Chapter 2 Value That Basic Research Delivers to Society

This chapter introduces examples of basic research projects where researchers' novel ideas and new discoveries defying conventional understanding created new markets, and the progress in the entire research area expanded the scope of the application and thus delivered great value to society.

As discussed in Chapter 1, Section 1, basic research is an activity of pioneering the frontier of knowledge. Due to its nature, basic research generally takes a longer time before we see a tangible result, and it is often difficult to immediately understand what the obtained result is useful for. However, truth, basic principles, and new knowledge elucidated and created as a result of such research efforts have the potential to break the limits of existing technologies and create innovative products and services that have never existed before.

The researchers that we will look at in the examples in this chapter dared to take on difficult paths because of their pure intellectual curiosity and clear vision to make the world better. As a result, they created new scientific value that had never existed before. In many cases, such new value had great economic and social impact and eventually brought the researchers prestigious awards both in Japan and overseas, including the Nobel Prize. At the same time, it is important to note that none of such glorious achievements were possible without the presence of positive competition among researchers that had produced a number of previous and similar studies. Thus, it goes without saying that support for diverse basic research projects is essential.

1 Realization of Blue LED that Opened the Era of LED

LEDs[1] used for lighting, traffic lights, and backlights for liquid crystal displays have an excellent energy-saving effect (they only consume about one-eighth of the energy of ordinary light bulbs) and a long life (about 40 times longer than ordinary light bulbs).[2] It is said that "the 21st century will be lit by LED lamps,"[3] and the global LED market is estimated to expand to approximately 2 trillion yen in 2025.[4] As red and yellow-green LEDs had been developed in the 1960s, it was said that LEDs could be applied to displays, if high-efficiency blue LEDs were developed and the three primary colors of light became available. AKASAKI Isamu, AMANO Hiroshi, and NAKAMURA Shuji brought a high-efficiency blue LED—the only primary color of light that had been missing—into reality using gallium nitride (GaN), which many researchers had thought impossible. The three researchers received the Nobel Prize in Physics in 2014 for this achievement.

Light decoration using approx. 300,000 blue LEDs
Source: Towada City (Arts Towada Winter Illumination)

Although GaN is highly stable and has some advantages for practical use, it had been difficult to obtain

1 Light Emitting Diode
2 Japan Lighting Manufacturers Association (JLMA) (https://jlma.or.jp/akari/led/tokuchou.html)
3 The Nobel Foundation, Press Release on October 7, 2014.
4 Fuji Chimera Research Institute, Inc., 2018 Survey on the LED/LD Market.

a high-quality GaN crystal. For this reason, many researchers were aiming to develop blue LEDs using other materials. Meanwhile, Akasaki chose GaN, considering it as the indispensable material to develop a blue LED, and conducted research with a view to contributing to Japanese industry. Amano joined Akasaki's laboratory, and succeeded in producing a high-quality GaN crystal and developing a blue LED using it for the first time in the world. Looking back on the days where he devoted himself to experimenting every day but New Year's Day, which also involved more than 1,500 failures in one and a half years, Amano says, "I was so immersed in experiment because it was such fun to think of ideas to make a crystal."[1] Meanwhile, Nakamura, who had been conducting research at Nichia Corporation, imposed a strict rule on himself that he "must develop and commercialize a blue LED using a completely unique method that no competitors could come up with." Modifying purchased crystal production equipment by himself extensively, he continued to experiment day after day. Nakamura eventually succeeded in developing and commercializing a high-efficiency blue LED that was 100 times brighter than ones using silicon carbide (SiC), which were already available commercially at the time. He made this possible by using a structure where InGaN crystals (made by adding indium to GaN) are sandwiched between AlGaN crystals (made by adding aluminum to GaN) and GaN itself.


