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BOUNDED RATIONALITY AND THE RATIONAL BOUNDING OF ENVIRONMENTAL MODELS

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ABSTRACT

Models of environmental systems find use in three primary applications. They might form the basis of scientific research, where they serve both to explain environmental functioning and to act as a means of prediction. They also form the basis of regulatory decisions, in which they are called upon to make predictions of risk under varying conditions. Finally, environmental models may be used to suggest engineering changes to the environment, changes designed to bring about a different state of the environment. Due to incomplete knowledge of environmental systems, however, the models used in these roles usually are bounded, meaning that they ignore (or cannot account for) specific aspects of an environmental system which play a part in the overall behavior of specific systems to which the models are applied. Despite this bounding, these models still may form a rational basis for action or decisions. This rationality may only be obtained, however, when the intention underlying use of a model is limited to the situations in which the bounded model is applicable. This article presents a general discussion of how rational decisions may be made in light of bounded models of the environment. It is suggested that the bounding of the model must correspond to the bounding of the rationality underlying the decision. An example is provided, using a model of the risk from radon in homes, which illustrates how the bounding of rationality may be reflected in the bounding of an environmental model.

We live in a world of intentions and consequences. Humans look at the environment and find in it the promise of an even better environment, one in which all of our best intentions are met by the consequences of our actions. The Environmental Protection Agency (EPA) intends to improve human health and so it controls the amount of industrial waste placed into a stream. The biotechnology industry intends to lower human hunger, and so it develops a

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strain of vegetable that will grow in the shallow soil of a tropical rain forest. In both cases, the intentions are laudable, above reproach. Still, the necessary actions must take place in an environment that is only poorly understood, yielding a possibility that intentions will not be realized in consequences. And so we look for a rational basis for action, a conceptual link between intentions and consequences. We look for a line of reasoning which will ensure, to the degree possible, that the consequences of action will be as intended. Rationality is founded on the hope that the environment we create may be brought in line with the one we intend through reasoned discourse.

To act rationally in the environment, then, is to lay out our intentions and to demonstrate that these intentions will be produced by our actions. But we quickly run into two large obstacles. First, our knowledge is uncertain, partial, tentative. Environmental systems are incredibly interwoven in ways that are only beginning to be perceived. For many systems, even the connection between compartments that have been identified are understood in sketch. With partial scientific theories and models, it is possible only to predict the behavior of simple systems in which the known compartments and connections (such as intercompartmental rate constants) dominate. Actions that take place in more complicated environmental settings will be characterized by doubt. In such a case, the rationality of the action may be called into question, since it cannot be assured that the intended effects will be produced.

The second limitation in the desire to be rational concerns the fact that environmental actions have a potentially infinite range of intentions and consequences. In controlling the amount of radioactive radon (Rn-222) allowed in home air, the EPA certainly intends to improve human health. But it also intends (among other things) to spend money wisely, to avoid actions that limit civil liberties, to act on the basis of certain knowledge, and so on. It is never clear, therefore, how to characterize the intentions of environmental actions.

Both of these limitations lead to the problem of bounding that forms the central topic of this article. The first limitation leads to what I will call epistemological bounding. By this, I mean the bounding of models so that they exclude certain aspects of the environment that are suspected of being an influence on the important functions of that environment, but which cannot be included formally because they are not understood. Some examples would be the removal of exposure pathways from environmental models used in risk analysis, or the choice to leave out chemical reactions in a model of the photochemistry of smog production. In each case, the model is bounded in the sense that only an artificially (but perhaps pragmatically) limited number of factors are included in the model. The model is bounded because it is unable to incorporate and explain all aspects of the environment thought to play a role in environmental actions and functions. The model does not serve the full purpose of a scientific answer, which should provide a base for understanding and predicting the full range of experiences to which the model is applied. In a very real sense, bounded models place boundaries on our ability to claim that well-formulated intentions will be met by actions guided by the predictions of the model.

