Design of the architecture of safety-critical systems

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Objectives

Fail-safe operation

Safe operation even in case of faults

Fail-stop behaviour	Fail-operational behaviour

• Stopping (switch-off) is a safe state
• In case of a detected error the system has to be stopped
• Detecting errors is a critical task
	• Stopping (switch-off) is not a safe state
	• Service is needed even in case of a detected error
	    • full service
	    • degraded (but safe) service
	• Fault tolerance is required

Architectural solutions (overview)

Safety in case of single random hardware faults

Fault handling

Composite fail-safety	Reactive fail-safety	Inherent fail-safety
• Each function is implemented by at least 2 independent components • Agreement between the independent components is needed to continue the operation	• Each function is equipped with an independent error detection • The effects of detected errors can be handled (compensated)	• All failure modes are safe • „Inherent safe” system

Objectives for fault tolerant behaviour

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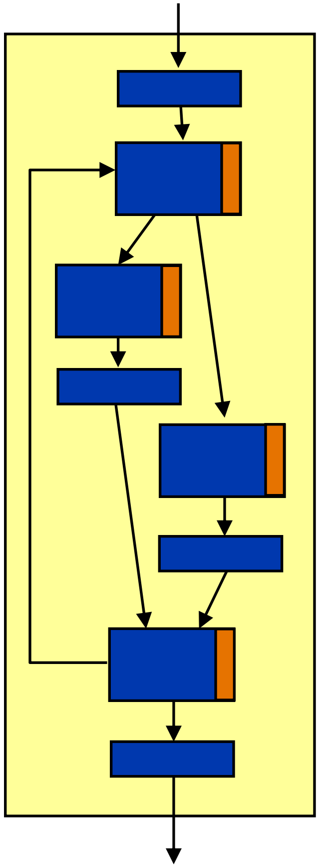
Typical architectures for fail-stop operation

1. Single channel architecture with built-in self-test

- Single processing flow
- Scheduled hardware self-tests
  - After switch-on: Detailed self-test to detect permanent faults
  - In run-time: On-line tests to detect latent permanent faults
- Scheduled software self-tests
  - Typically application dependent techniques
  - Checking the control flow, data acceptance rules, timeliness properties
- Disadvantages:
  - Fault coverage of the self-tests is limited
  - Fault handling (e.g., switch-off) shall be performed by the same channel

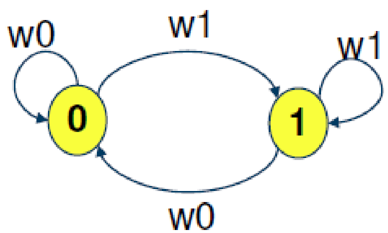


Implementation of on-line error detection

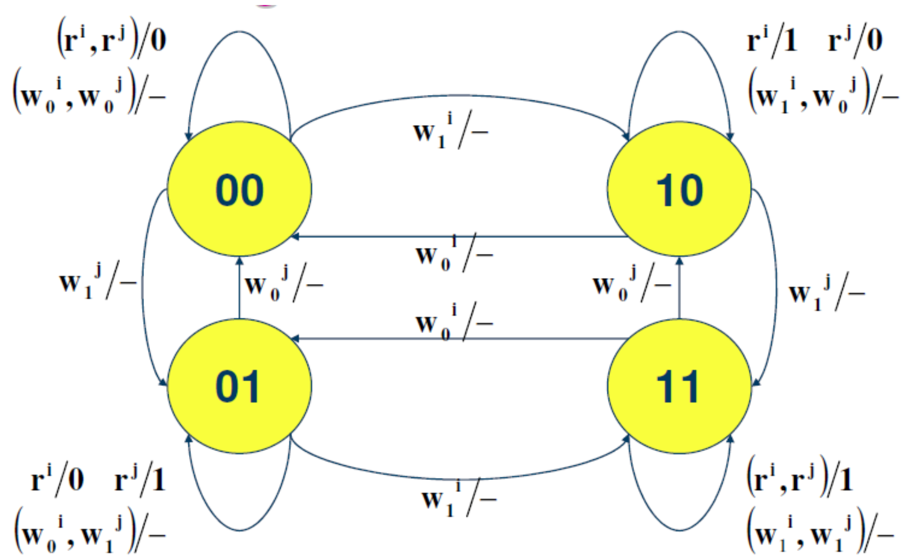
- Application dependent (ad-hoc) techniques
  - Acceptance checking (e.g., for ranges of values)
  - Timing related checking (e.g., too early, too late)
  - Cross-checking (e.g., using inverse function)
  - Structure checking (e.g., in linked list structure)
- Application independent (platform) mechanisms
  - Hardware supported on-line checking
    - CPU level: Invalid instruction, user/supervisor modes etc.
    - MMU level: Protection of memory ranges
  - OS level checking
    - Invalid parameters of system calls
    - OS level protection of resources

Example: Testing memory cells (hw)

States of a correct cell:

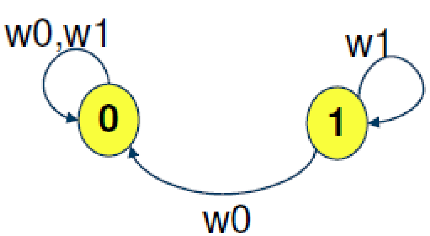


State transitions to check stuck faults:

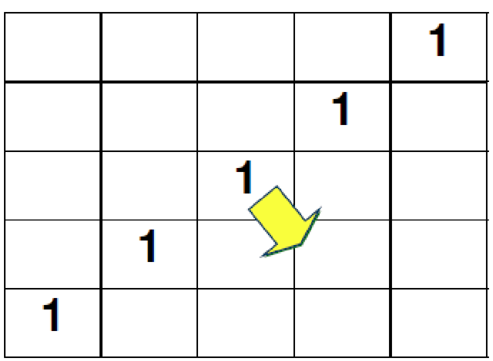


Stuck-at 0/1 faults:

Transition fault:



„March” algorithms:



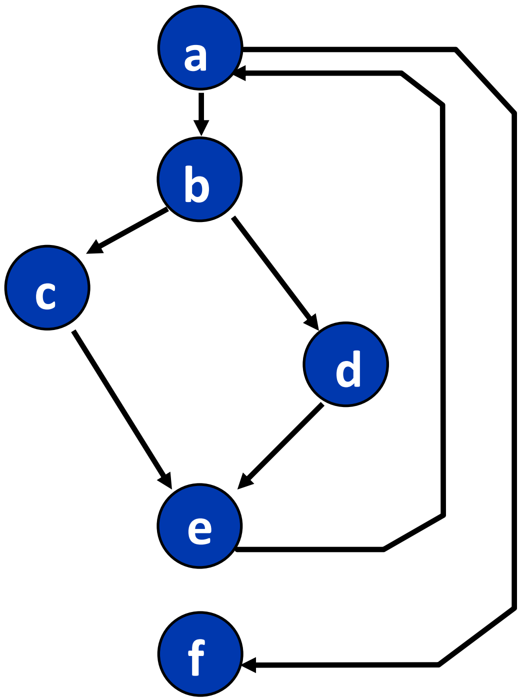
Example: Checking execution flow (sw)

- Checking the correctness of execution paths
  - On the basis of the program control flow graph
  - Actual run: Checked on the basis of assigned signatures

Instrumented source code:

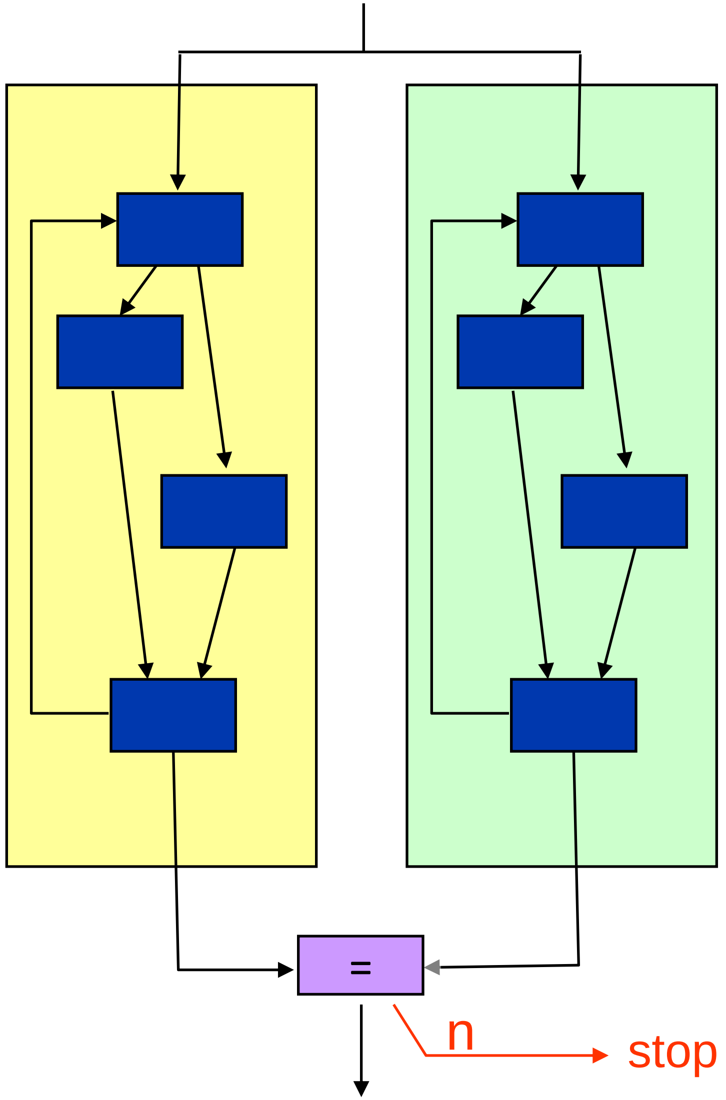
```
a:  S(a); for (i=0; i<MAX; i++) {
b:      S(b); if (i==a) {
c:          S(c); n=n-i;
        } else {
d:          S(d); m=m-i;
        }
e:      S(e); printf("%d\n",n);
    }
f:  S(f); printf("Ready.")
```

Control flow graph (reference):

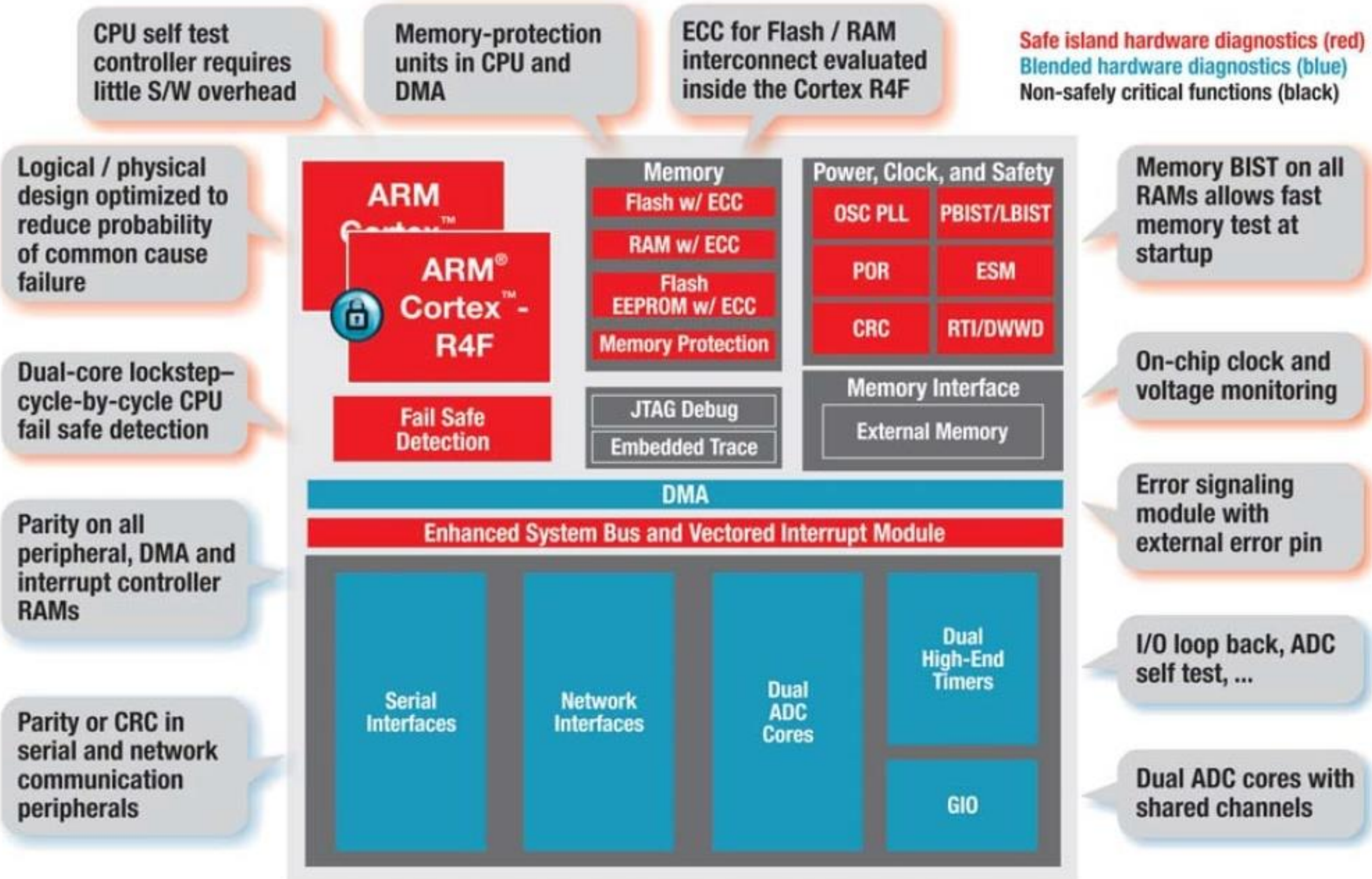


2. Two-channels architecture with comparison

- Two or more processing channels
  - Shared input
  - Comparison of outputs
  - Stopping in case of deviation
- High error detection coverage
- The comparator is a critical component (but simple)
- Special way of comparison:
  - Performed by the operator
- Disadvantages:
  - Common mode faults
  - Long detection latency

