Kenneth J. Hsü

Physical Principles of Sedimentology

A Readable Textbook for Beginners and Experts

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With 64 Figures

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Preface

This is a textbook for geology undergraduates taking their first course in sedimentology, for graduate students writing a term paper on sedimentology or preparing for their qualifying examinations, and for instructors, who deem it necessary to infuse a more physical-science approach to the teaching of geology. I also hope that some physics students might find the book readable and comprehensible, and that some of them might be inspired to start a career in the physics of geology.

This textbook is a revision of my lecture notes for my course *Principles of Sedimentology* at the Swiss Federal Institute of Technology. It is a twounit semester course given to second- or third-year undergraduate students, who have acquired a basic knowledge in physics, chemistry, mathematics, and geology. The purpose of teaching this course is to bridge the gap between what has been learned in middle school and in the first year of university to what shall be learned in geology during later years. I intend especially to impart the impression to my students that the study of geologic processes is applied physics, applied chemistry, and applied mathematics. The content of the book is somewhat more extensive than what I have taught, and could be used as a textbook for a three-unit semester course, or even for a two-semester course, if a lecturer chooses to do so. We teach a second course in sedimentology, for which the students are recommended to consult textbooks on depositional environments and facies models. This textbook is not intended to replace, but to supplement those.

James Hutton in the late 18th century and Charles Lyell in the middle of the last century established the natural-history approach to study geology, and the success of the method is witnessed by the progress of the science over the last 2 centuries. The logic is inductive reasoning: Noting that quartz sands are terrigenous detritus derived from deeply weathered terranes, quartz sandstones or orthoquartzites are given paleoclimatic significance. Observing that marine organisms lived, died and are buried in marine sediments, fossil ecology becomes a key to interpreting sedimentary environments. There needs to be no reference to Newtonian mechanics or to Gibbsian thermodynamics, because physical laws cannot be invoked to prove or falsify the interpretation.

The method is necessary, reliable, but, in some cases, insufficient.

Orthoquartzites may have been altered from radiolarian oozes, not from quartz sands. Shallow marine microfossils are found in some deep-sea sediments. Simple rules of thumb may not give the correct explanation of complex processes. While the natural-history approach is necessary, the method is, in some cases, insufficient, and we need to know the physics of the processes involved. What seems likely may be physically impossible. What seems improbable may be the only physically viable explanation. This is the physical-science approach to geology.

The diverse natural phenomena are infinite, and specialization of the earth sciences seems a necessity. Sedimentologists are specialists of sedimentary rocks; they are able to extract valuable data on earth history from the kaleidoscopic sedimentary record. Physical principles are, however, few in number and they are taught to geology students. Recongnizing that earth phenomena are physical processes, a person using the physical-science approach can apply the three laws of motion, three laws of thermodynamics, the principles of the conservation of energy and of matter, and perhaps a few other fundamental relations in science, to explain a diversity of geologic processes.

M. King Hubbert advocated and exemplifies the efficacy of the physicalscience approach in geology. Hubbert was a physics student in college, and may not have taken any undergraduate course in hydrology, petroleum geology, or tectonics. Yet, he made his greatest scientific contributions in these three fields of specialization: in hydrology with this theory of groundwater motion, in petroleum geology with his research on the oilproduction technique of hydraulic fracturing, and in tectonics with his analysis of the role of pore pressure in overthrust mechanics. Similarly, the concept of platetectonics, the new paradigm of geology, is innovated by students of geophysics who knew little geology and still less tectonics; they made a simple assumption that diverse earth phenomena are the physical consequences of moving rigid plates on the surface of the earth.

As I have indicated, my purpose in teaching this course is less to teach sedimentology, but rather to instill in students the skill to view earth phenomena as physical processes. In fact, my original aim was to write on the *Physical Principles of Geology*, and this was the title of the book which I was contracted in 1971 to write. After 2 decades, I see my limitations and elect only to write on those *Principles* as illustrated by sedimentary processes.

I have tried to avoid the authoritarian attitude in writing this textbook, although I realize that we cannot start out from kindergarden. Since my students are mostly freshmen or sophomores in college, I made middleschool physical sciences a prerequisite for my course, and I presumed that they have a rudimentary knowledge of differential and integral calculus. I expect the same for my readers.

