Hohenemser, C., R. E. Kasperson, and R. W. Kates, 1985. "Causal Structure", Robert W. Kates, Christoph Hohenemser, and Jeanne X. Kasperson, eds., Perilous Progress: Managing the Hazards of Technology, Westview Press, pp. 25-42.

# Causal Structure

*Christoph Hohenemser, Roger E. Kasperson, and Robert W. Kates*

If a tree falls in a forest far from human ears, is there a sound? This is a classic philosophical problem. For hazard control, the analogous question is: If a tree falls, is there a hazard? Trees fall from a variety of causes--disease, lightning, flood, fire, the sharp teeth of beavers, and the axes and chain saws of humans. Such occurrences may have no immediate human implications and we call them events. But trees may also crush people, maim livestock, and destroy buildings, dam streams, cause floods, and accelerate erosion. These and other impacts on humans we call consequences. As threats to humans and what they value, hazards consist at minimum of events and consequences, just as sound in the perceptual sense requires at minimum the physical excitation of sound waves and the receipt and perception of these by human ears and brains.

The division of hazards into events and consequences strongly implies three possible strategies for hazard control: (1) prevention of hazard events; (2) prevention of hazard consequences once events have taken place; and (3) mitigation of consequences once these have occurred. Prevention of events appears to be most fundamental, whereas mitigation is often regarded as unsatisfactory in the sense that "an ounce of prevention is worth a pound of cure." Yet, in any particular case, any one of the three strategies may be the most appropriate. Consider the following examples.

For catastrophic nuclear power accidents involving the release of massive amounts of radioactivity, neither consequence prevention nor consequence mitigation is especially feasible. Therefore, most control efforts concentrate on activities designed to prevent hazard events, that is, strategy (1) above.

In contrast, for intensive geophysical hazards (tornadoes, earthquakes), this strategy has little value since no one can prevent or significantly alter them. Even strategy (2), prevention of hazard consequences, is of only limited utility since geophysical hazards inevitably produce large losses, especially in developing countries (see chapter 6). Thus societies practice strategy (3), consequence mitigation, in the form of property-damage relief, medical attention to survivors, and reconstruction.

Most hazard management falls between the poles represented by catastrophic nuclear accidents and intensive geophysical hazards. For automobiles, for example, events (accidents) are preventable in principle, and society has expended much effort in this direction, as in eliminating curves in highways. Yet the high cost and relative ineffectiveness of accident prevention makes consequence prevention equally, if not more, relevant. Particularly in the last ten years, it has become clear that much can be done to block injury, via seatbelts or other restraints (see chapters 8 and 14), after an accident has occurred. Finally, coping with auto accidents involves a heavy dose of strategy (3), mitigation of consequences, usually in the form of insurance designed to distribute the burden of loss.

### The Causal Anatomy of Hazards

How, specifically, do prevention and mitigation occur? To this end, it is useful to recognize that events and consequences are members of a causal sequence; that is, events cause consequences. As such, events and consequences are connected by causal pathways, the logical places for blocking the sequence for the purpose of hazard control. The causal sequence can be expanded arbitrarily to reflect the details of causal structure. For the purposes of this volume we generally use a seven-stage sequence, defined as follows.

We refer to two classes of events, **initiating events** and higher-order events, which we call **outcomes**. Initiating events include any number of occurrences that trigger hazardous failures of technological systems. Outcomes follow initiating events and are defined as releases of energy and materials that are direct threats to humans. The pathways that connect the two kinds of events vary in complexity. Often several nearly simultaneous initiating events lead to a given outcome, which in turn has several possible consequences. In the example illustrated in Figure 1, a loose, flammable garment, a strong wind, the wearer's distraction by conversation, and a nearby fire are all initiating events required to produce the outcome of garment ignition; and this, in turn, leads to three consequences--a destroyed garment, burned skin, and smoke inhalation.

In many cases, outcomes do not lead so directly to consequences, and it is useful to insert the stage **exposure** between outcomes and consequences. Grinding wheels may well release dust (outcome), but it does not follow that humans will be exposed or subsequently harmed. Exposure in this case occurs through dust inhalation, which may be blocked by appropriate respirators.

Upstream of initiating events (in the causal sense), we expand the sequence to include **choice of technology**, **human wants**, and **human needs**. Diagramming the full scope of hazard in this way is particularly important for cases in which downstream stages pose special control problems. In the case of certain pesticides, for example, there is at best only circumstantial evidence of carcinogenic potential, and specific downstream control interventions between events and consequences are poorly understood (Figure 2). In such a situation, prudent hazard control recognizes the ineffectiveness of downstream blocks and concentrates on upstream options such as choice of technology or modification of human wants. Examples of such strategies are the use of biodegradable, nonpersistent pesticides and the toleration of blemished fruit.

The seven stages of the causal sequence--human needs, human wants, choice of technology, initiating events, outcomes, exposure,



