My Journey in Chemical Research
—Learning from People and Things

Hiroo Inokuchi

1. Introduction

Good afternoon, my name is Hiroo Inokuchi. I feel deeply honored to have been presented with the 23rd Kyoto Prize yesterday. I specialize in the field of chemistry.

I first began my study of chemistry in April 1945, upon enrolling in the Department of Chemistry in the Faculty of Science at The University of Tokyo. For some sixty years, I have devoted all my energies to the basic science of chemistry. Now I am astonished to find myself in the unexpected position of receiving the Kyoto Prize in Advanced Technology. I am also extremely moved by this award.

For the past sixty years, as I have just said, I have been accumulating and analyzing the results of experiments conducted in collaboration with numerous other researchers of exceptional talent. Such an accumulation takes time and involves repetition: it is an entirely unglamorous task. However, our painstaking experiments eventually elucidated the electronic properties of organic semiconductors. I think that my prize recognizes the contribution this work has made in building the foundations for the “advanced technology” of organic molecular electronics.

This prize is recognition for someone who has humbly traveled the great road of scholarship—a road which does not make distinctions between chemistry, physics or any other field of endeavor—and I am sure it will provide great encouragement to all researchers committed to the basic sciences.

2. From childhood to high school

As I have already mentioned, I chose the path of chemical research only after entering university. Home life may have offered an environment conducive to studying science, but as a child I was by no means a science fanatic.

My recollection of childhood is full of memories of playing outdoors. It is
more than seventy years ago now that I lived as a child in Hiroshima City, in a newly
developed area where some swamps and ponds still remained after the subdivisions
were finished. My neighborhood was called Danbara, a name that suggests that it was
once home to terraced fields. When the weather was fine, I would play on the vacant
lots from morning till night; in summer, I would walk one or two hours to nearby
farming districts and spend my days hunting for dragonflies in the rice paddies and lotus
ponds. In those days, we had no television or video games: we entertained ourselves
with the company of our families or at play with friends.

There are two things that those childhood days taught me. The first was
learned from my parents and grandparents. What I gained from my parents did not come
in the form of overt directions: rather, I learned by watching them live. My father, who
worked as a teacher in Hiroshima, spent all his time sitting at his desk writing, except
when he would join in our family conversations. My mother was a typical Meiji-era
type, always sacrificing her own needs as she worked to bring up my two brothers and
myself. One phrase that she sometimes used as a kind of admonition was: “Never give
anyone cause to talk about you behind your back.”

In those days, children made their own fun with pastimes such as catching
fish and dragonflies. Looking back now, I see that one other thing I learned was the
value of life itself. One influence was our family’s zealous observance of the tenets of
the True Pure Land sect of Buddhism, which taught that no living thing should be killed
on any account. Although we would catch roach and goby fish in the many streams
around Hiroshima, we would always release them later or keep them in ponds. My
favorite pastime was catching dragonflies: I recall the infinite pleasure it gave me, upon
returning home in the evening, to release my day’s catch and watch the creatures soar
high into the air, heading home towards Hijiyama.

Ensuring that the dragonflies came to no physical harm was an unwritten rule
observed within our group of friends. In order to protect the creatures’ wings, we
would avoid touching them with greasy hands, and would certainly not use sticky
birdlime. When we attached them to a line in order to catch more dragonflies, we would
wind the thread around their bodies between their two front legs and their four back legs,
gently securing it in a cross over their backs. This was to make sure they didn’t suffer
any injury and would still be able to fly back home when we set them free in the
evening. It is not something I learned specifically, but the principle that “life is important, and it should never be destroyed” seems to have become ingrained of its own accord. I believe that this principle has continued to govern my life ever since.

These childhood pastimes strengthened me physically—a valuable legacy for someone with a weak constitution like mine. One other thing that I learned from my father is that it’s important never to stop learning, no matter how old you are.

3. The way to chemistry

When I was in the fifth year of elementary school, I moved with my family to Tokyo. The following period of eight years (from 1937 to 1945) was a turning point in my life, as I progressed from junior to senior high school and chose to study the science of chemistry at university. More significant, however, was my experience of the tribulations of war during this period.

