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THE FUNCTION OF MATHEMATICS IN SCIENTIFIC RESEARCH[1]

MATHEMATICS embodies some of the earliest scientific developments and hence she was practically unrestricted in regard to the selection of her location in what became later the domain of science. Did she select for herself the most fertile available land or was she misled by superficial attractions in making her choice, while the richest mines were hidden under other land whose surface presented fewer attractions and whose development demanded more complicated machinery? One might naturally expect different answers to this question from the members representing the varied interests of this Science Club.

It is not our purpose to extol the advantages of location with respect to the mathematical mine. This location was pointed out to you in your youth and the impressions which it has left on your minds are too deep to be modified materially by a few general remarks. Moreover, some of the tunnels of the mathematical mine are used daily by many of you, who gladly speed through them for the purpose of saving time to employ your energies more effectively in the field of your own choice.

Notwithstanding these facts, all will agree that the mathematical mine has been developed extensively, and that its developments have been most helpful and are becoming more useful to various other sciences. As the rivers excavated unknowingly for possible railroad lines through the mountains

[1] Read before the Science Club of the University of Wisconsin, April 5, 1917.

long before the construction of such lines was undertaken, so mathematics has been preparing thought roads for sciences long before their development was seriously begun. Hence it does not appear inappropriate for a body of scientists to pause now and then for a few moments to reflect on the methods and ideals which have actuated the mathematical investigator. Such reflections may be inspired by a sense of respect for all that contributes to scientific progress, but they should also prove helpful in the formation of most comprehensive notions in regard to the great problems which confront us as a united band of workers to secure light, to dispel more of the superstitions and to present far-reaching thoughts in the simplest manner.

Among the questions which scientists as a body might be inclined to ask the mathematician is the following: What is the attitude of mind which has contributed most powerfully to mathematical progress? Such a profound question would naturally be answered somewhat differently by different men, and your speaker to-night is not so completely ignorant of his own limitations as to suppose that he can furnish a final answer to this question. He hopes, however, that he may not be entirely unsuccessful in making some illuminating remarks on it, and in interesting you by directing your attention to common thoughts which underlie the varied efforts by which we as a body aim to enrich the world.

With this reservation I would be inclined to say that *modesty* is the attitude of mind which has contributed most powerfully to mathematical progress. The great "Elements" of Euclid, for instance, are candidly based on assumptions or axioms and do not claim to prove everything *ab initio.* Moreover, this great work does not concern itself directly with such fundamental questions as truth, reality, life, death, etc., but it confines itself to deductions relating to matters which might appear as trivialities when compared with many other problems which then confronted and now confront the human race.

To understand the modesty of Euclid and his geometric predecessors it is necessary to bear in mind the fact that the "Elements" of Euclid were written at a time when other sciences made little or no demand for such results as these "Elements" embodied. Even such a closely related subject as surveying could then make little direct use of these results in view of the theoretic form in which they were presented. The work which is said to have passed through more editions than any other book except the Bible, which considers diametrically opposite questions, must have appeared to many of Euclid's contemporaries as dealing with comparatively trivial matters in a modest way, since it made no attempt to trace its fundamental principles to their sources, but explicitly started with axioms or postulates.

As another evidence of modesty in mathematics I may mention the special symbols for unknowns and the use of equations in these unknowns. The scientific method embodied in equations involving at least one unknown implies the careful study of relations involving something with respect to which we have openly acknowledged our ignorance. Like the axioms or postulates of geometry, it makes no pretention of complete knowledge, but is satisfied with an humble attitude of mind. The basis of mathematical development is thus seen to be characterized by a modesty which has led the investigator to do what he can do thoroughly rather than to try to do that which would naturally interest him more but which lies beyond his power.

Even in its most primitive form, count-

ing, mathematics clearly dealt with matters of secondary importance. Is not the finger more important than the number attached to it in view of its position in relation to the other fingers? Why should the primitive races then have turned their thoughts away from the most important to matters of secondary importance? As I understand it, this turning away from unfathomable but most enticing difficulties to the fathomable but less enticing ones is the great keynote of science, and mathematics was perhaps the first scientific subject to sound this keynote with decided clearness. It was, however, not always sounded with clearness by mathematicians. The Pythagoreans, for instance, endeavored to make it appear that numbers were endowed with noble properties which are entirely foreign to them. They were not yet sufficiently modest to study mathematics most effectively, and their spirit has its representatives even in our day.

