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"Creative Thinking in Science"
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(Woranda Lecture)

Lists of Participants
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KYOTO

JAPAN

Creative Thinking in Science

by Hideki Yukawa

(to be delivered on August 14th, 1967, in Montreal, Canada, on the occasion of the World Exposition)

1. ~~Creative Thinking in Contemporary Physics~~ Man and His Science

"Man and His World" is a theme, which has immensely many diverse aspects. Nobody can take up the theme in all its aspects. In this one lecture which I was asked to deliver, I ~~am going to~~ confine myself to "Man and His Science." Even this is too broad ~~a theme~~ to be dealt with in a limited time. I shall further narrow the subject later on, but, for a while, let us dwell on the ~~significance of~~ role played by science in shaping the world as environment of man.

What we call our environment today is not simply the part of Nature which happens to ~~be~~ surround man. Man built houses, manufactured clothing, created machines. ~~Man is~~ Science and technology intervened between man and Nature. Today man is in the midst of the man-made articles, ~~and~~ mixed up with Nature in its original form untouched by man. Man call the former "artificial" and the latter "natural" respectively, but we should not forget that they are not really distinct from each other. On the contrary, they are essentially the same ~~the~~ for the following two reasons: Firstly, the material is the same. — The raw material of any man-made article was there already in Nature before man appeared and touched it. Secondly, the same laws of Nature prevails on

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all things, ~~whether~~ irrespective of whether they are "natural" or "artificial". One may well say "Man created science", but one must not make mistake. Man could not create science from nothing. What man could do in creating science was to discover something hidden in Nature. The two most important things which man discovered in Nature were the raw material in its most fundamental sense and the universal laws of Nature.

Now the question arises: "How ~~could~~ can man ever discover them?" We know that there are answers to this question by the scientists themselves. Perhaps, the most well-known answer is that of Galileo Galilei who is one of the great initiators of modern science. He said that experience and reason are the two pillars, on which science is built. This is very true, but how can experience and reason work together in achieving new discoveries in science? Each one of us is accumulating experiences day by day. We are making efforts to think according to reason as much as we can, at least, when we are engaged in scientific investigation. However, it is only on a very rare occasion for a scientist to discover something of importance. Galilei taught us that the mere acceptance of stimulei, ~~from our~~ which come from the environment, and which result in the accumulation of memory in the brain, is insufficient for our purpose. He taught us by his own achievement that the experiments purposely designed are of vital importance in uncovering the truth hidden in Nature. He asked questions addressed to Nature and succeeded in receiving answers directly from Nature. In doing so, he needed rather simple devices. Today the physicists are carrying out experiments with the same spirit as Galilei's, but one ~~sh~~ cannot and should not ~~look over~~ overlook the immense change in the way of doing important experiments, which occurred during these twenty years or so. Let us take the example of big ~~accelerators~~ accelerators which are the devices to accelerate particles such as protons or electrons up to the speed very close to the velocity of light — three hundred thousand kilometers per second. These protons and electrons together with the neutrons are the common ~~constituent~~ constituents of ordinary matter. They are collectively called the elementary particles. In a sense, they are the *only* constituents of matter, being the raw ~~matt~~ material in its most fundamental sense. In another sense, however, this is an overstatement for the following reason: First of all, matter and energy are no longer entities which are completely separated from each other, but matter can change into energy and vice versa. According to Einstein's theory of relativity, matter is to be regarded as a form of energy. Furthermore, according to Planck's quantum theory, light, which is a form of energy, ~~cons~~ consists of small units of energy, or energy quanta. ~~Th~~ These energy ~~quantum~~ quanta behave ~~lig~~ like very small corpuscles, so that they are called photons today. Thus the photons are to be included in the family of elementary particles, but even ~~this~~ they are not the last members of the family. There are many other forms of energy, which are distinct from ordinary matter ~~and light or~~ as well as from light or electromagnetic energy in general. Accordingly, physicists have come to think of the possible existence of such particles as neutrinos and mesons, and confirmed it by experiments. Here we see a very interesting new feature of experiments concerned with elementary particles. Typical example is the case of mesons. They are discovered experimentally because they were created ~~natu~~ somehow, either naturally or artificially. Mesons are nowhere in ordinary matter. They are created naturally in cosmic rays, but they decay eventually into electrons and neutrinos. In order to create mesons artificially, it was necessary to construct an accelerators about ten times larger than the one which was the largest before the War. This was the start of almost endless race of constructing larger and larger accelerators in these twenty years after the War. The race is still going on. What was the fruit of this very expensive race? One may well say the fruit was rich enough. Physicists created and discovered a great variety of new elementary particles, ~~most~~ ~~to~~ of them being unexpected. I already told you that physicists cannot create something from nothing. They ~~discovered~~ could create ~~an~~ new particles by making use of accelerators, because there was the reason on the part of Nature to change the more familiar form of energy into a form which was new to man. ~~What we physicists do not know yet~~ So one may again say ~~"Science dis~~ "man discovered new things hidden in Nature". What we physicists do not know yet is the ~~reason~~ very reason why Nature responds ~~to~~ in such a complicated and unexpected ~~way~~ (manner) of giving rise to a great variety of new particles to man's questioning by way of experiments. We physicists today have to think very hard in order to find out the reason, which amount to the same thing as the reasonable and unified description of all kinds of elementary particles.