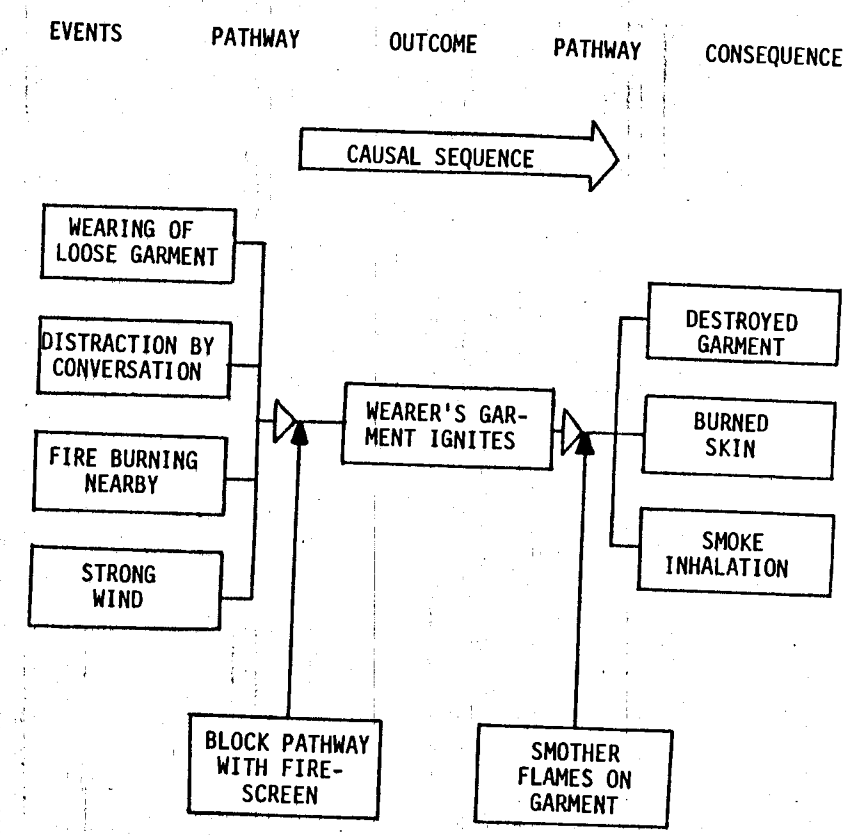


Figure 1. Events and consequences contributing to a fireplace accident. Note that several events contribute to the ignition of the wearer's garment and that this leads to several consequences. Coping with the hazard may be achieved by outcome prevention, illustrated here by a fireplace screen; and consequence prevention, illustrated by actions to smother the flames on the garment.

and consequences--are illustrated in Figure 3, which diagrams the full range of occurrences that lead from human needs to a burn injury. Also shown are appropriate control interventions that effectively block each step in the sequence. This simple example makes clear that there are many ways to control a hazard; and by implication, if one mode is ineffective or socially unacceptable, another may suffice.

Beyond the seven stages of Figure 3, one may usefully expand the sequence further if this yields additional meaningful opportunities for hazard control. Figure 4 provides two examples in which this is the case. In the first, several orders of consequences show how a burn may lead to eventual death. In the second, several orders of outcomes illustrate the process by which a corroded brake lining may result in an automobile crash.

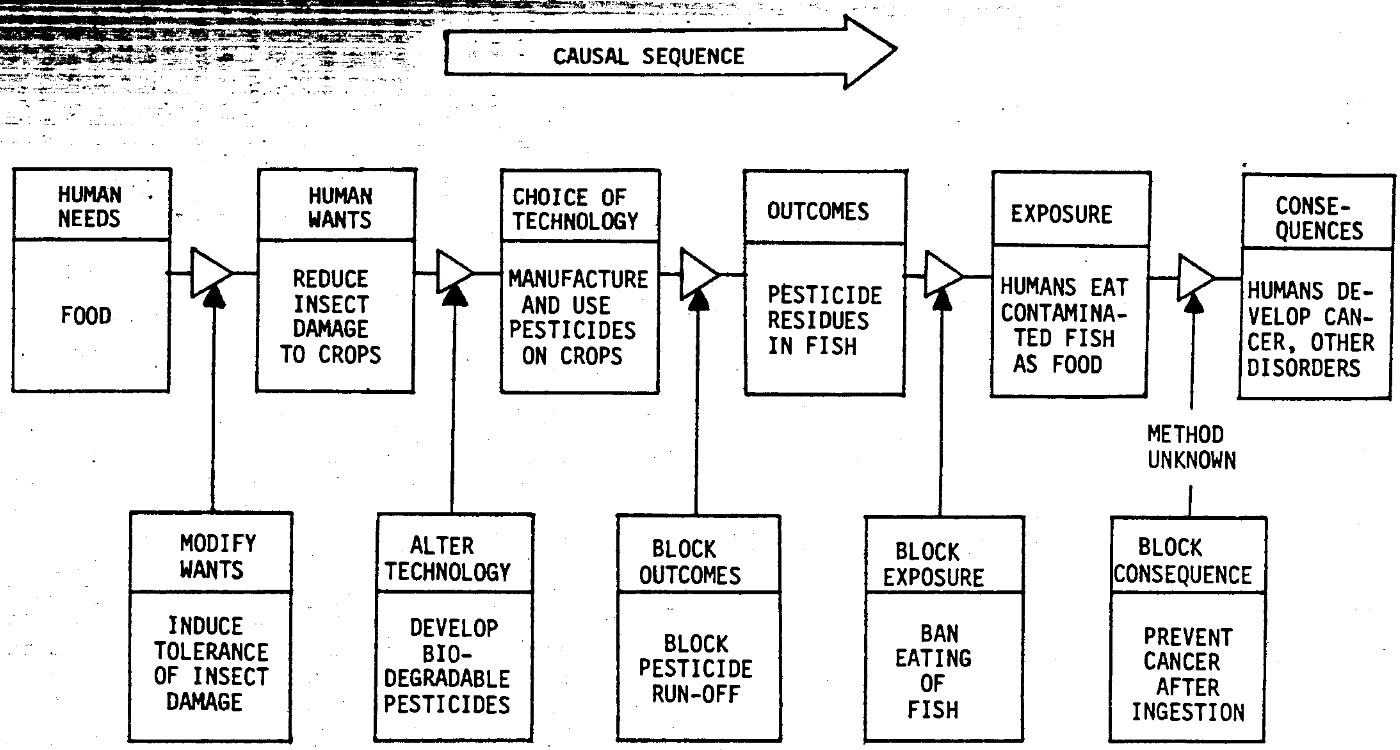


Figure 2. Hazard structure of pesticide use, illustrating the importance of upstream intervention when downstream intervention in hindered by insufficient knowledge.