Solar lanterns used at a tutoring school in Myanmar
Source: Panasonic Corporation

Thus, a high-efficiency blue LED was realized thanks to the constant efforts of these three researchers, which opened up the doors to the development of a white LED. It was Nichia Corporation that realized this faster than anyone, using a completely new method of combining a blue LED and a yellow phosphor, which emits a complementary color of blue. Since a high-intensity white LED can produce sufficient brightness for a long time period even with solar cells, the Nobel Foundation stated, "The LED lamp holds great promise for increasing the quality of life for over 1.5 billion people around the world who lack access to electricity grids." LEDs are used not only as lighting in our day-to-day lives, but also as a light source for endoscopes and lighting for plant factories. Furthermore, the application of GaN is spreading to next-generation devices for high-speed communication and power control, due to its excellent physical properties.

1 JST News, July 2011

2 Eradicating Parasitic Infections with a Substance Produced by Bacteria in Soil[1]

Parasitic infections affect many people, especially in developing countries, causing death and serious sequelae. The UN has set a goal of "ensuring healthy lives and promoting well-being for all at all ages" as one of the SDGs, with a view to treating and eradicating communicable diseases by 2030. OMURA Satoshi, who won the Nobel Prize in Physiology or Medicine in 2015, discovered in his research the compound Avermectin, which became the basis of a silver-bullet drug for parasitic infections that had plagued hundreds of millions of people in Africa and Latin America.

Omura welcomed by children saved from river blindness
Source: OMURA Satoshi, Distinguished Emeritus Professor at Kitasato University

"I always carry a plastic bag in my wallet." Omura's research style is epitomized in these words he gave at a press conference immediately after he received the Nobel Prize. In search of an unknown useful natural organic compound, he patiently and continuously collected soil from various places, cultivated microorganisms in the soil, and analyzed substances they produced. He was determined to never mock someone else's work, and went on with his research with an unwavering faith that he would someday succeed in achieving results that would serve people no matter how many times he failed. He eventually discovered more than 500 new compounds, 26 of which were put into use in human and animal pharmaceuticals and reagents for research. Avermectin, which Omura discovered in 1979 was extracted from microorganisms that lived in the soil collected from near a golf course in Ito City, Shizuoka Prefecture.

Ivermectin was developed from Avermectin by a U.S. pharmaceutical company that Omura collaborated with. It had a miraculous effect on various parasites found in cattle, dogs and humans. Thanks to this medicine, lymphatic filariasis,[2] which had been prevalent in Africa and Latin America, is expected to be eradicated in 2020 and river blindness[3] in 2025. The Karolinska Institute, the awarding body for the Nobel Prize in Physiology or Medicine, also praised the discovery of Ivermectin, stating, "(Its) consequences in terms of improved human health and reduced suffering are immeasurable."

1 Written based on BABA Rensei, *Omura Satoshi Monogatari: Nobel-Sho eno Ayumi* (Story of OMURA Satoshi: Journey to the Nobel Prize), Chuokoron-Shinsha, 2015.
2 Lymphatic filariasis is caused by nematodes transmitted from mosquitoes. It cases chronic swelling and leaves lifelong sequelae.
3 River blindness is an infectious disease caused by nematodes transmitted from black flies. It causes inflammation in the retina, resulting in decreased visual acuity or in the worst case, blindness.

3 Development of the World's Strongest Permanent Magnet Using Abundant Iron

Neodymium magnet (left) and ordinary magnet (right)
Source: NIMS

Currently, the strongest permanent magnet in the world[1] is a neodymium magnet made of neodymium, iron, and boron. Its global production exceeded 60,000 tons in 2018 and is expected to further grow to near 100,000 tons in 2025.[2] Neodymium magnets were developed in 1982 individually by Sumitomo Special Metals Co., Ltd. (currently Hitachi Metals, Ltd.) and General Motors (U.S.). It was SAGAWA Masato who invented a neodymium magnet and its mass production method at Sumitomo Special Metal Co., Ltd.