Textbooks are commonly not readable. After having written three books on geology for general readers, I find no reason why should I not also use the same "trade-book" style to compose a textbook for geology students. Several of my colleagues and students have read a draft of the manuscript and they found the claim of my subtitle - '*A Readable Textbook*' - justified.

I am indebted to many persons in having produced this volume, but I could single out only a few in this short acknowledgment. M. King Hubbert was the inspiration of my teaching philosophy. Several friends, especially Max Carman, Gerald Middleton, and Harvey Blatt gave me encouragement. Dave Kersey consented to be a co-author when I first began to write, but he had to back out because of his other commitments. My former assistants, Helmut Weissert, Guy Lister, David Hollander, Ulrich Henken-Mellies and Jon Dobson, helped in many ways in my teaching of the course, and their numerous corrections of the earlier drafts helped improve the manuscript.

I owe a special thanks to Ueli Briegel who not only instructed me in the use of the word-processor, but also consented to make a laser-print copy of the manuscript for photo-offset production. His effort preserves the aesthetics of the volume and at the same time reduces the cost to potential readers. Albert Uhr and Urs Gerber prepared the illustrations. I am indebted to the many colleagues and publishers who gave me permission for reproducing modified versions of their original illustrations.

The book is dedicated to the memory of my first wife Ruth. She grew up in the land where the word *Heimweh* originated. I promised her that i would write a textbook, so that I would become known, so that I might be offered a job in Switzerland, so that she could return to her native country. It has not turned out that way. Her ashes went to Basel first, before I was called to Zurich, before I became established, before this book was written. Life is full of its little ironies, as my favorite writer Thomas Hardy would say.

Zürich, Summer 1989 KENNETH J. HSÜ

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1 Introduction

Why lecturing? Why this Textbook? Why Physical Principles? Why a Readable Textbook?

I was a student once and I often thought that lectures were a waste of time. Some lectures are probably a waste of time, when students could use the same time getting more out of studying on his own. Yet, lecturing is still the *modus operandi* of instruction, from primary schools to universities. It has been time tested universally, and its value should not be underestimated. Furthermore, we teachers are hired to give lectures; we have little choice. I have, therefore, had to give much thought to the possibility of optimizing. Why would you want to attend my lectures? What can you not learn from reading a book or an article in a library?

I would like to see you here not because you have to be. As university students, you have a freedom of choice. You come, because you can learn from my lectures what you cannot in reading a book.

Students go to lectures, because textbooks are seldom readable. Few authors are used to writing in conversational style, and hardly any textbooks of science are published in that way. Richard Feynman, a noted physicist 20 years ago wrote a readable text on hydrodynamics, but he already had his Nobel Prize. Most authors are, however, required to be explicit, succinct, and, worst of all, comprehensive.

Comprehensive books serve as ready reference for teachers; they can choose what they want to learn from the encyclopedic coverage of comprehensive books. But textbooks are often nightmares for students; they do not know where they should start (and where they should end) in a big, thick textbook. Lectures have an advantage because they can never be truly comprehensive. A course has to be taught in so many hours. Constrained by time, a lecturer has to choose his materials. Attending lectures, students are told what is important and what is less important in a discipline where knowledge is unlimited. Students in our university, therefore, demand lecture notes from their instructors. These notes define a more limited area for candidates to prepare for their examinations. This book, like many other textbooks, is an outgrowth of my lecture notes. I have, however, not written this book because the lecture notes were there. I have the more ambitious aim of presenting my teaching philosophy for the consideration of other instructors. Perhaps some changes could be made in the way we teach sedimentology to our undergraduates. Perhaps some changes could be made in university teaching. Finally, I hope this unusual opus, if proven successful, might start a new trend in writing textbooks.

Books are seldom written with regard to a reader's current qualifications. If he can not understand now, he can come back tomorrow, or next year. Lecturers are, however, not supposed to ignore a student's capacity to learn. If they do, they would hear complaints. After 20 years of teaching and having a reputation for being a poor lecturer, I can finally appreciate the difference between what I should teach and what students could learn. I can assure you that it is not my purpose to teach you all that I know about sedimentology. I give lectures because I hope you might learn something which you should and which you could.

