dance as his club at university, and his experiences amassed as a post-doc overseas, were all a result of an honest adherence to fleeting sensations of "inspiration." Yamamoto's keen sensibilities are now being demonstrated in his education and research activities at Keio University.

Tell me a little about your childhood.

I was born in Shiga Prefecture and raised in Nagoya and Osaka. As the youngest of three brothers, my older brothers definitely helped toughen me up. I remember being made to play soccer, and chasing the ball with all my might.

In junior and senior high school, I was intensely absorbed in mathematics and would solve and enter problem contests I found in magazines as part of my search for challenging problems. The "Homework" column by Péter Frankl in the magazine *Daigaku e no Sugaku* ("Mathematics to University") in particular was replete with difficult problems which one does not learn at senior high school. In my second year of senior high school, I participated in a mathematics seminar chaired by Péter on the University of Tokyo Komaba Campus at which I studied alongside the other participants. My arrival in Tokyo was prompted by my wish to study mathematics at the University of Tokyo.

Why did you go the physics route rather than mathematics which you loved so much?

While my image of physics up until senior high school involved doing calculations using various formulae, at university I encountered quantum mechanics and the theory of relativity. As a result, I learned that physics could facilitate an understanding of the origins of the natural world such as the universe and elementary particles. This is what prompted my switch from mathematics to physics. In fact, as a senior high school student I studied quantum mechanics on my own initiative. Nevertheless, the complex wave function in the Schrödinger equation struck me as confounding that despite the fact that we are not able to measure the wave function itself, this has a tangible bearing on actual physical quantities. During my university classes, I learned about the historical background that led to quantum mechanics, and was able to achieve insights into its significance which had eluded me during my high school days.

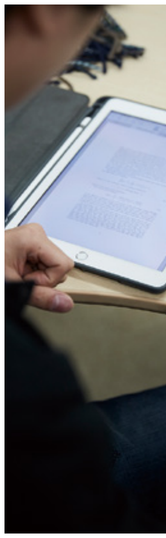
I see. So, you chose physics over mathematics because you wished to learn more about the universe and elementary particles?

While I was interested in both space and mathematics as a youngster, I was largely unaware of the best avenues to approach space, and this thus manifested in a vague yearning to become an astronaut. However, when I started university, I learned that physics can be regarded as a means to comprehend the actual phenomena occurring in the universe through logical thinking. This is not limited to the universe as it is today; neither are there limits in terms of distances from our own planet. Consequently, physics can allow us to envisage what the early universe looked like or what is happening in a far distant black hole or during a supernova. The access thus provided to space is of a broader nature than would be possible merely by going there.

I ultimately concluded that, if I am to compete on the world stage, theoretical physics would be the best path for me to make my mark.

What kind of place was your first lab at the University of Tokyo?

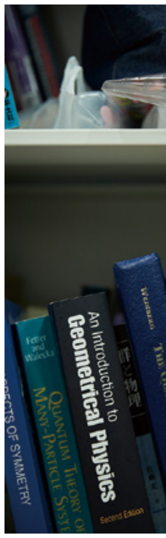
Tetsuo Hatsuda was my supervising faculty member while I was at graduate school at the University of Tokyo. He transferred to RIKEN in 2012, and has been researching as part of a new project called iTHEMS (Interdisciplinary Theoretical and Mathematical Sciences Program). He seems to be attempting to clarify various phenomena in physics and biology using mathematics, casting his net wide to recruit personnel and find potential academic solutions. Dr. Hatsuda's interests have been wide-ranging from the get-go, and he is very flexible in incorporating ideas from other fields and applying these to problems in his own field; or conversely, in putting forward his ideas to solve problems in other fields. I think that I am influenced by Dr. Hatsuda in the way in which I think about applying a particular perspective in physics to other fields.



You have also spent time overseas?

After getting my Ph.D. in March 2010, I made my way to the University of Washington under the JSPS (Japan Society for the Promotion of Science) Postdoctoral Fellows for Research Abroad program, where Dr. Dam Thanh Son, who I admired most at the time, was stationed. Son is a Vietnamese researcher who writes truly elegant papers.

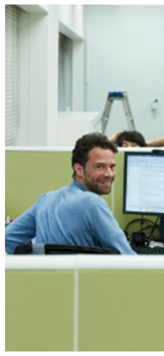
This was the first time that I had read a paper and become convinced that I was in the presence of a work of art. It was as if the scales fell from my eyes. My subsequent thoughts were that I would like to discuss directly and conduct joint research with Son in order to learn what allowed him to produce such a paper.

