Software Fault Tolerance

Sequential Fault Tolerance Techniques

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Overview

- Robust Software (Pullum 2.1)
- Design Diversity
  - Recovery Blocks (Pullum 4.1)
  - Acceptance Tests (Pullum 7.2)
- Data Diversity
  - Retry Blocks (Pullum 5.1)
  - Data Re-expression Algorithms (Pullum 2.3)

Robust Software (1)

- Software that can continue to operate correctly despite the introduction of invalid inputs [IEEE82]
- Invalid inputs are defined in the specification
  - Out of range inputs
  - Inputs of the wrong type
  - Inputs in the wrong format
  - Corrupted inputs (detected using error-detecting codes)
  - Wrong invocation protocol
  - Violation of pre-conditions

Robust Software (2)

- Goal: No degradation of functionality (that does not depend on the invalid input)
- Detect wrong inputs, then
  - Request new input from the source (probably a human operator)
  - Use last acceptable value
  - Use a predefined default value
- Signal input error to the outside
- Means: (interface) exceptions

Design Diversity (Reminder)

- Identical copies (replicates) of software cannot increase reliability in the presence of software design faults
  ⇒ Design diversity:
  Provision of identical services through separate design and implementations
- Components providing identical functionality are called versions, variants, alternatives, modules
- Make versions as diverse and independent as possible
  - Low probability of common-mode failures:
    Variants should fail on disjoint subsets of the input space
  - High reliability: At least one variant should be operational all times

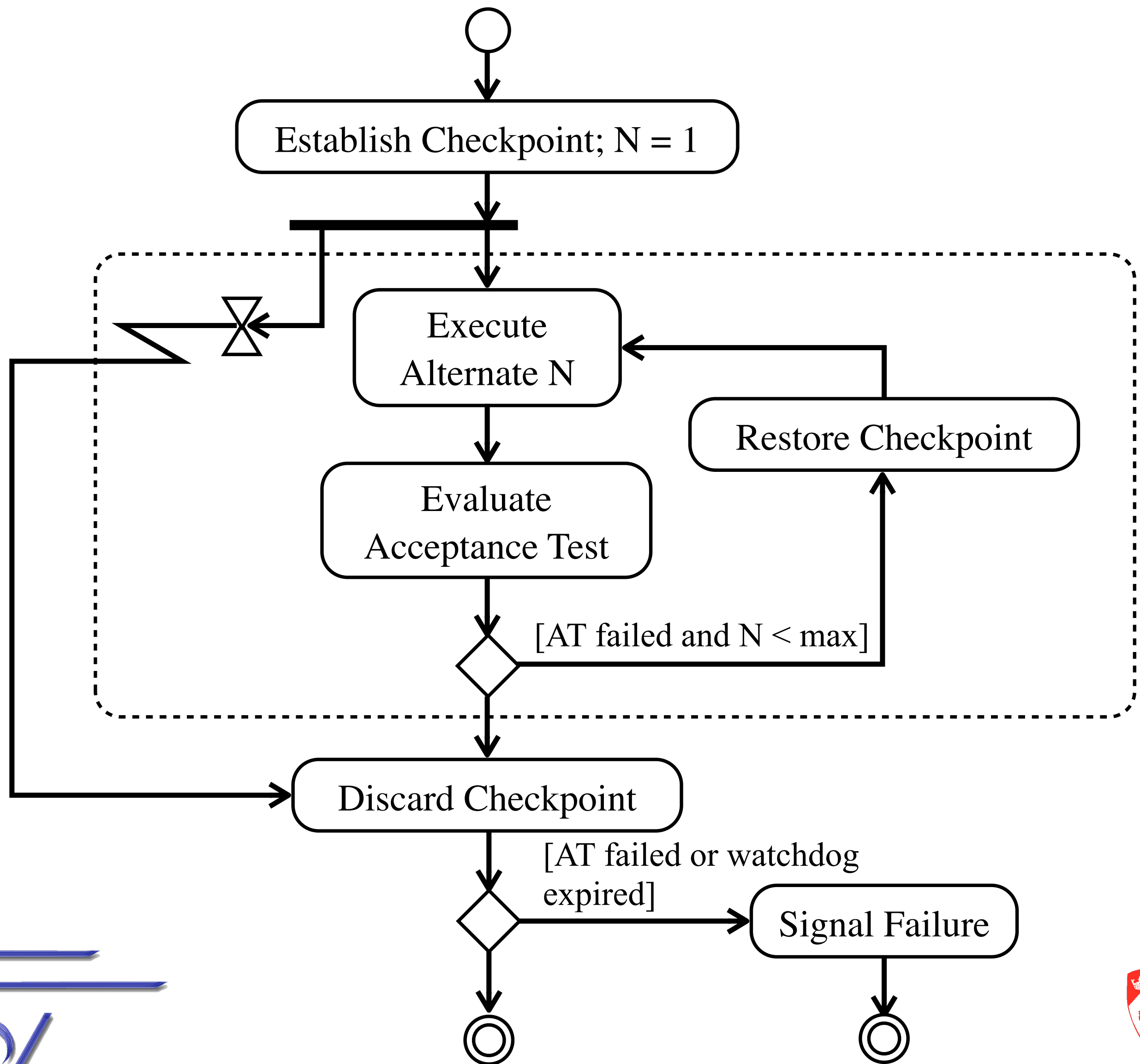
Recovery Blocks (1)

