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REDUNDANCY IN SOCIAL SYSTEMS: IMPLICATIONS FOR WARNING AND EVACUATION PLANNING

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This paper provides a basic introduction to the concepts and theory of redundancy in social systems. It examines the implications of redundancy as a design method in planning disaster response systems, with special attention given to warning and evacuation. It also examines some of the criticisms of redundancy and examines several problems associated with transferring the concepts of redundancy to social systems. Examples are used to illustrate the benefits of planned redundancy in the design of warning and evacuation systems.

Most theories of planning and management place a great deal of emphasis on coordination and the reduction or elimination of what is perceived to be unnecessary redundancy. The goal seems to be the creation of streamlined systems which function with the fewest possible number of operational units and personnel, while still being able to accomplish system goals. Some analysts, however, have challenged this view arguing that the great concern for eliminating duplication and overlap within and between organizations has given insufficient attention to the benefits which accompany redundancy (Lindblom 1964; Emery 1967; Landau 1969, 1973; Warren et al. 1974; Whetten 1977; Perrow 1984; Bendor 1985; Morgan 1986). For example, Scott (1985, p. 603) notes that duplication and overlap serve as "a repository of needed variety and heightened responsiveness, and provides an important safeguard against system component failure." From this perspective, redundancy is viewed as excess capacity which provides a system with options to maneuver in the face of uncertainty. Such options are believed to make the systems more effective in the sense that when one component of the system fails the entire system does not fail. Reliability, then, implies effectiveness. That is, systems are effective to the extent that they are able to maintain dependable and predictable performance in the face of environmental uncertainty and individual component failures.

Given the potential for a large number of unknown contingencies in a disaster, planned redundancy in the emergency response system is one strategy to increase the overall reliability of the system's response. Perrow (1984) notes that a tightly coupled response systems are highly vulnerable to complete system failure if a single key component is unable to perform its role. In such systems, buffers, substitutions, and back-ups must be designed into the system in advance of the crisis. For example, back-up generators for hospital emergency rooms in case of a power failure. To the extent that such redundancy allows the system to continue to function, even though some components of the system have failed, it is an important consideration for pre-disaster planning.

This paper explores the utility of redundancy in disaster planning. First, basic concepts of redundancy theory are outlined. This discussion is abstract in order to provide a conceptual base for the application of redundancy theory to the field of evacuation planning. Next, the implications of redundancy for disaster planning are examined, with special attention given to issues related to warning and evacuation. Third, criticisms of redundancy and problems associated with transferring the concepts of redundancy to social systems are discussed. Finally, conclusions and implications for redundant systems in warning and evacuation are presented.

ROOTS OF REDUNDANCY

While the idea of redundancy is relatively new to the social sciences, it is well established in the biological sciences and in technological fields such as engineering, computer science and system design. In the biological sciences, the idea of redundancy is embedded in the concept of self-organizing systems. Self-organization refers to a process where internal structure and functions evolve along with changing circumstances. Von Neumann (1956) noted that self-organizing biological systems are able to diagnose errors as they occur, readjust the organism to minimize the effect of errors, and to correct or block permanently the faulty component. For example, when damage occurs in one part of the brain it is common for another part of the brain to assume the functions of the damaged part (Morgan 1986).

In the fields of engineering and system design, the concept of redundancy is reflected in such terms as over-engineering, reserve power, safety-factors, and reliability engineering. In the design of such complex technologies as automobiles, computers, aircraft, and communication networks, reliability is no longer left to chance. The reliability of these complex systems can be enhanced to the extent that redundancies are designed into them (Goldberg 1981; Drury and Fox 1975; Dummer and Winton 1974). For example, the controversy over automobile safety in the 1960s lead to

the introduction of redundant features, such as dual braking systems, as standard elements of design (Landau 1969).

In this sense, redundancy is a strategy for containing individual component failures within a complex system and thereby reducing the risk of complete system failure. It postulates system reliability as a function of the amount of overlap among the components of the system, even if those components are individually unreliable. Engineers refer to such systems as failure-tolerant because they can continue to function even though some of their individual components have failed. When one component fails, another component is able to take its place so the system can continue to function. This back-up function of redundancy emphasizes failure absorption rather than failure correction.