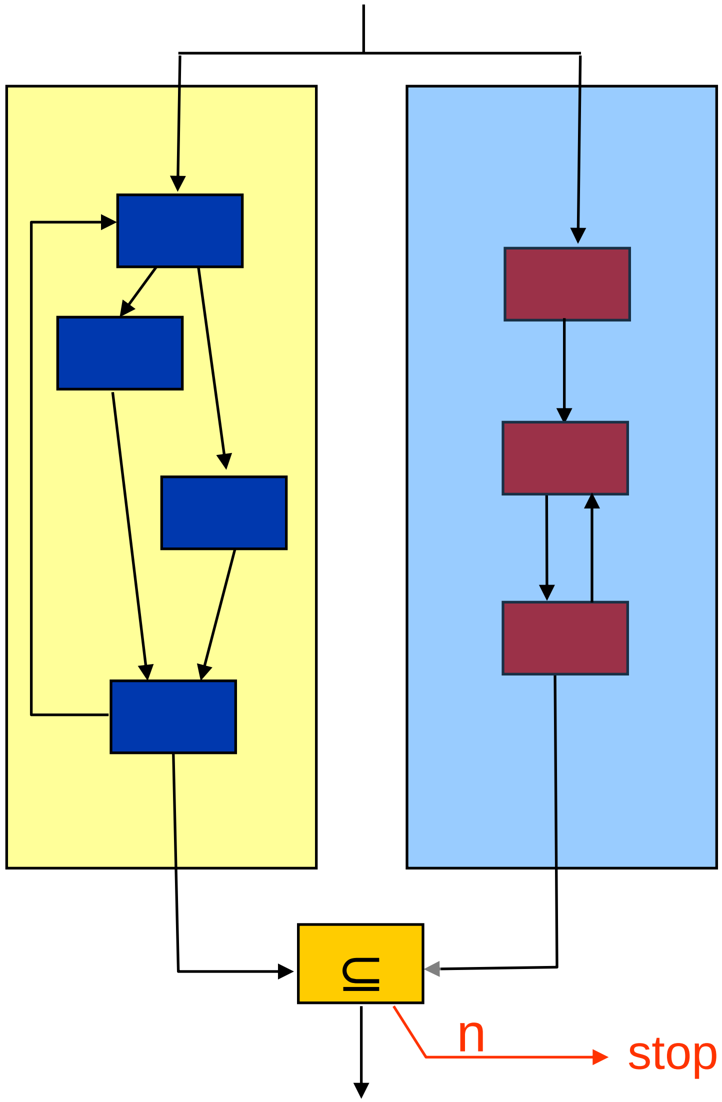


Example: TI Hercules Safety Microcontrollers

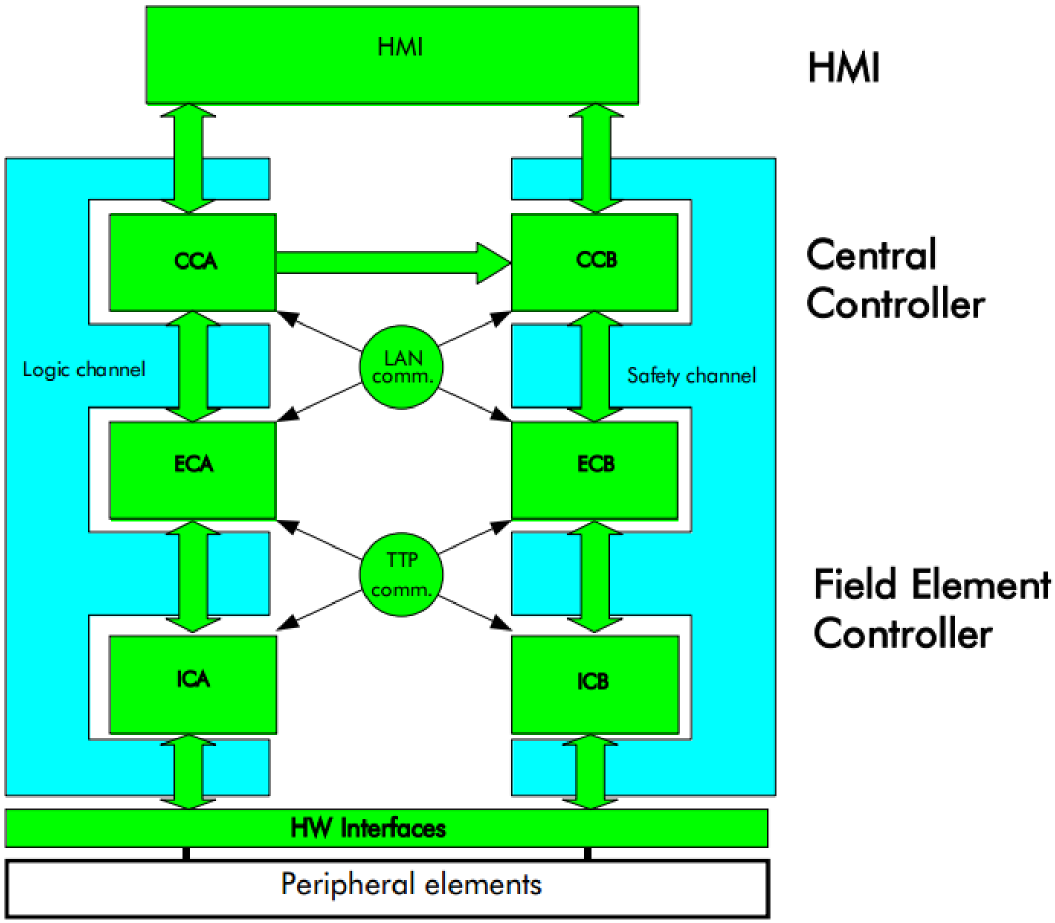


3. Two-channels architecture with safety checking

- Independent second channel
  - „Safety bag”: only safety checking
  - Diverse implementation
  - Checking the output of the primary channel
- Example:
  - Elektra railway interlocking system
  - Rules are implemented to check the primary channel



Example: Thales Elektra



Two channels:

- Logic channel:
  CHILL (CCITT High Level Language) procedure-oriented programming language
- Safety channel:
  PAMELA (Pattern Matching Expert System Language) rule-based language

Typical architectures for fault-tolerant systems

Objectives for fault tolerant behaviour

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Fail-operational behaviour

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Fault tolerant systems

- Fault tolerance: Providing (safe) service in case of faults
  - Autonomous error handling during operation (instead of stopping)
  - Intervening into the fault → failure chain
- Basic condition: Redundancy
  Extra resources to replace faulty components
  - Hardware
  - Software
  - Information
  - Time

  redundancy (sometimes together)
- Types of redundancy
  - Cold: The redundant component is inactive in fault-free case
  - Warm: The redundant component has reduced load in fault-free case
  - Hot: The redundant component is active in fault-free case

Forms of redundancy

1. Hardware redundancy
   - Extra hardware components
     - Inherent in the system or planned for fault tolerance
2. Software redundancy
   - Extra software modules
3. Information redundancy
   - Extra information
     - Example: Error correcting codes (ECC)
4. Time redundancy
   - Repeated execution (to handle transient faults)

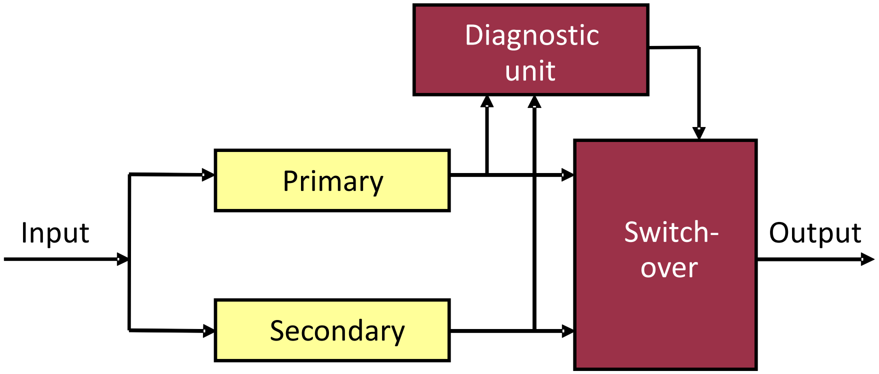
How to use the redundancy?