- Introduced in 1974 [Hor74], first implementations by Randell [Ran75]
- Idea: Most program functions can be performed in more than one way
- Different algorithms and design, with varying degrees of efficiency in terms of memory utilization, execution time, reliability, etc…
  - Most efficient variant: primary alternate (or try block)
  - Less efficient: secondary alternate (or try block)

Recovery Blocks (2)

```
ensure Acceptance Test
by Primary Alternate
else by Alternate 2
else by Alternate 3
…
else by Alternate n
else signal failure exception
```

Recovery Block Execution



Recovery Blocks (3)

- Based on acceptance test and backward error recovery
- Dynamic technique
  (selection of what output / result is to be used is made during execution based on the result of the acceptance test)
- May include a watchdog to support real-time

Recovery Block Discussion (1)

- Runs in a sequential environment
- Overhead in fail-free mode:
  - Establishing a checkpoint
  - Running the acceptance test
  - Discard the checkpoint
- Additional overhead for every alternate failure:
  - Restoring the checkpoint, executing the alternate, and running the acceptance test again
- Although unlikely, potential overhead is huge
  - Without watchdog not suitable for real-time applications

Recovery Block Discussion (2)

- Can be applied to small, critical software modules
- Watchdog version can detect "infinite loops"
- Requires a highly effective acceptance test
  - Undetected error can cause severe damage
- Communication with the outside can cause domino effect

Acceptance Test (1)

- Basic approach to self-checking software
  - To check post-conditions of operations
- Must verify that the system behavior is acceptable based on an assertion on the anticipated system state
  - Returns true or false
- Used in recovery blocks, consensus recovery block, distributed recovery block, retry block, atomic actions, coordinated atomic actions

Requirements for Acceptance Tests

- Simple
  - Keep run-time overhead reasonable
- Effective
  - Detect anticipated faults
  - Does not incorrectly detect “unfaulty” behavior
- Highly Reliable
  - Does not introduce additional design faults

Acceptance Test Trade-Offs

	Cursory Test	Comprehensive Test
Error Detection Capability	Low	
Design Complexity		High
Design Fault Proneness		High
Development Cost		High
Execution Time		Long
Storage Requirements		High

Acceptance Test (2)

- Test for what a program should do, or for what a program should not do?
  - Testing for what a program should do may require computation of the same magnitude than the main algorithms
  - Possibility of dependence between the acceptance test and the main algorithms
  - Testing for a violation of safety conditions is often simpler

