by Kenneth J. Hsu

A reform in earth science education after a revolution in earth science

Tarim Associates AG, Frohburgstrasse 96, 8006 Zurich, Switzerland

A reform in earth science is urgent. There should be an insight into the philosophy of science, and a realization of the impracticality of instituting rigid "requirements" to "prepare" for a student's career. Methodological courses should be minimized and the duration of study should be greatly shortened, to be complemented by continuing education. Theoretical geology should be taught, and the theoretical knowledge be applied to resource- and environmental engineering.

A physicist friend asked me recently of the significance of the earth-science revolution of the 1960s:

"Was it the plate-tectonic theory?"

"No, that is only a theory of mountain-building. The revolution is a change in the way of our thinking. We no longer indulge in descriptions of things. We start to analyze natural phenomena in terms of physical and/or chemical processes."

"So you are no longer stamp-collectors," he smiled. "You are now scientists."

He was referring to the arrogant remarks early in this century by the famous physicist Lord Rutherford: There is science which is physics, and there is stamp-collecting.

Science or stamp-collecting?

In the Middle Age of Europe, scholarship consists of deductions from axioms, which were considered self-evident truths. The axioms of the earth sciences were the first chapter of the Bible: *Genesis*. That was not science, but scholasticism. Francis Bacon effected an intellectual revolution in the 16th century when he emphasized the inductive approach: observations, of nature or experimental, have become the foundation of science. Geology replaced *Genesis*, when Hutton, Lyell, and others made observations and found simple and obvious answers. Basalts come out of volcanoes, they are igneous. Sedimentary layers are laid down one on top of another, this is the Law of Superposition. Identical fossils are found in the same bed, William Smith discovered the principle of paleontological correlation.

Inductive reasoning give *ad hoc* answers when specialists investigate isolated phenomena. Simple and obvious answers are often intuitive. Francis Bacon, for example, concluded that metal has a higher thermal conductivity than ceramics, after he observed that a cup of hot tea cooled down more slowly in a porcelain cup. It is self-evident truth, or tautology, because thermal conductivity is so defined. When geologists collect observations and come up with intuitive conclusions, their intuitions are often correct. However, when one searches for the more fundamental principle underlying apparently unrelated phenomena, the answers may be surprisingly counter-intuitive.

The Baconian philosophy of relying on observations did not give us modern science. People since the Stone Age have noticed that Sun rises in the east, and goes down in the west. The observa-

tions have been repeated again and again, at different times and different places. The obvious conclusion was that the Sun goes around the Earth. The theory could predict, without erring, the future timing and position of the sunrises, sunsets, solstices, eclipses, etc. People can make observations, random or systematic, until the doomsday and they will still arrive at the same conclusion intuitively. Observations alone, especially a single set of observations, will not provide the criteria of discriminating truth from falsehood.

Copernicus recognized the scientific logic when he exhumed a classic Greek theory that the Earth goes around the Sun. The observational data of his time were consistent with either the geocentric or the heliocentric theory. The Ptolemaic model was preferred, because it conformed to our intuition of a flat earth, and because the theory postulates circular orbit of the Sun's movement around the Earth. The Copernicus theory has to assume elliptical planetary orbits. Astronomers of his time thought that circles are more perfect than ellipses, and that celestial motions, being the perfection dictated by God, must have been circular and not elliptical. As it now turns out, the Medieval intuition is wrong: what seems intuitively more probable has proven to be bad science.

It should be pointed out that the Baconian philosophy of relying on observations was very productive when people had made few observations. But there are now all too many different natural phenomena to be observed, and one cannot observe them all. In science, we only need to learn the few fundamental principles and understand their implications. In stamp-collecting, however, even the Queen of England cannot have all the stamps issued by all the countries at all times, with all editions printed in various shades of colors on all kinds of paper, with all varieties of printing errors, etc., etc. Stamp-collectors have to specialize. The over-indulgence in data-collecting since the time of Francis Bacon has bred generations after generations of "stamp-collectors" in science.

Francis Bacon or his stamp collectors did not give us modern science; Isaac Newton did. Newton succeeded because he was not a stamp-collector, and he did not have to be a specialist. He took the problem of celestial motions out of the special realm of astronomy. He invented the concept of gravity, and invoked the fundamental principle to explain all cosmic phenomena: planets orbiting around the Sun, streams flowing downhill, and apples falling onto his head. He made a scientific revolution because of his interdisciplinary approach.

The secret of Newton's success escaped all but a few historians of science. We learned in school that Newton had his inspiration when an apple hit him on the head. The anecdote is a poor lesson in scientific methodology. Newton invented gravity, not because he wanted an *ad hoc* explanation why an apple fell. He had to assume gravity to explain the elliptical orbits of planets.

Yes, observations are important, but observations are not necessarily self-explanatory. We have also to think, to use a deductive and analytical approach to understand our observations. Tycho Brahe spent a lifetime making astronomical observations, and Johannes Kepler spent another processing the data. The breakthrough was, however, made by Isaac Newton when he searched for a physical explanation. The scientists of the 20th century led us to another direction. We were encouraged to make observations: that is where most of the research funding is going nowadays. We were

encouraged to process data, and we built ever bigger computers. But we are discouraged, by the positivism philosophy of science, from seeking physical explanations.