Sagawa's initial research objective was to improve the performance of samarium-cobalt magnets, which were the world's strongest magnets at the time. At the same time, he wondered why a strong permanent magnet could not be made with iron, which existed in abundance, and started research on iron-based magnets on his own. At that time, it was believed that permanent magnets could not be made without cobalt. However, by mixing a small amount of boron with neodymium and iron, Sagawa succeeded in developing a revolutionary material that outperformed samarium-cobalt magnets. Such an unconventional and unique idea would have never been come up with if Sagawa had been an expert of magnets. He became so passionate about the development of this magnet that he even quit the company he was working for at the time, and he eventually succeeded in commercializing neodymium magnets at Sumitomo Special Metal Co., Ltd. More than 35 years since its invention, neodymium magnets still remain as the strongest permanent magnets in the world.

Neodymium magnets are used in motors, contributing to power saving in electric vehicles and higher efficiency in wind power generation facilities. They are also used in drivers for magnetic heads in hard disks to increase HDD capacity. However, in recent years, problems with neodymium magnets have also become apparent, such as the uneven distribution of neodymium resources and the difficulty of securing rare elements necessary for improving the heat resistance of neodymium magnets. Creative and flexible ideas like Sagawa's are awaited to develop new materials that can solve these problems.

4 Rechargeable Lithium-Ion Battery That Contributed to the Spread of Portable Devices

Small-sized, large-capacity batteries are indispensable for the spread of portable devices such as mobile phones, laptop computers, tablets and digital cameras. However, there had been an issue that a sufficient voltage could not be obtained with a battery that uses an aqueous electrolyte, such as a nickel-cadmium or a lead storage battery. YOSHINO Akira, a researcher at Asahi Kasei Corporation, worked on this issue starting from the basic research phase, and led the team to the development of a rechargeable lithium-ion

1 A permanent magnet is a magnet that continues to generate a stable magnetic field for a long time without an inducing magnetic field or current.
2 Fuji Keizai, Co., Ltd., 2018 Survey on the Small-Size and Precision Motor Market.

battery (hereinafter referred to as "lithium-ion battery").

Yoshino says he had already predicted the rise of portable and wireless devices in the early 1980s, and was confident that he would see a new era where people carry electronic devices to everywhere in the future. Non-rechargeable batteries using metallic lithium had already been used at the time, but it was technically difficult to make a battery that allows for repeated charge and discharge using the same reaction principle. To solve this issue, Yoshino devised a completely new mechanism that allowed for stable charge and discharge by having lithium ions move between the positive and negative electrodes without causing a chemical reaction. He also used a new material for the positive electrode. He noticed that this material—which was not attracting much attention at the time as it was considered not suitable for metallic lithium batteries—was an ideal material for the mechanism he had devised.[1] Although it took 15 years from development to commercialization, lithium-ion batteries greatly contributed to the realization of the ICT society and the rise of the IoT society. The results of his basic research efforts changed our society in a magnificent way.

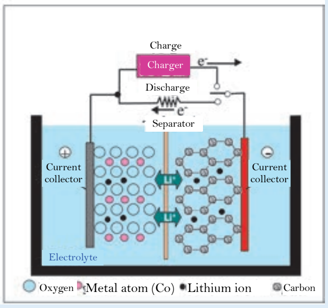
Figure 1-2-1/ Mechanism of a lithium-ion battery

Battery reaction equation

Positive electrode | Negative electrode

$$LiCoO_2 + C \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Li_{1-x}CoO_2 + Li_xC$$

Working principle of battery



Source: Asahi Kasei Corporation

The market for lithium-ion batteries is expected to grow rapidly from approximately 3 trillion yen in 2017 to approximately 7 trillion yen in 2022,[2] with the growth in demand for automotive batteries for electric vehicles. However, Chinese companies have greatly expanded their share not only in the final product market but also in the component market, such as electrodes and separators. Meanwhile, Japan is vigorously promoting research and development of all-solid-state batteries (batteries using solid, not liquid, electrolytes), the next-generation batteries with better capacity, output, and safety. Their commercialization is expected to come in the near future.

