TOPIC 7: RELIABILITY AND FAULT TOLERANCE

AIMS

- To understand the factors which affect the reliability of a system and introduce how software design faults can be tolerated
- To introduce
  - Safety and Dependability
  - Reliability, failure and faults
  - Failure modes
  - Fault prevention and fault tolerance
  - N-Version programming
  - Dynamic Redundancy

SAFETY AND RELIABILITY

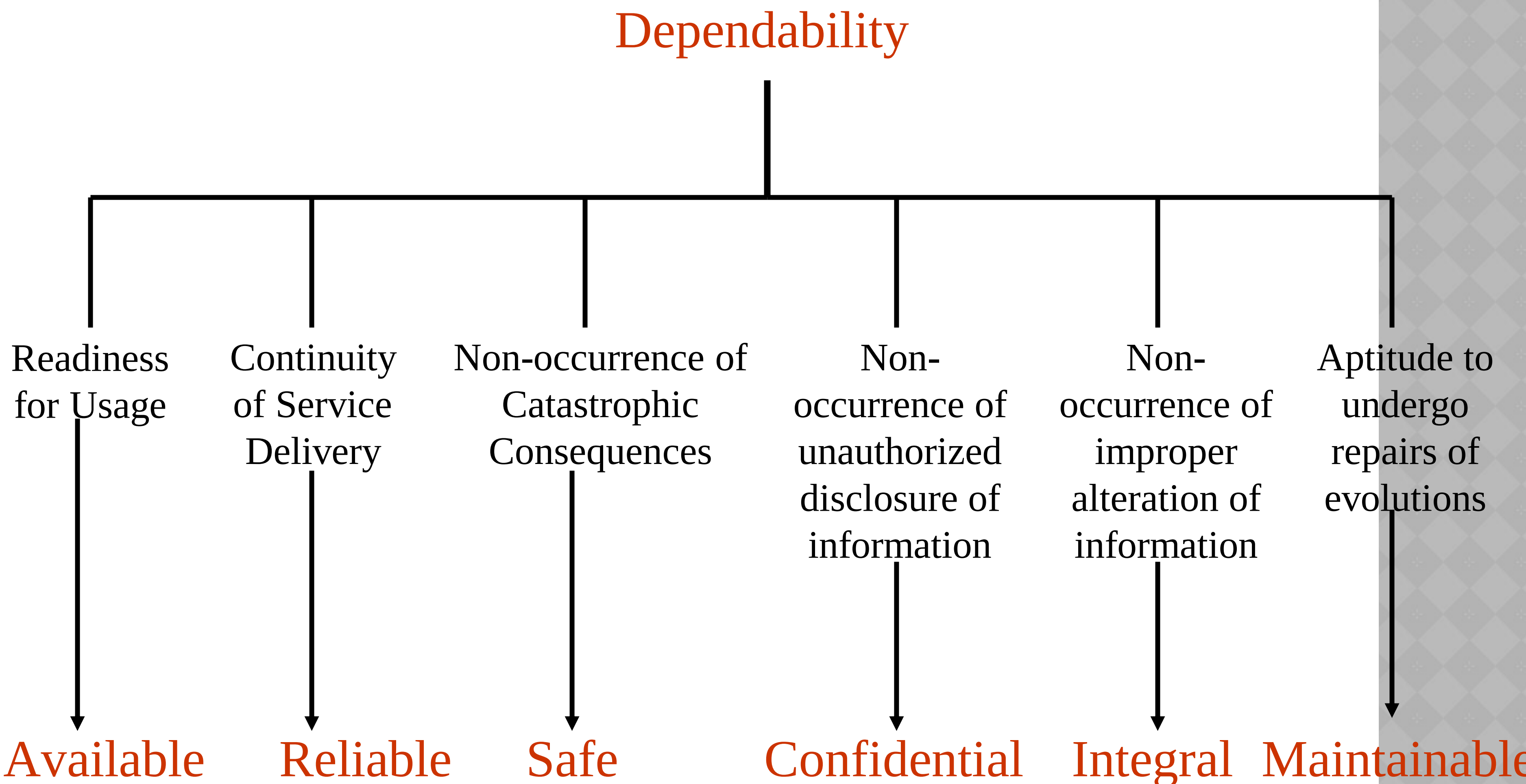
- **Safety**: freedom from those conditions that can cause death, injury, occupational illness, damage to (or loss of) equipment (or property), or environmental harm
  - By this definition, most systems which have an element of risk associated with their use as unsafe
- **Reliability**: a measure of 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