REDUNDANCY IN SOCIAL SYSTEMS

Redundancy in social systems has been describe in terms of two dimensions: form and function. The terms form and function refer to different design methods. Emery (1967) identified two kinds of redundancy in social systems: redundancy of parts and redundancy of functions. These design methods refer to how the subparts of the system relate to the whole.

Redundancy of parts is a machine metaphor which refers to a system where each component is precisely designed to perform specialized tasks and specific components are added to the system to control and to back-up or replace operating units whenever they fail. In systems designed with redundant parts, involvement of individual units in the whole is partial and instrumental. As applied to social systems, this design method is mechanistic rather than organic, resulting in highly specialized and formalized, hierarchically structured systems where each member of the system is responsible for a clearly defined set of tasks. Systems designed on the principle of redundant parts are organized and can be reorganized but they generally do not have the ability to self-organize (Morgan 1986).

When **redundant functions** are designed into a system, extra functions are added to each operating unit so that each component of the system performs a range of functions instead of a single specialized one. Unlike systems based on redundant parts, where the sum of the individual units make up the whole, systems based on redundant functions have the capacities required for the overall functioning of the system built into each part. This design method is much more adaptable to changing environmental conditions and is reliable when individual components fail.

Social systems which are designed with redundant functions are holographic because they are holistic and all-absorbing (Morgan 1986). Since each member of the system has a range of knowledge and skills relevant to the overall functioning of the system, the system possesses flexibility for responding to environmental uncertainty, and has the ability to reorganize built into each part. When changes in the environment require the system to perform new functions, it has the ability to alter either its overall operation or some aspect of it to meet the new demands.

Redundancy generally assumes one of two roles in social systems: stand-by or active. **Stand-by** refer to the back-up function of redundancy where one component takes over a function only if another component fails. Stand-by redundancy also serves to supplement the efforts of operating units when they are overloaded by changes in the environment. Trained volunteers who supplement professional staff in times of crisis and reserve units in the military represent stand-by redundancy.

Active redundancy, on the other hand, refers to a condition where two components are simultaneously performing the same role. If one component fails, the overall system capacity may be reduced, if the remaining units are unable to compensate for the failed component. But, to the extent that the remaining units have reserve capacity, they may be able to partially compensate for the failed unit. For example, in emergency communication systems ham radio operators and citizen-band radio clubs are often able to establish communication linkages in areas which are unavailable or inaccessible to official communication systems. While it is not part of their normal role to handle emergency communications, their established communications networks represent an active or ongoing redundancy in the overall communication system.

By combining the two dimensions, it is possible to identify four different types of redundancy based on the form and function (role) of redundancy. Figure 1 illustrates the four types. Types I and II represent redundancies based on components designed to perform specific tasks, with additional specialized units designed into the system to monitor, control, or replace operating units when they fail. Type III and IV redundancies represent a generalist rather than a specialist approach to system operation. Each part of the system has the capacity to perform multiple (redundant) functions. When crises arise within the system, the system is able to reallocate existing resources to cover the functions of any failed component in the system.

In reserve back-up redundancies, each component of the system is designed to perform a single specialized function. To ensure against com-

Figure 1. Four types of redundancy based on the form and function of redundancy.

		Form of Redundancy	
		Redundant Parts	**Redundant Functions**
Role of Redundancy	**Stand-by**	Reserve Back-up	Extraordinary Roles
	Active	Complementary Controls	Auxiliary Services

ponent failure or system overload, back-up units are incorporated into the system so that if one part of the system is unable to perform its specific tasks, a replacement can be called into action as a substitute for the failed component. The use of trained volunteers in a disaster response would represent this type of redundancy. To the extent that volunteers have been trained to perform specialized disaster relevant functions within the system, and they are mobilized as a back-up or to supplement professional staff, they would be reserve back-up redundancy. For example, during the forest fire which ravaged Yellowstone Park in 1989, auxiliary fire fighters were brought in from around the United States to supplement National Forestry Service fire fighters when they became fatigued after long hours on the fire-line. While many of these auxiliary fire fighters had specialized training in fire fighting, they were not part of the forestry service fire fighting system. Thus, they served an important back-up function which helped maintain an effective fire fighting operation.