The picture representing the attitude of mind which contributed most powerfully to mathematical investigation would, however, not be complete without uniting with modesty discretion and a love for mental travel and exploration. The traveler and the explorer are usually first attracted to regions which are easily accessible and whence it is easy to retrace one's steps. The attitude of mind which is exhibited by the common expression "safety first" has been largely responsible for the trend of developments in mathematics. With the passing of years these safe permanent thought roads have acquired historic interest and they have naturally been used as models by those who aim to open up scientific regions where mire and quicksand impede progress, and sometimes engulf roads which had been supposed to be secure.

The chief function of mathematics in scientific research is, however, not the cultivation of a feeling of modesty or of a desire for mental travel and exploration. The problem of the mathematical investigators is a much more difficult one, since it relates to the discovery and development of unifying processes which are sufficiently comprehensive to avoid bewilderment as a result of a maze of details, and yet sufficiently close to the concrete to become useful in the widely separated fields of scientific endeavor. With the growth of scientific knowledge in various fields, the problems of the mathematical investigators becomes more complex, and the world has never been in greater need for more mathematics than at the present time, since civilization never before called so loudly for perspicuity in science.

It is not an easy matter to characterize briefly and yet clearly the function of mathematics in the broad field of scientific endeavor. A prominent feature of mathematical work is that it changes postulates or assumptions into different forms, which are sometimes more readily accessible for experimentation than the original postulates were or are more directly useful in the solution of other scientific difficulties. The transformation of postulates, or accepted conclusions, is not peculiar to mathematics, but is common to all sciences. In mathematics these transformations, or the results derived therefrom, serve as a means to obtain new transformations, while in the other sciences they serve as a means to wrest from nature a new truth. Mathematics is commonly guided by current hypotheses about nature in the selection of her postulates, but after these are once selected, she is interested in building up a world for herself by constructions which are necessary consequences of these postulates. If these constructions represent only a small fraction of the interesting questions which appear to become clarified by logical

processes, mathematicians are perhaps not to be blamed for their reluctance in leaving extensive developments, which seem to admit of growth in every direction, for new fields where mathematical insight appears more or less uncertain.

The mathematicians, therefore, may be regarded as the old conservative party among scientists. They are the standpatters among the scientists of to-day. This does not say that they are making no progress. On the contrary, they have made and are making rapid progress, and are entering new fields, but fortunately the world is moving ahead so rapidly scientifically that no scientific party is able to embody in its platform all the desirable new features. In times of revolution conservatism is not apt to be popular, and in the midst of the scientific revolution in which we are finding ourselves the mathematical party is naturally receiving blows which the calmer days of the future will doubtless declare to have been too severe. These blows tend at the present time to work downward into our elementary and secondary education and they ought to be matters of great concern for all scientists; for, without the clarifying influence of mathematics, the whole structure of science would suffer seriously.

In recent decades the churches of our land have tended towards unity in action and towards a higher appreciation of the merits of the great common principles. Is it not likely that what is common to all the sciences, viz., the formation of ideas and the investigation of relationships existing between these ideas, will receive more emphasis as we understand better the value of scientific work? Monopoly in science is the worst type of monopoly. Mathematical ideas have an unusually wide range, but are comparatively barren in local content, for the richer an idea is, as regards local content, the poorer it usually is as regards range.

The present movement to organize research work is strongly represented in England by the Imperial Trust for the Encouragement of Scientific and Industrial Research and the Advisory Council. In America this same movement is represented by the Committee of One Hundred on Scientific Research of the American Association for the Advancement of Science, appointed in 1914,[2] and its various subcommittees appointed in 1916, and by the National Research Council, organized on September 20, 1916, by the National Academy of Sciences at the request of the President of the United States, and its plexus of committees representing the various domains of science.[3] This movement should tend to emphasize the common ground of scientific research as well as to clarify the atmosphere by directing attention to the fact that there are many grades of scientific research. It should be emphasized that the greatest danger of research to-day is that its popularity tends to research hypocrisy.

