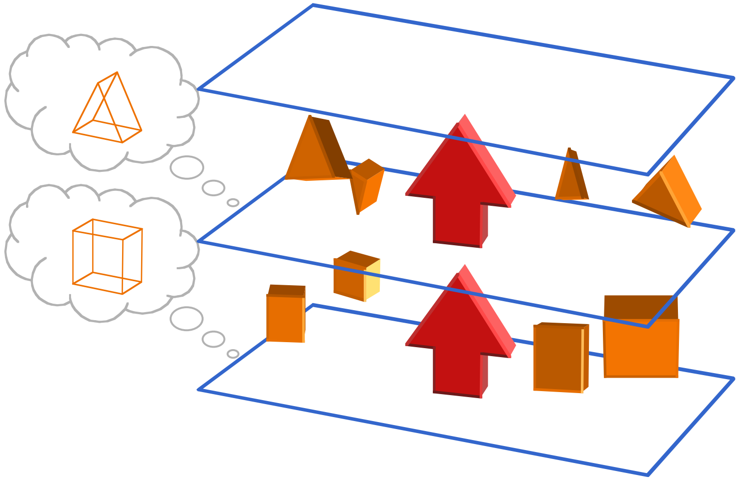

Towards Implementing Multi-Layer Reflection for Fault-Tolerance

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CNRS LAAS

Toulouse, France

DSN-2003, San Francisco, CA, USA June 22nd-25th

Context

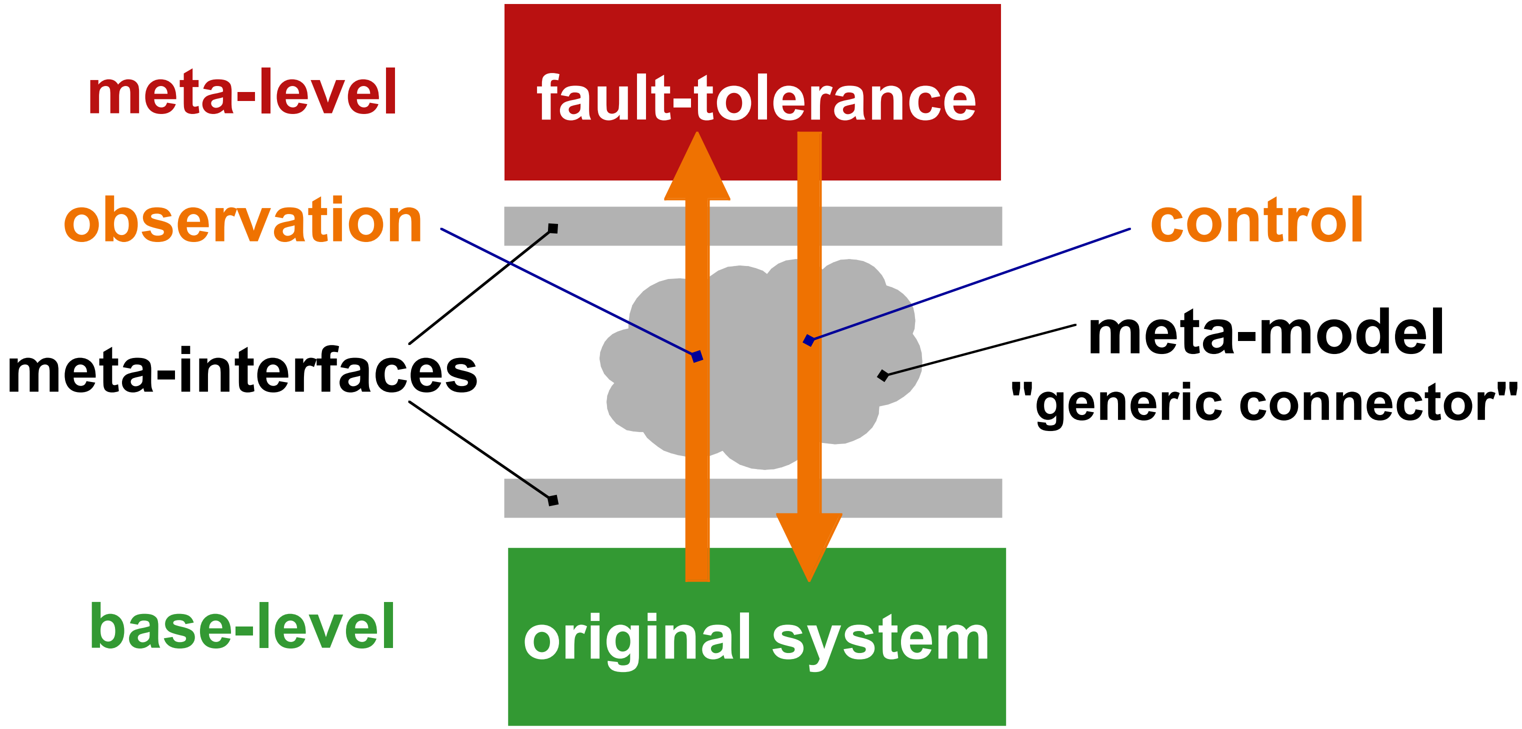
- Modern systems are large and complex
  - ➔ many software layers and components
  - ➔ heterogeneous abstraction levels
  - ➔ increased use of COTS
- Dependability is orthogonal to all system layers
- Adding fault-tolerance to those systems must be done:
  - ➔ separately from functional development to address complexity
  - ➔ encompassing all system layers for maximum coverage
- Our proposal: Multi-Layer Reflection

Outline

- What is Reflection?
- Why Multi-Layer Reflection?
- Development Approach
- Case Study: Replication of a Multi-Threaded Server
- Conclusion

What is Reflection?

