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some more progress and activity in these areas will be stimulated upon reading this forum.

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Ruminations on *The Limits to Growth* and the Fractured Academy

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The publication of *The Limits to Growth*[2] was a political event. In a matter of months, the amount of commentary—pro, con, and orthogonal—has exceeded the original text by a factor of several hundred. Like *Love Story* and *Greening of America*, it is simply not permissible to have nothing to say about *The Limits to Growth*.

To explain this avalanche of criticism will require a model, *Intelligensia Dynamics*, with at least one positive feedback loop. The propensity for academician B to comment on the work of academician A would appear to be proportional to the product of at least four factors: the number of previously published comments about the work, the credentials of academician A, the degree to which the work strays into the field of academician B while violating its established mores, and—last, but not least—the readability of the work. The first of these factors is enough to assure an exponential growth of commentary, limited—the model will say how—by the number of literate academicians. (A physical limit, the amount of available paper, probably does not operate.) The date of publication of *Intelligensia Dynamics*, of course, will be contained as a prediction in its basic equations.

The Limits to Growth emanates from MIT, strays in a threatening way into engineering, biology, geology, religion, politics, and above all economics, and is clearly written. It has a simple message: Current Trends of Growth Spell Disaster. There are three kinds of disaster: running out of food and starving, polluting our biosphere and choking, or depleting our resources and returning to the stone age. Neither of two alternative outcomes—perishing in a general nuclear war on the one hand, pulling ourselves together, on the other—is an available outcome. War is not included in the model, in spite of the large impact it has had and continues to have on population growth. "Pulling ourselves together" is inserted into the model from outside, when the authors, and Forrester before them,[3] finagle with coefficients; but automatic acts of self-improvement, in the form of loops of adaptation that mitigate stress, are not built into the model, and many critics have called for them.[4]

The inability of man-in-the-model to foresee and adapt to the oncoming disasters has been widely attacked. Yet clearly the *Limits* authors, and their Club of Rome sponsors, *themselves* believe that the real world is not populated by the men in the model; they would not have assumed an evangelical tone, carefully aiming their work at a broad audience of decision-makers, unless they believed there was some chance that *Limits* could change and reorient those who read it. Thus the model is inconsistent with the assumptions of its authors and sponsors about human nature, and contains the seeds of its own destruction.

It should not be hard to construct a model, closely paralleling the *Limits* model, that contains mechanisms by which people adjust their values in the face of documentation that doom lies ahead if a course is not changed. But such a model would be faulty in an essential respect unless, somehow, it could allow for the crucial fact that such documentation will always be incomplete and open to interpretation. The greatest shortcoming of the *Limits* model, I believe, is not its excessive aggregation, nor its lack of allowance for adaption, but its inability to deal with the uncertainty of our current and future knowledge. Let me illustrate by describing in considerable detail the treatment of pollution absorption in the *Limits* model.[5]

Pollution, one of the model's aggregated variables, satisfies a (coupled) first-order differential equation; it is generated by man (at a rate which is related to the level of capital in a well defined way) and it is absorbed by nature. Nature's absorption is modeled by a single graph of pollution absorption rate versus pollution load, and the form of that graph is assumed once and for all. Forrester's input graph (which, except for some details, the Meadows group did not change in *Limits*) has nature unable to absorb pollution any more than *four* times faster than the current rate. That maximum rate occurs when the pollution load reaches approximately *ten* times the current one. If the load builds up beyond this point, the pollution absorption rate decreases. See Fig. 1. Thus, Forrester's pollutants show the ability to injure the sink that is absorbing them (the curve falls below a straight line) and finally to clog the sink, so that large loads are absorbed even more slowly than middle-sized ones (the curve turns over).

Forrester's curve *is* a decent description of the way BOD (biological oxygen demand) is handled by streams, which at increased loads gradually lose their ability to oxidize further wastes (since the streams begin with a fixed amount of dissolved oxygen). On the other hand, a very different curve, a rising straight line, describes radioactivity. The reason for the straight

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[2]Meadows, Donella H., Meadows, Dennis, L., Randers, Jørgen, and Behrens, William, W., III, *The Limits to Growth*, New York, Universe Books, 1972, see also *World Dynamics*, by Jay W. Forrester, Wright-Allen Press, Inc., Cambridge, Mass. and its review by F. Collins in the December, 1972, issue of the JOURNAL OF DYNAMIC SYSTEMS, MEASUREMENT, AND CONTROL, p. 339.