The second limitation arises not from an inability to develop a complete predictive model, but rather from an inability to cope with the full range of intentions underlying any given action. Since environmental actions, particularly those involving environmental systems, occur on a very large scale and often require collective action affecting a large number of people from varying positions in society, it usually is true that there is a wide range of intentions behind each action. These may be subordinate to, or added onto, the explicit aim of the action. To be completely rational is to show that all of these intentions, however they might be formulated, will be satisfied by the particular environmental action. And yet, the range of intentions may get too large to handle conceptually. We may be unable to proceed with the analysis of environmental actions if the number of intentions becomes too large. In addition, we may find ourselves in a position of being unable to act because we spend all of our time simply trying to list our possible intentions.

At some point, we must claim that "enough is enough." We might lay out our central intentions and ignore the rest. When this occurs, we have a case of bounded rationality. Even if our explicit goals then are met by our actions, we have gained only a partial victory, have been only partially rational. Lying outside the boundaries of the rational decision are precisely those intentions we chose to ignore. These intentions may or may not be met by our actions; we cannot be sure one way or the other because an examination of these intentions was not part of the analysis of the environmental action.

These two forms of bounding usually are thought of as being distinct, the difference being that between facts and values. Bounded models of the environment seem to have an epistemological problem. They do not account properly for the functioning of the environment and cannot be claimed as representing the perfect knowledge required to ensure that actions produce the intended consequences. They ignore, or cannot account for, a body of facts accepted by the environmental scientists. Bounded rationality then would be viewed as an ethical problem or a problem of values. Not all values (in the form of stated intentions) are being included in the decision. The rationality ignores, or cannot account for, a body of values accepted by the decision maker.

The contention of this article is that the bounding of rationality and the bounding of environmental models are not separable, at least if we want to claim that a model is rationally bounded rather than simply incomplete (which I believe we do). This idea certainly is nothing new. It forms the basis of a book by Maxwell [1], in which he argues that most intellectual disciplines (science included) have become divorced from the purpose of that discipline as a basically rational enterprise. He argues that any discipline, including environmental science, can be rational only to the degree that it explicitely recognizes the intentions of the discipline and discusses these intentions. From this point, he proceeds to suggest that a truly rational discipline does not search only for abstract truth, but rather for knowledge that is useful in solving the major problems of the world (such as environmental problems). It is important, therefore, to ask why we have developed a particular model and whether the model will be satisfactory for our particular intentions.

At times, the intentions may be those of "pure" science, to provide a scientific understanding of an environmental system, with the ability to predict the outcome of any action performed on the system. At other times, however, the intention may be to develop a model that is useful in guiding actions even in cases where a full understanding is not available. In each case, the form of the model, and the manner in which it is bounded, should be dictated by the purpose of the model. The purpose of the model, in turn, must arise from our understanding of the bounded rationality we will employ in making decisions. Only in this way can the use of the bounded model be considered rational, at least in the sense of bounded rationality.

I want, then, to discuss the relationship between bounded rationality and the rational bounding of environmental models. In order to avoid fading into a rather vague philosophical discussion, I will use an example taken from my own work on a particular environmental system [2]. The example to be used is that of radon (a radioactive gas produced in the earth) in the water supplies of the United States. Radon is present in water supplies at levels that produce a risk far in excess of other substances regulated by the EPA Office of Drinking Water [3]. Measures currently are being taken by the EPA to mitigate the amount of radon present in the water and air of U.S. homes. The overall intention of the EPA action is to lower the number of citizens dying of lung cancer as a result of this radon. This effort requires that the EPA use models of the environmental system that brings radon into the home and removes it from that home. I will look at the manner in which these models might be used in the light of specific intentions, and how these intentions influence the bounding of the models. I want to ask: When is a bounded model for radon a rational basis for deciding on engineering changes of the environment?

WHY A MODEL?

Environmental models may be thought of as having three main purposes.

1. They might be viewed as representations of the state of our knowledge about the environment. In this role, they also function to guide scientific research which might ultimately produce a complete theory of the functioning of environmental systems.
2. They might be used to make predictions that form the basis for public concerns about the environment. For example, a model of the risk

produced by environmental radon might be used to calculate that risk, forming part of a regulatory decision concerning the need for limits on exposure.