Perhaps I have been dwelling a little to long on the present state of affairs in fundamental physics. I dwelt on it because it is relevant to the theme of my talk, ~~creative~~ but I stop here and must begin to deal with the subject which may be of interest not only to physicists, but also to those who are not concerned specifically with ~~present day~~ p the frontier of physics.

2. Analogical Thinking

Now, the subject is the way of thinking in science, which can be creative in the sense that it results in the discovery of truth in Nature hitherto unknown to man. We have been taught that there are two methods of thinking in science. The one is the method of induction which was advocated by Francis Bacon and effectively used by Galileo Galilei. It start with the comparison of more or less similar experiences or results of experiments. The other is the method of deduction which was employed by René Descartes consciously in guiding his own mental activities. It start with a few self-evident facts or principles. However, it is not at all easy to see where is the seed in each of these two methods, ~~to~~ which enables man's thinking really

creative, although we ~~know very well~~ are very well aquainted with these methods.
I have been interested in this problem for many years, because I had been frustrated so very often ~~after~~ in my work in theoretical physics. I came upon ~~a~~ fruitful new ideas only very rarely during my nearly forty years career. ~~More than twenty~~ It was more than twenty years ago that I asked a senior colleague of mine, who was professor of psychology of our university in Kyoto, an answer to ~~this~~ the problem just mentioned. He suggested the importance of analogical thinking. This ~~was~~ was not at all new to me, because I was well aware of it already at that time. As a matter of fact, ~~all~~ the articles and books dealing with the ~~creative think~~ problem of creative thinking, so far as I know, always begin with the importance of analogy. This is very true. If we look back history, we meet with a number of great thinkers or philosophers who appeared more than two thousand years ago in ~~to~~ such regions ~~of~~ on the earth as Greece, Israel, India and China. They taught people by making ample use of analogy or metaphor. ~~They used it not only for persuading others, but~~ It seems to me that they also for finding out truth hitherto unknown to themselves as well as to others. The essence of analogy as a form of creative thinking is the following: Suppose that there is something which a person cannot understand. He happens to notice the similarity of this something to ~~somethin~~ some other thing which he understands quite well. By

comparing them, he may come to understand the thing which he could not understand up to that instant. If his understanding turns out to be appropriate and nobody else has ever come to such an understanding, he can claim that his thinking was really creative.

In the course of development of natural philosophy, which grew up to modern physics, we can find many examples showing the effectiveness of analogical thinking. When Leucippus and Democritus conceived of the atoms for the first time in history, they must have imagined them as something ~~like~~ similar to visible body such as billiard balls, although they are too small to be seen by naked eyes. Newton in the seventeenth century seems to have believed in the existence of atoms as conceived by ancient Greeks judging from the queries at the end of his "Opticks", but, at the same time, he seems to have refrained from constructing his theory of motion ~~on the b~~ explicitly on the basis of atomistic concept because he thought the latter to be too hypothetical. In the nineteenth century, a number of great scientists such as ~~John~~ Dalton and Boltzmann took advantage of the similarity between the (presupposed) invisible atom and the solid body which is familiar to man.