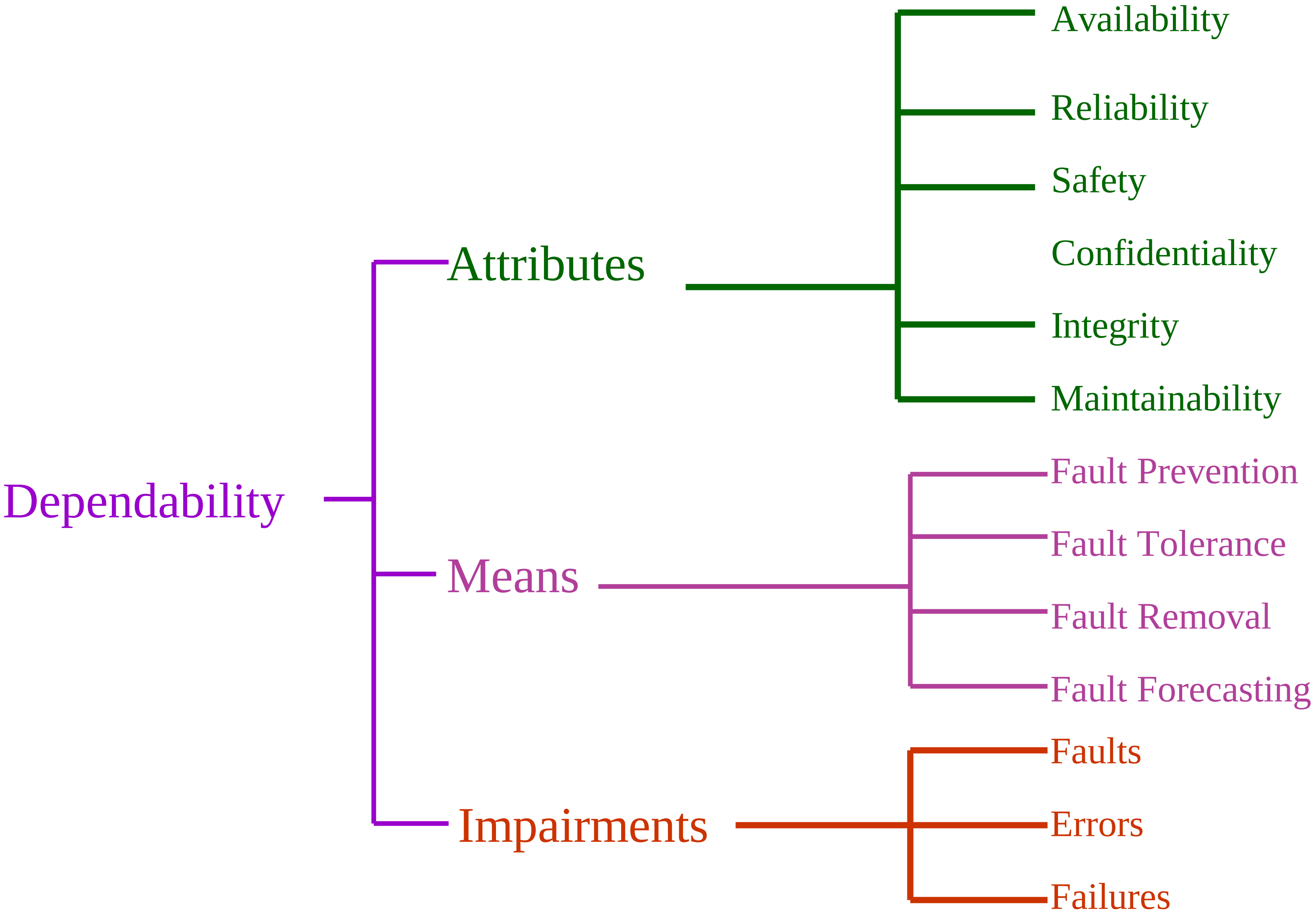
SAFETY

- 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



DEPENDABILITY TERMINOLOGY



RELIABILITY, FAILURE AND FAULTS

- The reliability of a system is a measure of the success with which it conforms to an 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 that eventually manifest themselves in the system's external behaviour
- These problems are called errors and their mechanical or algorithmic cause are termed faults
- Systems are composed of components which are themselves systems: hence
  - > failure -> fault -> error -> failure -> fault

