Towards a Scientific Definition of Cyber Resilience

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Abstract: Cyber resilience must be improved. Improving cyber resilience requires the quantitatively measuring it. However, before cyber resilience can be measured, it must first be scientifically defined. An effort to discover a consensus among researchers as to the scientific definition of resilience, in general, and cyber resilience, specifically, revealed that no such consensus exists. Experts from several disciplines agree that the word resilience is becoming a meaningless buzz word. This paper reviews the literature to establish the current state of the scientific definition of resilience. It briefly surveys the literature to discover what makes a valid scientific definition. It reviews and analyses the historic scientific use of resilience to discover the path from its original meaning to its current diverse and conflicting meanings. These concepts are decomposed using a genus-differentia analysis untangling the various connotations and separating the related but different concepts. Based upon this analysis, a proposal is made that resilience is part of a family of properties under the umbrella of tenacity. This family includes resistance, resilience, persistence, and perseverance. Finally, an initial operational definition of cyber resilience based upon key performance parameters under stress is proposed.

Keywords: Cyber Resilience, Scientific Definition, Stress, Strain, Resistance, Persistence

1. Introduction

Many are engaged in various efforts to improve cyber resilience. To improve cyber resilience, it must be measured (Kott and Linkov, 2021). “A valid definition of a concept is a prerequisite to valid measurement (Locke, 2003, p. 416).” Thus the formulation of a valid definition of cyber resilience is necessary before it may be quantitatively measured. Several authors have observed that progress in many areas of research is being hindered by a lack of definitions (Locke, 2003; Wacker 2004; Podsakoff, MacKenzie, and Podsakoff, 2016). Locke (2003) observed that some researchers fail to define the concept that they are studying, and others search the literature for a consensus on a definition without ever evaluating that definition. Hibberd observed that some concepts suffer from having too many conflicting definitions and cites three papers to substantiate his claim (Mulligan and Scherer, 2012; Maul, 2017; Rossiter, 2017, cited in Hibberd, 2019, p. 30). Brtis (2021, p. 1) observed, “One expert claims that well over 100 unique definitions of resilience have appeared.” Aburn, Gott, and Hoare (2016, p. 1) found, “there is no universal definition of resilience.” The concept of resilience is suffering from too many conflicting definitions.

1.1 Challenge

Locke (2003) asserts that good definitions are the epistemological foundation of scientific progress and sloppy definitions are a major factor retarding intellectual progress. Hibberd (2019, p. 29) observes that without rigorous definitions, “no discipline advances from vagueness and ambiguities of a less than technical language and the follies that result.” Björck et al. (2015, p. 1) observed, “In order for cyber resilience to gain momentum also as an academic research subject, it is important to define the term.” Hoffman and Hancock (2017, p. 564) observed that there has been considerable interest in resilience and that, “concepts that come to the forefront of concern in this manner are often diluted, simply to become the next ‘flavor of the month’ through both overselling and uncritical use.” Further, “In such evolutions or revolutions, the definition of terms often proves to be a problematic issue that frequently threatens to derail important conceptual progress” (Hoffman and Hancock, 2017, p. 565). Hosseini, Barker, and Ramierez-Marquez (2016, p. 49) conducted a review of definitions and measures of resilience and concluded, “The review of resilience definitions indicates that there is no unique insight about how to define the resilience.” Gigerenzer (2017) points out that building upon the work of others requires good scientific definitions. He further stated, “The practice of using the same label for logically and operationally different phenomena impedes progress” (Gigerenzer, 2017, p. 137).