You attend lectures because you do not always understand what you read. Often you may have difficulty to fathom the reasoning behind an author's statement. I remember my own frustrations as a student, especially when I had to read an article or a book involving the application of physics or mathematics. I was stopped because I encountered a technical term which I did not understand, or because I came across an elegant equation, which *is well known* , or which *can be proved* . Well, the term was probably defined in a technical dictionary which I did not have. The equation might be well known to an expert or easily proven by the knowledgable, but it was not known to me or it could not be proved by average users of a textbook.

When you face such a problem, you either waste many hours puzzling over a small point, or you give up and throw the book aside. You cannot face the author and expect an immediate answer to a question. Lecturing is different. Some professors do get away with bluffing, and claim that "it is well known", or "it can be proved". One could be stopped, though, someday by a bright young kid who calls his bluff. Any teacher with pride and sensitivity would thus not want to get into this embarassing situation. He has to be prepared to answer questions on any subject he brings up, and he has to know what he is talking about. Ultimately, no teacher can hide behind semantics in a lecture hall, and no student needs to be too shy to ask questions and to get to the bottom of things. This is the way learning should be. This is my intention in writing this book. I shall presume that you have learned middle-school mathematics and natural sciences and are taking courses at the university on those subjects; I shall start from there to discuss some physical principles of sedimentology.

Lecturing may be a monologue, but a thoughtful lecturer does try to interact with his audience. He will go back and repeat if he sees an abundance of puzzling expressions among his audience, or he will make a long story short when he sees them bored. One communicates with just so much repetition or omission as necessary. In contrast, an author pounds away on his typewriter. He tries to anticipate his readers, but he can never be sure.

We have to realize that lectures are tailor-made to students. If tailor-made clothes do not fit, the mistfit is irrevocable. Generations of my students have complained of my lectures, which have been specially designed for them. Yes, the designer has often misjudged the size of his customers, and I have had to change the content and methodology of my teaching. Authors of textbooks do not labour under such constraints.

Textbooks are not tailor-made to a particular group of readers. They have excesses and deficiencies, and I do not expect to produce a new edition to fulfil the wishes of any particular group of readers. Textbooks serve useful purposes because of that imperfection. A lecturer can use a textbook as a basis for his lectures; he can decide to subtract or add materials from what is written. A student can use this textbook as one of the books he chooses to teach himself sedimentology. He cannot expect to learn all he needs to know from one textbook. But if he could at least learn something from it, the book has justified its existence.

I have been giving lectures in sedimentology for 20 years. I have spent much time each year writing new lectures for each new class, because I usually forgot what I had taught the year before. Eventually, I realized that there is a "hardcore" which I had been teaching class after class for more than 20 years. I do not have to start from scratch again each year, if I write the basic principles down. Similarly a student can look up a subject in this book, many years after he has listened to my lecture; he does not have to learn the matter from scratch again from the incomplete lecture notes, which he may or may not have taken.

Lectures are transient yet final. Books are permanent, yet transient. These may sound like inscrutable quotes from Laotze's *Tao-te Chin*, but the fact remains that mistakes can be corrected if they are written down, and if they are read by the knowledgable. I realized that when I went over some notes taken of my lectures by students; errors which I made while writing on a blackboard were copied down and, in many cases," immortalized". There were other mistakes, they were made either because I did not master the subject matter or because they did not understand my explanation. Thus errors and mistakes made during a transient lecture are mostly irrevocable. Now that I have to write down what I said, I have an opportunity to correct error and remedy mistakes; I also can think over again some of the problems which I did not explain very well during my lectures and try to do better. If this printing or edition cannot do the job, there could be a second printing or a revised edition. What was said is said. What was written can always be changed.

A main reason which prompted me to write the book is the hope that my philosophy of teaching geology will survive my retirement 5 years from now. I often heard complaints of geology majors that they see no reason why they should take the many courses in physics, chemistry, and mathematics which are required of them. Unless they become geophysicists, they seem to need little chemistry, less physics, and almost no high mathematics at all in their professional practice. For a student who is to become an oil company employee, a course in sedimentology on facies models will do. He should be quite capable of reconstructing a depositional environment on the basis of facies analysis, and he sees little reason why he should have been subjected to examinations in Newtonian physics or Gibbsian thermodynamics.

