TTK4145 – Real-time Programming

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Contents

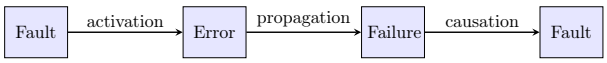
1 Fault Tolerance Basics

This chapter is based on Ch. 2 in Real-Time Systems and Programming Languages 4E (BW).

Reliability A measure of the success with which the system conforms to some autoritative specification of its behaviour.

Failure vs Fault vs Error A few definitions:

- *Failure:* A mechanical or algorithmic cause which, given the right conditions, produce an unexpected or incorrect result.
- *Fault:* An internal unexpected problem in a system, caused by activation of a fault.
- *Error:* System deviation from its specification.



Types of fault

- *Transient faults:* Occur at a particular time, remain in the system for a period, then disappear afterwards. An example of this is radioactivity.
- *Permanent faults:* A fault that persists in the system until it is fixed. All software faults are permanent faults.
- *Intermittent faults:* A special case of transient faults that occur repeatedly. Overheating is an example.

Failure modes Two general domains of failure modes can be identified:

- *Value failure:* The output is wrong or even corrupted/unusable.
- *Time failure:* The service is delivered at the wrong time.

Fault prevention Attempts to eliminate any possibility of faults creeping into a system before it goes operational. Two stages: fault avoidance and fault removal.

Fault tolerance Enables the system to continue functioning even in the presence of faults. Different levels of faults can be provided by a system:

- *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:* 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.

Redundancy All techniques for achieving fault tolerance rely on extra elements (redundancy) introduced into the system to detect and recover from faults. Can be implemented in both software and hardware.

Distinguish between static and dynamice redundancy for hardware:

- *Static:* Redundant components are used inside a system (or subsystem) to hide the effects of faults. (error masking)
- *Dynamic:* The redundancy supplied inside a component which indicates explicitly or implicitly that the output is in error. (error detection)

N-version programming Defined as the independent generation of N (where $N \geq 2$) functionally equivalent programs from the same initial specification. The programs execute concurrently without interaction, and the results (compared by a driver process) should be identical. However, if they do not produce the same result the driver might choose the most common result, ask the processes to compute it again, or simply terminate the faulty process.

To achieve diversity, different programming languages and different development environments could be used. Alternatively, if the same language is used, different compilers and support environments should be employed. (N-version programming is the software equivalent of static redundancy.)

Downsides to this solution:

- In a real-time system, the driver process and different programs may need to communicate – introducing a communication module.

- High cost of introducing a redundant language/hardware etc.
- Most software faults originate from the specification – all N versions may suffer from the same fault.

Dynamic redundancy The redundant components only come into action when an error has been detected. Has four stages presented in the following four paragraphs.

Error detection Two classes of error detection techniques can be identified.

- Environmental detection
- Application detection. Since the recovery system is not continually running, there needs to be some way to detect a fault. There are many triggers that could be used.
  - Replication checks –
  - Timing checks –
  - Reversal checks –
  - Coding checks –
  - Reasonableness checks –
  - Structural checks –
  - Dynamic reasonableness checks –

Damage confinement and assessment Concerned with structuring the system as to minimize the damage caused by a faulty component (also known as firewalling). Two techniques: modular decomposition and atomic actions.

Error recovery Once an error situation has been detected and the damage assessed, error recovery procedures must be initiated.

Forward error recovery: Attempts to continue from an erroneous state by making selective corrections to the system state. Although it is efficient, it is system specific and depends on accurate predictions of the location and cause of errors.

Backward error recovery: Relies on restoring the system to a safe state (recovery point) previous to that in which the error occurred. Straightforward if no threads, but gets complicated with more threads. A big advantage: Does not rely on finding the location or cause of fault. A huge disadvantage: It is difficult to undo eg. a missile launch...

Fault treatment Two stages: Fault location and system repair.

Domino effect If one thread needs to roll back due to an error, then it must undo the communication with the other threads. This may propagate further back and forth, and will end up in multiple threads having to roll back as well.

Recovery blocks Blocks in the normal programming sense except that at the entrance is an automatic *recovery point* and at the end an *acceptance test*. (dynamic recovery)

Acceptance test Used to test that the system is in an acceptable state after the execution of the block. It can utilize several of the methods discussed for error detection. If it fails, the program will be restored to the recovery point at the beginning of the block and an alternative module will be executed.

2 Fault Model and Software Fault Masking

This chapter is based on Ch. 3.7 in the book Transaction Processing: Concepts and Techniques (GR).

Fault model The one used in this chapter involves three entities: *processes, messages and storage.*

Unexpected faults Faults that are not tolerated by the design. Two categorizations:

- *Dense faults*: The algorithms will be n-fault tolerant. If there are more than n faults within a repair period, the service may be interrupted (in this case the system should be designed to stop).
- *Byzantine faults*: The fault model postulates certain behavior – for example it may postulate that programs are failfast. Faults in which the system does not conform to the model behavior are called Byzantine.