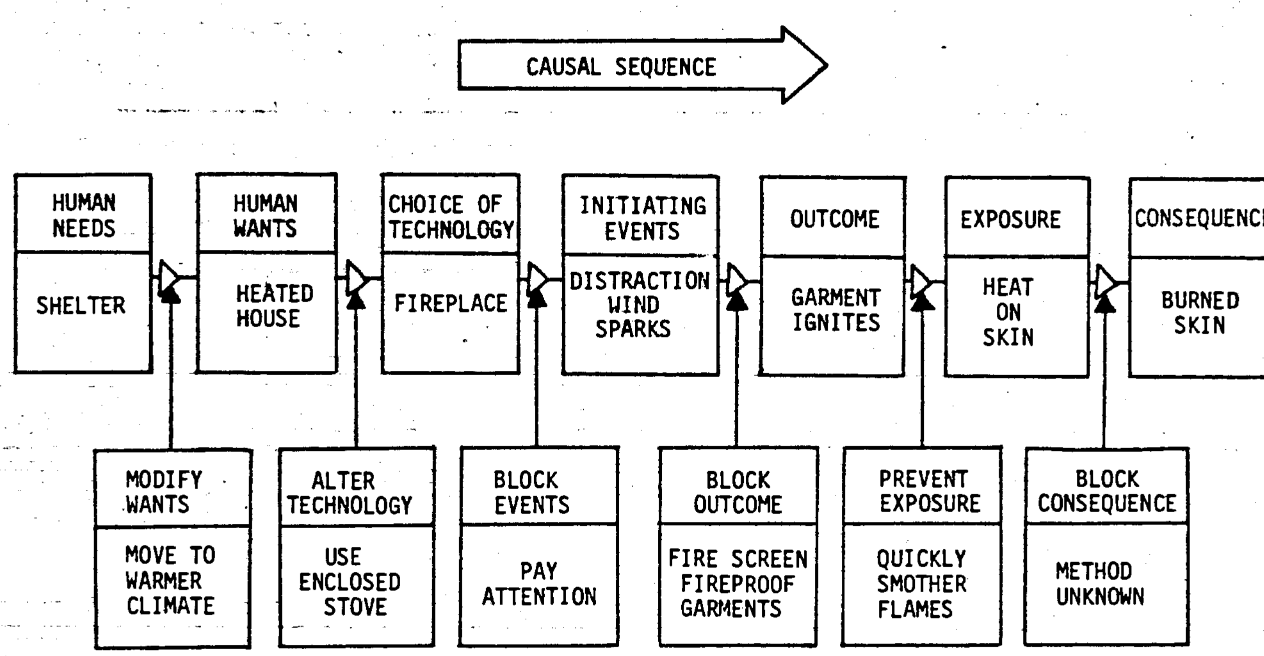


Figure 3. Seven-stage expansion of the hazard sequence, illustrated here for the case of the fireplace. Note the range of possible control interventions.

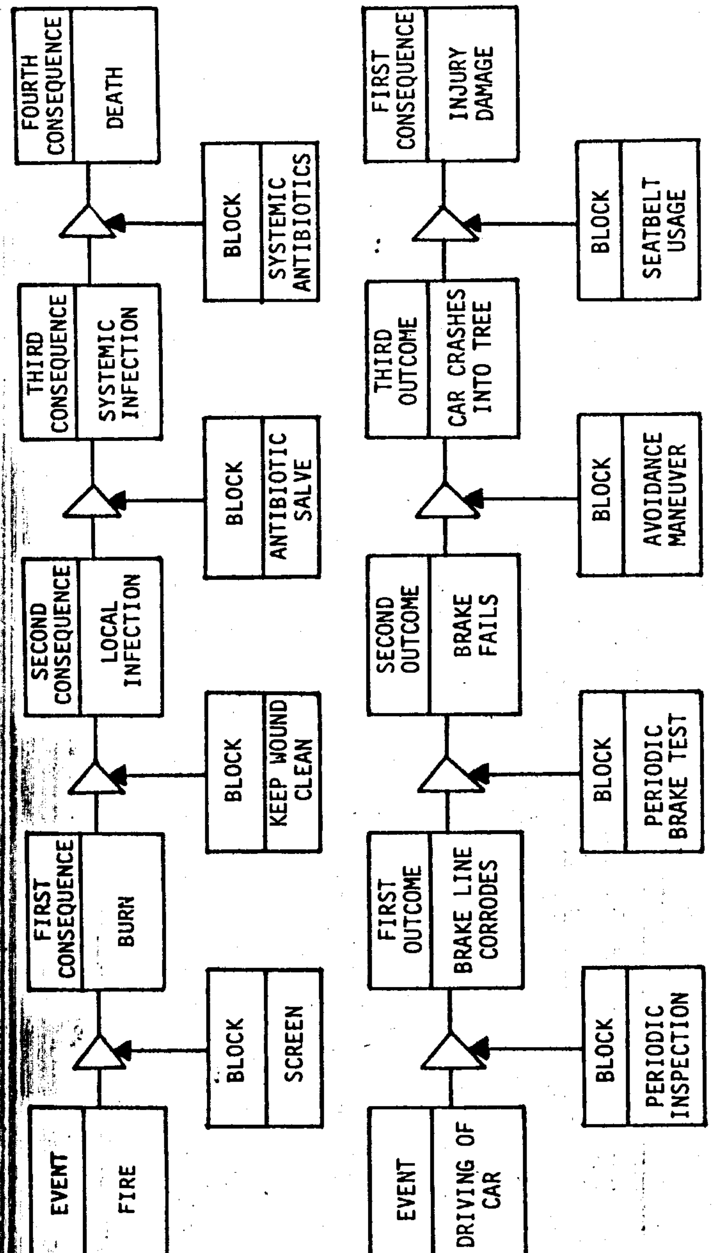


Figure 4. Expansion beyond the standard seven stages, illustrated here by the inclusion of several orders of consequences following a burn (top) and the inclusion of several orders of outcomes in an automobile accident (bottom). The variety of distinct control interventions available dictates the degree of expansion in each case.



Though the examples of Figures 1-4 involve a single causal chain, it happens quite often that a single technology generates several outcomes of significance. The entire cycle of coal-fuelled electric power, for example, involves release of air pollutants, coal dust, hot water, $CO_2$ and excessive kinetic energy which, respectively, may lead to respiratory disorders, black lung disease, damage to aquatic systems, climate change on a global scale, and a variety of injuries and fatalities. Each release involves a different causal sequence with a different set of consequences. As illustrated in Figure 5, the topology of the total hazard of "coal-fuelled electric power" resembles a pitchfork with a handle and several tines. More generally, the topology of complex hazard chains has a tree structure. In either case it is important to consider all branches and associated endpoints (consequences).