3. Finally, the model may be used to suggest engineering changes to the environment. Since the model identifies distinct parts of the environment (such as compartments and rate constants), it also is able to identify the role played by each part in producing the effect of interest (such as lung cancer). The model, therefore, acts as a guide in suggesting how a given effect may best be modified by engineered changes in the parts of the environment corresponding to parts of the model.

These three categories also can be subdivided. Starting first with the "pure" science approach to models, it is important to determine what a model is a model *of.* It is possible for an environmental model to provide a description of certain restricted (perhaps experimental) conditions in which the values of these conditions are known and fixed. For example, the model might describe how radon (or the decay products of radon) interacts with aerosol particles in a mixing chamber where the boundary conditions are controlled. A model might, however, be intended as a description of the external environment, outside the laboratory and uncontrolled by experimental conditions. In this case, the model must be more complete, allowing the modeler to determine the effect of varying the entire structure of the environmental system. The first category allows the modeler to simply predict the change in a dependent variable under a fixed structure to the system. The second allows the modeler to predict the manner in which this change is further influenced by changes in the structure of the system. We will return later to this distinction.

Consider now the problem of a model used to guide a decision, such as a desire to set a regulatory limit. The model may be used to determine whether a particular environmental system (such as a water supply in rural North Carolina) should be a focus of concern. The model might also be used to predict the average behavior of water systems in the United States, yielding an estimate of the average risk posed by radon in the United States. Alternatively, the model might be used as a simple screening tool, allowing the regulator to determine if it is at all likely that radon in water represents a significant risk in light of other sources of regulatory concern.

Finally, consider the case of a model used for making engineered changes in the environment. Two possibilities seem to be present. The model might be used to suggest how the environmental system itself must be bounded in order to gain predictive ability. In other words, if a model considers only chemical reactions found within water, but not reactions between the water and the banks or sediments of a river, then the model might be used to suggest that the lake be lined to stop the unconsidered reactions. The environmental structure is changed to fit the assumptions of the model. Greater predictive ability is obtained, but at the expense of the desire to make as small a change as possible in the natural environment. Alternatively, the model could be used to suggest engineering changes that leave the system intact, with an attendant decrease in the confidence that the model predictions will be produced by the changes. We will look at examples of each of these possibilities below.

BOUNDING THE MODELS

We turn first to the issue of model bounding when the model is developed as a tool for scientific research. Consider the case in which radon enters the home through the water supply. We will assume that the important feature to be modeled is the degree to which the radon is able to exert an effect on human health. Referring to the physical properties of radon, it is noted that radon undergoes radioactive decay, producing a series of new radioactive isotopes called its decay products. It also is noted that radon (and the decay products) exert their influence primarily through emanation of the radon from the water and into the home air, where humans are exposed by breathing [4]. Assume that the intent of the model is to characterize the concentration of radon and its decay products in the air.

A bounded model of this process usually is assumed, in which the compartments are water and air [2]. A transfer rate constant is specified, being the fractional rate at which radon moves from the water into the air. In addition, a removal rate constant for the home air is specified, yielding the fractional rate at which radon is removed from the air.

Notice that the model is bounded, referring only to the home air and water. The transfer rate constants are treated as fixed entities, a characteristic and inherent property of the water compartment and the air compartment. Applying this model to different homes, it has been noted that the removal rate constant for these homes appears to vary widely, spanning an order of magnitude. The question may be raised as to whether this model is an adequate description of the environment, given this measured variability in the terms appearing in the model.

Let's assume that the role of the model is to provide a complete description and prediction of the concentration of radon and its decay products in any specific home. Two possibilities then present themselves. Either the rate constants are irreducibly variable (a fundamental stochastic quantity such as those appearing in quantum mechanics) or the variability also is explainable in terms of some larger model. If the former is true, then nothing is to be gained by elaborating the model. We have reached a point of inherent and unexplainable variability in nature. Stopping the development of the model is entirely rational given the goal of explanation and prediction for particular homes.

