Bridging Gaps Among Scientific Disciplines

Paper Presented on IIASA's 20th Anniversary

Contributors: V. Koptyug, J. Ahearne, W. Weidlich, and P. Weaver

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Contents

Foreword

IIASA celebrated its twentieth anniversary on May 12–13 with its fourth general conference, *IIASA '92: An International Conference on the Challenges to Systems Analysis in the Nineties and Beyond.* The conference focused on the relations between environment and development and on studies that integrate the methods and findings of several disciplines. The role of systems analysis, a method especially suited to taking account of the linkages between phenomena and of the hierarchical organization of the natural and social world, was also assessed, taking account of the implications this has for IIASA's research approach and activities.

This paper is one of six IIASA Collaborative Papers published as part of the report on the conference, an earlier instalment of which was *Science and Sustainability*, published in 1992.

Professor Koptyug's paper is written from the viewpoint of a chemist, but of one who has an unusual consciousness of error in estimates of some of the vital parameters affecting the environment. He finds a variation of 100 percent between the low and high estimates of absorption of carbon dioxide by the oceans, and adding that to the similar variation in estimate of emissions and related quantities he ends up with a four-fold variation between the lowest and the highest rate of accumulation of carbon dioxide in the atmosphere.

Yet the paper does not argue from this that we should do nothing until we know more. We know in what directions we have to move as we try for stability, and are learning something about directions we should not try. A lesson was learned in this latter sense from the building of a dam across a bay in the Caspian Sea in order to reduce evaporation. The story is that with the agricultural and industrial development along the Volga River the level of the Caspian Sea fell by three meters between 1933 and 1977. It was hoped that the dam separating off the Black Jaws Gulf would counteract the withdrawal of water from higher up. But there seems at the same time to have been a flow of water of unknown origin into the Caspian Sea. The Gulf dried out by evaporation, while the Caspian Sea rose a wholly unanticipated 13 centimeters per year. Such a rise was disastrous for people living along the coast, and the dam is now to be destroyed.

For me the lesson is not that we should never do anything about the environment, but rather that we should look very closely and be very sure of our knowledge base before we try smart tricks with the planet in the hope of neutralizing the effects of irresponsible industrialization. One such smart trick that was fortunately checked before it started to be built was the diversion southward of four major rivers that flow into the Arctic Ocean. No one has any way of estimating what unanticipated results might come from that, what uncontrollable positive feedback loops it might initiate. These are among the things I have learned from Professor Koptyug's paper.

Committee for IIASA '92
Nathan Keyfitz (Chair)*

*Members of the Committee for IIASA '92 were: Nathan Keyfitz (Chair), Peter E. de Jánosi, Alexander Kurzhanski, Arkadii Maltsev, Nebojša Nakićenović, Roderick Shaw, Claudia Heilig-Staindl, Evelyn Farkas

Bridging Gaps Among Scientific Disciplines

Valentin Koptyug

This meeting is devoted to the 20th anniversary of the establishment of the International Institute for Applied Systems Analysis as an institution for international interdisciplinary studies of complex problems. It seems desirable to remind you of another noteworthy event held 20 years ago – the United Nations Conference on the Human Environment (Stockholm, 1972). In this connection it seems remarkable that we celebrate IIASA's 20th anniversary on the eve of the United Nations Conference on Environment and Development that will take place in Rio de Janeiro this year in June.

In my opinion, these coincidences are not accidental, and therefore the directions of IIASA's activity for years to come may be considered as predetermined by an historical process. It is evident that the role of systems analysis as applied to global environmental problems and to the realization of the sustainable development conception will significantly increase. Analyses and prognoses relating to processes in the environment, to technological achievements, economic processes and social life should serve as landmarks on the way to global sustainable development.

At present it is evident that the globality of problems lying on the way to sustainable development requires that the tendency for deep specialization of science typical of the 20th century is overcome. Entering into the 21st century, we should pay much more attention to inter- and multidisciplinary research than we have done

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Siberian Branch, Russian Academy of Sciences, Moscow, Russia.

earlier, to the integrated study of the whole Earth system that is being affected by human activity.

Goals and difficulties in the integration of scientific disciplines were discussed in detail in the course of the Bergen Conference on Sustainable Development, Science and Policy [May 1990, Norway (The Norwegian Research Council for Science and the Humanities, 1990)], at the ASCEND-21 Conference (November 1991, Vienna), and at some other conferences and workshops. Therefore, I will focus my report on some aspects of the approaches that are being used by basic (natural), environmental and socio-economic sciences to reveal some regularities in the processes under investigation and on some organizing measures that could stimulate inter- and multi-disciplinary research for bridging gaps between scientific disciplines.

Since scientific prognoses will be more widely used by governments and local authorities in the process of preparation and adoption of important political and economic decisions, the requirements for the reliability of such prognoses will increase greatly, too. At the same time, the world community needs prompt answers to many global questions. So, science turns out to be under the pressure of two factors – time and reliability.

In this connection, the Bergen Conference included the following general statement in its Executive Summary:

> ... it will be better to find out we have been roughly right in due time than to be precisely right too late.

This thesis can be accepted only if we understand the words "roughly right" to be an indication that the main moving forces of the process under consideration are recognized, a predicted tendency of its evolution is correct, but some doubts remain as to the rate of this evolution. A crucial requirement for such a situation is the assurance that all the most important factors affecting the process are recognized. If there are any doubts in this respect it is necessary to be careful when making any prognosis since the consequences of the wrong prediction can turn out to be very expensive. We should be especially considerate in making environmental prognoses on the basis of current tendencies, specifically observed by the methods of one scientific discipline, since many (not all, of course) natural processes have a complicated periodical character.

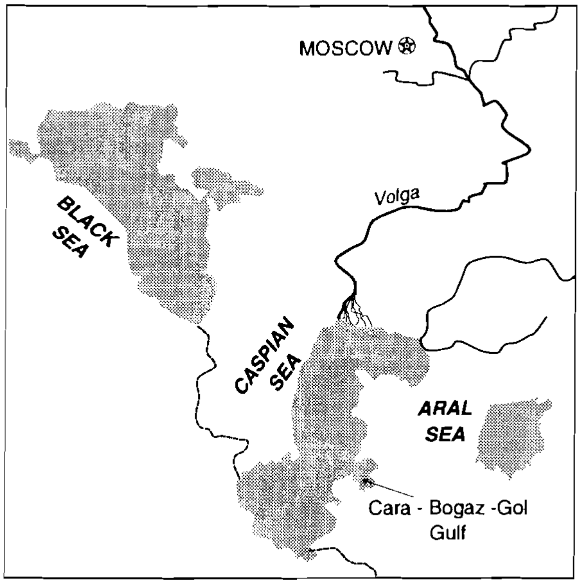


Figure 1. Seas in the southern part of the former Soviet Union.

An impressive example of wrong predictions may be the prognosis of expected changes in the water level of the Caspian Sea which was made by hydrologists in the middle of the 1970s on the basis of the observed tendency.

The Caspian Sea is an enclosed lake (*Figure 1*). Regular observations in the period 1830–1970 indicated that its mean level was 26 m below the open sea level with fluctuations of ± 1.5. These fluctuations were explained by the climatic influence on the balance of the water influx (first of all through the Volga river) and evaporation.