Mach's view has been the establishment philosophy: no statement is admissible in natural science unless it is empirically verifiable. The statement has actually no meaning because the phrase "empirically verifiable" does not have a precise significance. Is the Newtonian concept of gravity "empirically verifiable"? Mach apparently thought so. Karl Popper thought otherwise: no scientific statements can be proven, they are only falsifiable or proven wrong.

Rescuing Mach's positivism, scientists seek refuge in operationalism. Scientific statements may or may not be verifiable by our senses, but they are verifiable by mathematical relations. The ultimate arrogance was exemplified by a recent treatise on the physics of time, stating:

The mistake of pre-relativity physics was to identify time too closely with human experience. Relativity physics has shifted the moving present out of the superstructure of the universe, into the minds of human beings, where it belongs...In the absence of an acceptable theory of the mind in physics, any discussion of physical time must necessarily exclude the consideration of now, and the apparent forward of time, because these are meaningless concepts within the context of ordinary space-time.

Nobody can experience the physical reality of "ordinary space-time." So we are now taught to abandon our senses, including the sense to see or to make observations, and to blindly follow the incomprehensible operations of mathematical physics.

On the other end of the spectrum, phenomenological specialists are taking over in stamp-collecting. When I traveled in China, I was described as an "American specialist"; specialist and scientist have become synonyms. Of course, intuitive answers from simple sets of observations in Bacon's time were often correct. Four hundred years after Bacon, we have all too many observations. Scientists can no longer be "bothered" by observations outside of their field of specialization. Few physicists learn any geology, and few geologists consider the theory of relativity or quantum mechanics relevant to their professional activities. Data collected by specialists are interpreted intuitively within the framework of dogmas, without examining deductively the consequences of those intuitive conclusions. Pre-occupied with their observations, they have little time to seek physical explanations. Stamp-collecting science has thus been creeping back to the scholasticism of making deductions from axioms, except we now have a new set of axioms, or dogmas. This kind of stamp-collecting makes bad science, and it is done all too often in geology.

Knowledge and logic

When I was a graduate student, George Gaylord Simpson was our hero, and we read his *Tempo and Mode in Evolution*. He asked a theological question as to the meaning of evolution? What has evolution brought us and where are we going? He placed his faith in the acquisition of knowledge: God has created living organisms, and the species *Homo sapiens* evolved. The evolution of the civilizations is not biological but intellectual, consisting of an accumulation of knowledge. This is the ultimate goal of the human evolution, Simpson concluded.

What is knowledge? What I am writing now is knowledge. There are two components in the acquisition of this knowledge. Theappings of the keys are to provide information, and the information is then processed by the computer with its built-in softwares to produce a printout as the final product. Of course, theappings of the keys were not random: their sequencing is a product of another software which is the thinking process.

Observations are a form of knowledge processed by a software that is human intellect. Optical signals are the input to a human brain, and they give the knowledge that we are looking at, for example, a green meadow after the signals are processed. The observation is then called a "fact" to be stored and eventually processed together

with other "facts" to come up with a conclusion—the "printout": be it a guess, a speculation, a theory, or an uttering of truth. The "printout" in the form of a manuscript can then be sent to an editor.

Nowadays a manuscript has a great chance of being published if it contains a great deal of "facts". Guesses are permitted, but speculations are frowned upon, while a new theory based upon the processing of all relevant information through the application of a new "software",—a new theory, or a new way of analyzing a scientific problem—has little chance of being accepted. Gathering of "facts" are good stamp-collecting. Coming up with a new theory is speculation, an old-fashioned way of doing science. Editors of philately journals have no use for science.

Even when the field is flooded by observations which seem to make no sense, theoreticians who find meaning in the observations of other people's work cannot find a place in geology. Morley's manuscript on seafloor-spreading was not accepted, because he formulated a theory on the basis of "facts" collected by others; his speculation was not considered original research because he did not have a "stamp-collection" of his own. Vine and Matthews's theory had been formulated on the same set of "facts" which inspired Morley, but they had an opportunity to gather a similar set of "facts" at a different place to support the theory. Their manuscript was accepted, because they did the original research when they had collected a similar set of "stamps." Using the prevalent criteria, Isaac Newton might suffer Morley's fate if he tried to publish today his *Principia*. The referees of the manuscript would tell the editors that Newton did not make any original contribution: The astronomical observations were Tycho Brahe's, the data were processed by Kepler, and the author only offered a "speculation," which is not "empirically verifiable;" he only "speculated" on the existence of some entity called gravity without having actually observed it.