[3]Forrester, Jay, W., in *World Dynamics*, Cambridge, Mass., Wright-Allen Press, 1971, sets forth the basic strategy and spirit of the exercise that *Limits* has popularized. *World Dynamics* contains equations and detailed numerical relationships; the *Limits* authors have extended the Forrester model, but the details of this exercise are still not reported. The discussion in *Limits* is fully comprehensible on the basis of *World Dynamics* alone, and one can easily imagine that the writing of *Limits* and the extension of the Forrester model went on independently.

[4]Robert Boyd, in a brief paper "World Dynamics: A Note," *Science*, Vol. 177, 1972, pp. 516–519, has added loops of self-improvement in the form of one additional aggregated variable, called Technology, which increases with capital investment and in turn promotes the reduction of pollution generation and the reduction of resource depletion. As a consequence of this modification of the model, Boyd obtains many respectable, unspectacular futures.

[5]Harold Feiveson and Daniel Herrick have studied the pollution sector of the Forrester model in considerable detail, and I have benefited considerably from discussions with them. The interested reader is invited to write for their paper "Comments on the Project on the Predicament of Mankind. Long-Term Pollution Generation and Effect," Working Paper W-3, Center for Environmental Studies, School of Engineering, Princeton University.

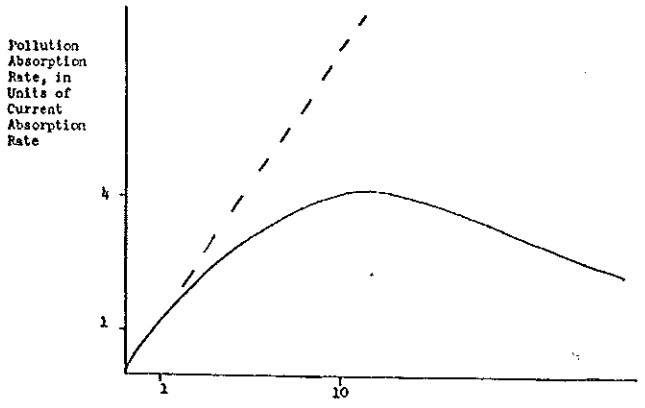

Fig. 1 The solid curve shows pollution absorption in the Forrester model (based on reference [3], Fig. 3–15, p. 57). In addition, Forrester assumes that at the current pollution absorption rate the current pollution load would be absorbed in exactly one year. The dotted curve shows the behavior of a pollutant which has a characteristic residence time of one year regardless of load. (A *Limits* computer program, revised April 6, 1972, uses a function that rises in the same fashion as the Forrester curve until near the latter's maximum, then flattens out instead of bending over, according to D. Herrick of Princeton University.)

line, of course, is that readioactive materials decay (get absorbed by nature) in a manner that is unaffected by anything else going on. Although no other pollutants are as inner-directed as radioactive isotopes, still, when small amounts of most pollutants are added to large sinks (metals to lakes and seas, sulfur oxides to the various zones of the atmosphere) the concept of a residence time (exactly analogous to the mean-life of an isotope) appears to be a useful one.

There are pollution catastrophes in the *Limits*[6] model and in Forrester's model[7] in which the pollution load goes through the roof. These catastrophes are directly traceable to the assumption that all the world is a murky stream.

Certainly the model of BOD in streams is a more cautious model of global pollution than the model of SO_2 in the atmosphere; and to assume that we are within a factor of four of the maximum absorption rate for "pollution" is to be especially cautious. Is Forrester's way of representing "the poisoning and destroying of the pollution clean-up mechanism"[8] *wrong*? Pollution absorption, in all its various forms in air, water, and soil, is too complex and poorly understood a subject to give a definitive answer. Our ignorance about pollution clean-up mechanisms is vast, and can be expected to persist—in spite of vigorous new research programs—well into the period that the models attempt to predict.