Testing for Satisfaction of Requirements

- Based on the program specification
  - In mathematical operations:
    - Test by applying the *inverse* operation (if it exists)
    - Example: square root
  - Sorting
    - Check that elements are in ascending order
    - Check that the result has the same number of elements
    - Check for the existence of each element in the original sequence
- Test must be independent in order to be effective
- Most effective when carried out on small segments of code [Hec79]

Accounting Tests

- Can handle larger sections of code than satisfaction of requirements tests
- *Checksum*
  - Number of records, sum of all fields
  - Invariants
- *Inventories*
  - Physically measurable (can be automated)
- Suits data-oriented applications with simple mathematical operations (banking systems, …)

Reasonableness Tests

- Based on physical constraints
  - Timing constraints
  - Physical laws
    - Temperature, Speed
    - Continuous rate of change
  - Boundary conditions in application environment
  - Sequencing of object states
- Suits process control / real-time applications
- Straightforward and efficient to implement

Run-time Tests

- Testing for anomalous states in the program
  - Divide-by-zero
  - Overflow / Underflow
  - Undefined operation code
  - Write-protection violation
- Range checks (e.g. Ada)
- Null pointer checks

Design Diversity Cost

- Cost for developing three-variant diversity is about twice that of single development [H88]
  - Cost for requirement specification, test specification and system test execution are not multiplied
  - Not all parts of a system are critical
  - Cost for design, coding and version testing is multiplied
- Recovery Blocks
  2 alternates: average cost 175%
  3 alternates: average cost 237 %
- N-Version Programming
  3 versions: average cost 225 %
  4 versions: average cost 301 % [L35]

Retry Blocks (1)

- Introduced in 1987 [AK87]
- Idea:
  Some algorithms fail on very specific input values (e.g. 0.0), but will succeed / be very efficient on related values
  - First try with original input
  - If attempt fails, re-express input and try again
- Data diverse complement of the recovery block