Underlying progression

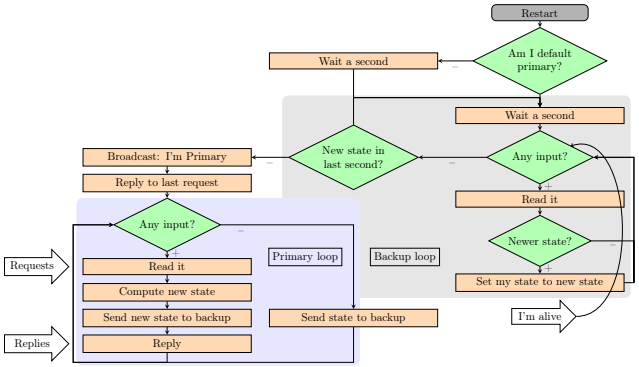
- *Failfast*: They either execute the next step, or they fail and reset to the null state.
- *Available*: Failfast + repairability
- *Reliable*: Continuous operation

Checkpoint-Restart Write state to storage after each acceptance test, but before each event. This approach can be somewhat slow (hours/days).

Process pairs OS generates a backup process for each new primary process. The primary sends *I'm Alive* messages to the backup on a regular basis.

The backup can take over in three different ways:

- *Checkpoint-restart.* The primary records its state on a duplexed storage module. At takeover, the backup starts by reading these duplexed storage pages. (quick repair)
- *Checkpoint message.* The primary sends its state changes as messages to the backup. At takeover, the backup gets its current state from the most recent message. (basic pairs must checkpoint)
- *Persistent.* The backup restarts in the null state and lets the transaction mechanism clean up (undo) any recent uncommitted state changes. (simple)



3 Transaction Fundamentals

This chapter is based on Ch. 1 in the book Java Transaction Processing (LMP).

Atomic operation An operation that is indivisible (it is not possible to decompose it into smaller operations), eg. a money transfer between two bank accounts.

Transaction Refers to the term *atomic transaction*, which provides an "all-or-nothing" property to work that is conducted within its scope. An atomic transaction has the same properties as an atomic action plus the added feature that if a failure happens, the components are returned to their natural state instead of being left possibly inconsistent as in an atomic action.

Controlling a transaction A few definitions:

- *Commit:* When all parts of the transaction commits, the transaction finishes and all its actions are made permanent.
- *Rollback:* An abortion of the transaction. All work done by the transaction is reverted.

ACID properties Properties of an atomic action:

- *Atomicity.* The transaction completes successfully (commits) or if it fails (aborts) all of its effects are undone (rolled back).
- *Consistency.* Transactions produce consistent results and preserve the internal consistency of the data it acts on.
- *Isolation.* Intermediate states produced while a transaction is executing are not visible to others. Furthermore, transactions appear to execute serially, even if they are actually executed concurrently.
- *Durability.* The effects of a committed transaction are never lost.

Termination A transaction can be terminated in two ways: *committed* or *aborted* (rolled back). When a transaction is committed, all changes made within it are made durable (forced onto stable storage). When a transaction is aborted, all of the changes are undone.

Coordinator Responsible for governing the outcome of the transaction. It can be implemented as a separate service or may be co-located with the user for improved performance. It communicates with enlisted participants to inform them of the desired termination requirements.

Transaction manager factory Responsible for managing coordinators for many transactions.

Two-phase commit This protocol is used to ensure consensus between participating members of the transaction (ie. ensure it has an atomic outcome).

In phase 1 the coordinator communicates with all the action participants to determine whether they will commit or abort. An abort reply, or no reply, from any participant acts as a veto, causing the entire action to abort. If the transactions commits, then phase 2 is entered and the coordinator forces the participants to carry out the decision. Each participant making a commit response to the coordinator in phase 1 is blocked until they have received the coordinator's phase 2 message.

Note that the two-phase commit protocol is not client-server based. It simply talks about a coordinator and participants, and makes no assumption about where they are located.

Interference free / Serializable If there are variables that are not shared between programs, some aspects of the programs can be executed concurrently. A partly concurrent execution order is termed serializable if it produces an equivalent result as doing it in serial order. If a program possess this property it is said to be atomic with respect to concurrency.

Concurrency control mechanisms Ensures serializability.

- *Two-phase concurrency control:* All operations on an object is of type "read" or "write". Many computations can hold a "read-lock", which is associated with an object by a computation before reading it. However, if someone wants to change (insert/modify/delete) the object, this requires a "write-lock". This can not be obtained if any of the other operations hold either a read or write lock on that object. This is to make sure that no one changes something others are using in their operations. If you have obtained a write-lock, this will block all other requests for read and write until you release the lock. All computations must follow a two-phase locking policy.