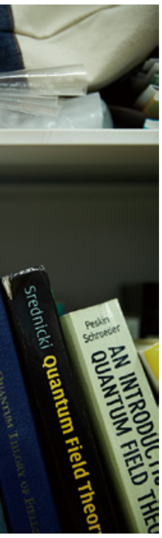


What do you mean when you say that the paper was elegant?

Firstly, if you look at the results alone the conclusions are far from foregone, and in fact quite surprising. Nevertheless, each step along the path to these conclusions is imbued with an exceedingly simple logic which even a master's student would be capable of following. Then, before you know it, you find yourself at a point extremely remote from the one at which you started.

In theoretical physics, where problems are set up and then tackled, the methodology of setting-up problems is especially important. I learned many things from Son in this regard. Also, the Chiral Transport Theory, which ties in with neutrino transport theory is something I put together in a paper with Son





in 2012.

What kind of place do you find Keio University to be?

I was first appointed to the faculty at Keio in 2014. What surprised me was that the students were extremely friendly, and that they would come to me with questions at the end of the class. They would ask about things that had no relation whatsoever to the class, saying: "Excuse me, but I didn't understand this from a book I read recently..." I was delighted to be approached in this way.

The relationships between the faculty members and the research environment are excellent, and in 2015, we launched the "Topological Science" Project (Strategic Research Foundation Grant-aided Project for Private Universities). This is an outcome of our wishing to get something started with the faculty members of the Physics Department at Yagami Campus and those teaching physics at Hiyoshi Campus. We invite researchers from Japan and overseas who are engaged in interesting research to talk as well as holding international symposiums.

I was selected as a member of the Keio Institute of Pure and Applied Sciences (KiPAS) at the Faculty of Science and Technology from the 2019 academic year, meaning that a research-conducive environment is at my disposal for five years. I am putting more energy than ever before into the problem of supernova explosions. My days are satisfying and productive, both as a faculty member and a researcher.

◎ Some words from students ... ◎

● Professor Yamamoto is a consistently sympathetic teacher who is also capable of pointed observations on the subject of physics. I took his class when I was an undergraduate student, and the emphasis he placed on the universal aspects of physics as opposed to unravelling a specific problem really resonated with me. I really wanted to debate things with Professor Yamamoto, and so I joined his lab.

His level of intuition when we are discussing and working through calculations and physics principles on the board is truly overwhelming. I believe that it is this thorough knowledge of physics which imparts the insight I need to unravel physics problems.(3rd year doctoral candidate)

(Interview and text writer : Akiko Ikeda)

For the full text of this interview
http://www.st.keio.ac.jp/kyurizukai

The real charm of physics is in finding its universal laws beyond the hierarchies from micro to macro.

Naoki Yamamoto

Specializes in theoretical particle and nuclear physics. 2005, Graduates from the Department of Physics, Faculty of Science, University of Tokyo. 2010, Completes doctoral degree at same university's Graduate School of Science. Ph.D. in Science. Assistant Professor at the Department of Physics, Faculty of Science and Technology, Keio University since 2014, following completion of a post-doc at the University of Washington's Institute for Nuclear Theory, Kyoto University's Yukawa Institute for Theoretical Physics, and the University of Maryland. In his current position since 2017. Concurrent appointment as a KiPAS principal investigator since 2019.

Naoki Yamamoto's ON and OFF

Here, I will look back from my graduate school days through to the present.

Doctoral Training Program in Italy

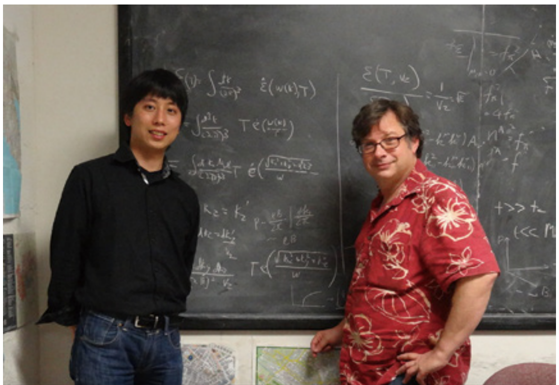
In the second year of my doctoral studies, I took part in a Doctoral Training Program for roughly three months at the European Center for Theoretical Studies in Nuclear Physics and Related Areas (ECT*), located in Trento, Italy. During this time, I shared communal living spaces in apartments with students from various countries (my chief role was "dishwasher"). Exactly ten years after this, a student from my own lab at Keio would come to participate in this same program.

