Tunable Replica Consistency for Primary-Backup Replication in Distributed Soft Real-time and Embedded Systems

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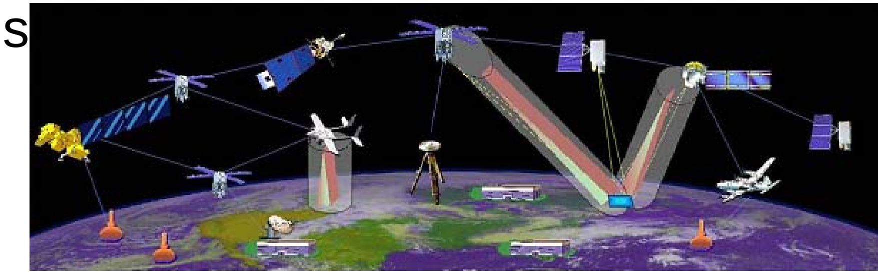
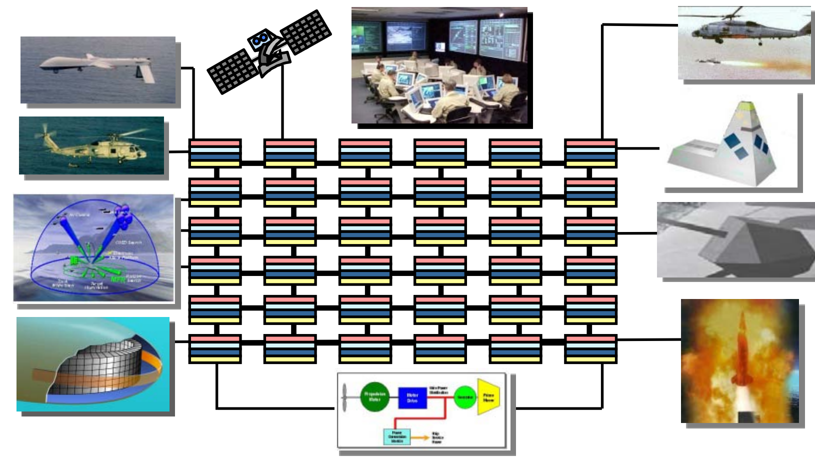
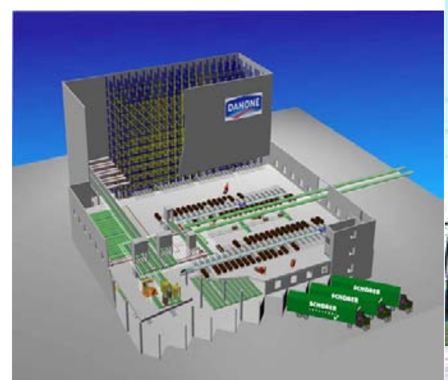
Focus: Distributed Real-time Embedded (DRE) Systems

- Heterogeneous soft real-time applications
- Operation in dynamic & resource-constrained environments
  - changing system loads
  - process/processor failures
- Stringent *simultaneous* QoS demands
  - high availability, satisfactory average response times, etc.
  - efficient resource utilization
- Examples include
  - NASA's Magnetospheric Multi-scale (MMS) mission
  - Total shipboard computing environment (TSCE)
  - Modern office environments



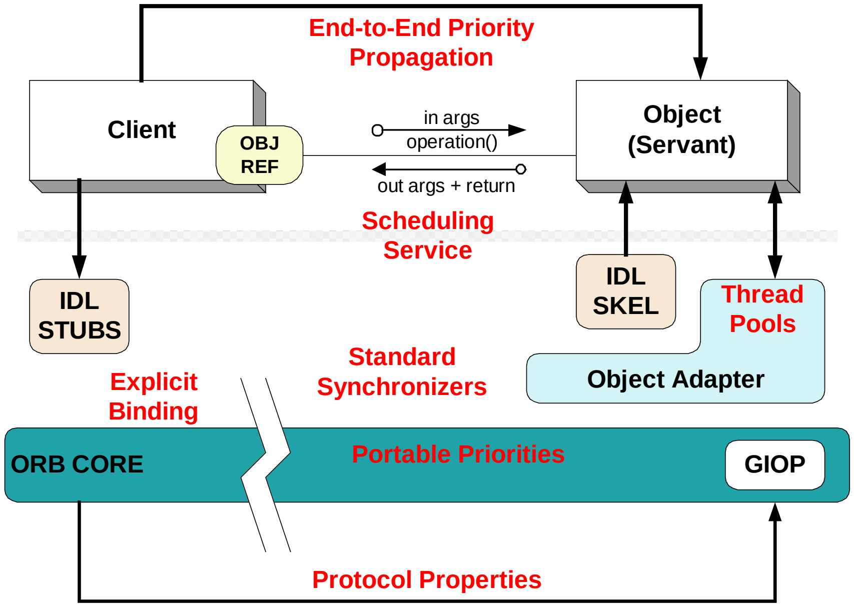


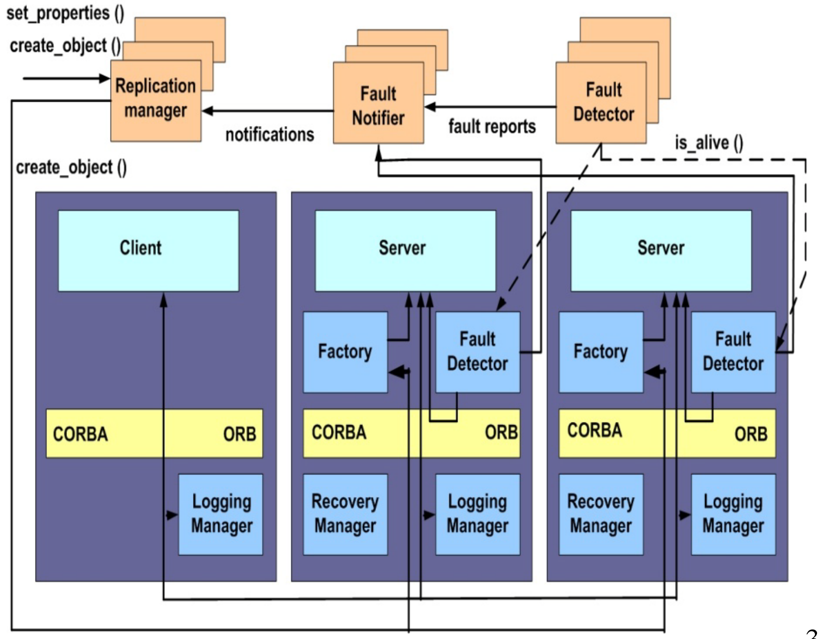


DRE systems need both high availability & soft real-time performance in resource-constrained environments