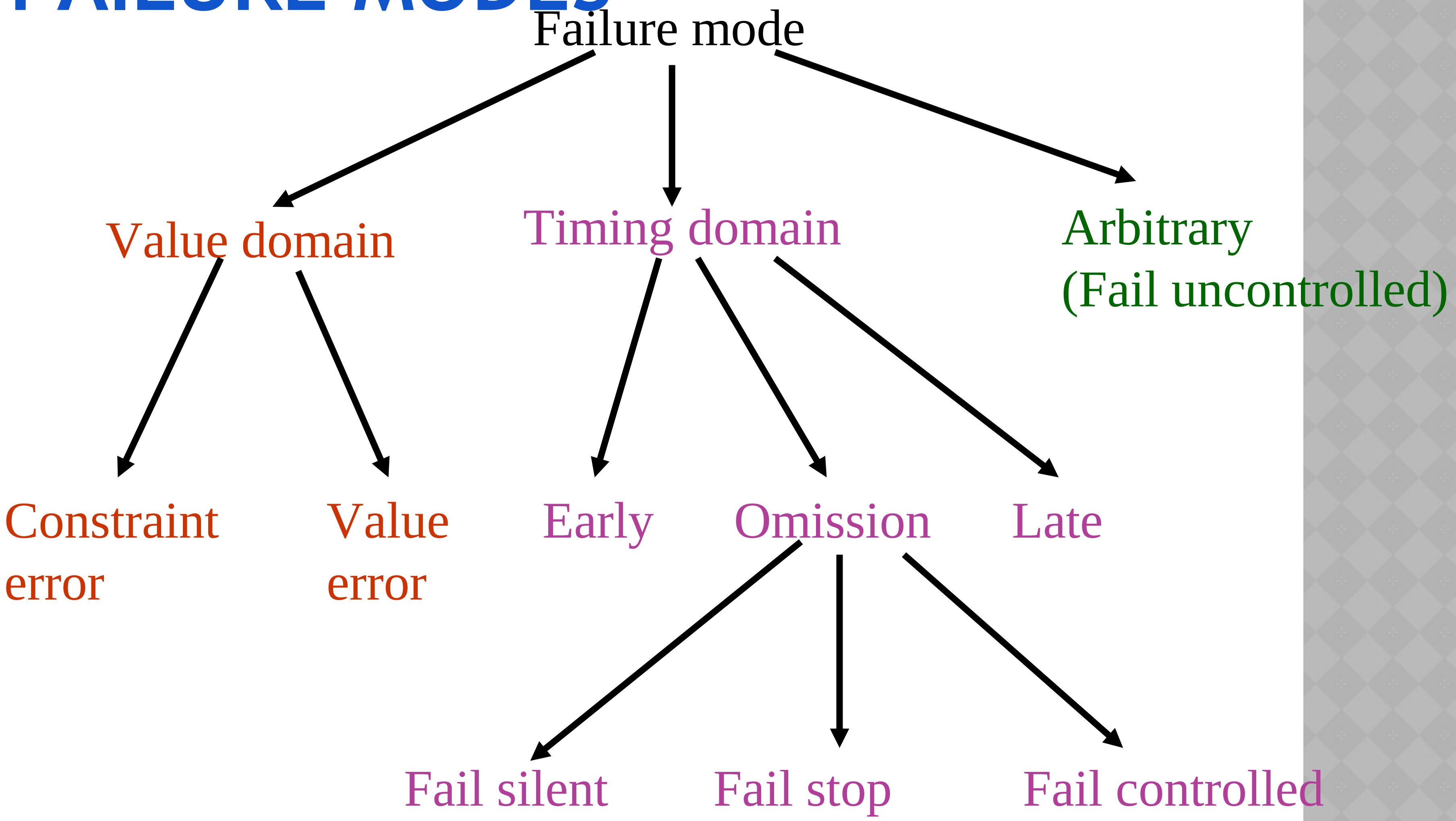
FAULT TYPES

- 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

SOFTWARE FAULTS

- Called Bugs
  - Bohrbugs: reproducible identifiable.
  - Heisenbugs: only active under rare conditions: e.g. race conditions
- Software doesn’t deteriorate with age: it is either correct or incorrect but
- Faults can remain dormant for long periods
  - Usually related to resource usage e.g. memory leaks

FAILURE MODES



APPROACHES TO ACHIEVING RELIABLE SYSTEMS

- 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 stages: fault avoidance and fault removal
- Fault avoidance attempts to limit the introduction of faults during system construction by:
  - 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