- Hardware design faults: (< 1%)
  - Hardware redundancy, with design diversity
  - Often are neglected (wide-spread components are used)
- Hardware permanent operational faults: (~ 20%)
  - Hardware redundancy (e.g., redundant processor)
- Hardware transient operational faults: (~ 70-80%)
  - Time redundancy (e.g., instruction retry)
  - Information redundancy (e.g., error correcting codes)
  - Software redundancy (e.g., checkpointing and recovery)
- Software design faults: (~ 10%)
  - Software redundancy, with design diversity

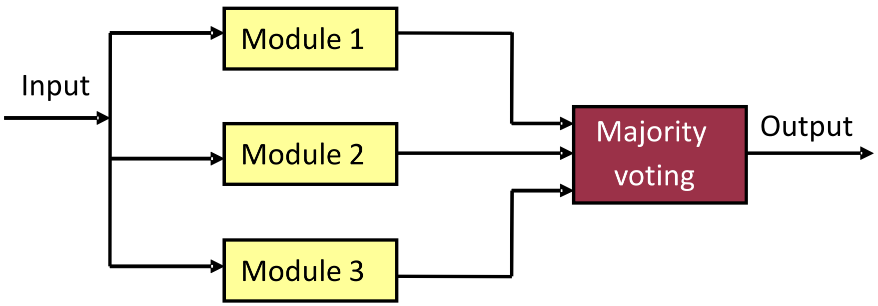
1. Fault tolerance for hardware permanent faults

Replication:

- Duplication with diagnostics:
  - With comparison:
    Error detection only!
  - With diagnostic support:
    Fault tolerance by switch-over



- TMR: Triple Modular Redundancy
  - Masking the failure
    by majority voting
  - Voter is a critical component
    (but simple)



- NMR: N-modular redundancy
  - Masking the failure by majority voting
  - Goal: Surviving a mission time with high probability (airborne systems)

Implementation of the replication

- Equipment/server level:
  - Servers: High availability server clusters
    - E.g., Linux HA Clustering, Windows Server Failover Clustering
  - Software support: Failover and failback
- Board level:
  - Run-time reconfiguration: “Hot-swap”
    - E.g., CompactPCI, HDD, power supply
  - Software support: monitoring, reconfiguration
- Component level:
  - Replication of components: TMR
  - Self-checking circuits (processing encoded information)

2. Fault tolerance for transient hardware faults

- Basic approach: Software supported fault tolerance
  - Repeated execution will avoid transient faults
  - The handling of fault effects is important
  - Transient faults are handled by setting a fault-free state and continuing the execution from that state (potentially with repeated execution)
- Four phases of operation:

1) Error detection
2) Damage assessment
3) Recovery
4) Fault treatment and continuing service

The four phases of operation 1/4

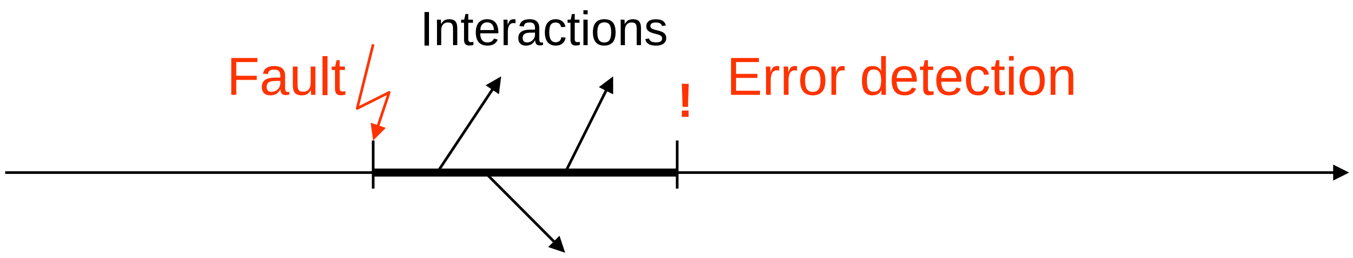
1) Error detection:

- Application independent mechanisms:
  - E.g., detecting illegal instructions at CPU level
  - E.g., detecting violation of memory access restrictions
- Application dependent techniques:
  - Acceptance checking
  - Timing related checking
  - Cross-checking
  - Structure checking
  - Diagnostic checking
  - …

The four phases of operation 2/4

2) Damage assessment:

- Motivation: Errors can propagate among the components between the occurrence and detection of errors



- Limiting error propagation: Checking interactions
  - Input acceptance checking (to detect external errors)
  - Output credibility checking (to provide „fail-silent” operation)
  - Checking and logging resource accesses and communication
- Estimation of components affected by a detected error
  - Analysis of interactions (during the latency of error detection)