At an international conference

It is essential for theoretical physicists to engage in discussions with other researchers. In this picture I am discussing with Mannque Rho at an international conference in Kyoto. Perhaps because our research intrigued him, he would subsequently use a diagram from our paper in the cover for a textbook he authored.

Food life in Seattle

This is a farewell party for a colleague completing a post-doc at the University of Washington in Seattle. Everyone is eating Ethiopian cuisine. As a general rule, we would rotate between restaurants every week in the vicinity of the university, which included Thai, Indian, Mexican, and Vietnamese cuisine, or sometimes go to eat somewhere serving other rarely encountered dishes.
This was usually followed by a group coffee trip.



During my post-doc days at the University of Maryland

With Tom Cohen, my boss during my time at the University of Maryland. A student I taught at Keio is now at the University of Maryland since graduate school and is currently researching under Tom. This is something I would have struggled to envisage at this time.

"Topological Science" Project at Keio University

Since its launch in AY 2015, the "Topological Science" project (in front is Dr. Nitta of the Faculty of Business and Commerce, who is a member of the Department of Physics at Hiyoshi) has been conducted with a focus on staff engaged in theoretical research on particle physics, nuclear physics, and astrophysics at Keio's Hiyoshi and Yagami campuses. The picture is of the project members as of March 2019. They have each actively engaged in their research activities to date in addition to undertaking post-docs from diverse backgrounds.

私の本棚
My favorite books

A data book to understand the universe.

This is a book which my father bought for me as a child. It uses photographs and illustrations to cover a vast amount of ground, with explanations ranging from the origins of the universe through to the elementary particles which make up matter and their interactions, the birth and evolution of celestial bodies, black holes, the solar system and earth, and the origins of life. I consequently believe that this was the starting point for my later life as a researcher. I glance back at this book from time to time to remind myself of my original motivations.

What is gravity?/Strong and weak forces

These are books which provide clear and attractive explanations of gravity, the fundamental interactions occurring in nature, and of the strong and weak forces, aimed at a general readership. They are written in such a readily understandable way as to make me wish that such books existed during my own childhood. I read them with great personal interest due to the appearances of my first boss during my post-doc days Dr. Son, as well as Dr. Hatsuda, my supervisor during my graduate school days in "What is gravity?" and "Strong and weak forces," respectively.

Lectures on Quantum Theory

This is a textbook of lectures on quantum theory, a subject I took in my first year at university. I was shocked by this world as described in terms of quantum mechanics, which at first glance seemed like a really strange theory to me, and at the same time, I realized I, who was still dominated by the worldview of classical mechanics, in fact really knew nothing about this world. In the latter half of the textbook, there are explanations covering quantum field theories and the difficulties involved in constructing quantum theories of gravity.

Quantum Field Theory in a Nutshell

This textbook elegantly explains applications of quantum field theory to various physical phenomena transcending scales, including the theory of elementary particles and gravitational theory, condensed matter physics, such as superfluidity and superconductivity, and the nonequilibrium physics of interface growth. It gives you a real feel for the universality and beauty of quantum field theory. I read it with the enjoyable sense that I was listening to a frank lecture.

Mechanics

A mechanics textbook which I first encountered after entering university. While I learned physical laws at high school as mere scripture, the scales fell from my eyes when I realized that simple theories could allow them to be comprehended logically. The ten volumes making up Evgeny Lifshitz and Lev Landau's "The Course of Theoretical Physics" including this on Mechanics, are fundamental to the thinking informing my current research. It is no exaggeration to say that a majority of theoretical physicists are engaged in research which aims to reveal the physics beyond the Landau paradigm.

"Homework" from childhood

Naoki Yamamoto

When I was around nine years old, my father bought me the book entitled "A Data Book to Understand the Universe." I was intensely fascinated by this book, which offered explanations of the universe, elementary particles, the life and death of stars, and the origins of life, via evocative photographs and illustrations. Two things remain with me most from the explanations found in this book. One is that, for whatever reason, of the elementary particles which are the basic components of matter known as quarks and leptons, the former do not today exist in space as singular entities. The other is that the universe may have been created from a vacuum-like nothingness which suddenly changed into a finite space somewhat like a bubble. However, at the time I was unable to understand what this meant, or why it was necessary to think about this. I thought that this idea of "creation of the universe from nothing" was merely a theory proposed by the Soviet-born physicist Vilenkin, and wondered at the fact that there are people in the world thinking about such unimaginable things. It is extremely appealing to imagine it might be possible to inquire into and understand fundamental problems not just of the universe but of the natural world.

