Synergy between biology and systems resilience

Ashik Chandra

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ABSTRACT

Resilient systems have the ability to endure and successfully recover from disturbances by identifying problems and mobilizing the available resources to cope with the disturbance. Resiliency lets a system recover from disruptions, variations, and a degradation of expected working conditions. Biological systems are resilient. Immune systems are highly adaptive and scalable, with the ability to cope with multiple data sources, fuse information together, makes decisions, have multiple interacting agents, operate in a distributed manner over a multiple scales, and have a memory structure to facilitate learning. Ecosystems are resilient since they have the capacity to absorb disturbance and are able to tolerate the disturbances. Ants build colonies that are dispersed, modular, fine grained, and standardized in design, yet they manage to forage intelligently for food and also organize collective defenses by the property of resilience.

Are there any rules that we can identify to explain the resilience in these systems? The answer is yes. In insect colonies, rules determine the division of labor and how individual insects act towards each other and respond to different environmental possibilities. It is possible to group these rules based on attributes. These attributes are distributability, redundancy, adaptability, flexibility, interoperability, and diversity. It is also possible to incorporate these rules into engineering systems in their design to make them resilient. It is also possible to develop a qualitative model to generate resilience heuristics for engineering system based on a given attribute. The rules seen in nature and those of an engineering system are integrated to incorporate the desired characteristics for system resilience. The qualitative model for systems resilience will be able to generate system resilience heuristics. This model is simple and it can be applied to any system by using attribute based heuristics that are domain dependent. It also provides basic foundation for building computational models for designing resilient system architectures. This model was tested on recent catastrophes like the Mumbai terror attack and hurricane Katrina. With the disturbances surrounding the current world this resilience model based on heuristics will help a system to deal with crisis and still function in the best way possible by depending mainly on internal variables within the system.
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INTRODUCTION

1.1 MOTIVATION

How do we design the resilience of engineering systems based on the resilience seen in nature?

This thesis focuses on understanding resilience in biological systems; to be able to draw conclusions from them that can be used for creating resilient engineering systems architectures. To achieve this goal an attempt is made to identify the heuristics that can describe resilience in biological and engineering systems with the intent to develop a qualitative model to select biologically inspired heuristics that can make engineering systems resilient. Social insect colonies and immune systems are examples of natural systems that show a great deal of resilience. For years biologists have studied social insects like ants, termites, and bees to find out how these creatures are all so organized and creative.

- How do social insects like ants, bees, and termites build arches, stack food, and build bridges?
- How do social insects and other animals coordinate their actions and achieve amazing system-level behaviors? Are there rules that these animals follow?
- How do birds in a flock keep their movements synchronized?
- Do fish traveling in schools collide when they swim so close? Never! They can turn, dive and move in unison like a ballet choreographed by nature where no one misses a beat.
- Do ants, bees, and termites follow certain rules in their exhibition of collective problem solving capabilities? Yes! Ants find the best and shortest routes from nest to a food source, form bridges, and cooperate while carrying large items.
- What can be learned from the above biological systems that can be helpful in managing unexpected disruptions and events that can affect engineering systems?
- What is it that makes the ants behave the way they do in the face of disturbances like their path being blocked by an obstacle?
- What makes these systems able to cope with change?
The whole ant colony can discover the shortest paths between their nest and food sources. The ants drop a substance called pheromone when they walk which is followed by other ants. The pheromones provide a complex signaling system for ants. The movement of an isolated ant is random but an ant that encounters a previously laid pheromone trail will detect it. This ant will decide to follow the trail and reinforce it with some more of the pheromone. Once the other ants smell this pheromone they have a tendency to choose a path with higher pheromone concentration. Thus a colony of ants will forage to the best food source available and they recruit other foragers by pheromone trails. After the ants have established a pheromone trail between their nest and pheromone source their trail could be interrupted by obstacles. The ants still find a way around the obstacle and can find the shorter path again. Once again the ants use pheromones, and the pheromones will be more concentrated around the shorter path which encourages more ants to follow that path.

The human immune system under normal circumstances can detect and eliminate harmful pathogens, thereby maintaining the health of the body by protecting it from bacteria, viruses and parasites. Biological immune systems deal with an enormous variety of disturbances and uncertainties, and can be thought of as a robust and adaptive system. Since the immune system needs to be able to detect and eliminate pathogens as fast as possible, there are mechanisms that help them adapt to specific types of antigens and to remember those adaptations for future responses.

A resilient ecosystem can withstand shocks and rebuild itself in times of need. Resiliency gives it the capability to deal with disturbances allowing most of the species to survive. Species diversity makes the ecosystem functions robust and the system behavior resilient. Resilience in social systems has the added capacity of humans to anticipate disturbances and respond effectively.

The normal source of resilience that helps a system to be successful against a threat of unexpected catastrophes can be revealed by a thorough analysis of their successes, incidents, and breakdowns. This knowledge will help in developing ways to recognize,
anticipate, and defend against unexpected disturbances or disruptions. This emphasizes
the need to identify the principles of behavior that helps biological systems succeed
against disruptions and use them to create resilient engineering systems that can
recognize, adapt to, and absorb variations.

1.2 RESEARCH OBJECTIVE

The goal of this research is to design and develop resilient engineering systems by
creating a collection of heuristics from natural and engineering systems. Finally, to
develop a qualitative model that will help to build the biologically inspired resilient
engineering systems.

The specific objectives are:

1. Identify rules that make biological and engineering systems resilient.
2. Develop a qualitative model that is based on biological and engineering systems
   resilience heuristics for architecting resilience for complex engineering systems.
3. Demonstrate value of the qualitative model developed for recent system disturbances
   experienced globally such as the Mumbai terror attack and destruction caused in
   Louisiana by hurricane Katrina.

1.3 THESIS LAYOUT

This thesis is organized into chapters. Chapter 2 follows the introduction and reviews
earlier research work done on resilience. It covers resilience definitions in different
perspectives; mainly resilience that is seen in biological and engineering systems and
their adaptations to changing conditions.

Chapter 3 describes the different biological and engineering systems in detail. The
resilience attributes are identified for biological and engineering systems. In Chapter 4,
development of a qualitative model obtained by combining the heuristics inspired from
resilient biological and engineering systems is described. The heuristics are based on the
biologically inspired system attributes that are selected in the previous chapter. The
qualitative model that is developed in the previous section is tested on the recent catastrophes that are either man-made or natural like the Mumbai terror attack, and hurricane Katrina, in chapter 5. This is done to evaluate how the system performed under stress. Architectures for these systems based on OV-1 DoDAF product are studied before and after applying the qualitative model. This analysis is a demonstration of the value of the biologically inspired model developed in the previous section. Finally chapter 6 summarizes the research results and provides direction for future research.

The qualitative model of resilience developed in this study is simple and it can be applied to any system since it is domain independent. The qualitative model developed for resilience is inspired by biological and engineering systems. There are heuristics that can be identified to explain the resilience in resilient systems. The uncertainties in the world now validate the need for design of resilient system using the attribute based heuristics as used in the model.
2. LITERATURE REVIEW

In this section previous published work done in architecting resilient systems is summarized and the need for studying resilience properties of biological systems is justified.

2.1 RESILIENCE

There are several definitions of resilience since the concept of resilience is shared by different disciplines. Depending on the branch of engineering, ecology, or system science the definitions of resilience will vary.

The Merriam-Webster Dictionary Online (Mish 2009) defines resilience as the

“the capability of a strained body to recover its size and shape after deformation caused especially by compressive stress”

“an ability to recover from or adjust easily to misfortune or change”

Resilience, from this definition therefore involves both the strength and robustness of a system as well as that system’s flexibility.

A system will perform its normal functions as long as it is not disturbed. After a large perturbation, system functionality is lost. Resilience comes from a structure that will provide ways to restore a system after a great perturbation. In order to come up with the definition of resilience used for this work there is a need to explain what resilience means in different disciplines. The term resilience is used in a variety of research settings to describe related characteristics. These may not be applicable to all systems, but it will help to study resilience in other systems in order to identify how researchers in different areas visualize the behavior of resilient systems.

The ability of material such as rubber or a spring to bounce back to shape after it is stretched can describe resilience in engineering. Therefore it refers to the quality of certain materials with regard to their elasticity and resistance. The deformation of a body is proportional to the force, and the original shape is retained once the force is removed. The strain is measured by the change in dimension divided by the dimension itself, called \((strain \, e = \Delta l/l)\). The stress is measured by the force divided by the area on which it acts
The ratio of stress to strain is a constant depending only on the material and is called modulus (Hibbeler, 2008). Hooke’s law states that the strain produced by several forces is the sum of the strains that would be produced by each force separately. The relation between stress and strain is the same for a force in each direction. For a complex engineering system it is difficult to measure this relationship.

Materials science defines resilience as “the ability of a material to absorb energy when deformed elastically and to return it when unloaded” (Hibbeler, 2008). This is usually measured by the modulus of resilience, which is the strain energy per unit volume required to stress the material from zero stress to the yield stress $\sigma$. The toughness of a material is its ability to absorb energy in the plastic range. Toughness is a measure of the ability of a material to absorb energy up to fracture.

Psychology defines resilience as “the process and outcome of successfully adapting to difficult or challenging life experiences, especially highly stressful or traumatic events” (Barbanel 2002). Resilient people bend rather than break during stressful conditions. Psychological resilience means that a person can withstand failure under extreme circumstances and also learn from those upsetting experiences. It is difficult to quantify resilience since there are a number of factors that contribute towards resilience. This includes the availability of resources, coping tools, and an individual or a group’s positive outlook about life. It is resilience that enables people to overcome difficult periods and emerge from them stronger and better than before.

What happens when an ant colony is disturbed? Once the colony gets disturbed they find a new site and relocate. Resilience is the ability of ant colonies to reassemble after disturbance or disruption that results in dissociation (Backen, et al. 2000). After a massive colony disruption, the individual workers are returned to their relative spatial positions by social resilience. The colony can maintain an efficient division of labor even in the absence of the colony’s components, such as the queen, the brood, and even a large number of the workers. Social resilience ensures that all workers are restored to their familiar tasks or to tasks in the neighborhood of their familiar tasks. Resilience is a
robust phenomenon that enables a colony to operate effectively, maintaining an efficient division of labor in the likely event that the components of the colony become lost during emigration.

Ecosystems have the ability to rebound from disruptions. Ecological systems have the ability to absorb disturbances and perturbations. It is resilience that allows an ecosystem to reorganize and renew itself when subjected to disturbance and change. Depending on the magnitude of the disturbance, ecosystems adapt to the changes in the environment and constantly evolve their states for their betterment. The concept of resilience was introduced by Holling (1973) in the field of ecology. Holling introduced the word resilience to the ecological literature by exploring ecological theory and the behavior of natural systems to find out if different perspectives of their behavior generate different insights and awareness useful in both theory and practice. One view of the world is individuals die, populations disappear, and the species eventually become extinct. The other view of the world depends on the number of organisms and the degree of their constancy. These are two different ways of viewing the behavior of systems. It is the properties of the systems that determine the usefulness of the view. An engineering design is supposed to result in a product that is expected to perform specific tasks under a range of predictable external conditions. Emphasis is on consistent performance and a slight departure from performance goal is immediately counteracted. This requires a quantitative view of the system. If, on the other hand the system is greatly affected by changes external to it and is always facing the unexpected, the constancy of the behavior becomes less important than the persistence of the relationships. Awareness now switches to the qualitative view of system behavior and to questions of existence or not. Holling categorizes two kinds of behavior of ecological systems. One is termed stability and it represents the ability of a system to return to equilibrium after a temporary disturbance; the faster it can return to equilibrium the more stable it would be. The other behavior is resilience and that is a measure of the persistence of systems and of their ability to absorb change and disturbance. Systems are not globally stable but can have distinct domains of attraction. In natural systems instability and fluctuations will introduce resilience and a capacity to persist. A system can be resilient and still fluctuate
greatly. According to Holling, “Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb change of state variable, driving variables, and parameters, and still persist”. Resilience viewpoint of the behavior of ecological system emphasizes domains of attraction and the need for persistence. The resilience framework requires only a qualitative capacity to devise systems that can absorb and accommodate future events in whatever unexpected form they may take.

Ecological resilience generally describes the property of an ecosystem that helps the system to tolerate and absorb disturbances. Resiliency is the ability to avoid, minimize, withstand, and recover from the effects of adversity, whether natural or manmade, under all circumstances of use. Holling attempted to refine the ecological definition by defining them as engineering and ecological resilience (Holling 1996). Engineering resilience focuses on efficiency, control, constancy and predictability- the attributes of perfect design. It is the resistance to disturbance and how long the system requires to return to the initial state. Ecological resilience focuses on persistence, adaptivity, variability, and unpredictability-all attributes with evolutionary or developmental perspective. It is measured by the magnitude of disturbance that the system can absorb before a system changes its structure by changing the variables and processes that control behavior. Ecological resilience stresses the grades of disturbances that the system can absorb before the system changes structure via variable or behavioral changes. However, both definitions were determined in the context of ecological systems.

Most species in an ecosystem persist at fairly constant levels despite perturbations. This persistence is modeled in most studies by imposing the constraint that species densities, when slightly perturbed from equilibrium, will return to that equilibrium. This is the condition of local stability. “Resilience depends not just on the characteristics of the individual species but also on the species’ interactions with other species in the community” (Pimm 1979). Species do not exist in isolation and so species recover from perturbation only after all the other species to which it is dynamically linked directly and indirectly have also recovered. Pimm addresses the question of stability in ecological
communities while trying to answer the question “How quickly will species recover following catastrophes?” According to Pimm ecology needs to address the five aspects of stability: stability in the strict sense, resilience, variability, persistence, and resistance. Pimm proposes a new alliance between theoretical and practical studies, and also makes distinct connections between theoretical work and the important concerns of practical conservation biology.

In 1973 when Holling introduced resilience to the field of ecology it was a way to help understand the non-linear dynamics found in ecosystems. It was earlier thought that interconnected elements in an ecosystem interacted to produce a stable equilibrium. It is now understood that this traditional ecological perspective is fundamentally flawed. Ecological systems do not maintain a single equilibrium but have the ability to change from one stability point to another when disturbed (Gunderson 2000). According to Gunderson, “Resilience in engineering systems is defined as a return to a single global equilibrium. Resilience in ecological systems is the amount of disturbance that a system can absorb without changing stability domains”. Adaptive capacity describes the processes that modify ecological resilience. It is the system robustness to changes in resilience. Loss of resilience is signaled as a resource crisis where the system state has changed. Once the system shifts to an undesirable stability domain, the management alternatives are to restore the system to a desirable domain, allow the system to return to a desirable domain by itself, or adapt to the new system state since the changes cannot be reversed.

Originally, resilience in ecology was used in the field of population ecology and it was mathematically based and math oriented. Since the early 1980’s, resilience has been used more in human environmental interactions. The research done on the resilience of social-ecological systems has resulted in the formation of a multidisciplinary research group called Resilience Alliance. According to Folke, et al. (2002), “Resilience for social-ecological systems is often referred to as related to three different characteristics: (a) the magnitude of shock that the system can absorb and remain in within a given state; (b) the degree to which the system is capable of self-organization, and (c) the degree to which
the system can build capacity for learning and adaptation.” Resilient social ecological systems are able to absorb larger shocks since resilient systems have the components needed for renewal and reorganization. Resilience is defined as the capacity of the system to undergo disturbance and maintain its function and controls (Gunderson and Holling 2001). Resilience is therefore measured by the magnitude of disturbance the system can tolerate and still persist. Resilience has the following three properties: (a) the amount of change the system can undergo (and implicitly, therefore, the amount of extrinsic force the system can sustain) and still remain within the same domain of attraction (that is, retain the same controls on structure and function); (b) the degree to which the system is capable of self-organization (versus lack of organization, or organization forced by external factors); and (c) the degree to which the system can build the capacity to learn and adapt. Adaptive capacity is a component of resilience that reflects the learning aspect of system behavior in response to disturbance (Carpenter, et al. 2001). A heuristic model of change involves four phases: exploitation, conservation, creative destruction, and renewal, and these constitute an adaptive cycle. This adaptive cycle is necessary for organizing the meaning of resilience (Gunderson and Holling 2001). Resilience changes throughout the adaptive cycle and major changes occur during the creative destruction and renewal phases. Adaptive capacity is a part of resilience the learning aspect of system behavior in response to disturbance (Gunderson 2000). In humans adaptive capacity is closely related to learning. The key feature in the idea of learning in adaptive systems is the need to consider a range of plausible hypothesis about future changes in the system. All the strategies possible against a set of potential future are weighed in and then choose the one that will favor actions that are robust to uncertainties, reversible, and likely to reveal crucial new information system function (Gunderson and Holling 2001).

Resilience of a system takes into account the three attributes that influence the system dynamics. Stability dynamics of systems that have both humans and nature linked together emerge from three complementary attributes: resilience, adaptability, and transformability. Resilience is defined as “the capacity of a system to absorb disturbance and re-organize while undergoing change so as to still retain essentially the same
function, structure, identity and feedbacks” (Walker 2004). Resilience is a feature of some systems that allows them to respond to sudden, unanticipated demands for performance and then to return to their normal operating condition quickly with a minimum decrement in their performance. Adaptability is the capacity of actors in the system to influence resilience. Transformability is the capacity to create a new system when the existing system is flawed.

Jackson (2007) stated “System resilience is the ability of organizational, hardware and software systems to mitigate the severity and likelihood of failures or losses, to adapt to changing conditions, and to respond appropriately after the fact”. It is the ability of a system to avoid, survive, or to recover from disruptions. A capable system will possess the basic characteristics defined by traditional systems engineering: requirements, verification, validation, interfaces, etc. A system should meet basic system safety requirements and must be reliable. A system can experience unexpected and undesirable properties that are explained by emergence. Adaptability is the other capability that is essential to survive disruptions. Management capabilities cover risk management and the cross-scale interactions among nodes of the system infrastructure. Systems success depends a lot on cultural paradigms and there should be ways to change the mindsets. The various nodes of the infrastructure need to operate as a whole and not as a collection of organizations in order to assure resilience. Understanding the concept of systems where all the component parts work together will result in a resilient system. In order to understand and design resilience, the role of humans needs to be understood. The fact is that humans are highly adaptable and are capable of creating solutions that are mind-boggling.

Resilience engineering is the work of Eric Hollnagel, David Woods, and associates and it uses insight from research on failures in common systems, and organizational contributions to risk. Resilience is the ability to recognize and adapt to and handle unanticipated disturbances. Anticipation, attention, and response are the three qualities that a system must have to remain in control when faced with a disturbance. These qualities have to be exercised continuously with the organization constantly watching and
ready to respond. The ability to create mental preparedness by anticipating the changing shape of risk before failure occurs is one way of measuring resilience (Woods 2005). Adaptive capacity is the ability to respond to and instigate change and is an important attribute of resilience.

Meadows (1999) explains about the places within a complex system (a corporation, an economy, a living body, a city, an ecosystem, etc.) where a small shift in one thing can produce big changes in everything. Three of Meadows leverage points will be helpful in designing systems with resilience. The most important leverage point is the power to add, change, evolve or self-organize system structure. System resilience is the mechanism in which a system can evolve and survive almost any change, by changing itself. For example, the human immune system has the power to develop new responses to diseases it has never before encountered. The next important leverage point is the rules of the system. The rules of the system define its scope, its boundaries, and its degrees of freedom. Information gets delivered to a place where it was not going before and this will result in making the people involved behave differently. Adding or restoring information can be a powerful intervention, since missing feedback is one of the most common causes of system malfunction. Creating conditions where instead of relying on government, the citizens need to take charge of their own protection. By getting people involved in a shared awareness, they can become an asset to resilience rather than a hindrance.

Resilience is found in everyday operations of complex systems. Self-organization was first introduced in 1947 by W. Ross Ashby and was taken up by physicists and people working on complex systems in the 1970s and 1980s. Self-organization can be compared to that of emergence in a system. When a large number of entities interact the resulting system can display features and behaviors which are not expressed by the individual constituents and this explains the concept of emergence. The most significant feature discriminating a ‘complex system’ from a ‘non-complex system’ is emergence. There can be self-organization without emergence and emergence without self-organization. The methodology proposed in the design of complex systems that is self-organizing is a
conceptual framework and a series of steps to follow that will enable the elements to find solutions by actively interacting among themselves. The elements of a complex system need to be designed so that they can find by themselves solution to problems that can arise. Gershenson in his PhD dissertation (2007) defines complexity and self-organization and proposes a methodology to aid the design and control of self-organizing systems. Self-organizing traffic lights will be able to adapt to changing traffic conditions thereby considerably improving the traffic flow. Examples of complex systems are a living cell, a society, an economy, an ecosystem, the internet, the weather, a brain and a city. The interactions between the numerous elements in these systems produce a global behavior that is different from the behavior of their separate components.