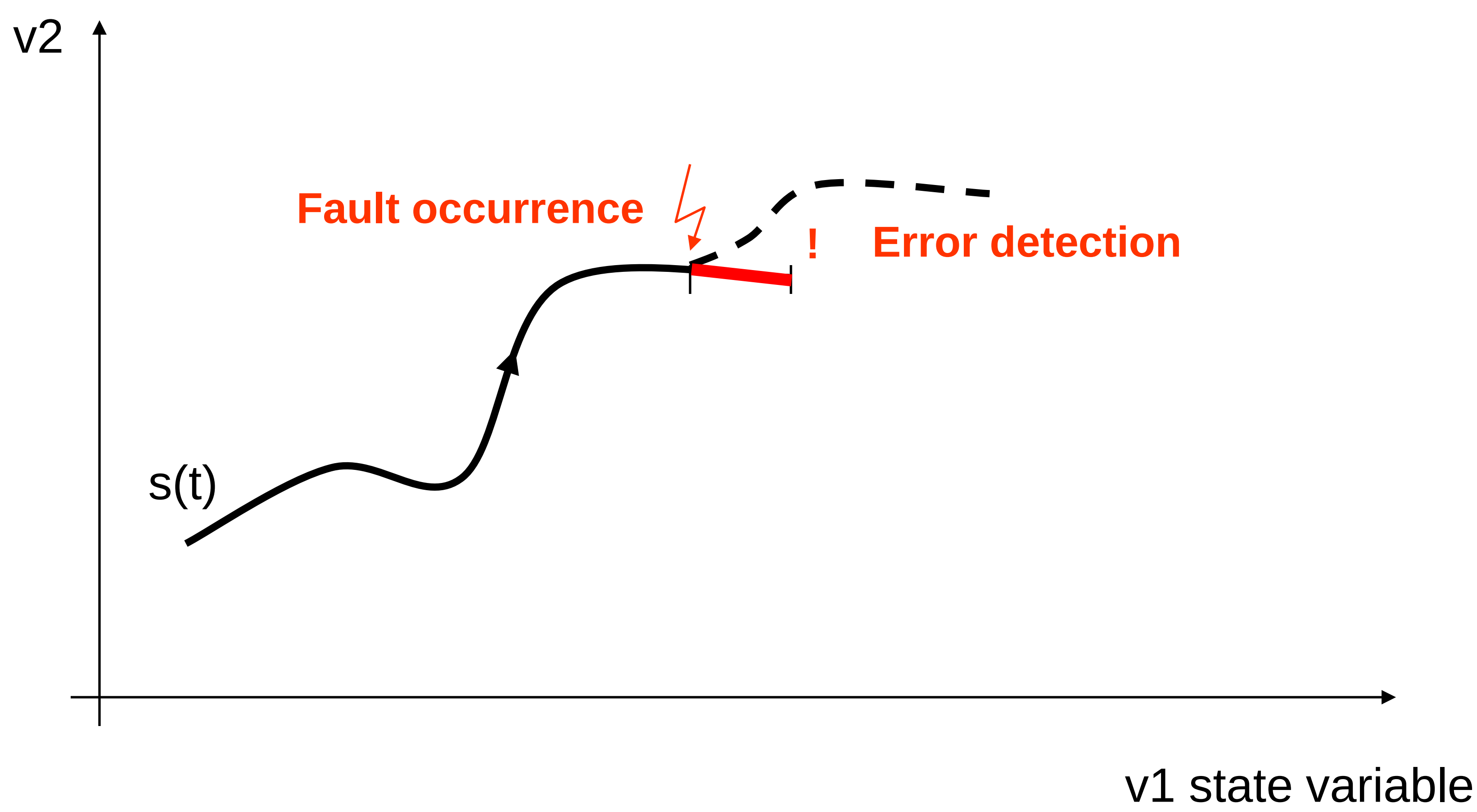
The four phases of operation 3/4

3) Recovery from an erroneous state

- Forward recovery:
  - Setting an error-free state by selective correction
  - Dependent on the detected error and estimated damage
  - Used in case of anticipated faults
- Backward recovery:
  - Restoring a prior error-free state (saved earlier)
  - Independent of the detected error and estimated damage
  - State shall be saved and restored for each component
- Compensation:
  - The error can be handled by using redundant information

Types of recovery

- State space of the system: Error detection



Types of recovery

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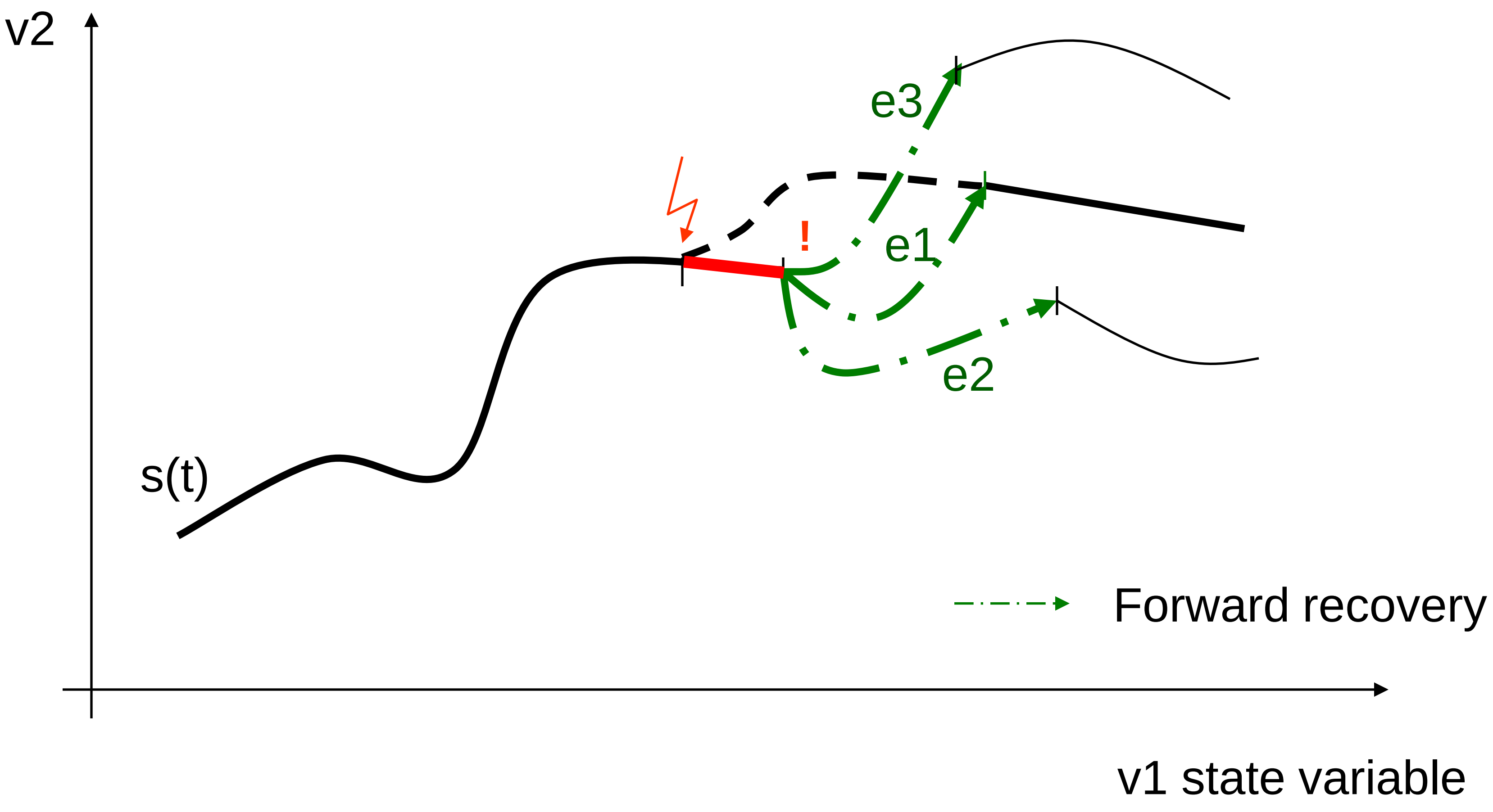

