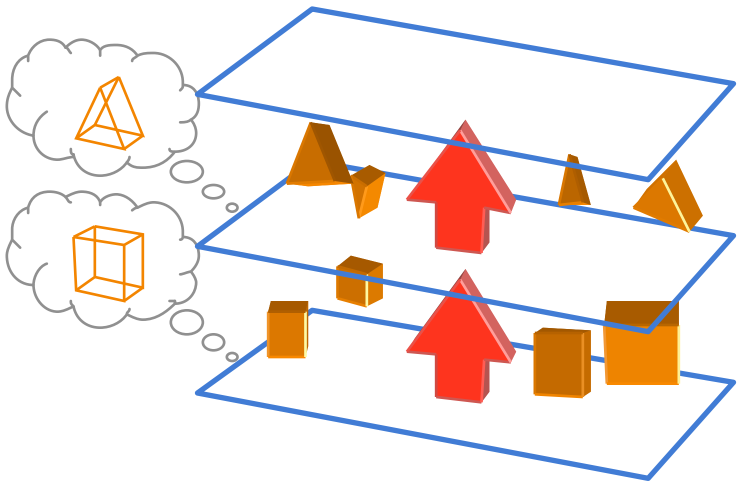

A Multi-Level Meta-Object Protocol for Fault-Tolerance in Complex Architectures

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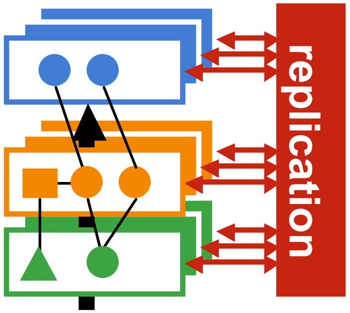
LAAS-CNRS ([(*)]: Now at Lancaster University)

DSN'2005, *The International Conference on Dependable Systems and Networks*, Yokohama, Japan, June 28 - July 1, 2005

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



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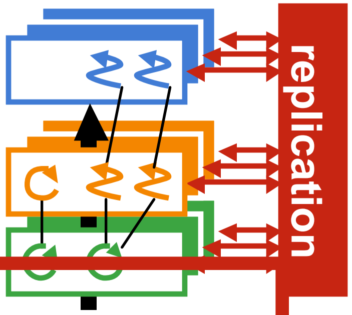
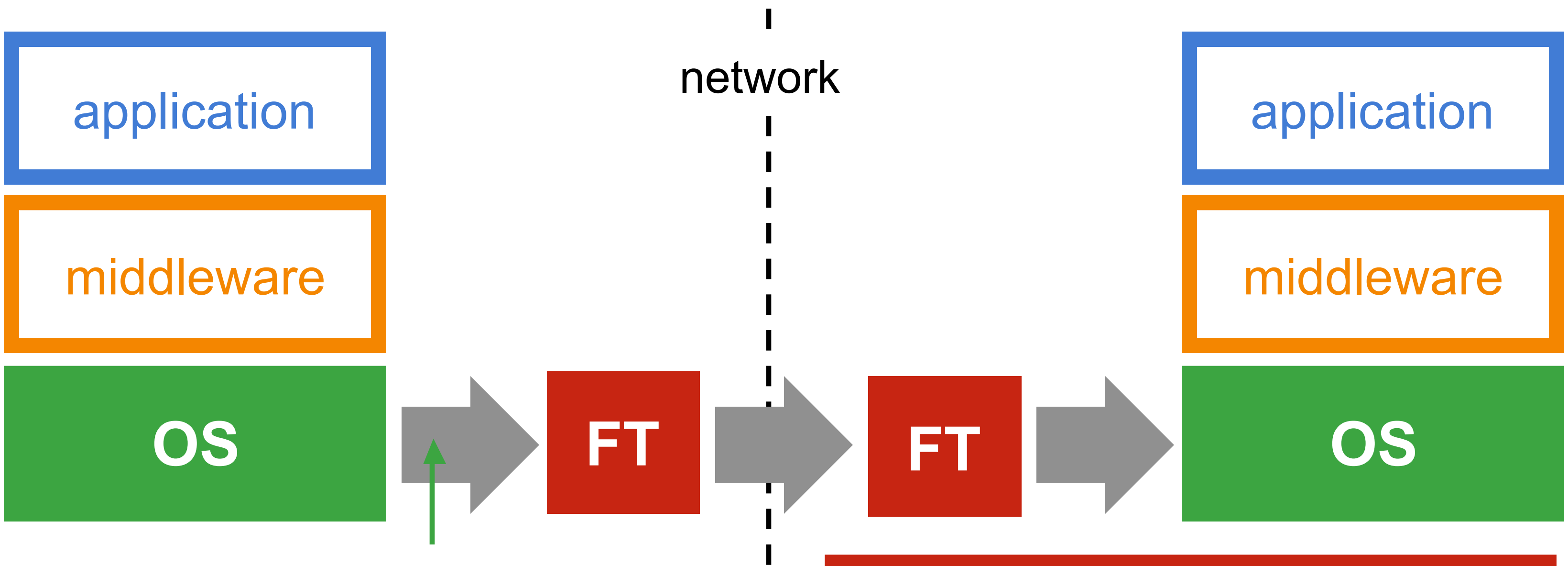


- ***Problem 2:*** control of **non-determinism**
  - ➔ assumption: **multi-threading** *only* source of non-determinism
  - ➔ how to replicate non-deterministic mutex decisions?

Enforcing Determinism: OS Only

- The same lock allocation can be enforced on all replicas.
  - ☺ All replicas reach the same state.
  - ☹ Only a small subset of the lock allocations impacts determinism.

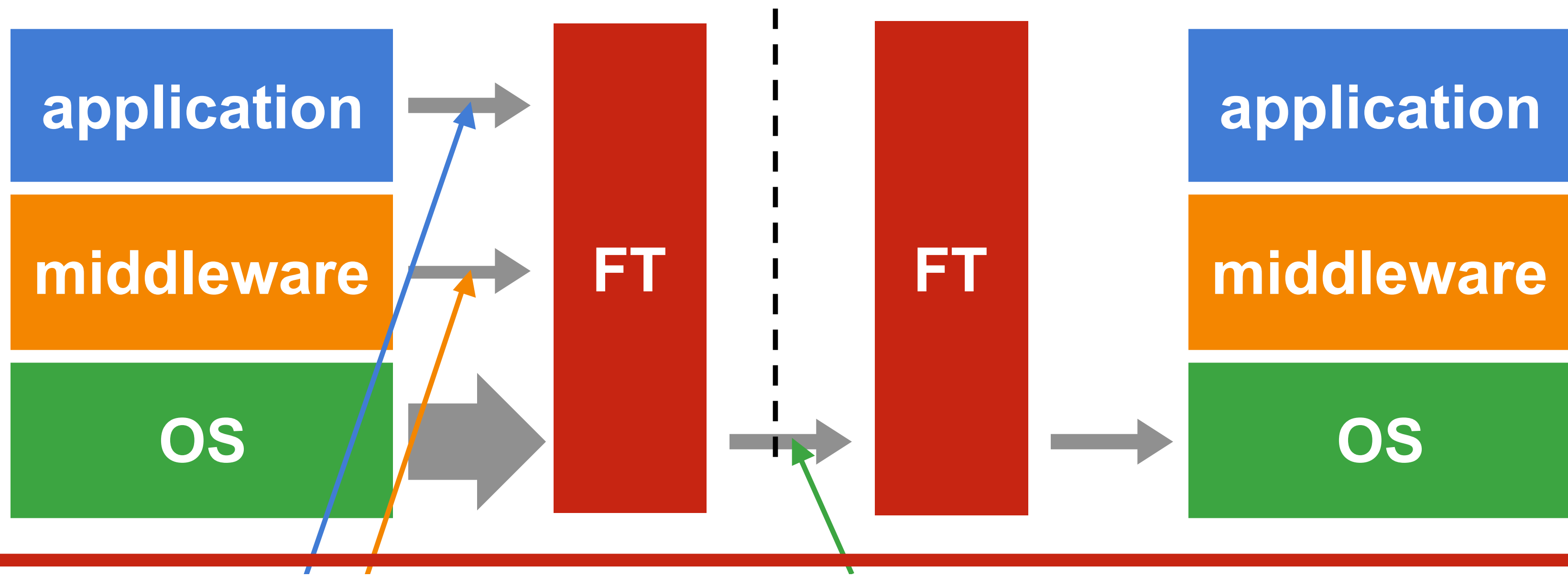


up to **203** synch. operations per request in middleware (ORBacus) [TAO: **52**, omniORB: **64**]