While the common ground of scientific research can not be said to be mathematics at the present time, it will doubtless be admitted that its ideal is mathematics. In fact, this common ground consists largely in so coordinating facts of observation or deduction as to lead to certain conclusions. These conclusions are not always necessary, but with the advance of knowledge they naturally tend towards becoming necessary. As soon as the conclusions become necessary, if certain explicit assumptions are made, and are not merely very probable, the reasoning becomes mathematical. Mathematical reasoning thus appears to be the goal towards which scientific reasoning is striving, and lack of sufficient knowledge furnishes the main reason why mathemat-

[2] SCIENCE, N. S., Vol. 39 (1914), p. 680; Vol. 45 (1917), p. 57.

[3] *Proceedings of the National Academy of Sciences*, Vol. 2 (1916), p. 607.

ical reasoning is not now more commonly used in scientific research. This may serve to explain the following assertion recently made by Professor H. S. White:

Most scientists can and will become mathematicians when their special problems reach the stage where measurements are possible.[4]

It may be desirable to direct attention to the fact that the mathematician might almost be said to cease to be a mathematician when he becomes an investigator. It is true that he needs a large and growing amount of mathematical knowledge in order to investigate successfully. The flood of valueless literature contributed in recent years by non-mathematicians who endeavored to solve the great prize problem, known as the Greater Fermat Problem, has emphasized the fact that, in mathematics, as well as in other sciences,

important advances in knowledge are far more likely to issue from the expert than from the inexpert. Indeed, the probability of extending knowledge by organizations conducted by disciplined investigators is so much greater than the probability of extending knowledge by the dragnet method that we not only may but should ignore the latter in comparison with the former.[5]

The mathematical investigator can clearly not afford to forget his knowledge of mathematics, but it is questionable whether he can afford to confine himself to mathematical reasoning while he is aiming to advance his subject. He needs imagination and ability to foresee results long before his mathematical machinery has enabled him to establish them. Unless we become like children in faith and fancy, we should not expect to add much that is fundamentally new to the kingdom of mathematics. As investigators we all have much more in common than as students of what has been done by others, and this common ground naturally increases with the originality of our investigations.

This common ground of investigators may serve to explain the fact that many of the most influential research organizations, like the National Academy of Sciences in our own country, embrace all the sciences. In recent decades there has been a tendency to organize research separately in the various subjects in the form of national societies named after these subjects. In fact, there are those who think that the latter have assumed such a preponderant sphere of influence as to threaten the very life of the former as serious factors in research. On the other hand, the maintenance of a common scientific life seems to be of the highest importance in view of desirable interactions and special emphasis on what is most fundamental.

The history of mathematics has taught us that some subjects which were apparently far apart and which were long developed separately were later seen to have most important common elements. The discovery of these common elements and their development has led to marked advances in the separate fields themselves. By way of illustration I need only refer to the fields of algebra and geometry so happily welded through the work of Descartes, Fermat and many others. In modern times the theory of groups and invariants has exhibited many important connections between subjects which had been supposed to be widely separated. The same tendency has, of course, manifested itself in other sciences and may be assumed to become more dominant as knowledge advances.

A pertinent difference between the mathematical investigators and investigators in other sciences is that the former are compelled to stay with their problems until a solution is reached which can be proved to be in accord with deductions from certain definite assumptions, while the latter enjoy

[4] H. S. White, Science, N. S., Vol. 43 (1916), p. 587.

[5] R. S. Woodward, Science, N. S., Vol. 40 (1914), p. 221.

much greater freedom in regard to the stage to which they may pursue a problem before announcing results. Hence these may hope for success in dealing with much more difficult questions than the mathematician could reasonably hope to solve at the present time. The limitations thus imposed upon the mathematician are compensated, at least in part, by the finality of his results as regards questions of rigor. Mathematical results *can* never be disproved, other accepted results *have* never been disproved. With respect to simplicity and style, the mathematical developments are seldom final, and in many cases, they appear to admit endless variations.

As instances of final mathematical results may be cited the useful tables which when once computed serve all succeeding generations. Such finality may be said to be a goal of all scientific endeavor, since the results enrich countless ages by increasing their capacity for accomplishments. In fact, such tables may be regarded as typical illustrations of the mathematical contributions to the advancement of knowledge even if they constitute a very minor portion of these contributions. The fact that mathematical results have increased the capacity of the world for doing things may be emphasized by noting, in particular, that in recent years prime numbers have been found which could not have been proved to be prime by the method employed by Eratosthenes, if the entire human race had been working in an organized manner on this single problem since the days of the ancient Greeks.