From 1933 to 1977 the level of the Caspian Sea decreased (with periodical oscillations) 3 meters compared with the mean value. It is important to note that a fall in the level of the Caspian Sea by 1 meter means the loss of 400 cubic kilometers of water. Such an enormous decrease in the sea level was explained by the increased use of water in the last forty to fifty years in the Volga river basin as a result of the rapid development of industry and irrigating agriculture. It is evident that this factor ought to diminish the water influx in the Caspian Sea. But to what extent? Assuming this factor to be the main one, and in order to prevent many negative consequences due to the enormous decrease in the sea level, it was proposed to compensate for the irrevocable water consumption in the Volga basin by partially diverting some northern rivers in Russia to the south into the Volga River basin, and simultaneously diminishing the loss of water from the sea through evaporation by the separation of the Cara-Bogaz-Gol (Black Jaws) Gulf from the Caspian Sea.

The first proposal was not realized due to strong public opposition. But the dam between the Cara-Bogaz-Gol Gulf and Caspian Sea was built in 1980, and by now the gulf has lost most of its water through evaporation.

Meanwhile, the Caspian Sea, in spite of the anthropogenic impact, began to rise in 1977 at the rate of 0.13 m per year, and at present the situation is becoming catastrophic for the coastal areas. As a consequence, the decision has been taken to destroy the dam between the sea and the gulf. But the problem is far from being settled.

At present we cannot predict how the situation will develop. However, it is evident that:

- Anthropogenic effects in this case were overestimated in comparison with the natural variations.
- In addition to the influx of rivers and the loss through evaporation, some other factors greatly influence the level of the Caspian Sea.

Among the additional factors, it seems reasonable to consider tectonic processes leading, for example, to the rise of the sea bed. At the same time there exists a semi-fantastic hypothesis that tectonic processes have opened an underground channel between the Aral Sea and the Caspian Sea. As the water surface of the Aral Sea lies 70 meters higher then the Caspian Sea, the underground water flux causes the catastrophic lowering of the Aral Sea level and simultaneous enormous rising of the Caspian Sea level.

By the way, the hydrologists who predicted the further falling of the Caspian Sea level and proposed the corresponding counteractions were sure that they were "roughly right in due time".

I believe that the success of systems analysis when applied to the problems of the environment and development is determined by the following requirements:

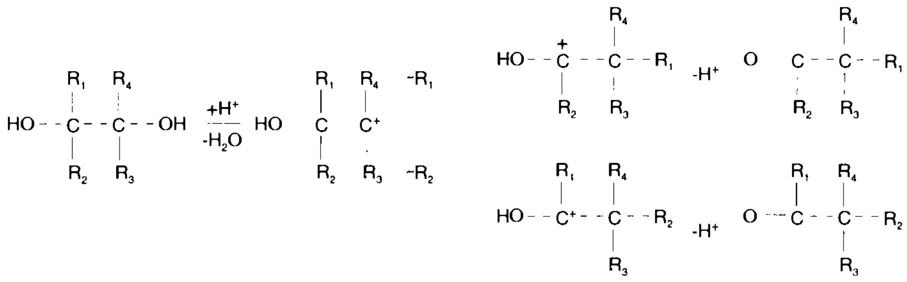
- Recognition of all the most important factors affecting the process under study.
- Clearing up of regularities on the effect of each of these factors, and in their mutual interactions.

The recognition of a number of critical factors that determine the complex behavior of a system under investigation, and the understanding of regularities in their effects should be the most important goals of the analysis, rather than the modeling of a large number of interacting factors. The main feature of science lies in the following statement – real understanding of a process or phenomenon (with the exception of systems having inherent uncertainties) usually leads to very simple equations describing their dynamics or evolution.

In many branches of the natural sciences a systematic approach to the recognition of the main factors and clearing up of regularities may be made easier by simplifying the objects under investigation by excluding some influential factors.

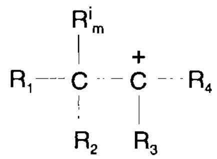
I would like to demonstrate this idea with an example taken from my own work in the area of carbocation chemistry (V. Koptyug, 1984).

There exists a very interesting type of chemical reaction – rearrangements of molecular structures under the influence of acid catalysts proceeding through the intermediate formation of carbocations. In simple cases such rearrangements are connected with the migration of a substituent from one position in a molecule to another. Since the beginning of this century chemists have been trying to reveal the relationships between the molecular structure and the rate of molecular restructuring. They believed it possible to construct a row of migration abilities of various substituents by comparing competitive migrations of pairs of substituents:



However, this attempt failed. The reason for the failure is evident – the competitive migration of substituents R_1 and R_2 proceeds on different backgrounds (when group R_1 migrates, we have group R_2 among other substituents in the skeleton and vice versa), and therefore the rates for two directions of rearrangement are incomparable in principle.

Taking into account this failure, the chemists decided to compare migrating abilities of various groups on the background of the same skeletons:

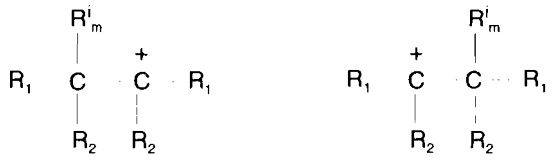


$$\mathrm{RMA}\,(R^i_m) = \frac{k(R^i_m)}{k(R^o_m)}$$

In the framework of this approach, rows of relative migrating abilities (RMA) were constructed for several skeletons, but the obtained rows turned out to be incompatible with each other.

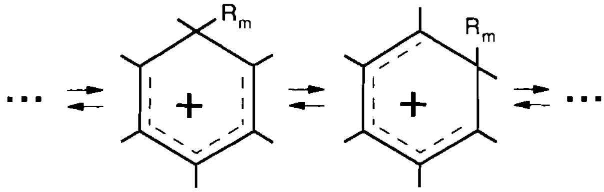
The reason for this is evident again. Any modification of the skeleton leads to a change in thermodynamic parameters of the reaction, since the difference in thermodynamic stabilities of the initial and final carbocations has been changed, and this factor disturbs a sequence of migrating abilities.

Thus, there was only one way to reveal regularities in such types of processes – it was to study the relative role of each factor separately; for example, to exclude the thermodynamic factor first, which means that the initial and final structures must be identical:



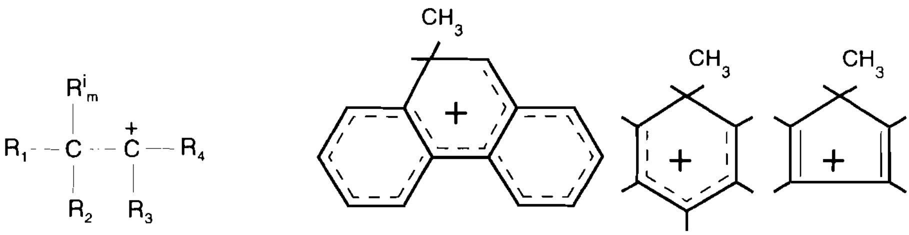
These curious types of reactions (chemists call them "degenerate") may have no practical application but are very interesting from the methodological point of view.

An opportunity to observe and to study degenerate rearrangements appeared 25 years ago as a result of the development of the nuclear magnetic resonance method. Using this method, we measured the rates of degenerate rearrangements of a series of substituted arenonium ions with various skeletons and migrating groups:



The results of this study permitted us to compare separately the data relating to the variations of the molecular skeleton and of substituents.

The migrating ability of a substituent very strongly depends on the type of the molecular skeleton:



k(0°), sec^{-1}: $> 10^9$ 7×10^3 8×10^{-2} 10^{-18}

However, this dependence is quite simple – the crucial factor is the value of a positive charge in the position to which the substituent migrates (*Figure 2*).

