Middleware for Embedded Adaptive Dependability (MEAD)

Real-Time Fault-Tolerant Middleware Support

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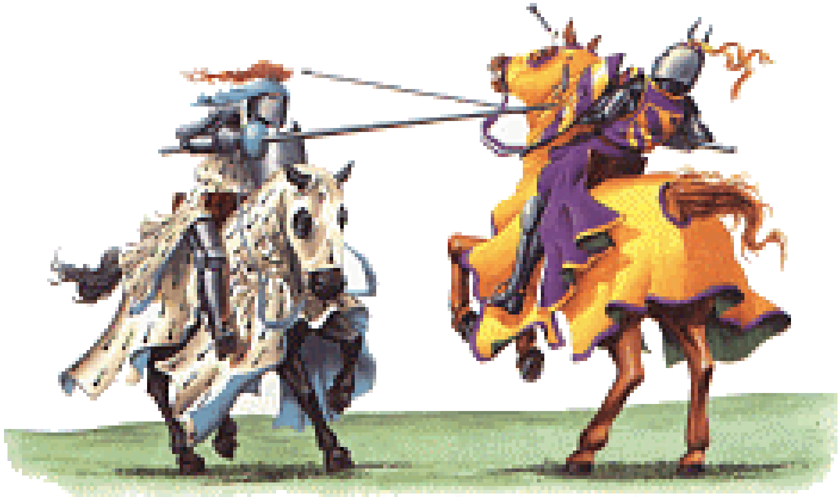
Motivation for MEAD

- **CORBA is increasingly used for applications, where dependability and quality of service are important**
  - The Real-Time CORBA (RT-CORBA) standard
  - The Fault-Tolerant CORBA (FT-CORBA) standard
- **But ……**
  - Neither of the two standards addresses its interaction with the other
  - Either real-time support or fault-tolerant support, but not both
  - Applications that need both RT and FT are left out in the cold
- **Focus of MEAD**
  - Why real-time and fault tolerance do not make a good "marriage"
  - Overcoming these issues to build support for CORBA applications that require **both** real-time **and** fault tolerance

Existing Technologies

- **The Real-time CORBA (RT-CORBA) standard**
  - Scheduling of entities (threads)
  - Assignment of priorities of tasks
  - Management of process, storage and communication resources
  - End-to-end predictability
- **The Fault tolerant CORBA (FT-CORBA) standard**
  - Replication of entities (CORBA objects or processes)
  - Management and distribution of replicas
  - Logging of messages, checkpointing and recovery
  - Strong replica consistency

Real-Time Systems	Fault-Tolerant Systems
Requires *a priori* knowledge of events	No advance knowledge of when faults might occur
Operations ordered to meet task deadlines	Operations ordered to preserve data consistency (across replicas)
RT-Determinism ⇨ Bounded predictable temporal behavior	FT-Determinism ⇨ Coherent state across replicas for every input
Multithreading for concurrency and efficient task scheduling	FT-Determinism prohibits the use of multithreading
Use of timeouts and timer-based mechanisms	FT-Determinism prohibits the use of local processor time



Combining Real-Time and Fault-Tolerance

- **Trade-offs between RT and FT for specific scenarios**
  - Effective ordering of operations to meet both RT and FT requirements
  - Resolution of non-deterministic conflicts (e.g., timers, multithreading)
- **Impact of fault-tolerance and real-time on each other**
  - Impact of faults/restarts on real-time behavior
  - Replication of scheduling/resource management components
  - Scheduling (and bounding) recovery to avoid missing deadlines
- **For large-scale systems**
  - Scalable fault detection and recovery
  - Considering nested (multi-tiered) middleware applications
  - Tolerance to partitioning faults

Architectural Overview

- **Use replication to protect**
  - Application objects
  - Scheduler and global resource manager
- **Special RT-FT scheduler**
  - Real-time resource-aware scheduling service
  - Fault-tolerant-aware to decide when to initiate recovery
- **Hierarchical resource management framework**
  - Local resource managers feed into a replicated global resource manager
  - Global resource manager coordinates with RT-FT scheduler
- **Ordering of operations**
  - Keeps replicas consistent in state despite faults, missed deadlines, recovery and non-determinism in the system

