Basic Concepts and Taxonomy of Dependable and Secure Computing

Algirdas Avižienis, *Fellow*, *IEEE*, Jean-Claude Laprie,
Brian Randell, and Carl Landwehr, *Senior Member*, *IEEE*

Abstract—This paper gives the main definitions relating to dependability, a generic concept including as special case such attributes as reliability, availability, safety, integrity, maintainability, etc. Security brings in concerns for confidentiality, in addition to availability and integrity. Basic definitions are given first. They are then commented upon, and supplemented by additional definitions, which address the threats to dependability and security (faults, errors, failures), their attributes, and the means for their achievement (fault prevention, fault tolerance, fault removal, fault forecasting). The aim is to explicate a set of general concepts, of relevance across a wide range of situations and, therefore, helping communication and cooperation among a number of scientific and technical communities, including ones that are concentrating on particular types of system, of system failures, or of causes of system failures.

Index Terms—Dependability, security, trust, faults, errors, failures, vulnerabilities, attacks, fault tolerance, fault removal, fault forecasting.

1 Introduction

This paper aims to give precise definitions characterizing the various concepts that come into play when addressing the dependability and security of computing and communication systems. Clarifying these concepts is surprisingly difficult when we discuss systems in which there are uncertainties about system boundaries. Furthermore, the very complexity of systems (and their specification) is often a major problem, the determination of possible causes or consequences of failure can be a very subtle process, and there are (fallible) provisions for preventing faults from causing failures.

Dependability is first introduced as a global concept that subsumes the usual attributes of reliability, availability, safety, integrity, maintainability, etc. The consideration of security brings in concerns for confidentiality, in addition to availability and integrity. The basic definitions are then commented upon and supplemented by additional definitions. **Boldface** characters are used when a term is defined, while *italic* characters are an invitation to focus the reader's attention.

This paper can be seen as an attempt to document a minimum consensus on concepts within various specialties in order to facilitate fruitful technical interactions; in addition, we hope that it will be suitable 1) for use by other bodies (including standardization organizations) and 2) for educational purposes. Our concern is with the concepts: words are only of interest because they unequivocally label concepts and enable ideas and viewpoints to be shared. An important issue, for which we believe a consensus has not yet emerged, concerns the measures of dependability and security; this issue will necessitate further elaboration before being documented consistently with the other aspects of the taxonomy that is presented here.

The paper has no pretension of documenting the state-of-the-art. Thus, together with the focus on concepts, we do not address implementation issues such as can be found in standards, for example, in [30] for safety or [32] for security.

The dependability and security communities have followed distinct, but convergent paths: 1) dependability has realized that restriction to nonmalicious faults was addressing only a part of the problem, 2) security has realized that the main focus that was put in the past on confidentiality needed to be augmented with concerns for integrity and for availability (they have been always present in the definitions, but did not receive as much attention as confidentiality). The paper aims to bring together the common strands of dependability and security although, for reasons of space limitation, confidentiality is not given the attention it deserves.

Preceding Work and Goals for the Future. The origin of this effort dates back to 1980, when a joint committee on "Fundamental Concepts and Terminology" was formed by the TC on Fault-Tolerant Computing of the IEEE CS and the IFIP WG 10.4 "Dependable Computing and Fault Tolerance." Seven position papers were presented in 1982 at a special session of FTCS-12 [21], and a synthesis was presented at FTCS-15 in 1985 [40] which is a direct predecessor of this paper, but provides a much less detailed classification, in particular of dependability threats and attributes.

- *A. Avižienis is with Vytautas Magnus University, K. Donelaicio 58 LT-3000 Kaunas, Lithuania and the University of California at Los Angeles, 4731 Boelter Hall, Los Angeles, CA 90024-1596. E-mail: aviz@adm.vdu.lt, aviz@cs.ucla.edu.*
- *J.-C. Laprie is with LAAS-CNRS, 7 Avenue du Colonel Roche, 31077 Toulouse, France. E-mail: laprie@laas.fr.*
- *B. Randell is with the School of Computing Science, University of Newcastle upon Tyne, Claremont Tower, Claremont Rd., UK NE1 7RU. E-mail: Brian.Randell@newcastle.ac.uk.*
- *C. Landwehr is with the Institute for Systems Research, 2151 A.V. Williams Building, University of Maryland, College Park MD 20742. E-mail: clandwehr@nsf.gov.*

Manuscript received 25 June 2004; accepted 25 Aug. 2004.
For information on obtaining reprints of this article, please send e-mail to: tdsc@computer.org, and reference IEEECS Log Number TDSC-0097-0604.

1545-5971/04/$20.00 © 2004 IEEE Published by the IEEE Computer Society

Continued intensive discussions led to the 1992 book *Dependability: Basic Concepts and Terminology* [41], which contained a 34-page English text with an eight-page glossary and its translations into French, German, Italian, and Japanese. The principal innovations were the addition of *security* as an attribute and of the class of *intentional malicious faults* in the taxonomy of faults. Many concepts were refined and elaborated.

The next major step was the recognition of security as a composite of the attributes of *confidentiality*, *integrity*, and *availability* and the addition of the class of *intentional nonmalicious faults, together with an analysis of the problems of inadequate system specifications* [42], though this account provided only a summary classification of dependability threats.

The present paper represents the results of a continuous effort since 1995 to expand, refine, and simplify the taxonomy of dependable and secure computing. It is also our goal to make the taxonomy readily available to practitioners and students of the field; therefore, this paper is self-contained and does not require reading of the above mentioned publications. The major new contributions are:

1. *The relationship between dependability and security* is clarified (Section 2.3).
2. *A quantitative definition of dependability* is introduced (Section 2.3).
3. *The criterion of capability* is introduced in the classification of human-made nonmalicious faults (Sections 3.2.1 and 3.2.3), enabling the consideration of *competence*.
4. *The discussion of malicious faults* is extensively updated (Section 3.2.4).
5. *Service failures* (Section 3.3.1) are distinguished from *dependability failures* (Section 3.3.3): The latter are recognized when service failures over a period of time are too frequent or too severe.
6. *Dependability issues of the development process* are explicitly incorporated into the taxonomy, including partial and complete *development failures* (Section 3.3.2).
7. The concept of *dependability is related to dependence and trust* (Section 4.2), and compared with three recently introduced similar concepts, including survivability, trustworthiness, high-confidence systems (Section 4.4).

After the present extensive iteration, what future opportunities and challenges can we foresee that will prompt the evolution of the taxonomy? Certainly, we recognize the desirability of further:

- expanding the discussion of security, for example to cover techniques for protecting confidentiality, establishing authenticity, etc.,
- analyzing issues of trust and the allied topic of risk management, and
- searching for unified measures of dependability and security.

We expect that some challenges will come unexpectedly (perhaps as so-called "emergent properties," such as those of the HAL computer in Arthur C. Clarke's "2001: A Space Odyssey") as the complexity of man-machine systems that we can build exceeds our ability to comprehend them. Other challenges are easier to predict:

1. New technologies (nanosystems, biochips, chemical and quantum computing, etc.) and new concepts of man-machine systems (ambient computing, nomadic computing, grid computing, etc.) will require continued attention to their specific dependability issues.
2. The problems of complex human-machine interactions (including user interfaces) remain a challenge that is becoming very critical—the means to improve their dependability and security need to be identified and incorporated.
3. The dark side of human nature causes us to anticipate new forms of maliciousness that will lead to more forms of malicious faults and, hence, requirements for new defenses as well.

In view of the above challenges and because of the continuing and unnecessarily confusing introduction of purportedly "new" concepts to describe the same means, attributes, and threats, the most urgent goal for the future is to keep the taxonomy complete to the extent that this is possible, but at the same time as simple and well-structured as our abilities allow.

2 The Basic Concepts

In this section, we present a basic set of definitions that will be used throughout the entire discussion of the taxonomy of dependable and secure computing. The definitions are general enough to cover the entire range of computing and communication systems, from individual logic gates to networks of computers with human operators and users. In what follows, we focus mainly on computing and communications systems, but our definitions are also intended in large part to be of relevance to **computer-based systems**, i.e., systems which also encompass the humans and organizations that provide the immediate environment of the computing and communication systems of interest.

2.1 System Function, Behavior, Structure, and Service

A **system** in our taxonomy is an entity that interacts with other entities, i.e., other systems, including hardware, software, humans, and the physical world with its natural phenomena. These other systems are the **environment** of the given system. The **system boundary** is the common frontier between the system and its environment.

Computing and communication systems are characterized by fundamental properties: *functionality*, *performance*, *dependability and security*, and *cost*. Other important system properties that affect dependability and security include *usability*, *manageability*, and *adaptability*—detailed consideration of these issues is beyond the scope of this paper. The **function** of such a system is what the system is intended to do and is described by the **functional specification** in terms of functionality and performance. The **behavior** of a system is what the system does to implement its function and is described by a sequence of states. The **total state** of a given system is the set of the following states: computation, communication, stored information, interconnection, and physical condition.

The **structure** of a system is what enables it to generate the behavior. From a structural viewpoint, a system is

composed of a set of components bound together in order to interact, where each **component** is another system, etc. The recursion stops when a component is considered to be **atomic**: Any further internal structure cannot be discerned, or is not of interest and can be ignored. Consequently, the total state of a system is the set of the (external) states of its atomic components.

The **service** delivered by a system (in its role as a **provider**) is its behavior as it is perceived by its user(s); a **user** is another system that receives service from the provider. The part of the provider's system boundary where service delivery takes place is the provider's **service interface**. The part of the provider's total state that is perceivable at the service interface is its **external state**; the remaining part is its **internal state**. The delivered service is a sequence of the provider's external states. We note that a system may sequentially or simultaneously be a provider and a user with respect to another system, i.e., deliver service to and receive service from that other system. The interface of the user at which the user receives service is the **use interface**.

We have up to now used the singular for function and service. A system generally implements more than one function, and delivers more than one service. Function and service can be thus seen as composed of function items and of service items. For the sake of simplicity, we shall simply use the plural—functions, services—when it is necessary to distinguish several function or service items.

2.2 The Threats to Dependability and Security: Failures, Errors, Faults

Correct service is delivered when the service implements the system function. A **service failure**, often abbreviated here to **failure**, is an event that occurs when the delivered service deviates from correct service. A service fails either because it does not comply with the functional specification, or because this specification did not adequately describe the system function. A service failure is a **transition** from correct service to incorrect service, i.e., to not implementing the system function. The period of delivery of incorrect service is a **service outage**. The transition from incorrect service to correct service is a **service restoration**. The deviation from correct service may assume different forms that are called **service failure modes** and are ranked according to **failure severities**. A detailed taxonomy of failure modes is presented in Section 3.

Since a service is a sequence of the system's external states, a service failure means that at least one (or more) external state of the system deviates from the correct service state. The deviation is called an *error*. The adjudged or hypothesized cause of an error is called a **fault**. Faults can be internal or external of a system. The prior presence of a **vulnerability**, i.e., an internal fault that enables an external fault to harm the system, is necessary for an external fault to cause an error and possibly subsequent failure(s). In most cases, a fault first causes an error in the service state of a component that is a part of the internal state of the system and the external state is not immediately affected.

For this reason, the definition of an **error** is the part of the total state of the system that may lead to its subsequent service failure. It is important to note that many errors do not reach the system's external state and cause a failure. A fault is **active** when it causes an error, otherwise it is **dormant**.

When the functional specification of a system includes a set of several functions, the failure of one or more of the services implementing the functions may leave the system in a **degraded mode** that still offers a subset of needed services to the user. The specification may identify several such modes, e.g., slow service, limited service, emergency service, etc. Here, we say that the system has suffered a **partial failure** of its functionality or performance. Development failures and dependability failures that are discussed in Section 3.3 also can be partial failures.

2.3 Dependability, Security, and Their Attributes

The original definition of **dependability** is the ability to deliver service that can justifiably be trusted. This definition stresses the need for justification of trust. The alternate definition that provides the criterion for deciding if the service is dependable is the **dependability** of a system is the ability to avoid service failures that are more frequent and more severe than is acceptable.

It is usual to say that the dependability of a system should suffice for the dependence being placed on that system. The **dependence** of system A on system B, thus, represents the extent to which system A's dependability is (or would be) affected by that of System B. The concept of dependence leads to that of **trust**, which can very conveniently be defined as *accepted dependence*.

As developed over the past three decades, dependability is an integrating concept that encompasses the following attributes:

- **availability**: readiness for correct service.
- **reliability**: continuity of correct service.
- **safety**: absence of catastrophic consequences on the user(s) and the environment.
- **integrity**: absence of improper system alterations.
- **maintainability**: ability to undergo modifications and repairs.

When addressing security, an additional attribute has great prominence, **confidentiality**, i.e., the absence of unauthorized disclosure of information. **Security** is a composite of the attributes of confidentiality, integrity, and availability, requiring the concurrent existence of 1) availability for authorized actions only, 2) confidentiality, and 3) integrity with "improper" meaning "unauthorized."

Fig. 1 summarizes the relationship between dependability and security in terms of their principal attributes. The picture should *not* be interpreted as indicating that, for example, security developers have no interest in maintainability, or that there has been no research at all in the dependability field related to confidentiality—rather it indicates where the main balance of interest and activity lies in each case.

The **dependability and security specification** of a system must include the requirements for the attributes in terms of the acceptable frequency and severity of service failures for specified classes of faults and a given use environment. One or more attributes may not be required at all for a given system.

2.4 The Means to Attain Dependability and Security

Over the course of the past 50 years many means have been developed to attain the various attributes of dependability and security. Those means can be grouped into four major categories:

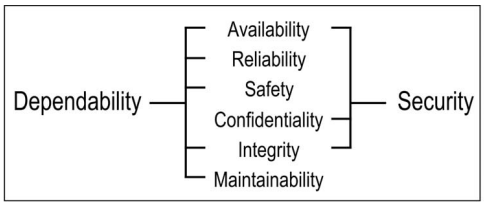


Fig. 1. Dependability and security attributes.

- **Fault prevention** means to prevent the occurrence or introduction of faults.
- **Fault tolerance** means to avoid service failures in the presence of faults.
- **Fault removal** means to reduce the number and severity of faults.
- **Fault forecasting** means to estimate the present number, the future incidence, and the likely consequences of faults.

Fault prevention and fault tolerance aim to provide the ability to deliver a service that can be trusted, while fault removal and fault forecasting aim to reach confidence in that ability by justifying that the functional and the dependability and security specifications are adequate and that the system is likely to meet them.

2.5 Summary: The Dependability and Security Tree

The schema of the complete taxonomy of dependable and secure computing as outlined in this section is shown in Fig. 2.

3 The Threats to Dependability and Security

3.1 System Life Cycle: Phases and Environments

In this section, we present the taxonomy of threats that may affect a system during its entire life. The **life cycle** of a system consists of two phases: *development* and *use*.

The development phase includes all activities from presentation of the user's initial concept to the decision that the system has passed all acceptance tests and is ready to deliver service in its user's environment. During the development phase, the system interacts with the development environment and *development faults* may be introduced into the system by the environment. The **development environment** of a system consists of the following elements:

1. the *physical world* with its natural phenomena,
2. *human developers*, some possibly lacking competence or having malicious objectives,
3. *development tools*: software and hardware used by the developers to assist them in the development process,
4. *production and test facilities*.