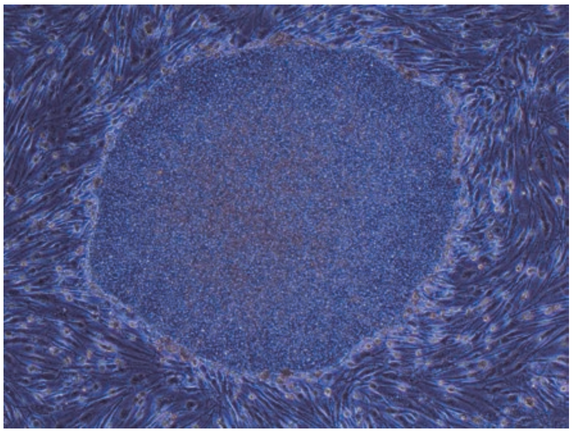
5 Possibility of Realizing New Regenerative Medicine by Somatic Cell Reprogramming (iPS cells)

Pluripotent stem cells, which have the ability to change into various types of cells, play an important role in the realization of regenerative medicine for all kinds of organs and tissues. However, the method using ES[3] cells derived from fertilized eggs comes with a bioethical problem of destroying embryos in the preparation stage, and also a risk of transplant rejection by the recipient's immune system. To tackle these issues, YAMANAKA Shinya developed a method to produce iPS[4] cells by reprogramming the patient's own somatic cells, paving the road to realizing regenerative medicine using pluripotent stem cells.

Yamanaka initially started his career as an orthopedic surgeon, but later on decided to help patients

1 The Japan Society for Analytical Chemistry, Bunseki, October 2013.
2 Fuji Keizai, Co., Ltd., 2018 Survey on the Battery Market No. 2.
3 Embryonic Stem
4 induced Pluripotent Stem

through basic research after encountering patients who could not be cured with medicine available at the time. In 1998, the world's first human ES cell was created, opening up the doors to regenerative medicine using pluripotent stem cells. At the same time, however, ethical issues surrounding it also became apparent. To solve such issues, Yamanaka set out a goal to produce pluripotent stem cells like ES cells by reprogramming skin cells, and devoted himself to the research. In 2006, he publicized his research finding that mouse skin cells could be initialized by introducing only four genes. This was an epoch-making discovery that defied the common understanding of life science at that time. As many people know, Yamanaka won the Nobel Prize in Physiology or Medicine in 2012 for this achievement.

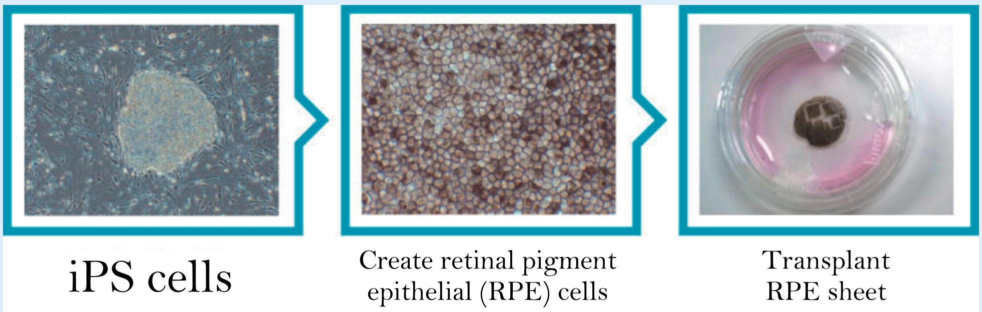


Human iPS cell colonies (aggregates) established from fibroblasts
Source: CiRA

Since the announcement of the establishment of human iPS cells in 2007, Japan has been making national efforts to support the research project as well as to formulate standards surrounding this technology, such as safety guidelines and ethical rules, with a view to its clinical application that was to come. In 2014, Japan conducted the world's first clinical research of transplantation of retinal cells prepared from iPS cells. In addition to the transplantation of iPS cell-derived brain neurons in 2018, clinical studies targeting various organs and tissues, such as the heart, spinal cord, platelets, and cornea, are also planned. Moreover, pathological studies and drug development research using patient-derived iPS cells are also being conducted.

