Reliability

Basic concepts and properties

Computadores II / 2005-2006

Characteristics of a RTS

- Large and complex
- Concurrent control of separate system components
- Facilities to interact with special purpose hardware
- Guaranteed response times
- **Extreme reliability**
- Efficient implementation

Reliability

- Goal
  - To understand the factors which affect the reliability of a system and how software design faults can be tolerated.
- Topics
  - Reliability, failure and faults
  - Failure modes
  - Fault prevention and fault tolerance
  - N-Version programming
  - Software dynamic redundancy
  - The recovery block approach to software fault tolerance
  - Dynamic redundancy and exceptions
  - Safety, reliability and dependability

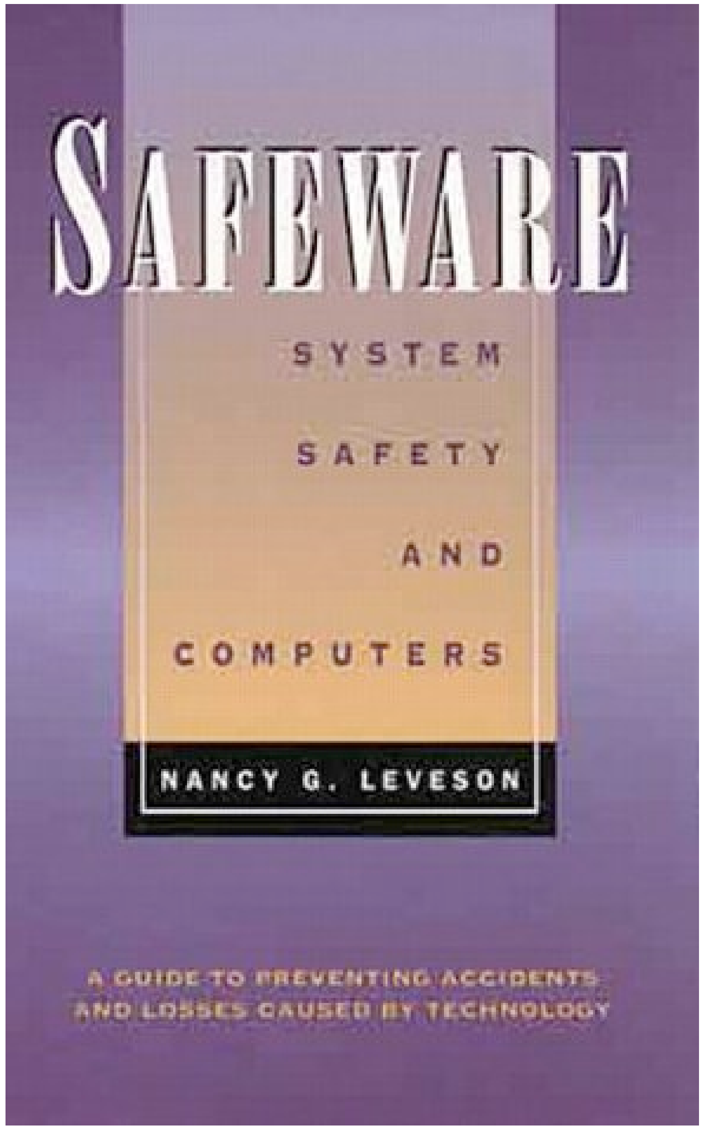
Scope

Four sources of faults which can result in system failure:

- Inadequate specification
- **Design errors in software**
- Processor failure
- Interference on the communication subsystem

Interesting reading

- Nancy Leveson
  Safeware: System Safety and Computers


SAFEWARE
SYSTEM SAFETY AND COMPUTERS
NANCY G. LEVESON
A GUIDE TO PREVENTING ACCIDENTS AND LOSSES CAUSED BY TECHNOLOGY

Reliability, Failure and Faults

- The **reliability** of a system is a measure of the success with which it conforms to some authoritative specification of its behaviour
- When the behaviour of a system deviates from that which is specified for it, this is called a **failure**
- Failures result from unexpected problems internal to the system which eventually manifest themselves in the system's external behaviour
- These problems are called **errors** and their mechanical or algorithmic cause are termed **faults**

  Fault → Error → Failure
- Systems are composed of components which are themselves systems: hence

