PROSPECTS OF MACROMOLECULAR SCIENCE AND TECHNOLOGY

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ABSTRACT

The limits of discoveries in macromolecular science can be foreseen only with respect to their possible structures. Essentially new types of sequences of chained atoms are not expected to yield useful new polymers because of the predicted instability or inability to form discrete linear chains.

Further development of macromolecular science will be based on refinements of existing knowledge. The rate determining component in this development is the structural research which makes it possible to correlate all structural parameters with reaction mechanisms and with performance characteristics in specific uses.

It is not easy to talk about the prospects of a science if its development presents us with unexpected and surprising facts. This is particularly true for a science which is developing as fast as macromolecular physics and chemistry. New and unexpected discoveries, still within living memory, have focused this science in new directions and started fantastic new developments of technology. Suffice it to recall the polymerization of olefins and the discovery of stereoregular polymerization which followed, and which nobody—not even the authors themselves—was able to predict. However, in the long period which had preceded these discoveries, the knowledge acquired in organic and macromolecular chemistry was sufficient for the existence of stereoregular polymers to be foreseen, although nobody had the slightest idea how they could be prepared. There is no doubt that the awareness of this possibility contributed to its realization.

At present, too, we might find it useful, for predicting future developments, to consider which of the hitherto unknown macromolecular structures are possible, and which of them can be excluded on the basis of reliable and well-known facts.

Optimistic extrapolations are doubtless more appealing than pessimistic ones. There is less risk involved of damage to our reputation if we admit, with unfailing optimism, the possibilities of further conquests of science and technology in such fields where experimental facts are lacking. On the contrary, we risk being considered fools if the future should show something to be possible which we doubted, small though our doubts may have been.

In the systematics of compounds, however, we can afford to make both

negative and positive forecasts without running any great risk of being wrong. The laws of chemical bonds and chemical structures derived therefrom are such a closed and harmonic system, especially in organic chemistry, that the gaps which remain experimentally unproved in this system, can be filled in speculatively with a high degree of probability. We can estimate which groupings of atoms are possible in principle; at the same time, groupings which would be thoroughly impossible or exceedingly unstable, can be excluded with certainty. It is these negative conclusions which can be of great value for the development of science, because they help us to save efforts which otherwise would have been spent on solving unsolvable problems.

Let us therefore first try to determine the limits of possible structures which can be considered in macromolecular compounds; at the same time, let us try to find out whether a chance still remains of discovering some essentially new types of macromolecular structures.

Organic polymers, the largest category of polymers, have been developed to such an extent that their limits can be seen best. The basic polymer chains composed of carbon atoms, or polymer chains where carbon atoms prevail, have already been prepared in almost all possible modifications. Combinations of all possible atoms or groups bonded with them have been prepared in great variety. It is therefore very difficult to imagine that some polymers with essentially new properties can still be discovered. In particular, not much room has been left for extrapolation if the raw material basis of organic polymer chemistry is specified. This basis has been exploited to such an extent that no sensational changes can be expected in this direction.

According to the type of the polymer carbon chain, only one possibility still remains open: a polymer with a long uninterrupted sequence of strongly conjugated double bonds. Up to now, only two routes are known to lead in this direction: (1) subsequent formation of conjugated bonds on the polymeric chain by an elimination reaction, and (2) polymerization of acetylenic monomers. So far, they have provided us with oligoconjugated systems, instead of polyconjugated ones.

Neither of these routes was able to give rise to sequences with much more than about ten conjugated bonds. This failure does not surprise us in the case of elimination reactions. If, for instance, polyacrylonitrile is changed to the well-known 'black orlon' by the cyclization and dehydrogenation reaction. the continuity of the orthocondensation of pyridine rings must be interrupted in many places. Bearing in mind that the probability of the formation of these rings in any part of the molecule and that the probability of right-hand and left-hand cyclizations are the same, a large number of odd units must eventually remain which interrupt the continuous sequence of conjugated bonds. What happens is similar to the cycloacetalization of polyvinylalcohol when some free hydroxy groups always remain. Even if we were able, by some kind of the zip-effect, to 'unwind' the cyclization reaction from one end of the molecule to the other, the conjugation would certainly be interrupted in many places by secondary reactions. Up to the present, no elimination reactions which occur in a straight and smooth way have been developed; there is not much hope, therefore, that long polyconjugations might be discovered in other similar reactions.