In 1944, when I was in the second year of the First High School (Daiichi Kōtō Gakkō, Fig. 1), the principal, Yoshishige Abe (Fig. 2), wrote a poem of encouragement to humanities students who were being sent to the battlefield. It went: “Go forth, brave men, and bring an eternal spirit to this life which knows not of tomorrow.” This was a perfect expression of the attitude that prevailed in those days towards the end of the war. Japan was a battlefield, with air raids day in and day out. As one who survived that time, I just accepted our miserable circumstances as something natural. After the war, the same experience came to fuel my passion for the rebuilding effort.

This was an era of spiritual uplift for me, as it was for so many other young men and women of the time. It was also the time when I entered university and started pursuing the study of chemistry. Luckily, The University of Tokyo’s Department of Chemistry (Fig. 3) was spared the ravages of war. Somehow or other, classes began from September 1945, a month after the war ended. “This is it. Here I go,” I resolved, and plunged into my task of absorbing knowledge like the parched earth welcomes the rain. One thing I learned from that period was that even if physical needs are left wanting—we had no reliable supply even of basic essentials like gas, water and electricity—one can still find the resolve to go on living, provided there is a clear goal ahead. This lesson is something for which I have been very grateful throughout my life.
I am indescribably indebted to my parents’ efforts and the support of my friends in creating the conditions for me to go on with my life in the face of such utterly wretched conditions. They demonstrated the kind of human love that touches you more deeply the direr your situation is. I believe that we should really hold on to the mood of that era and use it to prepare ourselves for unforeseen events that might confront humanity in the future.

It was April 1947 that I was taken in by Professor Jitsusaburo Sameshima, who was in charge of the No. 1 Physical Chemistry Laboratory in the Department of Chemistry, the Faculty of Science at The University of Tokyo. That makes it exactly sixty years since I began my long journey in the field of chemical research. The laboratory (Fig. 4) was actually well staffed in comparison with universities today, with one professor, two associate professors and two assistants. My senior colleagues at associate professor level had recently returned from the battlefields, and were throwing themselves into the task of rebuilding their careers after the grueling war effort. I call that period the golden age of the lab in terms of human resources. I gained first-hand experience of the immeasurable influence exerted not only by my professor, but all others senior to me. Still rough-hewn and uncouth, I was nurtured both as a researcher and as a human being by so many of my senior colleagues. I am convinced that this experience made me what I am today. I truly learned from people.

My seniors taught me so much that it is difficult to select specific examples. Here, I will relate just one of a myriad of experiences. It was during a power failure on a winter’s night at the end of 1947. I was in a dim room listening to a lecture on chemistry given by Tsurutaro Nakagawa (Fig. 5), a chemist who was later to become a professor in the Department of Polymer Science, the Faculty of Science at Hokkaido University. At the time, Nakagawa had the title of junior assistant in the Faculty of Science at The University of Tokyo, and was dressed in clothing that had been modified from the uniform he had worn as a commissioned technical officer in the former Japanese navy. To those of us attending the lecture, he was a philosopher ten years our senior. The lecture he was giving was on molecules, a specialized topic in the field of chemistry. A molecule forms as a combination of atoms, which are the most fundamental building blocks of a substance. I will talk about them in more detail later.

Nakagawa’s lecture went something like this: “Look at this single thread of silk, Mr. Inokuchi. The thread is actually a bundle of many molecules. Say we could
pull one of these molecules, the essential units in the silk’s structure, out of the bundle. If we stretched the molecule between our fingers it would appear as a row of carbon and nitrogen atoms bonded together (Fig. 6). What would happen if we pulled it? The force would be dispersed throughout the row and finally the bonds would break in unison, and the molecule would split into individual atoms, wouldn’t it?” This vivid description, delivered by the philosopher-like personage of Nakagawa, left me feeling that I had encountered one of the great mysteries of substances. “I see, all substances are made up of different combinations,” I thought. Of course no such ideal molecule exists. So, the weakest portion of the molecule would break in reality. Discussions like this gradually fuelled my interest in the idea of bonding, and led me to pursue a long career in the field of chemical research founded on the guiding principle that “the essence of chemistry is bonding.”