Standards-based Middleware Mechanisms

- Standards-based middleware mechanisms available for QoS management
  - end-to-end predictable behavior for requests (e.g., RT-CORBA)
    - priority bands
    - thread pools with lanes
    - eliminate priority inversion
  - support for highly available systems (e.g., FT-CORBA)
    - replication management
    - failure detection
    - multiple replication styles



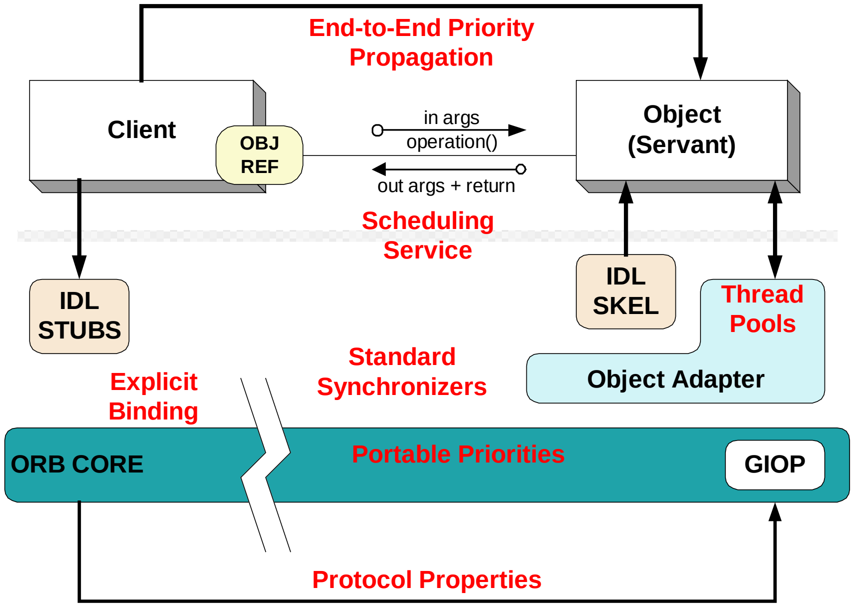


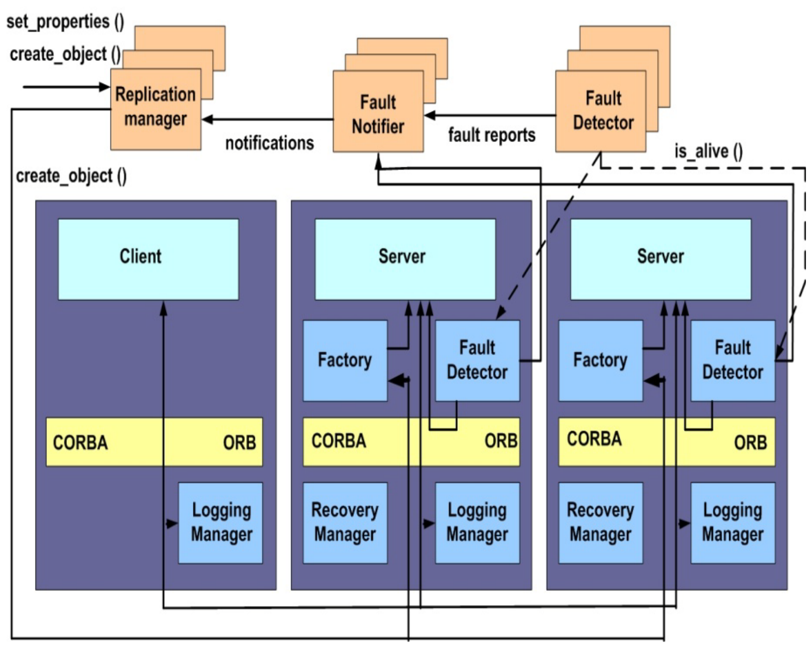
Standards-based middleware provide support for different QoS – ***but only one QoS at a time***

Problem – Providing Real-time Fault-tolerance

- Standards-based FT middleware provide only the mechanisms
  - e.g., checkpoint frequency
- No information on how to tune those mechanisms
  - e.g., what checkpoint frequency to use? Can it be changed?
- Ad-hoc ways to provide fault-tolerance do not consider resource usage of the object & the resource availability of the system
  - affects real-time performance

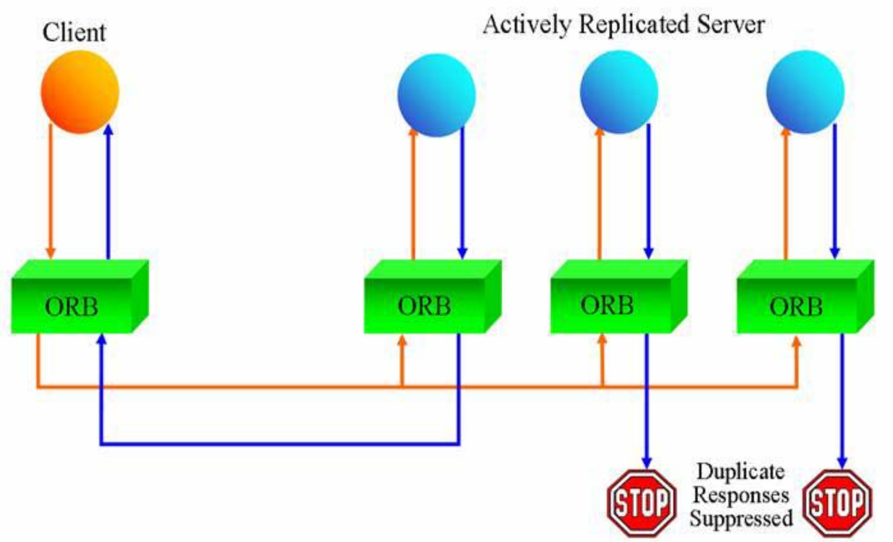
Fault-tolerant middleware needs to manage available resources efficiently to simultaneously provide & maintain soft real-time performance of applications