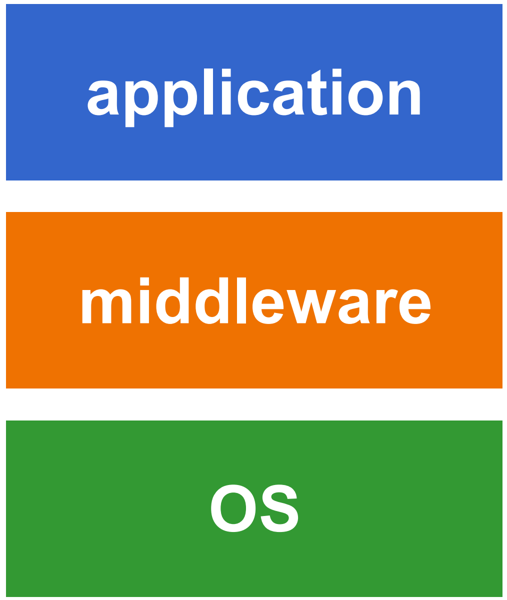
"the ability of a system to think and act about itself"



☞ separating **fault-tolerance** from **functional** concerns

Why Multi-Layer Reflection ?

- *Ad-hoc* fault-tolerance in a multi-layer system



Why Multi-Layer Reflection ?

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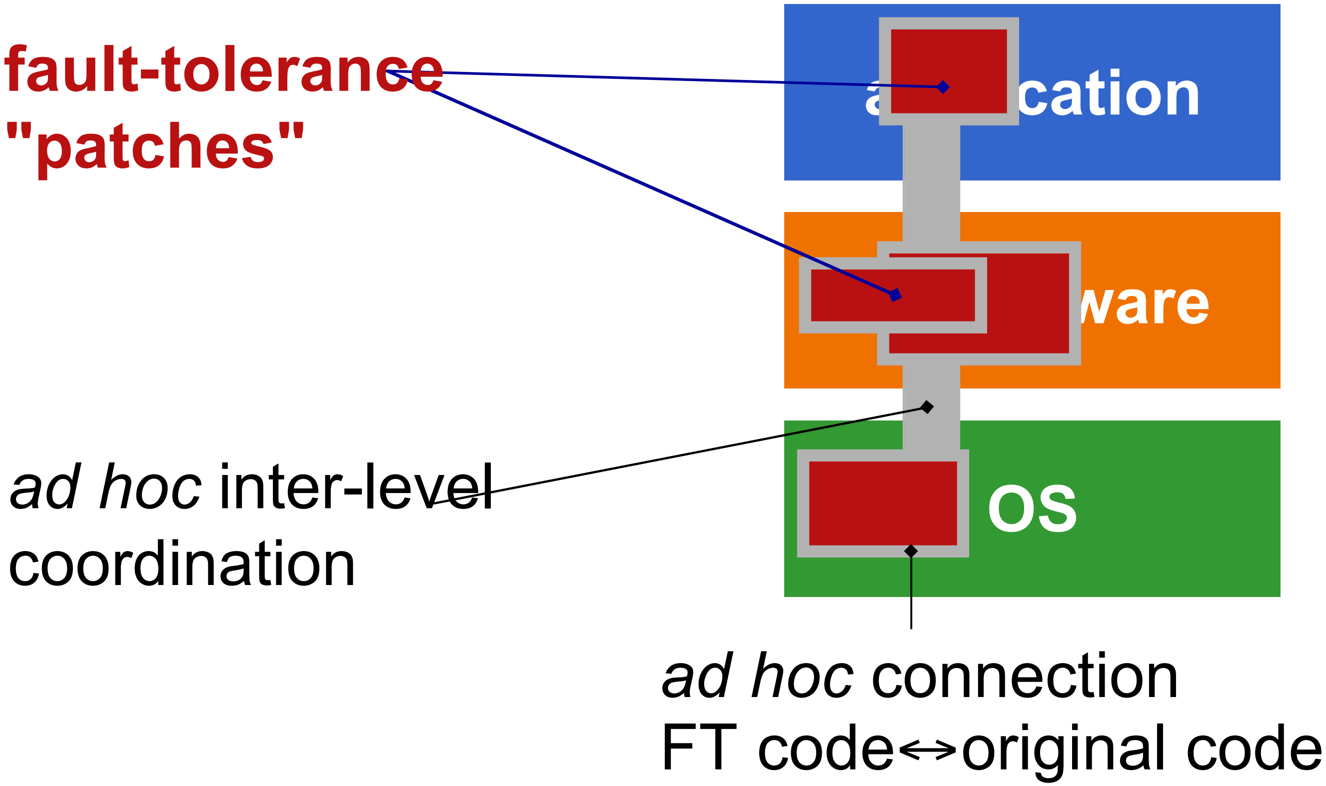
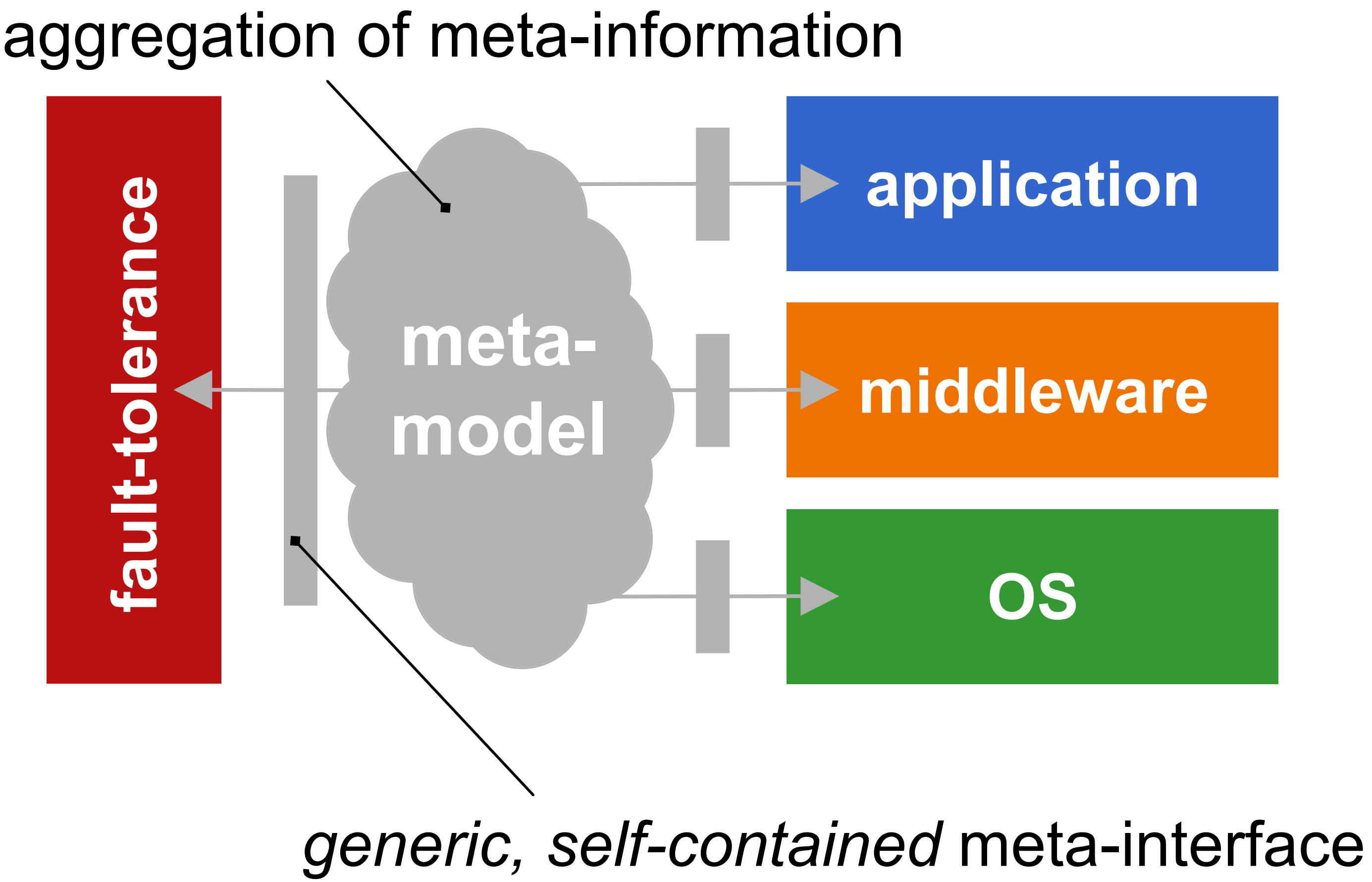
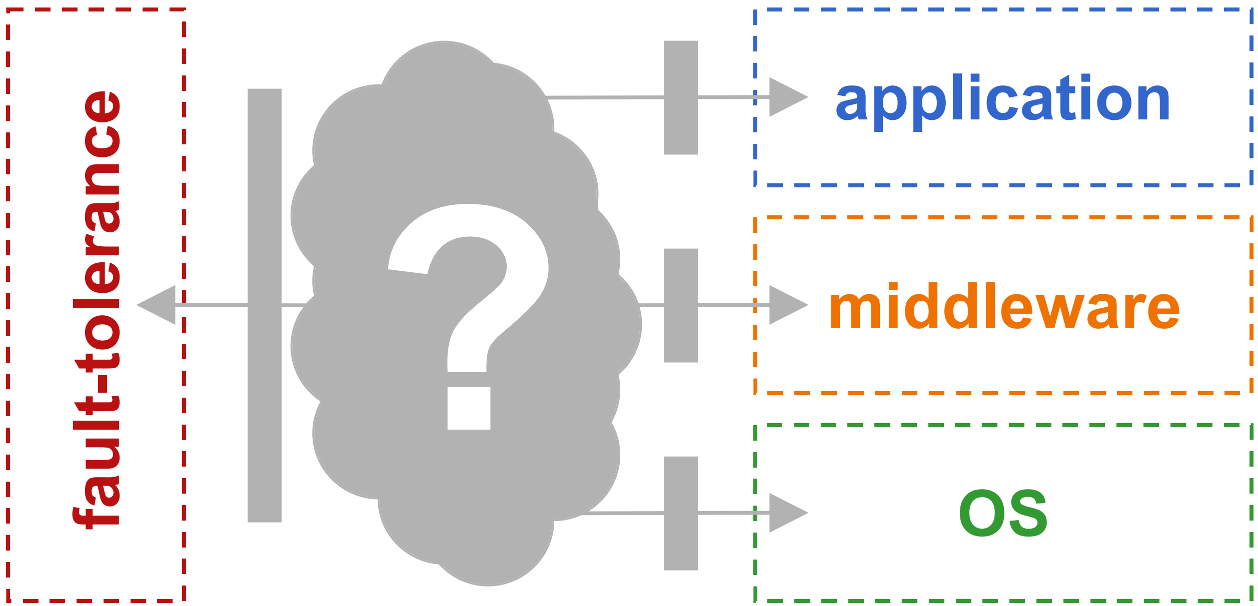