This brings me to my comparison of sedimentology to art history. I wrote in my 1983 book for lay readers, *The Mediterranean was a Desert*:

Sedimentologists are students of sediments; they describe and analyze sediments and sedimentary rocks. They would cut a chip off a piece of carbonate rock, grind the chip into a transparent thin-slice, and examine this under a microscope. They would crush a shale, pulverize it and bombard the powder with X-rays to determine its mineral composition. They would pound on a sandstone and shake it until the sand grains become loose enough to run through a series of sieves to analyze its size and sorting. They would dissolve an evaporite (a chemically precipitated rock) and process it through a mass spectrometer to determine isotopic ratios of various chemical elements. Their purpose is to learn more about the origin of a sediment. Is it a beach deposit, a lime mud laid down on a tidal flat, or an ocean ooze?

In some instances one does not have to go through complicated procedures nor use sophisticated instruments; one can immediately tell the genesis of a rock by the way it looks. Techniques of comparative sedimentology were developed shortly after the Second World War, and the financial backing by the oil industry contributed considerably to their success. Teams were sent out to study recent sediments in various environments: river sediments on coastal plains, deltaic sediments at the mouths of major streams, marine sediments on open shelves, oceanic sediments on abyssal plains, and so on. Distinguished features were defined, then described as "sedimentary structures", and those structures serve to characterize suites of sedimentary deposits at various places. When a core of an ancient sedimentary formation is obtained from a borehole or an oil well, one can now compare its sedimentary structures with a known standard, in much the same way an art historian identified a purported Rembrandt by comparing its composition, coloring, shading, and brush strokes with known Rembrandts. Sometimes the comparison is purely

empirical. Other times there are good theoretical reasons why a sediment should look the way it does.

During a recent trip to Holland with my family, I noted that my teenage son, Peter, who is no art historian, easily spotted a Rembrandt in the Mauritshuus after half a day in the Rijkesmuseum. Little did he realize that certifying Rembrandt is one of the most difficult tasks for an art historian, because the superficial characteristics are all too easily imitated.

Certainly, a picture-book approach can be successful to a certain extent and may lead to correct conclusions, but a deeper understanding is often required to distinguish the genuine from the imitation, the truth from the falsehood.

We need physics, because geologic processes are physical processes. Superficial appearances may help separate the probable from the improbable, but geology is science and scientific truth is approached through a discrimination of the possible from the impossible. Principles of physics determine what is physically impossible. A lacustrine turbidite may look like a varve, but it is not a varve, and physical law may help us to discriminate a true varve from a false one.

A deeper reason to study physics is to learn precision in thinking. Swiss educators insist that Latin should be taught in middle school because one learns not only a language, but also the logic of a language. Similarly, my own experience has suggested to me that a professor in geophysics, David Griggs, saved me from the dangerous habit of fuzzy thinking.

In 1950, I went to Los Angeles to study rock mechanics with Griggs. On his door, was a quote from Lord Kelvin:

I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of Science, whatever the matter may be.

We see descriptive terms such as steep slope, slow speed, poor sorting, etc., in sedimentology. The adjectives steep, slow, or poor are meaningless, unless we have some numerical values of the slope, of the speed, or of the sorting to compare to the numerical values of the angle of repose, of the critical Reynolds number, or of standard deviation in phi classes of well-sorted sand. To obtain numerical solutions of complex variables, one needs equations, and those equations have been derived from the consideration of equilibrium (forces, chemical potential, etc.), of conservation (momentum, energy, etc.), and of other physical principles.

Several excellent textbooks on *Sedimentology* have appeared during the last 2 decades, including some genuine efforts to relate sedimentology to elementary physics. Yet, the usual authoritarian approach is adopted. I could, for example, recognize two categories of textbooks on the basis of their discussion of settling velocity. In most texts, old and new, the velocity was simply stated, citing Stokes' Law:

$$u = \frac{1}{18} \frac{(\rho_s - \rho_f)\, g\, D^2}{\eta} \quad . \qquad (1.1)$$

Two new texts, one elementary and the other advanced, went so far as to explain that the law is derived from a consideration of equilibrium of forces, and that the fluid resistance is

$$F = 6\pi \cdot \eta \cdot \mu \cdot D/2 \ . \qquad (1.2)$$

Yet the reader is faced with the same frustration of having a "well-known formula" thrown at him — well known perhaps in its form but not in its content. He is told the same old story that the relation can be proved, but it is not proved. He is left with the same uncertainty as he is told that this formula is applicable if viscous resistance is dominant, but he does not know the meaning of dominant viscous resistance.