1.2 Frustration

A literature review search for a consensus of the definition of resilience, in general, and cyber resilience, specifically uncovered the only consensus on the definition of resilience is that there is no consensus on the definition of resilience. Klien, Nicholls, and Thomalla (2003) conducted a literature review of the definition of resilience. They observed that in the time from 1973 until 2003, resilience has transformed from a “straightforward concept used only in mechanics” to a “complex multinterpretable concept with contested definitions and relevance” (Klien et al., 2003, p. 40). Dillon (1947, p. 207) observed, “There seems to be almost as many different definitions of `resilience' as there are authors." Norris et al. (2008), conducted a literature review of the definition of resilience. They observed that the definitions in use in the social and psychological sciences had diverged so far from the original definition that they wondered if perhaps they should have created their own term (Norris et al., 2008). Reid and Botterill (2013, p. 31) conducted an overview of the multiple meanings of resilience in the literature. The key conclusion from their research is, "the term is highly ambiguous, it is used for different purposes in different contexts and in some cases the understandings of the term are diametrically opposed (Reid and Botterill, 2013, p. 31)." Arghandeh et al. (2016, p. 1), searched the literature for a definition of cyber-physical resilience in power systems and concluded, "There is no clear and universally accepted definition of cyber-physical resilience for power systems." Hosseini, Barker, and Ramierez-Marquez (2016) conducted a review of definitions of resilience in systems engineering. They discovered "Many overlap with a number of already existing concepts such as robustness, fault-tolerance, flexibility, survivability, and agility, among others (Hosseini et al., 2016, p. 48)." Xue, Wang, and Yang (2018) explored the science of resilience with a critical review and bibliometric analysis. They summarized the definition of resilience in social and ecological, engineering and disaster, and economic and organizational behavior domains and concluded, "The definition of resilience is still an important research area (Xue et al., 2018, p. 503)." Cottam et al. (2019) completed a structured literature review of the definition of resilience in engineered systems. After focusing only on resilience in engineering systems and excluding definitions from psychology, ecology, and socio-ecological system, they considered 54 papers. They "found no standard definition of resilience and the definitions found included a variety of means in their definitions of resilience (Cottam et al., 2019, p. 26)." Many researchers have thoroughly reviewed the definition of resilience in the literature and concluded that over the years the definition has expanded to the point of meaningless jargon (Xue et al., 2018).

1.3 Contribution

Having established the frustration in the literature about the definition of resilience in general and cyber resilience specifically, the contribution of this paper is to briefly review the literature for what constitutes a valid scientific definition. The history of the definition of resilience is then examined. This knowledge is then applied in a genus differentia analysis to propose a valid scientific definition of cyber resilience that will lend itself to a quantitative measurement. Although many have systematically reviewed the literature for the definition of resilience, I know of no other effort to apply the rules for definitions or conduct a genus differentia analysis of resilience.

1.4 Organization

Section 2 will review the literature searching for guidelines for scientific definitions. Section 3 will discuss the approach. Section 4 will trace the meaning of resilience from the Latin roots through the various fields of scientific endeavor, attempt to untangle the various conflicting definitions of resilience into the separate but related components using a genus differentia analysis, and consider an operational definition of cyber resilience. Section 5 will provide a conclusion and discussion of future work.

2. Background

Since the ancient Greeks, scientists and philosophers have struggled to find valid definitions of critical concepts. They principally used the genius-differentia method of definition assigning a concept to a family and describing what makes it different from other members of that family (Bayer, 1998). Locke (2003, p. 416) observes, "A valid definition of a word (i.e., concept) accomplishes two things: (a) it ties the concept to reality, and (b) it distinguishes the concept from other concepts." Robinson (1950) talked about real definitions as analysis, synthesis, and improvement of concepts. When he used the word analysis, he meant breaking a thing down into its component parts (Robinson, 1950). When he used the word synthesis, he was talking about discovering that the thing in question is part of a larger whole (Robinson, 1950). Real definitions are used to refine or improve concepts by substituting a similar concept which is superior (Robinson, 1950). Wacker (2004) provides eight rules for formal conceptual definitions. He encourages clarity and simplicity. Definitions should not use vague or ambiguous terms and they should also not expand the concept or make it less exclusive. Further new hypotheses should not be introduced in the definition (i.e., the definition should not include instances where only 'good' events happen (Wacker, 2004). Hibberd (2019) lists seven things that a scientific definition is not. She emphasizes that a scientific definition is concept or real definitions by stating that it is not one of several nominal definitions. Like Locke she asserts that a scientific definition must tie a concept to reality. She also concludes that scientific definitions are not operational definitions (Hibberd, 2019). An operational definition defines a concept by describing the technique used to measure it (Bridgman, 1927). Podsakoff MacKenzie, and Podsakoff (2016) provide ten recommendations for better concept definitions. They stress clarity and completeness like Wacker. They also warn against the use of various types of nominal definitions like Hibberd (Podsakoff et al., 2016). Cottam et al. (2019) observes that definitions should not contain the means of obtaining the object. They relate this to the "what not how" principle (Date, 2000). This illustrates the principle expressed by General Patton, "Never tell people how to do things. Tell them what to do, and they will surprise you with their ingenuity (Patton and Harkins, 1947)."