Thanks to Vine and Matthews and their seafloor-spreading theory and its verification by the JOIDES Deep-Sea Drilling Project, there has been "earth-science revolution." Textbooks of last decades introduce our knowledge of the earth with a presentation of the plate-tectonic theory. There is seafloor-spreading, there is plate-collision, there is mountain building, there is weathering and erosion, there is sedimentation, diagenesis, and, in some cases, deformation, metamorphism and magmatism, and the cycles repeat themselves. Students learn what they are taught, like children read their Bible in Sunday-schools. They had to specialize, to "collect the stamps" of their specialization. Petrologists study hard rocks. Sedimentary geologists study soft rocks. Paleontologists collect fossils. Geochronologists date rocks. They exhibit their collections in scientific journals, like stamp-collectors theirs in regional, national, or international exhibitions. Their "softwares" were written only to process optical signals into "facts", and the "facts" are processed according to the axioms, the dogmas, or the "softwares" available on the market. They acquire a tremendous wealth of knowledge, stored in monographs like stamps in albums, much of it is however irrelevant, irrelevant to our understanding of the dynamics of the Earth. They have no time to think.

I can illustrate the problem with a recent experience when I attended a PhD oral defense in an American university. The candidate made a study of a sedimentary breccia of peculiar origin. He found considerable evidence relating the genesis of the breccia to meteorite-impact, and concluded the breccia a tsunami deposit.

"Have you ever seen a tsunami deposit?"

"No, I have not."

"Have you ever read a description of a sediment deposited after a tsunami event?"

"No, I have not."

"How did you then come to the conclusion that the breccia was a tsunami deposit?"

"I read some articles describing the tsunami deposits formed after the K/T impact."

"How did those authors know that they were tsunami deposits formed by the water motions of tsunamis?"

"They reached their conclusion because there should have been tsunamis after the K/T meteorite-impact."

"Could there be other impact-related deposits?"

"I don't know."

Eventually his thesis adviser took me and another experienced geologist to the candidate's field area. We came to the conclusion that the breccia was not formed by tsunami, but a deposit of soft-sediment gravity-sliding, having slid downslope from the rim toward the center of an impact crater.

The morale of the story is that students have been taught to come up with *ad hoc* answers: his one-track mind was preoccupied with the question whether certain geological evidence is or is not consistent with the postulate of a current paradigm. After the answer was affirmative, he did not process his data with a "software" program of his own, and he reached a conclusion without going through the procedures of scientific logic, inductive or deductive. This instance is not exceptional. The lack of analytical thinking is the norm of our profession.

This experience among many others has prompted me to discuss with my colleagues on the need of reform in earth-science education. We do not need more stamp collectors. We need to have an educational policy to train scientists who can think, and who can do a good job in their profession.

Relevance of education

Swiss people like to tell stories about mentally retarded. My favorite is one who searches for the key at Basel City's market square. The story goes like this:

Toward midnight, a policeman saw a mentally retarded person walking back and forth on the market square. After some half an hour, the policeman asked the person what was he doing there. He lost his keys, it was replied. So the policeman joined in the search. It was all in vain after another half an hour. Becoming impatient, the policeman asked him again:

"Could you remember where you might have lost your key?"

"Oh, yes, I lost the key in the dark alley out there; I heard it when the keys fell on the ground."

"Why don't search down there then?"

"No, I cannot," replied the mentally retarded. "There is street lamp and I can see here, and it is dark down yonder."

We are training our students to be mentally retarded. Students are trained to perform some routine skill, to take examinations. When they become professional geologists, they do what they have been taught or what they have learned. The consequence has been, in numerous instances, catastrophic!

Take for instance the case when a geologist was asked by an electricity company if it is safe to drill a tunnel through a Triassic carbonate sequence. He was never taught to answer this question, because he only learned to do field geology and to write geological report. After six months, he turned in his report with beautiful maps and cross-sections, showing that the tunnel was to drill across Triassic formations in a syncline. He did not bother himself with the question if a tunnel penetrating an aquiclude into a syncline of aquifer-beds could cause a flooding of the tunnel. When the tunnel was eventually drilled, the flooding did take place, and three workers were drowned. The "mentally retarded" geologist excused himself because he was never taught that such a thing would happen.

A more fateful stupidity was the Vaiont tragedy. An engineering-geology team was hired to study the creep of a Middle Jurassic limestone down a dip-slope toward a reservoir lake. They made measurements and could predict that the limestone block was to be detached and to fall into the reservoir lake. The big event should happen tomorrow, but they did not think it necessary to alarm anyone. Their prediction was correct, the block fell into the lake the next day. The water spilled out of the reservoir-lake, crashed down a narrow gorge and drowned all the five thousand inhabitants of a village at the mouth of the gorge. The stupid geologists behaved like the mentally retarded: they thought that their job was to write a monograph to describe the creep of the slope, not to worry about the conse-

quences of the eventual breakaway. Their boss should have known better, and he committed suicide to atone for his negligence.

The world of liberty and freedom was, however, saved because of the stupidity of some Japanese geologists. My teacher Prof. Huang Jiqing told me that the Japanese explored for four decades in northeast China. They studied the Cretaceous sediments around the Songliao Basin, and they found the Daqing anticline. The sediments are non-marine, and the paleontologists could write several monographs on ostracod stratigraphy. Thinking that the center of the basin should be underlain by the same alluvial and shallow lacustrine sediments, they concluded that there should be no oil in Songliao; there seemed to be no source beds. The Chinese, Prof. Huang said, were more flexible. They went to Songliao in 1959, drilled 9 wildcat-wells and made six discoveries. If the Japanese had discovered Daqing oil occurrences, they would not have needed to invade southeast Asia for oil, and there would not have been a Pearl Harbour. Instead, the Japanese army would have marched across the Urals to join forces with Nazi Germany. The outcome of the WW II might have been different, and we might now be living under totalitarian regimes of Nazi Germany and militant Japan. Some mentally retarded geologists may have saved the free-world.