The use phase of a system's life begins when the system is accepted for use and starts the delivery of its services to the users. Use consists of alternating periods of correct service delivery (to be called **service delivery**), service outage, and service shutdown. A *service outage* is caused by a service failure. It is the period when incorrect service (including no service at all) is delivered at the service interface. A **service shutdown** is an intentional halt of service by an authorized entity. **Maintenance** actions may take place during all three periods of the use phase.

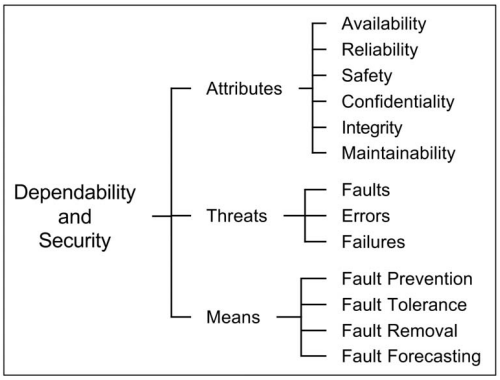


Fig. 2. The dependability and security tree.

During the use phase, the system interacts with its *use environment* and may be adversely affected by faults originating in it. The **use environment** consists of the following elements:

1. *the physical world* with its natural phenomena;
2. *administrators* (including maintainers): entities (humans or other systems) that have the authority to manage, modify, repair and use the system; some authorized humans may lack competence or have malicious objectives;
3. *users*: entities (humans or other systems) that receive service from the system at their use interfaces;
4. *providers*: entities (humans or other systems) that deliver services to the system at its use interfaces;
5. *the infrastructure*: entities that provide specialized services to the system, such as information sources (e.g., time, GPS, etc.), communication links, power sources, cooling airflow, etc.
6. *intruders*: malicious entities (humans and other systems) that attempt to exceed any authority they might have and alter service or halt it, alter the system's functionality or performance, or to access confidential information. Examples include hackers, vandals, corrupt insiders, agents of hostile governments or organizations, and malicious software.

As used here, the term **maintenance**, following common usage, includes not only repairs, but also all modifications of the system that take place during the use phase of system life. Therefore, maintenance is a development process, and the preceding discussion of development applies to maintenance as well. The various forms of maintenance are summarized in Fig. 3.

It is noteworthy that repair and fault tolerance are related concepts; the distinction between fault tolerance and maintenance in this paper is that maintenance involves the participation of an external agent, e.g., a repairman, test equipment, remote reloading of software. Furthermore, repair is part of fault removal (during the use phase), and fault forecasting usually considers repair situations. In fact, repair can be seen as a fault tolerance activity within a larger system that includes the system being repaired and the people and other systems that perform such repairs.

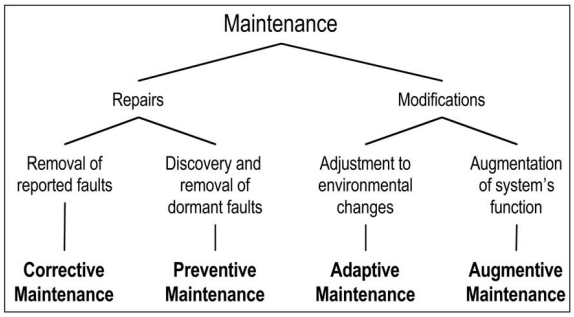


Fig. 3. The various forms of maintenance.

3.2 Faults

3.2.1 A Taxonomy of Faults

All faults that may affect a system during its life are classified according to eight basic viewpoints, leading to the *elementary fault* classes, as shown in Fig. 4.

If all combinations of the eight elementary fault classes were possible, there would be 256 different *combined fault classes*. However, not all criteria are applicable to all fault classes; for example, natural faults cannot be classified by objective, intent, and capability. *We have identified 31 likely combinations*; they are shown in Fig. 5.

More combinations may be identified in the future. The combined fault classes of Fig. 5 are shown to belong to three major partially overlapping groupings:

- **development faults** that include all fault classes occurring during development,
- **physical faults** that include all fault classes that affect hardware,
- **interaction faults** that include all external faults.

The boxes at the bottom of Fig. 5a identify the names of some illustrative fault classes.

Knowledge of all possible fault classes allows the user to decide which classes should be included in a dependability and security specification. Next, we comment on the fault classes that are shown in Fig. 5. Fault numbers (1 to 31) will be used to relate the discussion to Fig. 5.

3.2.2 On Natural Faults

Natural faults (11-15) are physical (hardware) faults that are caused by natural phenomena without human participation. We note that humans also can cause physical faults (6-10, 16-23); these are discussed below. *Production defects* (11) are natural faults that originate during development. During operation the natural faults are either *internal* (12-13), due to natural processes that cause physical deterioration, or *external* (14-15), due to natural processes that originate outside the system boundaries and cause physical interference by penetrating the hardware boundary of the system (radiation, etc.) or by entering via use interfaces (power transients, noisy input lines, etc.).

3.2.3 On Human-Made Faults

The definition of human-made faults (that result from human actions) includes absence of actions when actions should be performed, i.e., **omission faults**, or simply **omissions**. Performing wrong actions leads to **commission faults**.

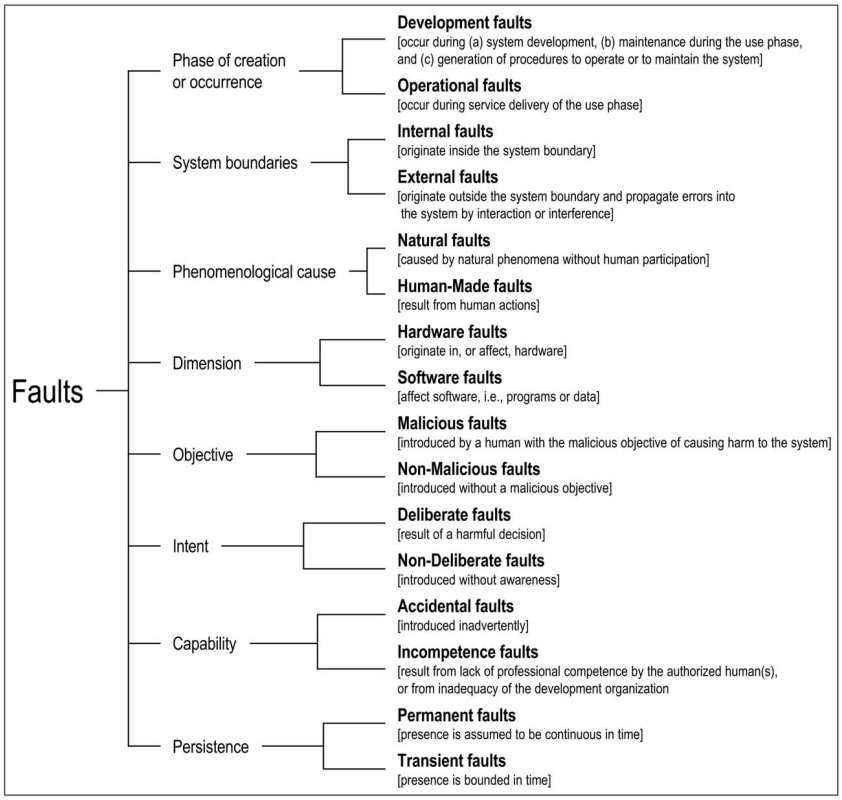
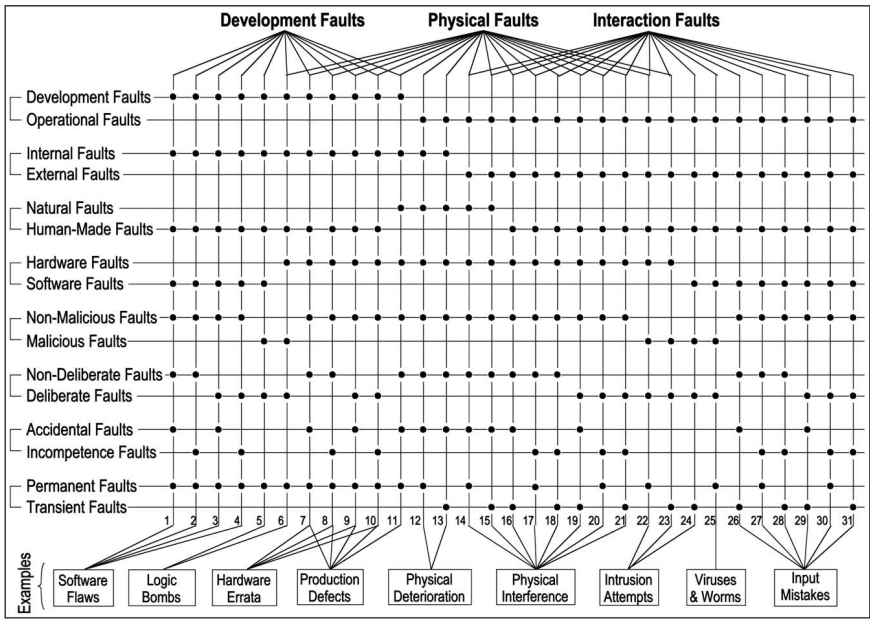
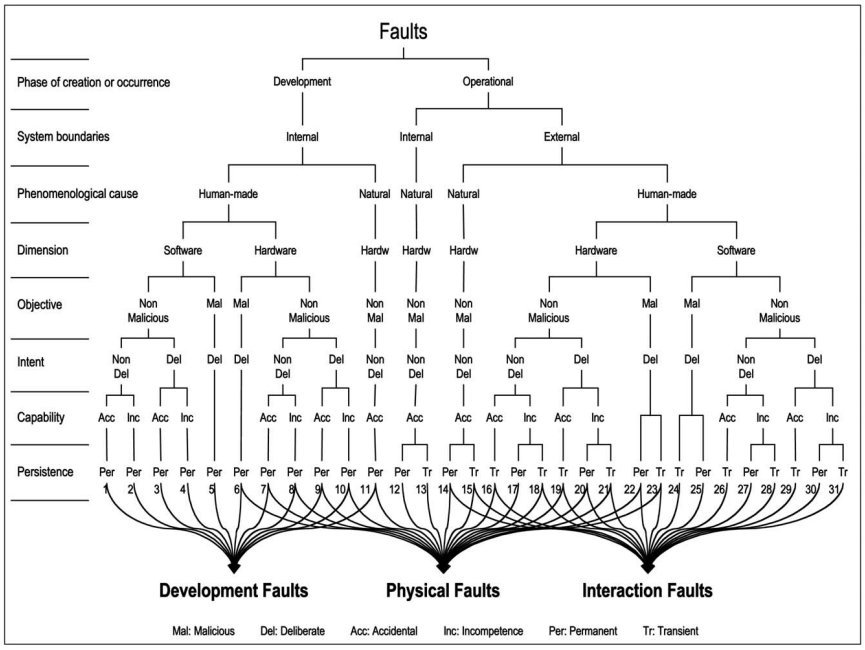


Fig. 4. The elementary fault classes.



(a)



(b)

Fig. 5. The classes of combined faults (a) Matrix representation. (b) Tree representation.

The two basic classes of human-made faults are distinguished by the *objective* of the developer or of the humans interacting with the system during its use:

- *Malicious faults*, introduced during either system development with the objective to cause harm to the system during its use (5-6), or directly during use (22-25).
- *Nonmalicious faults* (1-4, 7-21, 26-31), introduced without malicious objectives.

We consider nonmalicious faults first. They can be partitioned according to the developer's intent:

- *nondeliberate* faults that are due to *mistakes*, that is, *unintended actions* of which the developer, operator, maintainer, etc. is not aware (1, 2, 7, 8, 16-18, 26-28);
- *deliberate* faults that are due to *bad decisions*, that is, *intended actions* that are wrong and cause faults (3, 4, 9, 10, 19-21, 29-31).

Deliberate, nonmalicious, development faults (3, 4, 9, 10) result generally from trade offs, either 1) aimed at preserving acceptable performance, at facilitating system utilization, or 2) induced by economic considerations. Deliberate, nonmalicious interaction faults (19-21, 29-31) may result from the action of an operator either aimed at overcoming an unforeseen situation, or deliberately violat-

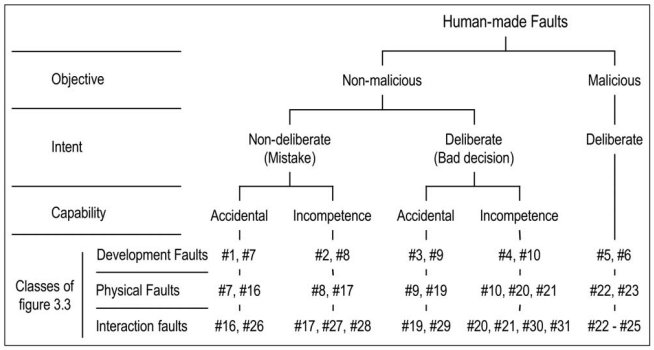


Fig. 6. Classification of human-made faults.

ing an operating procedure without having realized the possibly damaging consequences of this action. Deliberate, nonmalicious faults are often recognized as faults only *after* an unacceptable system behavior; thus, a failure has ensued. The developer(s) or operator(s) did not realize at the time that the consequence of their decision was a fault.

It is usually considered that both mistakes and bad decisions are *accidental*, as long as they are not made with malicious objectives. However, *not all* mistakes and bad decisions by nonmalicious persons are accidents. Some very harmful mistakes and very bad decisions are made by persons who lack professional competence to do the job they have undertaken. A complete fault taxonomy should not conceal this cause of faults; therefore, we introduce a further partitioning of nonmalicious human-made faults into 1) *accidental faults*, and 2) *incompetence faults*. The structure of this taxonomy of human-made faults is shown in Fig. 6.

The question of how to recognize incompetence faults becomes important when a mistake or a bad decision has consequences that lead to economic losses, injuries, or loss of human lives. In such cases, independent professional judgment by a board of inquiry or legal proceedings in a court of law are likely to be needed to decide if professional malpractice was involved.

Thus far, the discussion of incompetence faults has dealt with individuals. However, human-made efforts have failed because a team or an entire organization did not have the organizational competence to do the job. A good example of organizational incompetence is the development failure of the AAS system, that was intended to replace the aging air traffic control systems in the USA [67].

Nonmalicious development faults can exist in hardware and in software. In hardware, especially in microprocessors, some development faults are discovered after production has started [5]. Such faults are called "errata" and are listed in specification updates. The finding of errata typically continues throughout the life of the processors; therefore, new specification updates are issued periodically. Some development faults are introduced because human-made tools are faulty.

Off-the-shelf (OTS) components are inevitably used in system design. The use of OTS components introduces additional problems. They may come with known development faults and may contain unknown faults as well (bugs, vulnerabilities, undiscovered errata, etc.). Their specifications may be incomplete or even incorrect. This problem is especially serious when *legacy* OTS components are used that come from previously designed and used systems, and must be retained in the new system because of the user's needs.