Complementary control redundancies generally perform a system control function rather than a back-up function. Each component of the system is still designed around specialized functions but additional units are added to the system to monitor for potential problems in system operation and to take corrective actions when problems are detected. In a disaster, the Emergency Operations Center (EOC) often represent this type of redundancy. Specially trained units are responsible for monitoring and controlling the overall operation of the disaster response. As damage assessment information flows into the EOC, members of the emergency operations team make critical decisions about the priority of different situations created by the disaster and the allocation of resources to respond to those situations. Another example of this type of redundancy would be specialized teams which have been trained and equipped to handle hazardous material accidents. Investigation units of the National Transportation Safety Board which investigate airline crashes and other transportation accidents represent yet another example of this type of redundancy. The purpose of all of these units is to monitor the system, identify problems as they arise, and take corrective actions. Yet, they are considered redundant because they are not needed as long as other parts of the system are adequately performing their function.

Extraordinary role redundancies are based on single units which have the capacity to perform multiple functions but those units are not currently involved in the ongoing operation of the system. That is, they possess knowledge and skills which are transferrable from one situation to another. However, those redundant skills and knowledge are only activated in the face of a crisis. In disasters, private construction companies often become involved in the disaster response by diverting personnel and equipment from their normal activities to disaster relevant functions. While their normal function may be to construct buildings or build roads, their equipment and skills are easily transferrable to the new functions of search and rescue and debris removal. Voluntary associations and community service organizations also represent this type of redundancy. Boy Scout and Girl Scout troops, service clubs, fraternal associations, and church groups may assume new functions as part of the disaster response system. However, under normal conditions they perform quite different functions in the community.

In auxiliary service redundancy, the individual parts are actively involved in the ongoing operation of the system. Ham radio operators and other amateur radio groups represent Type IV redundancy in that their main function is recreational for the members of the group. However, the skills which they possess are easily transferrable to emergency communications in a disaster. They are not officially part of the emergency communications system, in terms of its day-to-day operations. However, they are considered active redundancy because many amateur radio groups regularly monitor emergency communications through police scanners and other electronics equipment. Therefore, they are aware of developing situations and may serve an auxiliary redundant component in the official communication system.

To a certain extent, the mass media represents a Type IV redundancy in the emergency communication system. The primary functions of mass

media, especially television and radio, is to inform, entertain, and some might argue to educate the public. Yet in a disaster they often perform a critical function of warning the public of an impending disaster. While the normal daily functions of the mass media are related more to the entertainment of its audiences, its technology and other resources, and the knowledge and skills of its personnel, are easily transferrable to the new function of disaster warning. Again, they are considered an active redundancy because they have ongoing involvement in the emergency communication system through the Emergency Broadcast System.

While examples of redundancy abound in social systems, it has not been widely recognized as a useful designed method in planning complex social systems. The four types of redundancy presented in Figure 1 provide a conceptual framework for thinking about planned redundancy in social systems. While much of the preceding discussion is abstract and theoretical, the next section will explore some of the practical implications of redundancy in planning warning and evacuation systems.

IMPLICATIONS FOR WARNING AND EVACUATION PLANNING

Warning and evacuation are inextricably connected. Several authors have conceptualized warning and evacuation as a complex social process involving the interaction of multiple inter-related social and technical systems (Perry 1985; Perry and Mushkatel 1984; Perry et al. 1981; Foster 1980; Janis and Mann 1977; Mileti et al. 1975). The effectiveness of the overall system depends to a large degree on the reliability of the individual subparts which make up the system. Foster (1980, p. 174) notes that like chains "warning systems are only as strong as their weakest link." Therefore, great care must be taken in designing warning systems and developing evacuation plans.

Several studies have shown that lives can be saved, even in the face of tremendous property loss, when people in the threatened area receive advanced warning of the impending disaster (Adams 1981; Drabek et al. 1981; Quarantelli 1982). But warning is only one piece of the puzzle. Not only must people be warned in advance of the disaster, they must also respond to the warning in an appropriate and timely manner. If people do not heed the warning and take steps to protect themselves and their family members, the benefits of early warning are greatly reduced.

To be effective, attention must to be given to both the technical and social components of warning and evacuation systems. Technical components include such things as communication equipment for monitoring threatening conditions and warning those in danger, transportation systems for handling evacuations, shelters and other living arrangements for those being evacuated. Social aspects refer to the factors which influence how people perceive and interpret the warning, and also how they make the decision to leave the threatened area. Because failures can occur in either the technical or social components of the system, planned redundancy can be viewed as one strategy for designing more reliable warning and evacuation systems.