Knowledge of pollution absorption will indefinitely take a probabilistic form: for any given pollution load (even of a single type of pollutant) all that will be available will be a distribution of expected levels of damage to the clean-up mechanism. A similar probabilistic form will indefinitely characterize the best available understanding of most of the other interactions that Forrester and the *Limits* authors model with a definite graphical function. Any model that permits a society to adapt to precise information but does not allow the society to receive imprecise information is not going to be very instructive.

I am skeptical that we know enough about people to model their response to certainties, not to say ambiguities, and so I would not want to be understood to be urging that modeling head in this direction. But, then, in the face of such enormous uncertainty about nature and the obvious necessity to aggregate a wide range of phenomena, what *is* global modeling good for? The answer, to me, is inescapable: It is good for getting us all talking to one another. It is an extraordinary visual aid. It has almost no predictive value, but it has exceptional heuristic value.

For those of us who believe that the problems *Limits* is wrestling with *are* fundamental, and who would rather err on the side of caution to call them urgent as well, the publication of *Limits* is welcome. There are enormous inductances in Academe which resist changes in institutional patterns; the net effect is to impede any serious effort to understand just how urgent they are. The publication of *Limits* has in all liklihood forced some new connections between specialized disciplines that are necessary preconditions to such an effort.

The more difficult task remains, which is to get us to *listen* to one another. One major problem is to get those who think in dollars and those who think in physical units to communicate. It really may be that continued growth measured in dollars, with choices mediated by prices and markets, is a package perfectly compatible with equilibrium measured in physical units (energy production, steel production, population). If people use additional income to substitute less environmentally aggressive activity for more environmentally aggressive activity (individuals taxing themselves via Green Acres bond issues to put aside open space for their grandchildren, corporations buying picture telephones which cut down air travel by their salesmen) the economy may become larger and less active at the same time. If people come to prefer being gentle to being nasty, and being future-oriented to being present-oriented, they will put a high price on what permits them to be gentle, and they will operate with a lower effective discount rate. The economists and ecologists both win. This possibility of agreement seems to get lost in the current quarreling, much of it now focused on *Limits*.

There is an urgent need for better listening, also, when both economists and ecologists talk to those who are primarily concerned about the distribution of goods between rich and poor. Spokesmen for the less developed countries and, to a certain extent, for the American poor, have been put in a combative mood by the ecology movement in the U.S. these past few years, and by *Limits* in particular. The presumption of such spokesmen is that if the prosperous segments of the more developed countries perceive there to be benefit to themselves in putting ceilings on the total amount of global economic activity, then necessarily they will begin by putting ceilings on the growth of the economic activity of the less developed countries, and the less developed sectors of their own country, in order to reserve as much as possible of the residual growth for themselves. But there is another possibility, articulated briefly in *Limits*,[9] which is that the perception by the prosperous that there are indeed ceilings on total global economic activity will destroy the "myth" that growth will take care of the poor in some automatic fashion, as everyone gets richer, and that this will force the prosperous to pay far greater attention to the equitable apportionment of the residual growth. If growth is limited, distribution becomes an inescapable matter, even if harder to solve.

The professional modelers may be able to help in this next stage of communication. But I am not sure how they can do so. The critical challenge is to sharpen the discussion while retaining its intrinsically psychological and moral components. These elude quantification.[10]

[6]Meadows, *op. cit.*, Fig. 36, p. 127.

[7]Forrester, *op. cit.*, Section 4.3.

[8]Forrester, *Ibid.*, p. 58.

[9]Meadows, *op. cit.*, p. 127f. See also "Toward a Stationary State Economy," by Herman E. Daly, in *Patient Earth* by John Harte and Robert H. Socolow, New York: Holt, Rinehart, and Winston, 1971, an essay cited in this section of *Limits*.

[10]A forceful analysis of the inadequacies of policy sciences in their present form when faced with issues that are value-laden and hard to quantify is to be found in Lawrence Tribe, "Policy Science: Analysis or Ideology," *Philosophy and Public Affairs*, Oct. 1971.