Types of recovery

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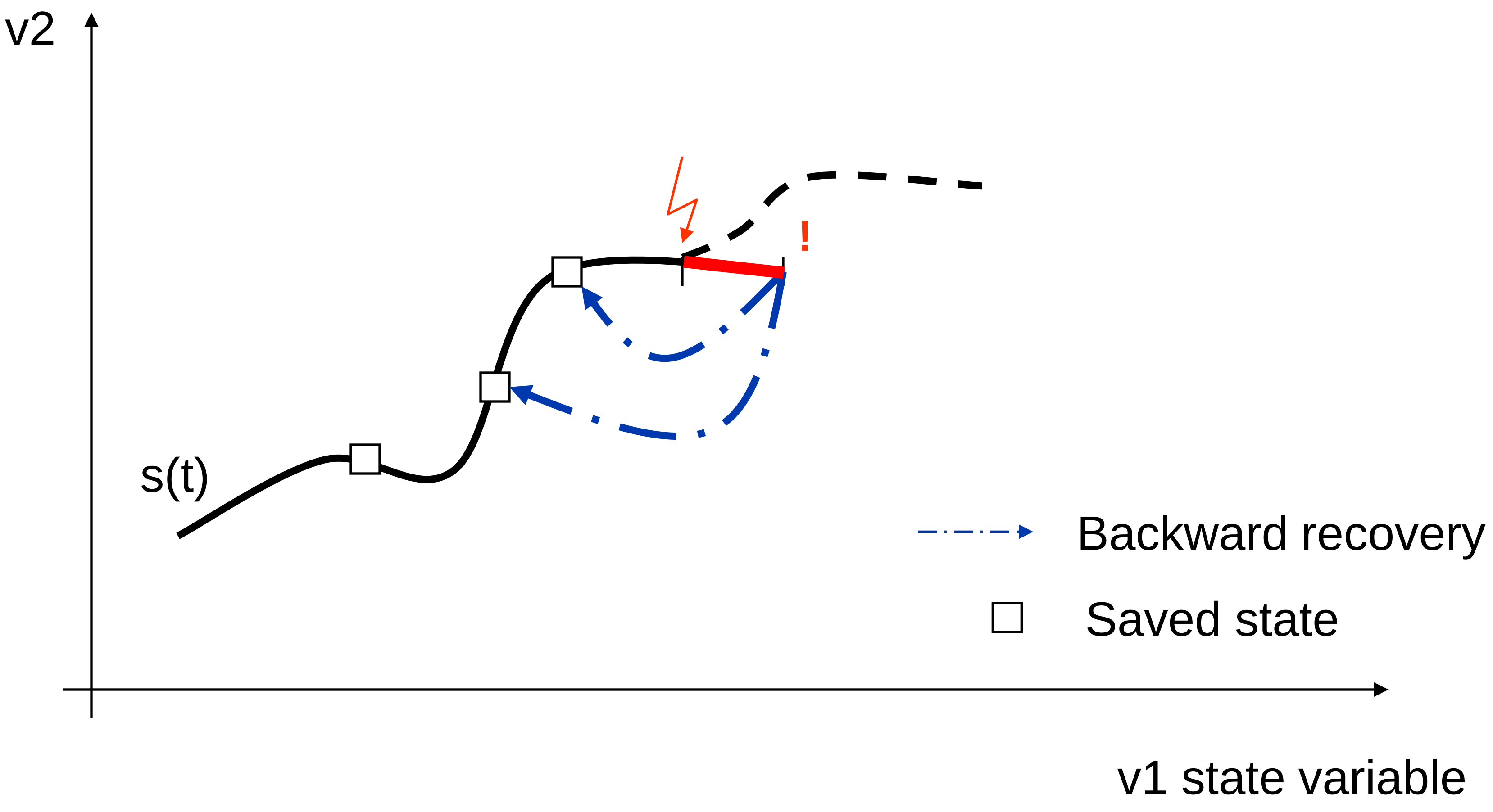
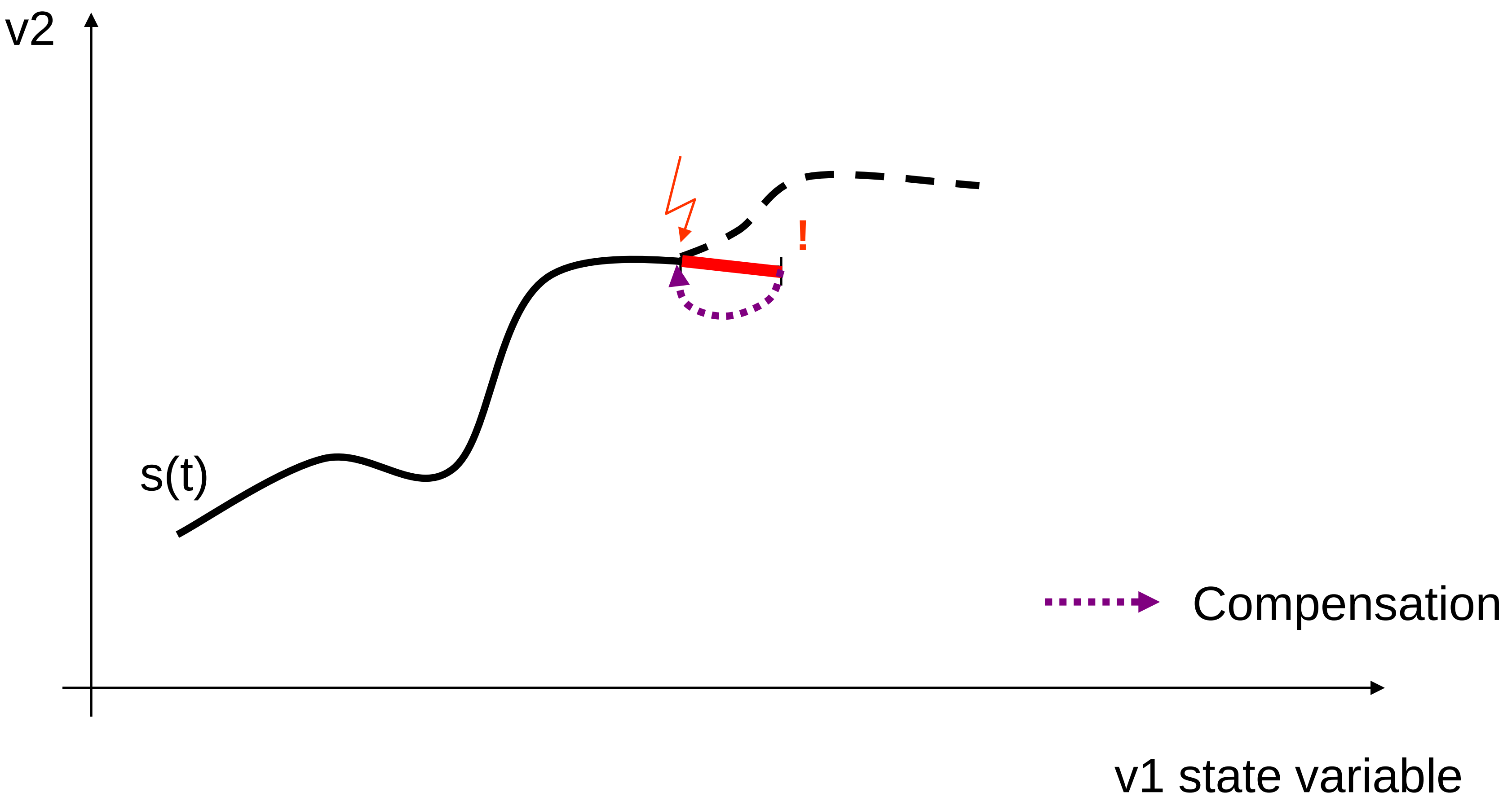