When an organization is resilient, it can manage its activities in such a way that in the event of a disturbance it is ready with an action plan. The resilience characteristic will enable the organization to anticipate threats and avoid them to some degree. Resilience helps the organization to recover, allowing continuing operations after a major disaster. Resilience involves systems that are a combination of humans, mechanical parts, and computer software. In order to account for the catastrophes that can happen it is necessary to do systems architecting based on the unpredictable aspects of humans and software. Organizations should be aware of and be ready for anything regardless of what the problem is. If redundancy or flexibility is built in the infrastructure it becomes easier to face any problem whether it is hurricane, earthquake or attack. What is required is information about changing vulnerabilities and the ability to develop new means of facing them. Resilient systems can function even when damaged. Resilience comes from simplicity of concept that allows easy understanding. Resiliency applied to the nation’s critical infrastructure is trustworthiness under stress and spans high availability, continuous operations, and disaster recovery. An institution that collects better facts about slow variables puts more importance on future returns, reducing the uncertainties present in the system and will have a better chance of withstanding disturbances.

The concept of resiliency in different areas established by all the discipline dependent definitions given to resilience will help in identifying the definition in this research.
Systems should be made resilient so that it can ensure that things do not get out of hand and that control is not lost. Disruptions are always anticipated in a resilient system even though it is impossible to pinpoint when or where it can happen or the intensity of the disruption. Resiliency lets a system to recover from disruptions, variations, and a degradation of expected working conditions. They are characterized by properties such as self-organization, emergent behavior, decentralized control, and adaptivity. Such a system can recover quickly from perturbations that could be a hurricane or flood or an earthquake. This property is a result of communication at all levels in the system. The system should have the capacity to adapt to the changes and act towards reorganizing. Resilience in this context requires understanding the elements of the system and its surrounding environment; anticipating how the system would respond to a disturbance. A resilient system has the ability to endure and successfully recover from disturbances.

One of the tools for resilience is diversity. Life has existed on earth for more than 3.6 billion years and during its tenure earth has faced disturbance in many forms, but life has flourished despite the disruptions in the form of volcanic eruptions, continents colliding and drifting apart, etc. Regardless of the magnitude of disturbance, diversity increases the chances of survival.

Another tool for resilience is functional redundancy. A well designed system will have parts that are renewable and replaceable. In case one of the components fails, another should be able to fulfill its function. Redundancy inevitably promotes resilience, since it permits elements in a system to malfunction with no danger to the entire system. In insect colonies loss of some part of colony does not affect the colony behavior.

Adaptation, an important element in resilience is the capacity to adjust and adapt to the disturbance. Adaptation requires anticipation (what to expect), attention (what to look for), and response (what to do) and they have to happen simultaneously in order to make a system resilient. Resilient systems can identify problems and mobilize the available resources to cope with the disturbance and this aspect is system resourcefulness. It is
necessary for resilient systems to collaborate and work as a team while ensuring awareness of the work processes at all levels with efficient communication.

Resilience that is seen in nature is discussed in detail in the section below. Learning how insect colonies and immune systems adapt to disturbances, and realign themselves after they are disrupted will help in identifying the rules followed by these systems to be resilient. Engineering systems also are discussed in detail to demonstrate their response to disruptions. Studying and looking in detail into the characteristics these systems, will help in comparing the engineering system to a natural system. Once the comparison is done the next step is to look at what is similar and what is not between these two types of systems in terms of resilience.

2.2 RESILIENCE IN BIOLOGICAL SYSTEMS

The biological systems have the natural ability to survive disturbances and are resilient systems. Ecosystems, ants, and immune systems are the biological systems discussed in this section. Understanding the resilience seen in biological systems will help in determining the characteristics that determine their resilience.

An ecosystem is defined as a structural and functional unit of biosphere consisting of a community of living beings, and the physical environment both interacting and exchanging materials between them (Tansley 1935). Odum (1971) referred ecosystem as the basic fundamental unit of ecology. An ecosystem is a biological functioning entity and the Figure 2.1 shows how the components of an ecosystem are linked together. The figure shows functional grouping where organisms that perform mostly the same kind of function in the system are grouped together. Primary producers are all the photosynthetic plants and they form a functional group. The interaction between elements is the system function and the result is the dynamics of the whole ecosystem. If an ecosystem is disturbed by too much rain (flood) or too little rain (drought) will have an impact on the vegetation. If the plants die, then the living creatures would have nothing to feed on and it is easy to see how changes in one element impact the entire ecosystem. After this
disruption the ecosystem displays resilient behavior by tolerating the disturbance without collapsing. Resilient ecosystems withstand shocks and are able to rebuild it if necessary.

![Figure 2.1: Components of Ecosystem](image)

Ecosystems are resilient since they have the capacity to absorb disturbance and are able to avoid disturbances. The elements of an ecosystem can be identified, numbered, and classified, and this is the structural aspect of organization seen in an ecosystem. Reservoirs in the ecosystem are where information is stored. This is the functional aspect of organization and allows the system to adapt its functioning. In ecosystems there is a communication network that allows information, matter, and energy exchange between the elements and the reservoirs. One example of communication network is a food web and the other types of network allow species to communicate by way of pheromones, sounds or vision. Ecosystems are *diverse, adaptive*, and can *self organize*. Biodiversity
make up the variety of life forms in the ecosystem and it includes *species composition* and *species redundancy*. Species composition is the number of different species present. Species redundancy is the presence of multiple species in ecosystems and this provides an assurance that ecosystem health is maintained in response to stress or disturbance. Different species that are present in an ecosystem compete or cooperate while interacting in their shared environment. Biological organisms adapt and they do so by undergoing variation and selection through signals. The basic functional network of an ecosystem is that it involves energy flows and cycling of matter. However, superimposed on the basic network is the information network and this helps in regulating the ecosystem (Patten and Odum 1981). The communication networks between and within species is in the form of signals. Communication signals could be visual, chemical or sound and these stimuli can trigger various responses occurring over different time scales. Resilience is the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker 2004). Ecosystems evolve successfully due to their diversity, adaptability, and redundancy, thereby enhancing their resilience.

Ants build colonies that are dispersed, modular, fine grained, and standardized in design. Ants use nothing unstable for its nest construction, and ant cities are found to contain chambers and galleries. Ant colonies satisfy a diversity of needs. Ants are small, mobile and fast. When under attack ants defense system has a very short lead time. They have early fault detection can repair colony damage quickly. Their operations are efficient and the wastes they produce are little. They are able to defend themselves when attacked. They can wage war for their best interests. It can be said ants are very resilient (Foster 1997). Ants eat a diverse variety of foods and they find their way through complex mazes and establish individual foraging routes. The information about food sources are passed on by tactile, chemical, vibratory and even auditory communications. Ant colonies manage to forage intelligently for food and also organize collective defense by the property of resilience.
Ant colonies foraging behavior display specialization. Specialization is a way of assigning different tasks to the animals belonging to a colony. A specialized system where tasks to be done are already assigned is supposed to be efficient since it eliminates the need to reassign the tasks to agents, which can be time consuming and will need a lot of communication. The presence of specialized individuals in the colony who collect experience from the tasks they perform, improve the overall performance of the system. They use division of labor to effectively feed their colonies and modify their surrounding environment for their benefit. This task allocation allows colonies to perform various tasks such as foraging, care of the young, and nest construction. The work in the colony is mainly done by females and they are called workers, and they care for young, feeding, cleaning, and attending to their every need. The colony food supply is provided by worker ants that collect grass seed and fungi. In the case of leaf cutting species the worker ants collect vegetable matter to fertilize their fungus gardens. In spite of this diversity ants have functional redundancy. Disruption of the ant colony could result in displacement of the colony to a new nest site. Resilience is the ability of ant colonies to reassemble after dissociation (Backen, et al. 2000). Social resilience enables individual workers to re-adopt their spatial positions relative to one another and resume their tasks without wasting any time in worker training. The individual ants in a colony are different and possess cognitive abilities since they are able to learn. The ants exhibit adaptability and self-regulatory capability of the whole colony. The mechanism underlying social resilience allows individual workers to return to their relative spatial positions under extreme conditions. By allowing for flexibility in the relative task profiles of workers, social resilience results in a colony level adaptive response to changes in supply and demand. The ant colony is always exploring new food resources and also exploiting its existing resources. A behavior pattern hides beneath the random behavior of ants that helps them to accomplish the desired outcome by self-organizing.

In social insects like ants communication is accomplished through the chemicals called pheromones. Once the ant that is foraging for food finds food, it will leave a trail of pheromones along the ground on its way back to the colony. This pheromone trail will be followed by other ants within a short time. The critical initial discovery of food
depends on having enough ants wandering around and finding the food source. The pheromone trail gets reinforced as it attracts more ants and eventually the food gets exhausted. Once the food source is used up the pheromone trail is no longer reinforced. This particular behavior of communication between ants would explain how ants are able to adapt to changes in the environment. Resnick (1995) developed algorithms that use a simplified set of rules to demonstrate the ants foraging behavior. Ants tend to follow the pheromone trace, but often lose the track: it can be said that pheromone works as a probabilistic guidance for ants (Hollnagel, et al. 2006). When one ant comes upon a prey it will automatically bite it and follow its own trace back to the nest. By putting down the pheromone it reinforces the chemical track, and the chance of another ant following the prey is increased. These small sets of simple individual behavioral rules like ‘follow the pheromone’, ‘bite prey’ will trigger a self-organizing auto-catalytic process that amplifies guidance to the prey. At the same time the possibility of individual ants losing track of the pheromone will allow for new prey discovery. A memory of positive past experience is written into the environment, leading to the collective strategy to collect food. The ants are able to leave an established path that has been blocked by an obstacle and seek new routes towards its desired location.

A flock of birds keep their movements orderly and synchronized. The birds were earlier assumed to play follow the leader with the bird in front leading the rest of the flock. Actually what happens is that each bird in the flock follows a set of rules and the flock patterns comes from local interactions, with each bird in the flock reacting to the movement of the birds adjacent to it (Bonabeau, et al. 1999). Flock of birds and school of fish react similarly when avoiding danger or changing course with a display of spontaneous collective behavior. The flock of birds functions as if it were a single unit. They generally move together in an elegantly synchronized manner by keeping a minimum distance and following the average direction of neighbors’ moves. Out of local interactions, emerges a global coherent pattern. The coordinated movements of flocks of birds or schools of fish are an example of emergent behavior. The behavior does not come from an individual but it emerges as a property of the group itself. The explanation for schooling in fish is by a self-organization mechanism where each fish applies a few
behavioral rules in response to local information from neighboring fish. The rules followed by each member of a fish school is to approach neighbors if neighbors are too far away and also avoid colliding with another fish. As long as these two rules are in effect and all neighbors are at a favorable distance, then that group maintains its coordinated movement in the same direction.

An immune system provide protection against infection by responding quickly to dangers or attacks by pathogens. Disease causing pathogens are the perturbations or disturbances in this system. The immune system is composed of the innate immune system and adaptive immune system. Innate immune system is made of static defenses like skin, and mucus that separate the individual from the pathogen and reacts to any pathogen that is recognized as being intruder. If the innate immune system is not able to contain the pathogen the adaptive immune system acts in order to produce a specific reaction to the infectious agent. The adaptive immune system consists of certain types of white blood cells called lymphocytes which circulate around the body. Lymphocytes co-operate in the detection of pathogens and help in the elimination of the pathogen. The immune system functional flow diagram is shown in Figure 2.2. The immune system faces the problem of identifying or detecting the pathogens, and then efficiently eliminating the pathogens, while at the same time minimizing harm to the body from both pathogens and the immune system itself. The detection problem is described as that of distinguishing “self” from “non-self”. The system is so designed that it can distinguish between self and non-self. It is then designed to make adequate response against the non-self pathogen that can kill the pathogen accurately, but leave the self untouched. This is done by recognizing the molecules of the pathogen and designing other molecules that fit like a lock and key with only the pathogen molecules. These molecules that are made by design carry with them the tools to kill the pathogen and are called antibodies.
Generating antibodies is one of the functions of immune system. The immune system is able to remember previously successful strategies when it encounters harmful invaders. It is composed of a large number of interacting cells and molecules that detect and eliminate infectious agents or pathogens. The immune system is a highly evolved biological system and its main function is to identify and eliminate foreign materials. The immune system functions continuously and autonomously by detecting and reacting to threats like disease causing pathogens. It is a distributed system consisting of components that is distributed throughout the body, serving all its organs. These components interact locally to provide global protection. There is no central control and therefore no single point of failure. Another attribute of the immune system is that it has its own communication links which is a network of lymphatic vessels. The immune system is a diverse system since different people are vulnerable to different pathogens and the body is able to recover gracefully from infection. The components of the system are continually created, destroyed, and is circulated throughout the body and the system
is adaptable since it can learn to respond to new pathogens and it can retain a memory of those pathogens to help aid in future responses.

The immune system has the powerful capability of learning, memory and pattern recognition. Once the immune system has learned to recognize a particular pathogen, this information is kept in memory. The system has cells called memory cells that will get reactivated in response to subsequent attacks by the same pathogen. This is how vaccination works. The flu vaccine works by triggering the body’s immune system response. Vaccination helps the body to recognize the flu virus as a foreign invader and produces antibodies to it. When the body encounters the flu virus the next time, it will remember the pathogen from past memory and quickly launch an immune attack to kill the virus. The surfaces of immune system cells are covered with various receptors, some of which chemically bind to pathogens and some of which bind to other immune cells or molecules. An activated receptor will produce local signals of recognition that mediates the immune response. The immune system is made of several types of cells and proteins. Proteins can fold into numerous configurations and therefore they can be organized into a set of basins that are resistant to external perturbations. These alternative basins of attraction are forms of explanation that express resilience (Yair 2004). The purpose of immune system is to give protection to the body from dangers presented by pathogens and other toxic materials, thereby ensuring that the body functions are continued with minimal harm to the body. Most immune system cells circulate around the body via the blood and lymph systems, thus forming a dynamic system of distributed detection and response. The detection and elimination of pathogens is the result of trillions of cells interacting through simple, localized rules (Janssen 2001). The immune system is able to cope with a diverse variety of disturbance because it is versatile and efficient. A few malfunctioning cells or even the loss of part of the system will not create a calamity for the immune system since the system is both decentralized and is tolerant of errors.

2.3 RESILIENCE STUDY IN ENGINEERING SYSTEMS

Cities are complex systems consisting of numerous elements with interrelated functions. The city system consists of people forming a community, society where people live and
work together, an infrastructure that is composed of buildings, roads, bridges, and networks for water, energy and data. Such a system is vulnerable to disturbance from natural hazards and terror attacks. The resilience of a city to disasters, natural or man-made depends on the vital infrastructure and the physical protection of people. What makes a city desirable is the architectural structures, population concentrations, and interconnected infrastructure systems. These attributes also put them at high risk to floods, earthquakes, hurricanes, and terrorist attacks (Godschalk 2003).

In order to create disaster resilient cities, Godschalk derives characteristics or principles of resilient systems that need to be taken into account for design and management of cities (Godschalk 2003):

- **Redundancy** - systems designed with multiple nodes to ensure that failure of one component does not cause the entire system to fail
- **Diversity** - multiple components or nodes versus a central node, to protect against a site specific threat
- **Efficiency** - positive ratio of energy supplied to energy delivered by a dynamic system
- **Autonomy** - capability to operate independent of outside control
- **Strength** - power to resist a hazard force or attack
- **Interdependence** - integrated system components to support each other
- **Adaptability** - capacity to learn from experience and the flexibility to change
- **Collaboration** - multiple opportunities and incentives for broad stakeholder participation

The resulting resilient city will be able to plan ahead when disrupted, and act spontaneously. The city based on the principle of resilient systems is endowed with strong central governance, as well as an important private sector and non-governmental institutions. Such a system is aware of the disruption, but not afraid to take risks. Instead of simple command and control leadership these systems prefer a network of leadership and initiative. Once the goals and objectives are set, they prepare themselves to *adapt* to the new situation. Godschalk's model emphasizes resilience as a way to cope with
disasters. We can rarely predict the frequency and magnitude of hazard agents, hence the vulnerability of community systems cannot be fully known before a hazard event. So cities must be designed with the strength to resist hazards, the flexibility to accommodate extremes without failure and the robustness to rebound quickly from disaster impacts.

According to Sheffi (2008) disruption risks a company or an organization faces could be traced to random events like floods, earthquakes, or accidents or negligence or intentional disruptions like a terrorist attack. The first step in dealing with disruption is to avoid them. The second step in building resilience is by implementing a detection system. Detecting a risk will help in initiating an early response which can be the most effective response. Sheffi considers the last step in resilience is the planning and preparation that lays the foundation for a collaborative response. All the organizations that are involved in the response should know each other and assign specific roles for each of them and the resulting recovery effort will be a joint effort. This process will involve the public-private partnerships and the use of volunteers. Companies and organizations should have a disaster preparedness plan that in turn will help in bouncing back from the unthinkable.

After examining dozens of organizations Sheffi (2005) came to this conclusion: A company’s ability to return to business depends more on the decisions it makes before a shock hits than those it makes during or after the event. This was explained by giving an example how the cell phone maker Nokia and its rival Ericsson were affected by a fire in a Philips chip plant in New Mexico. The accidents inconvenienced its customer Nokia, but it paralyzed Ericsson. The reason was in the case of Nokia its culture encouraged constant communication and that helped the company to react immediately and source its chips elsewhere. The response to the fire from Ericsson was slow, leaving the company high and dry. Organizations require people who are at the helm of their enterprise to be actively balancing the resilience needs with the other needs of the establishment. Sheffi found that the resilient companies communicate obsessively and that is the basis of resilience that is seen in the biological systems. When faced with challenge the rule is to attack the challenge without asking for permission. Understanding the mission of the organization instills a passion in being a part of that mission. This passion requires communicating what the company is about and its challenges. Resilience in a way
translates to communication, passion, flexibility and alertness and they are all interconnected.

Transportation resilience is the ability of transportation systems to react to unexpected disturbance. Transportation systems have elements that provide characteristics or performances required for transportation services. The system is complex since the elements of the system influence each other both directly and indirectly, often non-linearly, with many feedback cycles. Some elements of the system such as vehicles, infrastructures, etc. are technical. The mechanisms underlying the functionality and performance of these elements are related to travel demand and users’ behavior. Supply and demand create the network flow in transportation systems. Operation of a transportation system is done by organizations working within a complex social, political and economic environment. It will be sensible to know how people get things done in the real world of transportation. Analysis of travel demand plays an important role in understanding and designing transportation systems. Transportation needs of people are satisfied by providing transportation options when faced with vehicle breakdown, physical disability, or a decrease in income. This is transportation resilience at an individual level. In case of emergencies, special events or rallies, resilience evaluation is at the community level where transportation system need to safely and efficiently take into account the specific conditions. In order to acquire transportation resilience it is necessary to anticipate a wide range of possible conditions that could happen to the system. If the system has diversity, redundancy, efficiency, autonomy and strength in its critical components then the system resilience tends to increase too. Even if a link is broken this allows the system to continue functioning. Increasing transportation system diversity will enhance the system’s ability to accommodate unexpected disturbances without catastrophic failure resulting in its resilience or “the capacity to absorb shocks gracefully” (Foster 1993). Transportation system diversity includes providing multiple modes, routes and system components. There should be redundant maintenance and repair resources, communication systems and fuel sources. The system should be able to collect and distribute critical information under extreme conditions. The system is resilient if it has the capability to identify potential problems, communicate with affected people and
organizations, and is able to prioritize resources. System resilience could be increased by improving transportation system diversity.

Repeated past catastrophic events have demonstrated the vulnerability of engineering and social systems. In this world it is impossible to predict what is going to happen next since there are incidents and accidents that could alter the regular flow of life. A resilient system will be able to accommodate change gracefully, without any catastrophic failure which is critical in times of disaster (Foster 1997). If we knew in advance when, where, and how the disasters were to happen it would have been possible to engineer a system that will resist the disruptions following a disturbance. Foster identifies 31 components typically found in resilient systems. It does not indicate that just because a decision is resilient and more likely to withstand disruptions, it is correct. A decision that is poor, but resilient will cause more difficulties than an incorrect decision with no resiliency. The 31 principles for achieving resilience proposed by Foster are organized into categories: general systems, physical, operational, timing, social, economic, and environmental. *Resilient general systems* are independent, diverse, renewable and functionally redundant. *Resilient physical systems* are dispersed rather than site specific and are stable and use fail-safe design. *Resilient operating systems* are efficient, reversible, autonomous, and incremental. Their timing includes short lead times and rapid response to stimuli. *Resilient social systems* are compatible with diverse value systems, can satisfy multiple goals at the same time, and can distribute benefits and costs equally. *Resilient economic systems* provide a wide range of financial support, enjoy a high benefit-cost ratio, and give an early return on investments. *Resilient environmental systems* minimize the adverse impacts and they have a constant supply of resources. It can be seen that the dimensions of resilience for system characteristics are significance of internal variables, impact of external variables, *diversity* of components, and functional *redundancy*. If a system depends too much on external variables for its survival the chances of its failure are higher

Dalziell and McManus (2004) suggests encouraging organizations to be more resilient and this requires recognizing the need for greater resilience, being aware of the strategies
that are available for increasing resilience, and also willing to invest to achieve this resilience. The terminologies that are used in literature to explain system behavior under stress are vulnerability, adaptive capacity, and engineering resilience. Vulnerability describes the relative degree of risk, susceptibility, resistance and resilience to a disaster. Vulnerability is a degree to which a system is affected by stress or disturbance and resilience is the ability to absorb disturbances while retaining the same basic structure and functions. Adaptive capacity enables a system to respond to changes in its external environment and to recover from damage to internal structures that the system is made of. This could be achieved by using the existing resources or investing time and money to develop new and novel responses. Engineering resilience means increasing the efficiency of systems and processes to return and maintain the system at its original stable state as fast as possible. In some cases several systems may be working together towards a common goal. When systems are required to interact to perform a common purpose the chances of negative interactions are to be considered. To understand systems in the resilience perspective it is necessary to define the system being studied.

