Dependable Systems

Fault Tolerance Patterns

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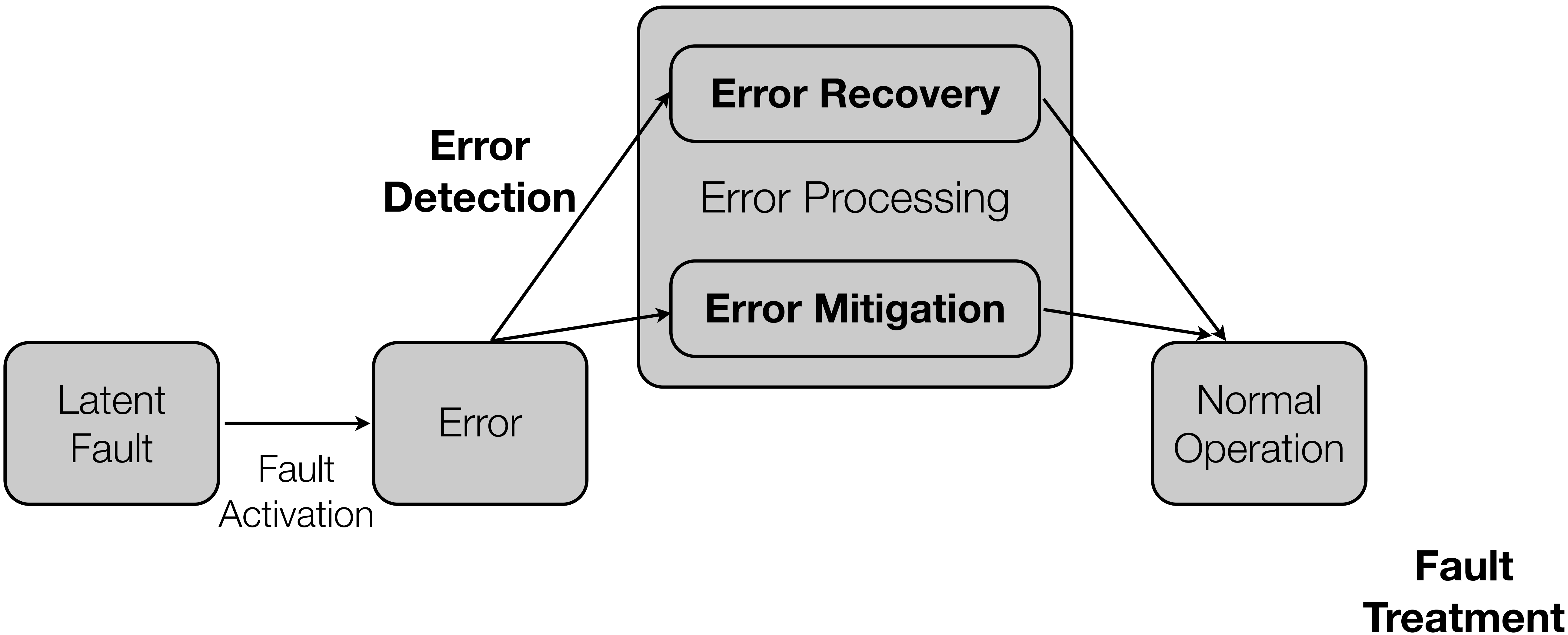
Source:

Hanmer, Robert S.: Patterns for Fault Tolerant Software. Wiley, 2007.

Phases of Fault Tolerance (Hanmer)



Design Pattern

- Definition from software engineering:
  „A general reusable solution to a commonly occurring problem“
  - No finished / directly applicable solution, but a template
  - On the level of components and interactions
- Popular approach in computer science (Gang of Four, Portland Pattern Repository)
- Fault tolerance patterns
  - ... might be suited for stateless / stateful / both kinds of system
  - ... are based on observers and monitors (humans / computers)
  - ... work orthogonal to primary function
- Note: ‚Hamner‘-Book is about software fault tolerance,
  but the patterns are generic (enough)

Fault Tolerance Patterns

- **Architectural patterns**
  - Considerations that cut across all parts of the system
  - Need to be applied in early design phase
- **Detection patterns**
  - Detect the presence of root faults, error states, and failures
  - Errors vs. failures -> a-priori knowledge vs. comparison of redundant elements
- **Error Recovery Patterns**
  - Methods to continue execution in a new error-free state
  - Undoing the error effects + creating the new state

Fault Tolerance Patterns

- **Error Mitigation Patterns**
  - Do not change application or system state,
    but mask the error and compensate for the effects
  - Typical strategies for timing or performance faults
- **Fault Treatment Patterns**
  - Prevent the error from reoccuring by repairing the fault
  - System verification
  - Diagnosis of fault location and nature
  - Correction of the system and / or the procedures

Architectural Patterns

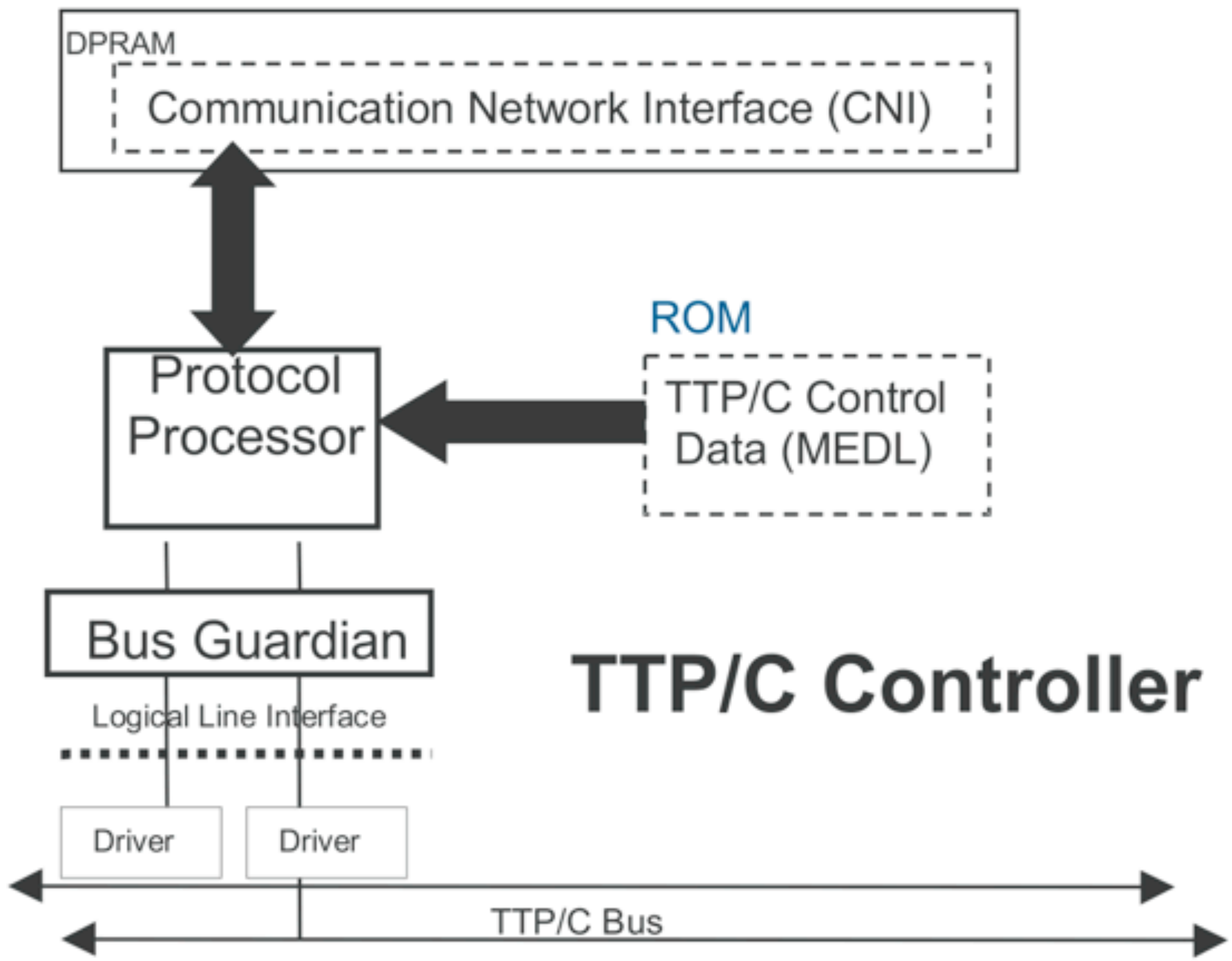
Architectural Patterns - Units of Mitigation

- Only parts of the system should potentially get into error state
- Design *units of mitigation* that contain errors and their error recovery mechanism
- Tradeoff:
  Component size vs. bookkeeping overhead vs. fault tolerance options
- Should contain independent atomic actions without communication focus
- Hints for granularity
  - Architectural style (n-tier)
  - Functional and resource (memory, CPU) boundaries
  - Choice of recovery action (e.g. restart)
- Should perform **self checks and fail silently**, act as barrier to an error state
- Units without any recovery / mitigation possibility are too small

Architectural Patterns - Error Containment Barrier

- Errors spread through several mechanisms - messages, memory, follow-up actions
- *Unit of mitigation* boundary implemented by *error containment barrier*
  - Treated as **separate system component**
  - Barrier must encapsulate error state, should trigger recovery / mitigation
  - In best case, perform detection close to the fault (structural proximity / time)
- Hardware: Isolate faulty components by state bit
- *Babbling idiot* problem
  - Suspicious nodes should never be in control of the communication bus
  - *Bus guardian* as barrier implementation

Guardian Example: Temporal Firewall in the Time-Triggered Architecture (TTA)



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Architectural Patterns - Correcting Audits

- Data element corruption can occur on hardware level (external physical faults) and software level (data types, currencies, pointers, ...)
- *Auditing data* demands *correctness criteria*
    - Structural properties of the data structure (linked lists, pointer boundaries, ...)
    - Known correlations (multiple locations, known conversion factors, cross linkage)
    - Sanity checks (value boundaries, checksums)
    - Direct comparison (duplication, mostly of static data)
- Automatic correction is usually easy, but must consider *item consistency*
- *Actions*: Correction, logging, resume execution
- Errors from faulty data easily propagate, common audit infrastructure helps