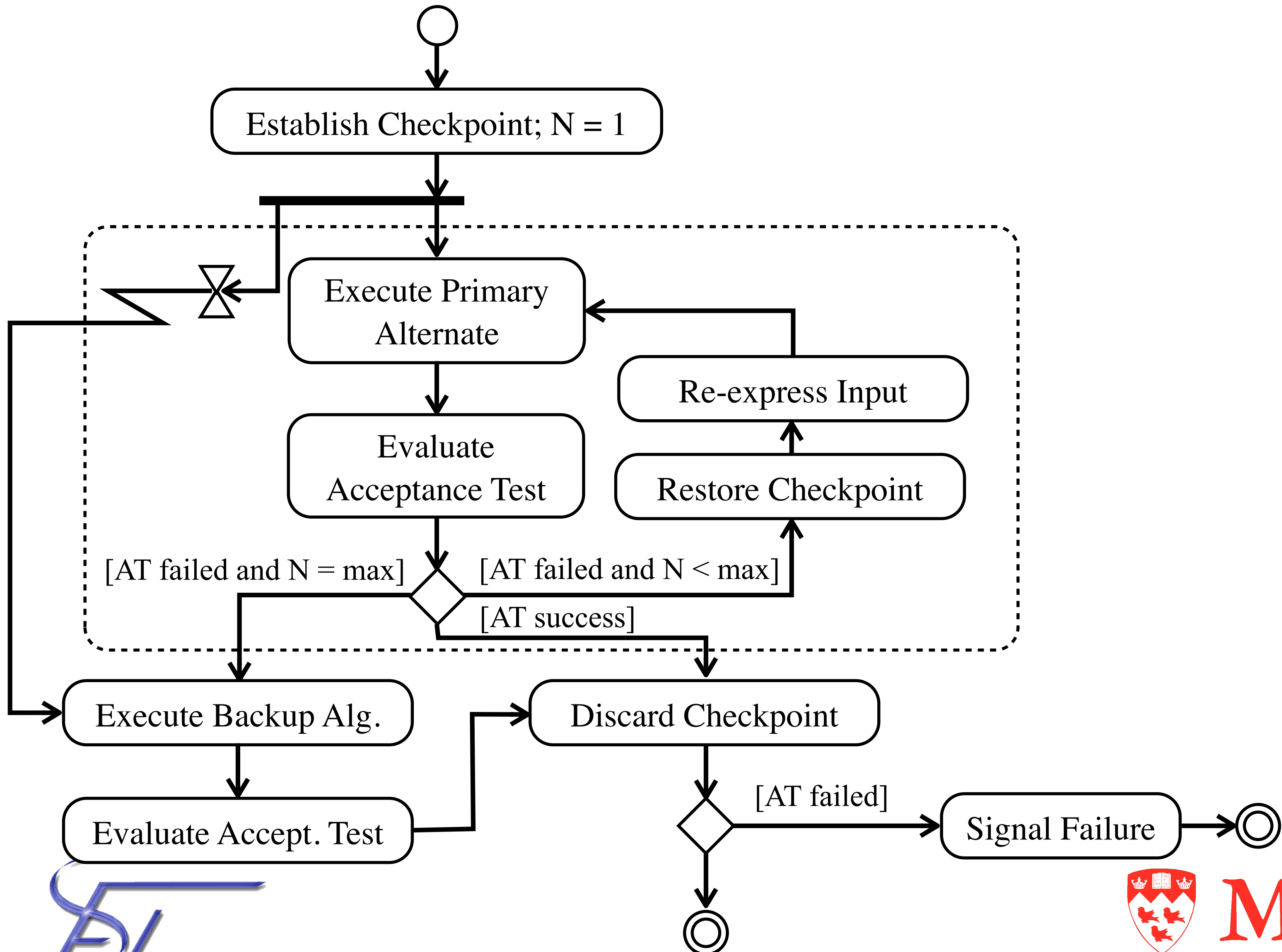
Retry Blocks (2)

```
ensure Acceptance Test
by Primary Algorithm (Original Input)
else by Primary Algorithm (Re-expr. Input)
else by Primary Algorithm (Re-expr. Input)
…
… [deadline expires]
else by Backup Algorithm (Original Input)
else signal failure exception
```

Retry Blocks (3)

- Based on acceptance test and backward error recovery
- Dynamic technique
  (selection of what output / result is to be used is made during execution based on the result of the acceptance test)
- May include a watchdog for handling real-time situations

Retry Block Execution



Retry Block Discussion

- Runs in a sequential environment
- Overhead in fail-free mode:
  - Establishing a checkpoint
  - Run the acceptance test
- Additional overhead in case of failure:
  - For each additional try: Restoring the checkpoint, executing the data re-expression algorithm, running the primary algorithm again, and running the acceptance test again
  - In case of deadline expiration or failure of all primary runs: Restoring the checkpoint, execution of the backup algorithm, running the acceptance test
- Although unlikely, potential overhead is huge
- Without watchdog not suitable for real-time applications