  Fault → Error → Failure → Fault → Error → Failure

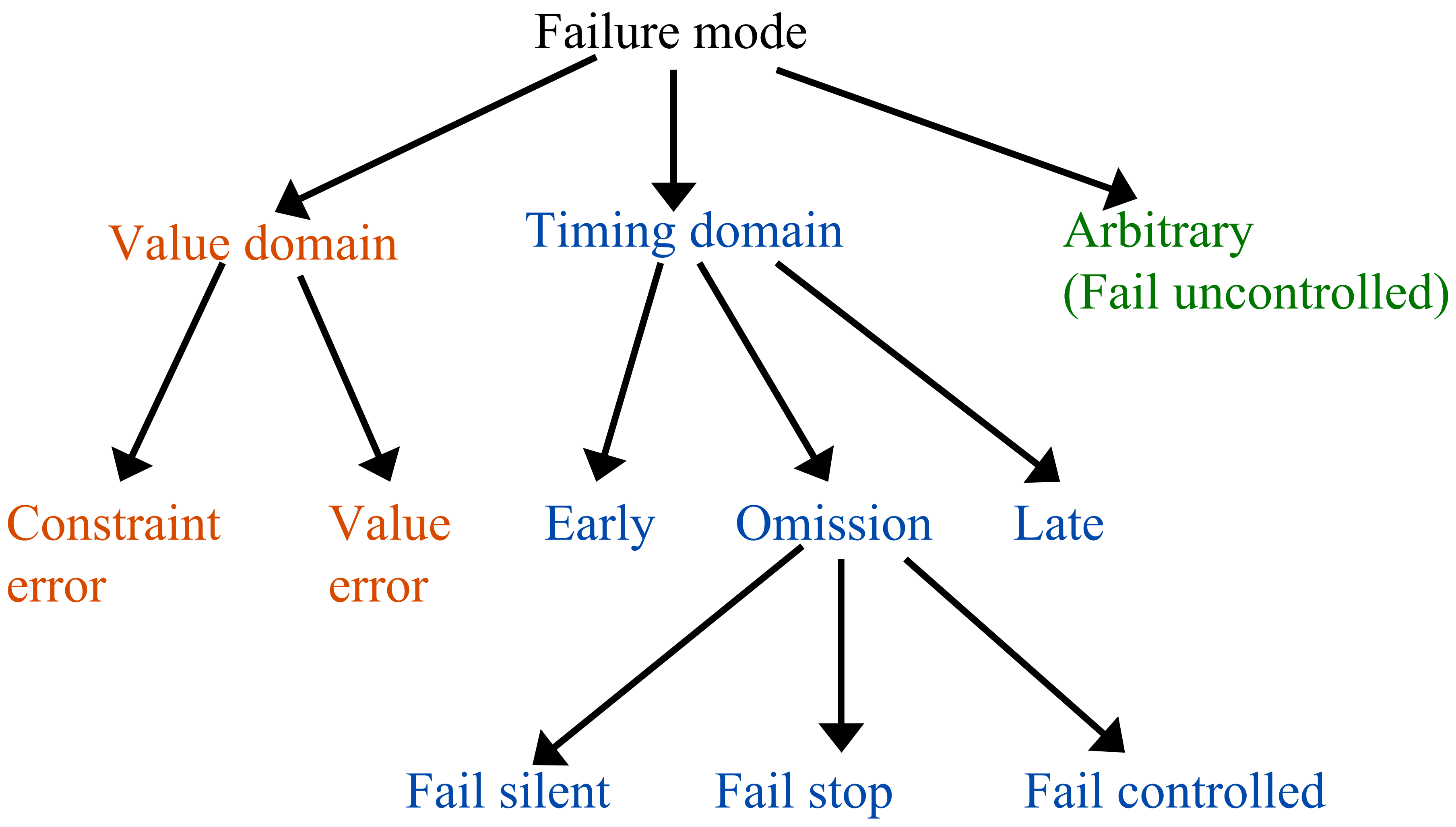
Fault Types

- A **transient fault** starts at a particular time, remains in the system for some period and then disappears
  - E.g. hardware components which have an adverse reaction to radioactivity
  - Many faults in communication systems are transient

- **Permanent faults** remain in the system until they are repaired; e.g., a broken wire or a software design error.

- **Intermittent faults** are transient faults that occur from time to time
  - E.g. a hardware component that is heat sensitive, it works for a time, stops working, cools down and then starts to work again

Failure Modes



Approaches to Reliability

- **Fault prevention** attempts to eliminate any possibility of faults creeping into a system before it goes operational
- **Fault tolerance** enables a system to continue functioning even in the presence of faults
- Both approaches attempt to produces systems which have well-defined failure modes

Fault Prevention

- Two modes/stages

- **Fault avoidance**
  - Not having faults
  - Attempts to limit the introduction of faults during system construction

- **Fault removal**
  - Removing them before manifesting
  - procedures for finding and removing the causes of errors; e.g. design reviews, program verification, code inspections and system testing

Fault avoidance

- use of the most **reliable components** within the given cost and performance constraints
- use of **thoroughly-refined techniques** for interconnection of components and assembly of subsystems
- packaging the hardware to **screen out** expected forms of **interference**.
- **rigorous**, if not formal, specification of **requirements**
- use of **proven design methodologies**
- use of languages with facilities for **data abstraction and modularity**
- use of **software engineering environments** to help manipulate software components and thereby manage complexity

Fault Removal

- In spite of fault avoidance, design errors in both hardware and software components will exist
- **System testing** can never be exhaustive and remove all potential faults
  - A test can only be used to show the presence of faults, not their absence.
  - It is sometimes impossible to test under realistic conditions
  - Most tests are done with the system in simulation mode and it is difficult to guarantee that the simulation is accurate
  - Errors that have been introduced at the requirements stage of the system's development may not manifest themselves until the system goes operational

Failure of Fault Prevention

- In spite of all the testing and verification techniques, hardware components will fail; the fault prevention approach will therefore be unsuccessful when
  - either the frequency or duration of repair times are unacceptable, or
  - the system is inaccessible for maintenance and repair activities

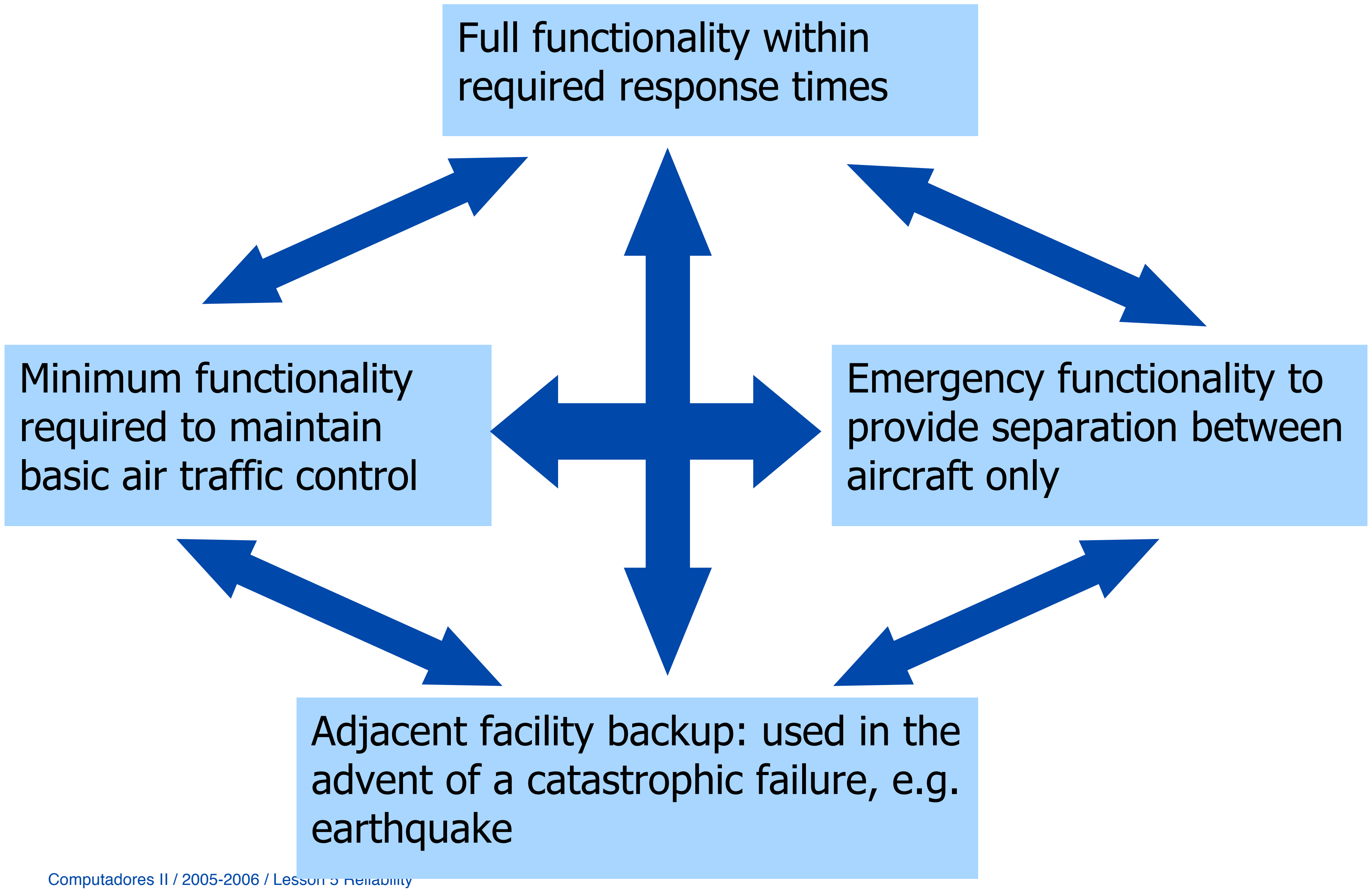
- An extreme example of the latter is a crewless spacecraft