I would like to discuss this principle more later on. Why I chose it as the guiding principle for my research is because chemistry is a discipline concerned with materials. There are 100 million different substances, so many people say that the field of chemistry is all about memory. All these substances, however, are made using only four types of bonds (Fig. 7). Thus, if we approach the study of substances from the perspective of bonding, classification becomes simple and we can gain a better overall picture of the nature of substances. This line of thinking has led me to other ideas, for example, “the essence of physics is statistics,” and “the essence of biology is time.” (Regarding the latter, it would perhaps be more accurate to say, “The essence of life is evolution.”) I now tackle many phenomena through simplifications of this kind.

Allow me to say some more about what I have learned from people. Don’t you agree that since we have entered the electronic age and begun to use computers, the time granted to direct communication between humans has diminished? This may sound like sour grapes coming from me, one who cannot keep up with the computer age himself, but I wish people would use computers more effectively to create more time to enjoy interacting with other human beings. In such interaction, there is human wisdom that can never be generated by a machine.

Once in a while I call to mind the words of Ken Sakamura: “Computers can do things that are impossible for humans-like working continuously for days on end without sleep. But no matter how hard they try, they are no match for the human
intellect.” I take this as an expression of the nature of intelligence in human beings.

Saburo Nagakura provided one other rule about computers that I cannot forget: “Scientists should make (good) use of computers. But they should not allow themselves to be used by them.” The statement is simply expressed, but it’s a weighty piece of advice.

I am sure that people of my generation will not be able to contemplate the speed and complexity with which electronic devices will evolve in the next ten or twenty years. I also believe, however, that whatever developments take place, we must never lose sight of human intelligence.

4. Learning from things

To this point, I have talked chiefly on the theme of “learning from people” through chemical research, rather than addressing the substance of that research itself. I have only used one piece of chemical terminology so far: “molecules.” Molecules are the key subjects of chemical research. To put it plainly, molecules are, in fact, just the things we see around us.

The discipline of chemistry concerns itself with the structure, properties, synthesis and analysis of substances. What are these substances? I would like to address this question because its answer leads directly to an understanding of chemistry itself. Please join me for a few minutes as we travel along the path to chemistry.

5. What are substances?

Once again I stress that chemistry is the field of academic endeavor concerned with substances. Thus it is important to understand what substances are. This is where the roots of my own research lie. All parts of the podium at which I now stand are made up of materials or substances. The lamp is a combination of substances, as is the desk, and the floor, and, of course, I myself. The units that make up these things are molecules. The properties of a substance depend on the properties of the molecules that make up the substance. Therefore, the type of substance corresponds to the kinds of molecules in it.
Let’s be a little more specific about molecules. Our education system does not divide us into different specialist fields at elementary and high school level. It is when we enter university that we split into the two fields of humanities and sciences. This is when humanities people become averse to hexagonal benzene ring structures, while those in the sciences start to dislike language. Among my contemporaries in junior high school, several who chose to study the humanities expressed a dislike for benzene rings. For those of us who study chemistry, however, the sight of a benzene ring diagram makes us feel right at home. Maybe this is what is meant by specialization.

I do hope, however, that you will bear with my benzene rings today as I attempt to explain the nature of chemistry. The benzene ring is a molecule made up of six carbon atoms linked in a uniform configuration. The lines between carbon atoms represent carbon-carbon bonds (Fig. 8). As shown in Figure 9, it is closer to the truth to say that electron clouds of the carbon atoms are overlapped to make up the molecule. With six hydrogen atoms around the perimeter to stabilize it, this molecule becomes the substance known as benzene. The diagrams (Fig. 10) used by pharmacists in advertising are simplifications of the actual molecular structure. Most molecules are made up principally of carbon, hydrogen, oxygen and nitrogen.