Are we more intelligent today? Probably not! American experts are telling the Chinese that there are no source beds under the Tarim Basin, because they did not find any organic-rich sediments on the periphery of the basin, and the Chinese believe the Americans. Are they now making the same mistake as the Japanese geologists did in the 1930s when they ignored the inevitability of sediment-facies change?

Why did so many of students of science become stamp-collectors instead of scientists? Why did some of them act like the mentally retarded? It is not their fault, the fault lies with our educational system. To theorize that water from aquifer-beds in a syncline may flood a tunnel drilled through an aquiclude would be speculation on some event that may happen in the future, geology is a history of the past. To predict that a big fallen mass displacing an equal volume of water in a reservoir lake would crash down a narrow gorge to drown 5000 persons would be speculation on some event that may happen in the future, geology is a history of the past. To theorize that the center of a big basin is underlain by deep-water deposit where only shallow-water sediments are found outcropping is speculation, and a good geologist does not speculate. Geology students are taught to be stamp-collectors, to collect data and to stick with the "facts". There is theoretical physics, theoretical chemistry, and theoretical biology, but theoretical geology is not taught anywhere.

Futility of preparation

I used to work for industry before I was a university professor. When I worked for an oil company, we were always reminded that our employment depended upon our usefulness. When I was a teacher, my "products" were students, and I was conscious of their employment by the society. Most of my students perform services for institutions, firms, or they are self-employed.

What do we teach our students?

I taught at the Swiss Federal Institute of Technology for 30 years, and taught since my retirement in 1994 in four institutions on three continents. The courses of instruction are everywhere about the same. There are science requirements in mathematics, physics, chemistry, and, in some universities, also biology. There are earth-science requirements such as geology, mineralogy, petrology, sedimentology, structural geology, geophysics, geochemistry, and, in a few universities, also paleontology. There are electives such as isotope-geology, Quaternary geology, advanced petrology, advanced geochemistry, advanced structural geology, regional tectonics, engineering geology, petroleum geology, seismology, paleomagnetism, geochronology, etc., etc.

I have attended many faculty meetings on curriculum-reform. Everyone emphasized the importance of "his subject". There are

always new requirements to be added, and seldom old requirements to be deleted. Students receive a more and more overburdened program, and the pet-solution is to prolong, *de facto* if not *de jure*, the duration of studies. The curriculum and the requirements for a PhD study were determined by special-interest groups who are blinded by arrogance to think that they know what is best for the students.

One of the greatest Swiss geologists, Albert Heim, finished his studies in 3 years and became professor when he was 23 years of age. Louis Agassiz was even more of a prodigy; he became professor at Neuchâtel and president of Swiss Society of Natural Sciences in his early 20s, when he shocked the world with his theory of Ice Age. That was the 19th century. Nowadays Swiss students have to struggle at least 4 years to get their Bs and 5 years in graduate school for their PhDs. A study by the U.S. National Academy of Sciences indicated an even more extreme development in North America: a PhD student takes nowadays from a minimum average of 8 years in chemistry and a maximum of 14 years in social sciences after the graduate student has received his bachelor of science degree! This is outrageous. Few except the British, are younger than 30 years of age, when they leave university.

I have always irritated my colleagues with the questions: *Are all those courses of instruction necessary? Are all those years of graduate research necessary?*

One often-heard argument is the need to *prepare* our students for their career. They have to have physics. They have to have physical chemistry. They have to have linear algebra. They have to distinguish quartz from calcite. They have to know the difference between granite and basalt. They have to know how rocks are dated radiometrically. They have to ... The arguments are endless, when we debate on what are necessary, and what are not. The key word is to *prepare*. How do we *prepare*? Is the present practice to stuff the students with course work the right *preparation*? My answer to the last question is emphatically negative.

I was a "hard-rock" student. I learned a great deal of crystallography, mineralogy, petrology, and chemistry, and I spent four years of doctoral study looking down a microscope tube. I was being prepared to be a professor of metamorphic petrology. After I completed my education, I could not find a job as a petrologist. I had to work with "soft rocks." Eventually, I have been variously labeled a sedimentologist, an isotope geochemist, an oceanographer, a micropaleontologist, or a Quaternary-geologist, even though I had never taken a course in sedimentology, or in isotope-geochemistry, or in oceanography, or in micropaleontology, or in Quaternary geology. I was an expert petrographer, but during the last three decades I did not even have a microscope in my place of work, and I hardly ever looked down a "tube". I was prepared for a profession which I could not practise, I was not very well prepared for my future career.

I do not think that my case-history is in extreme. But how many of us are prepared for our career? How many of us can be? How many of us should be?