The present seems to be an especially appropriate time to consider the interrelations of scientific research in view of the rapidly growing public appreciation of the value of such research. Several decades of comparative peace immediately preceding the present great and deplorable conflict were unusually rich in great scientific triumphs. As well-known instances we may cite wireless telegraphy and the construction of the great Panama Canal, which became possible by our advanced knowledge in regard to sanitation. The world-wide health activities under the auspices of the Rockefeller Foundation and the activities of our agricultural colleges in directing attention to advantages resulting from scientific methods of farming are strong forces working towards a popular appreciation of science. Since the great European war began it has become evident through the new elements introduced by the submarines and other scientific devices that the very existence of a great nation may depend upon the scientific attainment of its people, and hence the question of scientific research has taken a prominent place among those of national policy. It is perhaps significant that our National Academy was founded in the midst of the Civil War.

Scientific research is as old as civilization and has often been protected by kings in a patronizing manner, but it is a new experience in the history of the world to see kings turn to scientific research for protection. For centuries governments have recognized the value of science and have provided with growing liberality for her development, but now they are calling to her to save them from destruction. They have noticed that in spite of many excellencies in other directions the ignorance of causes may entail their destruction as separate nations. This new attitude towards our field of work may at first tend to gratify us, but a second thought reveals the fact that it is fraught with grave dangers. Kings in government and finance are interested in the dead results of science instead of in the great living and growing organism itself, whose growth seems to have just begun and whose development has always been more keenly inspired by love of truth than by hope of gain.

Is there not a danger that the sudden recognition of the great political importance of certain types of research will have somewhat the same effect on science as the discovery of gold in California and in Australia about the middle of the preceding century had on the development of the regions concerned? People flocked from one mining camp to the other and often neglected duties which are essential for the harmonious development of the resources of a country. Hence there seems to be a special need at present to urge our colleagues to remain at their posts of duty, notwithstanding glowing reports of chances to amass scientific fortunes quickly in certain newly discovered gold fields. The get-rich-quickly schemes in science should be scrutinized as carefully as similar schemes relating to the accumulation of money.

The remaining at one's post of duty in scientific research does not imply a lack of support in the solution of pressing problems or a lack of vacation trips and acquaintance with other fields of work. In fact, such support and acquaintance are highly desirable. It is, however, a question whether the nomadic scientific life, which seems to have become fashionable during the last few decades, at least in mathematics, is the one which will in the long run bring the best results. Science is not primarily a grazing country. Large tracts are suited for agriculture and mining. What is new is not necessarily good and what is good is not necessarily new, and prophesies in regard to the great importance of certain new developments have not always been fulfilled. On the other hand, it should be remembered that reasonable hope and optimism are essential for progress, and that we need prospectors as well as miners in the scientific world.

It should be noted that the miner needs some of the qualifications of the prospector since he is apt to meet with new situations and needs to take advantage of the available by-products. In fact, while he is mining for gold he may strike deposits of copper which are richer than the gold deposits which he was primarily seeking. Some of the richest mathematical discoveries were made while the investigator was looking primarily for other results, and even problems which have not been solved at all up to the present have been the source of very useful developments. I understand that similar conditions hold in other fields of scientific effort and these facts point to the great importance of freedom on the part of the investigator, and, incidentally to the danger of too much organization in scientific research.

As a very recent instance of an unexpected mathematical by-product, I may be pardoned for referring to a somewhat trivial case which has, however, the important property that it can be understood by all. It is well known that the theory of substitution groups was developed for the purpose of clarifying the theory of algebraic equations and not for the purpose of adding to the enjoyment of parties engaged in playing games of cards. In fact, the study of such an advanced mathematical theory as that of substitution groups might appear to involve concepts, which are at the opposite pole from those entering the minds of people seeking recreation at card tournaments.

Notwithstanding this apparent wide separation, I was pleased to be able to say recently to a friend, who desired to have each one of a large party play once and only once with each of the others during a series of successive games, that an arrangement of the players meeting this condition could be determined directly by means of substitutions of certain transitive groups. This should perhaps have been expected, since a transitive substitution group is an ideal republic treating all its letters in exactly the

same way. On the contrary, an operation group may have elements enjoying special privileges and hence it has more extensive contact in the actual world of thought.