Regenerative medicine using iPS cells still has many issues that need to be solved, including safety, cost, and public understanding towards them. However, the realization of regenerative medicine has great social and economic value. It is hoped that research results in this area will be applied in the real world as soon as possible.

■Figure 1-2-2/Preparation of transplant retinal pigment epithelial cells using iPS cells

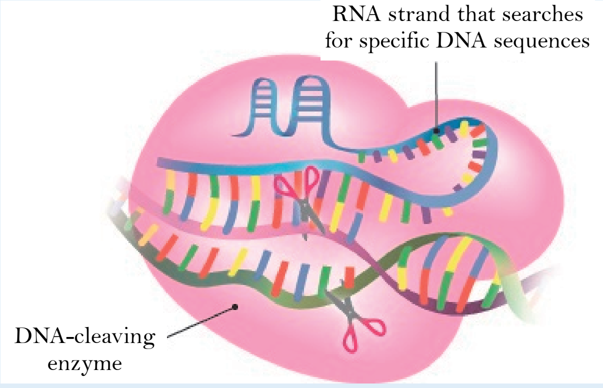


Source: Riken

6 New Tool That Enables Precise Editing of Genome Information

Artificial modification of genomes, which store all the genetic information of living organisms, is an important technique used in various fields, including basic research, medicine, industry, and agriculture. For example, genetic modification for the purpose of animal and plant breeding had already been performed using radiation or chemicals, but with these methods genome modification occurred only randomly and thus it required enormous effort and cost to develop target varieties. The genome editing technique developed in the 1990s made it possible to cut DNA at a desired location and efficiently modify part of DNA sequences.[1] In particular, the genome editing tool called the CRISPR[2]/Cas9[3] system invented by Jennifer Doudna and Emmanuelle Charpentier in 2012 was much more cost-effective and practical than conventional methods. This led to a rapid expansion of the use of genome editing. Japan has also promoted the practical application of this technology, such as developing tomatoes containing a large amount of the functional ingredient GABA,[4] and ultra-high-yielding rice.

■Figure 1-2-3/Structure of CRISPR/Cas9



Source: JST

CRISPR/Cas9 originally functions as an intracellular immune system of prokaryotic organisms, such as Escherichia coli, that selectively cleave foreign DNA, such as viruses. CRISPR is a genomic region with special base sequences, discovered by ISHINO Yoshizumi at Osaka University in 1987 in his research on Escherichia coli. Although it is now known that CRISPR is found in the genomes of many prokaryotes, the function of CRISPR could not be predicted or elucidated at the time of its discovery. It took 25 years of continuous basic research by overseas researchers to clarify the mechanism by which the CRISPR region and the enzyme called Cas cleave DNA, and to establish it as a genome editing tool.

Rice with sink capacity modified for ultra high yield
Source: NARO

It is worthy of note that such a useful technique was found in the process of exploring one of the vital functions of microorganisms. This is a good example to show the nature of basic research, where the understanding of fundamental principles can lead to unexpected applications even in research that does not seem useful at first glance. Ishino also said, "No one could imagine that CRISPR could be used for genome editing when it was first discovered. The elucidation of the function of CRISPR is a wonderful achievement itself, but I truly admire other researchers' efforts to

1 Deoxyribonucleic Acid
2 Clustered Regularly Interspaced Short Palindromic Repeats
3 CRISPR associated proteins 9
4 Gamma Amino Butyric Acid

apply it to develop new genome editing technologies."[1] Genome editing has many problems, such as safety and bioethical issues when applied to gene therapy and medical purposes, as well as impact on the ecosystem when used for animal and plant breeding, and social acceptability. However, it is a versatile technology with a wide range of possible applications. It is hoped that research and development will be promoted and value will be returned to society, based on an understanding formed through full-fledged dialogues between researchers and society.