Some development faults affecting software can cause **software aging** [27], i.e., progressively accrued error conditions resulting in performance degradation or complete failure. Examples are memory bloating and leaking, unterminated threads, unreleased file-locks, data corruption, storage space fragmentation, and accumulation of round-off errors [10].

3.2.4 On Malicious Faults

Malicious human-made faults are introduced with the malicious objective to alter the functioning of the system during use. Because of the objective, classification according to intent and capability is not applicable. The goals of such faults are: 1) to disrupt or halt service, causing **denials of service**; 2) to access confidential information; or 3) to improperly modify the system. They are grouped into two classes:

1. **Malicious logic faults** that encompass development faults (5,6) such as *Trojan horses*, logic or timing *bombs*, and *trapdoors*, as well as operational faults (25) such as *viruses*, *worms*, or *zombies*. Definitions for these faults [39], [55] are given in Fig. 7.
2. **Intrusion attempts** that are operational external faults (22-24). The external character of intrusion attempts does not exclude the possibility that they may be performed by system operators or administrators who are exceeding their rights, and intrusion attempts may use physical means to cause faults: power fluctuation, radiation, wire-tapping, heating/cooling, etc.

What is colloquially known as an "exploit" is in essence a software script that will exercise a system vulnerability and allow an intruder to gain access to, and sometimes control of, a system. In the terms defined here, invoking the exploit is an operational, external, human-made, software, malicious interaction fault (24-25). Heating the RAM with a hairdryer to cause memory errors that permit software security violations would be an external, human-made, hardware, malicious interaction fault (22-23). The vulnerability that an exploit takes advantage of is typically a software flaw (e.g., an unchecked buffer) that could be characterized as a developmental, internal, human-made, software, nonmalicious, nondeliberate, permanent fault (1-2).

3.2.5 On Interaction Faults

Interaction faults occur during the use phase, therefore they are all *operational* faults. They are caused by elements of the use environment (see Section 3.1) interacting with the system; therefore, they are all *external*. Most classes originate due to some human action in the use environment; therefore, they are *human-made*. They are fault classes 16-31 in Fig. 5. An exception are external natural faults (14-15) caused by cosmic rays, solar flares, etc. Here, nature interacts with the system without human participation.

A broad class of human-made operational faults are **configuration faults**, i.e., wrong setting of parameters that can affect security, networking, storage, middleware, etc. [24]. Such faults can occur during configuration changes performed during adaptive or augmentative maintenance performed concurrently with system operation (e.g.,

logic bomb: *malicious logic* that remains dormant in the host system till a certain time or an event occurs, or certain conditions are met, and then deletes files, slows down or crashes the host system, etc.

Trojan horse: *malicious logic* performing, or able to perform, an illegitimate action while giving the impression of being legitimate; the illegitimate action can be the disclosure or modification of information (attack against confidentiality or integrity) or a *logic bomb*;

trapdoor: *malicious logic* that provides a means of circumventing access control mechanisms;

virus: *malicious logic* that replicates itself and joins another program when it is executed, thereby turning into a *Trojan horse*; a virus can carry a *logic bomb*;

worm: *malicious logic* that replicates itself and propagates without the users being aware of it; a worm can also carry a *logic bomb*;

zombie: *malicious logic* that can be triggered by an attacker in order to mount a coordinated attack.

Fig. 7. Malicious logic faults.

introduction of a new software version on a network server); they are then called **reconfiguration faults** [70].

As mentioned in Section 2.2, a common feature of interaction faults is that, in order to be "successful," they usually necessitate the prior presence of a *vulnerability*, i.e., an internal fault that enables an external fault to harm the system. Vulnerabilities can be development or operational faults; they can be malicious or nonmalicious, as can be the external faults that exploit them. There are interesting and obvious similarities between an intrusion attempt and a physical external fault that "exploits" a lack of shielding. A vulnerability can result from a deliberate development fault, for economic or for usability reasons, thus resulting in limited protections, or even in their absence.

3.3 Failures

3.3.1 Service Failures

In Section 2.2, a *service failure* is defined as an event that occurs when the delivered service deviates from correct service. The different ways in which the deviation is manifested are a system's *service failure modes*. Each mode can have more than one *service failure severity*.

The occurrence of a failure was defined in Section 2 with respect to the function of a system, not with respect to the description of the function stated in the functional specification: a service delivery complying with the specification may be unacceptable for the system user(s), thus uncovering a specification fault, i.e., revealing the fact that the specification did not adequately describe the system function(s). Such specification faults can be either omission or commission faults (misinterpretations, unwarranted assumptions, inconsistencies, typographical mistakes). In such circumstances, the fact that the event is undesired (and is in fact a failure) may be recognized only after its occurrence, for instance via its consequences. So, failures can be subjective and disputable, i.e., may require judgment to identify and characterize.

The service failure modes characterize incorrect service according to four viewpoints:

1. the failure domain,
2. the detectability of failures,
3. the consistency of failures, and
4. the consequences of failures on the environment.

The **failure domain** viewpoint leads us to distinguish:

- **content failures**. The content of the information delivered at the service interface (i.e., the service content) deviates from implementing the system function.
- **timing failures**. The time of arrival or the duration of the information delivered at the service interface (i.e., the timing of service delivery) deviates from implementing the system function.

These definitions can be specialized: 1) the content can be in numerical or nonnumerical sets (e.g., alphabets, graphics, colors, sounds), and 2) a timing failure may be **early** or **late**, depending on whether the service is delivered too early or too late. Failures when both information and timing are incorrect fall into two classes:

- **halt failure**, or simply **halt**, when the service is *halted* (the external state becomes constant, i.e., system activity, if there is any, is no longer perceptible to the users); a special case of halt is **silent failure**, or simply **silence**, when no service at all is delivered at the service interface (e.g., no messages are sent in a distributed system).
- **erratic failures** otherwise, i.e., when a service is delivered (not halted), but is *erratic* (e.g., babbling).

Fig. 8 summarizes the service failure modes with respect to the failure domain viewpoint.

The **detectability** viewpoint addresses the *signaling* of service failures to the user(s). Signaling at the service interface originates from detecting mechanisms in the system that check the correctness of the delivered service. When the losses are detected and signaled by a warning signal, then **signaled failures** occur. Otherwise, they are **unsignaled failures**. The detecting mechanisms themselves have two failure modes: 1) signaling a loss of function when no failure has actually occurred, that is a **false alarm**, 2) not signaling a function loss, that is an *unsignaled failure*. When the occurrence of service failures result in reduced modes of service, the system signals a degraded mode of service to the user(s). Degraded modes may range from minor reductions to emergency service and safe shutdown.

The **consistency** of failures leads us to distinguish, when a system has two or more users:

- **consistent failures**. The incorrect service is perceived identically by all system users.
- **inconsistent failures**. Some or all system users perceive differently incorrect service (some users may actually perceive correct service); inconsistent failures are usually called, after [38], **Byzantine failures**.

Grading the *consequences of the failures* upon the system environment enables failure *severities* to be defined. The failure modes are ordered into severity levels, to which are generally associated maximum acceptable probabilities of occurrence. The number, the labeling, and the definition of the severity levels, as well as the acceptable probabilities of occurrence, are application-related, and involve the dependability and security attributes for the considered

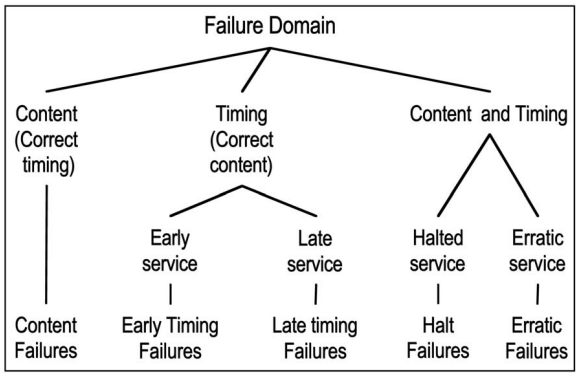


Fig. 8. Service failure modes with respect to the failure domain viewpoint.

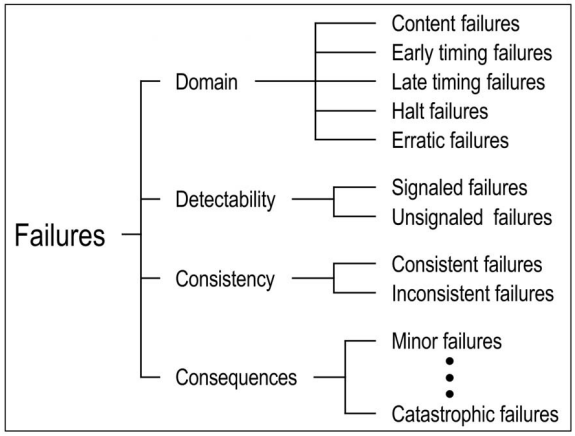


Fig. 9. Service failure modes.

application(s). Examples of criteria for determining the classes of failure severities are

1. for availability, the outage duration;
2. for safety, the possibility of human lives being endangered;
3. for confidentiality, the type of information that may be unduly disclosed; and
4. for integrity, the extent of the corruption of data and the ability to recover from these corruptions.

Generally speaking, two limiting levels can be defined according to the relation between the benefit (in the broad sense of the term, not limited to economic considerations) provided by the service delivered in the absence of failure, and the consequences of failures:

- **minor failures**, where the harmful consequences are of similar cost to the benefits provided by correct service delivery;
- **catastrophic failures**, where the cost of harmful consequences is orders of magnitude, or even incommensurably, higher than the benefit provided by correct service delivery.

Fig. 9 summarizes the service failure modes.

Systems that are designed and implemented so that they fail only in specific modes of failure described in the dependability and security specification and only to an acceptable extent are **fail-controlled systems**, e.g., with stuck output as opposed to delivering erratic values, silence as opposed to babbling, consistent as opposed to inconsistent failures. A system whose failures are to an acceptable extent halting failures only is a **fail-halt** (or fail-stop) **system**; the situations of stuck service and of silence lead, respectively, to **fail-passive systems** and **fail-silent systems** [53]. A system whose failures are, to an acceptable extent, all minor ones is a **fail-safe system**.

As defined in Section 2, delivery of incorrect service is an *outage*, which lasts until *service restoration*. The outage duration may vary significantly, depending on the actions involved in service restoration after a failure has occurred: 1) automatic or operator-assisted recovery, restart, or reboot; 2) corrective maintenance. Correction of development faults (by patches or workarounds) is usually performed offline, after service restoration, and the upgraded components resulting from fault correction are then introduced at some appropriate time with or without interruption of system operation. Preemptive interruption of system operation for an upgrade or for preventive maintenance is a *service shutdown*, also called a *planned outage* (as opposed to an outage consecutive to failure, which is then called an *unplanned outage*).

3.3.2 Development Failures

As stated in Section 3.1, development faults may be introduced into the system being developed by its environment, especially by human developers, development tools, and production facilities. Such development faults may contribute to partial or complete development failures, or they may remain undetected until the use phase. A complete **development failure** causes the development process to be terminated before the system is accepted for use and placed into service. There are two aspects of development failures:

1. *Budget failure*. The allocated funds are exhausted before the system passes acceptance testing.
2. *Schedule failure*. The projected delivery schedule slips to a point in the future where the system would be technologically obsolete or functionally inadequate for the user's needs.

The principal causes of development failures are: incomplete or faulty specifications, an excessive number of user-initiated specification changes; inadequate design with respect to functionality and/or performance goals; too many development faults; inadequate fault removal capability; prediction of insufficient dependability or security; and faulty estimates of development costs. All are usually due to an underestimate of the complexity of the system to be developed.

There are two kinds of **partial development failures**, i.e., failures of lesser severity than project termination. Budget or schedule **overruns** occur when the development is completed, but the funds or time needed to complete the effort exceed the original estimates. Another form of partial development failure is **downgrading**: The developed system is delivered with less functionality, lower performance, or is predicted to have lower dependability or security than was required in the original system specification.

Development failures, overruns, and downgrades have a very negative impact on the user community, see, e.g., statistics about large software projects [34], or the analysis of the complete development failure of the AAS system, that resulted in the waste of $1.5 billion [67].

3.3.3 Dependability and Security Failures

It is to be expected that faults of various kinds will affect the system during its use phase. The faults may cause unacceptably degraded performance or total failure to deliver the specified service. For this reason, a *dependability and security specification* is agreed upon that states the goals for each attribute: availability, reliability, safety, confidentiality, integrity, and maintainability.

The specification explicitly identifies the *classes of faults* that are expected and the *use environment* in which the system will operate. The specification may also require safeguards against certain undesirable or dangerous conditions. Furthermore, the inclusion of specific fault prevention or fault tolerance techniques may be required by the user.

A **dependability or security failure** occurs when the given system suffers service failures more frequently or more severely than acceptable.

The dependability and security specification can also contain faults. Omission faults can occur in description of the use environment or in choice of the classes of faults to be prevented or tolerated. Another class of faults is the unjustified choice of very high requirements for one or more attributes that raises the cost of development and may lead to a cost overrun or even a development failure. For example, the initial AAS complete outage limit of 3 seconds per year was changed to 5 minutes per year for the new contract in 1994 [67].

3.4 Errors

An *error* has been defined in Section 2.2 as the part of a system's total state that may lead to a failure—a failure occurs when the error causes the delivered service to deviate from correct service. The cause of the error has been called a fault.

An error is **detected** if its presence is indicated by an *error message* or *error signal*. Errors that are present but not detected are **latent** errors.

Since a system consists of a set of interacting components, the total state is the set of its component states. The definition implies that a fault originally causes an error within the state of one (or more) components, but service failure will not occur as long as the external state of that component is not part of the external state of the system. Whenever the error becomes a part of the external state of the component, a service failure of that component occurs, but the error remains internal to the entire system.

Whether or not an error will actually lead to a service failure depends on two factors:

1. The structure of the system, and especially the nature of any redundancy that exists in it:
   - *protective* redundancy, introduced to provide fault tolerance, that is explicitly intended to prevent an error from leading to service failure.
   - *unintentional* redundancy (it is in practice difficult if not impossible to build a system without any form of redundancy) that may have the same—presumably unexpected—result as intentional redundancy.
2. The behavior of the system: the part of the state that contains an error may never be needed for service, or an error may be eliminated (e.g., when overwritten) before it leads to a failure.

A convenient classification of errors is to describe them in terms of the elementary service failures that they cause, using the terminology of Section 3.3.1: content versus timing errors, detected versus latent errors, consistent versus inconsistent errors when the service goes to two or more users, minor versus catastrophic errors. In the field of error control codes, content errors are further classified according to the damage pattern: single, double, triple, byte, burst, erasure, arithmetic, track, etc., errors.

Some faults (e.g., a burst of electromagnetic radiation) can simultaneously cause errors in more than one component. Such errors are called **multiple related errors**. **Single errors** are errors that affect one component only.