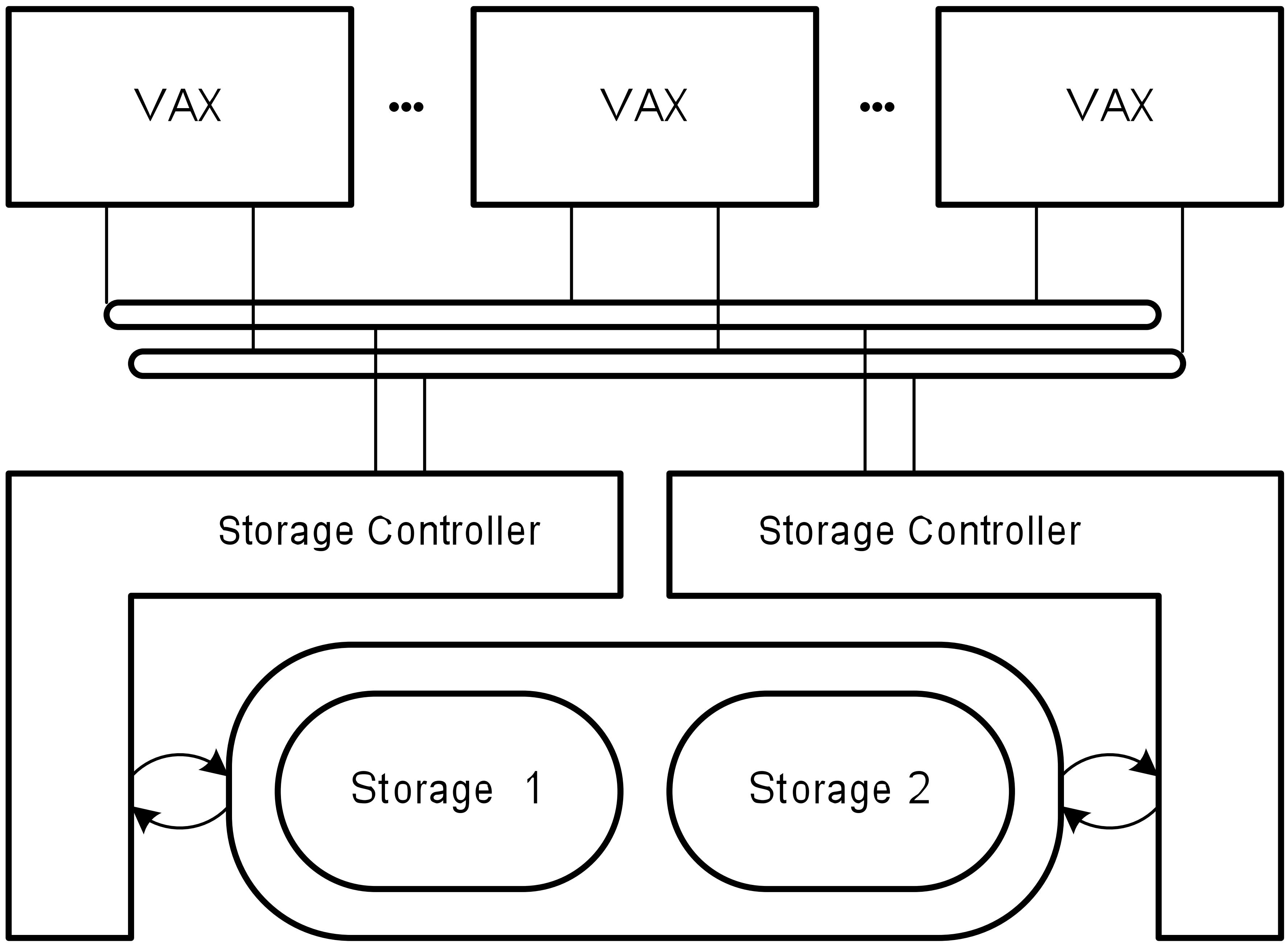
Architectural Patterns - Redundancy

- Improving availability by reducing MTTR is the easiest way
- Error recovery phase makes the effect undone, but must be short
- Idea: Resume execution before bad effects are undone, by using identical copy
  - Accomplish the same work on different hardware / software
  - Does not mean identical functionality, just perform the same work
  - Quick activation of redundant feature needed
- Redundancy types: **spatial, temporal, informational** (presentation, version)
  - Special issues with software redundancy regarding deterministic behavior
- Redundancy for performance improvement, availability then by excess capacity
- Example: Checkpointing vs. fail-over

Spatial Redundancy through Replication

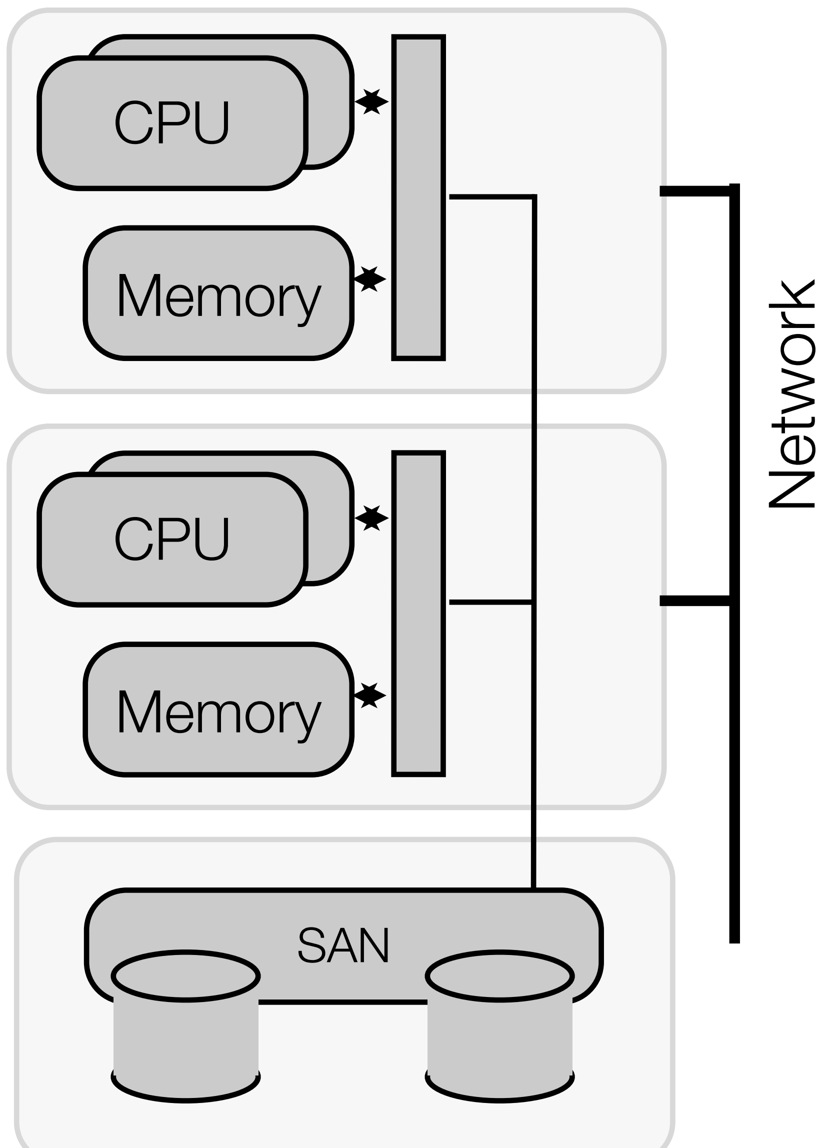
- **Replication**: Process of ensuring consistency between redundant resources
  - Mostly applied for data replication
  - *Active (synchronous) replication* performs the same activity on every replica
    - First introduced by Leslie Lamport as *state machine replication*
    - Demands a deterministic processing of activities
  - *Passive replication* performs activity on one replica, and transmits the delta
    - *Primary server* vs. *backup servers*
    - Delayed response in failover case
    - Works also for non-deterministic processes
  - Example: Master-Slave vs. Master-Master replication setup

Example: VAX Spatial Hardware Redundancy

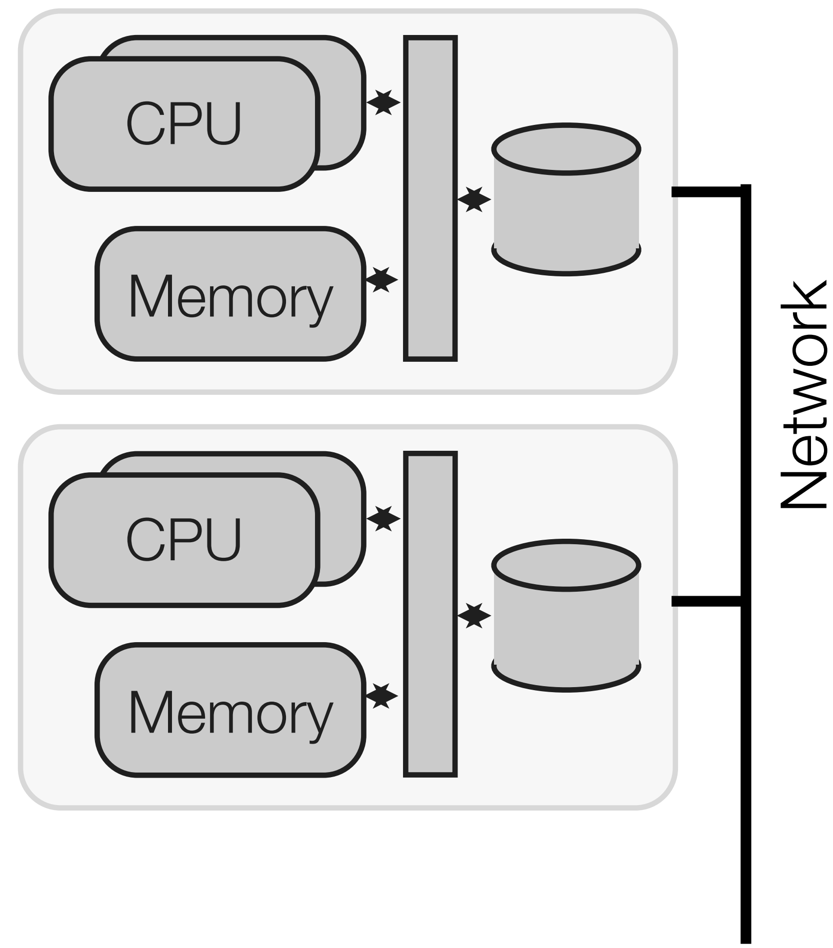


Example: Persistency in Redundant Systems

Shared Disk



Shared Nothing



Example: Persistency in Redundant Systems

	Shared Disk / ‚Multi-Homing‘	Shared Nothing
Advantages	• Good **availability** • Good **load-balancing**	• Very good **availability** • Unlimited **scalability** • Low cost due to standard components
Disadvantages	• Limited **scalability** • Synchronization for concurrent update	• Difficult for **load balancing** • Difficult for performance optimization

Example: PostgreSQL 9 Redundancy Options

- **Shared-Disk setup**
  - Avoids synchronization overhead, but demands network storage resp. file system
  - Mutual access exclusion from active / passive node must be ensured
- **Shared-Nothing setup**
  - **Block-device replication -** Operating system can mirror file system modifications (e.g. GFS, DRBD)
  - **Point-In-Time Recovery (PITR)** - Passive nodes receive stream of write-ahead log (WAL) records, after each transaction commit
  - **Master-Slave / Multimaster Replication** - Batch updates on table granularity
  - **Statement-Based Replication Middleware** - SQL is sent to all nodes

Example: PostgreSQL 9 Redundancy Options

Feature	Shared Disk Failover	File System Replication	Hot/Warm Standby Using PITR	Trigger-Based Master-Slave Replication	Statement-Based Replication Middleware	Asynchronous Multimaster Replication	Synchronous Multimaster Replication
Most Common Implementation	NAS	DRBD	PITR	Slony	pgpool-II	Bucardo	
Communication Method	shared disk	disk blocks	WAL	table rows	SQL	table rows	table rows and row locks
No special hardware required		•	•	•	•	•	•
Allows multiple master servers					•	•	•
No master server overhead	•		•		•		
No waiting for multiple servers	•		•	•		•	
Master failure will never lose data	•	•			•		•
Slaves accept read-only queries			Hot only	•	•	•	•
Per-table granularity				•		•	•
No conflict resolution necessary	•	•	•	•			•