In my lectures, and now, in this book, I have attempted to go back to the basic principles of physics, to Newtonian mechanics, and to Gibbsian thermodynamics for a derivation of the quantitative relations commonly cited in sedimentology. Only a thorough understanding of their origin could explain the limitation of the validity of the many equations familiar to us in sedimentology.

This book is written as a history of inquiry, especially my history of inquiry. Natural laws are not stated as self-evident truth, but as approximations of quantitative relations, deduced from imperfect experiments. The purpose is not so much to inform, but to invite inquiries to reduce the element of falsehood of our understanding.

Supported by a grant from the Guggenheim Foundation, I spent 6 months on this project in 1972, while I was taking a sabbatical leave at the Scripps Institution of Oceanography. The sabbatical ended before my book was written. I continued the effort in 1973, 1974, and 1975. Still incomplete, I was not happy with what I had written and the manuscript was shelved for more than 12 years. I started to work on it again in the spring of 1988, when I finally seemed to find an echo from my students. With their encouragement, I decided to carry the task to its completion.

My philosophy of teaching is expressed in the final words of this introduction. I often said that one should teach science like he teaches a foreign language. Students learn a foreign language by studying its grammar and acquiring enough of a vocabulary to read, speak, and write. The grammar of the language of science is scientific logic, and the vocabulary consists of the technical expressions, which are commonly abbreviations of scientific concepts. You learn to read, speak and write science by knowing the principles and terminology; you do not need to memorize all the information contained in an encyclopedia of science.

Geologists study the history of the Earth, and sedimentary rocks are an archive of the Earth's history. The books in the archive are, for the uninitiated, books written in a foreign language. I have no intention to summarize all the books in the archive. The purpose of this opus is to record my effort in teaching my students the skill to read those foreign-language books in the archive.

The title of the book is *Physical Principles of Sedimentology*. It bears some resemblance to the title of a 1970 book by John Allen: *Physical Processes of Sedimentation*. The difference is significant. Whereas Allen attempts to use physical principles to interpret all major physical processes of sedimentation, I shall attempt to elucidate all relevant physical principles involved in interpreting sedimentology with a few processes elucidated in illustrations. The derivation of each of the principles, such as Stokes' Law, Reynolds' criterion for turbulence, Chezy's equation, Shield's diagram, Hjulstrom's curve, Bernoulli's principle, Darcy's equation, mass-action law, Gibbs criterion of chemical equilibrium, etc., will be given.

Teaching, for me, is not primarily aimed at the transmission of information. Information is transmitted only to serve the purpose of illustrating analytical methodology, logic, and principles. For such illustrations, I have relied heavily on my own first-hand experience in geologic research. In doing this, I am following in the footsteps of Konrad Krauskopf when he wrote his textbook on geochemistry. If I have given my own publications a seemingly undue emphasis, it is not motivated by vanity, but by necessity since I have to teach what I know, and I know best that on which I have done research. I would like to make it clear that this is not a book for you if you expect a comprehensive treatment. Some important sedimentological processes are not mentioned, not because they are unimportant, but because this book is not intended as a textbook of comprehensive knowledge. Important sedimentological processes which do not illustrate the physical principles discussed in this textbook are taught in a second course which used the natural-history approach to study sedimentology, for which numerous textbooks are available on the market. The emphasis of this textbook is placed on the understanding of the fundamental principles, not on the knowledge of particular processes.

For brevity, the expression *chemical* did not appear in the title of my book. Chemical processes are important in sedimentology, but they are, strictly speaking, physical processes. Whereas the latter consider mainly the mechanical energy and work involved, the former take into consideration the heat and chemical energies as well. The basic axioms, such as conservation of matter and of energy, are the same.

The subtitle of the book *A Readable Textbook of Sedimentology,* is an advertisement of my unusual approach in writing this textbook. After having written three "trade books", or books on geology for general readers, I have learned a few things about writing a readable text. One of those is that illustrations disrupt the continuity of a readable text: A picture may be better than 10 000 words, but the art of writing is to use a few well chosen words in place of a picture. I often wonder if Darwin's success with his *Origin of Species* may be traced to the fact that the book is readable because it is virtually devoid of illustrations.