But suppose it is decided that the environment is much less variable than is suggested by the measurements and the model. It might be assumed that the observed variability in the rate constants is due to influences outside the boundaries of the model. This is the idea of lumped parameters, in which several factors are compressed (in an unknown manner) into a single factor. In other words, some unspecified factors are producing the variability and, if these factors were understood, the newer model would not display such extreme variability in any new rate constants. The concentration of radon and its decay products in homes does suggest that there is a great deal of variability in the removal rate constant determined by applying the bounded model to data obtained in different homes.

In this circumstance, it still might be rational to use the bounded model. Our goal might not be to predict the concentration in specific homes, but rather in some "generic" home, perceived as an average across the population. The scientific goal of the model might be to explain this average behavior of homes with respect to radon and the decay products. Realizing this, the simple bounded model then could retain its undesired and unexplained variability, but rate constants now must be established empirically in a large number of homes. Something unknown is causing the variability, but we might sample a large enough number of homes to ensure that this source of variability is averaged out over the sample. If we do this for a large enough sample, and if our sample is in some way representative of the full range of unknown environmental structures which produce the variability, then we will have a good measure of the average behavior of all such environmental systems. The model is no longer truly an explanation of individual homes, but it is at least a probabilistic model of the distribution of homes in the United States. Perhaps this is all that was intended by the model. It must be borne in mind, however, that the modeler can never be certain that the averaged model (bounded model) is correct for any new collection of homes, since it is not known what is producing the variability. Confidence rests on the ability to obtain a "representative" sampling of homes, while at the same time it is impossible to specify what is meant by the term representative.

There remains, however, a very real sense in which the bounded model may not prove a rational basis for scientific research. It might be argued that any model is unacceptable if it suggests variability in the rate constants. The intent of the model might be to explain this variability, to produce a complete understanding of the environment that may be applied to any *particular* home, and obtain an explanation specific to that home. Variability then is seen as a major source of concern which reduces the rationality of the model. The bounded model has at least helped in making the variability evident, and so may stimulate further research to explain the variability. But the model cannot be used to guide this further research, since the source of the variability clearly lies outside the boundaries of the model. The variability lies in factors not considered in the model. When predictive ability is needed for specific instances of the environment, bounded models characterized by variability do not provide a rational basis for further research. The boundaries must be extended.

But this problem with bounded models might go even deeper. To see this, consider that this journal is a journal of environmental *systems,* not just a journal of chemistry or atmospheric physics (for example). It might be said, therefore, that the intention of research into systems is to explore the manner in which the structure of the system, and not just the parts, influences the functioning of the environment. For example, we might state the intent of research into environmental radon as being a desire to explain how the structure of a complete environmental system influences the concentration of radon and its products in air. In that case, the intent is not to explain how the concentration depends upon the rate constants, but how the rate constants themselves are influenced by changes in environmental structure. This structure might include the particular shape and size of walls, floors, and windows of the home, or the physical relationship between air movements in a home and the production or deposition of aerosol particles. The simple bounded model discussed earlier cannot provide insight into this aim. It leaves the variability of rate constants unexplained. But from the discussion given here, it is precisely this variability, and its cause in environmental structure, that might be the focus of environmental research. Only a larger model that hypothesizes other structural features that act to produce a particular value of the rate constants would count as a rational basis for scientific research. The bounded model, with its lumped parameters, is rational only if we bound our rationality by ignoring the desire to reduce unexplained variability.

This brings us to the next role of a model; the guiding of public or private actions other than scientific research. The EPA currently wishes to set a limit on the amount of radon to be allowed in drinking water. Towards that end, it has developed a risk analysis of radon released from water into the home air [5]. This analysis uses a model of homes similar to the bounded model described earlier. In other words, it contains only the compartments of water and home air. Average values of the rate constants then are assumed for the purpose of suggesting a standard. Is the use of this bounded model for that purpose rational? Again, the answer depends upon the intention of the EPA in using the model.