PROSPECTS OF MACROMOLECULAR SCIENCE AND TECHNOLOGY

The other route, i.e. polymerization of acetylene or its derivatives, seems to be more promising, although even in this case the obstacles have not been overcome. Acetylene itself, whose properly controlled polymerization could be of particular importance, has not yet been transformed into regular polyconjugated polymers. In this case, the failure is due not to an interfering secondary reaction, but to the reactivity of the living polymer end which degenerates with the growth of the polymer. The 'living polymer end' is represented by an end carbon atom which contains either a free electron pair (in anionic polymerization), or an unpaired electron (in radical polymerization). After some ten monomeric molecules have been added to the chain the living end is no longer capable of binding further molecules of the monomer. So far, this phenomenon cannot be explained satisfactorily. The reactive end electrons are not situated in the plane of the π -electrons of the conjugated bonds, and therefore should not be stabilized with an increase in polyconjugation. Resonance stabilization could be achieved only if the end unit was distorted from the plane of the chain. If this explanation is true, then it can still be hoped that a catalytic system might be found which would prevent such torsion by the formation of a coordination complex. We should not therefore consider the polymerization of acetylene completely impossible, despite all the efforts that have failed so far.

Macromolecular polyconjugated systems seem to be attractive for two reasons. They can be expected to have high thermal stability, since this structure is a linear version of the planar graphitic structure. Even oligomers and polymers of this kind with interrupted conjugations exhibit extraordinary stability. Thus paracyanogen discovered by Gay–Lussac at the beginning of the last century, which was the first polymer of the same type as 'black orlon', can withstand heating to 800° without any substantial changes. Another property which is specific to polyconjugated polymers is their electrical conductivity. Quantum theory calculations do not exclude the possibility that the electrical conductivity of polyacetylenes with undisturbed conjugation, as well as the conductivity of linearly polycondensed polyacenes or polymers with condensed pyridine or pyrazine rings, could be very close to that of graphite.

A large group of polymers of high thermal stability, which have already acquired technical importance, are to a certain extent close to the above hypothetical structures with perfect polyconjugation. The chains of these polymers are formed by a concatenation of aromatic rings. Their stability should not of course be assigned to the conjugation of the whole chain, which is rather imperfect, especially when the aromatic rings are bonded in metaposition. Favourable effects are produced by the thermal and chemical stabilities of the aromatic chain units themselves as well as by the stability of semicyclic aromatic bonds with substituents. This is why fairly good stability can be found even with polymers, the aromatic rings of which are separated by short and perfectly isolating hydrocarbon bonds.

The rigidity of polyconjugated or mainly aromatic macromolecular chains and the corresponding high melting points and poor solubilities are causing difficulties in the processing of these polymers. It cannot be excluded that it is just this fact that may become a limiting factor in the application of polymers with more perfect polyconjugation, and that practical application

will be limited to some compromising cases only, in which better workability can be achieved by limiting the conjugation and thus reducing the stability of the polymers. In some cases a solution to this problem has been found in in the synthesis of polymeric precursors of these chains, which owing to their fairly good flexibility allow processing by current methods. The polymers in their final form are then transformed into the fully aromatic state.

An extraordinary variety of aromatic polymers has been demonstrated in recent macromolecular symposia by C. S. Marvel, whose collaborators have largely contributed to the development of the above category of polymers. There is no doubt that the route to obtaining further polymers of practical importance is still wide open, and that, in the future, not only improved types of thermostable aromatic polymers will be synthesized, but also the preparation of intermediates will be developed so that their wider use need not be restricted by high prices. It would be wrong, however, to expect some qualitatively new effects, despite the large research effort in this field as reflected in the wide scope of scientific and patent literature. Up to now, research work has proceeded in a rational manner, taking the line of least resistance towards the maximum issue. In these systems, the stability of organic polymers at 600°C in an inert atmosphere and at 400°C in air will probably not be exceeded too much. This is the limit of thermal stability of the aromatic rings which constitute the chains of these polymers.