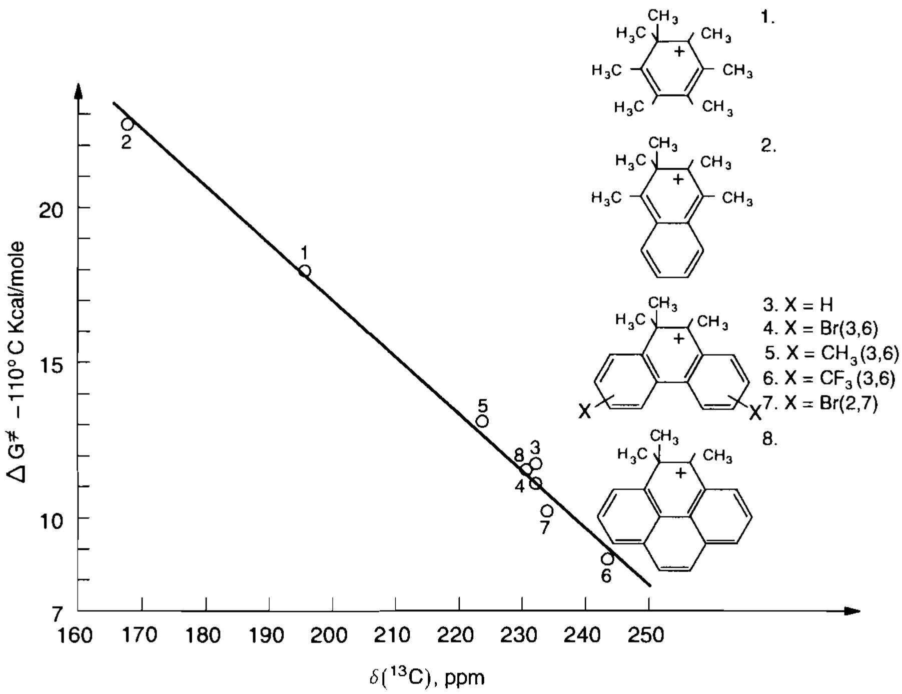
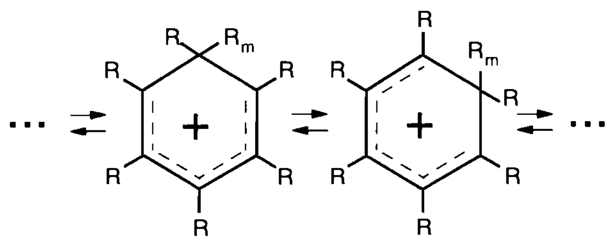


Figure 2. Linear dependence of the free energy of the methyl group 1,2-shifts on the value of the positive charge measured by ^{13}C-NMR spectra.

If now we look at the data relating to the degenerate migrations of various substituents on the background of the same skeleton we see a great variation in rate constants again:



$R = CH_3$

R_m	Br	H	NO_2	SO_3H	CH_3
k(0°), sec^{-1}:	2×10^6	3×10^4	8×10^2	2	8×10^{-2}

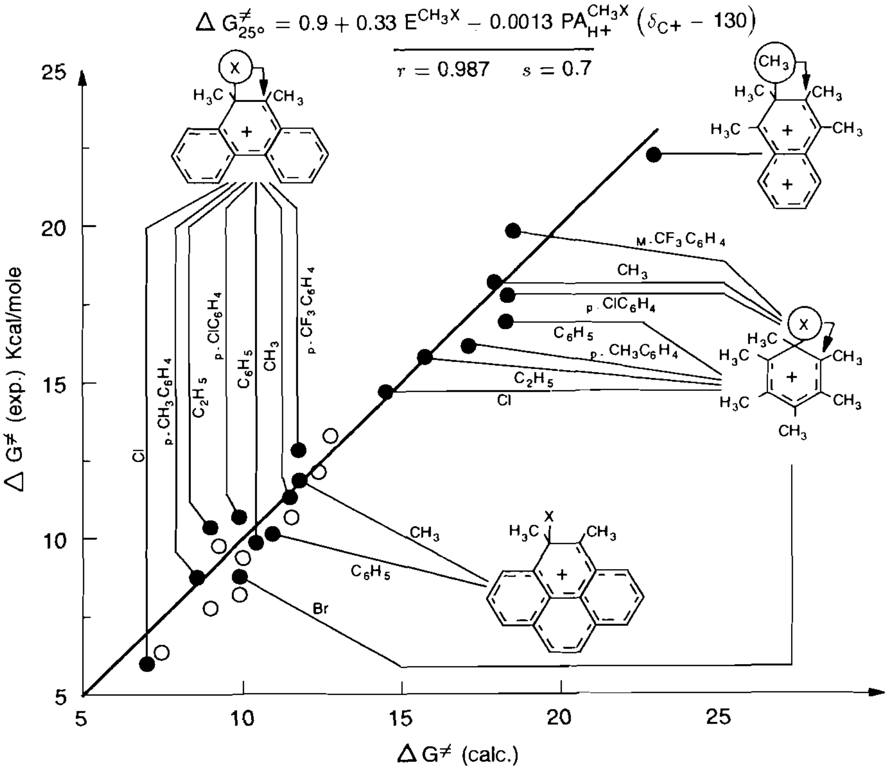


Figure 3. Correlation of calculated and experimental free energies of methyl 1,2-shifts for various arenonium ions.

Again the decisive factors are very simple – the strength of the C–R_m bond and the affinity of substituent R_m for positively charged centers.

Combining the revealed regularities, we arrive at the possibility of describing degenerate migrations of various substituents in different carbocations by one equation (*Figure 3*).

For the transition from degenerate processes to usual ones it was necessary to take into account the influence of the thermodynamic factor. This was done using the so called Marcus' relationship, and we made it possible to describe many practically important reactions quantitatively, i.e., isomerizations of aromatic compounds under the influence of acid catalysts.

This chemical digression from the main issue allows me to stress some differences in the application of a systematic approach to the objects and processes studied in basic research in the natural sciences, and to global environmental and socio-economic problems. In both cases we should take into account the influence of many factors. However, in the first case there are usually the following possibilities:

- To modify an object or process under study in order to separate effects of various factors.
- To receive a response on each modifying action very quickly.

Getting a quick response for the second case is impossible, as a rule, and the separation of effects of various factors is also very complicated.

These circumstances partly explain difficulties that are typical for environmental and social studies devoted to revealing and checking some regularities or equations dealing with the interactions of demographic changes, land use, industrialization and consumption. Therefore, the forecasting accuracy of such regularities and equations are usually weaker compared to those which involve physical, chemical or biological phenomena.

Difficulties connected with the clarification and estimation of the relative role of the main factors lead to various uncertainties in modeling global environmental and socio-economic processes. As a result, our estimations of potential risks are usually uncertain to some extent too, and may be changed over time. Therefore it is not easy to be "roughly right in due time".

It is a duty of each scientist to draw attention to every type of uncertainty relating to the factors that determine the process under study (insufficiency of reliable data, inadequacy of understanding, uncertainty inherent in a phenomenon). The International Union of Pure and Applied Chemistry (IUPAC) has purposefully initiated a set of projects on uncertainties concerning some chemical aspects of environmental problems. The first of them, "Assessment of Uncertainties in the Projected Concentration of Carbon Dioxide in the Atmosphere" was proposed with the allowance for the possible impact of the increase of CO_2 concentration in the atmosphere on climate and realized jointly by the IUPAC Commission on Atmospheric Chemistry and the Netherlands Energy Research Foundation (NERF).

Four main sources and sinks of CO_2 were analyzed by the international interdisciplinary team under the leadership of Dr. Sjaak Slanina and Dr. Peter Okken (1991).