In its logic, the causal chain of hazard that we have described is related to the partition of natural hazards into events and consequences (Burton, Kates, and White 1978) and to approaches widely used in risk assessment (Rowe 1977;Kates 1978). The causal chain may also be thought of as a simplified fault tree and as such is comparable to the methods used to analyze nuclear reactor safety (Nuclear Regulatory Commission 1975;Lewis 1978), to classify auto safety options (chapter 8), and to deal with a variety of consumer products (chapter 16).

Figures 1-5 show that the causal structure of hazards has several distinctive features:

- It focusses attention on outcomes and visualizes these as releases of energy and materials that exceed the level with which potential target organisms can cope.
- It is purposely simple, with a managerial focus designed to identify opportunities for blocking the evolution of hazard events.
- It is comprehensive and includes upstream options such as control of human wants and choice of technology.

In viewing the diagrams of Figures 2-5, it is essential to realize that for most stages of the model there are several causes similar in character to those noted in Figure 1. We have suppressed such multiple causes for two reasons. First, our main purpose--to describe where along the causal chain opportunities for control intervention reside--does not require detailed information on all possible necessary and sufficient conditions. Second, introducing all contributing multiple causes at each stage would complicate our diagrams beyond easy comprehension and is better left for such time as a full fault tree is needed. This is not to say that describing the full structure of multiple causation is unimportant. Indeed, such description will become central to the design of specific blocking actions or control interventions, which invariably involve the removal of one or more necessary conditions for a subsequent hazard stage.

## The Dynamics of Hazard Control

Thus far we have indicated control points without considering the dynamics of the control process. In many cases of hazard

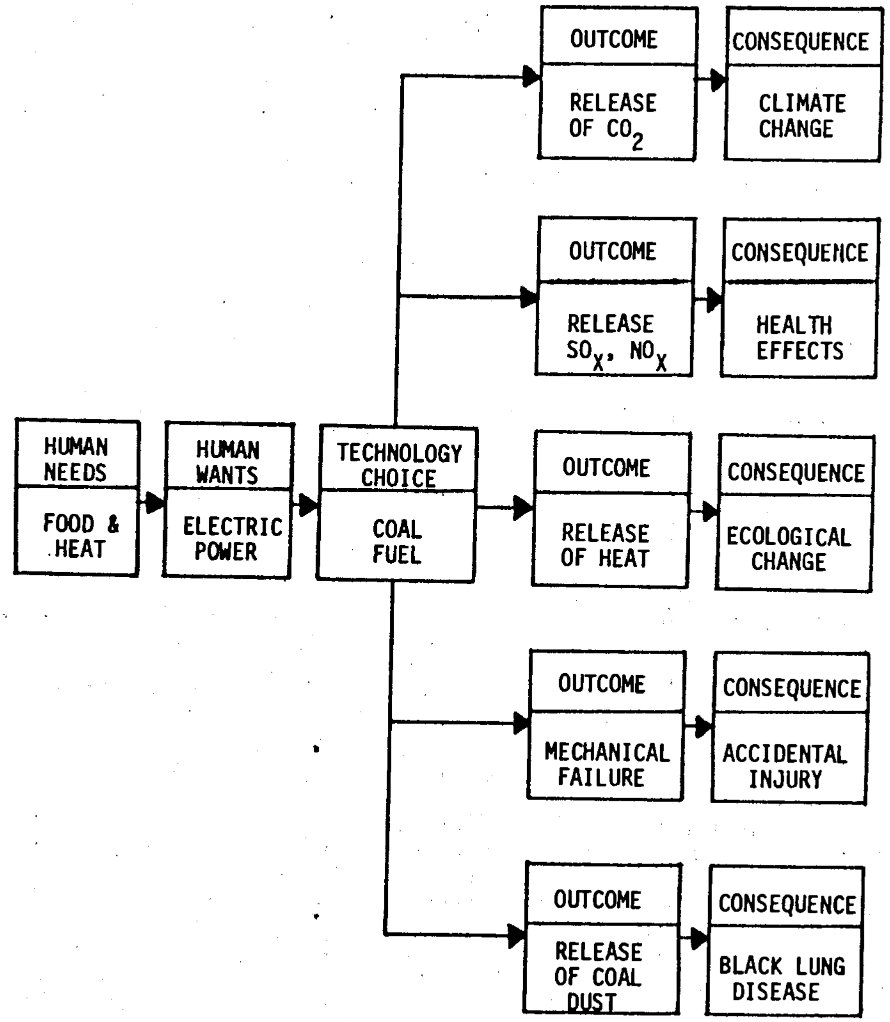


Figure 5. Illustration of the "pitchfork" topology of the hazards related to coal-fuelled electric power. There are at least five separate outcomes, each involving the release of different kind of energy or material and each leading to a distinct set of consequences.



control the simple sequence from "upstream" to "downstream" is an inappropriate description. Instead, a hazard is first recognized through an experienced release or consequence, and control action follows in time by inserting a block at appropriate upstream stages. In this sense, control intervention involves feedback: that is, information flows backward from downstream to upstream stages.

Feedback, in principle, may be either positive or negative. For reducing hazard, we desire negative feedback; that is, we seek upstream control intervention that blocks or reduces consequences. Unfortunately, hazard control has in many cases produced unintended positive feedback, or processes through which upstream control interventions increase the level of consequences.

In the field of hazard studies, one of the oldest and best-documented cases of unintended positive feedback involves the use of engineering technology to deal with the problem of flooding. Following the passage of the Flood Control Act of 1936 and subsequent amendments, the U.S. Army Corps of Engineers embarked on am ambitious program of flood dam, levee, and channel construction to protect flood plains. Not until 20 years later did research studies demonstrate that despite well engineered control interventions, flood damages were actually rising (Burton, Kates, and White 1968). In effect, the perceived safety of flood-plain location produced new settlements and overwhelmed the positive effects of less frequent flooding. The nature of the unintended feedback in the case of flood control is illustrated in Figure 6. Note that in addition to a negative or blocking action between initiating events and outcome, the control policy leads to a positive action—upstream of human wants—which intensifies wants.