It is worth considering the prospects of monomers with a multiple bond between the carbon and some other stem, for instance, C=O, C=N, C \equiv N or N=O, O=O.

The encouraging success of the polymerization of formaldehyde has aroused hope that other carbonyl compounds may also be applied in a similar manner. Now we can say with full responsibility that this hope is very poor. Formaldehyde holds, with respect both to its polymerization and to all other addition reactions (for instance, easy hydration) an extraordinary position among simple carbonyl compounds. This is why it is the only one among them that is able to form a polymer which is thermodynamically stable at room temperature. The ceiling temperature of its polymerization is 137°C, whereas acetaldehyde already has this limit as low as -40° C. This is one of the reasons why the polymers of acetaldehyde and of all higher aldehydes lie beyond the region of practical applicability, owing to their low stability. The polymers of acetone are situated even further in the same series. Those which were eventually prepared at very low temperatures decomposed spontaneously and very rapidly as soon as room temperature was reached. Even if we were successful in stabilizing polyaldehydes or polyketones to an acceptable degree, for instance by applying some chemical stabilizers, which seems very improbable indeed, we still could not expect them to have any extraordinary properties, by which they might differ from the more stable analogous polymers. Polyacetone for instance could not have mechanical and other properties essentially different from those of polyisobutylene or silicone rubber.

It can be stated unequivocally that the carbonyl bonds present in carboxylic acids or carbonic acid derivatives will be fully incapable of forming polymerization chains, owing to their conjugation with neighbouring atoms. Carbon dioxide, which would surely be the cheapest monomer, is no exception; we can be certain that it will never be polymerized to the carbonic acid polyanhydride of even minimum stability.

It cannot be denied, however, that some of these unsuccessful 'monomers' may become successful comonomers. Even the idea of the polymerization of carbon dioxide, absurd as it sounds in itself, does not exclude the possibility of incorporating carbon dioxide in a polyethylene (or some other) polymeric chain in the form of an ester group. After all, an oxygen or ozone molecule can be incorporated into the chain between other monomer units, or the N=O bond of nitrosotrifluoromethane can be introduced between the units of tetrafluoroethylene.

Addition, and thus also polymerization, properties of the carbonyl bond can be induced by adding atoms or groups having an electron-acceptor character. The pronounced tendency to polymerize observed with chloral is in agreement with the general reactivity of its C==O bond. Even in these polymers, however, no outstanding properties of practical value can be expected which could compete with more stable and easily available analogous polymers whose chain consists of carbon atoms only.

The same sceptical attitude can be assumed when considering polymerization possibilities of the other polar bonds between light atoms.

A common feature of organic polymers and of most inorganic compounds can be seen in the fact that they do not consist of small molecules. An overwhelming majority of these inorganic compounds, however, have no molecular character at all. In contrast with organic macromolecular compounds, most inorganic compounds cannot be characterized by discrete polyatomic particles. Neither can there be found polyatomic segments which would be bound rather loosely in a three-dimensional network, as is the case in organic gels. The huge majority of inorganic compounds are monolithic groupings of atoms which are able to form more bonds than are necessary for the simple formation of linear chains. This is why we cannot see in them any structural continuity in the sequence of polymers, low-molecular weight oligomers or model compounds, as can be found with organic polymers.

The main reason for this difference lies in a limited ability to block in a stable manner the excessive binding capacity of heavy 'inorganic' atoms. In particular, atoms which in organic chemistry form the surface of molecules, for various reasons fail to block the bonds of inorganic atoms.

The hydrogen atom, which is a strong ligand of the carbon atom and therefore an ideal surface atom of organic molecules, fails to be a ligand for all other atoms capable of chain formation. The covalent bonds of hydrogen with positive atoms of semi-metals or even of metals, are too unstable to be able to resist, as C—H bonds do, the usual atmospheric conditions, oxygen and humidity.

Halogens also can be end, or surface, atoms of organic molecules. Their bonds with more positive heavy atoms can have even higher thermal stability than carbon-halogen bonds. On the contrary, however, they too can be easily eliminated by the effect of air humidity. This elimination occurs by a polar mechanism; the same mechanism allows them to change places too easily with other ligands which have the same polar bonds. For all these reasons, halogens, too, are not suitable to cover the surface of inorganic molecules in a stable manner.