Multi-Layer Reflective Architecture



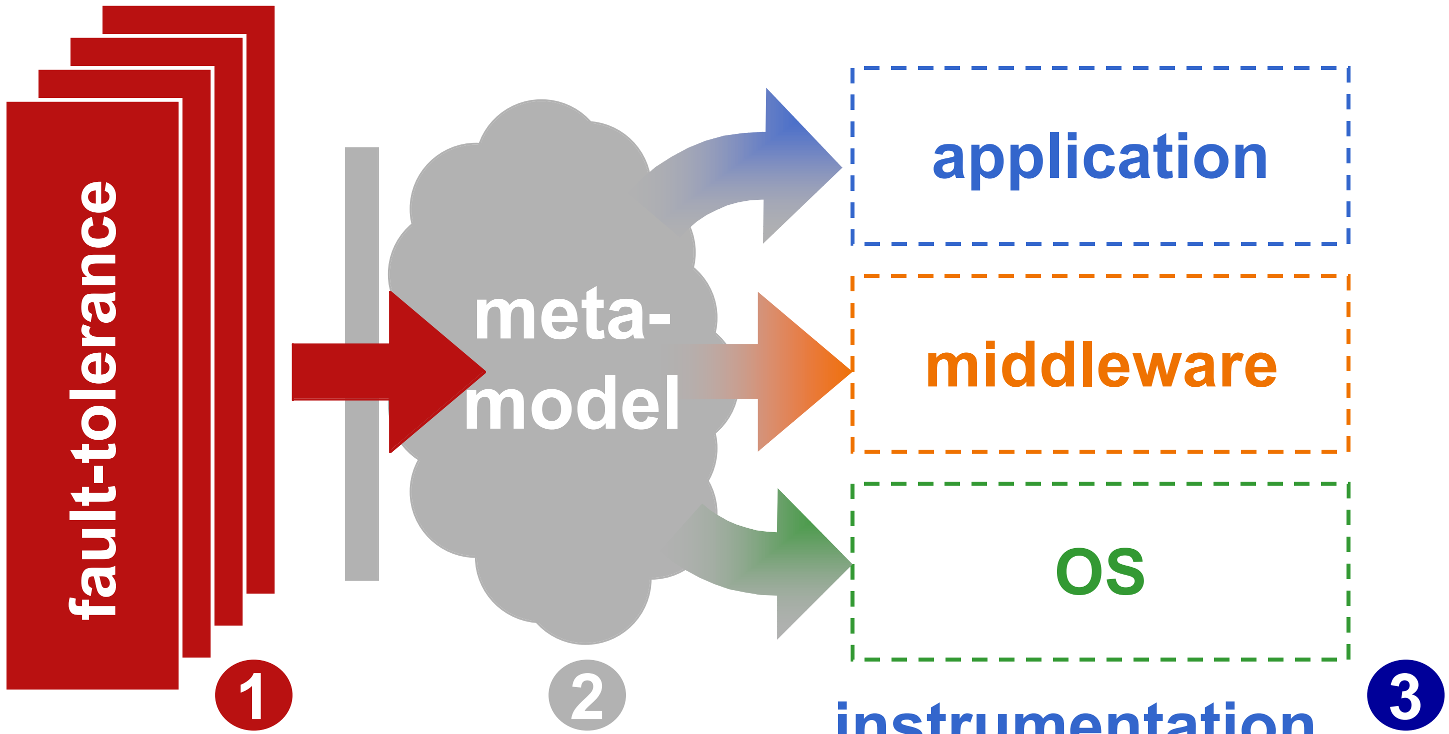
Multi-Layer Reflective Architecture



- Which information is needed for fault-tolerance?
- How and where to obtain this information?

[Multi-Layer Reflective Architecture]

Development Approach



family of mechanisms

reflective footprint

instrumentation of the chosen architecture

Obtaining the Reflective Footprint

- Analysis of a family of replication strategies
  - primary backup replication
  - active and semi-active replication
- Example of reflective features that are needed to implement the mechanisms of this family:
  - state capture (observation)
  - state restoration (control)
  - request message interception (observation)
  - request message dispatching (control)
  - non-deterministic decision points

[Development Approach]

Obtaining the Reflective Footprint

	Reflective Facets		
	Communication	***Execution***	***State***
Reification	RequestReception RequestSending ReplySending ReplyReception	ExecutionPointStart ExecutionPointEnd ExecutionPointReach NonDeterministicFlowChange	NonDeterministicPlatformCall
Introspection	getRequestContent getReplyContent	getExecutionPoint	getServerState getPlatformState
Behavioral Intercession	doSend doReceive	createExecutionPoint setExecutionPoint forceResultOfFlowChange	forceResultOfPlatformCall
Structural Intercession	piggyBackDataOnMsg		setServerState setPlatformSate

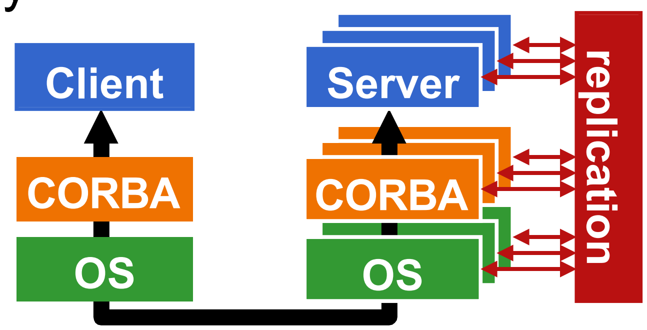
Instrumentation

- In a multi-component system: Information/control possible in different layers / abstraction levels
  - ➔ Higher layers (application, language):
    - ☞ abstract info / rich semantics
  - ➔ Lower layers (OS, middleware):
    - ☞ detailed info / poor semantics
- Goal of our approach:
  - ➔ to combine the best of both perspectives
  - ➔ requires understanding of inter-layer coupling
- We developed a reverse-engineering tool to help us construct model of inter-layer interaction
  - ➔ helps decide where to insert instrumentation points

Student Paper

Case Study: Replication & Multithreading

- Goal: Transparent replication of a CORBA server
  - ➔ multi-layer: **POSIX** (OS) + **CORBA** (middleware)
  - ➔ multithreaded: concurrent processing of requests
  - ➔ thread pool: upper limit on concurrency



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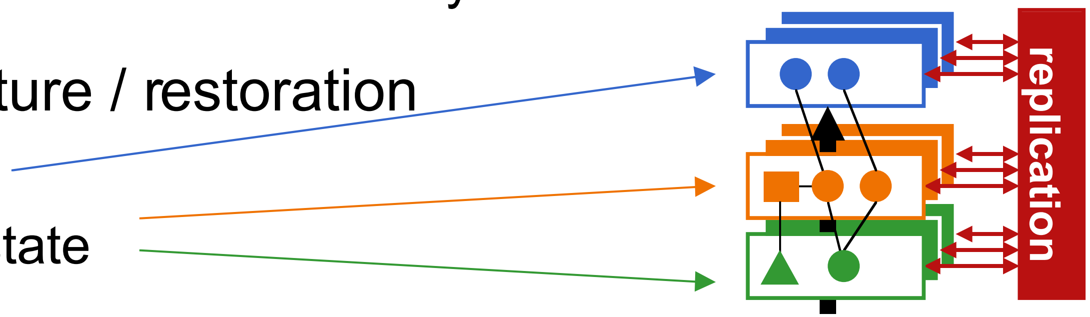
- *Problem 1:* state capture / restoration
  - ➔ application state
  - ➔ middleware + OS state