Thus, a molecule is made up of atoms that bond with each other. There are vastly more different molecules than there are different atoms. The number of different elements (equivalent to atoms) on the face of the earth, and in the entire universe for that matter, is 92. These come together in different combinations to create molecules. The combinations that form molecules remind me of the way in which the 48 characters of the Japanese phonetic alphabet are combined to compose a tanka poem. From long ago in the Manyo era (8th century), countless tankas have been produced by combining different characters. Just as the composition of tanka presents infinite possibilities, the variety of molecules that can be formed by combining the 92 kinds of atoms is also inestimable. This variety is made even greater by the fact that there is no limit to the number of identical atoms that can be present in a single molecule.

There is one remarkable project group that is engaged in counting all of the types of molecules made by humans. They comb through all sorts of literature on chemistry, and report up-to-the-moment figures on the number of molecules. The results of this work are illustrated in this table (Fig. 11). As you can see, there are researchers
working day in and day out to survey and register the number of molecules—that is, the number of different types of substances. Let’s look a little more closely at the actual work involved. There are around 8,000 different journals published worldwide that deal with chemical substances. There are also papers on patent applications for new synthetic substances. The project group goes through all these documents, taking care to avoid any duplication, and publishes reports on new synthetic substances. Today, on November 11, 2007, the total number reported is 92,329,363 (as of November 5).

There are two things I am trying to convey to you here: the importance of gaining an accurate grasp of the number of kinds of molecules here on earth, and the fact that there are many people working to support academic endeavor behind the scenes. Furthermore, the kind of work I have just described involves the exercise of individual human judgment. It requires the utmost vigilance, and puts considerable strain on the nerves. I think it is the same in all fields of endeavor. We cannot reach the peak without that kind of support. A volleyball match is a good example. Only a few players actually lay hands on the ball. A wider team provides support, and maintains the court by mopping it to ensure the players don’t slip. It is this kind of backup that makes a strong team. For me, there is no higher honor than to reach a position where I can engage in the “on-court” action. I always remind myself that I must repay the support of all those other individuals who have helped me reach this position.

To return to our discussion on the variety of molecules on the earth: I am not sure whether you think the number to be larger or smaller than anticipated, but the fact is that it is now approaching 100 million. From among those hundred million different types of molecules—that is, types of matter, those of us who specialize in chemistry select whichever ones we find interesting and study them. We all need some kind of policy to guide the selection process. My proposal is to apply the concept of “bonding” that I mentioned earlier. We are very fortunate that there are only four different types of bond that determine the nature of all substances. Categorization is therefore possible, regardless of whether there are 100 or 200 million different types of materials or substances. The difficult part is that these four types of chemical bonds can display many different characteristics when two or more of them are amalgamated together. Here is what this looks like in a single diagram (Fig. 12). This is derived from one that was included in the thesis I wrote while in the United Kingdom (Fig. 13). I reworked it into this diamond shape so that it should be possible to display all forms of substances.
at some point on the diagram.

This is a starting point for research: It provides a way to identify principles to guide researchers in selecting forms of matter that are of interest to them, out of the myriad choices available. In reality, choosing just one type or one group of substances out of 100 million is akin to finding a beautiful stone among the sand on a beach: an almost impossible task. Nevertheless, humans have managed to use this straightforward approach, in conjunction with another method that I am about to describe, to identify many useful substances. Human experience and lessons from nature learned over the long course of history have enabled us to sift through a near-infinite variety of materials or “things” and discover those forms that are of use in our lives. I will provide one concrete example of this. I hope it will show you how we have learned from the “things” available in nature.

6. Learning from materials (things) in nature—the story of dyes

We have learned much from nature to enrich our lives. Let me discuss this using the topic of clothing as an illustration.