More than a quarter of a century later, in September 2018, I took part in a conference in Sweden. All of the participants were assigned an office at this conference, and who did I find myself sharing mine with but the very same Vilenkin! As he was returning home on the same day that I would be giving a talk, I cornered him to discuss my recent paper on supernova explosions at the office (naturally I also mentioned that I had read this book when I was a child.) I would never have dared to imagine that our paths would one day cross, and that a day would come when I would be able to directly discuss my own ideas with him.

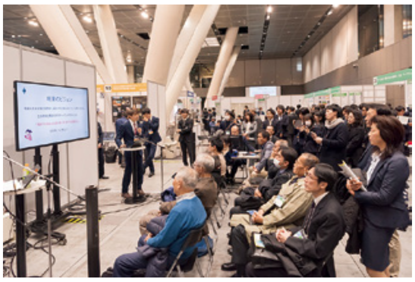
From my childhood through to today, it would appear that the number of "useful" things has increased considerably in the world, and also that various other fields have developed after gaining popularity. Nevertheless, even if many of the long-standing problems of the universe and matter remain unsolved, recent progress is also undeniable. We have established that the universe is around 13.8 billion years; confirmed the existence of the Higgs field which is the origin of the mass of elementary particles; and recently detected gravitational waves from the merger of black holes and neutron stars. Around one hundred years has elapsed between Einstein's theoretical prediction of gravitational waves and their direct observation. I have a genuine sense of amazement for humanity because we can scientifically ascertain over a long time span such things which far exceed the scale of the human being.

I aspire to make a contribution, however small, to clarifying the universal mechanisms of nature which have thus far remained obscure to all, despite their undeniable existence. I also hope to inspire interest in younger generations unbound by transient fads. Finally, I wish for a society that understands the significance and urgency of tackling these sorts of fundamental problems from various directions.

理工学 Information

Business Idea Contest

We hosted a business idea contest at the KEIO TECHNO-MALL 2019 (20th Annual Keio Science and Technology Exhibition).



Contest Overview

At the Keio Leading-edge Laboratory of Science and Technology (KLL) of Science and Technology, we actively create and invest in, offer technological support, and initiate tie-ups with business start-ups, to actualize and feed research outcomes by faculty members and students in the Faculty of Science and Technology through to the community at large. This contest involved introductions of the business ideas of students that will become "eggs" for the start-ups selected for KLL incubation and preparatory support initiatives in the current year, by way of a pitch contest consisting of short presentations of four minutes length.

Eight teams participated in the event, with one of these singled out for the Grand Prize and four other teams selected for Excellence Awards, following a screening of technical and business aspects of the various business ideas presented.

Participating teams and presenters, and screening results

Grand Prize "Zip Infrastructure,"
Takamasa Suchi (third-year undergraduate)

Excellence Award "Development for the practical use of a simple, rapid DNA quantitative diagnosis technology using conjugate gold nanoparticles"
Keiko Esashika (doctoral candidate)

Excellence Award "Toy Step",
Goki Yamamoto (master's student)

Excellence Award "SC-Ring",
Takuya Suga (master's student)

Excellence Award "LABLIC",
Tatsuho Nagatomo (doctoral candidate)

(Shown below in order of presentation)
"Information Bank aggregating people's searching behaviors,"
Ryo Onodera (fourth-year undergraduate)
"A proposal for the Live SNS,"
Saishi Kurata (fourth-year undergraduate)
"Smart Contract for Credit Assignment,"
Kiichiro Toyoizumi (second-year undergraduate)

Editor's postscript

The sight of Associate Professor Yamamoto's eyes sparking as he declares that, "There are many problems I would like to solve," was just one highlight of this deeply impressive interview. Indeed, he has had a professed love of "solving problems" since a young age, A sensation similar to what is felt when having solved a problem may be the driving force behind his willingness to try things he has never experienced or to take on something new upon entering university, whether it be through competitive dance, the martial arts, or by meeting a diverse array of people. (Izumi Hagiwara)

Cover of current issue : The cover was created using the "Supernova" that Associate Professor Yamamoto is currently studying as its background.

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