They believe that the following overview of fluxes can be given at present:

1. Emission by the use of fossil fuel – 5.5×10^{15} g C per year. The uncertainty is of the order of 5 to 10%.
2. Emissions (loss of uptake) by deforestation and changes in land use. This flux is much more uncertain and estimated to be of the order of 1 to 2×10^{15} g C per year.
3. Uptake in the oceans that is quite uncertain. The most probable range is between 1 and 2×10^{15} g C per year.
4. Uptake by CO_2 fertilization (growth of vegetation is enhanced at higher CO_2 concentration). This flux could range from 1 to 3×10^{15} g C per year.

Thus, the uncertainties in the estimation of fluxes 2, 3 and 4 are too large. Let us consider two extreme cases:

- Lower limit of total emissions (6.5×10^{15}) and upper limit of total uptake (5×10^{15}) give an excess of emissions over uptake of 1.5×10^{15} g C per year.
- Upper limit of total emissions (7.5×10^{15}) and lower limit of uptake (2×10^{15}) give an excess of 5.5×10^{15} g C per year.

One can see that the difference in the rate of accumulation of CO_2 in the atmosphere for two extreme cases is near the ratio 1:4. It is evident that the more detailed investigations of fluxes 2, 3 and 4 in the framework of multidisciplinary approaches are necessary in the future.

The second project "Uncertainties in the Projected Concentration of Methane in the Atmosphere" is financially supported by NERF, IUPAC and IIASA. A special interdisciplinary workshop on this issue will be held this year in Moscow.

In relation to this radiative active gas, it is necessary to stress that until recently not enough attention has been paid to such potentially important sources of methane emission to the atmosphere as deposits of "gas hydrates" – solid inclusion compounds of methane in an expanded crystal lattice of ice. Such compounds of small molecules exit only at elevated pressure and low temperatures.

Deposits of methane hydrate are discovered in the bottom sediments of shelf zones in oceans and seas. There are data indicating that such deposits exist also in continental permafrost areas. The total amount of methane in gas hydrate deposits is estimated to be 10^{16} cubic meters. Expected climate change should change global thermal fluxes in oceans and seas, and, as a result, thermobaric conditions at the bottoms of shelves. This, in turn, can lead to the decomposition of gas hydrates and the emission of methane into the atmosphere, further increasing the "greenhouse effect".

The problem of gas hydrates as a possible source of methane emission is now included in Russia's national program "Global Changes of the Environment and Climate". In the framework of this program a multidisciplinary project has been launched in field experiments and modeling behavior of gas hydrate deposits under the conditions of a changing climate.

Thus, in the case of methane we have uncertainty not only in the estimation of the effects of various factors (sources of emissions), but also in the recognition of a full set of potentially important factors.

It seems possible to conclude that in relation to many global environmental problems we do not have enough experimental data for revealing regularities that are necessary for reliable predictions. These gaps can be eliminated only by organizing broad international interdisciplinary research collaboration in corresponding areas. Fortunately, at present the integration process of the world scientific community is developing fast enough.

It is my opinion that there is a somewhat better situation with regard to the data in some areas of socio-economic problems, where we have enough statistical data. In spite of a great number of factors which are active in some cases, it allows the recognition of very interesting regularities in the development processes. To give examples, I would like to mention some regularities in the technological

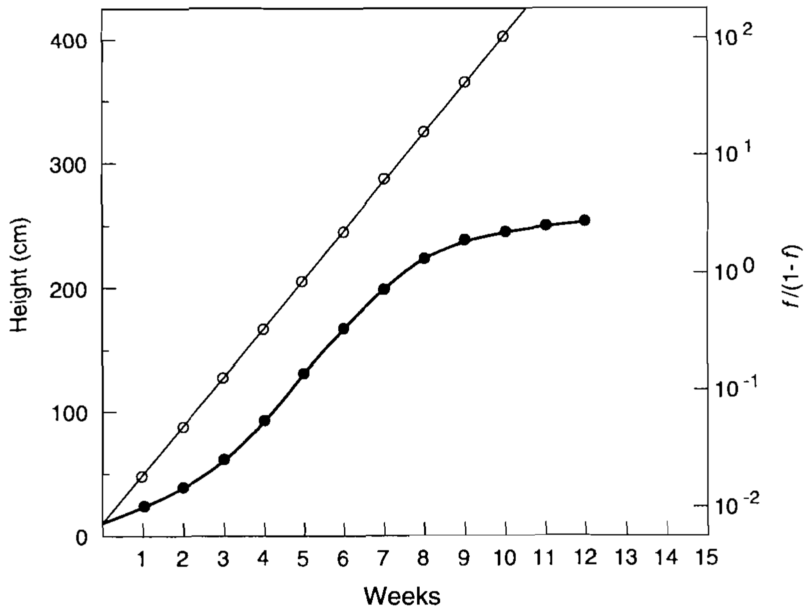


Figure 4. The growth of a sunflower (measured by height, $h_{max} = 2.6$ m).

development and replacement of technologies described in Jesse H. Ausubel's paper (1989).

It was noticed that in many cases the development of socio-technical systems is similar to the development of biological systems described by S-shaped functions (*Figure 4*) that could be linearized through the function $f/(1-f)$, where f is a ratio of the current measure of growth to its maximal value.

In comparison, *Figures 5* and *6* demonstrate the development of major transport infrastructures in the United States in terms of percentage of the length of the final saturation level. They show that the development of technical systems proceeds in a way similar to biological organisms through the stages of birth, rapid growth, stabilization and senescence.

Usually, new technologies are in market competition with old ones for an "econiche", and this leads to changing technologies.

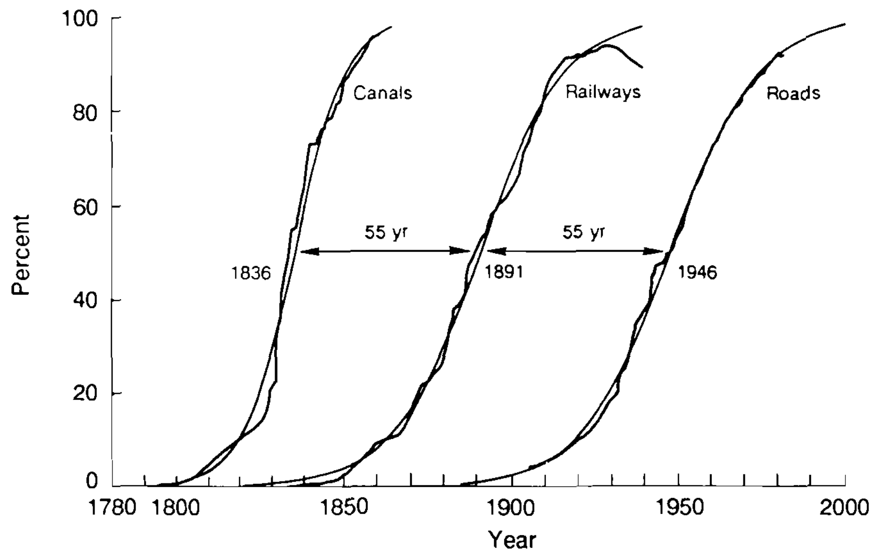


Figure 5. Growth of major transport infrastructures in the United States in terms of percentage of length of the final saturation level. (Source: Grübler, 1988; taken from Ausubel, 1989.)

Figure 7 shows this in respect of using primary energy sources in the United States.

In both cases a lot of factors are operating simultaneously, but all of them are covered by two laws – the law of growth and the law of substitution by new generations of technical and technological solutions. Other interesting examples are shown in *Figure 8*.