3. Approach

Many have conducted a literature review of resilience looking for a consensus and finding none. Rather than conducting yet another literature review, this article traces the history of the meaning of resilience in an effort track its evolution and understand the expansion that has led to the current state of meaninglessness. The standard account of the scientific definition has used the genus-differentia model that has been employed since the ancient Greeks. Although there is no longer a requirement that scientific definitions be stated in this form, this form of definition satisfies Locke's (2003) requirements. This exercise allows the examination of the words in common use surrounding the concept of resilience and establishes its place in that context. Then consideration is given to the operational definition of cyber resilience. Although a scientific definition is more than an operational definition, it is appropriate to give some thought as to how to measure this concept.

4. Results

4.1 History

4.1.1 Latin Root

The word resilience comes to English from the French *resiler* and the Latin *resilire*. It is composed of the *re* meaning back and *salire* meaning jump (Brown, 1993). The word carries the meaning of jumping back, recoiling, springing back, or resuming an original position (Brown, 1993; Hosseini, Barker, and Ramierez-Marquez, 2016).

4.1.2 1858 Civil Engineering and Mechanics

In 1858 Rankine used the word to describe the effects of stress and strain on solids (Rankine, 1858). In his discussion, he defined *stress* as the force applied to an object, and *strain* as the alteration observed in the object (Rankine, 1858). *Elasticity* is when the object recovers its original shape when the stress is withdrawn. *Plasticity* is when the object does not retain its original shape when the stress is withdrawn (Rankine, 1858). *Fracture* is the point at which the object is divided into parts. *Toughness* is the greatest strain which the body will bear without fracture (Rankine, 1858). *Resilience* is the quantity of mechanical work required to produce the proof strain (Rankine, 1858). Later this concept was expressed in a stress–strain graph, see figure 1. In this context, the properties of stiffness, resilience, and toughness have neither a negative nor a positive connotation.

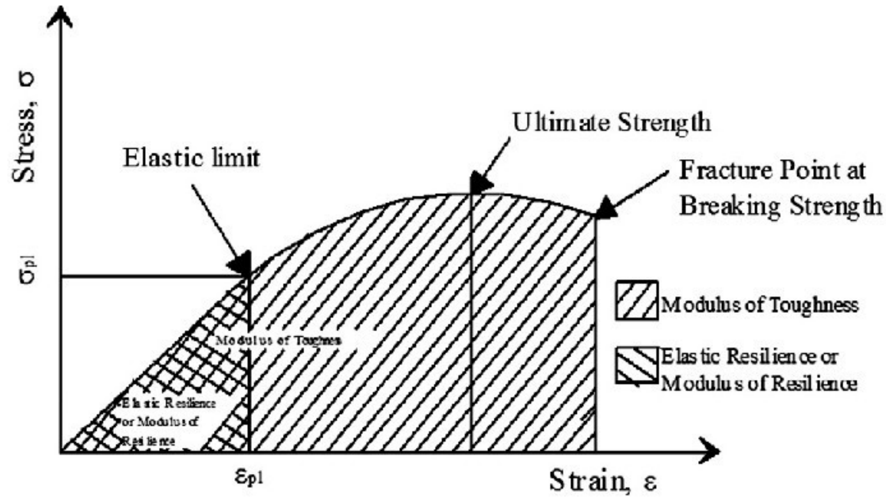

Figure 1. Stress–strain graph (Ahmmad et al., 2014).

4.1.3 1947 Fibres and Fabrics

In 1947 when Dillon wrote his article, "Resilience of Fibers and Fabrics," the definition of resilience in this context had grown and diversified until, "there seem to be almost as many definitions of `resilience' as there are authors. (Dillon, 1947, p. 207)" The materials that Rankine (1958) studied obeyed Hooke's law; however, some fibers and fabrics do not. Hooke's law states that within the elastic range the stress and strain scale linearly. This made the measure of resilience as a function of work problematic. Even though the basic distinction between stiffness, resilience, and toughness exists, Dillon (1947, p. 212) finishes his work saying, "The obvious conclusion from this study is that resilience is a much abused and poorly defined term and that much remains to be learned about its significance and the factors controlling it, in single fibers, bulked fibers, and fabrics."

Hoffman (1948, p. 141) defines resiliency as, "as the capability of a substance to return to its original state at some later time after the removal of the deforming stress." He adds time to stress and strain as a component of resilience. The materials that Rankine considered immediately returned to their original state once the stress was removed. Wool more gradually returns to its original state. His proposed definition is, "a stress–strain-time property of a material, characterizing the completeness of recovery from deformation and varying in kind with the modulus of elasticity and rate of recovery (Hoffman 1948, p. 148)."