3.5 The Pathology of Failure: Relationship between Faults, Errors, and Failures

The creation and manifestation mechanisms of faults, errors, and failures are illustrated by Fig. 10, and summarized as follows:

1. A fault is *active* when it produces an error; otherwise, it is *dormant*. An active fault is either 1) an internal fault that was previously dormant and that has been activated by the computation process or environmental conditions, or 2) an external fault. **Fault activation** is the application of an input (the activation pattern) to a component that causes a dormant fault to become active. Most internal faults cycle between their dormant and active states.
2. Error propagation within a given component (i.e., *internal* propagation) is caused by the computation process: An error is successively transformed into other errors. Error propagation from component A to component B that receives service from A (i.e., *external* propagation) occurs when, through internal propagation, an error reaches the service interface of component A. At this time, service delivered by A to B becomes incorrect, and the ensuing service failure of A appears as an external fault to B and propagates the error into B via its use interface.
3. A service failure occurs when an error is propagated to the service interface and causes the service delivered by the system to deviate from correct service. The failure of a component causes a permanent or transient fault in the system that contains the component. Service failure of a system causes a permanent or transient external fault for the other system(s) that receive service from the given system.

These mechanisms enable the "chain of threats" to be completed, as indicated by Fig. 11. The arrows in this chain express a causality relationship between faults, errors, and failures. They should be interpreted generically: by propagation, several errors can be generated before a failure occurs. It is worth emphasizing that, from the mechanisms above listed, propagation, and, thus, instantiation(s) of this chain, can occur via interaction between components or systems, composition of components into a system, and the creation or modification of a system.

Some illustrative examples of fault pathology are given in Fig. 12. From those examples, it is easily understood that

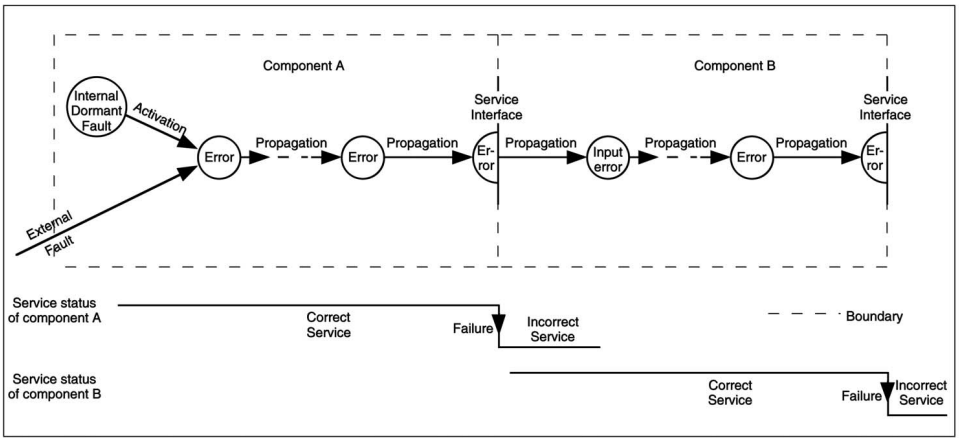


Fig. 10. Error propagation.

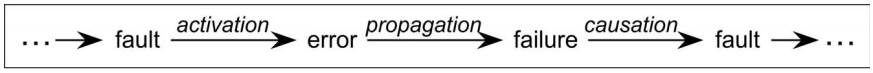


Fig. 11. The fundamental chain of dependability and security threats.

- A short circuit occurring in an integrated circuit is a *failure* (with respect to the function of the circuit); the consequence (connection stuck at a Boolean value, modification of the circuit function, etc.) is a *fault* that will remain dormant as long as it is not activated. Upon activation (invoking the faulty component and uncovering the fault by an appropriate input pattern), the fault becomes *active* and produces an *error*, which is likely to propagate and create other errors. If and when the propagated error(s) affect(s) the delivered service (in information content and/or in the timing of delivery), a *failure* occurs.
- The result of an *error* by a programmer leads to a *failure* to write the correct instruction or data, that in turn results in a *(dormant) fault* in the written software (faulty instruction(s) or data); upon activation (invoking the component where the fault resides and triggering the faulty instruction, instruction sequence or data by an appropriate input pattern) the fault becomes *active* and produces an *error*; if and when the error affects the delivered service (in information content and/or in the timing of delivery), a *failure* occurs. This example is not restricted to accidental faults: a l*ogic bomb* is created by a malicious programmer; it will remain *dormant* until activated (e.g. at some predetermined date); it then produces an *error* that may lead to a storage overflow or to slowing down the program execution; as a consequence, service delivery will suffer from a so-called *denial-of-service*.
- The result of an *error* by a specifier' leads to a *failure* to describe a function, that in turn results in a *fault* in the written specification, e.g. incomplete description of the function. The implemented system therefore does not incorporate the missing (sub-)function. When the input data are such that the service corresponding to the missing function should be delivered, the actual service delivered will be different from expected service, i.e., an *error* will be perceived by the user, and a *failure* will thus occur.
- An inappropriate human-system interaction performed by an operator during the operation of the system is an external *fault* (from the system viewpoint); the resulting altered processed data is an *error;* etc.
- An *error* in reasoning leads to a maintenance or operating manual writer's *failure* to write correct directives, that in turn results in a *fault* in the corresponding manual (faulty directives) that will remain *dormant* as long as the directives are not acted upon in order to address a given situation, etc.
- A failure often results from the combined action of several faults; this is especially true when considering security issues: a trap-door (i.e., some way to by-pass access control) that is inserted into a computing system, either accidentally or deliberately, is a development *fault*; this fault may remain *dormant* until some malicious human makes use of it to enter the system; the intruder login is a deliberate interaction *fault*; when the intruder is logged in, he or she may deliberately create an *error*, e.g., modifying some file (integrity attack); when this file is used by an authorized user, the service will be affected, and a *failure* will occur.
- A given fault in a given component may result from various different possible sources; for instance, a permanent *fault* in a physical component — e.g., stuck at ground voltage — may result from:
  - a physical *failure* (e.g., caused by a threshold change),
  - an *error* caused by a development *fault* — e.g., faulty microinstruction decoding circuitry propagating 'down' through the layers and causing an illegal short between two circuit outputs for a duration long enough to provoke a short-circuit having the same consequence as a threshold change.
- Another example of top-down propagation is the exploitation during operation of an inadvertently introduced buffer overflow for gaining root privilege and subsequently re-writing the flash-ROM.

Fig. 12. Examples illustrating fault pathology.

fault dormancy may vary considerably, depending upon the fault, the given system's utilization, etc.

The ability to identify the activation pattern of a fault that had caused one or more errors is the **fault activation reproducibility**. Faults can be categorized according to their activation reproducibility: Faults whose activation is reproducible are called **solid**, or **hard**, faults, whereas faults whose activation is not systematically reproducible are **elusive**, or **soft**, faults. Most residual development faults in large and complex software are elusive faults: They are intricate enough that their activation conditions depend on complex combinations of internal state and external

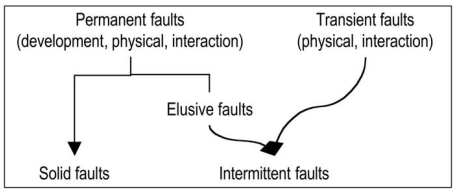


Fig. 13. Solid versus intermittent faults.

requests, that occur rarely and can be very difficult to reproduce [23]. Other examples of elusive faults are:

- "pattern sensitive" faults in semiconductor memories, changes in the parameters of a hardware component (effects of temperature variation, delay in timing due to parasitic capacitance, etc.).
- conditions—affecting either hardware or software —that occur when the system load exceeds a certain level, causing, for example, marginal timing and synchronization.

The similarity of the manifestation of elusive development faults and of transient physical faults leads to both classes being grouped together as **intermittent faults**. Errors produced by intermittent faults are usually termed **soft errors**. Fig. 13. summarizes this discussion.

Situations involving multiple faults and/or failures are frequently encountered. System failures often turn out on later examination to have been caused by errors that are due to a number of different coexisting faults. Given a system with defined boundaries, a **single fault** is a fault caused by *one* adverse physical event or *one* harmful human action. **Multiple faults** are *two or more* concurrent, overlapping, or sequential single faults whose consequences, i.e., errors, overlap in time, that is, the errors due to these faults are concurrently present in the system. Consideration of multiple faults leads one to distinguish 1) **independent faults**, that are attributed to different causes, and 2) **related faults**, that are attributed to a common cause. Related faults generally cause *similar errors*, i.e., errors that cannot be distinguished by whatever detection mechanisms are being employed, whereas independent faults usually cause *distinct errors*. However, it may happen that independent faults (especially omissions) lead to similar errors [6], or that related faults lead to distinct errors. The failures caused by similar errors are **common-mode failures**.

Three additional comments, about the words, or labels, "threats," "fault," "error," and "failure:"

1. The use of *threats*, for generically referring to faults, errors, and failures has a broader meaning than its common use in security, where it essentially retains it usual notion of potentiality. In our terminology, it has both this potentiality aspect (e.g., faults being not yet active, service failures not having impaired dependability), and a realization aspect (e.g., active fault, error that is present, service failure that occurs). In security terms, a malicious external fault is an *attack*.
2. The exclusive use in this paper of faults, errors, and failures does not preclude the use in special situations of words which designate, briefly and unambiguously, a specific class of threat; this is especially applicable to faults (e.g., bug, defect, deficiency, flaw, erratum) and to failures (e.g., breakdown, malfunction, denial-of-service).
3. The assignment made of the particular terms fault, error, and failure simply takes into account common usage: 1) fault prevention, tolerance, and diagnosis, 2) error detection and correction, 3) failure rate.

4 Dependability, Security, and Their Attributes

4.1 The Definitions of Dependability and Security

In Section 2.3, we have presented two alternate definitions of dependability:

- the original definition: the ability to deliver service that can justifiably be trusted.
- an alternate definition: the ability of a system to avoid service failures that are more frequent or more severe than is acceptable.

The original definition is a general definition that aims to generalize the more classical notions of availability, reliability, safety, integrity, maintainability, etc., that then become attributes of dependability. The alternate definition of dependability comes from the following argument. A system can, and usually does, fail. Is it however still dependable? When does it become undependable? The alternate definition thus provides a criterion for deciding whether or not, in spite of service failures, a system is still to be regarded as dependable. In addition, the notion of dependability failure, that is directly deduced from that definition, enables the establishment of a connection with development failures.

The definitions of dependability that exist in current standards differ from our definitions. Two such differing definitions are:

- "The collective term used to describe the availability performance and its influencing factors: reliability performance, maintainability performance and maintenance support performance" [31].
- "The extent to which the system can be relied upon to perform exclusively and correctly the system task(s) under defined operational and environmental conditions over a defined period of time, or at a given instant of time" [29].

The ISO definition is clearly centered upon availability. This is no surprise as this definition can be traced back to the definition given by the international organization for telephony, the CCITT [11], at a time when availability was the main concern to telephone operating companies. However, the willingness to grant dependability a generic character is noteworthy, since it goes beyond availability as it was usually defined, and relates it to reliability and maintainability. In this respect, the ISO/CCITT definition is consistent with the definition given in [26] for dependability: "the probability that a system will operate when needed." The second definition, from [29], introduces the notion of reliance, and as such is much closer to our definitions.

Terminology in the security world has its own rich history. Computer security, communications security, information security, and information assurance are terms that have had a long development and use in the community of security researchers and practitioners, mostly without direct

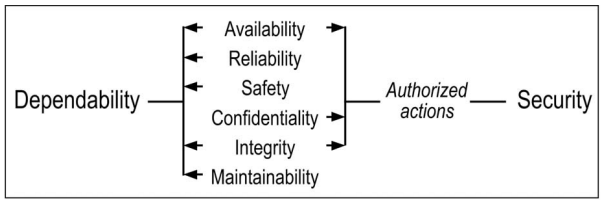


Fig. 14. Relationship between dependability and security.

reference to dependability. Nevertheless, all of these terms can be understood in terms of the three primary security attributes of confidentiality, integrity, and availability.

Security has not been characterized as a single attribute of dependability. This is in agreement with the usual definitions of security, that view it as a *composite* notion, namely, "the combination of confidentiality, the prevention of the unauthorized disclosure of information, integrity, the prevention of the unauthorized amendment or deletion of information, and availability, the prevention of the unauthorized withholding of information" [12], [52]. Our unified definition for **security** is the absence of unauthorized access to, or handling of, system state. The relationship between dependability and security is illustrated by Fig. 14, that is a refinement of Fig. 1.

4.2 Dependence and Trust

We have introduced the notions of dependence and trust in Section 2.3:

- The dependence of system A on system B represents the extent to which System A's dependability is (or would be) affected by that of System B.
- Trust is accepted dependence.

The dependence of a system on another system can vary from total dependence (any failure of B would cause A to fail) to complete independence (B cannot cause A to fail). If there is reason to believe that B's dependability will be insufficient for A's required dependability, the former should be enhanced, A's dependence reduced, or additional means of fault tolerance provided. Our definition of dependence relates to the relation *depends upon* [50], [14], whose definition is a component a depends upon a component b if the correctness of b's service delivery is necessary for the correctness of a's service delivery. However, this relation is expressed in terms of the narrower concept of correctness, rather than dependability, and, hence, is only binary, whereas our notion of dependence can take values on a measurable space.

By accepted dependence, we mean the dependence (say of A on B) allied to a judgment that this level of dependence is acceptable. Such a judgment (made by or on behalf of A) about B is possibly explicit and even laid down in a contract between A and B, but might be only implicit, even unthinking. Indeed, it might even be unwilling—in that A has no alternative option but to put its trust in B. Thus, to the extent that A trusts B, it need not assume responsibility for, i.e., provide means of tolerating, B's failures (the question of whether it is capable of doing this is another matter). In fact, the extent to which A fails to provide means of tolerating B's failures is a measure of A's (perhaps unthinking or unwilling) trust in B.

4.3 The Attributes of Dependability and Security

The attributes of dependability and security that have been defined in Section 2.3 may be of varying importance depending on the application intended for the given computing system: Availability, integrity, and maintainability are generally required, although to a varying degree depending on the application, whereas reliability, safety, and confidentiality may or may not be required according to the application. The extent to which a system possesses the attributes of dependability and security should be considered in a relative, probabilistic, sense, and not in an absolute, deterministic sense: Due to the unavoidable presence or occurrence of faults, systems are never totally available, reliable, safe, or secure.

The definition given for integrity—absence of improper system state alterations—goes beyond the usual definitions, that 1) relate to the notion of authorized actions only, and 2) focus on information (e.g., prevention of the unauthorized amendment or deletion of information [12], assurance of approved data alterations [33]): 1) naturally, when a system implements an authorization policy, "improper" encompasses "unauthorized," 2) "improper alterations" encompass actions that prevent (correct) upgrades of information, and 3) "system state" includes system modifications or damages.

The definition given for maintainability intentionally goes beyond corrective and preventive maintenance, and encompasses the other forms of maintenance defined in Section 3, i.e., adaptive and augmentative maintenance. The concept of **autonomic computing** [22] has as its major aim the provision of high maintainability for large networked computer systems, though automation of their management.

Besides the attributes defined in Section 2 and discussed above, other, *secondary*, attributes can be defined, which refine or specialize the *primary* attributes as defined in Section 2. An example of a specialized secondary attribute is **robustness**, i.e., dependability with respect to external faults, which characterizes a system reaction to a specific class of faults.