I was a young man in the audience listening during the 1950s to an address by the president of the Du Pont Company. He told us that the products of the company were constantly changing; less than 5% of 10-year products were still marketable. With the rapid development of science and technology, how could we hope to prepare anyone for a lifetime career. One reason why I did not look much down the "tube" in the last years is that I have found new methods which are better-suited for my purposes. I needed the four years until I was sufficiently proficient to use a microscope to determine every mineral in the book, to estimate the solid-solution component, and, in some cases, even the trace-element composition of a mineral. Nowadays we do not have to have a microscope for those chores. We have X-ray machines, flame photometers, emission-spectrographs, electron-microscopes with EDAX adapter, etc., etc. Furthermore, a modern petrographer does not even have to look down a "tube" anymore. He looks at a screen, and his computer-printouts give him the needed information.

I was prepared for a lifetime career as a petrology professor. If I had become a petrology professor as I was trained for, I might have met the same fate as a geochemistry colleague at ETH Zurich who

was no longer allowed to teach geochemistry. His tragedy was that he was prepared to teach students to make silicate-analysis from rock melts, at a time when geochemistry consisted mainly of Niggli-values. Young geochemistry professors do new and fancy things, which incidentally might also be longer fashionable in one or two decades.

There is no possibility to prepare for a lifetime's career, and there is no alternative to continuing education. There is no need to spend 8 or 10 or 15 best years of your life to learn something which will become largely irrelevant 10 or 15 years from now. When we can prepare for a career activity only for the next 10 years, we have to shorten the years of preparation in schools and universities. Perhaps a student ought to go to university for 3 or 4 years only, but are required to come back to university every year or two for short courses in continuing education. Swiss army, one of the more conservative organizations of the world, has a surprisingly modern educational policy: Instead of two or three years of military service, the Swiss recruits spend 15 weeks in the boot-camp, but they come back every year for 3 weeks of continuing education.

I did propose, before my retirement, that the years of study by a student should be shortened. My colleagues were vehement in their opposition. "Three years are just not long enough to program even a minimum of required courses in the curriculum" they insisted. Now I should point out that the word *required* is the key word. What course should really be *required*? And for whom are those courses *required*?

When I was an undergraduate being prepared for a lifetime career in the Chinese geological survey, our *required* courses in geology included one year of geomorphology, of mineralogy, of petrology, of invertebrate paleontology, of mining geology, and of field geology, two years of historical geology, of optical mineralogy, and of structural geology, and one-half year of blow-pipe analysis. How much did the requirement prepare me for the career of a sedimentologist-isotope geochemist-oceanographer-micropaleontologist-Quaternary geologist? The requirement was much too much and the preparation was much too little.

How much good did the four years of looking-down-the-tube in graduate school do for my career? It did some good, I am sure. On the other hand, did I need the four years?

The fundamental fallacy of the present educational policy is that we have to *prepare* ourselves for a lifetime career by taking all those *required* courses. I venture to propose that we do not need more required course in geology than an one- or two-year course on theoretical earth-science. Am I being radical? Is the idea practicable?

Uselessness of requirements

The idea is practicable if you take a different perspective of our learning processes. Many of us have come to the realization that our intellectual activities,—arts, literature, or science, are expressed by languages which take the form of music, paintings, drama, written words, or physics, chemistry, biology, geology, etc. Sciences are languages, and interdisciplinary studies are a search for a common language. What is *required* when we study a language?

My sister studied English Literature, and she graduated in 3 years after she became a major. She was not *required* to learn the whole compendium of the English Literature from Chaucer, Shakespeare, to Byron, Shelley and Keats, to Thomas Hardy, D. H. Lawrence, James Joyce, and Carson McCullers. She did not have to learn in her university years all those great poems, great proses, great dramas. She was only *required* to learn the skill of reading the literature of a foreign language. She did not have to do all the reading in the university; she had 50 years after her graduation to read all the wonderful literature of those masters. She could learn all her life through reading.

I have taught my students that mathematics, physics, chemistry, biology, geology, etc. are forms of languages. The literature written in those languages are comprehensible only to mathematician, physicists, chemists, biologists, geologists, etc., they are incompre-

hensible "foreign languages" to persons who have only learned languages of daily life. Now a Chinese cannot read English, if he does not know any grammar or if he has too limited a vocabulary. Likewise, a person who speaks only a language of daily life, English, German or Chinese, cannot read books or journal articles in physics, chemistry, biology, and geology.

The minimum educational need of a person is to acquire an ability to read. Musicians have to read notes, painters have to read pictures, sinologists have to read Chinese, and scientists have to read science journals. The minimum preparation, the minimum educational need, of an earth-science major is thus to acquire the ability to read journal articles in geology. With the advance of geology, the literature is not written in "geologese", but the text of a research article might be sprinkled by foreign phrases from the languages of mathematics, of physics, of chemistry, of biology. For geologists who are engaged in teaching and research, those texts could be indispensable, and they have to acquire the ability to read not only "geologese," but the languages of mathematicians, physicists, chemists, biologists, etc. For geologists who are engaged in performing only routine duties, such as well-sitting, matching logs, making subsurface correlations, describing stratigraphic sections, analyzing chemical or isotopic compositions, etc., do they have to acquire the same abilities to read all those different "foreign" languages? Furthermore, people never learn a foreign language if they are not interested; students do not learn to read mathematics, physics, and chemistry even if they take one or two years of required course in mathematics, physics, and chemistry. We asked all of our geology students to take linear algebra, quantum mechanics, and physical chemistry. I would venture to say that few, if any, of my dozens of students including those who are engaged in teaching and research, can read articles in *Physical Review* or *Chemical Abstracts*, and the majority of my students would not have been any worse geologists if they never had to be required to take those courses. They took courses only to satisfy the requirement, the requirement determined by professors who themselves cannot read articles in *Physical Review* or *Chemical Abstracts*, and who seldom if ever have the need to consult articles in *Physical Review* or *Chemical Abstracts*.