In general, the unintended impacts of control actions are of two kinds: those that involve amplification of an existing hazard chain, and those that create new hazard chains. The case of engineered flood control illustrated in Figure 6, is an example of the first kind. The case of TRIS, a fire retardant that was later found to be carcinogenic, is an example of the second kind (see Figure 7).

The control loop structure may involve primary negative feedback at any of several points in the chain. Two examples taken from the field of auto safety illustrate the range. The first involves the increase in highway fatalities attributable to subsidized driver education (Figure 8), and stems from a control intervention that is largely focussed on blocking initiating events. The second involves the increase in highway fatalities due to nonuse of seatbelts (Figure 9) and is based on a control intervention that blocks consequences in the last 0.1 second before injuries are incurred. These cases are interesting from another point of view. Whereas the effects of subsidized driver education were quite unexpected, yet recently observed (Robertson and Zador 1978), the effect of seatbelt use was expected by some but found recently not to exist (Buseck 1980).

Though the principal benefit of diagramming the feedback loops of hazard control may lie in the potential for discovering unexpected positive feedback, our brief catalog of feedback diagrams would not be complete without noting a different but related case. There are obviously many instances where hazard control involves the knowing acceptance of new hazards as a price for control of an

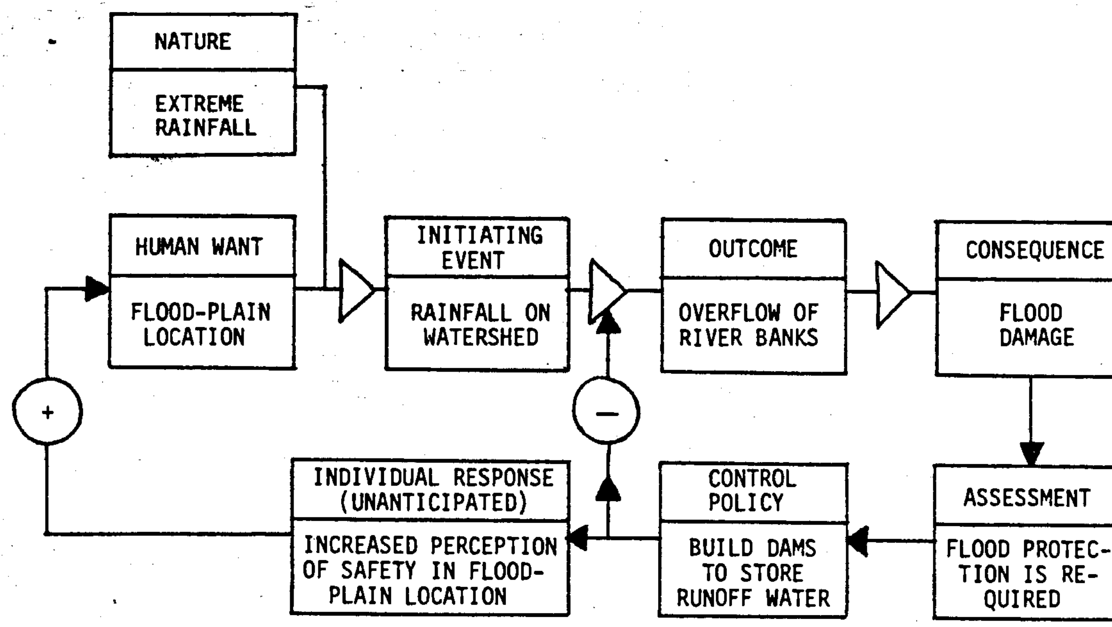


Figure 6. Feedback diagram for flood damage control. The unanticipated individual response of increased perceived safety in flood-plain location acts as a positive feedback and defeats the control policy.



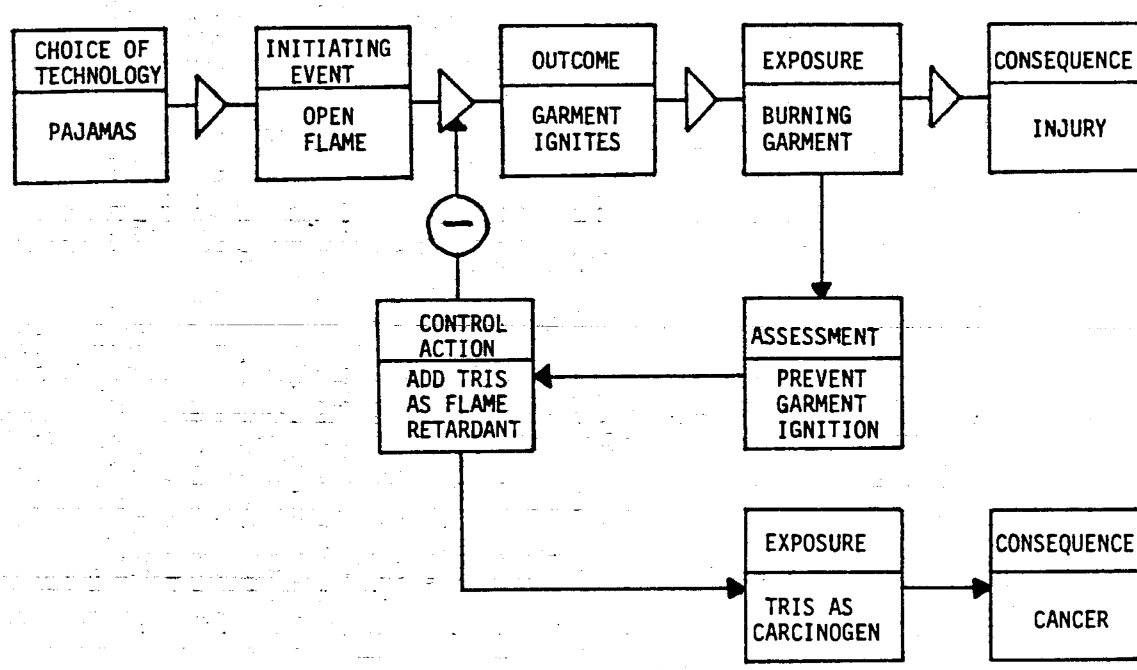


Figure 7. Feedback diagram for the use of flame retardants in children's pajamas. The control action leads to an unanticipated new hazard.