The notion of secondary attributes is especially relevant for security, and is based on distinguishing among various types of information [9]. Examples of such secondary attributes are:

- **accountability**: availability and integrity of the identity of the person who performed an operation;
- **authenticity**: integrity of a message content and origin, and possibly of some other information, such as the time of emission;
- **nonrepudiability**: availability and integrity of the identity of the sender of a message (nonrepudiation of the origin), or of the receiver (nonrepudiation of reception).

The concept of a **security policy** is that of a set of security-motivated constraints, that are to be adhered to by, for example, an organization or a computer system [47]. The enforcement of such constraints may be via technical, management, and/or operational controls, and the policy may lay down how these controls are to be enforced. In effect, therefore, a security policy is a (partial) system specification, lack of adherence to which will be regarded as a security failure. In practice, there may be a hierarchy of

Concept	Dependability	High Confidence	Survivability	Trustworthiness
Goal	1) ability to deliver service that can justifiably be trusted 2) ability of a system to avoid service failures that are more frequent or more severe than is acceptable	consequences of the system behavior are well understood and predictable	capability of a system to fulfill its mission in a timely manner	assurance that a system will perform as expected
Threats present	1) development faults (e.g., software flaws, hardware errata, malicious logic) 2) physical faults (e.g., production defects, physical deterioration) 3) interaction faults (e.g., physical interference, input mistakes, attacks, including viruses, worms, intrusions)	• internal and external threats • naturally occurring hazards and malicious attacks from a sophisticated and well-funded adversary	1) attacks (e.g., intrusions, probes, denials of service) 2) failures (internally generated events due to, e.g., software design errors, hardware degradation, human errors, corrupted data) 3) accidents (externally generated events such as natural disasters)	1) hostile attacks (from hackers or insiders) 2) environmental disruptions (accidental disruptions, either man-made or natural) 3) human and operator errors (e.g., software flaws, mistakes by human operators)
Reference	This paper	"Information Technology Frontiers for a New Millennium (Blue Book 2000)" [48]	"Survivable network systems" [16]	"Trust in cyberspace" [62]

Fig. 15. Dependability, high confidence, survivability, and trustworthiness.

such security policies, relating to a hierarchy of systems —for example, an entire company, its information systems department, and the individuals and computer systems in this department. Separate, albeit related policies, or separate parts of an overall policy document, may be created concerning different security issues, e.g., a policy regarding the controlled public disclosure of company information, one on physical and networked access to the company's computers. Some computer security policies include constraints on how information may flow within a system as well as constraints on system states.

As with any set of dependability and security specifications, issues of completeness, consistency, and accuracy are of great importance. There has thus been extensive research on methods for formally expressing and analyzing security policies. However, if some system activity is found to be in a contravention of a relevant security policy then, as with any system specification, the security failure may either be that of the system, or because the policy does not adequately describe the intended security requirement. A well-known example of an apparently satisfactory security policy that proved to be deficient, by failing to specify some particular behaviour as insecure, is discussed by [44].

Dependability and security classes are generally defined via the analysis of failure frequencies and severities, and of outage durations, for the attributes that are of concern for a given application. This analysis may be conducted directly or indirectly via risk assessment (see, e.g., [25] for availability, [58] for safety, and [32] for security).

The variations in the emphasis placed on the different attributes directly influence the balance of the techniques (fault prevention, tolerance, removal, and forecasting) to be employed in order to make the resulting system dependable and secure. This problem is all the more difficult as some of the attributes are conflicting (e.g., availability and safety, availability and confidentiality), necessitating that trade offs be made.

4.4 Dependability, High Confidence, Survivability, and Trustworthiness

Other concepts similar to dependability exist, such as **high confidence**, **survivability**, and **trustworthiness**. They are presented and compared to dependability in Fig. 15. A side-by-side comparison leads to the conclusion that all four concepts are essentially equivalent in their goals and address similar threats.

5 The Means to Attain Dependability and Security

In this section, we examine in turn fault prevention, fault tolerance, fault removal, and fault forecasting. The section ends with a discussion on the relationship between these various means.

5.1 Fault Prevention

Fault prevention is part of general engineering, and, as such, will not be much emphasized here. However, there are facets of fault prevention that are of direct interest regarding dependability and security, and that can be discussed according to the classes of faults defined in Section 3.2.

Prevention of development faults is an obvious aim for development methodologies, both for software (e.g., information hiding, modularization, use of strongly-typed programming languages) and hardware (e.g., design rules). Improvement of development processes in order to reduce the number of faults introduced in the produced systems is a step further in that it is based on the recording of faults in the products, and the elimination of the causes of the faults via process modifications [13], [51].

5.2 Fault Tolerance

5.2.1 Fault Tolerance Techniques

Fault tolerance [3], which is aimed at failure avoidance, is carried out via error detection and system recovery. Fig. 16 gives the techniques involved in fault tolerance.

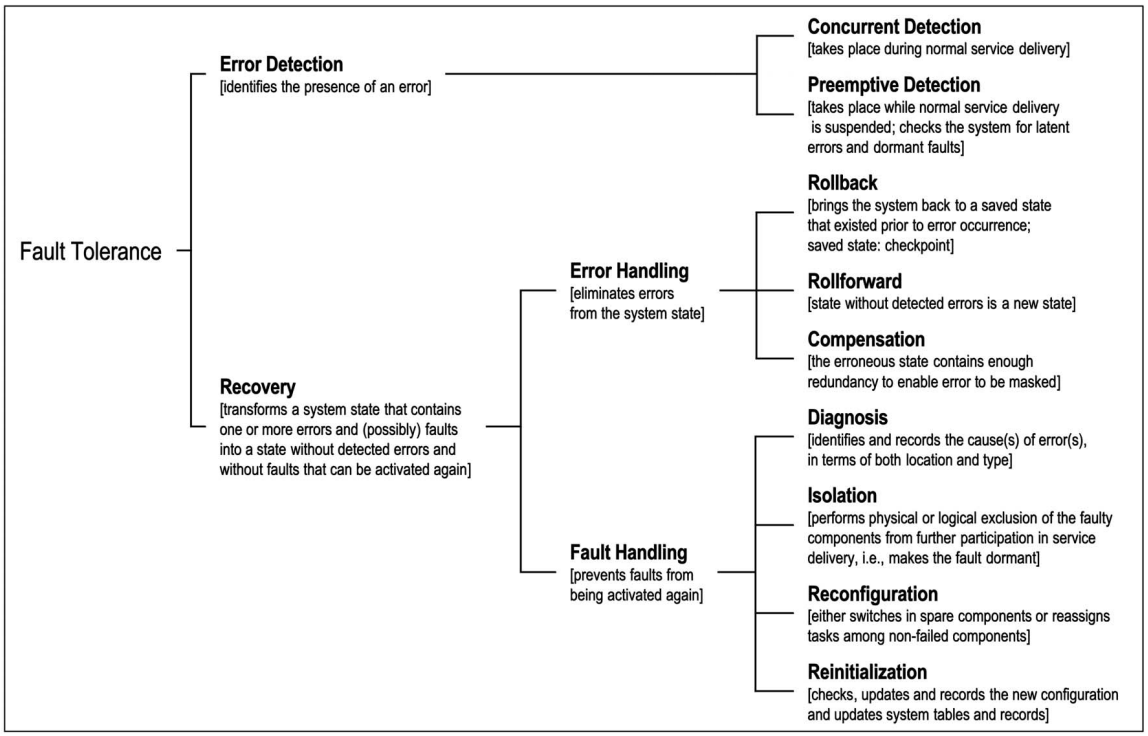


Fig. 16. Fault tolerance techniques.

Usually, fault handling is followed by corrective maintenance, aimed at removing faults that were isolated by fault handling; in other words, the factor that distinguishes fault tolerance from maintenance is that maintenance requires the participation of an external agent. Closed systems are those systems where fault removal cannot be practically implemented (e.g., the hardware of a deep space probe).

Rollback and rollforward are invoked on demand, after error detection has taken place, whereas compensation can be applied either on demand or systematically, at predetermined times or events, independently of the presence or absence of (detected) error. Error handling on demand followed by fault handling together form **system recovery**; hence, the name of the corresponding strategy for fault tolerance: **error detection and system recovery** or simply **detection and recovery**.

Fault masking, or simply **masking**, results from the systematic usage of compensation. Such masking will conceal a possibly progressive and eventually fatal loss of protective redundancy. So, practical implementations of masking generally involve error detection (and possibly fault handling), leading to **masking and recovery**.

It is noteworthy that:

1. Rollback and rollforward are not mutually exclusive. Rollback may be attempted first; if the error persists, rollforward may then be attempted.
2. Intermittent faults do not necessitate isolation or reconfiguration; identifying whether a fault is intermittent or not can be performed either by error handling (error recurrence indicates that the fault is not intermittent), or via fault diagnosis when rollforward is used.
3. Fault handling may directly follow error detection, without error handling being attempted.

Preemptive error detection and handling, possibly followed by fault handling, is commonly performed at system power up. It also comes into play during operation, under various forms such as spare checking, memory scrubbing, audit programs, or so-called **software rejuvenation** [27], aimed at removing the effects of software aging before they lead to failure.

Fig. 17 gives four typical and schematic examples for the various strategies identified for implementing fault tolerance.

5.2.2 Implementation of Fault Tolerance

The choice of error detection, error handling and fault handling techniques, and of their implementation is directly related to and strongly dependent upon the underlying fault assumption: The class(es) of faults that can actually be tolerated depend(s) on the fault assumption that is being considered in the development process and, thus, relies on the *independence* of redundancies with respect to the process of fault creation and activation. A (widely used) method of achieving fault tolerance is to perform multiple computations through multiple channels, either sequentially or concurrently. When tolerance of physical faults is foreseen, the channels may be of identical design, based on the assumption that hardware components fail independently. Such an approach has proven to be adequate for elusive development faults, via rollback [23], [28]; it is however not suitable for the tolerance of solid development faults, which necessitates that the channels implement the same function via separate designs and implementations [57], [4], i.e., through **design diversity** [6].

The provision within a component of the required functional processing capability together with concurrent error detection mechanisms leads to the notion of **self-checking component**, either in hardware or in software;

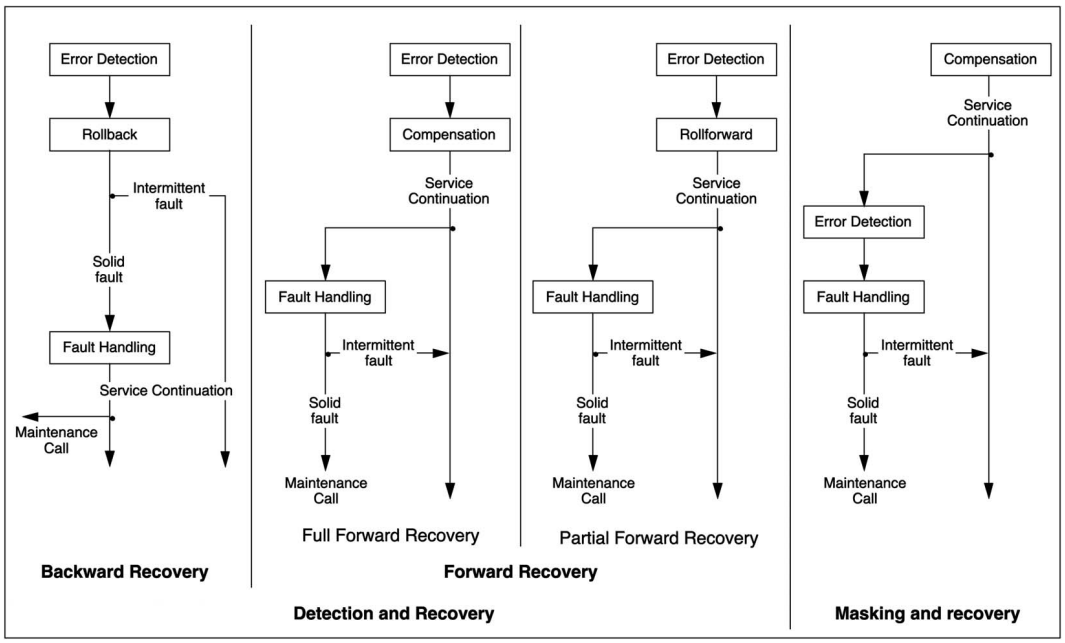


Fig. 17. Examples for the basic strategies for implementing fault tolerance.

one of the important benefits of the self-checking component approach is the ability to give a clear definition of *error confinement areas* [63].

It is evident that not all fault tolerance techniques are equally effective. The measure of effectiveness of any given fault tolerance technique is called its **coverage**. The imperfections of fault tolerance, i.e., the lack of *fault tolerance coverage*, constitute a severe limitation to the increase in dependability that can be obtained. Such imperfections of fault tolerance (Fig. 18) are due either

1. to development faults affecting the fault tolerance mechanisms with respect to the fault assumptions stated during the development, the consequence of which is a lack of *error and fault handling coverage* (defined with respect to a class of errors or faults, e.g., single errors, stuck-at faults, etc., as the conditional probability that the technique is effective, given that the errors or faults have occurred), or
2. to fault assumptions that differ from the faults really occurring in operation, resulting in a lack of *fault assumption coverage*, that can be in turn due to either 1) failed component(s) not behaving as assumed, that is a lack of *failure mode coverage*, or 2) the occurrence of common-mode failures when independent ones are assumed, that is a lack of *failure independence coverage*.

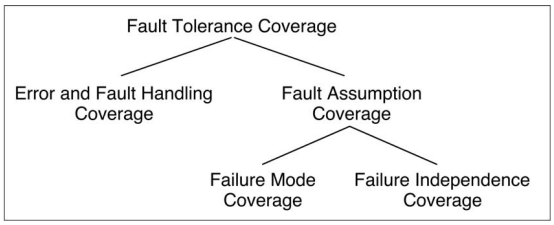


Fig. 18. Fault tolerance coverage.

The lack of error and fault handling coverage has been shown to be a drastic limit to dependability improvement [8], [1]. Similar effects can result from the lack of failure mode coverage: conservative fault assumptions (e.g., Byzantine faults) will result in a higher failure mode coverage, at the expense of necessitating an increase in the redundancy and more complex fault tolerance mechanisms, which can lead to an overall decrease in system dependability and security [54].

An important issue in coordination of the activities of multiple components is prevention of error propagation from affecting the operation of nonfailed components. This issue becomes particularly important when a given component needs to communicate some information to other components. Typical examples of such *single-source information* are local sensor data, the value of a local clock, the local view of the status of other components, etc. The consequence of this need to communicate single-source information from one component to other components is that nonfailed components must reach an agreement as to how the information they obtain should be employed in a mutually consistent way. This is known as the *consensus* problem [43].

Fault tolerance is (also) a recursive concept: it is essential that the mechanisms that implement fault tolerance should be protected against the faults that might affect them. Examples of such protection are voter replication, self-checking checkers, "stable" memory for recovery programs and data.

Systematic introduction of fault tolerance is often facilitated by the addition of support systems specialized for fault tolerance (e.g., software monitors, service processors, dedicated communication links).