I am not advocating that we should train geologists who do not know any physics, chemistry, or biology. On the contrary, I would like to see that every geologist, including those who are engaged in performing only routine duties, such as well-sitting, matching logs making subsurface correlations, describing stratigraphic sections, analyzing chemical or isotopic compositions, etc., acquire an ability to read articles in *Physical Review* or *Chemical Abstracts*, if they want to. Voluntary is the key word.

John Ramsay, one of the most distinguished geologists of our generation, told me that he was not *required* take university courses in physics, chemistry or biology; he did have his A-level and learned some physics, chemistry, and biology in British grammar school. When he was a geology student in a British university and tried to read journals in geology, he realized that a reading ability in mathematics and physics was essential for the practice of his profession. He had the incentive to learn more, and he did, when nothing is required. His classmates did not want to acquire a reading ability in those "foreign languages," but many have also become good geologists.

One time I asked a physicist friend why was Robert Oppenheimer considered a great physicist, he never received a Nobel Prize. He was great, I was told, that he could sit in a physics seminar and join the discussions no matter who was the speaker; normally a physicist could understand the "dialects" of a small fraction of speakers. Oppenheimer was a great physicist because he understood many "dialects" of the language of physicists. There were many other great physicists who did not understand many dialects. The fact is that there are too many "foreign languages". The ability to read one or more "foreign languages" is helpful, but is neither necessary nor sufficient guarantee for successes. If one does not have the interests or ability to learn effectively the use of a "foreign lan-

guage," the educational system should not force the "requirement" on him.

No, there should be no *required* courses. Student advisers might *recommend*, but never *dictate requirements*.

Need for logical thinking

Professional activities of most of my students are practical. They need to find the guilty party who polluted drinking water with nitrate. They need to find a place to dispose of chemical or nuclear wastes. They need to tell electricity companies where to drill their water tunnels. They need to advise builders where not to build. They need to tell oil corporations where to drill for oil, etc., etc. A few students became university professors, and they had to teach most of their students to perform services for institutions, firms or be self-employed.

How do we teach people to do practical things? We teach them on the job. There is a tradition since time-immemorial that artisans take apprentices. Even today, Swiss and German teenagers are accepted as apprentices by master carpenters, plumbers, stonemasons, builders, architects, photographers, mechanics, and they are accepted as trainees by banks, stores, factories, etc. They learn while they are on the job.

Several years ago, our continuing education program sent out questionnaires to alumni and asking if they need short courses in isotope geochemistry, rock-deformation, hydrology, sequence-stratigraphy, etc., etc. We were surprised by the replies: No, they do not need to take any short courses on fancy new subjects; they need to take a course to teach them to do their job better.

An apprentice learns to do his job better when he is doing it under the supervision of his master. Why should not an apprentice-geologist not learn to do his job better when he is learning under the supervision of his master—his professor?

A student can learn a lot of geology, when he is given an assignment to work on a project, practical or theoretical. One can learn more as apprentices from masters than from sitting in classes and preparing for examinations. The students of the Division of Natural Sciences at the Swiss Federal Institute of Technology instituted such an education reform called POST, i. e. project-oriented study. If POST has not been a resounding success, the fault did not lie with the idea, or with the students. The fault lay with the professors. Those incompetent did not know how to teach their students except by lecturing and giving examinations. Those competent were too busy with their own research and career ambitions.

Studies of global change, for example, are a hot theme today. Climatic changes in Switzerland during the last 10,000 years are recorded by the isotopic chemistry of the chalk deposits in Swiss lakes. A study of the records could be a good POST: While acquiring a reading ability in general sciences, geology-majors can be initiated into a project relating climate and lake sediments. They have to go to the field to obtain cores, work in the sediment-laboratory to get sedimentological data, and in mass-spectrometry laboratory to get isotope-data. To sample and process samples, they have to learn techniques of sampling, and to process data for conclusion, they have to learn principles of sedimentology, stratigraphy, oceanography, isotope-geochemistry, paleoclimatology, etc. With the "language" skill they are acquiring from the basic courses, the students can learn to read, and they must learn to read rapidly. He might acquire the Chinese skill of reading a page at a glance to acquire the essence.

When one works on a project, fellow-students, technicians, and young instructors are his best teachers. Students can be proficient in a laboratory after working day-and-night for a few months. They learned the lab problems and their solution by talking about it in the coffee-hour, or by asking the help of staff-specialists in the university. It is a favorite expression of students that they did not learn anything from their professors.