A little study of the stated problem revealed the interesting fact that when the number of tables is any power of 2 the substitutions of a well-known type of substitution groups and its group of isomorphisms exhibit directly how the players can be arranged so that each one will play once and only once with, and twice and only twice against, each of the others in a certain series of games. To make myself perfectly clear, I may say that if 8 tables, or 32 players, are involved, one can write directly by means of a certain regular substitution group of order 32 a set of possible arrangements so that in 31 successive games each one of these 32 players would play once and only once with each of the others and twice and only twice against each of them. This was, however, not the first solution of the general problem in question. In fact, about twenty years ago Professor E. H. Moore published a different solution of it in Volume 18 of the *American Journal of Mathematics* under the title "Tactical Memoranda."

I have referred to this matter here mainly for the purpose of emphasizing the fact that intellectual penetration is often attended by the most unexpected by-products, but I should also be pleased to have people know that certain kinds of recreation can easily be enriched by making use of results which the mathematician developed for a totally different purpose. Science should and does enrich both work and play. More than a thousand years ago the Hindu astronomer Brahmagupta said:

> As the sun obscures the stars, so does the proficient eclipse the glory of other astronomers in an assembly of people by the recital of algebraic problems, and still more by their solution.[6]

The playful question, Where do the finger nails find so much dark dirt to put under them? may serve to arouse a thoughtful attitude on the part of the boy who has been taught to keep his hands clean. In fact, our play and recreation are perhaps as fundamentally affected by questions of science as our serious work and the victrolas and moving pictures should have a marked influence on the popular attitude towards science in view of the fact that they reach so many people. If it is true that the greatest service which science is rendering the human race is the reduction of superstition, it is clear that the efficiency of science depends largely upon its popularity.

The hypothesis that space and the operations of nature are discontinuous clearly excludes the hypothesis that they are continuous, but it is interesting to note that the mathematics relating to the discontinuous does not exclude that relating to the continuous. On the contrary, there are the most helpful interrelations between these two types of mathematics. Such a subject as number theory, relating decidedly to discrete quantities, has been greatly extended by analytic methods relating to continuous quantities, and, on the other hand, processes relating to the study of continuous functions are largely based upon those relating to the discontinuous.

This may perhaps tend to show that even if our hypotheses in regard to the continuity of space and the operations of nature have to be largely modified, as seems now probable, the mathematical methods of attack may require less modification than might at first appear to be necessary. The language which mathematics has provided for science includes not only concepts relating to the continuous and the discontinuous, but fortunately it also shows relations between these concepts and these relations

[6] H. T. Colebrooke, "Algebra with Arithmetic and Mensuration from the Sanscrit," by Brahmagupta and Bhascara, 1817, p. 379.

become more pronounced with its development.

In view of the age of this language and its contact with various sciences it may be readily understood why mathematical history occupies a prominent place in the history of science. In fact, the history of science constitutes one of the fields where scientists may find common interests most fully represented, even if the past is too rich in events to be studied completely. It may therefore be appropriate on this occasion to refer to a few recent developments relating to the history of mathematics, especially since the interest in the history of science has increased rapidly during recent decades, as is partly evidenced by the efforts that are now being made to establish an institute of historical scientific research in our land.

One of the most interesting questions relating to the early history of mathematics is the use of positional values of numbers and the closely connected use of a symbol for zero. Until a decade or two ago it was commonly assumed by mathematical historians that the use of zero as a positional number symbol originated in India, and this view has not yet been entirely abandoned, notwithstanding the fact that the Babylonians employed numbers with positional value and a symbol which seems to have fulfilled the main function of our zero several centuries before the Christian era. On the other hand, the first definite evidence of the use of zero among the Hindus falls in the second half of the first millennium of this era.