Reflection, a technique for transparently and appropriately augmenting all relevant actions of an object or software component, e.g., in order to ensure that these actions can be undone if necessary, can be used in object-oriented software and through the provision of middleware [17].

Fault tolerance applies to all classes of faults. Protection against intrusions traditionally involves cryptography and

firewalls. Some mechanisms of error detection are directed towards both nonmalicious and malicious faults (e.g., memory access protection techniques). Intrusion detection is usually performed via likelihood checks [18], [15]. Approaches and schemes have been proposed for tolerating:

- intrusions and physical faults, via information fragmentation and dispersal [20], [56],
- malicious logic, and more specifically to viruses, either via control flow checking [35], or via design diversity [36],
- intrusions, malicious logic, vulnerabilities due to physical or development faults, via server diversity [68].

Finally, it is worth mentioning that 1) several synonyms exist for fault tolerance: **self-repair**, **self-healing**, **resilience**, and that 2) the term **recovery-oriented computing** [19] has recently been introduced for what is essentially a fault tolerance approach to achieving overall system dependability, i.e., at the level above individual computer systems, in which the failures of these individual systems constitute the faults to be tolerated.

5.3 Fault Removal

In this section, we consider fault removal during system development, and during system use.

5.3.1 Fault Removal During Development

Fault removal *during the development phase* of a system lifecycle consists of three steps: verification, diagnosis, and correction. We focus in what follows on **verification**, that is the process of checking whether the system adheres to given properties, termed the **verification conditions**; if it does not, the other two steps have to be undertaken: diagnosing the fault(s) that prevented the verification conditions from being fulfilled, and then performing the necessary corrections. After correction, the verification process should be repeated in order to check that fault removal had no undesired consequences; the verification performed at this stage is usually termed **nonregression verification**.

Checking the specification is usually referred to as **validation** [7]. Uncovering specification faults can happen at any stage of the development, either during the specification phase itself, or during subsequent phases when evidence is found that the system will not implement its function, or that the implementation cannot be achieved in a cost-effective way.

Verification techniques can be classified according to whether or not they involve exercising the system. Verifying a system without actual execution is **static verification**. Such verification can be conducted:

- on the system itself, in the form of 1) *static analysis* (e.g., inspections or walk-through, data flow analysis, complexity analysis, abstract interpretation, compiler checks, vulnerability search, etc.) or 2) *theorem proving*;
- on a model of the system behavior, where the model is usually a state-transition model (Petri nets, finite or infinite state automata), leading to *model checking*.

Verifying a system through exercising it constitutes **dynamic verification**; the inputs supplied to the system can be either symbolic in the case of **symbolic execution**, or actual in the case of verification testing, usually simply termed **testing**.

Fig. 19 summarizes the verification approaches.

Exhaustive testing of a system with respect to all its possible inputs is generally impractical. The methods for the determination of the test patterns can be classified according to two viewpoints: criteria for selecting the test inputs, and generation of the test inputs.

Fig. 20 summarizes the various testing approaches according to test selection. The upper part of the figure identifies the elementary testing approaches. The lower part of the figure gives the combination of the elementary approaches, where a distinction is made between hardware and software testing since hardware testing is mainly aimed at removing production faults, whereas software testing is concerned only with development faults: hardware testing is usually fault-based, whereas software testing is criteria-based, with the exception of mutation testing, which is fault-based.

The *generation* of the test inputs may be deterministic or probabilistic:

- In **deterministic testing**, test patterns are predetermined by a selective choice.
- In **random**, or **statistical**, **testing**, test patterns are selected according to a defined probability distribution on the input domain; the distribution and the number of input data are determined according to the given fault model or criteria.

Observing the test outputs and deciding whether or not they satisfy the verification conditions is known as the **oracle problem**. The verification conditions may apply to the whole set of outputs or to a compact function of the latter (e.g., a system signature when testing for physical faults in hardware, or to a "partial oracle" when testing for development faults of software [69]). When testing for physical faults, the results—compact or not—anticipated from the system under test for a given input sequence are determined by simulation or from a reference system (**golden unit**). For development faults, the reference is generally the specification; it may also be a prototype, or another implementation of the same specification in the case of design diversity (**back-to-back testing**).

Verification methods can be used in combination. For instance, symbolic execution may be used to facilitate the determination of the testing patterns, theorem proving may be used to check properties of infinite state models [60], and mutation testing may be used to compare various testing strategies [66].

As verification has to be performed throughout a system's development, the above techniques are applicable to the various forms taken by a system during its development: prototype, component, etc.

The above techniques apply also to the verification of fault tolerance mechanisms, especially 1) formal static verification [59], and 2) testing that necessitates faults or errors to be part of the test patterns, that is usually referred to as **fault injection** [2].

Verifying that the system *cannot do more* than what is specified is especially important with respect to what the system should not do, thus with respect to safety and security (e.g., **penetration testing**).

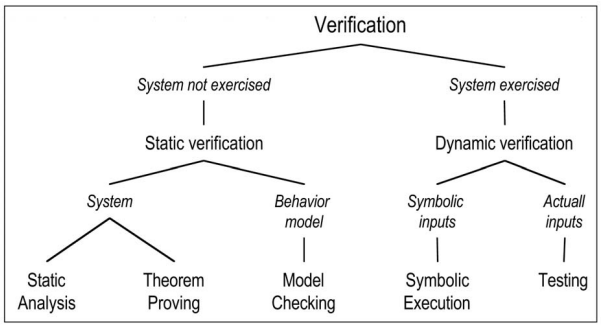


Fig. 19. Verification approaches.

Designing a system in order to facilitate its verification is termed **design for verifiability**. This approach is well-developed for hardware with respect to physical faults, where the corresponding techniques are termed **design for testability**.

5.3.2 Fault Removal During Use

Fault removal *during the use* of a system is corrective or preventive maintenance. Corrective maintenance aims to remove faults that have produced one or more errors and have been reported, while preventive maintenance is aimed at uncovering and removing faults before they might cause errors during normal operation. The latter faults include 1) physical faults that have occurred since the last preventive maintenance actions, and 2) development faults that have led to errors in other similar systems. Corrective maintenance for development faults is usually performed in stages: The fault may be first isolated (e.g., by a workaround or a patch) before the actual removal is completed. These forms of maintenance apply to nonfault-tolerant systems as well as to fault-tolerant systems, that can be maintainable online (without interrupting service delivery) or offline (during service outage).

5.4 Fault Forecasting

Fault forecasting is conducted by performing an *evaluation of the system behavior* with respect to fault occurrence or activation. Evaluation has two aspects:

- **qualitative**, or **ordinal**, **evaluation**, that aims to identify, classify, and rank the failure modes, or the event combinations (component failures or environmental conditions) that would lead to system failures;
- **quantitative**, or **probabilistic**, **evaluation**, that aims to evaluate in terms of probabilities the extent to which some of the attributes are satisfied; those attributes are then viewed as *measures*.

The methods for qualitative and quantitative evaluation are either specific (e.g., failure mode and effect analysis for qualitative evaluation, or Markov chains and stochastic Petri nets for quantitative evaluation), or they can be used to perform both forms of evaluation (e.g., reliability block diagrams, fault-trees).

The two main approaches to probabilistic fault-forecasting, aimed to derive probabilistic estimates, are *modeling* and *(evaluation) testing*. These approaches are complementary since modeling needs data on the basic processes modeled (failure process, maintenance process, system activation process, etc.), that may be obtained either by testing, or by the processing of failure data.

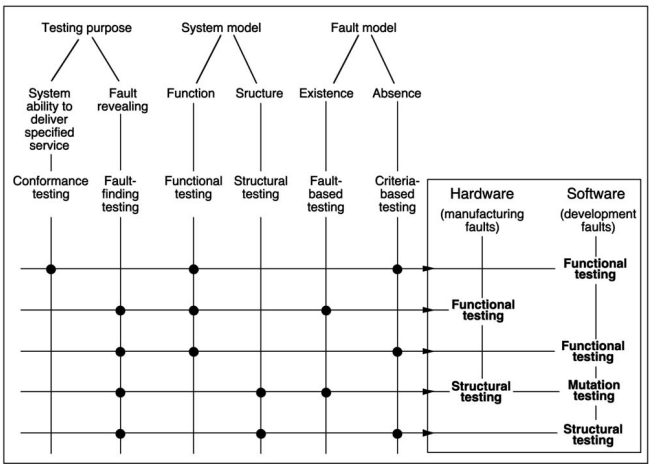


Fig. 20. Testing approaches according to test pattern selection.

Modeling can be conducted with respect to 1) physical faults, 2) development faults, or 3) a combination of both. Although modeling is usually performed with respect to nonmalicious faults, attempts to perform modeling with respect to malicious faults are worth mentioning [49], [61]. Modeling is composed of two phases:

- The *construction* of a model of the system from the elementary stochastic processes that model the behavior of the components of the system and their interactions; these elementary stochastic processes relate to failure, to service restoration including repair, and possibly to system duty cycle or phases of activity.
- *Processing* the model to obtain the expressions and the values of the dependability measures of the system.

Generally, several services can be distinguished, as well as two or more modes of service, e.g., ranging from full capacity to emergency service. These modes distinguish less and less complete service deliveries. Performance-related measures of dependability are usually subsumed into the notion of **performability** [45], [64].

Reliability growth models, either for hardware, for software, or for both, are used to perform reliability predictions from data about past system failures.

Evaluation testing can be characterized using the viewpoints defined in Section 5.3.1, i.e., conformance, functional, non-fault-based, statistical, testing, although it is not—primarily—aimed at verifying a system. A major concern is that the input profile should be representative of the operational profile [46]; hence, the usual name of evaluation testing is **operational testing**.

When evaluating fault-tolerant systems, the coverage provided by error and fault handling mechanisms has a drastic influence [8], [1] on dependability measures. The evaluation of coverage can be performed either through modeling or through testing, i.e., *fault injection*.

The notion of **dependability and security benchmark**, that is a procedure to assess measures of the behavior of a computer system in the presence of faults, enables the integration of the various techniques of fault forecasting in a unified framework. Such a benchmark enables 1) *characterization of* the dependability and security of a system, and 2) *comparison of* alternative or competitive solutions according to one or several attributes [37].

5.5 Relationships between the Means for Dependability and Security

All the "how to's" that appear in the definitions of fault prevention, fault tolerance, fault removal, fault forecasting given in Section 2 are in fact goals that can rarely if ever be fully reached since all the design and analysis activities are human activities, and thus imperfect. These imperfections bring in *relationships* that explain why it is only the *combined* utilization of the above activities—preferably at each step of the design and implementation process—that can best lead to a dependable and secure computing system. These relationships can be sketched as follows: In spite of fault prevention by means of development methodologies and construction rules (themselves imperfect in order to be workable), faults may occur. Hence, there is a need for fault removal. Fault removal is itself imperfect (i.e., all faults cannot be found, and another fault(s) may be introduced when removing a fault), and off-the-shelf components —hardware or software—of the system may, and usually do, contain faults; hence the importance of fault forecasting (besides the analysis of the likely consequences of operational faults). Our increasing dependence on computing systems brings in the requirement for fault tolerance, that is in turn based on construction rules; hence, the need again for applying fault removal and fault forecasting to fault tolerance mechanisms themselves. It must be noted that the process is even more recursive than it appears above: Current computing systems are so complex that their design and implementation need software and hardware tools in order to be cost-effective (in a broad sense, including the capability of succeeding within an acceptable time scale). These tools themselves have to be dependable and secure, and so on.

The preceding reasoning illustrates the close interactions between fault removal and fault forecasting, and motivates their gathering into **dependability and security analysis**, aimed at *reaching confidence* in the ability to deliver a service that can be trusted, whereas the grouping of fault prevention and fault tolerance constitutes **dependability and security provision**, aimed at *providing* the ability to deliver a service that can be trusted. Another grouping of the means is the association of 1) fault prevention and fault removal into **fault avoidance**, i.e., how to *aim for* fault-free systems, and of 2) fault tolerance and fault forecasting into **fault acceptance**, i.e., how to *live with* systems that are subject to faults. Fig. 21 illustrates the groupings of the means for dependability. It is noteworthy that, when focusing on security, such analysis is called *security evaluation* [32].

Besides highlighting the need to assess the procedures and mechanisms of fault tolerance, the consideration of fault removal and fault forecasting as two constituents of the same activity—dependability analysis—leads to a better understanding of the notion of coverage and, thus, of an important problem introduced by the above recursion: *the assessment of the assessment*, or how to reach confidence in the methods and tools used in building confidence in the system. **Coverage** refers here to a measure of the representativeness of the situations to which the system is subjected during its analysis compared to the actual situations that the system will be confronted with during its operational life. The notion of coverage as defined here is very general; it may be made more precise by indicating its range of application, e.g., coverage of a software test with respect to the software text, control graph, etc., coverage of an integrated circuit test with respect to a fault model, coverage of fault tolerance with respect to a class of faults, coverage of a development assumption with respect to reality.

The *assessment* of whether a system is truly dependable and, if appropriate, secure—i.e., the delivered service can justifiably be trusted—goes beyond the analysis techniques as they have been addressed in the previous sections for, at least, the three following reasons and limitations:

- Precise checking of the coverage of the design or validation assumptions with respect to reality (e.g., relevance to actual faults of the criteria used for determining test inputs, fault hypotheses in the design of fault tolerance mechanisms) would imply a knowledge and a mastering of the technology used, of the intended utilization of the system, etc., that exceeds by far what is generally achievable.
- The evaluation of a system for some attributes of dependability, and especially of security with respect to certain classes of faults is currently considered as unfeasible or as yielding nonsignificant results because probability-theoretic bases do not exist or are not yet widely accepted; examples are safety with respect to accidental development faults, security with respect to intentional faults.
- The specifications with respect to which analysis is performed are likely to contain faults—as does any system.

Among the numerous consequences of this state of affairs, let us mention:

- The emphasis placed on the development process when assessing a system, i.e., on the methods and techniques utilized in development and how they are employed; in some cases, a *grade* is assigned and delivered to the system according to 1) the nature of the methods and techniques employed in development, and 2) an assessment of their utilization [51], [58], [32], [65].
- The presence, in the specifications of some fault-tolerant systems (in addition to probabilistic requirements in terms of dependability measures), of a list of types and numbers of faults that are to be tolerated; such a specification would not be necessary if the limitations mentioned above could be overcome (such specifications are classical in aerospace applications, under the form of a concatenation of "fail-operational" (FO) or "fail-safe" (FS) requirements, e.g., FO/FS, or FO/FO/FS, etc.).