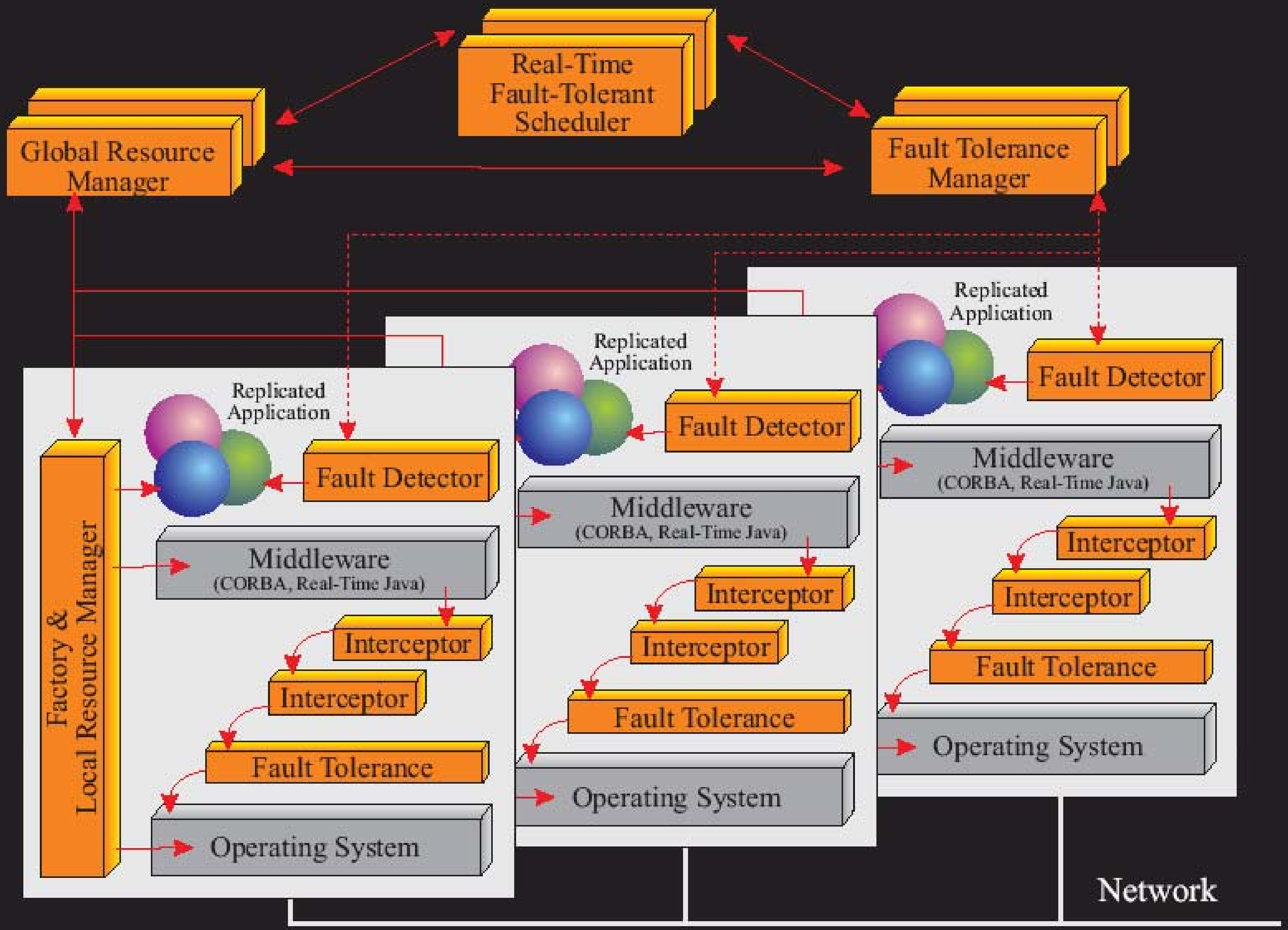
So, What Do We Want To Tolerate?

- **Crash faults**
  - ✓ Hardware and/or OS crashes in isolation
  - ✓ Process and/or Object crashes
- **Communication faults**
  - ✓ Message loss and message corruption
  - ✓ Network partitioning
- **Malicious faults (commission/Byzantine)**
  - ✗ Processor/process/object maliciously subverted
- **Omission faults**
  - ✓ Missed deadline in a real-time system
- **Design faults**
  - ✗ Correlated software/programming/design errors

Fault Model
Kinds of faults that MEAD
is designed to tolerate

MEAD (Middleware for Embedded Adaptive Dependability)

- **Our RT-FT Architecture**
- **Why MEAD?**
- **Legendary ambrosia of the Vikings**
- **Believed to endow its imbibers with**
  - Immortality (⇨*dependability*)
  - Reproductive capabilities (⇨*replication*)
  - Wisdom for weaving poetry (⇨*cross-cutting aspects of real-time and fault tolerance*)
  - Happy and long married life (⇨*partition-tolerance*)