What do professors do ?

They have to have good ideas to initiate good projects, to acquire funding for purchasing equipments and for financing the employment of assistants and technical personnel. They teach their students in seminars. Their greatest contribution is, however, to read their thesis, when they can teach logical thinking.

Going back to the experience of that doctoral defense, the candidate made a simple mistake in logic. The candidate identified

A = Alamo Breccia, the sedimentary deposit studied by him

B = Coarse sedimentary deposit related to meteorite-impact

C = Coarse sedimentary deposit laid down by tsunamis generated by meteorite-impact

Using the logic that if $A = B$ and $B = C$, he concluded that $A = C$, namely the Alamo Breccia was a coarse sedimentary deposit laid down by tsunamis generated by meteorite-impact. The flaw of his logic is his assumption that $B = C$, because this is what has been published in geological literature. A student usually does not have the experience to know that there could be logical alternatives: B could be equal to C, but B could also be equal to D, or E. It is not his job to take the first answer $B = C$. His task is to see if he could falsify the statements

$B = C$

$B = D$

So that the only remaining answer ($B=E$) is the correct one, however improbable it may seem.

In the case of the Alamo Breccia, C is the tsunami deposit, D is coarse sedimentary deposit of impact debris, and E is coarse sedimentary deposit laid down by downslope movement after an impact-event. During the two days in the field, his thesis adviser and other more experienced scientists could easily falsify the interpretations $B=C$ and $B=D$. The only remaining conclusion was that Alamo Breccia was formed by gravity-sliding when the shallow marine shelf-sediments beyond the outer rim of a crater move under gravitational instability toward the center of the crater.

This most difficult statement in the procedure of logical analysis is the conviction that B could be equal, and only equal, to C, D, or E. A few years hence, an imaginative geologist may study the same deposit and can come to the conclusion that B could be equal and only equal to C, D, E, G, or H. He could find evidence to falsify all interpretations except that $B=H$. This is the essence of the Popperian philosophy: scientific truth cannot be verified, only falsified. The limitations of the human intellect being what it is, there is always an H lurking out there, while the present generation of geologists think that E is the answer.

One of the greatest faults of geological education is to teach the students to judge on the basis of intuition what is more probable, when the Popperian criterion of falsification should be adopted.

If geology is a science, geological statements are falsifiable, and geologists should not continue to hold an intuitive prejudice to their heart long after it has been falsified. I was shocked recently when a noted geologist told me that he believed in plate-tectonics, but he did not believe in convection currents, he believed that the plates moved because of the tidal forces of sun and moon.

When he used the word "believe", he was treating geology as a religion. Belief in German is *Glaube*, and *Glaube* is a synonym of faith. People believe in Christ, not because the existence of Buddha has been falsified; people believe in Christ because he has been brought in the teaching of the Christian faith.

Whether convection can take place or not in Earth's mantle is not a question of faith; it is a problem in physics. One cannot say that I do or do not believe in turbulent flow, because turbulent flow is a physical phenomenon and turbulence will set in when the critical Reynolds number is exceeded. One cannot say that I do or do not believe in mantle convection, because mantle convection is a physical phenomenon and convection will take place when the critical Raleigh number is exceeded.

If geology is ever to be science, instead of stamp collecting, there should be theoretical geology. Theory consists of forcing functions or inevitable consequences: When A is so and so, B must take place. When B takes place, C must be the consequence...The science of geology must be taught as a sequence of inevitability. When

Raleigh number of the mantle exceeds a critical value, mantle convection has to take place. With mantle- convection seafloor-spreading is inevitable. With the expansion of the seafloor by spreading, subduction of ocean-plate is inevitable. With the subduction of ocean plate, the total consumption of ocean plate is inevitable. With the total consumption, collision of continents is inevitable. With the collision, orogenesis is inevitable. With the orogenesis, increase of topographic relief is inevitable. With the increase of topographic relief, weathering and erosion are inevitable. With the weathering and erosion, sedimentation is inevitable, etc. etc. Science can predict, and inevitability is a predictable outcome. Two hundred years of James Hutton, I think that there should be a reform in geological education. Geology is not just making random observations and offering intuitive *ad hoc* explanation. Geology is a science. Geology can still be taught as an anecdotal science in middle schools, but theoretical geology should be the first course of all geology majors in the universities.

Reality of life

After I retired from ETH in 1994, I served for three years as a guest professor in Asia, Europe and America. I could acquire a broad perspective of the present status of teaching and research in earth sciences. I see a stagnancy in science, especially earth science. More and more money is spent for less and less relevance. The earth science establishment fails to see the need of a revolutionary change. Distinguished earth scientists live in their ivory tower, preoccupied with their citation index and winning of awards and prizes; many of them could not see the triviality of their endeavors.

When I was in US during the first half of this year, I visited several old friends who are long past their normal retirement age, but the septuagenarians refused to retire. Why do they want to stay on?

No, it was not for financial reasons, they said: they would get a better deal if they select retirement. They stay on because they feel the need to defend their field of specialization. If they should retire, their professorship would be taken away from the Division of Earth Science and transferred to some other department such as informatics or biotechnology.