Finally, we can also exclude the remaining atoms which form surfaces of organic molecules by being bound by multiple bonds, namely, oxygen with a double bond and nitrogen with a triple bond. All heavier atoms are marked by their inability to form stable multiple bonds of the same type as carbon, nitrogen and oxygen. If such bonds were to arise somewhere, we would usually find, instead of them, oxygen or nitrogen as bridges between the heavier atoms.

A comparatively good blocking of inorganic bonds can be achieved by using hydrocarbon groups, methyl for instance, which can have satisfactory thermal and chemical stabilities if bonded with some heavy atoms of a less positive character. The most favourable conditions for this type of blocking were found with the silicon atom, which is close to the carbon atom by reason of its magnitude and low positivity. The C—Si bond is therefore almost equally stable towards homolytic cleavage as is the C—C bond. At the same time, it is fairly resistant to heterolytic cleavage, in contrast with the Si—H bond, which is easily subjected to hydrolytic cleavage.

This is where the unique success of the siloxane-type chain macromolecular compounds arises. Their excellent thermal stability is based on the high energy of the polar Si—O bonds, which form the backbone of siloxane macromolecules. This advantage, however, is compensated by the decrease in their stability towards nucleophilic agents which is due to the polar character of these bonds and to the substitution mechanism, started by the penetration of the nucleophilic agent in the 3d-orbitals of the silicon atom. Despite the uniform type of the polysiloxane backbone a wide space is left for the variations of organic groups bonded to the silicon atom; it still provides chemists with many opportunities of pursuing this theme for a long time, purposefully investigating interesting technical effects.

However, an expansion of the macromolecular chemistry of silicon beyond the region of siloxane chains can hardly be expected. In the confrontation of silicon with the chemistry of carbon it is necessary to eliminate all the analogies of organic compounds with the multiple bonds of carbon. At the same time, we should also eliminate all the silicon analogues which would necessarily require intermediate products having multiple bonds of the silicon atom. This limitation in itself leaves us with only a small fragment of organic chemistry to which an analogy can be found in the chemistry of silicon. A further limitation is caused by the low energy of the Si-Si bond which is not sufficient to render polymers, based on the chain formation of silicon atoms alone, a practically important analogue of any polymer with a purely carbon chain. So polymers of this type can also be cancelled from the programme of macromolecular chemistry because there exists no possibility of the preparation of monomers which would be an analogy of organic monomers with the C=C bond. Still another obstacle, already discussed in general terms, is the instability of the Si-H bonds which could produce an uncontrolled crosslinking as easily as the effect of air humidity.

If we investigate the possibility of blocking excessive functionalities in inorganic atoms other than silicon, we arrive at similar though much more pessimistic conclusions. Their bonds with the end atoms or with organic groups are even less stable. With an increase in the metallic character the energy of covalent bonds goes on decreasing. If these atoms are bonded by

PROSPECTS OF MACROMOLECULAR SCIENCE AND TECHNOLOGY

thermally stable polar bonds to negative atoms, the bonds are even more liable to a nucleophilic attack, for instance by hydrolysis, than similar bonds of silicon. For these reasons, the most promising method of blocking bonds of these atoms is seen in an oxygen bridge to the silicon atom, all three remaining bonds of which are blocked with methyl groups. This sophisticated trick has allowed us to prepare polymeric organometallosiloxanes and organometalloxanes, the basic chains of which can be derived from the siloxane ones by a partial or total substitution of silicon with aluminium, titanium, germanium, tin, chromium or antimony, followed by blocking of the excessive bonds of metals with $-O-Si(CH_3)_3$ groups.

For the preparation of stable macromolecular compounds containing phosphorus as an essential unit of the main chain, the same limitations are valid as have been given above for the heavier positive atoms. Virtually no homo-chains consisting of phosphorus atoms only can be considered; neither can we consider any compounds with P-H bonds, since in both cases the bonds are very unstable and can easily be substituted or rearranged. When speaking about organic macromolecules, the chain-like macromolecular derivatives of phosphoric acid, salts of metaphosphoric acid, and some chain-like compounds with alternating atoms of phosphorus and nitrogen are among the most frequently cited. For them all, however, it is true that their bonds are too easy to substitute with nucleophilic agents and undergo a spontaneous reorganization of bonds. Even polymeric phosphonitrilic chlorides which represent the only completely non-carbon elastomer rapidly lose their elastic properties under the effect of moisture, owing to the hydrolytic substitution of chlorine atoms with oxygen bridges, which in turn leads to an uncontrolled crosslinking.