All of these examples demonstrate that there exists the possibility of revealing quite simple regularities in cases of very complicated multi-factoral processes and multi-dimensional systems, if we have good sets of reliable primary data. Therefore, the reliability of our diagnoses and prognoses in relation to global problems of the environment and development to a great extent depends on the accessibility of reliable data. The formation of such databases is one of the important goals of interdisciplinary international collaboration, which in turn is an evident requirement for the world scientific community on the threshold of the 21st century.

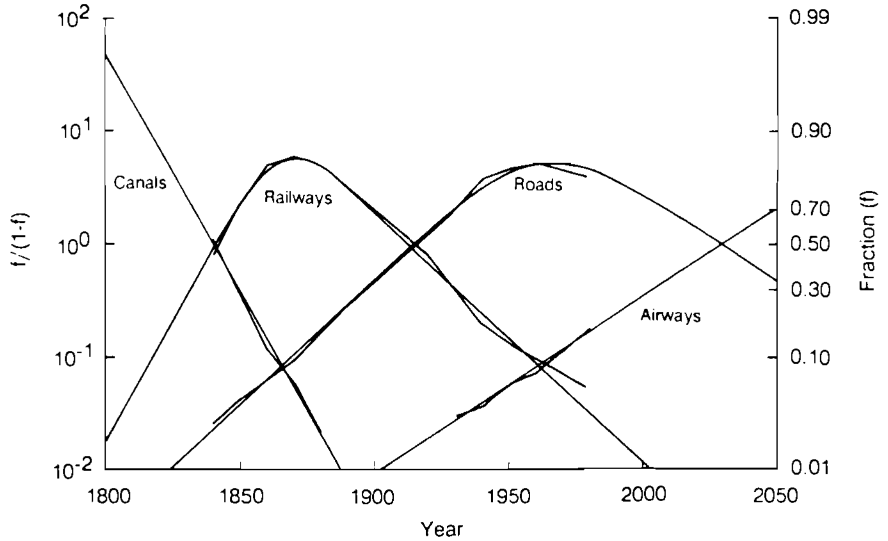


Figure 6. Shares of total operated intercity route mileage of competing transport infrastructures. (Source: Nakićenović, 1988; taken from Ausubel, 1989.)

Some interesting possibilities for the accumulation of data relating to the effects of some selected factors on the environment and on the health of populations are opened up by the studies of less industrialized regions.

If we compare, for example, the fallout of sulfates in Europe and around Lake Baikal, we see that it is almost impossible to find clean areas in Europe. On the contrary, in the Baikal basin polluted areas are to be found mainly locally, this is explained by the low density of industry in this basin. The exceptions are the industrial districts of Irkutsk and Ulan-Ude. In the other areas there are only some isolated plants (point sources of emission). This situation permits the detailed study of the negative effects of monofunctional (for example, pulp and paper) industrial productions.

Regular measurements of the degree of pollution of the Lake Baikal basin and monitoring the environment furnish the data that are very important for testing various models of the transport and

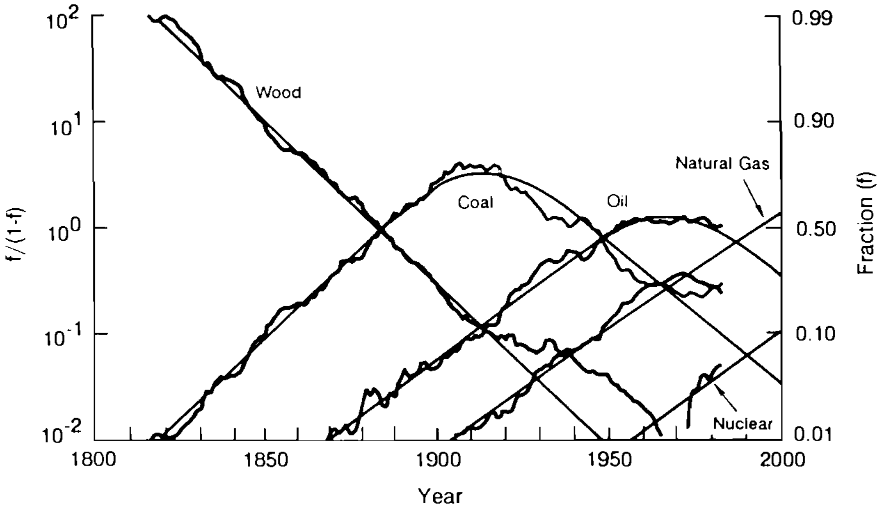


Figure 7. Primary energy substitution in the United States. (Source: Grübler and Nakićenović, 1988; taken from Ausubel, 1989.)

transformation of pollutants, and for the elucidation of specific industrial impacts of various branches of industry on human health.

We could use the areas of natural geochemical anomalies in the same way for the estimation of the long-term effect of various elements on human health and heredity. We know quite well the acute effects of many chemicals at high concentrations and have enough information on the exposure to medium concentrations of toxic substances in connection with the problems of safety at work places in industry. However, the long-term effect of low concentrations (higher than background but near to permissible) is a rather difficult problem for ecotoxicology. Reliable information for such cases could be received through the examination of people's health at medical and genetic levels in non-industrialized areas of natural geochemical anomalies with a simultaneously detailed bio-geochemical study of these areas.

For example, several years ago a joint team of specialists in geology, hydrology, geochemistry and biochemistry, medical science, etc., was organized by the Siberian Branch of the Russian Academy

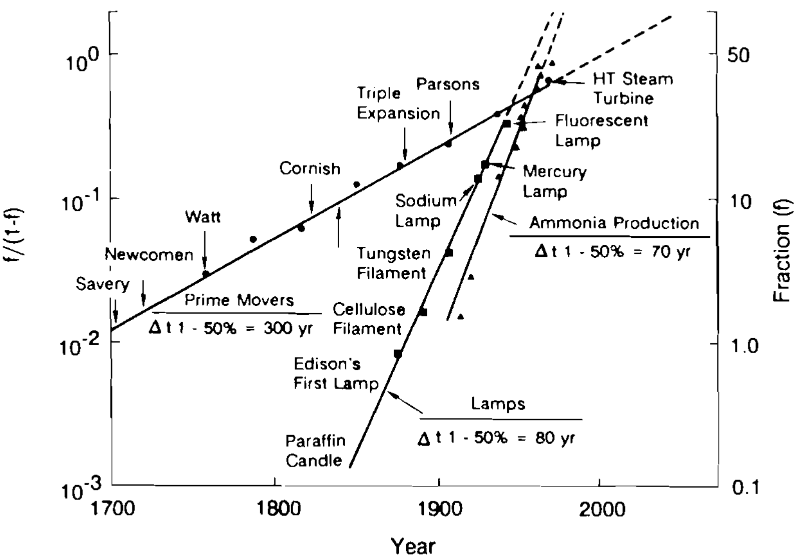


Figure 8. Increasing energy efficiency of prime movers, lamps and ammonia production. (Source: Marchetti, 1983; taken from Ausubel, 1989.)

of Sciences in order to study the situation in the Altai Mountain region located near the Russian and Mongolian borders and characterized by broad distribution of mercury ores.

Projects of this type are mainly carried out by national research groups. However, methodological assistance and inspection by international organizations (WHO, SCOPE, IUPAC) are very desirable in order to guarantee the reliability of analytical and medical data and outlined conclusions for the world scientific community. We should hasten to carry out these kinds of investigations because in 20–25 years it will be difficult to find non-industrialized or mono-industrialized areas.