Architectural Patterns - Humans

- *Minimize Human Interaction*
  - Error state root causes: Hardware, Software, Procedural / Operational
  - **Humans are bad** in: Long series of steps, routine tasks, operation, response time
  - Reduce failure risk due to mistakes in error treatment
    -> process errors automatically
    - Operational staff should be able to monitor, but not be required for the solution
- *Maximize Human Participation*
  - System should support experts in contributing to an error solution
    - **Humans are good** in drawing meaning from sequence of unrelated events
  - Examples: Reporting prioritization, context information (timestamp etc.)
  - Safe mode: Wait for human participation

Architectural Patterns - Maintenance Interface

- **Making maintenance task visible** to the outside world - additional form of input
- Separated interfaces and handling needed
  - Shed load approach or any other overload defense will affect operator
  - Intermixed interfaces might bring security problems
- Not a hidden trap door, but well well-protected dedicated path into the system
- Prevent application workload from using it
- Also useful for alike functions, such as log information fetching

Architectural Patterns - Someone in Charge

- Anything can go wrong, even during error processing
- If something does not work, some entity must be able to restart processing action
- For any fault tolerance activity, there must be a **clearly identifiable responsible**
  - Example: *Active* / *Passive* standby
- Single component in charge means single failure point, also increases complexity
  - Examples: Initialization module, cluster management node
  - Multiple fault tolerance activities may be needed at the same time
- Component must monitor progress and might initiate alternative actions
- Dual masters problem (also with *voting*)

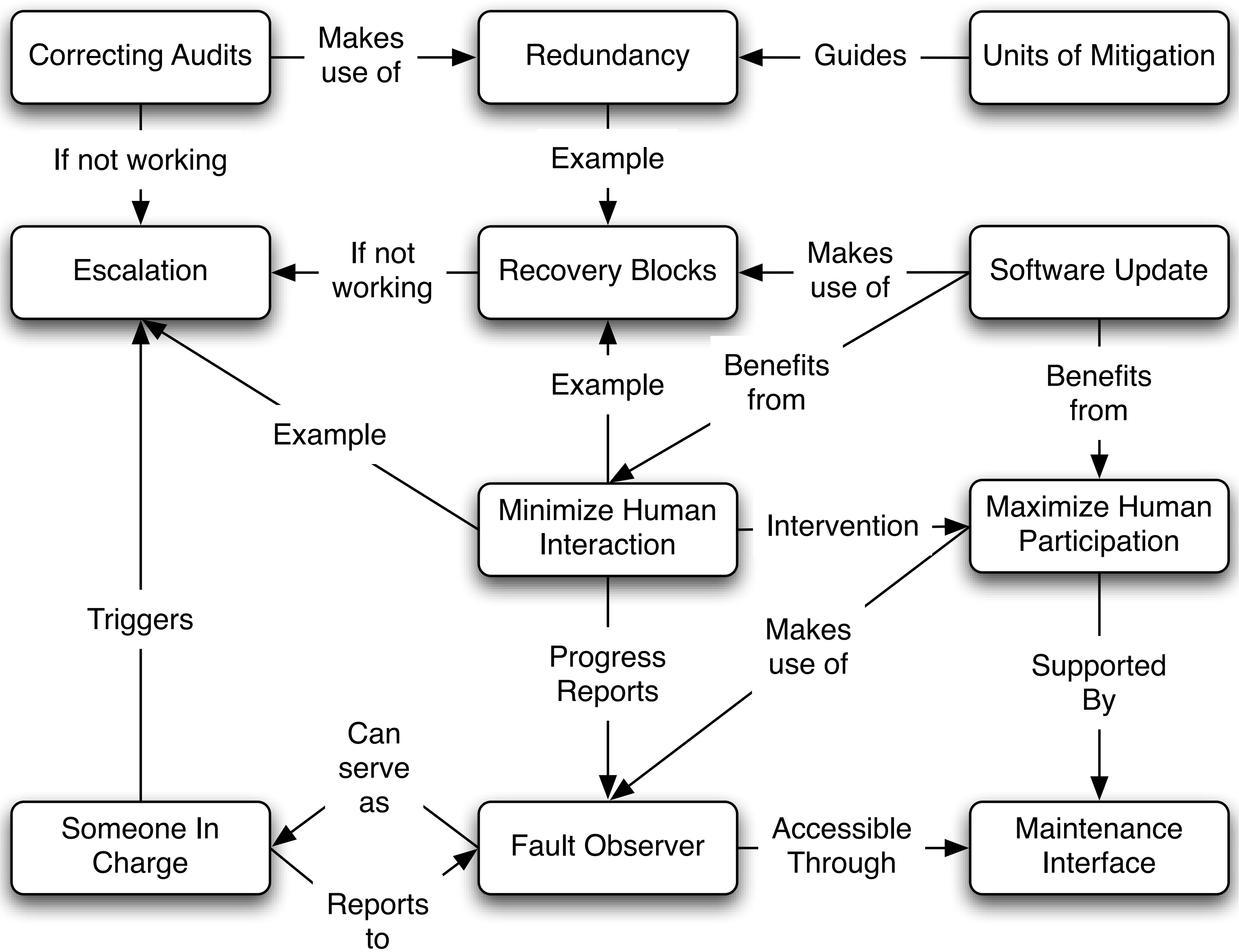
Architectural Patterns - Escalation

- Endless recovery attempts might be valid in some cases (transient faults)
- But error processing becomes stalled when:
  - *Correcting audits* remain unsuccessful
  - *Rollback / roll-forward* remain unsuccessful
  - Still *human intervention* should be *minimized*
- **Escalation** of the processing makes the errror less local and more drastic
  - Demands understanding of faults and failure modes
  - Some options: Resume partial operation, perform partial service degradation

Architectural Patterns - Fault Observer

- Faults and errors are detected and processed - tell all the interested parties
  - Observer can publish to humans through the *maintenance interface*
- Can be performed by an external entity
- Good application of publish / subscribe design pattern
- *Someone in charge* needs the information to steer the recovery process
- Report reception usually leads to logging
  - Make data storage again fault tolerant
- Typically part of some IT management software (‚cockpit‘)

Architectural Patterns - Examples for Pattern Relation



Detection Patterns

Detection Patterns - Fault Correlation

- Prerequisite: Early fault removal uncovered common error types
- Look at unique *signature of an error* to identify an according *fault category*
  - Enables the activation of a well-known matching error processing
  - Examples:
    - Many off-by-one errors found in testing, prepare system for this
    - On data errors, related data to be checked should be known beforehand
- Multiple errors can happen close in time - useful to triangulate the fault location
- *fault - error - error* chain
  - In best case, take care of the initial fault that started the error chain

Detection Patterns - System Monitor / Heartbeat

- **System Monitor**
  - How can one part keep track that another part is functioning ?
    - Monitor for system (or system parts) behavior
    - Might be part of *fault observer* or *someone in charge*, or separate element
  - Location of the monitor is highly application-dependent
- **Heartbeat**
  - How does *system monitor* knows that a task is still working ?
    - Send health reports at regular intervals (cost / benefit tradeoff)
    - Ping-alike messages, heartbeat function, push / pull approach

Detection Patterns - Acknowledgment / Watchdog

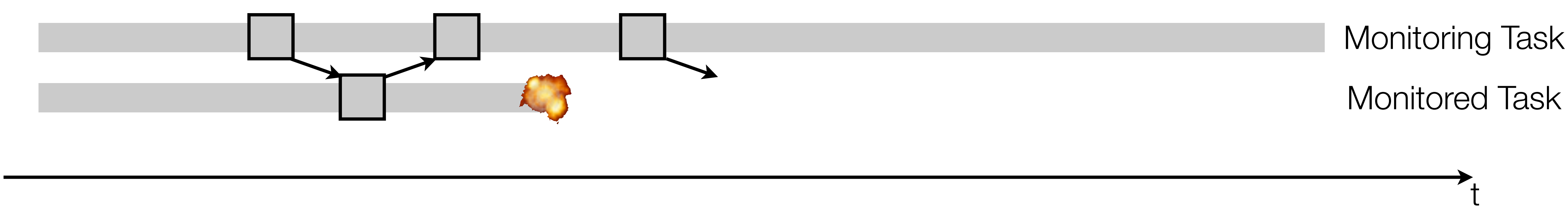
- **Acknowledgment**
  - Typical part of protocol definitions
  - Alternative for *heartbeat*, does not demand additional messaging
  - **Piggybacking** - Add acknowledgment information to response data frame
    - Prominent approach in bidirectional networking protocols
- **Watchdog**
  - Watch visible effects of the monitored task, without adding complexity to it
  - Ensure that a task is alive, without messaging / processing overhead
  - Strategies: Timers, peepholes, hardware test points

Detection Patterns - Realistic Threshold

- How much time should elapse before the system monitor takes action ?
  - **Message latency** (e.g. heartbeat interval) vs.
    detection latency (e.g. number of missed heartbeat messages)
- Balance between short intervals (hypersensitive monitoring) and long intervals (possibility for silent failures)
  - Influenced by communication round trip time and severity of undetected errors
- Message latency is typically worst case communication time + processing time
- Maximum unavailability > message latency + detection latency + repair time
- System can automatically adjust thresholds based on experience
- Example: Voyager spacecraft sends one heartbeat to command computer every 2s, failure when one is skipped
  - Overload condition detected during tests with 1s heartbeat

Detection Patterns - Realistic Threshold - Example

- Message roundtrip time: 50ms - 100ms
- Heartbeat message: Preparation on monitor task - 20ms, Processing and reply on monitored task - 15ms, processing of reply - 15ms
- Detection latency: One message
- Scenarios
  - Messaging latency = 50ms : All true failures reported, but many false errors
  - Messaging latency = 100ms: All true failures reported, but long reporting delay