- The alternative is **Fault Tolerance**

Levels of Fault Tolerance

- **Full Fault Tolerance** — the system continues to operate in the presence of faults, albeit for a limited period, with no significant loss of functionality or performance
- **Graceful Degradation** (fail soft) — the system continues to operate in the presence of errors, accepting a partial degradation of functionality or performance during recovery or repair
- **Fail Safe** — the system maintains its integrity while accepting a temporary halt in its operation
- The level of fault tolerance required will depend on the application
- Most safety critical systems require full fault tolerance, however in practice many settle for graceful degradation

Graceful Degradation in an ATC


Full functionality within required response times
Minimum functionality required to maintain basic air traffic control
Emergency functionality to provide separation between aircraft only
Adjacent facility backup: used in the advent of a catastrophic failure, e.g. earthquake

Redundancy

- All fault-tolerant techniques rely on **extra elements** introduced into the system to detect & recover from faults
- Components are redundant as they are not required in a perfect system
- This is often called protective redundancy
- Aim: minimise redundancy while maximising reliability, subject to the cost and size constraints of the system
- Warning: the added components inevitably increase the complexity of the overall system
- This itself can lead to less reliable systems
- It is advisable to separate out the fault-tolerant components from the rest of the system

Hardware Fault Tolerance

- Two types: **static** (or masking) and **dynamic** redundancy
- **Static**
  - Redundant components are used inside a system to hide the effects of faults; e.g. **Triple Modular Redundancy**
  - **TMR** — 3 identical subcomponents and majority voting circuits; the outputs are compared and if one differs from the other two that output is masked out
  - Assumes the fault is not common (such as a design error) but is either transient or due to component deterioration
  - To mask faults from more than one component requires **NMR**
- **Dynamic**
  - Redundancy supplied inside a component which indicates that the output is in error; provides an error detection facility; recovery must be provided by another component
  - E.g. communications checksums and memory parity bits

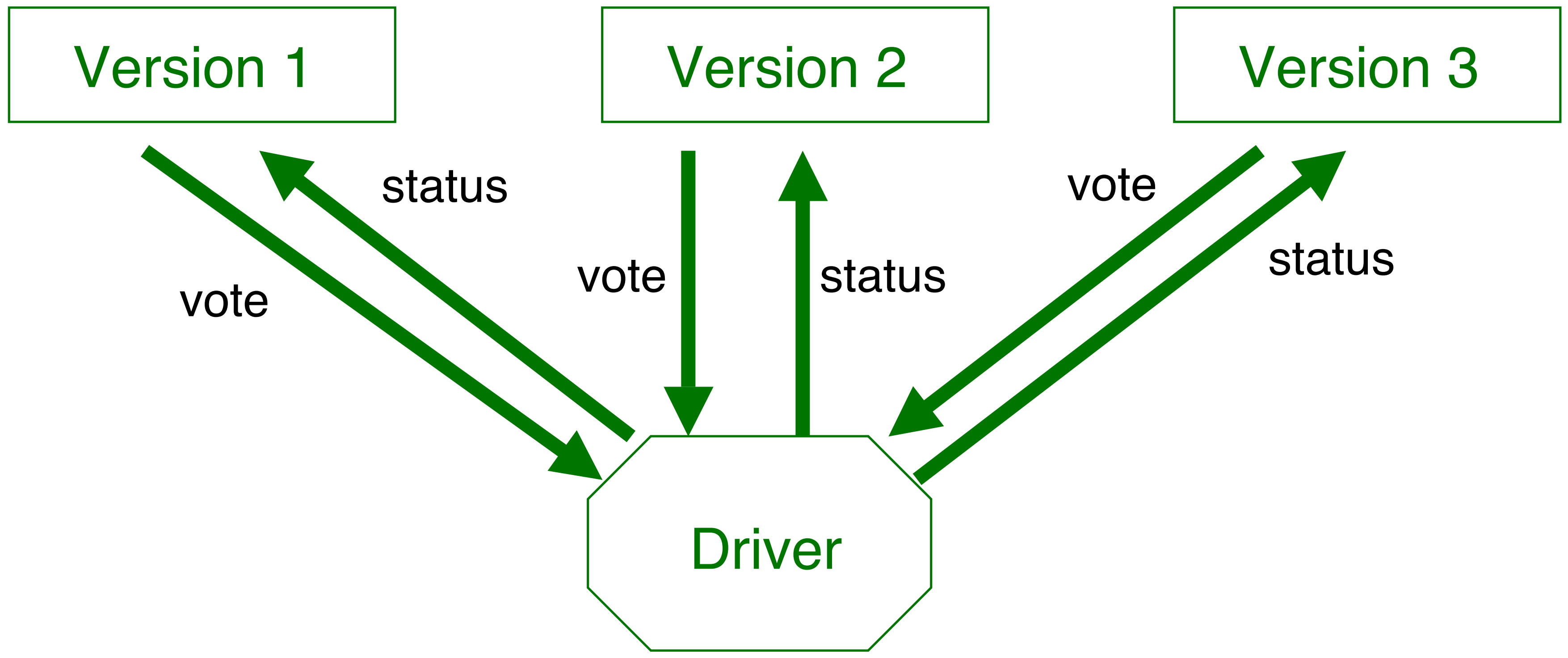
Software Fault Tolerance

- Used for detecting design errors
- Static — **N-Version programming**
- Dynamic
  - Detection and Recovery
  - Recovery blocks: backward error recovery
  - Exceptions: forward error recovery

