BASIC CONCEPTS AND TAXONOMY OF DEPENDABLE AND SECURE COMPUTING

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BASICS

• We have discussed the basic issues of dependable systems before.

• Now we will focus more on survivability-related issues of the aforementioned paper.

• Most of the material is directly taken from the paper and (to avoid visual clutter) will not be explicitly cited!
2) BASIC CONCEPTS

• System
  • entity that interacts with other entities
  • includes hardware, software, humans, physical world with its natural phenomena

• system boundary

• function is what it should do, often is described by functional specification in terms of functionality and performance

• behavior is what system does to implement its functions
  • behavior is described by sequence of states
2) BASIC CONCEPTS

- **Total State** of a System defined by following:
  - computation
  - communication
  - stored information
  - interconnection
  - physical condition
2) BASIC CONCEPTS

• Structure of a system
  • set of **components** that interact
  • each component is another system
    • recursive definition
    • stops with atomic component
      • i.e., no need or not possible to further break down
2) BASIC CONCEPTS

• Service delivered by a system
  • in its role as provider
• user is another system receiving service from the provider
• service interface is the boundary where service delivery takes place
• user sees external state of provider; remaining part is internal state
• user receives service at use interface
2) BASIC CONCEPTS

• Threats to Dependability and Security
  • **Service failure**, or just **failure**
    • delivered service deviates from correct service
  • **transition** from correct to incorrect service
2) BASIC CONCEPTS

- Threats to Dependability and Security
  - **Service outage**
    - period of delivery of incorrect service
  - **Service restoration**
    - transition from incorrect to correct service
  - deviation from correct service may assume different forms: *service failure modes*
2) BASIC CONCEPTS

• Failure, error, fault
  • Service is sequence of system’s external states
  • Service failure means \( \exists \) at least one external state of the system that deviates from the correct service state
  • That deviation is called an error
  • The cause of the error is called fault
2) BASIC CONCEPTS

• Faults

• internal fault or external

• 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
2) BASIC CONCEPTS

• typically: **fault** causes **error**, which can cause **failure**
  
  • fault is **active** when it causes an error
  
  • otherwise it is **dormant**
2) BASIC CONCEPTS

• If functional specification of a system includes a set of several functions, then
  • failure of one or more services that implement the function may leave system in a **degraded mode**
  • still offers subset of needed services
  • e.g., slower, limited service, emergency service
  • system is said to have suffered **partial failure**
2) BASIC CONCEPTS

• Dependability Security and their Attributes
  • original definition of **dependability**
    • “ability to deliver service that can justifiably be trusted”
  • alternate definition
    • “ability to avoid service failures that are more frequent and more severe than is acceptable”
2) BASIC CONCEPTS

• Trust
  • dependence of system A on system B represents the extend to which system A’s dependability is affected by that of system B
  • concept of dependence leads to that of trust,
    • trust = accepted dependence
• Dependability 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.
2) BASIC CONCEPTS

• when addressing security we add
  • **confidentiality**, the absence of unauthorized disclosure of information
  • Security is composite of the attributes
    • confidentiality
    • integrity
    • availability
2) BASIC CONCEPTS

- Dependability and security attributes

![Dependability and security attributes diagram]

Dependability
- Availability
- Reliability
- Safety
- Confidentiality
- Integrity
- Maintainability

Security
2) BASIC CONCEPTS

• Dependability and security tree

![Dependability and Security Tree](image-url)
2) BASIC CONCEPTS

- Means to attain dependability and security:
  - **Fault prevention**: prevent the occurrence or introduction of faults.
  - **Fault tolerance**: avoid service failures in the presence of faults.
  - **Fault removal**: reduce the number and severity of faults.
  - **Fault forecasting**: estimate the present number, the future incidence, and the likely consequences of faults.
3) THREATS TO DEPENDABILITY AND SECURITY

• 3.1: System Life Cycle: Phases and Environment

• Development phase: all activities from initial concept to green light

  • Development Environment of system consists of

    • physical world with its natural phenomena

    • human developers (+lacking competence, malicious objective)

    • development tools: software and hardware

    • production and test facilities
3) THREATS TO DEPENDABILITY AND SECURITY

• **Use phase**
  • System is accepted for use and starts delivering services.
  • Alternating periods of:
    Service delivery
    Service outage
    Service shutdown
  • Maintenance may take place during all three periods of use phase
USE ENVIRONMENT ELEMENTS:

• **Physical world**: with its natural phenomena

• **Administrators** (includes maintainers): have authority to manage, modify, repair and use system. Some authorized humans may lack competence of have malicious objectives
USE ENVIRONMENT ELEMENTS:

- **Users**: humans or other system that receive services
- **Providers**: humans or other systems that deliver services
- **Infrastructure**: entities that provide services to the system, e.g., information sources (time, GPS) communications equipment/links, power, cooling etc.
**USE ENVIRONMENT ELEMENTS:**

- **Intruders:** malicious entities (human or other systems)
  - attempt to exceed authority they have
  - alter services
  - halt them
  - alter system's functionality or performance
  - access confidential information
  - examples: hackers, vandals, corrupt insiders, governments, malicious software

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MAINTENANCE

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:

1. Development faults that include all fault classes occurring during development,
2. Physical faults that include all fault classes that affect hardware,
3. 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.
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-
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3.2.3 ON HUMAN-MADE FAULTS

• Non-malicious faults

  • introduced without malicious objectives

• non-deliberate fault: due to mistakes, i.e., unintended action, developer/operator/maintainer is not aware

• deliberate fault: due to bad decisions, i.e., unintended action that are wrong and cause faults
3.2.3 ON HUMAN-MADE FAULTS

- Non-malicious faults
  - further partitioning into:
    - accidental faults
    - incompetence faults
Fig. 6. Classification of human-made faults.
NON-MALICIOUS FAULTS

• Incompetence faults
  • individual, group, organization
  • e.g., Advance Automation System to replace aging USA air traffic control system
NON-MALICIOUS FAULTS

• Deployment faults
  • hardware
    • e.g., HW “errata” are listed in specification updates
    • may continue during lifetime of the product
  • software
    • software aging: progressively accrued error conditions cause performance degradation of failure
    • e.g., memory bloating/leaking, unterminated threads, storage space fragmentation, accumulation of round-off errors, ...
3.2.4 ON MALICIOUS FAULTS

• Malicious human-made faults
  • typical goals:
    • disrupt or halt service => denial of service
    • access confidential information
    • improperly modify the systems
3.2.4 ON MALICIOUS FAULTS

• Malicious logic faults
  • development faults: e.g., Trojan horses, logic or timing bombs, trapdoors
  • operational faults: e.g. viruses, worms, zombies
• Intrusion attempts
  • operational external faults. May be performed by system operators/admins
  • may use physical means to cause faults, e.g., power fluctuation, radiation, wire-tapping, heating/cooling
**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 propogates 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.
3.2.5 ON INTERACTION FAULTS

• Occur in use phase
  • elements of the use environment interaction with the system
  • all external
  • human-made

• Examples
  • configuration faults, reconfiguration faults
3.3 FAILURES

- Service failure
  - def.: event that occurs when the delivered service deviates from correct service
- service failure modes: different ways in which deviation is manifested
- content failure: content of info delivered deviates from implementing the system function
- timing failure: time of arrival (early or late) or duration of info delivered at service interface deviates from implementing the system function.
3.3 FAILURES

• Service failure cont.
  • both information and timing are incorrect:
    • *halt failure*: external state becomes constant
    • *silent failure*: no service is delivered at interface
    • *erratic failure*: service is delivered (not halted) but is erratic, e.g. babbling
3.3 FAILURES

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

• Consistency

  • consistent failures: incorrect service is perceived identically by all system users
  
  • inconsistent failures: some of all users perceive differently incorrect service.

Byzantine failures
SERVICE FAILURE MODES

Fig. 9. Service failure modes.
3.3.2 DEVELOPMENT FAILURES

• Budget failure
  • “broke” before system passes acceptance testing

• Schedule failure
  • schedule slips to a point in the future where the system would be technologically obsolete or functionally inadequate for user’s needs
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 AVI/C20.
EXAMPLES

- traditional hardware fault tolerance view
  - physical fault (may be dormant), e.g., stuck-at
  - produces error
  - may result in failure
EXAMPLES

• programming “bug”
  • error by programmer leads to failure to write the correct instruction or data
• this results in a (dormant) fault in code or data
• upon activation the fault becomes active and produces an error
• this error may result in failure
EXAMPLES