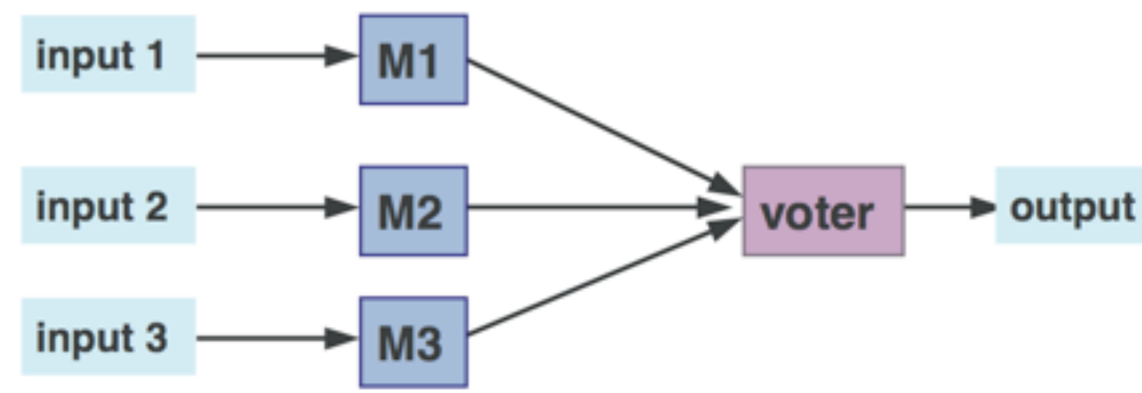


Detection Patterns - Voting

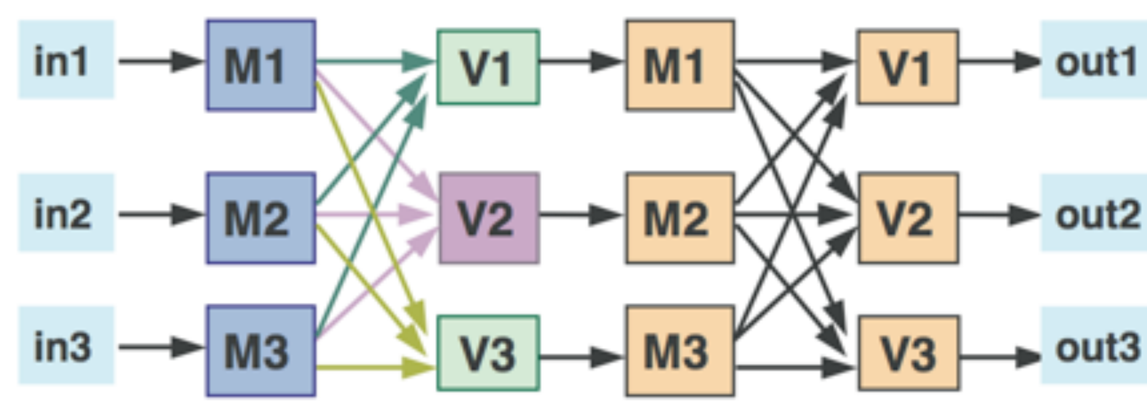
- Redundancy in space provides multiple answers - devise a voting strategy
  - **Exact voting**: Decision leads to correct result or uncertainty state notification
  - **Inexact voting**: Comparison might lead to multiple correct results
    - **Non-adaptive voting**: Use allowable result discrepancy, put boundary on discrepancy minimum or maximum
    - **Adaptive voting**: Rank results based on past experience
      - Predict what the correct value should be and take the closest result
      - Example: Weighted sum of the different results
        $R=W_1*R_1 + W_2*R_2 + W_3*R_3$ with $W_1+W_2+W_3=1$
- Different optimizations for large answers (e.g. compare only checksum)
- Communication latency shall not influence voter operation

Detection Patterns - Voting

- Selection in case of multiple events:
  - **Majority vote** (uneven node number)
  - **Generalized median voting** - select result that is the median, by iteratively removing extremes
  - **Formalized plurality voting** - divide results in partitions, choose random member from the largest partition
  - **Weighted average** technique
- Components that disagree (to some extend) with the vote are marked as erroneous



Triple Modular Redundancy (TMR)



Cascaded TMR

Detection Patterns - Maintenance and Exercises

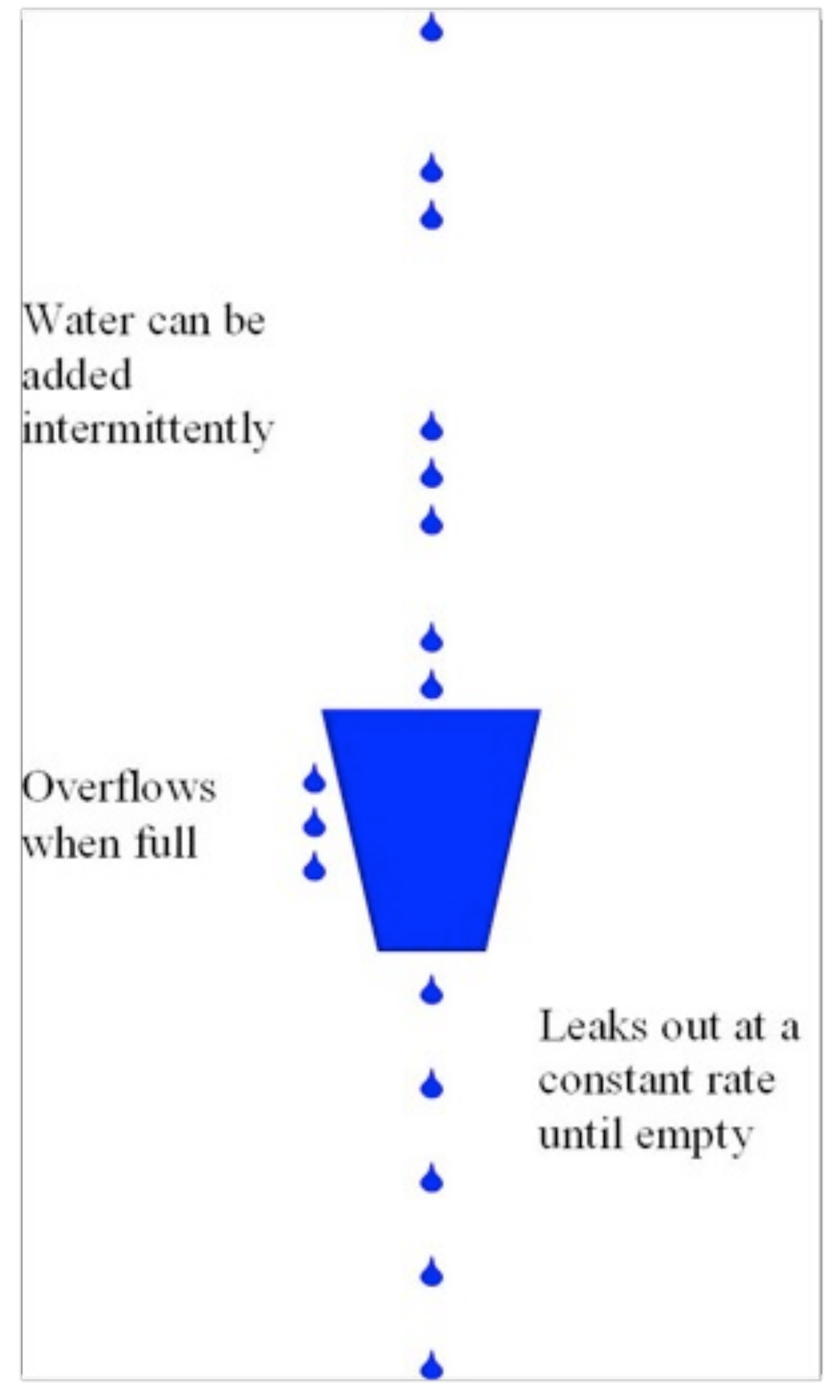
- **Routine Maintenance**
  - Through operator on the *maintenance interface*, or built in
  - Typical strategy in operating systems for idle processors
  - Relies on concept of checkable resources - connections, memory allocations, ...
- **Routine Exercises**
  - Make sure that *redundant* spare components truly work in the *failover* case
  - Identify latent faults by checks during light workload - typical in hardware
  - Reproducible error is still better than the failure case on high workload

Detection Patterns - Routine Audits / Checksums

- **Routine Audits (‚scrubbing‘)**
  - Find data errors in a controlled way, usually by low priority maintenance task
  - Logging is important for causal analysis - high possibility of related data errors
  - Identifies latent faults
- **Checksums**
  - Detect incorrect data by storing aggregate information along with the value
  - Example: Space shuttle counts number of integers in a data structure
  - Many options - parity bits, hashing
  - Checksums are only for detection, recovery through *error correcting codes*

Detection Patterns - Leaky Bucket Counter

- Distinguish between transient and intermittent repeating faults
- Assign a *leaky bucket counter* to each *unit of mitigation*
  - Increment for each event / fault
  - Decrement periodically until initial value -> fault events are periodically *leaked*
  - Exceeding the pre-defined upper limit of the bucket identifies a permanent fault
- Examples
  - Faulty messages filling a buffer
  - Correctable memory errors



Error Recovery Patterns

Error Recovery Patterns - Quarantine / Concentrated Recovery

- **Quarantine**
  - Activate the prevention of error spreading and work contribution
    - Relies on *units of mitigation* in the architecture
    - Activate barrier around the component
    - Example: State indicator from voting unit
- **Concentrated Recovery**
  - Minimize unavailability by focusing all resources on recovery activity
  - Inform *fault observer* about recovery activity, stay inside *unit of mitigation*
  - Establish *quarantine* around recovery activity
  - Well established in systems with high survivability demands (e.g. telco industry)

Error Recovery Patterns - Rollback / Roll-Forward

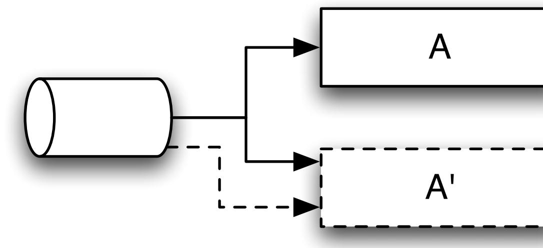
- How to resume processing after error recovery / error handler execution
- **Rollback**
    - Timing of the checkpoint / last requests decides about the rollback point
    - Consider side effects of repeated work
    - Errors might re-occur, so *limit retries*
- **Roll-Forward**
    - Resynchronization of systems tasks might be faster
    - Especially useful for event-driven stateless services
    - Demands proper damage mitigation and containment

Error Recovery Patterns - Restart / Limit Retries

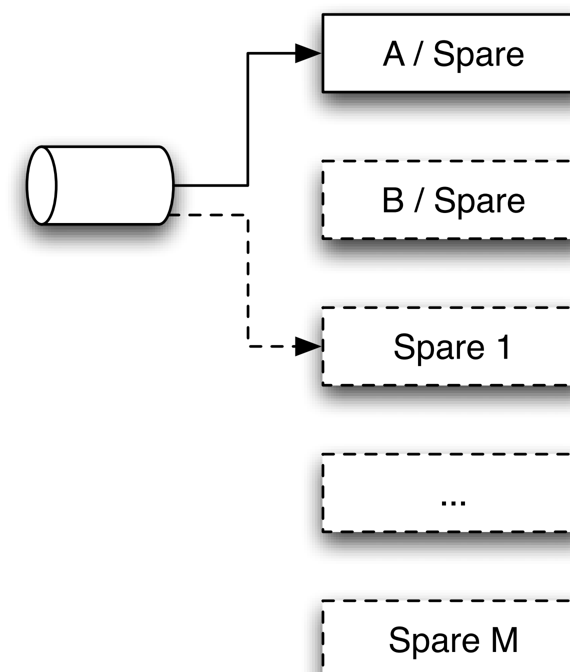
- **Restart**
  - Way to resume execution when *recovery / escalation* is not possible
  - *cold / warm restart* - skip some of the initial checks, hardware vs. software restart
  - Supported by *checkpoints*
- **Limit Retries**
  - Scenario: Faults are deterministic (latent fault -> same stimuli -> activation)
    - *Rollback* might not solve the problem when the error activation reason remains
    - Example: ‚Killer messages‘ marked as being unprocessed, faulty checkpoints
  - Problem: Propagation of error within itself, must be stopped by limiting retries
  - Solution: *Safeguarding* and *roll-forward*