~~In the At the~~ In the early years of the twentieth century, the structure of the individual atom itself has become the matter of concern and ~~the~~ different atom models were proposed by physicists such as J. J. Thomson and Nagaoka. Now, the way of thinking ~~by ma~~ which makes great use of models is rather common in physics and chemistry, but this is just a typical example of analogical thinking. When Rutherford ~~found out~~ proposed a ~~more appropriate~~ ~~well~~ better-founded atom model than others, he again made use of the analogy with the solar system. However, it turned out that his answer to the problem of structure of atom was not the final one. At this stage, an essentially new feature was added to the analogical thinking. That is the recognition of dissimilarity which lies side by side with the similarity. An atom with its nucleus at the center and a number of electrons moving around the nucleus cannot ~~be~~ simply be a miniature of the solar system, ~~because~~ because the electrons loose their energy by emitting light incessantly until the whole atom collapses in a comparatively short time. Thus, in contrast to the solar system, Rutherford's atom cannot be stable at all, unless it is endowed with some new property alien to ordinary material body of human scale. I just mentioned that an atom cannot be stable because of the incessant emission of light which was understood as a kind of electromagnetic wave without any doubt until the end of the nineteenth century. The revolution in physics started with Planck's ~~quantum~~ theory of energy quantum of light as I ~~also~~ mentioned earlier. So the physicists ~~have~~ had ~~been~~ been puzzled ~~by~~ already by the strange property of light. It was Niels Bohr who succeeded in accounting for the stability of atom by applying quantum theory to electrons in it. All this is ~~very well known~~ so well known that it is waste of time to talk ~~more about~~ any more. I took it up as a good

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Thus I wanted to point out that analogical thinking becomes all the more fruitful, when dissimilarity as well as similarity between two things is clearly recognized. In this connection, I beg to be allowed to say a few words about my own experience. When I tried to understand nuclear forces more than thirty years ago, I came across the idea of taking full advantage of the analogy with the electromagnetic force. However, I was also well aware of the dissimilarity between nuclear forces and the electromagnetic force. Consequently, the theory to which I reached had been destined to have some resemblance to quantum theory of electromagnetic field, but to be distinct from it in many respects.

Talking in this way, I have been always conscious of the point of vital importance which remains untouched. That is "How can a person ever find out such a kind of similarity between things that enables analogical thinking creative and fruitful?" In order to answer this question, we have to take a further step.

3. Pattern Recognition

Now, when we notice that one thing is similar to another, we admit that they are the same in some sense. For instance, to some of the physicists in the nineteenth century like Boltzmann, an atom was the same with solid elastic body except for the immense difference in size. In this case, ~~the~~ an atom was identified with an extremely small solid body. It seems to me that the process of identification is not only the starting point of analogical thinking, but also ~~the fundamental~~ ~~is~~ prevails in all ~~sorts~~ kinds of mental activities, so that the analysis of this process may well lead us to the understanding of the secret of creative thinking.

Now let us go back to very simple, but nevertheless very fundamental form of identification. That is ~~the pattern~~ what we call the pattern recognition. Man acquires the ability of recognizing such simple patterns as squares, circles and triangles, at a certain age. Such an ~~ability is prere~~ acquirement is prerequisite for the understanding of ~~Euc~~ Euclidean geometry. It is often too much emphasized that Euclidean geometry ~~which~~ we learn in school is a system of statements which are linked with each other through the procedures of formal or deductive logic. But, if we remind how we could understand ~~it~~ geometry at all, we are easily convinced ~~that~~ of the following situation: It was not the understanding of formal logic itself, but the preaquired power of pattern recognition that enabled us to ~~follow~~ comprehend what teacher taught us at the very beginning. For instance, the congruence of two triangles under certain conditions was evident to us, not because of logical necessity, but because we could imagine the movement of one triangles so as to overlap it completely with the other ~~triangle~~ triangle. The comprehension of formal logic as such comes afterwards.

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I would like to point out that man acquires an amazing ability of pattern recognition without being taught in school, whereas man has to learn formal logic in school. I would like to repeat that we came to comprehend formal logic because we had been acquiring beforehand unconsciously the ability of pattern recognition in childhood, as exemplified in the case of learning Euclidean geometry. In this connection, there is a very interesting experiment recently done by psychologists. A blind man by birth had an operation, so that he could see things for the first time. The psychologists tried to follow his line of vision carefully, when he was looking at a triangle in a dark room. At the beginning, the line of vision makes a random motion, but, after repeated practice, it moves more closely along the periphery of the triangle. This practice end up the very faithful motion of the line of vision along the periphery. This means that the identification between the given pattern and the locus of the line of vision has become complete and definite. Thus the man acquired the capacity of pattern recognition, at least, for such simple patterns as a triangle. We who are endowed with eyesight by birth must have also acquired the capacity of pattern recognition in a similar way in our childhood, although we do not remember it. However, the same psychologists tell us about the result of experiment which is even more striking and interesting.