N-Version Programming

- **Design/implementation diversity**
- The independent generation of N (N > 2) functionally equivalent programs from the same initial specification
- No interactions between development groups
- The programs execute concurrently with the same inputs and their results are compared by a driver process
- The results (votes) should be identical, if different the consensus result, assuming there is one, is taken to be correct

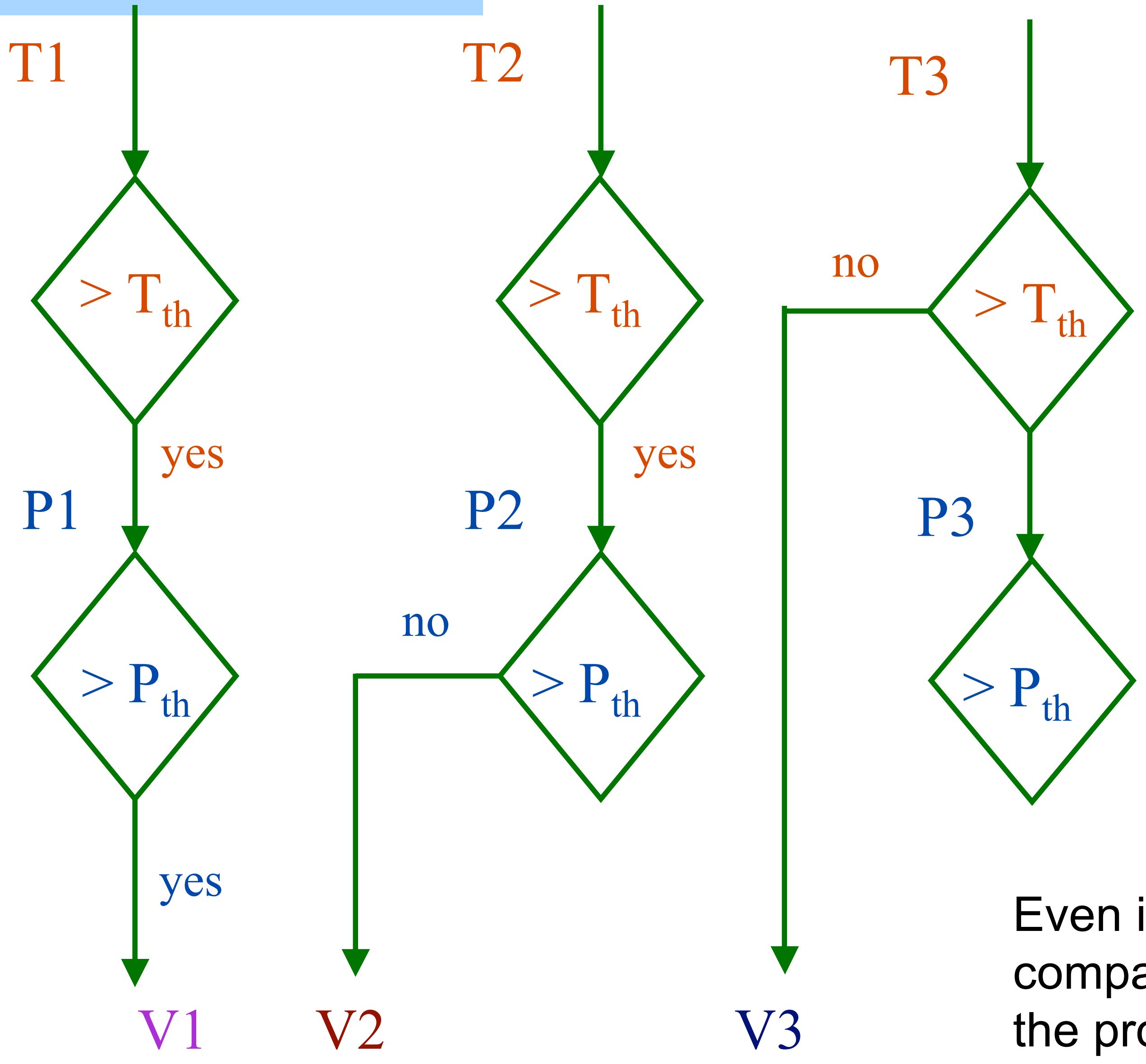
N-Version Programming



Vote Comparison

- To what extent can votes be compared?
- Text or integer arithmetic will produce identical results
- Real numbers $\rightarrow$ different values
- Need inexact -fuzzy- voting techniques

Consistent Comparison Problem



Each version can produce a **different but correct** result

Even if use inexact comparison techniques, the problem occurs

N-version programming depends

- **Initial specification**
  - The majority of software faults stem from inadequate specification? A specification error will manifest itself in all N versions of the implementation
- **Independence of effort**
  - Experiments produce conflicting results. Where part of a specification is complex, this leads to a lack of understanding of the requirements. If these requirements also refer to rarely occurring input data, common design errors may not be caught during system testing
- **Adequate budget**
  - The predominant cost is software. A 3-version system will triple the budget requirement and cause problems of maintenance. Would a more reliable system be produced if the resources potentially available for constructing an N-versions were instead used to produce a single version?

military versus **civil** avionics industry

Software Dynamic Redundancy

- Four phases
- **Error detection**
  - no fault tolerance scheme can be utilised until the associated error is detected
- **Damage confinement and assessment**
  - to what extent has the system been corrupted? The delay between a fault occurring and the detection of the error means erroneous information could have spread throughout the system
- **Error recovery**
  - techniques should aim to transform the corrupted system into a state from which it can continue its normal operation (perhaps with degraded functionality)
- **Fault treatment and continued service**
  - an error is a symptom of a fault; although damage repaired, the fault may still exist

Error Detection

- **Environmental detection**
  - hardware — e.g. illegal instruction
  - OS/RTS — null pointer
- **Application detection**
  - Replication checks
  - Timing checks
  - Reversal checks
  - Coding checks
  - Reasonableness checks
  - Structural checks
  - Dynamic reasonableness check

Confinement and Assessment

- Damage assessment is closely related to damage confinement techniques used
- Damage confinement is concerned with structuring the system so as to minimise the damage caused by a faulty component (also known as **firewalling**)
- **Modular decomposition** provides static damage confinement; allows data to flow through well-define pathways
- **Atomic actions** provides dynamic damage confinement; they are used to move the system from one consistent state to another

Error Recovery

- Probably the most important phase of any fault-tolerance technique
- Two approaches: **forward** and **backward**

Forward Error Recovery (FER)