In 1988, UNESCO and IUGS decided to organize an International Geochemical Mapping project as a contribution to environmental studies, to be managed through the Geological Correlation Program (Darnley, 1990).

As a response to the demands for reliable environmental data, programs of unprecedented scope, such as the ICSU "International Geosphere-Biosphere Program: A Study of Global Change" were proposed and launched. Programs of other international organizations (SCOPE, UNEP, UNESCO, etc.) complement the core projects of IGBP, emphasizing the technological, socio-economic and educational problems of sustainable development.

The efficiency of these programs will depend on the application of systems analysis, and on the coordination of interdisciplinary efforts at national and international levels within each program and between all the programs together. The problem of coordination was specially discussed in the course of the preparatory work for UNCED. Thus, one of the documents of the UNCED Preparatory Committee (A/CONF. 151/PC/36, item 7) emphasizes:

> It would be important ... to examine ... existing institutional arrangements and consider needs for supplementing and/or strengthening them and, in the case of non-United Nations organizations, of strengthening their cooperation and coordination with the United Nations.

IIASA could be considered as one of the top level nodes of the world structure supporting international, interdisciplinary research. But we should also have a network of regional nodes. Therefore, the Statement of the Second World Climate Conference (November 1990) calls for

> a special initiative that would create a network of regional interdisciplinary research centers, located primarily in developing countries and focussing on all the natural science, social science and engineering disciplines required to support fully integrated studies of global change and its impacts and policy responses ... and to study the interaction of regional and global policies.

Within IGBP, such an initiative will be realized within the framework of a core project "Global Change System for Analysis, Research and Training" (START).

The necessity of creating special regional networks that could later be integrated into the world system for coordination of environmental studies, and for the support of sustainable development, was recognized in the Siberian Branch of the Russian Academy of Sciences three years ago. As a result, several international research centers were organized in Siberia within the framework of a special program as open laboratories managed scientifically by the International Councils. The list of these centers includes:

1. Baikal International Center for Ecological Research
2. Altai International Center for Humanitarian and Biospheric Research
3. International Center for Closed Ecological Systems
4. Siberian International Center for Ecological Research of Boreal Forests
5. International Research Center for Northern Territories Development
6. Siberian Center of Solar-Terrestrial Physics
7. Siberian Center of Synchrotron Radiation
8. Siberian Tomography Center
9. International Center for Catalysts Characterization and Testing
10. Siberian Center of Aerophysical Studies
11. Siberian International Center for Regional Studies
12. International Scientific Center of Socio-Ecological Problems of the Lake Baikal Basin
13. International Center of Coal Research

The areas of their activities are described in a special booklet presented to this conference.

Let us take, as an example, the Baikal International Center for Ecological Research. Lake Baikal is the most ancient (20–30 million years), the deepest (maximal depth is 1632 m), one of the largest (20% of the world's fresh water) and the cleanest lakes in the world. Baikal is inhabited by some 2000 species, 2/3 of which are endemic, i.e., they do not occur elsewhere on Earth. The bottom sediments of Lake Baikal (up to 6 km) bear the record of Central Asia paleoclimates of many millions of years.

The Baikal International Center arranges joint research work among scientists from Russia and other countries on many topics, including:

- Multidisciplinary studies of the ecological system of Lake Baikal, applying methods of classical and physico-chemical biology, hydrochemistry, hydrodynamics, climatology, applied mathematics, limnology, satellite and other methods of remote sensing.

- Studies of mechanisms and chronology of the formation of endemic biological species of Lake Baikal by methods of classical biology, molecular genetics, biochemistry and paleolimnology.
- Multidisciplinary geological, paleogeographic, paleontological, geochemical studies of the history of Lake Baikal as a scenario of geodynamic processes with a special emphasis on global change, etc.

The Baikal International Center for Ecological Research is located in Irkutsk city (which is west of the southern part of the lake). On the opposite coast (southeast of the lake), in the city of Ulan-Ude the International Scientific Center of Socio-Ecological Problems of the Lake Baikal Basin is at present being organized.

The interaction of these two centers should bridge the gaps between studies relating to the problems of Lake Baikal based on the approaches of both natural and socio-economic sciences.

Research work by international, interdisciplinary teams within the framework of the above-mentioned 13 open centers is supported by the entire scientific potential of the Siberian Branch of the Royal Academy of Sciences. In this connection I would like to mention that throughout the territory of 10 million square kilometers our Siberian branch possesses 9 regional interdisciplinary scientific centers which unite over 100 research institutes collaborating with Siberian universities and institutes belonging to the Siberian branches of the Russian Academy of Agricultural Sciences and the Russian Academy of Medical Sciences. Thus, Siberia could be characterized as a region with good conditions for bridging gaps between scientific disciplines.

At present, a program designated "START Starts in Siberia" relating to the IGBP START Project is prepared for launching. Within the framework of this program we intend to use an existing research network for the integration of regional efforts with the efforts of the world scientific community, in order to intensify studies on the problems of the environment and development on the basis of a multidisciplinary approach.

We hope this attempt will be successful.

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Discussion

John F. Ahearne

The topics of this conference, challenges for Systems Analysis in the '90s and Beyond, and of this particular session, the Unity of Scholarship and Action, are appropriate in celebration of IIASA's 20th Anniversary. Professor Valentin Koptyug's paper addresses issues which are at the heart of IIASA's studies.

IIASA's studies have many unique characteristics. Two recent examples can be cited to indicate these unique features. These are "Saving Swedish Energy Policy: The Intelligence of Public Participation", by Ragnar E. Löfstedt (1992) and "A Comparative Assessment of Different Options to Reduce CO_2 Emissions", by Sabine Messner and Nebojša Nakićenović (1992).

Löfstedt's paper addresses the difficulties faced in Sweden by several pressures:

"The confluence of outside events, domestic politics, existing policies, and subsequent policy decisions, have brought Sweden face to face with the following energy dilemma: (*a*) nuclear power may be phased out in Sweden by 2010, if not sooner; while (*b*) no more free flowing rivers will be harnessed for hydropower purposes; (*c*) fossil fuels cannot be used to replace the electricity lost as this will substantially increase carbon dioxide emissions, which the government has pledged to stabilize by the year 2000; (*d*) other renewable energy sources do not seem to be economically viable or acceptable by the larger utilities; (*e*) energy conservation is an alternative that has already been widely implemented; while (*f*) the importation of electricity is not in the long term a lucrative alternative as it is

Sigma Xi, The Scientific Research Society, NC, USA.

likely that all excess electricity in Scandinavia will go to the highest bidder" (pp. 7–8).

This is a short, succinct description of the problems and the author notes that these problems combine technology, economics, and politics.

Furthermore, Löfstedt goes on to discuss problems related to expanding energy conservation and renewable energy sources: "Renewables could replace the remainder [of electricity needed] with projected price increases ranging from zero to over 200%" (p. 10). Löfstedt notes "This wide range of price change depends upon the person/organization creating the scenario" (p. 10). Thus, Löfstedt gives a neutral description but focuses attention on the large uncertainties in proposing that renewables are the answer to Swedish energy problems. In addressing how these problems could be solved, he notes, "energy policy makers must understand that the environment, the economy, and energy use form a unified system" (p. 12). Bringing these together is a good description of systems analysis and obviously is the way that system analysis must be applied in "the '90s and beyond".

Löfstedt writes with the frankness that has characterized many IIASA reports. He is quite critical of some of the policy approaches. He writes: "The former Center Party leader ... devised fantastic non-nuclear electricity scenarios.... Academicians have also advocated energy policies with little practical feasibility ... politicians disregard of public opinion ... most political decisions take place behind closed doors with little input from the public" (p. 13).