A readable book avoids subheadings, but I have given running titles to facilitate quick references. The book has to be sufficiently organized so that portions of the text can stand alone and be read without a great demand on the memory capacity of the reader. A readable book can be started from any page, and be read forward or "backward", on odd occasions, or in one sitting. I have "peppered" the text with anecdotes and autobiographical vignettes, in an effort to keep up interest, especially when discourses of physics are weighing a reader down. This style of writing has been called "change of pace", as I was taught by my editors. Finally, a readable book has plenty of one-syllable words.

The author of a trade book, as my editor told me, has to make the subject matter comprehensible for the readers; he has less need to convince them. The author of a scientific article, on the other hand, needs to be convincing; comprehensibility is of secondary importance. The author of a readable textbook, however, has to be concerned with comprehensibility and credibility. Facts and figures have to be presented and some illustrations are indispensable. I have, therefore, chosen a minimum for each chapter. The fact that numerous figures have been found necessary is perhaps an admission that I have not fulfilled my promise of readability. I am, in fact, not adamant on the matter whether I should have more or less illustrations, and I would revise my opus accordingly for a second edition, if I hear very loud complaints.

Undergraduate textbooks commonly do not cite references, because all the matters discussed are supposedly common knowledge. I shall refer to the authors and shall cite their work in the section "Suggested Reading" at the end of each chapter. I shall also, in a short readable text, call attention to those studies, which greatly helped formulate my thoughts in writing this book, while giving my reasons why and to whom the further reading could be beneficial. A list of the references, arranged alphabetically, will appear at the end of the book.

Suggested Reading

For undergraduates preparing for their examinations, no further reading is necessary; they are free to agree or disagree with my teaching philosophy. For teachers of sedimentology who may wish to adopt the textbook for their instruction, I would like to suggest that they read the several articles by M. King Hubbert on geological education.

When I joined Shell Development Company as a young post-doc, Hubbert was the general consultant of the company, a wise investment by the company to promote creative and productive achievements. When I got my first teaching job at SUNY Binghamton in 1963, I went to say farewell to Hubbert and to ask his advice. He gave me two reprints, his article on *The Place of Geophysics in a Department of Geology* (AIME Tech Publ, No 945, 1938) and his *Report on the Committee on Geologic Education of the Geological Society of America* (Interim Proc Geol Soc Am, 1949). Hubbert emphasized in 1938 that the phenomena of the earth studied by geologists are also phenomena of physics. He was not as arrogant as Lord Kelvin who claimed that there was stamp-collecting and there was science, which was physics. Hubbert did point out, however, in 1949 that the natural-history approach to geology, "wherein, with but minor recourse to the relationships established in other sciences, students are trained in the syntheses that can be made from direct geological observations, .." is a necessary approach but insufficient.

Anticipating the Earth Science Revolution of the 1960s, Hubbert and his committee advocated the "physical science approach" in geology. The most effective way of geological education, in their opinion, is **"that at all instructional levels ... only those inferences be presented to students for which the essential observational data and logical steps leading to the inferences have also been presented."** Hubbert deplored the practice of **"many widely used textbooks"**, which **"have lost sight of our intellectual foundations and ... have reverted to authoritarianism".**

In his Presidential Address of 1962 (Geol Soc Am Bull, 74: 365-378), Hubbert asked: *"Are we retrogressing in Science?"* He gave examples to illustrate that many of the propositions stated in textbooks are in fact incorrect, and that there were no valid derivations given, and propositions were "taken as true because the book said so". He further pointed out that in the whole field of science the master generalizations are few; "these include the three Newtonian Laws of Motion and the Law of Universal Gravitation, the three Laws of Thermodynamics, the two Maxwellian Laws of Electromagnetism, the Law of Conservation of Matter, and the atomic and molecular nature of chemical elements and their compounds." "These great generalizations encompass the whole domain of matter of energy — the whole domain of observable phenomena — that a modern scientist cannot afford to be ignorant of them. If he does have this type of knowledge, it is no longer necessary for him to burden his mind unduly with the infinity of details in whatever domain of phenomena he may choose to work."

Hubbert lamented the modern tendency of retrogressing in science and appealed to us that we should revert the trend to make it "mandatory for