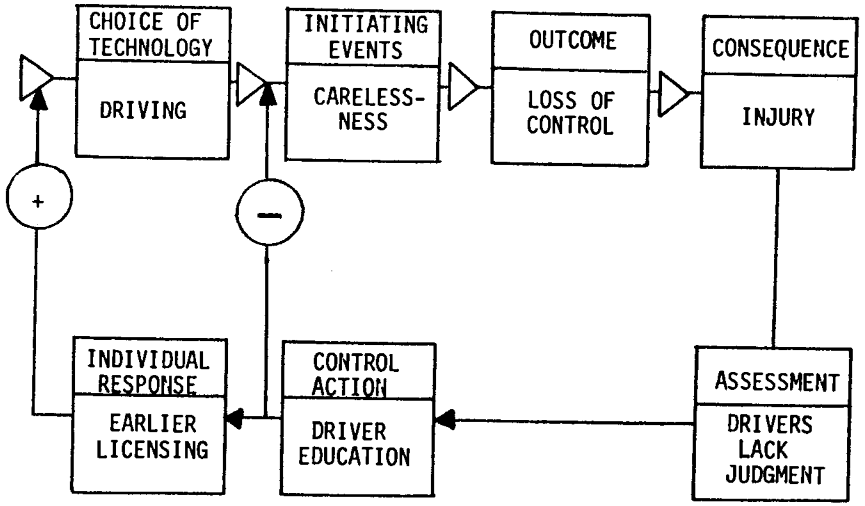


Figure 8. Feedback diagram associated with driver education. Driver education promotes earlier licensing, which increases the amount of driving by teenagers and defeats the initial control action.

existing hazard. A well-established example concerns the side effects of therapeutic drugs, illustrated in Figure 10 for the case of cancer chemotherapy. Other examples include the case of toxic waste dumps, where the risks of keeping large quantities in one place are traded for the higher risks of wide distribution; the case of non-persistent pesticides, in which short-term high-level exposure of workers is traded for long-term, low-level exposure of the general population; and the case of oral contraceptives (chapter 17) in which users trade the risks of unwanted births for a number of undesired medical side-effects.

Our analysis of the dynamics of hazard control suggests two conclusions. First, there are probably no "pure" control interventions that produce only their intended effects. Therefore, recognition of the amplification of an existing hazard or the creation of new hazards needs to be part of every control assessment. Second, it seems likely that diagramming a wide variety of control interventions will yield a small catalog of recurring types of interventions. Such a catalog could serve as a useful checklist for examining the efficacy of any proposed control intervention.

Beyond this, it is well to recognize that the present discussion abstracts a complex decision process and must therefore be applied with caution.

## Applications

The causal structure model is applied at a number of points in this volume. As a guide to these applications we provide a brief description of the most important cases.



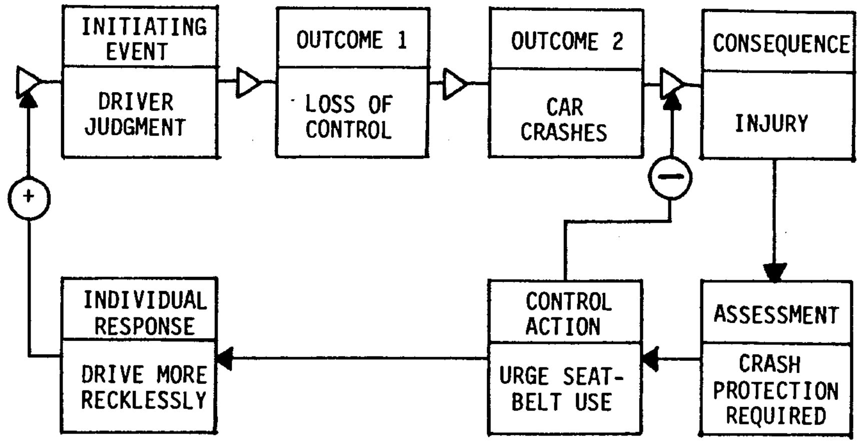


Figure 9. Hypothetical feedback diagram associated with the use of seatbelts. Research has shown that this type of feedback does not exist: i.e. belted drivers are less reckless than the average, not more reckless as indicated in the diagram.

### Hazard Management and Its Limits

Chapter 3 shows that the idea of a feedback loop serves usefully in organizing the functions of hazard management. It also shows that the causal model may be used in the construction of "effort maps," measuring levels of regulatory actions by hazard stage. This helps raise fundamental questions about optimization of effort; for example, in considering nuclear power regulation, it prompts the question of why so much effort is spent on upstream control interventions and almost none on consequence mitigation. A parallel application uses the model to conceptualize the timing of regulatory response.

### The Causal Taxonomy of Hazards

In chapter 4 we utilize the causal structure model as a template, and through quantitatively expressed social, physical, and biological descriptors, applied to successive hazard stages, obtain a 12-descriptor profile for each of 93 hazards. Because they apply to all stages of hazard evolution, our descriptor profiles considerably extend the conventional consequence-centered definition of "risk." Through factor analysis, we show that five linearly independent composite dimensions underlie the descriptor profiles. A pilot comparison to lay perception shows that our 12 hazard descriptors or five factors capture a large fraction of lay people's concern with hazard. Perhaps the most surprising result of the work is that annual mortality, the measure most frequently used by scientists to quantify risk, explains only a small portion of the variability of perceived risk.