In November 2006, after the second symposium on resilience engineering in Juan-les-Pins, France the participants all agreed that prevention of a disaster depends not solely in engineering expertise. Jackson (2007) summarizes the ideas of the participants and importance of a wide range of interconnected disciplines. Resilience to disaster and survival after disruptions are not purely technical subjects. After a disruption a resilient system should be able to return to its nominal function or a slightly degraded function. Work done by Jackson has identified a list of heuristics that could be applied to architecting a resilient system. A typical heuristic is that the system with two or more ways to perform a function is the most resilient. These heuristics need to be characterized depending on the systems they need to be applied. The basic architecture for system resilience has been described in detail by grouping into capabilities, culture, and infrastructure.

Identifying the current definitions of resilience and studying the resilience seen in different systems it is possible to describe the defining attributes of resilience. In the
following chapters immune system, ecosystem, social insects like ants, bees, and termites
and engineering systems are examined in detail to understand the resiliency. This will
provide a background for building the qualitative model that can generate resilience rules
based on the attributes identified for resilience. When a system is disturbed, a resilient
system should be able to generate rules to prevent severe consequences and also
remember the particular disturbance and be alert for similar problems in the future. With
the entire crisis or disturbances surrounding the current world, these rules will turn to be
extremely important in helping to deal with crisis in the best way possible.
3. RESILIENCE IN BIOLOGICAL AND ENGINEERING SYSTEMS

In this section a few examples in biological and engineering systems will be explained in order to identify resilience attributes and the resilience rules followed by these systems.

3.1 RESILIENCE IN BIOLOGICAL SYSTEM

In this section the biological systems like the immune system, ecosystem, and insects that exhibit social behavior like ants, termites, bees are explained in detail.

3.1.1 Immune System. Our body’s immune system functions with the help of macrophages, antigens, and antibodies. The immune system is a resilient system since it can protect the body against harmful microbiological invasions by recognizing and destroying harmful cells or molecules. It is distributed, diverse, and adaptable, and has the capability of learning, memory and pattern recognition.

The immune system has cells that can detect, identify, pursue and destroy an intruder; also accumulate knowledge on attackers, adopt behavior to new situations, and determine a proper response. Research in immunology has established these mechanisms result from the individual behavior of cells in the immune system has evolved to be highly efficient. The body initiates response against harmful pathogens after identifying them. Once harmful pathogens are detected, the immune system eliminates them in different ways. The problem is choosing the right response or choosing the right cell to respond for that particular pathogen. The immune system also retains the memory of successful strategies that helps to speed up future responses to those and similar pathogens. This adaptation occurs during the first response to a new pathogen. This initial response is slow and the organism will experience an infection, but the immune system retains memory of the kind of pathogen that caused the infection. If the body is infected again by the same kind of pathogen, the response of the immune system is faster, because it remembers its earlier response to this pathogen. Memory of the immune system comes from the fact that it is unable to contain a sufficient diversity of proteins to respond to all possible pathogens. The immune system contains 106 different proteins, whereas there
are potentially 1016 different foreign pathogens to be recognized. Hofmeyr (2001) provides a clear description of the immune system from the perspective of systems dynamics. Therefore, the immune system needs to contain enough diversity to respond to new kinds of pathogens. One of the main mechanisms for producing the required diversity is a pseudo-random process involving the recombination of DNA. Furthermore, the memory function of the immune system must be powerful enough to allow it to respond rapidly to pathogens that invade frequently. The immune system, therefore, balances the costs and benefits of innovation and memory.

The immune system is a collection of cells and organs that work together to provide immunity. **Innate immune system** is the type of immune system that every organism is born with and the innate immune response begins immediately in response to tissue damage. **Acquired immune system** responds more quickly and efficiently to a repeat infection, and adaptive immunity is antigen specific. This memory related immunity is dependent on both environment and inheritance as outlined below:

- Immune systems in organisms develop gradually and give protection to individuals from common pathogens.
- The immune system that a person is born with is innate immunity. Innate immunity activates in response to antigens.
- Innate immunity involves physical, chemical, and mechanical barriers to entry, phagocytes to engulf and digest extra cellular pathogens, and interferons and NK cells to block virus replication and kill virus infected cells.
- Innate immune responses occur at the site of inflammation where leukocytes are attracted to the infection site.
- Adaptive immunity is antigen specific and it varies from pathogen to pathogen.
- Adaptive immunity includes antibody, cytotoxic T cells, and inflammatory helper T cells.

Effective responses to novel challenges are provided by immune systems. Immune system defends us against disease organisms. Immune system could be ancient or
modern. The *ancient* immune system responds to general injury and to predictable challenges-first line of defense against disease for animals. This is composed of static defenses like skin and mucus that creates a barrier and thereby gives protection from potential threats. Phagocytes that are present in blood and body and other biochemical barriers too aid in this process. The innate immune system is responsible for a general category of problems and has a limited and predetermined set of responses. If the innate is not able to defend against a threat, then the adaptive immune system comes to act by producing a specific reaction to the infectious agent. The immune system architecture is multilayered with several layers of defense as shown in Figure 3.1. The immune system is mainly composed of white blood cells or lymphocytes that are produced in the bone marrow. The *modern* immune system will respond to both predictable and novel challenges. This ability to respond to both predictable and novel challenges is the key to the success of the vertebrates in adapting to new environments. Our bodies contain billions of immune cells known as T-cells and B-cells. Each individual cell recognizes and responds to a different antigen. There are cells within our immune system that can recognize flu, pneumonia, and polio. In fact, the variety of things our immune system can recognize is so vast that there are cells that can recognize our own tissues, and even cells that can recognize synthetic chemicals that don't exist in nature (Sompayrac, 1999).

The adaptive immune system adapts to defend against specific invaders and this immunity comes from the special proteins that circulated in the blood of immunized individuals. These proteins are called antibodies, and the agent that caused the antibodies to be made is called the antigen. Each antibody binds to a specific antigen. Adaptive (acquired) immunity: By manufacturing a class of proteins called antibodies, and by producing T-cells specifically designed to target particular pathogens, the body can develop a specific immunity to particular pathogens. This response takes days to develop, and so is not effective at preventing an initial invasion, but it will normally prevent any subsequent infection, and also aids in clearing up longer-lasting infections.
In the immune system a localized infection will result in a local response from a few immune cells. If the local response is unsuccessful in fighting the infection then a broader response occurs with the immune system beginning to manufacture more immune cells. Other systems get involved as the pathogen invasion progresses and the whole systems response in humans will involve systematic responses like shivering and behavioral changes. Resilience in the immune system can be attributed to the fact that the immune systems are diverse with components made of different immune cell types, and they operate individually, characterized by localized interactions among their components, and carry out some sort of selection. The ability of an immune system to respond to a given antigen in various ways shows the immune system has options. Thus the particular response of an immune system to an antigen is the result of internal processes of weighing and integrating information about the antigen (Wallace 2008).
This suggests some sort of communication in the immune system by a string of chemical signals. This comparison is suitable since human and immune languages have similarities such as syntax and abstraction. The immune system creates a language by linking two ontogenetically different classes of molecules which is the T and B-cell receptors for antigens and the molecules responsible for internal processing, in a syntactical fashion.

Remarkable properties of the immune system are uniqueness, diversity, robustness, autonomy, multilayered, self/nonself discrimination, distributivity, learning and memory, pattern recognition, resilience, etc. Its primary role is to maintain a dynamic internal state that allows for the differentiation and elimination of foreign elements and malfunctioning of self-elements. Thus the immune system maintains the health of the body by protecting from invasions of harmful pathogens. Pathogens cause diseases and it is necessary to detect and eliminate them. It also remembers successful responses to invasions and can re-use these responses in the event of another invasion by similar pathogens in the future. The immune system is a biological system with high complexity, high connectivity, extensive interaction between components, and has numerous entry points. The collective behavior of various types of defensive cells allows the immune system to be highly efficient with minimum response time and maximum utilization of its resources.

3.1.1.1 Resilience Attributes. In the case of the immune system the resilience attributes are:

♦ Distributability: This attribute of the immune system could be said to be the defining attribute of resilience. There is no central organ in charge of identifying foreign attackers, distribution, reproduction of antibodies, and immune system memory. Therefore there is no single point of failure. This attribute not only avoids bottlenecks and vulnerability but also provides a faster response toward resilience and could be accomplished by multi-agent approach.

♦ Agility: The immune system has multiple barriers or layers of defense to prevent a pathogen from causing harm. An attacker faces multiple barriers in order to enter and
damage a body. This principle found in immune system is desirable for a highly effective security system.

♦ **Diversity:** To fight against infection, the immune system produce antibodies called immunoglobulin. These antibodies will stick to the antigens or disease causing bacteria and viruses when they make their way into the body to attack. They bind antigen and flag them for elimination. These antibodies have to be extremely diverse in order to adapt to a wide variety of germs that enter the body. Vulnerability of the immune system is greatly helped by its diversity.

♦ **Self-organizing:** This attribute is accomplished by means of autonomous cells. The cells of the immune system work under no management. Each cell has its own way of determining the proper reaction to an attacker or even request help from other cells. It is this feature that provides the immune system with a fast reaction to an attack and quick determination of the proper response.

♦ **Adaptability:** The immune system is capable of recognizing new pathogens and figuring out the proper response in eliminating that pathogen. The adaptation mechanism is by way of detecting antigens and producing specific antibodies to kill them.

♦ **Dynamic Learning:** This attribute is seen in the form of memory. The immune system is capable of remembering antigens that it had attacked earlier. It can be seen in the way vaccination works against flu and other illness. In a system it is difficult to recognize new disturbances. A system should be able to learn to detect new disturbances based on past experiences with disruptions. It is possible to recognize disturbance through abnormal behavior.

♦ **Redundancy:** This attribute allows for back up plans if the first action plan goes wrong. Having multiple copies of antibodies increases the chances that an invading pathogen that matches these antibodies will be stopped.

♦ **Interoperability:** If a part of the immune system fails it can still function. It is modular since the immune system is not made up of a single component but instead it is made up of a multitude of genes, proteins, and external influences.

♦ **Flexibility:** The immune system produces antibodies depending on the need. More antibodies are added without any redesign.
Robustness: The immune system can function even when the pathogens that attack the body evolve and change. They can work in a wide range of conditions, being able to function in the presence of noise, and the ability to keep working even when multiple internal components fail.

3.1.1.2 Resilience Heuristics. The rules for resilience in the immune system based on the attributes of resilience are the following:

Individual units in a system perform only part of the complete task, but there are many of them working in parallel. A multi-agent approach is necessary to achieve distributabilty. Absence of a central command will allow the system to flourish when disturbed. A distributed system coordinates the action of multiple processes on a network such that all the components co-operate to perform tasks. A distributed system will be able to continue operating correctly even when the components fail. A system should process information in a parallel and distributed way, without the presence of a central command. The individual units in the system act in parallel and interact locally. This will ensure proper functioning of the whole system and not of its parts. The immune system is a distributed system where information and a stored collection of responses are present within the system with no central command. It is impossible to predict disturbance and disruption in different forms. This makes it a necessity to have a multilayer defense strategy that will work for any type of disturbance. The rule is the system manages to conceal itself against any disturbance which offers security against disruptions and this rule is based on the attribute of tolerance. More people looking at the same information can generate many views to a situation and in that diversity people are likely to find the information they need.

The system should have the capacity to detect any drift towards any unwanted disturbance and be capable of correcting itself without any outside control-autonomously. The attribute of self-organizing help the system to make independent decision at times of crisis.
The system should adjust to the disturbance by adapting to the new or unexpected situations without human intervention. The system can adjust to the changing situation or even cope with entirely new situations with the attribute *adaptation*. It is the transformative capacity that renders a system to be able to accommodate change by means of adaptable infrastructures.

Systems that have the attribute of *redundancy* will have parts that are renewable and replaceable. This lets the system function even when disrupted. Systems made of redundant units using different local resources will have different strategies for resilience. Redundancy will help the system to adapt by providing alternatives when disturbances disrupt the system. When system parts malfunction the entire system does not get disrupted. When a system is disrupted it loses the interconnection between the systems and this in turn leads to a decrease in hierarchical control.

The attribute of *interoperability* is provided by systems with a modular design. Modular design allows a system to transition from one interdependent whole to a set of independent modules that are tolerant to uncertainties and disturbances and to a newly decentralized system. The innate immune system provides rapid defense against any attack and the adaptive immune system can handle any protein molecule in the universe. However, the adaptive immune system does not have any idea which protein molecule is dangerous and which is not. It is the receptors in the innate immune system that can detect any type of disease causing pathogens and it is responsible for activating the adaptive immune system to take action (Sompayrac, 1999). After collecting information about the invading pathogen the innate immune system integrates all this information and then prepares a plan of action. This action plan is delivered to the adaptive immune system, detailing which weapons to mobilize and exactly where these weapons should be deployed within the body.

### 3.1.2 Colonies of Social Insects

The behaviors of social insects have intrigued people for ages. The colony of ants and bees exhibit tremendous co-ordination and their self-organization tactics have been widely studied. Nature has provided numerous
instances of intelligent behavior where simple organisms function collectively and exhibit complex behavior that would not have been possible by individual effort.

3.1.2.1 **Ants.** Ants live in colonies and as a group they work together collectively dealing with the need of finding food, building bridges, building homes, responding to external threats, etc.

3.1.2.1.1 **System Function.** An understanding of resilience seen in nature and how biological systems develop the ability to bounce back will help in building resilience strategies. The system should be able to adapt and move resources quickly. Ants are resilient. They are like humans since they farm by growing fungi and raise aphids as livestock (Foster 1997). An army of ants wage war with their enemies, cause confusion by spraying chemical sprays to fight, can capture slaves, and perpetually exchange information. One of the many ways ants ceaselessly exchange information or communicate with each other is by way of pheromones. The incredible capability to organize the ant colony behavior is supported by the way pheromones are used by them. The biological systems have demonstrated that the critical part of resilience strategy is by way of communication. Information about what is happening is essential in building a strategy for resilience and hence the importance of the role of communication in times of surprise. Desirable systems behavior of the colony comes from the integration of individual behavior within the colony. The network of paths that connect the colony to the available food source is accomplished by ants while following certain responsibilities. The foraging strategies for ant colonies are a result of the ability of individual ants to communicate their experience to other ants in the colony.

Ants can respond to any change in their environment. Taken individually, ants do not have memory and they do not have direct communication within their colony. Ants in a colony can find the shortest path from their nest to a food source, find their way back to the food source, organize themselves in a well structured manner, and harvest leaves to produce fungus. This is done by communicating with a chemical hormone called
pheromone which they release on their way. Ants can resist disturbances and is capable of restoring itself after being disrupted. It is the interaction of individual ants by means of pheromones that is responsible for the self organization. Adaptable nature of the ants is seen in their ability to react to any conditions new to their environment.

In ant colonies, each ant follows a pheromone trail led by other ants to get to the food source. The ant reinforces the trail by laying more pheromones of its own to get to the food source. Ants achieve reliability through redundancy, relying on decentralization via some individual “utility optimization” and transforming the environment into a grand shared database by active marking. Decentralization is useful in many cases since decentralized systems adapt in very sophisticated ways. Randomness in decentralized systems helps to create a flexible, creative, and rich structure. Ants are able to explore an environment more effectively due to the fact that they move in a random fashion and they do not follow any set pattern. If the ants did not have a random factor built-in, then they might settle for a poor food source a long way away rather than a richer one closer by. Positive feedback allows the ants to build trails to food sources that lead other ants there; the other ants build more trails which lead even more ants and so on. It is through self-organization that the ants collectively make a choice between two equivalent food sources. The initial stage forages is done equally between the two food sources. Slowly one of the sources gets favored and this is a random process that happens by recruitment which means more individuals get recruited to that particular source. If the food source is richer, this source gets exploited by foragers that will result in making more of the pheromone trail at this source than those foragers at the poorer source. The interplay between recruitment and travel time need to be a collective selection of the shortest path.

Individual ants make use of pheromone-a chemical while making random trips for food it puts down the pheromone trace. The other ants are guided by the pheromone which they tend to follow. On finding a prey, the ant bites on it automatically releasing the pheromone. The ants lose track of the smell, but it gets reinforced by ants as it still puts down the pheromone it allows other ants to follow the track of the prey. Thus by
following a set of individual behavioral rules like release pheromone, bite on the prey ants display self-organizing behavior. Ants show cooperation with a memory of past experience that result in an efficient and adaptive collective strategy to collect food (Bonabeau et al., 1999, 2000). Bonabeau, et al. (1999) defines swarm intelligence as an attempt to distributed problem solving devices inspired by the collective behavior seen in insects.

3.1.2.1.2 Resilience Attributes. Ant colony is flexible since it can adapt to changing environment. If some individuals in the colony fail, the colony can continue performing its tasks. Each individual acts autonomously without intervention from a controlling body. Ant colonies depict how complex group behavior comes from simple individual behavior. This emergent behavior that looks complex is actually derived from fairly simple rules. The organized behavior seen in ant colony is a result of the interactions among the individual ants in the colony.

In the colony, the ants interact directly when the interactions are obvious like mandibular contact, visual contact, chemical contact or trophallaxis (food or liquid exchange). Indirect interactions are not obvious and in an indirect interaction one individual will modify the environment and the other will respond to the new environment at a later time. Overall, the ant colony is efficient and well organized with each ant doing its job. The seamless integration of all individual activities of the ants with no one supervising the ants in a colony is evident when as a colony ants respond effectively and quickly to their environment.

The attributes are as follows:

♦ *Flexibility:* Insect colonies respond with flexibility to changes in stimuli and self organize. This is the result of the properties of individual ants that makes intelligent decisions by continuously talking to one another.

♦ *Self-organization:* This attribute in social insects often requires interactions among insects.
♦ **Interoperability**: One of the properties of resilience seen in ants is operational efficiency which comes from emergence. Since individual ants are not aware of the collective goal there is no need of grasping the conditions for collective efficiency at the individual agent level.

♦ **Adaptability**: Ants adjust their behavior according to need and this is done by switching between inactive and active states and by changing tasks.

♦ **Distributability**: In a colony, each ant works on its own with no central control or supervision. Each individual acts autonomously without intervention from a controlling body.

A key mechanism for resilience here is the interaction of agent components that produces an aggregate entity that is more flexible and adaptive than its component agents. The second property that is interesting is, they develop and stabilize ‘on the edge chaos’: they create order against chaos by way of invariants, rules, regularities and structures; but they need residual disorder to survive. This explains the fact that too much order leads to crisis. If no ant got lost while following the pheromone track to the prey, there would not be new prey discovery either for the colony. The direct or indirect interactions take place between individuals and the blending of the individual behaviors of the component agents introduces modifications into the shared environment making it resilient (Kube and Bonabue, 2000).

3.1.2.1.3 **Resilience Heuristics**. Ant’s rules can create complex behavior and deciphering those rules is a big challenge. However, the behavior of swarms emerges unpredictably from the actions of thousands or millions of individuals. Ants are not born with massive brains that work out complicated survival strategies. Yet, when necessary, they build bridges, construct columns, and dig amazingly complex nests-all by obeying a few rules. One of the more exciting breakthroughs that Couzin (2008) has made is the realization that swarms, no matter the species, all tend to follow the same basic rules. The integration of individual behaviors within groups results in collective behavior. There will be behavioral differences among individuals which influences the group behavior. The size of ant colony can range from 30 to millions of workers. The division
of labor is reproduction by queen, and defense is by specialized workers. Specialized workers are responsible for food collection, brood caring and nest building. Ants build nests and maintain them, displaying excellent division of labor and adaptive task allocation. They can discover the shortest path between nest and food and can bridge using sticks to get across water. Other interesting collective behaviors of ants are clustering and sorting (dead bodies, eggs, etc.), recruitment for foraging, cooperative transport, and the way they deal with obstacles by forming structures. Ant navigation depends on its sensory capabilities as well as characteristics of the environment and function within the colony. Ants make use of memory and learning, and meeting with other colony members that constitute the visual landmarks. When pheromones are involved with interactions between other colony members then that is chemical landmarks. Ants coordinate their actions to achieve amazing systems-level behavior. In ants, interactions among simple individuals can produce highly structured collective behaviors that can be described by self-organization. Self-organization consists of a set of dynamical mechanisms whereby structure appears at the global level as the result of interactions among lower-level components. The rules specifying the interactions among the system’s constituent units are executed on the basis of purely local information, without reference to the global pattern, which is an emergent property of the system rather than a property imposed upon the system by an external ordering influence (Bonabeau, et al., 1997).