Error Recovery Patterns - Failover

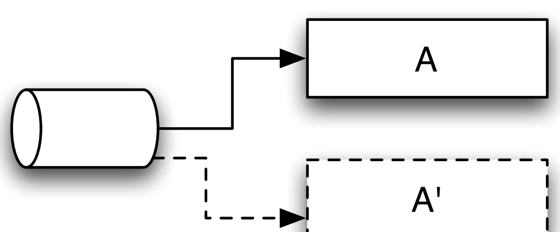
- Restoring of error-free operation in active element did not succeed
- Switch to redundant resource, based on *replication*
- Important factors are failover time and common data access
- Establish *someone in charge* for steering
- Needs proper *quarantine* for the faulty system part



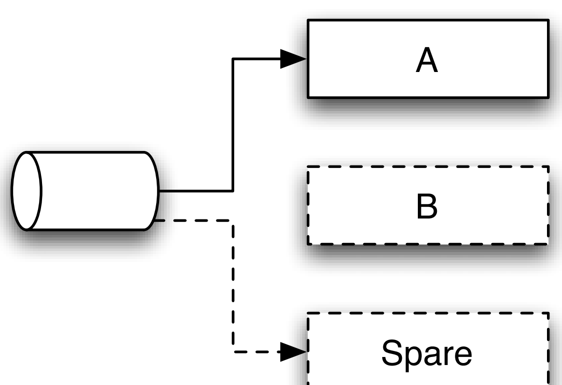
Active / Active



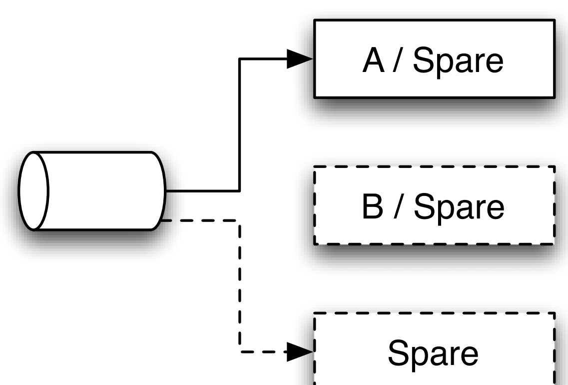
N + M



Active / Passive



N-to-1 (‚dedicated spare‘)



N+1 (‚roaming spare‘)

Redundancy Configurations for Failover

- *N-to-1* and *N+1* are special cases of *Active / Passive* with multiple services
- *Active / Active* has no downtime, but leads to degraded system performance in failover case and might demand specialized data *redundancy*
- *N-to-1* demands a fail-back step, which is not needed with *N+1*
- *Hot standby*: No ramp-up needed on failover, no service failure for the user
  - Natural property of *Active / Active* setups
  - Possible even with *Active / Passive* setting through continuous replication, stateless services or static data
- *Warm standby / log shipping*: Synchronize data block-wise on spare
- *Failover* is typically used as synonym for *Active / Passive*
- Orthogonal: *Shared Nothing* vs. *Shared Disk* data management

Failover - Dual Master Problem

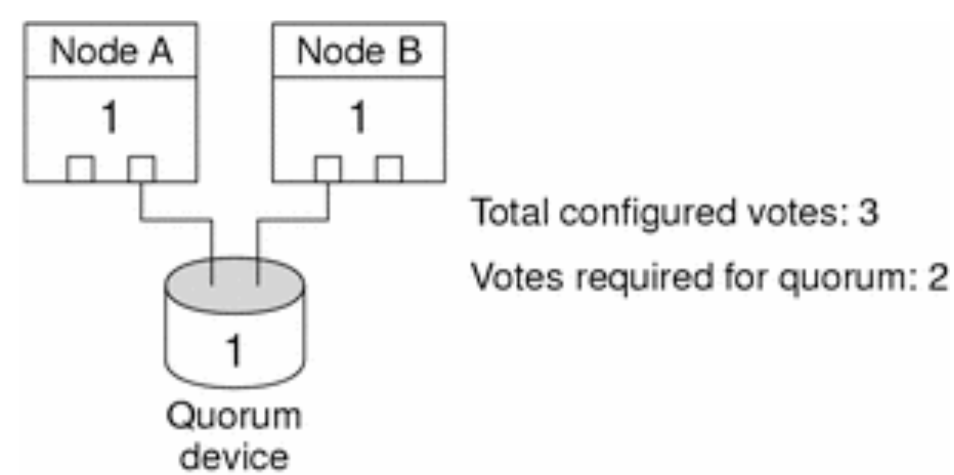
- Current active element might not relinquish control - **dual master** problem
- Typical problem in high-availability clusters
  - **Split brain** - Cluster interconnect is broken, several sub-cluster partitions start up
  - Establish **resource fencing** to let only one sub-group of the cluster work
  - **Amnesia** - Cluster restart with outdated configuration information
- **Quorum** - *„The number (as a majority) of officers or members of a body that when duly assembled is legally competent to transact business“* [Merriam-Webster]
  - ‚Transact business‘ in the sense of ‚provide service‘ - only one side should operate
  - Quorum allows fencing the other sub-cluster without communication
  - Loss of quorum should lead to node suicide, if possible

Failover - Quorum Approaches

- **Central arbitration** - Manual quorum, centralized server / admin sets master
- **Simple majority** - More than the half of the nodes must form a group
- **Weighted majority** - Votes for each node, group with higher vote count wins
  - Group decision is based on static data (nr. of votes, majority needed)
- **Tie-breaker** - Lightweight resolving strategy before decision inside the sub-group
  - Example: Ping response from common upstream router
- Whenever node connectivity changes, quorum decision should happen again
- Split brain has different faces
- Example in DRBD file system: Multiple replication masters by human error or temporary connectivity lost lead to difficult data merging demand

Failover - Weighted Majority with Quorum Device

- With even node number, provide additional external vote through **quorum device**
  - Number of votes by the quorum devices should be less than node votes
    - Allows cluster to operate with failed quorum device
  - Connection scheme of the quorum device decides upon valid cases of partitioning
  - Quorum device is typically a shared disk
  - Only used when communication with other nodes fails
  - Implemented by SCSI RESERVE,
    Fibre Channel, or iSCSI



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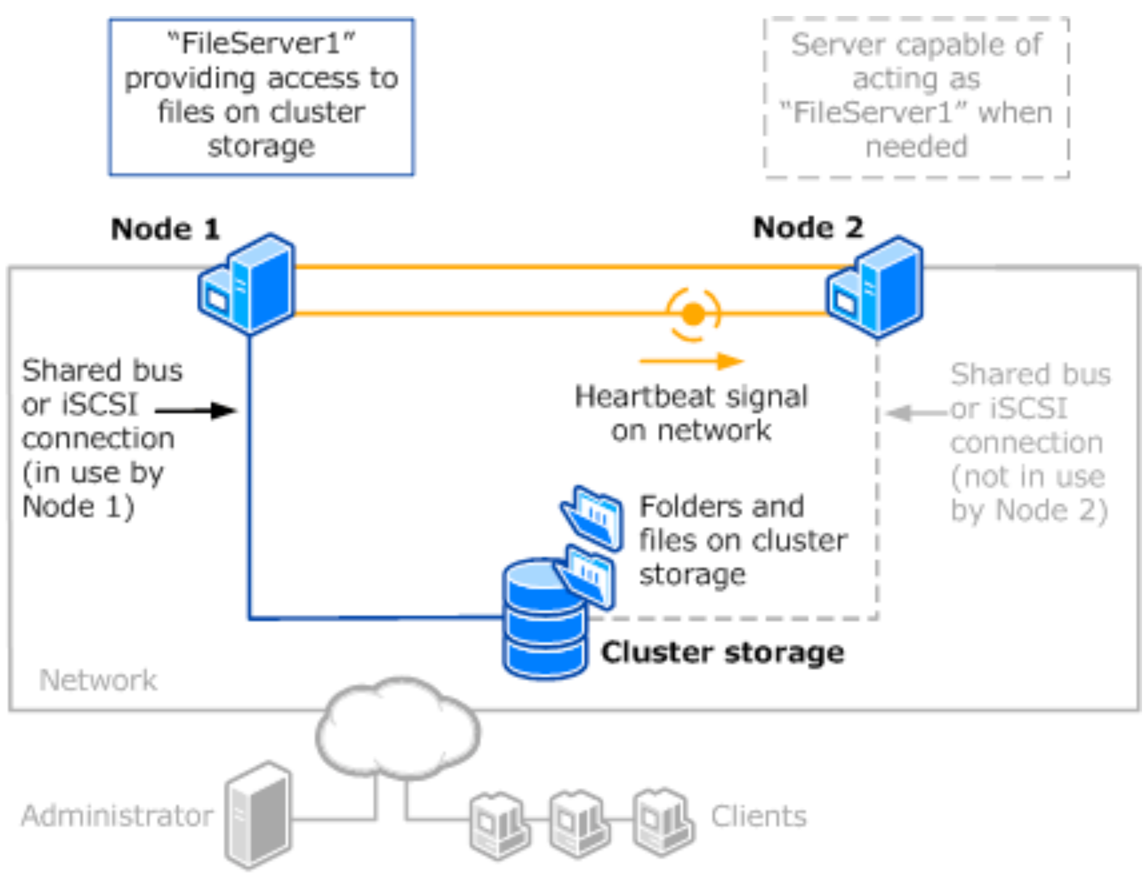
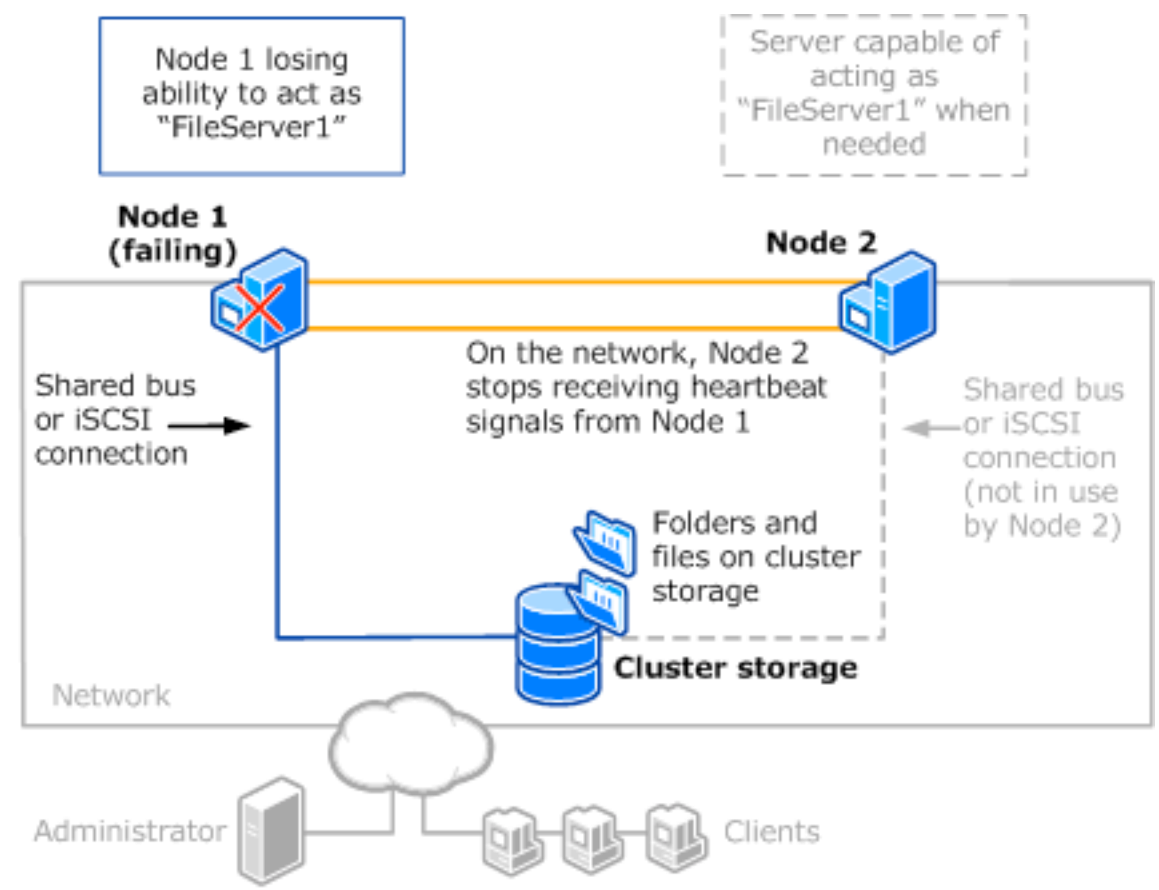
Example - Windows File Server