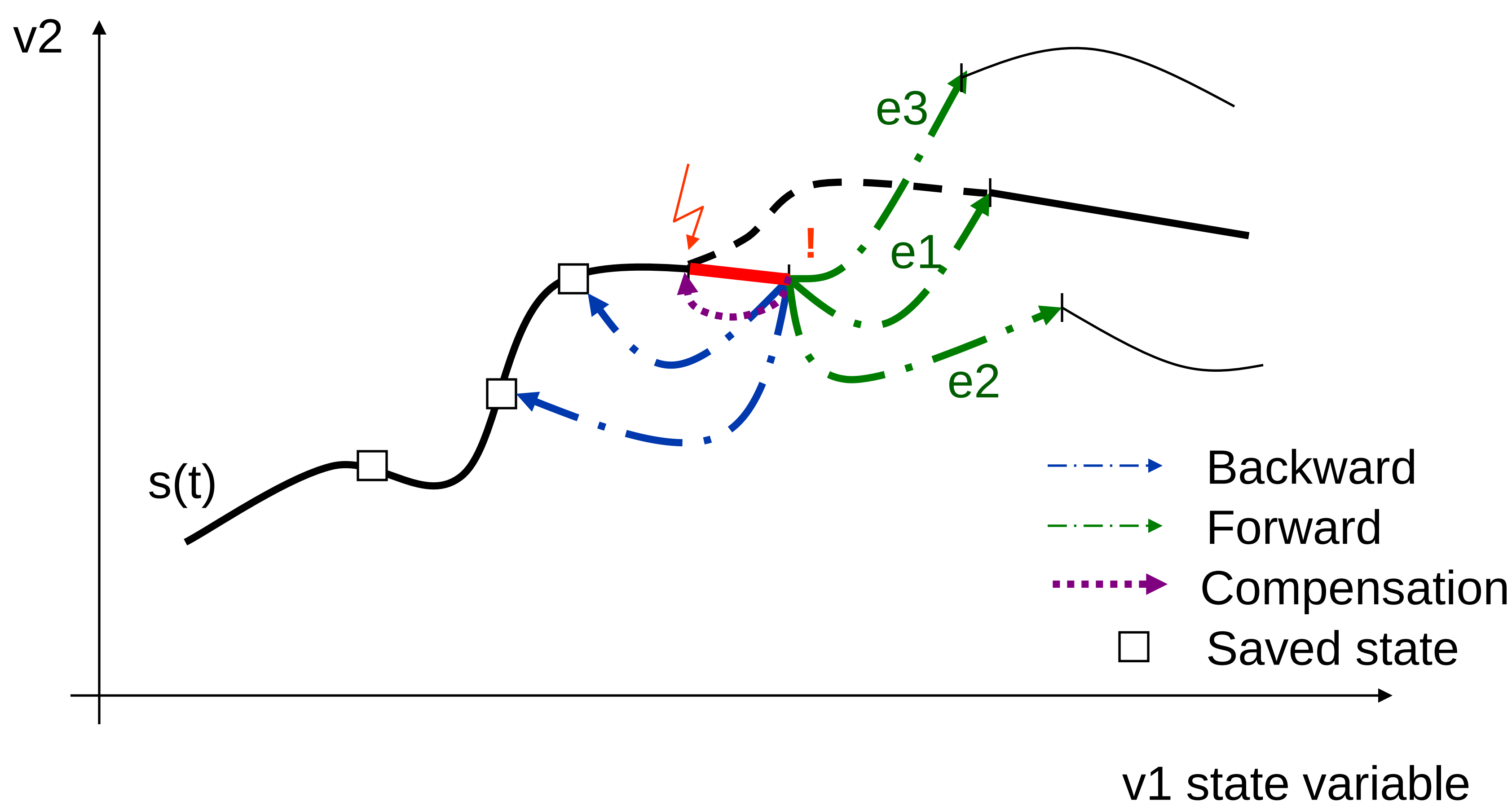
Types of recovery

- State space of the system: Compensation



Types of recovery

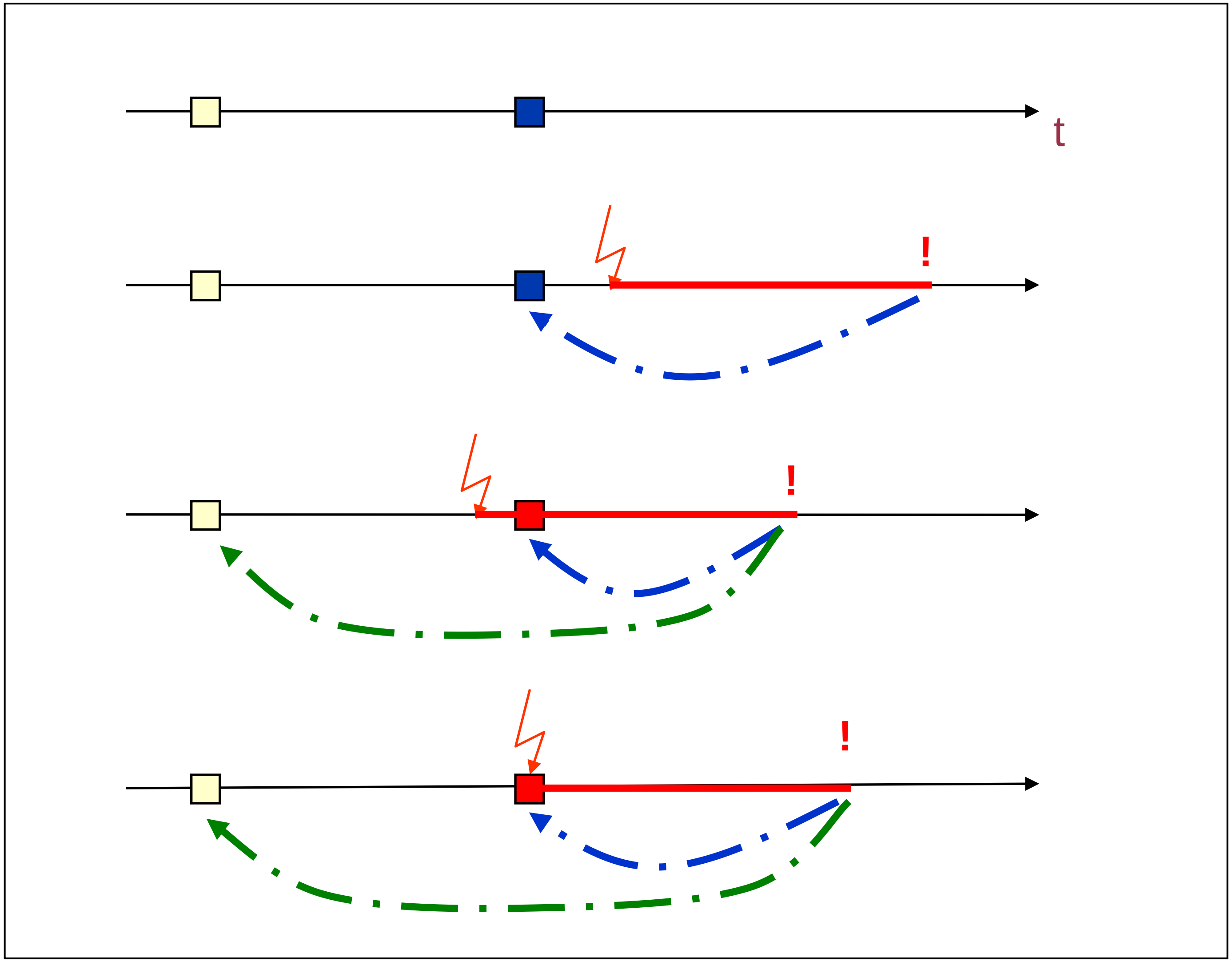
- State space of the system: Types of recovery



Backward recovery

- Based on saved state
  - Checkpoint: The saved state
  - Checkpoint operations:
    - Saving the state: periodically, after messages; into stable storage
    - Recovery: restoring the state from the stable storage to memory
    - Discarding: after having more recent saved state(s)
  - Analogy: “autosave”
- Based on operation logs
  - Error to be handled: unintended operation
  - Recovery is performed by the withdrawal of operations
  - Analogy: ”undo”
- It is possible to combine the two mechanisms

Scenarios of backward recovery



The four phases of operation 4/4

4) Fault treatment and continuing service

- Transient faults:
  - Handled by the forward or backward recovery
- Permanent faults:

  Recovery becomes unsuccessful (the error is detected again)

  The faulty component shall be localized and handled:
  - Diagnostic checks to localize the fault
  - Reconfiguration
    - Fault tolerance: Replacing the faulty component using redundancy
    - Degraded operation: Continuing only the safety related services
  - Repair and substitution