Forty years ago, I visited an exhibition of the Shōsōin repository in Nara. Among the artifacts on display, I remember seeing a beautifully dyed cotton jacket called a kyoukechi fuhou—an over-garment dyed using the itajime dye-blocking technique (Fig. 14). The cotton cloth used in this garment had been dyed using natural extracts of commonly known flowers such as saffron and safflower. Why I mention this here is that when the dyes in liquid extracted from these flowers were examined using modern chemical techniques, they were found, in terms of chemical theory, to possess a molecular structure that is ideally suited for use in dyeing cotton (Fig. 15). It is my guess that the dyes were discovered by people in former times who, in the course of traversing the natural world, had found that liquid extracts from certain types of flower petals stained cotton cloth particularly well. This is a true case of humans learning from nature. In modern times, we are able to replicate the molecular structures of these natural dyes to produce synthetic dyes that are now used in great quantities.

Extending this line of inquiry to fibers, we find that cotton was used in the Nara period (8th century) along with silk—a premium item that had reached Japan via the Silk Road. Silk provides the subject for my next example. The molecular structure
of silk that forms the core of silk fiber is illustrated in Figure 16. Once this structure became known, organic synthetic chemists, who specialize in creating new substances, took up the challenge of synthesizing the silk molecule. The unrelenting efforts of the American chemist Wallace Carothers finally yielded success in producing synthetic silk in 1935, some seventy years ago. The name given to the new synthetic fiber was nylon, which is now the king of textiles. Of course, the fiber produced by silkworms is encased in proteins and other compounds that give natural silk its distinctive character. Synthetic silk-nylon is considerably more durable than its natural equivalent, and as you well know, has now become indispensable to the daily lives of us all. This is another good example of how humans have learned from naturally occurring things.

7. Learning from things—the discovery of a chemical seasoning

I will give one further example. This relates to the chemical seasoning compound Ajinomoto, a discovery that Japan can be proud of. I mention this discovery particularly because it was made in 1907 (exactly 100 years ago) at the No. 1 Physical Chemistry Laboratory in the Department of Chemistry, the Faculty of Science at The University of Tokyo—the very place where I studied. As is well known, the person responsible for the discovery was Dr. Kikunae Ikeda. Of course I have no direct knowledge of the era in which the discovery took place, but I still cannot forget the emotion I felt upon seeing with my own eyes the very first Ajinomoto compound ever produced. I always find it really inspiring to see a genuine item first-hand.

This was back in June 1951. As I have already said I was attached to the laboratory of Professor Jitsusaburo Sameshima, who was Dr. Ikeda’s successor. Professor Sameshima retired in 1951, and in April of that year Dr. Hideo Akamatu, one of my teachers, succeeded to the professorial post. I helped out with the moving process together with my fellow student, the late Hiroshi Takahashi. In the professor’s office there was a sample cabinet, much larger than anything you would see today, with wooden doors. In the middle of this cabinet there was an ill-proportioned jar, like the one you see in Figure 17. At the bottom of the jar was a brownish amber-colored sample. This was the first Ajinomoto ever produced.

The discovery of Ajinomoto resembles the other examples I have given, in
that it is a case of “learning from natural substances (things).” It differs, however, in terms of what was learnt. Ajinomoto is a case of the scientific application of human wisdom, using kombu, seaweed that has been used as a flavor source in Japan since ancient times. In a search for the origins of that flavor, Dr. Ikeda extracted the active ingredient in kombu by boiling it with water. His report states that 30 grams of the active ingredient was extracted from 38 kilograms of kombu harvested offshore from the Miura Peninsula in Kanagawa Prefecture. The extraction process took just one month. The ingredient was glutamic acid, the amino acid that is used in the monosodium glutamate compound to make Ajinomoto today (Fig. 18).

There are two things I wish to point out about the story of Ajinomoto. The first is that although it is known as the “discovery of chemical seasoning,” it was in fact much more than that. In identifying umami (“savoriness”) as part of the human sense of taste, Ikeda had discovered a physiological activity for a chemical substance—a great achievement that comes close to the true essence of science. Secondly, Ajinomoto provides an example of how basic science can be instrumental in developing practical applications. It would not have been surprising if Japanese people, who had long used kombu to make stock, immediately caught on to the idea of adding umami to food. In reality, however, it was over ten years after the discovery of the umami molecule that Ajinomoto finally became available for widespread practical use. This example reminds us that the process of developing basic research into applied research for real-life uses is one that requires effort and patience beyond imagination.