My friends do not see that they are defending a lost cause. They are distinguished earth scientists and they are holding chairs in distinguished universities. Two or three decades ago, they were "explorers" at the frontier of the earth science, but they cannot admit that their fields of specialization have become increasingly irrelevant. They are frustrated. Their research applications to the National Science Foundation are turned down. They have only a few students, who stay on for many years, because they shall have difficulty finding employment in geology after they receive their doctoral degree. My friend's attachment to earth science is sentimental, not rational.

I served as a Keck Professor at the Colorado School of Mines, which has never been among the top five of United States. There has never been a member of US National Academy on their staff, or a winner of a major award in geology. I was impressed, however, by the very different atmosphere at CSM. Instead of a gloom which I encountered at Ivy League and California schools, the School of Mines is flourishing. When the undergraduate enrollment in name-schools is less than the number of professors, CSM has now more than 100 freshmen each year in geology, geophysics, and petroleum engineering. More important is the fact that their students would receive 2 or 3 job offers after they receive their bachelor of science degrees: they do not have to enroll in graduate school to acquire a subsistence minimum.

Why should there be this difference?

The answer is simple. Students go to university to prepare themselves for a professional career. Name schools provide opportunities for teaching and research, and those opportunities were increasing at an exponential rate during the 1960s and 1970s, when the expansion of the universities exploded because of post-war "baby-booms." Now the situation is changed. The baby-booms are

over. Teaching and research jobs are scarce, while the PhDs are "a dime a dozen", so that there are usually more than 100 or 200 applicants for each tenure-position in earth science at a US university. Most of the applicants have to be disappointed. Some find jobs in the industry, others change their profession.

The knowledge of theoretical sciences is ultimately applicable. Physics has many applications: Statics is applied to civil engineering, mechanics to mechanical engineering, hydraulics to hydraulic engineering, electricity to electrical engineering, etc. Chemistry has many applications, and there are more students in the department of chemical engineering of a US university than in department of chemistry. Biology has many applications, and biotechnology is one of the most relevant scientific disciplines in modern society. Theoretical geology too has many applications, but few universities have a department of geological engineering. The professors in ivory tower looked down on applied sciences; none of the elite-schools have departments of mining or petroleum engineering. Yet such career-oriented education is exactly the cause why CSM is flourishing. A further consequence of ignoring the importance of geological engineering is that the best minds are preempted by name-schools to engage in the irrelevance of ivory-tower activities, while the society cries in vain for help to solve urgent problems.

We all know that there has been a great change in earth science during the last half-century. When I was a graduate student during the late 1940s and early 1950s, there was a demand for exploring natural resources, metals such as uranium, gold, copper, etc. and hydrocarbons such as oil and natural gas. The industry needed innovative geology for exploration. Good geology made good exploration. In the 1970s and 1980s, good geology was common place, the industry needed more: innovative geophysical methods were indispensable for exploration. Good geophysics made good exploration, but good geophysics after 20 years no longer guarantee success. After half a century, there is still the demand for natural resources, metals such as uranium, gold, copper, etc. and hydrocarbons such as oil and natural gas. But there is not so much demand for exploration: we have found more than we need for the next half century. What we need now are better methods, more economic methods to exploit, i.e. to produce the natural resources which we have already found.

Challenged by the Chinese Ministry of Chemical Industries to exploit metals from brines of salt lakes, I started after my retirement to work on mining and petroleum technology.

In my efforts to promote the industrial applications of my patents, I made two observations:

When I went through hundreds, if not thousands, of patents on mining and petroleum technologies published during the last 20 years (in order to ascertain the novelty of my inventions), I did not find one single patent-holder with a university address. Most, if not

all, patents, representing minor improvements of existing methods, are held by the industry. No university known to me offers a course on innovative approaches to mining or petroleum technology. Earth scientists in the industry are known for their conservative mentality. Geologists or petroleum engineers working for industry took training course given by companies. Yes, there have been inventions, and the workers of industrial research did file the thousands of patents in petroleum- and mining-technology. Their inventions are, however, only useful in cutting costs and increasing efficiency; they are improvements, but not revolutionary innovations.

When I was working on industrial applications of geology, I faced three areas of great interests to the industries:

1. Exploitation of metal from brines or from seawater.
2. In-situ exploitation of metals from subterranean formations.
3. Improved recovery methods of hydrocarbons from depleted oil fields, coal, lignite, oil shale, tar sands, etc.
4. Direct recovery by in-situ burning of thermal energy from subterranean formations.

If the geological departments of our universities teach their students to apply theoretical geology to geological engineering, one might effect a revolution, and to cause a renaissance of geological education.

Kenneth J. Hsu was born in China in 1929. He graduated from Nanjing University, 1948, and received a Ph. D degree from U.C.L.A. in 1953. After industrial research and teaching in US, Hsu was called in 1964 to the Swiss Federal Institute of Technology, where he served as Professor of Experimental Geology until his retirement in 1994. Since then, he is the President of Tarim Associates AG Zurich. Hsu served many international organizations during his long career, including the chairmanship of the Marine Geology Commission of IUGS. He received numerous honors, including, among others, the Wollaston Medal of the Geological Society.