Replication of ***every*** non-deterministic decision
☞ highly **inefficient**

Smart Multi-Level Reflection

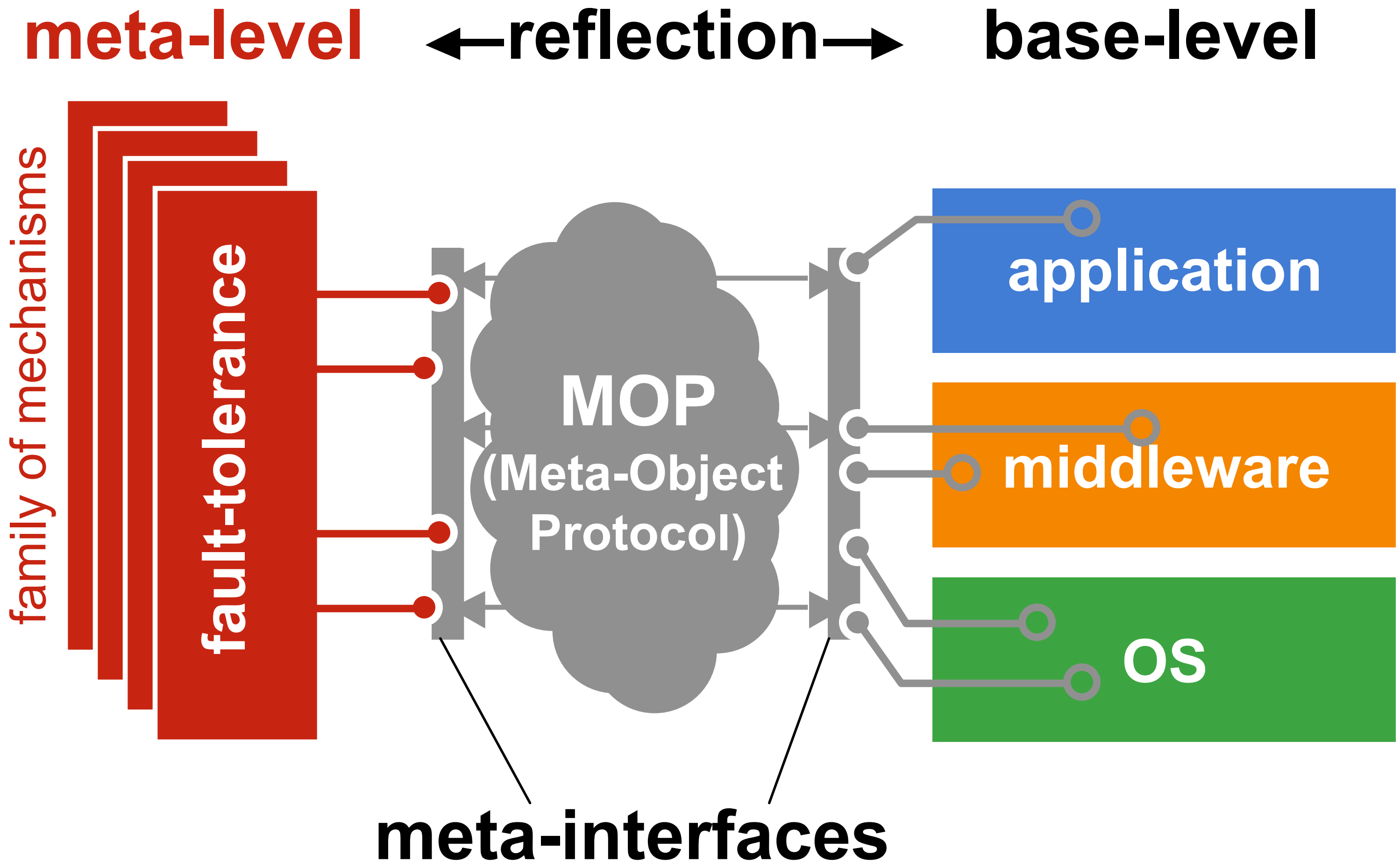
- With middleware and application semantics:
  - ➔ OS-level actions can be given a **higher level semantic**.
  - ➔ This semantic allows optimal use of OS level reflection.



Combining information obtained at **different levels** greatly **increases** the **efficiency** of **crosscutting** mechanisms.

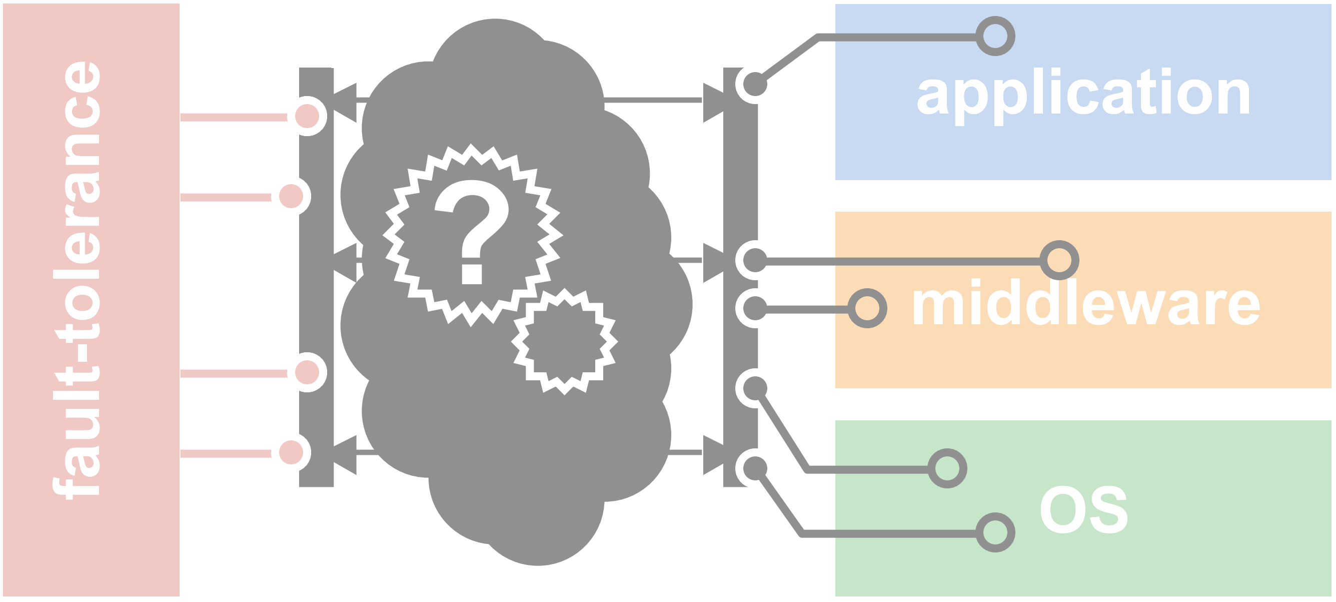
(Here: only 1.5% of MD synch. activity actually needs to be replicated.)