Löfstedt's is a short paper, concisely addressing major problems in one of the member countries, and written with frankness and knowledge.

Similarly, the CO_2 paper brings in the requirements of interdisciplinary work and addresses some of the major problems. Messner and Nakićenović note that "The burden of the developing countries is two-fold. They both need to increase their per capita energy consumption in order to improve the quality of life and are also more vulnerable to adverse consequences of climate change. While industrialized countries are in a better position to achieve emissions reductions they are also in a better situation to respond and adapt to climate change" (p. 2). The authors comment that "The main part of the research project at IIASA focuses on comprehensive assessment of a broad range of *options* (technologies, associated economic incentives and institutional frameworks for their implementation)..." (p. 3). They note that "the first results indicate that overall energy efficiency would be nearly doubled by application of the most efficient technologies available today" (p. 3).

The problems facing the world today require interdisciplinary work, research and the resulting scholarship, and finally, action – as the title of the session states: "the unity of scholarship and action".

There are examples of the kinds of problems upon which systems analysis in this interdisciplinary work should focus. I will give two. The first comes from the proceedings of a conference held by Sigma Xi in November, 1991 [*Global Change and the Human Prospect: Issues in Population, Science, Technology, and Equity*, (Sigma Xi, 1992)].

The summary of the conference presents eight major points that emerged during this forum. I have summarized them to identify issues that require interdisciplinary systems analysis.

1. Global Trajectory: "...the projected quality of human life on Earth in the 21st century and beyond is determined by the great forces of population growth, poverty, economic development, technology, and environmental stress". These must be addressed together, requiring interdisciplinary work.
2. Global Progress: "Progress has been made in some parts of the world on some global change problems.... Science and technology offer new options for solving human problems".
3. Poverty: "...poverty is stark for many – more than a billion people – and health problems and strains on resources are still enormous. ...the strains on the environment may be unbearable unless new approaches are found for development. The issues of human development and environment are inextricably linked".
4. An Equitable and Sustainable World: "...the mere recognition of global problems is not enough. These problems are in urgent need of attention, before they progress beyond our control....

[This] will require decades of effort by individuals and governments, but the task is possible".

5. Partnerships: "Partnerships are needed between industry and government, between the public and private sectors, between society and the research community, between the northern and southern hemispheres. ... Growing interdependence among the nations of the world is giving added validation to the concept of a global community...." Most of these features have characterized IIASA's work during its first 20 years. The challenge as we move into the next 20 years is to incorporate the southern hemisphere into IIASA's work.
6. Breaking Barriers: "Barriers must be broken between regions – North and South, East and West – and between countries".
7. Economic Development: "Environmentally sound industrial growth is required for economic development.... Population stabilization will require economic development and an equal role for women in society". These issues have been and are continuing to be addressed by some of IIASA's work.
8. Professional Tithing: "People are willing to work at local levels and in professional associations.... Among valuable activities, members can ...initiate public discussion of these topics". Obviously, to have good public discussion of these topics, there must be good materials, such as those developed by IIASA.

I do note that one of the recommendations made in the Sigma Xi proceedings is "that regional networks such as START ...reflect the interdependence of environment and human development". One of academician Koptyug's recommendations (p. 14) is to advocate "a core project 'Global Change System for Analysis, Research and Training' (START)".

Academician Koptyug's paper begins with reference to the United Nations Conference on Environment and Development (UNCED) and notes, "The role of systems analysis as applied to global environmental problems and to the realization of the sustainable development conception will significantly increase". It is exactly this UNCED conference that the forum from which I quoted was developed to address.

A second major area in which interdisciplinary systems analysis will be important is that of energy, for example, nuclear power and the radioactive waste generated by nuclear power plants. Addressing the radioactive waste problem will require involvement of science:

- To address the radiation effects, particularly low-level radiation epidemiology.
- To examine the transfer of radionuclides into the environment.
- And to scrutinize questions of the disposal advantages of spent fuel versus reprocessed waste.

Such studies also will require economics: examining costs of storage and the cost of disposal.

Such studies must include technology: they will require a detailed look at the technologies of reprocessing. For example, the Russian Federation is writing a new law for radioactive waste disposal in which one of the critical issues is whether or not reprocessing should be required. Russia must study many issues regarding reprocessing. Is there an economic advantage? Is there a scientific advantage? Is there an environmental advantage?

Radioactive waste is just one example of the broad scale problems of the environment that must be addressed, which include environmental damage, cleanup from pollution, and protection of both the environment and of individuals.

These examples, global change, radioactive waste and general environmental protection require the intersection of science, economics, and public understanding (as well as the understanding of the public). This last brings in sociology and psychology.

These are systems analysis topics. The world's problems are severe. They are here now, and they loom darkly in the future. We need multidisciplinary work. We need many cultural perspectives. But we also need facts and rigorous analysis. Therefore, systems analysis will be needed. In particular, we need scholarship, then action. IIASA is a particularly unique organization for this work. For example, sustainable development is a term that was perhaps originated here, at IIASA, by Bill Clark. It is now understood that we must go beyond sustainable development. The type of systems analytic work which IIASA has demonstrated and which academician Koptyug recommends will be critical for this "going beyond". I should note that "systems analysis" is not a term, at least in the US, that has only one clear meaning. However, the concept of doing interdisciplinary work, of recognizing that there are strong similarities among scientific disciplines in their approach to problems, in seeking understanding – all of these are facets of whatever definition one would use for systems analysis.

Finally, I note that there are two problems which must be addressed. First, academic institutions maintain barriers between disciplines. The boundaries between departments are sometimes so strong that they cannot be crossed. It is possible, however, to work around, across, or even through these barriers. This interdisciplinary work can be done much better in institutions like IIASA.

The second problem, which is a very big challenge as we address major world problems, is that there has been softness in some analysis. We must avoid letting what we want to be true to determine the analysis. Under pressures from funders, from the public, from political leaders, even from governments, analyses can be warped or conclusions reached on weak grounds. Academician Koptyug has used his basic area of carbocation chemistry to provide a discussion framework. The natural sciences, such as chemistry, are quite harsh in their elimination of errors. A reaction occurs or it does not. An experiment can be repeated to demonstrate whether the original result was correct. Much systems analysis does not have that easily checkable attribute. Therefore, the analyst must be ever on his or her guard to ensure rigor and use of the best possible data. As Academician Koptyug notes, we do have to avoid delaying: "...it will be better to find out that we have been roughly right in due time than to be precisely right too late" (quoting the executive summary of the 1990 Bergen Conference). However, we also must ensure that we are roughly right.

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Discussion

Wolfgang Weidlich

"... it will be better to find out we have been roughly right in due time than to be precisely right too late."

Professor Valentin Koptyug's paper is organized around this statement and gives a thorough analysis of the possibilities of its realization. His result – clearly, the following requirements are necessary:

- Recognition of all most important factors affecting the process under study.
- Elucidation of regularities (meaning the dynamics) in the effect of each of these factors and in their mutual interaction.

However, the realization of these requirements is different in natural science and on the other hand in more general (e.g., socio-economic or socio-political) problems of system science. In natural science – as Koptyug demonstrates in the case of his own work in carbocation chemistry – it is possible to separate influences and to study each factor separately. Thus he showed in an example how to compare separately data relating to the influence on rate constants of variations of molecular skeletons and of substituents in the case of certain sequences of chemical reactions.