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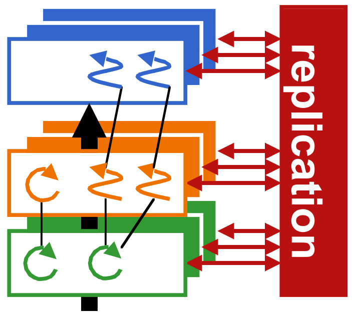
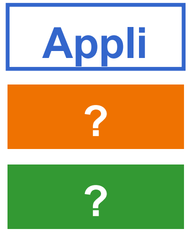
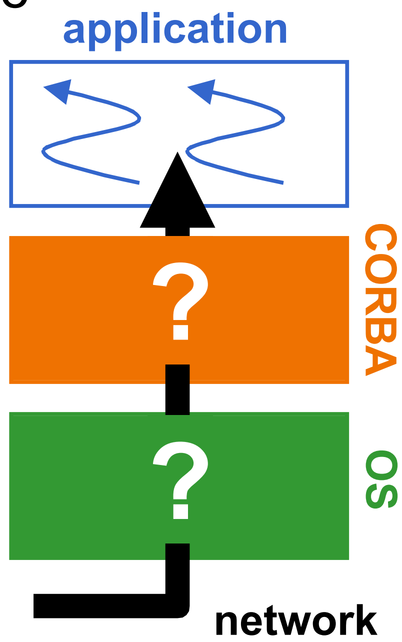


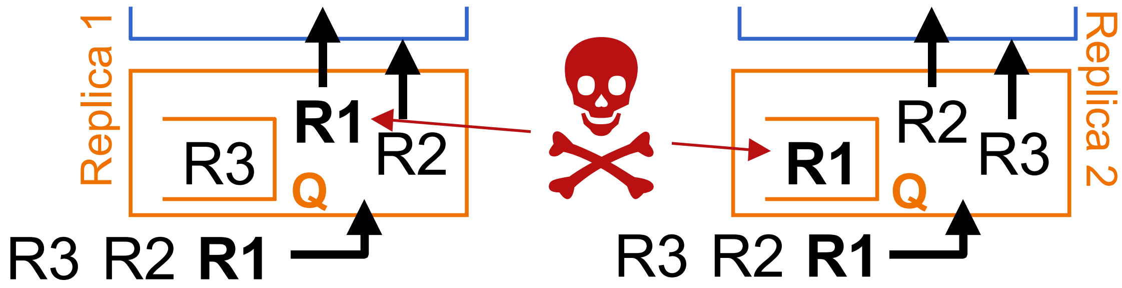
- *Problem 1:* state capture / restoration
  - ➔ application state
  - ➔ middleware + OS state
- *Problem 2:* control of non-determinism
  - ➔ assumption: multi-threading only source of non-determinism
  - ➔ how to replicate non-deterministic scheduling decisions?



Application Level only

- No guarantee on middleware behavior:
  - ➔ arbitrary scheduling of requests by middleware
- Replicating scheduling decisions observed in the application is not enough:
  - ➔ because of thread pool (for example size 2)
  - ➔ even with total order-multicast on the network

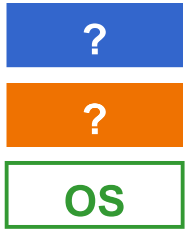




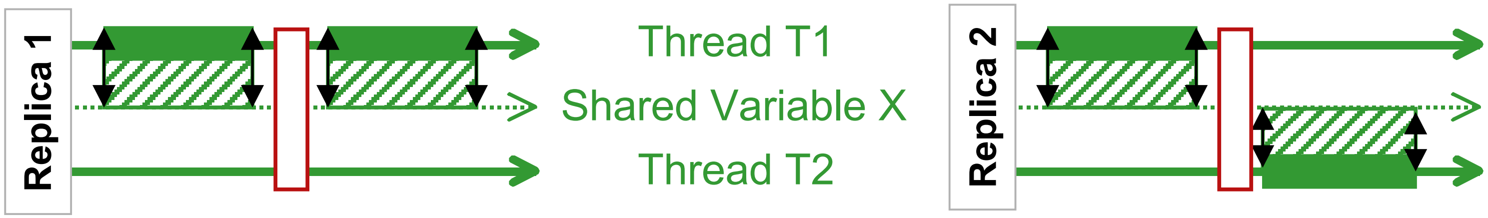
- ➔ The decision taken by the middleware regarding dispatching can't be controlled from the application.

[Case Study: Replication & Multithreading]

OS Level Only



- Low level thread synchronization can be controlled:
  - ➔ The same thread scheduling can be enforced on all replicas
  - ➔ Requests are dispatched and processed in the same order
  - ➔ All replicas reache the same state (assumption: MT = only source of non-determinism)
- But this over-constrains the replicas' execution:
  - ➔ impossible to relate OS level activities to request processing
  - ➔ impossible to distinguish scheduling decisions that influence determinism and those that do not.