7 Discovery of Superconductivity and Its Application in Medical and Transportation Fields

Superconductivity is a phenomenon where the electrical resistance abruptly drops to zero when a material is cooled down to below its unique critical temperature. The history of superconductivity is old; it was 1911 when the Dutch physicist Onnes discovered superconductivity. However, it was not until 1957, more than 40 years after the discovery, that the theory to explain the phenomenon was established. The next breakthrough came about 30 years later, in 1986, when a copper oxide superconductor was discovered. This was a groundbreaking discovery in that it was the first non-metallic superconductor and also in that its critical temperature was far higher (90K (about -180 °C)) than the estimated limit theoretically predicted at that time. This achievement opened up the whole new world of research on high-temperature superconductivity. In 2008, HOSONO Hideo of the Tokyo Institute of Technology observed the high-temperature superconductivity phenomenon using a new element other than metal and copper oxide materials, i.e. an iron-based material, which had been thought unsuitable for superconductivity.

Medical MRI
Source: Kofu National Hospital

Applications of superconductivity that we can see in our lives include MRI[2] and the Chuo Shinkansen (maglev line), which is scheduled to open in 2027. MRI is a technique for obtaining an arbitrary cross-sectional image of a body by applying a strong and uniform magnetic field. In this technique, superconducting magnets are used to generate a magnetic field. The Chuo Shinkansen is propelled and levitated by interaction between superconducting magnets mounted on the train body and electromagnets installed on both side walls of the guideway. In addition, superconductivity plays an important role in nuclear fusion, which is said to be future energy,

Superconducting maglev train running on the Yamanashi test line
Source: Central Japan Railway Company

1 JSBBA, Kagaku to Seibutsu, Vol.56 of 2018, No.4.
2 Magnetic Resonance Imaging

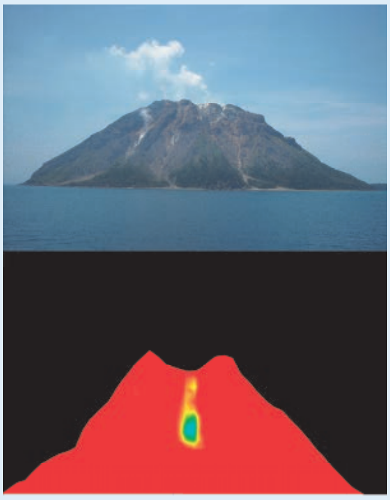
and in quantum computers, future computers.

Superconductivity took more than 50 years from discovery to application. Even today, after more than 100 years have passed, its entire picture has not been revealed yet and basic research is being continued. However, research outcomes in this area have brought great value to today's society and they have the potential to dramatically change our lives also in the future. This is what makes basic research valuable. It is important to continue long-term research efforts, rather than solely focusing on the presence or absence of short-term results.

8 Particle Physics for Exploring the Origin of the Universe and Its Applications in Day-to-Day Settings

Elementary particles are the smallest unit of components of a substance. Electrons and photons are kinds of elementary particles. The existence of elementary particles gradually became clear after many theoretical predictions and experimental observations. In this process, many researchers received the Nobel Prize. It is considered that the universe immediately after its birth was filled with elementary particles. Therefore, particle physics that explores the laws of motion of elementary particles can elucidate the origin of the universe.