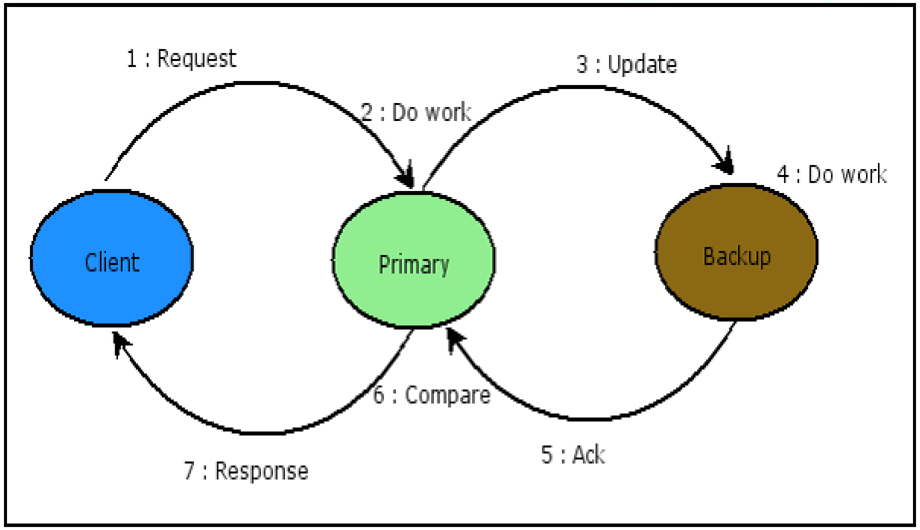




Prevalent Schemes for Fault-tolerance in DRE Systems

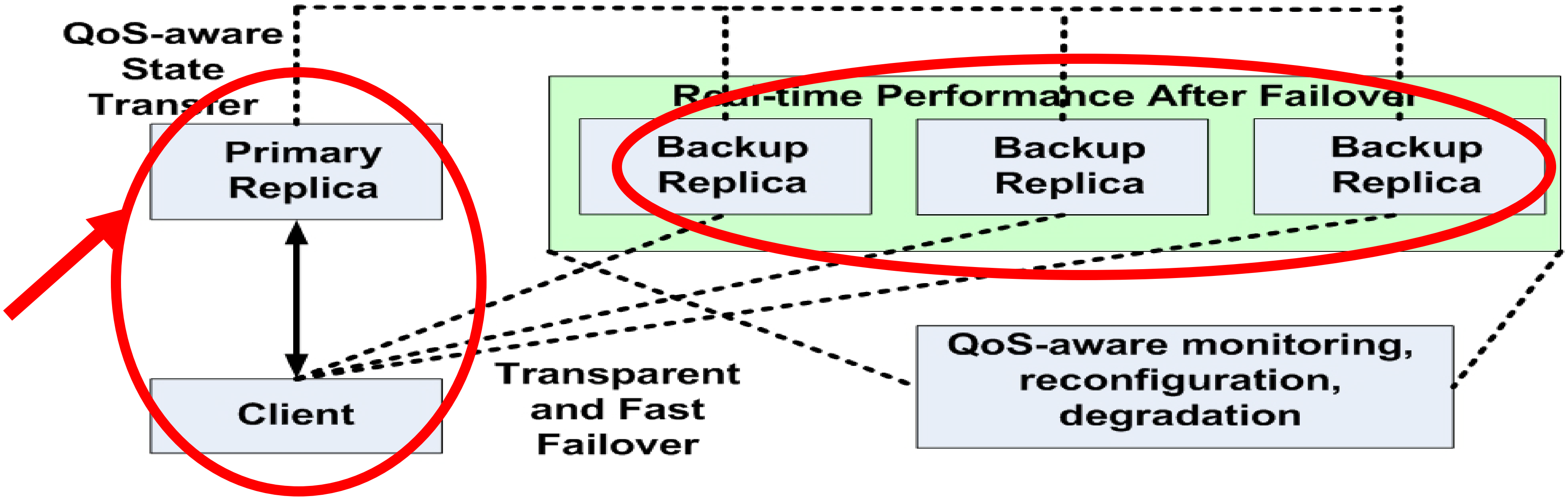
- Active replication?
  - client requests multicast & executed at all the replicas
  - faster recovery – as long as any one replica is alive
  - high communication/processing overhead
- Passive replication?
  - low resource/execution overhead – only primary executes requests
    - primary makes the state of the backup replicas consistent with itself
  - slower recovery time – clients redirected to one of the backups





Passive replication – better suited for resource-constrained DRE systems

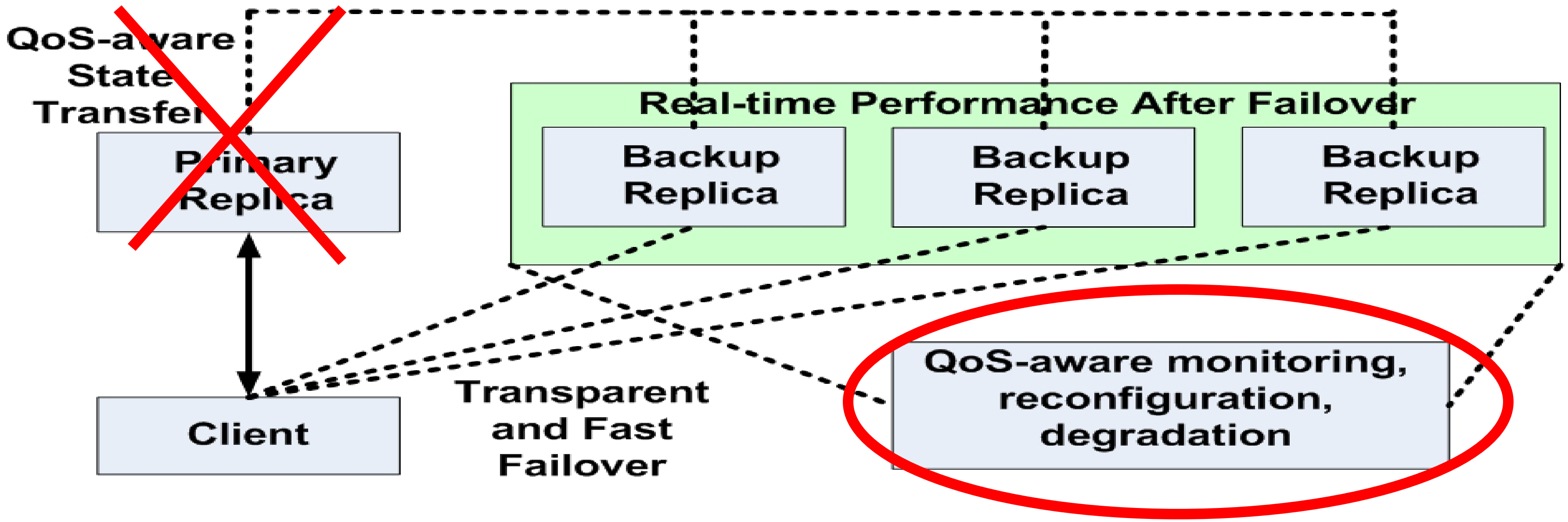
Our Prior Contributions: Deployment Phase