Biological systems follow certain simple rules that initiate behaviors depending on the need at that time. The collective intelligence of ants comes from the mechanics of communication. The same can be said for all the other social insects. Ants are versatile and they have adapted successfully to a huge range of environments. They are self-organizing and adaptable. Ants exhibit emergent behavior by defining a set of rules by which they interact with each other and with the environment. The rules are simple but the resulting behavior from this is usually complex. The emergent behaviors of the ant colonies do change as the colony grows and gets older. The ants’ behavior is based on the decisions of individual ants that operate with a relatively simple set of rules that is based on social contact and the surrounding environment. The responsibility of the ant
colony behavior comes from a single set of rules at the level of individual ant. As a colony ages, so do the ant behavior and these small modifications of the rules of interaction can lead to significant changes in the behavior of the ant colony as a whole. The rules that determine the interaction among the system’s constituent units is executed on the basis of local information. In foraging ants, the emerging structures are the networks of pheromone trails. Positive feedback is a behavioral rule that includes recruitment and reinforcement. Recruitment to a food source by ant colony depends on trail laying and trail following. Once the supply of food is ample there is a negative feedback to counterbalance the positive feedback. Multiple interactions between individuals in a group and their smart interactions result in a final organized structure. The adaptability, self organization, and emergent behavior of ants seen in nature proposes a new way of thinking that is aimed at solving unanticipated problems that arise in engineering. In times of catastrophes the various parts of the system need to interact in ways that will add up to the whole or almost whole functioning system again.

Ant colony involves agents that are simple that cooperate to achieve a behavior that result in finding solution to problems. The ant colony optimization (ACO) algorithm is an attribute based method focused on developing an adaptive behavior which helps ants with effective adaptive learning techniques. This agent based heuristic approach of solving problems is accomplished by ants by depositing pheromones that gives the ant colony system the ability to perform a search for the optimal logical conditions that involves values for attributes. ACO being a population based heuristic allows the system to utilize positive feedback between agents as shown by the rules that describe the ant behavior. These rules enable ants to interact with the environment adaptively.

Ants operate in a team and Resnick's artificial ant follows three simple rules (Resnick 1995): It will wander around randomly, until it encounters an object; if it was carrying an object, it will drop the object and continues to wander randomly; finally if it was not carrying an object, it picks the object up and continues to wander. A colony of ants is able to group objects into large clusters, independent of their initial distribution in the environment. Colonies of such ants try to disperse objects uniformly over their
environment rather than clustering them into piles. Communication among ants is highly efficient by using rules as seen in the foraging model. The ant foraging model expressed by a set of rules like Resnick’s algorithms. Rule 1 below show Resnick’s ant foraging behavior algorithm.

Rule #1: Resnick’s ant foraging behavior algorithm
1. Look for food
   - If pheromone trail is weak then wander
   - Otherwise move towards increasing concentration
2. Acquiring food
   ⇒ Once food is seen
     ➢ Pick it up
     ➢ Turn around
     ➢ Start laying pheromone trail
3. Returning to nest
   - Deposit pheromone
   - Decrease amount of food available
4. Depositing food
   ⇒ If at nest then
     ➢ Deposit food
     ➢ Stop laying pheromone trail
     ➢ Turn around
5. Repeat forever

Ants exchange information indirectly by way of pheromones using the environment as a medium of communication and are able adapt to the environment. The behaviors of ants are described by rules that use local information using indirect communication via the pheromones trails. It could be considered as a heuristic approach to solving problems that is based on adaptability attribute. It can be seen that ants wander around randomly until they find pheromone trail or food. The ants continue to travel until they find food. Once they find food they return to nest, with food, drop it and go back to where the food was
found. Resnick’s ant exhibits a similar pattern of behavior as real ants. The ant foraging model allows the ants to adapt to the changing environment. When an obstacle is placed in its path, the ants try to move around the object randomly. It is by the use of pheromones that it can identify the shorter path, since the pheromone concentration will be more at the shorter path around the object. The attribute of *flexibility* is displayed here. When more foragers are needed, the colony recruits more workers to get food with the *scalability* attribute. The attribute of dynamic learning is exhibited by the learning capability of ants. Each ant follows rules and the ant colony flourishes with the coordinated and co-operative behavior of each ant. The attribute that is attributed to this behavior is *distributability* and this is responsible for a fast response toward ordered behavior where all the ants in the colony co-operate to perform tasks.

The ant foraging model not only allows a path to be generated but also allows the established path to adapt to changes made in the environment and these are the characteristics required for wayfinding application (Soon and Maher 2006). The wayfinding swarm rules are presented in Rules 2-4 and they define how each individual creature makes the decision about a local move. The wayfinding swarm rules also define what each creature senses and how it reacts. Resnick successfully implemented these rules and simulated them in a 2D environment.

Rule 2 shows the overall rule for the swarm creatures. Rule 3 and 4 mention attractants and repellants which are electronic pheromones dropped by the swarm creatures as they move. Attractants and repellants are pheromones as they move about in the world. The explore world rule shows how a wayfinding creature explores the world looking for target. Until the target is located, every time it will check to see whether the target is located in adjacent locations. Once the target is located, the creature moves toward the target and create a teleport gate. It will keep looking for pheromones in adjacent locations and it will move to the location with the highest pheromone concentration.

**Rule #2: Overall behavior of ants**

```plaintext
Rule wayfinding_creature_behavior
Repeat
```
Explore world
Until Target_located
Return Home

The behavior of ants as decided by rules help the ants to interact locally and with the environment. The rule dictates how the individual agents (ants) should behave. The interactions between the agents (ants) result in the collective organized behavior of the ant colony. Heuristics are used as a method to solve problems using the attribute adaptability and self-organizing. The other attributes are interoperability seen in their cooperation and exhibition of team work and distributability since ants take actions without any central controlling body.

Rule # 3: Explore world rule

**Rule** Explore World

If Target is found in adjacent locations
Move to Target
Create a network

else

if attractant found in adjacent locations
move to location with highest concentration of attractants

else

Drop repellant in current

Wayfinding is the behavior that results from the explore world rule and is a highly beneficial navigating tool in a dynamic environment. In ants the attribute of adaptability leads to the heuristic that aids in adjusting to dynamically changing environments.

Rule 4 is followed by the wayfinding creature while returning home after the target is located. In the current location the creature drops an attractant. After this it tries to sense whether home is found in adjacent locations. After that it turns back again to explore the world. The adjacent location closer to home than the current location is chosen. These local rules of interaction in ants are governed by if-then rules.
Rule # 4: Return home rule

**Rule** Return Home

Drop attractant in current location

**Repeat**

If home found in adjacent locations

Move to home

else

Move to empty adjacent location closer to home

Until Home

It can be seen the role heuristics in ant colony system by helping the ants search for a feasible solution to its problems-solutions that are effective and efficient. The rules define how an individual ant decides about local environment and the action to be taken, resulting in a desirable behavior. Ants are able to adapt to environment by the resulting behavior that is based on adaptability. The rules decide the ant behavior and the same rules help ants to modify their behavior depending on the environment, helping the ant to adapt to any changes in the environment. Rules help ants to explore the world and adapt to changes in environment without a controlling body. It can be seen that a limited set of if-then rules is able to produce a complex behavior. Problems get solved by relying on elements of the system rather than a single intelligent authority. Ants choose to forage or not, based on patterns in their encounter with other ants-the attribute of interoperability. The emergent behavior seen in ants comes from living within the boundaries defined by rules. Ant colonies do not have a leader, but they rely on rules. Rules help them read patterns in the pheromone trail, when to change from foraging to nest-building, how to respond to other ants, and so on. Creating a collective intelligence would have been impossible in an ant colony without the local rules. Disruptions do not cause the ant system to fail since they survive and continue their system functions. It can be concluded that the ant behavior that result from if-then rules can be associated to the attributes like adaptability, interoperability, self-organizing, distributability, scalability, flexibility, dynamic learning, diversity, redundancy, and agility.
3.1.2.2 **Bees.** The honey bee exhibits a mix of individual traits and social cooperation and also provides a good example of multiple levels at which the bee expresses adaptations to its world.

3.1.2.2.1 **System Function.** A honey bee as an individual has only partial information about its environment whereas, the beehive as a whole knows the quality of the available food in its neighborhood and is able to choose the source that is the best one. The queen bee emits a pheromone that is essential for the functioning of the hive. Each hive has a distinct scent and this helps the hive members to recognize each other and repel foreign bees. The queen bee is not in command of the colony. The beehive collectively decides on a new site for setting up another hive. A few hundred worker bees will scout for possible sites and when they find one they come back and report to the swarm about the new site by a dance called the waggle dance. A dozen sites could be competing for attention. The more vigorous the scout dances while reporting the new nest site to the hive members by way of waggle dance the better the chance of that site being championed.

Food source selection relies on dances by bees and not on pheromones like the ants. When a honey bee finds a nectar source, it goes back to the hive with the nectar and gives it to another bee. After relinquishing the nectar it will dance indicating to the other bees the direction and the distance to the food source or it will continue to get the nectar without recruiting any of her nest mates. The bee can also abandon the food source too. If the colony is offered two identical food sources that are of equal distance from the nest, the bees make use of the two sources symmetrically. The probability of a bee abandoning a poor food source and dancing for a good food source has been experimentally proven. These simple behavioral rules allow the colony to select the better quality source. Foragers are able to concentrate on the best food source through a positive feedback mechanism caused by differential rates of dancing and abandonment based on food quality. While foraging for food, bees make use of non-pheromone based navigation.
3.1.2.2 Resilience Attributes. In a colony bees are able to integrate their activities so that the sum of colony functions is much greater than what each individual bee can achieve independently. To accomplish this, individual bees are able to communicate to other bees in the colony about available resources of food outside the nest. In bee’s communication and orientation mechanisms can function over long distances and this allows recruitment and exploitation of resources. Precise information about the distance, direction, and quality of food sources is communicated between individual workers by way of dances. The attributes are:

♦ Adaptability: Honey bees use the sun to navigate and to communicate by using the sun as a fixed reference point. The adaptability attribute is seen in honey bees dance as the bee continuously changes the orientation of its dance in order to compensate the changing azimuth of the sun.

♦ Redundancy: The waggle dance is done repeatedly by the bee in order to give the accurate location of food. Message gets recognized correctly when it is repeated.

♦ Scalability: This attribute is seen in large insect colonies when a large number of interacting individuals exhibit highly sophisticated and coordinated behavior. A bee colony consisting of thousands of honey bees can work cooperatively by differentiating tasks of collecting nectars, and pollen.

♦ Self-organization: Self-organization in bee colony is materialized through localized interactions.

♦ Interoperability: In a bee colony, there is no need for global coordination and communication. The colony gets organized by autonomous individuals that interact with their local environment and that dynamically adapt their behavior to their local environment.

♦ Dynamic Learning: The foraging behavior in honey bees is a display of compromise between food collection and information collection.

3.1.2.2.3 Resilience Heuristics. Honey bees orient themselves to the sun or natural patterns of polarized light during their waggle dance and their dancing behavior is covered by rules (Brines and Gould 1979). The honey bees have rules according to
which they dance to eliminate potential ambiguity in the dance message. The foraging honey bee after discovering a food source can compute its distance and direction from the hive. This information about the direction of the food source is encoded in a dance that specifies the location of the food. Frequently honey bees dance with some view of the sky, aligning themselves to the sun or natural patterns of polarized light.

The rules for bees dance language conventions use sun as the reference point, vertical is the direction towards the sun, and the number of waggles or sound bursts specifies the distance. This communication system among bees will be successful as long as all of the bees use the same reference system. However, on cloudy days bees will have to dance with limited view of the sky and it may not be possible to reach a consensus among the bees regarding what they see is the sun or the sky. Despite this problem, dancers seem to resolve possible ambiguities and successfully recruit other bees. There are three rules for horizontal dances that ensure that all the bees respond to the dance cues regarding the reference point consistently. The first rule is used to determine whether the observed cue is the sun or part of the sky, and therefore which of the two different dance directions to take. This rule results in certain patches of the sky being identified as the “sun”. It appears that all the bees interpret the patch in the sky as the sun. The two other rules are used when the observed cue is judged to be part of the sky. In the second rule, bees use the characteristics of polarized light to identify which part of the sky they see and then orient their dance to the food. The third rule is applied when bees see one of two physically identical patterns that are located the same distance from the sun. These rules are essential to the social communication in bees, and they ensure that both sender and receiver are using the same reference system.

Information about the food source is sent out in a timely manner in order to take appropriate action just-in-time. When a bee spots a good nectar source it will dance the waggle dance to show the other bees where the food is. Bees communicate information about the food source urgently and instantly by sending out just-in-time information about the food location and let everyone take action in an independent fashion. Exploiting the food source that was found needs to be done immediately before other
insects find it. There is no leader giving orders, as everyone in the colony has a vote in making a decision.

**3.1.2.3 Termites.** Termites are social insects that are blind and still can construct complex structures despite their limited perception and the absence of a global control system.

**3.1.2.3.1 System Function.** In a colony of termites building a nest, many aspects of building activities can be attributed to self-organization. In termite colonies, indirect communication takes place among individual termites through the evolving features of a structure. The building action of a termite worker is triggered by the stimulating configuration of a structure. This will result in transforming the configuration into another configuration and this may in turn change into still another configuration by being the trigger and forcing another action performed by the same termite or another termite worker. In termites, stimuli are organized in space and time to ensure a structured orderly building. In this case stimuli are concentrations of construction pheromones and this stimuli encountered by the termites in the course of pillar building will differ quantitatively. In order to build pillars termites use soil pellets impregnated with a pheromone. This is done in two phases. In the first phase—the non-coordinated phase is characterized by a random deposition of pellets. This phase lasts until the pellet reaches a critical size. Once the group of builders is sufficiently large, the coordination phase starts and pillars starts to form. The existence of an initial deposit of soil pellets stimulates workers to accumulate more material through a positive feedback mechanism. Once the material gets accumulated, the diffusing pheromones emitted by the pellets will reinforce the attraction of the deposits. The coordinated phase is the result of an autocatalytic “snowball effect”. If the number of workers is small, the pheromones will disappear between two successive trips by the workers. Since the amplification mechanism cannot work, only the non-coordinated phase is observed. The transition from non-coordinated to coordinated phase is simply by the increase in group size. An example of a termite nest is shown in Figure 3.2.
3.1.2.3.2 Resilience Attributes. When the termites start to build a nest, they modify the local environment by making little mud balls that are infused with a small quantity of pheromones. These mud balls are placed at random and the probability of depositing a mud ball at a given location increases with the presence of other mud balls and the pheromone concentration. Colony members are made of king, queen, workers, and soldiers. While building a nest, the termite colony gets the stimuli provided by the emerging structure as the information from the local environment. The system attributes are as follows:

♦ **Distributability:** The nest building process in termites could be explained by a process of decentralized coordination based on stigmergic labor activity, where it is the product of the work previously accomplished that drives the termites to perform additional work. Thus, the termite colony is a problem-solving system made up of relatively simple interacting entities.

♦ **Interoperability:** One of the properties from a resilience perspective seen in termites is operational efficiency which comes from emergence, with no understanding of the collective goal, since there is no need of grasping the conditions for collective efficiency at the individual agent level. Termites communicate by secreting
pheromones and each colony develops its own characteristic odor. The colony defends itself by means of the chemical pheromones as an intruder is instantly recognized and an alarm pheromone gets secreted that will trigger an attack on the intruder by the soldiers. When a worker finds a new source of food it uses the pheromone trail to recruit other termites to the food source.

♦ Self-organization: This attribute in social insects often requires interactions among insects. Sound is also used by termites as a means of communication. Soldiers and workers may bang their heads against the tunnels that will result in vibrations. These vibrations are perceived by other colony members and will serve to mobilize the colony to defend it. Colony members recognize each other by mutual exchange of foods. Depending on colony needs the proportion of termites in each caste within the colony is regulated chemically by pheromones.

♦ Flexibility: The attribute of flexibility allows them to adapt to changing environments

3.1.2.3. Resilience Heuristics. Termites follow the behavior similar to the behavior seen in ants and they communicate with each other in order to accomplish their task. If a termite bumps into too many other termites, the termite will add a little space to the mound. Termites wander at will, bump up against one another, and react. They observe what others are doing and manage to construct intricate tall towers by coordinating their own activity with the information about others activities. The colony success depends on regular and effective communication, as well as learning when and where to add to the structure by maintaining a high degree of connectivity to other termites in the colony.

It can be seen that ants in ant colony and bees in a hive, and termites in a colony, operate as a single intelligent organism. Flexibility, self-organization, and adaptability are the three traits that make social insects successful. A termite colony is flexible since it can adapt to changing environment. It is robust that even when some individuals fail in the colony, it can continue performing its tasks. Each individual acts autonomously without intervention from a controlling body. Social insect colonies depict how complex group behavior comes from simple individual behaviors.
3.1.3 Ecosystems. An ecosystem is a natural system with plants, animals, microorganisms, water, wind, minerals and it consists of land, water, and air. Resilience in ecosystem is a measure of how well an ecosystem can tolerate disturbance without collapsing. In ecosystem, resilience is not about one ideal ecological state, but an ever-changing system of disturbance and recovery.

3.1.3.1 System Function. The components of an ecosystem work together in order to keep things balanced. It is a system with no fixed boundaries and it is up to the beholder to decide the system boundary (Figure 3.3). An ecosystem could be small or large, since there is no specific size for an environment to be considered as an ecosystem. If the plants do not get enough water, light, or nutrients, the plants will die. This will result in death of animals that depend on these plants. The presence of a large diversity in the number of species will make the ecosystem less likely to be disrupted by disturbances in the form of natural disaster or climate change.

An ecosystem is said to be resilient when it can withstand and tolerate a disturbance without collapsing into a qualitative different state. It can tolerate disturbances such as fire, storms, pollution, etc. and the resilience helps in rebuilding after the disturbance which promotes renewal and innovation. According to Resilience Alliance, resilience in ecosystems is comprised of three characteristics:

- The amount of change the system can undergo and still retain the same control on function and structure
- The degree to which the system is capable of self-organization
- The ability to build and increase the capacity for learning and adaptation

The Great Barrier Reef in Australia consists of the world’s largest system of coral reefs, together with lagoons, sea grass meadows, mangroves, and estuarine communities (Figure 3.4). It includes over 2,900 reefs, around 940 islands and cays, and stretches 2,300 km along the Queensland coastline. The reef is immensely diverse with 1,500 species of fish, 359 types of hard coral, one third of the world's soft corals, 175 bird
species, six of the world's seven species of threatened marine turtle and more than 30 species of marine mammals including vulnerable dugongs. Also, there are 5,000 to 8,000 molluscs and thousands of different sponges, worms, crustaceans, 800 species of echinoderms (starfish, sea urchins) and 215 bird species, of which 29 are seabirds.

Figure 3.3: Components of Ecosystem
Figure 3.4: Diversity in the Great Barrier Reef

(http://www.bloggersbase.com/travel/great-living-wonder-the-great-barrier-reef/)
The Great Barrier Reef is the largest coral reef ecosystem on the planet and supports an outstanding array of plants and animals. It is a system, on a scale of thousands of kilometers, which is able to absorb recurring disturbance without catastrophic failure. The disturbances are in the form of climate change, catchment run-off, coastal development, and extractive use. Human activities can reduce resilience in ecosystems but management measures and practices can be undertaken to ensure better adaptation in the face of perturbations. The Great Barrier Reef is not just the coral and the beautiful fish, it includes the reef, the ocean surrounding it, sea grass beds, and the ocean that reaches the coastline and connects to the estuaries and rivers. The Great Barrier Reef covers more than 38 million hectares and it stretches over 2000km along the Australia’s northeast coastline.

The ecosystem in the Great Barrier Reef are subjected to frequent disturbances in the form of cyclones, crown-of-thorns starfish outbreaks and influxes of freshwater as well as from a wide range of human activities. These disturbances result in damage, stress, or kill components of the ecosystem. A resilient ecosystem will be able to recover fully after a disturbance and can become as biodiverse and healthy as before the impact. An understanding of ecosystem resilience will help in predicting the disruptions and its ability to recover from the disturbances. The ability of an ecosystem to recover from a disturbance depends on the biology and ecology of its components in the system and the nature and the degree of the disturbance. It represents one of the most complex and biologically diverse systems on earth. It is about 12,000 years old and for most of that period there was very little human presence. Since human settlement began near the coastal strip there has been a significant impact on The Great Barrier Reef, since the water is not as clean, there are fewer fish and some animals and birds are not as common as they were once. The form and structure of individual reefs show great variety. The reefs are classified into platform or patch reefs (resulting from radial growth), wall reefs (resulting from elongated growth), and fringing reef (Where reef growth is established on sub tidal rocks). Coral reefs are marine ecosystems and the view of coral reefs as relatively closed systems, within the boundaries of which accurate biotic and abiotic materials may be derived. Coral Reefs serve as a fine example for an ecosystem model
as a hierarchy with emergent properties (Hatcher 1997). They are massive structures formed by small colonial organisms. Ecosystem research helps to assess the status of reefs and predict their response to environmental change. Ecosystem research identifies the variables of state (net vertical gradual growth) and sets the boundary conditions (maximum sea level rise with which reefs can keep up).