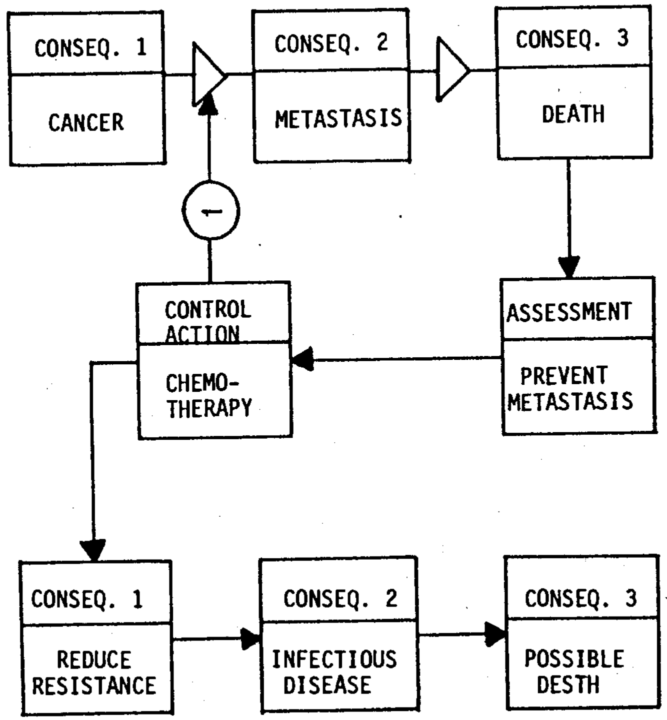


Figure 10. Feedback diagram for cancer chemotherapy. Initiating chemotherapy reduces the hazard of cancer but introduces new hazards of infectious disease. Unlike other cases where control action leads to new hazards, the hazard structure of chemotherapy is well-known to physicians, and the new hazard is accepted as the smaller of two risks.

**Estimates of Consequences**

By its divisions of hazards into events and consequences, the causal structure model lends itself naturally to an inventory of hazard consequences. Thus, chapters 6 and 7 give detailed estimates of mortality and economic losses, respectively. Though the separation of events and consequences, once recognized, is trivial, the tallies of mortality and economic loss obtained in chapters 6 and 7 are not and serve as our strong justification for society's continuing attention to the problem of technological hazards.

**Management Options**

The causal structure model provides useful descriptions of management options in the context of our case studies in Part 4. A particularly notable example is the discussion of highway and automobile safety (chapter 14), which shows that in recent years a major shift in regulatory effort has taken place. Other applications of the model occur in the discussion of PCBs (chapter 15) and the discussion of contraceptives (chapter 17).



**Mapping the Full Scope of Analysis**

Risk assessment, as described in chapter 11 and applied in Part 3 of this book, is only one of the family of methodologies related to hazard analysis. The causal structure model we have outlined lends itself well to mapping the full scope of hazard analysis. To diagram methods, we use double-line "forward jumpers," as shown in Figure 11. The loops created involve a forward flow of information and as such are distinct from the feedback loops used in describing control strategy. With this notation, the major methods of analysis may be summarized as follows.

**Risk Assessment**

This method links a specific technology design with subsequent stages of the model, including consequences. A good recent example is the Reactor Safety Study (Nuclear Regulatory Commission 1975), which proceeded from two specific reactor designs to event- and fault-tree analysis, and via explicit component failure probabilities to a range of outcomes. Each outcome involved specific radioactivity release and was assigned a specific probability. This was followed by a range of exposure models, each leading to a set of consequences.

**Technology Assessment**

This method is similar to risk assessment, but unlike the latter focusses on several design alternatives, with associated consequence scenarios for each. It also deals with benefits. Typical of this genre is the assessment of the SST (U.S. Dept. of Transportation 1976).

**Environmental Impact Assessment**

This method covers the same scope as technology assessment except that the consequence analysis is broadened to include environmental and social values to the fullest extent. A good example is the impact assessment of the breeder reactor (AEC 1974).

**Comprehensive Assessment**

Here, by movement of the origin further upstream, an effort is made to consider assumed or predicted human wants, expressed as "demand" in economic terms, or as "needs" in psychologic terms. Neither "demand" nor "need" is of course, value free. Thus, the use of "needs" for what are really wants purposefully blurs an important distinction; and the term "demand" implies an independence of other factors that is seldom found in industrial society. A good example of comprehensive assessment is the CONAES (Committee on Alternative and Nuclear Energy Systems) Report (National Research Council 1980). Like the Reactor Safety Study, it is concerned with nuclear reactors; but the CONAES Report includes an assessment of undeveloped designs, other energy alternatives, and the possibility of dampening human wants.