- Design errors (hardware and software) will exist
- Fault removal: procedures for finding and removing the causes of errors;
  - e.g. design reviews, program verification, code inspections and system testing
- 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
  - Requirements errors during the system's development may not manifest themselves until the system goes operational

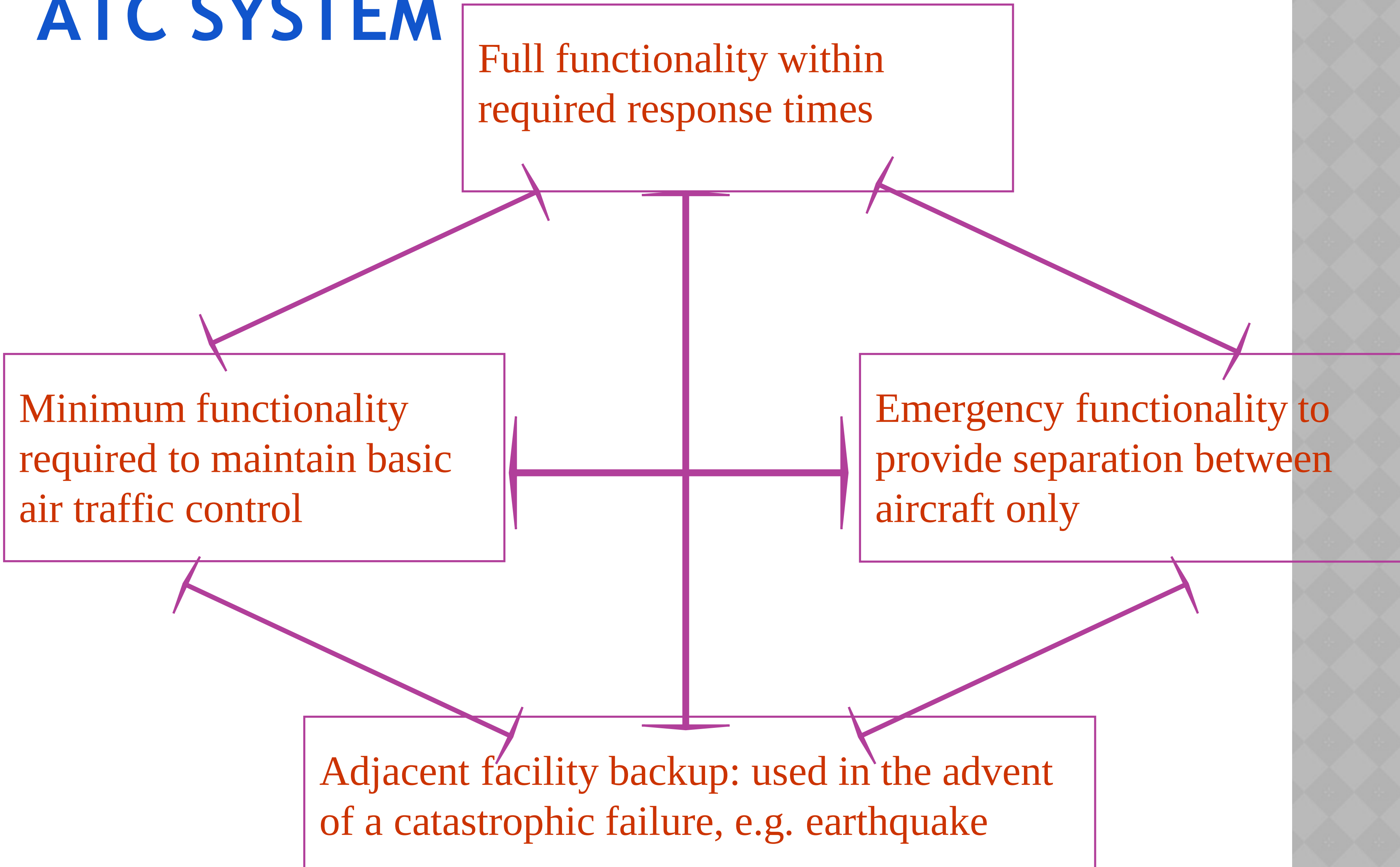
FAILURE OF FAULT PREVENTION APPROACH

- 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 the crewless spacecraft Voyager (currently 10 billions miles from the sun!)
- 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 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 SYSTEM



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
  - 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
  - E.g., first launch of the space shuttle
- 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