Perhaps the EPA desires to use the model only as a screening tool to determine if radon has the potential, in any home, to produce a hazard which warrants regulation, regardless of the cause of that hazard or the particular home in which it occurs. The model might be viewed as an analogy, a model of a fictitious home which exists nowhere in the United States, but possesses characteristics that are in some way "average." The EPA might make no pretense that the model yields a correct prediction of the radon (and decay products) found in any particular home. In this case, the bounded model may be completely adequate, at least under certain conditions. Those conditions require that the EPA obtain a sufficiently large sample of the rate constants in as wide a range of environmental systems (i.e., different homes) as possible. With this caveat in mind, it may be perfectly rational to use the bounded model, since the rationality itself has been bounded by looking only at the intent to predict the average behavior in homes.

At other times, however, the EPA may have more detailed concerns. It might, for instance, seek to set a limit on radon which will protect the public health in the most contaminated homes. Perhaps it wishes to keep the radon concentration in water sufficiently low to preclude the chance that *any* home air will pose a risk above a prescribed value. Even with this new intention, the bounded model may prove to be rationally bounded, assuming the distribution of the removal rate constants has been adequately measured. Instead of using the average value of the rate constant, the EPA simply would use the extreme values. A prediction then could be obtained of the radon concentration expected in the most "sensitive" homes. The model is not rationally bounded, however, if the EPA intends to make a prediction of the risk specific to any *given* individual, unless the rate constants have been measured for that specific home.

This all is a form of "blinded" regulation. A standard is set on the basis of an "average" or "sensitive" subpopulation of environmental systems, without understanding why they fall into these categories. Still, this might prove sufficient given the intention of the EPA. Suppose now that the EPA wanted to find these sensitive homes. For example, there are homes in the United States which allow the builup of very high concentrations of radon due to their structural characteristics. The EPA would like to locate these homes so that attention may be focused on them during a campaign to clean them up. The bounded model certainly does not prevent the EPA from finding these homes, provided money is available to sample the rate constant in all U. S. homes. The study simply would locate the homes in which the lumped rate constant was most extreme. But this is an expensive proposition, and it would be much less expensive to locate homes that were built in a certain manner which *produces* extreme values of the rate constant. Unfortunately, the bounded model is unable to provide the insight needed to find these homes without direct measurement of the lumped rate constant.

The rationality underlying use of the model becomes even less firm, however, if the intention of the EPA is changed. A different intention might be to specify the kind of home that will be sensitive, perhaps to guide the public in choosing new home designs to lower the risk of radon. In this case, the bounded model offers no rational basis for predicting which home designs might be sensitive due to their structural features, except to the extent that the EPA simply summarizes those home types in which past studies have found extreme values of the rate constants. As a guide to complete changes in home construction practices, in which the new homes are not simply a subset of the old home styles, the bounded model offers no insight. A more complete model is needed.

Finally, we come upon the major issue of this article: the role of the model in suggesting engineered changes to the environment. Before discussing this aspect, it will be necessary to review the nature of the hazard posed by radon. Following this, we will return to changes that might be made in a home to lower the hazard posed by radon in water.

Radon is an inert gas and, as such, does not undergo significant chemical reactions. It emanates freely from water and enters the home air, particularly when the water is heated and agitated. Once in the air, it will continue its radioactive decay, producing a series of radioactive decay products. These products are electrically charged and will attach to particles in the air. They also may escape attachment and remain free in the air. For a fixed concentration in air of each product, the risks posed by radon, attached decay products, and unattached (free) decay products vary widely [6]. The radon essentially is of no concern, the unattached decay products are of great concern, and the attached are of intermediate concern. An accurate prediction of the risk posed by contaminated air then requires information on the concentration of each decay product and its state of attachment to aerosol particles.