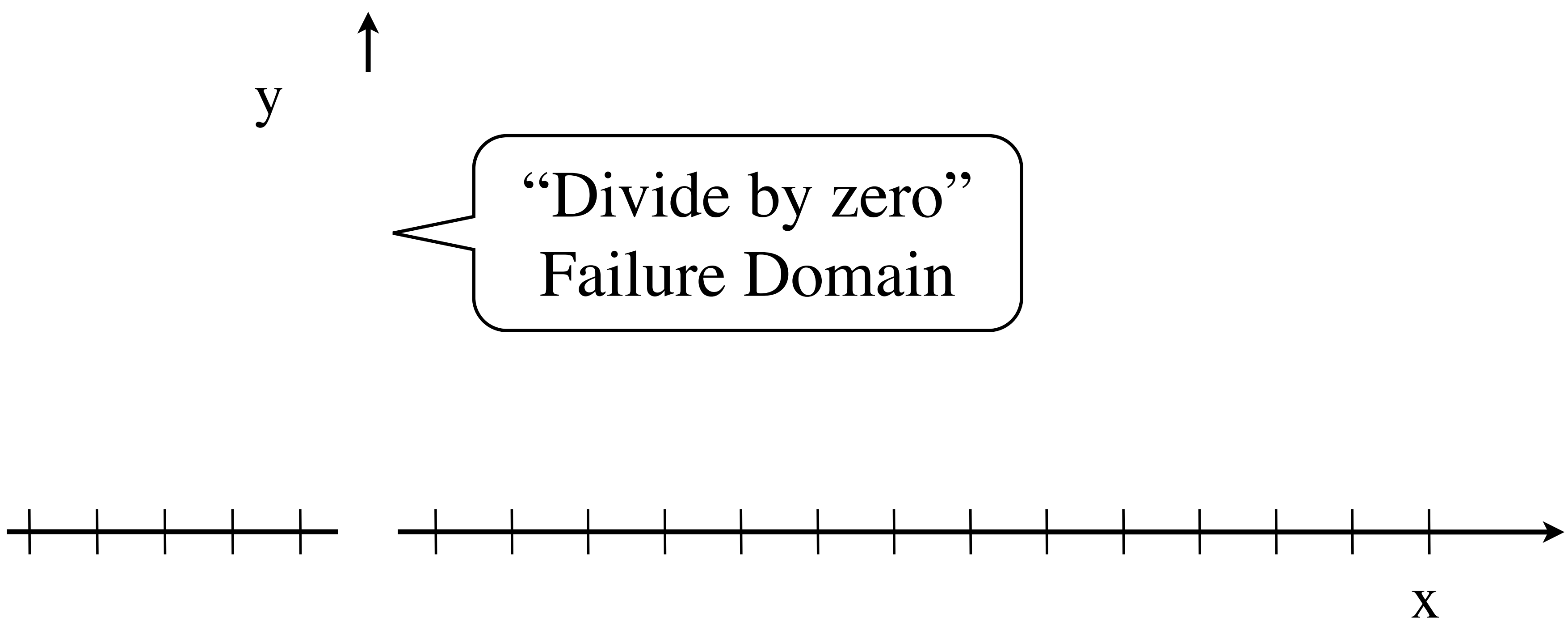
Retry Block Discussion (2)

- Can be applied to small, critical software modules
- Watchdog version can detect “infinite loops”
- Requires a highly effective data re-expression algorithm and acceptance test
  - Undetected error can cause severe damage
- Communication with the outside can cause domino effect

Retry Block Example (1)

- Program calculates f(x,y)
  - The two inputs x and y are measured by sensors with a tolerance of ± 0.02
- Original algorithm should not receive x = 0.0 as an input, or else `Divide_By_Zero` exception is thrown
  - Input can be close to 0.0, but due to lack of precision in the floating point data type, values such as 1e-10 are rounded down to 0.0
- Acceptance test: $f(x,y) \geq 100.0$

Retry Block Example (2)



Retry Block Example (3)

- Calculate f(0.7e-10, 2.2)

  1. Retry block executive establishes a checkpoint
  2. Primary algorithm is executed with ($0.7e^{-10}$, 2.2)
     ⇒ Divide_By_Zero exception
  3. The executive catches the exception, sets a flag indicating the failure of the first run, and restores the checkpoint
  4. The executive re-expresses the inputs by calling the data re-expression algorithm

Retry Block Example (4)

5. The DRA modifies x within x's limits of accuracy: $R(x) = x + 0.0021$
6. The executive calls the primary algorithm with the re-expressed input. Execution returns 123.45
7. The executive submits the result to the acceptance test, which is passed successfully
8. The executive discards the checkpoint and returns the results

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