The Vision


meta-level
←reflection→
base-level
family of mechanisms
fault-tolerance
MOP
(Meta-Object
Protocol)
application
middleware
OS
meta-interfaces

The Problem

How to design & implement such a meta-object protocol?



Outline

- Motivating Example: Reflection and Replication
- A New Multi-Level MOP: Concepts & Design
- Practical Application: CORBA & Linux

Implementing Multi-Level Reflection

- **Goal**: To provide a multi-reflective framework for the fault-tolerance of complex, non-reflective industrial platforms
- **Challenges**:
  - **Requirements**: What kind of information is needed for fault tolerant mechanisms? Where should this information be found?
  - **Design**: How to design a multi-level meta-object protocol that supports multi-level reflection?
  - **Instrumentation**: How to instrument an industrial, non-reflective platform in a non-invasive, transparent way?

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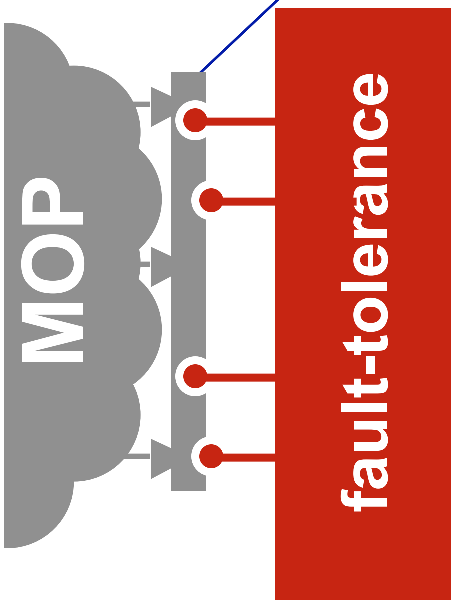
Requirements

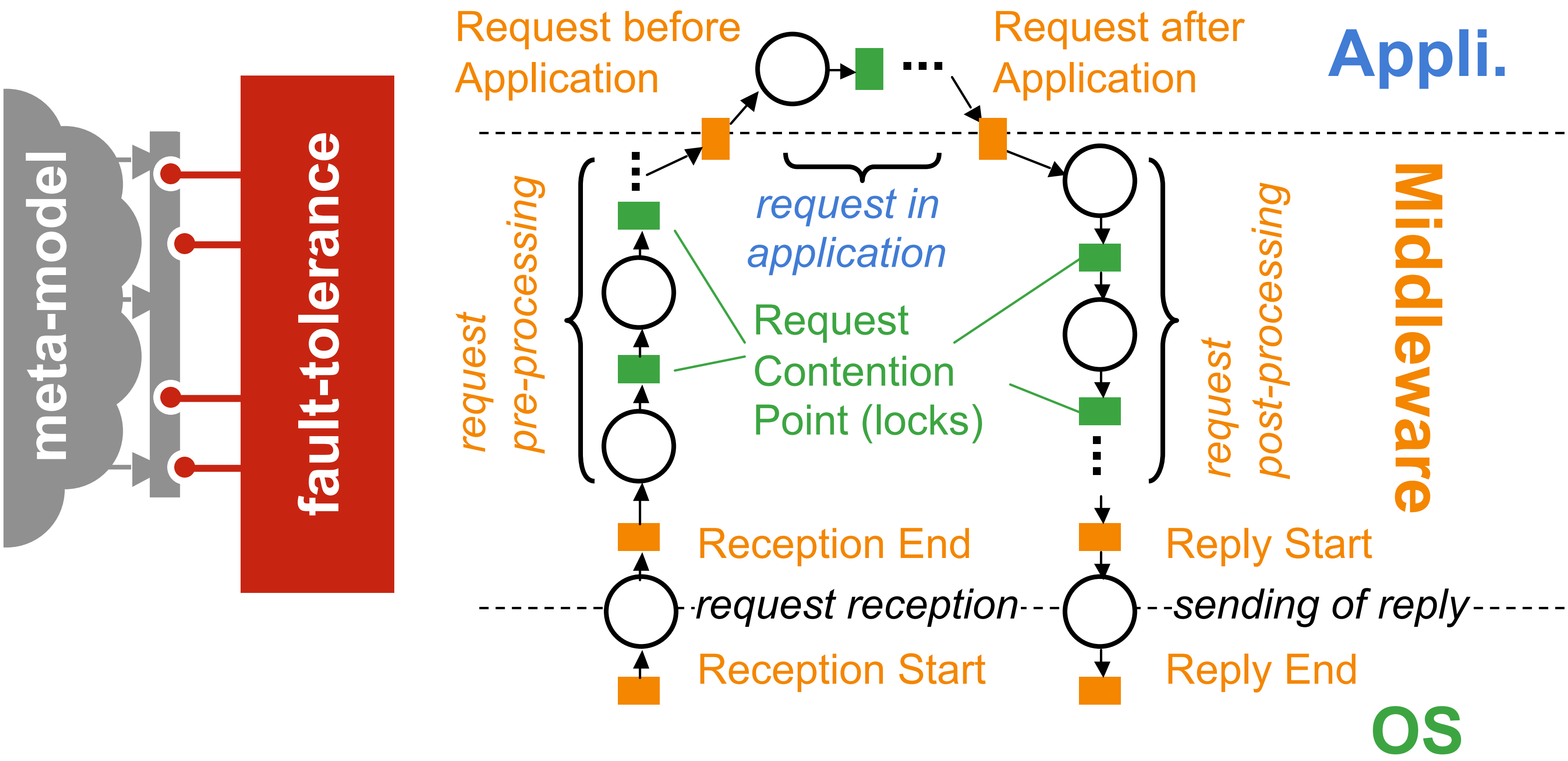
- Meta-interface for non-determinism [DSN-2003]




```
interface MetaRequestLifecycle {
   /** Communication **/
   requestHasBeenReceived (RequestID);
   replyHasBeenSent       (RequestID);
   /** Control Path **/
   requestBeforeApplication  (RequestID);
   requestAfterApplication   (RequestID);
   /** Synchronisation **/
   requestBeforeContentionPoint
     (RequestID, RequestContentionPoint);
   requestAfterContentionPoint
     (RequestID, RequestContentionPoint);
};
```

Requirements

- Multi-level nature of the meta-interface



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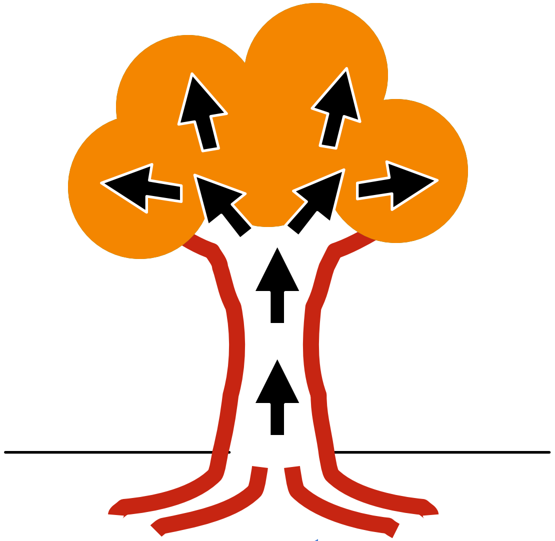
Semantics and Architecture