- Quorum case: Heartbeat line broken, Node 1 itself still alive
  - Demands utilization of cluster storage as quorum device





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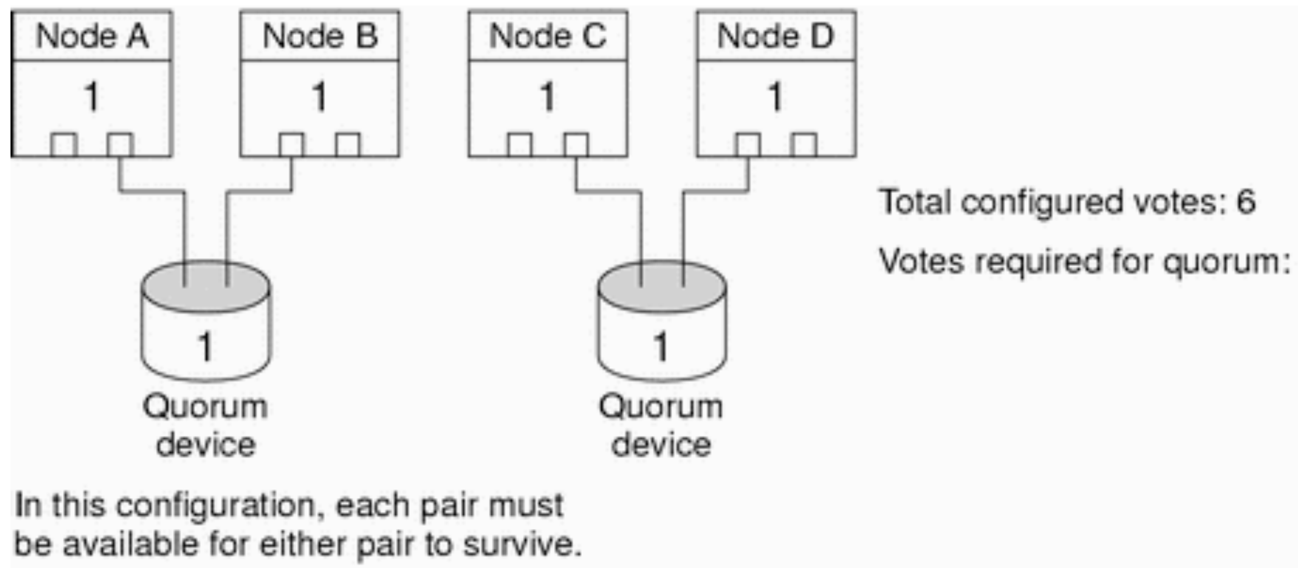
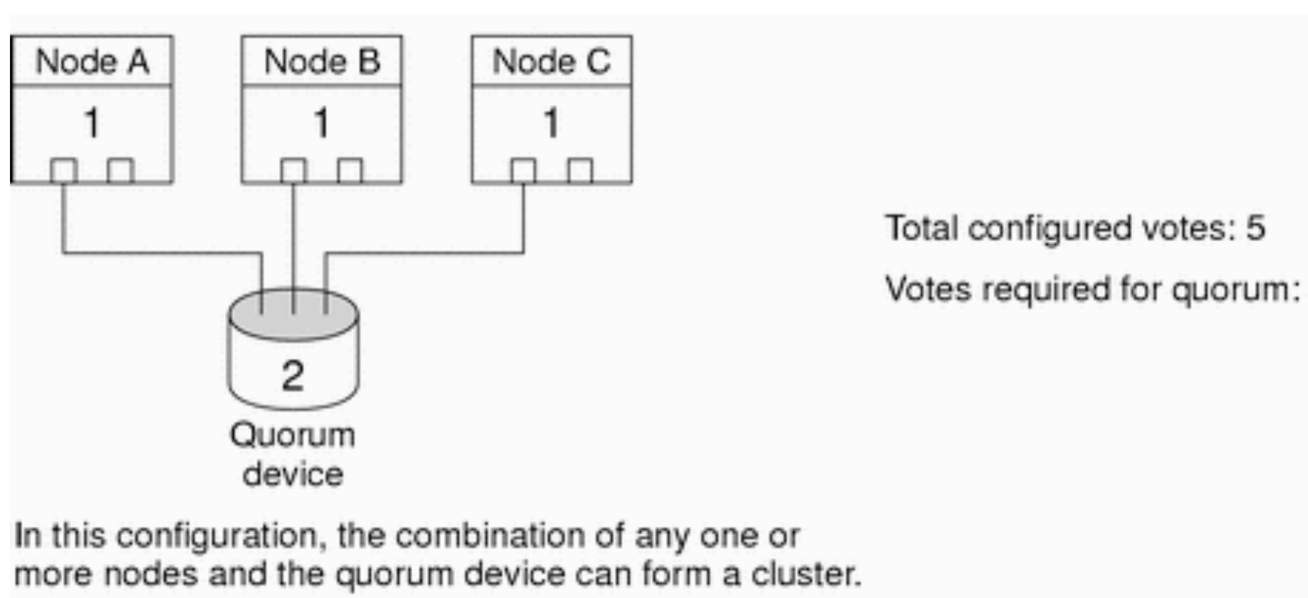
SCSI Quorum Device

- Only one SCSI device can use the bus at a time - *arbitration process*
  - LUN acts as priority, so host bust adapters typically have the highest one
- SCSI commands RESERVE and RELEASE allow to lock one SCSI device for exclusive usage by another device
  - Automated release on device / bus reset
  - Periodical renewing of reservation by driver, or persistent reservation feature
- Example MS Windows Cluster Server
  - Master node acts as *defender*, renews reservation every 3 seconds
  - One node communication loss, *challenger* nodes resets the bus, waits for 7 seconds, and tries to get the reservation again

Example - Quorum in Clusters





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Example - Windows Server 2008 Failover Cluster

- Voting elements: Nodes, disk witness, file share witness (= tie-breaker)
- Quorum modes
  - *Node majority*, works with odd node number
  - *Node and disk majority*, for even node number with shared storage
  - *Node and file share majority*, for even node number in multi-site cluster
  - *No majority: disk only*, disk-based quorum as in Windows Server 2003
- File share / disk contains information about most recent cluster configuration (amnesia prevention)
- Disk mode: Hardware must offer persistent arbitration (e.g. SCSI reserve and release)
- File share mode: Active node keeps open file lock on the share (SMB feature)

Example - Windows Server 2008 Failover Cluster

- Permanent point-to-point heartbeat surveillance on each node
- Process of achieving quorum
  - As the node comes up, determine if other cluster members can be contacted
  - Members compare their membership view on the cluster and agree on one (group communication)
  - Member collection determines if it has quorum
    - Without enough votes, it is waited for more members to appear
    - With quorum attended, resources and applications are brought into service

Example - Windows Multi-Site Clustered File Server

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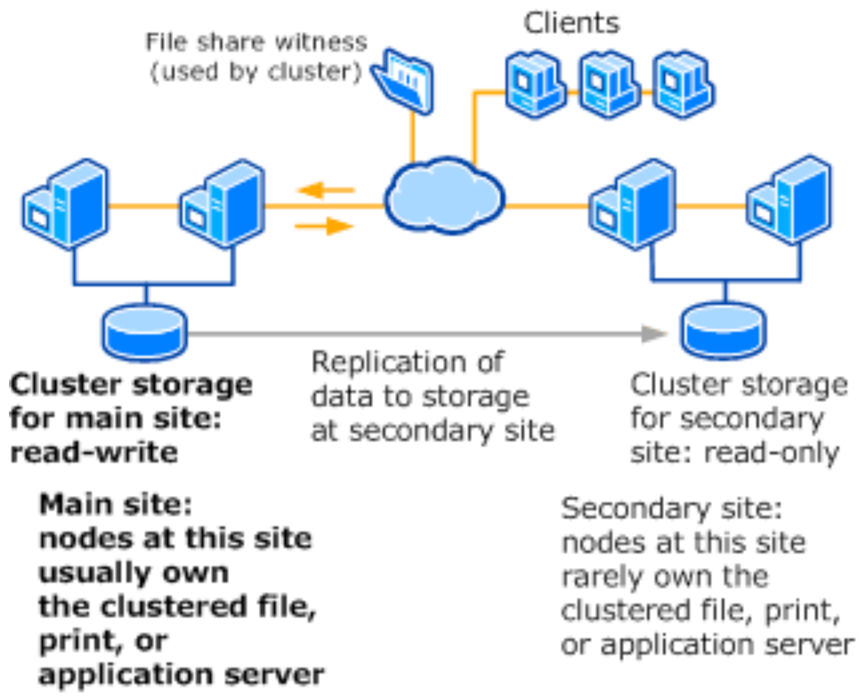
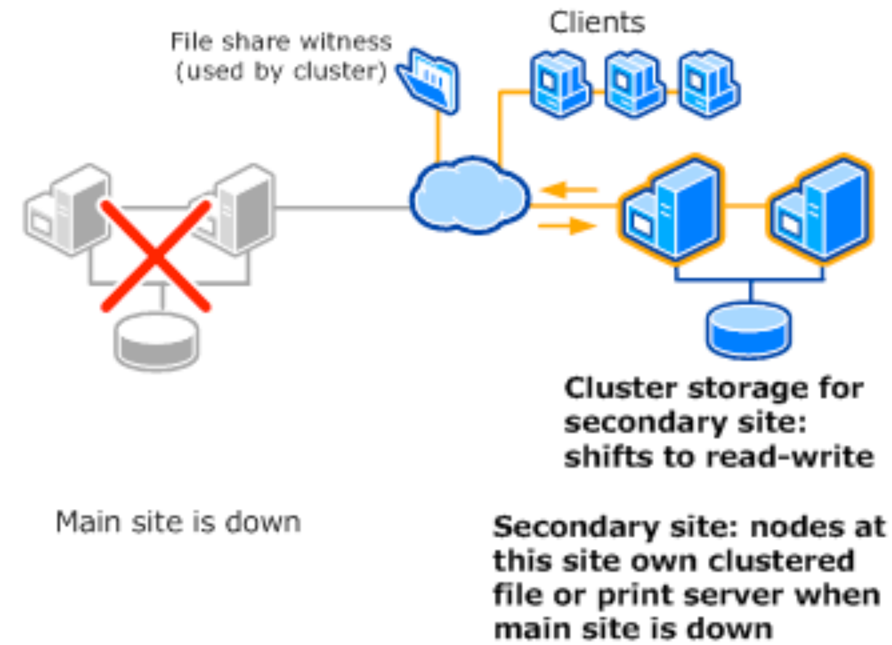
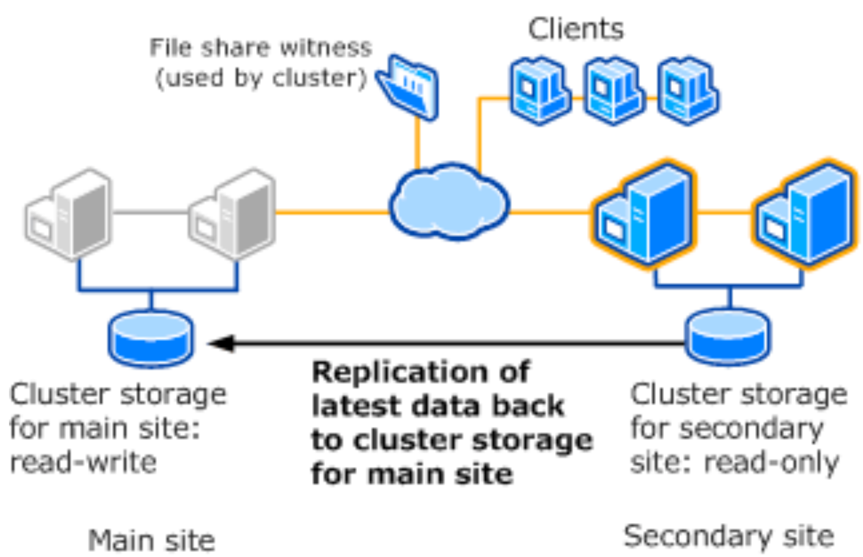