Boron itself, which departs completely from the series of heavy atoms, cannot be expected to contribute considerably to the building-up of polymeric backbones. Its B—B, B—C and B—H bonds are also very unstable; for the B—O and B—N bonds it is also true that they undergo rearrangement and substitution too easily, like the bonds of other semi-metallic atoms with negative atoms.

From what has already been said about the prospects of finding some basically new types of macromolecular compounds it can be concluded that there are not many unexploited opportunities left. Attention is therefore drawn to the elaboration and refinement of findings collected so far. In macromolecular science, as in other branches of science, empiricism preceded deeper knowledge, especially in the first phase of its development. Unexpected and surprising discoveries, which marked the new stages in the development of macromolecular chemistry and signified dramatic, if not revolutionary, changes in technical practice, although they fit logically into the preceding findings, were made by chance and as a rule have their roots in some research aimed at completely different goals. It was not Karl Ziegler's goal to synthesize polyolefins when he was studying aluminiumorganic compounds, but these syntheses would not have been discovered without Ziegler's works. Similarly, silicone polymers would probably not have been discovered at all, had they not been preceded by the pioneering experimental work of Frederick S. Kipping, who decided—out of pure scientific curiosity—to carry out the synthesis of an optically active compound with an asymmetric silicon atom,

not having the slightest intention of producing a plastic, although polymeric silicones were forming there on the spot, instead of silicoketones.

At a more advanced stage, sciences no longer grow via unexpected discoveries; much more important is systematic work which completes and develops the findings already acquired. It seems that macromolecular science has already passed beyond this romantic and extensive period and finds itself in the phase of intensive development.

The first condition for a systematic and thorough study of polymers, their properties, formation and transformations is an objective knowledge of their structure in the greatest possible detail. To characterize polymers fully we need to have their structure investigated on all levels. As to their basic chains, it is necessary to know the constitution of structural units, and if there are any asymmetric units, also their configuration. At the same time important information can be obtained on the conformation of the chain segments. Besides basic structural units, atypical units at the end or in the branching point of the chains, as well as various defective points, are also important for the chemical properties of polymers, for instance for their degradation. Their analytical treatment is particularly difficult, owing to their low concentration. On the molecular level, the polymer structure must be characterized by molecular weights and their distribution, by the degree and type of their branching; three-dimensional polymers must also be characterized by the length of their segments and by their distribution. On the supermolecular level, the type of aggregation of macromolecules is of importance, and in crystalline polymers their degree of crystallinity and crystal structure have to be determined.

To obtain information on so many structural parameters, about the same number of independent methods of investigation must be mobilized: thermodynamic methods, infra-red, ultra-violet, and Raman spectroscopy, mass spectroscopy, nuclear magnetic resonance, electron-spin resonance, gel GPC permeation chromatography, diffractometry, light scattering, sedimentation, rheology and microscopy.

The common interests of scientific research and technological development will go on promoting the expansion and refinement of these methods of measurement and providing a more perfect, theoretically well-founded interpretation of the results thus obtained. How far we still are from accurate and reliable results, can be illustrated by the confrontation being carried out at present concerning the data on the structure and performance characteristics of standard samples of some industrial polymers. The data were obtained in tens of laboratories all over the world; and in connection with this collaborative programme performed in the Macromolecular Division of the IUPAC by the working groups of Professors J. W. Barrett and H. Benoit it should be pointed out that there is a surprisingly large scatter of results even in the molecular weight values, and even if one and the same method was used.

As analytical tools are increasingly improved, more and more rational processes can be introduced into the projects of macromolecular research, along with empirical methods which have been prevailing till now. Chemical processes, by which macromolecular compounds are formed and transformed, leave traces in the structure of macromolecules which can be revealed

PROSPECTS OF MACROMOLECULAR SCIENCE AND TECHNOLOGY

by analytical structural research. This therefore becomes an important guide of chemical research.