not equivalent ☞ replication of every decision

Smart Replication of Scheduling

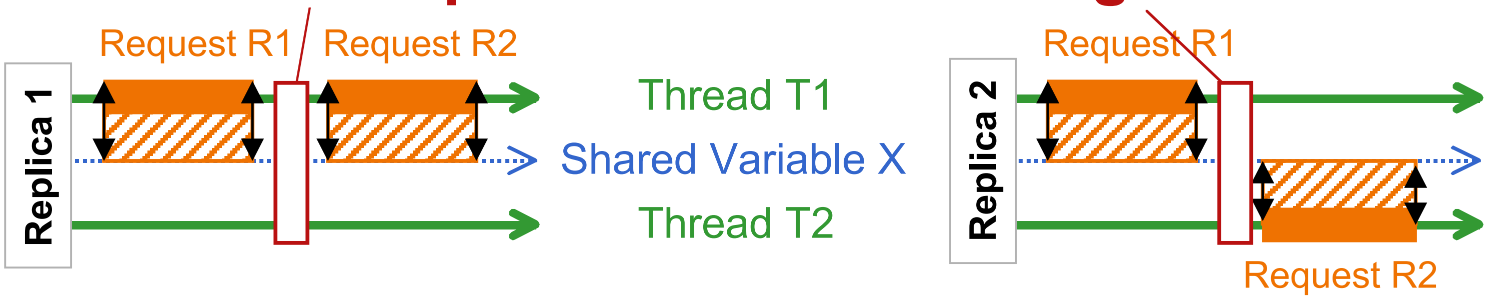
- With CORBA and application semantics:

Appli
CORBA
OS

  - ➔ Application and CORBA reflection give semantic to the actions taken by the application.
  - ➔ This semantic allows optimal use of OS level reflection.

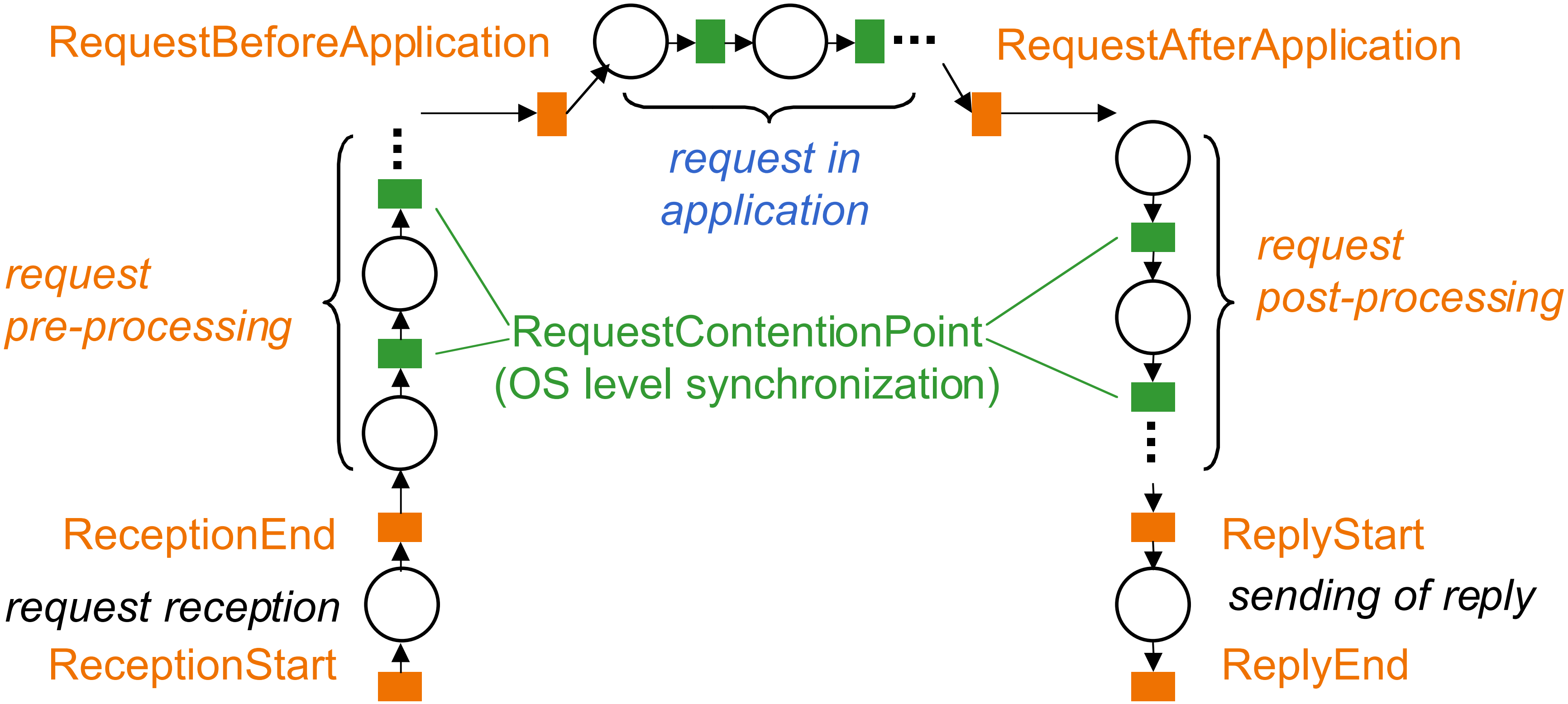
- Example: with a thread pool :
  - ➔ Which thread executes which request does not matter
  - ➔ The following 2 executions are equivalent:

no need to replicate this scheduling decision



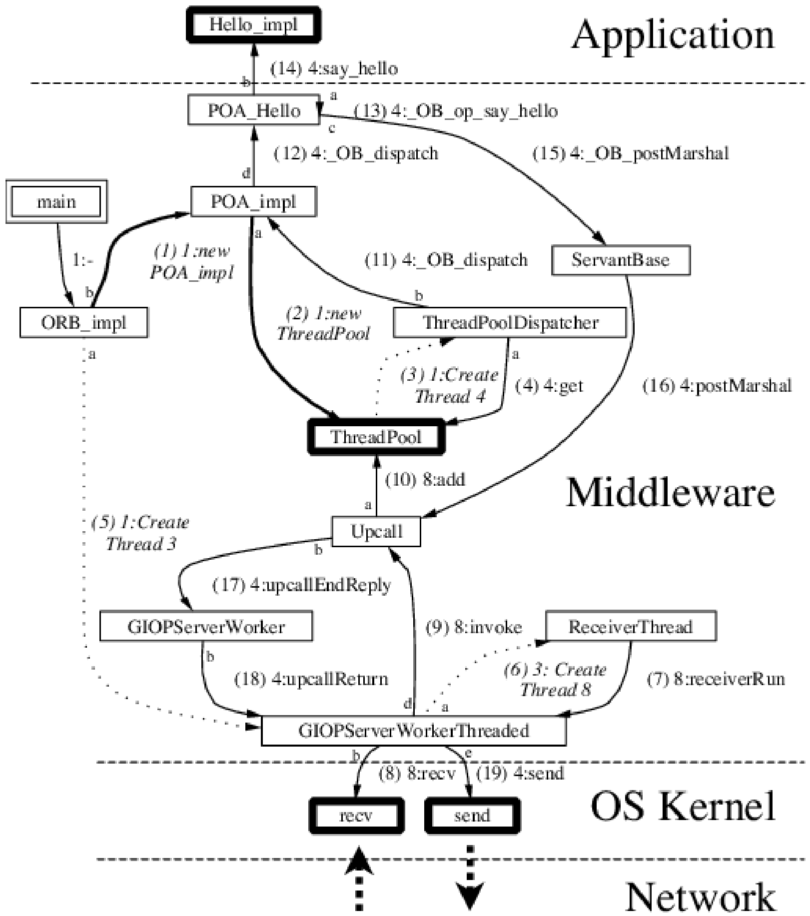
The Multi-Layer Meta-Model

- Meta-model centered on the lifecycle of a CORBA request
  - ➔ aggregates OS-level synchronization and request lifecycle



Middleware Instrumentation

- Behavioral middleware model:
  - ➔ relates OS level actions to application level operations
  - ➔ identifies points of instrumentation of meta-model



[Case Study: Replication & Multithreading]

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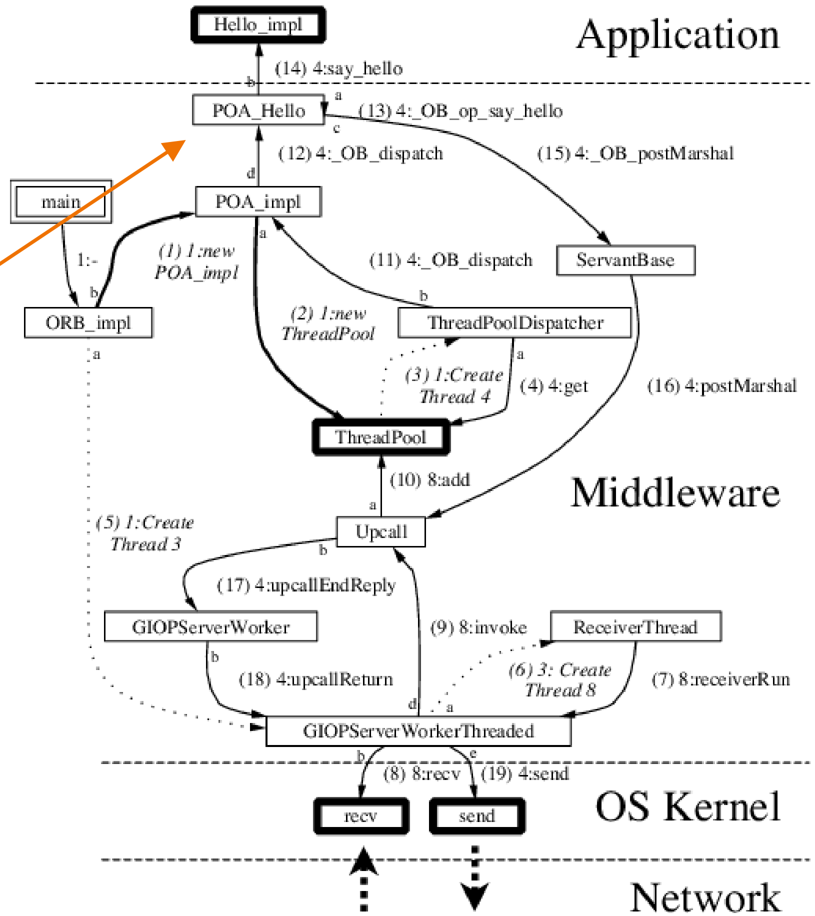
RequestBeforeApplication



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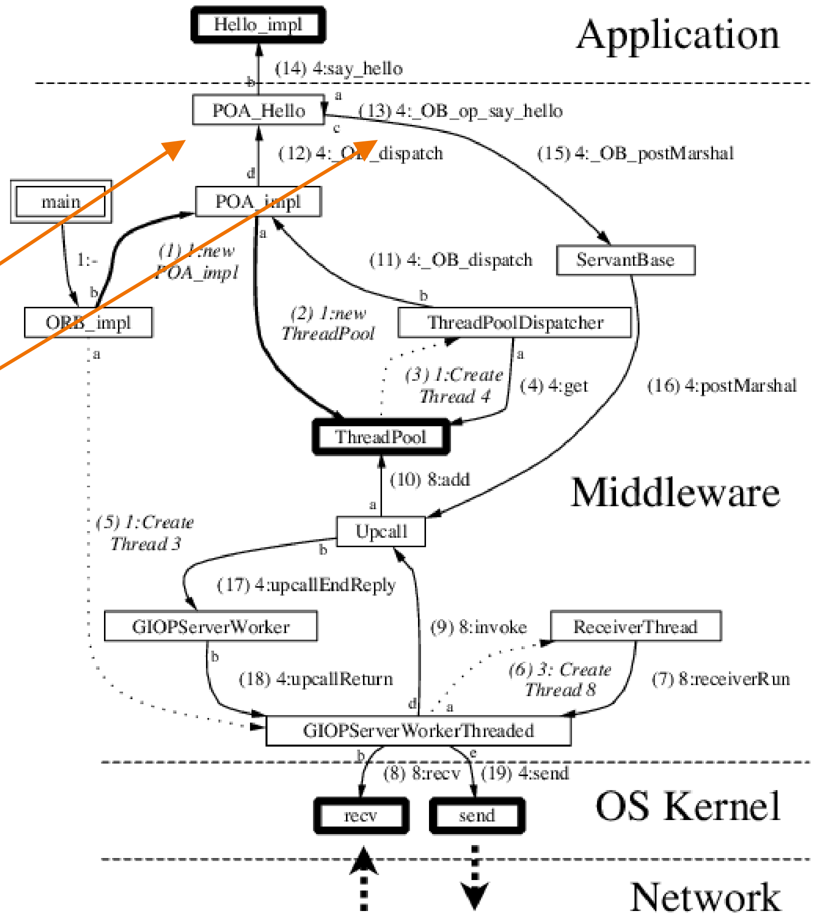