They tried to follow the line of vision of an ordinary adult. The motion of his line of vision is very much simplified compared with the new operated blind man. It totters along one side of the triangle and, when it comes to the corner, the motion is ended. In this simplified way, he can recognize the triangle. How is it possible at all? The information which the man ~~obtained~~ obtains by moving his line of vision is twofold. ~~The~~ One is the sharp and clear perception of ~~the~~ a small part of object ~~which happens to~~ to which the line of vision is directed. The other is more obscure, ~~perception of~~ but wide angled perception of the larger part of object surrounding the small part, on which the line of vision is focussed. These two kinds of information work together so as to abridge the process of pattern recognition to a ~~to a great deal~~ great extent. In this way, the process of identification, in general, and the process of pattern recognition, in particular, ~~are~~ ~~so~~ going on their road of evolution, while man is growing up, unnoticed by himself.

~~The more we think of the power of man's~~ man's power of pattern recognition, the more we are amazed. Just take the case of recognition of somebody with whom one is well acquainted. One can instantaneously recognize his acquaintance even in the big crowd. This is certainly a kind of process of identification, in ~~which~~ the sense that the present perception of the figure of a man is identified with the image of him in the memory. Evidently, these two are not exactly the same, but are different from each

4. The Evolution of the Process of Identification

other in various respects. The man may be wearing summer suit, whereas he appeared more often in the past wearing thicker cloth. He may ~~have become~~ look older than he was last time. All this does not disturb the identification. He is essentially the same man as the one in the memory. This we do not doubt, but what is essential for identifying two things which are not the exactly same, if we go into details?

Here comes the problem of intuition versus abstraction, about which I discussed to some extent on the occasion of the first Athens Meeting in 1964. ~~The~~ Two points I emphasized at that time was the following: ~~There is a~~ Firstly, Man's ability of abstraction was crucial for the creation of an exact science like physics. The appearance of the type of genius as Pythagoras, who could grasp natural laws in terms of simple and definite relations between numbers, and Democritus, who conceived of the invisibly small atoms and the abstract concept of void, was essential for the initiation in ancient Greece, and not in any other land, of natural philosophy, which developed into modern science as we see today. The second point was the importance of man's power of intuition. As a matter of fact, the abstraction cannot work by itself in its very nature. One must abstract something from something else which is more concrete and richer in content. In other words, man has to begin with intuition or imagination, and then can proceed ~~but he~~ by the help of his power of abstraction.

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If we look at the present state of affairs in contemporary science, particularly, in fundamental physics, ~~the~~ we notice that there are two mutually related tendencies: One is the ever growing tendency of building larger and larger machines like accelerators in order to carry out <u>creative</u> experiments as I mentioned earlier. The other is the overwhelming tendency of making use of the highly advanced and very abstract mathematics among ~~the~~ theoretical physicists working in the field of elementary particles.

We physicists are all very well aware of the inevitability of these trends. Nevertheless I am not very happy with them. The main objective of natural science like physics is the recognition of Nature which can be deepened and widened by continuing efforts of scientists. Ever increasingly more scientists have been cooperating in this great undertaking of man, ~~but~~ yet the recognition of Nature ~~is~~ stays to be the matter belonging to ~~the individual scientist.~~ each of scientists as individuals. It is true that the physical objects and physical laws being dealt with in physics today can best be expressed in terms of very abstract mathematics. The question remains, however, as to whether we have to be satisfied with these very abstract things or we may ask for something more. This is not an easy question. There can be ~~different~~ answers ~~by~~ differing from each other, depending on the scientists who try to answer. A physicist belonging to the younger generation is apt to care only for the agreement or disagreements between the experimental results obtained by big machines and the conclusions obtained by very abstract mathematical reasoning and nothing more. This is understandable. Actually, theoretical physics has been pursuing for more and more abstract formalism, since the advent of quantum theory and theory of relativity. Thereby, intuitive pictures cherished by nineteenth century physicists have become outmoded one after another. Yet my answer is different from the one justed mentioned in the following two respects; Firstly, as I pointed out already, abstraction can not work alone. There is always an interplay of intuition and abstraction in any fruitful scientific thinking. Not only something essential is to be abstracted from our rich, but somewhat obscure intuitive picture, but it is also true that the concept which was constructed as the ~~result~~ fruit of man's ~~abstraction~~ ability of abstraction ~~becomes~~ changes very often, in course of time, a part of our intuitive picture. From this newly constructed ~~init~~ intuition, one can go on his way of abstraction further. If I take an example from modern physics, the four-dimensional space-time world of Einstein's theory of relativity was very abstract compared with the space and time of Newtonian dynamics, but it is a part of intuitive picture of physicists today, which serves for the ground ~~of~~ to operate further abstraction. Secondly, we must not forget that the abstract mathematical formalism is always an end product of the scientific ~~thing, in which~~ thinking, in which intuition plays a rôle more important than is noticed usually.