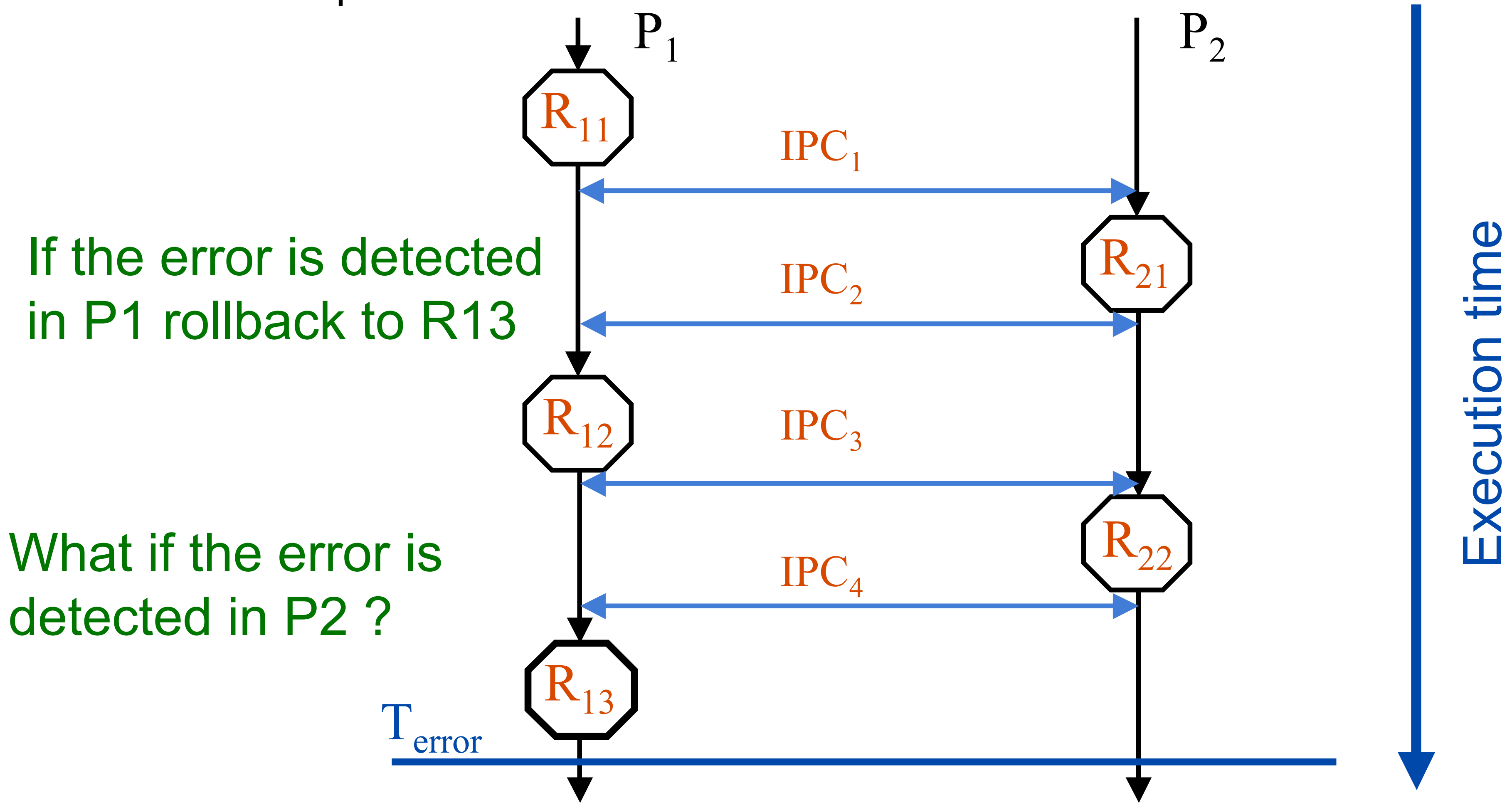
- FER continues from an erroneous state by making **selective corrections** to the system state
- This includes making safe the controlled plant which may be hazardous or damaged because of the failure
- It is system-specific and depends on accurate predictions of the location and cause of errors (i.e, damage assessment)
- Examples: redundant pointers in data structures and the use of self-correcting codes such as Hamming Codes

Backward Error Recovery (BER)

- BER relies on restoring the system to a previous safe state and executing an **alternative section** of the program
- This has the same functionality but uses a different algorithm (c.f. N-Version Programming) and therefore no fault
- The point to which a process is restored is called a **recovery point** and the act of establishing it is termed **checkpointing** (saving appropriate system state)
- Advantage: the erroneous state is cleared and it does not rely on finding the location or cause of the fault
- BER can, therefore, be used to **recover from unanticipated faults** including design errors
- But it cannot undo errors in the plant!

The Domino Effect

- With concurrent processes that interact with each other, BER is more complex



Fault Treatment

- ER returned the system to an error-free state; however, the error may recur; the final phase of F.T. is to eradicate the fault from the system
- The automatic treatment of faults is difficult and system-specific
- Some systems assume all faults are transient; others that error recovery techniques can cope with recurring faults
- Fault treatment can be divided into 2 stages:
  - fault location
  - system repair
- Error detection techniques can help to trace the fault to a component. For, hardware the component can be replaced
- A software fault can be removed in a new version of the code
- In non-stop applications it will be necessary to modify the program while it is executing!