- Allocate CPU & network resources efficiently at deployment-time
  - Applications & their replicas are deployed in their appropriate physical hosts => meets high availability requirements
  - CPU & network resource needs of applications are provisioned => meets response time requirements
  - Overcomes inefficient allocations – for both applications & replicas => conserves resources

DeCoRAM D&C Engine: Appeared in RTAS 2010

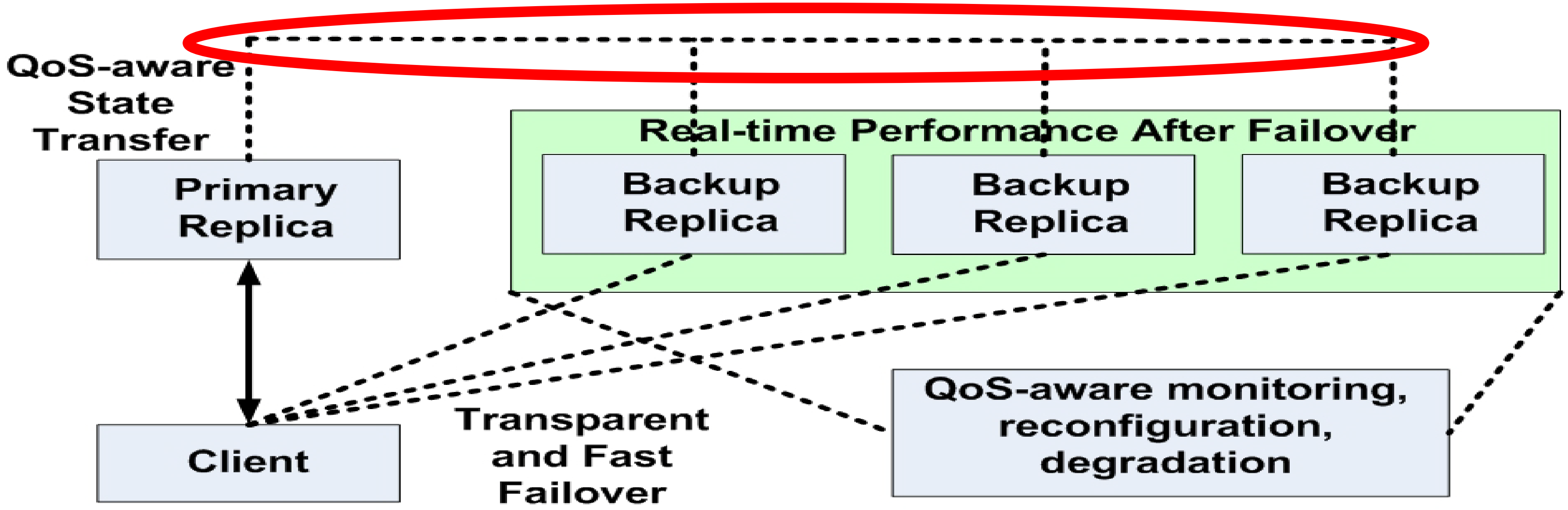
Our Prior Contributions: Runtime Phase



- Provide both high availability & soft real-time performance at runtime
  - Provide bounded-time failure detection & failure recovery => maintains soft real-time performance even in the presence of failures
  - Resource-aware failure/overload recovery => maintains soft real-time performance after recovering from failures/overloads
  - Overcomes need for ad-hoc mechanisms to detect & recover from failures/overloads that affect soft real-time performance of clients