RequestBeforeApplication

RequestAfterApplication

[Case Study: Replication & Multithreading]

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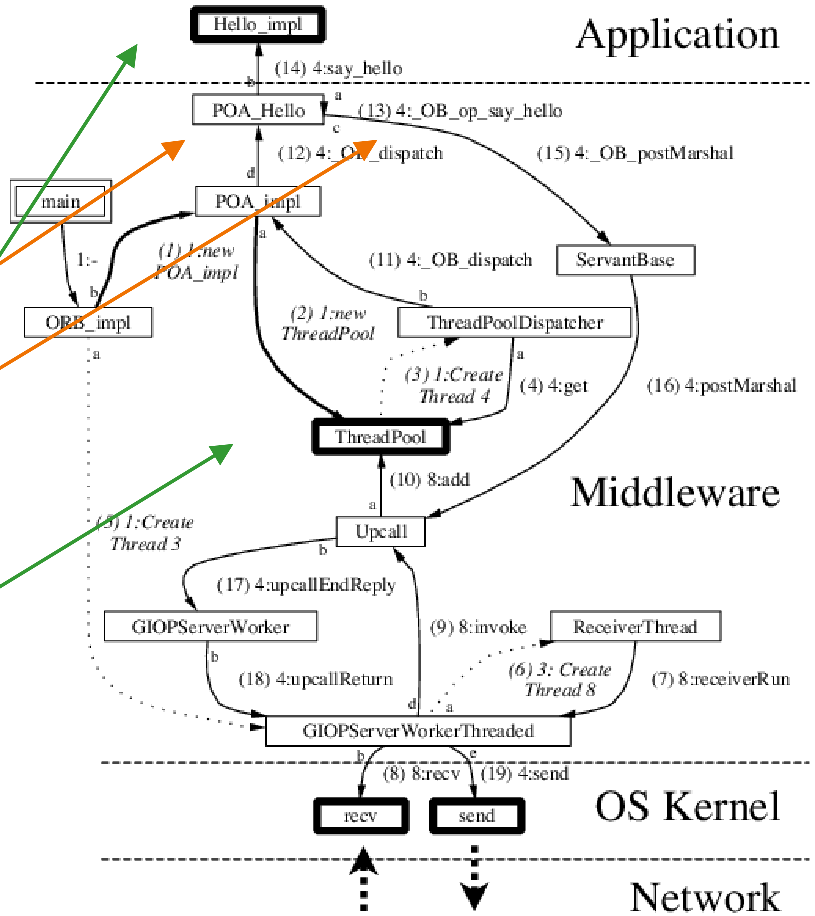
RequestBeforeApplication

RequestAfterApplication

RequestContentionPoint



Replication: The Whole Picture

- Behavioral control
  - ➔ interception of request execution life cycle steps
  - ➔ non-deterministic contention points can be controlled
- State observation and control
  - ➔ Middleware state can be recovered by "fast-reexecution"
    - re-injection of ongoing requests
    - dispatching of active requests to the pool
    - "shunting" execution for requests already processed
  - ➔ Application level state: reuse of other approaches
    - language based reflective approach to restore state variable
    - platform based approaches to restore OS dependent application state (e.g. thread stacks)

The Meta-Interface

```
class Request ;
class Thread ;
class StackChunk ;
class ReifiedEvent ;
class RequestLifeCycleEvent extends ReifiedEvent {
        public Request reifiedRequest ;
        public Thread  reifyingThread ;
}
class BeginOfRequestReception extends RequestLifeCycleEvent ;
class EndOfRequestReception  extends RequestLifeCycleEvent ;
class RequestBeforeApplication          extends RequestLifeCycleEvent ;
class RequestAfterApplication extends RequestLifeCycleEvent ;
class BeginOfRequestResultSend          extends RequestLifeCycleEvent ;
class EndOfRequestResultSend extends RequestLifeCycleEvent ;
class RequestContentionPoints extends RequestLifeCycleEvent ;

class IntercessionCommand ;
class ContinueExecution                 extends IntercessionCommand ;
class SkipCallToApplication  extends IntercessionCommand ;

interface MetaLevel {
        IntercessionCommand reifyEventToMetaSynchronous(ReifiedEvent e);
}
interface BaseLevel {
        State captureApplicationState ();
        void  restoreApplicationState (State s);
        StackChunk captureApplicationStack (Thread t);
        void       restoreApplicationStack (Thread t, StackChunk stack) ;
        void  InjectRequestAtCommuncationLevel(Request r);
}
```

Conclusion

- Complex fault tolerant systems :
  - ➔ Separation of concerns for reusability, adaptability, evolvability
  - ➔ Observability and controllability over multiple layers required
- Multi-layer reflection
  - ➔ Consistent and disciplined way to address this problem
  - ➔ Applicable to complex systems as it enables to master complexity
  - ➔ This is possible: our case study is a first step… more work to come!
- Recent and on-going work
  - ➔ DAISY : an adaptive fault tolerant system based on some limited off-the-shelf reflective mechanisms (CORBA PI, Java Serialization)
  - ➔ Some observability and controllability problems solved thanks to the multi-layer reflection concepts (e.g. additional reflective features introduced into Orbacus and Linux)

Prospective

- Components and OSS is not enough!
  - ☞ « Reflective component model »