In view of these facts it is extremely interesting to note the early use of zero, in connection with numbers having positional value, by the Maya, a people inhabiting the Atlantic coast plains of southern Mexico and northern Central America. One of the worthy alumni of your university recently referred to this matter in the columns of SCIENCE in the following words:

> Special interest attaches to the occurrence of zero-symbols and the principle of local value among the inhabitants of the flat lands of Central America, at a period as early as the beginning of the Christian era, if not much earlier. It would seem that in this invention, the Maya in Central America possessed priority over Asiatic people by a margin of five or six centuries.[7]

If further investigation will lead mathematical historians to agree that the zero as a symbol in a numerical notation with positional value was actually first used in America, according to the preserved records, it will effect a very fundamental change as regards interest in the early mathematical attainments of the American aborigines. Unfortunately these early mathematical attainments failed to become the source of extensive further developments on American soil. They exhibit clearly that central concepts may be discovered independently and they direct attention to the danger in trying to establish one source for a particular concept in historical investigation. They also show that the small strip of country marked now by Boston has not always been the intellectual hub of America.

The history of some of the mathematical attainments of the Maya people has recently been made more easily accessible through the publication of "An Introduction to the Study of the Maya Hieroglyphs," prepared by S. G. Morley and published as Bulletin 57 of the Bureau of American Ethnology, Smithsonian Institution of Washington. On page 92 of this bulletin a dozen different symbols for zero are noted and on page 131 numbers varying from 21 to 12,489,781, and involving the use of zero, are represented in the Maya notation. It is of interest to note that the

[7] F. Cajori, SCIENCE, N. S., Vol. 44 (1916), p. 715.

value of a unit in a higher position is always 20 times the value of a unit in the next lower position, except in the case of the third place, where its value is only 18 times that of the second place.

In historical research and elsewhere, the mathematician seeks cordial cooperation with other scientists, and he regrets that the confusion of tongues, resembling the experiences at the tower of Babel, is making it more and more difficult to understand each other. In the case of scientists this confusion is mainly due to a rapid growth of language in various directions. May we not hope that as many theories which were supposed to be distinct suddenly exhibited profound connections, so also this extensive language will tend towards unity and simplicity as we see more clearly the fundamental underlying principles. Science knows no bounds in method or in subject-matter and the artificial limitations set by man for his own convenience in making a start must break down before the onward march of truth. All science is a unit and all scientific investigators should be inspired by their common interests.

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SCIENTIFIC EVENTS

FORESTRY ORGANIZATION FOR THE WAR

A "forestry regiment," made up of foresters, practical woodsmen, loggers, portable sawmill operators and others experienced in lumbering operations, for service in France, will, it is announced, be raised immediately. The Forest Service, at the request of the War Department, will prepare plans for the organization and equipment of the force and will aid in securing suitable men. The regiment will form a unit of the Engineer Corps now being recruited to be sent abroad as soon as it can be organized and equipped.

The organization of this regiment is the result of a suggestion made by the British Commission. Similar forces have been raised in Canada and are rendering valuable services. The object of the American forestry regiment, it is said, will be to convert available timber into material suitable for bridges, railroads, trenches and other construction work with the least possible waste. At the same time the cutting will be done under the supervision of technical experts in cooperation with the French foresters. In this way the permanent damage to the forests incident to furnishing the imperatively needed timber, it is hoped, will be kept as small as possible.

The regiment will be organized in units capable of handling all kinds of woods work and will include a number of portable sawmill outfits. It will be officered by trained foresters and expert lumbermen who are thoroughly familiar with producing and delivering lumber. It will carry complete equipment for all kinds of woods work. The classes of men desired comprise axemen, teamsters, tie-cutters, millwrights, saw-filers, sawyers, portable sawmill men, farriers, blacksmiths, lumberjacks, cooks and carpenters, as well as motorcycle and motor-truck operators. As rapidly as enlistments are secured, the men will be assembled at six central points, which have already been designated.

EXPEDITIONS OF THE SMITHSONIAN INSTITUTION

A letter from Mr. H. C. Raven recounts the collection of many kinds of wild rats, shrews, bats, squirrels, etc., made in the East India Islands. The first shipment received at the National Museum included 319 mammals and about 300 birds. Mr. Raven recently explored the central part of Borneo, thence working southward by cart and pack train, and is now supposed to be in the southern part of the island. Another collection of miscellaneous matter just received from Mr. Raven includes ethnological specimens, mammals, birds, also reptiles, shells and insects.

Mr. Arthur deC. Sowerby, who has been exploring in China for the National Museum, has not been very successful owing to the conditions there, but managed to visit Shanghai and several places on the lower Yangtze. A