This procedure is, however, not possible in cases where no systematic experiments can be made, where an uncertainty of parameters is given, and where the most influential factors are not yet known. (For instance, in the case of the oscillations of the level of the Caspian Sea, the relative weight of influential factors is not yet

University of Stuttgart, Stuttgart, Germany

known at all, and as a result wrong predictions were made.) Typically, in social science also no experiments can be made! Koptyug concludes in view of the different structures of different problems:

- That it is the duty of each scientist to draw attention to the type (and magnitude) of uncertainties referring to the factors that determine the process under study.
- That international, interdisciplinary research is necessary to improve the data basis, wherever the uncertainty of data are the reason for uncertainties in predictions (this corresponds to the case of CO_2 increase where the uncertain estimates of production and absorption of CO_2 lead to a difference of 1:4 in predictions).

He sees international, interdisciplinarity collaboration as the most important goal for the 21st century. Even now there exist more fortunate cases in socio-technical systems, where relevant socio-economic predictions can be made, in spite of a great number of active factors in complex situations. As an example he mentioned the case of the development of socio-technical systems governed by a sequence of innovation and substitution processes, where the famous S-shaped logistic evolution function yields a surprisingly exact prediction of the evolution, as demonstrated in the case of the evolution of transport systems or primary energy sources in the United States.

Rapporteur's Report

Paul M. Weaver

1 Toward Broad Redefinition

It is easy to describe and explain the "gap" problem referred to in the workshop title. It is easy, too, to entreat for interdisciplinarity [see Frank (1988) for a review of experience to date in trying to achieve interdisciplinarity and Gvishiani (1988) on how the founding of IIASA and the promotion of systems analysis generally fit in relation to these attempts]. However, it is much harder to construct models in which the concepts of two or more disciplines are applied and actually intermesh. It is also becoming harder to generalize concepts and approaches among disciplines. Can we, nonetheless, suggest devices that may help these processes along and, more particularly, highlight areas where interdisciplinary studies would likely be most fruitful and yield new options for policy makers? Workshop participants took a normative approach to these questions, organizing their remarks around two broad recommendations.

1.1 The reframing of problem issues

Interdisciplinarity and constructive consensus will only come from a reframing – a redefinition – of problem issues, which depends upon a willingness to tackle real problems and a preparedness to conceptualize relevant systems of interest:

- as ones likely to transcend several disciplinary domains, and
- in non-divisive terms.

Environment and Development Project, IIASA, Laxenburg, Austria.

There was clear consensus that interdisciplinary study and approaches are possible but that interdisciplinarians as such are a rare, if not mythical, breed. The prevailing view was that interdisciplinary studies are possible only by bringing together an appropriate combination of specialists. This places initial emphasis firmly on defining the bounds of the problem without disciplinary presumption of what these might be. If a problem can be conceptualized in these terms, there is a greater probability of bringing together the mix of specialists who can contribute to its analysis and solution.

However, the additional requirement is that each of these specialists be sufficiently open-minded to contribute creatively, not only from the standpoint of his/her own disciplinary approaches and assumptions but from those of other disciplines. This demands that each scientist be willing to recast his/her analysis and to propose options that would be sound under such a presumption. The engineer, for example, would not presuppose that a technological solution, in principle capable of meeting a defined engineering need, would automatically be socially and culturally acceptable. He would rather seek solutions that would better fit with known social and cultural constraints. Meanwhile, the sociologist might work on ways of relaxing such constraints. The powerful tools of economic analysis would be applied with the supposition that biologists are right in believing that there are immutable environmental bounds; the biologists would work with the presumption that resources must be exploited for human benefit and so suggest areas of R&D that would expand those bounds.

In much the same way, there is a need to redefine problems so that they can be analyzed constructively and pragmatically, recognizing that policy makers and research users generally are themselves constrained and often disunited. Is the problem of environment, for example, isomorphic with the need to control human population or is it better defined in terms of the distribution and use of resources? In either form the initial characterization is inherently divisive. Analysis along these lines can only serve to further pry the fractures between developed and developing countries. Can the issue be reframed to be amenable to some cooperative solution?

The emerging notion (intrinsically interdisciplinary) that it is not humans per se, but the stresses their activities place on the environment that matter (and which should be modeled and controlled) provides scope for a more creative dialogue.

1.2 The focusing of interdisciplinary effort

If it is clear that interdisciplinary studies are more difficult to arrange and carry out, more prone to criticism by threatened disciplines, and less able to draw upon a body of established theory and methods for their defense, it becomes important to ensure the success and policy-relevance of those interdisciplinary studies that are arranged. Where might interdisciplinary effort be focused to have the better chance of revealing new insights, fuller explanations, and better policy options?

A feature of the sustainability debate is that many of the questions involved take us beyond the realms of past experience. In such situations, empirical observation and extrapolation from observation can lead to very wrong conclusions and to wrong policy advice. Many such phenomena lie at the interface of the natural and social realms and the dynamics that determine how the situation will develop depend upon mechanisms operating at that interface. The destruction of renewable resources owing to positive feedbacks in the interaction between the socio-economic and biological systems, the potential for almost indefinite expansion of Third World cities owing to positive feedback in the interaction between the political and economic subsystems, and the potential for economic polarization and growing indebtedness owing to interaction between the economic, political, and social systems, are examples of destabilizing mechanisms already included as the subjects of IIASA studies (Keyfitz, unpublished). Where such mechanisms are correctly identified, the way is open for devising other mechanisms – with negative feedback – that might counteract them. The conclusion for interdisciplinary research is that it should search for such mechanisms; for the positive feedbacks that destabilize and for the opportunity to create new linkages that might restore stability.

2 Specific Recommendations

The basic structural barriers to interdisciplinarity will not easily or quickly be broken down. At the same time as they need to be addressed, there is a need to begin a substantive refocusing of science. There are signs of progress on some of the structural problems. There are some experimental interdisciplinary courses for undergraduates that aim to combine breadth with depth of study (and provide full professional qualifications in more than one discipline). The success of programs like those at the Basel and Freiburg Universities should be monitored.

For the time being, however, interdisciplinary work is probably best done outside conventional academic institutions. There is a need for specifically created interdisciplinary institutions and fora; a worldwide network of regional centers for interdisciplinary work. Funding and proposal evaluation systems should be modified to provide greater opportunities for interdisciplinary work.

Such work is best fostered by a focus on an applied problem. It depends upon a conceptualization of the problem. For conceptualization, a simple but holistic understanding is better than a detailed but partial model (Shaw *et al.*, 1992). The tools required for conceptualizing problems belong to the domain of systems analysis but are not, in the first instance, sophisticated mathematical models. Rather they are the softer system tools that provide an opportunity for representing intangibles and for combining quantitative with qualitative information. Such tools have long been neglected and need urgently to be ascribed importance in methodological research. Could IIASA take the lead?

Influence in the policy arena cannot be won through dialogue with politicians and policy makers alone; it depends also upon communicating results to the public and upon working to create public awareness and understanding of scientific findings. Credibility rests upon scientists being more honest and open about the degree to which their results either reflect particular values or are prone to uncertainty. There is a greater probability of results being used if scientific work involves policy makers from its inception, so that the goals and methods can be agreed upon beforehand in relation to a specific policy question. IIASA has past experience with policy exercises and with the workshop approach favored by C.S. Holling (for example, Holling, 1978). Could it improve this work? Could IIASA also undertake research on the process by which results of R&D are disseminated throughout society? There is an urgent need to better understand and accelerate this process.

Finally, there is a need to examine successful examples of interdisciplinary work which have also achieved policy influence more closely and critically; the work on ozone depletion and preventative measures, the debt-for-nature swap agreements, etc. Is not IIASA ideally positioned to undertake such work?

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