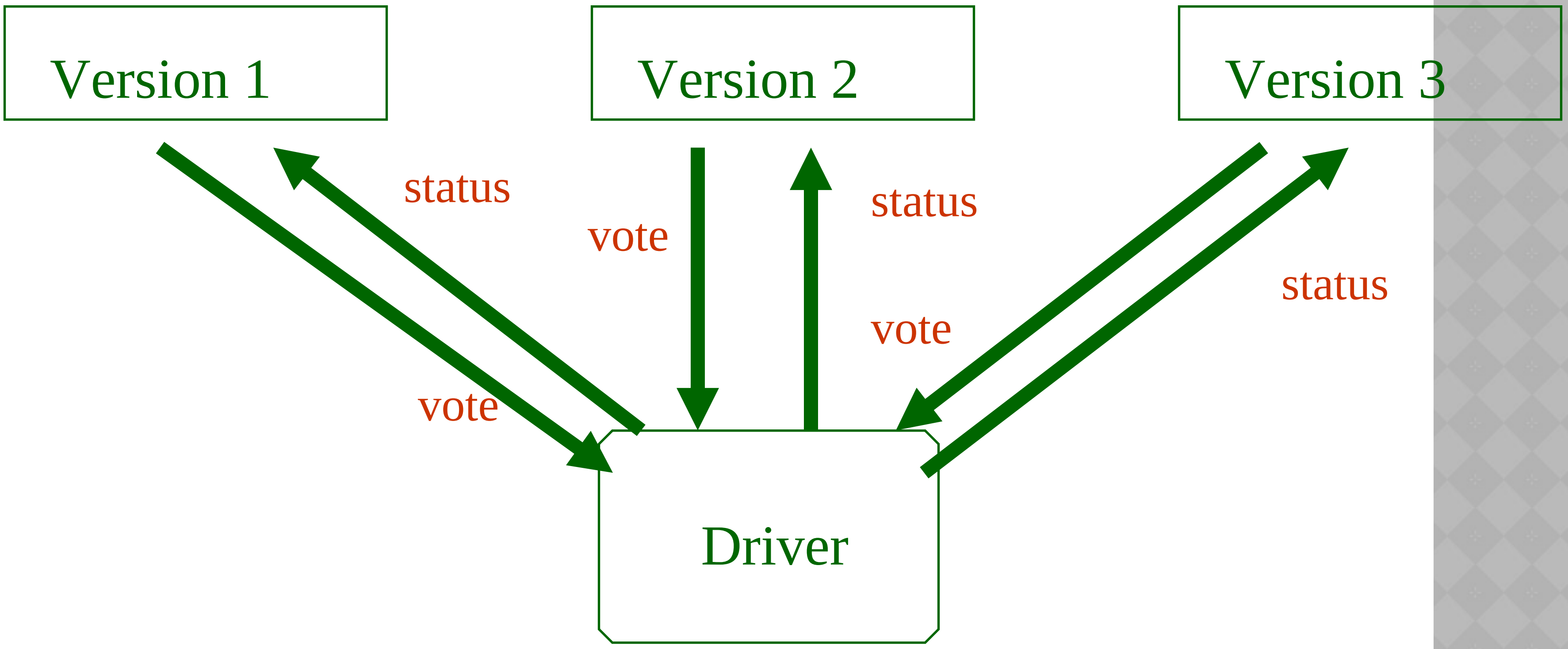
SOFTWARE FAULT TOLERANCE

- 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 diversity
- The independent generation of N (N > 2) functionally equivalent programs from the same initial specification
- No interactions between 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