- **Motivating Example**: middleware non-determinism
  - ➔ **request contention points** (mutex operations) must be **intercepted** at OS level
  - ➔ but **not** all mutex operations (otherwise highly inefficient)
  - ➔ **question**: How to **distinguish** between mutexes that are relevant and those that are not?
- **Proposal**: use of semantic context
  - ➔ We need to understand the **purpose** of OS level mutex operations in the more general context of the whole system activity

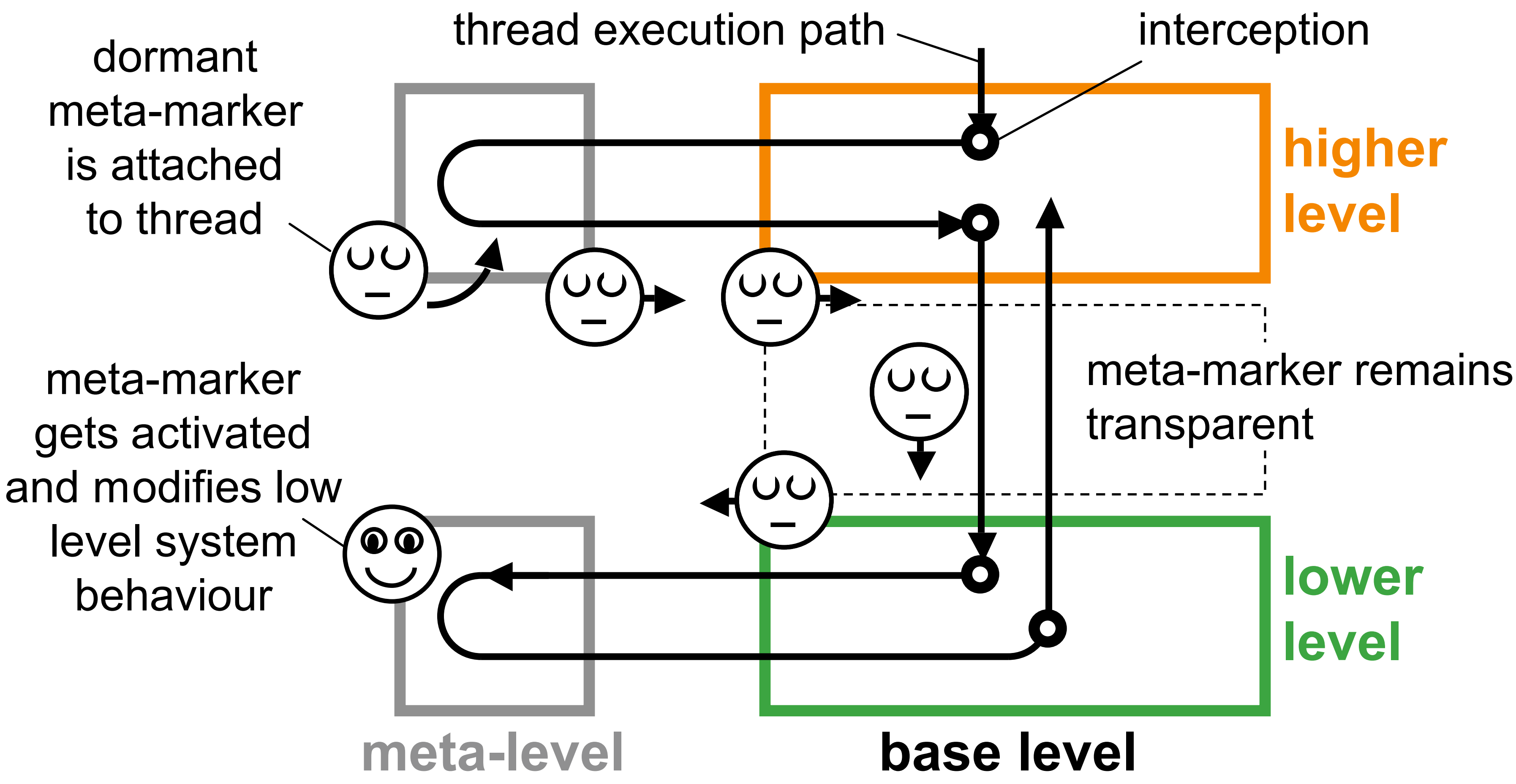
➔Approach: to **trace** the computation process that results in a low level OS operation being called

Meta-markers

- To **trace** semantic contexts, a mechanism is needed to **transport** information between different abstraction levels (software layers)
- A mechanism encountered in **plants**: in periods of droughts the root system communicates with the foliage using dedicated chemical substances call **phytohormones**
- Phytohormones travel through the sap
- Design based on this metaphore.
  - ➔ Sap = **threads**
  - ➔ Phytohormones = **metamarkers**



Inter-Level Communication with Meta-Markers



Using Meta-Markers for MOP Design

- Meta-markers can be used to design a multi-level MOP
- Example: synchronisation facet for middleware determinism

```
interface MetaRequestLifecycle {
  ...
  /** Synchronisation **/
  requestBeforeContentionPoint
    (RequestID, RequestContentionPoint);
  requestAfterContentionPoint
    (RequestID, RequestContentionPoint);
};
```

- Two issues to be solved by meta-markers:
  - ➔ **P1**: the global semantic context of mutex creation must be captured by meta-markers
  - ➔ **P2**: meta-markers must insure a correct instrumentation of the selected mutexes

Capturing Semantics

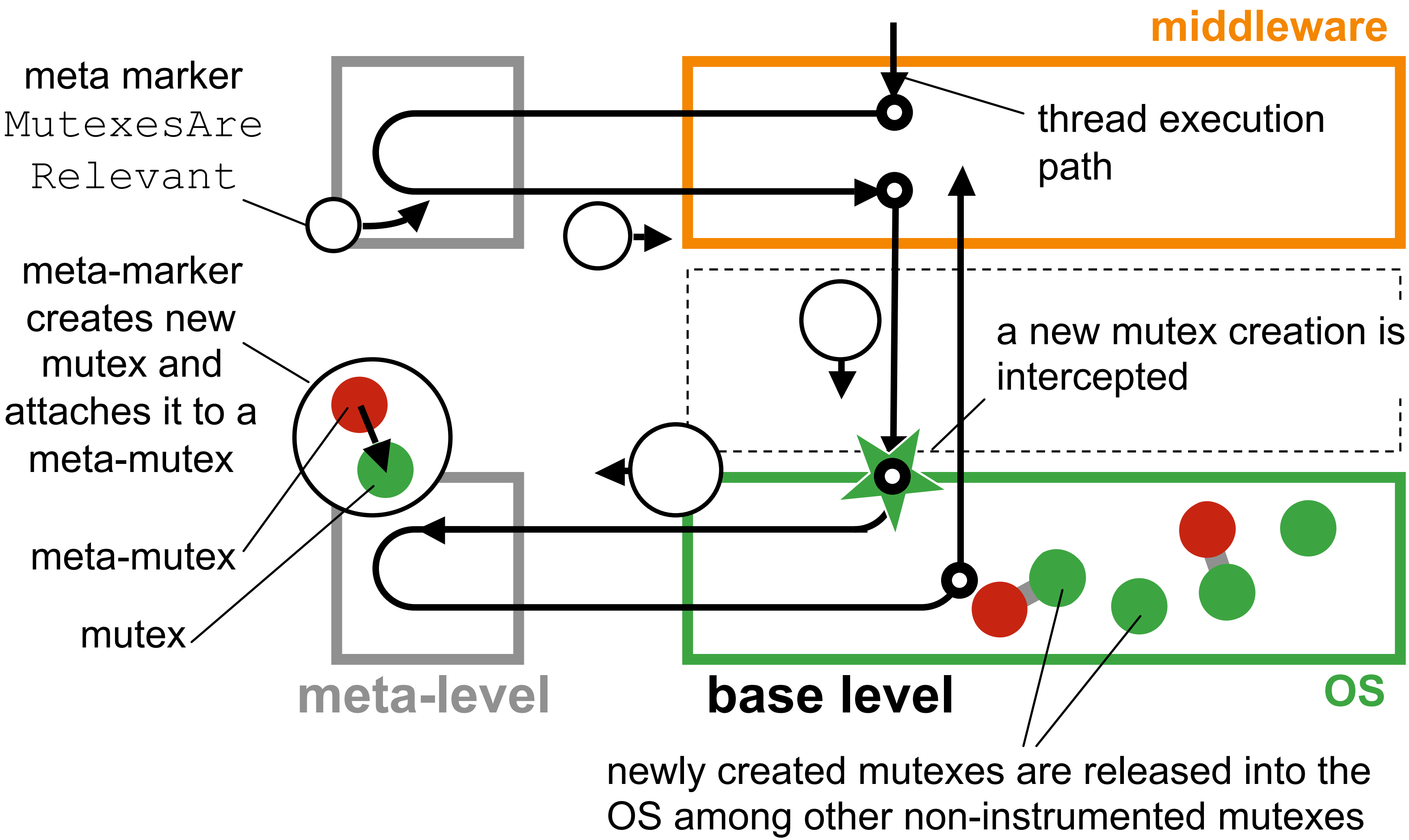
- Problem P1 is solved by source code annotation of semantic joint points:

```
init_and_run_middleware(..) {
  MutexesAreRelevant metaMarker() ;

  metaMarker.attachToThread() ;
  init_request_queue(..) ;
  metaMarker.detachFromThread() ;

  init_some_refcount_object(..) ;
  ...
  run_ORB();
}
```