Technical Components

Technological advances in the past 25 years have greatly increased our ability to monitor changing conditions in the environment and to issue hazard warnings to specific populations with a high degree of accuracy. In designing warning systems, great faith is often placed in this technology. And yet, the technology remains vulnerable to certain kinds of threats. For example, without a reliable power source most of this technology becomes inoperable.

Technical components in warning systems generally serve two purposes: (1) to gather information about an impending disaster, and (2) to disseminate the warning to the threatened population as quickly and accurately as possible. Information gathering is generally accomplished by placing various types of sensors throughout a threatened area to relay information to a central processing center. For example, electronic sensing equipment automatically and continuously monitors the flow of water along many rivers to signal the potential for flooding. Satellite imaging and weather radar systems monitor changing weather conditions to alert us of threatening weather conditions. Yet this equipment does not always function properly due to the impact of the disaster itself, unrelated technical problems, and even sabotage and vandalism (Foster 1980; Gruntfest 1977; White 1969).

One way in which planned redundancy has been used to deal with such component failures is to organize trained volunteers to physically monitor changing conditions and report them to an information processing center through telephones or two-way radios. In many parts of the country the National Weather Service has organized trained volunteers into weather networks to back-up or supplement the weather radar systems which are their primary source of information. In some areas these weather networks have expanded their operation to include monitoring the flow of water along rivers and streams when the potential for flooding exists. Such networks represent redundancies in the system which serve to make the information

gathering component of the warning system more reliable in the face of individual component failures.

Once a decision has been made to issue a warning, planned redundancies can improve the chances that the warning will be received by all those in danger. Foster (1980) argues that ideally, every warning system should be supported by an independent back-up system which is capable of operating in isolation if the primary system is rendered inoperable or incapable of functioning effectively. For example, the primary tsunami warning system in British Columbia is based on radio and telephone communications. A back-up system might include high speed aircraft flying above the speed of sound to get the attention of those in danger, followed by slower planes dropping flares (Sewell and Foster 1975).

As proposed by Sewell and Foster, this system represents a back-up redundancy which would only be called into action if the primary warning system malfunctions for some reason. However, it might be useful to view this back-up system as an active component of the warning system. Some people will not hear the warning because they do not have access to a radio or telephone. If this procedure were incorporated into the primary warning system as an active redundant component, it could greatly increase the likelihood that all people in the threatened area will receive the warning.

In designing warning and evacuation systems, it is essential to remember that the population of most communities is far from homogeneous. One potentially effective redundancy to deal with this situation is to use computers to contact at-risk populations by phone and give them recorded warning information. A non-profit organization called TelePatrol International is currently working to make this technology available (Heide 1990). This technological redundancy can be extremely flexible and can serve as a important back-up to more conventional approaches to warning (i.e., sirens, media broadcasts, etc.), especially when dealing with diverse populations. For example, non-English speaking households can be identified and the warning issued in the appropriate language. Households with members who are hearing impaired can be contacted through special telephones which produce printed messages rather than recorded warnings.

One advantage of this system is that is can handle two-way communications. In addition to its ability to carry warnings to the public, it can also receive and collate information from the public. For example, those who are disabled or need special assistance can call into the system to indicate that need. It can also identify those who have not responded to the warning by making follow-up calls to see if the household has evacuated the threatened area. If the initial call received a busy signal, the system can continue to redial the number until it gets a response. In some cases it may even be possible to break in on conversations to warn both parties at once. Of course, one must remember that this system is also vulnerable to the same kinds of failures as other technical components of the warning system. However, from the redundancy perspective, this type of added redundancy will help produce a more reliable system overall.

Social Components

In some ways its easier to identify redundancies in technical components than in social components. Perhaps, as discussed above, this is because the concept of redundancy as a design principle is rooted in such technical fields as engineering and computer science. Still, it is clear that redundancies can be designed into social systems to increase their reliability.

To a large degree, warning and evacuation systems are decision-making systems. At an organizational level, information is gathered and evaluated to determine the severity of the threat and a decision is made whether or not to issue a warning to the public. At the personal level, individuals and families evaluate the warning once it has been received and make a decision to either ignore it or heed the warning and take steps to protect themselves and their property. Planned redundancy can be designed into the system to facilitate timely and appropriate decision-making.