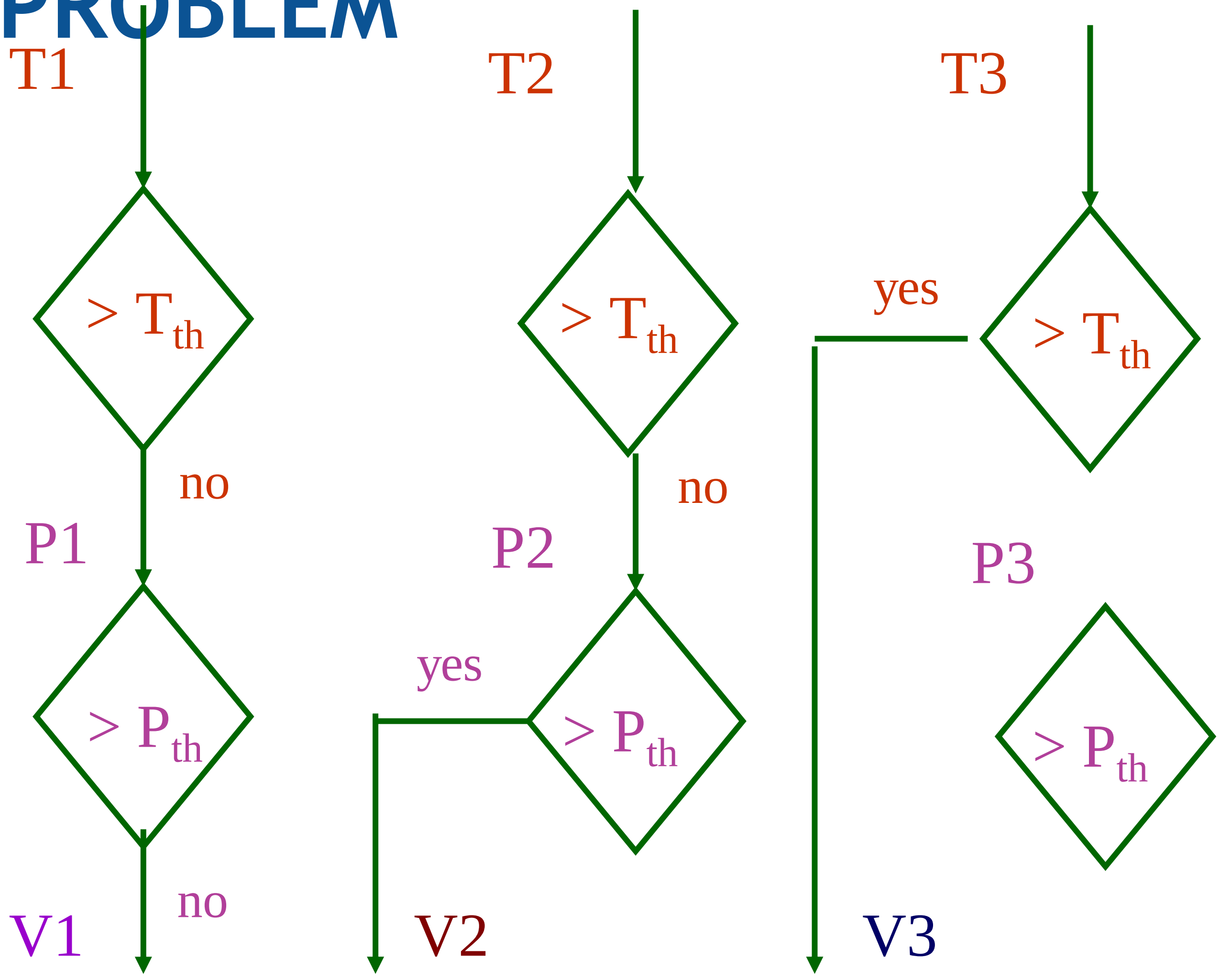
N-VERSION PROGRAMMING



VOTE COMPARISON

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

CONSISTENT COMPARISON PROBLEM



Each version will produce a different but correct result

Even if inexact comparison techniques are used, the problem occurs

N-VERSION PROGRAMMING DEPENDS ON

- Initial specification — The majority of software faults stem from inadequate specification
  - This will manifest itself in all N versions of the implementation
- Independence of effort — Experiments produce conflicting results
  - Complex parts of a specification leads to a lack of understanding of the requirements
  - If these 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

Alternative to static 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 the damage is repaired, the fault may still exist

ERROR DETECTION

- Environmental detection
  - hardware — e.g. illegal instruction
  - O.S/RTS — null pointer
- Application detection
  - Replication checks
  - Timing checks (e.g., watch dog)
  - Reversal checks
  - Coding checks (redundant data, e.g. checksums)
  - Reasonableness checks (e.g. assertion)
  - Structural checks (e.g. redundant pointers in linked list)
  - Dynamic reasonableness check

DAMAGE 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 (assuming strongly type language)

- 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 continues from an erroneous state by making selective corrections to the system state
  - This includes making safe the controlled environment 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)