What can be changed in order to lower the risk from radon in specific homes? Let's look at the problem first from the perspective of a complete understanding of the factors that control the risk, turning later to the bounded model. Certainly, taking the radon out of the water prior to entering the home will lower the risk, even if we do not know how the risk is related to environmental structure. Increasing the rate of ventilation in the home also would appear to lower the risk, given that the radon has entered the home air. The same could be said for stopping the emanation of the radon from the water into the air, perhaps by not heating the water except in a special, well ventilated, area. Since the decay products will, to an extent, be attached to aerosol particles, we could filter the air. Perhaps a filter might also be available for the free decay products. We also could filter the radon from the air using activated charcoal filters. All of these choices would lead to a reduction in the concentration of each decay product in the home air.

We might then determine whether the bounded model would yield insight into these potential changes. Certainly the model would suggest that removing the radon from the water is effective. This, in fact, is the method preferred by the EPA. The bounded model also would suggest that the emanation of the radon from the water to the air might be controlled. The bounded model also might suggest that filtering of the decay products is effective, although the model does not really suggest the state of these products or their susceptibility to filtering.

But many potential changes are left out of the bounded model. The model cannot predict the manner in which changing the home structure would affect the risk. For example, homes with a large surface-area-to-volume ratio for the inside walls tend to allow greater deposition of the decay products onto the walls (where they are of less concern). In addition, a simple technique such as placing a fan in a room will increase this deposition, thereby generally lowering the risk. These engineered changes will be missed by the bounded model due to the lumping of parameters containing terms for wall deposition. A more complete model would show that the removal rate constant for room air had several components, consisting of both ventilation and wall deposition. This larger model then would focus attention onto measures that might increase wall deposition. This possibility would be hidden from view in the lumped parameters of the bounded model.

Still, the bounded model would suggest that filtering the air might lower the risk, since it would remove the radon and decay products from the air compartment. From the perspective of the bounded model, which does not differentiate between attached and free decay products, any lowering of the concentration of the decay products would lower the risk. If the intention of the EPA simply was to lower the concentration of the radon and each decay product, the bounded model has been quite adequate in suggesting the use of filters.

A problem arises, however, when the EPA focuses on the risk from the decay products rather than their concentration in air. As mentioned earlier, this risk depends both on the concentration of the products and their state of attachment to aerosol particles. Those decay products that remain free in air are much more hazardous than those that are attached. In filtering the air to remove the decay products, the aerosol concentration in a room will be decreased. As a result, the fraction of the remaining decay products that are attached will decrease due to the lack of available aerosol particles. The net result of the filtering process, therefore, may be a decrease in the lumped concentration (free plus attached decay products) of the substances, but an increase in the risk posed to human health [7]. This phenomenon would not be predicted by the bounded model, since the model does not include the role of aerosol particles. Engineered changes using the bounded model may, therefore, have an effect very different from the intended and predicted effect.

Up to this point, attention has been directed to the desire by the EPA to lower the risk from radon emanated into the home. The bounded model does not depict the world outside the home, and so it encourages a focus on this isolated intention. The risk has been bounded by looking only at the risk from radon and decay products in the home air. Under this bounded rationality, it is perfectly reasonable to remove the radon from the water by use of an activated charcoal filter (by way of example). The intention simply was to lower the risk posed by home air, and this intention was met by the proposed engineered change.

The situation changes, however, if it is determined that the rationality has been bounded too severely. After all, the engineered change has removed the radon from the water and placed it onto the filter. This filter must be disposed of in some manner, perhaps in a municipal waste dump. The bounded model offers no hope of dealing with this new risk; since it fails to depict any part of the environment outside of the model compartments in the home. The possibility remains, therefore, that the route of disposal may actually present a greater risk to human health than would have been present if the radon was left in the water (this is not the case here, but it remains a possibility from the perspective of the bounded model). The bounded model was adequate when the intention is to lower the risk posed by the emanation of radon into the average home, but it is not a rational basis for assessing the risk of radon transported outside the boundaries of the model. This model will be inadequate if the intent is redefined as a lowering of the overall hazard posed by radon in water, regardless of the route of exposure.