The Recovery Block approach

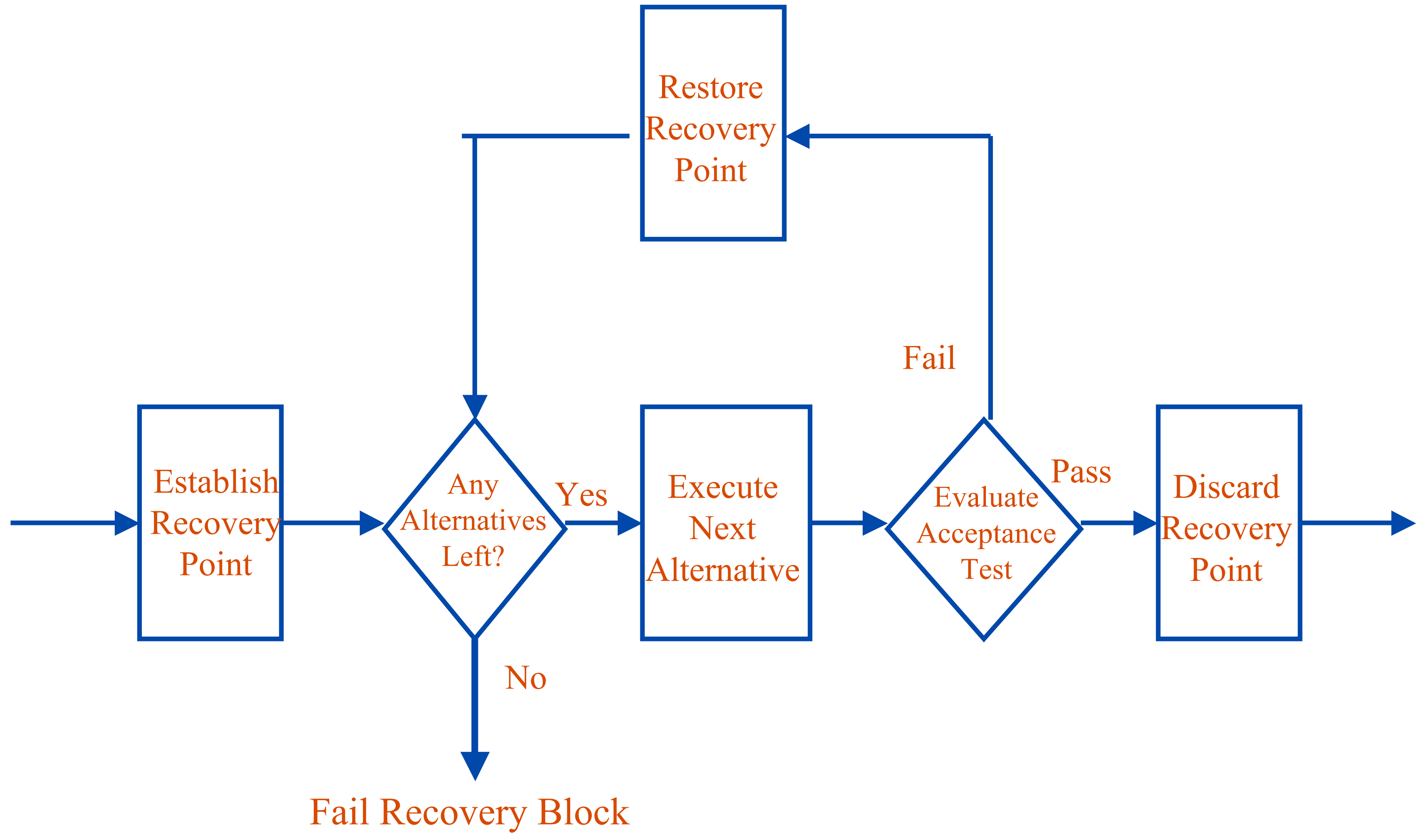
- Language support for BER
- At the entrance to a block is an **automatic recovery point** and at the exit an **acceptance test**
  - The acceptance test is used to test that the system is in an acceptable state after the block's execution (primary module)
  - If the acceptance test fails, the program is restored to the recovery point at the beginning of the block and an alternative module is executed
  - If the alternative module also fails the acceptance test, the program is restored to the recovery point and yet another module is executed, and so on
  - If all modules fail then the block fails and recovery must take place at a higher level

Recovery Block Syntax

```
ensure <acceptance test>
by
   <primary module>
else by
   <alternative module>
else by
   <alternative module>
   ...
else by
   <alternative module>
else error
```

- Recovery blocks can be nested
- If all alternatives in a nested recovery block fail the acceptance test, the outer level recovery point will be restored and an alternative module to that block executed

Recovery Block Mechanism



Example: Differential Equation

```
ensure Rounding_err_has_acceptable_tolerance
by
  Explicit Kutta Method
else by
  Implicit Kutta Method
else error
```

- Explicit Kutta Method fast but inaccurate when equations are stiff
- Implicit Kutta Method more expensive but can deal with stiff equations
- The above will cope with all equations
- It will also potentially tolerate design errors in the Explicit Kutta Method if the acceptance test is flexible enough

Nested Recovery Blocks

```
ensure rounding_err_has_acceptable_tolerance
by
  ensure sensible_value
  by
    Explicit Kutta Method
  else by
    Predictor-Corrector K-step Method
  else error
else by
  ensure sensible_value
  by
    Implicit Kutta Method
  else by
    Variable Order K-Step Method
  else error
else error
```

The Acceptance Test

- The acceptance test provides the **error detection** mechanism which enables the redundancy in the system to be exploited
- The design of the acceptance test is crucial to the efficacy of the RB scheme
- There is a trade-off between providing comprehensive acceptance tests and keeping overhead to a minimum, so that fault-free execution is not affected much
- Note that the term used is **acceptance** not **correctness**; this allows a component to provide a degraded service
- All the previously discussed error detection techniques can be used to form the acceptance tests
- However, care must be taken as a faulty acceptance test may lead to residual errors going undetected

N-Version Program vs Recovery Blocks

- **Static** (NV) versus **dynamic** redundancy (RB)
- **Design overheads**
  - both require alternative algorithms, NV requires driver, RB requires acceptance test
- **Runtime overheads**
  - NV requires N* resources, RB requires establishing recovery points
- **Diversity of design**
  - both susceptible to errors in requirements
- **Error detection**
  - vote comparison (NV) versus acceptance test(RB)
- **Atomicity**
  - NV vote before it outputs to the environment, RB must be structured to output only if following the passing of an acceptance test