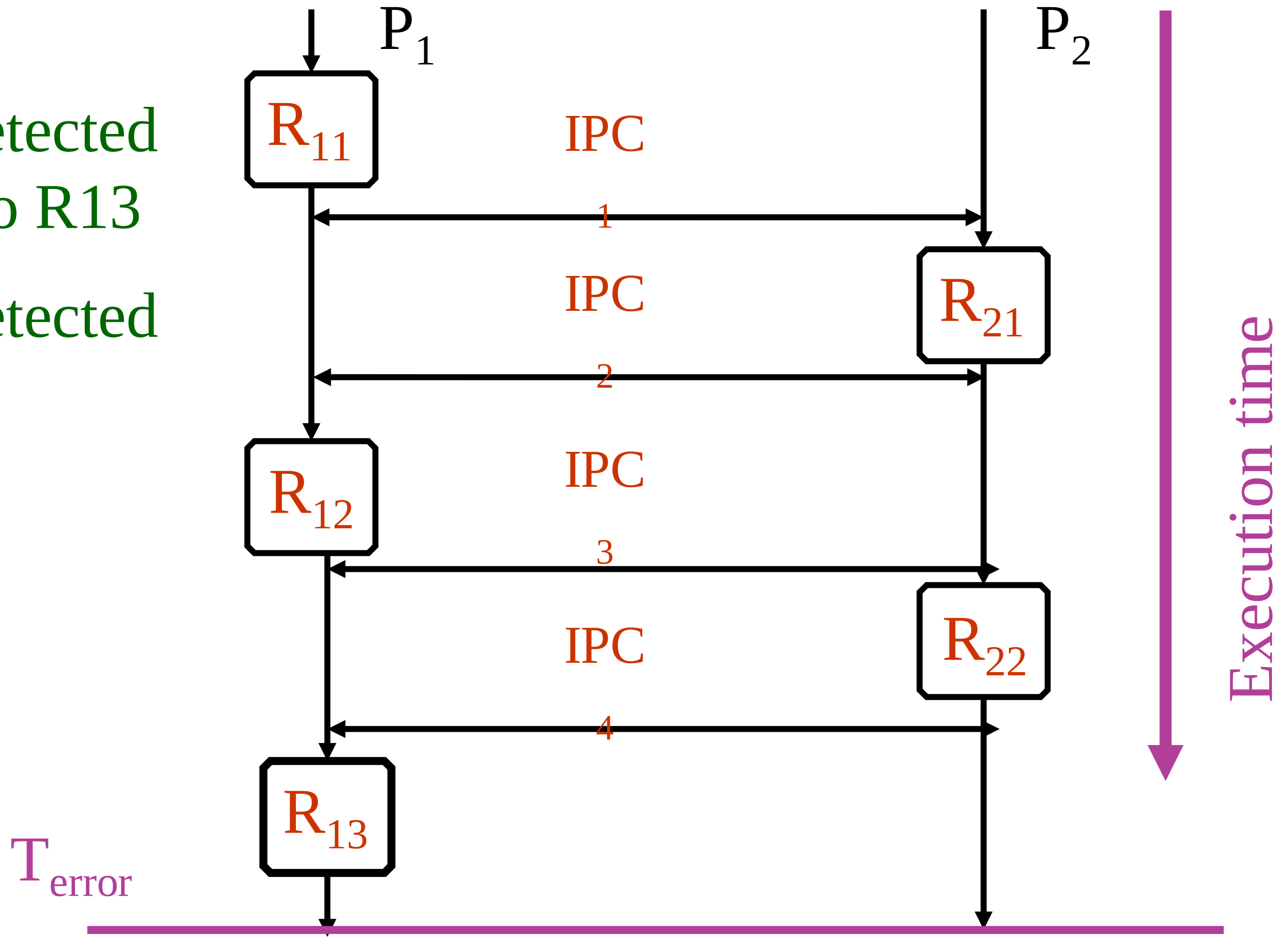
- BER relies on restoring the system to a previous safe state and executing an alternative section of the program
- This has the same functionality but uses a different algorithm (c.f. N-Version Programming) and therefore no fault
- The point to which a process is restored is called a recovery point 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
- Disadvantage: it cannot undo errors in the environment!

THE DOMINO EFFECT

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

If the error is detected in P1 rollback to R13

If the error is detected in P2 ?