3.1.3.2 System Attributes. Resilience emerges from dynamic interactions and change and relies on flexibility and adaptive capacity for change. Ecological resilience focuses on changes that preserve viability and adaptive flexibility for an uncertain future in which adaptive capacity in the face of disturbances requires change and some responsive flexibility for a system to flourish (Masten, and Obradovic 2007).

The attributes for the system are:

♦ Adaptability: A resilient system can withstand shocks and rebuild when necessary. Resilience in ecological systems is provided by adaptive capacity. It is the ability to live with change and uncertainty by re-configuring without any significant loss in crucial functions.

♦ Diversity: Diversity is required to retain functional and structural controls in the time of disturbance or change. For an ecosystem to be resilient, biodiversity is necessary for the ecosystem to reorganize after disturbance. One of the features to assess ecosystem resilience is ecosystem biodiversity which is the variation contained within species and between species. It is considered that biological diversity provides functional redundancy, such that if one species decline there will be some other species that is able to provide the same ecological service that can prevail and continue to function.

♦ Redundancy: In an ecosystem biodiversity provides functional redundancy. The greater the biodiversity of an ecosystem, the greater the likelihood that an organism can adapt to changing ecological conditions. This is because an organism is able to perform a different role in the system when the ecosystem is disturbed and this is known as the functional redundancy. When a disturbance hits and certain species are
temporarily taken out of the system there will be other species that are capable of carrying out the functions of the lost species.

- **Self-organization**: The emergence of ecosystem patterns as a result of new rules being formulated.

### 3.1.3.3 System Heuristics.

Resilience gets built by means of diversity, self-organization and adaptive learning. Ecological resilience is accomplished by processes that contribute to the systems regeneration and renewal and there is no single mechanism that guarantees maintenance of resilience (Gunderson 2000).

After studying ecosystems around the world it has been established that natural systems proceed through recurring cycles. These adaptive cycles are characterized by four phases: rapid growth, conservation, release, and reorganization. An ecosystem becomes efficient as it accumulates the resources in the rapid growth phase. The longer this phase lasts, the more efficient the system becomes in using resources and this will eventually lead to locking up of available resources (Walker, 2008). In this conservation phase, all the resources are locked up and the system becomes less resilient and more vulnerable to disturbances. Disturbances will result in the release of the accumulated resources by precipitating a collapse or disruption. This is the release phase after which the ecosystem reorganizes with a new growth phase of the next adaptive cycle.

Coral reef habitats recover from multiple short-term disturbances. The frequency of repeated disturbances can degrade the coral reefs of the Great Barrier Reef. Human impact reduces the resilience of the system. A less resilient ecosystem may fail to recover from a disturbance. The management approach that has evolved for the Great Barrier Reef is an example of how ecosystem-based management, marine spatial planning, and other management tools have been integrated across federal, state and local government jurisdictions (Young, et. al., 2007). “This includes complementary zoning (meaning the same rules apply in all waters, irrespective of the jurisdiction), joint permits (one-stop-shopping for most approvals), coordination/sharing of resources for day-to-day or field management (including formal and informal arrangements between agencies),
and the formal exchange of delegations to enable officers from different agencies to work cooperatively across the entire area.” Effective working partnership between agencies and the various levels of government is necessary to ensure ecosystem-based management of complex and interrelated issues that involve marine, coastal, and island areas. The reef management is successful by running a number of initiatives in parallel and not relying a single process.

The federal Great Barrier Reef Marine Park authority developed guiding principles for the development of zoning plan:

- A Scientific Steering Committee developed 11 biological and physical principles, including a minimum amount of protection needed for each different biological region.
- A Social, Economic, and Cultural Steering Committee developed 4 principles to maximize positive impacts and minimize negative impacts on Marine Park users and other interest groups.

Place-based management is a strategy that initiates integrative management of human activities occurring in spatially demarcated areas that are identified through a procedure that takes into account biophysical, socioeconomic, and jurisdictional considerations. Place-based management focuses on the distinctive features of individual places, thereby tailoring management regimes to the regional circumstances, and allowing adaptive management, and social learning. Also, it offers a constructive means of dealing with uncertainties that are associated with dynamic systems. Thus by explaining the meaning of rules as applied to specific places, and by enhancing monitoring, a place-based management makes implementing management procedures easier (Young, et. al., 2007).

3.2 RESILIENCE IN ENGINEERING SYSTEMS

In this section a few engineering systems like city water supply system is analyzed for their resilience when disturbed.
3.2.1 City Water Supply System. The function of a city water system is to provide safe reliable drinking water and meet current and future water demands. The city of Rolla water supply system was installed in the 1880’s. The city had to sell the property in 1924 due to mismanagement by the city officials (Bronson, 1975). In 1945 the system was purchased by the city of Rolla and after 27 years city again owned the electric and water system. The only water that was available for human consumption in the 1900’s came from shallow wells and cisterns. In 1965, the city installed a 1,800,000 gallon steel standpipe on Lanning Lane that made the capacity of the storage tank to 2,700,000 gallon and has drilled several wells in Rolla. Water samples from all the wells and the distribution system are continuously checked for quality.

3.2.1.1 System Function. The city water system is an engineering system designed to meet the needs of the city’s requirements of water. The water needs of a city will fall under domestic (drinking, cooking, cleaning, washing, flushing of toilets, watering lawns, use in private swimming pools, etc.), industrial (cooling and heating operations, chemical processes and cleaning), public use (street cleaning, watering of public lawns and gardens, community swimming pools, etc.), and other (irrigation of market gardens, firefighting, etc.). The main hydraulic feature of water supply system is that in pipes, water can rise under pressure.

A great deal of engineering work goes into the processes of operation and management of city water system. The design criteria in the engineering design of a water system will provide a water distribution system that is dependable and safe. The distribution system design is based on hydraulic analysis and pipe sizes (residential or commercial) and the system components such as transmission pipelines, storage reservoirs, pump stations, and distribution system pipelines. Hydraulic analysis of a water supply system can be done using computer modeling software, simulating the system’s response to average and peak demands, tank refills, and firefighting scenarios. Each condition creates different responses in the water system. The hydraulic analysis and its result will help to identify, gauge, and respond to conditions that could result in poor system performance. A water supply system consists of a network of connected pipes and reservoirs. The reservoir and
the thousands of vertical and rising mains that deliver water for the public consumption are the elements that constitute the water supply system of a city (Figure 3.5).

Water utilities construct, operate, and maintain water supply systems. Obtaining water from a source; treating the water to an acceptable quality, and delivering the desired quantity of water to the appropriate place at the right time is the basic function of water utilities. There are three major components of a water distribution system: distribution piping, storage, and pumping stations. These components are composed of subcomponents and these subcomponents are further divided into sub-subcomponents. The pumping station of the system is consists of structural, electrical, piping, and pumping unit subcomponents. The pumping unit is made up of sub-subcomponents such as driver, controls, power transmission, and piping and valves. The purpose of a water distribution system is to supply the system’s users with the quantity of water demanded under appropriate pressure for various loading conditions. The spatial pattern of demands that defines the users’ flow requirements is a loading condition. The one variable that describes the network’s hydraulic condition is the flow rate in individual pipes that result from the loading condition. The other descriptive variables are piezometric and pressure heads. The piezometric or hydraulic head is the surface of the hydraulic grade line or the pressure head (p/r) plus the elevation head (z) and is given by \( h = (p/r + z) \).

The operation and maintenance (O&M) of a water system is usually the responsibility of the public works division. The O&M is important in a water distribution system since it should be operated and maintained in a way that ensures a long and cost-efficient lifecycle. In order to ensure a continuous supply of water to the community, it is required to have day-to-day tasks in the operation of the water distribution system. Operation activities consist of controlling the system components, and even automated systems require significant operator input and monitoring. Documentation of water distribution system inventory and O&M tasks will help in evaluating the O&M procedures.
Figure 3.5: The components, subcomponents, and sub-subcomponents for a water distribution system
3.2.1.2 System Attributes. Water distribution systems are designed to ensure hydraulic reliability, which includes enough quantity and pressure of water for fire flow as well as for system attributes that make up the water supply system’s adaptability, redundancy, interoperability, and agility.

- **Adaptability:** The system should be able to adapt to changing circumstances. A resilient system should be able to withstand a shock without losing its basic functions. In other words the system should be capable of absorbing a disruption without loss of functionality.

- **Redundancy:** System components are made redundant so that if one does not work, the other could be used. This allows alternate options, choices and substitutions under stress. Designing for multiple demand conditions introduces redundancy to a network.

- **Flexibility:** The system should have the ability to tap the available resources and services when disrupted. Computer modeling and simulations will enable study of water-supply performance in the event of a disturbance and system performance can be assessed for a particular disturbance. This will allow the system’s ability to innovate and improvise in the event of a disaster.

- **Interoperability:** The water supply system along with the other engineering systems such as the transportation system, communication system, and a sewage system are components of the city system. The water supply system along with electric power, gas and liquid fuels, telecommunications, transportation, and waste disposal are six principal systems directly linked to the economic well-being, security, and social structure of the community. These systems are interdependent. Electric power is required for the functioning of water supply pumping stations. That means the water pumping station in the city system could not be operated if there is a power failure. Pumps could be activated by combustion engines, but there is a restriction on storage of fuel on site at pumping stations. Once the stored fuel runs out, refueling depends on the transportation system, which is also likely to be damaged after a disaster. Past disasters like World Trade Center (WTC) illustrates the interdependencies of critical infrastructure systems.
♦ Agility: The speed with which a system can overcome a disruption and restore its functionality.

3.2.1.3 System Heuristics. Water storage is an important element in the water system since this reflects the ability to provide an adequate and reliable water supply. Properly sized elevated tanks help to maintain constant system pressure. Elevated storage tanks permit the pumping station to operate at a uniform rate. Problems associated with water resources are the contamination of water making it unfit for human use and the extensive ecological deterioration caused by development of water supplies in some areas.

A distributed system coordinates the action of multiple processes on a network such that all the components co-operate to perform task or tasks. A distributed system will be able to continue operating correctly even when the components fail. System should process information in a parallel and distributed way, without the presence of a central command. The individual units in the system act in parallel and interact locally. This will ensure proper functioning of the whole system and not of its parts only.

The system should adjust to the disturbance by adapting to the new or unexpected situations without human intervention. The system can adjust to the changing situation or even cope with entirely new situations. It is the transformative capacity that renders a system to be able to accommodate change by means of adaptable infrastructures.

A system that has the attribute of redundancy will have parts that are renewable and replaceable. This allows the system to function even when disrupted. Systems made of redundant units using different local resources will have different strategies for resilience. Redundancy will help the system to adapt by providing alternatives when disturbances disrupt the system. When system parts malfunction the entire system does not get disrupted.
3.3 NEED FOR RESILIENCE HEURISTICS

The literature review done in the earlier section clearly indicates that it is possible to come up with system attributes that provide resilience to engineering and biological systems. After a disturbance, the system undergoes changes but still be able to retain its function and structure depending on the magnitude of the disturbance. It is necessary to identify the attributes of a system that renders it resilient. These attributes will enhance the system’s ability to function as before. Hence, it would be desirable to find out how these system attributes are created and have evolved in systems. Can we specify certain set of rules for a given system with a specific domain that will generate these systems attributes? For example Jackson (2007) lists the following rules for engineering systems to be resilient. The heuristics of systems resilience are categorized under four attributes: **capacity, flexibility, tolerance, and inter-element collaboration.** Capacity is defined as the system’s ability to absorb or adapt to a disruption without a total loss of performance or structure. Flexibility allows the system to restructure following a disruption. The system is able to adapt in response to disruptions due to the attribute of tolerance. The inter-element collaboration attribute handles the internal system interactions in response to disruptions.

The attributes desirable for a system to be resilient as seen from literature review are

*Adaptability*

*Diversity*

*Redundancy*

*Distributability*

*Self-organizing*

*Agility*

*Flexibility*

*Interoperability*

*Dynamic learning*

*Scalability*
3.3.1 Resilience Attributes. Resilience explains how a system when disturbed can change as well as survive the disruption. There are certain properties that resilient systems have. A resilient system can withstand a disturbance without losing its basic functions and is able to adapt to changing conditions. A resilient system is able to transform to a different way of functioning when operating under current conditions becomes no longer feasible. Jackson (2007) describes flexibility as an element for system resilience that is invaluable to the system’s ability to manage disruptions. Flexibility is defined as “a system’s ability to restructure itself in response to disruptions”. Flexibility is the ability of a system to undergo changes with relative ease in operation while disrupted. It is the ability to be flexible to changes in the environment and adapt quickly. The reorganization heuristic says that the system should be able to restructure itself in response to disruptions. The human backup heuristic means humans should be able to back up the automated system when the system is not able to handle the change and there is time for human intervention. The human-in-the-loop heuristic is that humans should be elements of the system when there is a need for human cognition. The heuristic-human in control states that the human operator should be in command. A skilled driver may be able to drive a vehicle that has no brakes and this supports the key flexibility attribute as the human at the sharp end of the system. The loose coupling heuristic for flexibility says that the organizational system should allow for flexibility in organizational processes and decisions. Ecosystems have a network structure that is decentralized and this facilitates the flow of information necessary for flexibility that is attained through positive feedback and flexible responses. Ants have the capability of overcoming obstacles. They have the attribute of flexibility to go around an obstacle, or over it or under it. Flexibility allows the ants to be comfortable even when disturbed. 

*Interconnected networks are one strategy that will help a system to be flexible.*

A system should be able to adapt, if the environment where the system exists is changing. Systems that survive a disruption to some degree are said to be adaptable. Jackson (2007) explains restructuring of the system as a key principle of adaptivity. The Apollo 13 mission was a good example of adaptivity. When the main power failed, the crew displayed adaptivity by moving to a smaller module and saving power. The immune
system is highly adaptable since it can learn to recognize and respond to new pathogens, and also it retains memory of those pathogens to assist in future responses. The system should have the ability to create mental preparedness by anticipating any disruption that could possibly happen. Adaptive capacity is an important attribute of resilience that gives the system the ability to respond to and instigate change. Adaptive capacity allows making timely and appropriate decisions in a crisis and helps the system to identify and maximize opportunities. Buffering capability is a second principle of adaptivity which will allow the system to absorb disruptions without performance breakdown. Restoration of power in New York City after the September 11, 2001 attack on twin towers is a good example of buffering. Tolerance is the ability of a system to adapt in response to disruptions. It is the behavior of the system near the boundary of its performance and is required for adaptability. Failure of the Chernobyl Power Plant was due to lack of tolerance, since it became highly unstable near the boundary of its performance. It is the transformative capacity that renders a system to be able to accommodate change by means of adaptable infrastructures. Ant colonies undergo processes like hybridization that allow them to build tolerance levels to conditions that were not normal.

The system should adjust to the disturbance by adapting to the new or unexpected situations without human intervention. The system can adjust to the changing situation or even cope with entirely new situations.

A system should be designed in a way that it can restructure with some degree of functionality after any disruption. The system with two or more ways to perform a function is the most resilient. The functional redundancy heuristic is that there should be an alternative method to perform each critical function that does not rely on the same physical systems. The physical redundancy heuristic is that physical redundancy should exist wherever possible. The redundancy attribute comes under capacity heuristics and it is that the system with two or more ways to perform a function is the most resilient (Jackson 2007). The functional redundancy heuristic is that there should be an alternative method to perform each critical function that does not rely on the same physical systems. Systems should have parts that are renewable and replaceable. Redundancy will help the system to adapt by providing alternatives when disturbances disrupt the system. When
system parts malfunction the entire system does not get disrupted. When a system is
disrupted it loses the interconnection between the systems and this in turn leads to a
decrease in hierarchical control.

The resource redundancy heuristic - Systems made of redundant units using different local
resources will have different strategies for resilience

Diversity (understood, in a wide sense, as heterogeneity of perspectives, behaviours,
characteristics, profiles, etc.), is one of these properties that are able to enhance a system's
resilience to certain external changes. Natural systems provide us with a nice example to
support this claim: Biodiversity (usually in combination with other characteristics like,
for instance, complex patterns of relationships between individuals and species) is known
to improve an ecosystem's resilience to changes on their environment (Peterson et al
1998). On the other hand, there are also valuable examples of resilience enhancement by
diversity in different social complex systems for instance, stock markets, where people
tend to diversify their investments in order to minimize risk to unexpected changes.
The diversity heuristic - The system should be made of a lot of different parts

The variety heuristic - The system should have a variety of ways of functioning and when
disturbed use the one that is best suited.

Diversity of stakeholders can result in innovative solutions to problems. The economic
system in United States is very diverse since it is diversity that supports resilience of the
economic system as such. A system in which stakeholders collaborate will come up with
innovative solutions when disrupted. Systems should be diverse and diversity helps in
facing different types of disturbances. Diversity could be heterogeneity of perspectives,
behaviors, characteristics, profiles, etc. and its ability to enhance system’s resilience is
seen in natural systems. An ecosystem that is diverse is able to regenerate and reorganize
itself after a disturbance.
The view diversity heuristic - More people looking at the same information can generate
many views to a situation and in that diversity; it is possible to find solution to problem
situations.
A need to motivate decision makers to respond quickly to changing conditions when there is a disturbance is the attribute of agility. Dove (2006) defines “Agility is effective response to opportunity and problem, within mission”. A response is effective when it is timely, affordable, predictable, and comprehensive. The objective of agility is effective response and it relies on quantitative results. Agility provides means to continuously manage response ability as the environment changes, and develop agile systems engineering processes. It helps to react to unexpected disturbances, and to respond quickly to new threats when recognized. The immune system of a healthy person who eats well, exercises, and gets good rest is a good example of a system that exhibits the attribute agility. The immune system swings into action when the body is threatened by a virus or bacteria, and puts on an aggressive defense. Once the immune system detects the attackers, it isolates them, and then work to keep it under control. The immune system rarely eliminates the pathogen, but it allows the body to keep functioning. A system with the attribute of agility can be both flexible and undergo change rapidly.

*The quick reaction heuristic*-A system should act quickly in response to changing environment by re-tasking or re-configuring them.

*The system mobility heuristic*-If the system has mobility, it should be able to move towards safe areas away from any disturbance as fast as possible. Mobility provides a means to react to change.

*The rectify heuristic*-A system should detect any change and take corrective action as needed

**Distributability**-There is no central organ in charge of identifying a foreign attacker, distribution, reproduction of antibodies, and immune system memory. Therefore there is no single point of failure. This attribute not only avoids bottlenecks and vulnerability but also provides a faster response toward resilience and could be accomplished by multi-agent approach. A distributed system coordinates the action of multiple processes on a network such that all the components co-operate to perform tasks. A distributed system will be able to continue operating correctly even when the components fail. A system should process information in a parallel and distributed way, without the presence of a central command. A distributed system can still function as a whole even after it loses...
some of its individual units due to disturbance. A distributed system can be repaired or
damaged units replaced without having to close down the whole system. The individual
units in the system act in parallel and interact locally. This will ensure proper functioning
of the whole system and not of its parts. An immune system is a distributed system
where information and a stock-up collection of responses are present within the system
with no central command. These responses are spread through the system depending on
the interactions between agents, self-non self interactions- Order to the system comes
from these interactions.

*Individual units in a system perform only part of the complete task, but there are many of
them working in parallel.*

*The multi-agent heuristic-A multi-agent approach is necessary to achieve distributability.*

*The loss of a central command heuristic- Loss of central command will allow the system
to flourish when disturbed.*

*The no central command heuristic-implies there is no single point of failure.*

*The communication heuristic-The system communicates by exchange of messages over a
network*

*Interoperability*-The intent awareness heuristic that comes under the inter-element
collaboration heuristics is that each element of the system should have knowledge of the
other’s intent and should back up each other when called on. The inter-element
impediment heuristic is that there should be no impediments to inter-element
collaborations. The systems that are involved should be interconnected with extensive
feedback processes. Interoperability allows the system components to exchange
information and use the information that has been exchanged.

*The porous boundary heuristic-While isolating the subsystems within the system, their
boundaries should be porous. Subsystems work independently, but with the porous
boundary, are interconnected. This will in turn helps in successful human intervention.*

Systems are highly scalable, since as many individual units can be added as desired.
Individual units interact only locally and this will not create any overload on any part of
the system. *Scalability* is the ability to maintain or improve performance while the system demand increases.