Meta-Markers as Meta-Mutex Factories



Back to the Meta-Interface

```
interface MetaRequestLifecycle {
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  /** Control Path **/
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  /** Synchronisation **/
  requestBeforeContentionPoint
    (RequestID, RequestContentionPoint);
  requestAfterContentionPoint
    (RequestID, RequestContentionPoint);
};
```

meta-markers to instrument appropriate sockets

meta-markers to transport request IDs

meta-markers to instrument appropriate mutexes

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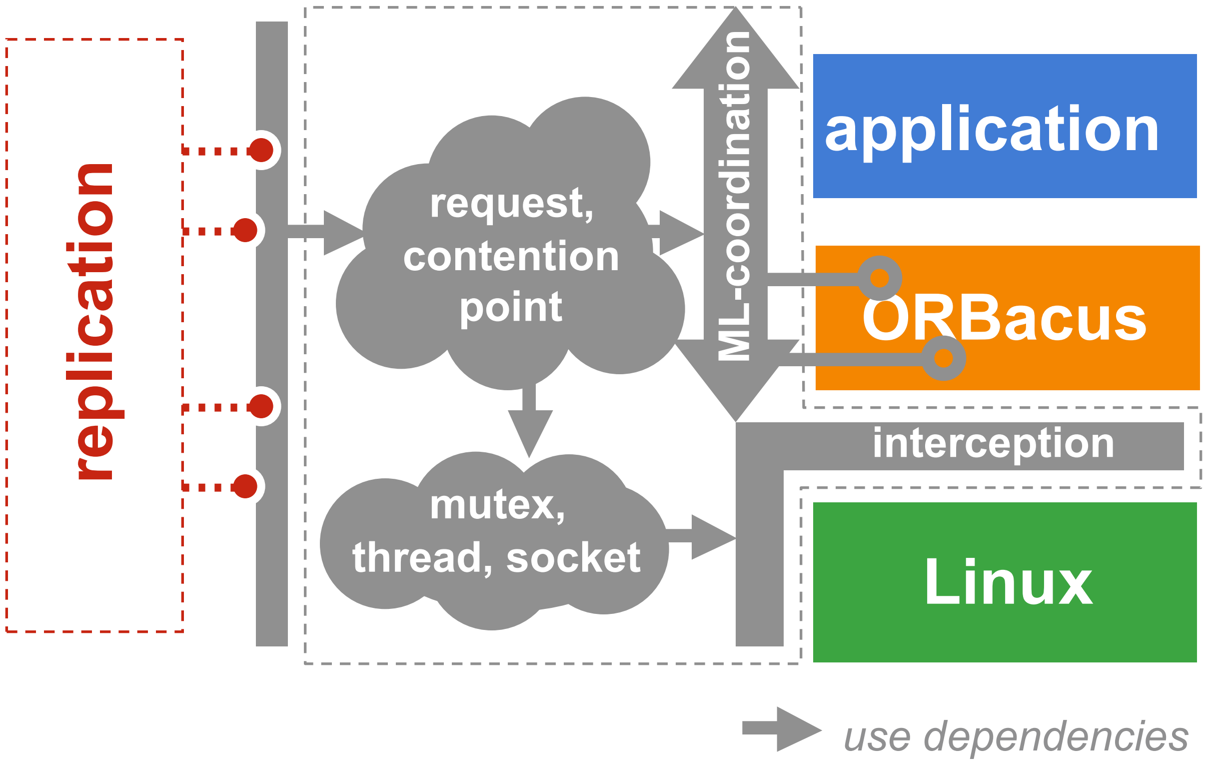
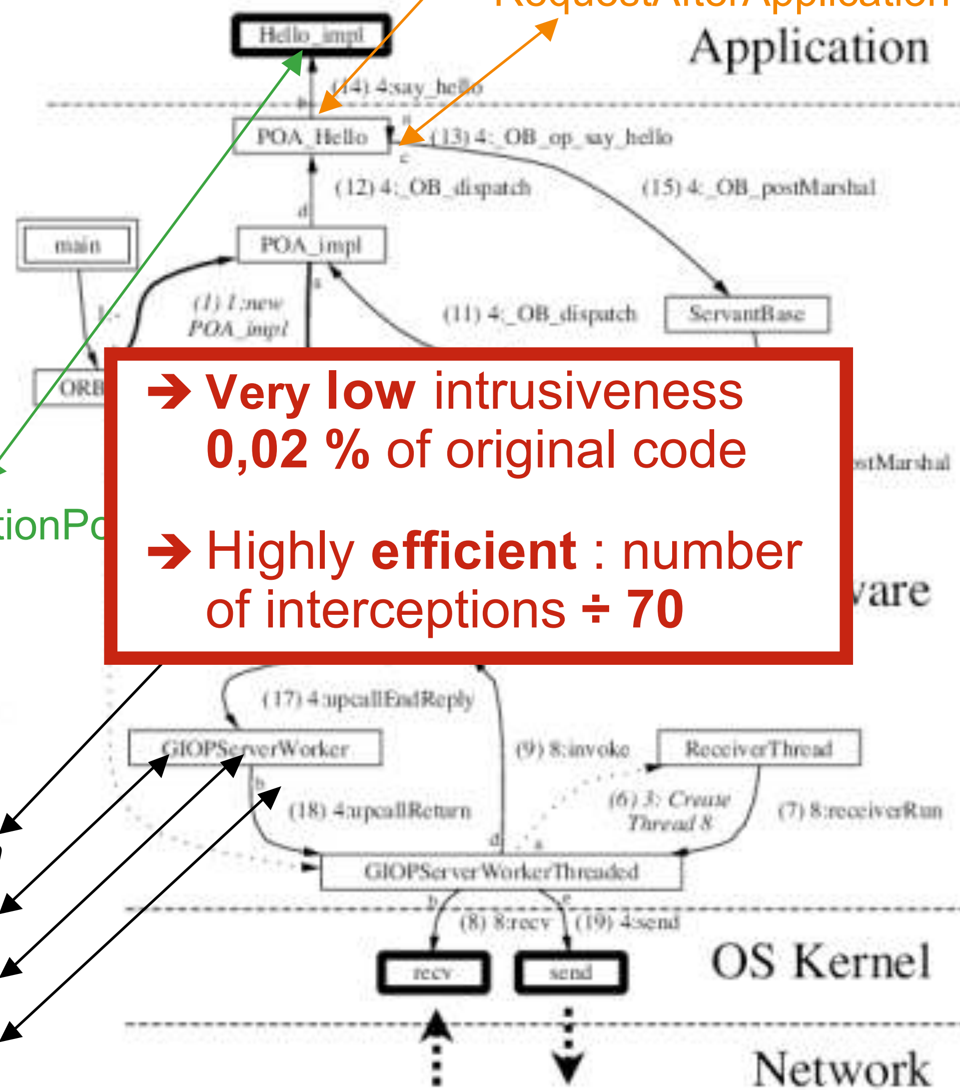
Implementation