• Specification related
  • error by a specifier leads to failure to describe a function
  • this results in a fault in a written specification, e.g., incomplete description of a function.
  • this incomplete function may deliver service different from expected service
  • user perceives this as error resulting in failure
EXAMPLES

• Inappropriate human-system interaction
  • inappropriate human-system interaction performed by operator during operation of system
  • results in external fault (from system’s viewpoint)
  • resulting altered processed data is an error...
EXAMPLES

• Reasoning

  • error in reasoning leads to a maintenance or operating manual writer’s failure to write correct directives

  • results in a fault in the manual (faulty directives) that will remain dormant as long as the directives are not acted upon...
EXAMPLES

• Combined action of several faults
  • consider trap-door (by-pass access control)
  • this is a development fault
  • remains dormant until exploited
  • intruder login is deliberate interaction fault
  • intruder may create an error -> service affected -> failure
HARD AND SOFT FAULTS

- Hard (or solid) faults
  - fault activation is reproducible
- Soft (or elusive) faults
  - not systematically reproducible

Fig. 13. Solid versus intermittent faults.
4. DEPENDABILITY AND SECURITY

• From definition point of view

Fig. 14. Relationship between dependability and security.
4. DEPENDENCE AND TRUST

• Dependence
  • 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.
  • 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.

• Trust
  • Trust is accepted dependence.
4. DEPENDENCE AND TRUST

• Levels of dependence
  • from total dependence to complete independence

• Accepted dependence
  • judgement that level of dependence is acceptable
  • judgement possibly explicit, e.g., contract between “parties”
  • judgement may be unwilling, e.g., there is no other option!

• 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 ATTRIBUTES OF DEP. & SEC.

• Availability, integrity, maintainability, reliability, safety, confidentiality...

• Don’t think binary, absolute, or deterministic

• Do think relative and probabilistic
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 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. HE MEANS TO A TTAIN D EPENDABILITY AND S ECURITY

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

<table>
<thead>
<tr>
<th>Concept</th>
<th>Dependability</th>
<th>High Confidence</th>
<th>Survivability</th>
<th>Trustworthiness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goal</td>
<td>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</td>
<td>consequences of the system behavior are well understood and predictable</td>
<td>capability of a system to fulfill its mission in a timely manner</td>
<td>assurance that a system will perform as expected</td>
</tr>
<tr>
<td>Threats present</td>
<td>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)</td>
<td>• internal and external threats • naturally occurring hazards and malicious attacks from a sophisticated and well-funded adversary</td>
<td>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)</td>
<td>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)</td>
</tr>
</tbody>
</table>
5.1 FAULT PREVENTION

• General engineering
  • e.g., prevention of development faults

• development methodologies
  • SW: e.g., information hiding, modularization strongly-typed programming languages

• HW: e.g., design rules
5.1 FAULT TOLERANCE

• Concepts
  • Diagnosis
  • Rollback recovery
  • Forward recovery
  • Fault masking
  • How are these concepts related?
one of the important benefits of the self-checking component approach is the ability to give a clear definition of error confinement areas. 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 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 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.

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: conservativ...
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The lack of error and fault handling coverage has been shown to be a drastic limit to dependability improvement. 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. 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. 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. Fault tolerance applies to all classes of faults. Protection against intrusions traditionally involves cryptography.

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5.3 FAULT REMOVAL

• During Development
  • Verification
    • the process of checking whether the system adheres to given properties, termed the verification conditions
  • Diagnosis
    • diagnosing the fault(s) that prevented the verification conditions from being fulfilled
  • Correction
    • after correction repeat verification: nonregression verification
5.3 FAULT REMOVAL

• Static Verification
  • Verification without actual execution
• On System:
  • use static analysis
  • theorem proving
• On Model of system behavior
  • model checking: state transition model
  • e.g., Petri net, state automata
SIDE NOTE

• What is the relationship between Specification and what has been implemented?
  • discussion on mapping in two directions
VERIFICATION APPROACHES

Fig. 19. Verification approaches.
5.4 FAULT FORECASTING

• Predictive approach

• **qualitative evaluation**, 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**, aims to evaluate in terms of probabilities the extent to which some of the attributes are satisfied; those attributes are then viewed as measures.