The analytical approach to macromolecular systems is of great importance for their classification and standardization. At present, a series of empirical or semiempirical tests for the characterization of polymers seems to be indispensable in their practical applications. If the performance characteristics thus obtained are then correlated, or replaced, by the appropriate structure data, the optimum properties of polymers for a given application could be achieved by the most direct route.

In a continuous extrapolation of the existing trend the programme of structure research will be determined not only by the internal needs of the macromolecular science itself and by the goals of the related industry, but also—in the field of biopolymers—by incentives which will be continuously provided by biochemistry and biology.

A similar systematic research programme can be expected for the decades ahead in the synthetic, i.e. chemical proper, part of macromolecular science. If we assumed that there are not many opportunities left in the synthesis of macromolecular compounds for discovering basically new structure types. it should be added, however, that there still remains a vast field for applying well-known methods in the preparation of an unlimited number of modifications of the known types. Besides, it cannot be excluded that new processes might be found which would not only allow better control of the synthesis of known polymers, but which could also lead to the preparation of types of polymers not yet synthesized. Even with polyvinyl chloride, which still holds its leading position among plastics and which is produced in an amount of several millions of tons a year, the steric control of its polymerization process has not yet been fully developed, although an important change in the properties of this polymer can be expected from a change in its tacticity. Moreover, not all possibilities have been exhausted which might reduce the number of defect structures in its molecule responsible for its comparatively low thermal stability.

If not all modifications of polymerization have been exhausted in the case of a single monomer, how much more numerous opportunities are offered by their combinations. Even as regards the simplest and most accessible monomers, nothing like all the possibilities of copolymerization have been exhausted. This can be exemplified by the copolymers of ethylene with polar monomers, vinylacetate or acrylates, which represent the beginning of a technologically important series of easily accessible materials having new and continuously varying properties.

With increasing knowledge of relations between structure and applied properties of polymers, and with the development of new polymerization processes, more and more occasions arise allowing the preparation of polymers 'tailored' according to the required properties and specific functions of the polymer. The application of synthetic materials goes on expanding into the regions of special conditions and complicated functions. We have already mentioned thermoresistant materials. Special types should be developed for outdoor exposure, for ensuring stability towards special kinds of mechanical impact, against chemical corrosion, biological attack, etc.,

always bearing in mind thermal extremes which might occur in the service of these materials. Along with the existing practice where new applications of a given polymer have been looked for, initiative is being shown, in a still increasing manner, on the side of possible applications asking for new types of materials.

Instead of presenting here an objective review of examples of such a reasonably reversed initiative, I would like to give an example which is familiar to me and which seems to be illustrative. What I have in mind are biomedical materials. They are designated for intimate contact with living tissue and should therefore fulfil some conditions which are not fulfilled satisfactorily in conventional plastics. To achieve maximum tolerance by living tissue, along with the corresponding mechanical properties and stability in a biological medium, we postulated the highest possible permeability for water-soluble compounds and absolute absence of extractable compounds, foreign to the body. Sparingly crosslinked polymers and copolymers of glycolmethacrylate, which were synthesized according to these demands and which are, in equilibrium with the living tissue, strongly plasticized with water, do actually have the expected tolerance. If for some types their antithrombogeneous properties are confirmed, it could mean significant progress in vascular and heart surgery.

On the whole, the substitution of biological materials with synthetic ones has many attractive and inspiring aspects. We have every right to expect that besides mechanical functions, it will also be possible to simulate some other isolated biological functions. For instance, we can imagine implants which would be able to act as kidneys, even though it were a simplified and onesided function. In this case, too, as in similar cases, success is bound to the condition of finding a suitable material for such a specific function.

We can be sure that biological systems and functions will permanently inspire macromolecular research. In a far and optimistic perspective it can be admitted that macromolecular systems might be attained which would be able to catalyse and selectively control chemical reactions, like enzymes do. This does not mean necessarily a pure copying of the enzyme structures; it could be, at first, the simulation of a very small section of their functions. It cannot be excluded that it might be possible to get free from the biological original to such an effect that macromolecular specific catalysts could also be applied to non-aqueous media. And just because the research of bioanalogous polymers will not involve a simple copying of biological functions, but would consist in the preparation of simplified models of living material, the recognitions thus obtained might contribute to the understanding of complex biological processes in living systems. This, too, is one of the reasons why the Macromolecular Division of the IUPAC has included into its programme interdisciplinary cooperation with the IUPAB.

