arable land is diminished, the marginal cost of land development, measured in terms of capital and energy, increases.

2. There is a limit to the amount of food that can be produced from each hectare of arable land each year. This limit can be approached by investment in agricultural inputs such as fertilizers, pesticides, and tractors. Eventually, however, there are diminishing returns to these inputs. The land yield limit can be decreased by very high levels of pollution or overintensive cultivation, and it can be restored to its original value by investment in land maintenance.
3. The stock of nonrenewable resources in the earth is finite. The absolute limit of available resources is the entire mineral content of the earth's crust. However, long before that limit is reached, the marginal cost—in capital and energy—of extracting and processing each unit of resource will rise to prohibitive levels.
4. There is a limit to the rate at which environmental pollutants can be rendered harmless by natural assimilation processes. Pollution levels can be kept below that limit by reducing the toxicity or quantity of industrial and agricultural emissions. However, pollution control requires capital investment, which is subject to diminishing returns. Moreover, the rate of natural pollution absorption can be lowered by the pollutants themselves if they reach levels that interfere with the environment's assimilation mechanisms.

In World3, physical limits provide negative feedbacks to population and capital growth, primarily through the assumption of diminishing real returns to the utilization of any physical resource. They become strong enough to balance the positive feedback forces of physical growth only when that growth brings capital or population close to assumed absolute limits. Negative feedback is also provided by various social mechanisms: shifts in relative prices, advances in technology, and changes in social values may operate to adjust the rate of approach of the growing population to the ultimate carrying capacity of the environment. These social feedback mechanisms are incorporated into World3 implicitly; they are interspersed throughout all five model sectors rather than being incorporated in separate sectors of their own. Since their representation in the model is indirect, and since they may be important in the development of new policies, it is worthwhile to describe the assumptions we made about these mechanisms while designing World3.

Social Feedback Mechanisms

Detailed system dynamics models of price change, technological advance, and social value change have been constructed by others.* The purpose and time horizon of our project made it unnecessary to include elaborate representations of these three factors in World3. Here we shall describe how simple social feedback mechanisms were included in World3 and how more complete representations of these subsystems might be constructed by anyone wishing to disaggregate the model.

Economic price is a function of two socially determined variables: the current

*System dynamics models of price change have been presented by Naill (1973), Meadows (1970), and Weymar (1968), Roberts (1964) developed a detailed representation of new technological development programs, and McPherson (1965) and Randers (1973) have constructed models of social change.

marginal value society places on a specific good or service, and the apparent marginal cost of supplying that good or service. Economists postulate that the price system performs a long-term stabilizing function in economic systems by signaling resource scarcity. When a material becomes scarce, the cost of obtaining it increases, and all products containing it will increase in price. The price increase may trigger numerous social responses. For example, the search for natural deposits of that material may be intensified; the recycling of discarded products containing it may be increased; manufacturers may learn to use the material more efficiently or to substitute another material; or consumers may decide to get along with less of each product containing it.

World3 includes several causal relationships between the supply of some material (such as food, nonrenewable resources, or industrial capital) and the response of the economic system to that material's scarcity (develop more agricultural land, allocate more capital to resource production, or increase manufacturing efficiency). These relationships are most realistically represented with price as an intermediate variable:

decrease in supply → rise in price → social response.

World3 simplifies the model of social response by eliminating explicit reference to price, the intermediate variable. We shortened the representation of the causal chain to:

decrease in supply → social response.

The ultimate regulating effect of the price system is thus included, but price does not explicitly appear in the model.

We assumed that the price system conveys its signals of scarcity to decision makers accurately and with a delay that is insignificant on a 200-year time scale. Thus the price mechanism was eclipsed to increase the model's simplicity and comprehensibility. If actual prices are biased or do not immediately reflect declining resource supplies in the real world, the global economic system will be less stable than its facsimile in World3. If price information is transmitted to institutions that adjust their production or consumption patterns only after a long delay, the economic system will be less able to adjust itself to any limit, and the tendency for the system to overshoot its limit will be increased. Our representation of the price system in World3 thus tends to overestimate the stability of the real-world system.

Technological advance, like price, is a social phenomenon; it results from applying man's general knowledge about the world to the solution of specific, perceived human problems. If we were to make a complete dynamic model of the development of a given technology, we would include the following:

1. A level of accumulating general knowledge, with the rate of accumulation dependent on the resources devoted to basic research.
2. A widespread perception of some human problem.
3. An allocation of physical resources, human effort, and time to search for a technical solution to the problem. If the level of basic knowledge is great enough, the solution will be found after some delay.