  In phase 1, the growing phase, locks are acquired, but not released. In phase 2, the shrinking phase, locks are released but can't be acquired. To avoid the cascade roll back problem (see under), all locks are released simultaneosly in the shrinking phase.

- *Pessimistic concurrency control:* When a resource is accessed, a lock is obtained on it. The lock will remain held on that resource for the duration of the transaction. Disadvantages with this style:

  - Deadlocks
  - Concurrency may be limited by the granularity of the locks
  - The overhead of acquiring and maintaining concurrency control information in an environment where conflict or data sharing is not high.

- *Optimistic concurrency control:* Locks are only acquired at the end of the transaction when it is about to terminate. When updating a resource, the operation needs to check if this conflicts with updates that may have occurred in the interim, using timestamps. Most transaction systems that offer optimistic concurrency control will roll back if a conflict is detected, which may result in a lot of work being lost.

- *Type-specific concurrency control:* Concurrent read/write or write/write operations are permitted on an object from different transactions provided these operations can be shown to be non-interfering. Object-oriented systems are well suited to this approach, since semantic knowledge about the operations of objects can be exploited to control permissible concurrency within objects.

- *Deadlock detection and prevention:* A transaction is *blocked* if it cannot acquire a lock on a resource it waits for to be released. In some systems, it is possible for transactions to wait for each other – the system is *deadlocked*.

  The only way to resolve a deadlock is for at least one of the transactions to release its locks that are blocking another transaction (it must roll back). Techniques for deadlock detection:

  - *Timeout-based:* A transaction waits a specified period of time, then rolls back assuming there is a deadlock.
  - *Graph-based:* Tracks waiting transaction dependencies by constructing a waits-for graph: nodes are waiting transactions and edges are waiting situations. Guaranteed to detect all deadlocks, but may be costly to execute in a distributed environment.

Two-phase commit optimizations There are several variants to the standard two-phase commit:

- *Presumed abort:* If during system recovery from failure no logged evidence for commit of some transaction is found by the recovery procedure, then it assumes that the transaction has been aborted, and acts accordingly. This means that it does not matter if aborts are logged at all, and such logging can be saved under this assumption.
- *One-phase:* If there is only one participant involved in the transaction, there is implicit consensus on whether to commit or not and the coordinator need not drive it through the prepare phase.
- *Read-only:* A participant may indicate to the coordinator if it is responsible for a service that did not do any work during the course of the transaction, and can be left out of the second phase.
- *Last resource commit:* It is possible for a single resource that is one-phase aware (no prepare, only commit or roll-back), to be enlisted in a transaction with two-phase commit aware resources. The coordinator executes the prepare phase on only the latter, and if the decision is to commit, then the one-phase aware resource is informed about this.

Heuristic transactions *Heuristic outcome:* The case in which the coordinator informs the participant that the outcome and the decision are contrary. (May happen when blocking occurs in the two-phase commit protocol (where it is used to ensure atomicity). To break the blocking, participants that are past the prepare phase are allowed to make decisions as to whether commit or rollback.) It has a corresponding *heuristic decision*.

There are two levels of heuristic interaction:

- *Participant-to-coordinator:* If a participant makes an autonomous decision, it must assume that it caused an heuristic and remember the choice. At this point the participant is in a *heuristic state*.

- *Coordinator-to-application:* If the choice is different from the coordinator, then a heuristic outcome must be reported to the application. The transaction will still be marked as committed of rolled back, but it will also be in a heuristic state.

Outcome	Description
Heuristic rollback	The commit operation failed because some or all of the participants unilaterally rolled back the transaction.
Heuristic commit	An attempted rollback operation failed because all of the participants unilaterally committed. One situation where this might happen is if the coordinator is able to successfully prepare the transaction, but then decides to roll it back because its transaction log could not be updated. While the coordinator is making its decision, the participants decides to commit.
Heuristic mixed	Some participants commited, while others were rolled back.
Heuristic hazard	The disposition of some of the updates is unknown. For those which are known, they have either all been committed or all rolled back.

Transaction log Registration of the participants and where they have reached in the protocol. After the coordinator's decision has been conducted, the participant log can be deleted and informed to the coordinator.

Nested transactions transaction!nested Transactions that are contained within the resulting transaction. The

enclosing transaction is referred to as a *parent* of a nested (or *child*) transaction → a hierarchical structure (with the root referred to as the *top-level transaction*).

The effect of a nested transaction is provisional upon the commit/rollback of its enclosing transaction (the effects will be recovered if the enclosing transaction aborts).