Dynamic Redundancy and Exceptions

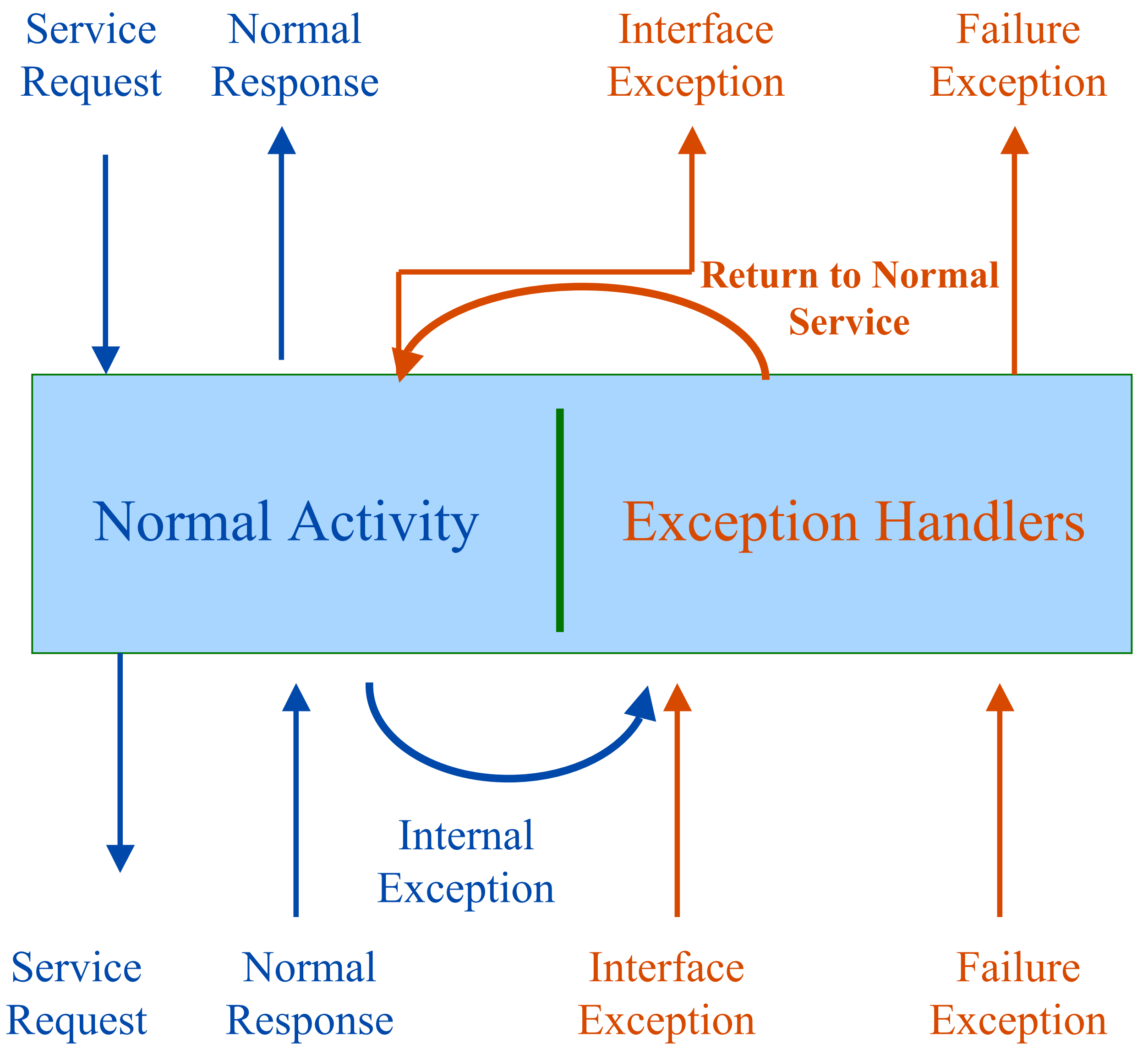
- An **exception** can be defined as the occurrence of an error
- Bringing an exception to the attention of the invoker of the operation which caused the exception, is called **raising** (or **signalling** or **throwing**) the exception
- The invoker's response is called **handling** (or **catching**) the exception
- Exception handling is a **forward error recovery** mechanism, as there is no roll back to a previous state; instead control is passed to the handler so that recovery procedures can be initiated
- However, the exception handling facility -for example in Java- can be used to implement backward error recovery

Exceptions

Exception handling can be used to:

- cope with abnormal conditions arising in the environment
- enable program design faults to be tolerated
- provide a general-purpose error-detection and recovery facility

Ideal Fault-Tolerant Component



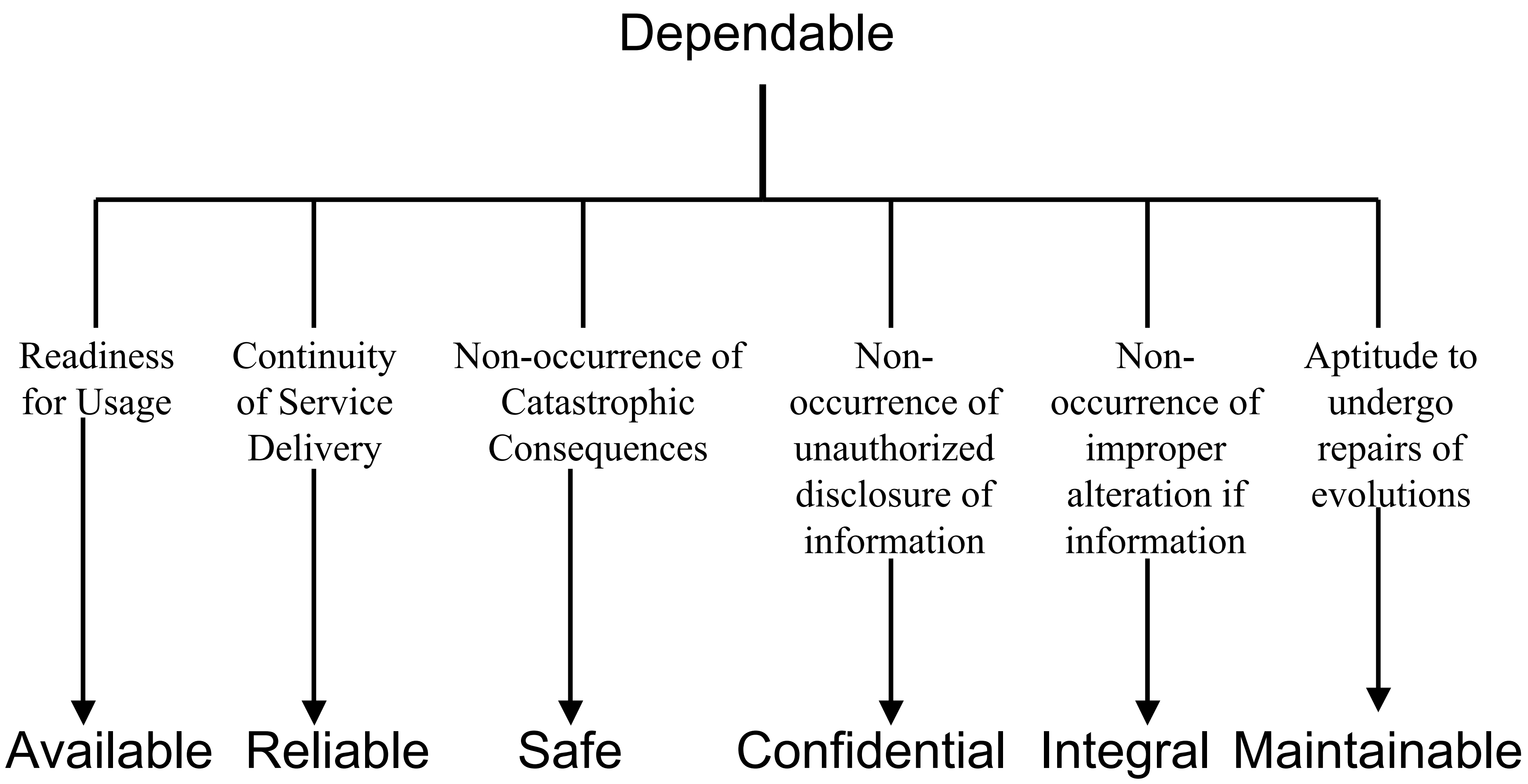
Safety and Reliability

- **Safety**: freedom from those conditions that can cause death, injury, occupational illness, damage to (or loss of) equipment (or property), or environmental harm
  - By this definition, most systems which have an element of risk associated with their use as unsafe
- A **mishap** is an unplanned event or series of events that can result in death, injury, etc.
- **Reliability**: a measure of the success with which a system conforms to some authoritative specification of its behaviour.
- **Safety**: is the probability that conditions that can lead to mishaps do not occur whether or not the intended function is performed