6 Conclusion

Increasingly, individuals and organizations are developing or procuring sophisticated computing systems on whose services they need to place great trust—whether to service a set of cash dispensers, control a satellite constellation, an airplane, a nuclear plant, or a radiation therapy device, or to maintain the confidentiality of a sensitive data base. In differing circumstances, the focus will be on differing properties of such services—e.g., on the average real-time response achieved, the likelihood of producing the required results, the ability to avoid failures that could be catastrophic to the system's environment, or the degree to which deliberate intrusions can be prevented. Simultaneous consideration of dependability and security provides a very convenient means of subsuming these various concerns within a single conceptual framework. It includes as special

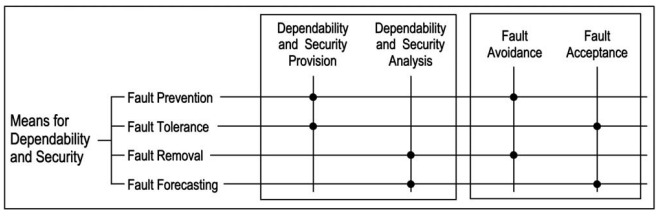


Fig. 21. Groupings of the means for dependability and security.

cases such properties as availability, reliability, safety, confidentiality, integrity, maintainability. It also provides the means of addressing the problem that what a user usually needs from a system is an *appropriate balance* of these properties.

A major strength of the concept formulated in this paper, is its integrative nature; this enables the more classical notions of reliability, availability, safety, confidentiality, integrity, and maintainability to be put into perspective. The fault-error-failure model is central to the understanding and mastering of the various threats that may affect a system, and it enables a unified presentation of these threats, while preserving their specificities via the various fault classes that can be defined. The model provided for the means for achieving dependability and security is extremely useful, as those means are much more orthogonal to each other than the more classical classification according to the attributes of dependability, with respect to which the development of any real system has to perform trade offs since these attributes tend to conflict with each other. The refinement of the basic definitions given in Section 2 leads to a refined dependability and security tree, as given by Fig. 22.

APPENDIX

Index of Definitions

Accidental fault 3.2.1 Accountability 4.3 Active fault 2.2
Adaptive maintenance 3.1 Atomic 2.1
Augmentive maintenance 3.1 Authenticity 4.3
Autonomic computing 4.3 Availability 2.3
Back-to-back testing 5.3.1 Backward recovery 5.2.1
Behavior 2.1 Byzantine failure 3.3.1 Catastrophic failure 3.3.1
Commission fault 3.2.3 Common-mode failure 3.5
Compensation 5.2.1 Component 2.1
Computer-based systems 2 Concurrent detection 5.2.1
Confidentiality 2.3 Configuration fault 3.2.3
Consistency 3.3.1 Consistent failure 3.3.1
Content failure 3.3.1 Correct service 2.2
Corrective maintenance 3.1 Coverage 5.5
Degraded mode 2.2 Deliberate fault 3.2.1
Denial of service 3.2.4
Dependability & security analysis 5.5
Dependability & security benchmark 5.4
Dependability & security failure 3.3.3
Dependability & security provision 5.5
Dependability & security specification 2.3
Dependability 2.3 Dependence 2.3
Design diversity 5.2.2 Design for testability 5.3.1
Design for verifiability 5.3.1 Detectability 3.3.1
Detected error 3.4 Detection and recovery 5.2.1
Deterministic testing 5.3.1 Development environment 3.1
Development failure 3.3.2 Development fault 3.2.1
Development phase 3.1 Diagnosis 5.2.1
Dormant fault 2.2 Downgrading 3.3.2
Dynamic verification 5.3.1 Early timing failure 3.3.1
Elusive fault 3.5 Environment 2.1 Erratic failure 3.3.1
Error 2.2 Error detection and system recovery 5.2.1
Error handling 5.2.1 External fault 3.2.1 External state 2.1
Fail-controlled system 3.3.1 Fail-halt system 3.3.1
Fail-passive system 3.3.1 Fail-safe system 3.3.1
Fail-silent system 3.3.1 Fail-stop system 3.3.1
Failure 2.2 Failure domain 3.3.1 Failure severity 2.2
False alarm 3.3.1 Fault 2.2 Fault acceptance 5.5
Fault activation 3.5 Fault activation reproducibility 3.5
Fault avoidance 5.5 Fault forecasting 2.4
Fault handling 5.2.1 Fault injection 5.3.1
Fault masking 5.2.1 Fault prevention 2.4
Fault removal 2.4 Fault tolerance 2.4
Forward recovery 5.2.1 Function 2.1
Functional specification 2.1 Functional testing 5.3.1
Golden unit 5.3.1 Halt 3.3.1
Halt failure 3.3.1 Hard fault 3.5 Hardware fault 3.2.1
High Confidence 4.4 Human-made fault 3.2.1
Incompetence fault 3.2.1 Inconsistent failure 3.3.1
Independent faults 3.5 Integrity 2.3
Interaction fault 3.2.1 Intermittent fault 3.5
Internal fault 3.2.1 Internal state 2.1
Intrusion attempt 3.2.4 Isolation 5.2.1
Late timing failure 3.3.1 Latent error 3.4 Logic bomb 3.2.4
Maintainability 2.3 Maintenance 3.1
Malicious fault 3.2.1 Malicious logic fault 3.2.4
Masking 5.2.1 Masking and recovery 5.2.1
Minor failure 3.3.1 Multiple faults 3.5
Multiple related errors 3.4 Mutation testing 5.3.1
Natural fault 3.2.1 Nondeliberate fault 3.2.1
Nonmalicious fault 3.2.1 Nonregression verification 5.3.1
Nonrepudiability 4.3 Omission 3.2.3 Omission fault 3.2.3
Operational fault 3.2.1 Operational testing 5.4
Oracle problem 5.3.1 Ordinal evaluation 5.4
Overrun 3.3.2 Partial development failure 3.3.2
Partial failure 2.2 Penetration testing 5.3.1
Performability 5.4 Permanent fault 3.2.1
Physical fault 3.2.1 Preemptive detection 5.2.1
Preventive maintenance 3.1 Probabilistic evaluation 5.4
Provider 2.1 Qualitative evaluation 5.4
Quantitative evaluation 5.4 Random testing 5.3.1
Reconfiguration 5.2.1 Reconfiguration fault 3.2.3
Recovery-oriented computing 5.2.2 Reinitialization 5.2.1
Related faults 3.5 Reliability 2.3 Resilience 5.2.2
Robustness 4.3 Rollback 5.2.1 Rollforward 5.2.1
Safety 2.3 Security 2.3, 4.3 Security policy 4.3
Self-checking component 5.2.2 Self-healing 5.2.2
Self-repair 5.2.2 Service 2.1 Service delivery 3.1
Service failure 2.2 Service failure mode 2.2
Service interface 2.1 Service outage 2.2
Service restoration 2.2 Service shutdown 3.1
Signaled failure 3.3.1 Silence 3.3.1 Silent failure 3.3.1
Single error 3.4 Single fault 3.5 Soft error 3.5
Soft fault 3.5 Software ageing 3.2.3 Software fault 3.2.1
Software rejuvenation 5.2.1 Solid fault 3.5
Static verification 5.3.1 Statistical testing 5.3.1
Structural testing 5.3.1 Structure 2.1 Survivability 4.4
Symbolic execution 5.3.1 System 2.1

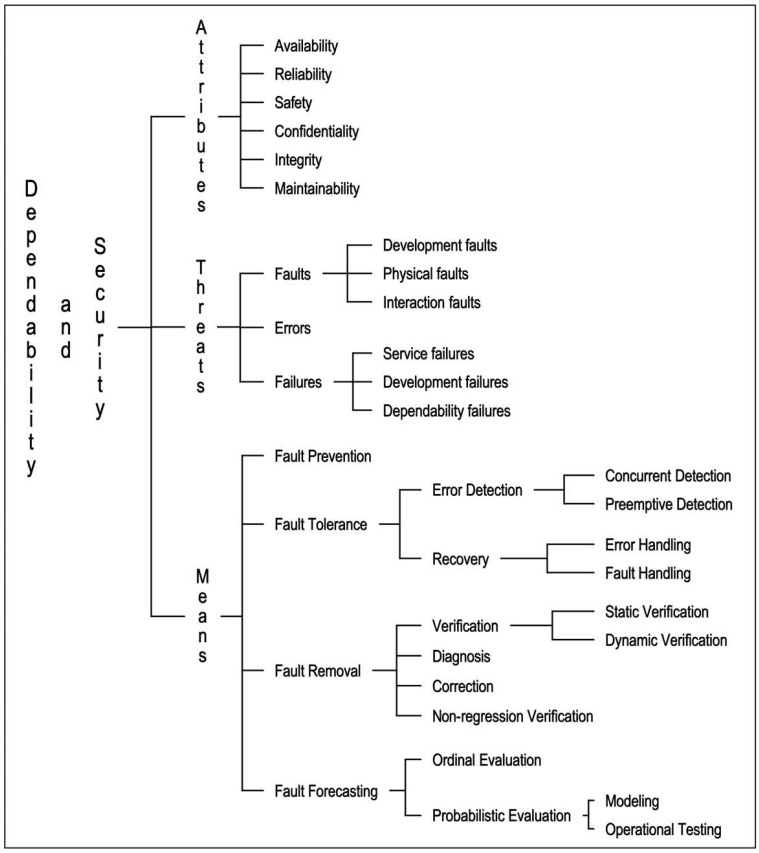


Fig. 22. A refined dependability and security tree.

System boundary 2.1 System life cycle 3.1
System recovery 5.2.1 Testing 5.3.1 Timing failure 3.3.1
Total state 2.1 Transient fault 3.2.1 Transition 2.2
Trapdoor 3.2.4 Trojan horse 3.2.4 Trust 2.3
Trustworthiness 4.4 Unsignaled failure 3.3.1
Use environment 3.1 Use interface 2.1 Use phase 3.1
User 2.1 Validation 5.3.1 Verification 5.3.1 Virus 3.2.4
Vulnerability 2.2 Worm 3.2.4 Zombie 3.2.4

ACKNOWLEDGMENTS

The authors are pleased to acknowledge many fruitful interactions with numerous colleagues, in particular Jean Arlat, Alain Costes, Yves Deswarte, Cliff Jones, and especially with fellow members of IFIP WG 10.4 on Dependable Computing and Fault Tolerance. Early part of this work received support from the CNRS-NSF grant "Tolerance to intentional faults."

REFERENCES

[1] T.F. Arnold, "The Concept of Coverage and Its Effect on the Reliability Model of Repairable Systems," *IEEE Trans. Computers*, vol. 22, no. 6, pp. 251-254, June 1973.

[2] D. Avresky, J. Arlat, J.C. Laprie, and Y. Crouzet, "Fault Injection for Formal Testing of Fault Tolerance," *IEEE Trans. Reliability*, vol. 45, no. 3, pp. 443-455, Sept. 1996.

[3] A. Avižienis, "Design of Fault-Tolerant Computers," *Proc. 1967 Fall Joint Computer Conf., AFIPS Conf. Proc.*, vol. 31, pp. 733-743, 1967.

[4] A. Avižienis and L. Chen, "On the Implementation of N-Version Programming for Software Fault Tolerance During Execution," *Proc. IEEE COMPSAC 77 Conf.*, pp. 149-155, Nov. 1977.

[5] A. Avižienis and Y. He, "Microprocessor Entomology: A Taxonomy of Design Faults in COTS Microprocessors," *Dependable Computing for Critical Applications 7*, C.B. Weinstock and J. Rushby, eds., pp. 3-23, 1999.

[6] A. Avižienis and J.P.J. Kelly, "Fault Tolerance by Design Diversity: Concepts and Experiments," *Computer*, vol. 17, no. 8, pp. 67-80, Aug. 1984.

[7] B.W. Boehm, "Guidelines for Verifying and Validating Software Requirements and Design Specifications," *Proc. European Conf. Applied Information Technology (IFIP '79)*, pp. 711-719, Sept. 1979.

[8] W.G. Bouricius, W.C. Carter, and P.R. Schneider, "Reliability Modeling Techniques for Self-Repairing Computer Systems," *Proc. 24th Nat'l Conf. ACM*, pp. 295-309, 1969.

[9] C. Cachin, J. Camenisch, M. Dacier, Y. Deswarte, J. Dobson, D. Horne, K. Kursawe, J.C. Laprie, J.C. Lebraud, D. Long, T. McCutcheon, J. Muller, F. Petzold, B. Pfitzmann, D. Powell, B. Randell, M. Schunter, V. Shoup, P. Verissimo, G. Trouessin, R.J. Stroud, M. Waidner, and I. Welch, "Malicious- and Accidental-Fault Tolerance in Internet Applications: Reference Model and Use Cases," LAAS report no. 00280, MAFTIA, Project IST-1999-11583, p. 113, Aug. 2000.

[10] V. Castelli, R.E. Harper, P. Heidelberger, S.W. Hunter, K.S. Trivedi, K. Vaidyanathan, and W.P. Zeggert, "Proactive Management of Software Aging," *IBM J. Research and Development*, vol. 45, no. 2, pp. 311-332, Mar. 2001.

[11] "Termes et Définitions Concernant la Qualité de Service, la Disponibilité et la fiabilité,"Recommandation G 106, CCITT, 1984.

[12] Information Technology Security Evaluation Criteria, Harmonized criteria of France, Germany, the Netherlands, the United Kingdom, Commission of the European Communities, 1991.

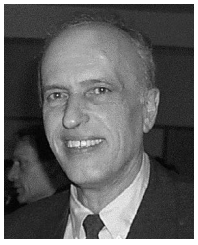
[13] R. Chillarege, I.S. Bhandari, J.K. Chaar, J. Halliday, D.S. Moebus, B.K. Ray, and M.-Y. Wong, "Orthogonal Defect Classification-A Concept for In-Process Measurements," *IEEE Trans. Software Eng.*, vol. 18, no. 11, pp. 943-956, Nov. 1992.

[14] F. Cristian, "Understanding Fault-Tolerant Distributed Systems," *Comm. ACM*, vol. 34, no. 2, pp. 56-78, 1991.