8. The discovery of penicillin: another case of learning from nature

Medicine is one field that provides many examples of how humans have discovered substances by learning from nature. The classic example is penicillin. There is no telling how many human lives have been saved by penicillin, a medicine discovered by British bacteriologist Alexander Fleming.

The discovery occurred while Fleming was studying staphylococcus, the bacteria causing conditions such as pneumonia, at a London hospital. He noticed that blue mold showed bacteriolysis against staphylococcus, inhibiting the bacteria’s activity. Seeking to identify the cause of this effect, Fleming isolated the active ingredient in the mold and named it penicillin. This was eighty years ago, in 1929. Penicillin, which was
born out of basic research activity, underwent successive improvements before coming into use in 1941 as an antibiotic. It proved to be an exceptionally effective treatment for ailments caused by staphylococcus. It was a revolutionary discovery, made possible by careful microscopic observation of the natural interaction between staphylococcus and blue mold. As I have described, scientists and pharmacists who learned of the potency of penicillin went on to complete the great work of determining the structure of its biologically active molecule, bringing great relief from suffering to the human race through the agency of antibiotics.

Allow me to relate a small anecdote from the days after the Second World War. I heard this from the great pharmacist Dr. Shoji Shibata. Upon learning the news from the West that blue mold contained a substance that was effective against staphylococcus, Dr. Shibata tried administering a liquid extract of blue mold from a mandarin orange as treatment for his grandmother’s erysipelas affliction. The grandmother enjoyed an immediate and complete recovery. Similarly, in 1946, my own grandfather suffered a suppurating wound due to a puncture with an old nail, and it progressed rapidly with catastrophic effects. A friend of mine from the United States brought a thousand units of penicillin with him. Just a few days after my grandfather was injected with the penicillin by my uncle, who was a medical practitioner, he recovered completely. I still cannot forget the marvelous effectiveness of that treatment.

9. I, too, learn from things: the quest for substances that are old but also new

I turn now to my own experience. It is one of learning from a substance that is all around us in limitless quantities: carbon.

I have already explained how I entered university in 1945—the year the war ended—and, in accordance with the system operating at universities in those days, chose my own field of specialization when I was a third-year student (or latter-stage student, as we were then known). Together with three colleagues, I was admitted to Professor Jitsusaburo Sameshima’s laboratory in the No.1 Physical Chemistry Course. As I have said, the course provided me with a way of understanding the study of chemistry—that is, an outlook on the concept of matter. My research topic at the time was “The measurement of the electrical resistance of carbons.”

In those days, students who entered the laboratory were treated as full-fledged
researchers, with each one using the knowledge they had accumulated up to that point to solve problems and pursue their own work. Therefore, I myself had no idea what carbon was or how to measure electrical resistance. I had to learn everything myself, calling on my senior colleagues to explain any areas that were unclear.

I am very fortunate that this experience revealed to me what a wonderful natural product carbon is. It is like the king of hexagonal ring structures: a collection of millions of hexagonal rings.

The greatest benzene ring structure we come across is graphite (Figs. 19 & 20). One close-to-home example of how graphite is used can be found in pencils. A pencil lead is actually made by mixing graphite and clay together well, then molding and firing it at high temperature before placing it in a wooden casing. (These days, some pencil leads are also made of carbonized polymers.) When you write on paper, the small scaly benzene ring particles in the graphite rub off on the paper and appear as black marks to form letters and images.

Allow me to sidetrack just a little to talk about human wisdom. The first person to use a pencil in Japan 400 years ago was none other than Ieyasu Tokugawa. The actual item he used is held in the Treasure Museum of the Kunouzan Toshogu Shrine in Shizuoka (Fig. 21). When I was working at the Institute for Molecular Science in Okazaki 30 years ago, I heard about this from a senior colleague at Nagoya University, and managed to get hold of a photograph of the item. Research to date suggests that the pencil consisted of a wooden casing around natural graphite from Mexico, then a Spanish colony. This was 400 years ago. It gives us a sense of the magnitude of human wisdom.