Real-Time
Fault-Tolerant
Scheduler
Global Resource
Manager
Fault Tolerance
Manager
Factory &
Local Resource Manager
Replicated
Application
Fault Detector
Middleware
(CORBA, Real-Time Java)
Interceptor
Interceptor
Fault Tolerance
Operating System
Replicated
Application
Fault Detector
Middleware
(CORBA, Real-Time Java)
Interceptor
Interceptor
Fault Tolerance
Operating System
Replicated
Application
Fault Detector
Middleware
(CORBA, Real-Time Java)
Interceptor
Interceptor
Fault Tolerance
Operating System
Network

Resource-Aware RT-FT Scheduling

- **Requires ability to predict and to control resource usage**
  - Example: Virtual memory is too unpredictable/unstable for real-time usage
  - RT-FT applications that use virtual memory need better support
- **Needs input from the local and global resource managers**
  - Resources of interest: load, memory, network bandwidth
  - Parameters: resource limits, current resource usage, usage history profile
- **Uses resource usage input for**
  - Proactive action
    - Predict and perform new resource allocations
    - Migrate resource-hogging objects to idle machines before they start executing
  - Reactive action
    - Respond to overload conditions and transients
    - Migrate replicas of offending objects to idle machines even as they are executing invocations

Proactive Dependability

- **What if we knew, with some confidence, when a fault was to occur?**
- **Needs input from a fault-predictor (error-log analysis)**
  - To determine when, and what kinds of, faults can occur
  - To schedule fault detection time based on prediction
- **Needs input from a recovery-predictor**
  - **Offline predictor**: Source code analysis for worst-case recovery time
    - Look at each object's data structures
    - Looks at the object's containing process and ORB interactions
    - Not comprehensive: unable to predict dynamic memory allocations
  - **Runtime predictor**: Object execution and memory allocation profile
    - Intercepts and observes runtime memory allocations (e.g., object instantiation, library loading), connection establishment, etc.
    - Prepares for the worst-case replica recovery time