At the organizational level, redundant functions can greatly increase system reliability. For example, Foster (1980) points out that since many key personnel in the organization may be ill, on holiday, or stranded when a disaster threatens, it is useful to develop a flexible command structure where responsibilities can be passed from one individual to another with a minimum of difficulty. This can be accomplished by training personnel to perform multiple functions rather than a single specialized task and providing them opportunities to practice the skills needed to perform those functions long before the disaster strikes. Pre-planning this type of redundant command structure can greatly reduce confusion over responsibility for information evaluation and decision-making. It can also save valuable time in making critical decisions and result in more timely warnings being issued to the public.

At the personal level, perceptions of the warning message and the decision to respond are influenced by a number of factors: the context of the message, the degree of specificity of the message, the number of times the warning is heard, the number of different sources of the warning, the perceived legitimacy of the sources, and the consistency of the message

katel 1984; Perry et al. 1981). The effectiveness of warnings can be greatly enhanced by planned redundancies designed to address these issues.

When people first hear warnings their initial response is often to try to confirm the validity of the message. One way this is done is to seek out additional sources of information. They may turn on the radio or television, observe the behavior of those around them, or call relatives, friends, and even public officials as a means of confirming the warning. Considerable evidence shows that hearing repeated messages from multiple sources greatly increases the likelihood that individuals will believe a warning and take protective actions (Drabek 1986, 1985; Adams 1981). In designing warning and evacuation system, it seem prudent to develop ways to ensure that such redundancies exist in the system.

Perry et al.(1981) note that when warnings are issued far enough in advance, ones personal network can be an important supplement to official warning systems. Warning systems designed to provide detailed and consistent information which is location specific, but disseminate it over large areas through multiple sources can facilitate the emergence of this informal warning system. Relatives and friends often relay additional information about the threat to those living in the effected area, thus serving as important confirmation sources for the warning. Another advantage of this informal warning system is that it may promote an appropriate response to the warning. Often friends and relatives encourage those in the threatened area to evacuate by extending an invitation to stay with them. Not only does this increase the likelihood that the warning will be taken seriously but it also reduces the need for publicly provided shelter for those who do want to leave the threatened area.

PROBLEMS IN ORGANIZATIONAL REDUNDANCY

The transfer of a mechanical system concept such as redundancy to social systems is not without its problems. For one thing, little direction is given for determining what level of redundancy is sufficient to ensure reliability under changing and uncertain environmental conditions. For example, Bendor (1985) points out that when the United States tried to rescue its hostages in Iran, the military planners believed six helicopters would be sufficient for the operation. To increase the probability that the mission would be successful, two extras were sent as reserve. When three machines malfunctioned, the mission had to be aborted. What seemed to be more than enough back-up during the planning phase proved to be inadequate during the actual mission.

The question then becomes what level of redundancy is enough to ensure a reliable outcome? Would four back-up helicopters have made the hostage rescue mission in Iran a success? No one knows for sure. What is known for sure is that in this particular case two back-ups were insufficient. But each added redundancy can create new problems beyond the cost of maintaining a back-up. In this case, each helicopter added to the secret mission created additional logistical problems which increased the potential for detection.

Systems with no redundancy are highly vulnerable to complete system failure in changing and unstable environments (Perrow 1984). At the other extreme, however, a completely redundant system would not only be highly inefficient but would probably be chaotic unless it contained well developed procedures for coordination and control. Georgopoulos (1972) argues that organizational effectiveness is achieved when organizations are able to find balanced solutions to their problems. For redundancy theory to be applied to social systems, greater knowledge about the optimal level of redundancy required to ensure system effectiveness under different environmental conditions is needed. Redundancy will be useful only to the extent that it balances the benefits to be gained from redundancy against the limited resources of the system.

A second problem has to do with the assumption that redundancies are independent. Classic theories of redundancy in mechanical systems do not allow for interactions between redundant components. Such interactions disrupt the functional independence essential to the back-up effect. However, in social systems, the assumption of independence is hard to accept. In organizations, what happens in one part of the organization often affects the operation of other parts. In organizational networks, a failure in one organization may result in subsequent problems for other organizations in the network. In fact, organizational interdependence is one of the basic concepts of interorganizational theory (Litwak and Hylton 1962; Gillespie and Mileti 1979). Therefore, it seems unreasonable to assume independence in organizational systems.