Carbon is a fascinating molecule. Its properties allow it to be used for many different purposes (Fig. 22). The reason that it has such interesting properties is because its characteristics vary depending on how many benzene rings there are. Carbon molecules with several million benzene rings make graphite, which is extremely stable in chemical terms and is therefore used in electrodes. Molecules with several hundred benzene rings make acetylene black, used for electrodes in the batteries we use every day. Molecules with tens of benzene rings make what is known as carbon black. This is used in great quantities, mixed with rubber to make tires for bicycles and automobiles. The black ink that is used so widely in Japan consists of carbon (soot) with up to a dozen or so benzene rings, hardened with glue. Dispersed in water, the carbon particles
are picked up by the writer’s brush and used to write. My first experiment was to establish a relationship between the number of benzene rings and the magnitude of electrical current that could be passed through the various forms of carbon.

Carbon has one other very interesting property. When it combines with oxygen to form an oxide, it becomes a gas. I am getting into a specialized area of chemistry here and it may be difficult to follow, but please bear with me for a moment. Many of the compounds most familiar to us are actually carbon oxides.

The carbon atom is written with the symbol C. When combined with oxygen (O), it becomes CO or CO₂. The carbon-oxygen compound CO₂ is what causes the global warming that is often talked about in the news media these days. It is a very odd fact that both CO and CO₂ are gaseous substances. This fact is an extremely important part of my research. Even if carbon is oxidized, the oxidation does not progress to the inside of the carbon material, but instead is confined to the surface area of the molecules. This is a point of difference from oxidation in most other elements: In iron, copper and almost all other metals, oxides develop rapidly right to the metal’s core.

Figure 23 shows the calligraphy of the Buddhist monk Kkai, done 1,000 years ago. This example of black-ink brushwork has retained its beauty for this long because oxidation of the carbon in which the letters were written has been confined to the surface area, and any oxides that may have been produced as a result have been discharged in gaseous form (or, to put it another way, burned off). Thus the surface is always fresh, and the core of the work does not deteriorate.

This interesting property of carbon actually forms this basis of my work on organic semiconductors. Two of the issues examined in my research are: the possibility of some electrical charge flowing through carbon with few benzene rings, despite the fact that flow becomes more difficult the fewer rings there are; and the question of why electricity flows between particles of carbon. The natural phenomenon of carbon oxidation contains an explanation for both these issues. Sixty years ago when I began my experiments, many things were still not known about carbon. When I tried packing powdered carbon (known as carbon blacks) into a tube and testing it for electrical resistance, I found that electricity could be passed through it. At first I just thought casually, “So it does conduct electricity,” in the next instant, however, I realized, “Come to think of it, that’s quite a mystery.” Why were electrons jumping from one carbon particle to the next?
By chance, I found some copper powder in the lab cabinet. Shiny and attractive, copper powder was used in many experiments as a reducing agent. As I had done for carbon, I put the copper in a tube and tested it (Fig. 24). I had expected it to conduct electric current well, but instead there was no current at all. When I thought it over, however, I realized that although they looked like pure metal, the powdered copper particles were actually covered in a fairly thick coating of oxide. With this oxide built up in tens and hundreds of thousands of layers, there was no way an electrical current could pass through. It was at this point that it occurred to me that in the case of carbon, the oxide layer would not become so thick—it would be released as a gas before it could build up. I was captivated by this marvelous natural property of carbon. It gave me the idea that in organic compounds with a small number of benzene rings—we call these polycyclic aromatic compounds—electricity should be able to pass from molecule to molecule too, because there is only one layer of displaced atoms around each ring structure.