- **Multilevel interception framework** to control non-determinism; *8000 LoC C++; based on CORBA and POSIX only; platform independent.*



Case Study: Orbacus

- Behavioural analysis: a reverse engineering tool dedicated to complex multi-layer systems
- This analysis indicates **where to annotate the source code**
- Instrumentation of **ORBacus**
  35 lines added
  ➔ 0,02 % of original code!
  (> 100 000 LoC)



➔ **Very low** intrusiveness
0,02 % of original code

➔ Highly **efficient** : number of interceptions **÷ 70**

Conclusion

- **Tension** between comprehensive and adaptable fault-tolerance, and the multi-component and multi-layered nature of modern complex software systems.
- Our proposal to solve this conflict :
  Multi-Level Reflection :
  - ➔ Combines reflective capabilities found in lower and higher levels in a global system overview.
- MLR supported by a **multi-level MOP** based on:
  - ➔ semantic contexts
  - ➔ meta-markers
- Outlook: **Aspect Orientation**
  - ➔ Deep Aspects
  - ➔ Make aspects aware of software "thickness"

Any Questions?

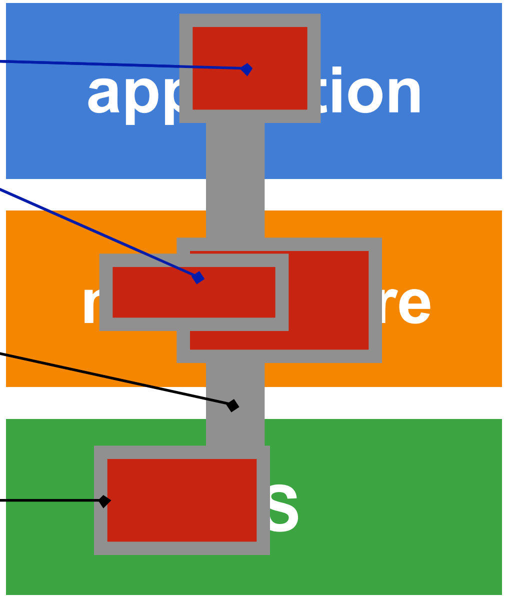
Motivation

- Increasingly complex Computer systems (COTS / Layers) are used for increasingly critical applications.
- Most COTS have ***not*** been built with dependability in mind.
- Dependability is a system-wide multi-level issue.

fault-tolerance "patches"

ad-hoc inter-level coordination

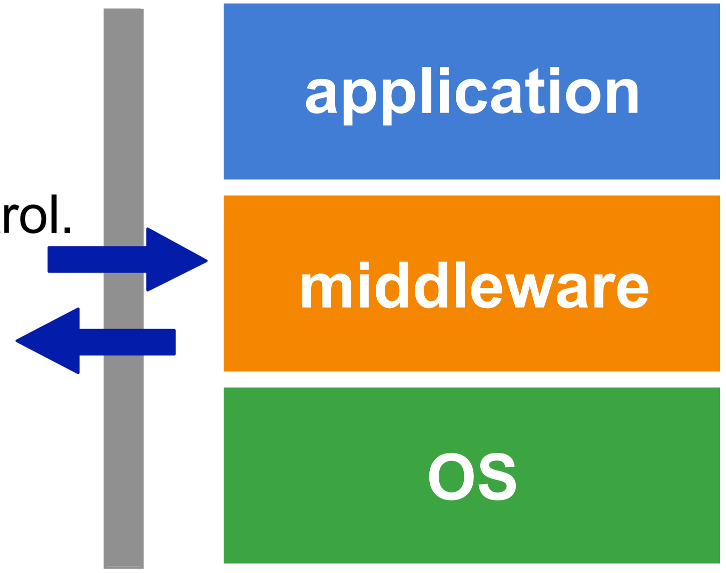
ad-hoc connection original code ↔ FT patches



⇨ How to add **fault-tolerance** to **complex multi-layered software systems** in a **transparent** and **disciplined** way?

Rationale behind Multi-Level Reflection

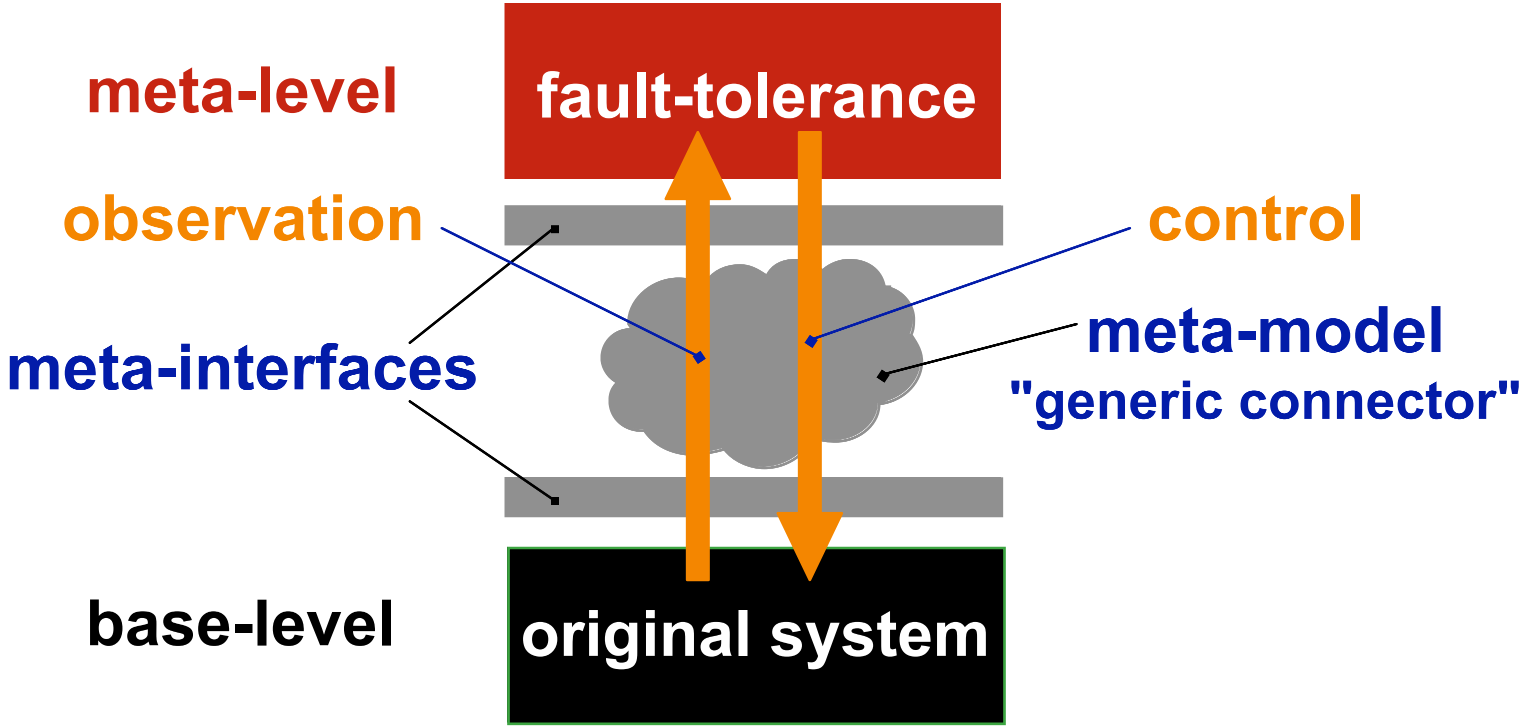
- Complex systems contain heterogeneous abstraction levels.
  ⇨ Available (meta)-information is heterogeneous .
- Higher levels :
  - ☺ Rich semantics
  - ☹ But they lack information / control.
- Lower levels :
  - ☺ Complete Information / control.
  - ☹ But lacking semantics