Resilience gains a positive connotation because fabrics with too much stiffness are uncomfortable to wear, and fabrics without resilience stretch becoming baggy in the joints. The word resilience begins to mean fit for a particular purpose (e.g., "An experimental tire made of woolen cords overheated badly; therefore, wool is not resilient (Hoffman, 1948, p. 141).")

4.1.4 1973 Ecology

In 1973 Holling applied the term resilience to ecological systems. He stated, "Resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist (Holling, 1973, p. 17)." Holling faced problems beyond the scope of previous research into resilience. How does one measure the ability of a system to return to a previous state when the state of the system is constantly changing? Ecologies may be said to exist in a stable equilibrium. Resilience measures the amount of stress that the system can absorb before a different stable equilibrium is established. Xue, Wang, and Yang (2018, p. 500) point to Holling's work as the beginning of an explosion in resilience research stating, "The definition of resilience in different categories are all derived from the ecology domain."

The distinction between stiffness and resilience starts to blur. Gruemm (1976) proposed a measurement of resilience based upon stability theory using differential topology where the state space of the system is divided into basins with each basin containing an attractor. A system is considered resilient against a certain stress if the system returns to the same basin (Gruemm, 1976). This treatment distinguishes fracture or extinction, plastic change when the system moves to a different basin, and elastic change when the system returns in the original basin. It does not distinguish no change from elastic change.

4.1.5 1971 Psychology

The study of resilience in psychology begin in orthopsychiatry. While studying individuals with high-risk factors for developing psychosis, it was discovered that some of the subjects thrived despite very high-risk factors. These individuals were originally called invulnerable, but this was later replaced with the term resilient (Garmezy, 1971; Egeland, Carlson, and Sroufe, 1993; Masten, 2001; Glantz and Slobada, 2002).

The line between resisting and rebounding is further blurred, and the connotation of growth through or despite trauma is introduced. The positive connotation of the word resilience grows significantly. Resilience is now seen as a very desirable quality.

4.1.6 1988 Social

Wildavsky (1988) considered the resilience of social systems and observed that stress may be necessary for the development of resilience. Adger (2000) merged the concepts of social and ecological resilience creating the concept of social-ecological systems (Berkes, Colding, and Folke, 2008). Efforts are undertaken to measure and improve the resilience of communities to disasters (Bruneau et al., 2003; Rose, 2007). Olsson et al. (2025) explain why the concept of resilience as positive growth after stress gains traction in this field and why resilience as rebound to a previous state is unappealing.

Natural and man-made disasters also illustrated the need for resilient organizations, and the means of building resilience began to creep into the definition of resilience. For example, the National Research Council (2012, p. 1) defined resilience as, “the ability to prepare and plan for, absorb, recover from and more successfully adapt to adverse events.”

4.1.7 2009 Cyber

These trends continued when resilience was introduced to the cyber domain. The scope of resilience expanded to encompass “the ability to provide and maintain an acceptable level of service in the face of faults and challenges to normal operations (Goldman et al., 2011, p. 236).” The means to achieving cyber resilience creep into the definition, “Cyber resilience (or resiliency) is the ability to anticipate, withstand, recover from, and adapt to adverse conditions, stresses, attacks, or compromises on cyber resources (Graubart and Bodeau, 2016, p. 1; Bodeau et al., 2018, p. iii).”

4.1.8 Summary

Since the early 1970s, the definition of resilience has expanded from elastic deformation to include every aspect of strength (i.e., stiffness, spring, and toughness.) It has grown beyond the original concept of strength to include positive change or growth. Phillips and Chao (2022, p. 7) go so far as to say, “Resilience is not simple survival, bounce-back, or homeostasis.” The implication here is that resilience no longer means what it has always meant. Most of Wacker’s (2004, p. 637) rules for good formal definitions deal with clarity; however, the sixth rule states, “Definitions should not make any term broader. New definitions should not expand the concept to make it broader and less exclusive.”

As the connotation of the word resilience gains in desirability and many are striving to encourage the improvement of resilience, means like adaptability and planning have been added to the definition. However, Cottam et al. (2019) observed that definitions should not contain the means of obtaining the object.