FLARe Middleware: Appeared in IEEE RTAS 2009

Missing Capabilities in Our Prior Work

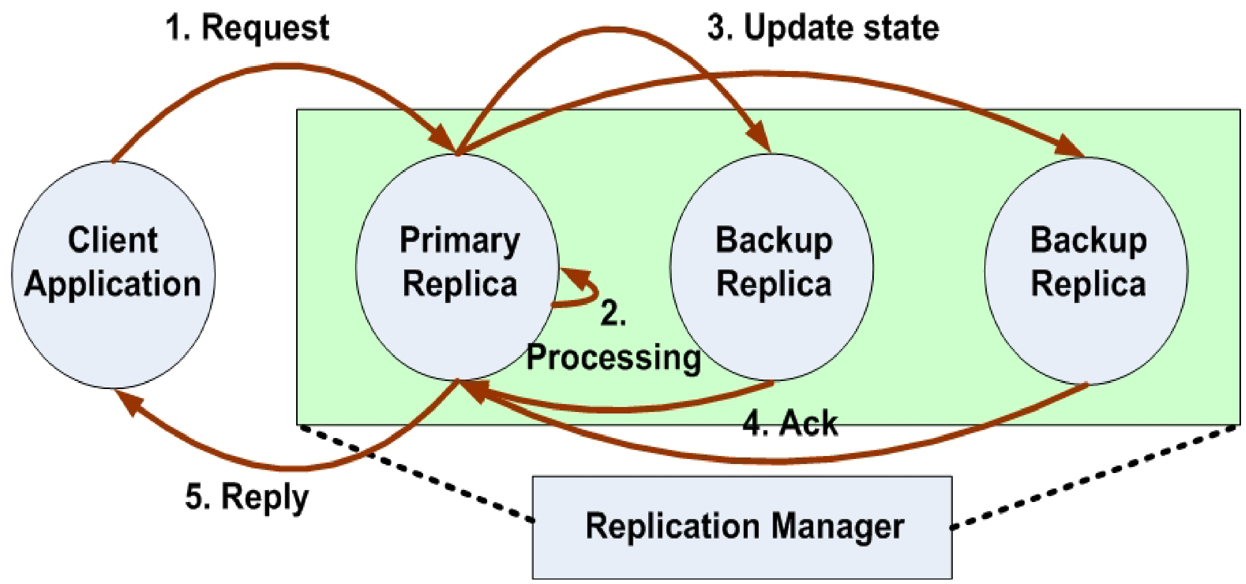


- Performance versus Fault-tolerance – optimize resource usage
  - Need for configurable application consistency management
    - support for range of consistency assurances – weak to strong
  - Need for analyzing & selecting trade-offs among FT & performance
    - resource usage for FT versus resource usage for performance
  - Need for multi-modal operations – degraded levels of FT & performance
    - dynamic adaptations to system loads & failures

Current Work: Resource-aware Replica Consistency Management

Replica & State Management in Passive Replication

- Replica Management
  - synchronizing the state of the primary replicas with the state of the backup replicas

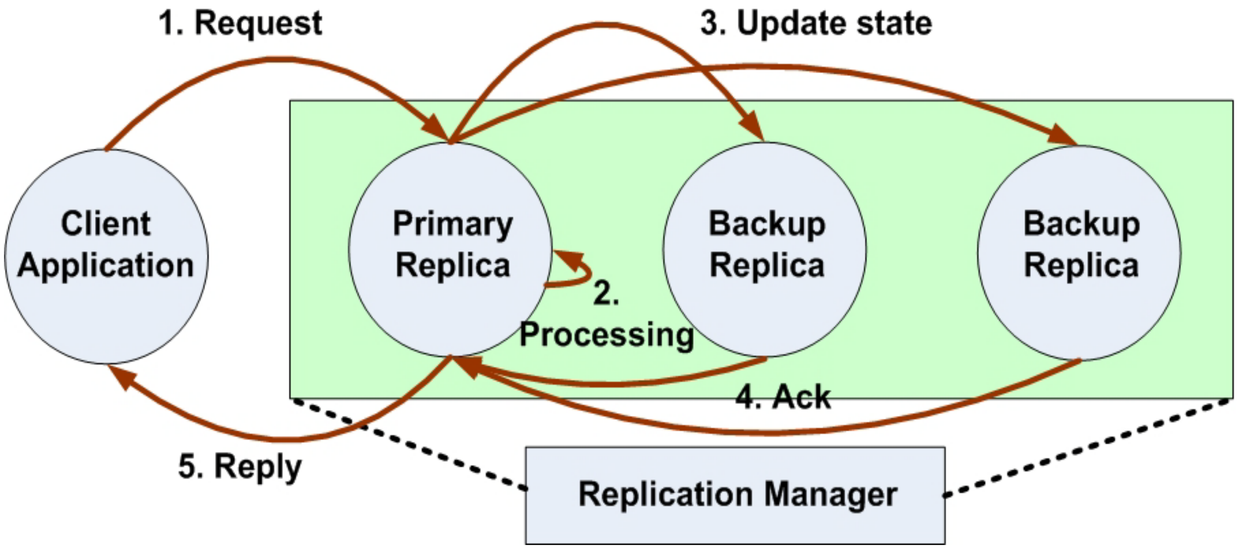


- Resource consumption trade-offs
  - performance (response times) versus fault-tolerance
  - e.g., if goal is better performance => lesser resources for state management => lesser levels of FT
  - e.g., if goal is better fault-tolerance => response time suffers until all replicas are made consistent

Resource consumption for FT affects performance assurances provided to applications & vice versa

Replica & State Management in Passive Replication

- Diverse application QoS requirements
  - for some applications, FT important
  - for others, performance important



- Need tunable adaptive fault-tolerance
  - cater to the needs of variety of applications
    - no point solutions
  - configurable per-application fault-tolerance properties
    - optimized for desired performance
  - monitor available system resources
    - auto-configure fault-tolerance levels provided for applications