_System should be able to handle increased workloads-modular units can be added as needed_

The *dynamic learning* attribute will allow the individual units in the system to interact, share control, and learn. A system with dynamic learning attribute will be characterized by distributed control, flexible, high levels of interaction and collaboration, a shared goal, and the system units work together in generating and sharing new knowledge. When disrupted by disturbance, these characteristics will allow the system to evolve and adapt to changed conditions. In a flock of birds, the behavior of the flock emerges from the desire of individual birds to avoid collisions while staying near to each other. Positive feedback occurs when the behavior of each bird affects its neighbors and vice versa. Flocking behavior in birds can be described by three rules: Maintain a certain minimum distance between nearby animals, Steer toward the approximate direction toward which the rest of the animals are heading, Move toward the average position of all the nearby animals. Emergent behavior is a spontaneous creation of order and is the result of system providing more complexity than the sum of its parts. The *motivational interaction heuristic*—The outcome of the system depends on the collection of individual behaviors and their interactions.

The system should self-organize and in order that a self-organized structure is generated, individual units need to exchange information with each other. This could be done by direct or indirect interactions among each other and this translates into communication. Efficient communication strategies could involve network of individuals or groups. It is essential to have a mechanism of communication that no disturbance can disrupt. This trusted source of information is maintained during stable times since during or after a disturbance there is no time to check the source for trustworthiness. This information is available only to those who need it. The communication strategy should begin locally since it is necessary to know the presence of a disturbance that can initiate a response from the system. The system should collect more reliable facts about slow variables and
give importance on future returns. This will reduce the uncertainties present in the system.

*The restructure heuristic*- *A system should be able to restructure itself after a disruption to recover some degree of functionality and performance.*

Termite mounds are constructions that are created by intelligent cooperation. The termite mounds consist of elaborate galleries and chimneys that control airflow in order to manage humidity. Individual termite does not have any idea of how to build a nest or even perceive the overall shape of the nest or design. The termites rely on chemical cues left behind by other termites, and temperature and airflow cues that are affected by the shape of the nest, wind currents, the amount of heat that the nest generates and other local phenomena. The behavior of termites affects the shape of the nest and the shape of the nest affects the termite’s behavior. Many individuals can contribute to a collective effort with immense coordination among different groups and the stimuli provided by the emerging structure itself.

*Local stimuli can be organized in space and time to ensure a complex structure and the individual units could respond to environment change independently.*

Robustness is the ability of a system to operate across a wide range of conditions correctly and to fail gracefully outside of that range or in other words, the ability to regain stability. Resilience is the ability to survive after being disrupted by disturbances whereas robustness refers to the ability to endure disturbances without adapting (Husdal, 2009). The new rules created for resilience are based on the biological rules seen in nature. Wouldn’t it be great to create a model from these rules?
3.3.2 The Available Attribute Based Heuristics. A system should be able to adapt if the environment where the system exists is changing. Systems resilience results from a set of attributes that the system should have and these attributes are the source of design heuristics. The following are a few attribute based heuristics that have been identified from literature review.

- **Flexibility**
  The loose coupling heuristic – The organizational system should allow for flexibility in organizational processes and decisions-Deference to expertise and a flexible culture
  The reorganization heuristic - The system should be able to restructure itself in response to disruptions or the anticipation of disruptions
  The human backup heuristic - Humans should be able to backup the automated system when there is a change in context the automated system cannot handle and there is time for human intervention
  The human-in-the-loop heuristic – Humans should be elements of the system when there is a need for human cognition.
  The human in control heuristic – States that the human operator should be in command.
  The informed operator heuristic – The human operator should be informed
  The human at the sharp end of the system is the key flexibility attribute of the system
  The predictability heuristic – Automated systems should behave predictably and allow human over-ride.
  The inspectability heuristic – The system should enable humans to take actions when needed without making unsubstantiated assumptions
  The simplicity heuristic – Automated systems should be simple to train, to learn, and to operate.
  The complexity avoidance heuristic – Complexity should only reflect the complexity demanded by the system functionality.
  The reparability heuristic - The system should be repairable.

- **Adaptability**
  Absorption heuristic – States that the system should be capable of absorbing a disruption.
  The margin heuristic – The system should have adequate margin to absorb disruptions.
The reorganization heuristic – The system should be able to restructure itself in response to disruptions.

The regroup heuristic – The system should be able to restructure itself after a disruption to recover some degree of functionality and performance.

The graceful degradation heuristic – The system should degrade gradually when exposed to a disruption.

The drift correction heuristic – Drift towards brittleness should be detected and corrected.

The neutral state heuristic – The system should be put into neutral if possible.

The automatic function heuristic – Functions should be automatic only if there is a good reason for doing so.

The organizational decision-making heuristic - Organizational decision-making should be monitored.

The organizational planning heuristic – Notice signs that call into question organizational plans, models and routines.

The mobility heuristic – The system should be able to avoid a threat by moving.

The prevention heuristic – The system should be able to suppress future potential disruptions.

The retaliation heuristic – The system should be able to retaliate to a disruption.

The concealment heuristic – The system should attempt to conceal itself against potential threats.

The deterrence heuristic – The system should attempt to deter hostile threats from attacking.

The regroup heuristic – The system should be able to restructure itself after a disruption to recover some degree of functionality and performance.

The absorption heuristic – The system should be capable of absorbing a disruption.

Margin heuristic – States that the system should have adequate margin to absorb disruptions.

For a biological system like the immune system, the heuristic for adaptability:

*Adaptability*- Immune system is capable of recognizing new pathogens and figuring out the proper response in eliminating that pathogen. The system tailors its activity according to the antigen it is fighting against, making it adaptable.
For ecosystems the heuristic for adaptability:

*Adaptability*-It is the extent to which a system can absorb recurrent natural and human perturbations and continue to regenerate without slowly degrading or even unexpectedly flipping into less desirable states. Resilience in this context is defined as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Folke et al. 2005, Walker et al. 2004).

Resilience measures the strength of mutual reinforcement between processes [operating at different scales], incorporating the ability of the system to persist despite disruptions and the ability to regenerate and maintain existing organization (Gunderson and Pritchard 2004).

- **Interoperability**

  Incorporate feedback mechanisms where possible. Base future decisions on analysis of the feedback received

  The system shall be capable of absorbing a disruption

  Inter-Element Collaboration Heuristic

  The informed operator heuristic – The human operator should be informed

  The collective intelligence of ants comes from the mechanics of communication via pheromones. Each individual ant follows a certain rule based on local information, initiating behaviors depending on the need at the time.

  Multiple interactions between individuals in a group and their smart interactions result in a final organized structure.

  Multiple interactions between individuals in a group could be regarded as smart interactions result in a final organized structure.

- **Agility**

  “Agility is effective response to opportunity and problem, within mission” (Dove, 2006)

  The drift correction heuristic – Drift towards brittleness should be detected and corrected

  Tolerance is mostly handled by monitoring the system to detect any drift.

  The drift correction heuristic – Drift towards brittleness should be detected and corrected.
The mobility heuristic – The system should be able to avoid a threat by moving
The reparability heuristic – The system should be repairable
The knowledge between nodes heuristic – Maximize knowledge between nodes
The drift correction heuristic – Drift towards brittleness should be detected and corrected.
The context spanning heuristic – The system should be designed to both the worst case and most likely scenarios.

- **Dynamic Learning**
  The dynamic learning attribute allows the individual units in the system to interact, share control, and learn.
  Ant navigation is based on sensory capabilities as well as environment characteristics and function within colony. They make use of memory and learning and meeting with other colony members that constitute the visual landmarks and when pheromones are involved with that it is chemical landmarks
  The foraging behavior in honey bees is a display of compromise between food collection and information collection

- **Distributability**
  In an immune system there is no central organ in charge of identifying foreign attacker, distribution, and reproduction of antibodies, and immune system memory.

- **Diversity**
  The diversity heuristic – There should be diversity within systems
  The knowledge between nodes heuristic – Maximize knowledge between nodes
  The drift correction heuristic – Drift towards brittleness should be detected and corrected
  The context spanning heuristic - The system should be designed to both the worst case and most likely scenarios
  The margin heuristic – The system should have adequate margin to absorb disruptions
  Predicting the future is impossible but ignoring it is irresponsible
  The reparability heuristic - The system should be repairable
Heterogeneity of perspectives, behaviors, characteristics, profiles, etc., and diversity is one of these properties that are able to enhance system's resilience to certain external changes.

Division of labor in ant colonies provides behavioral differences among individuals and this influences the group behavior.

In an ecosystem the variation contained within species and between species.

An ecosystem that is diverse is able to regenerate and reorganize itself after a disturbance.

An ecosystem exhibits some degree of genetic or species variety and this is the basis for their capacity to develop in response to change.

An immune system produces antibodies to fight against bacteria and virus. These antibodies have to be extremely diverse in order to adapt to a wide variety of germs that enter the body.

Diverse set of antibodies adapted to different antigens.

Diversity heuristic in immune system is having different mechanisms that can react to a similar antigen in a different way and each of these mechanisms has its own vulnerable or weak points.

- **Redundancy**

  The hidden interaction heuristic – Avoid hidden interactions
  The system should be designed to both the worst Tolerance Heuristics
  The graceful degradation heuristic – The system should degrade gradually when exposed to a disruption.
  The drift correction heuristic – Drift towards brittleness should be detected and corrected.
  The neutral state heuristic – The system should be put into neutral if possible.
  The automatic function heuristic – Functions should be automatic only if there is a good reason for doing so.
  The organizational decision-making heuristic -Organizational decision-making should be monitored.
  The organizational planning heuristic – Notice signs that call into question organizational plans, models and routines.
The mobility heuristic – The system should be able to avoid a threat by moving.
The prevention heuristic – The system should be able to suppress future potential disruptions.
The retaliation heuristic – The system should be able to retaliate to a disruption.
The concealment heuristic – The system should attempt to conceal itself against potential threats.
The deterrence heuristic – The system should attempt to deter hostile threats from attacking.
The regroup heuristic – The system should be able to restructure itself after a disruption to recover some degree of functionality and performance.
The knowledge between nodes heuristic – Maximize knowledge between nodes
Incorporate feedback mechanisms where possible. Base future decisions on analysis of the feedback received
The organizational decision-making heuristic – Organizational decision-making should be monitored.
Organizational Heuristics – Many problems cannot be solved alone. The organizational system shall allow for flexibility in organizational processes and decisions. In partitioning choose the elements so that they are as independent as possible, that is, elements with low external complexity and high internal complexity. Incorporate feedback mechanisms where possible. Base future decisions on analysis of the feedback received. The system shall be capable of absorbing a disruption. If we use it up today, it will not be here tomorrow
Predicting the future is impossible but ignoring it is irresponsible (Rechtin, 318).
The reparability heuristic - The system should be repairable
The knowledge between nodes heuristic – Maximize knowledge between nodes
The drift correction heuristic – Drift towards brittleness should be detected and corrected
The context spanning heuristic - The system should be designed to both the worst case and most likely scenarios
The margin heuristic – The system should have adequate margin to absorb disruptions
Practicing the context spanning heuristic and modeling a flock of birds during aircraft design and testing could have contributed to structural changes that would have made this aircraft robust to this disruption.

Aspects of the aircraft design also contribute to the survivability of this accident. When the engine power was lost a functionally redundant source provided power to the rest of the control mechanisms.

The waggle dance is done repeatedly by the bee in order to give the accurate location of food. The message gets recognized correctly when it is repeated.

Redundancy in Immune System: Redundancy attribute is seen in the form of having multiple copies of antibodies which allows for back up plans if the first action plan goes wrong. With this attribute therefore the better the chance that an invading pathogen that matches these antibodies will be stopped.

“Species redundancy enhances ecosystem resilience” (Naeem 1998).

- **Self-organizing**
  - Preoccupation with failure
  - Deference to expertise and a flexible culture
  - The distancing paradigm
  - The individual responsibility paradigm
  - The absorption heuristic – The system should be capable of absorbing a disruption
  - The reorganization heuristic – The system should be able to restructure itself in response to disruptions.
  - The diversity heuristic – There should be diversity within systems.
  - The drift correction heuristic – Drift towards brittleness should be detected and corrected

Take preventive steps to assure that the effects of fear loops are minimized.

Take steps to minimize the effects of the fear loop after it has begun.

Literature review suggested the role of system attributes toward achieving systems resilience in biological and engineering systems. It can be seen that system resilience can be architected in a system by using these resilience attributes as seen from the above biological and engineering systems. Systems resilience is the outcome of attributes that
the system possesses in order to be resilient. It is these attributes that can generate the heuristics for resilience. In the following chapter a qualitative resilience model is developed that is domain independent. This model will provide the required heuristics for resilience based on the system attributes.
4. BIOLOGICALLY INSPIRED QUALITATIVE ENGINEERING MODEL

In this section a qualitative model is developed for resilience based on the system attributes. In previous it was established that system resilience can be achieved using heuristics and these heuristics are based on attributes. The model is domain independent but the heuristics that are selected depend on the system and is based on attributes. The goal is to develop a model to generate resilience heuristics given a set of resilient attributes.

4.1 RESILIENCE ATTRIBUTES

The biologically inspired resilience heuristics is based on 10 system attributes namely; Adaptability, Diversity, Redundancy, Distributability, Self-organizing, Agility, Flexibility, Interoperability, Dynamic learning, and Scalability to achieve resilience in architecting complex engineering systems.

Adaptability: The attribute that is responsible for a system to accept change, seek out strategies to deal with the unknown, and shift their behavior to accommodate new situations and challenges. Adaptability is an important attribute of resilience that gives the system the ability to respond to and instigate change. This in turn allows making timely and appropriate decisions in a crisis and helps the system to identify and maximize opportunities.

Flexibility: The attribute that makes it easy for a system to be operational when the environment changes. The system can be modified easily by virtue of this attribute with the ability to respond to changes that are not planned.

Diversity: Diversity is the attribute that enhances a system’s resilience to disruptions. The attribute is due to the variation in the elements of the system that allows the system components to function in several ways that prevents failure.

Interoperability: The ability of two or more components in a system to exchange and use information. The intent awareness heuristic that comes under the inter-element collaboration heuristics is that each element of the system should have knowledge of the other’s intent and should back up each other when called on.
Distributability: This attribute not only avoids bottlenecks and vulnerability but also provides a faster response toward resilience and could be accomplished by a multi-agent approach. A distributed system coordinates the action of multiple processes on a network such that all the components co-operate to perform task or tasks. A distributed system will be able to continue operating correctly even when the components fail.

Redundancy: Redundancy will help the system to adapt by providing alternatives when disturbance disrupt the system. When system parts malfunction the entire system does not get disrupted. This attribute will allow the system to function in two or more ways.

Agility: Agility provides the means to continuously manage response ability as the environment changes, and develop agile systems engineering process. It helps to react to unexpected disturbances, and to respond quickly to new threats when recognized.

Scalability: Systems are highly scalable, since as many individual units can be added as desired. Individual units interact only locally and this will not create any overload on any part of the system. Scalability is the ability to maintain or improve performance while the system demand increases.

Dynamic learning: Dynamic learning allows the individual units in the system to interact, share control, and learn. A system with the dynamic learning attribute will be characterized by distributed control, flexible, high levels of interaction and collaboration, a shared goal, and the system units work together in generating and sharing of new knowledge. When disrupted by disturbance, these characteristics will allow the system to evolve and adapt to changed conditions.

Self-organizing: The system should self-organize and in order that a self-organized structure is generated, individual units need to exchange information with each other. This could be done by direct or indirect interactions among each other and this translates into communication. Efficient communication strategies could involve network of individuals or groups. It is essential to have a mechanism of communication that no disturbance can disrupt.
4.2 HEURISTICS SELECTED FOR RESILIENCE

The following are the set of heuristics that are required for systems resilience that are generated from this study based on the ten attributes that were selected for resilience:

1. Choice heuristic—System should be able to perform in alternate ways
2. Workflow management heuristic—An organizational system must adapt their defined processes and decision plans to any changing situations by making use of a workflow management system (by having a workflow management system available)
3. The human in control heuristic—The human at the sharp end of the system given the power to take actions when needed without making questionable assumptions
4. The focused and ready heuristic—Humans at the end of the interface should be provided sufficient training that enables a thorough understanding of the system, its procedures, shortcomings, and alternative means of recovery and instill a confidence that they have the power to improvise if necessary.
5. The motivated operator heuristic—Humans in the system should be motivated with a capacity to learn and adapt
6. The supply capability heuristic—Humans in the system should ensure resource required for system functioning is available at times the system gets disrupted
7. The autonomous network heuristic—The system should have interconnected networks for flexibility by choosing elements that can function as independently as possible
8. Task mobility heuristic—The system should demonstrate the ability to function by suspending some tasks that enables it to adapt automatically to disruption
9. Past re-collection heuristic—The system should be capable of remembering past disruptions as well as identify new threats so that they can function when disrupted
10. The communication heuristic—System need to communicate with other systems to withstand disruption
11. The integrated communication heuristic—Interactions between subsystems incorporating feedback mechanisms that can establish future decisions based on analysis of the feedback received and this means smart interactions towards an organized structure.
12. The information feedback heuristic—Components of the system should exchange data and information with minimal loss of information. Interaction between the
subsystems should involve exchange of information and data in a meaningful manner by using the information that is exchanged.

13. The feedback integration heuristic—Understand the processes, interactions and feedback mechanisms within the system components. Any decision regarding the system is based on the integrated approach between the subsystems.

14. The agility heuristic—Act quickly in response to changing environment by task mobility and demonstrate that some tasks can be suspended and then restarted in different environments.

15. The rectify heuristic—The system should detect any change and take corrective action as needed.

16. The system mobility heuristic—If the system has mobility, it should be able to move towards safe areas away from any disturbance as fast as possible. Mobility provides a means to react to change.

17. The failure detection heuristic—The system should identify early warning signs of any failure and permit rapid adjustments and modification as required based on the early warning system.

18. The anticipate and preemptive response heuristic—The system should anticipate and be prepared to guard crucial strategic vulnerabilities by deploying patches.

19. The no central Command heuristic—The system will not have a single point of failure.

20. The message exchange heuristic—The system communicates by exchange of messages over a network.

21. The decentralized heuristic—The agents that constitute the system constantly respond and adapt to each other where no one agent is in charge and the system’s overall behavior appear from the resultant agent interactions.

22. The diversity heuristic—The system should be made of a lot of different parts

23. The variety heuristic—The system should have a variety of ways of functioning and when disturbed it can use the one that is best suited.

24. The collaboration heuristic—where the diverse system components are able to work together

25. The inter-system interoperability heuristic—The system should have inter-system interoperability at interfaces, component-to-component interoperability, human-to-
system interoperability, and agility, human to technological and technological to technological interoperability.

26. *The backup heuristic*—Modular components where multiple components with equivalent functions are introduced for backup.

27. *The modularity heuristic*—System should be made of modular units, where subsystems are physically and functionally insulated so that failure in one module do not spread to other parts and leads to system wide catastrophe.


29. *The self-organizing heuristic*—The system can function without any external management or maintenance by eliminating or repairing compromised system components efficiently.

30. *The autonomous operation heuristic*—The system should continue to function by autonomous operation with emphasis on resilience rather than economic efficiency. The system will be functional because of the option of autonomous operation available for some parts of the system.

31. *The task assignment heuristic*—System components follow certain behaviors, thereby implementing a task allocation which collectively result in a network service.

32. *The modular library system heuristic*—The system should be able to handle increased workloads—modular units can be added as needed.

33. *The independent functioning heuristic*—The system should adjust to the disturbance by adapting to the new or unexpected situations without human intervention. This will enable the system to adjust to any changing situation or even cope with entirely new situations.

34. *The resource redundancy heuristic*—Systems made of redundant units using different local resources will have different strategies for resilience.

35. *The View diversity heuristic*—More people looking at the same information can generate many views to a situation and in that diversity; it is possible to find solution to problem situations.
36. *The multi-agent heuristic*—A multi-agent approach is necessary to achieve distributability.

37. *The loss of a central command heuristic*—Loss of central command will allow the system to flourish when disturbed.

38. *The porous boundary heuristic*—While isolating the subsystems within the system, their boundaries should be porous. Subsystems work independently, but with the porous boundary, are interconnected. This will in turn help in successful human intervention.

39. *The motivational interaction heuristic*—The outcome of the system depends on the collection of individual behaviors and their interactions.

40. *The restructure heuristic*—The system should be able to restructure itself after a disruption to recover some degree of functionality and performance.

41. *Renewable and replaceable heuristic*—A well-designed system will be renewable and replaceable. Failure of one system component results in another component capable of fulfilling its function.

42. *Task interchangeability heuristic*—The system with ability to interchange tasks by task mobility creates internal functional redundancy.

### 4.3 QUALITATIVE MODEL FOR RESILIENCE

Qualitative model will help in understanding of causes and effects making use of qualitative reasoning techniques. The compiled resilience heuristics are generated using the model that is developed (Figure 4.1). Depending on the system attribute, the system can be assessed and heuristics selected based on the attributes. The output is the heuristics and once that is identified it can be applied to the specific domain for its resilience architecture.
Earlier work done established ten biologically inspired attributes as resilience attributes. System assessment is done in the next step for system evaluation. The system attributes are fundamental in performing the system assessment. For each attribute check the appropriate assessment of a given system instance. System analysis based on the system attributes will provide details regarding the current state of the system. This is necessary to accurately identify and assess the system. System assessment will generate a value for a given system instance and is an effective way of evaluating the system behavior. It is important to know the biologically inspired attribute and the value from the evaluation. This in turn helps in getting the rule selector to decide which resilience heuristics is perfect for the system to be resilient.