Fortunately, quantum chemistry, which applied the principles of quantum physics to the field of chemistry, was rising to prominence just around that time. It had recently been announced that the behavior of electrons in solid carbon (graphite) could be explained in theoretical terms. Taking heart from this, I developed the following proposition: “Organic compounds, which are normally stabilized because of paired electrons, are a classic example of a nonconductor. However, electrical conduction should be possible in organic compounds that contain \( \pi \)-electrons like those in a benzene ring structure.” I went on to explore this in hundreds of experiments. Through repeated processes of purification, at which chemistry excels, I finally discovered organic semiconductors. My 60-year partnership with these semiconductors has been a long journey, but one that has brought me here today.

10. The future of chemistry

Through the long course of human history, chemistry has been used in many different ways. This is because chemistry supplies us with the materials and substances essential for all our basic needs, whether they are in the area of food, clothing or shelter. However, it is vital that we use substances efficiently if we are to ensure that all living creatures can continue to co-exist in a world of limited resources. To produce only the
types of substances needed in the quantities required—a no-waste approach—is surely something all of us who study chemistry aspire to. I believe that some day we will be able to ascertain the functions and properties of substances simply by referring to their structures (what chemists call the molecular structures). Although it may take many years, the time will also come when we can engage in molecular design, identifying a substance with a specific molecular structure that can cure a specific disease. I believe this is the ultimate goal for chemists and an important objective if we are to create a world without waste.

11. Establishing a materials cycle

A natural equilibrium is maintained on our planet through the cycling of matter in nature. In their desire for an ever-higher standard of living and greater instrumentality, humans generate superfluous substances and materials. A typical example is recycling. Although known as recycling, at the end of the day we are actually producing waste matter. This is where wastage occurs. Avoiding it will require us to learn from nature and establish an approach wherein these materials become part of a cycling process. This will be extremely difficult, but I believe that we researchers should work towards making it a reality.
昭和18年の一高（The First High School, 1943）

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貧困の化学実験室
(Laboratory in Pathetic State, shortly after the end of the world war)

中川鶴太郎先輩と私
(With My Senior, Torutaro Nakagawa)

絹の分子の骨格とその変形
(Molecular Structure and Deformation of Silk)
四つの結合 (Chemical Bonding)

共有結合 (Covalent Bond)

金属結合 (Metallic Bond)

イオン結合 (Ionic Bond)

分子間結合 (Molecular Bond)

ベンゼンの構造 (Molecular Structure of Benzene)

ベンゼンの電子雲 (Electron Cloud of Benzene)

アスピリン (Aspirin)

1965以降の合成物質数の増加 (Increase of Number of Synthetic Substance after 1965)

すべての物質はこの枠の中にある (All materials are in this frame consisted of 4 kinds of chemical bonds.)

結合 (Chemical Bond)
The Border-Line Compounds

Fig. 13

Fig. 14

染料の構造 (Molecular Structures of Dyestuffs)

Fig. 15

絹とナイロン (Molecular Structures of Silk and Nylon)

Fig. 16

グルタミン酸ナトリウム
(Monosodium Glutamate)

Fig. 17

Fig. 18
黒鉛（ベンゼン環の数が100万個以上）
Scheme of Basal Plane of Graphite

黒鉛の構造（層の先端）
(Scheme of Basal Plane of Graphite, End of Plane)

徳川家康が使った鉛筆
Antique Pencil used by Shogun, Tokuou Tokugawa

炭素の利用 (Application of Carbon)

<table>
<thead>
<tr>
<th>ベンゼン環の数</th>
<th>名称</th>
<th>用途</th>
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<tbody>
<tr>
<td>100万個以上</td>
<td>黒鉛</td>
<td>電極, 鉛筆芯</td>
</tr>
<tr>
<td>100個以上</td>
<td>アセチレンブラック</td>
<td>乾電池の電極</td>
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<tr>
<td>〜数十個</td>
<td>カーボンブラック</td>
<td>タイヤのフィラー</td>
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<td>〜数個</td>
<td>炭</td>
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空海の書
Penmanship of 'Kunkai'

グラファイト粉末と銅粉の電気抵抗測定
(Measurements of electric resistance of Graphite and Cu powders)