This can be a significant problem in the design of disaster warning systems. For example, two-way radios often serve as back-ups for telephone communications. But to the extent that they both require the same power source they could not be considered independent. Even battery back-ups for radios and computers do not make such systems completely independent because the limited duration of the batteries means that they require the same power source for periodic recharging. This, of course, does not mean that such redundancies do not make the system more reliable. It may be that

the two-way radio makes it possible to communicate when the telephone lines are overloaded or inoperable. But the overall system still remains vulnerable to a complete power failure. In this case, a back-up power generator may be an independent redundancy which would enhance total system reliability.

Another problem is that redundancy in mechanical systems generally guards against only one type of failure, say the malfunction of a warning siren. But in most social systems there are two types of system errors or failures (Landau and Stout 1979; Felsenthal and Fuchs 1976). For example, in disaster warning systems there are errors of omission as when a warning is not issued when in fact a disaster is imminent. However, there are also errors of commission when a disaster warning is made but the disaster does not occur. A perfectly redundant system would be completely reliable, guarding against both types of errors.

There may be trade-offs between these two types of reliability since guarding against unwanted actions may nullify efforts to ensure desired outcomes. In warning systems, redundancies may be designed into the system to guard against issuing a warning when there is no real threat (error of commission). But, such redundancies may increase the probability that a warning will not be issued when there is impending danger (error of omission). Introducing a particular type of redundancy without regard for the type of error already prevalent in the system can impair rather than improve overall system reliability.

Another problem is that designing redundancy in social systems is by its very nature a normative process. Because redundancy is primarily a strategy for reducing and containing the effects of component failures, its utility is related to the frequency and relative importance of the two different types of errors. If only one type of error has important consequences for the system, redundancies can be designed into the system to minimize those errors even though the total number of errors is increased. For example, warning systems may be biased in favor of issuing a warning when danger is not imminent because it is believed that issuing an unnecessary warning is less serious than failing to warn when the threat of danger is real.

When there exists in a system the possibility of two different types of errors, redundancy theory becomes much more complicated because of the trade-offs between the errors. It also becomes very political because of the lack of agreement about the relative importance of the errors. Classical redundancy theory as applied to hardware systems provides little help in answering these normative questions about the appropriateness of and optimal levels of redundancy.

CONCLUSION

In a perfect world were everything is certain and predictable, there would be no need for redundancy. Information gathering would be accurate and complete, warnings would be issued in a timely and consistent way, and all individuals in a threatened area would hear the warning and take appropriate actions to protect themselves and their families. However, the real world is full of surprises. Individuals do not always make accurate assessments of their level of risk nor act rationally in responding to disaster warnings. Equipment does not always function properly. Disasters create uncertainty in the environment. The greater the uncertainty, the greater the potential for failure in disaster warning and response systems. Therefore, uncertainty is a primary reason why redundancies exist in social systems.

In the area of planned redundancy, the applied fields of emergency management and disaster planning appear to be leading the development of redundancy theory in the social sciences. The question is not whether redundancy should exist in warning and evacuation systems, for redundancies do exist. Rather, the question should be whether redundancy is a reasonable design strategy for improving the reliability of warning and evacuation systems. The answer to this question, according to Landau (1969, 1973), seems to be yes. He argued persuasively that a correct arrangement of independent and functionally equivalent channels of communication, decision-making, and action can provide a level of reliability which nonredundant systems could never achieve.

This, of course, is not an argument in favor of wholesale duplication and overlap. Clearly, emergency managers and disaster planners have a responsibility to be conscious of the efficient use of limited resources. Rather, it is a recognition that there are benefits to be derived from carefully designed redundancies. While existing theories of management and planning provide little direction in designing and implementing redundancy as part of a rational problem solving process, there is growing awareness that in some cases the benefits derived from duplication and overlap may outweigh the costs. The challenge is to more clearly specify the forms which redundancy takes in social systems, design principles for incorporating redundancy into disaster warning and response systems, and identify the conditions under which the benefits of redundancy will be realized.

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