The sophisticated organism of a technically developed society will more and more be in need of giant analogues of living organs, which would help its complicated metabolism. If technical civilization is not to provoke increasing pathologic changes in our environment, the air in our towns and continents will need its lungs, and our waters will need their kidneys. Without giant kidneys capable of an economical desalination of sea-water, desert cannot be prevented from spreading farther. High polymer science and engineering are expected to solve tasks of tremendous importance; these tasks seem to be real, although the process of solving them has scarcely started.

The tremendous development of macromolecular technologies and the increase in the number of macromolecular research centres related to its, as well as their growing activities, seem to be a sufficient proof of the importance of macromolecular science as a research discipline. Solutions of most of the macromolecular problems, both pure and applied, requires teaming-up of various specialists. We have here a research field which is not uniform as to the methods applied, but has an interdisciplinary character. It is unified by its object, whose methodology involves many branches of chemistry, physics and biology. With such a large spread of interest, research cannot be pursued otherwise than by concerted efforts of specialists trained to use experimental methods with the best results and to have a profound understanding of the data obtained. The common target of their efforts thus becomes for them a means of understanding.

In this situation, it would be advisable to reflect upon the role played by education whose task it is to prepare new generations of specialists for macromolecular science and its practical applications. This is even more important since about half the chemists who are at present graduating at universities will in their further career be working in fields more or less connected with macromolecular science.

A natural development, corroborated by these external forces, should lead to an infiltration of the specific problems and interests of macromolecular science into all basic subjects taught at the schools of chemistry. There already exist universities where professors of organic chemistry, physical chemistry and physics have focused their attention on the topics of macromolecular science. They not only provide their postgraduate and postdoctoral co-workers with an opportunity of scientific research in this field, but also train their undergraduates so as to enable them to make rapid progress in macromolecular science.

In spite of, and at the same time due to, the rather rare occurrence of this possibility, it seems correct to insist on the establishment of independent departments of macromolecular science at universities. Their raison d'être should be seen in that they should not only recapitulate and promote knowledge of macromolecular systems for application purposes, but should also be expected to act upon their own school so as to shift the trend of teaching of the fundamental theoretical subjects towards the chemistry and physics of polymers.

The Macromolecular Division of the IUPAC intend to give continuous attention to the problems of education. A document on the present state of macromolecular education prepared by Professor G. Smets will provide the first detailed information on a world-wide scale. When it is completed with data on the countries which are rather slow in providing them, this document will constitute interesting evidence of the great progress that macromolecular science has also achieved in the field of chemical education. At the same time, it will be an incentive for this development to accelerate, to make universities and other schools involved in chemistry education keep

step better with the tremendous development of macromolecular theory and practice.

On the whole, it can be said that in the programme and internal structure of the IUPAC the development of chemical sciences and their applications is being recorded with high sensitivity. The IUPAC is also trying to react in a flexible manner to the continuous recrystallization of these sciences. In the last few years, we have been particularly aware in our Union of the fact that one of the most important topics of international cooperation is increasingly to be seen in such groupings of science and technology which owing to their complex methods acquire an interdisciplinary character. Macromolecular science and technology are a typical complex of that sort, requiring international contacts between individual scientists and individual laboratories.

The traditional Macromolecular Symposia, which have been organized for more than two decades by the Union, have grouped together research workers with macromolecular interests to form a large international family. It was in these Symposia that interesting and useful international activities originated, which were later realized with the help of the IUPAC committees. The incentives to a statutory promotion of these activities have come from the same source. By the decision of the conference held in Prague in 1967 macromolecular science and technology were constituted to form a single independent Macromolecular Division. This was in a certain sense a symbolic move, by which the Union manifested the importance of this science; in the first place, however, it was a concrete step taken to provide the combined efforts of macromolecular chemistry and technology with an even better tool for international cooperation.

It is a great privilege for me to be allowed, on behalf of this new Division, to welcome this Congress and particularly its macromolecular section.