Focus on operating region for FT as opposed to an operating point

Replica & State Management in Passive Replication

- Diverse application QoS requirements
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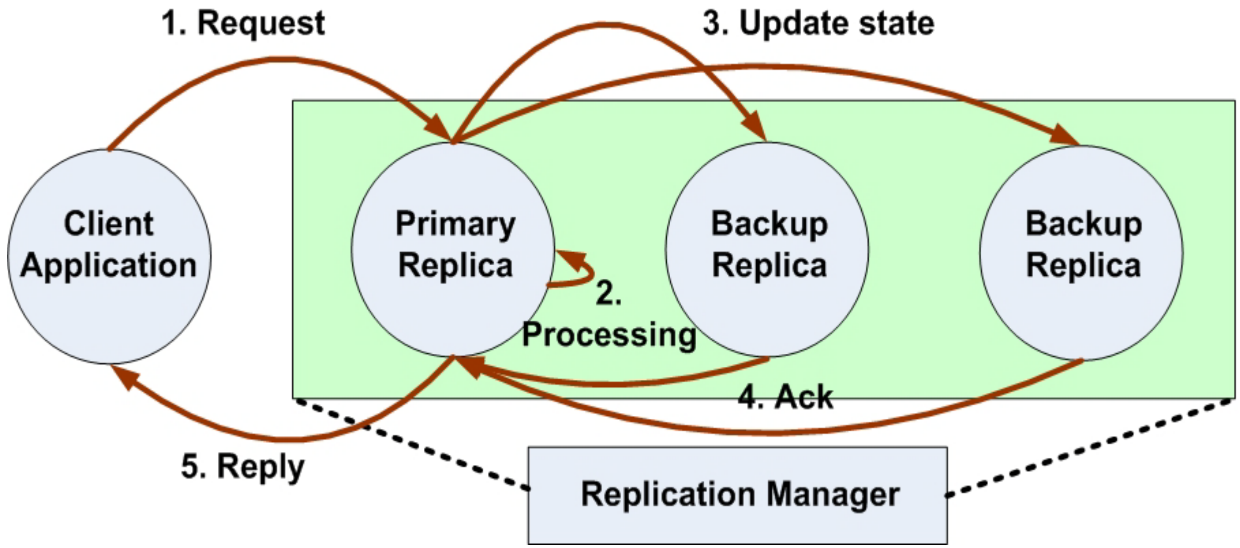
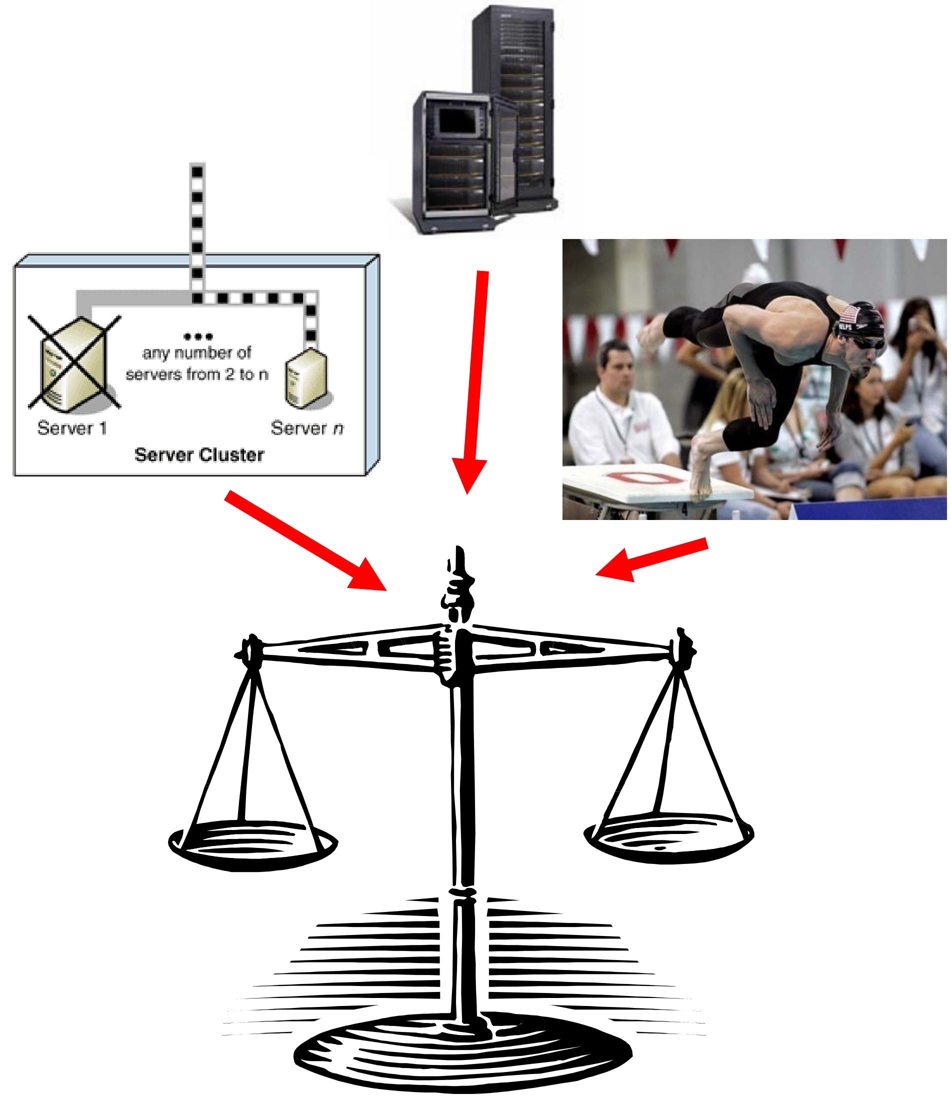


- Need tunable adaptive fault-tolerance
  - input → available system resources
  - control → per-application fault-tolerance properties
  - output → desired application performance/reliability
  - fairness → optimize resource consumption to provide minimum QoS
  - trade-offs needed in resource-constrained environments
    - goal → maximize both performance and fault-tolerance
    - degrade QoS – either of FT or performance – as resource levels decrease

Focus on operating region as opposed to an operating point

Resource Optimizations in Fault-tolerant Systems

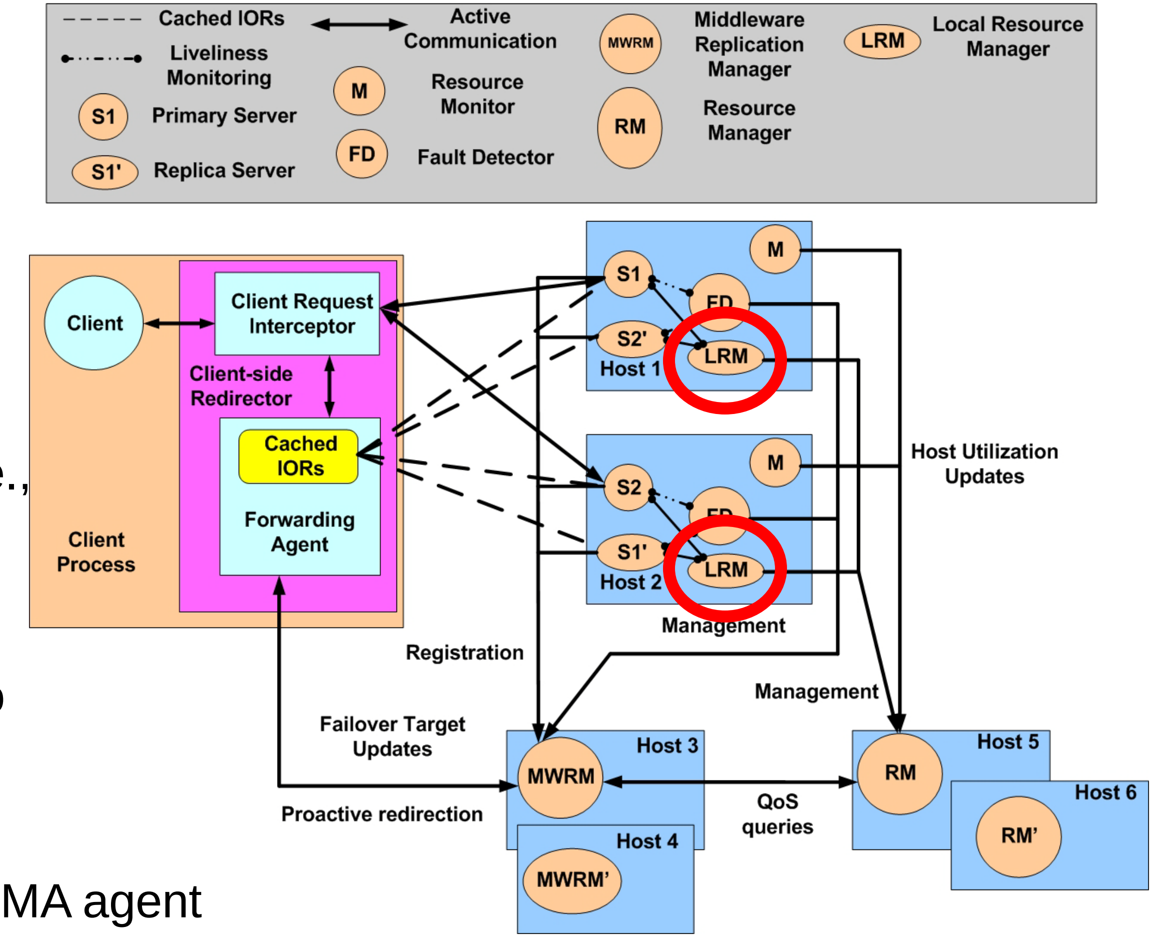
- Different applications have different requirements
  - e.g., FT more important than performance and vice-versa
- Configurable resource consumption needed on per-application basis
- Under resource constraints
  - trade-offs need to be made to balance the use of available resources for
    - fault-tolerance
    - response times