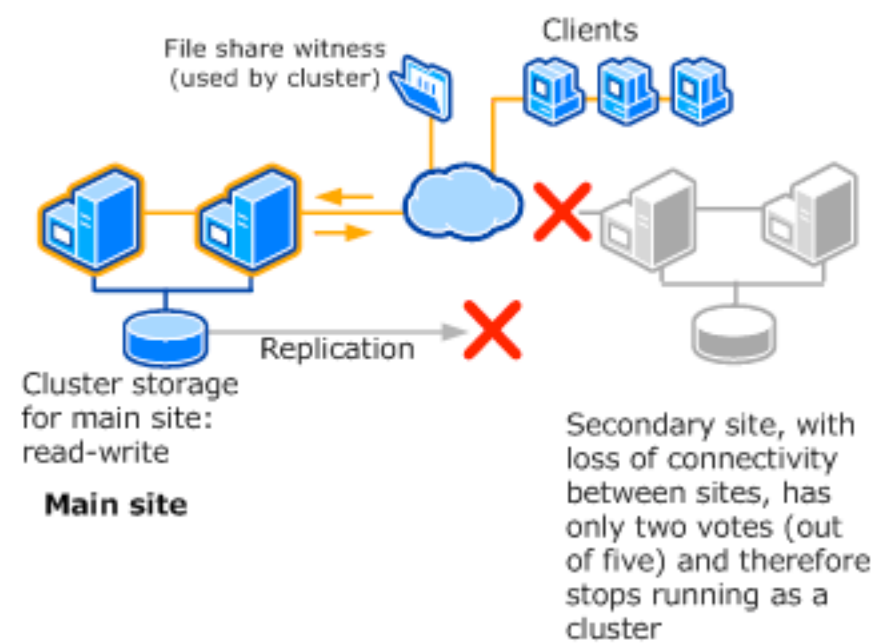
Normal Conditions



Main Site Gone



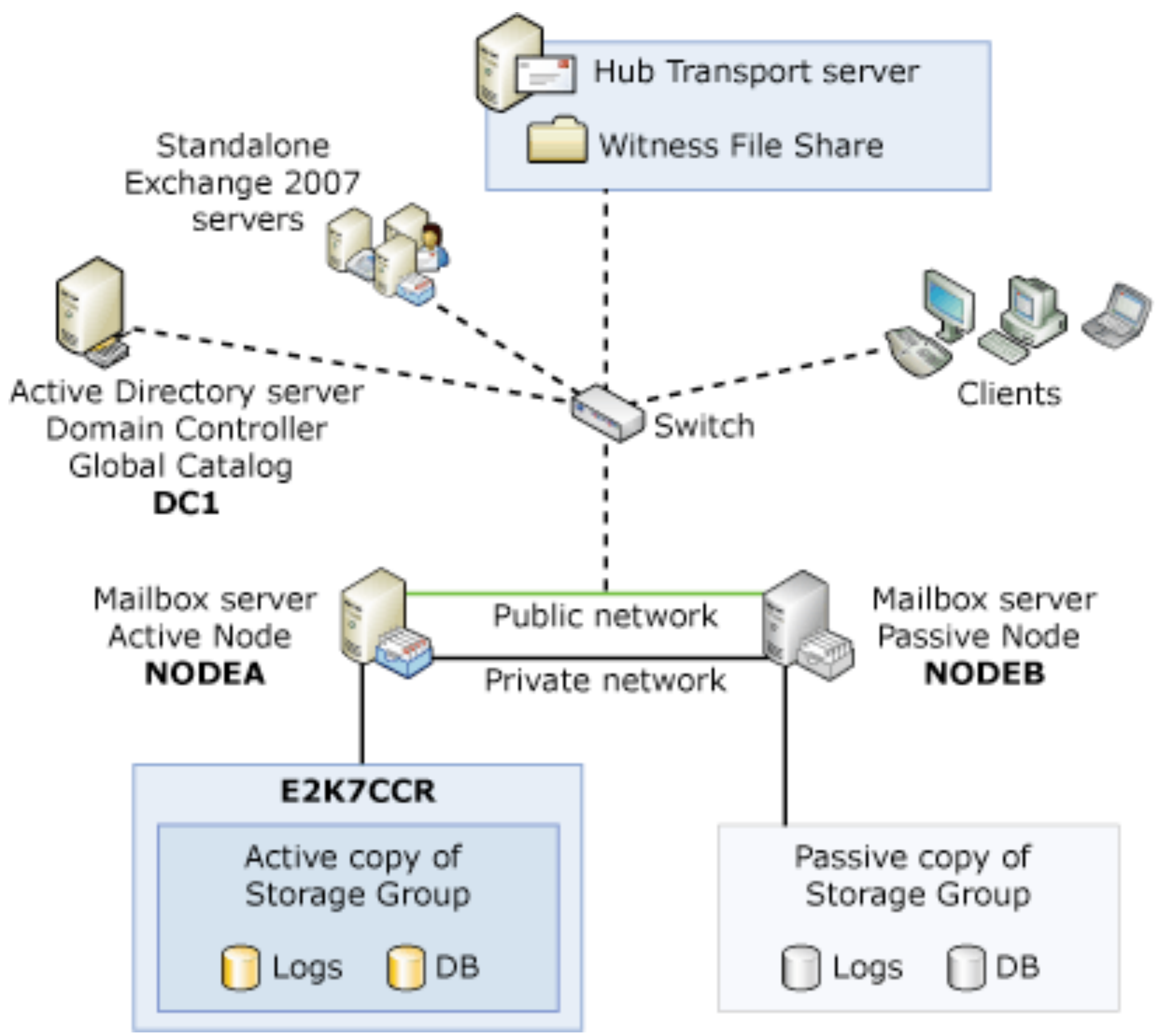
Main Site Back



Communication Lost

Split Brain

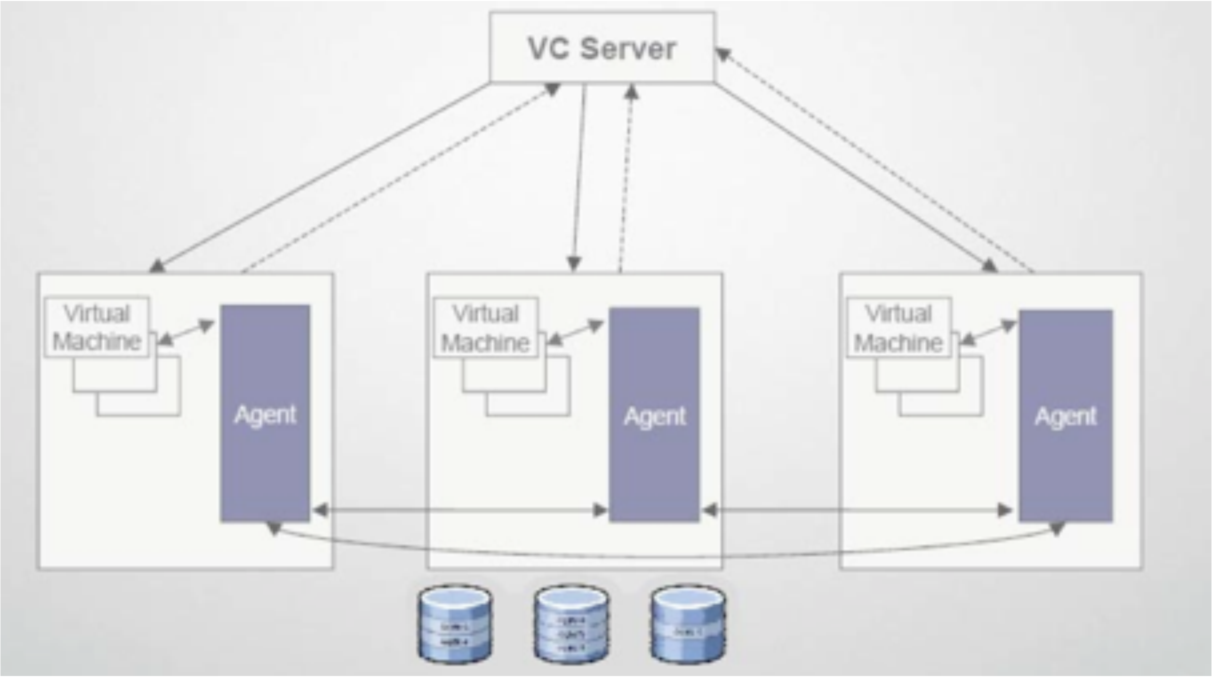
Example - Exchange 2007 Clustering



- Hub Transport Server allows messaging about the witness file share
- Witness share is checked ...
  - ... when a cluster node comes up and only one cluster node is available
  - ... when a previously reachable node is gone
  - ... when a node leaves the cluster (release lock)
  - ... periodically for validation purposes