- **Complementary** roles : **lower level information & control** needs to be enriched with **higher level semantics**

What is Reflection?

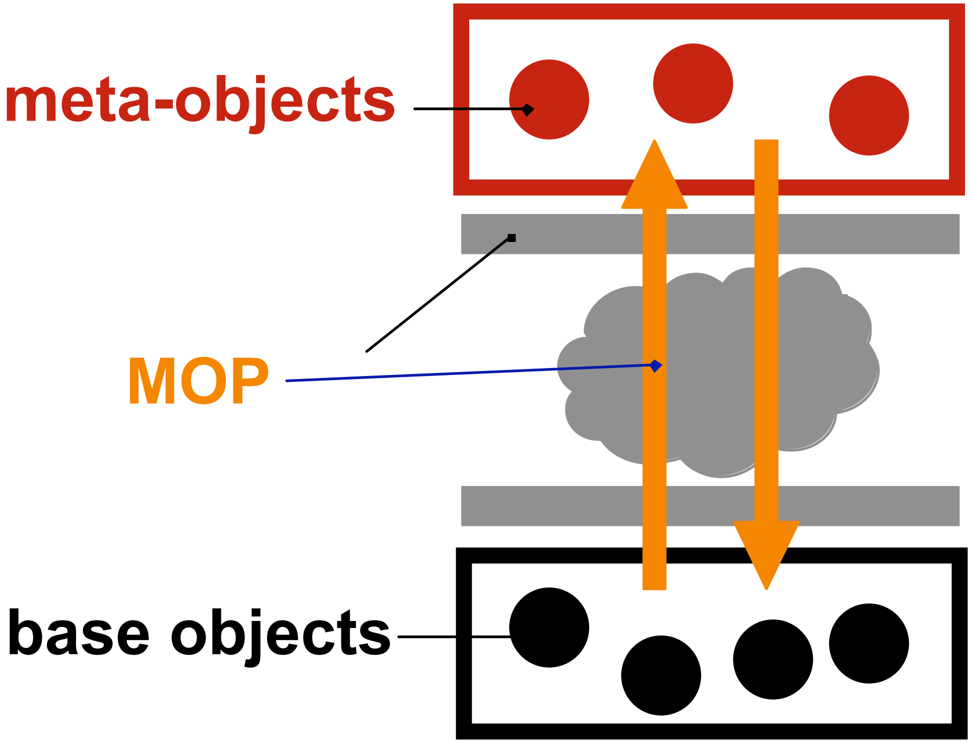
"the ability of a system to think and act about itself"



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

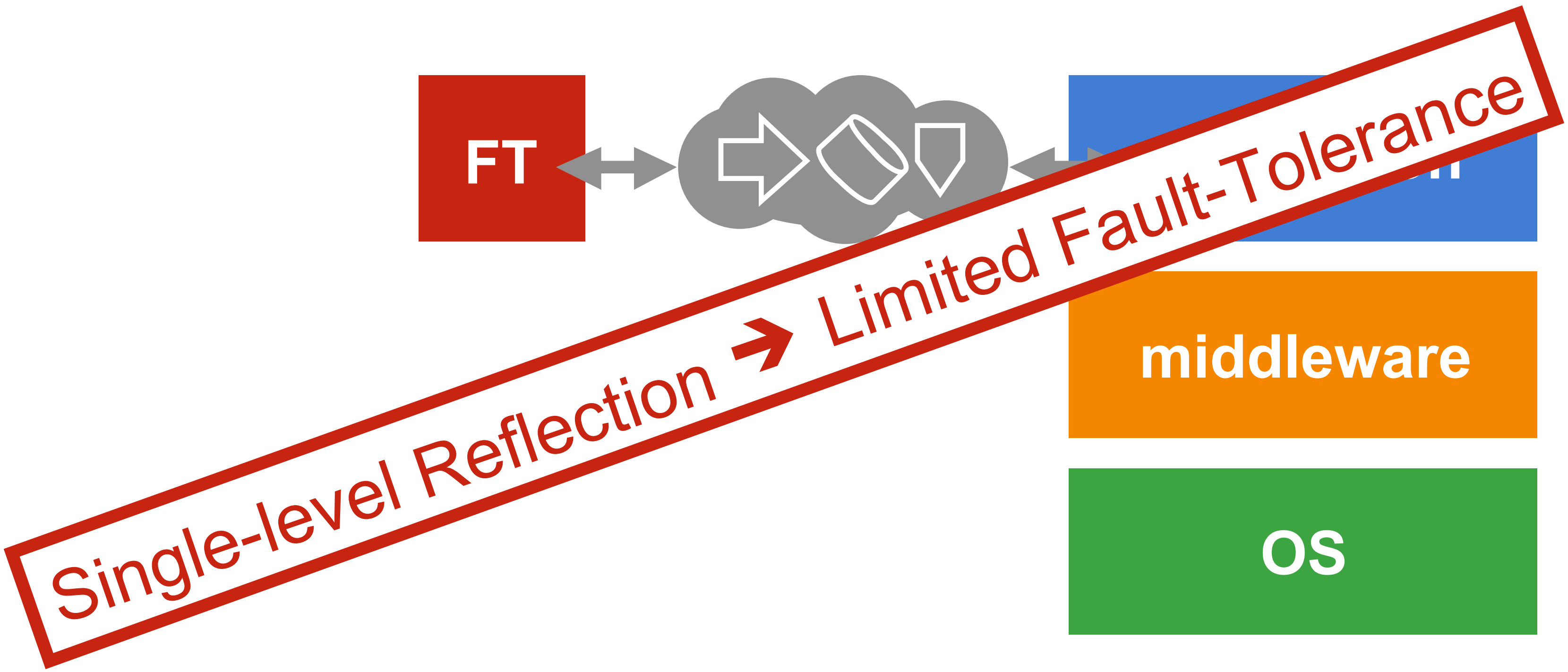
What are Meta-Object Protocols?

A particular way of organising a reflective system



Reflection & Fault Tolerance

- Reflection has been used to add FT to complex systems but:
  - ➔ Only one level of abstraction at a time considered so far.