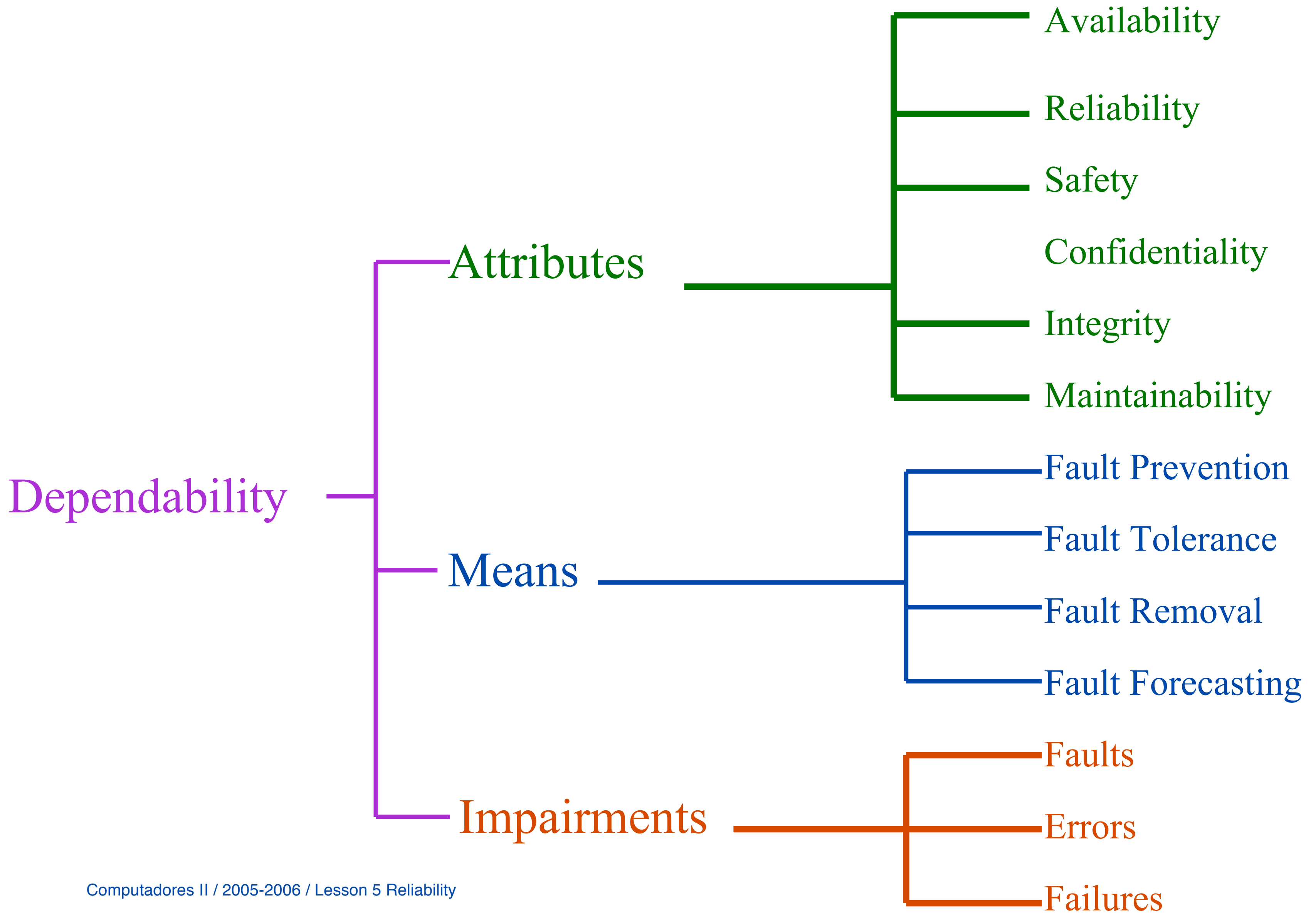
Safety

- E.g., measures which increase the likelihood of a weapon firing when required may well increase the possibility of its accidental detonation.
- In many ways, the only safe airplane is one that never takes off, however, it is not very reliable.
- As with reliability, to ensure the safety requirements of an embedded system, system safety analysis must be performed throughout all stages of its life cycle development.

Aspects of Dependability


Dependable
Readiness for Usage
Continuity of Service Delivery
Non-occurrence of Catastrophic Consequences
Non-occurrence of unauthorized disclosure of information
Non-occurrence of improper alteration if information
Aptitude to undergo repairs of evolutions
Available
Reliable
Safe
Confidential
Integral
Maintainable

Dependability Terminology



Summary

- **Reliability**: a measure of the success with which the system conforms to some authoritative specification of its behaviour
- When the behaviour of a system deviates from that which is specified for it, this is called a **failure**
- Failures result from **faults**
- Faults can be **accidentally** or **intentionally** introduced into a system
- They can be **transient**, **permanent** or **intermittent**
- **Fault prevention** consists of **fault avoidance** and **fault removal**
- Fault tolerance involves the introduction of **redundant components** into a system so that faults can be detected and tolerated

Summary

- **N-version programming**: the independent generation of N (where N >= 2) functionally equivalent programs from the same initial specification
- Based on the assumptions that a program can be completely, consistently and unambiguously specified, and that programs which have been **developed independently** will **fail independently**
- **Dynamic redundancy**: error detection, damage confinement and assessment, error recovery, and fault treatment and continued service
- Atomic actions to aid damage confinement

Summary

- With **backward error recovery**, it is necessary for communicating processes to reach consistent recovery points to avoid the domino effect
- For sequential systems, the **recovery block** is an appropriate language concept for BER
- Although **forward error recovery** is system specific, **exception handling** has been identified as an appropriate framework for its implementation
- The concept of an **ideal fault tolerant component** was introduced which used exceptions
- The notions of software **safety** and **dependability** have been introduced