Example - VMWare HA Split Brain Situation

- Even number of hosts run virtual machine images, stored on iSCSI / NFS
- Virtual machine image is protected by file lock with timeout
- Single host running a VM looses overall network connectivity
  - Other hosts restart the VM (due to lost external reachability)
  - Prevent the case that the VM on primary host will continue to run in this case
- Primary host gets connectivity back
  - Takes back the virtual machine image file since it has the according processes

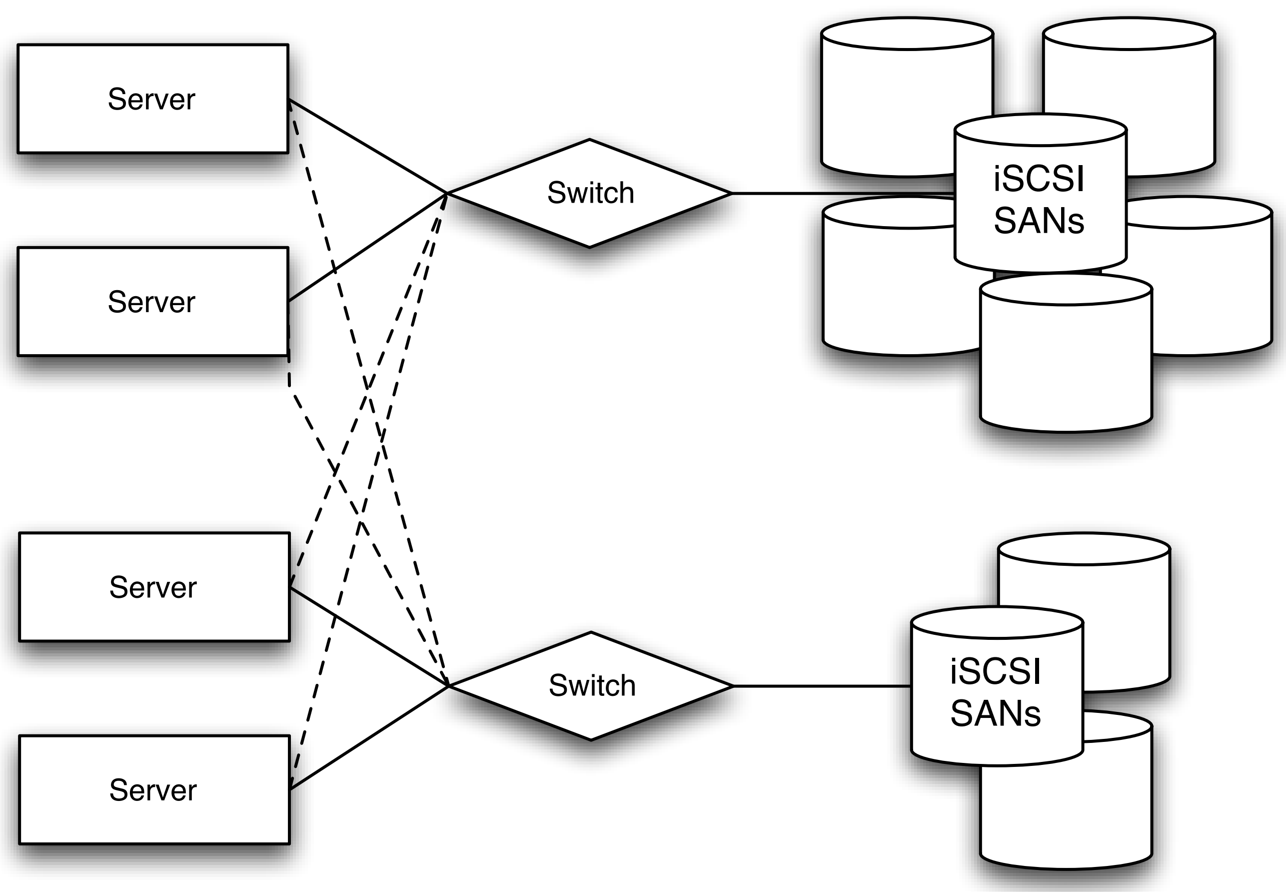


Error Recovery Patterns - Checkpoint

- Avoid loss of results during recovery by saving global state information
  - Focus on long duration data that is hard to achieve
  - Checkpoint data consistency and checkpointing interval are relevant
- The „snapshot“ problem - how to achieve global (distributed) consistency ?
  - Global state == local states + messages
  - Snapshot algorithms: Determine past, consistent, global state
  - Chandy & Lamport (1985) landmark paper
    - Relies on flushing principle of FIFO communication channels
    - Control messages ‚push out‘ pending messages

Error Recovery Patterns - Remote Storage

- Storage location for checkpoints is relevant in failover / rollback case
  - Should not be the single point of failure
  - Pattern is good decision point for level of redundancy needed
- Real-world application: iSCSI Multi-Homing



Error Recovery Patterns - Individuals Decide Timing / Data Reset

- **Individuals Decide Timing**
  - **Independent checkpoints**: Opposite approach to global checkpoints
    - Each process takes a **dynamic local snapshot** when it needs to
    - Consistency establishment overhead at recovery time vs.
      global checkpoint overhead during operation
- **Data Reset**
  - Recover from an uncorrectable data error by taking / computing initial values and approximate value
  - Relationship to *return to reference point* pattern - data reset is often a correlated activity

Error Mitigation (= mostly Overload Handling) Patterns

Error Mitigation Patterns - Marked Data

- Data error detected, but no recovery option available, error mitigation is acceptable
- Data should be *quarantined* - do not use it, do not derive actions from it
- Example: IEEE ‚Not a Number‘ (NaN)
  - Result of division by zero, square root of -1, ...
  - IEEE 754-1985: Standard representation for binary floating point numbers
  - Rules for computation when operand is NaN - typically result is again NaN
    - Options: Assume default value, skip operation, mark result as erroneous

Error Mitigation Patterns - Overload Toolboxes

- Handle overload situation with too many requests for the system
- Each resource class needs dedicated overload treatment
  - Memory: Exhaustion hinders new request from entering the system
  - CPU: Overload slows overall processing down
    - Patterns: *Fresh work before stale, share the load, shed load*
  - Tangible resources: Processing demands exclusive system resources
    - Network ports, shared storage, devices, ...
    - Patterns: *Queue for resources, equitable resource allocation*
- Consider user demands
  - Patterns: *Fresh work before stale, finish work in progress*

Error Mitigation Patterns - Shed Load

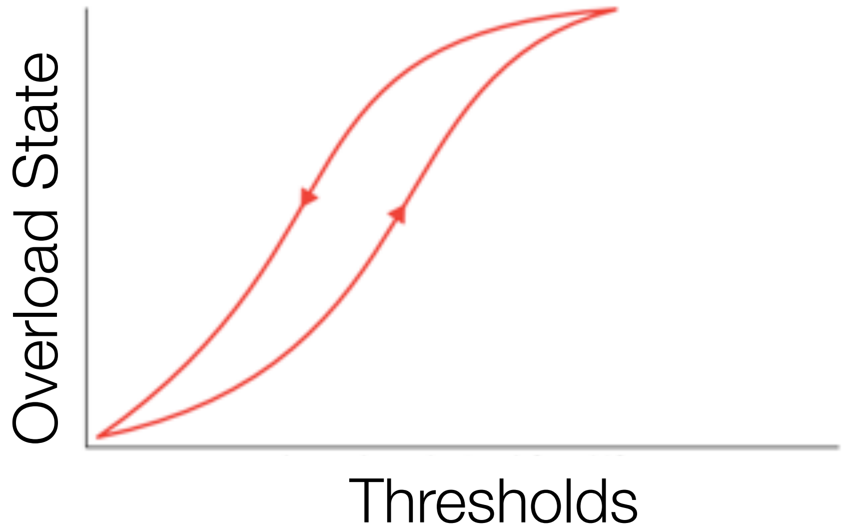
- Throw away a minority of requests to serve the majority
  - As early as possible, to minimize resource consumption
  - Rejection method to be considered, e.g. do not send acknowledgements
- Example: ICMP
  - Type 3: Destination Unreachable - not time-out on client host
  - Type 4: Source Quench - typically only between routers, also used by mail servers
  - Type 11: Time Exceeded - through congestion (or circular packets)
- Example: HTPP 5XX error codes
  - 503: Service Unavailable
- Specialized case: **Shed work at periphery**

Error Mitigation Patterns - Finish Work in Progress / Fresh Work Before Stale

- **Finish Work in Progress**
  - What to process, what to reject ?
    - Best case is labeling of requests: „new“ vs. „continuation“
    - Distinuish ‚continuation‘ processes on their resource usage
    - Try aggressively to get rid of resource hogs
  - Can lead to oscillation when system is „starving“ for new requests after cleanup
    - Solution: Let small portion of new requests through
- **Fresh Work Before Stale**
  - If requester gives up, his retry eats up even more resources
  - Perform LIFO queue handling or non-queueing for premium requesters

Error Mitigation Patterns - Slow It Down

- Handle overload cases and avoid saturation by multi-step *escalation*
  - Restrict request processing with increasing severity per level
  - Goal: Slow things down until the system can catch up with the load
  - Feedback system, demands dedicated resources for the controller part
  - Add **hysterisis effect** to prevent oscillation for level changes
    - Different trigger values to enter / leave an escalation level



Error Mitigation Patterns - Deferrable Work / Equitable Resource Allocation

- **Deferrable Work**
  - High load: Shed incoming work vs. shed routine maintenance workload
  - Make routine work (only relevant in error case) deferrable
- **Equitable Resource Allocation**
  - Scenario: Handling of many requests for a set of resources, some of them are rare
  - Request-level handling would render some resources unnecessarily idle
  - Solution: Pool similar requests, allocate resources to pools
  - Additional bookkeeping needed for managing the requests and their related resource demands
  - Might lead to priority-inversion scenario

Error Mitigation Patterns - Expansive / Protective Automatic Controls

- **Expansive Automatic Controls**
  - Design some system parts for only being used in case of overload
    - Example: No 100% CPU utilization in normal operation of HA clusters
    - Example: Dynamic Offloaded Work - Cloud Computing
  - Increases request processing overhead, so take only as temporary solution
- **Protective Automatic Controls**
  - Overload options: Shed internal work, shed incoming load, do nothing
  - Put restrictions on how much work the system accepts while still functioning
  - System throughput can drop due to contention, but should not drop to zero

Fault Treatment Patterns

Fault Treatment Patterns - Let Sleeping Dogs Lie / Reintegration

- **Let Sleeping Dogs Lie**
    - Treating faults by system change can introduce new faults
        - Known latent fault: Risk of reoccurrence, damage assessment possible
        - Potential new fault: Additional risk of miss-applied correction, no damage assessment possible for accidentally added faults
- **Reintegration**
    - Different steps needed to reintegrate repaired component
        - Take off *riding over transient* and *isolation* lists
        - Watch new component for a while: **hardening / soaking / trailing**
        - Follow deterministic procedure, use as *standby* if possible

Fault Treatment Patterns - Reproducible Error / Small Patches / Revise Procedure

- **Reproducible Error**
  - Apply stimuli again under *quarantine* in order to prove fix
    - Can be automated (regression test)
    - Compare system output with *golden unit* output
- **Small Patches**
  - Design system update as small as possible
- **Revise Procedure**
  - When predetermined procedures contributed to failure duration, fix them