4.2 Genus-differentia

At a high level one can say that resilience is a quality attribute. Miller (1996) defines quality as, “fitness for use” with the understanding that this has two aspects: “product features that meet customer needs and freedom from defects (Miller, 1996, p. 3 citing Juran 2003).” Barbacci et al. (1995, p. 3) define software quality, “Software quality is the degree to which something possesses a desired combination of attributes (e.g., reliability, interoperability).” However, the concept of quality has expanded to cover almost every aspect of a system. Barbacci et al. (1995) decompose quality into performance, dependability, security, and safety.

Since Laprie (2008) defines resilience in terms of dependability, “dependability when facing changes,'' dependability seems to be appropriate aspect of quality to pursue. Dependability is defined as the set of systems properties “that allows us to rely on a system functioning as required (Littlewood and Strigini, 2000).” This definition is further refined, “Dependability is that property of a computer system such that reliance can justifiably be placed on the service it delivers. Dependability has several attributes, including availability, reliability, safety, confidentiality, integrity, maintainability (Barbacci et al., p. 15)''

It is important to differentiate between dependability and security since both dependability and security are concerned with availability, confidentiality, and integrity. When Bishop (2003) defines computer security, he talks about requirements, policies, and mechanisms. Security is about having the mechanisms to implement the policies that fulfil the requirements aligning well with the “fitness for use” aspect of quality. Dependability is about these mechanisms working correctly and continuing to work correctly during adverse conditions aligning well with the “free from defects” aspect of quality.

Woods (2015) describes four concepts of resilience: rebound, robustness, graceful extensibility, and sustained adaptability. Robustness is “the ability of a system to function correctly in the presence of disturbances (Rungger and Tabuada, 2016, p. 2108).” A robust system is one where small disturbances lead to small deviations and the effect of sporadic disturbances disappear over time (Tabuada et al., 2014). A robust system would be more resilient than a fragile system; however, a system could be robust and still ineffective in a hostile environment since the only requirement is that it be able to recover from sporadic disturbances.

The concepts of graceful extensibility and sustained adaptability map directly to the dependability concept of maintainability. These are certainly desirable qualities and could contribute to the resilience of a system if measured over a system’s lifetime; however, they would contribute very little if resilience is measured over a mission. Therefore, they would be better considered as a means of implementing resilience than as part of the definition of resilience itself. This leaves the concept of rebound, which maps directly to the lexical definition of resilience.

Barbacci et al. (1995, p. 16) defines reliability as “a measure of the ability of a system to keep operating over time.” Since reliability applies without any unforeseen or external stress, a more precise word for reliability in the face of stress might be strength or tenacity. Tenacity may be further decomposed into stiffness or resistance, resilience, and toughness or persistence. Resistance speaks to a system’s ability to withstand stress without a perceptible degradation in performance. Resilience speaks to a system’s ability to absorb stress elastically, that is performance will perceptibly degrade but return when the stress is removed or nullified. Toughness or persistence speaks to a system’s ability to absorb stress plastically, that is the system will continue to function at an acceptable level of performance in the face of stress. It also carries the idea of bending but not breaking easily. In addition, there is the special case of perseverance or adaptability. Perseverance is plastic change; however, this change improves the tenacity of the system. An example would be recovering from an illness where the recovery builds immunity providing enhance resistance in the future. All of these are important concepts that many of the definitions of resilience in the literature confuse making it difficult to distinguish between them.

Resilience then is a property of tenacity. Where tenacity describes the ability of a system to withstand stress without failure. Resilience specifically is the elastic response to stress where the system is measurably impacted but returns to the former state when the stress is removed or nullified

4.3 Operational Definition

If we restrict the definition of cyber resilience to the cyber stress that a system can absorb through elastic deformation, the most straightforward measure would be cyber stress. Although there are some discreet measures of cyber stress, there is no continuous measure that would be necessary for a quantitative measure of cyber resilience. Although the stress itself cannot be quantitatively measured, the strain or degradation of key performance parameters (KPPs) can be. The family of cyber strength may be measured by the difference in KPPs without and with cyber stress.

5. Conclusion

The recent explosion in the popularity and varying definitions of resilience have left it a panchreston. If the concept of resilience is to have any scientific significance, its meaning must be better focused. The proposed method of focusing the meaning of resilience is to understand it as part of a family of properties that describe the relationship between stress and strain on a system. Cyber resilience is the ability of a cyber system to recover from stress that causes a reduction of performance. This may be measured by the degradation of KPPs caused by the stress. There is still much work to be done to take this general concept of cyber strength in general and cyber resilience particularly and mathematically model and quantitatively measure it.

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