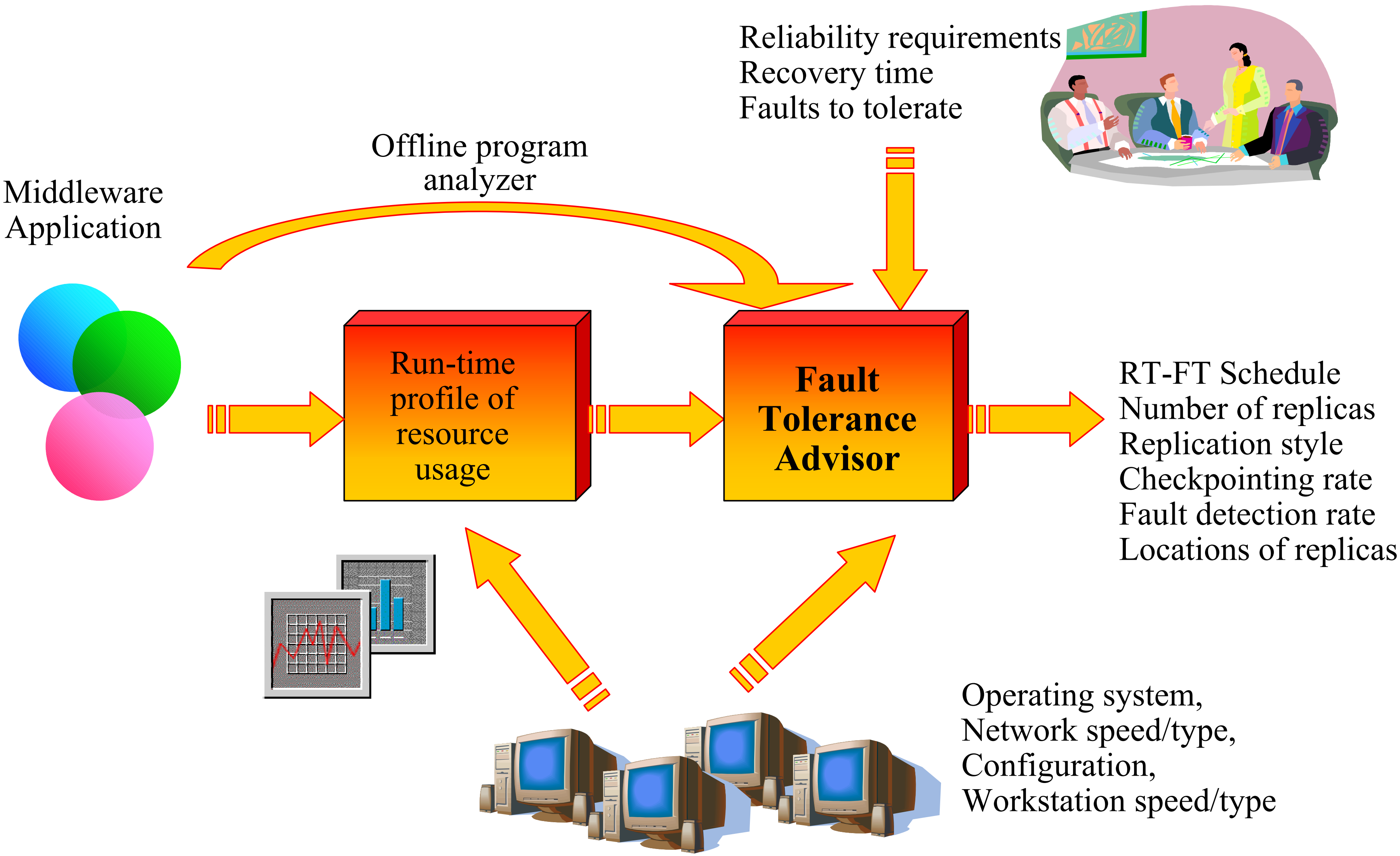
Offline Program Analysis

- **Application may contain RT *vs.* FT conflicts**
- **Application may be non-deterministic**
- **Program analyzer sifts interactively through application code**
  - To pinpoint sources of conflict between real-time and fault-tolerance
  - To determine size of state, and to estimate recovery time
  - To determine the appropriate points in the application for the incremental checkpointing of the application
  - To highlight, and to compensate for, sources of non-determinism
    - Multi-threading
    - Direct access to I/O devices
    - Local timers
- **Offline program analyzer feeds its recovery-time estimates to the Fault-Tolerance Advisor**

Fault-Tolerance Advisor

- **Configuring fault tolerance today is mostly ad-hoc**
- **To eliminate the guesswork, we deployment/run-time advice on**
  - Number of replicas
  - Checkpointing frequency
  - Fault-detection frequency, etc.
- **Input to the Fault-Tolerance Advisor**
  - Application characteristics (using output from Ask Andy)
  - System reliability characteristics
  - System's and application's resource usage
- **Fault-Tolerance Advisor works with other MEAD components to**
  - Enforce the reliability advice
  - Sustain the reliability of the system, in the presence of faults

Fault-Tolerance Advisor



Mode-Driven Fault-Tolerance

- **Most applications have multiple modes of operation**
  - Example: an unmanned aerial vehicle (UAV) might be modal
    - Surveillance mode
    - Target recognition mode
    - Tracking mode
    - Feedback/Control mode
- **Each mode might require different fault-tolerance mechanisms**
  - The critical elements in the path might differ
  - The resource usage might differ, e.g., more bandwidth used in some modes
  - The notion of distributed system “state” might be different
- **MEAD aims to provide the “right mode-specific fault-tolerance”**
  - Based on the Fault-Tolerance Advisor’s inputs
  - In response to (omens heralding) mode changes

Looking Ahead ....

- **OMG RT-SIG in the process of drafting an RFP for RT-FT CORBA**
- **Consider (and seek means to reconcile) the fundamental conflicts/tensions between real-time and fault-tolerance**
  - To avoid point solutions that might work well, but only for well-understood applications, and only under certain constraints
  - To allow for systems that are subject to dynamic conditions, e.g., changing constraints, new environments, overloads, faults, ……
- **Expose interfaces that support the**
  - Capture of the application's fault-tolerance <u>and</u> real-time needs
  - Tuning of the application's fault-tolerance <u>and</u> real-time configurations
  - Query of the provided "level" of fault-tolerance <u>and</u> real-time
  - Scheduling of <u>both</u> real-time and fault-tolerance (fault-detection, fault-recovery and fault-forecasting) activities

Summary

- **Resolving trade-offs between real-time and fault tolerance**
  - Ordering of tasks to meet replica consistency and task deadlines
  - Bounding fault detection and recovery times in asynchronous environment
  - Estimating worst-case performance in fault-free, faulty and recovery cases
- **MEAD's RT-FT middleware support**
  - Tolerance to crash, communication, timing and partitioning faults
  - Resource-aware RT-FT scheduler to schedule recovery actions
  - Proactive dependability framework
  - Fault-tolerance advisor to take the guesswork out of configuring reliability
  - Offline program analysis to detect, and to compensate for, RT-FT conflicts
- **Ongoing research and development with RT-CORBA and RT-Java**
- **Intention to participate in the standardization efforts of the OMG**

For More Information on MEAD

http://www.ece.cmu.edu/~mead

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