4.3.1 System Assessment. Assessment is done by checking the system modularity, system interface complexity, system capacity, communication channels, and the identification of stakeholders role and responsibility.

Modularity Assessor:
Modularity of the system is used for system assessment what it means is system is made of modules or smaller parts that can function independently. The degree of modularity in a system is given values of high, medium, and low. The values correspond to the number of components, interfaces shared among the components, and the degree of substitutability. The attributes for modularity are flexibility, adaptability, distributability, interoperability, and diversity. Modularity accommodates uncertainty, since modularity...
in a system allows functionality of the system as a whole even when modules get replaced or substituted within the system. Degree of modularity is high if there are many components and their interfaces are shared and simple, and the components are interchangeable.

The value for modularity is low if components are not many and that they are not interchangeable. The value is medium when the system has some system components that have shared interfaces and some of them are interchangeable with a low degree of substitutability. Modularity in a system is analyzed by taking into account the three variables and they are the number of components, number of interfaces, and level of substitutability. A value of high indicates that the components have a high degree of independence. The weak interaction between the module means that there is minimum interdependence between the subsystems. This means that the system as a whole will not suffer if some subsystems or components are damaged or disrupted.

Assessment Value: **High, Medium, or Low**

**Interface Assessor:**

Interface is the place where two system components connect and communicate. A simple interface lets a system adapt to the user and makes it easier for users to be in control of the interface. The attributes that are to be considered in this assessment are *adaptability*, *flexibility*, *interoperability*, *diversity*, *scalability*, and *redundancy*. Simplifying the interfaces minimizes the breakup of system performance and is therefore desirable in a system. A simple interface lets a system adapt to the user and makes it easier for users to be in control of the interface.

Assessment Value: **High, Medium, or Low**

**System capacity Assessor:**

System capacity is the capability of the system. The assessment of current capacity of system is done by identifying the system purpose, the system components, and their number and their roles. What is the system supposed to do? Once the system components are identified identify the quantity and then find out what each component does and how well it can do the work. The attributes that contribute the assessment is *adaptability*,
flexibility, self-organizing, and diversity. Depending on the system, the system capacity can be high or low

Assessment Value: **High, Medium, or Low**

**Communication Channel Assessor:**
A group of people can link themselves together to exchange information. The outcome of this exchange of information is the emergence of a well defined pattern of communication. Communication could be written, verbal, nonverbal, visual, or electronic and each has its own significance and value. Technologies involved are the internet, television, electronic mail (E-mail) and humans are a necessary component in this. The communication network is assessed based on the attributes flexibility, adaptability, agility, scalability, redundancy interoperability, and distributability. System analysis based on the system attributes will provide details regarding the current state of the system. This is necessary to accurately identify and assess the system. Once the system is analyzed for all the resilient attributes of the system, the resulting system assessment will have a value. This value determines the heuristics that will get generated based on the rule selector. Heuristics when applied will make the system adapt to accommodate change or disturbance and still function-helps in control and improve the system. Heuristics will provide creative responses using the systems own resources.

Assessment Value: **Present or Absent**

**Stakeholder Identification:**
Stakeholders are people who have rights or interests in a system. Stakeholders can be individuals, communities, social groups, or organizations. The stakeholders role and task allocation analysis will also vary with each system. The stakeholders are usually the owners, users, customers, clients, managers of the system. The assessment of stakeholders role and task allocation is done by first identifying the stakeholders. Once the stakeholders are identified their roles in decision making and their responsibility toward the system can be found out. In some cases the stakeholders responsibility may be well defined and clearly recorded, but sometimes in some systems stakeholders responsibility may be vague and not clearly stated.

Assessment Value: **Clear or Vague**
4.3.2 Rule Based Heuristic Selection. After checking System Modularity:

If flexibility and adaptability are required and modularity is low
then select heuristic 2, 4, and 5
If flexibility and adaptability are required and modularity is medium
then select heuristic 8 and 32
If flexibility and adaptability are required and modularity is high
then select heuristic 27 and 31

If self-organizing is required and modularity is low
then select heuristic 9, 15, 30
If self-organizing is required and modularity is medium
then select heuristic 41
If self-organizing is required and modularity is high
then select heuristic 7, 29

If redundancy is required and modularity is low
then select heuristic 42
If redundancy is required and modularity is medium
then select heuristic 6
If redundancy is required and modularity is high
then select heuristic 34

If diversity is required and modularity is low
then select heuristic 23
If diversity is required and modularity is medium
then select heuristic 35
If diversity is required and modularity is high
then select heuristic 1, 22

The heuristics that gets selected can be put in table for each assessment of the system. Table 1-5 gives the heuristic selection after the system assessment as shown below:
Table 4.1: Rule Based Heuristic Selection after Checking Modularity

<table>
<thead>
<tr>
<th>REQUIRED ATTRIBUTES</th>
<th>ASSESSMENT VALUE</th>
<th>HEURISTIC SELECTION</th>
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</thead>
<tbody>
<tr>
<td>Flexibility and Adaptability</td>
<td>Low</td>
<td>2, 4, 5</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>8, 32</td>
</tr>
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<td></td>
<td>High</td>
<td>27, 31</td>
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<tr>
<td>Self-organizing</td>
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<td>9, 15, 30</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>7, 29</td>
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<tr>
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<tr>
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<td>6</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>34</td>
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<tr>
<td>Diversity</td>
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</tr>
<tr>
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<tr>
<td></td>
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<td></td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
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<td></td>
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Table 4.2: Rule Based Heuristic Selection after Checking Interface Complexity

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<td></td>
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<tr>
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<tr>
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<td>High 35</td>
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<td>Distributability</td>
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<tr>
<td></td>
<td>High 4</td>
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Table 4.3: Rule Based Heuristic Selection after Checking System Capacity

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<tr>
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<td>-----------------------------</td>
<td>------------------</td>
<td>---------------------</td>
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<td>Absent</td>
<td>3</td>
</tr>
<tr>
<td>Self-organizing</td>
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</tr>
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<tr>
<td>Agility</td>
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</tr>
<tr>
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<tr>
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Table 4.5: Rule Based Heuristic Selection after Identifying Stakeholders

<table>
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<th>HEURISTIC SELECTION</th>
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</tr>
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<tr>
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<td>High</td>
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<tr>
<td>Dynamic Learning</td>
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<tr>
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<td>Scalability</td>
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<tr>
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<td>40</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>4</td>
</tr>
</tbody>
</table>
The model operates by evaluating a system by system assessment using a modularity assessor, Interface assessor, system capacity assessor, communication assessor, and a stakeholder identifier. System assessment value varies with each system and the values are given a level. Based on the system assessment value obtained for each system the rule based heuristic selector decides the particular heuristic to be used. Some systems do have a natural amount of resilience. The resilient attributes have a significant role in satisfying the requirement for a system to be resilient to all disruptions. Humans and organizations are capable of adapting to changes and disturbances. Resilience can be built into a system by applying these resilient attributes. The heuristics that are selected for resilience are from the 42 heuristics that are generated from this study. It is possible to generate them in a non linear way. Using the model it is possible to compute and generate the heuristics required for resilience. The architecture can be modified based on the heuristics that gets generated from this model.

The developed model will generate heuristics and the heuristics are selected based on attributes. This qualitative model selects biologically inspired resilience heuristics based on 10 system attributes namely; Adaptability, Diversity, Redundancy, Distributability, Self-organizing, Agility, Flexibility, Interoperability, Dynamic learning, and Scalability to achieve resilience in architecting complex engineering systems. The qualitative resilience model that is developed is domain independent. This model is simple and it can be applied to any system. It is the system attributes that decides the heuristic that need to be generated for a particular system that will provide creative responses using the system’s own resources. The use of the qualitative model is demonstrated for recent system disturbances experienced globally such as; the Mumbai terror attack and hurricane Katrina. The resilience model is thus evaluated on the Mumbai terror attack and hurricane Katrina in the next chapter.
5. MODEL EVALUATION

The qualitative model that is developed is tested on recent catastrophes like Mumbai terror attack and hurricane Katrina.

5.1 MUMBAI TERROR ATTACK

The spate of attacks in Mumbai, India that took place on 26th of November, 2008 lasted for over 50 hours and left close to 195 individuals dead. The attack is an example of a system that failed due to lack of resilience.

5.1.1 System. The Taj attack claimed the lives of citizens of 15 different nationalities and therefore could well be considered a global terror attack. The incident has revealed the deficiencies of India's police, coast guard, commando force and its intelligence apparatus. It is evident that the system was flawed and efforts should be made to make it robust against any future attacks from the lessons learned from this massacre. A system that included the central government, state government, local officials, law enforcement officers, and the private citizens lacked resilience. Mainly the resources were not available and there was an absence of communication between the system components.

India was not adequately prepared for this type of terror attack. The system was not resilient since it took India two days to get in control of the situation. When a terror attack does happen, the resilient system may bend from the impact but will not break. The system resilience should come from a distributed response where each level of the system contributes to its survival. The individuals involved should have an understanding of the challenges a society faces and take decisions accordingly. With this shared awareness, conditions are created where citizens do much more to protect themselves. Since threats evolve, the response should adapt too and people should be involved in the creation of the resilient system. The private sector, the public, and the government form a relationship that is based on openness, sharing information, and feedback. This would create better response against terror attack. Also, a mechanism to share information
between various agencies would have to be undertaken to ensure that all movements on the terrorism front are monitored.

Before a catastrophe, the public buildings department and emergency management office should make a plan that will involve local police, fire, and health departments. The plan needs review and updates as system changes or other new threats come up. The plan should help determine alternate action anticipating failure of normal communication systems, no electric power, and the possibility of massive deaths or injuries. Conducting regular emergency drills may be desirable to keep the plan up-to-date. Communications between the agencies are important to build intra agency relationships. It will help if the leaders of each of the agencies who respond to an emergency situation knew each other beforehand. It is critical to identify the resources to execute the plan and it could be people, equipment, or facilities. Radio communication capability is a must since cell phones may not work in emergencies and there is a need to make sure that there will be multiple communication systems available. All employees should undergo background checks and everyone should display their identification at all times. Communication is the key and so the key responders should talk face-to-face coordinating their recovery action.

5.1.2 System Attributes. The Mumbai system attributes are *Adaptability, Flexibility, Agility, Distributability, and Interoperability*

*Adaptability*: The system was unable to absorb the disruption and regain control because of the absence of this attribute. Mumbai system did not have enough security in the buildings that were attacked. Indian forces ignored advanced intelligence warnings and the police officers ran away from the scene, since they lacked weapons and their bulletproof vests were defective. The Indian coast guard does not have night-vision equipment and according to the Research and Analysis Wing, India's equivalent of the CIA: intercepts of satellite telephone conversations indicated that the terrorists would arrive by sea, and attack five-star hotels in Mumbai. They were undetected since security authorities lack night-vision gear or other sensors that can detect a low-profile skiff or rubber dinghy. If the alleged advance intelligence about the plot was shared with the
coast guard or the Indian Navy, they probably would have been vigilant. Although, India has the world's third-largest military, its 4,500-mile coastline is largely unprotected. The federal government set aside funds to purchase 26 boats for the country's eight coastal states, but Maharashtra state, where Mumbai is, refused them, saying it lacked the funds for maintenance. There is also a severe shortage of helicopters available to the coast guard. The armed men reportedly did arrive by sea, hijacking a fishing trawler in the western Indian state of Gujarat, killing the crew, and sparing the captain until he piloted the ship to near Mumbai harbor, where they killed him. This would not have happened if there were coastal guards guarding the city.

*Agility:* Indian security forces reached the site 10 hours after the terror attacks began. The system failed due to lack of communication that resulted in the delay in the launching of the commando force. This delay may well explain why it took days for India’s security forces to overpower ten assailants who killed 195 people and wounded more than 280. Poor execution of response plans since anti-terrorist squads were slow to react to the situation and were not properly trained.

*Distributability:* The chief minister of Maharashtra state was aware of the attack within 10 minutes after the first terror strike, but it took 90 minutes before he could get in contact with the country’s top law enforcement official to request 200 commandos to be flown to Mumbai. He could not take action because of the lack of this attribute and he had to wait for decision to be made from higher authority. The "Black Cats," as the commandos are known, are headquartered in Gurgaon, south of New of Delhi, and have no bases anywhere else in the vast country and no aircraft. The only plane available to transport 200 commandos was a Russian-built IL-76 transport plane, but it was in Chandigarh, 165 miles north of New Delhi. The pilot had to be awakened, the crew assembled, and the plane fueled. The aircraft reached New Delhi at 2 a.m., picked up the commandos and took-off for Mumbai at 2:25 a.m. — five hours after the attacks began. By commercial aircraft, it takes two hours to fly from Delhi to Mumbai, but flying on the IL-76, the commandos did not reach Mumbai until 5:25 in the morning. There they were met not by helicopters, but by a bus, which they boarded at 6:05 a.m. After being briefed,
they divided into groups and set out on their mission. Some counterterrorism experts say that trained commandos must reach the scene of a terrorist attack no later than 30 minutes after an assault begins. However, in Mumbai nearly 10 hours had elapsed after the terror attack began. Presence of distributability attribute would have provided a faster response towards resilience by avoiding bottlenecks and vulnerability. Indecision from the part of government led to delay in response to the situation.

*Interoperability:* Focus on wide sharing of information about risks and safety measures in order to build public commitment to, and participation in, mitigation programs. The ability to rebound from any attack without falling into chaos is important and this can be achieved if the system is designed in advance to anticipate, and recover from the impacts of the attack. There was no coordination between the security agencies and police. Emergency responders did not coordinate their actions with the security agencies either.

*Self-Organizing:* This attribute was missing as evident by the government response to the attack. Everyone involved in decision making waited for someone else to tell them what to do.

### 5.1.3 Application of the Model for Resilient Heuristics

Assess the system for modularity, system interface complexity, system capacity, stakeholders role, and the communication channels as shown in Figure 5.1. The value obtained after the system evaluation results in heuristic selection. Depending on the value of system assessment and the required attributes different heuristics will get generated.
If resilience attribute and modularity is low then select heuristic …………….

If resilience attribute and interface complexity is high then select heuristic …………….

If resilience attribute and system capacity is low then select heuristic …………….

If resilience attribute and communication channel is absent then select heuristic …………….

If resilience attribute and stakeholders role and task is vague then select heuristic …………….

Figure 5.1: Qualitative Resilience Model for Mumbai System
Table 5.1: Mumbai System Heuristic Selection after Checking Modularity

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Heuristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility and adaptability</td>
<td>Heuristic 2, 5</td>
</tr>
<tr>
<td>Self-organizing</td>
<td>Heuristic 9, 15, 30</td>
</tr>
<tr>
<td>Redundancy</td>
<td>Heuristic 42</td>
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<tr>
<td>Diversity</td>
<td>Heuristic 23</td>
</tr>
<tr>
<td>Distributability</td>
<td>Heuristic 21, 37</td>
</tr>
<tr>
<td>Interoperability</td>
<td>Heuristic 25</td>
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<tr>
<td>Agility</td>
<td>Heuristic 28</td>
</tr>
<tr>
<td>Dynamic learning</td>
<td>Heuristic 4</td>
</tr>
<tr>
<td>Scalability</td>
<td>Heuristic 3</td>
</tr>
</tbody>
</table>

Options for Resilience:

Once the heuristics are identified the next step is to apply it. When the attack happened, a lot of time was wasted on transporting the commandos to Mumbai. The workflow management heuristic allows decision process to be linked together and they collectively help the system to adapt to the changed situation, allowing for changes in the system’s defined processes and decision plans. Agencies and personnel required for security could be added to the system without any delay. It is the people in control who can make these decisions. People can make incorrect decisions with the best intentions, usually under pressure or due to lack of experience. The humans involved should be trained in dealing with disturbances to act wisely and make decisions regarding. Modularity lets a system manage complexity since by creating system components that have a high degree of independence. Even though after the system analysis, the level of modularity for Mumbai system was low, the heuristics that get selected introduce some degree of modularity into the design.
Table 5.2: Mumbai System Heuristic Selection after Checking Interface

<table>
<thead>
<tr>
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<th>Heuristic(s)</th>
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</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>Redundancy attribute and high interface complexity</td>
<td>34</td>
</tr>
<tr>
<td>Diversity attribute and high interface complexity</td>
<td>35</td>
</tr>
<tr>
<td>Distributability attribute and high interface complexity</td>
<td>37</td>
</tr>
<tr>
<td>Self-organizing and high interface complexity</td>
<td>38</td>
</tr>
<tr>
<td>Interoperability attribute and high interface complexity</td>
<td>25</td>
</tr>
<tr>
<td>Agility attribute and high interface complexity</td>
<td>3</td>
</tr>
<tr>
<td>Dynamic learning attribute and high interface complexity</td>
<td>2</td>
</tr>
<tr>
<td>Scalability attribute and high interface complexity</td>
<td>4</td>
</tr>
</tbody>
</table>

**Options for Resilience:**

A system has a complex interface if it has too many components. Assessment value for the Mumbai system interface complexity was given a level of high after system assessment due to its interface to humans and to other systems. The heuristics help in managing with the change in the system due to disruption by reducing the system interface complexity and allowing coordination between the system components.
Table 5.3: Mumbai System Heuristic Selection after Checking System Capacity

If flexibility and adaptability is required and system capacity is low then select heuristic 5
If self-organizing is required and system capacity is low then select heuristic 17
If redundancy attribute is required and system capacity is low then select heuristic 6
If diversity attribute is required and system capacity is low then select heuristic 35
If distributability attribute is required and system capacity is low then select heuristic 36
If interoperability attribute is required and system capacity is low then select heuristic 13
If agility attribute is required and system capacity is low then select heuristic 14
If scalability attribute is required and system capacity is low then select heuristic 40
If dynamic learning attribute is required and system capacity is low then select heuristic 8

Options for Resilience:
Identification of the system components, their number and function and how efficiently each component does its work will give a value for system capacity. Once the level of system capacity is known, the model chooses the heuristic for the system. Terror attacks cannot be predicted. Once the resilient attributes are applied to the system resilience can be built into the system after a terrorist attack. Humans by virtue of their cognitive ability, can analyze and respond to unpredictable situations.
Table 5.4: Mumbai System Heuristic Selection after Checking Communication Channels

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Heuristic</th>
</tr>
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<tbody>
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<td>If flexibility and adaptability is required and communication channel is absent</td>
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<tr>
<td>If self-organizing is required and communication channel is absent</td>
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</tr>
<tr>
<td>If redundancy is required and communication channel is absent</td>
<td>34</td>
</tr>
<tr>
<td>If diversity is required and communication channel is absent</td>
<td>24</td>
</tr>
<tr>
<td>If distributability is required and communication channel is absent</td>
<td>36</td>
</tr>
<tr>
<td>If interoperability is required and communication channel is absent</td>
<td>13</td>
</tr>
<tr>
<td>If agility required and communication channel is absent</td>
<td>4</td>
</tr>
<tr>
<td>If dynamic learning is required and communication channel is absent</td>
<td>4</td>
</tr>
<tr>
<td>If scalability is required and communication channel is absent</td>
<td>42</td>
</tr>
</tbody>
</table>

**Options for Resilience:**
The system components should be able to communicate with each other effectively and the system assessment level for communication channel is given either present or absent. In the Mumbai system the value gotten after the evaluation is absent. The heuristic selected after the system evaluation will help in providing the options for achieving the required communication capability.
Table 5.5: Mumbai System Heuristic Selection after Identifying Stakeholders Role

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Heuristic(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>If flexibility and adaptability is required and stakeholders role and task is vague</td>
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</tr>
<tr>
<td>If self-organizing is required and stakeholders role and task is vague</td>
<td>8, 30</td>
</tr>
<tr>
<td>If redundancy is required and stakeholders role and task is vague</td>
<td>34</td>
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<tr>
<td>If diversity attribute is required and stakeholders role and task is vague</td>
<td>27</td>
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<tr>
<td>If distributability is required and stakeholders role and task is vague</td>
<td>33, 19</td>
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<tr>
<td>If interoperability is required and stakeholders role and task is vague</td>
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<tr>
<td>If agility attribute is required and stakeholders role and task is vague</td>
<td>16, 17</td>
</tr>
<tr>
<td>If dynamic learning is required and stakeholders role and task is vague</td>
<td>9</td>
</tr>
<tr>
<td>If scalability attribute is required and stakeholders role and task is vague</td>
<td>26</td>
</tr>
</tbody>
</table>

**Options for Resilience:**

After analyzing the system for stakeholders role and task allocation, the stakeholders are identified their roles in decision making and their responsibility toward the system are found out. In the Mumbai system, stakeholders responsibility is given a level vague. It is important to assess the stakeholders role and task allocation for the success of the system function. Stakeholders can be individuals, communities, social groups or organizations.
The heuristics that are generated from the model will provide resilience by using the biologically inspired attributes.