4. Fault tolerance for software faults

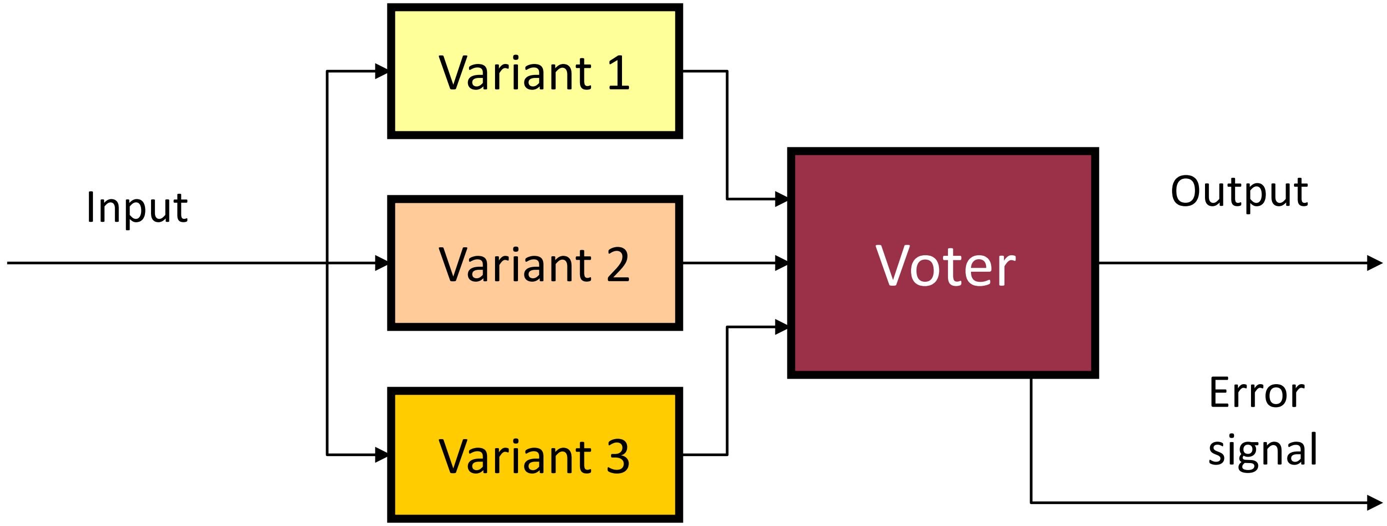
- Repeated execution is not effective for design faults
- Redundancy with design diversity is required!

  Variants: redundant software modules with
  - diverse algorithms and data structures,
  - different programming languages and development tools,
  - separated development teams

  in order to reduce the probability of common failures
- Execution of variants:
  - N-version programming
  - Recovery blocks

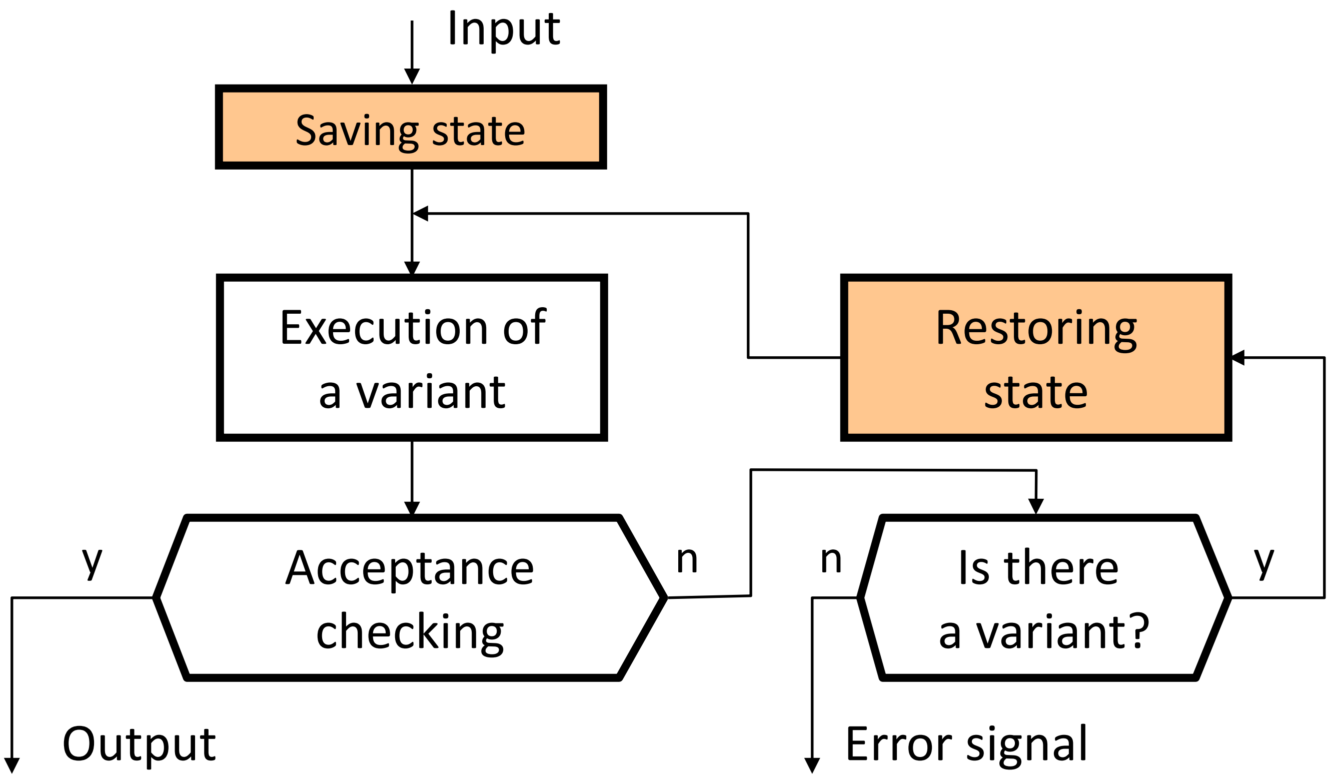
N-version programming

- Active redundancy:
  Each variant is executed (in parallel)
  - The same inputs are used
  - Majority voting is performed on the output
    - Acceptable range of difference shall be specified
    - The voter is a single point of failure



Recovery blocks

- Passive redundancy: Activation only in case of faults
  - The primary variant is executed first
  - Acceptance checking on the output of the variants
  - In case of a detected error another variant is executed



Comparison of the techniques

Property/Type	**N-version prog.**	**Recovery blocks**
Error detection	Majority voting, relative	Acceptance checking, absolute
Execution of variants	Parallel	Serial
Execution time	Slowest variant (or time-out)	Depending on the number of faults
Activation of redundancy	Always (active)	Only in case of fault (passive)
Tolerated faults	[(N-1)/2]	N-1
Fault handling	Masking	Recovery

Summary

Summary: Techniques of fault tolerance

1. Hardware design faults
    - Diverse redundant components are used
2. Hardware permanent operational faults
    - Replicated components are used: TMR, NMR
3. Hardware transient operational faults
    - Software techniques for fault tolerance
        1. Error detection
        2. Damage assessment
        3. Recovery: Forward or backward recovery (or compensation)
        4. Fault treatment
    - Information redundancy: Error correcting codes
    - Time redundancy: Repeated execution (retry, reload, restart)
4. Software design faults
    - Variants as diverse redundant components (NVP, RB)

Redundancy in resources and time