In order to elucidate this last point more clearly, Let us go back again to ~~the~~ man's ability of pattern recognition, which is a typical form of intuition. Perhaps, it ~~is~~ would be most useful to compare man and the man-made high speed electronic computor with respect to the capacity of pattern recognition. Certainly, one can construct a computor which can recoginize simple geometrical patterns. It can identify alphabet and Arabic figures, if they are printed exactly according to prescribed rules, but can ~~not~~ not identify letters written by man casually. Man's ability of pattern recognition is far more ~~so~~ flexible. It is not necessary for man to draw geometrical figures precisely with ruler and compass in order to prove a certain theorem of Euclidean geometry. Man's ability of pattern recognition evolved to the stage of ~~the~~ constructing a general concept of the triangle, for instance, without referring any one triangle actually drawn precisely. This is the result of cooperation of intuition and abstraction.

I already told you that the process of identification underlies what we call the recognition of something. Thus the development in man's intelligence can be looked upon as a kind of evolution of the process of identification. The most naive form of identification can be seen, when a child is identifying his toy automobile, for instance. ~~H~~ His present perception of the toy automobile is identified with the memory of the toy which he acquired an instant ago. The identification process ~~of the chil~~ goes on incessantly in such a way that the child

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think the toy moving here and there. The most highly evolved form of the process of identification can be seen in the discovery of laws of Nature by great scientists. There is a famous legend that Newton came ~~to think of~~ across the notion of universal gravitation when he chanced to see an apple falling. It is said that he asked himself why an apple falls to the ground, while the moon does not. I do not know how much truth there is in this story, but it can be regarded as a typical example of analogical thinking. However, Newton's creativity is shown ~~at the~~ at a level higher than mere analogy. What he discovered was the law of Nature prevailing not only on the earth, but also everywhere in the solar system. If there is some truth in ~~the~~ the legend, it is the conception by Newton of something essentially the same ~~to the~~ in the motions of an apple and ~~of~~ the moon. What was to be identified, however, turned out to be rather abstract and general in nature. What was to be discovered was not the identity of matter ~~substances~~ which constitutes the moon with matter on the earth, but was the identity of laws which govern the motion of the moon with those which govern the motion of a body on the earth. Thus, ~~to be discov~~ he succeeded in finding out the universal laws of motion together with the universal law of gravitation. In short, he ~~identified not the two~~ did not identify one thing with another, but identified the relation between things in one case with the relation between things in

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another case. As I mentioned earlier, Newton seems to have been concerned ~~not~~ also with the identity of things, which lead him to believe in atomism. But, perhaps, he thought it too premature to deal with atoms ~~in any~~ systematically.

Now, we physicists know a great deal about the ~~universal laws~~ laws of motion of invisibly small atoms or electrons, which turned out to be quite different from the laws of motion of visible things which had be discovered by Newton. We know now the identity of fundament constituents of matter and energy. ~~Two electr~~ Any two electrons, for instance, are identical to each other, there being no mark whatsoever to discriminate one from the other. If we further ask why they are completely the same, ~~we may~~ the answer may be that they are created ~~by the same laws of~~ according to the same laws of Nature. In this sense, the laws of Nature play the role of molds for creating various kinds of particles, one particle of a certain kind being identical to ~~one~~ any other of the same kind. In contradistinction to the case of Newton, there is no longer clear distinction between the identification of laws of motion of different things and the identification of fundamental constituents of matter and energy. The process of identification must evolve to the stage, on which unified description of elementary particles of all kind is achieved, in the sense that both the reason of their

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existence and the reason of their specific behavior are explained by the same laws. This is ~~what is expected~~ the great expectation of physics today and to ~~fullfil~~ realize the expectation the creative thinking of physicists is needed today ~~the~~ as much as in the past.