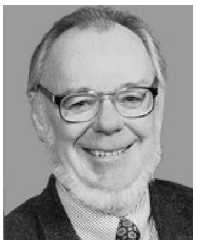
[15] H. Debar, M. Dacier, M. Nassehi, and A. Wespi, "Fixed vs. Variable-Length Patterns for Detecting Suspicious Process Behavior," *Proc. Fifth European Symp. Research in Computer Security,* Sept. 1998.
[16] R.J. Ellison, D.A. Fischer, R.C. Linger, H.F. Lipson, T. Longstaff, and N.R. Mead, "Survivable Network Systems: An Emerging Discipline," Technical Report CMU/SEI-97-TR-013, Carnegie Mellon Univ., May 1999.
[17] J.C. Fabre, V. Nicomette, T. Perennou, R.J. Stroud, and Z. Wu, "Implementing Fault Tolerant Applications Using Reflective Object-Oriented Programming," *Proc 25th IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-25),* pp. 489-498, 1995.
[18] S. Forrest, S.A. Hofmeyr, A. Somayaji, and T.A. Longstaff, "A Sense of Self for Unix Processes," *Proc. 1996 IEEE Symp. Security and Privacy,* pp. 120-128, May 1996.
[19] A. Fox and D. Patterson, "Self-Repairing Computers," *Scientific Am.,* vol. 288, no. 6, pp. 54-61, 2003.
[20] J.M. Fray, Y. Deswarte, and D. Powell, "Intrusion Tolerance Using Fine-Grain Fragmentation-Scattering," *Proc. 1986 IEEE Symp. Security and Privacy,* pp. 194-201, Apr. 1986.
[21] "Fundamental Concepts of Fault Tolerance," *Proc. 12th IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-12),* pp. 3-38, June 1982.
[22] A.G. Ganek and T.A. Korbi, "The Dawning of the Autonomic Computing Era," *IBM Systems J.,* vol. 42, no. 1, pp. 5-18, 2003.
[23] J.N. Gray, "Why do Computers Stop and What Can Be Done About It?" *Proc. Fifth Symp. Reliability in Distributed Software and Database Systems,* pp. 3-12, Jan. 1986.
[24] J. Gray, "Functionality, Availability, Agility, Manageability, Scalability—the New Priorities of Application Design," *Proc. Int'l Workshop High Performance Trans. Systems,* Apr. 2001.
[25] R. Grigonis, "Fault-Resilience for Communications Convergence," Special Supplement to CMP Media's Converging Comm. Group, Spring 2001.
[26] J.E. Hosford, "Measures of Dependability," *Operations Research,* vol. 8, no. 1, pp. 204-206, 1960.
[27] Y. Huang, C. Kintala, N. Kolettis, and N.D. Fulton, "Software Rejuvenation: Analysis, Module and Applications," *Proc. 25th IEEE Int'l Symp. Fault-Tolerant Computing,* pp. 381-390, June 1995.
[28] Y. Huang and C. Kintala, "Software Fault Tolerance in the Application Layer," *Software Fault Tolerance,* M. Lyu, ed., pp. 231-248, 1995.
[29] *Industrial-Process Measurement and Control—Evaluation of System Properties for the Purpose of System Assessment,* Part 5: Assessment of System Dependability, Draft, Publication 1069-5, Int'l Electrotechnical Commission (IEC) Secretariat, Feb. 1992.
[30] "Functional Safety of Elected/Electronic/Programmable Electronic Safety-Related Systems," IEC Standard 61505, 1998.
[31] "Quality Concepts and Terminology," part 1: Generic Terms and Definitions, Document ISO/TC 176/SC 1 N 93, Feb. 1992.
[32] "Common Criteria for Information Technology Security Evaluation,"ISO/IEC Standard 15408, Aug. 1999.
[33] J. Jacob, "The Basic Integrity Theorem," *Proc. Int'l Symp. Security and Privacy,* pp. 89-97, 1991.
[34] J. Johnson, "Chaos: The Dollar Drain of IT Project Failures," *Application Development Trends,* pp. 41-47, Jan. 1995.
[35] M.K. Joseph and A. Avižienis, "A Fault Tolerance Approach to Computer Viruses," *Proc. Symp. Security and Privacy,* pp. 52-58, Apr. 1988.
[36] M.K. Joseph and A. Avižienis, "Software Fault Tolerance and Computer Security: A Shared Problem," *Proc. Ann. Joint Conf. Software Quality and Reliability,* pp. 428-432, Mar. 1988.
[37] "DBench Dependability Benchmarks," DBench, Project IST-2000-25425, K. Kanoun et al., eds., pp. 233, May 2004.
[38] L. Lamport, R. Shostak, and M. Pease, "The Byzantine Generals Problem," *ACM Trans. Programming Languages and Systems,* vol. 4, no. 3, pp. 382-401, July 1982.
[39] C.E. Landwher, A.R. Bull, J.P. McDermott, and W.S. Choi, "A Taxonomy of Computer Program Security Flaws," *ACM Computing Survey,* vol. 26, no. 3, pp. 211-254, 1994.
[40] J.C. Laprie, "Dependable Computing and Fault Tolerance: Concepts and Terminology," *Proc. 15th IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-15),* pp. 2-11, June 1985.
[41] *Dependability: Basic Concepts and Terminology,* J.C. Laprie, ed., Springer-Verlag, 1992.
[42] J.C. Laprie, "Dependability—Its Attributes, Impairments and Means," *Predictably Dependable Computing Systems,* B. Randell et al., eds., pp. 3-24, 1995.
[43] N.A. Lynch, *Distributed Algorithms.* Morgan Kaufmann, 1996.
[44] J. McLean, "A Comment on the 'Basic Security Theorem' of Bell and LaPadula," *Information Processing Letters,* vol. 20, no. 2, pp. 67-70, 1985.
[45] J.F. Meyer, "On Evaluating the Performability of Degradable Computing Systems," *Proc. Eighth IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-8),* pp. 44-49, June 1978.
[46] J. Musa, "The Operational Profile in Software Reliability Engineering: An Overview," *Proc. Third IEEE Int'l Symp. Software Reliability Eng. (ISSRE '92),* pp. 140-154, 1992.
[47] *An Introduction to Computer Security: The NIST Handbook,* Special Publication 800-12, Nat'l Inst. of Standards and Technology, 1995.
[48] National Science and Technology Council, "Information Technology Frontiers for a New Millennium,"Supplement to the Prsident's FY 2000 Budget, 2000.
[49] R. Ortalo, Y. Deswarte, and M. Kaaniche, "Experimenting with Quantitative Evaluation Tools for Monitoring Operational Security," *IEEE Trans. Software Eng.,* vol. 25, no. 5, pp. 633-650, Sept./Oct. 1999.
[50] D. Parnas, "On the Criteria to be Used in Decomposing Systems into Modules," *Comm. ACM,* vol. 15, no. 12, pp. 1053-1058, Dec. 1972.
[51] M.C. Paulk, B. Curtis, M.B. Chrissis, and C.V. Weber, "Capability Maturity Model for Software," Technical Reports CMU/SEI-93-TR-24, ESC-TR-93-177, Software Eng. Inst., Carnegie Mellon Univ., Feb. 1993.
[52] C.P. Pfleeger, "Data Security," *Encyclopedia of Computer Science,* A. Ralston et al., eds., Nature Publishing Group, pp. 504-507, 2000.
[53] D. Powell, G. Bonn, D. Seaton, P. Verissimo, and F. Waeselynck, "The Delta-4 Approach to Dependability in Open Distributed Computing Systems," *Proc. 18th IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-18),* pp. 246-251, June 1988.
[54] D. Powell, "Failure Mode Assumptions and Assumption Coverage," *Proc. 22nd IEEE Int'l Symp. Fault-Tolerant Computing (FTCS-22),* pp. 386-395, June 1992.
[55] "Conceptual Model and Architecture of MAFTIA,"MAFTIA, Project IST-1999-11583, D. Powell and R. Stroud, eds., p. 123, Jan. 2003.
[56] M.O. Rabin, "Efficient Dispersal of Information for Security, Load Balancing and Fault Tolerance," *J. ACM,* vol. 36, no. 2, pp. 335-348, Apr. 1989.
[57] B. Randell, "System Structure for Software Fault Tolerance," *IEEE Trans. Software Eng.,* vol. 1, no. 2, pp. 220-232, June 1975.
[58] "Software Considerations in Airborne Systems and Equipment Certification,"DO-178-B/ED-12-B, Requirements and Technical Concepts for Aviation/European Organization for Civil Aviation Equipement, 1992.
[59] J. Rushby, "Formal Specification and Verification of a Fault-Masking and Transient-Recovery Model for Digital Flight Control Systems," *Proc. Second Int'l Symp. Formal Techniques in Real Time and Fault-Tolerant Systems,* 1992.
[60] J. Rushby, "Formal Methods and Their Role in the Certification of Critical Systems," Technical Report CSL-95-1, SRI Int'l, 1995.
[61] W.H. Sanders, M. Cukier, F. Webber, P. Pal, and R. Watro, "Probabilistic Validation of Intrusion Tolerance," *Supplemental Volume Int'l Conf. Dependable Systems and Networks (DSN-2002),* pp. 78-79, June 2002.
[62] *Trust in Cyberspace.* F. Schneider, ed., Nat'l Academy Press, 1999.
[63] D.P. Siewiorek and R.S. Swarz, *Reliable Computer Systems, Design and Evaluation.* Digital Press, 1992.
[64] R.M. Smith, K.S. Trivedi, and A.V. Ramesh, "Performability Analysis: Measures, an Algorithm, and a Case Study," *IEEE Trans. Computers,* vol. 37, no. 4, pp. 406-417, Apr. 1988.
[65] "Dependability Assessment Criteria," SQUALE project (ACTS95/AC097), LAAS Report no. 98456, Jan. 1999.
[66] P. Thevenod-Fosse, H. Waeselynck, and Y. Crouzet, "An Experimental Study on Softawre Structural Testing: Deterministic Testing Versus Random Input Generation," *Proc. 21st IEEE Int'l Symp. Fault-Tolerant Computing,* pp. 410-417, June 1981.
[67] USA Department of Transportation, Office of Inspector General, "Audit Report: Advance Automation System,"Report AV-1998-113, Apr. 1998.
[68] A. Valdes, M. Almgren, S. Cheung, Y. Deswarte, B. Dutertre, J. Levy, H. Saïdi, V. Stavridou, and T. Uribe, "An Adaptative Intrusion-Tolerant Server Architecture," *Proc. 10th Int'l Workshop Security Protocols,* Apr. 2002.

[69] E.J. Weyuker, "On Testing Nontestable Programs," *The Computer J.*, vol. 25, no. 4, pp. 465-470, 1982.
[70] A. Wood, "NonStop Availability in a Client/Server Environment," Tandem Technical Report 94.1, Mar. 1994.

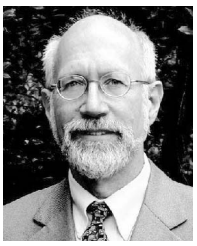
Algirdas Avižienis received the PhD degree from the University of Illinois, USA in 1960. He is a research professor and Professor Honoris Causa at Vytautas Magnus University in Kaunas, Lithuania and Professor Emeritus of UCLA (University of California, Los Angeles). In 1960, he joined the Jet Propulsion Laboratory of Caltech, Pasadena, California, and initiated research on long-life computers for interplanetary spacecraft. There he originated the concept of fault tolerance (1967) and led the construction of the experimental JPL-STAR self-repairing spacecraft computer, for which he received a US Patent (1970). He joined the faculty of UCLA (University of California, Los Angeles) in 1962. He was the director of the Dependable Computing and Fault-Tolerant Systems Laboratory from 1972 to 1994. There he led research on fault-tolerant architectures, software fault tolerance, and design methodology for fault-tolerant systems. He has supervised 31 PhD dissertations and authored or coauthored more than 150 research publications. He became professor emeritus at UCLA in 1994. In 1990-1993 (on leave from UCLA), he served as the first rector of restored Vytautas Magnus University (VMU), the National University of Lithuania, closed by the USSR government in 1950 and reopened in 1989. Starting with 180 first-year students, VMU currently has an enrolment of 7,000, including about 800 master's and 200 doctorate students. He has served at VMU as a research professor since 1994, working on fundamental concepts of dependable computing and on an Immune System Paradigm for design of fault-tolerant systems. His extensive professional activities include service as the founding chairman of the Technical Committee on Fault-Tolerant Computing (IEEE Computer Society) in 1969-1973, and founding chair of IFIP WG 10.4 (Dependable Computing and Fault Tolerance), 1980-1986. His awards include NASA Apollo Achievement Award (1969), fellow of IEEE (1973), AIAA Information Systems Award (1979), NASA Exceptional Service Medal (1980), IFIP Silver Core (1986), D.H.C. degree from IPN of Toulouse, France (1985), IEEE CS Golden Core Member (1996), election to Lithuanian Academy of Sciences (1990).



Jean-Claude Laprie is "directeur de recherche" at CNRS, the French National Organization for Scientific Research. He joined LAAS-CNRS in 1968, where he founded the research group on fault tolerance and dependable computing in 1975, that he directed until he became the director of LAAS in 1997. His research has focused on dependable computing since 1973 and especially on fault tolerance and on dependability evaluation, subjects on which he has authored and coauthored more than 100 papers, as well as coauthored or edited several books. He has also been very active in the formulation of the basic concepts of dependability and the associated terminology; the views developed being widely adopted by the scientific community. His activities have included a large number of collaborations with industry, culminating in the foundation of LIS in 1992, the Laboratory for Dependability Engineering, a joint academia-industry laboratory, that he directed until 1996. He has several high-level involvements in the French community, including the chairmanship of the National Coordination Committee for the Sciences and Technologies of Information and Communication. He has also been very active in the international community, including the chairmanship of the IEEE Computer Society Technical Committee on Fault-Tolerant Computing in 1984-1985, of the IFIP (International Federation for Information Processing) WG 10.4 on Dependable Computing and Fault Tolerance from 1986 to 1995, of IFIP TC 10 on Computer System Technology from 1997 to 2001. He is currently a vice-president of IFIP, and the representant of France in its General Assembly. He received in 1992 the IFIP Silver Core, in 1993 the Silver Medal of the French Scientific Research, and in December 2002 the National Merit Medal.



Brian Randell graduated in mathematics from Imperial College, London in 1957 and joined the English Electric Company where he led a team that implemented a number of compilers, including the Whetstone KDF9 Algol compiler. From 1964 to 1969, he was with IBM in the United States, mainly at the IBM T.J. Watson Research Center, working on operating systems, the design of ultra-high speed computers and computing system design methodology. He then became professor of computing science at the University of Newcastle upon Tyne, where, in 1971, he set up the project that initiated research into the possibility of software fault tolerance, and introduced the "recovery block" concept. Subsequent major developments included the Newcastle Connection, and the prototype distributed secure system. He has been principal investigator on a succession of research projects in reliability and security funded by the Science Research Council (now Engineering and Physical Sciences Research Council), the Ministry of Defence, and the European Strategic Programme of Research in Information Technology (ESPRIT), and now the European Information Society Technologies (IST) Programme. Most recently, he has had the role of project director of CaberNet (the IST Network of Excellence on Distributed Computing Systems Architectures), and of two IST Research Projects, MAFTIA (Malicious- and Accidental-Fault Tolerance for Internet Applications) and DSoS (Dependable Systems of Systems). He has published nearly 200 technical papers and reports, and is the coauthor or editor of seven books. He is now emeritus professor of computing science and a senior research investigator at the University of Newcastle upon Tyne. He is a member of the Conseil Scientifique of the CNRS, France, and has received honorary doctorates from the University of Rennes, and the Institut National Polytechnique of Toulouse, France, and the IEEE Emanuel R. Piore 2002 Award.



Carl Landwehr is a senior research scientist at the University of Maryland's Institute for Systems Research. He is presently on assignment to the US National Science Foundation as a coordinator of the new Cyber Trust theme in the Computer and Information Science and Engineering Directorate. For many years, he headed the Computer Security Section of the Center for High Assurance Computer Systems at the Naval Research Laboratory, where he led research projects to advance technologies of computer security and high-assurance systems. He was the founding chair of IFIP WG 11.3 (Database and Application Security) and is also a member of IFIP WG 10.4 (Dependability and Fault Tolerance). He has received best paper awards from the IEEE Symposium on Security and Privacy and the Computer Security Applications Conference. IFIP has awarded him its Silver Core, and the IEEE Computer Society has awarded him its Golden Core. His research interests span many aspects of trustworthy computing, including high assurance software development, understanding software flaws and vulnerabilities, token-based authentication, system evaluation and certification methods, multilevel security, and architectures for intrusion tolerant systems. He is a senior member of the IEEE.