■Figure 1-2-4/Internal imaging of a volcano on Satsuma Iōjima



Source: Earthquake Research Institute, University of Tokyo

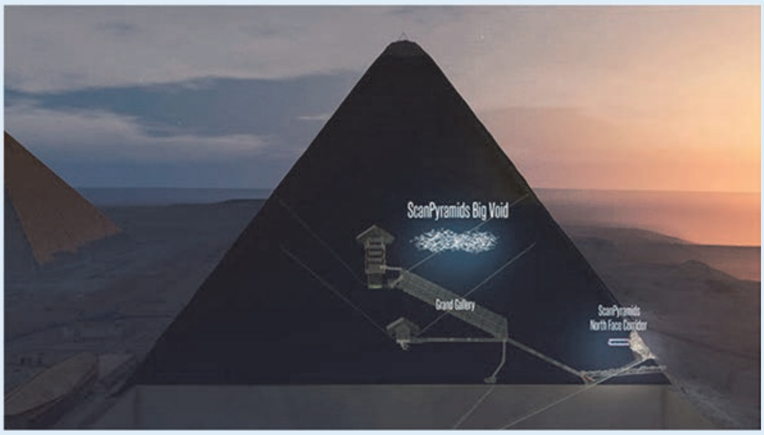
In recent years, we are starting to see applications of the law of motion of elementary particles in real settings. For example, a technique has been developed that allows us to see through the inside of various structures by observing muons, which are elementary particles that are constantly generated by cosmic rays and fall from the space, using a special photographic film that shows their tracks as they pass through it. By this method, Nagoya University discovered an unknown huge space in the center of King Khufu's pyramid, while the University of Tokyo is conducting research aimed at preventing disasters and accidents by seeing through and observing the inside of volcanoes and underground faults. In addition, the phenomenon where collisions of electrons and positrons[1] (both of which are elementary particles) emit gamma rays (photons, a kind of elementary particles) has been applied in PET[2] screening for cancers.

KAJITA Takaaki, who won the Nobel Prize in Physics in 2015, said in an interview immediately after the award that the study of elementary particles "may not be useful immediately but expands the horizon of human knowledge." Particle physics is a basic research area that still stores many mysteries. However, as the laws of motion of elementary particles became increasingly clear and as researchers became able to control and observe the particles at will, it has become possible to see things that had not been possible to observe or detect before. These achievements were made possible only by continuous basic research to elucidate basic principles. This is a good example to show that basic research is valuable not only in that it pioneers intellectual

1 An elementary particle that has a positive charge, opposite to that of an electron, and has the same mass and spin as an electron.
2 Positron Emission Tomography

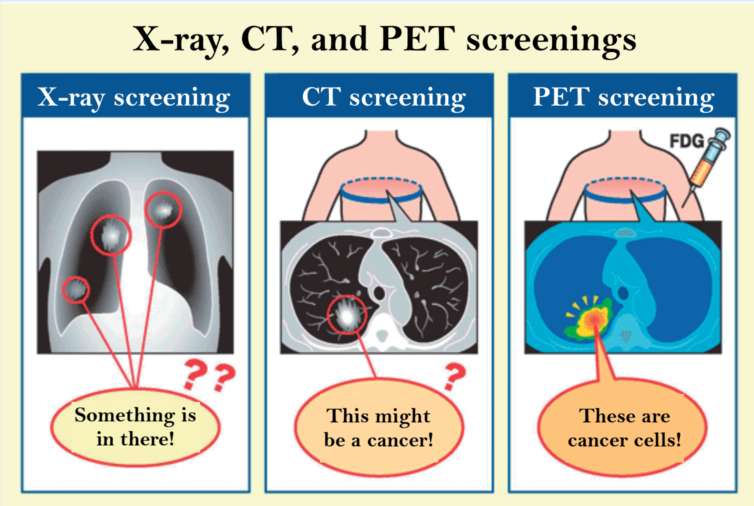
frontiers, but also in that it can deliver tangible value to our day-to-day lives.

Figure 1-2-5/Image of the observed internal structure of King Khufu's pyramid



Source: Nagoya University (ScanPyramids)

Figure 1-2-6/Comparison of X-ray, CT, and PET screenings



Source: National Center for Global Health and Medicine