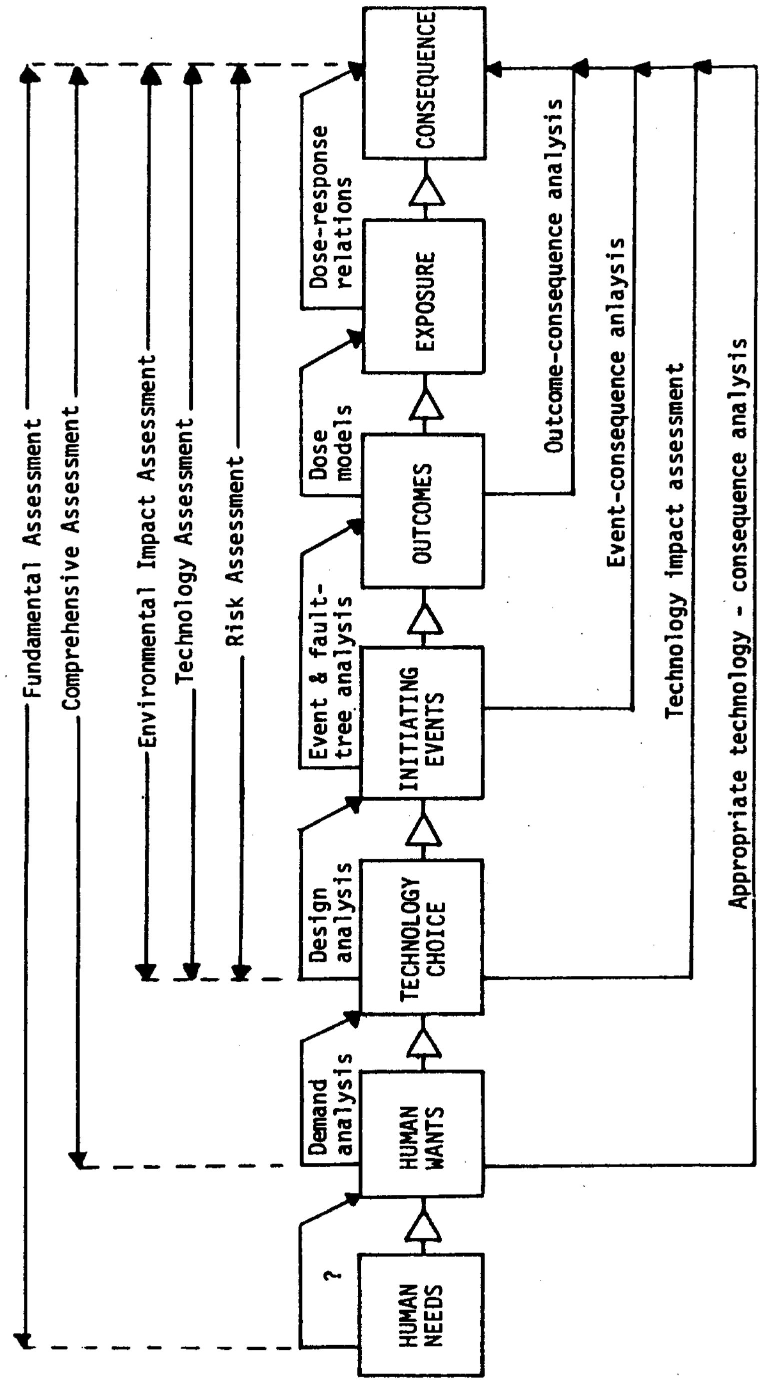


**Figure 11. Modes of analysis is illustrated via the causal structure model of hazards.**



**Fundamental Assessment**

Beyond human wants lie real, biologically determined needs. This ultimate origin of hazards must surely be recognized, though it is rarely, if ever, included in analysis. We therefore propose the term "fundamental assessment" to describe its inclusion. Interestingly, in the preparation of the CONAES **Report**, a primitive attempt was made to consider a "scenario" of life-style change involving a less "demanding" translation of needs into wants, but the Committee did not venture so far as to include it among the conventional "demand" scenarios. Thus, the discussion of the first link in fundamental assessment is left to the Maine Times, Mother Earth News, the Whole Earth Catalog, and the myriad of movements that argue for a simpler, less technological life. Meanwhile, a comprehensive assessment of hazards resulting from alternative life-styles remains to be made.

The lower portion of Figure 11 indicates a series of analytic methods that are largely implicit. In general, they seek only empirically derived correlations between earlier and later stages of hazard evolution. In later stages of the model, they are exemplified by actuarial statistics connecting, let us say, age- and sex-specific accident rates with particular geographical locations. In earlier stages, they fall within the purview of futurists, social critics, and philosophers who are concerned with technology evaluations that lack explicit treatment of the stages of hazard evolution. Both actuarial and implicit technology evaluation are useful in that they may alert society to potential problems and issues; but they do not suffice for design of hazard control.

Our discussion of methods of analysis in terms of the structure of hazards suggests two immediate conclusions:

- **Completeness.** The causal structure model easily accommodates all current practice of assessment and analysis, and does not require the use of new and unfamiliar terms; at the same time it provides a new sense of linkage that "puts into place" the current mélange of methods.
- **Potential for generalization.** It is likely that methods of analysis that work for one hazard may be generalized to other hazards and hazard groups with similar structure. Such generalization, in principle, will be a strong step toward a real discipline of hazard assessment.

Beyond this, it seems plausible that the more upstream the origin of analysis, the more fundamental are the derived results. For this reason, we prefer analysis that originates well upstream from the stage outcome. Our enthusiasm for such analysis is tempered only by the difficulties involved. Thus, the most reliable information is available in the area of empirically derived dose-response models, which incorporate only the last two stages of hazard; and analysis techniques that jump several stages but provide less adequate quantitative results are probably the least reliable.

Despite these reservations, we find powerful arguments for moving the origin of analysis upstream. It is becoming increasingly clear that many traditional analyses, particularly for toxic chemicals, are fundamentally blocked by the trans-scientific nature of the experiments required to establish reasonably explicit exposure-consequence relations (Gori 1980).

Therefore, control analysis must move upstream or achieve nothing. In addition, from a strictly practical point of view, it is clear that control analysis will lose its race with new hazards if it persists in dealing with one hazard at a time (see chapter 4).

**Summary and Conclusions**

We have described the time development of hazards as a causal sequence with well-defined stages and have indicated that the central stage in this sequence is the release of energy and materials. The causal sequence, which indicates the nature of feedback control, shows several characteristic patterns. We have shown how the causal sequence lends itself to a classification of methods of analysis, from narrowly focussed exposure-response relations to the most comprehensive methods.

In the next chapter we place causal structure analysis into the larger context of hazard management.

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# 3 Hazard Management

*Roger E. Kasperson, Robert W. Kates, and Christoph Hohenemser*

Hazard management is the purposeful activity by which society informs itself about hazards, decides what to do about them, and implements measures to control them or mitigate their consequences. Management is not the only way society deals with hazards; people adapt to hazards biologically and culturally over the long term and hazard control and mitigation often occur as incidental byproducts of other activities.

In the United States today, society's management of technological hazards is a significant undertaking. Chapter 6 reveals that technological hazards in the United States are associated with 20-30 percent of male and 10-20 percent of female mortality. Tuller (chapter 7) estimates federal, state, and local expenditures on hazard management at $99-132 billion in 1979, with another $80-150 billion accounted for by damages and losses. Later in the volume (chapter 19), Branden Johnson shows that between 1957 and 1978 Congress passed 179 laws dealing with technological hazards. Coping with such hazards, it is evident, is a formidable managerial task.

In the discussion that follows, we focus on society's management of technological hazards. We describe the principal participants in the management process, discuss the structure of management activity, identify major problems, and indicate ways of utilizing these concepts in the analysis and praxis of hazard management.

**Major Participants in Management**

Who manages technological hazards? Although it is increasingly common to think of managers as regulators, regulators constitute only one of several classes of managers. In all likelihood, private individuals make the largest management effort in the United States, and industry, rather than government, undoubtedly carries the principal institutional management burden. In our view, there are five major types of hazard managers:

- **Individuals.** Historically, individuals have been the principal managers of hazards. Despite an increasing government and industry role, they are still the prime managers of hazards. And for many hazards, the individual is the most appropriate point of control in