Need mechanisms that can focus on an operating region rather than an operating point to tune state management

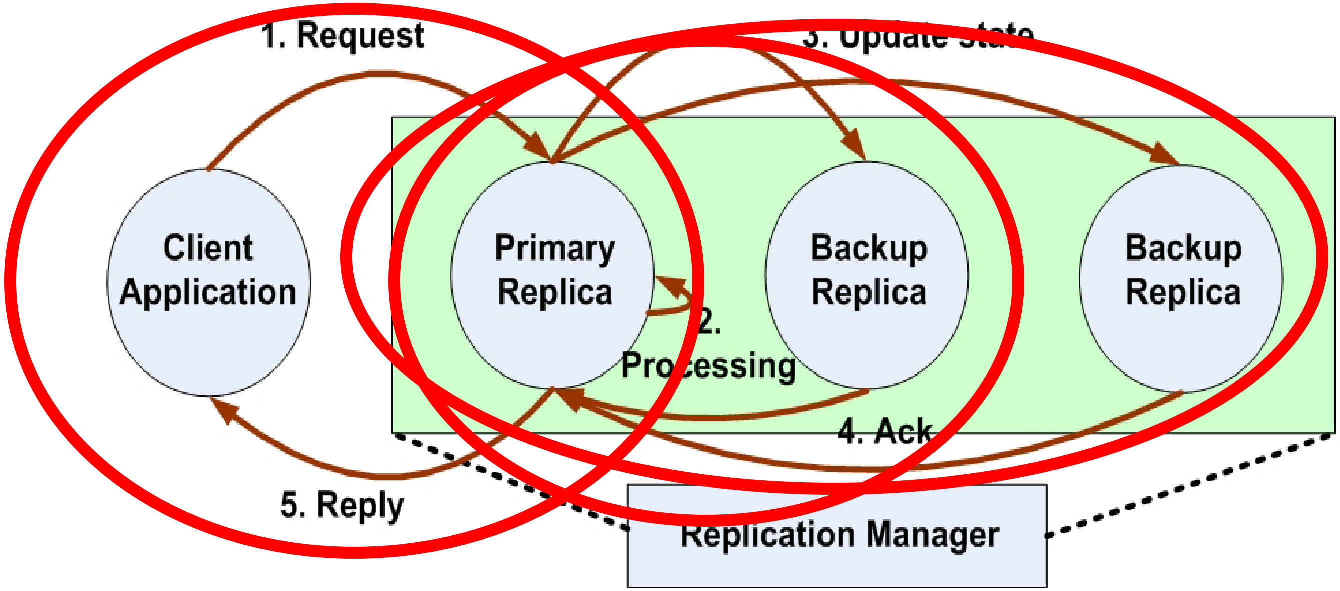
Solution Approach: TACOMA

- Tunable Adaptive COnsistency Management middlewAre (TACOMA)
  - built on top of the FLARe middleware
  - configurable consistency management middleware
    - resource-aware tuning of application consistency – i.e., number of replicas made consistent with the primary replica
    - use of different transports to manage consistency – e.g., CORBA AMI, DDS



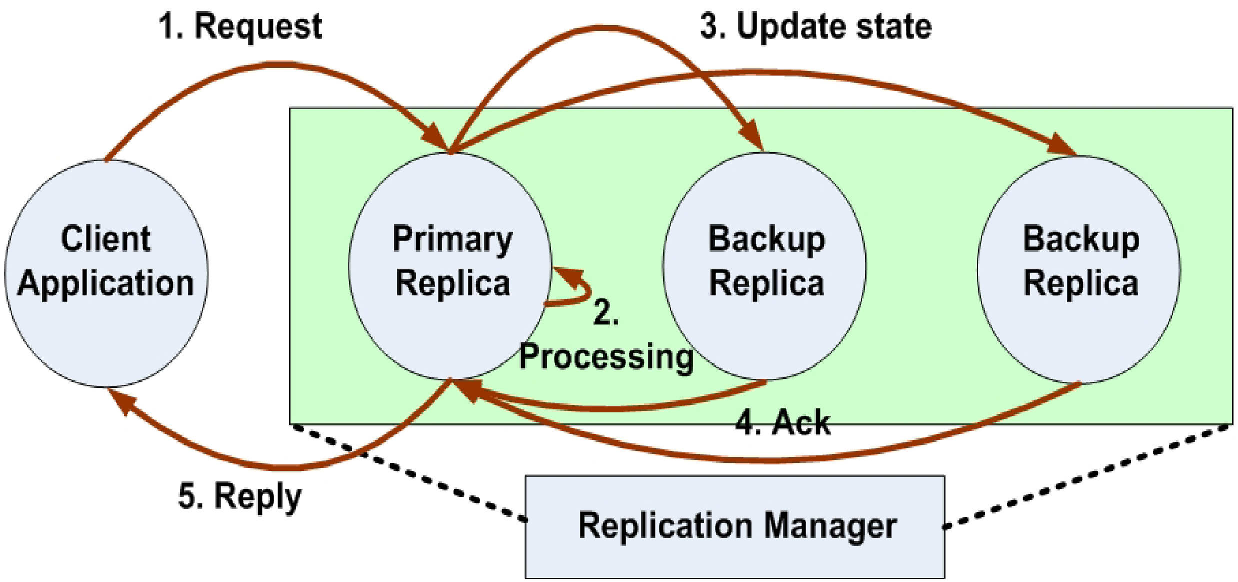
- Local Resource Manager – TACOMA agent
  - added on each processor hosting primary replicas
  - application informs the agent when state changes
  - agents synchronize the state of the backup replicas
    - works with FLARe replication manager to obtain object references