Subtransactions are useful for two reasons:

- *Fault isolation:* If the subtransaction rolls back then this does not require the enclosing transaction to roll back.
- *Modularity:* If there is already a transaction associated with a call when a new transaction is begun, then the transaction will be nested within it. If the object's methods are invoked without a client transaction, then the object's transaction will be top-level, otherwise they will be nested within the scope of the client's transactions.

Because nested transactions do not make any state changes durable until the enclosing top-level transaction commits, there is no requirement for failure recovery mechanisms for them.

Interposition The technique of using proxy (or subordinate) coordinators. Each machine that imports a transaction context may create a subordinate coordinator that enrolls with the imported coordinator as though it was a participant.

When and why interpositions occurs:

- *Performance:* If a number of participants reside on the same node, or are located physically close, can then improve performance for a remote coordinator to send a single message to a subcoordinator that is co-located with those participants and for that subcoordinator to disseminate the message locally, rather than send the same message to each participants.
- *Security and trust:* A coordinator may not trust indirect participants and vice versa, that makes direct registration impossible.
- *Connectivity:* Some participants may not have direct connectivity with a specific coordinator, requiring a level of indirection.
- *Separation of concerns:* Many domains and services may simply not want to export (possibly sensitive) information about their implementations to the outside world.

4 Atomic Actions

This chapter is based on Ch. 7 in Real-Time Systems and Programming Languages 4E (BW).

Atomic actions The activity of a component is said to be atomic if there are no interactions between the activity and the system for the duration of the action.

Nested atomic actions An atomic action, even though viewed as indivisible, can be composed by internal atomic actions.

Two-phase atomic actions For efficiency and increased concurrency, it is advantageous if tasks will wait as long as possible before requiring resources, and freeing them as soon as possible. This could however make it possible for other tasks to detect a change in state before the original task is done performing the atomic action.

To avoid this, atomic actions are split into two separate phases, a 'growing' phase where only acquisitions can be made, and a 'shrinking' phase where resources can be released while no new acquisitions can be made. This way, other tasks will always see a consistent system state.

Atomic transactions Has all the properties of an atomic action plus the added feature that its execution is allowed to either succeed or fail.

If an atomic action fails, the system may be left in an inconsistent state. If an atomic transaction fails, the system will return to the state prior to the execution.

There are two distinct properties of atomic transactions:

- *Failure atomicity:* The transaction must complete successfully or have no effect.
- *Synchronizations atomicity:* The transaction must be indivisible so that no other transaction can observe its execution.

Even though transactions provide error detection, they are not suitable for fault-tolerant systems. This is because they provide no recovery mechanism in case of errors, and will not allow any recovery procedures to be run.

Requirements for atomic actions For implementation of atomic actions in a real-time system, it is necessary with a well-defined set of requirements which must be fulfilled.

- *Well-defined boundaries:* Each atomic action should have a start, and end and a side boundary. A start boundary is the locations in the task where the action is initiated; the end is the location where the action will end in the task. The side boundary is the separation of the tasks involved in an action from the rest of the system.

- *Indivisibility:* Atomic actions must not allow any exchange of information between the tasks inside and outside the action. Additionally, there are no synchronization at the start of atomic actions, but there is an implied synchronization at the end; tasks are not allowed to leave the atomic action until all tasks are willing and able to leave.

- *Nesting:* Atomic actions may be nested as long as they do not overlap with other atomic actions.

- *Concurrency:* It should be possible to execute different atomic actions concurrently.

Asynchronous notification The key to implementing error handling is the asynchronous messages, and most programming languages have some feature allowing asynchronous messages to be sent. There are mainly two principles for this: Resumption and termination.

Resumption model: Behaves like a software interrupt. A task contains an event handler which will handle prede ned events. When the task is interrupted, the event handler is executed, and when it is finished, the task will continue execution from the point where it was interrupted.

Termination model: Each task specifies a domain in which it will accept an asynchronous signal. If the task is in the defined domain and receives an asynchronous signal, it will terminate the domain (*asynchronous transfer of control*, ATC. If a task is outside the defined domain, the ATC will be queued or ignored. When the ATC is finished, the control is returned to the calling task at a different location than from where it was called.

Main reasons for using asynchronous notifications: (enables a task to respond quickly)

- *Error recovery:* When errors occur it can mean that the system states are no longer valid, that processes may never finish or a timing error may have occurred. There is no longer a point of waiting for a process to finish, and the best solution is to respond immediately.
- *Mode changes:* A real-time system often has several modes of operation. When sudden changes in modes happen, we want the system to respond immediately – for example when a transition to an emergency state occurs.
- *Scheduling using partial/imprecise computations:* Many algorithms calculating specific results operates by giving more accurate results for each iteration. The task must be interrupted to stop further refinement of the result.
- *User interrupts:* Whenever a system receives interrupts from a user, for example when an error occur, the response must be immediate.