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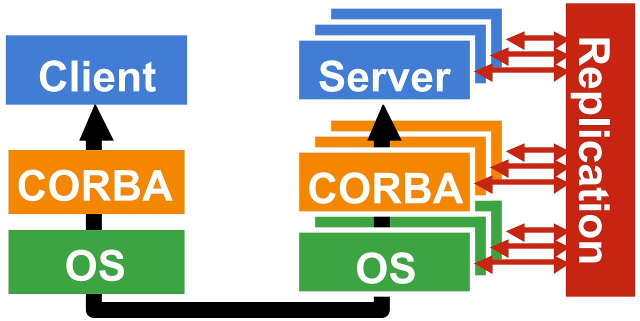
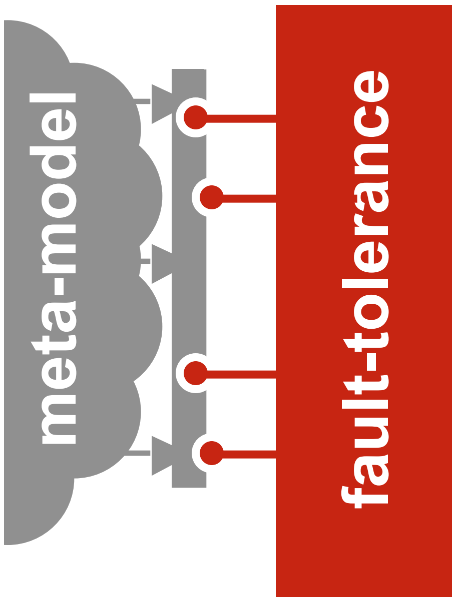
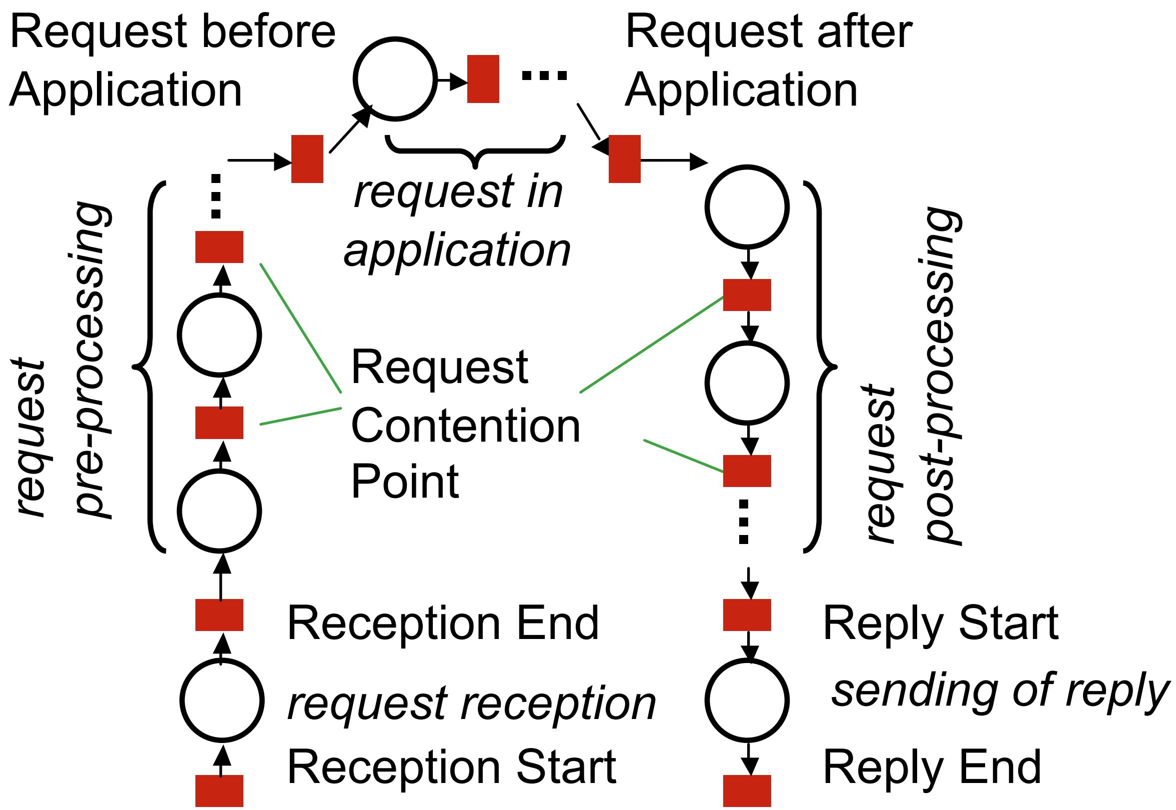


Requirements

- Example: CORBA Middleware Determinism



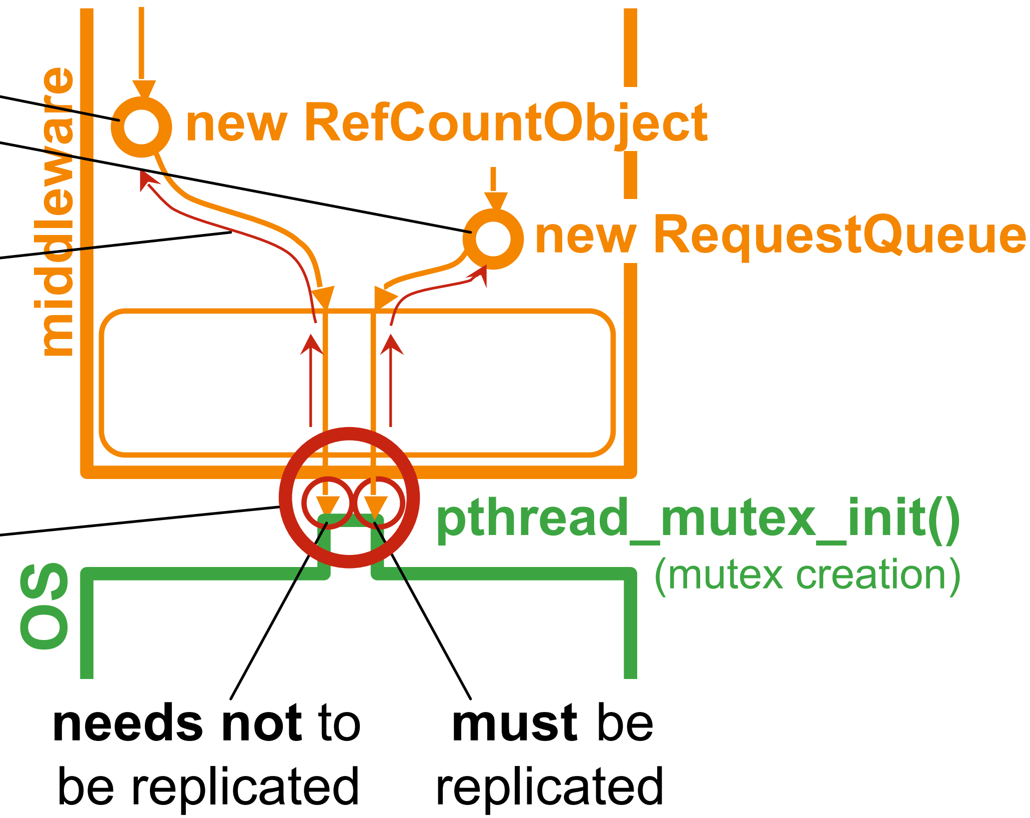


Semantic Joint Points

"Semantic joint points": source code location where global purpose becomes apparent

The global purpose becomes apparent when backtracking the computation process that causes the low level calls

Two low level calls with different semantics



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