TACOMA: Configurable Consistency Management (1/2)



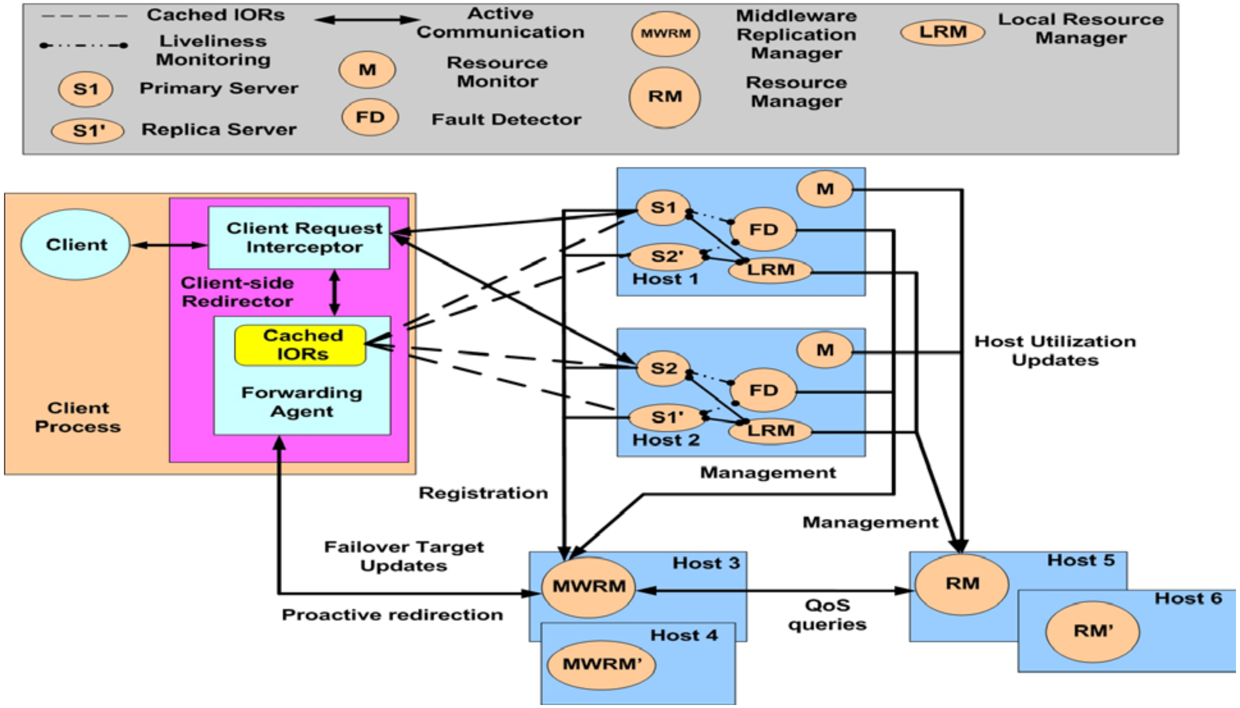
- Determine configurable consistency for each application
  - to respond to a client within a certain deadline, the state of how many backup replicas can be made consistent with the primary replica by the TACOMA agent?
  - Time taken to make one backup replica consistent equals
    - the worst case execution time of an update task initiated by the TACOMA agent in the primary replica
  - Sum of worst case execution times of update tasks at all backup replicas + processing time at primary replica = client response time

TACOMA: Configurable Consistency Management (2/2)



- Determine worst case execution times of update tasks
  - use time-demand analysis
- Tunable consistency management
  - input → available system resources
  - control → per-application consistency depth
  - output → desired application performance/reliability
  - fairness → provide minimum QoS assurances
- Configure TACOMA agents with the consistency depth determined

TACOMA Evaluation Criteria



- **Hypotheses:** TACOMA
  - is customizable & can be applied to a wide range of DRE systems
    - consistency depth range (1 to number of replicas)
  - utilizes available CPU & network resources in the system efficiently, & provides applications with the required QoS (performance or high availability)
    - response times are always met – no deadline misses
  - tunes application replication consistency depth at runtime, as resource availability fluctuates
    - consistency depth decreases from MAX (number of replicas) to MIN (1)

Concluding Remarks

- Passive Replication is a promising replication scheme for DRE systems
  - Crucial for resource-constrained environments
- Problems using passive replication for DRE systems
  - Lack of resource-aware FT decisions
    - potential to cause cascading failures
    - potential to cause clients not meet their performance requirements
  - Lack of Adaptive Fault-tolerant Middleware
    - no opportunities for customization & (re)configuration to provide both RT & FT capabilities
- TACOMA is work-in-progress implemented on top of TAO & FLARe

- Our FT-RT contributions include:
  - Resource-aware adaptive fault-tolerant middleware
    - deployment & allocation of applications driven by model-driven QoS allocation engine
    - adaptive fault-tolerant middleware reacts to failures & overloads, & maintains soft real-time requirements simultaneously
  - Replica consistency management middleware that optimizes trade-offs between resource usage, performance, & fault-tolerance
    - Exploit results from RT scheduling theory to understand the implications of FT on performance & resource usage