The ability to rebound from any attack without falling into chaos is important and this can be achieved if the system is designed in advance to anticipate, and recover from the impacts of the attack. By applying the model to the Mumbai system, we can generate the heuristics that are required to make it resilient (Figure 5.2). The goal is to adapt to the disruption in a limited time with the available resources.

Figure 5.2: Application of the Model to Mumbai
India was not adequately prepared for this type of terror attack. The system was not resilient since it took India two days to get in control of the situation (Figure 5.3). The Mumbai system did not have enough security in the buildings that were attacked. Advanced intelligence warnings were ignored by the people in charge. *The backup heuristic*-This heuristic lets modular components where multiple components with equivalent functions are introduced into the system for backup. This heuristic would have allowed for more security to be added when the intelligence was received earlier regarding the impending attack.

Figure 5.3: Mumbai System OV-1 Architecture at the time of Attack
The redundancy heuristics would have provided resilience when some components failed. The 200 commandos would have reached the site on time had the distributability heuristic been applied from the model. Valuable time would not have been lost and more lives would have been saved. The communication channels that link the systems components would have been possible with the qualitative model application. There would have been robust communication between the system components based on the integrated approach through the key attribute of interoperability. The resilience heuristics were generated from the qualitative model to satisfy the resilient attributes. The Mumbai system resilience architecture is given in Figure 5.4. The biologically inspired attributes result in selection of resilience heuristics that in turn helps to create the resilience architecture for the system.

Figure 5.4: Mumbai System OV-1 Resilient Architecture
5.2 HURRICANE KATRINA

A hurricane is a type of ecological disturbance and can cause massive disturbance through intense winds, flood, and rainfall. The city of New Orleans, situated on the Mississippi River, has been a commercial seaport since the city was developed around the river. Major portion of the city being below sea level, the city has a system of levees and canals to protect it from floods. When Hurricane Katrina moved inland from the Gulf of Mexico in August 2005 and passed over the city, the resulting storm raised the water level of the surrounding open waters. A number of levees failed, resulting in the flooding. Nearly 80% of the city was submerged and some areas remained under water for weeks following the storm. Hurricane Katrina damages were immense, with much of the famous city destroyed, leaving around 1500 people dead. Billions of dollars worth of infrastructure was lost and lots of people lost their homes. The number of levees that broke under the water pressure was recorded as fifty and most of the levee system need to be rebuilt. The flooding that happened after the hurricane Katrina saw the city falling apart. Once the communication failed, the governance, medical facility, law enforcement, and utilities all failed. The key agent that contributed to the failure of the system was human.

The city was aware of the imminent hurricane threat, but still was unprepared. Homeland Security was formed after September 11, 2001 to make the country safe as a powerful force to every threat hurled at this country by man or nature. It was supposed to be a good bureaucracy, designed to coordinate all federal disaster efforts into one single focused solution. City and state officials were unprepared for the disaster and did not evacuate the city of New Orleans in advance of the impending storm. After the storm, real time information flowed through government agencies and yet this information was never used or read due to lack of communication among the people who were in-charge of disaster. Homeland Security, instead of streamlining Washington’s ability to perform, created new layers of bureaucracy, and stovepipes of information. The events that led to the disruption to the New Orleans disaster recovery system following hurricane Katrina should have been foreseen and plans put into place in a timely manner in order to mitigate the effects.
5.2.1 **System.** Hurricanes cause a significant loss of life and property damage. Several failures were involved in the response to hurricane Katrina in 2005 and the subsequent flooding of New Orleans, and the surrounding Gulf Coast. The flooding of the city of New Orleans was a major catastrophe and the city of 450,000 people suffered when the governance, law enforcement, utilities, communications, and medical care all failed. Even though Katrina had failures at all levels, the most serious was the failure of federal government in response to early and continuing signals of disaster. The breakdown of law enforcement in the city was mainly because local police had the same problem the public were having, since the storms flooded their homes too. Instead of patrolling the streets and doing their work, they were getting their families to shelter.

An emergency evacuation plan should specify the action to be taken when faced with a catastrophe. The plan should address the safe and practical method of evacuating people, especially those with special needs. The evacuation plan should take into consideration the capacity of the roads that will be used for evacuation, and the number of people who have access to a vehicle. Emergency management teams in New Orleans were not prepared for the disaster and the flooding that resulted after the levee system gave away. The lack of co-operation between local, state, and federal agencies did not help the disaster recovery system. The officials involved delayed ordering mandatory evacuation of New Orleans until 19 hours before the hurricane hit. The federal government should have designated the impact of hurricane Katrina on the Gulf Coast an Incident of National Significance (INS) at least two days before the storm. Understanding the impact of a category 5 storm would have on the region, untimely deaths could have been prevented. Given an INS designation would have made easier the release of federal resources to the state in a timely manner. After the storm, when the levee system gave away it was impossible to recover the capability of the disaster recovery system. The New Orleans levee system was designed to handle a storm upto category 3 and hurricane Katrina was category 4. This was a problem that the Army Corp of Engineers was aware of for many years and if the need arise they had a plan for draining the city, if the levee design problem became a reality. Hurricane Katrina, a disruption to the natural
environment, resulted in the levee failing. Once the levee failed, there were other entities that failed that were the transportation system, and the network functionality.

5.2.2 Resilience Attributes. The attributes that was lacking in the system:

♦ *Adaptability:* The key attribute that is necessary for a system to be resilient was absent in the system for New Orleans. The emergency responders did not have any idea of the National Response Plan (NRP). They were overwhelmed by the events that kept unfolding that it was impossible to focus on any one task. The emergency responders did not have adequate resources necessary to sustain an extended requirement of assistance. The first responders as they reacted to the crisis as it unfolded realized that the bureaucracy was stiff and inflexible at all levels that contributed to the delay in recovery action. The system should adjust to the disturbance by adapting to the new or unexpected situations without human intervention. The system can adjust to the changing situation or even cope with entirely new situations.

♦ *Diversity:* School buses, trains, charter buses, and public transit could have been used as alternate for transporting people. The system had all sorts of problems related to collaboration between government agencies. The care and maintenance of the New Orleans levee system were under different agencies. With so many local authorities in-charge of maintaining the levee system, the repair responsibility was confusing and the leaks that were reported on the levee system prior to Katrina ever hitting the city was not repaired.

♦ *Flexibility:* The city of New Orleans clearly was lacking in flexibility since the system was unable to sustain itself by allowing flexibility in organizational processes and decisions.

♦ *Interoperability:* This is an essential attribute for collaboration among the different government agencies that play vital roles in disaster aid. The system was plagued with this problem from the beginning and it escalated to communication break down at all levels of government. Failure of the levee was the result from the lack of
interoperability between government agencies. Absence of this attribute resulted in the lack of communication between local, state, and federal government agencies that eventually led to the inability to pass information between one another. There was no communication between government agencies at the time of crisis and this led to the system failing catastrophically.

♦ Redundancy: Transportation was lacking this critical attribute. Redundancy would have provided alternate ways to reach safe destinations and this would have helped in the evacuation of the city without much causality.

♦ Distributability: This attribute avoids bottlenecks by coordinating the activities required so that the system components co-operate to perform the tasks. There was disagreement over authority and the lack of communication among top level decision makers subsequently resulted in the failure to define who is in charge. Available resources did not get utilized properly because of the absence of distributability attribute.

5.2.3 Application of the Model for Resilient Heuristics. System assessment is done by checking the system modularity, system interface complexity, system capacity, communication channels, and the identification of stakeholders role and responsibility. Figure 5.5 shows the qualitative model for engineering resilience for the Katrina system. Table 6-7 provides the resultant heuristic selection that follows the system assessment. The heuristics that get selected provides the system with options for resilience.
RULE-BASED HEURISTIC SELECTOR (Table 1)

If resilience attribute and modularity is low then select heuristic ……………

If resilience attribute and interface complexity is high then select heuristic ……………

If resilience attribute and system capacity is low then select heuristic ……………

If resilience attribute and communication channel is absent then select heuristic ……………

If resilience attribute and stakeholders role and task is vague then select heuristic ……………

Figure 5.5: Qualitative Resilience Model for Katrina System
Table 5.6: Katrina System Heuristic Selection after Checking Modularity

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Select Heuristic(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility and adaptability</td>
<td>8, 32</td>
</tr>
<tr>
<td>Self-organizing</td>
<td>41</td>
</tr>
<tr>
<td>Redundancy</td>
<td>6</td>
</tr>
<tr>
<td>Diversity</td>
<td>35</td>
</tr>
<tr>
<td>Distributability</td>
<td>24</td>
</tr>
<tr>
<td>Interoperability</td>
<td>39</td>
</tr>
<tr>
<td>Agility</td>
<td>18</td>
</tr>
<tr>
<td>Dynamic learning</td>
<td>9</td>
</tr>
<tr>
<td>Scalability</td>
<td>31</td>
</tr>
</tbody>
</table>

Options for Resilience:

After identifying the heuristics it can be applied to the system to help in the survival and recovery. The system components need to work together and needed components can be added enabling the system’s ability to withstand the disruption.
Table 5.7: Katrina System Heuristic Selection after Checking Interface Complexity

<table>
<thead>
<tr>
<th>Option</th>
<th>Heuristic Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>If flexibility and adaptability is required</td>
<td>4, 5, 38</td>
</tr>
<tr>
<td>and interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If redundancy attribute is required and</td>
<td>34</td>
</tr>
<tr>
<td>interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If diversity attribute is required and</td>
<td>35</td>
</tr>
<tr>
<td>interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If distributability attribute is required</td>
<td>37</td>
</tr>
<tr>
<td>and interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If self-organizing is required and</td>
<td>38</td>
</tr>
<tr>
<td>interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If interoperability attribute is required</td>
<td>25</td>
</tr>
<tr>
<td>and interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If agility attribute is required and</td>
<td>3</td>
</tr>
<tr>
<td>interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If dynamic learning attribute is required</td>
<td>2</td>
</tr>
<tr>
<td>and interface complexity is high then select</td>
<td></td>
</tr>
<tr>
<td>If scalability attribute is required and</td>
<td>4</td>
</tr>
<tr>
<td>interface complexity is high then select</td>
<td></td>
</tr>
</tbody>
</table>

**Options for Resilience:**

A system has a complex interface if it has too many components. Assessment value for system interface complexity was given a level of high after system assessment due to its interface to humans and to other systems. The heuristics help in managing with the change in the system due to disruption by reducing the system interface complexity and allowing coordination between the system components.
Table 5.8: Katrina System Heuristic Selection after Checking System Capacity

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Heuristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility and adaptability is required</td>
<td>5</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Self-organizing is required</td>
<td>17</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Redundancy attribute is required</td>
<td>6</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Diversity attribute is required</td>
<td>35</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Distributability attribute is required</td>
<td>36</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Interoperability attribute is required</td>
<td>13</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Agility attribute is required</td>
<td>14</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Scalability attribute is required</td>
<td>40</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
<tr>
<td>Dynamic learning attribute is required</td>
<td>8</td>
</tr>
<tr>
<td>System capacity is low</td>
<td></td>
</tr>
</tbody>
</table>

Options for Resilience:
Identification of the system components, their number and function and how efficiently each component does its work will give a value for system capacity. Once the level of system capacity is known, the model chooses the heuristic for the system. The Katrina disaster resulted from a hurricane which is a natural phenomenon. Hurricanes can be predicted and it is possible that resilient attributes can be architected to the system using the heuristics generated by the model.
If flexibility and adaptability is required and communication channel is absent then select heuristic 3

If self-organizing is required and communication channel is absent then select heuristic 30

If redundancy is required and communication channel is absent then select heuristic 34

If diversity is required and communication channel is absent then select heuristic 24

If distributability is required and communication channel is absent then select heuristic 36

If interoperability is required and communication channel is absent then select heuristic 13

If agility required and communication channel is absent then select heuristic 4

If dynamic learning is required and communication channel is absent then select heuristic 4

If scalability is required and communication channel is absent then select heuristic 42

**Options for Resilience:**
The system components should be able to communicate and co-operate with each other effectively. The system assessment level for communication channel for Katrina after system evaluation is given absent. All the components were disconnected in the Katrina system. The heuristic selected after the system evaluation will help in providing the options for achieving the required communication capability.
Table 5.10: Rule-Based heuristic Selection after Identifying Stakeholders Role

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Heuristic(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility and adaptability</td>
<td>3</td>
</tr>
<tr>
<td>Self-organizing</td>
<td>8, 30</td>
</tr>
<tr>
<td>Redundancy</td>
<td>34</td>
</tr>
<tr>
<td>Diversity attribute</td>
<td>27</td>
</tr>
<tr>
<td>Distributability</td>
<td>33, 19</td>
</tr>
<tr>
<td>Interoperability</td>
<td>39</td>
</tr>
<tr>
<td>Agility attribute</td>
<td>16, 17</td>
</tr>
<tr>
<td>Dynamic learning</td>
<td>9</td>
</tr>
<tr>
<td>Scalability attribute</td>
<td>26</td>
</tr>
</tbody>
</table>

**Options for Resilience:**

Evaluation of the system for stakeholders role and task allocation will identify their roles in decision making and their responsibility toward the system. Stakeholders can be individuals, communities, social groups or organizations. The system assessment value after identifying the stakeholders role and task allocation is obtained as vague. The
heuristics that are generated from the model will provide resilience by using the biologically inspired attributes.

Figure 5.6 shows the application of the model to the Katrina system. Katrina began as a hurricane and it ended up as a disaster due to planning and management failures. Hurricanes Katrina OV-1 architecture is shown in figure 5.7. The system was not resilient at the time. There was no effective plan to evacuate transit dependent residents. Neither public buses nor trains were deployed for evacuation of the city. Even federal emergency officials failed to deploy buses for evacuation as planned. After the hurricane hit the city, material and human resources were available and ready for deployment, but because of the lack of co-operation and understanding between the different relief agencies water, food, and skilled rescuers were turned back. Poor coordination among public officials led to a slow and confused official response to the emergency situation, leaving people affected by the hurricane without food, water, medical supplies, and public services. Figure 5.8 shows the resilient OV-1 architecture for the Katrina system.

Lack of communication was main reason that the system failed. There was absolutely no communication and coordination between the government and the various relief agencies. The heuristics generated that helps the system to communicate and collaborate are:

*The human in control heuristic*—The human at the sharp end of the system given the power to take actions when needed without making questionable assumptions

*The focused and ready heuristic*—Humans at the end of interface should be provided sufficient training that enables a thorough understanding of the system, its procedures, shortcomings, and alternative means of recovery and instill a confidence that they have the power to improvise if necessary.

*The feedback integration heuristic*—Understand the processes, interactions and feedback mechanisms within the system components. Any decision regarding system is based on the integrated approach between the subsystems

*The collaboration heuristic*—where the diverse system components are able to work together
Figure 5.6: Application of the Model to Katrina System
Figure 5.7: Katrina System OV-1 Architecture
It can be seen that by applying the model to a system like hurricane Katrina, it is possible to generate the heuristic that will allow the system to recover following a disruption. The attribute of flexibility, diversity, and redundancy result in a multi-modal transportation system following the disturbance which would have provided a variety of mobility options. After a disturbance, the model helps the system to use its own resources by means of the heuristics to heal and recover the functionality that is damaged or lost. Incorporating resilience into the architecture by using resilience heuristics to system maximizes the system efficiency helping the system to return to the desired state.

Figure 5.8: Katrina System OV-1 Resilient Architecture
relatively easily. The resilience in hurricane Katrina system can be architectured by using attributes that the system should have to be resilient. The development of the biologically inspired qualitative model for resilience would have provided some resilience to the hurricane Katrina system, even though the levees there were not built appropriately with adequate strength prior to hurricane Katrina. Thus, the system is allowed to function even if a link is broken, a particular decision maker is not available, or even if a particular resource is no longer available.
6. CONCLUSIONS AND FUTURE WORK

A resilient system has the ability to endure and successfully recover from disturbances by identifying problems and mobilizing the available resources to cope with the disturbance. Resiliency lets a system to recover from disruptions, variations, and a degradation of expected working conditions. Resilience characteristics from both engineering and biological systems helped in formulating heuristics that enables them to become resilient under unexpected disturbances. The developed qualitative model selects biologically inspired resilience heuristics based on 10 system attributes namely; Adaptability, Diversity, Redundancy, Distributability, Self-organizing, Agility, Flexibility, Interoperability, Dynamic learning, and Scalability to achieve resilience in architecting complex engineering systems. The use of the qualitative model is demonstrated for recent system disturbances experienced globally such as; Mumbai terror attack and Katrina hurricane. By applying the model to the Mumbai system, it was found that we can generate the heuristics that are required to make it resilient. Resilience heuristics were generated from the model to satisfy the attributes within the system. It can be seen that by applying the model to a system like hurricane Katrina, it is possible to generate the heuristic that will allow the system to recover following a disruption. After a disturbance, the model helps the system to use its own resources by means of the heuristics to heal and recover the functionality that is damaged or lost.

The rules seen in nature and the resilience rules in an engineering system are integrated to incorporate the desired characteristics of strength, robustness and flexibility for system resilience. Flexible and adaptable systems that deal with crisis through renewal will tend to survive. This is, in other words, a classic collective action problem. The central determinant of a system’s resilience is the ability to act collectively, coherently, and with the right balance between short and long-term interests. This trait is performed effectively and successfully by insects and other animals by following simple rules. The one requirement should be the ability to choose an action that will further the system’s functions, like the ability to respond to the unknown, and the ability to act at the appropriate time scale. The shape of the structure of an organization is determined by the components in it and their interactions through protocols that summarize the policies and
governance rules. Once an ordered rule and collective action is created, it becomes easier to reduce the chaos and restore the system optimal functionality. In an event of catastrophe, the model that is developed in this study will generate heuristics that is domain specific. These heuristics will lay the foundation for emerging resilient structure that will help in the timely deployment of dynamic, and short-living organizational structures necessary for emergency response operations. Thus, resilience gets built into the architectural requirements.

Biological systems are highly resilient and they follow certain rules to attain this. These rules were grouped together based on attributes. These attributes are distributability, redundancy, adaptability, flexibility, dynamic learning, interoperability, self-organizing, scalability, agility, and diversity. Similar attributes are present in engineering systems too. The resilience seen in immune system, ecosystem, social insects like ants, bees, termites, and engineering systems provided a background for building the qualitative model generated resilience rules based on the attributes identified for resilience. When a system is disturbed, a resilient system will generate rules to prevent severe consequences, and also remember the particular disturbance and be alert for similar problems in the future. The biologically inspired resilience model is applied to systems to generate the heuristics and the source of the heuristics is the system attributes. The model developed is simple requiring no specialized knowledge and uses a set of attributes that the system should have. The result is a resilient system capable of anticipating, perceiving, and responding to disturbances. It also provides basic foundation for building computational models for designing resilient system architectures.

The qualitative model developed for resilience is inspired from biological systems. In insect colonies, rules determine the division of labor and how individual insects act towards each other and respond to different environmental possibilities. The messages passed in the insect world are chemical and happen through moment to moment communication via pheromones. The resilience rules in insects based on algorithms create a flexible behavior pattern that provides maximum efficiency for the insect world. Similarly, the resiliency exhibited by the immune system is achieved through rules by
generating the code for rules and the conditions in which to apply the rule through agent interactions. The developed model generates the resilience rules for any system that outline ideal system performance based on the attributes. This domain independent model will provide sufficient knowledge about system capability to optimally adapt to changes in their environment.

Disturbances and disruptions can challenge the normal system function, and when this happens having resilience architecture will keep the system under control in the face of disruptions. Also, the presence of a resilient architecture in turn will improve the ability of the system to anticipate and respond when challenged by difficult situations. System resilience in the architecture enables the system to identify any kind of variations the system experiences and constantly test the system’s ability to handle the different kinds of variations. This resilience architecture is based on a qualitative model and is simple and it can be applied to any system by using attribute based heuristics that are domain dependent. The basis of this qualitative model is qualitative reasoning techniques that will allow for valid predictions in situations where mathematical models cannot be used. It is possible to associate this qualitative model with mathematical models, thus providing a conceptual framework for building equations. The resilience model addresses the problems presented by disasters (man-made and natural) as shown by the Mumbai and Katrina systems. Mumbai and Katrina are examples of systems that failed at the time of a catastrophe and the associated cause of the failure suggest similarity. The biologically inspired attributes that were considered resilient attributes were missing in both the systems. This model is promising and can result in the building of computational models for resilient architectures for future work. Once the system function gets disrupted instead of causing a catastrophic failure, the resilient heuristics based on biologically inspired resilient attributes will allow the system to recover and continue to function.
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(Accessed on Nov. 4, 2009)


http://www.flickr.com/photos/brewbooks/3491333666/

VITA

Ashik Chandra was born on September 26, 1962 in Tellicherry, India. She earned her B.S. degree in Life Science in 1983 and her M.S. degree in Life Science in 1985 from University of Calicut, India. She obtained her M.S. degree in Chemistry from Missouri S&T (formerly University of Missouri-Rolla) in 1993. She later enrolled for her M.S. degree in Systems Engineering as a part-time student since Fall 2007. She will be continuing her work at U.S. Geological Survey after graduation.