CONCLUSIONS

The discussion given here could be expanded to include a much larger number of considerations involved in calculating and changing the risk posed by radon in drinking water. Since the intent of this article has been to sketch only the major features involved in the rational use of bounded environmental models, these additional considerations will not be discussed. They simply are elaborations of the general ideas presented in the article. My bounded intent was to present some general arguments, and so my bounded examples should be adequate.

I think it is clear that bounded models play an important role in environmental science and risk analysis. After all, it probably is not possible to include all of the complexities of the environment into a model. Actions would never occur because all of our time would be spent in a search for progressively larger factors to place into the model. The role of the bounded model, however, must then be bounded by a willingness to redefine intentions to meet the limitations of the model. Bounded models ignore additional compartments and rate constants between compartments. They also ignore features internal to a compartment, such as transformation processes that might influence the risk posed within a compartment. Finally, they lump together rate constants that might otherwise provide valuable tools for suggesting engineering changes (if the lumping did not occur).

From the standpoint of scientific research, two problems seem to dominate the use of bounded models. Such models offer no insight into the cause of variability in empirical quantities like rate constants. Instead, the model leaves the rate constants as inherent properties of the compartment, rather than as properties of the environmental system in which the compartment is placed. The scientist using a bounded model must be willing to live with an irreducible variability, content to stop at that point without an explanation of the source of that variability. If the intent is to develop a completely explanatory model, applicable to any specific environmental system, then the bounded model does not represent a rational point at which to stop the inquiry. In addition, the intention of environmental science (particularly system analysis) might be to explain how empirical quantities such as lumped rate constants depend upon the structural features of the system. To the extent that variability in parameters is suspected to be a function of structures outside the boundaries of the model, it may prove irrational to accept the bounded model as a tool for research (other than as a stimulus for more detailed research).

Bounded models also may prove adequate for making decisions if the intention of the decision is appropriately bounded. Decisions requiring information on the average behavior of a large number of environmental systems may be arrived at by use of the bounded model in which variability is unexplained. This requires, of course, that the decision maker have access to information on the values of these parameters under the full range of environmental systems included in the decision. It never will be possible to ensure that the sampling has not missed an important subset of systems in which the parameter values differ systematically from those in the sample. It should be possible, however, given appropriately randomized sampling, to obtain a good degree of confidence that an average value of a parameter has been obtained (approximated) by the sample. Problems remain, of course, if the model then is used to predict the response of a completely new environmental system in which the structural features outside the model boundaries have been changed.

Engineered changes are best made in light of only loosely bounded models since these offer the greatest range of flexibility in choosing engineering options. Whenever unexplained variability appears in a model, the engineer loses the potential to manipulate the environmental structures that produce this variability. Any rational changes then must occur on the basis of the "internal" properties of the model (i.e., those factors included formally in the model). At times, this limitation may not be important. Radon in homes certainly can be controlled by stopping the influx of radon. Even a bounded model predicts this to be true. The same bounded model, however, fails to provide rational insight into how the influx can be left unaffected while at the same time lowering the risk. This situation arises because the model fails to display how environmental structure plays a role in determining how a given influx of radon manifests itself as a risk to human health. The model draws attention only to the compartments in the model, rather than to the relationship between these compartments and others outside the boundaries of the model.

As we have seen, bounded environmental models can provide insights into scientific research, public decisions, and engineering solutions. They do so, however, at the expense of other possibilities that might be met by more elaborate models. The ideal model would provide a complete explanation and prediction of the response of any particular environmental system to any proposed change. This model would leave no source of variability unexplained. It would be useful for calculating the total influence on a human concern (such as risk) when a substance is taken from one compartment and placed into any other compartment of the environment. Use of such a model then would be rational, since the model was able to deal with any intention underlying its use. To the degree that a model lacks these abilities, it must be recognized that it will satisfy only a circumscribed list of intentions. A rationally bounded model then arises when the boundaries placed onto the model are accepted because of the boundaries placed on the requirements of the model. As long as we recognize what lies outside of a model, and structure our intentions to circumvent any reference to these factors, we will have at least gained a measure of rationality, however bounded.

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