FAULT TREATMENT AND CONTINUED SERVICE

- Error recovery 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 and 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 TO FT

- 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**

EXAMPLE: SOLUTION TO 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

THE ACCEPTANCE TEST

- The acceptance test provides the error detection mechanism; it 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
- 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 discussed can be used to form the acceptance tests
- Care must be taken as a faulty acceptance test may lead to residual errors going undetected

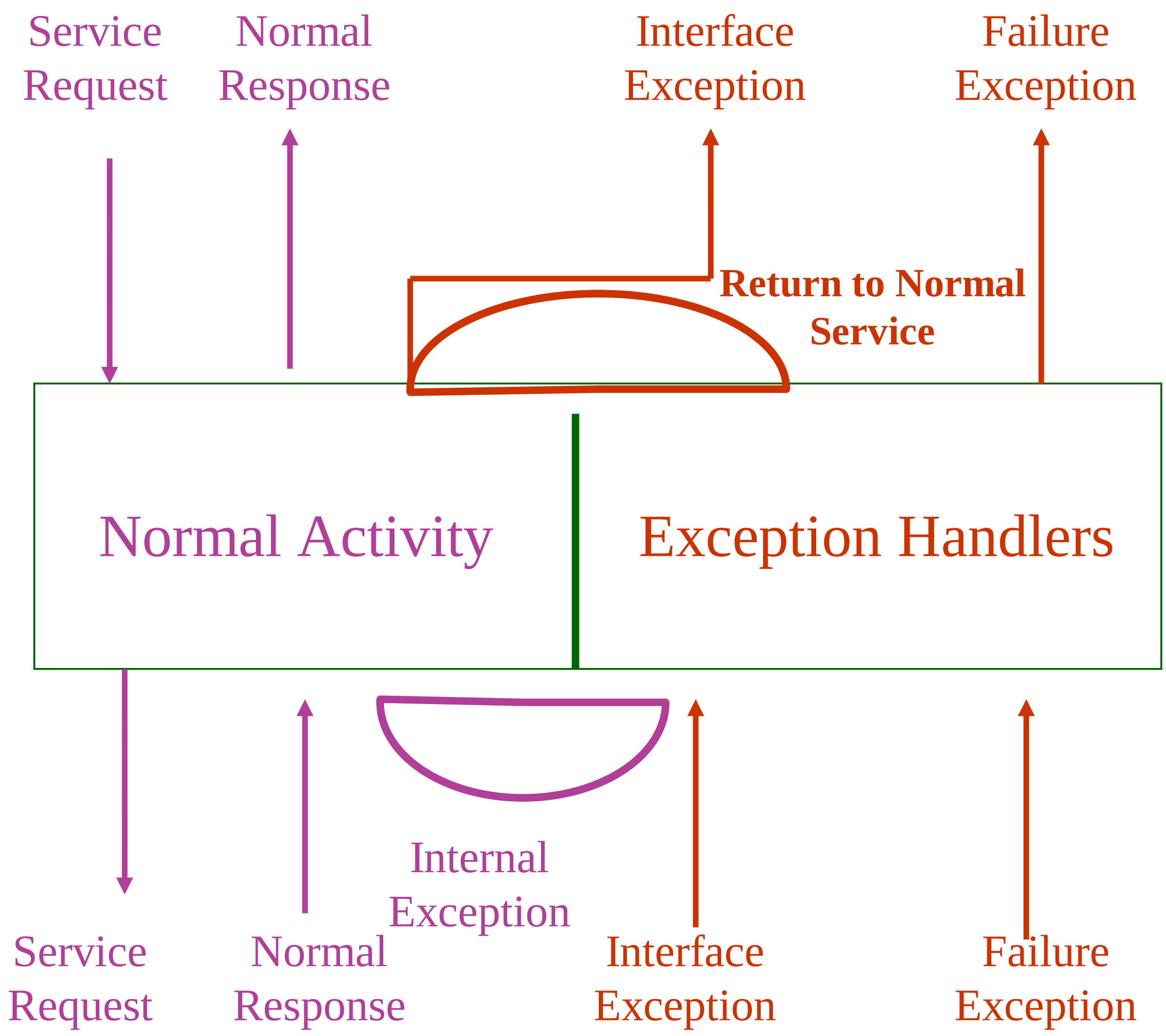
N-VERSION PROGRAMMING VS RECOVERY BLOCKS

- 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 votes before it outputs to the environment, RB must be structure to only output following the passing of an acceptance test

DYNAMIC REDUNDANCY AND EXCEPTIONS

- 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
- 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



SUMMARY I

- Defined dependability, safety, reliability, failure, faults
- Faults:
  - accidental or intentionally
  - transient, permanent or intermittent
- Fault prevention consists of fault avoidance and fault removal
- Fault tolerance: static and dynamic
- N-version programming: the independent generation of N functionally equivalent programs from the same specification
- Based on the assumptions that a program can be completely, consistently and unambiguously specified, and that programs that have been developed independently will fail independently

SUMMARY II

- Dynamic redundancy: error detection, damage confinement and assessment, error recovery, and fault treatment and continued service
- 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